

The Free Electron Laser at Jefferson Lab: The Technology and the Science

Photoemission from a semiconductor wafer, accelerated and magnetically compressed, can deliver a ten-thousand-watt beam of IR light for imaging, spectroscopy, and measurements.

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ABSTRACT | We discuss the physics and technology which is driving the evolution of high-brightness fourth-generation accelerator-based sources. Some of the first user facilities are in the THz and IR spectral ranges. Specifically, a new generation of sources, called energy recovery linacs, will be described and reviewed with particular emphasis on their utility for imaging, spectroscopy, and dynamics, as well as their novel applications to nonlinear phenomena.

KEYWORDS | Coherent; free electron laser; infrared; synchrotron radiation; THz

I. INTRODUCTION

In this paper we will describe a new generation accelerator-based light source, called an energy recovered linac [1], [2] (ERL), in which energy is stored, rather than electrons. The source combines the peak brightness found in a free electron laser (FEL), with the continuous pulse structure found in a storage ring. Fig. 1 shows a schematic of the Jefferson Lab (JLab) ERL that is currently operating as a light source. In this machine, electrons are created in bunches by photoemission from a cesiated GaAs wafer, injected into the superconducting linac at 10 MeV, and accelerated. They are then compressed in a magnetic chicane from which THz light is extracted, and they then

traverse a wiggler at the center of an optical cavity of the FEL and emit laser light. About 1% of their energy is extracted. As example of the relevant parameters, if the electron beam current is 10 mA at 100 MeV, the beam energy is 1 MW, and the extraction 10 000 W. The electron beam, still carrying 99% of its energy, is then recirculated back into the linac but out of phase so that it decelerates, giving up its energy to the cavity. The energy is used to accelerate future bunches. The spent electrons are dumped at 10 MeV.

Such a light source offers infrared beams that are at least eight orders of magnitude brighter than storage ring sources because of multiparticle coherence [3], [4]. We will discuss this concept later. In addition, since the electron beams circulate only once, the electrons can be made to occupy a much tighter volume of phase-space than in a storage ring, where electron-electron repulsion spreads them out. In ERLs the horizontal and vertical sizes are essentially the same, rather than the former being 100 times the latter as in storage rings. Further, the longitudinal phase space is compressed to subpicosecond levels. This opens up additional opportunities in ultrafast time-domain spectroscopy, both linear and nonlinear.

Major technical advances that enable such a light source are the superconducting linear accelerator structures, in which the energy can be stored without significant loss, and photocathode driven electron guns of low emittance. The availability of multiple synchronized photon beams is an added feature that has already been used for novel electrooptic detection [5], leading to knowledge of propagating electric fields, with knowledge of phase. Such techniques will bring new dimensions to spectroscopy and imaging, as well as the study of out of equilibrium dynamics.

Manuscript received February 27, 2007; revised March 14, 2007. This work was supported in part by the Office of Naval Research, in part by the Army Night Vision Laboratory, in part by the Air Force Research Laboratory, in part by the Joint Technology Office, in part by the Commonwealth of Virginia, and in part by the U.S. Department of Energy under Contract DE-AC05-06OR23177, under which Jefferson Science Associates operates Jefferson Lab. The authors are with the Jefferson Lab, Newport News, VA 23606 USA (e-mail: awthomas@jlab.org; gwyn@jlab.org).

Digital Object Identifier: 10.1109/JPROC.2007.898905

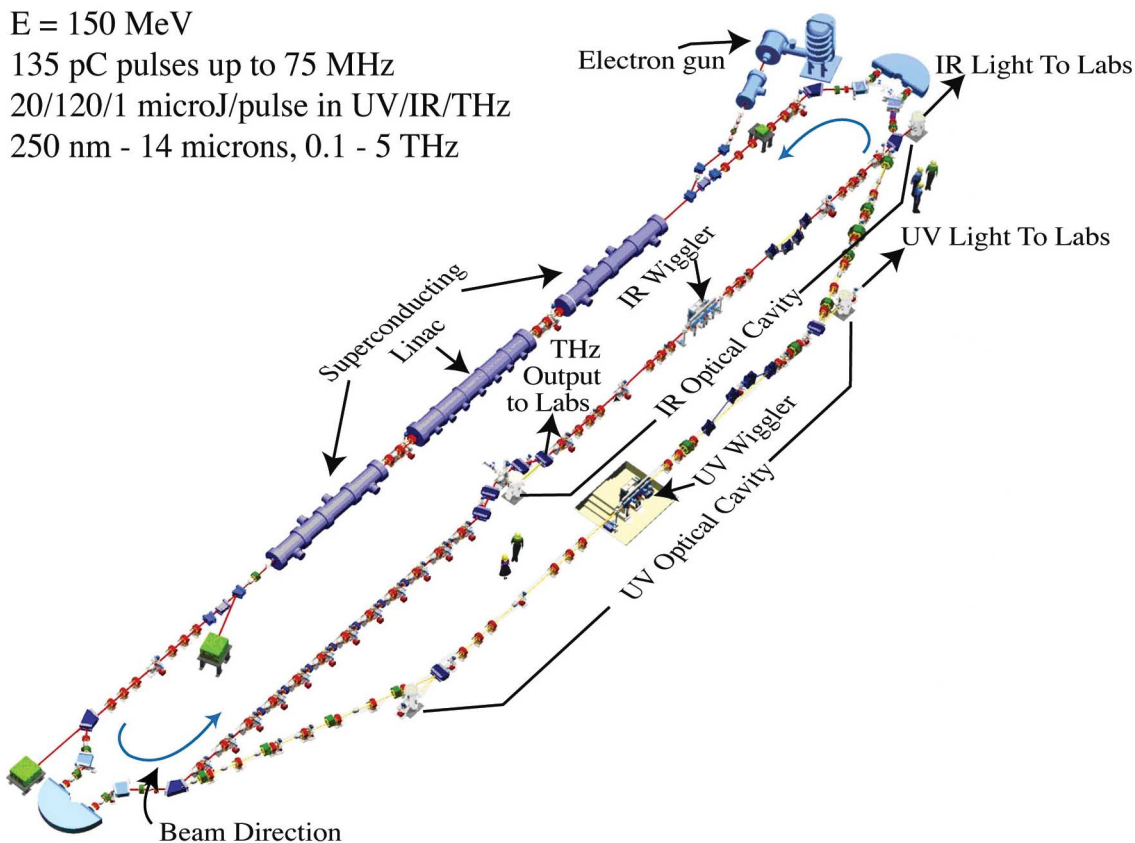


Fig. 1. The energy recovering linac accelerator that is operating as a light source at Jefferson Lab, offering subpicosecond narrowband FEL beams and broadband THz beams at repetition rates up to 75 MHz.

II. MULTIPARTICLE COHERENCE

Multiparticle coherence [4], [6] occurs when electrons are tightly packed compared to the radiating wavelength, so that their electric fields add in phase. There are two situations of interest. In one, which is of particular interest to THz production, the electron bunch length is shorter than the wavelength, so that all the electrons radiate in phase. In the other, which applies to FELs, the electrons are microbunched within the main bunch, with each microbunch being of the order of the lasing wavelength. This all stems from the fact that in most accelerators, the electrons, N at a time, are accelerated in bunches related to the radiofrequency linacs used to boost or replace their energies. These bunches have two time structures, one on the scale of the ability to resolve the \sqrt{N} statistical noise, and one related to the passage of the entire bunch. The former is related to the Lorentz transform of the opening angle of the radiation from a single electron, and the other to the length of the whole bunch. The Fourier transforms of the fields generated by the passage of these bunches thus have two components, a fast component whose electric field is proportional to $\sqrt{N} \times e$ (e being the charge on an electron), and a slow component whose electric field is proportional to the whole bunch N . The relative intensities

of these two components are proportional to N and N^2 , respectively. The fast component is the term familiar to most users of synchrotron radiation. The N^2 term is the one generated and utilized by the new generation of machines.

III. THz BRIGHTNESS AND POWER CALCULATIONS

We present generic calculations of the average spectral output of the JLab facility, in Fig. 2. In this figure we show other light sources for comparison, noting that the brightness of these machines is close to that obtained using an emittance of λ^2 . The peak brightness is at least 10^4 times higher than the average because of the duty cycle of 1 ps every 10 ns. At Jlab we have obtained bunches shorter than 300 fs full width at half-maximum (FWHM) to date.

IV. DETAILED DESCRIPTION OF THE OPTICS OF THE THz FACILITY

We now describe the design of the beamline, which is designed to deliver into a user laboratory, an approximately $f/8$ beam that is about 2 mm vertical \times 3 mm horizontal in size. Under the present configuration, the

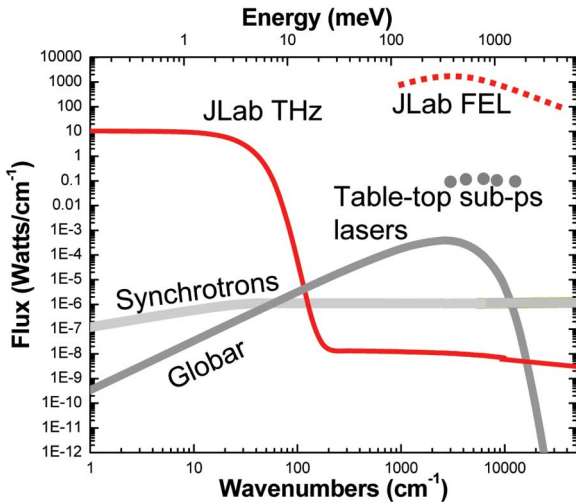


Fig. 2. Calculated output power of the JLab facility.

beam is 60% vertically polarized. The beamline extracts light emitted into a subtended angle of ~ 200 mrad horizontal by ~ 135 mrad vertical. The FEL is in an underground vault for shielding reasons, and the laboratories lie one floor above, necessitating a long transport system. A further constraint on the optical design is the desire for a jog in the optics to allow radiation shielding to be installed that blocks line of sight between the FEL and the laboratory.

The philosophy of the optical design is to use a relay optics configuration to transport the beam via reflection off metal mirrors through a series of focal points. Thus the beam is focused at F1 onto a diamond window with unit magnification, then refocused at an intermediate point F2, and finally refocused at F3 at a second diamond window in user laboratory 3a. The final focus is a 1 : 1 image of the source. The difference in elevation between the electron beam and the beam delivery in laboratory 3a is 5.8 meters.

The optical system is based on 6'' optics and is shown schematically in Fig. 3. M1 is a 1 : 1 ellipsoidal mirror of focal length 625 mm, which reflects the beam vertically upwards using s-polarization providing a focus at F1. M2 and M4 are an identical pair of ellipsoids with focal lengths 705 and 2426 mm arranged such that M2 provides a source image at F2 magnified by 3.4, while M4 reduces this image by the same factor to give the 1 : 1 image on the final diamond window at F3. F3 is 1 m above the floor in user laboratory 3a. Mirror M3, is a plane mirror at the bottom of the very long vertical pipe.

The initial part of this beamline is in the FEL machine vacuum of 10^{-9} torr. Mirror M1 is provided with a copper braid for cooling and is remotely controllable. The optical mount is a standard one with stepping motor driven screws. At the F1 focus, there is a 20 mm diameter 1° wedged diamond window which separates machine vacuum from the 100 mtorr vacuum of the remainder of

the beamline. M2 is also remotely controllable, while M3 and M4 can be controlled manually but in vacuum.

The full beamline design incorporates safety shutters, valves, and cameras to view light images on insertable screens, plus alignment lasers to enable preliminary alignment to take place in the absence of beam.

The optical scheme was developed using the Synchrotron Radiation Workshop (SRW) code [7]. This code performs a full calculation of the electric field from a relativistic electron. It does not handle multiparticle coherent enhancement, but is significantly different from all the other synchrotron radiation calculations because it retains a term called the Coulomb, or near-field term. In almost all cases of normal synchrotron radiation beamlines this is an unimportant term due to the parameters, but it is very important in the JLab case. In addition to calculating the electric field and from this, the intensity, the code also allows one to propagate the field through optical focusing elements and apertures.

The patterns of light at various locations in the transport system obtained from the SRW code and calculated for 1 THz are also shown in Fig. 3. The circles indicate the approximate sizes of the apertures at the optical elements. The calculations were performed for a 100 MeV beam. Note that the ring pattern originates from interference between the electric field generated by the magnetic field change on leaving one magnet and the one generated on entering the next magnet (Maxwell's equation $\nabla \times E = -(\partial B/\partial t)$). The synchrotron radiation is manifest as the double increase in the center of the vertical stripes to the left of the figure (Maxwell's equation $\nabla \times H = J_{Free} + \epsilon_0(\partial E/\partial t) + (\partial P/\partial t)$). Taking account of the finite electron beam emittance made no discernible difference to the patterns, changing the electron beam energy from 80 MeV to 150 MeV made a discernible but unimportant difference. We also experimented with

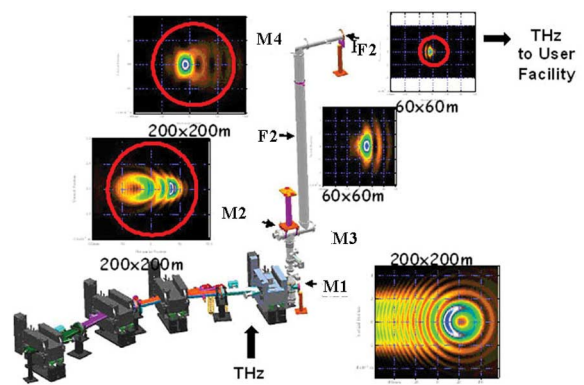


Fig. 3. 3-D schematic of the JLab THz beamline showing the FEL electron beam chicane at the bottom, and showing the radiation power patterns at indicated locations with the brightest being $100 \times$ the threshold fringes, on a linear scale.

toroidal mirrors but there was no significant advantage, and since we do not wish to change the anamorphic ratio, we retained ellipsoidal figures. Actually the differences between elliptical and toroidal figures are small.

The beam exiting the final diamond window in user laboratory 3a passes into a beam conditioning vacuum chamber which allows attenuation, collimation, and/or beam splitting to take place for imaging, spectroscopy, and pump-probe measurements.

V. SUMMARY

We have described a new generation light source that started operating as a user facility in 2000, and in the present machine configuration earlier in 2005. The machine is based on same-cell energy recovery, a low emittance photocathode 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 power of the circulating current of 10 mA by many orders of magnitude over a storage ring, even though the latter may circulate many hundreds of mA. It is to be expected that ERLs will slowly increase in brightness as higher beam currents are used. Also, it is fair to say that operating

experiences with ERLs are different from storage rings. There are different sources of noise; for example, intensity fluctuations are more significant than beam orbit instabilities. Also, different utilizations of multiple photon beams are expected for time-resolved out of equilibrium pump-probe experiments [8]. Even the multiplicity of the user operations is different, but our experiences so far, as well as those at other facilities such as CLEO [9] and FELIX [10] are that our ability to conquer noise, and our cost metrics, are similar to those of storage rings.

For applications it is important to distinguish between broadband and narrowband sources. The JLab source is broadband and ideal for applications to imaging and spectroscopy. The source allows analysis using FTIR techniques, for example. For imaging, either the entire spectrum or a filtered portion of it may be used. ■

Acknowledgment

This work was supported by the Office of Naval Research, the Army Night Vision Laboratory, the Air Force Research Laboratory, the Joint Technology Office, the Commonwealth of Virginia, and by the U.S. DOE under Contract DE-AC05-06OR23177. The THz beamline was designed and built by Advanced Energy Systems.

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