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A NEW DYNAMICS FACILITY COMBINING A STORAGE RING WITH A SYNCHRONIZED FEL

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Abstract

Jefferson Laboratory currently operates a kilowatt average power, sub-picosecond mid-IR Free Electron Laser as a user facility. We present plans to add an electron storage ring to this facility. Pulses of light from both sources will be synchronized at repetition rates up to 125 MhZ to allow pump-probe dynamics experiments to be performed. We will present an outline of the new facility together with the operational parameters of the 2 sources. The new facility could be on line as a user facility in 2004.

1. Introduction and Motivation.

Jefferson Lab currently operates the world's "best-in-class" infrared Free Electron Laser (FEL) [1] and recently acquired a compact electron storage ring. Both use superconducting technology and both operate at a sub-harmonic of the 1497 JLab master oscillator, which is used for the CEBAF machine. Our plans are to install and operate both accelerators in the same building so that users can select beams from either or both machines for dynamics experiments.

Pump-probe measurements using a synchrotron radiation source synchronized to a mode-locked Ti-sapphire laser have been demonstrated at the NSLS, Brookhaven [2,3] and LBNL [4]. The success of these and other experiments [5] motivated the present effort, which will offer tunable, high peak power for the pump, with shorter pulses for the probe (σ = 30 ps compared to 300 ps for the NSLS). One can also envisage utilizing beam slicing [6] to reach down further into the ultrafast domain with the storage ring probe. Furthermore the Jlab FEL also produces synchronized femto-second x-rays[7] as well as synchronized pulses of far-IR or THz light[8]. These together with harmonically generated light using crystals pumped by the FEL provide a large suite of tools for fast dynamics studies of materials.

Note that the technique applies to processes that repeat and recover, such as electron and vibrational relaxation processes, and chemical reactions in which the recovery is by replenishment. The use of a pulsed probe source establishes the time resolution, and the technique does not require a fast detector. Measurements are signal averaged with a fixed time delay between pump and probe and the experiment repeated for a range of such delays.

2. The Free Electron Laser

The FEL at Jefferson Lab is a world "best in class" by a factor of 100 in providing up to > 2 kilowatt of average power. The machine is based on a photo-injected dc gun, and a superconducting radio frequency, energy-recovered linac (SRF linac). That is to say that the electron beam after passing through the laser section, is recycled back into the linac, but 180^0 out of phase, so that it is decelerated, yielding its energy to the new electron beam. This feature combined with the superconducting nature of the linac, minimizes the amount of energy required to run the FEL, resulting in major cost savings in terms of energy as well as installed radio-frequency power.

The main characteristics of the FEL are shown in Table 1. The laser is based on a near-concentric optical resonator cavity surrounding a wiggler and pumped by radiation emitted by a quasi-continuous electron beam from the SRF linac. Accelerator operations provide routine, reliable, delivery of light to one of six labs. The laser operates in the range from 3-7 microns in the fundamental, with sub picosecond pulses containing up to 20 μ Joules of energy each and at a repetition rate of 18.7, 37.4 or 74.85 MHz delivering a maximum average power up to 1.0 kW to users. The high beam power in a very tightly focused spot with a variable wavelength makes the FEL an ideal pump for pump-probe experiments.

The FEL is currently being upgraded to operate in a wider wavelength range, namely from 300 nanometers in the ultraviolet, to 15 microns and with average powers up to 10 kW. In the upgraded machine the energy will be increased from 40 MeV to 160 MeV by the addition of two superconducting linac modules, the average beam current will be increased from 5 to 10 mA and the extraction efficiency will be increased by a factor of two using an optical klystron. A separate optical cavity and wiggler will be used for the ultraviolet region. It is expected that the upgraded machine will begin commissioning in the Fall of 2002.

3. The Storage Ring

Helios-1 is a superconducting electron storage ring which operates at 700 MeV with a critical wavelength of 10Å and stored beam currents up to 800 mA. Producing more than 30 kW of synchrotron radiation in the x-ray to IR range, Helios-1 is a perfect probe for pump-probe experiments.

Built by Oxford Instruments, Helios-1 is a racetrack machine with overall dimensions of ~3×5 meters and a machine circumference of 9.6 meters. Beam is injected into the machine from a 100 MeV linac, captured and then accelerated to the full energy of 700 MeV. The energy is limited by the maximum magnetic field of the superconducting dipoles of 4.5 Tesla, which imposes a bending radius of 0.519 meters. Each 180^0 dipole is equipped with ten ports for extracting the synchrotron light. With a radio frequency of 499.2 MHz the machine operates at a harmonic number of 16. Filling only four symmetrically spaced bunches yields a pulse frequency of 124.8 MHz.

In addition to its potential use for 2 photon spectroscopy, Helios-1 is an ideal source for Proximity X-ray Lithography, (PXL), and other uses of the storage ring as a stand-alone device are envisaged including IR, VUV and soft x-ray spectroscopy. The addition of a superconducting wiggler could provide harder x-rays of use for macromolecular crystallography.

4. Facility Integration

In order to provide two-color, or pump-probe capabilities based on synchronous operation of the JLab FEL and Helios-1, the machines need to be housed in a common building, so that they can feed light beams into a common laboratory. In our case, there is sufficient space in the existing FEL building to house the linac, the additional shielding that it requires, and most of the power supplies. The proposal is to add a 2-story building addition of approximately 80 × 120 ft. that would house Helios-1, the synchrotron radiation beamlines, and additional set-up space. The FEL beam will be brought into proximity with the Helios-1 beam, since it is easier to transport IR than x-ray beams. To provide one-on-one synchronization, the optical cavity will have to be lengthened to provide for a pulse repetition rate of 124.75MHz, which is the 12^{th} sub-harmonic of the 1497MHz linac frequency. Helios will then be run at 499.0 MHz with 4 bunches to match this repetition frequency. The orbit can straightforwardly be lengthened by the ~mm required to accommodate this.

We show a schematic of the combined facility in Fig. 3. On this drawing, we also show a several infrared and soft-x-ray beamlines to set a scale.

5. Summary

In conclusion, we are in the process of establishing a new synchronized laser/FEL/synchrotron radiation facility. Examples of experiments that will be enabled by this facility are relaxation processes in the 100 ps to 100 attosecond time-scale such systems as semiconductors, superconductors, adsorbates at surfaces, and certain photochemical and photo-biological reactions.

In addition to the synchrotron radiation capabilities, we note that the FEL produces Thompson-scattered x-rays in the 5-30 keV range with sub picosecond pulse lengths, and a peak brightness of 10^{10} photons/sec/0.1% bandwidth/mm^2/mrad^2. Eventually this will increase to > 10^{11} photons/sec/0.1% bandwidth/mm^2/mrad^2. These x-rays are exactly synchronized with the IR pulses.

The short electron bunches also give rise to multi-particle coherent synchrotron radiation emission [8] in the far-IR or THz range. The average power produced in this range is ~ 1 watt /cm^{-1}, while the peak power is more than 4 orders of magnitude higher [9]. This is to be compared with typical average powers of 10^{-6} watts/cm^{-1} produced by conventional laser techniques. Again, these pulses are exactly synchronized with the IR pulses from the FEL and will extend the utility of this unique light source.

Acknowledgements

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Parameter	Measured value
Electron beam energy	48 MeV
Average current	4.8 mA
Bunch charge	Up to 60 pC
Bunch length (rms)	0.4 ± 0.1 ps
Peak current	Up to 60A
Trans. emittance (rms)	7.5 ± 1.5 mm mr
Long. emittance (rms)	26 ± 7 keV deg
Pulse repetition frequency	18.7 MHz (up to 74.8 MHz)
Wavelength	3-6.2 μm in fundamental
Average Power to users	Up to 1.0 kW
Pulse Length	0.3 – 1.7 ps
Pulse Repetition Freq.	74.85, 37.425, 18.7 MHz
Micro pulse energy	Up to 25 μJoules
Bandwidth	0.3 – 2%
Polarization	> 6000:1
Transverse mode	$< 2 \times$ diffraction limit
Beam diameter in lab	1.5 – 3.5 cm
Amplitude jitter	< 10% p-p

Table 1. Parameters of the Jefferson Lab Free Electron Laser

Parameter	Measured value
Electron Beam energy	700 MeV
Stored Beam Current	800mA
Dipole Field	4.5 Tesla
Bending Radius	0.519 meters
Source size vertical (typical)	sigma = 0.7mm
Source size horizontal (typical)	sigma = 0.7 mm
Radio-frequency	499.7 MHz
Harmonic Number	16

Table 1. Parameters of Helios-1

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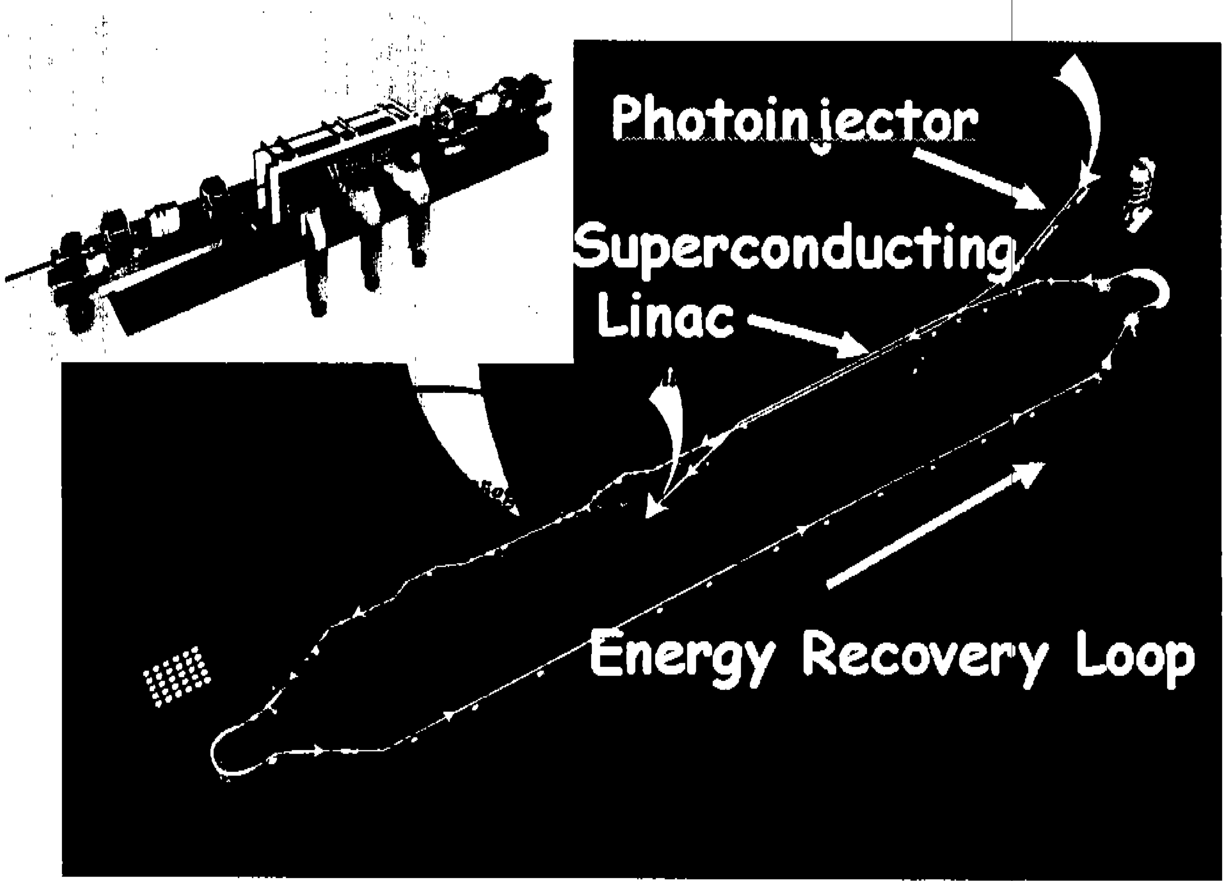
Figure Captions

Fig. 1. Schematic of the JLab Free Electron Laser, which is based on a photoinjected energy-recovered superconducting linac.

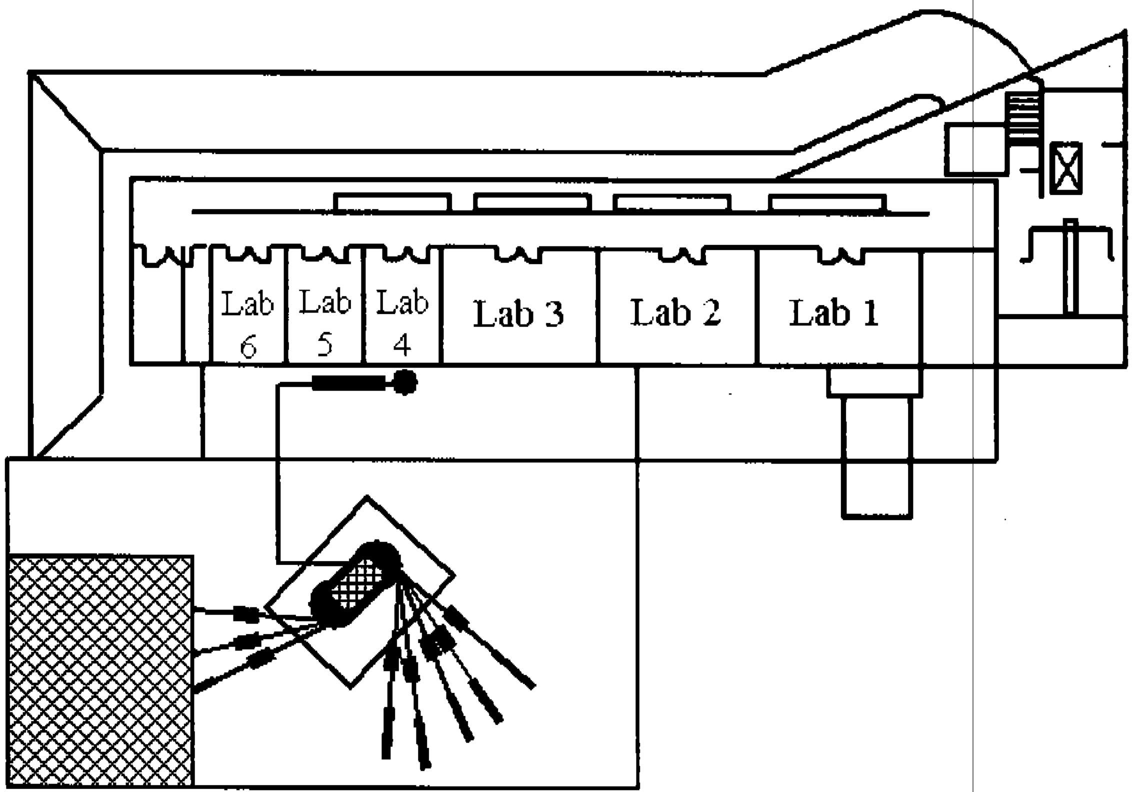
Fig. 2. The superconducting electron storage ring Helios-1 at Jefferson Lab. The synchrotron radiation ports are sealed by valves and can be seen on the right of the photo. L – R. Andrew Hutton, Ron Lauzé and Gwyn Williams.

Fig. 3. Layout of Helios-1 in a building addition extending out from the Jefferson Lab Free Electron Laser building at the lower left. The hatched area within the addition is a clean area for x-ray lithography. The labs at the top belong to the FEL and a beam from the lab area will be transported to the floor of the Helios-1 addition.



Dylla, Hutton, Neil and Williams, Fig. 1

Dylla, Hutton, Neil and Williams, Fig. 2



Dylla, Hutton, Neil and Williams, Fig. 3