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RADIOFREQUENCY SUPERCONDUCTIVITY APPLIED TO FREE-ELECTRON LASERS

COURTLANDT L. BOHN* and STEPHEN V. BENSON

Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, VA 23606, USA

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Low wall losses and low wakefields inherent in superconducting radiofrequency (srf) cavities make them attractive candidates for accelerators that operate efficiently at high continuous-wave (cw) gradients. Such accelerators are desirable for free-electron lasers (FELs) that extract high-power cw light from a high-average-current electron beam, or that produce ultrashort-wavelength light from a high-energy electron beam. Efficiency is a prime consideration in the former case, while high electron-beam quality is a prime consideration in the latter case. This paper summarizes the status of FEL projects involving srf accelerators. It also introduces Jefferson Lab's srf FEL and surveys its design because it is a new machine, with commissioning having commenced in October 1997. Once commissioning is complete, this FEL should produce tunable, cw, kW-level light at 3–6 μm wavelength.

Keywords: Superconductivity; Radiofrequency; Cavities; Free-electron lasers

INTRODUCTION

A generic free-electron laser (FEL) consists of an accelerator that prepares a relativistic electron beam and sends it through a periodic magnetic field, a wiggler. The magnetic field causes the electrons to oscillate transversely and radiate electromagnetic waves. These waves bunch the electrons, causing them to radiate coherently near a

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[*] Corresponding author. Tel.: 757-269-7690. Fax: 757-269-7352.
E-mail: clbohn@jlab.org.

resonant wavelength. The resonant wavelength λ_r is related to the wavelength of the magnetic field λ_w by way of a Lorentz transform and a Doppler shift, i.e., $\lambda_r \propto \lambda_w/(2\gamma^2)$, in which γ is the total electron energy divided by the electron's rest-mass energy. Saturation of the gain process occurs in conjunction with overbunching brought about by the electron–photon interaction. It can be catalyzed by inserting the wiggler between two mirrors forming an optical cavity. Alternatively, an external laser can be used to send coherent light into the wiggler as an optical seed. However, to generate ultrashort wavelengths, e.g., X-rays, neither mirrors nor seed lasers are available. In this case lasing arises from self-amplified spontaneous emission (SASE) starting from noise, and a relatively long wiggler is needed.

For efficient lasing, the bulk of the electrons must participate in the lasing process. This sets a condition on the root-mean-square (rms) normalized transverse emittance: $\varepsilon_n \leq \gamma\lambda_r/(4\pi)$.[1] High gain is assured provided the electron beam has low emittance and high peak current, conditions that correspond to high brightness $B = I_p/(2\varepsilon_x\varepsilon_y)$, in which I_p denotes peak current and $\varepsilon_{x,y}$ denote the rms emittances in the transverse (x, y)-planes.

In general, FELs produce optical pulse lengths that roughly correlate to the electron bunch lengths. Thus, if the accelerator and electron-transport system generate short bunch lengths at the entrance to the wiggler, the optical pulses are also short. For this reason, FELs can be used to generate picosecond-length optical pulses, two orders of magnitude shorter than pulses generated in typical synchrotron light sources. Consequently, by generating such short pulses, FELs enable an experimentalist to study transient phenomena of solid-state physics without unwanted complications stemming from plasma formation associated with nanosecond-pulse sources.

Electron beams for FELs are generally produced using storage rings or linear accelerators. Storage rings can produce very stable high-brightness electron beams with an energy in the range of about 250–1500 MeV. Consequently, according to the resonance condition, they can produce short-wavelength light. Storage rings elegantly remove the energy spread that lasing imposes on a beam bunch by synchrotron cooling the bunch. However, the efficiency by which the wiggler converts electron-beam energy to light is limited in that it cannot introduce more energy spread than the synchrotron cooling can remove. More precisely, at all energies the efficiency of storage rings is limited to a few percent by the Renieri limit, which says that the maximum average coherent power that can be generated by a storage-ring FEL is roughly proportional to the total incoherent synchrotron-radiation power emitted in the ring itself divided by the number of magnetic-field periods in the wiggler.[2] Their emittance, and therefore their brightness, is limited at low energies by collective effects (specifically, Touschek scattering[2]), and at high energies by quantum excitation and longitudinal and transverse wakefield instabilities. Thus, outside the 250–1500 MeV range, linear accelerators (linacs) provide superior brightness. In turn, linacs are preferred for FELs that operate with high efficiency and/or produce long-wavelength light. They are also preferred for production of ultrashort-wavelength light for which mirrors may be unavailable to comprise an optical cavity. In that case the wiggler is designed to be long enough to provide gain that is sufficiently high to produce saturated lasing in one pass.

Superconducting radiofrequency (srf) linacs comprise high-Q accelerating structures that establish stable high continuous-wave (cw) accelerating gradients. Because shunt impedance is relatively unimportant in srf cavities vis-à-vis normal-conducting cavities, srf linacs also provide large beam apertures with correspondingly low wakefields. Therefore, srf technology offers several potential advantages over normal-conducting technology, including: generation of high average currents for high-average-power FELs, generation of high-brightness electron beams for ultrashort-wavelength FELs, efficient energy recovery from the electron beam, and better energy and phase stability for user applications. Existing and planned srf FEL facilities are designed to exploit at least one of these advantages.

EXISTING SUPERCONDUCTING RADIOFREQUENCY FELs

Presently there are three existing FEL facilities: Stanford, Darmstadt, and JAERI, all of which are designed to generate mid- to far-infrared radiation at modest power levels. Their top-level parameters are listed in Table I. (In Tables I and II, f denotes the operating frequency of the linac cavities, E is the electron beam energy at the wiggler, Q is the charge per bunch, I is the long term average beam current, λ is the

TABLE I Existing srf FELs

Existing	f (MHz)	E (MeV)	Q (pC)	I (mA)	λ (μm)	P (W)	ε_n (mm-mr)
Stanford*	1300	20–40	13	0.02	3–100	0.6	8
Darmstadt	2997	30–50	6	0.06	2.5–10	4	<50
JAERI†	499.8	13–23	200	0.04	20–80	10	>20

*Duty factor limited to 10%.
†Duty factor limited to 1%.

FEL wavelength, P is the FEL power, and ε_n is the normalized rms transverse emittance.)

The Stanford FEL has operated in various forms since the mid-1970s. It incorporates a thermionic dc electron gun and it is presently configured with two superconducting linac sections, one generating 20 MeV beam, and both together generating 40 MeV beam.[3] The machine also incorporates two wigglers, one located after the first linac section for generating far-infrared wavelengths, and the other located after the second linac section for generating mid-infrared wavelengths. The light output is quite stable, with wavelength stability better than 0.1% peak-to-peak and amplitude stability usually better than 5% peak-to-peak. The linac never operated at 100% duty factor due to electron loading in the srf structures; however, it has routinely operated at high duty factor, up to about 30%. Presently it is limited to 10% duty factor, this being due to an overall degradation of cavity performance over the years. Consequently, Stanford is in the process of replacing the linac sections with TESLA technology as described in the next section.

The Darmstadt FEL[4] first lased in December 1996 in the mid-infrared, and it operated again in June 1997.[5] Its driver accelerator incorporates a thermionic dc electron gun that injects beam at 250 keV into the linac (S-DALINAC[6]) which consists of an injection linac and a main linac. The injection linac includes a 5-cell capture section and a standard cryomodule housing two 20-cell cavities to take the electron-beam energy up to 10 MeV. After an isochronous 180° bend, the beam enters the main linac which consists of four cryomodules each containing two 20-cell cavities, and it is thereby accelerated to a nominal energy of 40 MeV. Upon exiting the linac, the beam then bends through another 180° turn and passes into the wiggler.

The JAERI FEL was completed in 1995.[7] It incorporates srf technology similar to that used at DESY. The accelerator consists of a thermionic electron gun followed by a buncher, two single-cell pre-accelerating cavities each housed in its own cryomodule, and two main cryomodules, each housing a 5-cell cavity. The cryomodules are distinctive in that each one is equipped with its own helium refrigerator to keep the cavities at 4 K temperature. The accelerator operates with nominally 1% duty factor; its rf system is limited to 3% duty factor.[8] After acceleration, the electron beam passes through a 180° achromatic bend that directs it to the wiggler.

To date, there is some ambiguity whether the JAERI FEL has lased. Most recently (as of this Workshop) it generates considerable gain in the wiggler, but the gain has not persisted on time scales exceeding about 100 μs.[8] The cause of this circumstance remains to be identified.

Both the Stanford and Darmstadt FELs involve electron beams with low charge per bunch, and therefore correspondingly low space-charge forces within the bunch. By contrast, the JAERI FEL operates with high charge per bunch and low electron-beam energy. Consequently, space charge is potentially important in the JAERI machine.

PLANNED SUPERCONDUCTING RADIOFREQUENCY FELs

Top-level parameters of planned srf FELs are provided in Table II. All but one take advantage of the srf technology under development for TESLA. The sole exception is that constructed at Thomas Jefferson National Accelerator Facility (Jefferson Lab, formerly known as CEBAF), which incorporates CEBAF srf technology. In all of these machines, the charge per bunch is relatively large, so space

TABLE II Planned SRF FELs

Planned	f (MHz)	E (MeV)	Q (pC)	I (mA)	λ (μm)	P (W)	$\gamma\lambda/4\pi$ (mm-mr)
Stanford	1300	20–40	85	1	3–100	63	17
Drossel (I/II)	1300	20/40	85	1	10–200	30	32
DESY (I/II)*	1300	390/1000	1000	0.072	6–42 nm	10–100	1
Jefferson Lab	1497	42	135	5	3–6	1000	20

*Duty factor targeted at 0.8%.

charge is a concern, particularly at low energies in the respective injectors, and the srf accelerating structures will be heavily beam loaded.

As mentioned in the previous section, Stanford is in the process of replacing its srf linac with TESLA structures to boost its duty factor to 100%. The new cryomodules will contain two 9-cell TESLA cavities operating at 10 MV/m cw accelerating gradient. They will enable generating milliamp-level average current for a hundred-fold increase in the FEL power output at mid- to far-infrared wavelengths. The upgrade is envisioned to be complete by mid-1998.[9]

The Drossel collaboration, of which key participants are Rossendorf Laboratory, DESY, and Budker, is planning a machine similar to Stanford's that will be installed in a new facility at Rossendorf Lab in Dresden, Germany. Unlike the Stanford FEL, this machine is envisioned to incorporate a srf electron gun currently under development,[10] with the principal motivation being to provide maximum flexibility in electron-beam production for an array of experiments that include bremsstrahlung generation, channeling radiation, and parametric X-rays for nuclear-physics experiments, as well as the FEL itself. Development of the Drossel machine is likely to proceed in two major phases (indicated in Table II) corresponding to successive installation of the two 20 MeV linac sections. The collaboration is funded, and work has just begun to clear the land for the facility. Completion of the machine is projected for early 1999.[11]

At the end of September 1997, Jefferson Lab had just begun to commission its machine. An overview of its design is provided in the following section, and more details are available elsewhere.[12] It is configured to produce kW-level light in the mid-infrared with recirculation of the electron beam back to the linac for deceleration and conversion of 75% of its energy to rf power. An intermediate step is production of first light exceeding 100 W at a wavelength of about 5 μm without energy recovery. Thus, in its first-light configuration, the Jefferson Lab FEL is also similar to the upgraded Stanford machine. Plans are to obtain first light in Spring 1998, follow it with a user experiment, and then proceed with energy recovery and full-power operation.

By contrast, DESY's primary emphasis is on generating ultrashort-wavelength light, with only a secondary emphasis on high power output. As a consequence, their FEL will rely on SASE in a long

(30 m) wiggler, rather than on an optical cavity as in the other tabulated FELs. The wiggler will consist of six 5 m-long sections. Progress is projected to proceed through two intermediate phases, ultimately leading to a 50 GeV linac for production of Angstrom-level wavelengths. The DESY machine will evolve from activities in the TESLA Test Facility.[13] Phase I incorporates three TESLA cryomodules for production of a 390 MeV electron beam. Each cryomodule houses eight 9-cell cavities operating at a nominal accelerating gradient of 15 MV/m.[14] The beam is then sent straight into a three-section (15 m-long) wiggler. The experimental program for Phase I is restricted to studies of the SASE process; no user experiments are presently envisioned. Phase II, on the other hand, will comprise a user facility. In Phase II, five TESLA cryomodules will be added to the linac to produce a 1 GeV electron beam, and the wiggler will be extended to its full length. In both phases, the linac must produce a high-brightness, low-emittance beam for efficient lasing, which is another distinctive feature of the DESY program. Phase I is projected to be completed by early 1999, and Phase II by late 2001.

JEFFERSON LABORATORY'S SUPERCONDUCTING RADIOFREQUENCY FEL

Jefferson Lab's srf FEL, hereafter referred to as the "IR Demo," is pictured in Figure 1. It is a kW-level FEL that uses a 10 MeV injector and a 32 MeV linac to produce a 42 MeV, 5 mA cw electron beam for lasing. The wiggler extracts about 0.5% of the electron-beam energy, thereby producing kW-level light to user laboratories located above the FEL. After lasing, a high-acceptance magnet lattice transports the electron beam back to the linac for deceleration down to 10 MeV, then to a dump. Thus, about 75% of its energy is put back into rf power for use in accelerating other electrons, thereby reducing rf-power requirements. Energy recovery also reduces waste heat and radiation, allowing use of a compact beam dump of uncomplicated design.

The IR Demo incorporates, where possible, components that are commercially available and/or are standard in Jefferson Lab's nuclear-physics accelerator (CEBAF). The injector comprises a 350 kV dc photocathode gun driven by a commercial Nd : YLF laser.

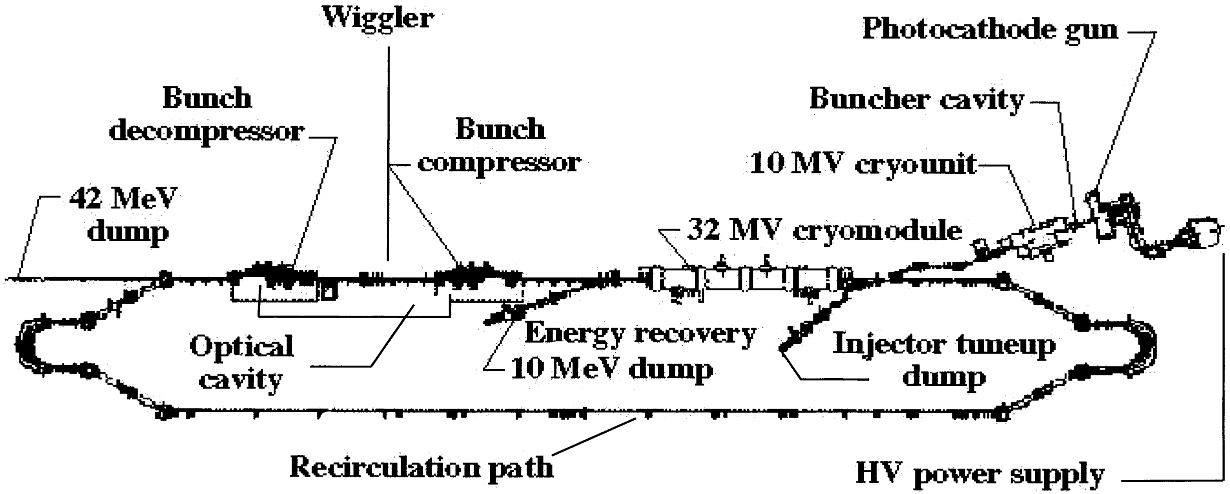

FIGURE 1 Schematic of Jefferson Lab's high-power FEL.

The drive laser is built to operate at 74.85 MHz, but an electro-optic modulator is used to halve the frequency to 37.425 MHz, or 1/40th of the fundamental frequency of the cavities, as a compromise between required cathode quantum efficiency, peak current, and beam quality. A lower repetition rate would involve a higher bunch charge and peak current, producing more gain but at the expense of poorer beam quality and less margin for quantum efficiency, while a higher repetition rate would provide insufficient peak current. The gun is followed by a copper buncher cavity and a CEBAF-type 1497 MHz srf cryounit to generate an average accelerating gradient of 10 MV/m, boosting the beam to 10 MeV. The accelerator uses a full CEBAF-type 1497 MHz srf cryomodule to generate an average accelerating gradient of 8 MV/m, boosting the beam to 42 MeV energy. Two commercial 50 kW klystrons power the injector's cryounit. A commercial wiggler and modifications of CEBAF's rf system, control system, and safety system are also included.

The CEBAF-derived srf components are modified for high-current operation. Modifications include adding higher-order-mode loads that deposit mode power into the cryostat's 50 K shield, increasing the intercavity pipe aperture from 3.8 cm to 5 cm to inhibit beam impingement, and replacing the 5 cm valves with 7.6 cm valves to reduce impedance. Magnetostrictive tuners have also been added for use during startup in the energy-recovery mode to enable simultaneous fine detuning of the linac cavities should it become necessary.

As previously mentioned, the specified voltages of the cryounit and cryomodule are 10 MV and 32 MV, respectively, both with unloaded $Q_0 = 5 \times 10^9$. Prior to installation of the cryounit in the FEL facility, horizontal tests of the installed cavities in the injector cryounit without electron beam indicated an accelerating gradient in the first (entrance) cavity of 11 MV/m at $Q_0 = 5 \times 10^9$, with field emission limiting its performance, and in the second (exit) cavity of 9 MV/m also at $Q_0 = 5 \times 10^9$, with an arc fault in the waveguide being the limiting factor.[15] Correspondingly, the total accelerating voltage on crest was 10 MV, as desired. Operation off crest may prove necessary as part of prebunching the electron beam, which would reduce this value. Horizontal tests of the installed cavities in the cryomodule are pending. Vertical tests of these cavities prior to installation were promising, indicating a total voltage of 42 MV if their performance was to be unaltered in the horizontal configuration.[16] None of these test results involved special cavity processing; helium processing will eventually be invoked if an increase in operating gradient is deemed necessary.

Beam impingement must be kept low throughout the machine ($< 5\,\mu\text{A}$ at $> 25\,\text{MeV}$) to mitigate radiation damage, shielding requirements, and electronic noise. Low beam loss, aided by the intrinsically large apertures of the cavities and by designing large apertures into the electron-transport system, also permits safe hands-on maintenance. The recirculation lattice is likewise based on a mature design, that was used in the MIT-Bates accelerator.[17]

Principal technical risks are performance of the high-brightness injector and achievement of energy recovery from the high-power electron beam while lasing. Space charge is important along the injector beamline, and the cryounit will be heavily beam-loaded. If cathode lifetime becomes a concern, an alternative cathode or cathode-preparation procedure can be used. Though energy recovery has been demonstrated experimentally,[18] the approach has never been implemented with high-power beam. A scraper is located in the first leg of the first recirculation bend as a precaution against beam loss. Specifications were established that permit the scraper to serve as a diagnostic of the energy distribution and the halo in the electron beam after lasing, in addition to being a safeguard for machine protection.

Coherent synchrotron radiation (CSR) will be present in the magnetic bends and can potentially cause growth in the transverse emittance.[19] Theoretical estimates indicate growths of about 10% in each optical chicane surrounding the wiggler, and about 50% in each recirculation bend.[20] Concerns about CSR-induced beam degradation motivated placement of the wiggler at the exit of the linac rather than following the first recirculation bend, resulting in a correspondingly larger machine footprint. However, the calculations carry considerable uncertainty, and the machine is an ideal platform for CSR experiments. Parametric studies of emittance growth in the bunch decompressor following the wiggler and in the first recirculation arc are planned. Results of the study will be of interest for the other planned srf FELs that incorporate magnetic chicanes for bunching (e.g., the DESY machine) or magnetic bends to direct the beam to the wiggler (e.g., the Drossel machine).

The wiggler location also permits early first light, i.e., 5 μm light at 100 W cw power without energy recovery using a 1.1 mA beam comprising bunches of 60 pC charge. The IR Demo incorporates an upgraded power supply for the klystrons driving the cryomodule. The power supply enables them to run at 8 kW rather than their 5 kW CEBAF specification, permitting operation with higher beam current without energy recovery. Without the upgraded power supply, and in the absence of energy recovery, the average current would have been limited to under 0.7 mA with proportionately lower bunch charge and correspondingly lower laser gain.

The FEL facility that houses the IR Demo and user labs is complete. Construction of the machine is nearly complete, with the balance of installation proceeding through Fall 1997. Injector commissioning began in late September 1997. Key target dates are: Early 1998 for initial data on CSR, Spring 1998 for first light, Summer 1998 for first user experiment, and Fall 1998 for high-power operation.

CONCLUSIONS

Potential advantages of superconducting rf technology for FELs include generation of high average currents for high-average-power FELs, high-brightness electron beams for ultrashort-wavelength FELs, efficient energy recovery from the electron beam, and better energy and phase stability for user applications. These advantages motivated considerable activity to develop the three machines presently in existence. New machines on the horizon include one presently in commissioning and three more projected to be completed within the next two years. They will present opportunities for comprehensively demonstrating the potential of the technology by collectively capitalizing on all of its advantages. In the process, the new machines will likewise provide new opportunities to users requiring high-power light at wavelengths spanning all the way from the far-infrared down to X-rays.

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