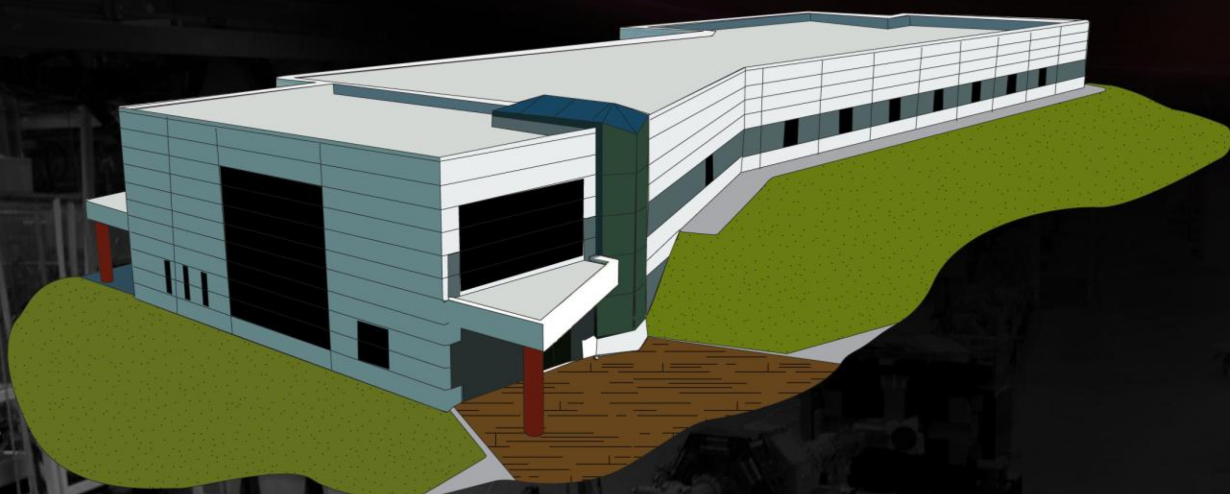
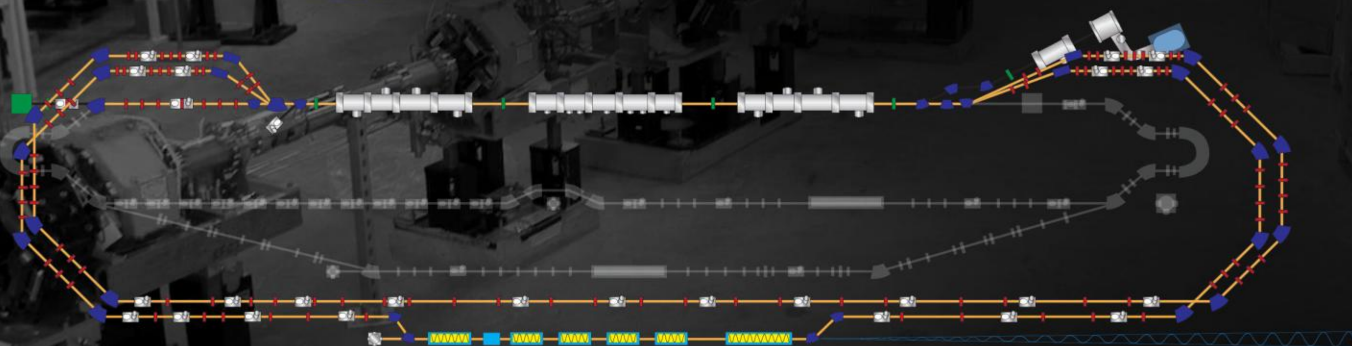
Jefferson Lab

The JLAMP VUV/Soft X-ray User Facility

A Proposal by Thomas Jefferson National Accelerator Facility submitted to the U.S. Department of Energy, Office of Basic Energy Sciences





JSA

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Executive Summary

Jefferson Lab (JLab) is proposing JLAMP (JLab AMPlifier), a 4^{th} generation light source covering the range 10–100 eV in the fundamental mode with harmonics stretching towards the oxygen k-edge. The scientific purpose is to study ultrafast dynamics in complex systems as a pathway to the understanding and creation of novel materials and devices, with a twin focus on changing our approach to the use of energy and on improving our stewardship of the environment. Expert groups of physicists and chemists have identified the game-changing science offered by such a light source. The machine will be based on an energy upgrade to an existing energy-recovering linear accelerator at JLab, made possible by advances in superconducting accelerator technology. Specifically, accelerating gradients of 20 MV/m and electron-beam recirculation will allow electron-beam energies of >600 MeV to be achieved at repetition rates up to 4.68 MHz with continuous wave RF. The average brightness will substantially exceed existing light sources in this device's wavelength range of 100 nm down to 10 nm, extended by harmonics towards 2 nm. Multiple photon sources will be made available for pump-probe dynamical studies. Due to the many advantages conferred by JLab's existing infrastructure, such a facility can be established for $96M, including overhead and escalation and contingency, and achieve first light in FY15. To build JLAMP and operate it for users will be to advance substantially the science and technology of accelerators and light sources in ways that will enhance performance and reduce costs for future large projects.

Glossary

AFM	atomic force microscopy
AFRL	Air Force Research Laboratory
ANL	Argonne National Laboratory
ARC	Applied Research Center
ARPES	angle-resolved photoemission spectroscopy
ATTA	atom trap trace analysis
BBU	beam breakup
BCM	beam cavity monitor
BES	Basic Energy Sciences
BESAC	Basic Energy Sciences Advisory Committee
BNL	Brookhaven National Laboratory
BPM	beam position monitor
BLM	beam loss monitor
CASA	Center for Advanced Studies of Accelerators
CD-0	DOE approves mission need
CD-1	DOE approves expenditure of funds for preliminary design
CD-2	DOE approves performance baseline
CD-3	DOE approves start of construction
CDW	charge density wave
CEBAF	Continuous Electron Beam Accelerator Facility
COTR	coherent optical transition radiation
cryomodule	cryostat containing SRF accelerating cavities
CSR	coherent synchrotron radiation
CVD	chemical vapor deposit
cw	continuous wave
DIMAD	a charged-particle optics code used in accelerator design
DOE	U.S. Department of Energy
EBSD	electron backscatter diffraction
ELIC	electron-ion collider
ESCA	electron spectroscopy for chemical analysis
EEHG	echo enhanced harmonic generation
ELSA	Electron Stretcher and Accelerator (Bonn University)
EOS	equation of state
ERL	energy-recovering linac (energy-recovering linear accelerator)
ETC	estimate to complete
EUV	extreme ultraviolet (also XUV)
EXAFS	extended X-ray absorption fine structure
FEL	free-electron laser
FIB	focused ion beam
FIR	far infrared
FLASH	Free-electron Laser in Hamburg, Germany
FRIB	Facility for Rare Isotope Beams

FTIR	Fourier transform infrared (spectrometer)
FWHM	full width half maximum
GIXD	grazing-incidence x-ray diffraction
GLS	generation light source (as in 4th generation light source)
GTS	gun test stand
HGHG	high-gain harmonic generation
HHG	high harmonic generation
HOM	higher order mode
ID	insertion device (an electron beam viewer or other diagnostic)
INP	Innovative Naval Prototype
IR	infrared
ISR	incoherent synchrotron radiation
IXS	inelastic x-ray scattering
JAEA	Japan Atomic Energy Agency
JLab	Jefferson Lab
JEOL	a maker of special instruments
KEK	Japan's High Energy Accelerator Research Organization
LBNL	Lawrence Berkeley National Laboratory
LCLS	Linac Coherent Light Source
LEED	low-energy electron diffraction
LEUTL	a SASE experiment (now decommissioned) at Argonne National Laboratory
LHe	liquid helium
linac	linear accelerator
LIPSS	light pseudoscalar or scalar search
LSC	linear space charge
MBI	multibunch instabilities
NC	normal conducting
NEXAFS	near-edge x-ray absorption fine structure
NIF	National Ignition Facility
NRE	non-recoverable engineering
NSF-MRI	National Science Foundation - Major Research Instrumentation (Program)
NSLS	National Synchrotron Light Source
OPCPA	optical parametric chirped pulse amplification
OTR	optical transition radiation
OTS	optical transport system
PARMELA	a computer code in accelerator/beam physics
PED	project engineering and design
PEEM	photoemission electron microscopy
PES	photoemission spectroscopy

PRF	pulse repetition frequency
PSI	phase-shifting interferometric
P-T	pressure-temperature
QD	quantum dot
R&D	research and development
RF	radiofrequency
RHIC	Relativistic Heavy Ion Collider
RIXS	resonant inelastic x-ray scattering
rms	root mean square
SASE	self-amplified spontaneous emission
SAXS	small-angle x-ray scattering
SEM	scanning electron microscopy
SLAC	SLAC National Accelerator Laboratory
SNS	Spallation Neutron Source
SPES	scanning photoelectron spectromicroscopy
SPP	surface plasmon polariton
SRF	superconducting radiofrequency (accelerating technology)
STEM	scanning transmission electron microscopy
STFC	Science and Technology Facilities Council
STXM	scanning transmission x-ray microscopy
TEAM	transmission electron aberration-corrected microscopes
TEM	transmission electron microscope
THz	terahertz
ToF/SIMS	time of flight secondary ion mass spectrometer
UV	ultraviolet
VHF	very high frequency
VLSGM	variable line space grating monochromator
VUV	vacuum ultraviolet
WAXS	wide-angle x-ray scattering
WBS	work breakdown structure
WDM	warm dense matter
WiFEL	Wisconsin Free-Electron Laser
XANES	x-ray absorption near edge structure
XAS	x-ray absorption spectroscopy
XES	x-ray emission spectroscopy
XPCS	x-ray photon correlation spectroscopy
XPS	x-ray photoemission spectroscopy
XRD	x-ray diffraction
XUV	extreme ultraviolet (also EUV)

1. Background and Introduction

As identified in a number of DOE Basic Energy Science Advisory Committee (BESAC) position papers (summarized in "Directing Matter and Energy: Five Challenges for Science and the Imagination," listed in Appendix A) there is a strong need for advanced photon sources to support materials research. Jefferson Laboratory is uniquely positioned to meet those needs for VUV/soft x-ray photon sciences by virtue of large investments in its energy recovering linac (ERL)–based free-electron laser (FEL). The proposed facility—called JLAMP, for ***J**efferson **L**ab* ***AMP**lifier*—would immediately provide world-leading capability in a region not covered by lasers or existing light sources and provide complementary capabilities to other proposed or existing light sources in the USA as shown in Figure 1.1. Actual parameters for these sources are presented in Table 1.1.

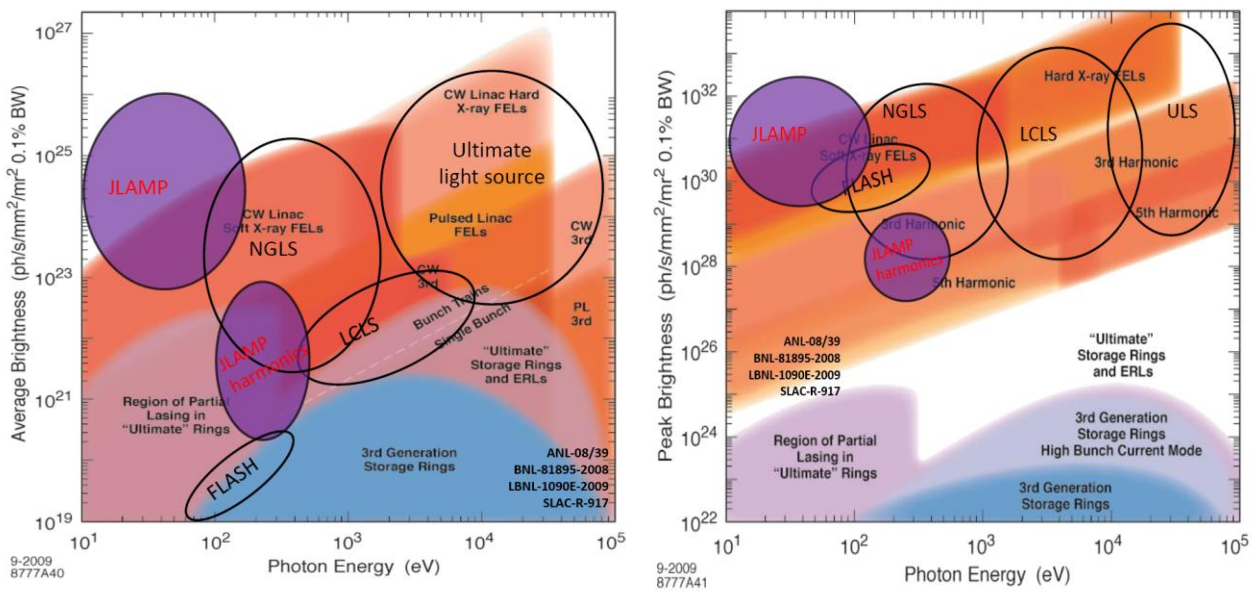


Figure 1.1. *Average and peak brightness landscape of new light sources. The Linac Coherent Light Source, LCLS, is operating at Stanford; FLASH is operating at DESY, Hamburg, Germany. The Next Generation Light Source is a soft x-ray source whose conceptual design was done by Lawrence Berkeley National Lab, and the ultimate light source is a high repetition rate hard x-ray source yet to be designed.*

The science drivers for these new light sources have been identified in several reports and white papers from national and international laboratories, and other scientific institutions (Appendix A). To further quantify this need, Jefferson Lab has held workshops to identify a number of key fundamental scientific challenges which could be addressed by JLAMP in both hard and soft matter, and in the atomic, molecular and optical arena. The working group reports are presented in Section 2. The central theme of these studies is ultrafast dynamics both in and out of equilibrium, studied primarily via electronic excitations.

JLAMP is achieved by taking advantage of an existing machine, and by upgrading in four ways to produce a 600 MeV beam with 200 pC per bunch at up to 4.68 MHz:

1) Replace the three superconducting linac “cryomodules” with a new design of higher gradient
2) Add two new bends
3) Add a low-emittance (1 micron) gun
4) Add two undulators, one for VUV/soft x rays and one for terahertz, plus the associated photon beamlines and a new lab attached to the existing building.

The configuration is illustrated in Figure 1.2. This achieves the required electron beam energy to 600 MeV in two passes of acceleration. At 600 MeV the electron beam traverses an undulator designed to produce light in the 10–100 eV range in the fundamental, with useful 3rd and 5th harmonics up to 540 eV, and then traverses a THz wiggler to produce synchronized pulses. The beam then makes two recirculations for energy recovery before being dumped at its injection energy, which is less than 10 MeV.

Light will be generated initially by amplifying a seed laser, but the 4.68 MHz maximum rep rate allows additional experiments to explore self-seeding. For such experiments the high gain of the undulator allows tests of an oscillator, since with gains of 1000 or more one can easily tolerate mirror reflectivities of 20% or less in normal incidence with relaxed figure tolerances, and which are available commercially in the soft x-ray region. Out-coupling of the fundamental and higher harmonics would be by means of a hole.

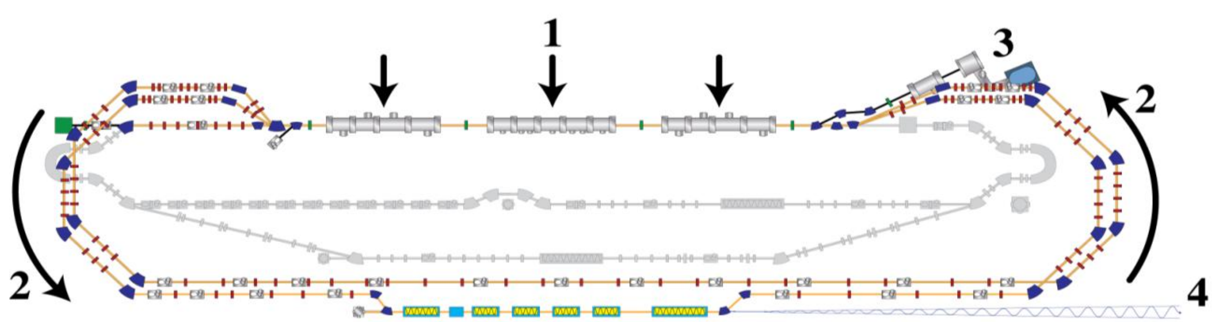


Figure 1.2. *Illustration of the four modifications to the JLab FEL to make JLAMP: 1) replace three cryomodules; 2) add two recirculation beamlines; 3) upgrade the present injector; and 4) provide soft x-ray and THz undulators for light production. (Lattice is schematic, not real design.)*

To accomplish our goal, Jefferson Lab has initiated collaborations with Lawrence Berkeley and Brookhaven National Laboratories, each of which has considerable experience in photon and user programs. Specifically, JLab will collaborate with LBNL to enable Step 3, the normal conducting low emittance RF gun and laser technology, and with BNL to enable Step 4, the beamlines, experimental facilities, and the first user programs.

A prototype of a VHF gun is under development at LBNL and we plan to integrate a gun of the same design into JLAMP so that it could be both utilized and evaluated as a high gradient, high repetition rate injector in comparison to our own high brightness DC gun which also has potential to meet the requirements. BNL has a long history in the development of optical beamlines, and have further enhanced their capability for NSLS-II. JLab will also collaborate scientifically with LBNL and BNL partners, both having strong photon science programs in this photon energy range.

The wavelength progression in average brightness of the JLab FEL from the JLab UV FEL and VUV harmonics to JLAMP performance and harmonics in the XUV/soft x-ray region is shown in Figure 1.3. For comparison we show the average brightness of generic 2nd and 3rd generation light sources and several 4th generation sources. The blue curve is the physical limit for 1 nC bunches at 100 MHz and 3 GeV. JLAMP would operate some 5000 hours per year as a facility both for photon science and for R&D for the next generation of light sources, addressing identified goals of BES in both areas.

For science JLab is proposing two experimental capabilities for initial integration. One focuses on techniques for studying charge, lattice and spin dynamics in complex systems, namely ultrafast angle-resolved photoemission spectroscopy of coherently controlled complex materials, both in and out of equilibrium. The other focuses on atomic, molecular and optical studies of excited gas-phase dynamics. Both are areas of strong interest in meeting the BES-identified needs for "New Science for a Secure and Sustainable Energy Future" [http://www.sc.doe.gov/bes/reports/list. html].

While the science drivers for this light source justify its need, there are a number of additional benefits of this program. Building and operating such a facility would allow JLab to address many of the scientific and technological challenges facing any of the new generation of light sources. These challenges have been identified in a recent (Sept. 2009) workshop sponsored by BES. It is anticipated that these new sources will be based on *cw* SRF, will have electron beam emittances which yield photon beams close to coherent limits, will have pulse lengths of <50 fs, and will be capable of pulse repetition frequencies in the MHz range.

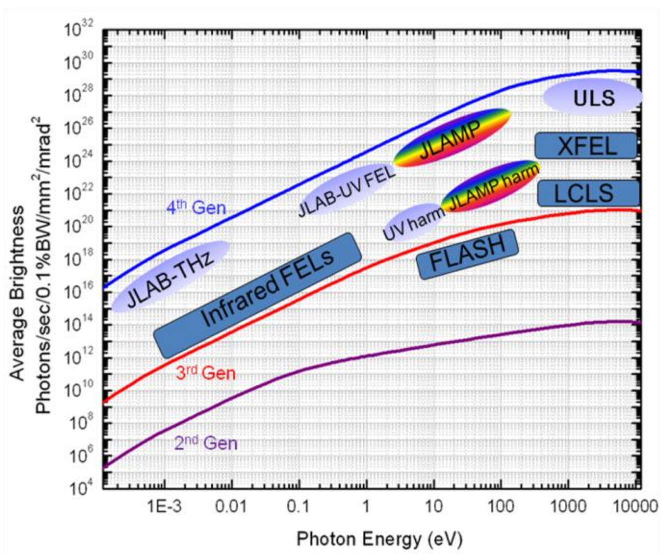


Figure 1.3. *The wavelength progression in average brightness of the JLab FEL from the JLab –UV FEL and VUV harmonics to JLAMP performance and harmonics in the XUV/soft x-ray region. For comparison we show the average brightness of generic 2nd and 3rd generation light sources and several 4th generation sources. The blue curve is the physical limit for 1 nC bunches at 100 MHz and 3 GeV.*

Accelerator technology presently does not enable full achievement of the required goals of hard x-ray 4th generation sources either technically or at a potentially reasonable cost. However, the advances required are within the reach of a modest research program as described recently in reports from a BES-sponsored workshop. JLAMP will permit the study of the required SRF advances and approaches for cost reduction without the costly and time-consuming development of a new specialized facility, as would be required elsewhere. There will also be important validation of designs and simulation codes relating to the initial generation of electrons in *cw* injectors and subsequent transport of such high brightness electron beams through bends and chicanes as well as validation of their capabilities in amplification of seed lasers.

The output of this technology development would be the knowledge required to build and operate a 4th generation x-ray user facility based on the then-proven advanced linac developments not only at JLab but at the other 3rd and soon-to-be 4th generation light source facilities around the world.

	Wavelength (nm)	Photon Energy (keV)	Pulse Duration (FWHM) (fs)	FEL Beamline repetition rate (Hz)	Peak Brightness	Average Brightness (CW)	Average Brightness (bunch trains)	Photons per pulse coherent	Bandwidth
NGLS	1–10	1.2–0.12	0.3–500	10^5+	10^{30}–10^{32}	10^{19}–10^{25}		10^9–10^{13}	10^{-2}–10^{-6}
*LCLS**	*0.15*	*8.2*	*80*	*120*	2x10^{33}	*2x10^{22}*	10^{24}	2x10^{12}	2x10^{-3}
	1.5	*0.82*	*240*	*120*	3x10^{31}	*8x10^{20}*	5x10^{22}	2x10^{13}	4x10^{-3}
JLAMP	**10 -1 00**	**0.1 – 0.01**	**50-100**	**4.7x10^6**	**10^{30}–10^{32}**	**10^{23}–10^{26}**	**10^{23}–10^{26}**	**6x10^{12}**	**10^{-3}–10^{-4}**
FLASH	*6.8*	*0.18*	*10–50*	*5*	*10^{29}–10^{30}*	10^{16}–10^{17}	*3x10^{19}*	2x10^{12}	10^{-2}
	47	*0.026*	*10–50*	*5*	*10^{29}–10^{30}*	10^{16}–10^{17}	*3x10^{19}*	2x10^{12}	10^{-2}
XFEL	0.1–6.3	12.4–0.2	100	10	10^{31}–10^{33}	10^{20}–10^{21}	10^{23}–10^{25}	10^{12}–10^{14}	~10^{-3}
SPring8 XFEL	0.1	12.4	50	60	10^{33}			10^{11}	~10^{-3}
FERMI @elettra	3–10	0.41–0.12	~40	50	10^{32}	10^{20}		10^{11}–10^{12}	~10^{-4}
NLS	1.24–2.5	1–0.5	20	1000	10^{32}	10^{21}		10^{11}–10^{12}	~10^{-4}
SwissFEL	0.1–7	12–0.17	0.6–28	100	10^{31}–10^{33}	10^{20}–10^{21}		10^{11}–10^{13}	10^{-3}–10^{-4}

Items in blue are estimates not from official project sources *Items in italic font are measured on operational facilities* ** parameters still evolving*

Table 1.1. *Parameters for proposed and existing new light sources.*

2. Scientific Case

JLAMP is motivated by the science that it enables, and indeed its parameters were chosen by potential users. In this section we present highlights of the scientific case for such a machine, which was developed by two working groups, one in condensed matter physics, the other in chemical/atomic, molecular and optical physics. In addition, another group identified opportunities in imaging. The chairs and participants are listed at the beginning of this document. JLab has made only minor edits to these reports, which are presented below.

Each group was charged with identifying both the key science and key machine parameters required within the constraint that the photon energy range of the fundamental will be from 10–100 eV. And while JLAMP may be competitive initially in the 100's of eV range using harmonics, dedicated sources at higher energy will ultimately be the ones of choice for this range. We have chosen to include the science described in 2.1.1, 2.1.2 and 2.2.2 for initial funding as part of the proposal, but we note that the provision of the photon transport systems means that additional experiments such as 2.2.3 would typically require only end stations.

2.1 Condensed Matter Physics – Andrea Cavalleri (Chair)

Overview: There is a strong scientific impact for a source based on the base design of the JLAMP facility. Key contributions to condensed matter research would arise from time-resolved and nonlinear photoemission spectroscopy and inelastic or coherent soft x-ray scattering experiments. The following recommendations are made.

- The source should be seeded, to shape temporal and spectral characteristics and to provide synchronization to external lasers. Seeding would open many new possibilities if, depending on the problem at hand, one could run JLAMP either with trains of ultrashort pulses and correspondingly broader bandwidths or longer pulses and ultra-narrow linewidths.
- JLAMP should also have a THz-IR undulator, in order to produce pulses of relatively narrow bandwidth that could be used to stimulate matter in a selected way. To achieve sufficient selectivity, the undulator should have at least 10 poles (10% BW). The generation of only broadband radiation from a single dipole does not provide sufficient spectral selectivity for many interesting experiments.
- Lasing in the base design should extend to 110 eV at the 1st harmonic of the source, thus allowing the oxygen K edge to be reached in the 5th harmonic. The group also strongly recommends, either in the base design or through an upgrade path, to extend the 1st harmonic to 180 eV, which would reach the oxygen K edge in the 3rd harmonic, and all the transition metal L edges in the 5th harmonic.

Three areas of fundamental research were identified:

2.1.1 Ultrafast Photoemission Spectroscopy of Coherently Controlled Complex Materials

Ultrafast x-ray science is an important emerging field of research, which aims at studying the structural and electronic evolution of matter at the fundamental time scale of a vibrational period, ≈100 fs. This is the relevant time scale for atomic structural changes that govern the formation and breaking of bonds and crystallographic symmetry changes during structural phase transitions. Recently, ultrafast dynamics of strongly correlated electron systems [1,2] have been examined with ultrafast x-rays [3,4] and with ultrafast photoemission probes in the ultraviolet [5,6]. Especially promising in time resolved experiments is the ability to excite the system coherently and to stimulate a subset of the degrees of freedom selectively. If the source is intense enough, it is also possible to probe collective excitations based on, say, the nonlinear response of the medium; ultrafast pulses allow this to be accomplished with a minimum of excitation density. Ultrafast time resolution provides a means for separating the coupled interactions in complex materials [7] or coherent vibrational excitation [8,9]. This is in contrast to what is achieved in static measurements, where temperature, doping, and pressure are tuned, affecting equally all excitations in the solid.

Angle Resolved Photoemission Spectroscopy (ARPES) is one of the most important techniques to study charge, lattice and spins in complex correlated electron systems [10]. In ARPES experiments, electrons with binding energies near the Fermi level are emitted by ultraviolet radiation and measured as a function of energy and angle. With energy resolutions of a few meV, and momentum resolutions of better than 1% of a typical Brillouin zone size, the band structure and momentum anisotropy of the microscopic, many-body interactions can be revealed [11].

An example of a time-resolved ARPES experiment is shown in Figure 2.1, demonstrating the transient population and time evolution of the electronic structure in the charge density wave system $TbTe_3$.

Time-resolved ARPES is, so far, limited to laser-based experiments in the laboratory, which are at low photon energies (typically 6 to 7 eV). In some early cases, laser-based high-harmonic sources have been used; however, the discrete tunability of these sources has limited their wider use. Consequently, access to the Brillouin zone is limited and matrix element effects make it difficult to detect important aspects of the physics.

The JLAMP light source would provide unique new possibilities.

- The high-repetition-rate JLAMP FEL would allow for high average flux in a narrow bandwidth, achieved through seeding without monochromators. This high flux, delivered in trains of short pulses, could be applied to static and dynamic experiments alike. Particularly promising is the application to high intensity photoemission experiments, such as spin resolved photoemission [12].
- A synchronized set of lasers, and a THz undulator to generate tunable radiation from the same "lasing" electron bunch, would greatly expand our ability to target selected excitations close to the ground state ($kT_{room}/h \sim 6$ THz). The only example demonstrated to date is "phonon pumping" [8,9], but many other interesting modes (e.g. Josephson Plasma Resonances, phason excitations in CDW systems, electronic gaps) could be targeted. These new capabilities to excite the system would open the perspective of controlling the dynamics of matter by phase locked excitations, possibly

inducing new materials properties away from the ground state (e.g. superconductivity or other exotic ordering phenomena).

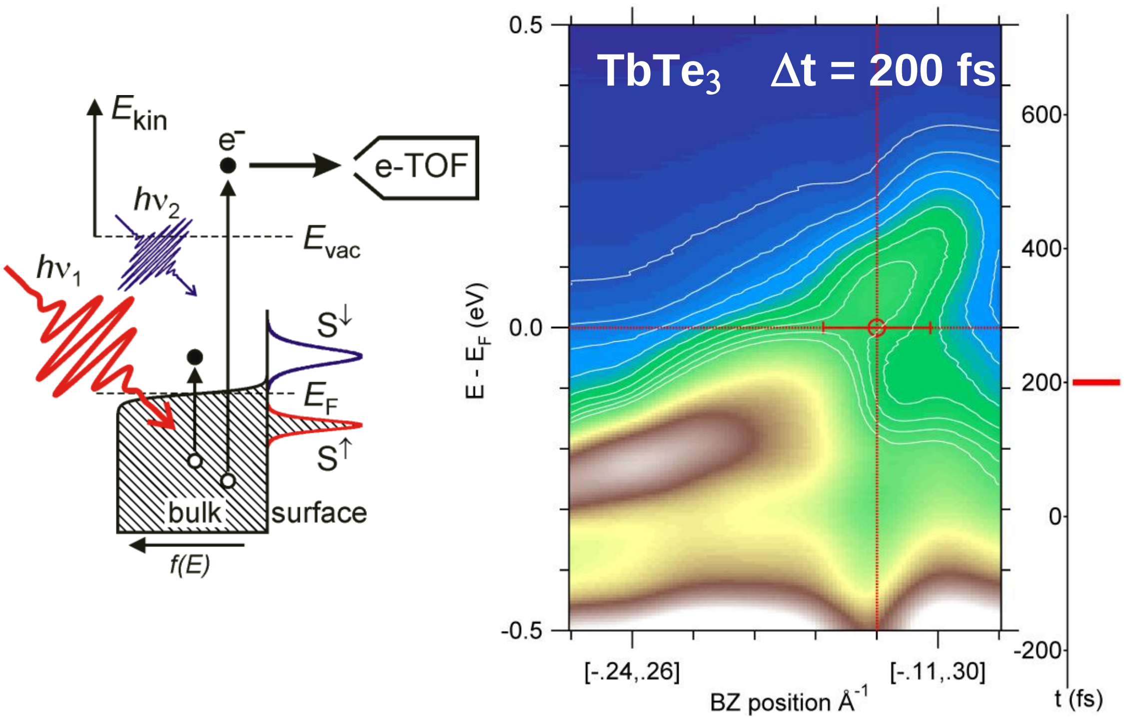


Figure 2.1. *Schematic diagram of time-resolved ARPES (left): An ultrashort pump pulse ($h\nu_1$) photoexcites a solid and changes the electron population of both occupied and unoccupied electronic states. These changes in the electronic structure are probed by a second, time-delayed UV pulse, which excites the electrons above the vacuum level where their kinetic energy and momentum are detected. Right panel: Energy and momentum resolved snapshot of the electronic structure of the charge density wave system $TbTe_3$ at a time-delay of 200 fs after photoexcitation [F. Schmitt et al., Science* ***321****, 1649 (2008)].*

One area of condensed matter research in which time resolved photoemission will have an important set of distinct advantages is high T_c superconductivity. Determining the mechanism responsible for high T_c remains one of the biggest challenges for condensed matter physics. Obtaining an understanding of the underdoped pseudogap regime is thought by many to be the key to a final understanding of the complex phase diagram of these materials. In particular, the pseudogap regime is characterized by a gap in the spectral function of a crystal even when the sample is in its normal state above the superconducting transition temperature. Thus an important question remains to be answered. Does the pseudogap reflect the formation of paired electrons, a requisite for superconductivity, but without the long range phase coherence associated with the superconducting state, or does it reflect the presence of some competing ground state?

In particular, the pseudogap, observed in the so-called "anti-nodal" direction, along the copper-oxygen bonds, shows little temperature dependence on going through the superconducting transition. In the nodal region, corresponding to the minimal gap in the superconducting state, the gap opens up with the onset of superconductivity. Thus the question is posed as to whether these materials are characterized by one gap or two gaps, the latter possibility again pointing to the possibility of competing orders.

JLAMP offers the possibility of using pump-probe techniques to excite from one side of the gap, the occupied side, to the unoccupied state and then probe the lifetime of the "pair". By performing such an experiment in both the anti-nodal region and the nodal region one may gain insight into whether or not the gaps have the same origin. By exciting specific phonon resonances, one could also gain important insight into the pairing mechanism itself, probably the key question in high Tc superconductivity.

Such experiments will require THz pump photons in the energy range 10–60 meV and probe photons in the range 8–12 eV or higher in order to access the full Brillouin zone and to exploit matrix element effects. The pulse width of such photons can be in the 10's of fsec range. To avoid space charge broadening the rep rate should be of the order of 250 kHz or higher.

2.1.2 Femtosecond Pump/Probe ARPES in Artificial Nanosystems

In the last decade, laser-based nonlinear optical (principally two-photon photoemission [13]) photoemission systems have been used to explore a wealth of dynamical phenomena involving normally unoccupied states. In these experiments, a pump/probe approach can be used to interrogate, using photoemission, an excited state or state of polarization of the condensed matter medium. Even without time resolution, these measurements provide a spectroscopic technique, which has the same capabilities for examining the dispersion and electronic structure of excited (or unoccupied) bands as inverse photoemission [14] measurements; however, nonlinear photoemission can provide the same extremely high-resolution momentum and energy data as with synchrotrons via use of high-resolution electron analyzers. High-repetition-rate and ultrashort-pulse lasers are key tools for this method since they minimize space-charge broadening.

In addition to this capability, the use of advanced spectroscopic tools such as pump-probe methods and coherent spectroscopy have, when coupled with nonlinear photoemission, enabled measurements of completely different phenomena than is possible with synchrotron sources. Pump/probe spectroscopy enables, for example, direct temporal measurement of quasiparticle lifetimes, while coherent spectroscopy allows direct measurement of the dephasing times of transition dipoles.

One key emerging area in ultrafast condensed matter physics for coherent and pump/probe measurements is investigation of the physics and electron dynamics in artificial nanosystems. These systems can be and have been made via precise reconstructions on vicinal cut surfaces [15]. The initial studies in this area focused on whether true low dimensional systems can be artificially formed, the extent of coupling between neighboring surface nanosystems, and the interactions of such systems with the bulk substrate. Emerging questions are the development of collective modes and electron correlation effects versus the size of the nanosystem, a comparison of metal versus insulator response, and the dynamics of strongly excited systems.

Thus far relatively low-energy UV fs laser systems have been used, typically ~4 eV, although early experiments in semiconductors did use low-order high harmonic sources for the photoionization step [16]. As a result, these sources have thus far been limited in photon and pulse energy, and in many cases it is not possible to achieve continuous wavelength tunability.

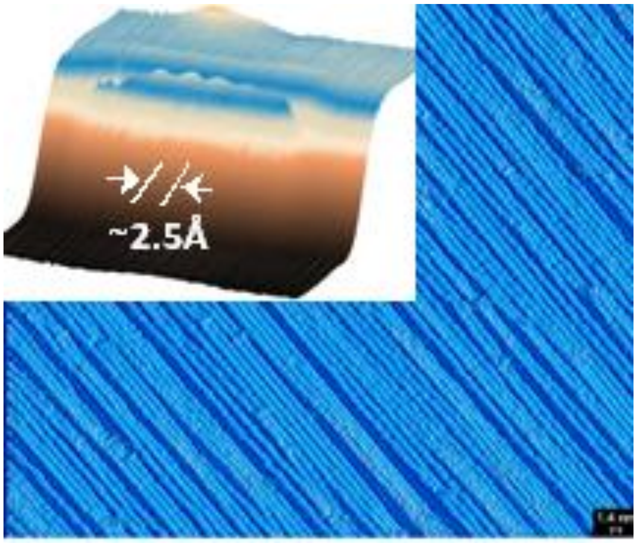


Figure 2.2. *A regular array of 1.4-nm-spaced steps on bare, vicinal Cu(775), which are typical of surfaces used to understand the formation of lateral superlattices on metal crystals. The inset shows one of these steps after depositon of Co atoms. The magnetic Co atoms are 0.25 nm apart and appear as rounded protuberances on the stepedge. (Zaki, Johnson, Osgood, Sutter, unpublished)*

JLAMP opens up several important new experimental opportunities, which are well matched to research in this growing area. In particular, its short wavelength plus its tunability will enable a much wider range of materials systems to be examined than is now possible using laser sources or even high-harmonic sources. These materials include wide bandgap oxides, carbon, and many metal crystals. Second, the short wavelength also allows the possibility of vastly increased spatial resolution in probing the surface via the use of focusing with a zone plate or proximity field enhancement using atomically sharp tips. The ability to interrogate a particular nanometer-scale spatial area is a particularly important tool for selecting a specific set of nanosystems, or even a single nanosystem. Third, the high-repetition-rate and short-pulse operation will minimize space-charge broadening of the energy distribution of the photoemitted electrons

2.1.3 Determining Electronic Ground States and Excitations in Strongly Correlated Electron Systems with Soft X-ray Scattering

Strongly correlated electron systems are controlled by their electronic degrees of freedom (spin, charge and orbital) and their interplay with each other and the lattice degrees of freedom. Understanding these materials, and moving towards exploiting their unique potential, thus requires a detailed understanding of the electronic ground states, and their excitation spectra. Here soft x-ray resonant scattering experiments can have a big impact since they probe the relevant electrons directly. Elastic scattering experiments provide information on the ground states, the real space structure and the slow dynamics, while inelastic scattering can probe the *spontaneous* ultrafast dynamics, i.e. those connected to thermal fluctuations of the system. Importantly, inelastic scattering provides a momentum-resolved probe of the full excitation spectrum, from phonons, to magnons, to d-d excitations to charge-transfer excitations. Given sufficient integrated intensity of a new light source, such experiments will radically revise our understanding of these systems. JLAMP will provide this intensity. Key experiments include studies of the real-space structure and dynamics of cuprate stripes,

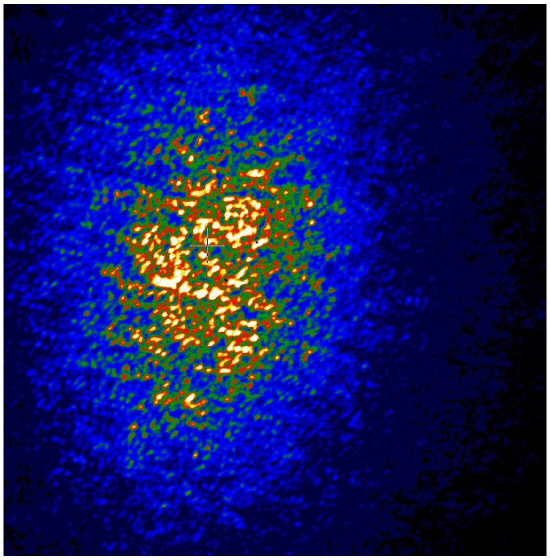


Figure 2.3. *Coherent diffraction pattern from orbital order in a doped manganite, $Pr_{0.5}Ca_{0.5}MnO_3$ (see J. Turner et al. N. J. of Phys.* ***10****, 053023 (2008)) . At existing synchrotron sources such patterns take several minutes. At the proposed JLAMP source, 4 orders of magnitude increase in coherent flux will make time scales down to microseconds accessible. In addition, one will be able to utilize pulse splitters and delay lines to study fluctuations down to the nanosecond time scale. These experiments will open up an entirely new window on the dynamics of electronic order in strongly correlated systems. Among the first experiments to be performed will be studying fluctuating stripe order in high-temperature superconductors.*

searches for hidden order parameters in the pseudogap phase and competing orders in the vortex phase, and detailed measurements of the spin Hamiltonian in low dimensional cuprates.

The opportunities at JLAMP for scattering experiments in the field of strongly correlated systems are immense. Here we discuss two classes of experiments: coherent scattering studies of electronic order (charge, orbital and spin) and inelastic x-ray scattering studies of the electronic excitation spectrum. Both classes of experiments utilize absorption edges to enhance the scattering. Key absorption edges are the oxygen K-edge (540 eV) and transition metal L-edges (e.g. Mn=640 eV, Ni=830 eV, Cu=930 eV). It is highly desirable to reach as many of these as possible using harmonics of the fundamental energy, which can be increased eventually by increasing the electron beam energy. Although these harmonics are reduced in intensity relative to the fundamental, they will still be significantly brighter than any other source and thus provide world-leading capabilities. Further, there are several properties of the JLAMP beam that make it uniquely suited to these experiments. The first of these is the very high repetition rates (4.7 MHz), which provide very high average brightness if the oscillator can be used. The second is the fact that it is a seeded FEL, which means that the energy—and pointing—stability from pulse to pulse is very high compared to SASE-based FELs.

(i) Coherent Scattering

The following is predicated on the assumption that JLAMP will reach 540 eV in the 5^{th} harmonic. In assessing the performance of JLAMP in these experiments, a key figure of merit is the time averaged flux. In the fundamental mode there are projected to be $6x10^{12}$ photons/pulse, which at 4.7 MHz repetition rate yields a total photon dose of $3x10^{19}$ photons/sec. Taking the *n*th harmonic as being 10^{-n} of the fundamental, then there will be $3x10^{14}$ photons/sec at the O K-edge (in the 5^{th} harmonic). **This is four orders of magnitude more intense than the coherent flux at existing scattering beamlines at synchrotron sources.** Thus this source will dramatically transform our ability to carry out high-optical-field experiments. In particular, for measurements of dynamics—in which one studies the correlations between images taken at a time interval, Δt, to measure the dynamic scattering factor $S(q,\Delta t)$—the shortest accessible time scales as B^2, where B is the source brightness. This means that times eight orders of magnitude shorter will be accessible at JLAMP. The seeded nature of the JLAMP beam is an absolute requirement for such experiments, since they require high pointing and energy stability from pulse to pulse in order to ensure that the changes in the diffraction pattern arise from fluctuations within the sample and not from the beam. Thus these experiments will not be possible at SASE-based FELs.

One can also invert the coherent diffraction pattern to obtain a real space image of the ordered structure. This is also called lensless imaging or coherent diffraction imaging. In principle, the resolution of this image is limited only by the wavelength, and a resolution of 2 nm should be possible using soft x-rays. Such a resolution, when applied to electronic structures, would have a large impact on the field, allowing, for example the study of domain wall formation and dynamics for such electronic orders as stripe order or magnetic order in the cuprates. However, in practice, signal-to-noise issues dominate at existing sources and the resolution is limited by how far one can still observe intensity away from a Bragg peak. Typically, this translates to a resolution of the order of 300 Å. Again, the significant coherent flux at JLAMP would transform this field.

(ii) Inelastic Scattering

Soft x-ray resonant inelastic x-ray scattering (RIXS) has undergone a revolution in the last few years, transforming it from a technique with “potential” to a technique of real power. In particular, recent work with the cuprates has demonstrated the ability to measure the full panoply of excitations crucial to understanding the behavior of strongly correlated systems. Specifically, phonons, orbitons, d-d excitations, charge transfer excitations and most impressively magnons and bi-magnons have all been observed. It should be emphasized what a remarkable achievement this is. To be able to measure the spin wave dispersion in 1000 Å of a cuprate is phenomenal. Neutron scattering, the only other technique that is able to measure the dispersion of such excitations, requires relatively large samples, i.e. many grams in weight—something that is impossible to obtain in most cases.

Current RIXS instruments have fluxes on the sample of the order of 10^{13} photons/sec/100 meV and current resolutions are on the order of 100 meV. Ideally one would like to push this down to 10 meV or lower. There are technical challenges to doing so (grating manufacture), but the principal showstopper is flux. Even assuming such optics could be as efficient as the lower resolution optics in use today (an extremely optimistic scenario), then at, say 6 meV resolution the flux on the sample would be 6×10^{11} photons/sec, and experiments would take prohibitively long. However, since JLAMP is transform limited, one can obtain very narrow bandwidth beams “for free”. Thus a 100 fs pulse length would correspond to 6 meV bandwidth. The significance of this is that all the photons would be within this bandwidth, and there would be no need for a monochromator—thus at the oxygen K-edge (5^{th} harmonic) one would have 3×10^{14} photons/sec delivered to the sample—a 500-fold increase. This would be a truly revolutionary source for inelastic x-ray scattering.

One technical point is worth emphasizing. At the oxygen K-edge one creates two magnons at a time and it is impossible to observe single magnon scattering. This latter phenomenon is where the most important dispersion information lies. Single magnon scattering, however, can be observed at the Cu L-edge. If the fundamental energy can be raised to 190 eV such that the Cu L-edge (930 eV) is in the 5th harmonic, this would be truly game changing, creating a world-leading capability, a source capable of such remarkable feats as measuring spin wave dispersions in a single layer of copper oxide. It is difficult to overemphasize the impact such a source could have in the study of electronic excitations.

References for Section 2.1

[1] Kaindl RA, Woerner M, Elsaesser T, Smith DC, Ryan JF, Farnan GA, McCurry MP, Walmsley DG *Science* **287**, 470 (2000).

[2] J. Carson, J. Orenstein et al. *Phys. Rev. Lett.* **85**, 2572 (2000).

[3] A.Cavalleri, Cs Toth, C.W. Siders, J.A. Squier, F. Raksi, P. Forget, J.C. Kieffer "Femtosecond structural dynamics in VO_2 during a solid-to-solid phase transition." *Physical Review Letters* **87**, 237401 (2001).

[4] A. Cavalleri, M. Rini, H. Chong, S. Formaux, T.E. Glover, P.A.Heimann, J.C. Kieffer, R.W. Schoenlein, "Band-selective Measurement of Electronic Dynamics in VO_2 with Femtosecond Near Edge X-ray Absorption", Phys. Rev. Lett. **95**, 67405 (2005).

[5] L. Perfetti, P. A. Loukakos, M. Lisowski, U. Bovensiepen, H. Berger, S. Biermann, P. S. Cornaglia, A. Georges, and M. Wolf, "*Time Evolution of the Electronic Structure of 1T-TaS2 through the Insulator-Metal Transition*", Phys. Rev. Lett. 97, 067402 (2006).

[6] F. Schmidt et al. *Science* **321**, 1649 (2008).

[7] A. Cavalleri, Th. Dekorsy, H. H. W. Chong, J. C. Kieffer, and R. W. Schoenlein, "Evidence for a structurally-driven insulator-to-metal transition in VO_2: A view from the ultrafast timescale", Phys. Rev. B 70, 161102 (2004).

[8] M. Rini, R.I. Tobey, N. Dean, Y. Tomioka, Y. Tokura, R.W. Schoenlein & A. Cavalleri "Ultrafast Control of the Electronic Phase of a Manganite by Mode-selective Vibrational Excitation", *Nature* **449**, 72 (2007)

[9] R.I. Tobey, R. Prabakharan, A.T.J. Boothroyd, A. Cavalleri, "Nonthermal Orbital Melting in $La_{1.5}Sr_{0.5}MnO_4$ by Coherent Excitation of a Mn-O Vibration", *Physical Review Letters* **101**, 197404 (2008).

[10] A. Damascelli, A., Z.X. Shen, and Z Hussain, "Angle-resolved photoemission studies of the cuprate superconductors", Rev. Mod. Phys. **75**, 473 (2003).

[11] T. Cuk, F. Baumberger, D. H. Lu, N. Ingle, X. J. Zhou, H. Eisaki, N. Kaneko, Z. Hussain Z, T. P. Devereaux, N. Nagaosa, Z. X. Shen, "Coupling of the B-1g phonon to the antinodal electronic states of $Bi_2Sr_2Ca_{0.92}Y_{0.08}Cu_2O_{8+\delta}$", Phys. Rev. Lett. **93**, 117003 (2004).

[12] P.D. Johnson "Spin Polarized Photoemission", Reports on Progress in Physics, **60** 1227 (1997).

[13] H. Petek and S. Ogawa, Prog. Surf. Sci. **56** 239 (1997); W. Steinmann and Th. Fauster, in: H.L. Dai, W. Ho (eds.), "Laser Spectroscopy and Photochemistry on Metal Surfaces", (World Scientific, Singapore, 1995) p. 184. R.M Osgood, Jr. and X. Wang, "Image States on Single-Crystal Metal Surfaces." Chapter in Solid State Physics, H. Ehrenreich and F. Spaepen, eds., (Academic Press, 1998).

[14] P. D. Johnson and S. L. Hulbert, Rev. Sci. Instrum. **61**, 2277, (1990); F. J. Himpsel, Surf. Sci. Rep. **12**, 1 (1990).

[15] J. Ortega, M. Ruiz-Oses, J. Cordon, A. Mugaza, J. Kuntze, and F. Schiller, "One Dimensional versus two-dimensional states in vicinal surface", New J. Phys, **7**, 101 (2005); F. J. Himpsel, K. N. Altmann, R. Bennewitz, J. N. Crain, A. Kirakosian, J. L. Lin, and J. L. McChesney "One-Dimensional Electronic States at Surfaces." J. of Phys.-Condens. Matter **13**, 11097 (2001).

[16] R. Haight, Surf. Sci. Rep. **8**, 275 (1995).

2.2 Chemical Physics and Atomic, Molecular, Optical Physics (AMO) with Laser-like VUV Pulses – Erwin Poliakoff (Chair)

Overview – why small, bright, and fast are important: Many scientific breakthroughs have been catalyzed by the development of new tools. There is now a need for new tools that can help in the understanding of electronic and structural characteristics of species that cannot be "put into a bottle," such as transient and reactive species. However, developing an understanding of such targets is a daunting task because they cannot be prepared except in temporally or spatially dilute conditions. The proposed JLAMP facility will provide insights into the behavior of such targets, as the intensity, energy range, and time structure will be ideal for probing targets of AMO and chemical physics interest at their most basic level. Some examples are given, and we note that these are simply illustrative of the possibilities, and that they are a small subset of what will be both feasible and useful to study.

Three areas of fundamental research were identified:

2.2.1 Matter at Small Dimensions: Size-Selected Clusters and Nanoparticles

Background and scientific vision: Clusters and nanoparticles represent a state of matter intermediate between molecular complexes and the solid state and exhibit physical and chemical properties which are distinct from both size limits. Generally, the electronic and atomic structures of clusters with fewer than 100 atoms (≤ 1 nm) are markedly dependent on cluster size and are not scalable to the bulk material. With physical dimensions on the order of charge carrier (e^- and h^+) diffusion [1-4] lengths and high surface to volume ratios which place a large fraction of the atoms at or near the surface, small clusters can exhibit completely novel electronic, magnetic and chemical behavior. Through variations in size and chemical composition, these properties can be tailored so as to make functional nanomaterials for a wide range of technological applications such as high density magnetic storage and chemical catalysis [5]. The unprecedented photon intensity and timing characteristics of the JLAMP FEL will enable new experimental probes of *size-selected* targets in a variety of chemical environments, i.e., in the gas phase, in matrices, and deposited on surfaces, that will significantly enhance our understanding of matter at small dimensions and allow for novel technological applications.

Since the chemical synthesis of clusters with an exact number of atoms is not usually possible, it is desirable to sort them by size before interrogating their properties. This is typically accomplished by mass selecting clusters from a beam of cluster ions produced by a gas-phase cluster source (laser ablation, ion sputtering, electric discharge) [2]. Even with the best sources and high throughput mass spectrometers, beam densities of size-selected clusters are only 10^4–10^6 ions/cm^3, which is at least 10^4 times smaller than those found in dilute seeded molecular beams typical of gas phase experiments. Small densities place severe constraints on the kinds of photon-based experiments that can be performed on size-selected clusters, especially with soft x rays from synchrotron radiation sources which have low average power. While recent progress at FLASH has shown the potential and desirability for studies on low target density ion beams [6], such experiments would be possible on a much wider variety of systems as a result of the several order of magnitude increase in flux that JLAMP would provide. Moreover, pump-probe-experiments on free clusters appear to be out of reach with present SASE-FEL sources.

With the JLAMP FEL, a wide array of pump-probe experiments become possible, including the direct inner-shell photoionization of *size-selected neutral clusters* with photon energies well above conventional laboratory lasers (10–300 eV with high harmonics) and at much higher photon fluxes than those available from laser- or arc-based XUV harmonic generation sources. The ability to access shallow core levels in metals and other elements will allow the application of powerful spectroscopic techniques using soft x rays (XPS, NEXAFS). Specifically, these x-ray spectroscopies will probe the local atomic and electronic structure of small clusters with *elemental specificity*.

A number of experiments using mass-selected clusters can be envisioned that would not otherwise be possible without the unique characteristics of the JLAMP FEL source. These generally fall into two categories: (1) electronic and geometric structure and dynamics of size-selected clusters and nanoparticles and (2) chemical reactivity of these species. One of the novel aspects of the proposed experiments is the ability to probe *size-selected neutral clusters* which could be generated by photodetachment from the corresponding cluster anion clusters, which goes far beyond the first results obtained with soft x rays [6]. Such studies are made possible by the high intensity of the JLAMP XUV radiation for ionization detection of very dilute samples. For all ultrafast dynamics experiments, a pump-probe arrangement with other laser sources (tunable IR or VIS/UV) synchronized with the FEL pulse structure is essential, as well as a suite of cluster ion beam sources that are optimized for different types of cluster and nanoparticle materials (e.g., metals, oxides). The latter could include electrospray injection and aerosol generators that volatilize large organic molecules or other types of molecular clusters and nanoparticles that are relevant to atmospheric or environmental chemistry [7]. The short pulse duration (~100 fs) of the proposed FEL-XUV radiation means that most pump-probe measurements can be performed with sub-ps time resolution, which opens up the possibility of studying the time evolution of electronic and nuclear motions of photoexcited systems. A few specific examples where the JLAMP FEL facility could make important breakthroughs in cluster science are outlined below.

(i) Atomic and Electronic Structure of Size-Selected Clusters

The lack of structural information remains one of the biggest challenges for isolated small clusters, as they are too small for direct imaging by scanning transmission microscopy or x-ray diffraction (even as deposited nanoclusters) yet too large for ab initio theory to provide reliable structures. X-ray diffraction studies on single, size-selected microclusters have not been published to date, and this is a result of low target density. Electron diffraction on gas-phase clusters has been demonstrated, but is limited to charged clusters that can be stored in an ion trap [8]. Current probes of electronic structure for size-selected clusters are constrained to the valence shell (photodetachment spectroscopy).

There are a few classes of experiments on size-selected clusters that are possible at JLAMP, the first using tunable THz-IR radiation from a pump laser to vibrationally excite a size-selected cluster followed by ionization detection using the XUV FEL radiation. This approach is best suited to cluster compounds which have vibrational modes in the mid- and far-IR (e.g., metal carbides, oxides, sulfides) that could be use for fingerprinting the cluster structure. This would provide structural information which is not currently available from any existing experimental method. The second approach is to use higher energy XUV radiation (including FEL harmonics) to perform photoelectron (XPS) or XANES/EXAFS type measurements from shallow core levels of the constituent atoms to probe the local electronic structure, including charge distributions (e.g., oxidation state) and structural information with elemental specificity. Such experiments have been recently demonstrated with table-top XUV sources [9], but the JLAMP FEL would provide significantly better photon tunability and orders of magnitude more intensity. Moreover, these experiments could be performed in conjunction with ultrafast pump lasers to investigate the dynamics of internal energy redistribution, cluster fragmentation and photoreactions involving adsorbed molecules.

(ii) Chemical Reactivity of Size-Selected Neutral Clusters and Nanoparticles

Experiments to date on size-selected clusters have been limited to charged species (anions or cations) due to the need to size-select by mass spectrometry. In some cases, the charge on the clusters is an inherently important aspect of their behavior, e.g., the enhanced reactivity of Au_n^- clusters compared to the corresponding cation and neutral clusters [10]. In addition, electron photodetachment spectroscopy of anion clusters provides a direct measurement of the valence electron energy level structure, e.g., density-of-states and band gap, for comparison with electronic structure calculations. In many cases, however, direct probes of the neutral cluster would be more useful, particularly for reactivity studies. This is because the addition (anion) or subtraction (cation) of one electron from the frontier orbitals and the long range charge–dipole interaction with an incoming molecule can modify the reaction kinetics and even the product distributions. Moreover, fully charged clusters exist only in the gas phase (e.g., atmospheric chemistry) or in solution (charge balanced by counter ions), whereas the chemistry of neutral clusters is more appropriate to model studies of "nanocatalysis" where the neutral clusters are supported on solid surfaces. To perform such experiments, we envision a pump-probe experiment where an ion beam containing a size-selected anion cluster is photodetached by a UV laser beam (*cw* or pulse synched to the FEL). The resulting neutral clusters then pass through a temperature-controlled, high-pressure reaction cell containing reactant molecules. The product species exiting the reaction cell would be detected by XUV-FEL ionization and a mass spectrometer. Momentum changing collisions and product recoil that cause the products to spread axially about the beam direction could be countered by focusing the XUV radiation as a vertical sheet intersecting the beam path. Experiments could be performed as a function of temperature, reactant pressure and beam energy and thereby completely map out the reaction kinetics and barriers. Such experiments are only possible with the high ionization efficiency of the intense FEL-XUV radiation source and can be extended to metals, bimetallics, metal oxides and metal sulfides, all of which play essential roles in thermal catalysis for chemical feedstock production, and energy production and utilization.

(iii) Time-resolved nanoscale "surface" dynamics

The dynamics of energy and charge transfer at gas- or liquid-solid interfaces are central to understanding the mechanisms of technologically important photochemical processes such as photodegradation of air- or water-borne pollutants and solar water splitting on semiconductor surfaces. As the active substrate shrinks to become a nanoparticle or cluster, the dynamics of electron or hole induced surface chemistry can be drastically altered by quantum confinement in which the spatial extent of particle (e^-/h^+) excitations is comparable to the cluster size. The latter shifts energy levels (e.g., band gap for semiconductor), and alters the rate of carrier relaxation via electron-electron or electron-phonon collisions and electron-hole recombination. Changes in carrier lifetimes will strongly influence charge transfer rates at the surface, and hence, the probability for photoreaction. Finally, the heat generated by carrier relaxation into phonons is also confined to the small particles, which unlike the solid material cannot be transferred away from the surface into the bulk. This could lead to rapid heating of the cluster which can induce "thermal" reactions that boil off adsorbates (desorption) or induce cluster fragmentation. We propose to investigate the dynamics of photoexcitations of small clusters without the complicating effects of a supporting surface which could modify the dynamics through particle-support interactions. The experiments involve size-selecting charged or neutral clusters and nanoparticles with a number of simple adsorbates, e.g., O_2, CO, H_2O, and following the time dynamics of the charge carrier evolution and molecular desorption via pump-delayed-probe experiments [11]. Different pump excitations would probe different phenomena, i.e., THz for rapid "thermal" heating or UV light for plasmon excitations in metallic clusters and above band gap excitations in metal oxides. Charge carrier dynamics can be followed by valence band photoemission using XUV FEL ionization or mass spectrometry to observe the adsorbate reaction/desorption and/or fragmentation of the cluster. Final state distributions (momenta) of the cluster and neutral desorbed molecules could also be measured through the use of XUV-FEL "sheet" ionization and a 2D time-and-position area detector. Such experiments would be the most detailed exploration of cluster photodynamics attempted, and the knowledge gained could be used to understand more complex environments found in the solid state.

2.2.2 Molecular movies - following electronic and structural changes in real time

(i) Background and scientific vision

"Making the molecular movie" is an often-cited claim for motivating the utility of the novel sources of ultrashort VUV and x-ray pulses. A closer look, however, reveals that a source that would allow the broader chemical physics community to actually make such a 'movie' should combine the stable laser-like properties of a laser-based source with the power, versatility and availability of an accelerator-based facility. JLAMP is the source that exactly satisfies this demand. Its well-controlled ultrashort VUV pulses will enable highly selective electron and ion spectroscopy of shallow core-levels delivering detailed information on the instantaneous electronic and structural properties of molecules. The high intensity and repetition rate will allow application of this approach to very dilute species down to a single-molecule-per-shot level.

The electrons emitted after an excitation of molecules with VUV pulses provide us with a wealth of dynamical information on photoinduced molecular processes. In the following, two complementary methodological approaches are proposed, which detect the kinetic energy and the momenta of photoelectrons in order to resolve the evolution of the electronic as well as the geometrical structure of molecules, respectively.

(ii) Probing electronic dynamics with time-resolved ESCA

Electron Spectroscopy for Chemical Analysis (ESCA) probes the electronic environment of specific atomic species in a molecule [12]. Excitation of atomic core-levels with VUV radiation provides element specificity. In addition, the electronic environment is reflected in chemical shifts of the binding energies, which are accessible through a measurement of the photoelectrons' kinetic energies. Sampling the latter at different delays between a UV/visible stimulus and the VUV probe will therefore allow following the evolution of the electronic environment [13] of a marker atom during ultrafast molecular processes like dissociation, isomerization or electron and proton transfer.

While this concept is straightforward in principle, the feasibility for dynamical studies on free molecules has yet been realized for only two previous experiments, both on Br_2. They utilized femtosecond VUV pulses from high harmonic sources [14,15]. The low flux of high harmonic generation (HHG) sources, however, imposes serious constraints on the required target density and the achievable sensitivity. FEL sources based on self-amplified spontaneous emission, on the other hand, lack the necessary high stability and small bandwidth. The requirements for establishing time-resolved ESCA as a versatile method are:

- For the *probing* VUV pulses: Photon energies of more than 50 eV, high average flux, high rates rather than high energies per pulse in order to avoid space charge effects, pulse durations of 100 fs and below together with the highest possible spectral resolution for resolving also minor chemical shifts.
- For the *pumping* pulses driving photodynamics: UV/visible pulses at a few µJ pulse energy, pulse durations well below 100 fs, synchronization to the VUV pulses on a few tens of fs level.

JLAMP will provide a suitable combination of these beam properties. Its high flux together with perfect repeatability will allow studies of molecular targets that can be prepared only in a very diluted form, like complex organic molecules, metal-to-ligand-charge transfer complexes or even bio-molecules. Its laser-like pulses with a spectral resolution at the theoretical (Fourier) limit will provide optimal resolution for studies of processes that are expected to exhibit only subtle chemical shifts, like isomerization or partial charge transfer.

(iii) Imaging Molecules from Within: Time-Resolved Photoelectron Diffraction in Gas-Phase Molecules

Photoelectron diffraction is a well established method in solid state and surface physics, in which angle- and energy-dependent scattering of inner-shell photoelectrons yields information about the structure and environment of the electron emitter. It is used, for example, to determine orientation and geometry of molecules adsorbed on surfaces [16], thus enabling a detailed insight into physical or chemical processes at surfaces such as catalytic reactions. In the gas phase, the random orientation of gas-phase molecules averages out most of the intensity variations that contain the structural information. In order to measure molecular-frame photoelectron angular distributions (see Figure 2.4), which contain the photoelectron diffraction signal, the molecules therefore have to be "fixed in space", e.g. by means of electron-ion coincidence measurements [17,18]. Such measurements have been performed in a non-time resolved manner at synchrotron light sources around the world, and have given access to an unprecedented level of detailed information, such as localization of charges [19] and core holes [20], interferences in molecular double-slits [21,22], phases of photoelectron waves [23,24], and, last but not least, the electronic potentials and the molecular structure via photoelectron diffraction [25,26]. Extending this technique to the time domain will reveal direct three-dimensional structural information for vibrating, dissociating, or fragmenting molecules in real time. Such experiments will have a profound impact on our understanding of reaction mechanisms and reaction dynamics and allow following chemical reactions with atomic resolution in real time. The elemental and site specificity of core photoelectron emission allows probing the local environment of a specific site in the molecule as well as obtaining structural information on variable length scales by adjusting the de Broglie wavelength of the photoelectrons, thus achieving Angstrom resolution with the photon energies available at JLAMP. By changing the photon energy and thus the de Broglie wavelength of the emerging electron [26], the latter can be "adjusted" to any length scale of interest for the respective molecule, possibly even to large-scale structures such as the folding patterns of proteins, in an "inside-source holography" arrangement [27].

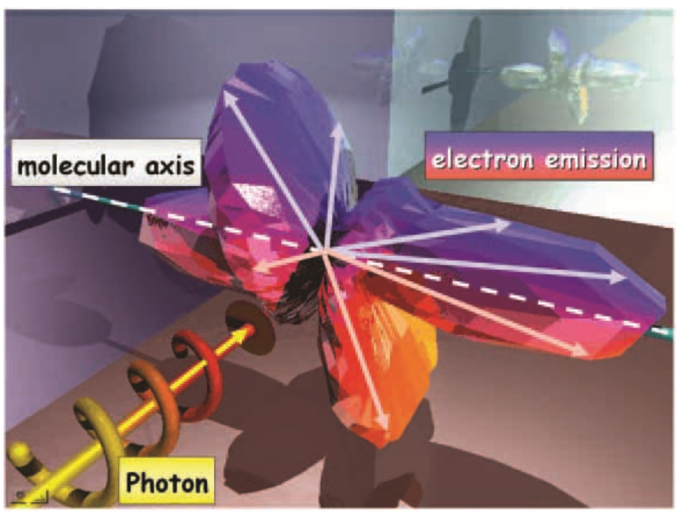


***Figure 2.4**. Experimentally determined molecular-frame 3-D photoelectron (E_{kin}=10 eV) angular distribution for N_2 after core ionization with circularly polarized synchrotron radiation [28]. Each vertex represents one data point with a maximum corresponding to about 1000 counts.*

While pump-probe experiments that study the time-dependent evolution of molecular *valence* orbitals have recently been performed with high-harmonic laser sources [29], shorter wavelength probe pulses access localized *inner-shell* electrons, which are essential for structural determination via electron diffraction since they allow launching the photoelectron from *specific* sites within the molecule. Depending on the system under investigation, this could either be an atom naturally contained in the molecule or a special marker atom attached in a specific molecular site.

The source requirements for establishing time-resolved photoelectron diffraction as a versatile method for gas-phase molecules are identical to those listed in the previous section.

Just to make the ideas more clear, we present a simple illustration of the type of experiments that one can envision. It is known that illumination of iodo-benzene C_6H_5I with UV radiation leads to fission of the bond between the iodine atom and the benzene ring. As this photochemical process has previously been investigated with a visible probe [30], the capabilities of the VUV-probing methods described above can directly be compared. Simultaneous application of time-resolved ESCA as well as time-resolved electron diffraction will aid in disentangling electronic from structural changes, thus developing a comprehensive picture of bond-breaking dynamics in these molecules. The requirements on the light source are:

- probe pulses at 80 eV–90 eV photon energy in < 300 meV bandwidth, 100 fs pulse duration, focal spot size 30 µm, pulse energy of about 1 µJ,
- pump pulses at 267 nm (third harmonic of 800 nm) with > 10 µJ pulse energy and less than 100 fs duration, focal spot size of 50 µm, repetition rate would ideally lie between 100 kHz and 500 kHz.

For iodo-benzene the symmetry of the fragmentation will yield structural information as an average over a rotation of the plane of the benzene ring around the molecular axis. Complete three-dimensional information will be obtained in a fragmentation of 1,2-diodo-benzene into three fragments, the detection of which will unambiguously determine the orientation of the benzene plane in space.

2.2.3 New Generation of Ultrasensitive Trace Analyzer of Noble Gas Isotopes

The high *cw* VUV power of the proposed JLAMP facility will provide a unique opportunity to efficiently excite noble gas atoms such as krypton and argon from the ground level to the metastable level, and enable a new generation of ultrasensitive trace analyzers of noble gas isotopes. A particular beneficiary would be Atom Trap Trace Analysis (ATTA) invented and demonstrated by scientists at Argonne National Laboratory, a novel method based on laser trapping and counting of individual noble gas atoms in the metastable level. ATTA is capable of analyzing trace isotopes with an isotopic abundance at the parts-per-trillion (10^{-12}) level [31,32]. By combining the high excitation efficiency made possible by JLAMP FEL and the super selectivity of ATTA, a near perfect ultrasensitive trace analyzer can be realized for a wide range of applications.

ATTA has been used to analyze both ^{81}Kr (half-life=229,000 years, isotopic abundance ~ 1×10^{-12}) and ^{85}Kr (10.8 years, ~ 10^{-11}) in environmental samples. The cosmogenic ^{81}Kr is the ideal tracer isotope for dating water and ice in the age range of 10^5–10^6 years, a range beyond the reach of ^{14}C-dating. ^{85}Kr is a product of nuclear fission. Monitoring ^{85}Kr in air can serve as a means to help verify compliance with the Nuclear Non-Proliferation Treaty. As the first real-world application of ATTA, ^{81}Kr-dating was performed to determine the mean residence time, or the “age”, of the old groundwater in the Nubian Aquifer located underneath the Sahara Desert [33].

In ATTA, an atom of a particular isotope is selectively captured by resonant laser light in a magneto-optical trap and detected by observing its fluorescence (Figure 2.5). Trapping krypton atoms in the $5s[^3/_2]_2$ metastable level (lifetime = 40 s) is accomplished by exciting the $5s[^3/_2]_2$ –

$5p[^5/_2]_3$ atomic transition using laser light with a wavelength of 811 nm generated by a system of diode lasers. When the laser frequency is tuned to the resonance of the desired isotope, ^{81}Kr or ^{85}Kr, only atoms of this particular isotope are trapped. Atoms of other isotopes are either deflected before reaching the trap or are allowed to pass through the trap without being captured. An atom can be trapped and observed for 100 ms or longer, during which 10^6 fluorescence photons can be induced from a single trapped atom and as many as 10^4 photons can be detected, thereby allowing the counting of single atoms to be done with a high signal-to-noise ratio as well as a superb selectivity. Indeed ATTA is immune to interference from other isotopes, elements, or molecules.

While the selectivity of the present ATTA instrument (ATTA-2) [34] is already sufficient for the detection of isotopes at the level of 10^{-12}–10^{-15}, the efficiency and the rate of atom counting still have room for large improvements. Figure 2.6 shows the "ruler of progress" for ^{81}Kr dating of old groundwater and polar ice. With ATTA-2, an analysis requires a sample of approximately one ton of water, which is often not feasible. A new instrument, ATTA-3, is under development at Argonne with the goal of further improving the efficiency to approximately 1% and reducing sample size for ^{81}Kr dating down to ~10 kg. There will be no radical changes from ATTA-2 to ATTA-3. Instead, each individual component of the ATTA-2 system is being optimized for a small gain of a factor of 1.5–2. If successfully developed, ATTA-3 will enable routine analysis of groundwater as well as a few proof-of-principle measurements on polar ice.

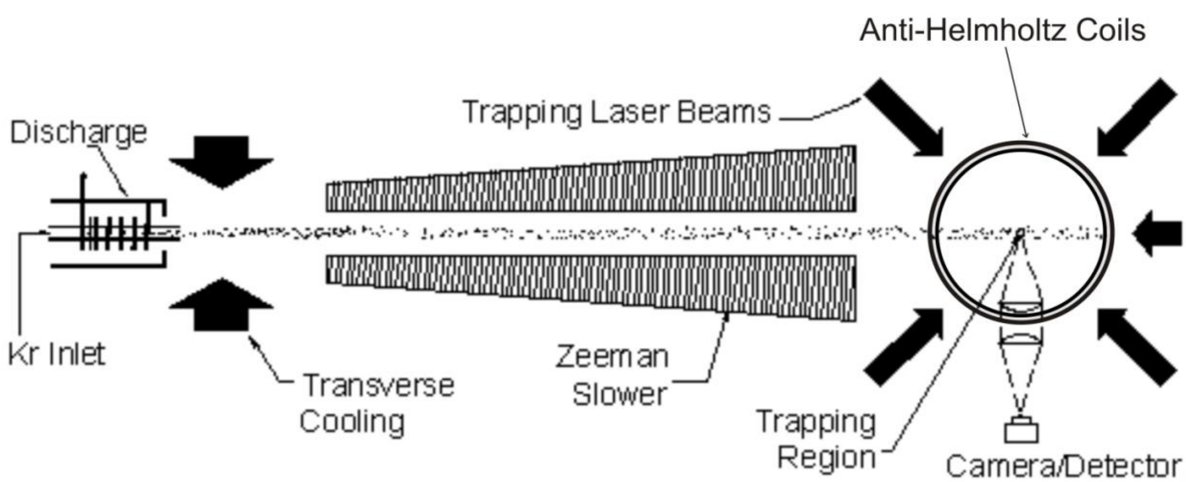


Figure 2.5. *Schematic layout of the krypton ATTA apparatus [34]. Metastable krypton atoms are produced in the discharge. The atoms are then transversely cooled, slowed and trapped by the laser beams shown as solid arrows. The fluorescence of individual trapped atoms is imaged to a detector. Total length of the apparatus is about 2.5 m.*

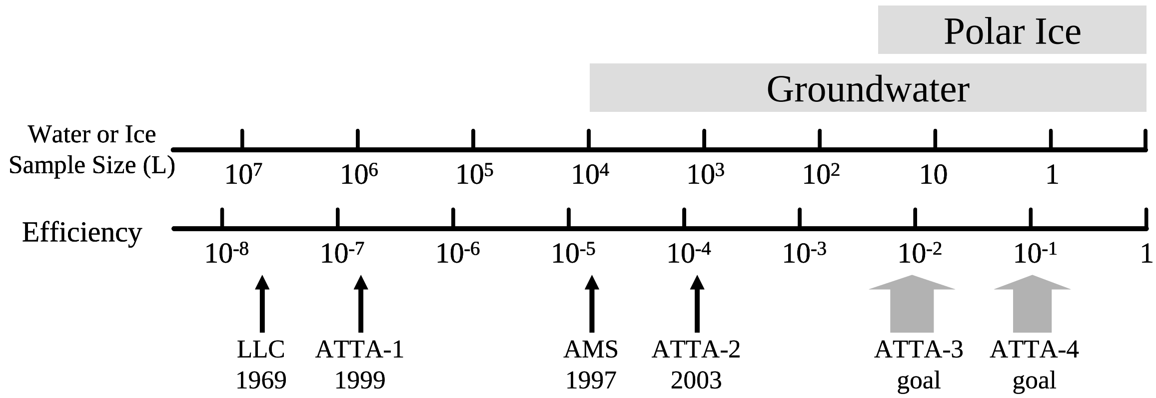


Figure 2.6. *Ruler of progress. As the efficiency of the analyzer approaches unity (100%), the required water or ice sample size for ^{81}Kr dating reduces to a fraction of one liter. Bars show the sample size required for dating water and ice.*

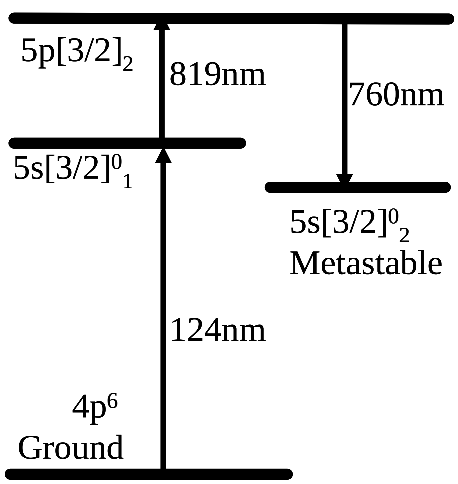


Figure 2.7. *Atomic energy diagram of Kr. The new excitation scheme (124 nm + 819 nm) is shown.*

Lacking a *cw*, narrow-bandwidth laser at 124 nm, laser trapping of krypton atoms can only be realized with atoms at the metastable $5s[3/2]^0_2$ level, which we denote Kr* (Figure 2.7). In ATTA-2 or ATTA-3, the excitation of Kr atoms to the metastable level is done by colliding atoms and electrons in a plasma discharge. This process causes serious limitations to the analyzer: The collisional excitation has a low efficiency (Kr*/Kr ~ 10^{-4}); the collision process causes the atomic beam to diverge; in the plasma, Kr^+ ions are slowly embedded into surfaces, causing a loss of sample, only to re-emerge later in subsequent analyses, and thereby inducing cross-sample contamination; moreover, a discharge requires a certain minimum gas pressure to operate, which raises the minimum amount of sample needed to support the operation of the discharge.

It has been demonstrated that Kr atoms can be transferred from the ground level to the metastable level via a two-photon resonant excitation process (Figure 2.7): excitation with a vacuum ultraviolet photon at 124 nm and an infrared photon at 819 nm, followed by a spontaneous decay at 760 nm [35,36]. All three transitions are of the allowed E1 type. Provided a powerful vacuum ultraviolet (VUV) laser is available, this optical production scheme is a clean and efficient way of producing a well-collimated beam of metastable Kr* atoms, and would lead to ATTA-4 with even higher counting rate and efficiency, and with less susceptibility to cross-sample contamination.

If JLAMP were to produce 20 nJ per pulse at 75 MHz, or 1.5 W of time-averaged power, with ~ 0.1 mW of light within a 1 GHz bandwidth resonant (124 nm) to the $4p^6 – 5s[3/2]^0_1$ transition in krypton, nearly 10% of the atoms would be excited. Since the second-step excitation at 819 nm can be readily saturated with a regular infrared laser, the efficiency of producing metastable krypton atoms can be very high. This would bring the ATTA method to near perfection in both selectivity and sensitivity. ATTA-4 is expected to find applications in environmental and earth science, nuclear waste management, reactor safety, and nuclear non-proliferation, as well as basic research in nuclear and particle physics.

Chemical & AMO physics summary: Important new scientific breakthroughs in chemical and AMO physics would be generated with the availability of JLAMP. The combination of tunable VUV and soft x-rays with extremely high average intensity, as well as with a convenient time structure for ultrafast pump-probe experiments, would enable new classes of experiments on ultradilute samples that cannot be performed otherwise. The result will be unambiguous understanding of important new systems, including molecular movies with elemental specificity, and unambiguous structural data on nanoparticles and surface chemical reactions. These are some obvious opportunities that are foreseeable, and they are only a small subset of what will be realized by this enabling technology.

References for Section 2.2

[1] Arenz, M.; Gilb, S.; Heiz, U. Size Effects in the Chemistry of Small Clusters. In Atomic Clusters from Gas Phase to Deposited; Elsevier: Amsterdam, 2007; **Vol. 12**; 1.

[2] Binns, C. Surface Science Reports 2001, **44**, 1.

[3] Wilson, K.; Zou, S.; Shu, J.; Rühl, E.; Leone, S. R.; Schatz, G. C.; Ahmed, M.: Nano Lett. 2007, **7**, 2014.

[4] Bresch, H.; Wassermann, B.; Langer, B.; Graf, C.; Flesch, R.; Becker, U.; Österreicher, B.; Leisner, T.; Rühl, E.: Faraday Discuss. 2008, **137**, 389.

[5] Alivisatos, A. P.: J. Phys. Chem. 1996, 100, 13226; Murray, C. B.; Norris, D. J.; Bawendi, M. G.: J. Am. Chem. Soc., 115 (1993) 8706; Henzie J.; Lee J.; Lee M. H.; Hasan W., Odom T. W., Ann. Rev. Phys. Chem. 2009, **60**, 147.

[6] Senz, V.; Fischer, T.; Oelßner, P.; Tiggesbäumker, J.; Stanzel, J.; Bostedt, Ch. ; Thomas, H.; Schöffler, M.; Foucar, L.; Neville, J.; Neeb, M.; Möller, Th.; Wurth, W.; Rühl, W.; Dörner, R.; Schmidt-Böcking, H.; Eberhardt, W.; Ganteför, G.; Treusch, R.; Radcliff, P.; Meiwes-Broer, K.-H.: Phys. Rev. Lett. 2009, **102**, 138303.

[7] Kulmala M.; Kerminen V. M.: Atm. Res. 2008, **90**, 132.

[8] Xing, X.; Danell, R. N.; Garzon, I. L.; Michaeleian, K.; Blom, M. N.; M.Burns, M.; Parks, J. H. Physical Review B 2005, **72**, 081405R.

[9] Bauer, M.; Lei, C.; Read, K.; Tobey, R.; Gland, J.; Murnane, M. M.; Kapteyn, H. C. Physical Review Letters 2001, **87**, 025501.

[10] Lang, S. M.; Popolan, D. M.; Bernhardt, T. M. Chemical Reactivity and Catalytic Properties of Size-Selected Gas-Phase Metal Clusters. In Atomic Clusters from Gas Phase to Deposited; Elsevier: Amsterdam, 2007; **Vol. 12**; pp 53.

[11] Pontius, N.; Bechthold, P. S.; Neeb, M.; Eberhardt, W. Applied Physics B: Lasers and Optics 2000, **71**, 351.

[12] K. Siegbahn, ESCA: Atomic, Molecular and Solid State Structure Studied by Means of Electron Spectroscopy, Almqvist & Wiksells (1967).

[13] M. Drescher, Z. Phys. Chem**. 218**, 1147 (2004)

[14] L. Nugent-Glandorf, M. Scheer, D. A. Samuels, A. M. Mulhisen, E. R. Grant, X. Yang, V. M. Bierbaum, and S. Leone, Phys. Rev. Lett. **87**, 193 002 (2001).

[15] Ph. Wernet, M. Odelius, K. Godehusen, J. Gaudin, O. Schwarzkopf, and W. Eberhardt, Phys. Rev. Lett. **103**, 013001 (2009).

[16] D.P. Woodruff, A.M. Bradshaw, Rep. Prog. Phys. **57**, 1029 (1994).

[17] A.V. Golovin et al., Opt. Spectrosc. **71**, 537 (1991); Z. Phys. **D 24**, 371 (1992)

[18] R. Dörner et al., Physics Reports **330**, 95 (2000)

[19] F. Martin et al., Science **315**, 629 (2007)

[20] M. Schöffler et al., Science **320**, 929 (2008)

[21] D. Rolles et al., Nature **437**, 711 (2005)

[22] D. Akoury et al., Science **318**, 949 (2007)

[23] S. Motoki et al., Phys. Rev. Lett. **88**, 063003 (2002)

[24] O. Geßner et al., Phys. Rev. Lett. **88**, 193002 (2002)

[25] A. Landers et al., Phys. Rev. Lett. **87**, 013002 (2001)

[26] B. Zimmermann et al., Nature Physics **4**, 649 (2008)

[27] A. Szöke, in: Short Wavelength Coherent Radiation: Generation and Applications, Eds. D. T. Attwood and J. Boker, AIP Conf. Proc. No. 147, American Institute of Physics, New York 1986 (p. 361)

[28] T. Jahnke et al., Phys. Rev. Lett. **88**, 073002 (2002)

[29] E. Gagnon et al., Science **317**, 1374 (2007)

[30] P. Y. Cheng, D. Zhong, and A. H. Zewail, Chem. Phys. Lett. **237**, 399 (1995)

[31] C.Y. Chen, Y.M. Li, K. Bailey, T.P. O'Connor, L. Young and Z.-T. Lu (1999), Ultrasensitive isotope trace analyses with a magneto-optical trap, Science **286**, 1139.

[32] P. Collon, W. Kutschera and Z.-T. Lu (2004), Tracing noble gas radionuclides in the environment. Ann. Rev. Nucl. Part. Sci. **54**, 39.

[33] N.C. Sturchio, X. Du, R. Purtschert, B.E. Lehmann, M. Sultan, L. J. Patterson, Z.-T. Lu, P. Mueller, K. Bailey, T.P. O'Connor, L. Young, R. Lorenzo, B.M. Kennedy, M. van Soest, Z. El Alfy, B. El Kaliouby, Y. Dawood and A.M.A. Abdallah (2004) One million year old groundwater in the Sahara revealed by krypton-81 and chlorine-36, Geophys. Res. Lett. **31**, L05503.

[34] X. Du, R. Purtschert, K. Bailey, B.E. Lehmann, R. Lorenzo, Z.-T. Lu, P. Mueller, T.P. O'Connor, N.C. Sturchio and L. Young (2003), A new method of measuring 81Kr and 85Kr abundances in environmental samples, Geophys.l Res. Lett. **30**, 2068.

[35] L. Young, D. Yang, W. Dunford (2002), Optical production of metastable rare gases. J. Phys. **B35**, 2985-2992.

[36] Y. Ding, S.-M. Hu, K. Bailey, A.M. Davis, R. Dunford, Z.-T. Lu, T.P. O'Connor and L. Young (2007), A thermal beam of metastable krypton atoms produced by optical excitation, Rev. Sci. Instrum. **78**, 023103.

2.3 Imaging Biological and Soft Condensed Matter Systems – Harald Ade (Chair)

The harmonics of JLAMP are bright enough to offer path-breaking opportunities for high resolution structural determinations of non-periodic materials and dynamic studies of soft matter systems. Further, they would allow the development of techniques for proposed new light sources with fundamental wavelengths in the 100's of eV range. Because some of the techniques are new, some of the ideas may develop along different lines, but here we present them as they presently stand.

X-ray diffraction imaging and holography, also known as lensless imaging, are well documented, rapidly developing methods whose goal is to achieve single shot, high resolution imaging from biological molecules and non-periodic samples as well as out of equilibrium pump-probe imaging for very fast dynamic studies [1-4]. These methods are well matched to a relatively low repetition rate, high peak power source such as FLASH, the European XFEL, or LCLS. Opportunities afforded by lensless imaging are already being vigorously pursued at a number of facilities and well documented. The rational for lensless imaging could be directly translated to JLAMP. The unique opportunity offered by JLAMP would be operation in the vicinity of the carbon absorption edge in third harmonic. At these energies, selective and improved contrast mechanisms can be achieved for a wide range of organic materials [5]. Presently, the carbon edge can not be reached by FLASH at the brightness levels expected from the high repetition rate of JLAMP, nor by the LCLS.

This same high average brightness also presents unique opportunities along the time "dimension", using X-ray Photon Correlation Spectroscopy (XPCS). The exploitation of this method for soft matter systems is completely analogous to the use delineated in section 2.1.3. (i) for magnetic and correlated materials. Anticipated increases in coherent flux of four orders of magnitude over existing facilities would lead to eight orders of magnitude improved time resolution Δt to measure the dynamic scattering factor $S(q, \Delta t)$. These dynamics studies can again be combined with selective and enhanced contrast by operating near the carbon edge. An important scientific application would be the study of the dynamics of lipid rafts in membranes [6,7] and a range of colloids.

A promising development would be to develop optics that would allow imaging of laser-matter interactions at high resolution, in 3D, including propagation of shocks, cracks, ablation and processing of materials; imaging of flowing or replenishable systems, such as flying cells, dynamics of lipid rafts in membranes, colloids; imaging of liquid systems (dynamics, fluctuations, mixing); single shot imaging of bio materials to overcome radiation damage limits; fast magnetic imaging; rapid sequencing of intact DNA; spectroscopic measurements of protein folding, of conformal changes, and of photoactivated reactions.

It is possible that a new generation of high resolution spectroscopies, including four-wave mixing, 2D spectroscopy, interferometry, non-linear optics and soft x-ray laser pumping could be developed. This would allow, for example, second-harmonic imaging to study distributions of non-centro symmetric molecules.

However, this section would not be complete without mentioning radiation damage. The measure and destroy approach pursued by lensless imaging avoids this by acquiring data fast enough and before the sample is altered. An important difference between dynamics studies with XPCS and lensless imaging is, however, that only ensemble averages and their dynamics are studied with XPCS. This allows the radiation to be spread over many features or structures of interest, and also allows the x-ray beam to be scanned, or the sample replenished in some way, e.g. via a flow cell. The increased experimental complexity is not that challenging, but would require some engineering. The high time resolution and combination with soft x-ray energies would provide unique opportunities in the Nation if not worldwide to characterize soft matter systems.

References for Section 2.3

[1] H. N. Chapman, "X-ray imaging beyond the limits", Nature Materials **8**, 299 (2009).

[2] H.N. Chapman, A. Barty, M. J. Bogan, S. Boutet *et al.*, "Femtosecond diffractive imaging with a soft-X-ray free-electron laser", Nature Physics **2**, 839 (2006).

[3] D. Shapiro, P. Thibault, T. Beetz, V. Elser, M. Howells, C. Jacobsen, J. Kirz, E. Lima, H. Miao, A. M. Neiman, and D. Sayre, "Biological imaging by soft X-ray diffraction microscopy", Proceedings of the National Academy of Sciences of the United States of America **102**, 15343 (2005).

[4] S. Eisebitt, J. Lüning, W. F. Schlotter, M. Lorgen, O. Hellwig, W. Eberhardt, and J. Stöhr, "Lensless imaging of magnetic nanostructures by X-ray spectro-holography", Nature **432**, 885 (2004).

[5] H. Ade and A. P. Hitchcock, "NEXAFS microscopy, resonant scattering and resonant reflectivity: composition and orientation probed in real and reciprocal space", Polymer **49**, 643 (2008).

[6] S. Munro, "Lipid rafts: Elusive or illusive?", Cell **115**, 377 (2003).

[7] C. Eggeling, C. Ringemann, R. Medda, G. Schwarzmann, K. Sandhoff, S. Polyakova, V. N. Belov, B. Hein, C. von Middendorff, A. Schonle, and S. W. Hell, "Direct observation of the nanoscale dynamics of membrane lipids in a living cell", Nature **457**, 1159 (2009).

3. FEL Accelerator

In this section we describe the design of the JLAMP facility, including the injector, accelerator, insertion devices and optical components, end stations and expected performance. The accelerator system is designed with two passes of recirculation to double the beam energy and with energy recovery of the beam in another two passes to reduce the RF power requirements, eliminate the need for a high power beam dump, and essentially eliminate activation from photo-neutrons in the facility. The FEL operates as an amplifier with seeding in its baseline configuration but we have also provided capability to operate as a high gain oscillator or with high gain harmonic generation to bootstrap the system to shorter wavelengths. These alternate operating modes have been provided both for experimental flexibility as well as risk reduction at short wavelengths should seed laser technology not progress as rapidly as desired. Responding to user requests, we have also included a THz wiggler to provide a long wavelength pump/probe source.

Upgrades described in this section are relative to the existing machine layout shown in Figure 3.1. The machine as it stands delivers 7 micron emittance bunches of 135 pC at average currents up to 10 mA (74.85 MHz repetition rate). The present beam energy is limited to 120 MeV although it has operated up to 160 MeV in the past. The system has lased in the 0.7 to 11 micron region and produced up to 14.3 kW of average power at 1.6 microns. At lower powers (optics limited) it can tune rapidly over factors of 7 in wavelength. The stable performance of this machine over many years establishes a foundation for the upgrade of the system to VUV and soft x-ray production.

It is comprised of a 10 MeV injector, a linac consisting of three Jefferson Lab cryomodules generating a total of 80 to 160 MeV of energy gain, and a recirculator. The latter provides beam transport to, and phase space conditioning of, the accelerated electron beam for the FELs and then returns and prepares the drive beam for energy recovery in the linac.

The injector produces up to 10 mA at 10 MeV. The current is produced by a single bunch charge of 135 pC while maintaining a 75 MHz repetition rate. The linac comprises three cryomodules; the first and third incorporate conventional five-cell CEBAF cavities, and the central module is based on seven-cell JLab cavities [1]. The beam is accelerated (energy recovered) off crest (off trough) so as to impose a phase energy correlation on the longitudinal phase space used in subsequent transport to longitudinally match the beam to the required phase space at the wiggler (dump). That is to say, the bunch is kept relatively long during acceleration, compressed to high peak current and ~100 fs pulse lengths just before the wiggler, then temporally expanded before reinsertion into the energy recovery phase of the linac.

The electron beam can be sent through the IR wiggler beam path or alternatively through the UV wiggler. Switching between the operational modes requires simply setting new current values for the magnets.

The energy recovery transport consists of a second Bates-style end loop followed by a six-quad telescope [2]. The beam is matched to the arc by the second telescope of the FEL insertion; the energy recovery telescope matches beam envelopes from the arc to the linac acceptance. Because energy recovery occurs off-trough, the imposed phase-energy correlations are selected to generate energy compression during energy recovery, yielding a long, low momentum spread bunch at the dump. Measurements indicate that the upgrade will tolerate an induced energy spread from the FEL of 15%—compressing it to a final spread of order ±1%—despite the large ratio of final to initial energy. Calculations and measurements show that the emittance growth due to coherent synchrotron radiation (CSR) is not a problem for this design [3] but may impact operation at higher charge.

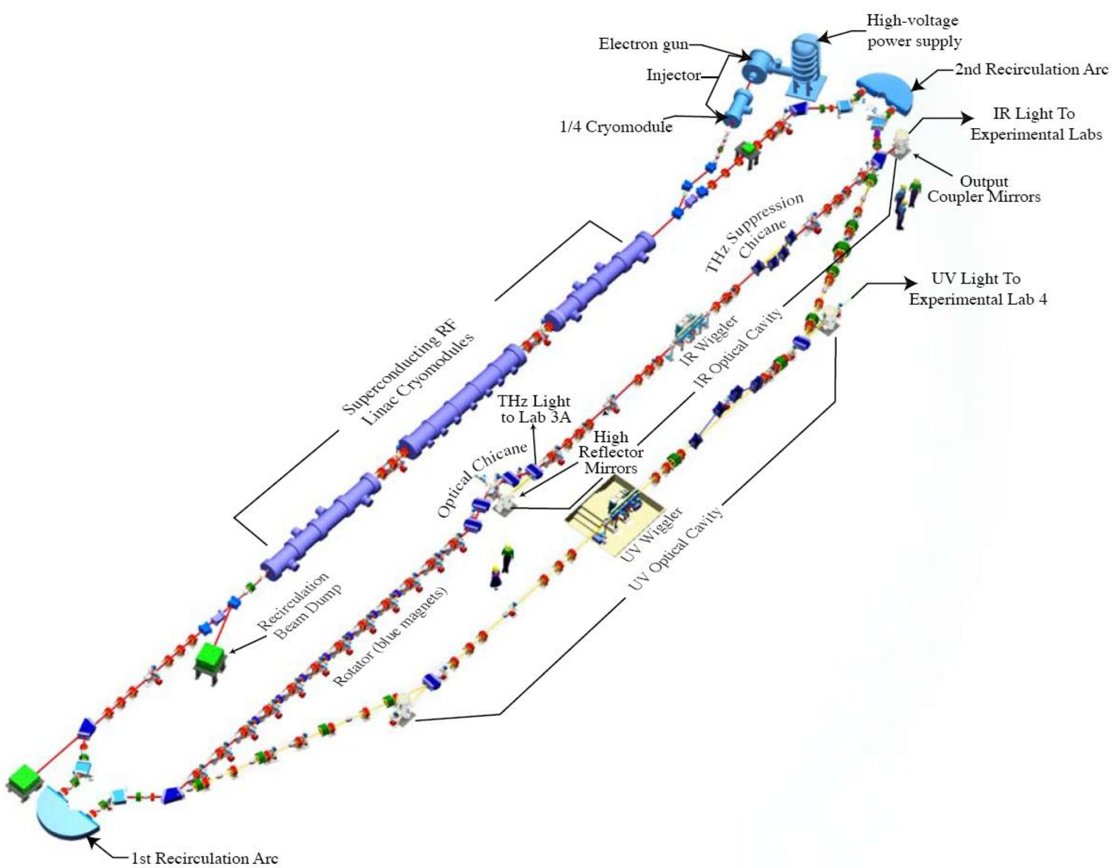


Figure 3.1. *Schematic of the existing JLab light source facility.*

The machine delivers beams of high power THz, IR, and soon UV to a set of user labs for scientific and applied studies. Past studies on the IR Demo, an earlier iteration of the same machine, were extremely successful in exploring vibrational dynamics of interstitial hydrogen in crystalline silicon, carbon nanotubes, and pulsed laser deposition [4,5]. Future applications will include those as well as microengineered structures, nonlinear dynamics in atomic clusters, and metal amorphization.

References for Section 3

[1] Robert Rimmer, Richard Bundy, Gary Guangfeng Cheng, Gianluigi Ciovati, Edward Daly, Richard Getz, James Henry, William Robert Hicks, Peter Kneisel, Stephen Manning, Robert Manus, Karl Smith, Mircea Stirbet, Larry Turlington, Lynn Vogel, Haipeng Wang, Katherine Wilson, Genfa Wu, "JLab High-Current *cw* Cryomodules for ERL and FEL", Proceedings of PAC 07, Albuquerque, New Mexico, p. 2493.

[2] D. Douglas, et al., "Driver Accelerator Design for the 10 kW Upgrade of the Jefferson Lab IR FEL", Proc. XXth International Linac Conference, Monterey, CA August 2000.

[3] S. Benson, G. Biallas, J. Boyce, D. Bullard, J. Coleman, D. Douglas, F. Dylla, R. Evans, P. Evtushenko, A. Grippo, C. Gould, J. Gubeli, D. Hardy, C. Hernandez-Garcia, K. Jordan, J. M. Klopf, W. Moore, G. Neil, T. Powers, J. Preble, D. Sexton, M. Shinn, C. Tennant, R. Walker, S. Zhang and G.P. Williams, "The 4th Generation Light Source at Jefferson Lab", Nucl. Instrum. Methods **A582**, 14-17 (2007).

[4] G. Luepke, X. Zhang, B. Sun, A. Fraser, N. H. Tolk, and L. C. Feldman, "Structure-Dependent Vibrational Lifetimes of Hydrogen in Silicon", Phys. Rev. Lett. **88**, 135501, 2002.

[5] A. Reilly, C. Allmond, S. Watson, J. Gammon and J-G. Kim, "Pulsed laser deposition with a high average power free electron laser: Benefits of subpicosecond pulses with high repetition rate" J. Appl. Phys. **93** 3098 (2003).

3.1 Facility Status and Ongoing Program

We are working through an Air Force Research Labs (AFRL) effort to replace one cryomodule. This will boost the electron beam energy by 40 MeV to the 160 MeV necessary to achieve lasing in the UV. In addition, we are funded by BES to design, build, and test a new superconducting radiofrequency linac for our injector, which would also help set the stage for the short wavelength output. The UV FEL, which is currently being commissioned, has the potential to achieve kilowatts of average power at 300 nm, which implies watts of power in the third harmonic at 100 nm. This places the average output flux 2–3 orders of magnitude higher than FLASH, but with a lower peak power.

3.2 Hardware Upgrade

For JLAMP, we will increase the electron beam energy by replacing three cryomodules with more advanced C100 modules and add new control modules. We will also add a recirculation line and 10 m undulator. This process will boost the electron beam energy by 150 MeV to 300 MeV in a single pass. (See Figure 3.2.) Incorporating recirculation accelerates the beam to 600 MeV. Implementing soft x-ray high harmonic generation (HHG) seeds will permit amplification of light in the 1 to 30 nm range in ultrashort pulses of 30 fs or less. The narrow bandwidth and short pulse length of the seed laser can be retained, and through the use of an advanced elliptical undulator, soft x rays with controlled polarization can be produced. Wavelengths of 40 nm and longer can easily be directed into our existing user facility with mirrors. For wavelengths shorter than 40 nm, we envision a dedicated soft x-ray end station located to the east of the existing FEL building. Light transport can be achieved by simply boring through an existing FEL wall, making the new end station just slightly below grade with modest shielding requirements due to the relatively "clean" electron beam produced by our superconducting linac. The 40' by 60' new end station is relatively simple to construct and is a flexible and cost-effective way to provide for user needs. Several end station systems can be set up in the room and moved into the beam path as desired.

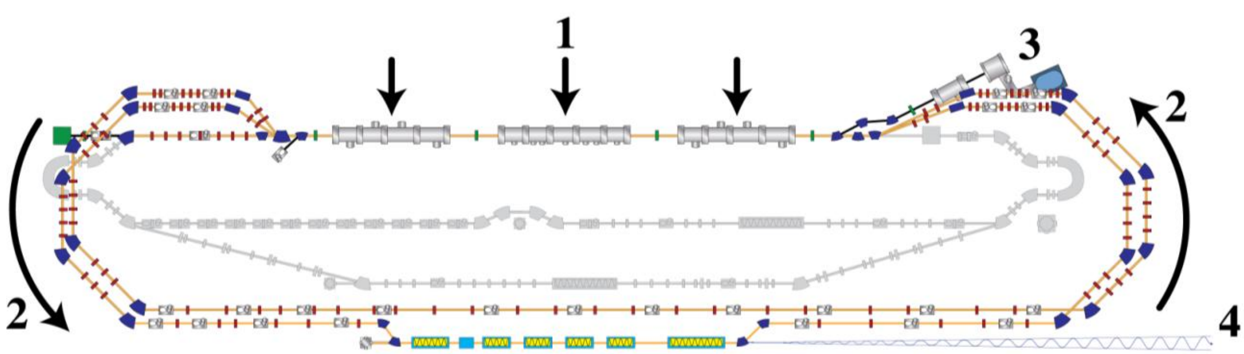


Figure 3.2. *Schematic showing the four modifications that will be made to the JLab FEL to make JLAMP: 1) replace three cryomodules; 2) add two recirculation beamlines; 3) upgrade the present injector; and 4) provide soft x-ray and THz undulators for light production. (Lattice is schematic, not real design.)*

3.3 Technical Risks and Justification of Approach

The desire for shortest possible wavelength operation drives the demand for highest beam energy possible, lowest emittance achievable and shortest undulator wavelength technically feasible with a reasonable gap. Critical to this design is the transport of a low emittance beam around a recirculation path. Details are reported in Ref. [1].

The electron beam energy that can be achieved from the linac is based on the available real estate for acceleration and the cavity gradients that can be achieved. It is the tremendous progress that has been achieved in SRF gradient performance that permits consideration of this program. When CEBAF accelerator construction started in 1990, each cryomodule containing eight accelerator cavities was specified at 20 MV of acceleration. By the time the construction was completed the best modules were actually producing double this acceleration, 40 MV. Since that time substantial progress in the processing of cavities as well as better engineering designs permit 100 MV acceleration per module. Such is the specification of the cryomodules (Figure 3.3) for the CEBAF 12 GeV Upgrade presently under construction. In the FEL facility there is room for three of these modules so that 300 MeV electron beams can be produced in a single pass. It may in fact be feasible to achieve energies higher than 300 MeV, and we will aggressively pursue the development of higher gradient operation as it will provide access to even shorter operating wavelengths than indicated in the baseline. However, 300 MeV is insufficient energy to reach the highest photon energies desired by many users. The final design of the cryomodules will be determined based on our experience with 12 GeV and also on the results of our BES funded program to test linacs with a cell shape and damping better optimized for light sources.

The CEBAF accelerator uses five passes through two linacs to produce its present 6 GeV electron beam. Several groups are pursuing the use of recirculation in their 4^{th}GLS designs. An example is KEK, which is presently constructing the prototype for their 4^{th}GLS and will involve two passes through a 120 MeV superconducting linac [2]. The primary issue in recirculating such beams is the concern that coherent synchrotron emission will cause a growth in electron beam emittance and ruin the brightness. The strength of this effect goes as the square of the charge and inversely with the bunch length. Certainly there are serious issues at the 1 nC levels of charge originally set as the LCLS specification; hence we have designed our system to operate at 200 pC and lower. We have also chosen a lattice design which keeps the bunch length long until high current is needed for gain at the FEL itself. The paragraphs below present an overview of that transport system.

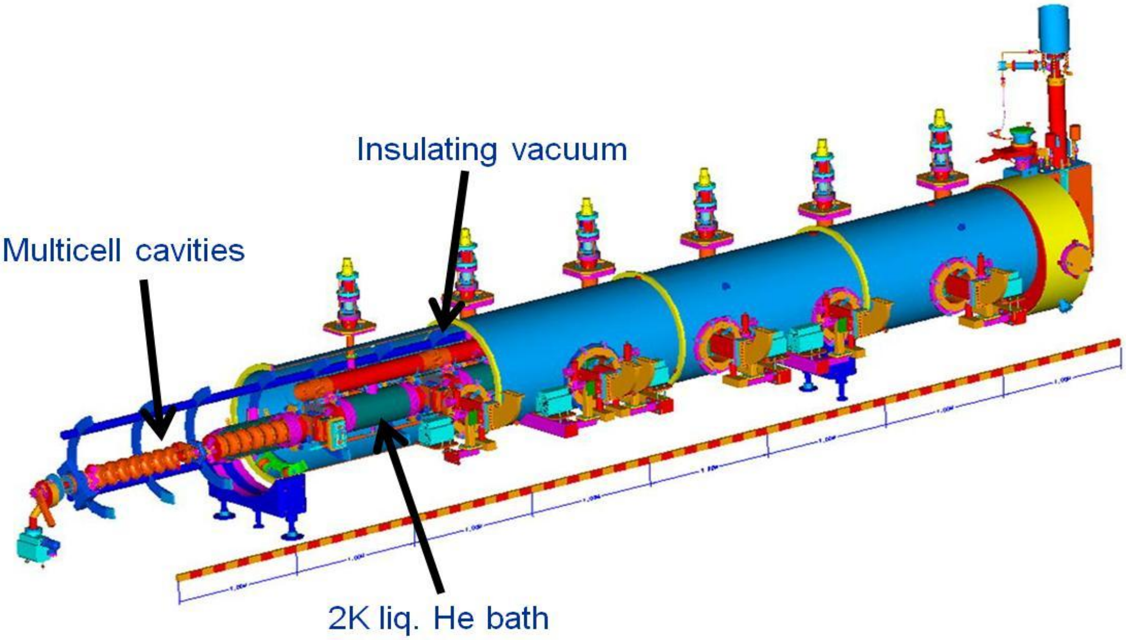


***Figure 3.3**. Jefferson Lab's 100 MV cryomodule for the upgrade of the CEBAF accelerator to 12 GeV. Components are out for bid.*

References for Section 3.3

[1] D. Douglas and C. Tennant, "Use of Re-circulation in Short Wavelength FEL Drivers", JLab Tech Note 09-046 (2009).

[2] ERL09: Energy Recovery Linac 45th ICFA Beam Dynamics Workshop, Cornell, June 8-12, 2009.

3.4 Accelerator Transport

Providing a *cw* drive beam for a short-wavelength FEL requires:

1. A high brightness electron source.
2. An injector and injection line that preserve beam quality.
3. A phase space management scenario using the beam provided by the injector; in particular, there must be a longitudinal matching scenario giving adequate bunch compression/peak current at the wiggler and appropriate provision for transverse matching.
4. The ability to maintain beam brightness during the acceleration, transport and compression process by avoiding the impact of lattice aberrations (chromatic and geometric) and collective effects such as beam breakup (BBU), other wakefield/impedance effects (e.g. the microbunching instability (MBI), resistive wall, etc.), space charge, and coherent synchrotron radiation (CSR).

These challenges have been/are being met in pulsed FEL systems (experimental demonstrations such as LEUTL, VISA, FLASH, LCLS, FERMI) and there is a consensus that they can be met in a continuous wave FEL driver with "linear" topology (i.e., without recirculation) such as WiFEL. The details of an analysis which shows that the brightness objectives can be met in recirculation is presented in Ref. [1] of subsection 3.3. We briefly summarize the points from that section in the paragraphs below, detailing additional challenges introduced, and present a notional approach for addressing a key issue—specifically, the problem of beam quality preservation during recirculation.

It should be noted that success of this approach would have major implications in the cost of a 2.5 GeV 4^{th}GLS by reducing substantially the amount of linac, RF, and cryogenics required. Thus a secondary goal of this program is to demonstrate important technology for future hard x-ray next generation user facilities.

The cost impact of recirculation is significant even at the modest gradient planned for JLAMP: a seven-cell 1497 MHz cavity at 20 MV/m accelerating two passes of 1 mA beam will draw ~30 kW RF power without energy recovery, but (depending on the choice of Q_L) may draw only 1 to 2 kW with recovery. This represents a savings of ~1/4 MW RF drive—a cost reduction of order 2.5 M$—per cryomodule.

Many issues are, however, introduced by the use of recirculation, including:

1. The need for an appropriate (beam-quality preserving) injection merger.
2. The potential impact of additional beam transport length; in particular, the effect of wakefields, environmental impedances (with their potential to aggravate multibunch instabilities (MBI)), and space charge.
3. Additional complexity in longitudinal matching.
4. Use of common transport for multiple beams (during energy recovery).
5. Possible beam breakup (BBU) limitations.
6. The impact of lattice aberrations and coherent synchrotron radiation (CSR) during recirculation.

Experience with our operation in the IR/UV Upgrade FEL has shown that managing the longitudinal aspects correctly can relieve the impact of collective effects. First we must provide for the introduction of the linac beam to the arcs. To add in the system to our present beamlines we consider the use of a spreader/recombiner as show in Figure 3.4.

Figure 3.4a: *IR upgrade configuration.*

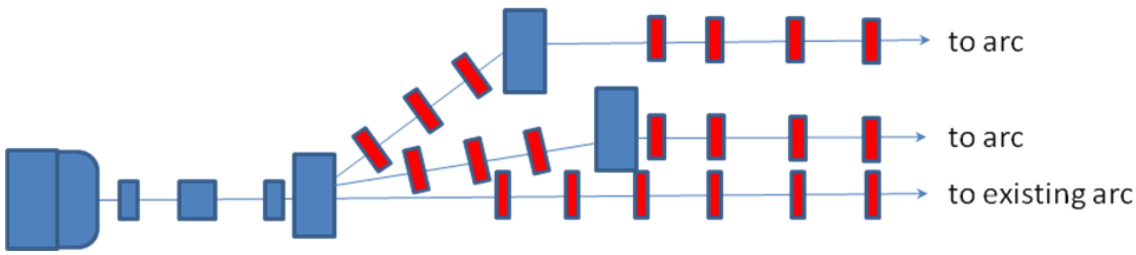


Figure 3.4b. *Notional JLAMP configuration.*

3.4.1 Recirculation Arc

Following separation of the various passes, we recirculate the beam using a 180^{o} bending arc comprised of several periods of FODO (quad-dipole-quad) cells. This will make the arc footprint nearly circular (giving the most efficient utilization of available space), will provide periodicity and symmetry for aberration management and tuning capability (e.g. control of momentum compactions and dispersion), and—given that we are accelerating the first pass beam on the rising part of the RF waveform—will decompress the bunch length and thereby alleviate CSR effects.

The specific choice of numerology is driven by the design and optimization process. We find that adequate performance is provided by using twelve dipole-quad-dipole cells tuned (using the quad strength as a single family and the field index in the dipoles) to give 1/6 integer phase advance in the bending plane and 1/4 integer phase advance in the non-bending plane. With this choice, the arcs are second order achromats, coupling error effects are suppressed (because of the split tunes), and the system momentum compactions can be tuned using periodically spaced "subfamilies" of the quads. Specifically, the second, fifth, eighth, and eleventh quads are separated by 180^{o} in betatron phase in the bending plane and 270^{o} in the non-bending plane. They therefore can be used to perform a one-knob dispersion bump and modify M_{56} (energy/path length correlation) while keeping the arc achromatic; the quarter-integer separation in the non-bend plane serves to suppress perturbation of the out-of-plane betatron match. The specific choice of sixth integer horizontal phase advance ensures this bump occurs across three dipoles (rather than two as would occur for a quarter integer tune), providing potentially greater dynamic tuning range. Sextupoles at these locations can be similarly used to adjust T_{566} (and higher order correlation); similar multipoles at the locations of other focusing elements serve to manage linear and nonlinear dispersion.

The use of twelve cells over a roughly 6 m radius transport ensures that the matched Twiss parameters and dispersions are small. This alleviates aberrations and error sensitivity, reduces response to CSR, and keeps the beam size relatively small—even during recovery of a potentially large energy spread beam.

We use dipole fields of ~10 kG, corresponding to a 1 m radius bend over a length of ~1/4 m. The higher energy (600 MeV) line is expected to use similar peak bend field, yielding a 2 m bend radius and requiring dipoles of length ~1/2 m. These appear to be adequate to limit ISR to tolerable levels (see following analysis). Aberration management and nonlinear compaction control will be provided by way of sextupole components in the dipoles and in or near the quadrupoles. The latter can be the subject of a trade study to determine which of several methods is most cost-effective.

The return arc at the east end of the vault is taken to be identical to the first arc. The momentum compactions of each add, debunching the beam without parasitic compression. Observe that care must be taken to control environmental impedances; the longitudinal phase space is stretched rather thin over much of this transport and is thus susceptible to wake effects. However, as the bunch is elongated the peak current is very low, so there is little driving term to couple to the environment. Detailed analysis will be required to establish and enforce an impedance policy and to certify that microbunching effects are not problematic.

3.4.2 Backleg Transport

This line must cleanly transport the beam to the return arc without introducing aberration effects. It will also provide space for utility functions, such as diagnostic stations and path length control chicanery. In the full energy arc, the FEL will be embedded in the backleg as well. In this exercise, we choose a simple quadrupole FODO array. Phase advance is chosen to assist in aberration suppression. The first and final two cells are half-length to provide good beam envelope control while smoothly matching the arcs (with small matched beta, order 2 m peak) to the backleg transport (with rather larger matched beta, order 10 m peak). The uniform transport region comprises 8 FODO cells, with, as mentioned, two upstream and two downstream half-length cells used as five-quad matching telescopes. Recombination is done in a manner similar to the original spreader.

3.4.3 Beam Envelopes

Figure 3.5a presents (zero charge) optics for the linac (the recirculator arcs are modeled as zero length matrices at locations denoted by the heavy vertical black lines).

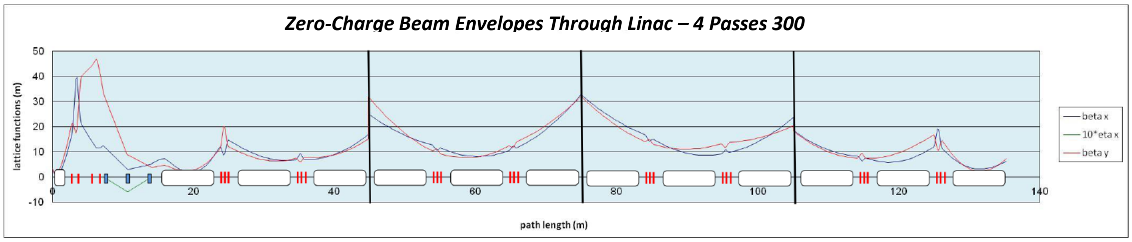


***Figure 3.5a**. Linac on each pass; recirculator transforms denoted by heavy black lines.*

Figure 3.5b shows the propagation of these through the first pass of the 300 MeV recirculation line.

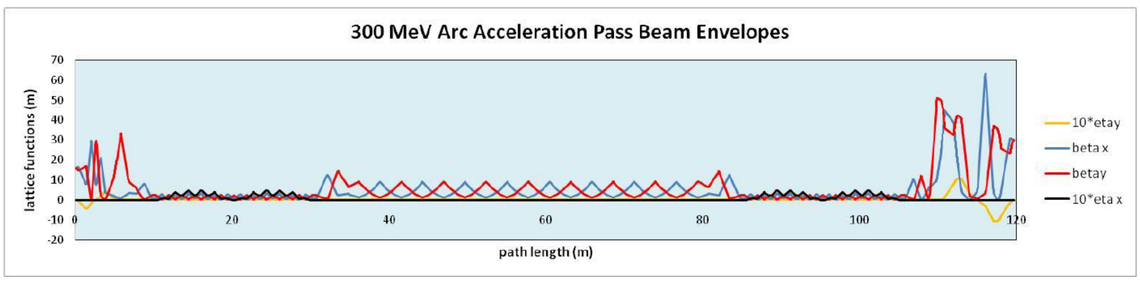


***Figure 3.5b**. Beam envelopes through 300 MeV recirculator (based on generic input values of β=16 m, α=-1, match to generic output values β=30 m, α =1).*

Figure 3.5c shows the same for the recovery cycle pass. Values are modest, suggesting that error and aberration sensitivities and halo will be manageable and that BBU thresholds will be reasonable. As one would expect, there is moderate mismatch during transitions into/out of the linac, but peak beam envelopes remain reasonable.

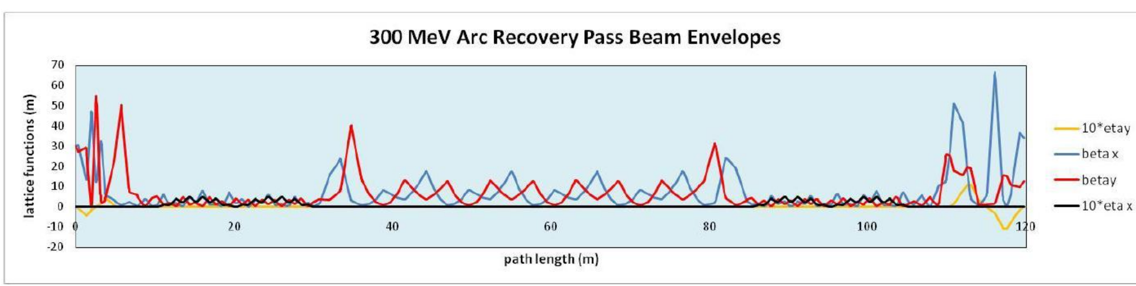


***Figure 3.5c**. Beam envelopes through 300 MeV recirculator (based on generic energy recovery input values of β=30 m, α=-1).*

3.4.4 Aberration Analysis

DIMAD analysis of both chromatic and geometric aberrations across the full recirculation arc (linac to linac) has been performed and indicates that aberration management is adequate. Momentum scans indicate that beam quality of the accelerated beam will be well maintained (as parameters are extremely flat over ±1% moment spread) and that orbit and Twiss parameters are under reasonable control over a rather larger range so that energy recovery can be successfully executed. The results of analysis of geometric aberration indicate the transverse phase space remains regular out to 100 times the nominal emittance (100 mm-mrad normalized) across a moderately large momentum range (±1%), indicating the core beam will remain undistorted, halo will propagate cleanly, and the system should show reasonable freedom from orbit dependences in the optics.

We have, in addition, done a ray-trace simulation of the first pass for a 6σ Gaussian beam with 1 mm-mrad normalized transverse emittance and 50 keV-psec longitudinal emittance. The longitudinal match is intended to be modeled as above so that the rms momentum spread is 0.5%. The linac is simulated by injecting a fully upright beam with this momentum spread and bunch length appropriate to the longitudinal emittance, and then back-chirping the beam with a (linear) matrix transform to impose the appropriate path length energy correlation. Essentially no emittance growth is observed.

3.4.5 Impact of Coherent Synchrotron Radiation (CSR)

CSR-driven emittance dilution is the primary concern for this design study. The design conceptually avoids the issue by chirping the bunch by accelerating on the rising portion of the waveform (and thereby also alleviating LSC effects), decompressing the chirped bunch during transport through arcs with $M_{56}>0$, and providing isochronicity by recombining the beam with a staircase achromat with $M_{56}<0$ just prior to reinjection.

Effects of CSR in the 300 MeV transport were simulated using a 1-d model in DIMAD [1]. We find that at 200 pC, the effects are modest, with little transverse effect and moderate but regular distortion in the longitudinal phase space. Results of the simulation are shown in Figure 3.6. Results are almost indistinguishable between the cases. However, the computed longitudinal emittance has in fact doubled. The nature of the effect can be seen if the bunch charge is raised to 1 nC [Ref. 1 of subsection 3.3].

The effect of the wake is then apparent, as is a palliative measure; we simply adjust the lattice higher orders to compensate for the CSR effects. It is apparent that the distortion of the longitudinal phase space can be largely compensated, in analogy to the compensation of such effects in transverse phase space proposed over a decade ago by Dowell [2], although—in as much as this transport is common to both the accelerated and recovered beams—care must be taken to insure this does not adversely influence the energy recovery process. The compensation can equally well be done at full energy in the final compression, where it will not influence energy recovery at all.

The CSR tracking results indicate that CSR is adequately managed, and also indicate that lattice aberrations are not an issue.

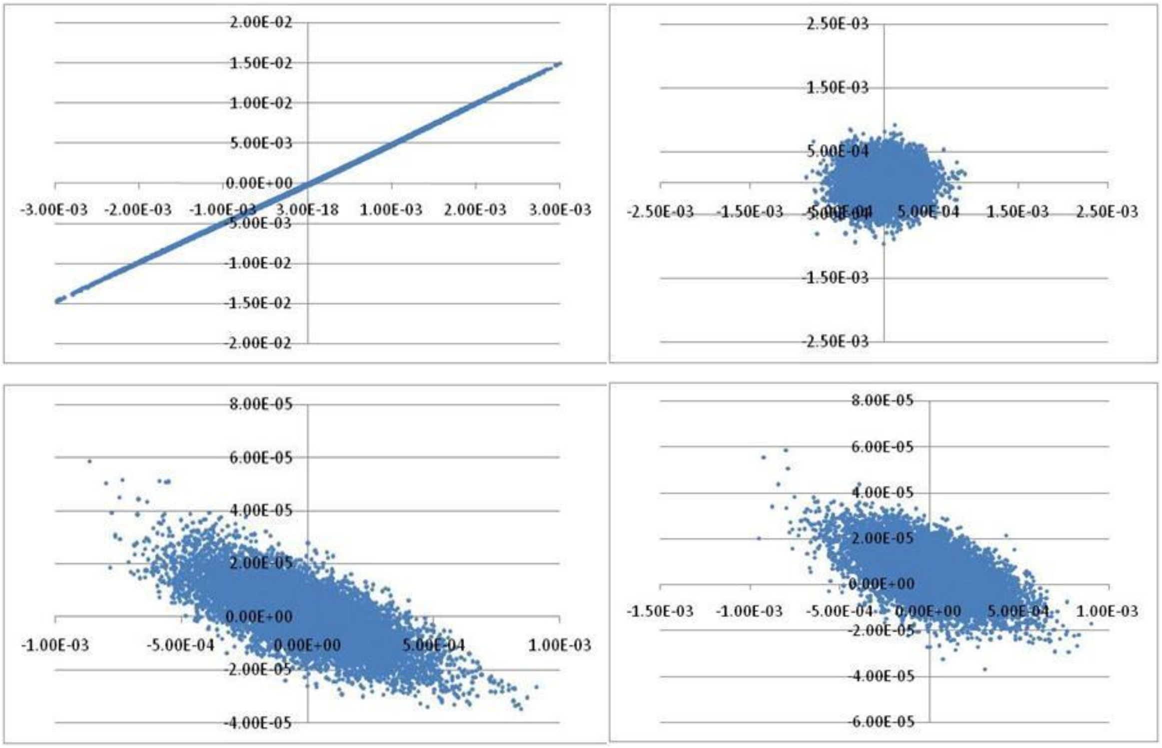


***Figure 3.6**: Results of ray-trace simulation of 200 pC 6σ beam with 1 mm-mrad normalized transverse emittance and 50 keV-psec longitudinal, with linear chirp equivalent to first pass acceleration through linac 10^o ahead of crest and CSR effects. Top: l-δp/p (left), xy (right); bottom: xx' (left), yy' (right).*

We have also extended our analysis to higher charge bunches of 1 nC to determine sensitivities. The CSR-induced curvature can be compensated using trim on the lattice T_{566}. See Ref. 1 of subsection 3.3 for these results.

While studies and design optimizations are still ongoing it is clear that recirculation can be used successfully in the JLAMP design for significant cost reduction with little performance penalty. A successful demonstration would establish the basis for even greater benefits to a future hard x-ray next generation user facility.

References for Section 3.4

[1] D. Douglas, "Suppression and Enhancement of CSR-Driven Emittance Degradation in the IR-FEL Driver", op. cit.

[2] D. Dowell, "Compensation of Bend-Plane Emittance Growth in a 180 Degree Bend", Proc. IEEE PAC 1997.

3.5 Low Emittance Gun and Injector

In order to realize the JLAMP FEL performance presented here, the electron beam delivered to the FEL must have a bunch charge of 200 pC and a normalized transverse emittance of less than 1 mm mrad. Operating at a 4.68 MHz repetition rate this corresponds to a *cw* average beam current of 1.0 mA. At present, there is no definitive method of producing such a bright *cw* beam. The injector performance is critical as the electron beam properties can only deteriorate during transport to the FEL.

The injector can be defined as the region of the accelerator where the beam is generated and where the energy is still so low that transverse space charge forces must be managed. This is dependent on the charge of the electron bunch. However, it has been shown experimentally that a 5 MeV beam can be injected into the JLab FEL while preserving emittance [1]. Based on this experience, the JLAMP injector is expected to operate in the 5 to 10 MeV range.

There are three differing injector technologies that may potentially meet the JLAMP injector requirements. Each of these schemes assumes the use of a photocathode and a laser to generate the electron beam. These are:

1. The very high frequency (VHF) normal conducting (NC) RF gun injector, for example the LBNL 187MHz [2] and ELSA 144MHz [3] guns.
2. The DC gun injector, as used at the JLab FEL [4], Cornell ERL [5] and in design for the KEK/JAEA [6] ERL light source.
3. The superconducting radiofrequency (SRF) gun injector, as designed for WiFEL [7].

All of these approaches have advantages as well as some technical challenges. Table 3.1 summarizes each gun's characteristics. The potential of each gun technology to meet the JLAMP specification is roughly equal; however, each is at a different stage of development. JLab has existing expertise with normal conducting cavities, SRF technology, DC guns, photocathode and drive laser operations, and ultra high vacuum technology. This experience ideally places JLab to apply any of the above-described options.

We have chosen to collaborate with Lawrence Berkeley National Laboratory (LBNL) in the development of a VHF NC gun as the baseline design for the JLAMP injector. LBNL designed and modeled this quarter-wave VHF NC gun, which is capable of *cw* operation and is predicted to produce an emittance of 1 mm mrad with 1 nC electron bunches [2]. This work is being funded at LBNL by BES following panel recommendations from the BES Workshop on Accelerator Physics for Future Light Sources. A prototype cavity is being constructed and is expected to be assembled for testing late in FY2010.

The additional components comprising the injector system can be designed to be flexible enough to accommodate any of the gun technologies, so a new JLab DC gun approach will remain a viable backup should unforeseen issues develop with the baseline. Likewise, should an SRF injector technology eventually prove to be superior, we will be in a position to take advantage of that development.

DC gun	Very high frequency NC gun	SRF gun
Advantages a. Demonstrated *cw* operation in an ERL FEL delivering ~15000 C since 1998 b. Demonstrated 9 mA average current, higher than required c. Extremely good vacuum in the gun chamber (~10^{-11} Torr) for long cathode lifetime (550 C or 30 hours operation at 5 mA *cw*) d. Not sensitive to contamination by cathode material e. Only system to demonstrate use of a GaAs:Cs cathode, with the lowest thermal emittance	*Advantages* a. 750 keV gun exit energy b. Gradients up to ~ 20 MV/m possible. c. Emittance compensation can be used in its classical way (demonstrated and understood) for potentially high brightness at charges up to 1 nanocoulomb. d. Based on mature copper RF cavity technology e. Not sensitive to contamination by cathode material	*Advantages* a. Potentially very high gun exit energy b. Potentially very high peak accelerating field of ~ 40 MV/m c. Extremely good vacuum in the gun cavity which should lead to very good cathode lifetime
Challenges a. Relatively low beam energy at the exit of the gun, 350 keV @ JLab. (New gun is designed for 500 keV) b. Accelerating gradient in the gun is smaller than that of RF systems, (~ 4 MV/m at JLab) c. Drive laser spot displaced from electrostatic center, not the best arrangement for complete emittance compensation	*Challenges* a. Demonstrating an acceptable vacuum level to allow for good cathode lifetime b. Mechanical stability of the relatively big cavity c. Low level of field emission	*Challenges* a. Operation with a normal conducting cathode. Thermal isolation of the cathode is needed and cavity contamination from the cathode must be prevented. b. If a superconducting cathode is used, a high-power UV drive laser is required c. No data on how scattering of the UV laser on a cathode or the cavity walls will limit the average current of the system d. More restrictions on where emittance compensating solenoids can be placed e. Survival of a photocathode in both an RF and cryogenic environment

Table 3.1. *Advantages and challenges for differing gun option.*

3.5.1 VHF NC Gun Development at LBNL

The LBNL photo-injector was designed to be broadly useful for 4th generation light sources. A cross section of the gun cavity and its principal features is shown in Figure 3.7. The low frequency 187 MHz cavity is compatible with both 1.3 and 1.5 GHz superconducting technology. This design is suitable for use in JLAMP as the frequency is already a sub-harmonic of the JLab FEL fundamental frequency, 1.497 GHz.

The cavity geometry was optimized to maximize the shunt impedance, minimize the wall power density, reduce the mechanical stress, simplify fabrication, maximize vacuum performance and facilitate photocathode replacement. The large cavity size allows for conventional cooling when operating *cw*, which is not possible with higher frequencies where thermal loads from ohmic losses are problematic. Additionally, the long RF wavelength permits large high conductance vacuum ports necessary for achieving 10^{-11} Torr vacuum.

The cathode gradient will be ~20 MV/m, low enough not to represent an issue with field emission and voltage breakdown. The beam output energy will be 750 keV, higher than that demonstrated by DC guns. Extensive multipactoring simulations with several different codes have been performed showing that a broad region around the operating voltage is free of multipactoring resonances. The long transit time for the electron bunch in the cavity gives longitudinal dynamics similar to a 750 keV DC gun, so a normal conducting buncher cavity may be required.

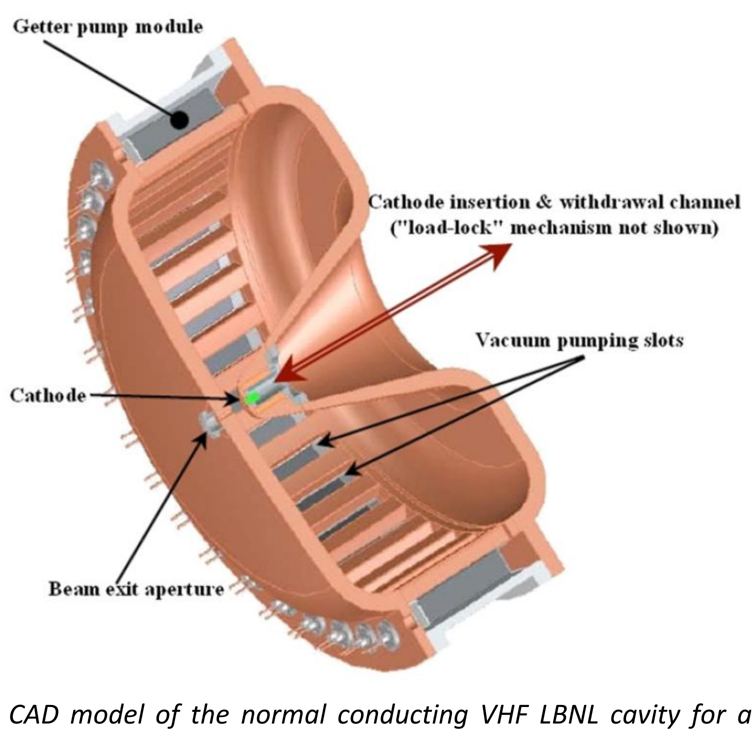


Figure 3.7. *The 3-D CAD model of the normal conducting VHF LBNL cavity for a high repetition rate photo-injector. The cavity internal diameter is 0.694 m.*

A solenoid embedded in the cathode nose will be used as "bucking" coil to nullify the magnetic field on the cathode surface, or for generating a correlation in the transverse plane required for emittance exchange techniques.

The photo-cathode will be located on the top of a cathode puck, which is part of the load-lock vacuum system that will allow for cathode replacement. The load-lock system will be based on the present design operating at the FLASH FEL. One cathode option under consideration uses the relatively robust Cs_2Te cathode combined with a Ti:Sapphire laser with ~ 1 W power in the infrared converted to the 3rd harmonic (~ 5% conversion efficiency is assumed). Another option under investigation is to use alkali antimonides photo-cathodes, e.g., $SbNa_2KCs$ combined with a ~ 100 mW average power Nd:YVO4 laser frequency doubled to 532 nm. The photoemission in the green permits the use of a relatively low power laser system. It is also possible to achieve more effective and easier laser pulse shaping required for improving the beam dynamics performance. Multi-alkali antimonides are potentially capable of more than 10% quantum efficiency. However, such cathodes are very sensitive to contamination and require the low vacuum pressures that the VHF gun should be able to generate.

A preliminary injector simulation study has been performed assuming the layout shown in Figure 3.8. Here the gun is followed by an emittance compensation solenoid and six nine-cell Tesla-like cavities at 1.3 GHz. The thermal emittance of a Cs_2Te cathode was included in the simulation. One result from an optimization study, shown in Figure 3.9, gives the 95% normalized transverse emittance as 1 mm mrad for a 1 nC electron bunch.

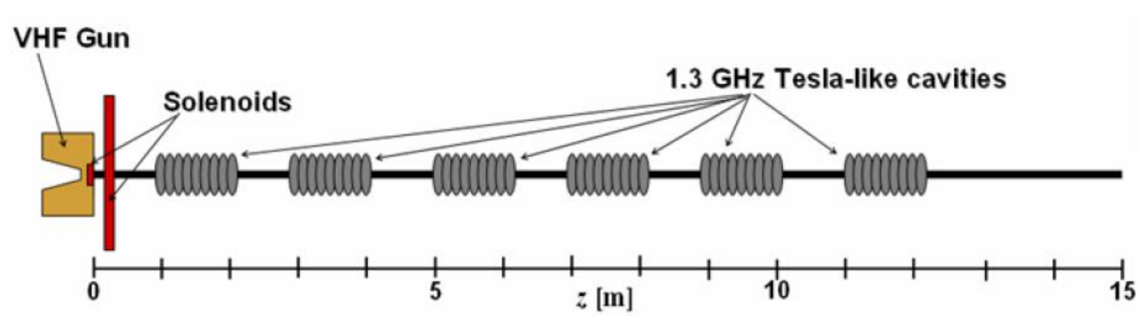


Figure 3.8. *Injector layout used in the simulations.*

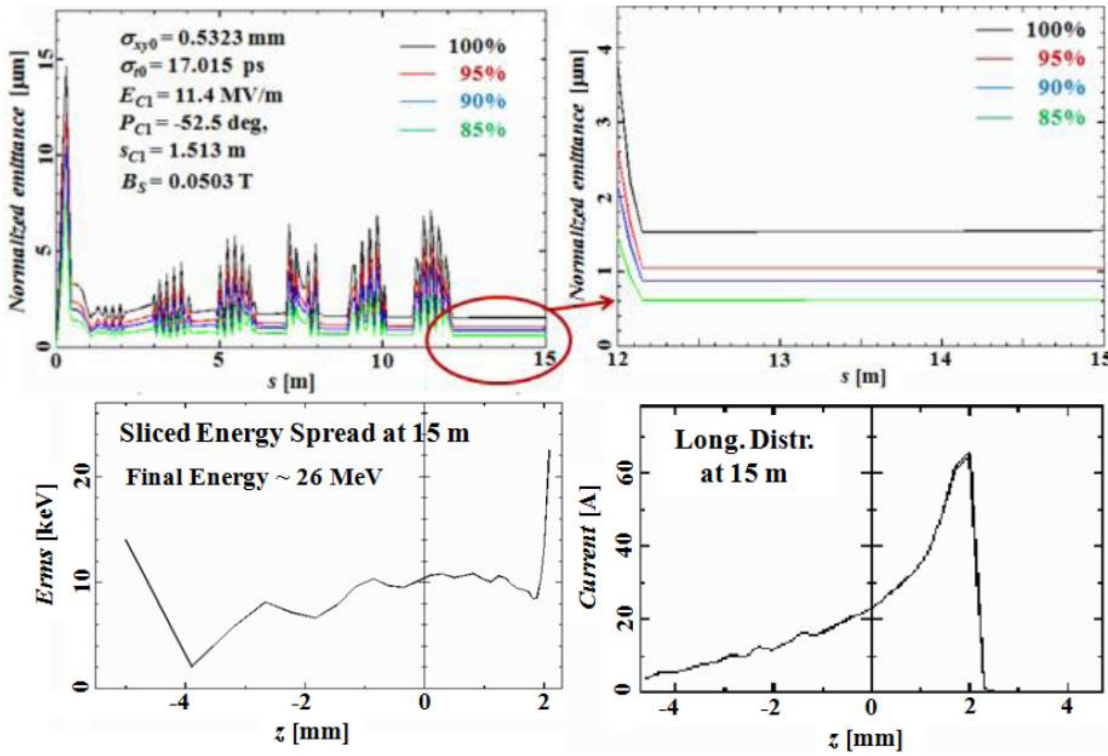


Figure 3.9. *Simulation results from one optimization solution.*

3.5.2 DC Gun Development at JLab

It is desirable to operate DC guns at the highest voltage and gradient possible to achieve the brightest beam production. The present JLab FEL gun is limited to operation below about 350 kV. Experience with this and other DC guns has shown that limits on both gun voltage and gradient are the result of field emission from the cathode electrode. This becomes the limiting factor when the electrical field gradient at the surface of the electrode reaches a critical value around 9 MV/m and field-emitted electrons are accelerated (due to the gun geometry) towards the ceramic insulator and lead to charge buildup on the insulator. This, in turn, leads to high voltage (HV) breakdown and insulator punctures. If this did not occur, the ceramic insulators by themselves would withstand the desired voltage of 500 kV.

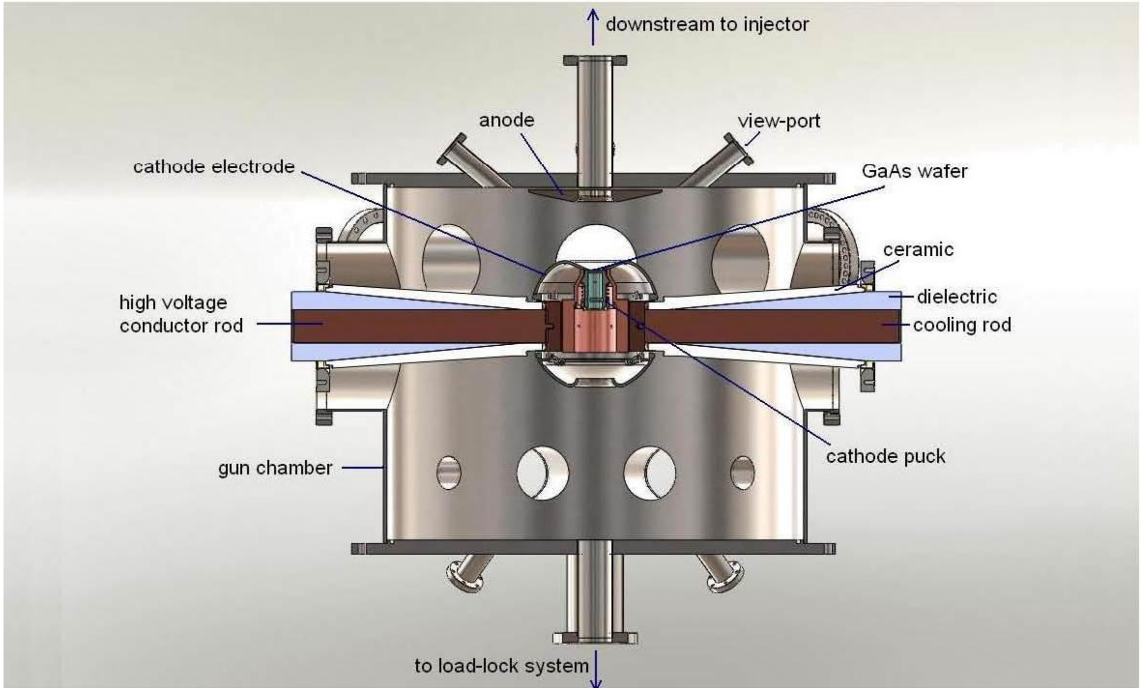


Figure 3.10. *Top view schematic of the new DC gun under construction at JLab. It is designed to operate at 500 kV. The vacuum chamber diameter is 0.762 m.*

A new 500kV JLab FEL DC gun is under construction, where geometry and charging of the insulator were taken into account; see Figure 3.10 [8]. The gun geometry was changed in such a way that even if there are field emitted electrons (inevitable during HV conditioning), they would be accelerated towards the metallic gun chamber wall and not towards the ceramic insulators, reducing the possibility of charge buildup. Furthermore, a ceramic with small bulk conductivity will allow for charge bleedoff. Advantage will be taken of new surface processing techniques developed at JLab for SRF applications to reduce the amount of initial field emission. The cathode electrode of the new gun will therefore be made of niobium rather than the stainless steel currently in use. Two options for the niobium surface treatment are being developed: electro-polishing for small grain niobium, and use of large grain niobium where buffered chemical polishing gives the best result. The modular approach of the electrode design means that the surface of the cathode electrodes can be replaced while keeping the internal cathode-receiver parts the same. This provides the possibility to test different materials and methods of preparing the electrodes.

The beam dynamics aspects of the DC gun warrant detailed consideration. The results of numerical modeling at Jefferson Lab and much more extensive modeling made at the Cornell University [9] show that emittance compensation can be successfully utilized with DC photocathode guns. This has been confirmed experimentally with the Cornell photo-injector, where measurements are in very good agreement with the numerical modeling [10]. It is important to note that to achieve the required small transverse emittance, emittance compensation and 3D shaping of the drive laser pulse will be required regardless of the kind of electron gun used. When this is implemented correctly and small emittances are achieved, the cathode thermal emittance contribution to the overall emittance becomes sizable. Therefore using the cathode with the smallest thermal emittance is desirable; GaAs:Cs cathodes presently have the smallest thermal emittance measured[11]. DC photo-guns are the only type of gun to demonstrate vacuum conditions sufficient for the use of the GaAs:Cs cathode with reasonably long cathode lifetime through minimization of ion back bombardment. Biased anodes may also be used to extend cathode life [12].

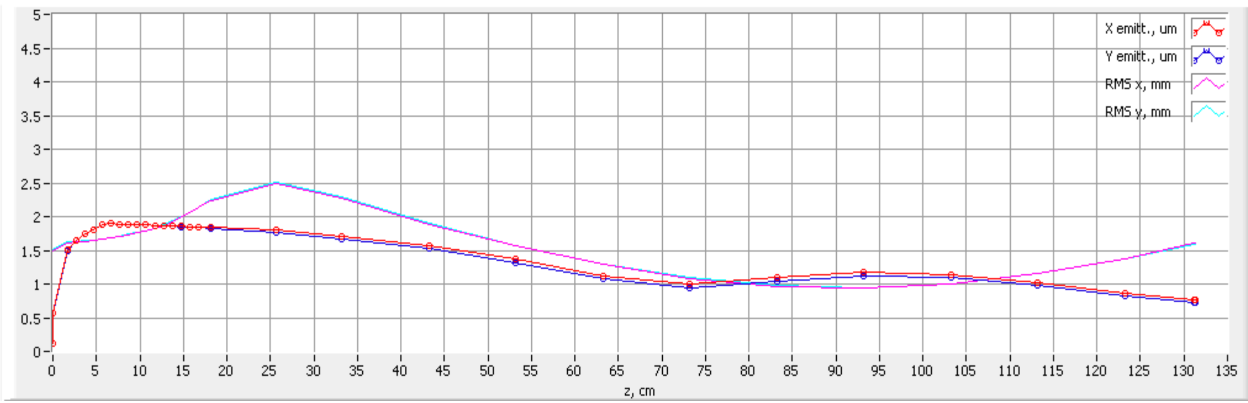


Figure 3.11. *Transverse emittance and RMS beam size vs. longitudinal position.*

Shown in Figure 3.11 are the results of a preliminary study to demonstrate that the emittance of the new DC gun approaches the required value. The beam dynamics calculation, made with PARMELA, is for a bunch charge of 200 pC generated using a drive laser pulse with a multi-Gaussian longitudinal distribution of 100 ps FWHM (made of eight Gaussian pulses superimposed to provide a flat top distribution). The thermal emittance of the cathode is roughly included. The diameter of the drive laser spot on the center of the cathode is 6 mm. Figure 3.11 shows the evolution of the transverse beam size emittance downstream of the gun in a drift space. Figure 3.12 shows the transverse phase space distribution at the end of the drift space with the value of the transverse emittance and Twiss parameters. A transverse emittance of about 0.75 mm-mrad is predicted in this configuration. This is an indication that the requirements can be met using the new DC gun. However, a thorough optimization of the beam dynamics through the whole injector must be performed. The design and layout can be generated using a genetic algorithm optimization technique that has previously been employed at Jefferson Lab and Cornell University [13,9].

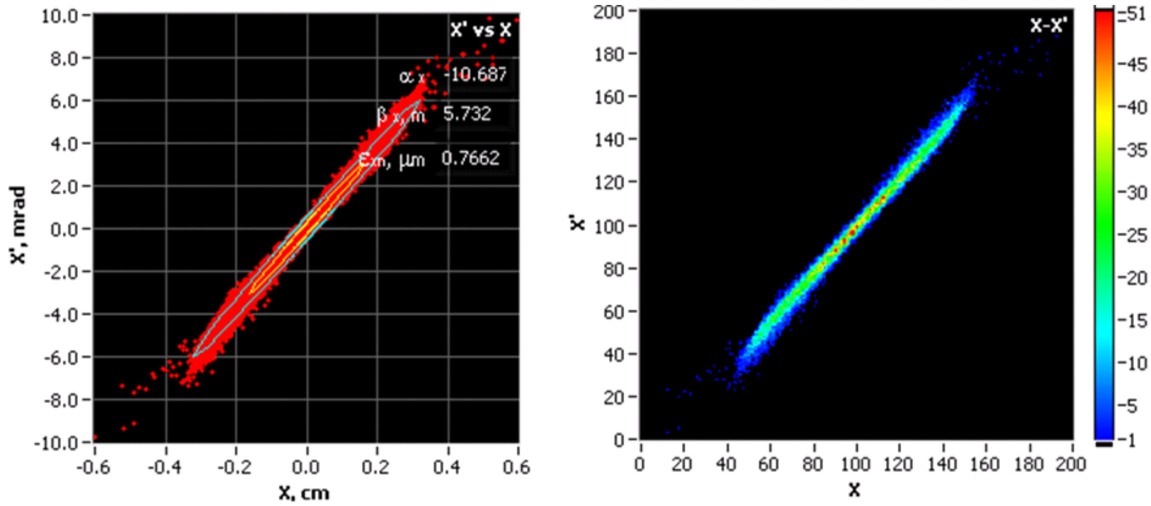


Figure 3.12. *Transverse phase space distribution at the end of the drift space. The picture on the right shows the same data as on the left presented as a 2D histogram.*

3.5.3 Injector Outlook

In moving towards the design for the JLAMP injector, both the LBNL VHF normal conducting and JLab DC options will be actively pursued. The LBNL VHF gun is currently at a more advanced stage of construction, and RF testing will commence in the coming year. The tests with the photo-injector will be performed in two phases. The first stage is already funded and scheduled for the second part of 2010. Full RF tests, tests with the electron beam at the gun operation energy, and the characterization of different photo-cathodes will be all performed. In the second phase, which requires funding continuation, the beam will be accelerated up to a few tens of MeV and a full characterization of the 6-D beam emittance at different electron bunch charges will be performed. This progress should integrate well with the expected timeline for the JLAMP project.

The new DC gun development at JLab will also be ongoing as an alternate choice. This is in an early phase of construction, with high voltage testing scheduled for late 2010 under funding by ONR. Regardless of gun technology, the cathode preparation and load-lock system must also be figured into the development plan. Producing high quantum efficiency cathodes that can be inserted into the gun without degradation will be challenging. In addition a load-lock will be necessary to change cathodes with minimum down-time when the quantum efficiency becomes too low.

References for Section 3.5

[1] K. Jordan, et al., "JLAMP: An Amplifier-based FEL in the JLab SRF ERL Driver". Proc. PAC, p. 1329 (2007).

[2] K. Baptiste et al., "A *cw* normal-conductive RF gun for free electron laser and energy recovery linac applications". Nuclear Instruments and Methods in Physics Research A 599 (2009) 9–14.

[3] R. Dei-cas et al., "Status report on the low-frequency photo-injector and on the infrared FEL experiment (ELSA)". Nuclear Instruments and Methods in Physics Research A 296 (1990) 209.

[4] C. Hernandez et al., "Performance and Modeling of the JLab IR FEL Upgrade Injector". Free Electron Laser Conference, p 558, 2004.

[5] B.M. Dunham et al., "Performance of a Very High Voltage Photoemission Electron Gun for a High Brightness, High Average Current ERL Injector", Particle Accelerator Conference, p 1224, 2007.

[6] R. Hajima et al., "Development of a Photocathode DC Gun at JAEA-ERL". Asian particle Accelerator Conference, p 175, 2007.

[7] R. Legg et al., "Half Wave Injector Design for WIFEL". European Particle Accelerator Conference, p469, 2008.

[8] F.E. Hannon et al., "An Inverted Ceramic DC Electron Gun for the Jefferson Laboratory FEL". Free Electron Laser Conference, 2009.

[9] I.V. Bazarov, C.K. Sinclair, "Multivariate Optimization of a High Brightness DC Gun Photoinjector". Physical Review Special Topics Accelerators and Beams, 8, 2005.

[10] I.V. Bazarov et al., "Benchmarking of 3D Space Charge Code Using Direct Phase Space Measurements from Photoemission High Voltage DC Gun". Journal of Applied Physics, 2008.

[11] I.V. Bazarov et al., "Thermal Emittance and Response Time Measurements of Negative Electron Affinity Photocathodes". Journal of Applied Physics, 2007.

[12] J. Grames et al., "A Biased Anode to Suppress Ion Back-Bombardment in a DC High Voltage Photoelectron Gun". AIP Conference Proceedings No. **980**, (2008).

[13] F.E. Hannon and C. Hernandez-Garcia, "Simulation and Optimisation of a 100mA DC Photo-Injector". European Particle Accelerator Conference, p 3550, 2006.

3.6 Undulator

JLAMP will utilize a series of undulators as shown in Figure 3.13, starting with a modulator, then a buncher, and finally four radiator sections. A THz wiggler will be situated downstream of these undulators. There are several types of undulators possible. We have decided on a short wavelength in-vacuum system based on the Cornell elliptically polarized DELTA undulator (Figure 3.14) [1]. This system can provide the shortest wavelengths achievable for a given gap in a configuration that permits production of circularly polarized radiation of either polarization. It can switch between configurations in a few seconds. It takes advantage of the fact that no large transverse aperture is required in an ERL system so you can surround the beam with magnetic material. This means that diagnostics and external focusing must be provided in between wiggler segments.

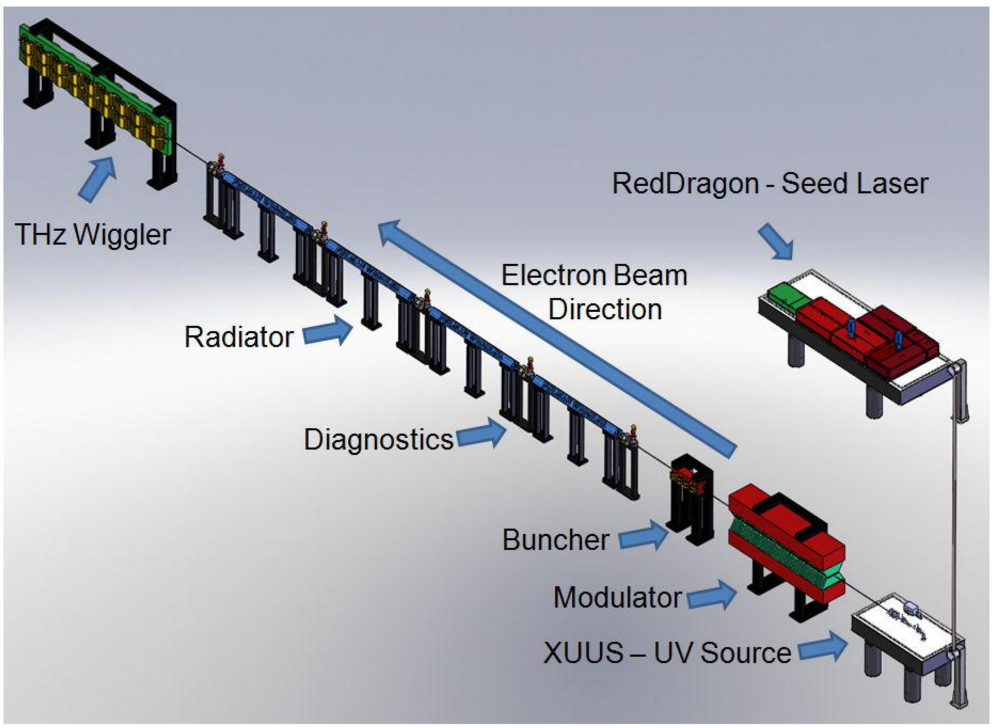


Figure 3.13. *JLAMP undulators.*

The challenge of a system like this is maintaining beam focus with high energy electrons, handling the image currents and heat that such currents generate (resistive wall heating), controlling beam loss in a narrow aperture, and providing for diagnostics within the wiggler to allow optimization of electron beam steering and focusing. Superconducting wigglers capable of polarization switching have problems achieving the required field quality, are difficult to arrange with beam diagnostics, and would have great difficulty dealing with the heat generated by our *cw* beam. In addition, studies at LBNL have shown that superconducting wigglers cannot produce any stronger field than an in-vacuum wiggler unless one uses ceramic or high temperature superconductors [2]; using such new superconductors would require an extensive development program.

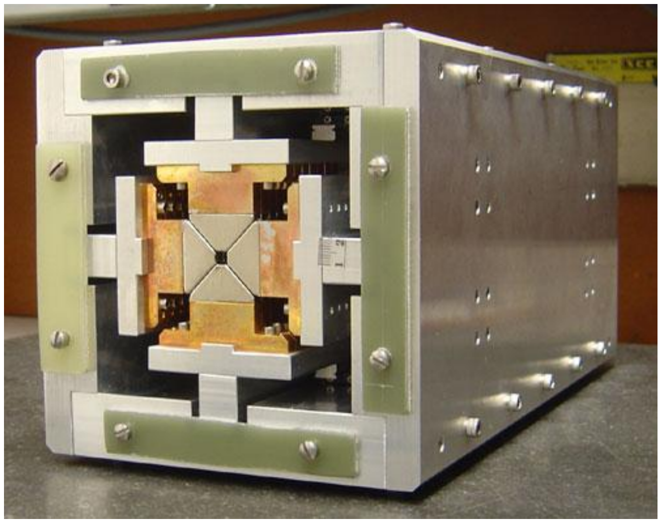


Figure 3.14. *The DELTA undulator prototype at Cornell University [2].*

We intend to have a 10 m wiggler system consisting of four 2.1 meter wiggler sections with strong focusing capability in between the sections along with electron beam position monitoring as is done in the LCLS wiggler. The diagnostic and focusing sections are 40 cm in length. The wiggler parameters assumed in the performance calculations in this document are based on such a wiggler. It is assumed that the wiggler strength tuning is accomplished with phase tuning, in which the wiggler jaws move longitudinally rather than transverse to the beam [3].

The choice of wiggler wavelength is always a compromise between short wavelength reach and tuning range. The wavelength is constrained by the wiggler gap. Too small a gap will lead to excessive resistive wall heating and wakes. The attainable field varies exponentially with the gap and the field required to attain a given wiggler strength varies inversely with the wavelength. Due to these considerations it is very difficult to reduce the wavelength much less than 2 cm while maintaining reasonable gain. If one wants the rms wiggler parameter to be greater than unity then the wiggler gap must be as small as 5 mm for a 1.8 cm period. Such a short period would allow reasonable gain lengths for a 600 MeV beam with wavelengths as short as 9 nm but would allow very little tuning range via the wiggler strength. The resistive wall wake might increase the gain length as well, so this is a very risky approach. We have chosen to increase the wavelength to a still aggressive but more tunable 2.1 cm. This wavelength allows a reasonable tuning range of close to a factor of two at any given energy while achieving a useful gain length at 11.5 nm and providing a more reasonable gap of 7 mm. If it is found that the laser performs well at the highest photon energy, we might want to try a shorter wavelength in the future.

We discuss the operational modes of the FEL below in subsection 3.8. In particular we analyze performance in the baseline mode as a seeded amplifier and the photon science drivers that led us to that decision. The system has additional capabilities and while the baseline design is for operation as a “straight” seeded amplifier, other operational modes may be more advantageous to push performance to shorter wavelengths. The highest repetition rate available from the linac is 4.68 MHz, whereas high pulse energy, short pulse drivers for the seed are presently available only to around 200 kHz. In addition, the efficiency of HHG seed production will fall significantly at photon energies above 30 eV. In that case it may be advantageous to operate the FEL in an HGHG mode (see Figure 3.13). This is feasible if one provides a prebunching wiggler to resonate at the 30 eV photon energy available and then resonate the primary undulator at an odd harmonic of this wavelength—say the third, fifth or seventh harmonic [4]. The gain in the second wiggler is substantially enhanced because of the pre-bunching at the longer wavelength so that saturation at wavelengths otherwise unachievable may be obtained. We will incorporate this capability into our wiggler train.

The modulator wiggler chosen is the same as an undulator A from Argonne's Advanced Photon Source [5]. This allows us to tune to the third subharmonic of the FEL over most of the short wavelength tuning range of the FEL. The wiggler is 4–6 gain lengths, so the seed laser does not have to be very high in power. The buncher is a simple electromagnetic chicane magnet similar to one used on the JLab FEL IR Upgrade optical klystron [6]. It should be able to provide strong bunching from the energy modulation produced in the modulator.

Users would like to have a long wavelength photon pulse synchronous to the FEL beam. This has been provided at the FLASH facility at DESY using a "THz" wiggler to produce long wavelength coherent radiation. We would use a similar wiggler with nine 40 cm periods and 1.1 T field strength to produce a source that can tune out to as long as 200 microns in the fundamental with coherent pulses of light with an electron beam energy of 470 MeV. The wiggler is a conventional electromagnet with 22 poles, 4.2 m in length. Due to the very high electron beam energy it is difficult to get to very long wavelengths but the FLASH group has demonstrated that it can produce far-infrared pulses using this wiggler. At higher energies the maximum wavelength will vary with the energy squared. As an example the resonant wavelength will be 122 microns for 600 MeV beam. The rms bunch length at 600 MeV will be only 25 microns, so the wiggler should produce strong enhancement up to the 5th harmonic. One can also lower the wiggler strength and produce fundamental light at 25 microns for users. At longer FEL wavelengths the THz wavelength can also be longer. The ratio of the THz wavelength to the FEL wavelength will typically be 5500:1.

References for Section 3.6

[1] A. B. Temnykh, "Delta undulator for Cornell energy recovery linac", PRST AB **11**, 120702 (2008).

[2] S. Prestemon, S. Marks, and R. Schlueter, "New Developments in Light Source Magnet Design", Proceedings of the 2007 PAC Conference, p. 3751 (2007).

[3] Roger Carr, Nucl. Instrum. Methods Phys. Res., Sect. **A 306** 391 (1991); Roger Carr and Heinz-Dieter Nuhn, Rev. Sci. Instrum. **63** 347 (1992).

[4] L. H. Yu, et al., "High-Gain Harmonic Generation Free-Electron Laser", Science Vol. 289 (11 Aug. 2000), pg. 932 and/or A. Doyuran, et. al., "Characterization of a High-Gain Harmonic Generation Free-Electron Laser at Saturation", Phys. Rev. Lett., Vol. 86, (25 Jun 2001) p. 5902.

[5] I. B. Vasserman et al., "Magnetic Measurements And Tuning Of Undulators For The APS FEL Project", Proc. PAC 1999.

[6] Benson S, "Operation of an optical klystron with small dispersion", Nuclear Instruments and Methods **A507** 40 (2003).

3.7 Seed Laser

For FEL amplifiers the output pulse characteristics are determined by the input seed. Generating an appropriate seed laser pulse in the 10 to 100 eV energy range is not trivial, but substantial progress has been made in the last few years in extending the technology of high harmonic generation (HHG) [1] in gas jets to produce high (30^{th} or more) harmonics of 1 micron conventional laser pulses. The HHG process, first described in 1987 [2], takes advantage of the high electric fields generated by ultrafast laser systems to distort the potential well that the electrons move in about their parent nucleus from the well-known harmonic oscillator function. In fact, the field ionizes the gas atoms, then recollides them with the parent ion in less than an optical cycle. When the electron recombines with the ion, it gives up the kinetic energy it acquired by emitting a photon. The maximum energy of the photon is well determined using a semi-classical approach described by Corkum [3]:

$$E_{max} = I_p + 3.2U_p \qquad 3.7.1$$

where I_p is the ionization potential of the atom and U_p is the quiver, or ponderomotive energy of the electron:

$$U_p = e^2E^2/4m\omega^2 \qquad 3.7.2$$

where e and m are the electron charge and mass, and E and ω are the field's amplitude and frequency. Since the field about the ion has been distorted, the emitted energy occurs at harmonics of the driving field. However, even though the potential about the ion is distorted by the driving field it is still centrosymmetric, and thus only the odd harmonics are present. An example of this is shown in Figure 3.15.

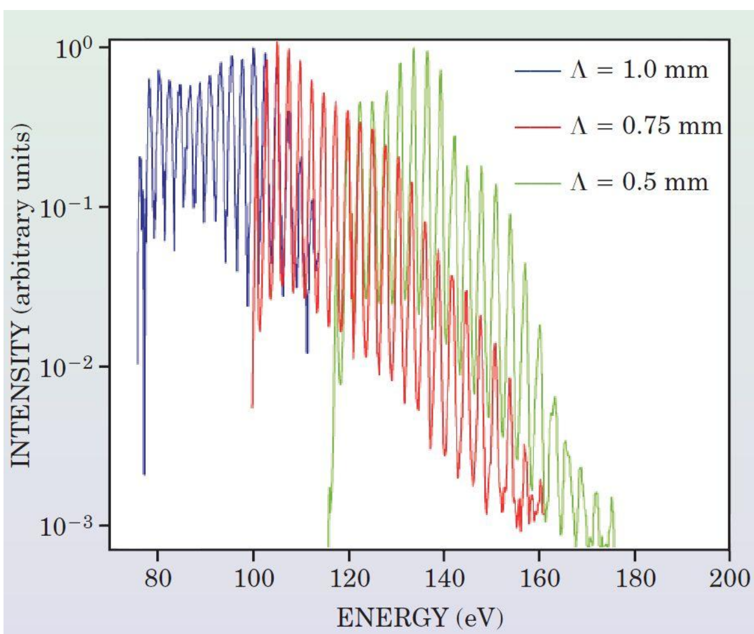


Figure 3.15. *The characteristic curve for HHG emission, showing the plateau region, followed by a rapid decrease to the cutoff energy. The legend indicates the period for a structured waveguide. Taken from Ref. [3].*

The efficiency of conversion to 100 eV of such pulses is in the 10^{-6} to 10^{-7} range. Therefore, to achieve 1 GW of output at 100 eV with 10^3 to 10^4 gain from the undulator, the HHG peak power needs to be of order 10^5–10^6 W. This can be achieved with a commercial table-top TW system with an output in the 3–30 mJ range. If we instead choose to deliver seed pulses at a lower energy (30 eV) we gain about two orders of magnitude in HHG efficiency and can lower the seed energy requirements proportionately. We have budgetary estimates from several vendors that give us confidence that we can provide ultrafast pulses of the required energy at pulse repetition frequencies (PRFs) as high as 10 kHz, offering the research community several orders of magnitude higher data acquisition rates. An example of such a system, the KM Labs Griffin-I/RedDragon laser system, is shown in Figure 3.16. This is our initial PRF specification.

We wish to extend the PRF beyond that achievable from state-of-the-art ultrafast systems. Interactions with one company make us confident in proposing an enhanced seeded mode that extends our PRF to at least 100 kHz and possibly 200 kHz. This system could be at JLab, undergoing integration with our accelerator controls, in less than a year after receiving funding.

Figure 3.16. *Griffin-I/RedDragon seed laser system (courtesy KM Labs).*

There is no demonstration as of yet of the requisite peak powers at the MHz repetition rates desired for our amplifier since a brute force scaling of a ~ 1 micron ultrafast laser system would require an average power of order 1 kW. Referring to Eqn 3.7.2, the maximum photon energy can be increased by working at longer wavelengths, because of the λ^2 scaling of the ponderomotive interaction. New sources based on optical parametric chirped pulse amplification (OPCPA) offer the possibility of reaching higher repetition rates with lower peak power from the seed laser, since they operate in the 3 micron region [4]. We propose to study the efficacy and limits of this approach using the current JLab FEL, as we have demonstrated average power in excess of 5 kW in the same spectral region with 200 fs pulses. Power levels of this magnitude, coupled into a continuous gas jet will require modifications to the usual phase-matching scheme in a gas-filled hollow core fiber. While we believe the technology development is straightforward, it is important to initiate this effort promptly so as to be able to deal with any issues that arise. This would be useful more broadly not only as seeds for FEL amplifiers, but as a soft x-ray source in its own right for less demanding research at university laboratories. Collaborations with other national laboratories that have the same needs will be utilized to ensure the best technology is applied.

We also want to provide an option for narrower linewidth XUV by modifying a standard femtosecond laser such as the RedDragon system to provide a longer pulse option. A straightforward way to meet the requirement is to limit the pulse bandwidth with passive elements while keeping the same laser amplifiers. It should be noted that the longer pulse, while reducing the spectral bandwidth, also lowers the efficiency, which means the HHG pulse energy is lower. In the meantime, we continue to follow advances in HHG technology, such as the use of multi-color pump beams to increase the conversion efficiency and wavelength range. To stay abreast of this rapidly developing area we have established collaborations with leading international experts on HHG to make sure the most effective approach is adopted.

Seed laser and infrastructure

As mentioned earlier, our baseline seed laser system for JLAMP is the Griffin-I/RedDragon system produced by KM Labs (Boulder, CO). The system specified is an incremental increase in output energy above what they currently deliver, but the company is confident they can reach the output parameters specified in Table 3.2:

Parameter	Value
Pulse energy (mJ)	40
Pulsed width (fs)	<25
Rep rate (Hz)	1000
Amplitude stability (%)	<1
Angular stability (μrad)	< 20
Timing jitter (fs)	<200fs

Table 3.2. *KM Labs output parameters.*

KM Labs believes the timing jitter specification to be conservative, and is planning on bringing one to our facility early next year for us to assist them in determining the phase noise (the rms value is directly related to timing jitter).

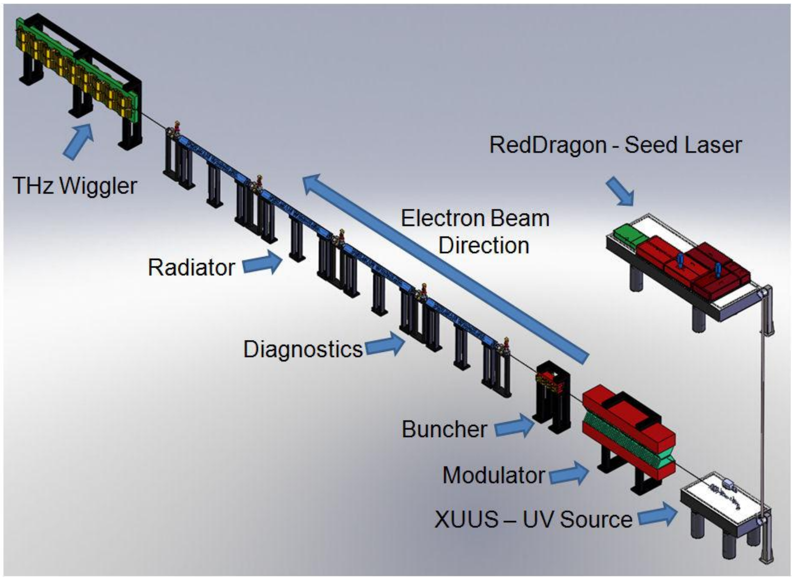
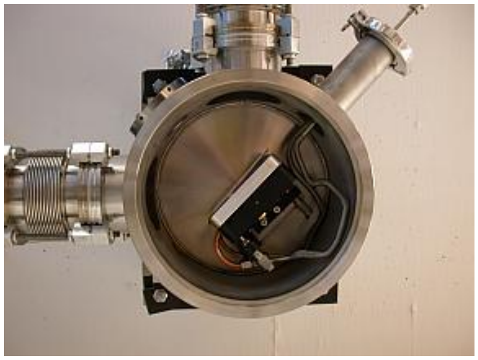
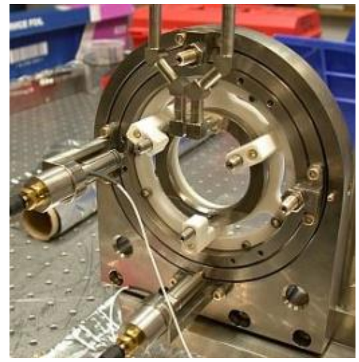


Figure 3.17. *Seed laser and HHG source in relation to the undulators.*

As shown in Figure 3.17 the seed laser is mounted on a table in a user lab on the second floor of our facility. The table and laser are surrounded by a temperature-controlled (< +/- 1 °C) hutch to minimize beam and cavity length drifts; the Griffin-I oscillator is also temperature stabilized to further minimize cavity drift. The KM Labs system provides its own pulsewidth diagnostics, so at this time we plan only to install a pellicle beam splitter for the addition of future diagnostics and mode-matching optics before the beam is launched through a thin calcium fluoride Brewster window and into the optical transport system (OTS). Using Brewster windows minimizes back-reflections, and hence "ghost" pulses. A gimbal-mounted, temperature-stabilized set of mirrors routes the beam from the second floor to the accelerator vault through an enclosed tube that is partially evacuated to minimize passage of dust in the beam as well as beam position jitter. The beam exits through a near-Brewster window which takes the weak reflection and routes it to a fast photodiode for synchronization with the electron beam, as is done with our four other lasers. The equipment just described is all standard hardware designed, tested and in routine use by the JLab FEL's optics group, so there is minimal risk in terms of cost, performance, or schedule. Examples of the enclosures and the gimbal mounts are shown in Figures 3.18a and 3.18b. This hardware, with no active stabilization, will maintain the angle of a higher average power beam (several 100 W) to < 20 μrad after eight reflections, rather than the mere two required here. After the window the beam then traverses two temperature-stabilized fast steering mirrors and a pellicle beam splitter before entering the XUUS™ HHG module. The weak reflection from the beam splitter falls on a position sensitive detector (PSD), the output of which is used by a feedback system with the fast steering mirrors to lock the position and angle of the input beam. The XUUS system output has vacuum flanges, and from this point on the HHG beam travels in vacuum. It passes through a filter wheel system to minimize the launching of undesirable harmonics, and then into the undulator sections.



(a)



(b)

Figure 3.18. *Turning mirror can (a) and actuated gimbal mount (b).*

References for Section 3.7

[1] H.C. Kapteyn, M.M. Murnane, and I.P. Christov, Physics Today, **58**, 39 (March 2005).

[2] A. McPherson, G. Gibson, H. Jara, U. Johann, T.S. Luk, I.A. McIntyre, K. Boyer, C.K. Rhodes, J. Opt. Soc. Am. B - Opt. Phys. **4**, 595 (1987).

[3] P.B. Corkum, Phys. Rev. Lett. **71**, 1994 (1993).

[4] O. Chalus, P.K. Bates, M.Smolarski, and J. Biegert, Optics Express **17**, 3587 (2009).

3.8 FEL Performance

Analyses and calculations were used to determine the performance of the FEL system in the various wavelength bands. Two codes, both of which have been extensively benchmarked against experiments, gave comparable results. A system such as we envision is quite flexible and can operate as a seeded amplifier in High Gain Harmonic Generation (HGHG) mode, bootstrapping itself to shorter wavelength performance, or as a high gain oscillator. The baseline design of the FEL is as a seeded amplifier for ease of control of the photon parameters for users. In addition, for risk reduction and operational flexibility, we have included the capability for operation in the oscillator or HGHG modes. Analysis of our baseline mode of operation as a seeded amplifier is described below.

Seeded amplifiers have the advantage of being able to more easily control the FEL temporal and bandwidth characteristics at the price of additional complication in the generation of the seed and arranging its proper timing with respect to the electron pulse. The output pulse length is set by the seed pulse assuming the likely scenario that it is shorter than the electron pulse in the FEL. With seeded amplifiers, output pulses less than 30 fs can be produced, a huge advantage in dynamics studies.

The seed power available for photon energies below 30 eV is on the order of 0.1 to 1 MW. Above 30 eV the conversion efficiency drops so that perhaps only 1 to 10 kW of seed is available and a larger number of gain lengths will be required to reach saturation. This is still more than sufficient for FEL seeding since it dominates the FEL noise power that is at the 10 W level. The saturated power of the FEL will be in the range of 0.5 to 5 GW depending on beam quality. It will take approximately 18 gain lengths to reach saturation, so a saturated FEL output will only be achieved for gain lengths shorter than about 0.6 m.

Figure 3.19 shows the results of scaling calculations from a paper by Ming Xie [1] which have shown good agreement with recent measured LCLS performance. To show the impact of emittance we also modeled a beam normalized emittance of 5 microns to compare with the baseline specification performance at 1 micron.

FEL simulations can accurately take into account the beam focusing, effect of longitudinal emittance, etc. The predictions from the code are shown in Figure 3.20 for the gain length, and 3.21 for the saturation power as a function of wavelength.

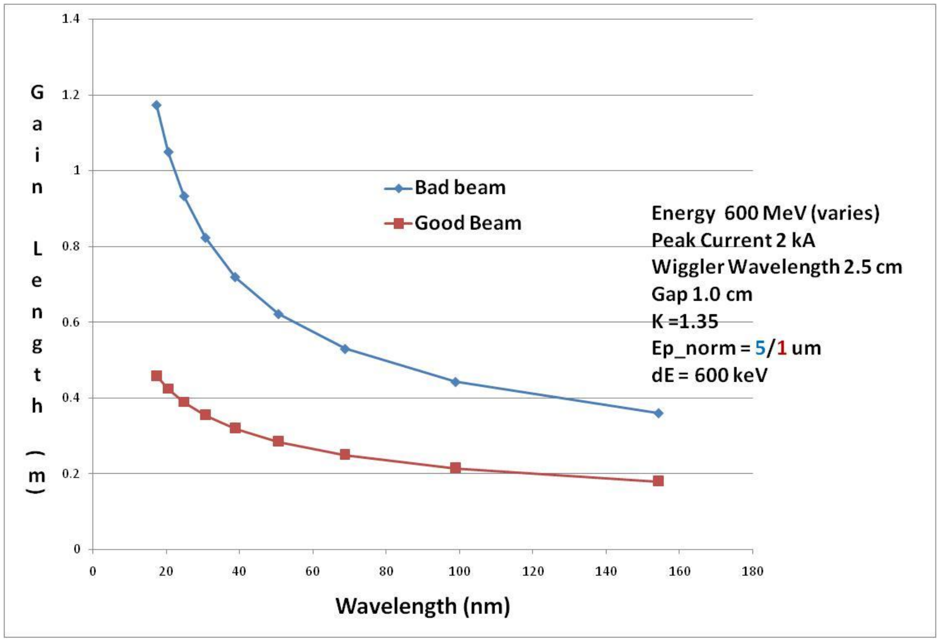


Figure 3.19. *Gain length vs. wavelength (from Ming Xie scaling). This assumes circular polarization and strong focusing between the wigglers.*

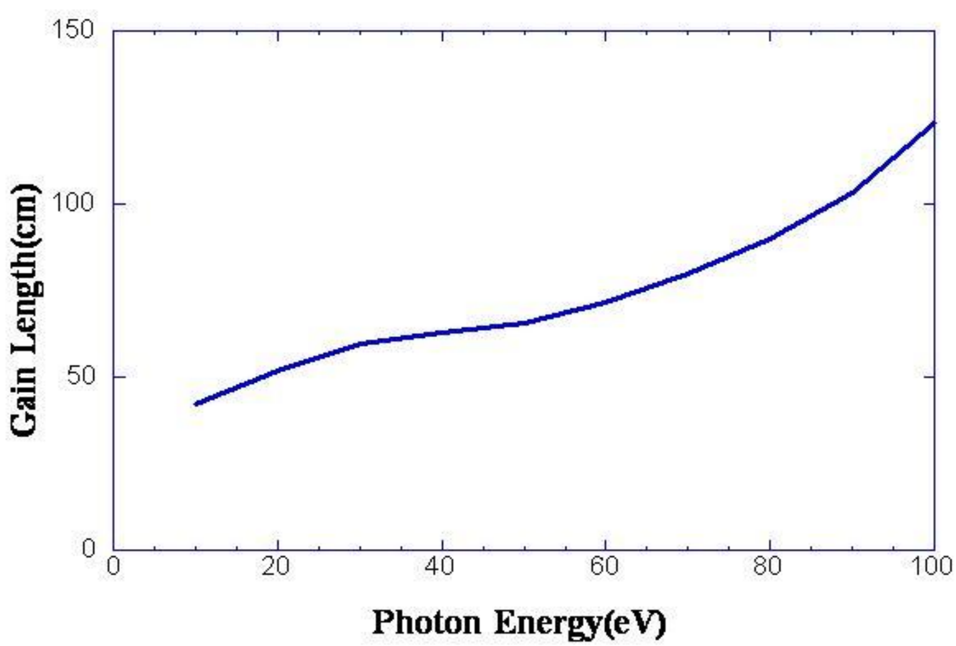


Figure 3.20. *Gain length from an FEL amplifier code calculation. The plot assumes 600 MeV electrons with 1 µm emittance and a wiggler with 2.5 cm period and rms K^2 maximum of 1.6. This is for linear polarization.*

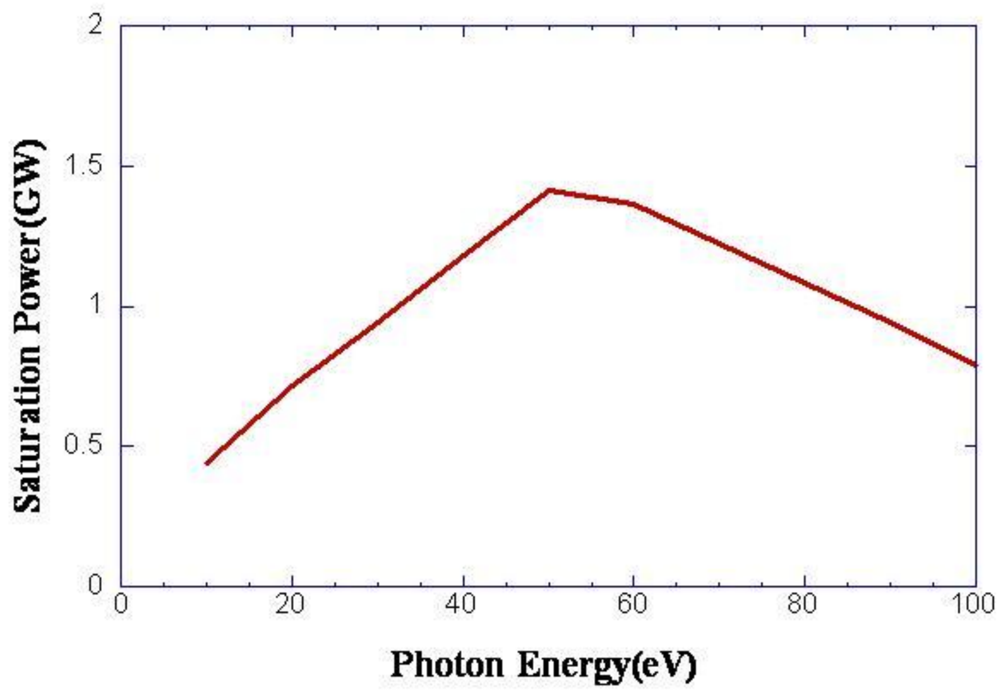


Figure 3.21. *Gain length and saturated power from more accurate FEL amplifier codes. The plot assumes 600 MeV electrons with 1 µm emittance and a wiggler with 2.5 cm period and rms K^2 maximum of 1.6. This is for linear polarization. Circular polarization will be slightly shorter.*

The energy per micropulse is on the order of 100 µJ if the full electron pulse length of 100 fs is utilized. With seeded operation at shorter pulse lengths the energy will be proportionately less. The minimum bandwidth is set by the Fourier transform limit of the pulse length.

For all cases there will be harmonics of the fundamental produced at powers roughly 10^{-H} below the fundamental. This offers the potential of significant brightness even for 500 eV photons and beyond.

With the repetition rate at 5 MHz the average brightness projected to be produced is as already shown in Figure 1.1. The performance levels of the LCLS, FLASH and the XFEL projections are shown for comparison. While the JLAMP x-ray reach in terms of photon energy does not meet the best of these systems because of its lower accelerator energy, the brightness achieved is world class by virtue of its *cw* operation on an SRF linac.

Table 3.3 shows the performance specifications for the fundamental output with the baseline amplifier compared to the backup oscillator operation.

	Oscillator		Amplifier	
	Min	Max	Min	Max
Wavelength (nm)	12	124	12	124
Wavelength (eV)	100	10	100	10
Pulse Length FWHM (fs)	100	100	50**	200
Pulse energy (μJ)	10	100	10	100
Photons/pulse @$\lambda_{min,max}$	6 x 10^{12}	6 x 10^{12}	6 x 10^{12}	6 x 10^{12}
$d\lambda/\lambda$ @$\lambda_{min,max}$ (rms)	10^{-4}	10^{-3}	10^{-4}	10^{-3}
Brightness (average) (ph/s/0.1%BW/mm^2/mrad^2)	10^{26}	10^{24}	2 x 10^{25}	2 x 10^{23}
Brightness (peak) (ph/s/0.1%BW/mm^2/mrad^2)	2 x 10^{32}	2 x 10^{30}	2 x 10^{32}	2 x 10^{30}
prf (MHz)	4.68*			1.17
	* + 50 μs macropulses any prf		** +10 fs @ 1 kHz prf	

Table 3.3. *Fundamental specifications.*

Table 3.4 shows the harmonic performance. Other parameters are similar to the fundamental.

Harmonic of 12 nm	2nd	3rd	4th	5th
λ (nm)	6	4	3	2.5
λ (eV)	200	300	400	500
Pulse energy (nJ)	100	100	10	10

Table 3.4. *Harmonic specifications.*

While the baseline operating mode is as a seeded amplifier it may be possible to extend the operating wavelength range of the FEL by use of HGHG as discussed above. The extent to which the wavelength can be “bootstrapped” to shorter regions is still under study. Efforts at BNL and elsewhere have successfully shown lasing to the 5th harmonic of the initial seed. The ability to operate the FEL beyond 500 eV would provide wavelengths of strong user interest but will require higher energy from the accelerator since the wavelength from the undulator scales inversely as the square of the energy. Providing 180 eV fundamental lasing would raise the harmonic output at 540 eV by two orders of magnitude as compared to 5th harmonic on 100 eV fundamental. To accomplish this will necessitate an accelerator energy of 740 MeV or 124 MeV per cryomodule, above our baseline but perhaps in reach of a modest R&D effort.

Another backup mode is to operate the FEL as a high-gain, low-*Q* oscillator. In this approach a small amount of power from the output is fed back to the start to seed the next pulse. This provides an advantage in tunability since the mirrors are relatively broadband and the wavelength is controlled by the beam energy and the wiggler parameters. Because the power fed back is only 10^{-3} of the output, mirror reflectivities, and even surface figure do not have to be particularly high quality nor does the cavity length have to be held to a particularly high tolerance. Output power limits normally set by thermal distortion in mirrors of continuous FEL oscillators are also mitigated by the small fraction of light that is recycled. The high repetition rates naturally available from the linac will provide very high average brightness for the fundamental and especially for the high harmonics. The pulse length in the oscillator mode will be determined primarily by the electron bunch length, e.g. greater than 100 fs. Our measurements have shown that the bandwidth of the output will be close to transform limited. It will not be possible to operate at frequencies below 2.34 MHz because of the optical cavity length or to achieve the ultra-short pulse lengths available in the amplifier mode.

Reference for Section 3.8

[1] Y. H. Chin, K. J. Kim, and M. Xie, “Three- dimensional Theory of the Small-Signal High-Gain Free-Electron Laser Including Betatron Oscillations”, Phys. Rev. A, Vol. 36 (1992) 6662.

3.9 Beamlines and Experimental Stations

We are proposing to provide a total of three new optical beamlines, one VUV, one soft x-ray and one THz. These beamlines will terminate into dedicated user end stations and supplement the existing UV, IR, and THz CSR beamlines.

1. For the ARPES experiments, which require photon energies in the VUV range below 30 eV, we plan to direct the beam upstairs using angles of incidence of 45^{o}, to existing user laboratories in the facility.
2. For the AMO experiments, which require photon energies in the soft x-ray range, we plan to direct the beam at grazing angles into a building addition in line with the optical beam from the undulator.
3. The THz beam, which is generated downstream of the main VUV/soft x-ray beam, will also be transported into the experimental hall in the building addition.

A total of two experimental end stations will be provided, one for ARPES, and one for the AMO experiments.

This part of the proposal is based on discussions with staff at the NSLS and the cost estimates are closely aligned with their current experience for a facility such as JLAMP. They are quite different from beamlines at the NSLS-II for example. We have also relied extensively on the conceptual design study presented in the WiFEL (Wisconsin FEL) [1] proposal and the BESSY FEL Technical Design Report [2]. In addition, we consulted with private companies familiar with the design, fabrication, and installation of beamline optics and instrumentation.

There are significant new challenges unique to FEL beams relative to 3rd generation light sources. Due to the ultrashort pulse nature of the FEL source, damage to optical surfaces by ablation can occur if the peak power density (W/cm^2) and fluence (J/cm^2) are too high. This has been examined through simulations and demonstrated in tests at the TESLA Test Facility FEL at DESY [3]. The primary method for staying below the damage threshold is to place the first beamline optic at a sufficient distance from the source point, such that the beam is spread over a sufficiently large area. The maximum fluence for the FEL output is typically achieved at the highest photon energy in the fundamental. This is where the beam divergence is smallest and the pulse energy is high. In the harmonics, while the photon energy is higher, the photon flux is reduced from the fundamental, and thus the energy/pulse is lower. The conceptual designs for the beamlines presented here are based upon the preliminary estimates of the JLAMP FEL beam source size, divergence, and pulsewidth.

To address the average power thermal loading of the beamline optics, the methods used in 3rd generation light sources will transfer to the beamline designs presented here. Water cooling of beamline mirrors is a common technique, but cryogen cooled mirrors have also been considered in some systems. In 2006, a cryo-cooled output coupler was installed and tested on the existing IR FEL oscillator [4]. The result was a record setting power run, achieving a stable average power output of 14 kW. The experience we have gained from the testing of that cryo-cooled mirror provides us with the expertise to implement a similar system if further simulations indicate such cooling to be necessary.

For the end stations, the instrumentation and design are driven by our discussions with the scientists from the JLAMP Scientific Workshop in July 2009, as well as scientists actively researching at other light sources. The final design will be detailed in collaboration with our users who will provide input on the general end station requirements. This will be coordinated by the JLAMP Chief Scientist.

3.9.1 VUV Beamline

For photon energies below 30 eV, it is possible to use 45^{o} incidence mirrors to direct the beam vertically up to an existing user lab on the second floor of the FEL building. The beam will be extracted using an insertable mirror, transported in an ultrahigh vacuum beamline, and directed and refocused onto the entrance slit of a normal incidence monochromator located in the upstairs laboratory.

One problem that can arise in an amplifier type of FEL is the out of band spontaneous emission that copropagates with the FEL beam. To reject this unwanted emission, a double-monochromator would be considered. The first grating in this type of system allows the beam to be dispersed and the out of band signal rejected. A second grating recombines the dispersed wavelengths that have been allowed to pass. It should be noted though that by adjusting the bandwidth passed by the monochromator, the pulsewidth delivered to the end station is affected. The bandwidth and pulsewidth of the FEL pulses are fundamentally related by the Fourier transform limit, given by

$$\Delta E \ \Delta T \geq \frac{h}{4\pi}; \tag{3.9.1}$$

thus a narrowing of the spectral bandwidth necessarily results in a lengthening of the pulsewidth. The finite beam size and divergence put further limitations on the achievable time bandwidth product, and further FEL simulations will be necessary to set the specifications of the monochromator.

The VUV transport optics will be comprised of metal coated mirrors optimized for short wavelength reflectance at the specified angle of incidence for each bounce. The beam path will be designed for the fewest number of mirror bounces, thus minimizing transport losses. The mirrors also affect polarization, so the transport optics will be designed to preserve the polarization of linearly polarized beams. For circular or elliptically polarized beams, the phase shifts for the different polarizations at each reflection will alter the final polarization delivered to the user end station. These effects can be compensated by tuning the polarization of the FEL. The surface figure of the VUV transport mirrors is also critical since surface errors will distort the wavefront, effectively stretching the pulse. We plan to collaborate with scientists from the NSLS to assist with the metrology and characterization of the beamline optics to enhance our existing capabilities and instrumentation.

The final set of beamline optics will be a single or a pair of focusing mirrors following the monochromator. This optic will focus the beam onto the sample location at the end station equipped with a Scienta high resolution electron energy analyzer for performing photoemission spectroscopy measurements. Discussions with users have yielded a modest request for the spot size at the sample of no larger than 100 μm. This should be easily achievable and careful simulations of beam transport will determine the smallest spot size possible over the spectral range intended for this beamline.

In addition to the Scienta analyzer, instrumentation will be provided on the end station to fully enable a user program. A basic cryostat and a sample manipulator will be provided as part of the end station to facilitate exact positioning and orientation of the sample to the beam and to allow for measurements on low temperature samples such as superconductors and highly correlated systems. We have also specified for a Mott polarimeter to provide capability for measuring the spin of the photoemitted electrons. These systems will enable a wide range of measurements under a range of conditions. To characterize and calibrate these systems, we also plan to provide a low-energy electron diffraction (LEED) system and can provide a local laser source with a photon energy of several eV (e.g. 6 eV from a quadrupled Ti:Sapphire). We have found in consultation with photoemission spectroscopists that these instruments are very useful for taking baseline and calibration measurements.

3.9.2 X-ray transport

To provide users access to the highest energy soft x-ray beam generated by the JLAMP FEL, a beamline with grazing incidence optics will be necessary. One option is to provide the natural full beam of the JLAMP FEL to an experimental end station at the termination of a straight-ahead beamline from the JLAMP wiggler. This provides for a relatively simple solution and users are able to benefit from the full spectral bandwidth intrinsic to the ultrashort transform-limited pulses from the FEL.

For many experiments though, and in particular the AMO measurements proposed here, the users will require much narrower bandwidth for high spectral resolution measurements. To achieve this type of beam, a set of mirrors and a monochromator are needed.

The optical layout of the envisioned beamline design is depicted schematically below in Figure 3.22. The first optical element will be a pair of grazing incidence collimating mirrors in the Kirkpatrick-Baez (K-B) arrangement. The K-B mirror pairs have been selected over a single ellipsoidal or toroidal mirror because it is easier to achieve the necessary surface figure on the plane K-B mirrors. Also, since each mirror in the K-B mirror pair focuses only in one plane, they can more easily accommodate a larger range of focus using a fixture to control the radius of curvature. This is important since the source point moves longitudinally due to the dependence of the gain length on the resonant wavelength of the FEL. Full simulations of the FEL source will determine the range of focus required for these mirrors.

From the mirror chamber, the collimated beam can be delivered straight ahead or spectrally narrowed by an insertable variable line space grating (VLSGM) monochromator. With the straight-ahead beam, users will be able to take advantage of the ultrashort pulsewidths for time-resolved measurements such as pump-probe experiments requiring sub 100 fs time resolution. This branch of the beamline can also be equipped in the future with additional photon diagnostics that require the full spectrum beam, such as an autocorrelator for measuring the pulsewidth.

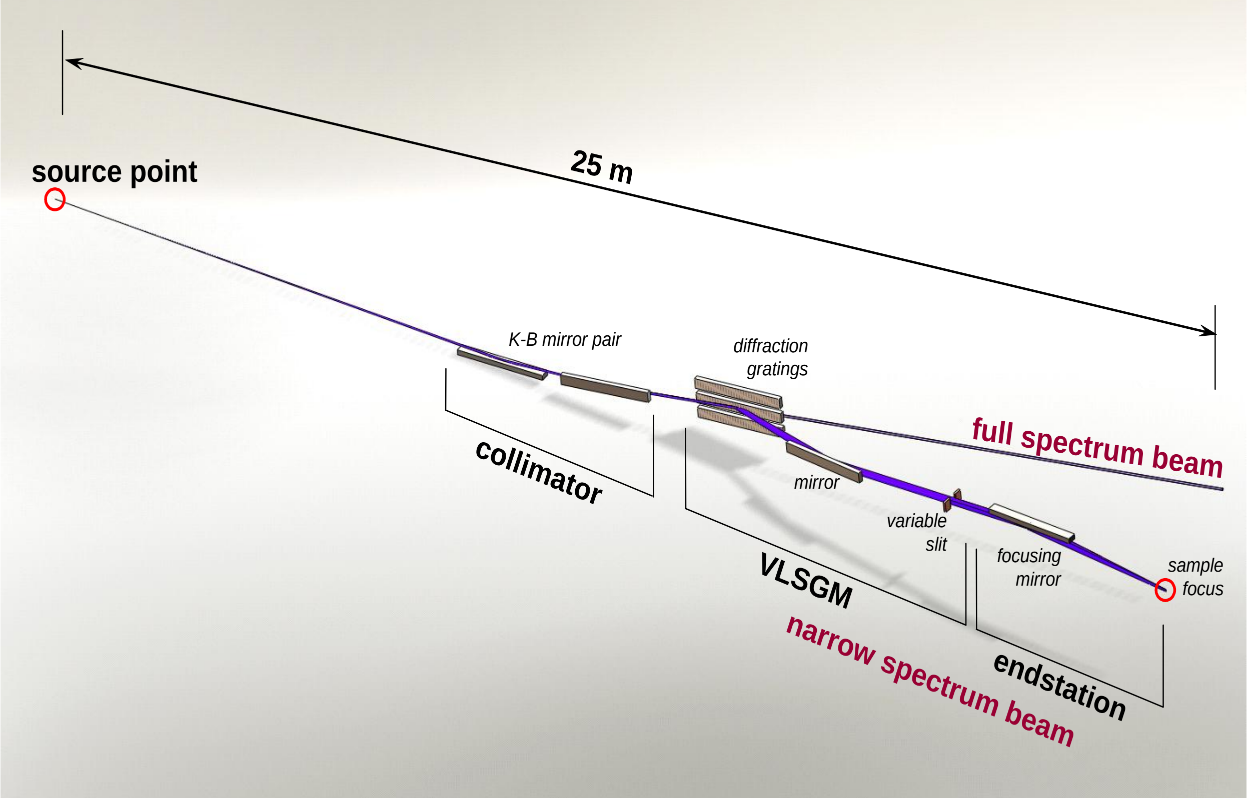


Figure 3.22. *Conceptual design for the JLAMP FEL VUV/x-ray beamline shown in isometric view. All mirrors are depicted for a 3^{o} grazing incidence angle and the variable line space grating monochromator (VLSGM) is depicted with a set of three selectable gratings. When no grating is inserted, the full spectrum beam is delivered to a separate end station.*

The monochromator for the narrowband soft x-ray branch will have several selectable plane gratings that can be translated into the beam. Multiple gratings will provide a good range of resolving power over the entire span of operating parameters available with the JLAMP FEL. Downstream of the grating in the monochromator will be a mirror with a set of controls to steer the diffracted beam onto a slit. The slits will have a variable width control to provide the spectral bandwidth required by each user. The beam is then focused onto the sample location using a single ellipsoidal or toroidal mirror. A single focusing optic can be used in this case since the focal distance is fixed to be the separation between the slits and the last mirror.

This design is not unlike beamline systems already in use at the FLASH FEL at DESY, where a low-duty-factor VUV/x-ray FEL beam is delivered to one user end station at a time. This beamline design provides for a wide range of beam characteristics at the user end stations within the modest footprint of the JLAMP FEL vault as proposed here. Further FEL simulations will be necessary to determine how far the first mirror must be positioned to keep the fluence and power density below the damage threshold. It is desirable though to place the monochromator in the first third of the beamline to allow enough distance to spatially separate the two end stations for the two beamline branches. The beamline is envisioned to be around

25-30 m in length. The K-B mirror pair used for collimation would be located within the existing FEL enclosure. This results in the beam passing through the FEL shield wall at an angle, eliminating the need for a penetration into the FEL vault with a line-of-sight to the accelerator. In the beamline layout depicted in Figure 3.22, the beamline length is 25 m and the terminations at the end stations are separated by ~ 2.2 m.

3.9.3 THz Beamline

The ultrashort pulses of the JLAMP FEL are ideal for many pump-probe type of experiments where time-resolved measurements can be made. The user community has expressed great interest in having the ability to also bring a long wavelength low energy photon pulse onto the sample to provide for non-degenerate two color pump-probe experiments. The FIR wiggler downstream of the VUV/soft x-ray resonator will provide a tunable source of coherent low energy photons in the far and mid infrared.

As the FIR wiggler and the VUV/soft x-ray resonator are coaxial, the two beams will copropagate into the photon beamline. The divergence of these two beams is quite different though, with the FIR beam having a much larger opening angle. This allows for separation of the two beams by placing a large mirror with a hole in the center on the beam axis. The low divergence VUV/soft x-ray beam will transmit through the hole, while nearly all of the FIR beam will be reflected by the mirror into the FIR beamline. This design follows the successful use of this method on the FIR beamline at FLASH/DESY [5].

The FIR beamline optics will be comprised of elliptical metal mirrors to transport the beam, and a delay line to control the relative path length between the FIR and VUV/soft x-ray pulses. To allow for operation of the FEL over a range of repetition frequencies, the electron bunches will be injected in pairs separated by a fixed time delay. The first bunch precedes the arrival of the seed pulse in the amplifier, and thus does not lase. The second bunch arrives at the amplifier overlapped with the seed pulse, thereby producing the VUV/soft x-ray pulse at a fixed delay after the FIR pulse. This results in VUV/soft x-ray pulses at a micropulse frequency of $f_{\mu p}$ and FIR pulses arriving at $2f_{\mu p}$. This scheme produces a constant delay between the FIR and VUV/soft x-ray pulses, which will be compensated for in the FIR transport to nominally bring the two into temporal overlap at the sample. A variable delay line will also be incorporated into the FIR beamline for fine control of the arrival time of the FIR pulse at the sample.

References for Section 3.9

[1] J. J. Bisognano, D. E. Moncton, H. Höchst, K. D. Jacobs, et al., (2007), see Appendix A.

[2] D. Krämer, E. Jaeschke and W. Eberhardt, (2004), see Appendix A.

[3] J. Krzywinski, M. Jurek, D. Klinger, R. Nietubyc, et al., *Interactions of intense ultrashort XUV pulses with different solids. Results from the TESLA Test Facility FEL Phase I*, presented at 26th Annual Free Electron Laser Conference, Trieste, Italy, 675-678, (2004).

[4] H. P. Freund, M. Shinn and S. V. Benson, *Simulation of a high-average power free-electron laser oscillator*, Phys Rev Spec Top-AB, **10**, 030702, (2007).

[5] M. Gensch, L. Bittner, A. Chesnov, H. Delsim-Hashemi, et al., *New infrared undulator beamline at FLASH*, Infrared Physics & Technology, **51**, 423-425, (2008).

4. Conventional Facilities

In this section we describe the cryogenic refrigerator system to support the JLAMP superconducting cryomodules. Also, a civil construction summary is provided which includes the addition of an x-ray user lab to the existing FEL facility, and needed utilities.

4.1 Cryogenic Refrigeration System

To support the JLAMP superconducting cryomodules, superfluid helium at 2.1 K is utilized. The systems utilized by Jefferson Lab for CEBAF and the 12 GeV CEBAF Upgrade are cryoplants capable of providing 4600 W of refrigeration at 2.1 K. Major components of the system include warm helium gas compressors, 4.5 K refrigerator, and 2 K cold compressors. Subsystems required to support the major components include helium gas storage tanks, liquid nitrogen dewar (for helium gas pre-cooling), gas management system, control system, oil removal equipment (to remove all traces of oil carryover from the helium compressors), a helium gas purification system (to remove all gas and moisture impurities within the system), a guard vacuum system (used to intercept any possible air leakage into the subatmospheric portions of the system), instrument air system, electric motor control centers, and the cryogen transfer lines from the refrigeration system to the cryomodules.

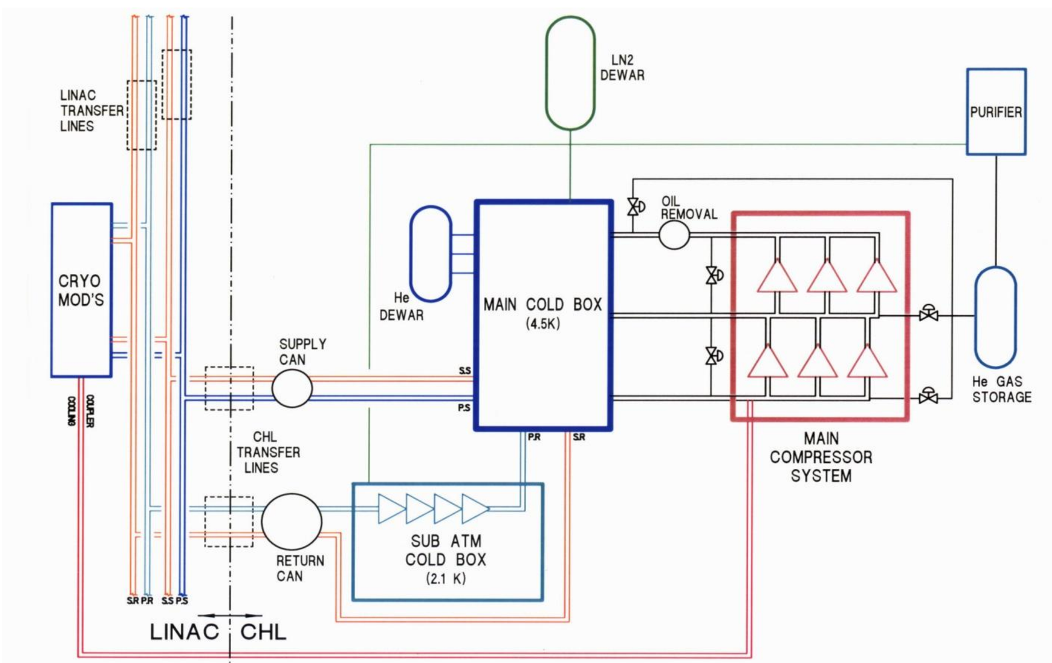


Figure 4.1. *Major equipment relationship in the cryogenic system.*

An overview of the typical type of major cryogenic component relationship is shown in Figure 4.1. The warm helium gas storage tanks provide helium to the warm helium gas compressors. The warm helium gas compressors compress the gas to pressures which are used in the main 4.5 K cold box to produce the refrigerated helium gas to be supplied to the cryomodules. A liquid nitrogen dewar (holding tank) provides liquid nitrogen to the 4.5 K cold box to pre-cool the helium gas to -320 degrees F. To lower the temperature further, to as low as -450 degrees F, the 4.5 K cold box uses turbine expansion engines which extract energy from the compressed helium gas, which in turn lowers the supply gas temperature. Leaving the 4.5 K cold box via the supply can and vacuum insulated transfer line piping, gas is maintained at 3 atmospheres of pressure. Each of the cryomodules is equipped with an inlet flow control valve that maintains the liquid helium level within the cryomodule.

The pressure within each of the cryomodules is controlled to maintain a steady 0.031 subatmosphere pressure. As the refrigerated gas passes through the cryomodule inlet supply valve, its pressure is reduced from 3 to 0.031 atmospheres. It is this drop in pressure which causes the cold helium gas to turn into liquid. The temperature of the liquid produced is determined by the pressure within the cryomodule. The 0.031 atmosphere cryomodule pressure corresponds to a temperature of 2.1 K, or approximately -456 degrees F. As the beam energy boils off the helium liquid within the cryomodule into gas, the cold gas is returned to the 4.5 K cold box via the subatmospheric cold box, which houses cryogenic vacuum pumps. These pumps compress the cold return gas from 0.031 atmosphere to 1.1 atmosphere as well as regulating the pressure with the cryomodules. The 1.1 atmosphere pressure helium is passed through the 4.5 K cold box and on to the warm helium compressor inlet for recompression. From here the complete flow cycle is then repeated. The major equipment is shown in Figure 4.2.

To support the new superconducting modules in the FEL in a robust way for year-round operation, an increase in the supplied refrigeration is required. The estimated refrigeration required is on the order of 900 W, which requires 55 to 60 gm/sec of LHe flow, or about 30–35 gm/sec more flow than presently used for the UV Upgrade FEL. We have considered three approaches to supply this extra refrigeration: a new refrigerator, compensating load reductions in other areas, and enhanced processing of the SRF cavities for reduced losses. While the most direct approach is to purchase a new helium refrigerator, budgetary estimates of such a system came to $18.9M in this-year dollars for the refrigerator and another $7M in conventional facilities. To that cost would be added contingency in any proposal. The schedule for such a construction is also a challenge: commissioning beginning 3 ½ years from date of order.

A second approach is to relieve load on the refrigerator in other areas to make available refrigeration for the FEL. The original CEBAF accelerator system and its supporting cryogenics were installed before 1995, and advances in the technology since that time permit substantial reduction in cryogenic losses. By replacing four of the installed old style CEBAF cryomodules, sufficient refrigeration capacity can be made available to support JLAMP. This is a low risk option which can be performed on a reasonable schedule in parallel with the JLAMP contruction and is the approach we have costed.

A final option is to use advanced electropolishing processing on the superconducting cavites for both the CEBAF 12 GeV project and JLAMP to reduce their RF losses. We have data from a limited number of cavities that suggests that if this process is adopted in the CEBAF 12 GeV project and JLAMP the helium refrigerator will have sufficient excess capacity to cool JLAMP with no other changes required. The cost of this advanced processing is essentially the same as the existing approach. The reason we have not adopted this approach as our cost baseline is that defensible data supporting this reduced loss will not be available until November 2011. The timeline for this decision on the refrigeration matches the proposed CD2 of JLAMP. At that time we will evaluate the status of this technology and make a choice of cryogenic approach. We intend to carry the higher cost option on the books until such time as the electropolish option is proven, but if successful, it will reduce project costs by order of $10M. In any case we propose an upgrade of the cryogenic transfer line for improved capacity and reliability as required for a user facility.

Figure 4.2. *Typical major cryogenic system components.*

4.2 Civil Construction

Conventional facilities to support JLAMP consist of an addition to the existing FEL facility to provide an x-ray user lab, and additional electrical distribution to support this improvement.

A 2,500 to 3,000 SF x-ray user facility will be constructed as a simple addition to the existing Free Electron Laser (FEL) facility. The floor elevation will match the existing FEL vault floor elevation to allow installation of a beamline from the existing FEL vault to the proposed x-ray user facility. See Figures 4.3 and 4.4. The east wall and foundation of the FEL will need to be underpinned to accommodate construction of the addition. No tunneling is required. Access to the addition will be by stairs from the FEL lower lobby. A secondary emergency exit will also be provided. Material and equipment will be moved to the proposed user lab by way of a freight elevator. The new addition will have sufficient space to allow several experimental setups and mirrors to permit switching between setups quickly. The user lab is anticipated to have no restrictions on occupation during experiments beyond normal safety training requirements.

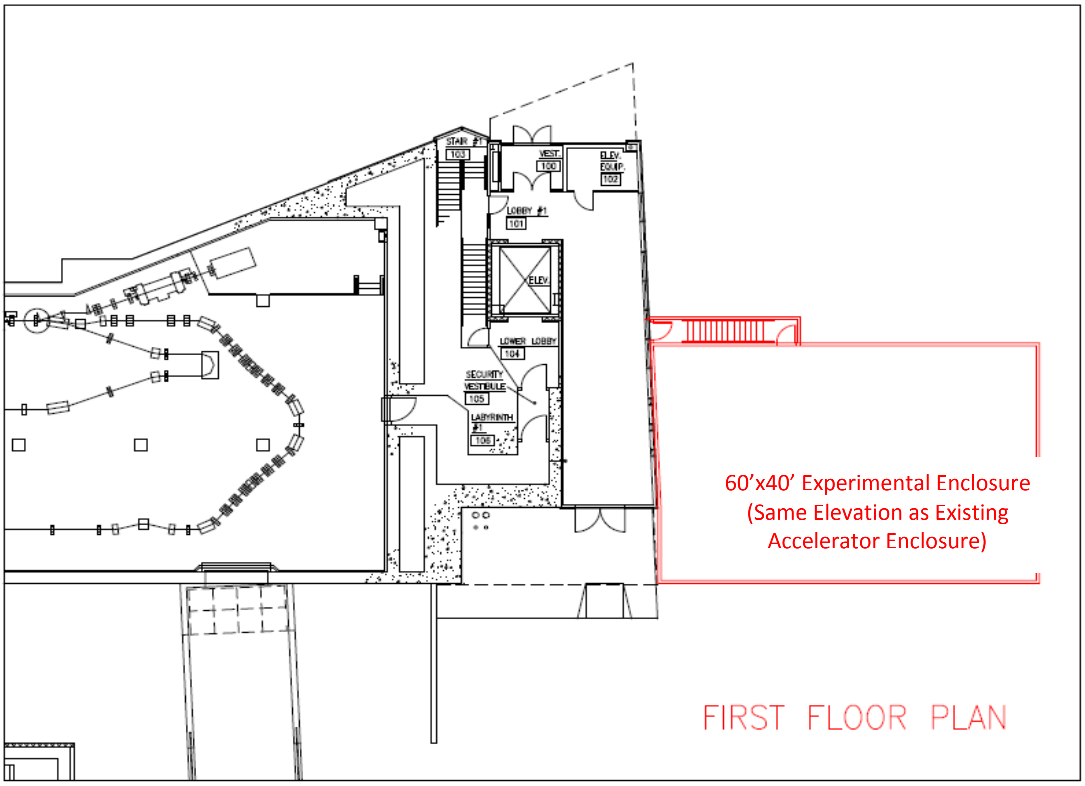


Figure 4.3. *Plan view of proposed x-ray user facility addition to existing FEL facility for JLAMP.*

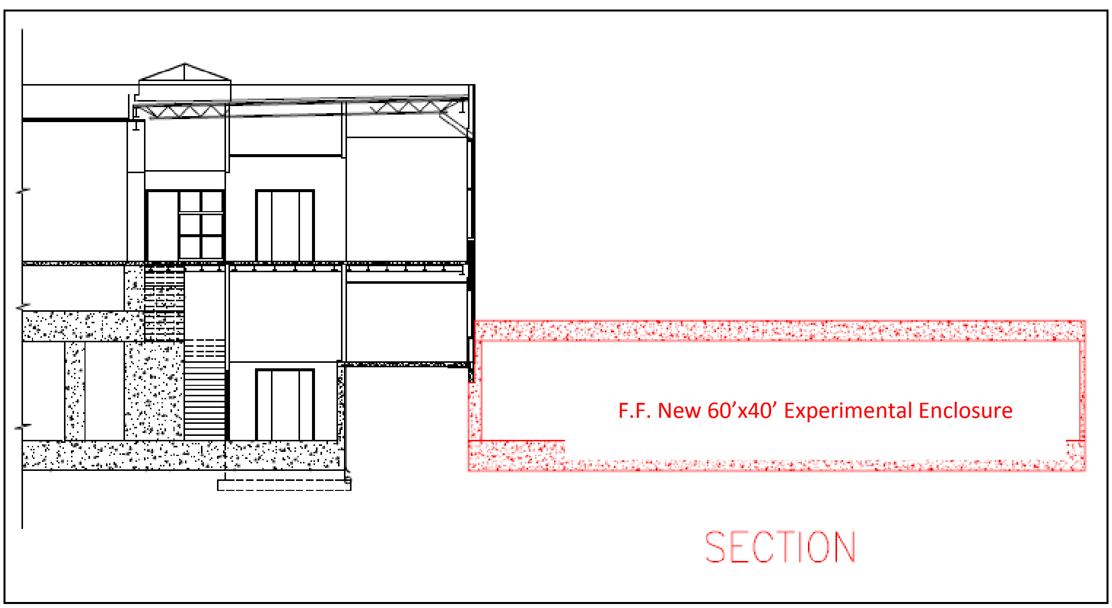


Figure 4.4. *Elevation view.*

Shielding analysis for the higher energy beam finds no significant shielding issues due to the 15' of compacted earth between the new user lab and the existing vault. The new operating point at 1 mA, 600 MeV does not produce significantly higher radiation than the existing 10 mA, 160 MeV infrared operations.

5. Light Source R&D at JLAMP

5.1 Background

JLAMP will provide numerous opportunities to perform R&D required to build light sources at higher photon energies and repetition rates. In this section we identify critical areas of emphasis, and discuss how they are addressed by the JLAMP project. Such R&D-driven design optimization is essential to achieve the advanced performance capabilities required by hard x-ray 4^{th} generation light sources. Due to the stringent demands on electron beam emittance and peak current, it is at present impossible to design such a 4^{th} generation source without additional R&D. In addition, the cost of such a facility is high and is driven by critical components in the linear accelerator and its support systems. Ongoing R&D will yield substantial savings in both capital investment and operating cost; a key secondary goal of this proposal is thus the demonstration of technologies important to next-generation hard x-ray user facilities. Further, after commissioning of the machine significant beamtime will be made available for user research proposals in accelerator science and technology. The JLab FEL facility has already demonstrated significant accelerator physics collaborative studies in areas such as beam breakup, HOM generation, optical transition radiation diagnostics, collective THz synchrotron radiation diagnostics, and advanced RF control module development. The JLAMP machine will enable further studies in recirculation dynamics, space charge effects, halo formation and control, and coherent synchrotron emission, among others. Areas available for study include most of the topics identified as priorities at the recent BES Workshop on the Accelerator Physics of Future Light Sources (Bethesda, Sept. 15–17, 2009).

5.2 Light Source Advancement in JLAMP Construction

Jefferson Lab already has demonstrated relevant capabilities in the areas of electron beam dynamics, superconducting radiofrequency linacs, electron guns, FEL performance, and diagnostics—all of which are required for next generation sources and JLAMP. This experience provides a foundation for the additional effort that will be provided in JLAMP construction through collaboration with other laboratories both in the US and worldwide.

5.2.1 SRF Accelerator Technology

The JLAMP project will decisively address two accelerator technology problems critical to the success of the next generation of light sources. The first is the development and demonstration of superconducting RF cryomodules optimized for light source applications. Key issues limiting present designs include the relatively low “real estate” gradient (i.e., the acceleration voltage delivered per meter of tunnel), cryogenic losses, which must be dealt with by a helium refrigerator with high operating and capital cost, and the damping of higher order modes (HOMs) driven by the electron bunches as they traverse superconducting RF cavities. Failure to sufficiently damp such modes can lead to degradation of the electron beam brightness or instabilities that can disrupt the beam during acceleration, recirculation, and energy recovery.

JLab has made great progress in cryomodule design and is now producing a module for the CEBAF 12 GeV program which delivers > 100 MeV of acceleration in a 10 m insertion length. It is also desirable to further reduce the cryogenic losses while obtaining the highest possible gradients. We have initiated a program under BES accelerator R&D funding to carry out this development.

A second accelerator research area with immense payoff for the next generation light source community is the development of techniques for, and investigation into the limitations of, beam recirculation. This technique is used by the CEBAF accelerator to send the electron beam through the same SRF cavities five times to achieve the desired beam energy, thereby achieving a substantial cost reduction in the accelerator. The cost of a *cw* 2.5 GeV next generation light source may exceed $1B, of which >50% is associated with the accelerator, tunnel, cryogenic, and RF systems. Reduction of this fraction of the facility cost by even a small number would be of huge benefit. The challenge in doing this is showing that it is possible to maintain the required electron beam brightness in the bends while avoiding beam-degrading effects such as wakefields, longitudinal space charge instabilities, and coherent synchrotron emission. We have modeled "existence proofs" of such a design and conclude from simulation that this recirculation-based approach will be viable in JLAMP [1]. It is however a challenging simulation problem, so questions as to the limits of viability of recirculation will endure until a program like JLAMP demonstrates success. It is highly desirable to have such an answer to this question before the designs (and budgets) of the next generation hard x-ray light source construction get frozen.

5.2.2 Seed Lasers

The generation of seed laser pulses by HHG has been under intense study over the last half decade and the mechanisms of harmonic generation are understood. The remaining difficulties are in implementing the technology: issues include improving conversion efficiency, producing high-repetition-rate drive laser pulses at 0.8 to 1.6 microns at high average power, dealing with the gas jet in a high-power, high-repetition-rate laser environment, and improving the power and beam focus quality delivered to the FEL input. Work is underway at a number of labs and commercially to develop the required high frequency drive lasers, so this technology is expected to progress apace as the FEL sources are constructed. The lead laboratory in FEL-related applications is presently DESY in Germany; we will utilize the best available technology and collaborate in efforts by LBNL and other labs to extend the capability from the 10 kHz rates presently achievable to the MHz level desired.

5.2.3 Undulators

As with the seed laser, a number of labs around the world are developing undulator technology to provide high fields with high quality at short wavelengths. The technology is pushed to its limits in the effort to achieve these high fields in undulators designed for *cw* current, where the concern for beam interception leads to large magnet gaps. Substantial progress has been made, but designs need to be carried from the existing short prototypes where the total forces are modest to the two meter scale section lengths required, where forces are measured in tons but micron tolerances are required. Developments by Cornell, Daresbury Lab and others will be leveraged in producing and demonstrating the performance of the next generation of variable-ellipticity undulators by involving those labs in the production and testing of the prototype undulator section.

5.2.4 FEL Gain

The FEL itself is relatively well understood in straightforward amplification thanks to a quarter century of R&D. For example, the gain measured at the LCLS in the 1.5 Angstrom regime agrees well with simple scaling laws published by M. Xie in 1995 [2]. Codes also predict well such parameters as bandwidth, emittance degradation, etc. Less well known are the limits to bootstrapping to shorter wavelength through high gain harmonic generation (HGHG) or even more advanced techniques such as Echo Enhanced Harmonic Generation (EEHG). Measurements of gain sensitivity are most accurately done on a *cw* system such as JLAMP, and validation of any of the techniques may enable significantly lower electron beam energy and thus lower accelerator cost for any next generation light source.

5.2.5 Timing and Synchronization

One challenge under investigation at MIT, LBNL, SLAC, FLASH, and elsewhere is the development of timing systems with low jitter and, even more importantly, low drift so that the various components of a next generation machine can be reliably linked and synchronized. This is no mean achievement when these systems may produce pulses of 10 fs or less and the facility itself may extend over distances of a kilometer or more. The FEL will not amplify the seed pulse if it drifts beyond the sub-100 fs electron pulse length. Moreover, it is important to know and maintain the relationship of additional components such as pump/probe lasers for accurate scientific studies to be accomplished. Present technology is at the threshold of the requirements, but more development and demonstrations are essential to make a hard x-ray next generation light source truly practical. We intend to incorporate the best of available technologies through collaborations with laboratories experienced in this field and advance the technology as we adapt and develop it for our own users' needs.

5.3 Accelerator R&D User Capabilities in JLAMP Operations

The JLAMP driver accelerator must generate, accelerate, and deliver to the FEL a properly configured electron drive beam, and recover it to low energy following the FEL interaction. This must be done while preserving electron beam brightness during transport to the FEL and—as it is a high power machine—avoiding beam loss throughout the system. This will, further, be accomplished in a small footprint using high gradient SRF cavities and multiple passes of beam recirculation during both acceleration and energy recovery. As a consequence, the accelerator serves as a user-facility test bed for virtually all phenomena of interest in the design of either class of linac-based fourth generation light sources (FEL or ERL). These issues include timing and synchronization, generation, acceleration, and beam quality preservation of high-brightness beams, management of collective effects and instabilities, and formation and evolution of halo in intense beams. All of the phenomena will be the subject of collaborative investigation, user experimentation, and analysis. The specifics of the accelerator physics user effort will obviously depend on submitted proposals, but it is expected that the topics in the paragraphs that follow will be included in the early years' efforts.

5.3.1 Potential Accelerator R&D Topics on JLAMP

System user opportunities will include state-of-the-art timing distribution networks and triggering systems so as to ensure synchronization of photocathode drive lasers, accelerator RF and diagnostics, FEL seed lasers and auxiliary lasers for use in user laboratories. Development and validation of low jitter/low drift timing systems to increasingly tighter tolerances is anticipated. This will allow users to test and certify systems as stable for use in next-generation machines. Formation of the required high-brightness *cw* electron beam will provide opportunity for user tests of various cathode drive laser technologies and will leverage and advance—through direct experimentation—understanding of photocathode dynamics. Investigation of a range of materials and methods so as to improve beam brightness and performance through the use of pulse shaping, low-thermal-emittance materials, and prompt emitters will be possible. As the system is *cw* at moderately high current, facility users will be presented opportunities for studies of cathode lifetime.

Electron gun options providing the high brightness required by the FEL are discussed elsewhere [3]; here we note that the driver accelerator injector will be able to utilize any of a variety of guns (DC, NCRF, SRF) and will thus provide users an opportunity to make direct comparisons of FEL performance as a function of choice of source. The injector will—as a state of the art, high brightness injector—allow experimental studies of the effects of emittance compensation and evaluation of emittance preservation scheme— in the presence of space charge effects. It will serve as the starting point for studies of halo formation (from processes due to beam dynamics of beam formation, the interaction of the beam with its electromagnetic environment, and the interaction of beam with itself and residual gas in the accelerator vacuum; an example is given in Figure 5.1). Once at injection energy, the transport of the beam from the injector to the ERL will allow users to study the impact of mergers on beam quality, and give immediate guidance on methods for emittance control during this process. Inasmuch as beams with extremely high brightness are not yet at equilibrium even at injection energy, the embedding of the injector in a full-energy ERL will allow characterization of the manner in which “injector” dynamics continue to evolve throughout the beam delivery process.

The JLAMP driver ERL will provide users opportunity to investigate beam dynamics, emittance preservation and operations issues associated with either ERL-based or FEL-based sources of synchrotron radiation. As it is a multi-pass, relatively-high-current, very high gradient *cw* SRF system, users can empirically evaluate methods for BBU mitigation and characterize propagating higher order modes, and test new RF drive and control systems. As the electron beam is extremely bright, there will be unparalleled opportunity for user experiments on the effects of wake and environmental impedance driven effects, including such beam-environmental interaction as resistive wall and RF heating. The small beam emittance will provide potential opportunity for observation of the impact of scattering phenomena such as intra-beam scattering, the Touschek effect, and beam-gas scattering – understanding of which is critical to successful operation of large-scale next-generation light sources. Anchored by the aforementioned halo studies in the injector, JLAMP experimenters will be uniquely positioned to observe the formation and evolution of halo.

As JLAMP is an evolution of the JLab IR/UV Upgrade FEL, it will utilize modern beamline design methods to control and mitigate phenomena leading to beam quality degradation. The system will therefore provide means of operationally altering both lattice and beam properties such as transfer matrix elements, betatron matches, phase advances, chromatic and geometric aberrations, dispersions, horizontal-vertical coupling, beam phase/path length and compactions to high order so as to controllably mitigate or enhance collective effects, utilize beam-based analysis and tuning, and characterize beam quality with high resolution. This allows users an unprecedented degree of experimental flexibility in tests of beam self- and environmental-interactions such as space charge (including longitudinal space charge), ISR, CSR, and microbunching instabilities.

JLAMP operation will corroborate ISR analyses performed for previous high energy recirculators and transport systems (SLC, CEBAF, and the CEBAF 12 GeV upgrade), thus confirming projections the accuracy of which is vital to the success of high energy ERL programs and relevant to the design of bunch compressors in high energy X-FEL systems. Users will test and validate advanced concepts in bunch length compressor design—including multistage compression over multiple passes and use of vacuum chamber shielding of CSR [4]—and thus leverage and build on the accelerator science community's CSR knowledge base that has seen explosive growth due to advances in the X-FEL community [5]. Simulations of the phenomena will continue to advance but would benefit from an extensive period of testing with variable shielding in a well instrumented arc such as on JLAMP. We anticipate early proposals in this area. Use of SRF technology ensures that accelerator component impedance and wake effects will be meticulously characterized. JLAMP will employ and enforce a detailed impedance budget so as to ensure that the interaction of the beam with all system components will be understood and managed, and wakefield degradation of beam brightness and microbunching instabilities will be avoided. This detailed characterization of system properties will, in turn, provide users with opportunities for exceptionally well controlled testing of wake and impedance effects on beam quality and will allow them to benchmark beam-environmental interactions for follow-on linac-based light sources.

Magnet field quality looms as an under-recognized issue in the construction and operation of large-scale ERLs, and can pose significant constraints on the energy recovery process [6]. JLAMP will—through use of carefully specified, characterized, and controlled transport components—allow detailed experimental analysis of the impact of magnetic inhomogeneities on system performance. In addition, though collimation systems are largely unnecessary at nominal JLAMP operating currents, the facility will provide users opportunity for analysis and testing of the systems that will be required in high current/high energy ERL systems such as those in design at Cornell and ANL. We hope to see outside proposals for careful characterization of magnetic field effects in beam degradation. All capabilities and testing will be supported by a full suite of diagnostics for characterization of both accelerator and electron drive beam properties in high brightness/high power systems.

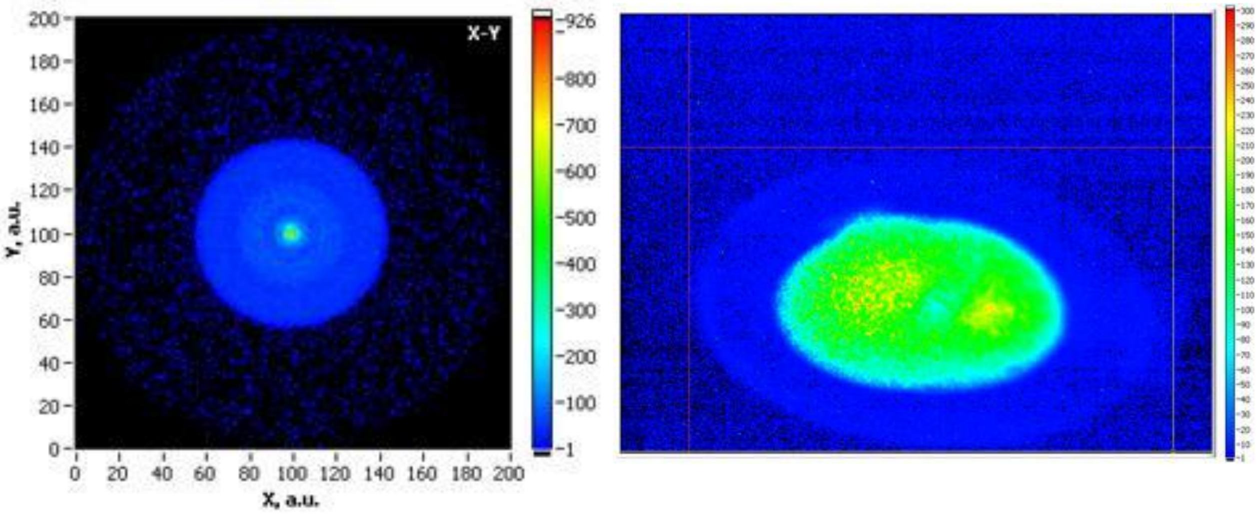


Figure 5.1. Modeled (left) and observed (right) halo in JLab IR/UV Upgrade Injector [7].

5.3.2 Technical Support for Accelerator User R&D

JLAMP accelerator operation and user experiments will be supported and enabled by an extensive suite of beamline diagnostics and instrumentation, although it is anticipated that through our user R&D new and more advanced diagnostics will continue to be incorporated in JLAMP. Existing beam position monitors (BPMs) [8] include multi-pass capability and allow lattice characterization and tuning through use of differential orbit measurements of the accelerator transfer map, monitor energy loss due to CSR effects during bunch length compression, and measure the extraction efficiency of the FEL. Beam cavity monitors (BCMs) [9] are tied to the accelerator RF/laser synchronization system and provide a measure of both beam current and time of flight. They are used by the accelerator phase transfer function measurement system [10], which evaluates time (phase) response of the beam at an observation point to upstream variation in timing (phase), thereby allowing direct tuning of time-of-flight- and energy-related accelerator parameters such as the transport system momentum compaction. Beam current is cross-referenced using inductively coupled toroidal pickups such as Unser monitors [11] and by measurement of the recovered current at the beam dump.

Electron beam size is measured for operators and users with a variety of beam-profile monitors distributed through the system. At low (tuneup) beam powers, optical transition radiation (OTR) monitors and phosphor-coated viewers provide reliable positional and profile data with good resolution. Synchrotron radiation from bending magnets is imaged and utilized as a non-intercepting beam position and profile measurement that is useful at all levels of beam power. Flying (and perhaps laser) wire monitors are utilized for profile measurements of high- and medium-power beams, especially where coherent optical transition radiation (COTR) produced by the high-brightness electron beam after compression degrades the resolution of other intercepting measurements (such as those based on OTR). Diffraction-radiation-based profile monitors will be made available at high energy as the available technology evolves [12].

Transverse beam profiles obtained from all of these methods serve as the basis for the emittance characterization systems JLAMP uses for determining beam properties and performing betatron matching. The injector employs systems such as multislit or pepperpot based emittance monitors appropriate to the space-charge dominated beam [13]. At higher energy, multi-monitor measurements and quadrupole scans provide the spot size information needed for emittance measurements in support of machine operations and user studies. As an alternative, an interferometric emittance monitor under development at the University of Maryland will be available to characterize both core and halo emittance [14]. Data obtained from all these systems is used for tomographic reconstruction of the transverse phase space so as to evaluate in detail the evolution of the electron beam in the presence of the previously described beam dynamical processes.

Longitudinal phase space is similarly characterized through use of various bunch-length diagnostics and spectrometer-based methods for energy measurement using BPMs, synchrotron radiation monitors, and beam viewers. Martin-Puplett interferometers [15] are used to measure bunch lengths with resolutions of (10's of) microns during low-power operation. These results are cross-referenced, even at high powers, though the use of Fourier-Transform Infrared (FTIR) spectrometers. Both classes of device provide information necessary for longitudinal matching of the beam to the accelerator lattice (which has been, in turn, characterized by use of the phase transfer function measurement system) and evaluate beam performance. Beam energy and energy spread are precisely measured with spectrometer-based methods employing BPMs, beam viewers, and imaged synchrotron radiation from recirculator bending magnets.

Output from various optically based diagnostics can be directed to a streak camera for user and operational analysis of short-time-scale effects; the streak camera provides measurements of the drive laser temporal distribution on the cathode and will allow direct measurement of the beam energy and time of flight (bunch length) distributions. Together with bunch length, energy, and energy spread data, this allows tomographic reconstruction of the longitudinal phase space.

JLAMP beam brightness is consistent with that of both X-FEL drivers and ERL x-ray sources. It is, in addition, in an intermediate range of beam current (few mA rather than <1 mA or 10's of mA) lying between the two generic architectures. As a consequence, it is well suited for user studies of halo formation and evolution. These investigations are aided by the diagnostics described above, a periodic transport lattice—which will allow introduction and diagnostic use of collimation—and presence of various halo monitoring diagnostics. These include variable interceptive apertures coated with large-dynamic-range phosphor that can be plunged into the beam to obtain halo profiles without intercepting the core [16], and the University of Maryland interferometric emittance monitor, which can distinguish core and halo emittances and has similar large dynamic range [14].

5.3.3 Historical Context: Collaborative Accelerator R&D with the JLab FEL

The accelerator science and technology discussed above are a natural extension of the JLab IR Demo and IR/UV Upgrade projects, and have evolved through the collaboration of universities, federally funded laboratories, and industry. We have had a number of outside groups do research on the FEL accelerator, producing significant results in injector performance, beam dynamics, beam diagnostics with THz and edge radiation and the development of advanced RF control systems. Examples of such successful outside user activities follow.

JLab has—in collaboration with Cornell University and Daresbury Laboratory—built and operated a series of DC photocathode guns providing record *cw* brightness in support of both the nuclear physics and FEL programs [17]. Most recently, nC-level performance has been achieved in the JLab Gun Test Stand (GTS), a flexibly reconfigurable and well-instrumented test-bed available for gun studies and operation [18]. Operation and analysis of this system has been underway for nearly 15 years, and has profited from collaborative studies with Cornell University, Daresbury Laboratory, Northern Illinois University, and industrial partners such as Advanced Energy Systems [19]. Recently this collaboration has produced the design of an inverted DC gun which is expected to substantially improve the high voltage operating capability of such systems. Ceramics efforts led by Daresbury and Cornell contributed to the high voltage feed through design.

In high current ERLs a crucial question involves control of the RF fields during energy recovery of a high power beam. Cornell University performed tests of their advanced digital RF control module on the JLab FEL [20] for high gradient/high power operation and measured beam stability during high current operations to characterize beam and FEL performance [21]. The success of these tests formed the basis of their RF control module development included in their high power ERL proposal to NSF.

The JLab FEL was the first and remains the highest power energy recovering linac. Suppression of the beam breakup instability was crucial to its success. Some of the initial measurements and analysis which confirmed theoretical and analytical understanding of the phenomena of beam breakup performance were performed as a collaborative outside user effort involving Stanford University [22].

Space charge has been the subject of analysis for both its transverse and longitudinal effects [23] and has been detailed using streak camera measurements [24], and the impact of CSR—a topic of great concern—has been extensively evaluated. JLab operates a record-brightness THz source [25] and as a consequence has considerable experience with design and operational management of CSR effects. High power operation of the JLab IR/UV upgrade FEL overcame THz/CSR heating effects in the FEL optical cavity [26]; the success of this effort was vital to achieving 10 kW operation and involved a significant collaborative component involving both measurement and modeling based analysis [27]. The effects of vacuum chamber shielding have been under analysis for some time and are the subject of a planned study in collaboration with Cornell University [28].

Finally, significant ongoing diagnostic development efforts by groups from Cornell University, the University of Georgia and the University of Maryland have led to advances in traditional electromagnetically based devices such as beam position monitors [29], as well as photon based diagnostics using synchrotron bend radiation and coherent synchrotron radiation to analyze beam properties such as bunch length [30], emittance, and halo [31]. These developments by outside users at the FELs have increased our understanding of beam phenomena and enhanced our ability to control the high power energy recovering linac.

5.4 Conclusion

In summary, the JLAMP program will be a significant advance in scientific capability for users, and the technologies developed as a result have great potential to enhance DOE's ability to construct a technically and economically viable next generation hard x-ray user facility. Active collaborations with other DOE and international laboratories will ensure the best and most appropriate approaches are utilized and that costly duplication of efforts is avoided. Finally, the utilization of the existing infrastructure and experience base at JLab means that the JLAMP program for a soft x-ray user facility is cost-effective and highly leveraged in its benefits to *cw* next generation hard x-ray user facilities wherever they may be built. We have designed the system with use for accelerator R&D by external researchers in mind. In support of that we have provided a strong set of accelerator diagnostics to support anticipated measurements and further expect the enhancement of those capabilities as the user research program proceeds.

References for Section 5

[1] D. Douglas and C. Tennant, JLab Tech Note 09-046 (2009).

[2] Y. H. Chin, K.-J. Kim, and M. Xie, "Three-dimensional theory of the small-signal high-gain free-electron laser including betatron oscillations", Phys. Rev. A, Vol. 46 (1992) 6662.

[3] See references for subsection 3.5.

[4] R. Li, Proc. PAC, p. 118 (1999).

[5] See, e.g., K. Bane et al., Phys. Rev. ST Accel. Beams **12**, 030704 (2009).

[6] D. Douglas, JLAB Tech Note 02-002 (2002); D. Douglas, 45th ICFA Workshop on ERLs (2009).

[7] P. Evtushenko, 45th ICFA Workshop on ERLs (2009).

[8] G. Krafft et al., Proc. PAC, p. 912 (1997), D. Sexton, ECE486 Final Report, Old Dominion University (2004).

[9] G. Krafft, op. cit.

[10] G. Krafft, et al., Proc. PAC, p. 2429 (1995); D. Hardy et al., Proc. PAC, p. 2265, (1997).

[11] K. Jordan, private communication.

[12] P. Evtushenko et al., Proceedings of 13th Beam Instrumentation Workshop (BIW08), Tahoe City, California, USA p. 133.

[13] P. Piot et al., Proc. PAC, p. 2204 (1997).

[14] M. Holloway et al., Phys. Rev. ST Accel. Beams 11, 082801 (2008).

[15] P. Evtushenko et al., Proc. FEL, p. 736 (2006); G. Krafft et al., Proc EPAC, p. 1580 (1998); U. Happek, et al., Phys. Rev. Lett. **67**, 2962 (1991).

[16] K. Jordan, private communication.

[17] C. Hernandez-Garcia et al., Proc. PAC p. 3117 (2005).

[18] C. Hernandez-Garcia et al., to appear in Proc. DEPS Symposium (2009).

[19] P. Piot et al., Proc. DEPS Symposium (2008); A. Todd et al., Proc. PAC, p. 977 (2003); A. Todd et al., Proc. PAC, p. 2292 (2005).

[20] J. Delayen et al., Proc. SRF Workshop, p. 230 (2007); M. Liepe et al., Proc PAC, p. 2642 (2005).

[21] P. Evtushenko, Proc. FEL, p. 517 (2008).

[22] C. Tennant et al., Phys. Rev. ST-AB **8**, 074403 (2005); D. Douglas et al., Phys. Rev. ST-AB **9**, 064403 (2006); C. Tennant, Ph.D. thesis, The College of William and Mary (2006).

[23] C.Hernandez-Garcia, Proc. FEL, p. 363 (2004); P. Evtushenko et al., Proc. PAC, p. 1323 (2007).

[24] S. Zhang, op. cit.

[25] J.M. Klopf et al., Nucl. Instrum. Methods A582, 114-116 (2007).

[26] See, e.g., "Jefferson Lab Free-Electron Laser Upgrade Project Annual Progress Report for FY2006"; S. Benson et al. op. cit.

[27] O. Chubar, P. Elleaume, Accurate and efficient computation of synchrotron radiation in the near field region, in: Proceedings of the EPAC98 Conference, 22–26 June 1998, pp. 1177–1179.

[28] R. Li, op. cit.

[29] J. Yan et al., Proc ICALEPS, p. 720 (2007); D. Sexton, op. cit.

[30] P. Evtushenko et al., Proc. FEL, p. 736 (2006); G. Krafft et al., Proc EPAC, p. 1580 (1998); U. Happek, et al., Phys. Rev. Lett. **67**, 2962 (1991).

[31] M. Holloway et al., op. cit.

6. Operation as a User Facility

Once constructed and commissioned, the JLAMP FEL will be utilized as a user facility for photon science and for accelerator studies. We plan on running the system approximately 5000 hours a year, that is, 24/7 operation for around 30 weeks a year. We anticipate that running time to be divided roughly 80% for photon science and 20% for accelerator studies but will make schedule adjustments based on user need. The following subsections detail our plans for user support in both photon and accelerator science, for procedures for submitting proposals, for staffing support, and for expanding our technical capability in the soft x-ray region to support the expected user community.

6.1 User Procedures and Support

Jefferson Lab as an institution has an established record of user support in the nuclear physics community with over 1200 users a year working at Jefferson Lab, including a strong international component. Approximately one third of the nuclear physics Ph.D.'s produced each year in the US are associated with activities at Jefferson Lab. The procedures, training and infrastructure required to support this community have already been ported over to FEL operations. We utilize the same user office, have training requirements established with most training available online, and have established documentation and approval processes for user activities. The process can be examined at http://www.jlab.org/FEL/fel_get_started.html.

We have a guest house on site and additionally have many low cost hotels nearby. We are within an hour of three major airports, Newport News (2 miles away), Norfolk (25 miles away) and Richmond (58 miles away).

Typically it takes about a half day to register, get through the training, and get a user badge which gives access to the FEL and accelerator facility. To this is added user lab specific training that depends on the particular hazards associated with the laboratory. For example, laser exposure, either FEL or conventional, or access to controlled radiation areas requires additional course work and, in the case of laser exposure, an eye exam.

Although we have not received any funding to support operation of the FEL as a user activity, we have managed to perform a few outside user experiments each year on a parasitic basis in addition to an extensive set of internal studies on FEL performance in both photon and accelerator science. The outside user experiments have encompassed a broad band of photon energies and a broad range of experiments from the LIPSS search for dark matter [1,2], to materials modification (3-8), studies of interstitial hydrogen in silicon [9-12], and THz production [13, 14]. Users have also utilized the FEL accelerator itself for R&D, including beam breakup studies, RF module development and THz spectroscopy with Cornell University and transition radiation emittance measurements with the University of Maryland [15].

The proposal and experiment process is detailed from the web site noted above. Proposals follow a format similar to that of the DOE-BES light source facilities. A Program Advisory Committee reviews and prioritizes the proposals based on scientific merit. A second part of the review process concerns safety, which is covered in an Experimental Safety Approval Form, and which contains a task hazard analysis, experiment description and procedures. Beam time is scheduled by the FEL Operations Coordinator, with operations directions for the FEL operators detailed in a separate operation plan. New configurations of hardware necessitate a walkthrough and approval of the setup by the safety officer before experiments can proceed. Safety is our primary concern and failure to follow approved procedures risks loss of operating privileges. We have operated the highest power FEL in the world as well as five other Class 4 conventional lasers at JLab for 13 years without a laser associated injury and we intend to continue that record. The full details of our user process and requirements are specified in the JLab Safety Manual with access available at http://www.jlab.org/ehs/ehsmanual/index.html.

As we operate JLAMP we intend to follow guidelines from BES regarding the proposal process and beamtime assignment. We will follow the NSLS calendar with three calls per year for proposals and scheduling in order to minimize any waiting time for new idea implementation by users. We anticipate most of the users coming under the general user category, but JLab does have a legal framework for dealing with proprietary users. All users, including personnel associated with specific beamlines that form part of the initial suite, will be required to submit proposals and safety forms. Similar requirements will exist for user submitted programs in accelerator science. Depending on the nature of any linac modifications, there may be additional documentation required to comply with DOE accelerator safety orders. We believe it is unlikely that any accelerator user would cause modifications to the accelerator safe operating envelope, but all accelerator modifications will be reviewed for such compliance.

6.2 FEL Technical Infrastructure

The existing FEL facility comprises an accelerator vault below grade with a control room and seven user labs above ground. A layout of the facility is shown in Figure 6.1. We presently have assigned particular technical areas in each lab to focus capabilities of support equipment. Lab 1 to date has served as a general purpose lab with, for example, recent experiments including medical tests on tissue necrosis performed by a group from the Wellman Institute of Harvard, a search for dark matter led by Yale University with JLab contributors, and generation of carbon nanotubes for a NASA-led collaboration. All of these labs support the use of the existing FEL beam and many other Class 4 lasers with safety interlocks consistent with ANSI Z136 standards in compliance with all DOE regulations and guidance. The labs and the Laser Personnel Safety System have repeatedly passed external and internal reviews and audits. The existing IR/UV and THz beams are brought upstairs to the labs in a high power vacuum beamline with a wavelength-dependent beam diameter of around 1 cm and Rayleigh range of order 60 m. We have continuous monitoring of our user beam using an optical system that picks off approximately 0.1% of the laser pulse, and sends it to a diagnostic table. Beam quality is excellent with an M^2 less than 2.0; position jitter is less than 10% of the beam diameter; angular jitter is on the order of microradians. Temporal jitter is governed by the drive laser jitter, presently of order 100 fs.

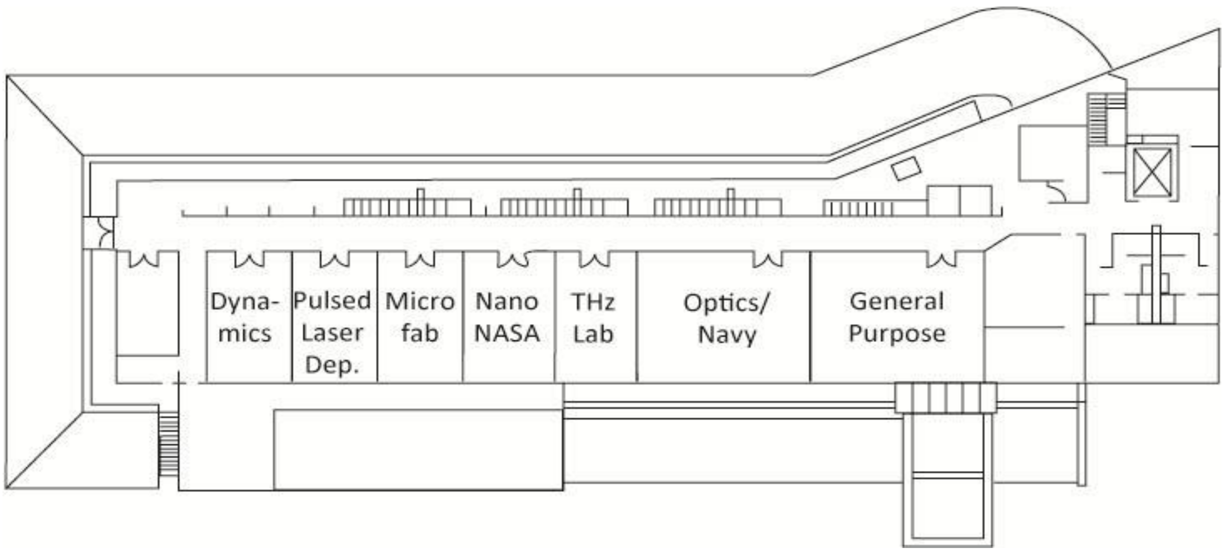


Figure 6.1. *Layout of the Jefferson Lab Free Electron Laser facility.*

The JLAMP proposal will require modifications to the facility to support soft x-ray operations which cannot be efficiently reflected to the existing user labs on the second floor. For such operations, we will provide a new user lab directly downstream of the FEL. This conventional facility is described in subsection 4.2 of this proposal. It is basically a large room, slightly below grade with sufficient room for experiments not only straight ahead but in several adjacent stations. The optical beamlines contain safety shutters, mirrors and monochromators where necessary. A layout of the proposed beamlines is described in subsection 3.9. The facility will allow user stations to be staged in the area and then quickly moved into position on the beamline. The facility is designed for easy delivery and setup of user stations with access to the facility by means of a ramp. The facility is shielded from the accelerator vault sufficiently that full access can be allowed during machine operations [16].

Many experiments will utilize conventional lasers for pump/probe studies, and these must be synchronized to JLAMP. We have significant experience doing this already with several high power lasers in the FEL facility. Synchronized lasers include not only the drive laser for the photocathode (a custom TimeBandwidth oscillator amplified in several stages of diode pumped amplifiers by Q-Peak providing up to 18 W average power in the green at 74.85 MHz synchronized to the RF master clock with a jitter of 200 fs FWHM) but also a Spectra-Physics Tsunami, a Quantronix Titan Oscillator/Regenerative Amplifier, and two Coherent Antares Oscillator/Amplifiers as discussed in Appendix B. As part of the construction effort we will be upgrading our timing system to meet the stringent jitter requirements envisioned for short pulse operation in the future. For example, it will be essential to get operation of the seed laser synchronized to the electron pulse to better than 10 fs. This has been achieved in other laboratories and we intend to make use of the best approaches developed to date to synchronize the electron beam and other supporting lasers. Efforts in this regard are included in the R&D associated with this project.

Optical metrology is also essential to support development in beamlines and seed lasers. Jefferson lab has a very good suite of optical metrology for examining optical quality and surface figures. These instruments include a WYKO NT1100 Noncontact Profilometer, a Wyko RTI4100 Laser Interferometer, a Thermo Nicholet FTIR spectrometer, a Zeiss Axiolab polarizing microscope, a Spirocon Pyrocam III, a FLIR A26 IR camera and a Hamamatsu High Speed Streak Camera. Further materials characterization instrumentation available locally is discussed in Appendix B.

6.3 FEL Staffing and Operations

As crucial as the physical infrastructure will be the skill sets encompassed by the FEL team. These skill sets naturally divide into those required to design and build the JLAMP device, those required to run and support the JLAMP efforts for accelerator R&D, and those required to support the soft x-ray user community. Résumés of key personnel are listed in Appendix D. We have an extensive set of skills in accelerator technology, especially superconducting RF acceleration but also fundamental beam propagation physics, with world class efforts in DC injectors, CSR simulation, and beam breakup, among others. As part of our contribution to growing new capability in this field, we have taught courses at the US Particle Accelerator School in the past and will host a USPAS hands-on class in FEL operation in FY11. We host each summer 6 to 10 students to work in the FEL, and occasionally their projects have turned into research publications—a great way to get students enthusiastic about carrying forward their higher education in light source technology.

We also have a deep experience base in lasers with the 10 kW IR FEL and its optics developed and analyzed, and also the experience that comes from working with a significant number of Class 4 lasers used for materials tests, diagnostics, drive lasers and the like. Two members of the team have over 20 years experience at VUV-soft x-ray user facilities. This skill set serves as a significant base to support the development of a VUV/soft x-ray user community, but we recognize that we will have to grow our capability in several areas to meet the needs of a world class soft x-ray effort. The construction of the x-ray beamlines (see subsection 3.9) is to be managed through collaboration with Brookhaven National Laboratory, a facility with extensive experience and capability in this area. With these construction and installation efforts we will become familiar with the technology and gradually develop our own capability onsite.

Support of users is especially critical in their early encounters with the facility operations. Each experiment in photon and accelerator science will be assigned a local scientist backed up by sufficient technical staff to assist in the initial installation and operation of their equipment with JLAMP. As the user group becomes more familiar with our operations and how their own system functions while operating on JLAMP, it might be envisioned that the need for such close scientific support will diminish. In fact, as user desires grow for more technical capabilities this partnership may even grow into a full collaboration. In either situation we intend to ensure that in each case, the users have the required local knowledge and support to make their experiment a success.

We intend to hire in several key positions for this program. To lead the scientific development of the x-ray facility as a whole we will hire a chief scientist of recognized capability in soft x-ray science. It is expected that this scientist will perform his/her own experiments on JLAMP and will serve as an interface for outside users to the FEL team. This is to ensure that in the design and operation of the machine, user needs are being met. We also intend to have a single early career scientist or postdoc assigned to each of the two beamlines to support outside users as they install and conduct their experiments. These scientists are to provide the local experience and knowledge required to help outsiders deal with the unique characteristics of the facility and provide more assistance in finding and engaging local resources. Each beamline will also have use of a dedicated group of technicians with skill sets covering electronics, mechanical assembly, vacuum technology, software and controls, alignment, lasers, x-ray optics, etc., for assistance in performing the experiment. In our use of the existing FEL we have found such assistance invaluable to ensure success of user experiments. Often such users are working without the availability of their home support group with such skills, and problems can often appear during setup and operation which would prevent successful conclusion of the work. Similar support is available for accelerator based experiments from the accelerator operations and maintenance crew. We intend to provide most labor involved in hardware installations and modifications required for accelerator science user experiments, and the labor required for modest efforts is included in our estimates. It is envisioned that proposals for major machine modifications (say, testing an entirely new injector) would require separate proposals to BES to cover the major equipment construction and installation staff.

6.4 FEL Annual Operating Budget

The required staffing after completion of construction and commissioning can be estimated from the operation of the present FEL system. The FEL core staff has been stable at 25 to 30 individuals for eight years. Because they are supplemented by JLab staff for major maintenance and installation activities, the FEL has funded 40 to 50 FTEs from JLab while typically operating for 2000 hours per year. This staff includes 15 scientists and senior engineers with the rest being technologists and technicians.

JLAMP is intended to operate 5000 hours per year and so will require an increase in support staff. The accelerator system as a whole will increase moderately from the present three older-style CEBAF cryomodules and two electron beam-paths to three upgraded CEBAF-style cryomodules and four beam-paths, necessitating a modest increase in maintenance staff. The increased operation will lead to higher component failures and increased preventative maintenance for about a 25% increase in maintenance staff.

A more major change will be in the operations group. Presently the FEL is operated by staff scientists and engineers rather than dedicated operators. Because this is not desirable for a dedicated user facility, a more formal operations staff must be established. It requires two staff to operate the FEL: one operator would serve as a Beam Operator and Safety System Operator; the other as Crew Chief and Beam Operator. For 24/7 operation allowing for vacation and training this is 15 FTEs to achieve 5000 hours of operation including a group leader and two deputies. This is 60% of the CEBAF Accelerator Operations group. Adding in the need for a chief scientist lead, two junior scientists, and four technicians to support the photon user labs brings the minimum staffing to support operation of a facility such as this to 82 FTEs, of which 20% are scientists or senior engineers.

The estimated operating cost must include electricity (about 2.8 MW, 1.5 MW for the cryogenic refrigerator, and 1.3 MW for the FEL itself) at $970k per annum for the helium refrigerator and $480k per annum for the FEL power based on $0.074k/MW-hr with the refrigerator on 24/7 and the FEL running 5000 hours. It must also include cryogens (approximately $500,000/year scaled from the $1,500,000 per year used by the 4.7 MW CEBAF Central Helium Liquefier). Other equipment and consumables will be required as in any accelerator facility. We estimate these at $1,000,000 per year. We intend to provide $1,000,000 per year in general user equipment upgrades including any modest accelerator physics study hardware required. The total operating cost of the facility is thus estimated at roughly $17M/year. This estimate will be more fully developed during the construction phase of the JLAMP Program.

References for Section 6

[1] A. Afanasev, O. K. Baker, K. B. Beard, G. Biallas, J. Boyce, M. Minarni, R. Ramdon, M. Shinn, and P. Slocum, “New experimental limit on photon hidden-sector paraphoton mixing”, Physics Letters **B679** 317 2009.

[2] Afanasev, O.K. Baker, K.B. Beard, G. Biallas, J. Boyce, M. Minarni, R. Ramdon, M. Shinn, P. Slocum, “Experimental limit on Optical Photon Coupling to Light Neutral, Scalar Bosons”, Phys. Rev. Lett. **101** 120401 (2008).

[3] P. Schaaf, R. Serna, J. Lunney and E. Fogarassy, “Laser Synthesis and Processing of Advanced Materials”, Applied Surface Science **254** 789 (2007).

[4] D. Höche, M. Shinn, G. Rapin and P. Schaaf, “FEM Simulations of the laser plasma interaction during FEL laser nitriding of titanium”, Applied Surface Science **254** 888 (2007).

[5] D. Höche, G. Rapin, J. Kaspar, M. Shinn and P. Schaaf, “Free Electron laser nitriding of metals: from basic physics to industrial applications”, Applied Surface Science **253** 8041 (2007).

[6] D. Höche, M. Shinn, J. Kaspar, G. Rapin, and P. Schaaf, “Laser pulse structure dependent texture of FEL synthesized TiNx coatings”, J. Phys. D: Applied Physics **40** 818 (2007).

[7] Ettore Carpene, Michelle Shinn and Peter Schaaf, “Synthesis of highly oriented TiN coatings by free electron laser processing of titanium in nitrogen”, Appl. Phys. **A80**, 1707-1710 (2005).

[8] Ettore Carpene, Michelle Shinn and Peter Schaaf, “Free-electron Laser Surface Processing of Titanium in Nitrogen Atmosphere”, Appl. Surface Science **247**, 307-312 (2005).

[9] G. Lupke, X. Zhang, B. Sun, A. Fraser, N. H. Tolk, and L. C. Feldman, “Structure-Dependent Vibrational Lifetimes of Hydrogen in Silicon”, Phys. Rev. Lett. **88**, 135501, 2002.

[10] M. Budde, G. Lüepke, C. Parks Cheney, N. H. Tolk and L. C. Feldman, "Vibrational Lifetime of Bond-Center Hydrogen in Crystalline Silicon," Phys. Rev. Let. **85**, 1452 2000.

[11] M. Budde, C. Parks Cheney, G. Lüpke, N. H. Tolk, L. C. Feldman, “Vibrational Dynamics of Bond-Center Hydrogen in Crystalline Silicon”, Phys. Rev. **B63**, 195203-21 (2001).

[12] G. Lüpke, N. H. Tolk, L. C. Feldman, “Vibrational Lifetimes of Hydrogen in Silicon”, J. Appl. Phys. **93**, 2316-33 2003.

[13] Gwyn P. Williams, “Filling the THz Gap”, Reports on Progress in Physics **69** 301 (2006).

[14] G.L. Carr, M.C. Martin, W.R. McKinney, K. Jordan, G.R. Neil and G.P. Williams “High Power Terahertz Radiation from Relativistic Electrons”, Nature **420** 153-156 2002.

[15] M.A. Holloway, R.B. Fiorito, A.G. Shkvarunets, et al., “Multicomponent measurements of the Jefferson Lab energy recovery linac electron beam using optical transition and diffraction radiation”, Phys. Rev. ST Accel. Beams **11** 082801 (2008).

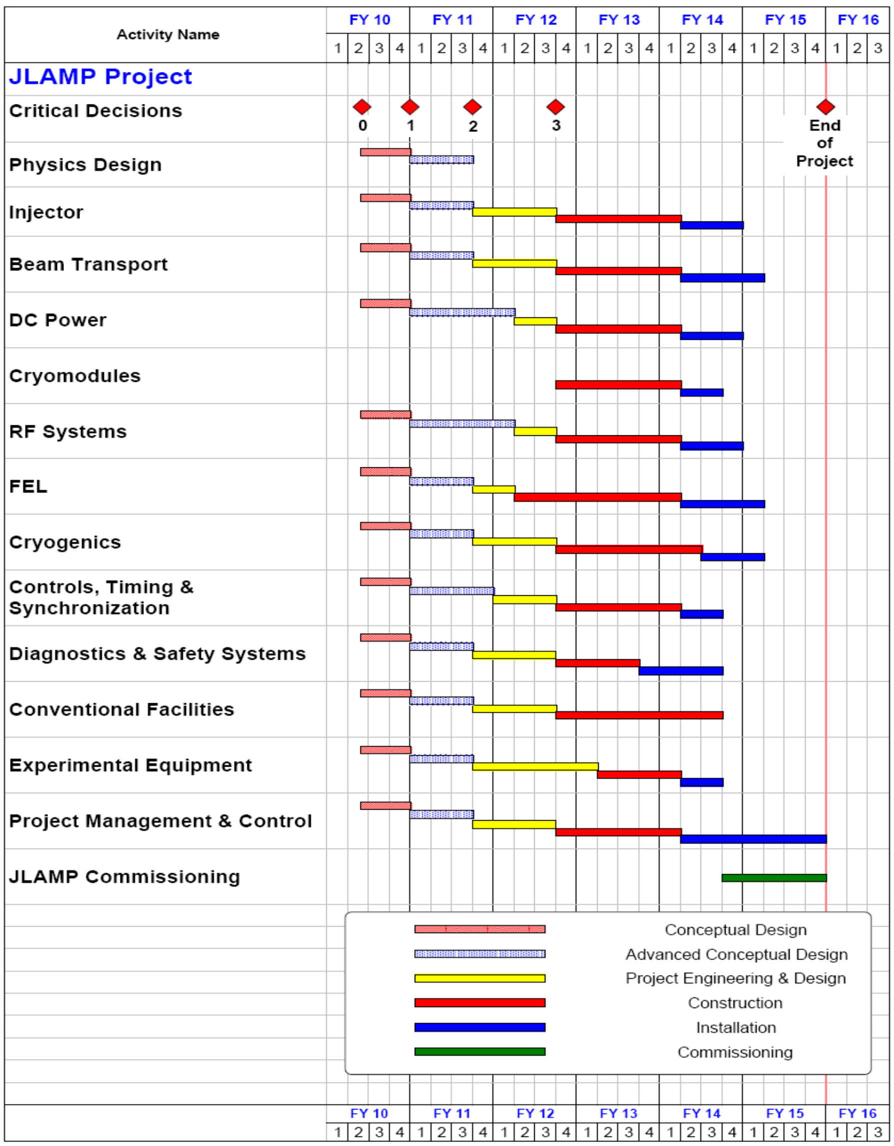
[16] Vashek Vylet and George Neil, “Preliminary Shielding Assessment for JLAMP’, JLab-TN-09-058.

7. Schedule and Cost

This chapter presents the proposed schedule and cost for the JLAMP effort. The schedule shown here makes certain assumptions about the availability of funding and the pace at which DOE approval is received. The project cost can also be influenced by extended schedules through increased escalation and oversight activities which must be maintained. We have therefore tried to optimize the construction schedules as presented to minimize programmatic delays. After discussing the schedule in subsection 7.1 we present a summary of the cost estimates in subsection 7.2. Subsection 7.3 addresses the risk management approach, an essential part of any major construction activity.

7.1 JLAMP Schedule

We propose a construction schedule as shown in Figure 7.1 assuming a CD-0 in FY10. Not in this proposal but also underway are activities toward optimizing SRF designs for hard x-ray 4thGLS user facilities under separate auspices. We have received initial funding from BES to



pursue such development. The initial phase of that effort will be to demonstrate the performance of an SRF cavity with a design optimized for light source use including features such as high gradient, low cryogenic losses and excellent HOM damping. We anticipate a gradual increase in the user activities at the existing FEL as we develop the new machine. Harmonics of our UV FEL in addition to the IR and THz light produced by the existing system will be utilized for a number of experiments until such time as the FEL must cease operations so the new hardware can be installed.

7.2 JLAMP Cost

A summary of estimated costs of the JLAMP Project by WBS element is shown in Table 7.1 along with a pie chart of that data in Figure 7.2. We have performed estimates of the labor and procurements in each WBS area and escalated the estimates to the proposed year of performance or hardware procurement utilizing inflation factor guidelines provided by DOE. Summary budget sheets for each WBS level 2 element are shown in Appendix E specifying the cost breakdown from that element and the basis of estimate utilized. The proposed project annual financial commitment profile by funding type/project phase is shown in Figure 7.3 with the cumulative values shown in Figure 7.4. This cost estimate is predicated on receiving an overhead burden rate of 0.12 from JLab on project labor and procurements < $50K. This is justified as the scope of this effort is outside the range of standard JLab activities but does not require substantial additional staff infrastructure for support.

To develop the overall contingency we have assigned a risk contingency percentage separately for each level 2 or level 3 element, used that to produce a cost contingency, and then summed all the contingencies to be held at the project level. Details of the risk management approach are discussed next in subsection 7.3.

Project Work Area	Cost
Physics Design	$2,009,065
Injector	$5,889,718
Beam Transport	$9,369,153
DC Power	$2,217,055
RF Systems	$4,549,458
FEL	$13,580,194
Cryogenics	$11,204,271
Controls, Timing & Synchronization	$1,521,424
Diagnostics & Safety Systems	$2,060,767
Conventional Facilities	$4,256,538
Experimental Equipment	$4,105,618
Cryomodules	$7,176,457
Project Management & Control	$907,917
Commissioning	$1,372,507
Sub Total:	**$70,220,142**
Escalation	$5,941,158
Contingency	$19,430,011
Total:	**$95,591,311**

Table 7.1 *JLAMP costs by project work area.*

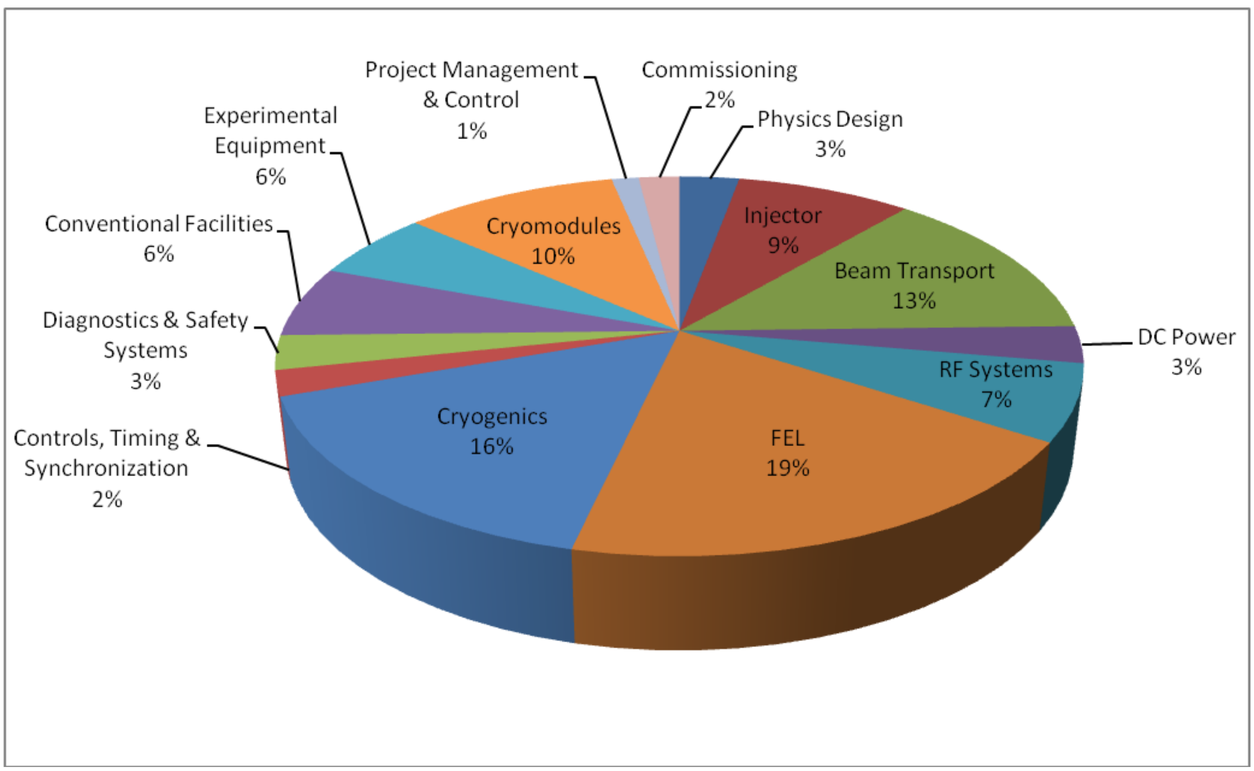


Figure 7.2. *JLAMP costs by project work area.*

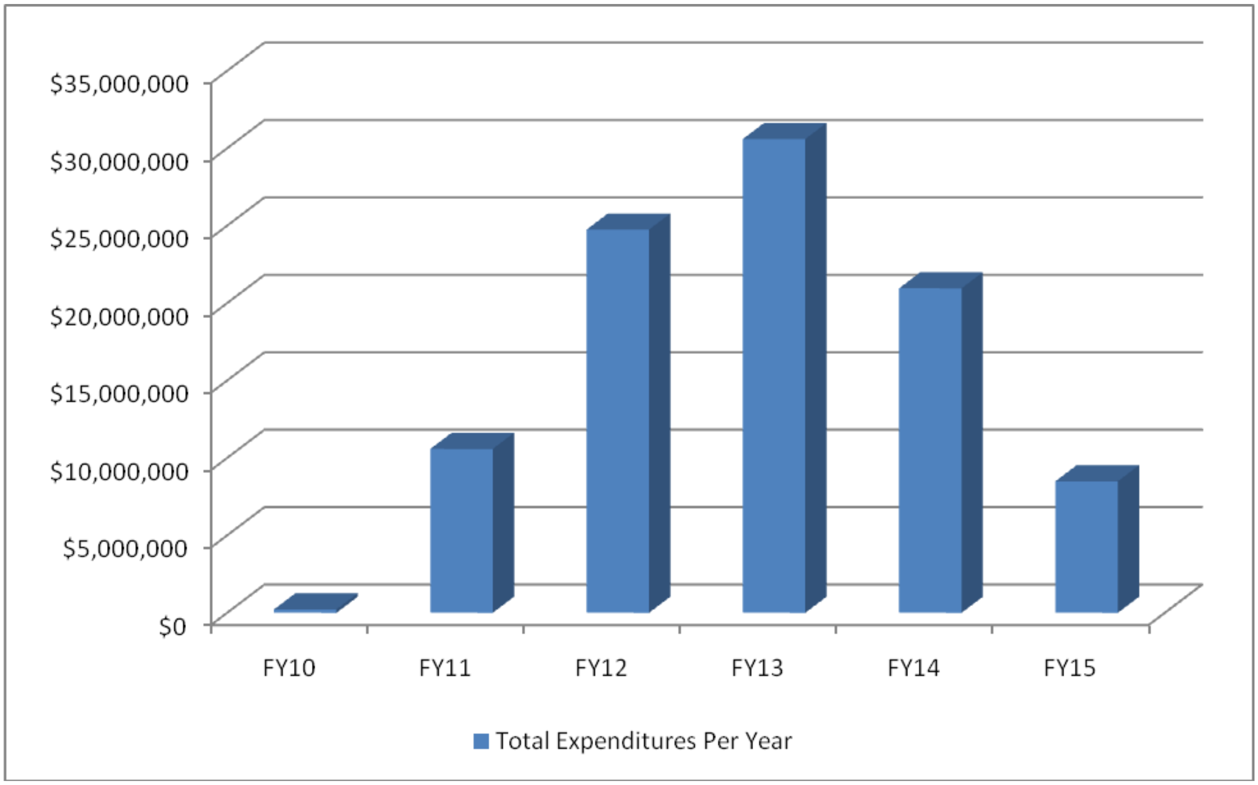


Figure 7.3. *JLAMP commitment profile by year.*

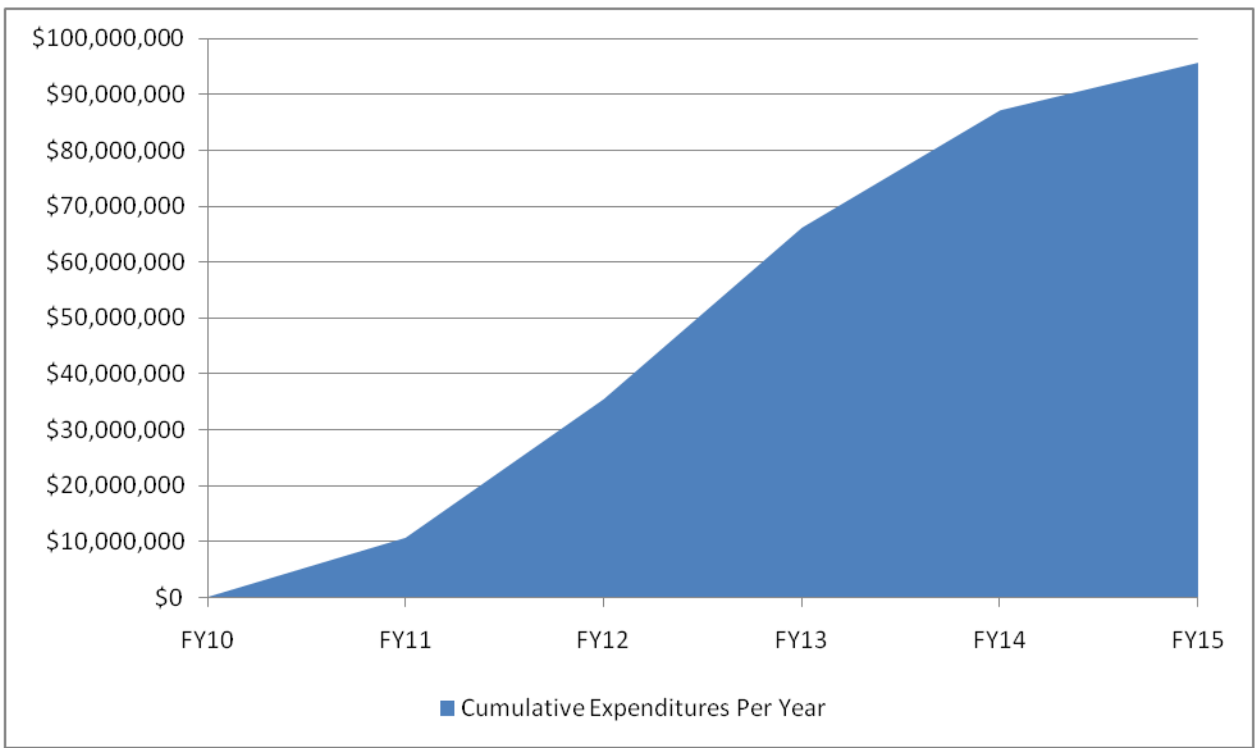


Figure 7.4. *JLAMP cumulative commitments by year.*

7.3 Risk Management

We will include assessments of technical, cost, and schedule risks. During project planning, a formal risk assessment will be conducted to identify and quantify risks. Once identified, these risks will be incorporated into a risk management plan that characterizes them by both likelihood and potential impact. Additionally, a risk response plan will be established for areas of particular concern that will allow emergent risks to be quickly identified and addressed.

In the technical areas, we are comfortable with the FEL modeling and with our ability to fabricate superconducting cryomodules which meet specifications, to develop and build diagnostics which can adequately monitor beam characteristics, and to design and build magnets and power supplies which meet specifications. The primary technical risk is the development of an injector which meets the brightness requirements on a continuous basis. A number of labs have designs utilizing various approaches which on paper meet the goals, but until a concept is demonstrated this remains a potential limitation. The impact of a shortfall in the beam brightness would be the ability to meet the proposed brightness specification at the shortest wavelengths. First data from our proposed gun, the LBNL radiofrequency gun, is due in FY11. Secondary technical risks would be:

a) The ability to maintain the beam brightness through the recirculation arcs. Simulations based on our experience with the existing FEL and CEBAF at JLab, and data from the LCLS in bunching chicanes, suggest charges of this magnitude can be successfully handled. A shortfall would impact beam emittance at the wiggler and thus shortest wavelength FEL operation.

b) The ability to meet field requirements, and wakefield and resistive wall limits in the DELTA undulator. A prototype has met the requirements for field but field quality must be maintained in a full length module. The LCLS undulator met our wakefield and resistive wall requirements for a smaller bore, but it has not been shown on a vacuum undulator such as DELTA. Excessive heating would limit pulse repetition rate below full specification.

c) The ability of seed lasers to meet the required repetition rate. Presently 1 kHz is fully commercial and 10 kHz is considered feasible by laser manufacturers. Extensions above that rate are developmental. Shortfalls would impact the ability to get full repetition rate output in amplifier operation but would not affect oscillator performance.

Cost risk is managed through the assignment of contingency to the project. The contingency is kept at the project level to be allocated as required during the performance of the project by the Project Leader advised by the Engineering Review Board. Total project contingency will be kept constant or increase as a percentage of ETC during the PED and construction phases. A relative cost risk has been assigned each WBS element at level 2 and in some cases level 3 based on technical risk and design maturity. The percentage assigned was used and multiplied by the projected cost for that element and then the total contingency summed to develop a project level contingency budget.

Schedule risks are managed using a *schedule baseline* document that explicitly identifies the milestones and checkpoints used to verify the project's actual vs. planned performance. Additionally, the schedule baseline includes a resource calendar that tracks the availability of human and material resources during project execution and assists in identifying and eliminating resource bottlenecks or conflicts.

The JLAMP project will be conducted in accordance with the project management requirements established by DOE Order 413.3A, "Program and Project Management for the Acquisition of Capital Assets." Cost and schedule performance will be monitored and managed using an accredited Earned Value Management System as described in the Jefferson Lab Project Control System Manual and certified by the DOE Office of Engineering and Construction Management (OECM).

During project planning a set of sub-WBS-element milestones will be generated to support the delivery of the proposed project milestones shown in the schedule above. Critical paths will be analyzed and sufficient schedule contingency applied to ensure that the project can meet its goals in a timely manner. The JLab Project Management group will conduct earned value analysis on a monthly basis and will report to the lab director as well as to DOE BES. Cost or schedule variances exceeding 20% in any JLAMP control account will be highlighted and trigger the development of a corrective action plan.

7.4 Building Core X-ray Photon Expertise

To successfully achieve a cutting edge soft x-ray program will require building the device and establishing a highly qualified and energetic user community. We must be proactive in ensuring that the best minds are involved in planning and executing experiments on JLAMP. We will take the steps described to establish such a vital user community of the highest scientific quality.

The user community from our workshops who developed the science case for this proposal will serve as our entry to the area. While that group of scientists listed in the front of this document will guide the initial development of system specifications, we will hire an ultrafast soft x-ray scientist of international reputation to be on site to coordinate and guide the effort. This will occur early in the program, as soon as possible after CD1 and program funding. The Project Scientist will be encouraged to bring along post docs to help coordinate and plan the initial set of experiments on JLAMP. We will set aside a specific budget for the development of this user science base. It is anticipated that the Project Scientist will need to perform proof of principle experiments and other tests on other existing light sources such as FLASH to prove techniques and prepare for the 3 to 6 orders of magnitude increase in brightness that JLAMP will provide. This will also ensure proper accounting for any course corrections required in the plan as the field develops and as discoveries are made during the several years it takes to construct the light source. The effort supports the specification of the beamlines and user equipment to be fabricated in the project scope.

Initially our efforts will concentrate on publicizing the terrific opportunity that JLAMP represents through talks and colloquiums at light sources and other venues worldwide. The Project Scientist will be expected to issue announcements of the opportunity and organize workshops, at least one for each technical area in the year after CD1 and more frequently as the program progresses. Several of these will be targeted toward specific technical goals such as described in Section 2. We will work with the community to develop and define the scope of the experiemental projects. These workshops are not only intended to foster ideas for experiments but to carry forward the growing collaborations which will entice other scientists into the JLAMP user community. Both single user experiments and multiuser collaborations will be encouraged as will the development of independent proposals to BES and other agencies for major instrumentation packages. A major enticement for a group to establish a strong collaboration with vital science will be the prospect of early beam time on JLAMP with unparalleled capabilities in its operating range. As the construction project continues, additional photon science and technology hires at JLab will establish the core internal photon science group at JLab. At this time it is envisioned that initially the local group will be 5 to 10 beamline physicists split half and half between established researchers and early career post graduates or junior faculty. They will serve as an interface to the JLab community to foster the needs of photon science as well as serving as a local experts experience base for outside users to draw on when they arrive at JLab for the first time.

We intend to be guided by user suggestions in adapting our present proposal review process as described earlier in the proposal and in the establishment of selection priorities for these early experiments. We anticipate that the representatives of the user group will play a strong role in defining the experiment call procedures, annual selection process, etc. They will also recommend scientists to the Lab Director for participation in the lab's Photon Program Advisory Committee. Local Virginia and southeast universities will also play a role in building programs and hiring faculty in these research areas. In the Nuclear Physics area university members of the Southeastern University Research Association were proactive in establishing a large number of Jefferson Lab Distinguished Professorships throughout the southeast.

We recognize that the accelerator R&D program will need to develop a user community base. We expect this to grow from existing expertise at JLab, established international collaborations and local groups. Local support includes our own Center for Advanced Study of Accelerators and Old Dominion University's new Center for Accelerator Science with significant faculty hires and establishment of a graduate student research effort in the area. Workshops and opportunity announcements for such R&D also will be central to establishing this program and a coordinated user group. Ongoing programs in accelerator physics and technology, such as our work addressing accelerator technology for future light sources as funded by BES, will be able to utilize the JLAMP accelerator hardware for measurements and tests. A key part of the continuing accelerator R&D effort to be funded will involve code development and validation. A specific example would be the advancement of techniques to accurately calculate the impact of Coherent Synchrotron Emission. We intend to extend our participation and support of workshops addressing key accelerator development needs for future light sources and encourage the broader accelerator community to propose and collaborate in tests at the facility through open calls for research proposals. This will especially encourage the career development of early career accelerator scientists we intend to hire in support of the project execution.

Appendix A

Major Reports Outlining the Scientific Case for Next Generation Light Sources

1. DOE-BES Basic Research Needs workshops
   www.science.doe.gov/bes/reports/list.html
2. 4th Generation Light Source, UK
   http://www.4gls.ac.uk/documents.htm
3. New Light Source Project, UK
   http://www.newlightsource.org
4. SLAC/LBNL
   http://www-ssrl.slac.stanford.edu/aboutssrl/documents/future_xrays_09.pdf
5. Cornell
   http://erl.chess.cornell.edu/gatherings/erl%20workshop/index.htm
6. UW Madison, Wisconsin FEL
   http://www.wifel.wisc.edu/
7. BESSY, DESY, Germany
   http://hasylab.desy.de/facilities/flash/publications/selected_publications/fel_laboratories_and_proposals/index_eng.html
8. DOE-BES "Directing Matter and Energy: Five Challenges for Science and the Imagination"
   http://www.sc.doe.gov/bes/reports/files/GC_rpt.pdf
9. DOE-BES "New Science for a Secure and Sustainable Energy Future"
   http://www.sc.doe.gov/bes/reports/files/NSSSEF_rpt.pdf

Appendix B

JLab Technical Infrastructure

B.1 JLab Facilities and Capabilities

Critical to the high repetition frequency that makes JLAMP unique is a continuous-wave superconducting linear accelerator. Jefferson Lab is unique in the USA in operating a superconducting recirculating linac at up to 6 GeV (CEBAF), and an energy recovering linac–based light source (JLab FEL). Both facilities have been operating in excess of 10 years, and between them they operate 346 superconducting cavities.

JLab has a deep infrastructure for producing and supporting superconducting linacs, having built over 500 cavities in the past 20 years. JLab has processed over half of the world's superconducting cavities and has produced the highest *cw* cavity gradients of any organization. The lab has a major 30,000 sq. ft. facility, with a larger one (70,000 sq. ft.) with enhanced capabilities funded for a construction start in 2010. We are the only organization that provides top to bottom capability from cavity physics design through construction and operation of cryomodules.

Jefferson Lab has some of the best facilities available anywhere for conducting research in superconducting radiofrequency technology. The Vertical Test Area—with eight dewars, six of which are equipped with RF—and the cavity preparation facilities are some of the finest in the world. Both are shown in Figure B.1. Jefferson Lab also has clean facilities to assemble simultaneously two cryomodules (Figure B.2) and test them in a low ambient magnetic field cryomodule test facility (Figure B.3).

Figure B.1. *Vertical Test Area (left), and closed chemistry and high-pressure rinsing cabinet (right) in class 100 clean room.*

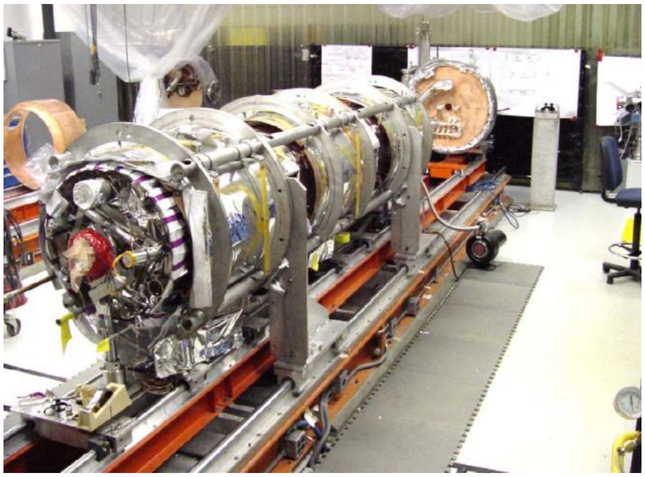


Figure B.2. *Cryomodule assembly area.*

Figure B.3. *Low magnetic field (< 50 mG) cryomodule test facility.*

The latter is used to continue measurements of the dynamic behavior of superconducting cavities and to test low-level RF control systems and microphonics reduction schemes.

Being the site of the largest installed base of superconducting structures in the world, JLab also has an extensive RF and electronic capability for the development and testing of RF control systems. The test stand consists of two RF signal generators, a controls system analyzer (Vector), the ability to develop both VME and VXI based systems, as well as an HP-UX work station and a PowerPC-based Input/Output Controller (IOC) running EPICS, using VxWorks platform. We have installed Oracle Database on the HP-UX to store and retrieve quantities such as calibration constants. In addition, data acquisition hardware is available for automated testing.

JLab's cryogenic operations are supported by a central helium liquefier that provides over 5000 W of LHe cooling capability at 2 K and operates 24/7 year round. There is another plant of this size already on order to support the CEBAF 12 GeV Program and several significant satellite plants operating at 2 K to 4 K. Advances made by the cryogenics group are providing improved electrical efficiency and substantial cost savings at other facilities such as RHIC at BNL and for NASA utilizing the Ganni cycle, named for the JLab cryogenics engineer who conceived this advance.

In addition to this expertise in superconducting linacs, Jefferson Lab has demonstrated key capabilities in the areas of electron beam dynamics, electron guns, FEL performance, and diagnostics—all of which are required for JLAMP.

The JLab DC injector is the highest-brightness high-average-current injector extant. It has the potential, with upgrades, to achieve the brightness required to meet the next generation light source needs. An existing BES program initiates upgrading the SRF booster. In parallel we are developing, under an ONR contract, a higher voltage version of the DC gun. The marriage of these technologies offers a near term path to an injector with an emittance of a few microns at low bunch charge. We also intend to monitor closely and participate through collaborations in efforts at other DOE labs, especially LBNL in the development of alternative injector technologies which could lead to *cw* high brightness output. We have designed our accelerator to utilize the best injector performance regardless of where it originates.

In high charge beam transport we have many published reports detailing our theoretical and experimental work defining both the limits and capabilities of our systems. This experience allows us to further refine the beam acceleration components and transport optics for not only machines such as JLAMP but other SRF-based research accelerators under study and development, such as ELIC and FRIB. JLab was a major contributor to the construction of the Spallation Neutron Source, providing all the superconducting cavities for that major research facility.

Key accelerator physics and technology issues to be resolved include production of high brightness bunches, maintenance of the longitudinal and transverse emittance during acceleration and recirculation, and control of beam halo at high average current. Such parameters are easily degraded by coherent synchrotron emission and longitudinal space charge, but JLab staff have considerable experience in mitigating such effects.

To further this work, we have established collaborations with key BES labs including BNL, ANL, and LBNL. We intend to continue to grow this collaboration, inviting participation in the key aspects of studies such as recirculation and seeding, including HHG studies and initial studies of amplification. The first of these is technically difficult to perform while maintaining high brightness, but has the potential to save hundreds of millions of dollars in construction costs for a next generation light source if the feasibility can be demonstrated. The seeding studies would include HHG studies using our IR-FEL.

In other areas where we have relatively little experience at present, such as VUV/x-ray beamlines, we have embraced collaborations with experienced groups at BNL and WiFEL for guidance in JLAMP requirements and designs while we build up our own experience base through key hires and running experience.

B.2 Analytical Capabilities at Jefferson Lab

Superconductivity at the microwave frequencies used in particle accelerators occurs in the outermost 50 nm of the niobium cavities, making performance exquisitely surface sensitive. University labs and JLab facilities located on site house important analytical capabilities used in research aimed at improved SRF and cavity production processes. Surface topography is understood to be a major contributor to performance decline. Research aims at reliably attaining the smoothest cavity interior surfaces, approaching the nanometer scale. Thus, topography characterization is crucial as is elemental cleanliness. This same instrumentation can be brought to bear in support of advanced materials research for JLAMP users.

Figure B.4. *On-site SEM.*

Topographic Imaging: Microscopy

Two major instruments on site in the College of William & Mary (W&M) joint laboratory supporting advanced materials characterization are:

A. Hitachi 4700 Field-Emission SEM. The image resolution of this instrument (Figure B.4) approaches 1 nm, but the specimen must be placed within the instrument yielding an effective size limit of a few cm. Replicas can be used for larger objects, though with less resolution. Specimens must also be vacuum-worthy and not subject to electron beam damage.

B. Hirox Digital Optical Microscope. An object of significant size can be examined under ambient conditions. The opportunity for through-focal image series collection extends useful magnification to beyond 5000X. Resolution is essentially at the wavelength limit. A particular advantage is that a large number of items can be examined in a reasonable time, or collectively to provide a systematic view.

JLab has an upgraded Amray 1830 SEM with a new elemental analysis accessory (EDS) and electron backscatter diffraction (EBSD) for structure determination. It also has an attached field emission scanner accessory to locate field emitter points on a surface and characterize their emission. Stage indexing permits locating the same point after transfer into the main chamber, so that microstructures can be analyzed. This instrument provides a unique opportunity to directly correlate surface features with functionality.

Topographic Measurement: Roughness

We also have extensive instrumentation to examine the surface roughness of materials including:

A. Profilometry: JLab SRF has a KLA Tencor instrument with a sufficiently small probe to measure features as small as 2 microns.

B. Scanning Probe: W&M on-site has a Digital Equipment Nanoscope IV, which is used extensively for topography measurements on SRF materials. Smallest lateral features are about 30 nm.

Microstructure

Present SRF cavities are made from Nb sheet having a grain size of several tens of microns. The response of individual grains to the final etching treatment varies considerably, some becoming quite rough. Current research here seeks to determine if crystal orientation is responsible, making microstructure determination important. A newly acquired EBSD (below) provides capability to determine individual grain orientation, which can then be correlated with etching. Similar measurements are feasible on silicon and diamond structures of interest to the semiconductor x-ray optics industry. The following instruments support microstructure measurements:

A. TEM. ODU on-site has a modern JEOL instrument capable of about 0.1 nm resolution (Figure B.6). A proposal has been submitted for focused ion beam (FIB) instrument for specimen preparation. In the meantime, a normal-incidence Gatan ion mill is used instead.

Figure B.5. *On-site TOF-SIMS.*

B. XRD. Norfolk State University on-site has a Panalytical X'pert machine equipped for a wide range of techniques, aimed principally at thin films, including glancing incidence and reflectometry.

C. EBSD. Electron back-scatter diffraction provides structural determination capability for the SEM. JLab SRF is currently installing EBSD on their Amray SEM. W&M on-site expects to submit an NSF-MRI in FY10 to get EBSD for the on-site W&M Hitachi 4700 also.

Composition

We have on site several instruments to analyze elemental composition for materials science research:

A. Element Composition: Energy dispersive x-ray spectroscopy. All the local SEM's and the ODU TEM have it. Spatial resolution in the SEM is a micron or so and sensitivity is about 0.1%. Special manipulations in specific instances may extend these limits.

B. Molecular Composition: There is an existing FTIR at W&M, on-site with all accessories except a microscope. Another Nicolet FTIR is installed in the FEL laboratory.

C. Surface Composition: A PHI TRIFT-II ToF/SIMS (Figure B.5) at the on-site W&M Applied Research Center has sub-monolayer sensitivity and lateral resolution approaching one micron. This instrument is suited to organics and soft materials. A proposal for a user XPS for W&M on the JLab site has been submitted to the NSF-MRI program. It can determine the elemental composition and valence state of top few nm to about 0.1 % sensitivity, with lateral spatial resolution smaller than niobium sheet grain size.

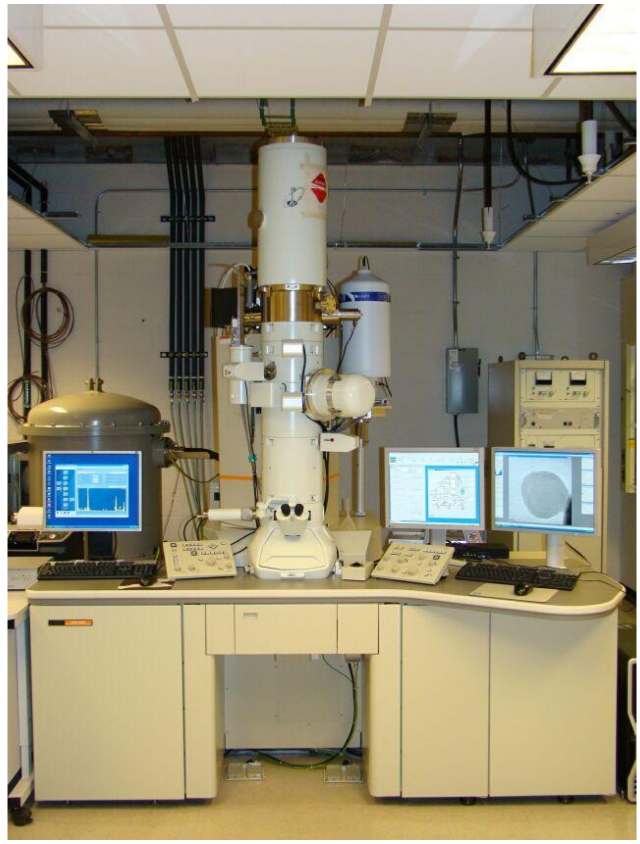


***Figure B.6**. On-site TEM.*

Optics Characterization

Since the inception of the FEL Program, Jefferson Lab has by necessity acquired the staff and metrological equipment to ensure that the optics we purchase meet specifications. The majority of the hardware is based at the FEL User Facility and is applicable, with the appropriate fixturing, to confirm the specifications of the beamline optics. The facility is well-equipped with monochromatic sources and calibrated energy and power meters, as well as beam profilers utilizing CCD and pyroelectric cameras. A short list of available optical diagnostics is as follows:

Noncontact profilometer: Wyko NT1100
Laser Interferometer: Wyko RTI4100
Thermo Nicholet FTIR spectrometer
Zeiss Axiolab polarizing microscope
Spiricon Pyrocam III
FLIR A26 IR Camera

Our optical metrology instruments that are directly applicable to this project are the two Wyko (now Veeco/Tucson) units. The NT1100, Figure B.7, has two levels of vertical resolution. In phase-shifting interferometric (PSI) mode, the range is from ~ 0.1 to 150 nm; in vertical scanning interferometric (VSI, or white light) mode, it is from 1 nm to 1 mm. The lateral resolution is selectable with different objectives and field of view lens combinations; for our machine it ranges from ~ 50 nm to 15 μm.

The NT1100 has a computer-controlled stage that allows us to "stitch" an area as large as 100 mm by 100 mm. This is as large as the largest optics we usually check, and will cover the beam footprint of any optics deployed on JLAMP.

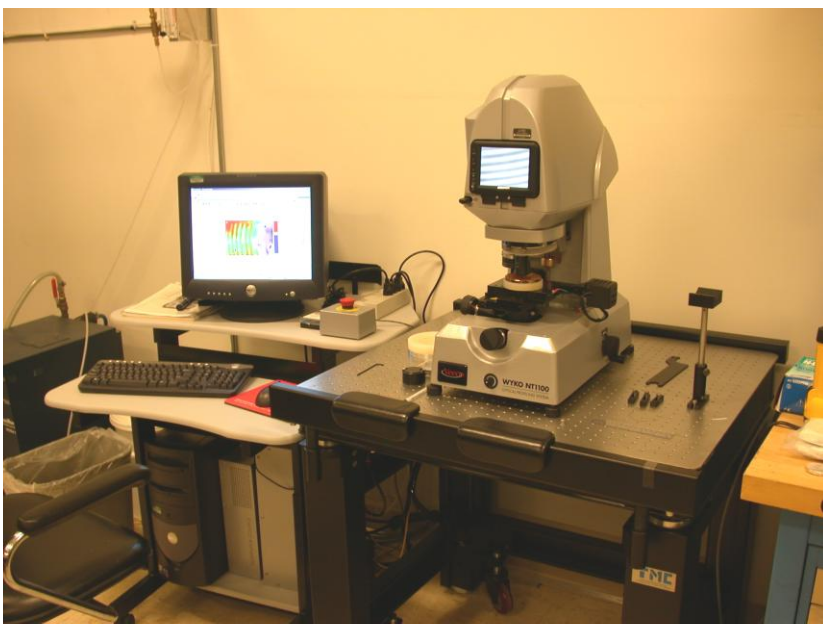


Figure B.7. *NT 1100 noncontact interferometer.*

The RTI 4100 (Figure B.8) is a laser interferometer capable of measuring an optic as large as 4" in diameter, with an absolute accuracy of $\lambda/200$ (λ = 632.8 nm) P-V. Slopes as steep as 7 waves/mm can be measured at high magnification (the RTI 4100 has a continuous zoom of up to 7X). We routinely use this to measure the radius of curvature (ROC) of mirrors in the 14–30 m range. For ROC's in the 15 m range, a circular region with a 2.5 cm diameter can be measured with an accuracy of about a 50th of a wave. At longer ROCs the measurable area grows, until we generally can measure the entire surface for ROC values greater than 80 m.

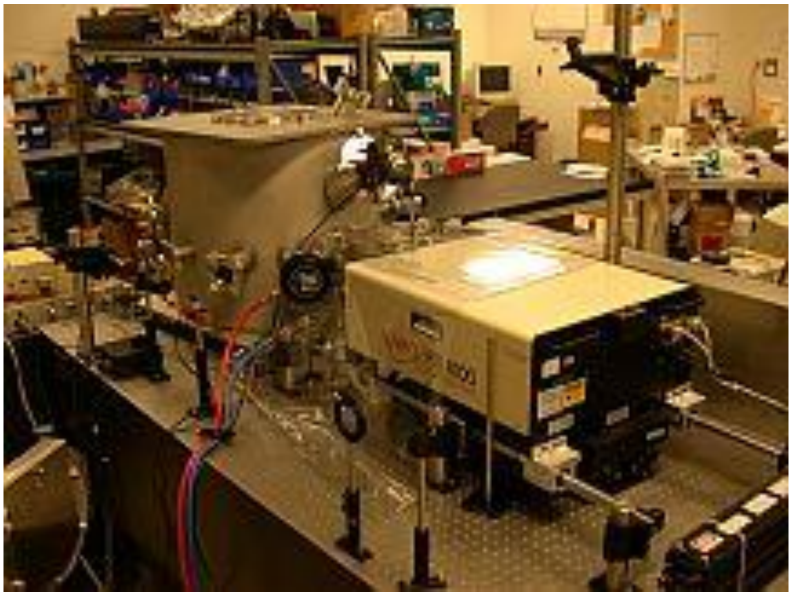


Figure B.8. *RTI 4100 laser interferometer and Mirror Test Stand.*

The interferometer is set to observe a region inside an evacuable chamber known as the Mirror Test Stand. With this added capability we can mount an optic in an environment similar to that in JLAMP, cool and actuate it, and then thermally load it and determine what aberrations ensue.

Synchronized Lasers

We are well-versed in laser/e-beam synchronization techniques and possess the hardware to accurately measure the phase noise of our laser sources relative to the RF master oscillator to high precision. Currently we have four lasers that are synchronized to the FEL's 74.85 MHz pulse train; see Table B.1.

Manufacturer/developer	Model	Laser Type/Specs	Application
Coherent	Antares	Flash-pumped Nd:YLF, actively mode-locked, 40ps/20W(1053nm) /5W(527nm)/75MHz, synch to RF with phase loop control	ERL drive laser
Time-Bandwidth/ Q-Peak/JLab	Custom	DPSSL/MOPA/50W(1064nm)/25W(532 nm)/75&750MHz/20~50ps with pulse shaping, synch. to RF with phase loop control	ERL drive laser
Spectra-Physics	Tsunami	KLM Ti:sapphire DPSSL/80fs/ 800nm/1W/75MHz, synch to RF with phase loop control	Ultrafast diagnostic
Coherent/Quantronix	Mira/ Titan	DPSSL CPA (Osc., Regen, Multipass amp) /5mJ/800nm/150fs/1kHz, synch. to RF with phase loop control	Ultrafast laser source/ measurement
Coherent/JLab	Antares/ Minilite	Osc./ Ampl. 40ps/1mJ/532nm/10Hz	Photocathode/ injector study

Table B.1. *FEL synchronized lasers.*

Comprehensive research (refs 1–6) has been carried out in regard to the characterization and suppression of phase noise from different laser systems including femtosecond Ti:sapphire lasers, picosecond diode-pumped solid-state lasers and fiber lasers. Our IR FEL program has produced the highest average power injector cathode drive laser. It is built utilizing advanced technologies such as phase noise tracking and active control. We have synchronized different femtosecond lasers to the accelerator RF systems, and also phase-locked independent kHz-mJ femtosecond Ti:sapphire lasers to the RF clock. Over and above the possession of state-of-the-art measurement instruments like the Agilent E5052B SSA, used for measuring phase noise, is the experience of a strong team of world-leading experts. These include scientists working in advanced RF technologies along with laser scientists who have an extensive R&D background in developing and characterizing state-of-the-art, high repetition rate, ultrashort pulse lasers. We've also established collaborations with world leading experts in the field of ultra-short x-ray lasers, which we deem essential in successfully implementing this activity. We are thus well-positioned to seed JLAMP as well as assist users with pump-probe experiments.

References for Appendix B

[1] S. Benson and M.D. Shinn, "Development Of CEBAF Accelerator-Ready Photocathode Drive Laser", PAC 1997.

[2] M.D. Shinn, S. Zhang, and J.F. Gubeli III, "A Comprehensive Study of Phase Noise in Mode-Locked Laser Systems", International FEL Conference (FEL03) Tsukuba, Japan.

[3] S. Zhang, et al., "Characterization and Performance of a High-power Solid-state Laser for a High-current Photocathode Injector", Proceedings of FEL 2005, JACoW eConf C0608213 351 (2005).

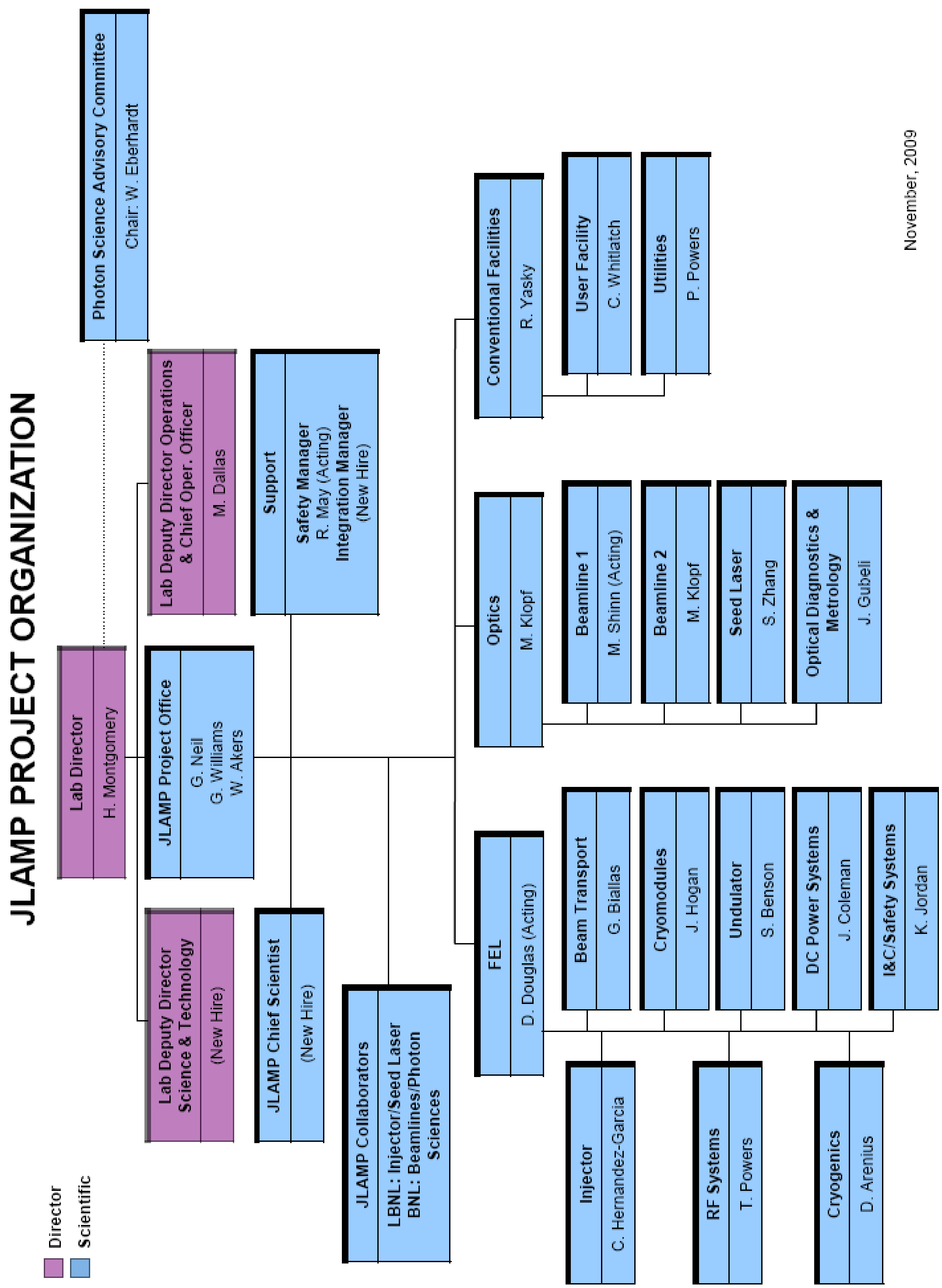
[4] S. Zhang, et al., "Phase noise comparison of short pulse laser systems", Proceedings of the 28th International FEL Conference (FEL06), August, 2006, Berlin, Germany.

[5] S. Zhang, et al., "Study of Optical Frequency Chirping and Pulse Compression in a High-Gain Energy-Recovery-Linac-Based Free-Electron-Laser", Proceedings of FEL Conference, August, 2009, LIVERPOOL, UK.

[6] S. Zhang, et al., "Drive Laser Systems for Electron Accelerators and Free-Electron-Lasers Based on Photocathode-Injector Energy-Recovery-Linac", invited talk, ERL 2009, June, 2009, Ithaca, NY, USA.

[7] S. Zhang, et al., "The Challenges of Drive Laser Systems for MW-Class Free-Electron-Lasers Based on Photocathode-Injector Energy-Recovery-Linac", 12th Annual Directed Energy Symposium, November, 2009, San Antonio, Texas, USA.

Appendix C



JLAMP PROJECT ORGANIZATION
Director
Scientific
Photon Science Advisory Committee
Chair: W. Eberhardt
Lab Director
H. Montgomery
Lab Deputy Director Operations & Chief Oper. Officer
M. Dallas
JLAMP Project Office
G. Neil
G. Williams
W. Akers
Lab Deputy Director Science & Technology
(New Hire)
Support
Safety Manager
R. May (Acting)
Integration Manager
(New Hire)
JLAMP Chief Scientist
(New Hire)
JLAMP Collaborators
LBNL: Injector/Seed Laser
BNL: Beamlines/Photon Sciences
Conventional Facilities
R. Yasky
User Facility
C. Whitlatch
Utilities
P. Powers
Optics
M. Klopf
Beamline 1
M. Shinn (Acting)
Beamline 2
M. Klopf
Seed Laser
S. Zhang
Optical Diagnostics & Metrology
J. Gubeli
FEL
D. Douglas (Acting)
Beam Transport
G. Biallas
Cryomodules
J. Hogan
Undulator
S. Benson
DC Power Systems
J. Coleman
I&C/Safety Systems
K. Jordan
Injector
C. Hernandez-Garcia
RF Systems
T. Powers
Cryogenics
D. Arenius
November, 2009

Appendix D
JLAMP Key Personnel

JLab Division	Title	Expertise
1. Free Electron Laser Division		
George Neil	Associate Laboratory Director	Accelerator Physics
Gwyn Williams	Deputy Division Head	Photon and Materials Science
Steve Benson	Senior Staff Scientist	FEL Physics/Undulator
George Biallas	Senior Staff Engineer	Beam Transport/Mechanical Support
David Douglas	Senior Staff Scientist	FEL Accelerator Physics
Pavel Evtushenko	Staff Scientist	Operations and I&C
Fay Hannon	Staff Scientist	Gun Injector Systems
Carlos Hernandez-Garcia	Gun/Injector Systems Head	Gun/Injector Systems
Kevin Jordan	Staff Electrical Engineer	I&C/Safety Systems
Michael Kelley	Applied Research Program Mgr.	Chemistry and Materials Science
Michael Klopf	Staff Scientist	Photon Beamlines
Tom Powers	Staff Electrical Engineer	RF/SRF Technology
Michelle Shinn	Senior Staff Scientist	Optical Diagnostics & Metrology
Chris Tennant	Staff Scientist	FEL Accelerator Physics
Richard Walker	Staff Engineer	RF and HV Systems
Shukui Zhang	Staff Scientist	FEL Optics/Seed Laser
2. Accelerator Division		
Dana Arenius	Cryogenics Manager	Cryogenics
Jean Delayen	Principal Scientist	Accelerator Physics
Andrew Hutton	Associate Laboratory Director	Accelerator Construction/Ops
Geoff Krafft	Director, CASA	Accelerator Physics
Rui Li	Staff Scientist	Coherent Synchrotron Radiation & BBU

GEORGE R. NEIL

ASSOCIATE LABORATORY DIRECTOR
Free Electron Laser
Jefferson Lab, Newport News, VA 23606

Education

B.S. Engineering Science, University of Virginia, granted June 1970
PhD in Nuclear Engineering, University of Wisconsin, granted September 1977. Thesis: "Infrared Emission and Scattering from the Dense Plasma Focus".

Professional Experience

2007-present – Associate Director and Head of the Free Electron Laser Division, Jefferson Lab, Newport News, VA 23606.
1995-2007 – Deputy Free Electron Laser Program Manager and Principal Scientist, Jefferson Lab, Newport News, VA 23606.
1990-1995 – Linac Department Manager Jefferson Lab, Newport News, VA 23606.
1977-1990 – FEL Program Manager and FEL Chief Scientist, Optics and Directed Energy Laboratory, TRW Space and Defense Systems Group, Redondo Beach CA, 90278.

Representative Publications: 17 out of 130 total.

G.L. Carr, M.C. Martin, W.R. McKinney, K. Jordan, G.R. Neil and G.P. Williams "High Power Terahertz Radiation from Relativistic Electrons", Nature **420** 153-156 (2002).
G.L. Carr, M.C. Martin, W.R. McKinney, K. Jordan, G.R. Neil and G.P. Williams "Very High Power THz Radiation at Jefferson Lab" Journal of Physics in Medicine and Biology, **47** 3761-3764 (2002).
G.L. Carr, M.C. Martin, W.R. McKinney, K. Jordan, G.R. Neil and G.P. Williams, "Very high Power THz radiation Sources", Journal of Biological Physics, **29** 319 2003.
George R. Neil and Gwyn P. Williams, "Evolution of the High Power THz Source Program at Jefferson Lab", Infrared Phys. and Tech. **45**, 389 (2004).
S. Zhang, G. Neil, M. Shinn "Single-element laser beam shaper for uniform flat-top profiles", Optics Express **11,** 1942 (2003).
R. H. Austin, A H, Xie, L. van der Meer. M. Shinn and G. Neil, "Self-trapped states in proteins?", J. Phys-Condensed Matter **15,** S1693 (2003).
M. N. Petrovich, A. Favre, D. W. Hewak, H. N. Rutt, A. C. Grippo, J. F. Gubeli III, K. C. Jordan, G. R. Neil, M. D. Shinn, "Near-IR Absorption of Ga:La:S and Ga:La:S:O Glasses by FEL-based laser calorimetry" J. Non-crystalline Solids **326-327,** 93-97 (2003).
A. Christodoulou, D. Lampiris, K, Polykandriotis, W.B. Colson, and P.P. Crooker, S. Benson, J. Gubeli, and G.R. Neil, "Study of an FEL Oscillator with a Linear Taper " Phys. Rev. E **66,** 056502 (2002).
George R. Neil and Lia Merminga, "Technical Approaches for High Average Power FELs, Reviews of Modern Physics **74**, 685 (2002) (INVITED).
George R. Neil, S. V. Benson, G. Biallas, J. Gubeli, K. Jordan, S. Myers, and M. D. Shinn, "Second Harmonic FEL Oscillation, Phys. Rev. Lett. **87**, 084801(2001).
G. R. Neil, C.L.Bohn, S. V. Benson, G, Biallas, D. Douglas, H. F. Dylla, R. Evans, J. Fugitt, A. Grippo, J. Gubeli, R. Hill, K. Jordan, R. Li, L. Merminga, P. Piot, J. Preble, M. Shinn, T. Siggins, R. Walker, and B. Yunn, "Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery" Phys. Rev. Lett. **84,** 662-665(2000).
H. P. Freund and G. R. Neil "Free Electron Generators of Microwave Radiation" in *Electron Beam Generators of Microwave Radiation* Proc. IEEE **Vol. 87,** No. 5, 782-803 (May, 1999). (INVITED).
Hongxiu Liu and George R. Neil, "Laser-Powered Beam-Conditioner for Free-Electron Lasers and Synchrotrons", Phys. Rev. Lett. **70,** 3557-3560(1993).

J.A. Edighoffer, G.R. Neil, S. Fornaca, H.R. Thompson, Jr., T.I. Smith, H.A. Schwettman, C.E. Hess, J. Frisch, and R. Rohatgi, "Visible Free-Electron-Laser Oscillator (Constant and Tapered Wiggler)", Appl. Phys. Lett. 52, 1569 (May, 1988).
J. A. Edighoffer, G. R. Neil, C. E. Hess, T. I. Smith, S. W. Fornaca, and H. A. Schwettman,"Variable-Wiggler Free-Electron-Laser Oscillation", Phys. Rev. Lett., **Vol. 52**, 344 (1984).
Jacqueline O. Berg, Thomas E. Christensen, Philip W. Kidd, George R. Neil, and John G. Conway, "Identification of U III and U IV Lines", J. Opt. Soc. Am., **Vol. 70**, 716 (1980).
G. R. Neil and co-authors: U.S Patents No. 4,129,772; 4,933,942; 4,763,079; 4,809,281; 4,742,522; 5,541,994; 5,805,620; 6,986,565; 6,844,688; 6,714,346; 6,885,008; 6,809,291; others in disclosure.

Professional and Honorary Organizations

1990 – present, Member of the FEL International Executive Committee
2003 – present, Member International Organizing Committee IEEE IRMMW-THz Conference
2003 – present, Member of the Button Prize Selection Committee
2000 Co-Winner, International FEL Prize
2003 Fellow of the American Physical Society, Division of Beams
2006 Fellow of the Directed Energy Professional Society
2005 Co-Winner, R&D 100 Award for "The Tunable Energy Recovered High Power Infrared Free-Electron Laser".

Synergistic Activities

Journal referee: Physical Review Letters, Phys. Rev., Rev. Sci. Instr., Nucl. Instr. Methods.
Reviewer for National Nuclear Security Agency and DOE, the National Ignition Facility at LLNL (Large Optics and Line Replaceable Chair) (3 years)
Reviewer for DOE LCLS Construction Project**,** Linac and Injector Systems (4 years)
2003 – 2007, **Editor**, Journal of Infrared Technology
2009 – present, **Editorial Board**, Journal of Infrared, Millimeter, and Terahertz Waves.
2008 – present, **Member,** FEL Prize Committee
2007 – present, **Member**, Fellowship and Award Committee Directed Energy Professional Society
2007-present ERL'07, ERL'09 Program Committee
2003-2008 **Chair**, International Advisory Committee, 4GLS Light Source, Daresbury Laboratory, UK.
2005 **Conference Chair**, 25th International Conference on Infrared and Millimeter Waves and 13th International Conference on Terahertz Electronics, Williamsburg, September 2005.
1987, 2003 **Member** Program Committee IEEE Particle Accelerator Conference,
LINAC'94, LINAC'96, LINAC'98, LINAC'2000, LINAC'02, Program Committee, International Conference on Linear Accelerators
1998 **Conference Chair** 20th International Free Electron Laser Conference, Williamsburg, August 1998.

Identification of Potential Conflicts of Interest or Bias in Selection of Reviewers
Recent Collaborators (past 48 months) Not Listed Above: R. Rox Anderson, (Harvard / Mass. General), William Farinelli, (Harvard / Mass. General), Hans Laubach, (Harvard / Mass. General), Dieter Manstein, (Harvard / Mass. General), Anna N. Yaroslavsky, (Harvard / Mass. General), Alan Todd, Advanced Energy Systems, Ilan Ben-Zvi (Brookhaven National Labs), Dinh Nguyen (Los Alamos National Labs), William Colson (Naval Postgraduate School)

GWYN P. WILLIAMS
DEPUTY ASSOCIATE DIRECTOR
Free Electron Laser
Jefferson Lab, Newport News, VA 23606

Education

B.S. Honors in Physics and Mathematics, Hull University, UK, granted June 1968
PhD in Physics, Sheffield University, UK, granted September 1971. Thesis: “Stress-Induced Dichroism in Si and Ge”.

Professional Experience

2000-present - Deputy Division Head and Basic Research Program Manager, Free Electron Laser, Jefferson Lab, Newport News, VA 23606.
1979-2000 - Physicist, National Synchrotron Light Source, Brookhaven National Laboratory, Upton, New York 11973.
1977-1979 - Postdoctoral Assistant Montana State University.
1971-1977 – Postdoctoral Research Associate U.K. Science Research Council, Leicester University, England, 1971-1977.

Representative Publications: 10 out of 240 total.

W.D. Duncan and G.P. Williams, “Infra-red Synchrotron Radiation From Electron Storage Rings”, Applied Optics **22**, 29l4 (1983).
Gwyn P. Williams, “Intense, Broadband, Pulsed I-R Source at the National Synchrotron Light Source”, Int. Journal of Infrared and Millimeter Waves **5**, 829 (1984).
Carol J. Hirschmugl, Michael Sagurton and Gwyn P. Williams, “Multiparticle Coherence Calculations for Synchrotron Radiation Emission”, Physical Review **A44**, 1316, (1991).
S.L. Hulbert and G.P., Williams, "Synchrotron radiation sources." In Handbook of Optics: Classical, Vision, and X-Ray Optics, 2nd ed., vol. III, chap. 32. Michael Bass, Jay M. Enoch, Eric W. Van Stryland, and William L. Wolfe (eds.). New York: McGraw-Hill, pp. 32.1--32.20 (2001).
G.L. Carr, M.C. Martin, W.R. McKinney, K. Jordan, G.R. Neil and G.P. Williams “High Power Terahertz Radiation from Relativistic Electrons”, Nature **420** 153-156 (2002).
G.L. Carr, M.C. Martin, W.R. McKinney, K. Jordan, G.R. Neil and G.P. Williams “Very High Power THz Radiation at Jefferson Lab” Journal of Physics in Medicine and Biology, **47** 3761-3764 (2002).
G.L. Carr, M.C. Martin, W.R. McKinney, K. Jordan, G.R. Neil and G.P. Williams, “Very high Power THz radiation Sources”, Journal of Biological Physics, **29** 319 2003.
Gwyn P. Williams, “Filling the THz Gap”, Reports on Progress in Physics **69** 301 (2006).
Gwyn P. Williams, “Electrons and lasers sing THz tune”, Nature Physics **4** 356 (2008).
S.L. Hulbert and G.P. Williams, “Calculations of synchrotron radiation emission in the transverse coherent limit”, Rev. Sci. Instr. **80** 106103 (2009).

Professional and Honorary Organizations

2009 – present, Surface Science Division Board Member, AVS
2008 – present, FLASH Program Review Committee, DESY, Germany
2003 Invited Lecture to the Royal Society, London, UK.
2001 Fellow of the American Physical Society.
1991 National Science Foundation International Collaboration award with CNRS, France.
1990 Winner R&D 100 Award for Wavefront Dividing Interferometer.

Synergistic Activities

Journal referee: Physical Review Letters, Phys. Rev., Nature, Optics Express, Rev. Sci. Instr., Nucl. Instr. Methods.
2003-present, Director of High Power Broadband THz Facility, JLab.

2000-present, Adjunct Professor, College of William and Mary
2000-present, Visiting Professor, University of Virginia.
1987 – present, North American Editor, Synchrotron Radiation News.
1985-2000, Head Infrared Facilities, NSLS, Brookhaven Natl. Lab.

Identification of Potential Conflicts of Interest or Bias in Selection of Reviewers

Recent Collaborators (past 48 months) Not Listed Above: A. Otto, (U. Duesseldorf), P. Lilie (U. Duesseldorf), M. Pilling, (U. of Manchester, UK), Matthew Coppinger, (University of Delware), Nathan Sustersic, (University of Delware), James Kolodzey, (University of Delware), R. Rox Anderson, (Harvard / Mass. General), William Farinelli, (Harvard / Mass. General), Hans Laubach, (Harvard / Mass. General), Dieter Manstein, (Harvard / Mass. General), Anna N. Yaroslavsky, (Harvard / Mass. General), Chien Aun Chan, (U. Adelaide, Australia), Samuel P. Mickan, (U. Adelaide, Australia), Derek Abbott, (U. Adelaide, Australia), I. Ben-Zvi, (Brookhaven National Lab).

STEPHEN V. BENSON
SENIOR STAFF SCIENTIST
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Education

B.S. University of Md. College Park, granted December 1976
PhD in Physics, Stanford University, granted June 1985. Thesis: "Diffractive Effects and Noise in Short Pulse Free-electron Lasers".

Professional Experience

2002-present – Senior Research Scientist, Free Electron Laser division, Jefferson Lab, Newport News, VA 23606.
1992-2002 – Research Scientist III, Free Electron Laser division, Jefferson Lab, Newport News, VA 23606.
1989-1992 – Research Assistant Professor, Duke University, Durham NC.
1986-1989 – Research Associate Stanford University, Stanford CA.

Representative Publications: 10 out of 240 total.

1. S. Benson et al., "Optical autocorrelation function of a 3.2 µm free-electron laser", *Physical Review Letters,* **48** (1983) 235–238.
2. S. Benson and J. M. J. Madey, "Demonstration of harmonic lasing in a free-electron laser", *Phys. Rev. A,* **39** (1989) 1579–1581.
3. S. Benson, P. S. Davidson, R. Jain, P. K. Kloeppel, G. R. Neil, and M. D. Shinn, "Optical modeling of the Jefferson Laboratory IR demo FEL", *Nucl. Inst. and Meth.* **A407** (1998) 401–406.
4. G. Neil et al., "Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery", *Phys. Rev. Lett.*, **84**, (2000) 662.
5. G. Neil, S. Benson, G. Biallas, J. Gubeli, K. Jordan, S. Myers, and M. D. Shinn, "Second Harmonic FEL Oscillation", *Phys. Rev. Lett.* **87**, 084801 (2001).
6. S. Benson, G. Neil, M. Shinn, "Lasing with a Near-Confocal cavity in a high power FEL" **SPIE Proc. 4632** (2002).
7. S. Benson, J. Gubeli, and M. Shinn, "Mode Distortion Measurements on the Jefferson Lab IR FEL" *Nucl. Inst. and Meth*., **A483**, 434 (2002).
8. A. Christodoulou et al., "Study of an FEL Oscillator with a Linear Taper" *Phys. Rev. E,* **66** 056502 (2002).
9. H. Freund, M. Shinn and S. Benson, "Simulation of a high average power free-electron laser oscillator", Phys. Rev. ST Accel. Beams, **10** 030702 (2007).
10. P. Crooker et al., "Short Rayleigh length free electron laser: Experiments and simulations", Phys. Rev. ST Accel. Beams **11** 090701 (2008).

Professional and Honorary Organizations

2005 Winner R&D 100 Award for High Power Free-electron laser.
2002 Fellow of the American Physical Society.
2000 Co-winner of the 2000 FEL prize.
1998 Program committee chair and proceedings editor for the FEL '98 conference.

GEORGE BIALLAS
ELECTRON BEAM TRANSPORT MANAGER
Free Electron Laser
Jefferson Lab, Newport News, VA 23606

Education:
B.S.M.E. - University of Illinois, 1966

Professional Experience:
1995-present – Senior Engineer, Electron Beam Transport Manager, Free Electron Laser, Jefferson Lab, Newport News, VA 23606.
1987-1995 –Senior Engineer, Systems Engineer and Cost Account Manager for Beam Transport, CEBAF, Newport News, VA 23606.
1985-1987 –Engineer, Systems Engineer for Acceleration and Vacuum Systems, CEBAF, Newport News, VA 23606.
1969-1985 – Engineer, Fermi National Accelerator Laboratory, Batavia, Ill.
1966-19697 – Engineer, Enrico Fermi Institute at the University of Chicago, Chicago Ill.

Representative Publications:

F. Liu and I. Brown, L. Phillips, G. Biallas and T. Siggins “A Method of Producing Very High Resistivity Surface Conduction on Ceramic Accelerator Components Using Metal Ion Implantation”, PAC’97 (1997)

G. Biallas, D. Bullard, D. Douglas, A. Guerra, L. Harwood, T. Hiatt, J. Karn, T. Menefee,
K. Sullivan, K. Tremblay, R. Wolfley, V. Christina, T. Schultheiss, F. Tepes “Making Dipoles to Spectrometer Quality Using Adjustments During Measurement”, PAC’99

The Dipole Magnet System for the JLab THz/IR/UV Light Source Facility, “The Dipole Magnet System for the JLab THz/IR/UV Light Source Facility”, FEL’03

G. H. Biallas, K. Baggett, D.R. Douglas, T. Hiatt, R. Wines, T.J. Schultheiss, V.A. Christina, J.W. Rathke, A. Smirnov, D. Newsham, Y. Luo, D. Yu " Magnetic Modeling VS Measurements of The Dipoles for the JLAB 10 kW Free Electron Laser Upgrade" PAC’03

George H. Biallas, Stephen V. Benson, Tommy Hiatt, George Neil, Michael Snyder, “Making an Inexpensive Electromagnetic Wiggler Using Sheet Materials for the Coils”, FEL’04.

G. Biallas[#], S. Benson, T. Hiatt, G. Neil, M. Snyder “AN 8 cm Period Electromagnetic Wiggler Magnet with Coils Made from Sheet Copper”, PAC’05

George H. Biallas[#], Nathan Belcher, David Douglas, Tommy Hiatt, Kevin Jordan, “Combined Panofsky Quadrupole & Corrector Dipole”, PAC’07

G, Biallas[#], M. Augustine, K Baggett, D. Douglas, R. Wines, “The “SF” System of Sextupoles for the JLAB 10 kW Free Electron Laser Upgrade”, PAC’09

A. Afanasev, O.K. Baker, K.B. Beard, G. Biallas, J Boyce, M. Minarni, R. Ramdon, M. Shinn, P. Slocum, “Experimental Limit on Optical-Photon Coupling to Light Neutral Scalar Bosons”, Physical Review Letters 101 120401 (2008).

Professional Organizations
2005 – present, CASA (Center for Advanced Studies of Accelerators) at Jefferson Lab

Identification of Potential Conflicts of Interest or Bias in Selection of Reviewers
None

DAVID R. DOUGLAS
SENIOR STAFF SCIENTIST
Free Electron Laser
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Education

B.Sc. Physics, Eastern Nazarene College, Quincy, MA, 1976.
Ph.D. Physics, University of Maryland, College Park, MD, 1982. Thesis: "Lie Algebraic Methods for Particle Accelerator Theory".

Professional Experience

1985-present – Staff Scientist, Jefferson Lab, Newport News, VA 23606.
1982-1985 – Staff Scientist, Lawrence Berkeley Laboratory, Berkeley, CA, 94720.

Representative Publications

1. A. J. Dragt, F. Neri, G. Rangarajan, D. R. Douglas, L. M. Healy, and R. D. Ryne, "Lie Algebraic Treatment of Linear and Nonlinear Beam Dynamics", Annual Review of Nuclear and Particle Science, 38, Page 455-496, Dec 1988.
2. G. R. Neil, C. L. Bohn, S. V. Benson, G. Biallas, D. Douglas, H. F. Dylla, R. Evans, J. Fugitt, A. Grippo, J. Gubeli, R. Hill, K. Jordan, G. A. Krafft, R. Li, L. Merminga, P. Piot, J. Preble, M. Shinn, T. Siggins, R. Walker, and B. Yunn, "Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery" Phys. Rev. Lett. 84, 662-665 (2000)
3. D. Douglas, "CEBAF-ER: An Energy Recovery and Current Doubling Operational Mode for the Continuous Electron Beam Accelerator Facility", JLAB-TN-01-045, 19 September 2001.
4. Christoph W. Leemann, David R. Douglas, and Geoffrey A. Krafft, "The Continuous Electron Beam Accelerator Facility: CEBAF at the Jefferson Laboratory", Annual Review of Nuclear and Particle Science, 51, Page 413-450, Dec 2001
5. P. Piot, D. R. Douglas, and G. A. Krafft, "Longitudinal Phase Space Manipulation in Energy Recovering Linac-Driven Free-Electron Lasers", Phys. Rev. ST Accel. Beams 6, 030702 (2003)
6. Lia Merminga, David R. Douglas, and Geoffrey A. Krafft, "High-Current Energy-Recovering Electron Linacs", Annual Review of Nuclear and Particle Science, 53, Page 387-429, Dec 2003
7. C. D. Tennant, K. B. Beard, D. R. Douglas, K. C. Jordan, L. Merminga, E. G. Pozdeyev, and T. I. Smith, "First Observations and Suppression of Multipass, Multibunch Beam Breakup in the Jefferson Laboratory Free Electron Laser Upgrade", Phys. Rev. ST Accel. Beams 8, 074403 (2005)
8. J. Sekutowicz, S. A. Bogacz, D. Douglas, P. Kneisel, G. P. Williams, M. Ferrario, I. Ben-Zvi, J. Rose, J. Smedley, T. Srinivasan-Rao, L. Serafini, W.-D. Möller, B. Petersen, D. Proch, S. Simrock, P. Colestock, and J. B. Rosenzweig, "Proposed Continuous Wave Energy Recovery Operation of an X-Ray Free Electron Laser", Phys. Rev. ST Accel. Beams 8, 010701 (2005).
9. David R. Douglas, Kevin C. Jordan, Lia Merminga, Eduard G. Pozdeyev, Christopher D. Tennant, Haipeng Wang, Todd I. Smith, Stefan Simrock, Ivan V. Bazarov, and Georg H. Hoffstaetter, "Experimental Investigation of Multibunch, Multipass Beam Breakup in the Jefferson Laboratory Free Electron Laser Upgrade Driver", Phys. Rev. ST Accel. Beams 9, 064403 (2006)

Professional and Honorary Organizations

2005 Fellow of the American Physical Society.

PAVEL EVTUSHENKO
STAFF SCIENTIST
Free Electron Laser
Jefferson Lab, Newport News, VA 23606

Education

B.S. in physics, Novosibirsk State University, Russia, granted June 1996,
Thesis: *"Mass spectrum of the hydrogen ion source"*
M.S. in plasma physics, Novosibirsk State University, Russia, granted June 1998,
Thesis: *"Radio frequency plasma emitter of the hydrogen atomic injector and measurements of the ion beam parameters"*
Ph.D. in physics, Technical University of Dresden, Germany, granted October 2004,
Thesis: *"Electron beam diagnostic for the ELBE Free Electron Laser"*

Professional Experience

2005-present – Staff Scientist, Jefferson Lab, Newport News, VA 23606, US
2002-2005 – physicist, Radiation Source ELBE, FZ-Rossendorf, Dresden, Germany
1999-2002 – **graduate student,** Institute for Nuclear and Hadron Physics, FZ-Rossendorf, Dresden, Germany
1995-1999 – undergraduate student, graduate student Budker Institute of Nuclear Physics, Novosibirsk, Russia

Representative Publications:

1. P. Evtushenko, A. Büchner, H. Büttig, P. Michel, R. Schurig, B. Wustmann, FZR, Germany, K. Jordan JLab, USA, *"Stripline beam position monitors for ELBE"*, Proceedings of 5th European Workshop on Diagnostics and Beam Instrumentation, ESRF, Grenoble, France, May 13-15, 2001
2. P. Evtushenko, P. Michel, *"System for measurements of the electron beam profile and position inside the undulator at the ELBE FEL"*, Proceedings of 23nd International Free Electron Laser Conference, Darmstadt, Germany, August, 2001
3. A. Büchner, P. Evtushenko, F. Gabriel, U. Lehnert, P. Michel, C. Schneider, J. Teichert, and J. Voigtländer for the ELBE crew, *"First Operation of the ELBE Super-conducting Electron Linear Accelerator"*, Proceedings of 23rd International Free Electron Laser Conference, Darmstadt, Germany, August, 2001
4. P. Evtushenko, U. Lehnert, P. Michel, C. Schneider, R. Schurig, J. Teichert, *"Electron Beam Diagnostics at the Radiation Source ELBE"*, Proceedings of 10th Beam Instrumentation Workshop, Brookhaven National Laboratory, Upton, NY, May, 2002
5. P. Evtushenko, U. Lehnert, P. Michel, J. Teichert, *"Bunch length measurements at ELBE"*, Nuclear Physics Spring Meeting Münster, March 11-15, 2002
6. D. Janssen et al., *"First operation of a superconducting RF-gun"*, NIM A Volume 507, Issues 1-2, 11 July 2003, Pages 314-317
7. J. Teichert, H. Büttig, P. Evtushenko, D. Janssen, U. Lehnert, P. Michel, C. Schneider, *"Review of the Status of SRF Photo-Injectors"*, Proceedings of 11th Workshop on RF-Sperconductivity SRF 2003, September 8 -12, Luebeck/Travemuende, 2003
8. T. Kamps, P. Evtushenko, V. Durr, K. Goldammer, D. Kramer, P. Kuske, J. Kuszynski, D. Lipka, F. Marhauser, T. Quast, D. Richter, U. Lehnert, P. Michel, J. Teichert, I. Will, *"Diagnostics Beamline for the SRF Gun Project"*, Proceedings of the 27th International Free Electron Laser Conference, Palo Alto, California USA, August 21-26, 2005
9. P. Evtushenko, J. Coleman, K. Jordan, J. Klopf, G. Neil, G. Williams, "Bunch Length Measurements at the JLab FEL Using Coherent Transition and Synchrotron Radiation", Proceedings of the 12th Beam Instrumentation Workshop, Fermilab Batavia, Illinois USA, May 1– 4, 2006

10. P. Evtushenko, A. Freyberger, C. Liu, A. Lumpkin, *"Near-field Optical Diffraction Radiation Measurements at CEBAF"*, Proceedings of the 13th Beam Instrumentation Workshop, Lake Tahoe, US, 2008
11. P. Evtushenko, *"Electron Beam Timing Jitter and Energy Modulation Measurements at the JLab FEL"*, Proceedings of the 13th Beam Instrumentation Workshop, Lake Tahoe, US, 2008
12. P. Evtushenko, S. Benson, *"Measurements of an FEL oscillator sensitivity to the electron beam phase noise"*, Proceedings of the 30th International Free Electorn Laser Conference, Gyeongju, Korea, 2008
13. P. P. Crooker, William Colson, Joe Blau, D. Burggraff, J. Sans Aguilar , Stephen Benson, George Neil, Michelle Shinn, Pavel Evtushenko, *"Short Rayleigh length free electron laser: Experiments and simulations"*, Phys. Rev. ST Accel. Beams 11, 090701 (2008).
14. M. A. Holloway, R. B. Fiorito, A. G. Shkvarunets, P. G. O'Shea, S. V. Benson, D. Douglas, P. Evtushenko, K. Jordan, *"Multicomponent measurements of the Jefferson Lab energy recovery linac electron beam using optical transition and diffraction radiation"*, Phys. Rev. ST Accel. Beams 11 082801 (2008).
15. F. Hannon, C. Hernandez-Garcia, P. Evtushenko, G. Biallas, M. Marchlik, D. Bullard, F. Ellingsworth, K. Jordan, S. Benson, *"An inverted ceramic DC electron gun for the Jefferson Lab FEL"*, submitted to FEL09, August 23-28, Liverpool, UK, 2009
16. P. Evtushenko, *"Instrumentation needs for Energy Recovery Linacs"*, to be published in ERL09 proceedings, Ithaca, US, 2009

Professional and Honorary Organizations

2009 – Winner of "2009 Young Scientist FEL Award", International FEL conference 2009
2009 – program committee of the international workshop on Energy Recovering Linacs (ERL09)
2007 – program committee of the international workshop on Energy Recovering Linacs (ERL07)

FAY ELIZABETH HANNON
STAFF SCIENTIST
Free Electron Laser
Jefferson Lab, Newport News, VA 23606

Education

PhD in Engineering, University of Lancaster, 2008.

Thesis "A High Average-Current Electron Source for the Jefferson Laboratory Free Electron Laser"

Master of Engineering with Honors in Electronics and Electrical Engineering, University of Edinburgh, 2001

Professional Experience

2008 – present Staff Scientist. Free Electron Laser, Jefferson Laboratory

2005 – 2008 PhD Student. Superconducting RF and Free Electron Laser groups, Jefferson Laboratory

2001-2005 – Accelerator Physicist. Daresbury Laboratory, Accelerator Science and Technology Centre, U.K.

2000 – Research Student. U.K. Astronomy Technology Centre, Royal Observatory Edinburgh

Publications:

I.V. Bazarov, B.M. Dunham, X. Liu, M. Virgo, A.M. Dabiran, F. Hannon, H. Sayed, "*Thermal emittance and response time measurements of a GaN photocathode",* Journal of Applied Physics 105 (2009) 083715

I.V. Bazarov, B.M. Dunham, C. Gulliford, F.E. Hannon, Y. Li, X. Liu, C.K. Sinclair, K. Soong, "*Benchmarking of 3D space charge codes using direct phase space measurements from photoemission high voltage DC gun*", Physical Review Special Topics: Accelerator Beam 11 (2008) 100703

I.V. Bazarov, B.M. Dunham, Y. Li, X. Liu, D.G. Ouzounov, C.K. Sinclair, F. Hannon, T. Miyajima, "*Thermal emittance and response time measurements of negative electron affinity photocathodes*", Journal of Applied Physics, 103 (2008) 054901

Sample Conference Proceedings:

Status of the Jefferson Lab ERL FEL DC Photoemission Gun, ERL 09
Phase Space Tomography Using the Cornell ERL DC Gun, EPAC 08
Thermal Emittance Measurements from Negative Electron Affinity Photocathodes, PAC 07
A Phase Space Tomography Diagnostic for Pitz*, EPAC 06*
Simulation and Optimisation of a 100 mA DC Photo-Injector*, EPAC 06*
Commissioning of an APPLE-II Undulator at Daresbury Laboratory for the SRS, PAC 05
ERLP Gun Commissioning Beamline Design*, LINAC 04*
Construction of an APPLE-II Type Undulator at Daresbury Laboratory for the SRS, *EPAC 04*
Injector Design for the 4GLS Energy Recovery Linac Prototype*, EPAC 04*

Synergistic Activities

Journal referee: Physical Review Special Topics – Accelerators and Beams

CARLOS HERNANDEZ-GARCIA
GUN/INJECTOR SYSTEMS HEAD
Free Electron Laser
Jefferson Lab, Newport News, VA 23606

Education

B.S. Industrial Physics Engineering, Monterrey Institute of Technology (ITESM), Mexico 1993
PhD in Physics, Vanderbilt University, Nashville TN, granted September 2001. Thesis: "*Photoelectric Field Emission from Needle Cathodes induced by cw and Pulsed Lasers*".

Professional Experience

2004-present – Gun/Injector Systems Head, Free Electron Laser, Jefferson Lab, Newport News, VA 23606.
2001-2004 – Staff Scientist, Free Electron Laser, Jefferson Lab, Newport News, VA 23606.

Representative Publications: 10 out of 25 total s:

Carlos Hernandez-Garcia, S. Benson, G. Biallas, D. Bullard, P. Evtushenko, K. Jordan, M. Klopf, D. Sexton, C. Tennant, R. Walker, and G. Williams, "DC High Voltage Conditioning of Photoemission Guns and Jefferson Lab FEL", AIP Conf. Proc. Aug 4, 2009, Volume 1149, pp. 1071-1076, SPIN PHYSICS, 18th International Spin Physics Symposium.
Carlos Hernandez-Garcia, Patrick O'Shea, and Marcy Sutzman, "Electron Sources for Accelerators", Physics Today, 61 44 (2008).
T. Rao, A. Burril, X. Y. Chang, J. Smedeley, T. Nishitani, C. Hernandez-Garcia, M. Poelker, E. Seddon, F. E. Hannon, C. K. Sinclair, J. Lewellen, D. Feldman, "Photocathode for energy recovery linacs", Nucl. Instr. Meth. A557 124 (2006).
C. Herrnandez-Garcia, et al., "A high average current DC GaAs photocathode gun for ERLs and FELs" Proceedings of the 2005 Particle Accelerator Conference, Knoxville, TN, May16-20 2005, pp 3117-3119.
Carlos Hernandez-Garcia, Kevin Beard, Stephen Benson, George Biallas and Others, "Performance and Modeling of the JLab IR FEL Upgrade Injector", Proceedings of FEL Conference, Trieste, Italy, 558 (2004).
C. Hernandez-Garcia, et al., "Longitudinal Space Charge Effects in the JLAB IR FEL SRF Linac", Proceedings of FEL Conference, Trieste, Italy, 363 (2004).
C. Hernandez, T. Wang, N. D. Theodore, T. Siggins, D. Bullard, H.F. Dylla, D. M. Manos, and C. Reece, "DC field-emission analysis from GaAs and plasma-source ion-implanted stainless steel", J. Vac. Sci. Technol. A21 1115 (2003).
C. Hernandez-Garcia and C. A. Brau, "Pulsed photoelectric field emission from needle cathodes", Nucl. Instr. Meth. A483 273 (2002).
C. Hernandez-Garcia and C. A. Brau, "Electron beams formed by photoelectric field emission Nucl. Instr. Meth. A475 559 (2001).
C. Hernandez-Garcia and C. A. Brau, "Photoelectric field emission from needle cathodes", Nucl. Instr. Meth. A429 257 (1999).

Synergistic Activities

Journal referee: Nucl. Instr. Methods,
2009, Invited to Chair, "Injectors section", 2009 Particle Accelerator Conference, Vancouver, Canada, May 2009.
2007, M. Sc. Thesis advisor, "PARMELA based simulations on Jefferson Lab Free Electron Laser" by D. K. Koppunuru, Department of Electrical Engineering, Old Dominion University, December 2007.

2006, Ph. D. Thesis committee member, “Silicon Oxynitride, a field emission suppression coating” by N. D. Theodore, Department of Applied Science, The College of William and Mary, April 2006.
2005 Winner R&D 100 Award among a group of scientist and engineers within the FEL team
2004, Chair, “Materials, Fabrication and Integration Working Group”, High Average Power and High Brightness Beams Workshop, UCLA, Los Angles, CA, November 2004.

Identification of Potential Conflicts of Interest or Bias in Selection of Reviewers

Recent Collaborators (past 48 months) Not Listed Above: B. Dunham, (Cornell U), L. Jones & R. Smith (ALICE, Daresbury Lab, UK), P. Piot, (Northern Illinois U).

KEVIN JORDAN PE
STAFF ELECTRICAL ENGINEER
Free Electron Laser
Jefferson Lab, Newport News, VA 23606

Education

AAET Madison Area Technical College, 1977
B.S. Electrical Engineering, Old Dominion University, 1991
P.E. Registered Professional Engineer, 1995

Professional Experience

1996 - present – Founding team member; Free Electron Laser, Jefferson Lab, Newport News, VA 23606.
1987 - 1996 – Electrical Engineer, Superconducting Radiofrequency Div. Jefferson Lab, Newport News, VA 23606.
1985 - 1987 – SRF/MHF team member, HERA div. DESY, Hamburg, Germany
1978 - 1985 – Electronics Technician, EE Support Div, Fermi Lab, Batavia, IL, 60510
1977 - 1978 – Electronics Technician, Test Equipment Construction & Calibration, Wescom Telecommunications, Downers Grove, IL

Recent Publications:

Michael W. Smith, Kevin C. Jordan, Cheol Park, Jae-Woo Kim, Peter T. Lillehei, Roy Crooks, Joycelyn S. Harrison, "Very long single- and few-walled boron nitride nanotubes via the pressurized vapor/condenser method" 2009 *Nanotechnology* **20** 505604
M.A. Holloway, R.B. Fiorito, A.G. Shkvarunets, P.G. O'Shea, S.V. Benson, D. Douglas, P. Evtushenko, K. Jordan, "Multicomponent measurements of the Jefferson Lab energy recovery linac electron beam using optical transition and diffraction radiation", Phys. Rev. ST Accel. Beams **11** 082801 (2008).
C. Park, K. E. Wise, J. H. Kang, J.-W. Kim, G. Sauti, S. E. Lowther, P. T. Lillehei, M. W. Smith, E. J. Siochi, and J. S. Harrison, and K. Jordan, "Multifunctional nanotube polymer nanocomposites for aerospace applications: adhesion between SWCNT and polymer matrix", Adhesion Society Meeting, Austin TX, Feb (2008)
K. Jordan, D. Douglas, S.V. Benson, P. Evtushenko, "FEL-accelerator related diagnostics", Proceedings of the 8th International Topical Meeting on Nuclear Applications and Utilization of Accelerators (AccApp'07), Pocatello, Idaho. ANS Order #: 700330 ISBN: 0-89448-054-5
M. Shinn, C. Behre, S. Benson, D. Douglas, F. Dylla, C. Gould, J. Gubeli, D. Hardy, K. Jordan, G. Neil, S. Zhang, "Xtreme Optics – the behavior of cavity optics for the Jefferson Lab Free Electron Laser", Proc. SPIE Boulder Damage Symposium XXXVIII, **SPIE 6403** page 64030Y-1 (2006).
G.L. Carr, M.C. Martin, W.R. McKinney, K. Jordan, G.R. Neil and G.P. Williams "High Power Terahertz Radiation from Relativistic Electrons", Nature **420** 153-156 (2002).
G.L. Carr, M.C. Martin, W.R. McKinney, K. Jordan, G.R. Neil and G.P. Williams "Very High Power THz Radiation at Jefferson Lab" Journal of Physics in Medicine and Biology, **47** 3761-3764 (2002).
G.L. Carr, M.C. Martin, W.R. McKinney, K. Jordan, G.R. Neil and G.P. Williams, "Very high Power THz radiation Sources", Journal of Biological Physics, **29** 319 2003. M. N. Petrovich, A. Favre, D. W. Hewak, H. N. Rutt, A. C. Grippo, J. F. Gubeli III, K. C. Jordan, G. R. Neil, M. D. Shinn, "Near-IR Absorption of Ga:La:S and Ga:La:S:O Glasses by FEL-based laser calorimetry. Journal of Noncrystalline Solids, **326-327** 93-97 (2003)
P. C. Eklund, B. K. Pradhan, U. J. Kim, and Q. Xiong , J. E. Fischer , A. D. Friedman and B. C. Holloway , K. Jordan, M.W. Smith, "Large-Scale Production of Single-Walled Carbon Nanotubes Using Ultrafast Pulses from a Free Electron Laser," Nano Letters, American Chemical Society, Volume 2, Issue 6 (June 12, 2002).

Professional and Honorary Organizations

2007 – present, Beam Instrumentation Workshop (BIW) Organizing Committee
2005 – present, Materials Research Society
2003 – present, Directed Energy Professional Society

Inventions, Patents:

a. Actuators and sensors fabricated with Boron Nitride Nanotubes (BNNTs) and BNNT Polymer Composites (patent pending)
b. High-Pressure Boron Vaporization Synthesis of Few-Walled Boron Nitride Nanotube Fibers. (patent pending)
c. Apparatus for Free Electron Laser Ablative Synthesis of Carbon Nanotubes. (patent pending)
d. The Application of High Average Power Ultrafast Laser Ablation for the Synthesis of Carbon Nanotubes (Patent awarded Aug. 2009)
e. Process for Optimizing Yield and Production Rate of Single-Walled Carbon Nanotubes Using Free Electron Laser Synthesis. (patent pending)
f. Boron Nitride Nanotube Fibrils and Yarns. (patent pending)
g. Use of Magnetic Chicane for THz Radiation Management (patent pending)

Synergistic Activities

2003-present, JLab PI for NASA funded Boron Nitride & Carbon Nanotube synthesis project

MICHAEL J. KELLEY
APPLIED RESEARCH PROGRAM MANAGER
Free Electron Laser
Jefferson Lab, Newport News, VA, 23606

Education

BS in Physics Rensselaer Polytechnic Institute, Troy NY. 1966; PhD in Materials Engineering 1973 Thesis: "Low temperature mechanical properties of ultra-pure Fe-Cr alloys"

Professional Experience

1999- Present: Applied Research Program Manager, Jefferson Laboratory, Newport News, Va, (Joint appt with College of William & Mary)

1999- Present: Professor (full, tenured) Dept. of Applied Science, Coll. of William & Mary, Williamsburg Va, Courses: Characterization of Materials, Materials Science of Surface and Interfaces; Applied Solid State Science (all graduate)

1973-1999 Research Engineer, Sr. Research Engineer, Research Associate, **SR. RESEARCH ASSOCIATE** Central Science and Engineering Laboratories, Experimental Station, E. I. du Pont de Nemours & Co.,

1978-1995 Off-Campus Faculty, Department of Chemical Engineering, University of Delaware, Newark DE 19716.

Representative Publications

Joan E. Thomas, Michael J. Kelley; "Interaction of mineral surfaces with simple organic molecules by diffuse reflectance IR spectroscopy (DRIFT)" J.Coll.Int.Sci., 322 (2008) 516-522.

Hui Tian, Sean G. Corcoran, Charles E. Reece, Michael J. Kelley; "The Mechanism of electropolishing of niobium in hydrofluoric sulfuric acid electrolyte"J. Electrochem. Soc., 155 (9) (2008) D563-D568

Michael J. Kelley, George R. Neil; "Free electron lasers" Landolt-Bőrnstein New Series VIII/1B2. Chapt.6.1. 189-201 (2008)

Hui Tian, Charles E. Reece, Michael J. Kelley, Shancai Wang, Lukasz Pulczinski, Kevin E. Smith, Matthew Nowell; "Surface studies of niobium chemically polished under conditions for superconducting radio frequency (SRF) cavity production". Appl. Surf. Sci. 253 (2006) 1236-42

Michael J. Kelley, E.W.Kreutz, Ming Li, Alberto Pique (eds.) "Ultrafast lasers for materials science" Mat.Res.Soc.Proc. 850 (2005) (book)

Zhengmao Zhu, Michael J. Kelley; "Grafting onto poly (ethylene terephthalate) driven by 172 nm UV light." Appl.Surf.Sci.252 (2005) 305-310

Michael J. Kelley; "High-Power, Tunable ps-Laser User Facility" Proc. ICALEO 2002. Pub.594 (2002) Laser Institute of America. 904

Christine F. Conrad, Catherine J. Chisholm-Brause and Michael J. Kelley; "Pb(II) Sorption to γ-Al_2O_3 Surfaces at the Oxide-Water Interface: A Novel Approach Using Planar Oxides" J.Coll. Int. Sci., 248 (2002) 275-282,

Michael J. Kelley; "High-Power Lasers in Manufacturing" Proc.SPIE 3888 (2000) X.Chen, T.Fujioka and A.Matsunawa eds.; 598 – 605

Adrienne E.H.Shearer, James S. Paik, Dallas G. Hoover, Sharon L. Haynie, Michael J. Kelley; ."Potential of an Antibacterial Ultraviolet-Irradiated Nylon Film" Biotech.Bioeng.67 (2000) 141–146

Synergistic Activities

Journal Referee: J.Colloid Interface Science, Applied Surface Science. J.Phys.Chem.
1998-2005: Founding chair of Laser Processing Consortium at Jefferson Lab.
1996-2006: Advisory Board, Center for Materials Research, Norfok State University, an HBCU.
Adjunct Professor – Materials Science & Engineering, Virginia Tech; Physics, Old Dominion University

Recent Collaborators–

Peter Abbamonte (BNL), Eric Bradley (W&M), Elizabeth Canuel (VIMS), David Clark (VT), Fred Dylla (JLab), Michael Hochella (VT), Dallas Hoover (UDel), Gunter Luepke (W&M), Dennis Manos (W&M), George Neil (JLab), Alberto Pique (NRL), Charles E. Reece (JLab), Kevin E. Smith (BU), Kate Stika (DuPont), **Thesis Advisor**: Norman S. Stoloff (Rensselaer). **Recent Students & Post-Docs-** Joseph Ametepe Christine Conrad, Jesse Diggs, Silvina Pagola, Hui Tian, Adrienne Shearer, Raja Singaravelu, Binping Xiao, Chen Xu, Liang Zhao, Xin Zhao, Zhengmao Zhu

J. MICHAEL KLOPF
STAFF SCIENTIST
Free Electron Laser
Jefferson Lab, Newport News, VA 23606

Education:

B.S., Physics, minor Mathematics, Louisiana State University, May 1993
Ph.D., Engineering Physics, University of Virginia, October 2005. Thesis: "Ultrafast Carrier Dynamics Measured by the Transient Change in the Reflectance of InP and GaAs Films".

Professional Experience:

2008-present – FEL Staff Scientist, Free Electron Laser, Jefferson Lab, Newport News, VA 23606.
2005-2008 – THz Postdoctoral Fellow, Free Electron Laser, Jefferson Lab, Newport News, VA 23606.
1998-2005 – Graduate Research Assistant, (NSOM Laboratory, Microscale Heat Transfer Laboratory), University of Virginia.
1993-1997 –Research Associate, Center for Advanced Microstructures and Devices, Louisiana State University.

Representative Publications:

Y. Vladimirsky, K. Morris, J. M. Klopf, O. Vladimirsky, et al., X-ray exposure system for induced chemistry and dry processes in microlithography, J. Vac. Sci. Technol. B, 13, 3109-13, (1995).
Y. Vladimirsky, O. Vladimirsky, K. J. Morris, J. M. Klopf, et al., PMMA as an X-ray Resist for Micro-machining Application: Latent Image Formation and Thickness Losses, Microelectronic Engineering, 30, 543-546, (1996).
E. E. Waali, J. D. Scott, J. M. Klopf, Y. Vladimirsky, et al., One- and Two-Dimensional Nuclear Magnetic Resonance Spectra of X-ray-Degraded Poly(methyl methacrylate), Macromolecules, 30, 2386-90, (1997).
S. M. Ford, M. Kar, S. McWhorter, J. Davies, et al., Microcapilary Electrophoresis Devices Fabricated Using Polymeric Substrates and X-ray Lithography, Journal of Microcolumn Separations, 10, 413-22, (1998).
J. M. Klopf, J. L. Hostetler and P. M. Norris, Transient Reflectance Response to Hot Electron Relaxation in InP Based Films, presented at 2002 ASME International Mechanical Engineering Congress & Exposition, New Orleans, LA, IMECE2002-39625, 1-5, (2002).
P. M. Norris, A. P. Caffrey, R. J. Stevens, J. M. Klopf, et al., Femtosecond Pump-Probe Nondestructive Evaluation of Materials, Rev. Sci. Instrum., 74, 400-406, (2003).
J. M. Klopf and P. M. Norris, Subpicosecond Observation of Photoexcited Carrier Thermalization and Relaxation in InP Based Films, International Journal of Thermophysics, 26, 127-140, (2005).
P. E. Hopkins, J. M. Klopf and P. M. Norris, Influence of interband transitions on electron-phonon coupling measurements in Ni films, Appl. Opt., 46, 2076-2083, (2007).
J. M. Klopf and P. Norris, Probing nonequilibrium dynamics with white-light femtosecond pulses, Applied Surface Science, 253, 6305-6309, (2007).
J. M. Klopf, A. Greer, J. Gubeli, G. R. Neil, et al., The Jefferson Lab High Power THz User Facility, Nucl. Instrum. Methods A, 582, 114-116, (2007).
J. M. Klopf, M. Coppinger, N. Sustersic, J. Kolodzey, et al., High-Power Terahertz Source Opens the Door for Full-Field Video-Rate Terahertz Imaging, Opt. Lett., (submitted).

Identification of Potential Conflicts of Interest or Bias in Selection of Reviewers
***Recent Collaborators (past 48 months) Not Listed Above*:**

G. Larry Carr (Brookhaven National Lab), Michael Gensch (FLASH, DESY), Harvey N. Rutt (U. of Southampton, UK), Jill McQuade (US Air Force Academy), Gerald Wilmink (US Air Force Research Laboratory), Alan Todd (Advanced Energy Systems), Hans Bluem (Advanced Energy Systems), Henry Helvajian (Aerospace Corp.), Frank Livingston (Aerospace Corp.), Richard Haglund (Vanderbilt University), Ken Schriver (Vanderbilt University), Sergey Avanesyan (Vanderbilt University), Hee Park (AppliFlex LLC), Gunter Luepke (William & Mary University), Erik Spahr (William & Mary University), Pierre Kaufmann (U. Presbiteriana Mackenzie, Sao Paulo, Brasil), John Singleton (Los Alamos National Lab), Michael W. Smith (NASA Langley Research Center), Ruben Reininger (BNL).

THOMAS JOSEPH POWERS
STAFF ENGINEER, ELECTRICAL
Free Electron Laser
Jefferson Lab, Newport News, VA 23606

Education

B.S. Electrical Engineering, Old Dominion University, granted May1980.

M.E. Electrical Engineering, granted August 1987. Thesis: "Magnetic Control of Diffuse Discharges."

Professional Experience

1987-present – Staff Electrical Engineer, RF/SRF engineer Free Electron Laser Division. Previous positions include Superconducting Radio Frequency (SRF) Division Lead Electrical Engineer, Staff Engineer Beam Diagnostics Department, Staff Engineer Low Level RF department.

1985-1987 – Graduate Research and Teaching Assistant, Old Dominion University.

1980-1985 – Electrical Engineer, Navigations Systems Department, Naval Sea Combat Systems Engineering Station, Norfolk VA.

1978-1980 – Undergraduate Research Assistant, Old Dominion University, Norfolk VA.

Representative Publications: 10 out of 59 total.

"Acceptance Test Results for a High Current Booster Superconducting Radio Frequency Cryomodule," T. Powers, Directed Energy Professional Society Symposium, Oct. 2009.

"High Power RF Tests on WR-650 Pre-stress Planar Windows" T. Powers, et. al., Directed Energy Professional Society Symposium, Oct. 2009.

"RF Controls Experience with the JLAB IR Upgrade FEL," T. Powers, ERL workshop, June 2009.

"Implications of Incomplete Energy Recovery in SRF-based Energy Recovery Linacs," T. Powers, C. Tennant. ERL workshop, May 2007.

"Commissioning and Operational Experience with an Intermediate Upgrade Cyromodule for CEBAF 12 GeV Upgrade," T. Powers, et. al. (TJNAF), SRF 2005.

"Waveguide Arc Restrike Test Results," Tom Powers, et. al., JLAB-TN-04-039.

"Upgrade to Cryomodule test facility at Jefferson Lab," T. Powers, et. al., SRF Workshop 2003.

"Design, commissioning and operational results of wide dynamic range BPM switched electrode electronics," Tom Powers, et. al., BIW 1996.

"Arcing phenomena on CEBAF RF-windows at cryogenic temperatures," Tom Powers, Peter Kneisel, SRF Workshop 1996.

"Two Applications of Direct Digital Down Converters in Beam Diagnostics," Tom Powers, et. al., BIW 2000

Synergistic Activities

Examples of Engineering Support to Other Institutions:

2006 to Present: Laboratori Nazionali di Legnaro. Provide SRF technology support and instruction to graduate students from Padova University.

2006 to Present: Fermi National Laboratory. Assisted in the design, development and commissioning of the SRF Vertical Test Facility.

2005 to Present: Daresbury National Lab. Provide technical support for the operation and maintenance of SRF systems.

2002 – 2007 Spallation Neutron Source, Oak Ridge National Lab. Member of Design Review teams for beam diagnostics systems, vacuum system and cryogentic systems development; provide follow on support for SRF cavity installation and operation.

MICHELLE D. SHINN
SENIOR STAFF SCIENTIST
Free Electron Laser
Jefferson Lab, Newport News, VA 23606

EDUCATION
Ph.D. in Physics, December 1983, Oklahoma State University.
M.S. In Physics, July 1980, Oklahoma State University
B.S. in Physics, Minor: Mathematics, July 1978, Oklahoma State University.

EMPLOYMENT
1984-1990, Physicist, ICF Program, Lawrence Livermore National Laboratory
1990-1995, Associate Professor, Department of Physics, Bryn Mawr College, Bryn Mawr, PA.
1995-present, Senior Staff Scientist, FEL Dept., Thomas Jefferson National Accelerator Facility, Newport News, VA.

SELECTED AND RELEVANT PUBLICATIONS

G. R. Neil, G. Biallas, C. Bohn, D. Douglas, H.F. Dylla, R. Evans, J. Fugitt, R. Hill, K. Jordan, G. Krafft, R. Legg, R. Li, L. Merminga, G.R. Neil, D. Oepts, P. Piot, J. Preble, M. Shinn, T. Siggins, R. Walker, and B. Yunn, "Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery," Phys. Rev. Letter **84**(4), 662-665 (2000).

George R. Neil, S. V. Benson, G. Biallas, J. Gubeli, K. Jordan, S. Myers, and M. D. Shinn, "Second Harmonic FEL Oscillation, Phys. Rev. Lett. **87**, 084801 (2001).

M.D. Shinn, G. R. Baker, C. P. Behre, S. V. Benson, M. E. Bevins, L.A. Dillon-Townes, H. F. Dylla, E. J. Feldl, J. F. Gubeli, R. D. Lassiter, F. D. Martin, and G. R. Neil "Design of the Jefferson Lab IR Upgrade FEL Optical Cavity," NIM **A507** 196 (2003).

George R. Neil, G. L. Carr, Joseph F. Gubeli III, K. Jordan, Michael C. Martin, Wayne R. McKinney, Michelle Shinn, Masahiko Tani, G. P. Williams and X.-C. Zhang, "Production of High Power Femtosecond Terahertz Radiation", Nuclear Instruments and Methods **A507** 537 (2003).

Michelle Shinn, Christopher Behre, Stephen Benson, David Douglas, Fred Dylla, Christopher Gould, Joseph Gubeli, David Hardy, Kevin Jordan, George Neil, and Shukui Zhang, "Xtreme Optics – the behavior of cavity optics for the Jefferson Lab Free-Electron Laser", to be published in Proc. SPIE Vol. 6403 pp 64030Y-1 (2007)

P.J.M. van der Slot, Henry Freund, W.H. Miner, K.-J. Boller, Stephen Benson, Michelle Shinn, "Time-dependent, three-dimensional simulation of free-electron-laser oscillators," Phys. Rev. Letts. **102** 244802 (2009).

"Basics of Lasers and Laser Optics" – book chapter (2009)

Professional and Honorary Organizations
Member, SPIE
Member, The American Physical Society
Member, Direct Energy Professional Society
Sigma Pi Sigma – Oklahoma State University

Synergistic Activities

2006-present, Member, Advisory Board, Delaware State University Center for Research and Education in Optical Sciences And Applicatons Resource Center.

2009-present, Member of International Program Committee, Boulder Damage Symposium

2000-present, Member, Editorial Advisory Board, Laser Focus World.

CHRISTOPHER D. TENNANT
STAFF SCIENTIST
Free Electron Laser
Jefferson Lab, Newport News, VA 23606

Education

B.A. Physics *(summa cum laude),* Mathematics minor, Ithaca College, Ithaca, NY, May 2001
M.S. Physics, College of William and Mary, Williamsburg, VA, December 2002
Ph.D. Physics, College of William and Mary, Williamsburg, VA, May 2006
Thesis: "Studies of Energy Recovery Linacs at Jefferson Laboratory"

Professional Experience

2000-present: Staff Scientist I, Free Electron Laser, Jefferson Lab, Newport News, VA 23606

Representative Publications: *10 out of 62 total*

D. Douglas and C. Tennant, "Use of Recirculation in Short-Wavelength FEL Drivers" Jefferson Laboratory Technical Report No. 09-046, (2009).

S. Benson, D. Douglas, P. Evtushenko, F. Hannon, K. Jordan, J. Klopf, G. Neil, C. Tennant, G. Williams and S. Zhang, "JLAMP: A Next Generation Photon Science Facility at Jefferson Laboratory" Proceedings of the 31st International Free Electron Laser Workshop, Liverpool, UK (2009).

C. Tennant, "Progress at the Jefferson Laboratory FEL" Proceedings of the 2009 Particle Accelerator Conference, Vancouver, BC (2009).

C. Tennant and D. Douglas, "Design Considerations for the INP 100 kW FEL Driver" Jefferson Laboratory Technical Report No. 08-054, (2008).

D. Douglas, C. Tennant, "A Remark on One-Dimensional Models of CSR" Jefferson Laboratory Technical Report No. 08-050, (2008).

G. Biallas, S. Benson, D. Douglas, P. Evtushenko, C. Hernandez-Garcia, K. Jordan, G. Neil, T. Powers, R. Rimmer, M. Shinn, C. Tennant, R. Walker and G. Williams "A Light Source Proposal to the National Science Foundation" (2006).

D. Douglas, K. Jordan, L. Merminga, E. Pozdeyev, C. Tennant, H. Wang, I. Bazarov, G. Hoffstaetter, S. Simrock, T. Smith "Experimental Investigation of Multipass, Multibunch Beam Breakup in the Jefferson Laboratory Free Electron Laser Upgrade" Physical Review Special Topics - Accelerators and Beams, 9, 064403 (2006).

E. Pozdeyev, J. Bisognano, R. Hajima, M. Sawamura, T. Smith, C. Tennant "Multipass Beam Breakup in Energy Recovery Linacs" Nuclear Instruments and Methods in Physics Research, Section A, 557, 176 (2006).

G. Neil, C. Behre, S. Benson, M. Bevins, G. Biallas, J. Boyce, J. Coleman, L.A. Dillon- Townes, D. Douglas, H. Dylla, R. Evans, A. Grippo, D. Gruber, J. Gubeli, D. Hardy, C. Hernandez-Garcia, K. Jordan, M. Kelley, L. Merminga, J. Mammosser, W. Moore, N. Nishimori, E. Pozdeyev, J. Preble, R. Rimmer, M.Shinn, T. Siggins, C. Tennant, R. Walker, G. Williams, S. Zhang "The JLab High Power ERL Light Source" Nuclear Instruments and Methods in Physics Research, Section A, 557, 9 (2006).

C. Tennant, K. Beard, D. Douglas, K. Jordan, L. Merminga, E. Pozdeyev, T. Smith "First Observations and Suppression of Multipass, Multibunch Beam Breakup in the Jefferson Laboratory Free Electron Laser Upgrade" *Physical Review Special Topics - Accelerators and Beams, 8, 074403 (2005).*

Professional and Honorary Organizations

Member American Physical Society

Synergistic Activities

1. Design and simulation of CSR managed bunch compression systems
2. Analytic study and simulation of the effects of incomplete energy recovery on ERLs utilizing SRF cavities
3. Optimization of FEL driver linacs with space charge
4. Analytic study and simulation of beam motion for off-axis transport in SRF cavities and its implications for the multipass beam breakup instability
5. Contributed to the design of three ERL projects and have operational experience with three different ERLs at Jefferson Laboratory

Identification of Potential Conflicts of Interest or Bias in Selection of Reviewers

Recent Collaborators (past 48 months) Not Listed Above: G. Bassi (University of Liverpool and Cockcroft Institute) J. Bisognano (University of Wisconsin at Madison) A. Freyberger (Thomas Jefferson National Accelerator Facility), R. Hajima (Japan Atomic Energy Agency), G. Krafft (Thomas Jefferson National Accelerator Facility), F. Marhuaser (Thomas Jefferson National Accelerator Facility), Y. Roblin (Thomas Jefferson National Accelerator Facility), M. Sawamura (Japan Atomic Energy Agency)

RICHARD L. WALKER
RF & HVPS MANAGER
Free Electron Laser
Jefferson Lab, Newport News, VA 23606

Education

B.S. Electrical Engineering, Iowa State University, granted June 1960
M.S. Electrical Engineering, Arizona State University, granted September 1967.

Thesis: "Design of an 8 Bit Paper Tape Communication System".

Professional Experience

1991 – Present	**RF & HV Engineer**	Jefferson Lab	Newport News, VA
1989 – 1991	**Engineering Manager**	Schlumberger	Paris, France
1985 – 1989	**V.P. of Engineering**	M.A. Kempner	Deerfield Beach, FL
1983 – 1985	**Operations Manager**	Ungermann-Bass	Boca Raton, FL
1981 – 1983	**Consultant**	Walker Engineering	Boca Raton, FL
1979 – 1981	**Program Manager**	GenRad	Concord, MA
1978 – 1979	**General Manger**	NAICO	Bedford, NH
1977 – 1978	**V.P. of Engineering**	Memodyne	Newton, MA
1976 – 1977	**Engineering Manager**	MFE	Salem, NH
1967 – 1976	**Engineering Manager**	EG&G	Salem, MA
1966 – 1967	**Senior Engineer**	Motorola	Scottsdale, AZ
1963 – 1966	**Design Engineer**	General Electric	Phoenix, AZ

Major Accomplishments

- Completed design and made operational Jefferson Lab's low level RF Control Module.
- As RF Group Leader, was responsible for installation and checkout of RF systems for Jefferson Lab's Continuous Electron Beam Accelerator.
- Designed, simulated, and commissioned the 385 kW power supplies for the 100 kW klystrons used in FEL Injector.
- Developed and had on the market in less than 4 months, a family of smartcard pay telephones.
- Developed a complex automatic telephone polling system within six (6) months. Four (4) months later, had 60 systems delivered and operational world-wide.
- In 3 months, developed for production a CCD camera, amplifier, and 20 MHz A/D converter with 6 bits of precision from a .006" square area moving at 100 in. / sec.
- Developed a precise 3 element optical filter to give a silicon photodiode the wavelength response characteristics of the human eye.
- Managed the development, initial manufacturing, and market introduction of the 2270 In-Circuit Tester. It is a complex computer controlled in-circuit board tester with a "bed of nails" interface to the board being tested. The system was completed within 6 months, on schedule, and generated over $40 million in sales its first year.
- Managed a start-up company and developed its product line of oceanographic instruments and buoy systems. The company was profitable by the end of the first year with increasing sales.
- Co-authored of winning proposal for Central Computer & Sequencer for Mariner Mars '69 space probe; Cognizant Engineer for assembly and testing hardware.
- Designed and built a complete data acquisition system for gathering oceanographic data *in situ* for up to 3 months underwater.

Patents

- Dual Design Resistor and Mechanism for High Voltage Conditioning.
- Phototransistor Amplifier and Mechanism to Sense Low Tape Condition on Magnetic Tape Reel.
- Photodiode Differential Amplifier and Mechanism to Sense EOT/BOT Strips on Magnetic Tape.
- DC to DC Converter to Efficiently Power and Control Low Resistance Loads.
- Electro-Optical Tachometer for Miniature DC Motor Speed Control.
- Automatic Telephone Polling Device with the ability to decode responses from both DTMF and rotary telephones over both local and long distance lines world-wide.

Publications

"Operating Experience and Reliability Improvements on the 5 kW *cw* Klystron at Jefferson Lab", delivered at *cw* and High Average Power RF Systems Conference, 2004 & 2008
"Can Smart Cards Be Multi-Functional", delivered to SCAT conference, 1991.
"Visibility Conditions at Logan Airport", delivered to American Meteorological Society, 1974.
"Pressing Problems and Projected National Needs in Optical Radiation Measurments", co-authored and delivered at Council of Optical Radiation Measurements meeting at NBS, 1972.

Professional and Honorary Organizations

1991, Member, ANSI Technical Committee on Smart Cards
1972, Chairman on Detectors, Council of Optical Radiation Measurements
1972, Member of U.S. Technical Committee 1.2, Commission Internationals de L'Eclairge
1960 – 1976, Member, IEEE

SHUKUI ZHANG
RESEARCH SCIENTIST
Free Electron Laser
Jefferson Lab, Newport News, VA 23606

EDUCATION

PhD in Ultrafast Optics and Lasers, received in 1996, Tianjin University, China.
Thesis title: "*Theoretical Simulation and Experimental Study on Generation and Amplification of Femtosecond Optical Pulses*".

PROFESSIONAL EXPERIENCE

2001-present, Research Scientist, Thomas Jefferson National Accelerator Facility.

1998-2000, Research Scientist, Institute of Laser Technology/Institute of Engineering, Osaka University, Japan.

1996-1997, Research Scientist, National Laboratory for Laser Plasma Physics, China.

PROFESSIONAL ORGANIZATION AND SYNERGISTIC ACTIVITY

Member of Optical Society of America, member of Sigma Xi.

Regular referees for four international journals.

SELECTED RECENT PUBLICATIONS

S. Zhang, et al., "Study of Optical Frequency Chirping and Pulse Compression in a High-Gain Energy-Recovery-Linac-Based Free-Electron-Laser", Proc. of FEL'2009, Liverpool, UK.
S. Zhang**,** and JLab FEL Team, "Drive Laser Systems for Electron Accelerators and Free-Electron-Lasers Based on Photocathode-Injector Energy-Recovery-Linac", invited talk, ERL'2009, Ithaca, NY.
C. Liu and S. Zhang, "Study of the Singular Radius and Surface Boundary Constraints in Refractive Beam Shaper Design", OPT. EXPRESS **16** 6675 (2008).
S. Zhang, "A Simple Bi-convex Refractive Laser Beam Shaper", JOURNAL OF OPT. A: PURE AND APPL. OPT. **9**, 945(2007).
S. Zhang, et al., "Longitudinal Phase Space Characterization of Electron Bunches at the JLab FEL facility", Proc. of the 28th Int. FEL Conf., 740 (2006).
JLab FEL team, and S. Zhang, "First Lasing of the IR Upgrade FEL at Jefferson", NUCL. INSTR. METH IN PHY. RESEARCH, A **528**, 19 (2004).
S. Zhang, et al., "Single-element Laser Beam Shaper for Uniform Flat-top Profiles"**,** OPT. EXPRESS **11** (16): 1942 (2003).
S. Zhang, et al., "Gain and Spectral Characteristics of Broadband Optical Parametric Amplification", JPN. JOURNAL of APP. PHYS **40**, 3188 (2001).
S. Zhang**,** et al.**,** "Generation of Ultra-high Peak Power Optical Pulses by OPCPA", CHINESE JOURNAL of LASERS, B**10**, III-14 (2001).
S. Zhang, et al., "Optical Parametric Amplification of Broadband Chirped Pulses at 1micron", Tech. Digest/Conf. on Lasers and Electro-Optics (CLEO 2000). TOPS **39**, 249 (2000).

DANA M. ARENIUS
CRYOGENICS DEPT HEAD
Engineering Division
Jefferson Lab, Newport News, VA 23606

Education

B.S.E.E Lowell Technological Institute, Lowell MA, 1972
MIT Cambridge, MA, 1975, Graduate Courses, Cryogenic Engineering

Professional Experience

Present- Cryogenic Systems Engineering Dept Head, Engineering Division, Jefferson Lab
Cryogenic Research and Development Co-Director, Collins Cryogenic R&D Institute, Jefferson Lab
2000-2008- Cryogenics Systems Group Leader, Accelerator Division, Jefferson Lab, Newport News, VA 23606
1989-1999 – Cryogenics Systems Deputy Group Leader, Accelerator Division, Jefferson Lab, Newport News, VA 23606
1981-1988 – Senior Cryogenics Systems Design Engineer, Koch Process Systems, Westborough, MA
1975-1981– Cryogenic Systems Design Engineer, CTI Cryogenics Inc., Waltham, MA

Representative Publications: recent 5 out of 37 total.

J. Homan, M. Montz, V. Ganni, A Sidi-Yekhlef, P. Knudsen, J. Creel, D. Arenius, "Floating Pressure Conversion and Equipment Upgrade of Two 3.5kW, 20K Helium Refrigerators", Advances in Cryogenic Engineering, Vol 55, pending publication, (2009)

J. Homan, M. Montz, V. Ganni, A Sidi-Yekhlef, P. Knudsen, D. Arenius, "The Liquid Nitogen System for Chamber-A change for Original Forced Flow design to a Natural Flow (thermo siphon) System", Advances in Cryogenic Engineering, Vol 55, pending publication, (2009)

V. Ganni, D. Arenius, P. Knudsen, F. Casagrande, M. Howell, "Screw compressor Characteristics for Helium Refrigeration Systems", Advances in Cryogenic Engineering, Vol 53, 309 (2007)

R. Than, J. Trozzolo, A. Sidi-Yekhlef, V. Ganni, D. Arenius, "The Relativistic Heavy Ion Collider (RHIC) Cryogenic System At Brookhaven National Laboratory; Review of the Modifications and Upgrades since 2002", Advances in Cryogenic Engineering, Vol 53, 578 (2007)

D. Arenius, J. Creel, K. Dixon, V. Ganni, P. Knudsen, A. Sidi-Yekhlef, "An Overview of the planned Jefferson Lab 12 GeV Helium Refrigerator Upgrade", Advances in Cryogenic Engineering, Vol 53, 588 (2007)

Professional and Honorary Organizations and Awards

2007– Presidential White House "Closing the Circle Award" for Environmental Stewardship
2007– DOE P2 "Best in Class" Award, Cryogenic Refrigeration Improvements at Jefferson Lab, Waste and Pollution
2006-present Cryogenic Society of America, Board Member
2005-present Cryogenic Systems Operations Workshop Founding Board Member
2005-present Co-Instructor, Short Course "Design of Optimal Cryogenic Helium Refrigeration Systems", Cryogenic Engineering Conference (2005, 2007, 2009)

Identification of Potential Conflicts of Interest or Bias in Selection of Reviewers

Recent Collaborators (past 48 months) Not Listed Above: Dr. Fabio Casagrande (SNS, ORNL, TN), Dr. Al Zeller (MSU, MI), Dr. Yatming "Roberto" Than (BNL, NY), Arkadiy Klebaner (FNAL, IL), Dr. Thomas Peterson (FNAL, IL), Dr. Igor Sekachev (TRIUMF, Vancouver, B.C.), Dr. Jay Theilacker (FNAL, IL), Dr. John G. Weisend II (SLAC, CA), Jonathan L. Homan (NASA Johnson Space Center, TX)

JEAN R. DELAYEN
DIRECTOR, CENTER FOR ACCELERATOR SCIENCE
Old Dominion University
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Jefferson Lab, Newport News, VA 23606

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Accelerator Division
12000 Jefferson Avenue, Newport News, VA 23606
Tel: (757) 269-7420 Fax: (757) 269-5024
email: delayen@jlab.org

EDUCATION

MBA (*with Honors*)	Graduate School of Business , University of Chicago	1994
PhD	Low Temperature Physics, California Institute of Technology	1978
	Thesis: Phase and Amplitude Stabilization of Superconducting Resonators	
MS	Engineering Science, California Institute of Technology	1971
Ingénieur (*with Honors*)	Ecole Nationale Supérieure d'Arts et Métiers, Paris, France	1970

PROFESSIONAL EXPERIENCE

2006-Pres. **Old Dominion University,** Physics Department
2009-Pres. *Director, Center for Accelerator Science and Professor of Physics*
2006-2009 *Jefferson Laboratory Professor of Accelerator Science*

1995-Pres. Principal Scientist, **Thomas Jefferson National Accelerator Facility,** Accelerator Division
2009-Pres. *Director, Center for Accelerator Science*
2001-2009 *Fellow, Center for Advanced Study of Accelerators*
1995-2001 *Head, Accelerator Development Department*

1987-1995 **Argonne National Laboratory**, Technology Development Division
Group Leader and Program Manager for Accelerator Physics and RF Superconductivity

1977-1986 **California Institute of Technology**, Low Temperature Physics
1980-1986 *Senior Scientist*
1977-1980 *Scientist*

AWARDS

Fellow of the American Physical Society
Director's Award for Exceptional Achievement, Argonne National Laboratory
Prize for Excellence in Theoretical Subjects, ENSAM, Paris

Patents: "RFQ Device for Accelerating Particles", J. R. Delayen and K. W. Shepard
"Digital Self Excited Loop" (pending), T. Allison, J. Delayen, C. Hovater, J. Musson, T. Plawsky
"Particle Beam Crabbing and Deflecting Cavity" (pending), J. R. Delayen

PROFESSIONAL ACTIVITIES

US Particle Accelerator School Governing Board	2008-Pres.
Editorial Board, Physical Review Special Topics, Accelerators and Beams	2008-Pres.
Publication Committee, Division of Physics of Beams, American Physical Society	2006-Pres.
US Particle Accelerator School Curriculum Advisory Committee	2004-Pres.
Advisory Committee, LHC-CC, CERN, Geneva, Switzerland	2009-Pres.
Machine Advisory Committee, Turkish Accelerator Center, IR-FEL, Ankara, Turkey	2009-Pres.
International Advisory Committee, European Spallation Source Bilbao Initiative, Spain	2008-Pres.
International Steering Committee, SARAF Accelerator, Yavne, Israel	2003-Pres.
Machine Advisory Committee, Next Linear Collider, SLAC	2000-2004
Strategic Advisory Board, College of Engineering and Technology, Old Dominion University	1997-1998

Program Committee International Linear Accelerator Conference (2010)
Program Committee, LHC-CC09 (2009)
Program Committee, European Spallation Source Bilbao Initiative Workshop (2008)
Program Committee, Particle Accelerator Conference (2007, 2009)
International Program Committee, SRF International Conference (2007, 2009)

Reviewer: Physical Review, Nuclear Instruments and Methods
Review of Scientific Instruments, Journal of Applied Physics

Proposal Reviewer: DOE, NSF, Australian Research Council
Natural Sciences and Engineering Research Council of Canada

RELEVANT PUBLICATIONS

J. R. Delayen, H. Wang, "New Compact TEM-type Deflecting and Crabbing RF Structure", Phys. Rev. ST Accel. Beams **12**, 062002 (2009)

Juhao Wu, Alexander W. Chao, Jean R. *Delayen, «* Transverse Effect due to Short-range Resistive Wall Wakefield", Proc. 2007 Particle Conference, Albuquerque, NM, 25-29 June 2007.

J. R. *Delayen,* Juhao Wu, "Transverse Effects due to Random Displacement of Resistive Wall Segments and Focusing Elements", Proc. 2007 Particle Conference, Albuquerque, NM, 25-29 June 2007.

J. R. Delayen, "Ponderomotive Instabilities and Microphonics", Physica C 441 (2006) 1-6

J. R. Delayen, "Cumulative Beam Breakup in Linear Accelerators with Time-dependent Parameters", Phys. Rev. ST Accel. Beams **8,** 024402 (2005).

J. R. Delayen, "Superconducting Cavities for Proton and Ion Linacs (Invited)", Proc. High Power Superconducting Ion, Proton, and Multi-Species Linacs Workshop, Naperville, IL, 22-24 May 2005.

J. R. Delayen, "Intermediate-Velocity Superconducting Structures (Invited)", Proc. LINAC 2004, Lubeck, Germany, 16-20 August 2004.

J. R. Delayen, "Cumulative Beam Breakup in Linear Accelerators with Random Displacement of Cavities and Focusing Elements", Phys. Rev. ST Accel. Beams **7,** 074402 (2004).

J. R. Delayen, "Cumulative Beam Breakup in Linear Accelerators with Arbitrary Beam Current Profile",
Phys. Rev. ST Accel. Beams **6**, 084402 (2003).

K. W. Shepard, P. N. Ostroumov, J. R. Delayen, "High-Energy Ion Linacs Based on Superconducting Spoke Cavities", Phys. Rev. ST Accel. Beams 6, 080101 (2003).

ANDREW HUTTON
ASSOCIATE LABORATORY DIRECTOR
Accelerator Division
Jefferson Lab, Newport News, VA 23606

Education

Ph.D. in Physics at London University, England

M.A. (Honours) Natural Sciences, Cambridge, England

B.A. (Honours) Natural Sciences, Cambridge, England

Professional Experience

1995-Present – Director of Operations, Accelerator Division, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606
1992-1995 – Deputy Director of Operations, Accelerator Division, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606
1983-1992 – Head of B Factory Machine Design Group, Stanford Linear Accelerator Centre, Stanford University, California 94025
1986-1989 – SLC Project, Arc System Commissioner, **Head of Beam Delivery Section**, Stanford Linear Accelerator Centre, Stanford University, California 94025
1983-1986 – SLC Project, System Manager for the Damping Rings, Stanford Linear Accelerator Centre, Stanford University, California 94025

1980-1982 – Parameter Coordinator, LEP Division, CERN, Switzerland

1975-1980 – Physicist, ISR Division, CERN, Switzerland

1970-1975 – Physicist, Institute of Photochemistry & Radiation Chemistry, Bologna, Italy
1966-1970 – Ph.D., Institute of Cancer Research, Sutton UK

Representative Publications (10 out of 148 total)

- Y. Derbenev, A. Afanasev, K. Beard, L. Cardman, S. Chattopadhyay, P. Degtiarenko, J. Delayen, R. Ent, A. Hutton, G. Krafft, R. Li, N. Merminga, B. Poelker, B. Yunn, P. Ostroumov, 'ELECTRON-ION COLLIDER AT CEBAF: NEW INSIGHTS AND CONCEPTUAL PROGRESS', EPAC 2004
- C. Tennant, K. Beard, S. Bogacz, Y. Chao, S. Chattopadhyay, D. Douglas, A. Freyberger, A. Hutton, N. Merminga, M. Tiefenback, H. Toyokawa, '1 GEV DEMONSTRATION OF ENERGY RECOVERY OPERATION AT CEBAF', published: *Physical Review Letters* 2004*.*
- N. Merminga, K. Beard, Y. Chao, J. Delayen, Y. Derbenev J. Grames, A. Hutton, G. Krafft, R. Li, B. Poelker, B. Yunn, Y. Zhang, 'ELIC: AN ELECTRON – LIGHT ION COLLIDER BASED AT CEBAF', EPAC *2002*.Proceedings, Page(s) 203-205, June 3-7, 2002
- A. Hutton, 'DOUBLING THE INTENSITY OF AN ERL BASED LIGHT SOURCE', PAC 05
- H. F. Dylla, A. Hutton, G. Neil, and G. P. Williams*, '*A NEW DYNAMICS FACILITY COMBINING A STORAGE RING WITH A SYNCHRONIZED FREE ELECTRON LASER', Revue of Scientific Instruments Vol. 73, No 3, March 2002
- R. W. Longman, R. Akogyeram, J.-N. Juang, A. Hutton, 'CONTROL LAW DESIGN FOR ELIMINATING PERIODIC DISTURBANCES ABOVE NYQUIST FREQUENCY', American Institute of Aeronautics and Astronautics, AIAA-2000-4353, August 2000
- A. Hutton, 'ACCELERATOR PROSPECTS FOR PHOTON PHYSICS', Photon 92, San Diego California Mar 23-26, 1992 and SLAC-PUB-5462, May 1992

- The B Factory Machine Design Team (58 Authors), 'INVESTIGATION OF AN ASYMMETRIC B FACTORY IN THE PEP TUNNEL', LBL PUB-5263, SLAC-359 and CALT-68-1622, March 1990
- W. Davies-White, A. Hutton (SLAC), A. Harvey (Los Alamos), 'THE ELECTRON DAMPING RING FOR THE SLAC LINEAR COLLIDER', 10th International Conference on Magnet Technology, Boston, MA, Sept.21-25, 1987 and SLAC-PUB-4447, Oct. 1987.
- A. Hutton, W. Davies-White, J.-P. Delahaye (CERN), T. Fieguth, A. Hofmann, J. Jager, P.K. Kloeppel (CEBAF), M. Lee, W. Linebarger, L. Rivkin, M. Ross, R. Ruth, H. Shoaee, M. Woodley, 'STATUS OF THE SLC DAMPING RINGS', IEEE Trans. Nucl. Sci. NS-32, 1659, 1985.

Professional and Honorary Organizations

- Chairman of the Machine Advisory Committee of KEKB, the B Factory built at KEK, Tsukuba, Japan.
- Chairman of the Machine Advisory Committee of DAFNE, the Φ Factory built at INFN, Frascati, Italy.
- Member of the Division Review Committee for LANSCE, the Los Alamos Neutron Science Center, USA
- Member of the Accelerator Advisory Committee for SNS, the Spallation Neutron Source.
- Frequent member of Accelerator Review Committees in the USA - APS at Argonne, RHIC at Brookhaven, Main Injector at Fermilab, NLC at SLAC and NIF at Livermore (Team Leader for Commissioning and Operations).
- Member of the PAC Program Committee (Particle Accelerator Conference).
- Chairman of the Board of Directors of the Virginia Quality Institute, a non-profit organization providing workforce development support to local academic institutions. Coordinated exchange of best practices between industry, military bases, local government, and federal agencies.
- Lecturer on Project Management at the United States Particle Accelerator School.
- Member of the Governing Board of the ODU Research Foundation of Old Dominion University.

Synergistic Activities

- Member of the Machine Advisory Committee SLS, the Swiss Light Source built at PSI, Villigen, Switzerland.
- Member of Ultimate Storage Rings Working Group at the BES workshop on Physics of Future Light Sources.
- Member of the HEPAP Subpanel on AARD (Advanced Accelerator R&D), Team Leader for short and medium term R&D).

Identification of Potential Conflicts of Interest or Bias in Selection of Reviewers

None that I am aware of.

GEOFFREY A. KRAFFT
SENIOR SCIENTIST
Center for Advanced Studies of Accelerators
Jefferson Lab, Newport News, VA 23606

Position Title: Jefferson Lab Professor, Department of Physics, Old Dominion University, Norfolk, VA and Senior Scientist, Thomas Jefferson National Accelerator Facility, Newport News, VA.

a. Professional Preparation

Ph.D. Physics, June 1986, University of California, Berkeley, California (Lloyd Smith, mentor)
M.A. Physics, June 1980, University of California, Berkeley, California
B.A. Physics and Mathematics, May 1978, Rutgers University, New Brunswick, New Jersey

b. Appointments

April 2009-present:	Director, Center for Advanced Studies of Accelerators, Thomas Jefferson National Accelerator Facility
Oct 2006-present:	Jefferson Lab Professor, Old Dominion University.
May 2002-present:	Senior Scientist, Thomas Jefferson National Accelerator Facility.
Jan 1986-May 2002:	Staff Scientist, Thomas Jefferson National Accelerator Facility.

c. (i) Five Publications Most Closely Related to Proposed Project (Total Journal Publications 30)

1. G. A. Krafft, “Spontaneous Radiation Emission from Short, High Field Strength Magnetic Devices,” Phys. Rev. ST-AB, 9, 010701 (2006)
2. G. A. Krafft, A. Doyuran, and J. B. Rosenzweig, “Pulsed-laser nonlinear Thomson scattering for general scattering geometries,” Phys. Rev. E 72, 056502 (2005)
3. G. A. Krafft, “Compact high-power terahertz radiation source,” Phys. Rev. ST-AB, 7, 060704 (2004)
4. G. A. Krafft, “Spectral Distributions of Thomson Scattered Photons from High-intensity Pulsed Lasers,” Phys. Rev. Lett, 92, 204802 (2004)
5. P. Piot, D. R. Douglas, and G. A. Krafft, “Longitudinal phase space manipulation in energy recovering linac-driven free electron lasers,” Phys. Rev. ST-AB, 6, 0030702 (2003)

c. (ii) Five Other Significant Publications

1. L. Merminga, D. R. Douglas, and G. A. Krafft, “High-Current Energy-Recovering Linacs”, Annual Reviews of Nuclear and Particle Science, **53**, 387-429 (2003)
2. C. W. Leemann, D. R. Douglas, and G. A. Krafft, “CEBAF at Jefferson Lab”, Annual Reviews of Nuclear and Particle Science, **51**, 413-450 (2001)
3. Donald H. Bilderback, I. V. Bazarov, K. Finkelstein, S. M. Gruner, H. S. Padamsee, C. K. Sinclair, Q. Shen, R. Talman, M. Tigner, G. A. Krafft, and L. Merminga, “Energy-recovery linac project at Cornell University”, *J.~Synchrotron Rad.*, **10**, 346 (2003)
4. G. R. Neil, *et al.*, “Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery,” Phys. Rev. Lett. 84, 662 (2000), Erratum 84, 5238 (2000)
5. D. X. Wang, G. A. Krafft, and C. K. Sinclair, “Measurement of Femtosecond Electron Bunches Using a RF Zero-phasing Method,” Phys. Rev. E 57, 2283 (1998)

d. Patents

"Method for the Production of Wideband THz Radiation," G. A. Krafft, U.S. Patent No. 7,315,141 B1, Jefferson Science Associates LLC, Jan. 1, 2008

"Intense and Compact TeraHertz Radiation Source," G. A. Krafft, U.S. Patent No. 6,753,662 B1, Thomas Jefferson National Accelerator Facility, Jun. 22, 2004.

"Application Accelerator System Having Bunch Length Control," D. X. Wang and G. A. Krafft, U.S. Patent No. 5,914,492, Thomas Jefferson National Accelerator Facility, June 22, 1999.

Synergistic Activities

e. Courses Taught Since 1993

Electromagnetic Theory (2009) Old Dominion University, Graduate Level

US Particle Accelerator School, "Recirculated and Energy Recovered Linacs", University of California, Santa Cruz, Santa Rosa, CA, Jan. 14-18 2008

Introduction to Accelerator Physics (2007) Old Dominion University, Advance Undergraduate/Graduate Level

Introduction to Accelerator Physics (2006), University of Virginia, Graduate Level

US Particle Accelerator School, "Recirculated and Energy Recovered Linacs", Cornell University, Ithaca, NY, June 27-July 1 2005

US Particle Accelerator School, "Fourth Generation Light Sources II: Energy Recovery Linacs and Thomson Sources", Louisiana State University, Baton Rouge, LA, Jan 13-17 2003

f. Recent Service Activities

- Program Committee, International Linear Accelerator Conference, TRIUMF, Victoria, BC, Canada 29 Sept.-3 Oct., 2008.
- American Physical Society, Fellowship Committee, Division of Physics of Beams, (2005-present).
- Department of Energy Small Business Innovation Research (SBIR) peer review panel, Superconducting RF Accelerators and Linear Accelerators (2000-present).
- National Science Foundation Small Business Innovation Research (SBIR) peer review panel, Accelerator Physics.
- Program Committee, Energy Recovery Linac Workshop 2005, Jefferson Lab, Newport News, VA, 19-23 March, 2005.

g. Recent Awards

- Fellow, American Physical Society, Division of Physics of Beams, 2002.

h. Collaborators & Co-editors & Other Affiliations

(i) Collaborators

- Prof. M. Havey, Old Dominion University
- Prof. B. Norem, University of Virginia, Charlottesville, VA
- Prof. S. Gruner, Prof. M. Tigner, and Dr. C. Sinclair, Cornell University, Ithaca, NY
- Prof. Kwang-Je Kim, University of Chicago, Chicago, IL
- Prof. J. Rosenzweig, University of California, Los Angeles, CA

(ii) Co-editors: none

(iii) PI's graduate and postdoctoral advisors: See Session A.

(iv) Summary of Students and Postdocs Directed: Postdoc: D. X. Wang, E. Price, J. Jackson, D. Kehne, R. Kazimi; Students: N. Sereno, P. Liger, P. Piot.

RUI LI
STAFF SCIENTIST
Center for Advanced Studies of Accelerators,
Jefferson Lab, Newport News, VA 23606

Education

B.S. in Physics, Beijing University, China, 1984
PhD in Physics, University of Maryland, 1990. Thesis: "Analytical and Numerical Investigation of the Longitudinal Coupling Impedance".

Professional Experience

1990-present – Staff Scientist, Jefferson Lab, Newport News, VA 23606.

Selected Publications:

R. Li, "Curvature-Induced Bunch Self-Interaction for an Energy-Chirped Bunch in Magnetic Bends", Phys. Rev. ST. Accel. Beams 11, 024401 (2008).
R. Li, Ya. S. Derbenev, "Discussion on the Cancellation Effect on a Circular Orbit", Proceedings of the 2005 Particle Accelerator Conference, Knoxville (2005).
R. Li, Ya. S. Derbenev, "Canonical Formulations and Cancellation Effect in Electrodynamics of Relativistic Beams on a Curved Trajectory", JLAB-TN-02-054 (2002).
R. Li, "Cancellation Effects in CSR Induced Transverse Dynamics in Bends", Proceedings of EPAC 2002, Paris (2002).
R. Li, "Sensitivity of the CSR Self-Interaction to the Local Longitudinal Charge Concentration of an Electron Bunch", Nucl. Instrum. Meth. Phys. Res. A475, 498 (2001).
R. Li, "Progress on the CSR Effects", The 2nd ICFA Advanced Accelerator Workshop on "The Physics of High Brightness Beams", Los Angeles (1999).
R. Li, "The Impact of Coherent Synchrotron Radiation on the Beam Transport of Short Bunch", Invited Talk on the 1999 Particle Accelerator Conference, New York (1999).
R. Li, "Self-Consistent Simulation of the CSR Effect", Nucl. Instrum. Meth. Phys. Res. A429, 310 (1998).
R. Li, C. L. Bohn, J. J. Bisognano, "Shielded Transient Self-Interaction of a Bunch Entering a Circle from a Straight Path", Proceedings of the 1997 SPIE Conference, San Diego (1997).
R. Li, C. L. Bohn, J. J. Bisognano, "Analysis on the Steady-State Coherent Synchrotron Radiation with Strong Shielding", Proceedings of the 1997 Particle Accelerator Conference, Vancouver (1997).
R. Li and J. J. Bisognano, "Strong-strong simulation on the beam-beam effect in a linac-ring B factory", Phys. Rev. E48, 3965 (1993).

Professional Organizations

2007 – 2008, member of the Doctoral Research Award Committee, Division of Physics of Beams, APS.

Synergistic Activities

Journal referee:
Outstanding Referee of Physical Review and Physical Review Letters (to be recognized in the 2010 APS March Meeting

FRANK MARHAUSER
STAFF SCIENTIST III
Institute of Superconducting Radio Frequency Science and Technology
Jefferson Lab, Newport News, VA 23606

Education

1996 Diploma granted in Physics May 1996, Johann Wolfgang-Goethe University of Frankfurt/Main, Germany, Diploma title, "Beam Dynamical Investigation of an RFQ-Injector for a Cyclotron", in German
1996-1999 Doctorate at the Institute for Applied Physics in Frankfurt/Main, Germany

2002 PhD granted in Physics, Disputation March 2009, Johann Wolfgang-Goethe University of Frankfurt/Main, Dissertation title: "Theoretical and Experimental Investigations of Trapped Modes in 9-cell TESLA Cavities", in German

Professional Experience
2007-present Physicist at the Thomas Jefferson National Accelerator Facility in Newport News, Virginia, USA (since 1st March 2007)
1999-2007 Physicist at the Berliner Elektronenspeicherring-Gesellschaft für Synchrotron-strahlung m.b.H. (BESSY) (now Helmholtz-Zentrum Berlin), Berlin, Germany (1st Dec. 1999 to 28th Feb. 2007)

Representative Publications
F. Marhauser, R.A. Rimmer, K. Tian, H. Wang, "Enhanced method for cavity impedance calculations" JLAB-ACC-09-982, May 4, 2009. 3pp. Presented at Particle Accelerator Conference (PAC 09), Vancouver, BC, Canada, 4-8 May 2009.

A. Arnold, H. Büttig, D. Janssen, U. Lehnert, P. Michel, K. Möller, P. Murcek, Ch. Schneider, R. Schurig, F. Staufenbiel, J. Teichert, R. Xiang, T. Kamps, D. Lipka, F. Marhauser, G. Klemz, I. Will, W.D. Lehmann, J. Stephan, V. Volkov, "A high-brightness SRF photo injector for FEL light sources", Published in Nucl.Instrum.Meth.A, 2008.

F. Marhauser, W. Clemens, G. Cheng, G. Ciovati, E.F. Daly, D. Forehand, J. Henry, P. Kneisel, S. Manning, R. Manus, R.A. Rimmer, C. Tennant, H. Wang, "Status and Test Results of High Current 5-Cell SRF Cavities Developed at JLAB", Proceedings of the European Accelerator Conference 2008, 23.-27.06.2008, Genoa, Italy.

F. Marhauser, M. Dirsat, A. Meseck, D. Richter, V. Dürr, E. Weihreter, G. Asova, J. Bähr, H.J. Grabosch, S. Khodyachykh, S. Korepanov, M. Krasilnikov, A. Oppelt, B. Petrosyan, L. Staykov, F. Stephan, F. Tonisch, O. Kalekin, J. Roensch, "A high average power RF-photoinjector gun cavity developed for the BESSY soft X-ray FEL", Proceedings of the 28th International Free Electron Laser Conference (FEL 2006), Berlin, Germany, 27 Aug - 1 Sep 2006, 560-563.

D. Janssen, F. Marhauser, V. Volkov, "High peak current design of a superconducting cavity for a SRF photoinjector", Proceedings of the 28th International Free Electron Laser Conference (FEL 2006), Berlin, Germany, 27 Aug - 1 Sep 2006, 571-574.

F. Marhauser, E. Weihreter, "First Tests of a High Power HOM-Damped 500MHz Cavity", Proceedings of the European Particle Accelerator Conference 2004, 05.07.-09.07.04, Lucerne, Switzerland.

D. Janssen, H. Buttig, P. Evtushenko, U. Lehnert, P. Michel, K. Moller, C. Schneider, J. Stephan, J. Teichert, S. Kruchkov, O. Myskin, A. Tribendis, V. Volkov, W. Sandner, I. Will, T. Quast, K. Goldammer, F. Marhauser, P. Yla-Oijala, "Superconducting RF guns for FELs", Proceedings of the 25th International Free

Electron Laser Conference (FEL 2003) and 10th FEL User Workshop, Tsukuba, Ibaraki, Japan, 8-12 Sep 2003. Published in Nucl.Instrum.Meth.A528:305-311, 2004.

F. Marhauser, E. Weihreter, D.M. Dykes, P. McIntosh, "HOM-Damped Cavity Design for 3rd Generation SR Sources", Proceedings of the Particle Accelerator Conference 2001, 18.06.-22.06.01, Chicago, Illinois, USA.

F. Marhauser, H.-W. Glock P. Hülsmann: "Search for Trapped Modes in TESLA Cavities", Proceedings of the Particle Accelerator Conference, 12.-16.05.1997, Vancouver, Canada.

A. Schempp, O. Engels, F. Marhauser .A VE-RFQ-Injector for a Cyclotron, Proceedings of the 16th IEEE Particle Accelerator Conference (PAC 95) and International Conference on High-energy Accelerators (IUPAP), Dallas, Texas, 1-5 May 1995, pp 914. May 1995.

Professional and Honorary Organizations

1997-2001 Scholarship holder of the German Research Foundation in the Research Training Group "Physics and Techniques of Accelerators"

Identification of Potential Conflicts of Interest or Bias in Selection of Reviewers

Recent Collaborators (past 48 months) Not Listed Above: Michael Cole, Alan Todd, Doug Holmes, John Rathke (Advanced Energy Systems, NY), Chet Nieter, David Smithe, Peter Stoltz (Tech-X Corporation, Boulder, CO), Ender Savrun (President, Sienna Technologies, Inc., Woodenville, WA)

ROBERT A. RIMMER
DIRECTOR
SRF Institute
Jefferson Lab, Newport News, VA 23606

Education

Ph.D. 1988, "High Power Microwave Window Failures in the Daresbury SRS."
B.Sc. 1985, Physical Electronic Engineering, Lancaster University, UK.

Professional Experience

2/06-present: Director of the Institute for Superconducting RF Science and Technology (ISRFST), Chief RF scientist, Jefferson Lab.
2002-2006 Deputy director ISRFST, with responsibility for cavity and cryomodule production. Chief RF scientist.
1988-2002: **Staff scientist** (physicist) at the Lawrence Berkeley National Laboratory, Accelerator and Fusion Research Division, Center for Beam Physics.

Responsibilities include design, simulation, fabrication and measurement of RF structures, beam impedance calculations and measurements, simulations, supervision of R&D, engineering and manufacture of cavities, cryomodules and components, safety coordination, teaching at USPAS.

Sample Publications:

"The JLab Ampere-class cryomodule", R.A. Rimmer et. al, proc 12^{th} SRF workshop, Cornell University, July 10-15 2005.
"Fabrication of the prototype 201.25 MHz Cavity for a muon ionization cooling experiment", R.A. Rimmer et. al, Proc. PAC 2005, Knoxville, TN.
"A High-Power L-Band RF Window", R.A. Rimmer et. al., Proc. PAC 2001, Chicago., LBNL-47968, LAUR 01-2574., CBP note 384.
"An RF Cavity for the NLC Damping Rings", R.A. Rimmer et. al., Proc. PAC 2001, Chicago. LBNL 47969, CBP note 385. http://www-library.lbl.gov/docs/LBNL/479/69/PDF/LBNL-47969.pdf
"Comparison of calculated, measured, and beam-sampled impedances of a higher-order-mode-damped RF cavity", R.A.Rimmer, J.M. Byrd, D. Li, Physical Review Special Topics -Accelerators and Beams, Vol. 3, 102001 (2000).
'High Power Microwave Window Failures', Ph.D.thesis, Lancaster University, October 1988. (Copies are available from the British Thesis Service at the British Library Document Supply Centre [address is British Library D.S.C., Boston Spa, Wetherby, West Yorks. LS23 7BQ]. Reference DX77343).

Professional and Honorary Organizations

Fellow of the American Physical Society.

Other Projects

SRS, ALS, PEP-II, LUX, LEDA (RF windows), NLC, Muon Collaboration/MICE, CEBAF, SNS, JLab FEL, JLab 12 GeV upgrade, ILC,

Appendix E

JLAMP Project Budget Pages

This appendix summarizes the cost estimate, and the basis for the estimate, for each designated WBS project area. Detailed cost information will be provided to DOE at the CD-1 Review of JLAMP.

DOE F 4620.1	**U.S. Department of Energy**	OMB Control No.
(04-93)	**Budget Page**	1910-1400
All Other Editions Are Obsolete	(See reverse for Instructions)	OMB Burden Disclosure
	JLAMP	Statement on Reverse

ORGANIZATION				Budget Page No: 1	
Thomas Jefferson National Accelerator Facility					
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR				Requested Duration: **58** (Months)	
George Neil					
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested by Applpicant	Funds Granted by DOE
1. **(See Appendix D)**					
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. ( ) TOTAL SENIOR PERSONNEL (1-6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
Senior Scientist/Engineer	**44**				
Scientist/Engineer	**810**				
Technician	**1052**				
Project Manager	**65**				
Clerical	**49**				
Machine Shop	**9**				
TOTAL SALARIES AND WAGES (A+B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				**$15,742,421**	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
Injector Components			**$3,841,200**		
Beam Transport System			**$7,499,654**		
DC Power System			**$1,251,760**		
Cryomodules			**$5,400,000**		
RF System Components			**$3,613,000**		
FEL System			**$10,892,885**		
Cryogenics			**$8,910,000**		
Controls, Timing & Synchronizaton			**$423,250**		
Diagnostics and Safety Systems			**$1,672,500**		
Conventional Facilities			**$3,881,500**		
Experimental Equipment			**$3,670,000**		
Project Team Equipment			**$255,000**		
TOTAL PERMANENT EQUIPMENT				**$51,310,749**	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					
2. FOREIGN					
TOTAL TRAVEL				**$0**	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST				**$0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**$420,000**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				**$420,000**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**$67,473,170**	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
G&A: ~12% for labor and first $50K of procurement					
TOTAL INDIRECT COSTS				**$2,746,972**	
J. TOTAL DIRECT AND INDIRECT COSTS					
1. TOTAL DIRECT AND INDIREECT COSTS (H+I)				**$70,220,142**	
2. ESCALATION				**$5,941,158**	
3. PROJECT CONTINGENCY				**$19,430,011**	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				**$95,591,311**	

JLAMP Project Area: Physics Design		
Control Account Manager: David Douglas		
WBS Dictionary	This WBS element includes the engineering and design effort for lattice design, magnet and cavity sensitivity study, machine modeling, magnet design and specification, machine layout and magnet power supply tolerances.	
Basis of Estimate	The estimate for this engineering and design effort is based on experience gained from the original CEBAF project, the 1994-5 IR/UV system design, the IR Demo Design, the IR Upgrade Design, and our participation in the Innovative Naval Prototype. Labor types required to accomplish this work scope include mechanical/electrical/software engineers and collective effects/design physicists. Level of effort and complexity was assumed to be similar to IR plus UV Upgrades, labor costs have been updated to reflect current salary scales.	
Project Personnel	**Person-Days**	**Salaries, Wages & Fringe Benefits**
Senior Scientist/Engineer	550	
Scientist/Engineer	2295	
Technician	330	
Total Salaries, Wages & Fringe Benefits		**$1,793,808**
Project Equipment		**Equipment Costs**
Total Equipment Costs		**$0**
Travel		
Domestic		
Foreign		
Total Travel		**$0**
Other Direct Costs		**$0**
Total Direct Costs		**$1,793,808**
Indirect Costs		**$215,257**
Project Area Total		**$2,009,065**

JLAMP Project Area: Injector		
Control Account Manager: Carlos Hernandez-Garcia		
WBS Dictionary	This WBS element includes the physics and engineering, design, fabrication, and installation of the Injector system comprising the initial production of the electron beam to where it joins the linac with an energy of approximately 10 MeV. The physics design will set the cryounit (or booster) and the merger technical requirements, and the injector beamline layout. The engineering design of the booster, the merger and the rest of the injector beamline layout follows. The fabrication and installation scope includes the VHF photocathode gun with its load-lock chamber, the cryounit, the merger and other injector components such as drive laser, buncher cavity, solenoids and transport magnets, and associated RF systems.	
Basis of Estimate	The estimate for the Project Engineering and Design labor effort is derived by taking the man-days devoted to the physics model of the present FEL injector and scaling up using the LCLS injector as a guideline. The labor estimate for the engineering design and fabrication of the cryounit is based on prior SRF experience of similar systems. The merger and the rest of the injector engineering design estimate are based on prior experience with the FEL injector and other beamline components for the IR Upgrade FEL. The fabrication manpower estimate for the VHF gun and its associated RF systems procurement come directly from the LBNL Light Source group that is currently building it. The fabrication and installation cost estimates for the VHF gun stand and bakeout system as well as the injector magnets and diagnostics are based on recent experience with the Gun Test Stand Photocathode gun and associated beamline, completed and commissioned in the Spring of 2008. The overall injector parts count is taken from the existing FEL injector layout. The cost of RF systems associated with the seed laser is based on the 12 GeV upgrade low level RF control with an allowance for modifying the system so that in can be adapted to the drive laser. There has been a substantial allowance for firmware development for the drive laser controls as well as a moderate allowance for designing new or adapting existing optical sensors to the level of phase stability necessary to meet the machine requirements. The buncher cavity and buncher RF system design and fabrication costs are based on building similar cavity systems for CEBAF and the existing FEL.	
Project Personnel	**Person-Days**	**Salaries, Wages & Fringe Benefits**
Senior Scientist/Engineer	77	
Scientist/Engineer	2117	
Technician	1581	
Total Salaries, Wages & Fringe Benefits		**$1,712,655**
Project Equipment		**Equipment Costs**
Photo-Cathode Gun		$848,000
Injector Components		$1,356,600
Load-Lock		$135,000
Drive Laser		$338,600
RF Systems		$1,163,000
Total Equipment Costs		**$3,841,200**

Travel		
Domestic		
Foreign		
Total Travel		**$0**
Other Direct Costs		**$0**
Total Direct Costs		**$5,553,855**
Indirect Costs		**$335,863**
Project Area Total		**$5,889,718**

JLAMP Project Area: Beam Transport		
Control Account Manager: George Biallas		
WBS Dictionary	This WBS element includes the engineering, design, fabrication, and installation of the Beam Transport system. Scope includes Dipoles, Quadrupoles, Trim Dipoles, Support Stands with girders and Vacuum Chambers, Pipes, Valves and Pumps. This does not include power supplies and controls.	
Basis of Estimate	The magnet procurement estimates are based on the following procurements, modified for inflation and scaled for approximate size and complexity. Since no complete transport lattice has yet been designed we utilized an assumed sample lattice structure: 11 standard and 2 half Dipoles in each arc scaled in cost from GW Procurement 05-C0344; 35 each, 4 inch Quad/Sextupoles from SF Sextupole Procurement 05-C0128; and 10 each of QB Quadrupole from QP/QR PO 09-C1433. Procurements of Stands, Girders and Chambers is by reference to procurements for the IR Upgrade with engineering judgment increases due to increased stand complexity. Vacuum valves and pumps are from recent vendor quotations with counts based on an assumed lattice structure. Design and construction monitoring, measurement, assembly and installation hours are by comparison to UV Upgrade experience in FY09.	
Project Personnel	**Person-Days**	**Salaries, Wages & Fringe Benefits**
Senior Scientist/Engineer	0	
Scientist/Engineer	1495	
Technician	2235	
Total Salaries, Wages & Fringe Benefits		**$1,534,194**
Project Equipment		**Equipment Costs**
Dipoles		$1,509,684
Quadrupoles		$630,000
Higher Order Multipoles		$2,210,000
Trims		$175,000
Stands and Girders		$1,317,000
Vacuum		$1,657,970
Total Equipment Costs		**$7,499,654**
Travel		
Domestic		
Foreign		
Total Travel		**$0**
Other Direct Costs		**$0**
Total Direct Costs		**$9,033,848**
Indirect Costs		**$335,305**
Project Area Total		**$9,369,153**

JLAMP Project Area: DC Power		
Control Account Manager: Tom Powers		
WBS Dictionary	This WBS element includes the engineering, design, fabrication, and installation of the DC Power systems. Scope includes 4 Dipole Magnet Strings, Shunt Hardware for 6 dipole magnets, 310 Trim Power Supplies, and Misc Magnet Hardware used for interlocking the system and interfacing it to the control system.	
Basis of Estimate	The bulk of the estimate are extrapolations on the 12 GeV upgrade installations with adjustments for the different current requirements for the trim and dipole power supplies which are based on the lower beam energies. The number of magnets is based on the same assumed lattice design used for the magnet count. All personnel effort charged to this project will be for services specific to the project and is based on known past job practices and procedures.	
Project Personnel	**Person-Days**	**Salaries, Wages & Fringe Benefits**
Senior Scientist/Engineer	0	
Scientist/Engineer	762	
Technician	1174	
Machine Shop	68	
Total Salaries, Wages & Fringe Benefits		**$826,164**
Project Equipment		**Equipment Costs**
Dipole Magnet Strings		$234,600
Shunt Hardware		$27,660
Trim Power Supplies		$969,800
Misc Magnet Hardware		$19,700
Total Equipment Costs		**$1,251,760**
Travel		
Domestic		
Foreign		
Total Travel		**$0**
Other Direct Costs		**$0**
Total Direct Costs		**$2,077,924**
Indirect Costs		**$139,131**
Project Area Total		**$2,217,055**

JLAMP Project Area: Cryomodules		
Control Account Manager: Bob Rimmer		
WBS Dictionary	This WBS element includes the procurement, fabrication, assembly, installation and commissioning of three linac cryomodules. A cryomodule includes all cavities, power couplers, cryostat components, and instrumentation contained from beamline valve to beamline valve in the assembly delivered to the accelerator.	
Basis of Estimate	This estimate is based on the current 12 GeV project C100 cryomodule cost book with minimal modifications. Procurements are scaled (increased 30%) to account for the smaller quantities while the labor and expense estimates are retained. It is assumed that no significant design modifications will be required.	
Project Personnel	**Person-Days**	**Salaries, Wages & Fringe Benefits**
Senior Scientist/Engineer	0	
Scientist/Engineer	440	
Technician	2900	
Total Salaries, Wages & Fringe Benefits		**$1,195,051**
Project Equipment		**Equipment Costs**
Linac Cryomodule Procurement		$5,400,000
Total Equipment Costs		**$5,400,000**
Travel		
Domestic		
Foreign		
Total Travel		**$0**
Other Direct Costs		
Expenses		$300,000
Installation & Commissioning		$120,000
Total Other Direct Costs		**$420,000**
Total Direct Costs		**$7,015,051**
Indirect Costs		**$161,406**
Project Area Total		**$7,176,457**

JLAMP Project Area: RF Systems		
Control Account Manager: Tom Powers		
WBS Dictionary	This WBS element includes the engineering, design, fabrication, and installation of the RF Systems. Scope includes, upgrading 6 high power amplifier assemblies —3 for the linac and 3 for the injector with new interlock interfaces necessary to support the new LLRF systems. It includes replacement of 27 Low Level RF systems with modern digital systems which will provide an order of magnitude better performance with respect to phase stability. The WBS also includes the replacement of the existing master oscillator system with a fiber based system which has been demonstrated to provide the phase stability necessary for a seeded FEL Amplifier.	
Basis of Estimate	It is assumed that the existing RF amplifiers are sufficient to power the C100 modules at the required gradient. The estimates for the HPA interlock upgrade and LLRF systems are based on the procurement and installation costs for the 12 GeV upgrade. The cost estimates for the fiber optic based master oscillator distribution system are based on costs incurred with a similar system that was designed by Lawrence Berkley Laboratory for use at LCLS at SLAC. The estimates include the NRE necessary to adapt that design to the JLAMP frequencies as well as to support the technology transfer between the three facilities.	
Project Personnel	**Person-Days**	**Salaries, Wages & Fringe Benefits**
Senior Scientist/Engineer	59	
Scientist/Engineer	704	
Technician	854	
Machine Shop	93	
Total Salaries, Wages & Fringe Benefits		**$751,373**
Project Equipment		**Equipment Costs**
Machine Synch System		$50,000
LLRF		$1,067,600
HPA		$2,495,400
Total Equipment Costs		**$3,613,000**
Travel		
Domestic		
Foreign		
Total Travel		**$0**
Other Direct Costs		**$0**
Total Direct Costs		**$ 4,364,373**
Indirect Costs		**$185,085**
Project Area Total		**$ 4,549,458**

JLAMP Project Area: FEL	
Control Account Managers: Michelle Shinn / Steve Benson / Mike Klopf	
WBS Dictionary	This WBS element includes the engineering, design, fabrication and installation of the major FEL systems. Scope includes the Seed Laser and Input Optical Transport, Soft X-ray Optical Cavity, Undulator, THz Undulator, and Optical Transport.
Basis of Estimate	**Seed Laser and Input Optical Transport** The seeding system (laser and HHG) cost is based on budgetary estimates from the vendor (KM Labs) comprising systems the vendor currently produces, slightly scaled up for power. The JLab-produced conceptual design for the optical transport was developed in 2007 for the National High Magnetic Field Laboratory FEL proposal to the NSF and then updated in 2008. Transport mirrors and opto-mechanics such as mirror holders, bases, posts, etc. as well as the fast-steering mirrors and position sensitive detector are all catalog parts. **Soft X-ray Optical Cavity** For the soft x-ray (100 eV) oscillator, pricing for items we will duplicate, like the ultraviewers to align the optical cavity, is based on quotes from the JLab machine shop. These once again were generated for the FSU proposal and updated in 2008. The mirror substrates and coating price are based on vendor quotations, while the cost for the vacuum vessels and internals are estimated from the turning mirror cassettes built for our IR Upgrade FEL optical transport, scaled down as the optics are far smaller and only one mirror set will be deployed at the outset. **Undulators** The undulator cost estimates are derived from ROMs (dated 11/25/2009) from STI Optronics. The modulator undulator is a nearly off-the-shelf device. For the radiator undulator the prototype 2 meter Delta undulator cost was reduced by 20% with the understanding that cost efficiencies and designs will come out of ongoing work at Cornell and Daresbury with that new design. The rest of the wiggler is a fairly standard in-vacuum hybrid with several international vendors available. The THz wiggler is similar in scope to the IR Upgrade optical klystron design scaled by length and costs incremented for inflation. **Optical Transport** The THz beamline costing for parts and labor is based on a detailed design utilizing primarily catalog parts costs presented in the National High Magnetic Field Laboratory FEL proposal to the NSF, in addition to our experience with the design and construction of the existing THz beamline in the JLab FEL. Parts of the VUV (<30 eV) beamline will be similar to existing IR and UV beamlines on which we base our estimate. For certain optical elements and instrumentation that will be different for the higher energy photons we base our estimates on comparable beamlines operating at other light sources (NSLS, ALS, SRC, FLASH, etc.) and detailed discussions with their respective beamline managers and users. We have also received quotations from vendors of beamline instrumentation (Advanced Design Consulting, McPherson) to further refine our estimates. Both the vendors and the beamline managers were consulted for the estimation of the integration and installation costs.

	For the soft x-ray (100 eV) beamline, our estimates are based on comparable beamlines operating at other light sources (FLASH, NSLS, ALS, etc.) and detailed discussions with their respective beamline managers and users. We have also received quotations from vendors of beamline systems and instrumentation (Advanced Design Consulting, McPherson). Both the vendors and the beamline managers were consulted for the estimation of the integration and installation costs.	
Project Personnel	**Person-Days**	**Salaries, Wages & Fringe Benefits**
Senior Scientist/Engineer	116	
Scientist/Engineer	2334	
Technician	2874	
Total Salaries, Wages & Fringe Benefits		**$2,289,638**
Project Equipment		**Equipment Costs**
Seed Laser & Input Optical Transport		$1,290,000
Undulator		$6,176,000
THz Undulator		$500,000
Optical Transport		$2,926,885
Total Equipment Costs		**$10,892,885**
Travel		
Domestic		
Foreign		
Total Travel		**$0**
Other Direct Costs		**$0**
Total Direct Costs		**$13,182,523**
Indirect Costs		**$397,671**
Project Area Total		**$13,580,194**

JLAMP Project Area: Cryogenics		
Control Account Manager: Dana Arenius		
WBS Dictionary	This WBS element includes the engineering, design, fabrication, and installation of associated cryogen transfer lines and instrumentation and controls. It also includes supplementary work to reduce the overall load on the Central Helium Liquefier to free sufficient capacity to support JLAMP. It does not include any associated conventional facilities and utilities to support such installation.	
Basis of Estimate	This estimate is based on engineering judgment, prior experience, data from existing designs, and recent vendor quotes/scaling associated with the CEBAF 12 GeV Upgrade. The major equipment includes four C100 modules for reduced losses and a cryogen distribution system extending the capability of existing designs.	
Project Personnel	**Person-Days**	**Salaries, Wages & Fringe Benefits**
Senior Scientist/Engineer		
Scientist/Engineer	727	
Technician	4966	
Total Salaries, Wages & Fringe Benefits		**$2,032,385**
Project Equipment		**Equipment Costs**
Cryogenic Capacity Enhancement Units		$7,760,000
Compressor Spare		$700,000
Cryogen Transfer Line		$450,000
Total Equipment Costs		**$8,910,000**
Travel		
Domestic		
Foreign		
Total Travel		**$0**
Other Direct Costs		**$0**
Total Direct Costs		**$10,942,385**
Indirect Costs		**$261,886**
Project Area Total		**$11,204,271**

JLAMP Project Area: Controls, Timing & Synchronization		
Control Account Manager: Kevin Jordan		
WBS Dictionary	This WBS element includes the engineering, design, fabrication, and installation of the Controls and Timing & Synchronization systems. Effort includes development of IOCs and associated software and procurement of a drive laser pulse control system. The IOC additions listed in the cost estimate will partially be a distributed system.	
Basis of Estimate	This estimate is based on cost and effort for the IR Demo FEL & the Upgrade projects. The use of distributed processors, including advances in PLC technology, will migrate a number of electronic systems out of expensive MVE crates to a distributed, TCP/IP based system. The timing & synchronization system was modeled after proven designs and operational systems (LBNL & LCLS).	
Project Personnel	**Person-Days**	**Salaries, Wages & Fringe Benefits**
Senior Scientist/Engineer	0	
Scientist/Engineer	1346	
Technician	700	
Total Salaries, Wages & Fringe Benefits		**$946,146**
Project Equipment		**Equipment Costs**
Controls		$373,250
Timing & Synchronization		$50,000
Total Equipment Costs		**$423,250**
Travel		
Domestic		
Foreign		
Total Travel		**$0**
Other Direct Costs		**$0**
Total Direct Costs		**$1,369,396**
Indirect Costs		**$152,028**
Project Area Total		**$1,521,424**

JLAMP Project Area: Diagnostics & Safety Systems		
Control Account Manager: Kevin Jordan		
WBS Dictionary	This WBS element includes the design, fabrication, and installation of the electron beam diagnostics and safety systems. This includes all systems required to monitor and control electron beam parameters in the linear accelerator. It also includes all devices required to ensure personnel and machine protection.	
Basis of Estimate	Diagnostics counts are based on the same sample lattice assumed for the magnet and power supply costing. A 2" beamline was assumed. Diagnostic designs (beam viewers and beam position monitors) are copied from the present JLab FEL systems in most places. Timing systems are assumed to be updated to deal with the tighter JLAMP tolerances in this regard.	
Project Personnel	**Person-Days**	**Salaries, Wages & Fringe Benefits**
Senior Scientist/Engineer	0	
Scientist/Engineer	474	
Technician	76	
Total Salaries, Wages & Fringe Benefits		**$276,649**
Project Equipment		**Equipment Costs**
Beam Diagnostics		$1,622,500
Machine Protection System		$50,000
Total Equipment Costs		**$1,672,500**
Travel		
Domestic		
Foreign		
Total Travel		**$0**
Other Direct Costs		**$0**
Total Direct Costs		**$1,949,149**
Indirect Costs		**$111,618**
Project Area Total		**$2,060,767**

JLAMP Project Area: Conventional Facilities		
Control Account Manager: Rusty Sprouse		
WBS Dictionary	This WBS element includes the design and construction of an x-ray user lab to be used in conjunction with the FEL. Scope includes design and construction of improvements to the electrical distribution system to support JLAMP.	
Basis of Estimate	Estimate is based on similar items priced under other current lab projects such as 12 GeV (North and South Access Additions and utilities, CHL Addition) and Test Lab Cooling Tower replacements. Some of these contracts have already been awarded and are currently under construction. Estimate is based on recent construction projects at JLab. The user lab is assumed to be 2400SF at $500/SF. Power requirements were scaled from RF supply, and magnet draws. A substation and electrical distribution to support these are included.	
Project Personnel	**Person-Days**	**Salaries, Wages & Fringe Benefits**
Senior Scientist/Engineer	0	
Scientist/Engineer	130	
Technician	45	
Project Manager	315	
Clerical	20	
Total Salaries, Wages & Fringe Benefits		**$227,177**
Project Equipment		**Equipment Costs**
Soft X-ray Experimental Hall		$3,881,500
Total Equipment Costs		**$3,881,500**
Travel		
Domestic		
Foreign		
Total Travel		**$0**
Other Direct Costs		**$0**
Total Direct Costs		**$4,108,677**
Indirect Costs		**$147,861**
Project Area Total		**$4,256,538**

JLAMP Project Area: Experimental Equipment		
Control Account Manager: Gwyn Williams		
WBS Dictionary	This WBS element includes procurement of the AMO endstation for the 100 eV beamline and the ARPES end station for the 30 eV beamine. Included are the design, engineering, and installation costs plus the associated labor.	
Basis of Estimate	The costing for the instrumentation and end station chambers was determined through consultation with users who have designed, tested, and installed similar end stations. In the case of the ARPES end station on the 30 eV beamline, the estimation is based primarily on the cost of existing systems already in use at BNL and consultation with the instrument manufacturers. The cost estimation for the AMO end station on the 100 eV is somewhat more challenging due to the relative lack of similar existing systems. Nonetheless, our cost basis is derived from direct discussions with AMO users, and the cost for the AMO end station that is installed at the LCLS.	
Project Personnel	**Person-Days**	**Salaries, Wages & Fringe Benefits**
Senior Scientist/Engineer	0	
Scientist/Engineer	256	
Technician	660	
Total Salaries, Wages & Fringe Benefits		**$354,659**
Project Equipment		**Equipment Costs**
AMO Station		$3,000,000
30eV ARPES		$670,000
Total Equipment Costs		**$3,670,000**
Travel		
Domestic		
Foreign		
Total Travel		**$0**
Other Direct Costs		**$0**
Total Direct Costs		**$4,024,659**
Indirect Costs		**$80,959**
Project Area Total		**$4,105,618**

JLAMP Project Area: Project Management & Control		
Control Account Manager: George Neil		
WBS Dictionary	This WBS element includes the labor for project management and administration, office supplies/computer systems procurements.	
Basis of Estimate	Labor based on 0.5 FTE Management effort with supporting administrator during PED and full time manager during construction. Estimate based on prior experience and JLab FY10 labor rates. This management is supplemented by JLAB project control personnel for financial and milestone tracking.	
Project Personnel	**Person-Days**	**Salaries, Wages & Fringe Benefits**
Senior Scientist/Engineer	0	
Scientist/Engineer	0	
Technician	0	
Project Manager	880	
Clerical	880	
Total Salaries, Wages & Fringe Benefits		**$577,069**
Project Equipment		**Equipment Costs**
Project Team Office Supplies		$250,000
Computer Systems		$5,000
Total Equipment Costs		**$255,000**
Travel		
Domestic		
Foreign		
Total Travel		**$0**
Other Direct Costs		**$0**
Total Direct Costs		**$832,069**
Indirect Costs		**$75,848**
Project Area Total		**$907,917**

JLAMP Project Area: Commissioning		
Control Account Manager: George Neil		
WBS Dictionary	This WBS element includes the labor for the system commissioning.	
Basis of Estimate	Labor based on one full time manager and 0.5 FTE technician during system commissioning. Estimate based on prior experience and JLab FY10 labor rates.	
Project Personnel	**Person-Days**	**Salaries, Wages & Fringe Benefits**
Senior Scientist/Engineer	0	
Scientist/Engineer	1760	
Technician	880	
Total Salaries, Wages & Fringe Benefits		**$1,225,453**
Project Equipment		**Equipment Costs**
Total Equipment Costs		**$0**
Travel		
Domestic		
Foreign		
Total Travel		**$0**
Other Direct Costs		**$0**
Total Direct Costs		**$1,225,453**
Indirect Costs		**$147,054**
Project Area Total		**$1,372,507**