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IR/UV FEL Upgrade Project Accelerator Physics Plan

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Keeper: D. Douglas, x7512, douglas@jlab.org

The IR/UV FEL Upgrade Project presents unique opportunities for accelerator physics development at Jefferson Lab. Several accelerator systems, including source, injector, cryomodules, and beam transport, will require performance enhancements to meet Upgrade design performance goals. These challenging specifications must be achieved in the presence of a variety of fundamental physical effects, such as the FEL/RF interaction and collective effects – space charge, BBU, CSR, and other wakefield/impedance-related phenomena – while providing system operability commensurate with that needed for a user facility. Once completed, the system will further serve as a test-bed for ongoing research on topics such as Thomson scattering x-ray production and FEL dynamics.

The following provides a summary discussion of each of these issues and presents manpower estimates for the accelerator theory, design, and experimental support component of ongoing IR Demo operations and the Upgrade. This planning is based on experience gained during the UV Industrial Demo Design Study [1], IR Demo design, construction and commissioning [2], and draws freely on a summary of IR Demo accelerator physics opportunities presented at a recent institutional review [3].

Physical Phenomena

The IR/UV upgrade will be subject to the same physical issues as the IR Demo, *viz.*, all the effects associated with high current beams used to drive an FEL in an SRF environment. These include potential instabilities in the FEL/RF system and numerous collective effects.

FEL/RF Interaction

The coupling of energy losses in an energy-recovering FEL to its RF drive system *via* recirculator momentum compaction can lead to performance-limiting instabilities. The existence of this instability, predicted at LANL, has been demonstrated in the IR Demo; it is well controlled by the accelerator RF feedback system [4]. Extension of machine performance to 10 kW IR Upgrade levels will require certification of the RF system and accelerator design. A model of the effect has been developed, but requires experimental benchmarking.

Collective Effects

Generation, acceleration, and transport of high current beams introduces numerous opportunities for the manifestation of collective effects. These include space charge phenomena, beam break-up (BBU), coherent synchrotron radiation (CSR) and other impedance/wakefield-related effects, such as the coupling of beam electromagnetic fields to their environment in the accelerator vacuum system. Many of these issues are presently under investigation as a part of IR Demo machine operation; they all represent issues that may prove limiting to the performance of the IR/UV Upgrade.

Space Charge – Though present system performance is demonstrably adequate for 1 kW IR FEL operation, the dynamics of the IR Demo electron source and injector are not at present well characterized either theoretically or experimentally. A major factor in this ambiguity is lack of detailed understanding of space charge effects from the cathode forward through the machine to injection (at 10 MeV) into the cryomodule. IR Upgrade operation will require a factor of two higher charge per bunch than presently normally provided with phase space performance similar to that presently available; UV operation will require the higher charge in a smaller phase space [5]. To ensure these performance goals are met, we must improve the consistency of hardware characteristics, simulations, and experimental results in the IR Demo and carefully extrapolate this understanding into the IR/UV Upgrade parameter regime. The same methodology is applicable to the next generation CEBAF polarized source; FEL upgrade work may thus be leveraged to provide technologies of benefit to the Jefferson Lab nuclear physics program.

BBU [6] – Higher order modes (HOMs) are a stability and cryogenic concern for all SRF applications. They couple beam power and cavity fields in a manner that can lead to performance limiting instabilities in single and multipass accelerators. Ongoing experiments at the IR Demo have allowed unprecedented measurements of HOM structure and damping performance of couplers; data obtained through these measurements will serve as fiducials for benchmarking the simulation code TDBBU. This in turn will allow confident extrapolation of machine performance into the higher current regime needed for the 10 kW IR Upgrade, and will support HOM design and development for Jefferson Lab cryomodules based on 7-cell cavities to be used in both the FEL and nuclear physics programs.

CSR – As beam brightness has increased (and associated bunch lengths have decreased to levels commensurate with the wavelength of emitted synchrotron radiation), beam quality degradation through CSR has become a topic of considerable interest. The IR Demo lives in a parameter range of interest for this phenomenon; CSR is a potentially serious and poorly understood effect that might have adversely affected system performance and thus drove the machine geometry [7]. Higher bunch charge and pre-existing significant geometric constraints (the wiggler must be in the machine backleg to accommodate the optical cavity within the existing vault) make this effect a concern in the IR/UV Upgrade. A state of the art simulation of this effect has been developed and is being applied to various systems [8]. Experiments at the IR Demo must be used to benchmark the computational approach and provide confidence that the more aggressive IR/UV Upgrade performance parameters and geometry will provide adequate beam quality at the wiggler.

Other Impedance/Wakefield Related Effects – Various other impedance and wakefield related effects have been observed in the IR Demo. There is some evidence that the beam couples to the impedance of the matching horn downstream of the wiggler vacuum chamber, with resulting changes in beam quality [9]. Initial operation of the machine at high currents encountered apparent cavity window heating that later proved to be due to HOM power deposition on the wave guide IR detectors [10]. Throughout the IR Demo design process, effort was made to control the beam environment upstream of the wiggler (through the use of shielded beam line components) so as to avoid beam quality degradation.

These experiences suggest appropriate attention be paid to this class of effect during the IR/UV Upgrade design, construction and commissioning. In particular, impedance policing and careful analysis of beam line components upstream of the wiggler will be needed to ensure performance goals are met.

Source

Source performance in the IR Demo has steadily and dramatically improved throughout the commissioning process, with cathode lifetimes well in excess of 1 kC, machine operation at 100 pC/bunch, and gun availability at very high levels [11]. However, gun voltage has declined from 350 to 320 kV and, as noted above, beam performance has not been carefully characterized at either normal (60 pC) or elevated bunch charges. Cathode change-out is still a protracted process with some delicacy required in the post-change-out HV processing and operation of the gun. Detailed study and analysis of the dynamics and operation of the present system is therefore needed to appropriately guide gun improvements planned as a part of the IR/UV Upgrade Project.

Injector

As noted above, understanding of the injector is incomplete. This is not limited to space charge phenomena, but extends to various operational features. These include

- cavity calibration and phasing,
- the sensitivity of phase space performance to gun voltage and steering through SRF components (important, for example, for moving the drive laser spot on the cathode), and
- ambiguity as to why certain system diagnostics (the multi-slit and Happek device upstream of the cryomodule) do not register beam.

Improved injector performance will be required to meet IR/UV Upgrade design goals; better injector operability may be need to insure FEL system availability consistent with that needed for a user facility when operating at higher performance levels.

Cryomodule Development

Ongoing BBU studies on the IR Demo have provided and will continue to provide valuable information about the HOM structure of standard 5-cell CEBAF cavities and cryomodules. The derived knowledge will enable confident extrapolation of IR Demo performance to levels required from the first two IR Upgrade modules [12]. This includes development and testing of HOM loads for ~1000 times higher power dissipation than that originally envisioned for CEBAF. The third IR/UV Upgrade module is presently expected to be a 7-cell module [13], the design of which will also benefit from ongoing BBU studies. In addition, IR Demo accelerator physics efforts and the IR/UV Upgrade design study will provide direct input to the design of the RF control module for the 7-cell cavity system [14].

Beam Transport

Beam transport in energy-recovering FELs involves a sequence of transverse and longitudinal matches to provide proper beam behavior at the wiggler and ensure beam confinement through the energy recovery process [15]. Successful operation of the IR Demo has given considerable information on the details of this process [16], but also indicates that even greater challenges will exist in the design, construction, and operation of the IR Upgrade. This is due to both the larger required momentum acceptance (10%, a consequence of higher FEL extraction efficiency) and reduced symmetry in the machine geometry (the optical cavity must reside in the machine backleg to fit in the vault). In addition, existing design tools (most are perturbative – a weak approximation for 10% momentum spreads – and none have details of new 7-cell cavity dynamics) do not directly address the problems that will be encountered. Development of new tools, or at least new features for old tools, will therefore be required.

Operability

Improvements in system operability will be an ongoing theme for the IR Demo facility. Machine studies, procedure development and accelerator improvement processes must be supported. Lessons learned from these activities will be applied to the IR/UV upgrade. Ongoing accelerator physics resources will be required for this task.

Further Opportunities

Continued operation of the IR Demo and initiation of Upgrade operations will provide significant opportunities for other accelerator physics research. Examples of programs presently in progress, which will require further support, include the Thomson x-ray scattering program [17] and studies of FEL dynamics [18]. These may evolve, respectively, to provide a local source of ultra-short x-ray pulses and a means of continuing studies of FEL technologies such as scaleable optical cavities and harmonic lasing.

Manpower Estimates

Comparison of the above accelerator physics program to those executed during the UV Industrial Demo study and IR Demo design, construction, and commissioning shows that the scope of work is similar in all three projects. This in turn indicates staffing requirements will be similar in all three cases. In the two previous projects, six to seven accelerator physicists (Ph.D s or Ph.D-equivalents) were occupied full time in the execution of the program for the duration of the project. The IR/UV Upgrade may therefore be expected to require some 20 to 25 man-years of accelerator physics work, or 7 to 8 FTE equivalents for the 3 year duration of the construction project, with similar staffing needs for commissioning and subsequent operations.

Anticipated task assignments and likely staffing roles are presented in Tables 1 and 2, which, respectively, summarize the accelerator physics issues to be addressed (and status thereof at the time of this note) and detail the staffing required to execute the program of studies.

Table 1: IR/UV Upgrade Project Accelerator Physics Task List

Issue	*Task*	*Comments/Status*
Source	Charge/Bunch	100 pC achieved in operation, 135 pC required
	Lifetime	kiloCoulomb lifetime demonstrated
	Beam Quality	Adequate at 60 pC; need to certify at 135 pC; further work needed before UV possible
	Gun Voltage	Below nominal; requirement review appropriate; improvement may be needed/can be provided
	Reliability/Availability	Dramatically improved; further improvement likely
Injector	Calibration	Need further hardware calibration, diagnostic work
	Simulation	Need to benchmark, improve prediction ability
	Performance	Beam quality adequate for 1 kW tests; higher current needs certification for 10 kW IR; improvement needed for UV
	Operability	Adequate for 1 kW tests; improving but not fully understood; further work needed to serve as facility source
Driver	Linac – linear optics	Concept complete; Need modeling for 7-cell cavity
	Linac – skew quad	Need compensation scheme
	Recirculator – Transport to wiggler	Need conceptual, engineering designs, CSR analysis, error analysis, component specifications
	Recirculator – energy recovery transport	Large momentum acceptance an issue; need conceptual, engineering designs, error analysis, component specifications; need longitudinal matching scheme for energy compression/recovery (octupole order)
Systemic issues	BBU/HOM	Continue IR Demo experiments; Benchmark TDBBU Simulations for upgrade
	CSR	Benchmark model (IR Demo, other systems); Apply to IR/UV Upgrade
	FEL/RF interaction	Continue IR Demo experiments to benchmark model; extrapolate to IR/UV Upgrade
	Operations Planning/Support	IR Demo ops support – debugging, performance improvement, shift support, etc.
	Upgrade Commissioning Planning/Support	Upgrade commissioning support – modeling, analysis, procedures, shift support

Table 2: IR/UV Upgrade Project Accelerator Physics Staffing Requirements

Position	*Commitment*	*Description*
Source physics	Full	Source/Injector design, development, operation
Beam transport	Full	Accelerator design and operation
System integration	Full	Accelerator system implementation and operation
Simulation, electromagnetic effects	Full	Beam dynamics/electromagnetic modeling (PARMELA, TTBBU, MAFIA, POISSON, etc); impedance policing
Theory – beam dynamics	Full	Beam dynamics, RF effects, FEL/RF interaction, RF controls
Theory – general	Full	Wakefield effects, CSR, nonlinear effects
Experimental – machine studies support	Full	Machine operations/design interface; experimental support and studies
Diagnostic systems	Half	Diagnostic development and implementation

Schedule and Budget

Accelerator physics schedule and budget are presently under development and will be addressed in separate documentation.

Plan Update Access

This plan will be periodically updated (note revision number and date). Revisions and other information will be posted at:

http://www.jlab.org/~douglas/FELupgrade/masterindex.html

Notes and References

[1] Laser Processing Consortium, “Free Electron Lasers for Industry, Volume 2: UV Demo Conceptual Design”, May 1995.

[2] See, for example, G. Neil, S. Benson, C. L. Bohn, G. Biallas, D. Douglas, R. Evans, J. Fugitt, J. Gubeli, R. Hill, K. Jordan, G. Krafft, R. Li, L. Merminga, D. Oepts, P. Piot, J. Preble, M. Shinn, T. Siggins, R. Walker, and B. Yunn, “First Operation of an FEL in Same-cell Energy Recovery Mode”, to appear in the Proceedings of the 1999 FEL Conference, August 23-28, 1999, Hamburg, Germany.

[3] F. Dylla, “Free Electron Laser Project”, presentation at the Jefferson Lab Science and Technology Review, September 14-16, 1999.

[4] L. Merminga *et al.*, “FEL-RF Instabilities in Recirculating, Energy-Recovering Linacs with an FEL”, to appear in the Proceedings of the 1999 Free Electron Laser Conference, August 23-28, 1999, Hamburg, Germany.

[5] Present source operations usually provide 60 pC bunches to the wiggler at transverse normalized emittances of ~10 mm-mrad in an rms bunch length of ~0.4 psec with an rms momentum spread of ~1/4%. The machine has been operated lasing and energy recovering with bunch charges in excess of 100 pC, but with uncharacterized phase space performance. 10 kW IR operation will require a phase space similar to that provided in the IR Demo, but at a higher bunch charge of 135 pC. UV operations will demand this higher bunch charge with perhaps a factor of two smaller emittance and shorter bunch length.

[6] I. E. Campisi, D. Douglas, L. Merminga, B. C. Yunn, “Beam Breakup Simulations for the Jefferson Lab FEL Upgrade”, to appear in the Proc. 1999 I.E.E.E. Part. Accel. Conf., New York, March 29-April 2, 1999, and I. E. Campisi, D. Douglas, C. Hovater, G. A. Krafft, L. Merminga, B. C. Yunn, “Beam Current Limitations in the Jefferson Lab FEL: Simulations and Analysis of Proposed Beam Breakup Experiments”, to appear in the Proc. 1999 I.E.E.E. Part. Accel. Conf., New York, March 29-April 2, 1999.

[7] The choice of the wiggler position downstream of the cryomodule, prior to recirculation, was in part driven by this concern.

[8] R. Li, “Improvement of the Self-Consistent CSR Simulation”, to appear in the Proceedings of the 1999 Free Electron Laser Conference, August 23-28, 1999, Hamburg, Germany.

[9] S. Benson, unpublished.

[10] A number of people worked on this problem, particularly L. Merminga, I. Campisi, R. Walker, J. Preble, K. Jordan, and G. Krafft. To my knowledge, the information derived from their work has not been published. I apologize if I have failed to properly credit other individuals involved the analysis of this effect.

[11] T. Siggins, unpublished.

[12] These are presently expected to be 50 MV/5-cell modules, with gradients equivalent to those provided by 70 MV/7-cell CEBAF upgrade modules: see F. Dylla, *op. cit.*

[13] J. Preble, presentation in IR/UV FEL Upgrade design meeting, 4 October 1999.

[14] L. Merminga, private communication, C. Hovater, presentation in IR/UV FEL Upgrade design meeting, 1 November 1999.

[15] D. Douglas, “Lattice Design for a High-Power Infrared FEL”, Proc. 1997 I.E.E.E. Part. Accel. Conf., Vancouver, May 1997.

[16] D. Douglas, “Lattice Issues Affecting Longitudinal Phase Space Management During Energy Recovery, or, ‘Why the FEL Needs Sextupoles’”, JLAB-TN-98-025, 9 July 1998; D. Douglas, “Modeling of Longitudinal Phase Space Dynamics in Energy-Recovering FEL Drivers”, JLAB-TN-99-002, 14 January 1999; D. Douglas, “Beam Transport Issues in the Fall/Winter 1998 FEL Run”, JLAB-TN-99-007, 9 April 1999; D. Douglas, “Beam Transport Issues in the Winter/Spring 1999 FEL Run, JLAB-TN-99-008, 9 April 1999.

[17] J. Boyce and G. Krafft, research in progress; G. Krafft, “Use, of Jefferson Lab’s High Average Power FEL as a Thomson Backscatter X-Ray Source”, Proc. 1997 I.E.E.E. Part. Accel. Conf., Vancouver, May 1997.

[18] See, for example, G. Neil *et al.*, *op. cit.*; S. Benson and G. Neil studies of tapered wigglers (in progress); L. Merminga *et al.*, “FEL-RF Instabilities in Recirculating, Energy-Recovering Linacs with an FEL”, *op. cit.*; E. Gillman *et al.*, “Harmonic Lasing of a FEL – Wavelength Agility for Material Science Applications”, to appear in the Proceedings of the 1999 Free Electron Laser Conference, August 23-28, 1999, Hamburg, Germany.