The VUV/IR/THz Free Electron Laser Program at Jefferson Lab

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Abstract

Jefferson Lab operates a pair of oscillator-based continuous-wave Free Electron Lasers (FELs) as a linac-based next generation light source with pulse repetition rates up to 75 MHz. The facility uses an energy recovered linac design for efficiency of operation. Recent advances in superconducting technology have been implemented to produce higher acceleration gradients in the linac to produce higher electron beam energies that result in higher photon energies. Thus, while the system originally operated only in the IR, it now covers the photon energy range from the UV to THz, with harmonics upwards of 10 eV with an average spectral flux that is calculated to be 5×10^{17} photons/sec/0.1%BW. Pulse lengths are in the sub-picosecond regime, and the fully coherent nature of the source, both transversely and longitudinally, results in peak and average brightness values that are several orders of magnitude higher than storage rings. The system provides an R&D test-bed for studies of electron beam dynamics in a regime appropriate for next generation light sources operating at MHz repetition rates.

Facility Description

The Jefferson Lab light source facility [1,2] is shown schematically in Fig. 1. It comprises a DC gun-based photoinjector, booster, three linac modules, and two recirculation paths, each containing an oscillator-based FEL comprising an undulator at the center of a 32m optical cavity (round-trip time 4.678 MHz). The electron and photon beam parameters are given in Table 1, but we note that cryo-cooled mirrors are required to satisfy the higher repetition rates at full power per pulse. We also note that each high power mirror set is designed for high reflectivity and thus has only a few % tunability. In the present system, except for the cryo-mirrors, we can exchange up to 4 sets of cavity mirrors without breaking vacuum.

Focusing now on the details, in the injector, which is shown at the top left of Fig. 1, electrons are created in bunches by photoemission from a cesiated GaAs wafer, and then accelerated to 10

MeV in a booster. They then pass into a linac comprising three JLab cryomodules generating a total of 80–140 MeV of energy gain. The first and third modules incorporate conventional five-cell CEBAF cavities, while the central module is based on new seven-cell JLab cavities [3]. The central module design has demonstrated 82 MV of continuous acceleration, surpassing all previous such systems. In these modules, the electron beam is accelerated (energy recovered) off-crest (off-trough) so as to impose a phase-energy correlation on the longitudinal phase space. This is used in subsequent transport to longitudinally match the beam to the required phase space at the FEL (dump). That is to say, the bunch is kept relatively long during acceleration, compressed to high peak current just before the undulator, then temporally expanded before reinsertion into the energy recovery phase of the linac.

During the electron bunch compression in the in-board magnetic chicane that causes the electron beam to deviate around the first optical cavity mirror, broadband THz light from collective edge and synchrotron radiation is extracted. From the undulators inside the 32 meter long optical cavities, the electron bunches emit tunable narrow-band light, which is retro-reflected twice so that it can be propagated co-linearly with the electron bunches that follow, to produce gain by longitudinal modulation. At the downstream out-coupling mirror, ~10% of the optical power is extracted with full transverse, as well as longitudinal coherence [4]. This corresponds to a conversion of about 1% of the electron beam energy.

The “spent” electron beam still carrying 99% of its energy is then re-circulated back into the linac. The energy recovery transport consists of a Bates-style end loop followed by a six-quad telescope [5]. The beam is matched to the arc by the second telescope of the FEL insertion so that 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 temporally long, low momentum spread bunch at the dump. Measurements indicate that the accelerator will tolerate an induced full energy spread from the FEL of as much as 15%—compressing it to a final spread of order 5%—despite the large ratio of final to initial energy.

Comparison to other light sources

The light source as described offers photon beams that are many orders of magnitude brighter than storage ring sources. In particular the photon flux is increased by many orders of magnitude

60 due to phase coherence between wave-fronts emitted by different electrons, i.e. longitudinal, or
61 multiparticle coherent emission [6]. For the 135 pC typical bunch charges used in the Jlab FEL,
62 this enhancement is over 8 orders of magnitude, all of which is realized in the THz beamline [7],
63 and most of which is achieved in the FEL oscillator.

64 In addition to the dramatic increase in photon flux, the brightness of the FEL source is enhanced
65 compared to storage rings by the spatial coherence (small transverse source sizes), which is
66 present in both lateral directions. When electron bunches circulate only once, the electrons can
67 be made to occupy a much tighter 6-dimensional volume of phase-space than in a storage ring,
68 where electron-electron effects and/or quantum excitation spreads them out. In ERL's the
69 horizontal and vertical sizes are essentially the same, rather than the former being ~ 100 times
70 the latter as in storage rings. In our case the rms values of the transverse and longitudinal
71 electron beam sizes are ~ 150 microns. The primary advantage, however, of an ERL driver-
72 based FEL is (in addition to wall-plug efficiency), that of any linac-based source; extremely high
73 longitudinal brightness and the availability of fully coherent light.

74 Major technical advances that enable such a light source to be built and operated are the
75 superconducting linear accelerator structures, which can run cw RF and store energy without
76 significant loss, and photocathode driven electron guns of low emittance.

77 **Scientific Program**

78 With the present FEL, the main interest is in the third harmonic of the UV-FEL which is capable
79 of electronic excitations above the work-function of metals, and above the bandgaps of most
80 insulators. We are in the process of characterizing the third harmonic light, in preparation for its
81 possible utilization for experiments which are summarized in the next 3 paragraphs. Even
82 though the output here is down 2-3 orders of magnitude from the fundamental, light of these
83 photon energies is unobtainable from conventional table-top lasers, and is orders of magnitude
84 brighter than existing storage ring sources, or than High Harmonic Generation (HHG) light [8]
85 see Fig. 2. Additionally the pulses are much shorter than storage ring pulses, and the availability
86 of multiple synchronized photon beams is an added feature that has already been used for novel
87 electro-optic detection [9] leading to measurements of propagating electric fields, with
88 knowledge of phase. Such techniques will bring new dimensions to spectroscopy and imaging,
89 as well as allowing studies of out of equilibrium dynamics.

A unique application of the JLab VUV source is photoemission studies at higher energy and momentum resolution of highly correlated systems such as high T_c materials [10]. Emitted electron energy and momentum analysis can be done conventionally by dispersion, but can also be done using time of flight techniques, which offer resolution advantages.

Another example from Atomic, Molecular and Optical physics, is studies of combustion dynamics [11], as an extension of work already being performed at storage rings. Here the higher brightness and time resolution is used to ionize and study reaction intermediate species of low cross-section in real reaction conditions.

A third and final example of a unique scientific application is Atomic Trap Trace Analysis [12], the implementation of the ionization of ^{81}Kr to a metastable state so that it can be used as a tracer isotope for dating water and ice in the range $10^5 - 10^6$ years, a range beyond the reach of ^{14}C dating and using only liter quantities. This would enable polar ice cores to be dated, for example, using a clock that is significantly longer (229,000 years half-life) than ^{14}C (5730 years).

Potential upgrade path

Increases in electron beam energy from continuing advances in superconducting technology result in increases in photon energy, which scales as electron beam energy squared. With current designs, cryomodules similar to the ones used in the FEL can achieve 100 MV of acceleration each. Using a recirculating linac scheme, then, with new beam transport around the ends, it is possible to conceive of a 600 MeV electron beam, that with appropriately scaled undulators could make 100 eV light in the fundamental. Such a machine would allow studies of the dynamic structure factor of materials via inelastic scattering. This would open a new door for studying the dynamics of materials in which quasiparticle-quasiparticle interactions dominate physical behavior. Many of these materials, such as the high temperature superconductors, have huge technological potential.

Anticipated performance of such a machine is shown in Fig. 2. An electron beam with a lower normalized emittance of 1 micron, compared with 6 microns at present, would be necessary for this, so we are undertaking studies for such an injector, as well as detailed studies of the beam dynamics of such high brightness electron beams. Issues such as coherent synchrotron radiation (CSR), beam breakup (BBU), and thermal effects in narrow chambers due to high peak currents are examples of issues unique to these sources. The existing machine is a useful test-bed in this

regard. With continuing advances in High Harmonic Generation (HHG) for seed pulses in the range up to 100 eV an amplifier could be designed. However, the high repetition rates possible with superconducting linacs and the use of energy recovery could also enable oscillators. We continue to study these possibilities also, since they could be realized in our existing facility.

Summary

We have described a new generation of light source that started operating part-time as a user facility in 2000, and which, while not funded as a full-time dedicated user facility, has been used continually by users as funds have permitted, with a full proposal and Program Advisory Committee system. The facility was upgraded to the present multi-laser machine configuration in 2010. The machine is based on same-cell energy recovery, a low emittance photo-cathode gun, and a superconducting linac, with each electron making a single trip around. The output of this machine is based almost entirely on multiparticle coherent enhancement which boosts the output photon brightness from the circulating current of 10 mA up by about 8 orders of magnitude over a storage ring even though the latter may circulate many 100's of mA. Also, it is fair to say that operating experiences with ERL's are different than storage rings. There are different sources of noise, for example, as well as potentially unique opportunities for utilization of multiple photon beams in time-resolved out of equilibrium pump-probe experiments [13]. Even the multiplicity of the user operations is different, but our experiences so far are that our ability to conquer noise, and our cost metrics, are similar to those of storage rings.

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	IR FEL	UV FEL
Photon energy range of fundamental	0.1 – 1.4 eV	1 – 3.4 eV
Photon energy per pulse	100 microJoules	20 microJoules
Repetition rate	4.678 – 74.85 MHz	4.678 – 74.85 MHz
Photon Pulse length (FWHM)	100 fs – 2 ps	100 fs – 2 ps
Nominal pulse bandwidth	1%	.2%
Electron Beam Energy	80 – 140 MeV	80 – 140 MeV
Charge per electron bunch	135 picoCoulombs	60 picoCoulombs

Table 1. Parameters of the JLab FEL

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Figure Captions

Fig. 1. Layout of the JLab FEL facility, showing the injector at the top, the superconducting linac on the upper left, with 2 re-circulation paths each containing an oscillator-based FEL.

Fig. 2. Lightsource landscape for average spectral brightness, showing 2nd, 3rd, and 4th generation sources, with the JLab FEL operational parameters indicated. These generic plots were made using an electron beam energy of 3 GeV, a bending radius of 5m, and for 1nC electron bunches at 100 MHz (100 mA). Source sizes used were 500×1000 , 10×100 , and 5×5 microns respectively for the 2, 3 and 4th generation sources. 3rd generation sources were elevated by 500 for insertion devices, and 4th generation sources were elevated by a further 10^{10} to account for longitudinal coherence.

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S. Benson et al. Fig. 1.

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S. Benson et al Fig. 2.

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