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Technical approaches for high-average-power free-electron lasers

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Free-electron-laser (FEL) oscillators have only recently achieved their original promise as producers of high-power, short-wavelength, tunable radiation. Room-temperature accelerator systems have generally had limited duty factor due to excessive Ohmic losses on cavity walls. The application of superconducting radio-frequency (SRF) technology has now permitted an increase by more than two orders of magnitude in FEL average power due just to increased duty factor in continuous-wave operation. A concurrent technical development that leveraged the high efficiency of SRF linacs was the demonstration of beam energy recovery while lasing. This leads to high overall efficiency and scales favorably to systems with even higher average power. This paper will discuss the issues relating to high-average-power light sources. The planned and demonstrated performance of several FEL facilities will illustrate the sizable advantages that superconducting radio frequency offers for high average flux and output multiplexing for several simultaneous users. An important new class of light sources, energy-recovering linacs, will be introduced.

CONTENTS

I. INTRODUCTION

The key components of a free-electron-laser (FEL) oscillator include an electron accelerator and a wiggler (also called an undulator), which "wiggles" the electrons (see Fig. 1). These accelerating charges radiate, and mirrors feed back, the optical power that modulates the electron bunch at the chosen wavelength, introducing amplification, that is, stronger emission or gain until nonlinear processes take over and the system saturates. A portion of the light can be transmitted through one mirror or otherwise outcoupled for use external to the optical cavity. If the gain of the FEL is sufficiently large it may be operated without mirrors in what is called self-amplified spontaneous emission (SASE) mode. This is advantageous for regions of the electromagnetic spectrum where good mirrors do not exist, but it can introduce other issues since the system starts from noise. The radiation appears at a shorter wavelength than the wiggler period, due to the Lorentz transformation of the wiggler to shorter wavelengths in the electron frame and the Doppler shift of the radiation coming back to the lab frame.

The basic physics of the FEL process is well understood. The interaction between the electron beam and the output radiation field in an FEL is mediated by a periodic wiggler magnetic field. As the electron beam traverses the wiggler field it is periodically accelerated transversely and initially emits incoherent radiation. It is necessary for the electron beam to bunch longitudinally to give coherent emission. This can occur when a light wave traverses, with the electrons, an undulatory magnetic field such as a wiggler because the field of the wiggler and the electromagnetic wave combine to produce a beat wave of slowly varying ponderomotive force. It is the inverse of a surfer on an ocean wave: the electrons (in the surfer role) transfer energy to the wave (the electromagnetic field) when they travel at slightly above the (ponderomotive) wave velocity.

To understand how a wiggler and a forward-propagating electromagnetic wave (whose electric and magnetic fields are oriented transversely to the electron beam) give rise to energy extraction and an axial ponderomotive force, consider the particle motion. The wiggler is the predominant influence on the electron trajectories. If the electrons slip back exactly one optical period per wiggler wavelength [the resonance condition described by Eq. (1) below] then when the electrons wiggle, for example, left they can see an electric field in the same direction as their motion. When they then wiggle right in the next half period the electric field has changed direction, too, since it also slipped back a half an optical period, and the motion is again in the direction of the electric field. Thus negative work is always done on the electron by the transverse *electric* field and energy extracted into the field. The interaction between the transverse wiggler-induced velocity with the transverse *magnetic* field of an electromagnetic wave induces

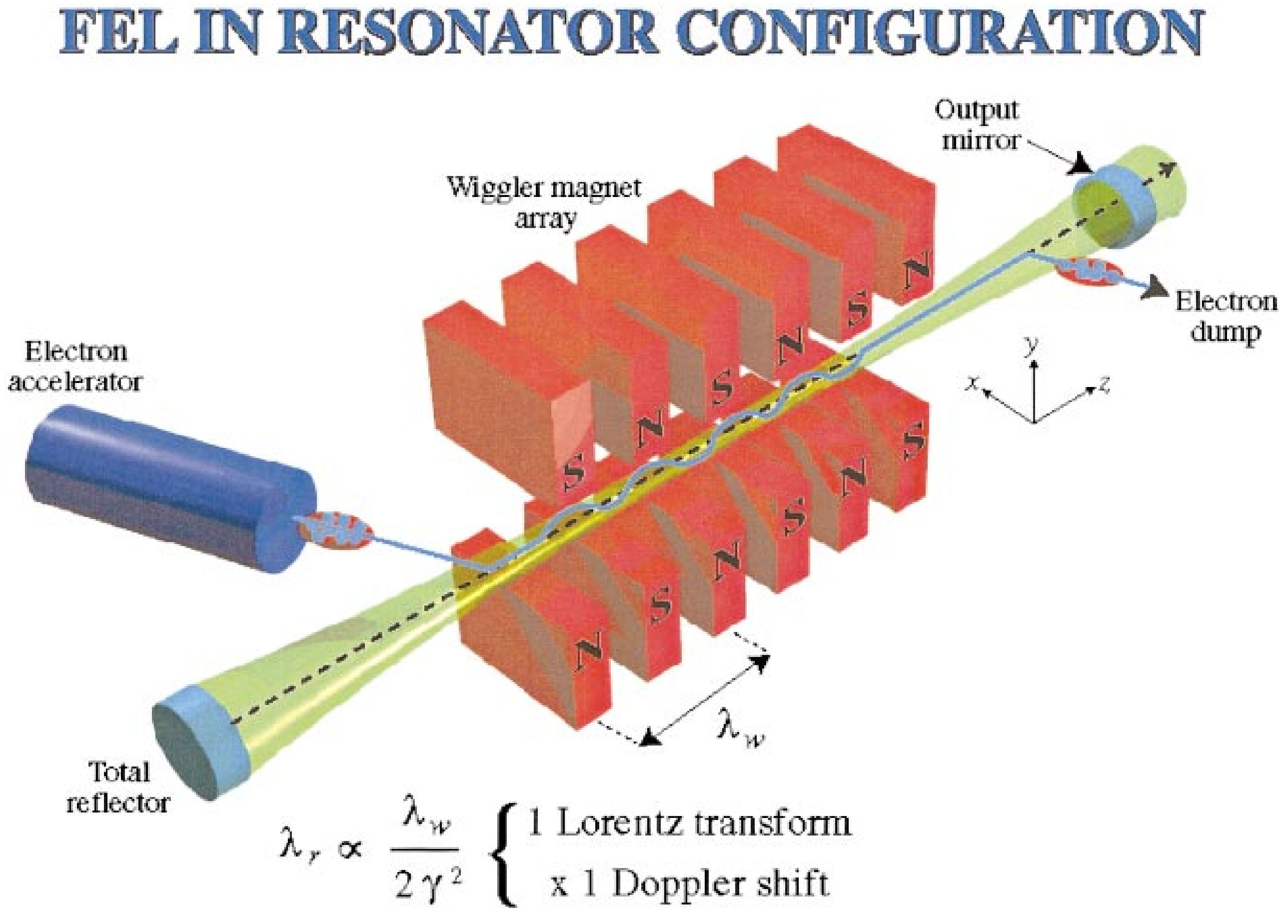

FIG. 1. Components of a free-electron-laser oscillator [Color].

the ponderomotive force normal to both in the axial direction with a period equal to the radiation wavelength. The electrons thus tend to form longitudinal bunches at the optical wavelength, which radiate coherently in the forward direction as they wiggle. As they pass through the wiggler an initially relatively uniform-density bunch of electrons becomes a longitudinal series of tiny nanobunches at the optical wavelength. These oscillate in synchrony to produce coherent forward-directed output.

The physics and technical status of FEL's is covered by the books of Brau (1990) and Freund and Antonsen (1996) and recent review articles (Freund and Neil, 1999; Freund and O'Shea, 2001; Colson *et al.*, 2002), to which we refer the interested reader. This paper will not attempt to replicate that effort but rather discuss those aspects of the physics and accelerator technology important for high-average-power FEL output followed by specific examples of such systems.

Free-electron lasers place stringent demands on the electron beams produced by the driver accelerators. The electron energy must be high to deliver wavelengths as set by the basic FEL resonance equation,

$$\lambda_\gamma = (\lambda_w / 2\gamma^2)(1 + K^2), \tag{1}$$

where λ_γ is the output wavelength, λ_w the wiggler wavelength, γ the electrons' relativistic factor, 1 plus the ratio of the electrons' kinetic energy to their rest mass of 0.511 MeV, and K the wiggler strength parameter. $K = 0.934\, B_{\rm rms}(T)\lambda_w(\rm cm)$ with $B_{\rm rms}$ the wiggler field. Achievable values of field for a given gap depend on the type of wiggler and wavelength. Electromagnetic wigglers typically have lower cost for wavelengths longer than around 5 cm. Hybrid permanent magnet wigglers produce higher K's for wavelengths shorter than around 5 cm due to the difficulty in cooling the coils of electromagnetic wigglers. (In the synchrotron community a distinction is made between wigglers that kick the beam strongly with $K \gg 1$, to produce high harmonics, and undulators with $K \sim 1$ which are optimized for fundamental output. The terms tend to be used interchangeably in the FEL field.)

The FEL requires high peak currents in order to achieve sufficient gain to lase. This charge must be delivered with minimal degradation of the transverse and longitudinal emittances if the high gain is to be preserved. This design challenge becomes especially acute at short wavelengths. The small signal gain of the FEL is given by (Brau, 1988; Dattoli, 1992; Benson, 1994)

$$G = 29.4(I/I_A)(N_w^2/\gamma)B\,\eta_l\eta_f\eta_\mu, \tag{2}$$

where I is the current, I_A is a characteristic current=17 kA, N_w is the number of wiggler periods, and B

$=4\xi[J_0(\xi)-J_1(\xi)]^2$ where $\xi=K^2/[2(1+K^2)]$. The last three terms (η_l,η_f,η_μ) account for emittance and energy spread effects, gain degradation due to imperfect beam overlap, and slippage between the electrons and the optical pulse.

What gain is desirable? That is set in high-power oscillators by the amount of power that mirrors can take, since the power circulating in the cavity is inversely proportional to the outcoupling for a fixed output power. When operation at the kilowatt level and above is considered, the mirror distortions introduced by high average power can be limiting unless the best possible materials and coating technologies are used (Neil *et al.*, 1997; Benson *et al.*, 2000). It is always desirable to maximize the outcoupling fraction consistent with having the saturated gain sufficiently high to provide extraction efficiencies of $\geqslant 1/(4N_w)$. The efficiency can be double this value or more when operating the FEL at the peak of the detuning curve. As for stable operation and optimum efficiency, one typically designs the oscillator to have an outcoupling of about $\frac{1}{3}$ to $\frac{1}{4}$ of the small signal gain.

Given this scaling there are several approaches taken to optimize the system. One can see that Eq. (2) suggests increasing the peak current, increasing the number of wiggler periods, increasing the magnetic field of the wiggler, and lowering the beam energy to increase gain. Each of these has its own limitation that prevents arbitrary increases in the gain.

The maximum peak current that can be achieved is set by the longitudinal emittance of the electron beam and the charge in the bunch. It is now commonplace to perform bunching of the electron beam by riding off the peak of the rf phase, thus providing an energy slew to the electron micropulse. The beam is sent through an electron-beam transport such as a chicane with a path-length/energy correlation. Higher-energy electrons take a shorter path through the chicane and catch up with the earlier, lower-energy electrons by the exit of the chicane to produce a short pulse of high peak current. This can produce sizable peak currents; multikiloamps are planned for the proposed Linac Coherent Light Source (LCLS) device at Stanford in a 200-fs pulse (Cornaccia, 1997). Ultimately this is limited by the intrinsic energy spread, nonlinearities in either the rf field or magnetic transport, or emittance growth due to coherent synchrotron emission (Li, 1999).

Increasing the number of wiggler periods seems like an obvious way to increase the gain but it comes at the price of reduced energy spread acceptance, that is, tighter specifications on the electron-beam longitudinal emittance. Two other factors work specifically against high-power FEL's. One is the saturation efficiency. That goes inversely with N_w as discussed above. The second is the optimization of the optical mode overlap with the electron beam. That drives the optical Rayleigh range longer proportionately to the wiggler length. Since high-power FEL oscillators produce high thermal flux on the cavity mirrors, having a longer Rayleigh range and smaller optical modes on the mirrors is undesirable.

Increasing the wiggler field drives one to longer wavelengths through K in Eq. (1) unless the energy is also increased. This runs counter to the goal of increasing the gain. For high-average-power FEL's, a near optimal situation results if one sets the linac to the highest energy achievable. To maintain gain the wiggler wavelength is shortened until $K\sim 1$ for the shortest-wavelength output desired. Then longer-wavelength operation is accomplished by keeping the beam energy (and power) maximized and increasing the wiggler K by gap adjustment in hybrid wigglers or current in electromagnetic systems.

The option of using microwigglers is considered risky in high-power FEL's because of the need to get very high average currents through the wiggler vacuum chamber without scraping. Experience at Jefferson Lab suggests that the electron-beam loss varies as the square root of the local beta (envelope function) of the matched electron beam in the wiggler divided by the aperture (Douglas, 2000). When the aperture is greater than 20 σ plus a couple of millimeters the losses are essentially zero. Thus a good starting point for a high-power design is to assume $K=1$, and for a desired output wavelength one gets a ratio of (λ_w/γ^2), which one can subject to the above criteria: ability to make $K\sim 1$ at the desired lasing wavelength. There are two additional factors that may push the designer to higher beam energies. One is the desire for higher beam power, the product of the average current and the beam energy. The second is the need to minimize degradation of gain by finite emittance effects.

The last three terms in Eq. (2) are all equal to 1 for perfect electron beams. They account for effects of finite energy spread, and emittance. For optimum coupling to occur the optical beam must overlap the electron beam through the wiggler. In addition, due to finite emittance the betatron motion of electrons in the wiggler causes them to sample variations in the wiggler field, leading to an effective energy spread. This sets a soft limit on the emittance ε of the electron beam for achieving a particular wavelength, given by

$$\varepsilon<\lambda/4\pi,\ \ (\lambda/4\pi)(\beta/L_{1\mathrm{D}}) \tag{3}$$

for oscillators (Brau, 1990) and amplifiers (Xie, 1995). Here β is the matched envelope function of the wiggler and $L_{1\mathrm{D}}$ is the one-dimensional gain length. Since this emittance is equal to the normalized emittance divided by γ, one can, in principle, get to shorter wavelengths by increasing the beam energy to alleviate this restriction.

Likewise the gain of the FEL falls off if the energy spread is too large in both oscillators and amplifiers because the electrons tend to fall out of resonance with the ponderomotive wave:

$$\sigma_E/E<1/(4\pi N_w),\ \ (1/4\pi)(L_{1\mathrm{D}}/\lambda_w). \tag{4}$$

These criteria, though soft, allow for the choice of FEL accelerator performance essentially from first principles.

Additional performance goals are often specified. Exceptional wavelength stability translates directly into a desire for linac energy stability (the wavelength moves 2% for every 1% energy shift). Phase stability requirements of the beam at the wiggler set stability limits on the master oscillator system, the rf phase control, and, through dispersive path-length coupling, the beam energy stability. Treatment of these is beyond the scope of this article except to say that continuous-wave (cw) operation of the linac generally offers significant advantages in phase and amplitude control for stability. We refer the reader to Bohn (1997).

These qualities are desired at high duty factor, either to achieve high average power or to supply light to many different users through a switching system. Superconducting rf technology is uniquely suited to meet these requirements and provide additional benefits besides. We discuss these design drivers in depth below, provide some frequency scaling arguments, and then illustrate their implications by example in several systems.

II. LINAC DESIGN CHOICES

In choosing a linac technology—copper or superconducting rf (SRF)—for an FEL linac there are both physics issues and system level design factors which lead one to the SRF approach when high power or high duty factor is desirable. In this regard the design drivers for high-power FEL's are similar to those of other high-current systems such as B factories, and reviews such as those of Kirchgessner (1993) or Padamsee (2001) offer excellent guidance in design choices. For an introduction to SRF technology see Cornell (2001) and Schwettman (1999). The accelerator physics issues to consider include beam breakup instabilities and transverse and longitudinal wakefield generation. The system level design drivers include continuous-wave operation for high duty factor and/or high average power, and the ability to incorporate energy recovery for reduced capital investment, higher operating efficiency, and reduced operating costs. The physics issues are discussed first, highlighting specifically their frequency dependence.

A. Physics issues and frequency scaling

Every relativistic beam transport system causes some degradation to the electron-beam quality. It is important to ensure that this degradation does not lead to a significant reduction in performance of the FEL. As was shown above there are fairly sharp cliffs beyond which good performance of the FEL is impossible. While one cannot state *a priori* that a particular design choice cannot be made to meet a set of energy spread or emittance criteria, there are guidelines which ease the constraints. These are summarized below; we refer the reader to Merminga, Neil, *et al.* (2001) for a more complete derivation and a detailed discussion of the assumptions involved. We first discuss longitudinal effects, then transverse effects. Finally the issue of beam breakup is introduced.

Wakefields are produced any time a relativistic beam passes through a cavity, aperture, or change in pipe diameter. These longitudinal and transverse electromagnetic waves can excite higher-order modes in the resonant linac structure that can have deleterious effects on the beam properties. Some of these modes may propagate down the beam line; some may be trapped in the cavity to be damped by wall losses or specially designed higher-order mode loads. It is particularly important to ensure that higher-order modes are sufficiently well damped if the cavity modes happen to occur in resonance with the excitation spectrum of the linac pulses.

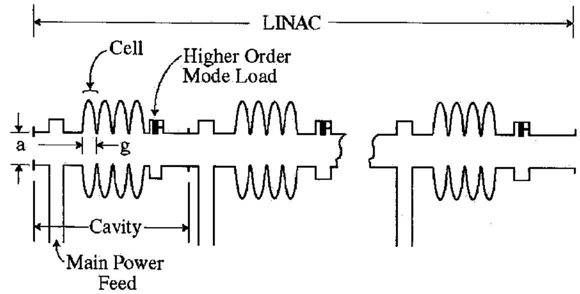

FIG. 2. Illustration of general linac components used in Eqs. (5)–(8).

In a linac, longitudinal wakefields broaden the energy spread of the micropulse charge Q given by $dE \approx 2k_{\parallel}Q$ where $k_{\parallel}$ is the longitudinal loss factor for the accelerator cavity. The value of $k_{\parallel}$ is given in the high frequency limit approximately by $(Z_0 c/2\pi^2 a)\sqrt{g/\sigma}$ where Z_0 is the impedance of free space, c the velocity of light, g the gap, a the aperture, and σ the rms micropulse length. Under a set of assumptions about the rf communication between accelerator cells this energy spread can be shown to scale like

$$dE \sim QN_{\text{cavities}}(gN_{\text{cell}}/\sigma)^{1/2}/a, \tag{5}$$

where N_{cavities} is the number of accelerator cavities in the linac and N_{cell} is the number of cells per cavity. See Fig. 2 for an illustration of the relevant components.

While the micropulse length has no particular dependence on whether the design is copper or SRF, the other terms do depend on this. We need to establish the comparative gradient scaling with frequency between the two systems before we can plot comparisons using Eq. (5). To reach a particular energy requires a certain number of cells and cavities operating at a particular gradient. We have chosen a specific copper cavity design and a SRF cavity design from Kirchgessner (1993) to illustrate the frequency dependencies. For this comparison the wakefield loading of a copper cavity was 0.34 V/pC, while an identical-frequency SRF cavity was 0.11 V/pC. (These low values come from long pulse lengths in B-factory operation. Typical linac values could be almost 100 times higher due to shorter pulse lengths. The copper/SRF relative strength holds for identical pulse lengths.) This is primarily due to the smaller copper cavity aperture chosen to enhance the shunt impedance for rf efficiency. Enhancing the longitudinal impedance carries a concomitant enhancement of the longitudinal wakefield. Since the shunt impedance is not such a design driver for SRF cavities, much larger apertures are generally used.

The maximum gradient achievable depends on frequency and whether the system is pulsed or continuous wave. For copper systems with continuous-wave operation, the gradient limit is set by the cooling capability so the heat flux is held constant as frequency is varied. This results in gradient scaling as $(\text{frequency})^{-1/4}$. In pulsed operation the gradient limit is field emission, which has an entirely different dependence. The operational limits are generally chosen as some factor times the *Kilpatrick limit* (Wangler, 1998) E_{Kp}, given (in transcendental form with E_{Kp} in MV/m and f in MHz), by

$$f = 1.64\ E_{\mathrm{Kp}}^2 e^{-(8.5/E_{\mathrm{Kp}})}. \tag{6}$$

This typically drives continuous-wave copper machines to low frequency and pulsed machines to the highest frequency at which the beam will remain controlled and rf sources are available. A value of 3 MV/m at 405 MHz for continuous wave and 50 MV/m for pulsed operation at 2700 MHz set the absolute scales for illustration in what follows. These should not, however, be considered absolute limits but rather representative parameters. The value for pulsed copper may be optimistic based on recent work on linear collider structures. Higher acceleration than that cited for pulsed copper cavities have caused erosion at the beam aperture in high-frequency structures. At very high frequencies (11.4 and 30 GHz have been tested) this leads to group-velocity-dependent limits on the acceleration field of order 50–70 MV/m, i.e., substantially below the Kilpatrick breakdown projected from Eq. (6). Maximum surface fields in the cavity are four to six times this value. This ongoing area of research is beyond the scope of this article. Status of recent research into copper technology pulsed gradient limits and wakefield effects can be found in the work of Adolphsen *et al.* (2000), Adolphsen (2001), and Snowmass (2001).

For the SRF cavities different factors come into play and in the past the scaling limits for an ensemble of cavities have been dominated by surface imperfections during cw operation (Padamsee, Knobloch, and Hays, 1998). Empirically, the gradient scales as $(\text{surface area})^{-1/4}$. Significant differences are often found between single-cell cavities at a particular frequency and multicell cavities. Reductions in operating gradient are also invoked between vertical test stand data and beam operations in horizontal cryostats. As surface cleaning techniques and the quality of niobium have improved, these scaling limits have become less clear. There are many examples now of high gradient cavities at low frequencies that exceed previously believed limits by substantial margins (Fig. 3). See Padamsee (2001) and Cornell (2001) for SRF technology. Especially in an active research field such as SRF it is worth checking the latest proceedings of the (biennial in odd years) International Conference on RF Superconductivity for the latest results (SRF, 1999; SRF, 2001). There should be still further improvement as one goes to higher frequencies, and so we have conservatively chosen a linear scaling with frequency to illustrate the beam scaling factors, but when the true limits are discovered these curves should be updated appropriately.

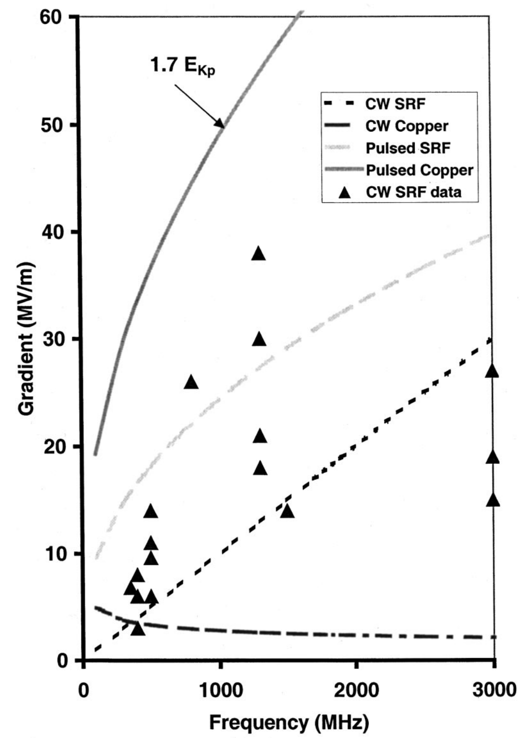

FIG. 3. Gradient limits for pulsed and continuous-wave copper and superconductive rf (SRF) linacs assumed in the stability calculations below with some illustrative recent SRF results. E_{Kp} is the Kilpatrick limit specified in Eq. (6).

The difference in limits between pulsed and continuous-wave operation are not as clearly established as in the case of copper machines but factors of 2 differences between cw and pulsed operation have been seen. It seems likely that SRF cavities are subject to Kilpatrick limits just as copper machines are, although the care with which SRF cavities are generally treated and the excellent vacuum environment suggests that different safety factors may be applied. There are only a few experimential data available so a value of half the pulsed gradient limit of copper cavities at the same frequency was used. One example is the Tesla Test Facility (TTF; Rossbach, 2001) design value of 24 MV/m for their nine-cell 1300-MHz cavity. A pulsed copper cavity at this frequency could operate at 55 MV/m. This choice should be revisited as further data become available. Care should be used in applying these results since there are many cavity parameters that depend on operating conditions and could materially affect the results. Nonetheless, it is a useful starting point for system trades. Figure 3 shows the gradient limits assumed in the stability illustrations that follow.

With the above gradient scaling we are now prepared to make a system comparison using Eq. (5). Figure 4 shows the longitudinal frequency scaling for copper and SRF machines operating pulsed or cw. It is clear from the curves that no particular wakefield advantage for SRF exists if operating at low duty factor, due to the high gradients that copper machines can achieve. Continuous-wave operation brings a sizable competitive

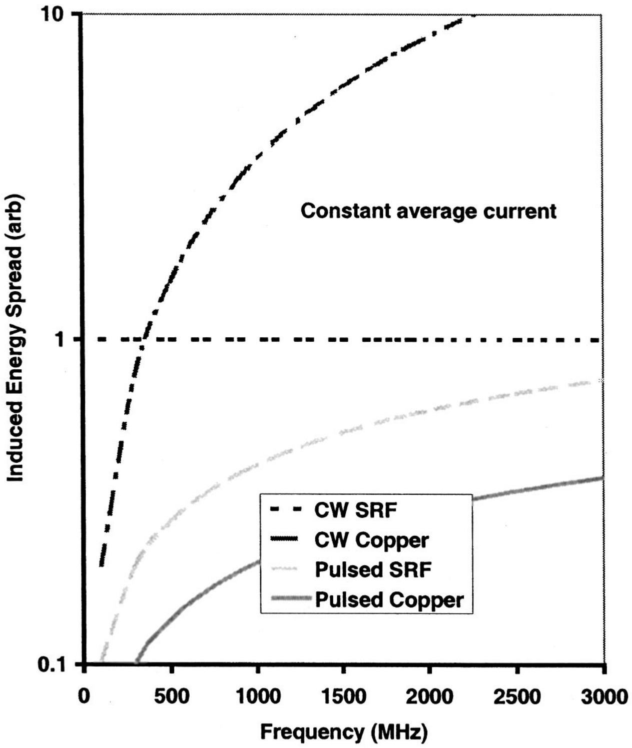

FIG. 4. Total longitudinal heating in arbitrary units as a function of frequency. The scaling has assumed a fixed total energy $\langle I \rangle$, R/Q's for each system are the values quoted in the text, and micropulse length and cavity geometry $\sim 1/f$. This illustrates the frequency dependence in Eq. (5).

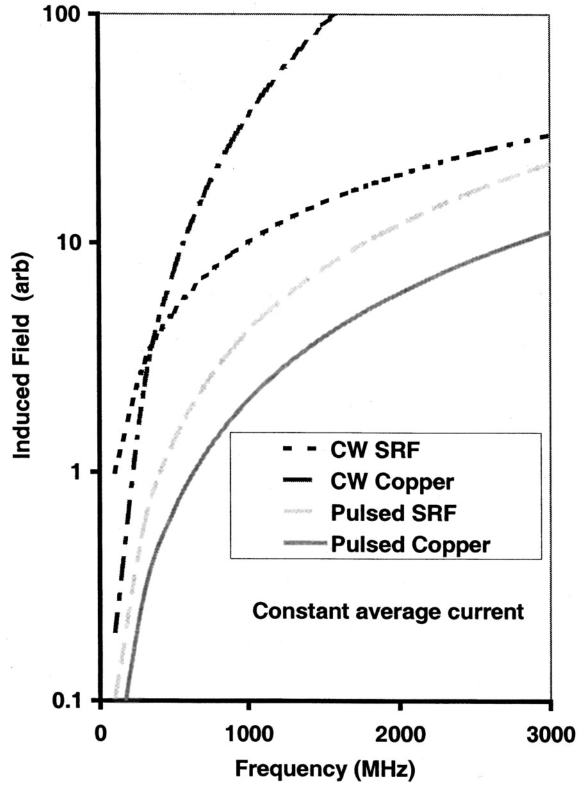

FIG. 5. Transverse heating in arbitrary units as a function of frequency. Similar assumptions to those in Fig. 3. The field excited in transverse modes depends on the beam offset, but this illustrates the frequency dependence in Eq. (7).

advantage to SRF linacs in terms of minimizing beam degradation by longitudinal effects. See Bisognano and Fripp (1989) for details on the requirements that must be met. In addition longitudinal modes may generate significant power, which can be destructive to machine components or thermally load the cryogenic system. This power must be extracted in an efficient way (Baboi *et al.*, 2000; Joestingmeier *et al.*, 2000; Merminga *et al.*, 2000).

Transverse modes, cavity modes with deflecting fields, affect both single bunches and the multibunch beam train by increasing the emittance and under certain conditions, by inducing unstable behavior. It is inevitable that the beam and cavity axis not be perfectly aligned, and the deflecting fields are proportional to the product of the beam current and the distance off-axis. The proportionality constant is called the *transverse impedance*. We discuss emittance degradation effects on a single bunch first.

The transverse impedance of a single cavity is given by $k_\perp \approx (Z_0 c/4\pi a^3)\sqrt{\pi g \sigma}$ in the high frequency limit. The fractional emittance degradation due to transverse wakefields can be expressed as

$$\frac{d\varepsilon}{\varepsilon} = \frac{x_0 \eta}{2\pi}\sqrt{\frac{\gamma_i}{\beta \varepsilon_n}} \quad \text{for small} \quad \eta, \tag{7}$$

where x_0 is the beam offset, γ_i is the entering beam relativistic factor, β is the local betatron function $(2\pi/k_\beta)$, and ε_n is the normalized emittance. To deal with the impedance of an ensemble of cavities Chao *et al.* (1980) derive an expression for η that is proportional the total transverse impedance of the linac per unit length $(k_\perp/l)$ assuming no emittance compensation schemes between the initial (E_i) and final energy (E_f):

$$\eta \approx \frac{6Q(k_\perp/l)L_{\text{acc}}}{k_\beta(E_f - E_i)} \ln\left(1 + \frac{E_f - E_i}{E_i}\right). \tag{8}$$

The expression for the single cavity $k_\perp$ can be extrapolated to a multicell structure (Merminga, Neil, *et al.*, 2001) by accounting for rf interference between cells. One obtains

$$\eta \approx (6/\sqrt{N_{\text{cell}}})(Q/a^3)(\pi\sigma/g)^{1/2} L_{\text{acc}} \tag{9}$$

up to $N_{\text{eff}} = ka^2/l_{\text{cav}}$, the number of cells that contribute to the effect. Here L_{acc} is the linac length, l_{cav} the cavity length, and k is the wave number of the crucial mode. Figure 5 illustrates the results of this transverse scaling versus frequency. Again there is no particular advantage to SRF operating pulsed. In cw operation the copper cavities can never overcome the severe handicap given by the small apertures in the system.

Finally, the effects on the bunch train are considered. Insufficiently damped transverse higher-order modes can interact with the beam in a recirculating linac and induce a multibunch beam breakup (BBU) instability (Bisognano and Gluckstern, 1987; Krafft and Bisognano, 1987). The instability can arise when a bunch excites a transverse mode. This and subsequent pulses get kicked by the deflecting field and can return after recirculation with an enhanced offset from the axis. The return pulses passing through the cavity at this increased offset further amplify the transverse mode, provided the pulses have an appropriate phase relationship. If the net amplification is greater than the damping of the mode, then an instability occurs. The specific current threshold for regenerative BBU to occur is lattice dependent, but that decision is essentially independent of copper versus SRF technology and so is ignored. We also ignore pulsed systems since regenerative BBU has little time to grow in a pulsed system, and recirculating a pulsed beam generally offers little advantage. The estimated threshold for BBU scales as (Merminga, Neil, *et al.*, 2001)

$$I_{\rm th} \sim 1/[\omega^2 \times L_{\rm acc} \times Q_{\rm HOM}]. \tag{10}$$

$Q_{\rm HOM}$ refers to the quality factor Q of a particular higher-order mode.

From Eq. (10) if $Q_{\rm HOM}$ is damped then the threshold is higher. Damping of the higher-order modes may be required for a cw high-average-current machine; otherwise the fields can build up to levels that are destructive to the beam. The specifics of what is required depend not only on the cavity and its damping but also on the electron transport details, the rf feedback in the system, and the micropulse frequency. Partially benchmarked analytical treatments and simulation codes exist to calculate specific BBU thresholds that can be applied to a particular design (Krafft and Bisognano, 1987). This goes beyond the scope of this review; we refer the reader to Merminga *et al.* (1999) and Merminga, Campisi, *et al.*, (2001). Nonetheless some general guidance as to frequency dependence can be given based on Eq. (10). The benefit to SRF operating cw is shown in Fig. 6.

It is also clear from Figs. 4–6 that if cw operation is desired then there is a significant impetus toward lower frequencies. On the other hand the high gradients achievable at 1.3 GHz in SRF and the technological maturity there permit cost-effective system designs with 100-mA average currents, more than sufficient for most applications. At the lowest frequencies copper cavities become competitive in terms of physics performance.

B. System implications

Operation in a continuous-wave mode is natural for SRF systems. The low wall losses and large Q's mean the small penalties in providing refrigeration for operating a machine cw are offset by the relative ease with which cw radio frequency can be generated and controlled with feedback. In comparison to typical copper machines, which operate at 10^{-3} duty factor, operating cw can provide sizable increases in FEL output power without invoking new laser physics. This is best illustrated by Fig. 7, which shows the operation barrier reached by FEL's before the availability of cw operation in SRF machines. Such a breakthrough in technical approach is expected to produce not only further power advances but in the reasonably near future a fourth-generation x-ray user facility providing coherent light to many end stations at fluences five orders of magnitude or more higher than are available today!

As a second benefit the SRF machine offers the clean and stable transport of a larger average current. This

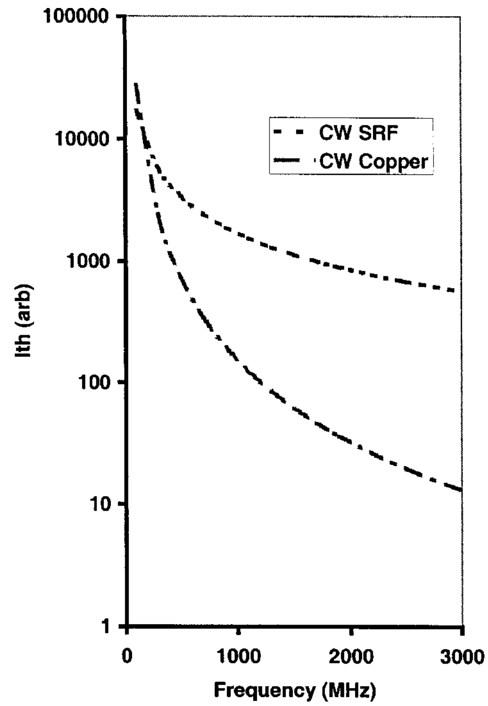

FIG. 6. Beam breakup (BBU) limits as a function of frequency. The thresholds are design dependent but the frequency scaling applies for a specific transport design. Based on Eq. (10) in the text.

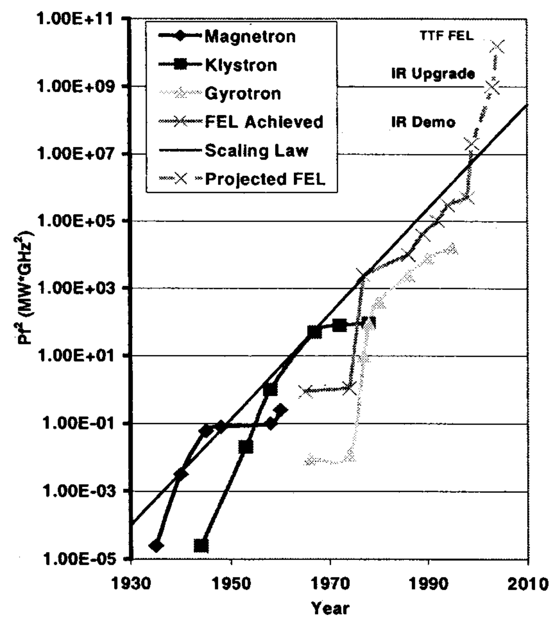

FIG. 7. A time history of progress in electron-operated radiation devices. Projected performance of the Jefferson Laboratory IR upgrade and the Tesla Test Facility free-electron laser are also shown. Adapted from Freund and Neil, 1999.

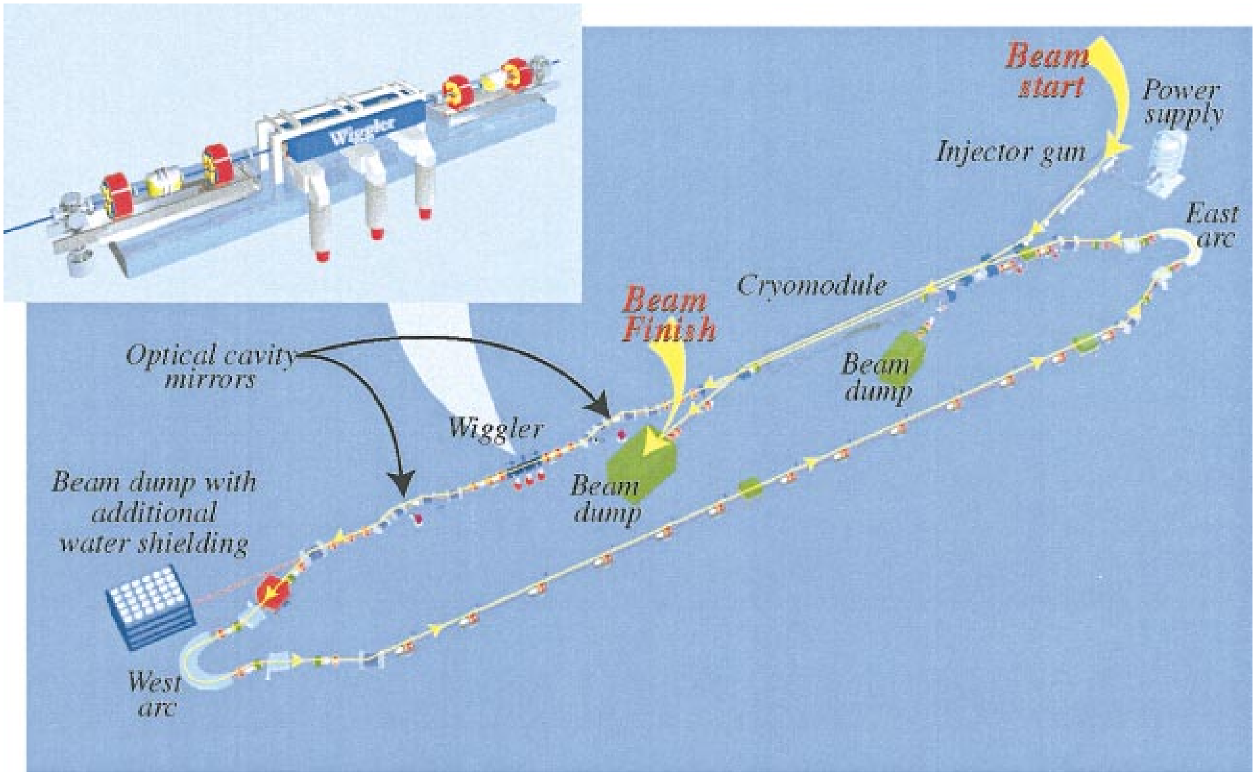

FIG. 8. A layout of the IR demonstration FEL at Thomas Jefferson National Accelerator Facility (Jefferson Laboratory). The distance between recirculation arcs is approximately 30 m. A more compact system would result from placing the wiggler in the return leg, but this was not done in the initial configuration due to fear of emittance growth induced by coherent synchrotron radiation (see Bohn, 1997). That effect has now been shown to be inconsequential for this system's operational parameters [Color].

capability may be put to effective use by recirculating the beam to higher energies in one linac (the approach that CEBAF uses to get a 5-GeV beam from 1 GeV of linac) or operating the return pass 180° out of rf phase to decelerate the beam and convert back its power. Such a technique was proposed in 1965 (Tigner, 1965) and used with FEL lasing in a copper accelerator but utilizing a second accelerator to decelerate the beam and couplers to feed the energy back to the first structure (Feldman *et al.*, 1987). Instabilities were observed under some operating conditions. The technique of same-cell energy recovery has also been demonstrated without lasing (Smith, 1987) and more recently while lasing (Neil *et al.*, 2000).

A schematic representation of the infrared demonstration FEL at Thomas Jefferson National Accelerator is shown in Fig. 8. The FEL is placed at the exit of the linac, and the electron beam is deflected around the two optical cavity mirrors into a recirculation loop based on the isochronous achromats used in the Bates accelerator (Flanz and Sargent, 1985). This path allows the electron beam to be recirculated for energy recovery and decelerated to a 10-MeV dump (Laser Processing Consortium, 1995; Neuffer *et al.*, 1996).

Several technical issues must addressed to take advantage of such an energy recovery approach: stability of the electron beam, stability of the lasing process in such an energy-recovered system, management of transport of large-energy-spread beams with low beam loss, and minimization of emittance growth induced by coherent synchrotron radiation. These were all successfully handled by design optimizations as discussed in the references (Douglas, 1997; Campisi *et al.*, 1999; Merminga *et al.*, 1999). The cost of the recirculation arcs, while significant, is less than the rf savings.

III. HIGH-POWER COHERENT LIGHT SOURCES

Table I lists the operational and planned SRF free-electron-laser facilities around the world (see Colson, 1999, for a complete listing of short-wavelength FEL's; a link to many facilities is UCSB, 2001). Progress in this area has been steady and encouraging. There are now five operational SRF FEL facilities around the world, and of those two are user facilities where outside researchers can perform photonics research using the FEL (see BES, 1999, and DOE, 2000, for a summary of proposed applications of FEL light and Colson *et al.*, 2002, for some recent application highlights). Substantial advantages are gained through the use of the SRF technology in applications directed toward high-duty-factor user facilities. Below are several examples of operational and planned high-power SRF facilities and one counter-example of a high-power, room-temperature, recirculating, energy-recovering system under construction.

TABLE I. A listing of the superconducting rf free-electron-laser facilities around the world. Those in italics are in construction or commissioning. The operating range is shown under the column heading λ, τ_p refers to the rms micropulse length, E_b/I_b is the beam energy/peak micropulse current, $P_{\rm peak}$ and $P_{\rm avg}$ are the micropulse peak and macropulse average power, and under the accelerator frequency column is indicated whether the machine is operated in a macropulsed or continuous-wave mode.

Country	Institution	Device	λ(μm)	τ_p(ps)	E_b/I_b (MeV/A)	$P_{\rm peak}$ (MW)	$P_{\rm avg}$ (W)	Accelerator freq. (MHz)
USA	Stanford U	FIREFLY	15–85	2–10	20/14	.3	.4	1300 pulsed (*cw*)
		SCA/FEL	3–15	0.7–3	37/10	10	1.2	1300 pulsed (*cw*)
	JLab	IR Demo	3–8	0.2–2	48/60	25	1700	1497 cw
		IR/UV upgrade	*.2–25*	*0.5–2*	*160/100*	*150*	*10 000*	1497 cw
Germany	*Rossendorf*	*ELBE*	*5–150*	*1–2*	*40/50*			*1300 cw*
	DESY	*TTF FEL*	*0.04–0.2*	*.8*	*390/500*	*2000*	*7200*	*1300 pulsed*
	Darmstadt	S-DLINAC	6–8	2	50/2.7	.15	3	3000 cw
Japan	JAERI	SCARLET	21–30	10	20/30	1	0.2	500 pulsed (*cw*)

A. The Jefferson Laboratory IR Demo free-electron laser

The IR demonstration FEL at Thomas Jefferson National Accelerator Facility in Newport News, Virginia was completed in September 1998. The injector is the critical technology for operation of systems such as this; it must produce high average currents at high brightness. Although a SRF photocathode gun like that under development in Dresden (Janssen *et al.*, 1997) may ultimately be the most desirable, this system utilizes a dc photocathode operating at 320 kV to produce a 74.85-MHz pulse train of 60 pC (Engwall *et al.*, 1997).

This gun produces the highest average brightness of any injector gun in the world. The cathode of this device has delivered in excess of 5.3 kC from a single GaAs crystal, with only occasional cleaning and re-cesiations (Siggins *et al.*, 2001) required in its two-and-a-half-year life. It regularly delivers over 1% quantum efficiency operating in the green from a doubled Nd:YLF laser beam. The 20-ps beam is bunched by a copper fundamental cavity to around 3 ps and accelerated to 9.5 MeV in an SRF cavity pair operating at 1497 MHz. The beam is then accelerated to between 36 and 48 MeV in a slightly modified CEBAF cryomodule.[1] The beam is bent around the optical cavity mirror in a chicane, compressed by the chicane dispersion working on a slight energy slew of the micropulse, and sent through the wiggler with roughly 60 A peak current in a micropulse of less than 1 ps full width at half maximum (FWHM). Approximately 0.5% of the electron-beam FEL energy is extracted in the NdBFe hybrid wiggler with 41 periods of 2.7 cm. The waste beam now has a large energy spread; full width can exceed 6%. Nonetheless, the beam is brought around the second mirror in an identical chicane, then through a 180° arc based on the Bates design (Flanz and Sargent, 1985). A FODO lattice[2] brings the beam to another arc and the beam is reinjected to the accelerator in the deceleration phase of the rf. As the beam decelerates, its energy spread is compressed by the sinusoidal rf field variation sampled over the finite pulse length. The resultant beam is dumped at 10 MeV, now with less than 6% full energy spread.

When operated without energy recovery the beam current is limited by rf power to 1.1 mA average, producing over 300 W from the FEL. In recirculation mode the recovered beam energy permits operation to the average current limit of the gun's high-voltage power supply, 5 mA. Figure 9 shows the measured rf power in several cavities, illustrating the independence of rf power on accelerated current. Nearly 250 kW of electron-beam power is being generated from 66 kW of rf without the limitations of electron cooling time or instabilities that would occur in a storage ring system.

The motivation to use energy recovery as a key feature in the IR Demo design was to demonstrate the efficient and cost-effective scalability of the system to very high average powers (Benson *et al.*, 1999). Because of the low electron-beam energy (48 MeV) it does not yet substantially improve the FEL wall plug efficiency (only 2× to 3×). The tables show ac power use, but it should be emphasized that several subsystems (including rf) have not been optimized for low power consumption. For the Jefferson Laboratory IR upgrade scaleup to 10 mA, 160 MeV presently under construction, energy recovery will improve system performance by roughly 78%, reducing ac power draw from ~4700 kW to ~1075 kW. The required rf generation by klystrons will be reduced by over 1700 kW, saving over $5 million in capital costs. These factors become even more significant at the power of an industrially useful device (~100 kW). See Tables II and III.

[1]This is a 1.3-GHz cryogenic accelerator module used in the Continuous Electron Beam Accelerator Facility, as the Jefferson National Accelerator was originally named.

[2]A FODO lattice is an arrangement of quadrupole magnets along the beam line in the following order: focusing quadrupole (F), drift space with no focusing (O), defocusing quadrupole (D), another drift space (O).

TABLE II. ac wall plug powers with and without energy recovery (ER) of the IR demonstration FEL at Thomas Jefferson National Accelerator Facility.

	With ER	Without ER
Injector rf	220 kW	220 kW
Linac rf	175 kW	700 kW
He refrigerator	70 kW (est.)	70 kW (est.)
Magnets, computers, etc.	43 kW	23 kW
Total	508 kW	1013 kW

TABLE III. 10-kW upgrade and 100-kW industrial prototype ac wall plug powers with and without energy recovery (ER)

	Upgrade with ER	Upgrade without ER	Prototype with ER
Injector dc & rf	350 kW	350 kW	1550 kW
Linac rf	525 kW	4200 kW	525 kW
He refrigerator	100 kW (est.)	100 kW (est.)	100 kW
Magnets, computers, etc.	100 kW	100 kW	40 kW
Total	1075 kW	4690 kW	2275 kW

The use of energy recovery brings additional benefits to the IR Demo beyond reducing the rf capital cost and improving the system's electrical efficiency:

(1) It reduces the dissipated power in the beam dumps by a factor of more than 4. The electron beam is transported with virtually no losses to the dump, so the power that must be handled on the dump face is reduced by the energy ratio (10 MeV/48 MeV=0.21) down to 50 kW from 240 kW. The IR upgrade advantage is even more striking: a reduction to 100 kW from 1600 kW.

(2) It virtually eliminates induced radioactivity in the dump region by dropping the terminal energy below the photoneutron production threshold. For a copper beam dump, reducing the energy to below 10 MeV can essentially eliminate the neutron production which activates surrounding components. Operating experience on the IR Demo has reduced radiation backgrounds during energy-recovered running by 10^4 or more.

The laser has produced up to 2.1 kW at 3 μm, 150 times the cw average power of any other FEL. The wavelength produced by the FEL is controlled by tuning the electron-beam energy but suitable mirrors must be used for each wavelength band. To date the system has lased in three primary wavelength bands, around 3, 5, and 6 μm as shown in Fig. 10. In addition, the system has produced 4 W of power lasing on the fifth harmonic at 1 μm. It can produce significant amounts of power at the third harmonic. Recent tests have shown the ability to produce 300 W continuously in this mode (Benson *et al.*, 1999) and, even beyond this, conversion to green and UV at high efficiency in doubling, tripling, and quadrupling crystals. Up to 10^9 photons/sec of Thompson-scattered x rays in the 5–15-keV range are produced when the FEL pulse scatters off the subsequent electron bunch (Boyce, 2000). The system also synchronously produces $>10^4$ more THz power (50 W) in subpicosecond pulses than any other source in the world (Carr *et al.*, 2002).

An upgrade to the system is underway to establish lasing at 1 μm and increase the power to >10 kW (see Fig. 11). The system will be similar in layout but utilize three cryomodules, including a new upgraded cryomodule with 40% more active length and high gradient capability. The addition of a short-wavelength optimized wiggler and second optical cavity will also permit multikilowatt average power operation in the ultraviolet.

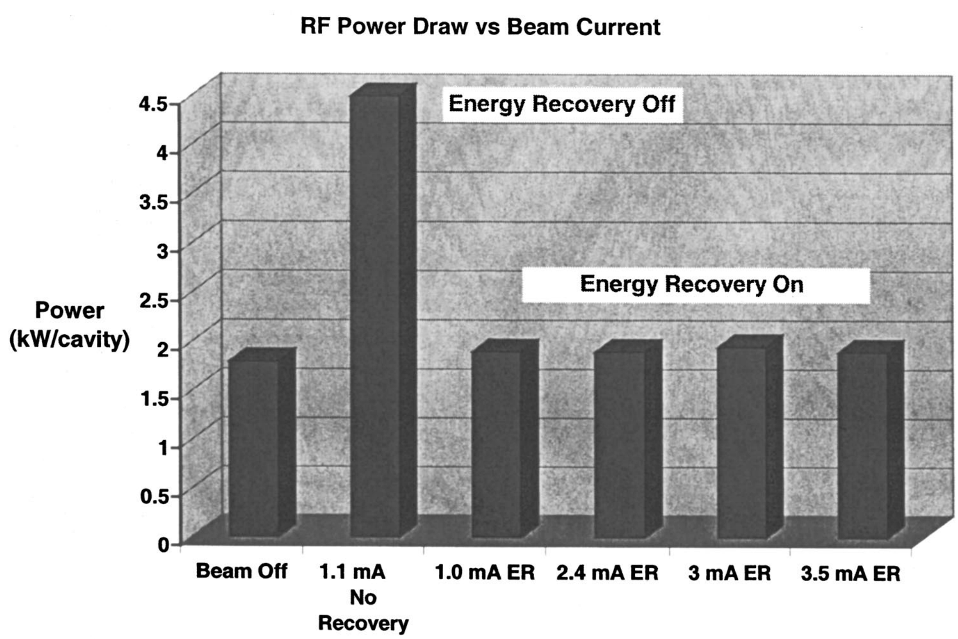

FIG. 9. Measured average rf power to each linac cavity with and without energy recovery as a function of current. At zero current power is still required to establish the acceleration fields in the cavity (in equilibrium the power is reflected back to a load, except for a minor amount which gets dissipated on the cavity walls), but no additional power is required as current is increased provided energy recovery is utilized.

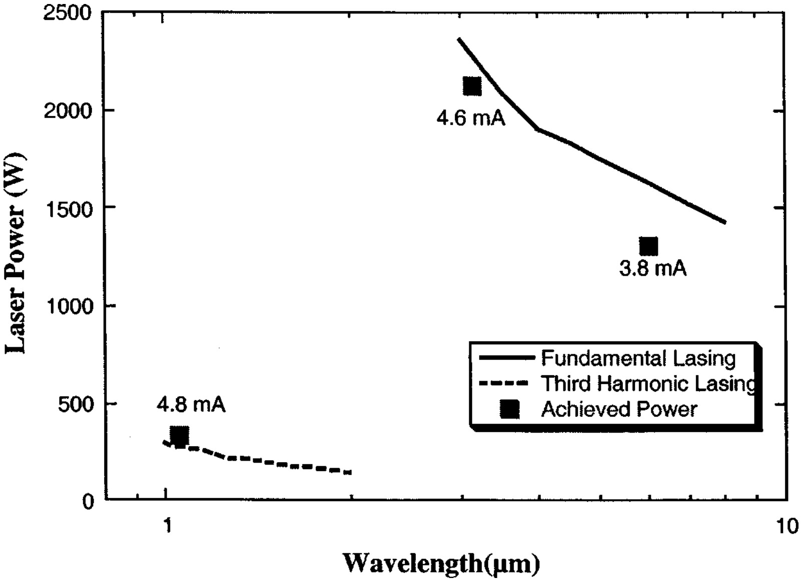

FIG. 10. Projected and achieved performance of the IR demonstration FEL at Jefferson Laboratory. The full available performance can be achieved by using specialized mirrors for each wavelength band. Calculations by S. Benson.

B. The JAERI free-electron laser

Efforts are underway for an upgrade of the Japan Atomic Energy Research Institute (JAERI) FEL to high duty factor (Minehara *et al.*, 2000a, 2000b). This machine has already lased at over 2.3 kW in a 1-ms macropulse mode at 10 Hz and there are plans to incorporate energy recovery and other modifications to permit full cw operation. The linac accelerates 4 mA at 15.8 MeV. One of the interesting things about this system is the use of solid-state rf power, which is made feasible by 500-MHz operation. Because of the low-frequency cavities in the system it is quite feasible to plan for operation at very high average currents; eventually outputs of 100 kW for industrial applications are envisioned. The system uses a 230-kV triode thermionic gun to produce over 0.51 nC in a 0.81-ns pulse at 10.4 MHz. The injector has a 83.3-MHz normal conducting subharmonic buncher followed by two single-cell SRF cavities at 499.8 MHz. Final compressed pulse width is 5 ps FWHM for 100-A peak current within a 20 π mm mrad normalized emittance. Extraction efficiency of the FEL has been as high as 6%, a record for oscillators at short wavelength. The system is unique in having demonstrated stable lasing at zero desynchronism (Hajima *et al.*, 2001). The wiggler is a 52-period 1.7-m-long hybrid wiggler with $K = 0.7$. They utilize copper cavity mirrors with a scraper outcoupler for a broad tuning range. Present efforts are focussed on incorporation of energy recovery and production of 40 kW of light at 1.3 μm for industrial applications using several tens of mA of electron-beam current. In this mode the beam will operate cw.

C. The Stanford Superconducting Accelerator free-electron lasers

The original FEL oscillator work was performed on the Stanford Superconducting Accelerator (Deacon *et al.*, 1977) and since that time the facility has been a center for research into FEL's and their application (Schwettman, Smith, and Swent, 1996; Smith, 1999). The focus of the facility over the last decade has been the utilization of the FEL with a wide range of other laser

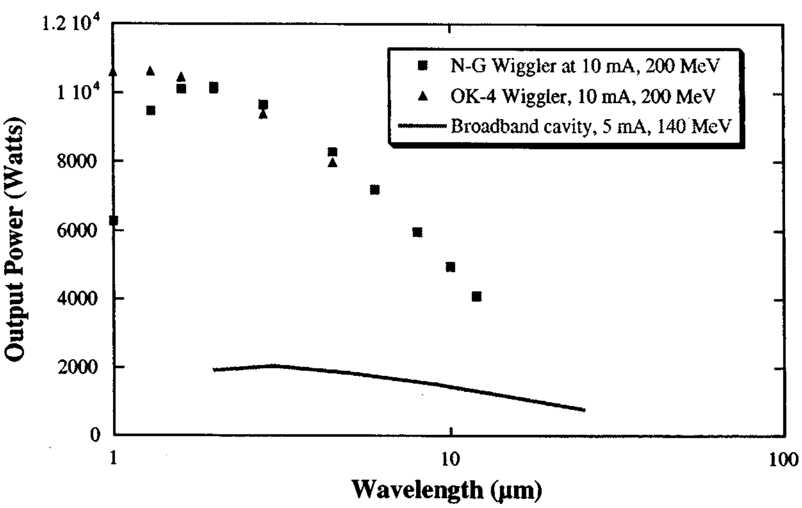

FIG. 11. Projected performance of the IR upgrade with two electromagetic wigglers: N-G, a 20-cm-period optical klystron donated to JLab by Northrup-Grumman, and the OK-4 10-cm-period optical klystron built at Novosibirsk and currently in use at Duke University. Operation with a broadband optical cavity is at lower power because of higher mirror absorption. Calculations by S. Benson.

sources to perform materials research with picosecond pulses. The accelerator itself was pioneering in its use of rf superconductivity and was the genesis of the major programs around the world today. At present two FEL's are installed on the linac. An initial set of 1.3-GHz accelerator structures bring the beam to around 20 MeV, where it traverses a magnetic chicane, then passes through a far-infrared (FIR) wiggler. It then undergoes acceleration by two more accelerator structures before entering a mid-infrared (MIR) FEL. The FIR system produces 1 W of 15–85-μm light from a tunable 25-period electromagnetic wiggler. The optical cavity is very long on this device, with the second mirror upstairs in a user lab to permit intracavity experiments. The MIR system produces 2 W in the 3–15-μm range from a 12.68-m optical cavity around a 72-period hybrid wiggler of 31-mm wavelength. The FEL's can be made to lase on alternating macropulses with essentially independent control of the optical output. Several other laser sources are synchronized with the FEL for pump/probe studies in the user labs.

Both FEL's produce picosecond pulses (0.7–3 ps for the MIR and 2–10 ps for the FIR) at an 84.6-ns interpulse spacing in a macropulse of up to 5 ms pulse width at 20 Hz. They are exceptionally stable, with 0.01% rms spectral jitter and less than 2% rms amplitude jitter. The present linac uses cavity designs from the 1970s and limits the operation to macropulses because of regenerative field emission in the cavities (multipacting). As a result the facility is currently undergoing a major upgrade to cw operation by replacing the cavities with DESY-style modules. Initial testing of the structures is underway. The beam current from the gridded gun thermionic injector should increase by a factor of 5 to 1 mA, operate in a continuous-wave mode, and permit the production of up to 500 W in the far infrared.

D. The ELBE free-electron laser

The Rossendorf ELBE (for **EL**ektronenbeschleuniger der quasikontinuierliche (cw) Strahlen von hoher **B**rillanz und geringer **E**mittanz liefert, that is, an **E**lectron **L**inac that will produce quasicontinuous (cw) beams of high **B**rilliance and low **E**mittance) is under construction in Dresden, Germany (Bucher *et al.*, 1999). This machine is a 40-MeV superconducting accelerator utilizing 1.3-GHz DESY-style cavities. The layout is patterned after the pioneering Stanford Superconducting Accelerator FEL's. Four nine-cell cavities, each powered by 10-kW klystrons divided between two cryostats, operate at up to 15 MV/m gradient. The large apertures of 70 mm yield comfortable alignment tolerances and negligible wakefield production. Energies from 12 to 40 MeV are envisioned, producing radiation outputs ranging from 5 to 150 μm. An electromagnetic wiggler is planned for long-wavelength output and a separate section with undulator units of the DESY TTF-FEL design (see discussion below) are to be installed. They will be set up with a variable gap and even tapering permitted. The initial gun is a relatively conventional 250-kV thermionic one producing 85 pC per pulse at 11.8 MHz with 1.6 mm mrad normalized emittance. At the entrance of the first superconducting cavity (=exit of the injector), the transversal emittance of the standard gun is about 13 π mm mrad, whereas the longitudinal emittance is up to about 50 π keV°.

An advanced SRF gun (Barhels *et al.*, 2000) has been tested without the cathode to gradients of 31.8 MV/m, and it is expected that the excellent vacuum surrounding the cathode material due to cryopumping at LHe temperatures will provide substantially enhanced cathode life [work on the photogun at Jefferson Laboratory has shown the ultimate cathode lifetime limitation is back bombardment of ions produced from residual background gas by the electron stream (Siggins *et al.*, 2001)]. A 3.5-cell geometry is expected to operate with the cathode at 18 MV/m and produce a 10-MeV beam (Janssen, 1997). To overcome the inability to impose a compensating magnetic field in the rf cavity, the cavity shape has been altered from the basic TESLA design to have a conical back wall. This provides equivalent rf focusing. Key technical questions that will be answered soon include the loss of Q due to the cathode insertion, the ability of the cathode mount choke joint to survive the high circulating currents, and any poisoning of the cavity walls by the cathode material.

E. Fourth-generation light sources and the TTF free-electron laser

There are a number of groups investigating the exciting prospect of using self-amplified spontaneous-emission FEL's to produce coherent vacuum ultraviolet (vuv) and ultimately x-ray light (see Pellegrini, 2001, and Rossbach, 2001 for status reports). This technology has made substantial progress, working its way into the vuv with the limitation set by accelerator energy and electron beam brightness. The former is a matter of adding additional acceleration while the latter is the focus of a number of research efforts. Major efforts are underway at the Stanford Linear Accelerator Center (LCLS, 1998; Emma, 2001), Brookhaven National Laboratory (Yu, 2000; Wang, 2001), Argonne National Laboratory (Milton *et al.*, 2000, 2001), and the Deutsches Elektronen-Synchrotron (DESY) (Rossbach, 1996; Andruszkow *et al.*, 2000). For details on the updated design see also Materlik and Tschenscher (2001). These will lead to several user light sources with high peak brilliances in wavelength regions that are currently inaccessible. Since most of them are not specifically directed toward high average flux production but rather exceptional peak powers, their specifics lie outside the scope of this paper. The reader is directed to the references for the design and performance.

The Tesla Test Facility (TTF) free-electron laser is an SRF-based system heading directly toward a user facility. It is now in commissioning at DESY (Rossbach, 2001), and produced substantial gain in the UV already, and has the prospect of producing high repetition rates. While SRF technology is not required to reach the short

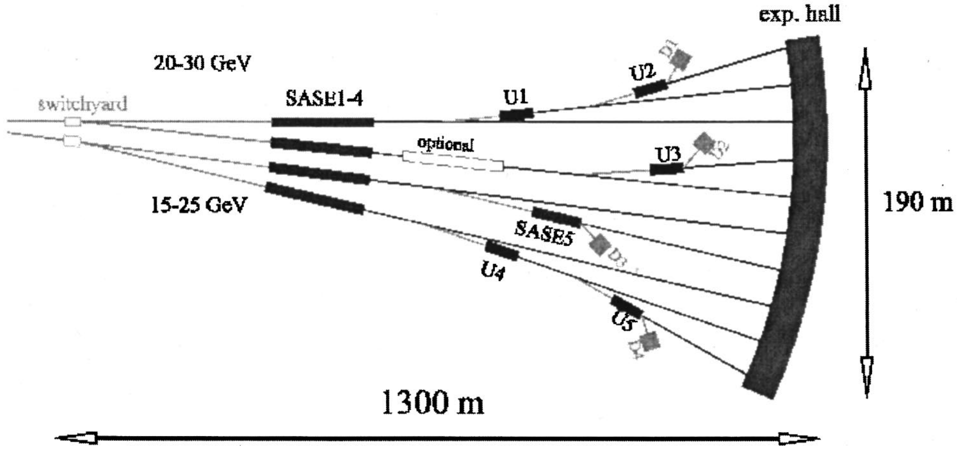

FIG. 12. The proposed beam switchyard layout of the Tesla Test Facility (TTF) FEL. Multiple wigglers permit rapid switching between users. In some cases the spontaneous emission from undulators is utilized without SASE lasing as indicated under U1 to U5. Figure courtesy of J. Rossbach.

wavelengths, its use is essential for a fourth-generation user facility to achieve the duty factor necessary to service many users. The concept is to switch the beam among a farm of wigglers with a user experiment at the output of each, as shown in Fig. 12.

The brightness produced from this device in coherent subpicosecond pulses goes orders of magnitude beyond what is currently available (see Fig. 13). Initial full capability of the machine will be 40 nm; beam is already being produced in a section of the linac and ground-breaking demonstrations of amplification are underway in the vuv region. The desired wavelength is so short that efficient mirrors do not exist. Therefore the machine operates in a self-amplified spontaneous-emission (SASE) mode, where sufficient gain per pass exists to amplify shot noise to saturation in a single pass through the wiggler. Such systems require extremely high peak currents and exceptional beam quality. The TTF plan is to eventually reach a wavelength of 6.5 nm using a 1-GeV 2500-A electron-beam pulse. The wiggler will be 27 m long to saturation and have a peak field of 5 kG with a period of 2.73 cm. The peak power is anticipated to reach 2–3 GW. Later an energy upgrade to 50 GeV will result in photon energies up to 10 keV and average brilliances of 10^{26} photons/sec/mm^2/0.1 % BW. This extraordinary light source will offer unprecedented opportunities for research into the fundamentals of photon/matter interactions (Rossbach, 1996).

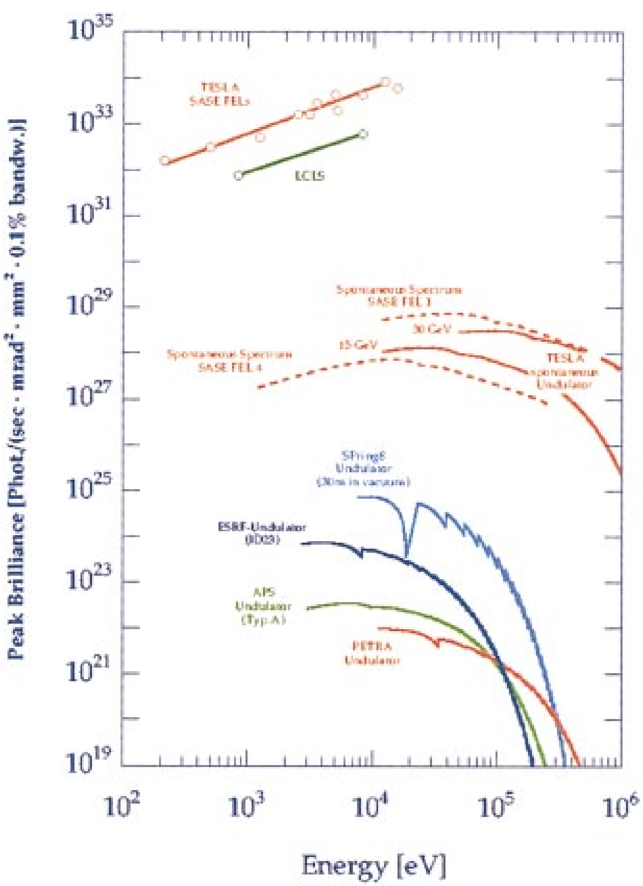

FIG. 13. Performance of the Tesla Test Facility FEL device, the linac coherent light source, and some existing sources. Figure courtesy of J. Rossbach, DESY [Color].

At present the linac operates at 250 MeV and the system has a 14-m wiggler installed. The injector delivers 1 nC of charge within 4 π mm mrad normalized emittance before subsequent compression to an rms bunch length of 250 μm in a magnetic chicane before the wiggler. The system has produced the shortest output wavelength yet from any FEL at 98 nm, and up to 0.5 GW of 12-eV photons are eventually anticipated with this configuration. The studies currently underway fully confirm the theory of SASE, including noise characteristics and saturation behavior. Since the SASE system starts from shot noise, it is to be expected that fluctuations in the output intensity and spectrum will occur. A substantial amount of theoretical effort has gone into studying such behavior. In order to smooth the output and control the spectral characteristics, a grating monochrometer is under consideration for installation part of the way down the wiggler to clean up the source term and allow a more uniform output.

F. Energy-recovering linac light sources

A complementary approach to self-amplified FEL's is now contemplated for a next-generation light source with less peak brilliance but higher average fluxes and

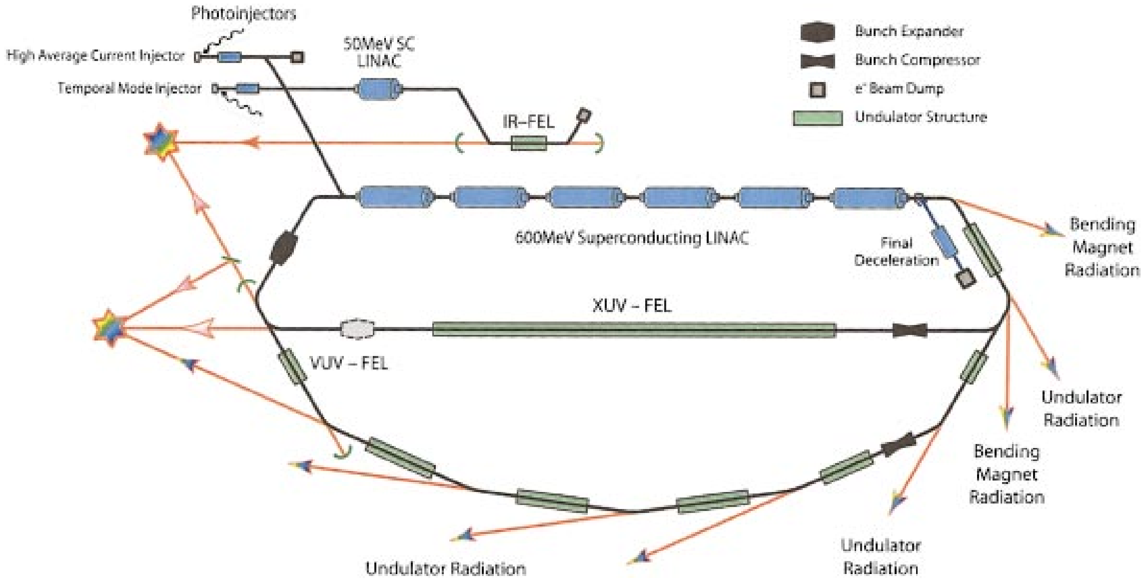

FIG. 14. The proposed 4GLS system at Daresbury Laboratory. The Facility will consist of FEL's and an energy recovering linac with a self-amplified spontaneous-emission FEL capability. Figure courtesy E. Seddon [Color].

many simultaneous users. In a move to capitalize on the high current capability of SRF technology, groups are proposing to build light sources based on energy-recovering linacs (ERL's) at Cornell (Bazarov *et al.*, 2001; Tigner *et al.*, 2001), Brookhaven (Ben-Zvi, 2001; Ben-Zvi *et al.*, 2001), Lawrence Berkeley Laboratory (Corlett *et al.*, 2001), and Daresbury Laboratory (Daresbury, 2001). The beam is sent through a number of wigglers, undulators, and bend magnets before being sent back through the linac for energy recovery as illustrated in Fig. 14. These devices could accelerate up to 100 mA of current up to 7 GeV and from this enormous beam power radiate ~700 kW of synchrotron light! The proposed Cornell system utilizes a dc photoinjector producing 77 pC at 1300 MHz with less than 1 mm mrad of normalized emittance. The advantage of such a system over present light sources is that higher brightnesses may be obtainable from cw photoinjectors than is presently achievable in third-generation sources due to stochastic heating of the beam (Shen, 2001); see Fig. 15.

An even more significant advantage is the flexibility that a linear geometry allows: longer wigglers and undulators, reduced sensitivity to beamline impedances, more flexibility in choice of beam matching functions, and ease of future upgrades as better injector and beamline components become available. Finally it is important for a number of applications that a linac source be easily able to produce subpicosecond light pulses, perhaps even shorter than 100 fs. The pulse characteristics can be easily manipulated at the injector or in dispersion sections at high energy. These light source designs still retain the large number of user ports that present synchrotrons utilize, giving high operational multiplicity for a low per-user cost. These very exciting opportunities are possible only because of the high cw gradients and high system efficiency possible in energy-recovered systems using SRF technology. Key issues in the design of such systems include the production of the highest possible brightness high-average-current beams, minimization of deleterious effects on the beam during acceleration, damping and control of the high-order modes that will be produced by high-average-current short-pulse beams (since substantial powers of higher-order modes can be produced and some of this power ends up heating the SRF structure, the effect on refrigeration cost can be

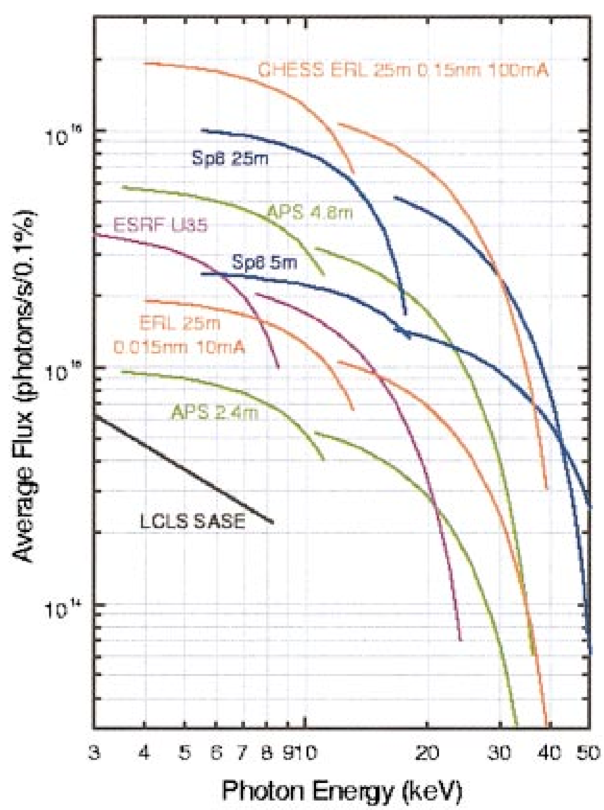

FIG. 15. Projected performance of the energy-recovering linac (ERL) device at Cornell University. Figure from Shen (2001) [Color].

significant), and cost minimization. With such long high-energy linacs involved, the cost per MeV of acceleration is critical (Krafft, Merminga, and Bazarov, 2001). A formal proposal has been submitted to NSF by Cornell to perform design studies and benchmarking tests. Other groups are also well on the way toward formal proposals for construction or design studies.

G. The Budker Institute Recuperator

One high-power energy-recovering room-temperature system is presently under construction at Novosibirsk, a device called a recuperator. (Erg *et al.*, 1993; Gavrilov *et al.*, 1997; Vinokurov *et al.*, 1997). In order to achieve the high current capability needed for operation at the planned 50-mA current the group uses 181-MHz copper-on-steel single-cell structures. Each of the 16 cavities gives approximately 0.8 MeV of energy gain. Higher-order modes are managed by using two tuners to correct the resonant mode frequencies so they avoid beam instabilities. The fundamental R/Q is 227 Ω with a Q of 42 000. The injector is thermionic with a 300-kV gun producing 1-ns bunches at 22.5 MHz followed by acceleration to 2.0 MeV. The bunch length is 100 ps as the beam enters the first bend, but varies with longitudinal focusing in each pass, eventually compressing to 10 ps and 100 A peak before the wiggler.

In order to reduce the linac cost, the beam is recirculated through the structures nine times. Although ~150 kW of power is Ohmically dissipated on each cavity's walls, this is not a major fraction of the 70 kW×9 electron-beam power produced. The FEL operates as a master oscillator/power amplifier with a novel electron-beam outcoupling scheme for the light. The 9-cm-period wiggler consists of four sections of 40 periods each, separated by magnetic dispersion sections. To reduce mirror loading and to permit low pulse repetition rate lasing, the initial master oscillator will have a 79-m-long optical cavity operating in the 2–10 μm region. Up to 100 kW is projected in the IR and consideration is being given to a fourth-generation vuv light source based on this concept (Kulipanov, Skrinsky, and Vinokurov, 2001). As of late fall 2001, 18 MeV of linac has been constructed and installation and commissioning is underway. To get a more complete view of the tradeoffs involved in choosing SRF technology versus copper technology for high-average-power machines we encourage the reader to examine the details of this system.

IV. CONCLUSION

Superconducting radio-frequency accelerator technology has provided the capability for high-duty-factor operation of FEL's, which has wide-ranging implications. It offers improved beam quality and permits the use of system designs incorporating same-cell energy recovery for high efficiency at high FEL power, now 150 times over competing copper systems. It is being utilized for a high-power SASE ultraviolet demonstration system and ultimately will form the basis for a fourth-generation light source user facility by multiplexing the beam among many groups. Several groups around the world are applying the advantages of SRF technology to construct FEL light sources for user facilities. Superconducting radio frequency will also be incorporated into exciting new energy-recovering linac light sources with substantial flexibility and brightness improvements over existing third-generation sources while retaining the programmatic advantages of third-generation facility multiuser operation. It is expected that continuing improvements in SRF gradient performance will make the desirability of such systems even more compelling.

ACKNOWLEDGMENTS

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