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COMPACT X-RAY LASERS IN THE LABORATORY*

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Abstract

Compact x-ray lasers in the laboratory can be produced with ultrahigh gradient rf linacs based on recent advances in linac technology by an SLAC-LLNL-LBL collaboration and on the development of bright, high current electron sources by BNL and LANL. The GeV electron beams generated with such accelerators can be converted to soft x rays in the range of 2–10 nm by passage through short period, high field strength wigglers. Alternatively, the beam can pump a low density dielectric to produce x rays via recombination. Such linear light sources can produce trains of picosecond (or shorter) pulses of extremely high spectral brilliance suitable for flash holography of biological specimens *in vivo* and for studies of fast chemical reactions.

Introduction

Over the past decade the material, chemical, and biological science research communities have demonstrated an ever-increasing interest in using sources of XUV and soft x-ray radiation. The most important sources in this spectral region are storage ring facilities that produce broadband, incoherent synchrotron radiation. The spectral brilliance of storage ring sources is restricted both by the incoherence of the radiation process and by limitations in beam intensity. Moreover, the minimum pulse lengths available exceed 20 ps.

As an alternative to storage ring sources, it is now feasible to develop compact sources of intense, coherent, soft x rays with extremely high peak and time average spectral brilliance (Fig. 1), very short pulse duration (picosecond or less), and broad frequency tunability. The x rays are generated by self-amplified spontaneous emission from an intense electron beam traversing a wiggler in a single-pass free electron laser (FEL) architecture. X-ray FELs driven by ultrahigh gradient rf linacs could find a wide range of uses because of the possibility of constructing instruments with unique characteristics tailored to the specific needs of the user.

The basic elements of the linear x-ray source, as illustrated in Fig. 2, are (1) a laser-driven, high-gradient rf electron gun plus a conventional S-band post-accelerator; (2) an ultrahigh gradient linac to produce a GeV beam; and (3) and a high field strength, short-wavelength wiggler with a precision beam control system. If the lasing is produced by recombination processes in a dielectric, the wiggler is replaced by a set of magnetic and/or plasma lenses to focus the beam into the lasing medium.

Scaling Basis for the X-Ray FEL Design

Compact accelerators may be combined with high field strength wigglers in two different FEL architectures:

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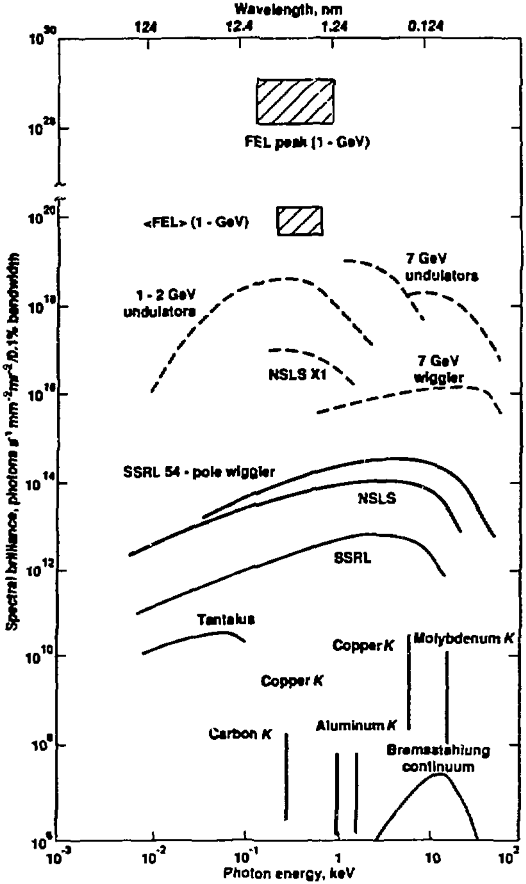


Figure 1. Comparison of radiation sources.

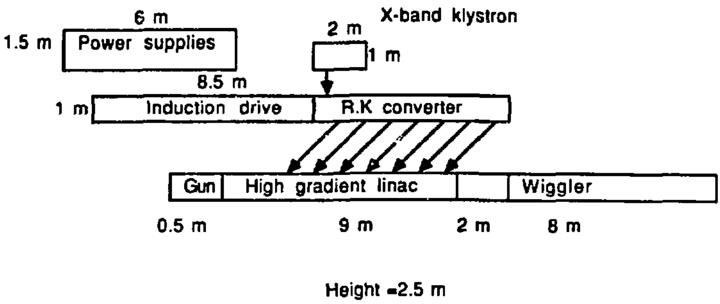


Figure 2. Layout of compact ≈1 GeV x-ray FEL linac powered by relativistic klystron.

1. Single-pass growth from self-amplified spontaneous emission (SASE).
2. Multipass oscillator within the temporal envelope of the power drive.

Single pass architectures will require a small-signal gain of more than 10^6, whereas multipass architectures would be feasible with a small-signal gain of 10. The prospects for the oscillator architectures are greatly enhanced by the recent development at LLNL and other laboratories of multilayer mirrors capable of >50% reflectivity at normal incidence of radiation with a wavelength less than 10 nm. Still, at present, the SASE architecture is the most practical.

Building a compact, soft x-ray FEL presents two main design difficulties: (1) producing a high energy electron beam with sufficiently high density and sufficiently small momentum spread as required to generate high gain, and (2) producing high precision, high field strength wigglers. The architecture for the FEL relies on single pass growth from self-amplified spontaneous emission starting from beam noise in a long undulator [1,2]. This process is a natural extension of the emission of synchrotron radiation from an undulator. If the undulator is long enough and if the beam intensity is high enough, the spontaneous emission will be amplified by the beam itself, and the output radiation will grow exponentially until the FEL amplifier saturates. This process has been demonstrated (Fig. 3) in quasi-optical experiments with 2- and 8-mm radiation in the ELF experiment at LLNL [3].

The usual resonance condition connecting the beam energy, γ, the wiggler wavelength, λ_w, and the wavelength of the radiation, λ, is

$$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1 + a_w^2\right) \quad . \tag{1}$$

where a_w is the dimensionless vector potential of the planar wiggler:

$$a_w = e\,\lambda_w B_0 / 2\sqrt{2}\,\pi\, m_e c^2 \ . \tag{2}$$

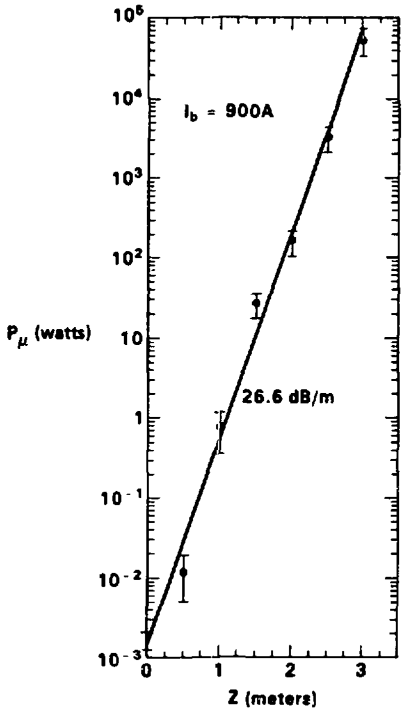


Figure 3. Small signal gain of ELF experiment (λ_s = 8 mm; E_b = 3.5 MeV in waveguide).

A simple expression for the amplification in a planar wiggler can be estimated in the cold beam limit of the one-dimensional FEL theory [1]. The power grows exponentially with an e-folding length of

$$L_g = \frac{\lambda_w}{4\pi\rho}, \tag{3}$$

where

$$\rho = \left(\frac{a_w \omega_p}{4\omega_w}\right)^{2/3}. \tag{4}$$

In Eq. (4), ω_p is the beam plasma frequency divided by γ^3, and ω_w is the wiggler frequency. The amplifier will saturate in $N_u \approx \rho^{-1}$ periods, at which point the power in the radiation field will be $P_{fel} = \rho P_{beam}$. For the parameters of interest for x-ray FELs, the efficiency at saturation can be approximately 0.1%. At this point additional energy can be extracted from the electron beam by tapering the wiggler, or the electrons can be diverted to a second converter for the production of harder, incoherent x rays.

The resonance condition constrains the allowable spread of longitudinal velocities of the electrons in the beam such that the electrons do not slip more than a small fraction of an optical wavelength per gain length. This consideration leads to constraints on the beam emittance, ε_n, and energy spread; namely,

$$\frac{\Delta\gamma}{\gamma} = \frac{\rho}{4} \tag{5}$$

and

$$\varepsilon_v \le \lambda\gamma/2\pi\,. \tag{6}$$

Equation (5) should be applied in the restrictive sense of a constraint on the spread in longitudinal component of γ. Another design condition for the FEL comes from requiring that diffraction not take energy out of the beam in a distance equal to a gain length, L_g. Hence the gain length of the laser must be shorter than the Rayleigh range, Z_R:

$$Z_R = \frac{\pi a^2}{\lambda_s}. \tag{7}$$

Hence,

$$a^2 > \frac{\lambda_s \lambda_w}{4\pi^2 \rho}, \tag{8}$$

where a is the size of the beam in the wiggler. If the wiggler employs natural focusing, the betatron wavelength in the wiggler and the beam size are related by

$$\lambda_\beta = \frac{\lambda_w \gamma \sqrt{2}}{a_w}. \tag{9}$$

Additional focusing may be employed to increase ρ as long as the constraints on longitudinal velocity spread remain satisfied. If enough focusing can be added to keep λ_β constant with increasing energy, then one can show [4] that

$$\rho \sim \gamma\lambda^{1/2}, \tag{10}$$

a far more favorable scaling with wavelength than obtains for atomic lasers.

To go beyond the estimate of FEL performance based on scaling laws, one must use particle simulation codes to calculate the performance of the x-ray SASE amplifier and to assess the sensitivity of the gain to energy spread, emittance, and wiggler errors. Calculations at LLNL, Brookhaven, and Rocketdyne indicate that the scaling laws do in fact provide a valid tool for scoping the design of the laser and for setting accelerator requirements. An example of the design requirements and performance for a 5-nm x ray is given in Table 1.

As confirmed by the simulations, the amplifiers saturate in ≈1000 wiggler periods to yield powers of ≈1 GW. The simulations also indicate that errors in the magnetic field must be kept to ≈0.1%. Considerable progress in the design of long, high precision

Table 1. Design requirements for 5-nm x-ray FEL.

Beam parameters		Output	
Energy (GeV)	1.02	Wavelength	5.0
Peak current (A)	1000	Efficiency	0.16%
Pulse length (ps)	1.2	Gain length (m)	1.0
Pulse length (mm)	0.4	Peak power (GW)	1.5
Norm emit (mm-rad)	0.001	Spectral brilliance	7.9×10^{28}
N-part	7.4×10^{9}	Average brilliance	9.8×10^{19}
Wiggler			
Wiggler period (cm)	2.0		
B-actual (T)	0.8		
Wiggler gap (cm)	0.5		
Wiggler length (m)	12.9		
N-periods	642.0		
A-w	1.0		

wigglers using diverse magnet technologies has been made over the past four years. For example, the 25-m long Paladin wiggler at LLNL—a hybrid electromagnet design with curved pole faces [5] and 8-cm period—has ≈300 periods with a measured uncorrelated field error <0.1%. An alternative approach, especially attractive for wigglers with a periodicity shorter than 4 cm, is a pure permanent magnet (PPM) structure. An 80-period, 2-m long, PPM wiggler built by Rocketdyne for experiments at the Stanford Mark III accelerator [6] has demonstrated precision control of electron trajectories equivalent to an uncorrelated field error of 0.055%.

Description of Accelerator Components

Although the use of SASE eliminates the need for mirrors, single pass architectures will require $>10^6$ small signal gain to yield x-ray beams of high spectral brilliance. A prerequisite for such high gains is the generation of extremely bright, high current electron beams. Recent advances at LANL, BNL, and other laboratories include developing electron guns with a brightness exceeding that of operating storage rings such as the SLC damping ring (greater than 10^{10} A/m^2-rad^2). These electron injectors are based on the technology of laser driven photocathodes (both metallic and semiconductor) in cavities with very high accelerating fields (10 to 100 MeV/m) followed by magnetic compression to reduce space charge effects at low beam energy. For example, the rf gun built at Los Alamos [7], using a Cs_3Sb cathode in a 1.3-GHz cavity, has produced a beam of ~300 A with a normalized rms emittance of 10^{-5} m-rad at a beam energy of 1.1 MeV and a pulse length of ≈50 ps. This gun is illustrated in Figs. 4(a) and (b).

Limitations on the emittance of an electron gun are imposed by several physical effects: the maximum current density available from the cathode, nonlinear electromagnetic forces in the rf cavity, and space charge forces. One means of reducing the space charge forces is to apply a very strong rf field at the cathode surface in order to accelerate the beam rapidly to relativistic velocities. This approach is being followed in an injector now being built at BNL [8]. The BNL gun is expected to produce a beam of 200 A in 3 ps with a normalized rms emittance of $\approx 3 \times 10^{-6}$ m-rad and a pulse length of <5 ps. In the BNL gun, a mode-locked, frequency-doubled Nd:YAG laser is used to drive a metallic photocathode in a 2.87 GHz cavity ($1^1/_2$ cells) to emit a beam with a current density >600 A/cm^2. A single master oscillator locks the phase of the electron bunch with the rf power

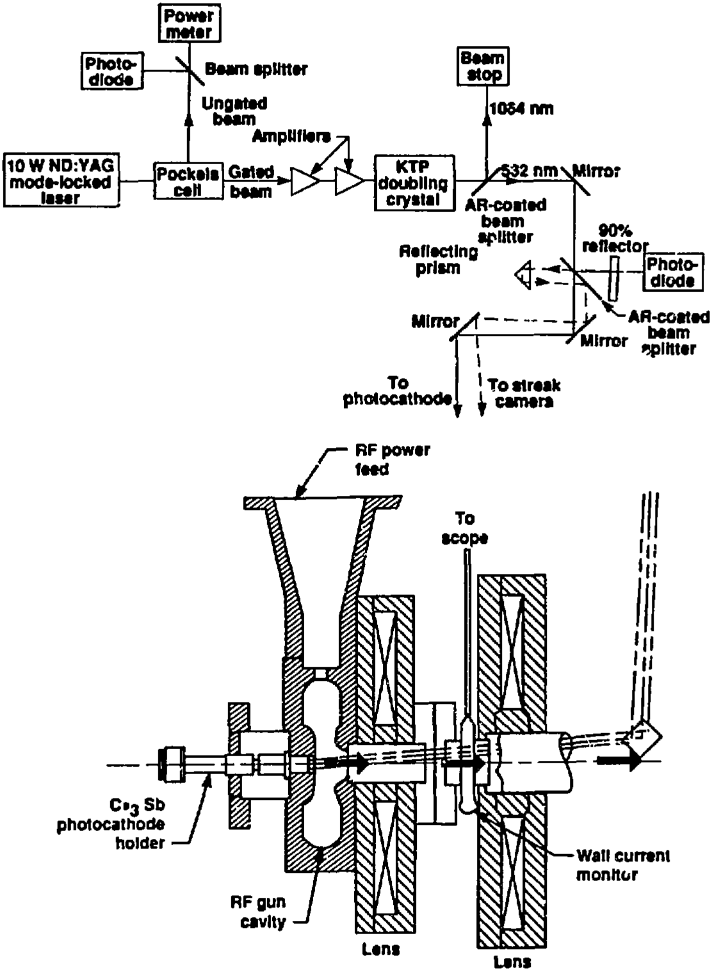


Figure 4. (a) Block diagram of the mode-locked laser system. (b) The rf gun cavity.

drive of the injector. Accelerating fields as high as 100 MeV/m raise the beam energy to 4.8 Mev in <8 cm. Such a gun could produce a useful x-ray FEL based on SASE in the range of 5–10 nm. Where combining this approach with magnetic compression at high energies, it should be practical to construct guns with ≈1 kA of peak current in 1 ps at a normalized rms emittance of 10^{-6} m-rad. Such a bright gun should extend the accessible wavelength range to 1 nm.

The GeV-class linear accelerator that drives the x-ray FEL can be made far more compact than present rf linacs through the use of the ultrahigh gradient structures now under investigation by an SLAC-LLNL-LBL collaboration for a linear collider at TeV energies. The performance goals [9] for these structures are gradients exceeding 200 MeV/m and costs <$1 M/GeV. The peak currents will be ~1kA at a normalized brightness of about 10^{12} A/(m^2 -rad^2) in a train of ~20 micropulses each of ~1ps duration and spaced by 0.1–1 ns. The pulse train is repeated at a frequency of 100–1000 Hz; the rms energy spread through the macropulse must be <0.1%.

The physical phenomenon that forms the basis for scaling the gradient in rf linacs from the 17 MeV/m of the Stanford Linear Collider to the desired ≈200 MeV/m for compact linear light sources is the increase in peak electric field that can be sustained without breakdown [10] with increasing rf frequency and with shortening duration of the rf power. For disk-loaded waveguide structures, the peak field that can be maintained is

$$E_{pk} = 120\ \text{MV/m}\ (f / 2.87\ \text{GHz})^{7/8}. \qquad (11)$$

The accelerating field is a factor of ≈2 less than the peak value. The total peak rf power needed to drive the accelerator based on a $2\pi/3$ disk-loaded waveguide can be estimated as

$$P_{rf} \approx 6\ \text{GW}\ (E_a / 200\ \text{MeV/m})^2\ (\gamma / 2000)\ (\lambda_{rf} / 105\ \text{mm})^{1/2}. \qquad (12)$$

For compact 1-GeV linacs to be practical and affordable a new class of rf power sources is needed. One of the most promising approaches to power compact linacs is the relativistic klystron [11] driven by an induction linac, as illustrated in Fig. 5. In the relativistic klystron, a multi-kA, multi-MeV beam produced with an linear induction accelerator (LIA) is modulated at the desired rf frequency (10–15 GHz); the modulated high current beam then excites an rf-generating transfer structure. The high peak power rf is then fed via waveguides to the miniaturized rf cavities of the high-gradient rf linac.

Initial experiments [12] at LLNL have extrapolated a conventional, high gain klystron design using velocity modulation to >1 MV operation to produce a source of more than 200 MW of rf power at 11.4 GHz (X-band). This source has been used to power a 25-cm long section of X-band, disk-loaded waveguide structure (Fig. 6) to obtain an accelerating gradient exceeding 135 MeV/m in a demonstration earlier this year.

For the 1-GeV linac needed to drive the FEL described in Table 1, one injects the beam from a photocathode gun into a linac at a conventional gradient which acts as a matching section for bringing the beam into the high gradient structure operating at 11.4 GHz. The characteristics of the X-band linac with its relativistic klystron power supply can be determined from well known scaling laws [9, 13] and are listed in Table 2. This linac would produce a train of five micropulses spaced by 0.26 ns. Operating at a repetition rate of 200 Hz, the FEL driven by such an accelerator would produce x rays with a peak spectral brilliance of ≈7.9×10^{28} photons–s^{-1}–mm^{-2}-mrad^{-2} per 0.1% bandwidth. The time average brilliance for this design is ≈1.1×10^{20} photons–s^{-1}–mm^{-2}-mrad^{-2} per 0.1% bandwidth.

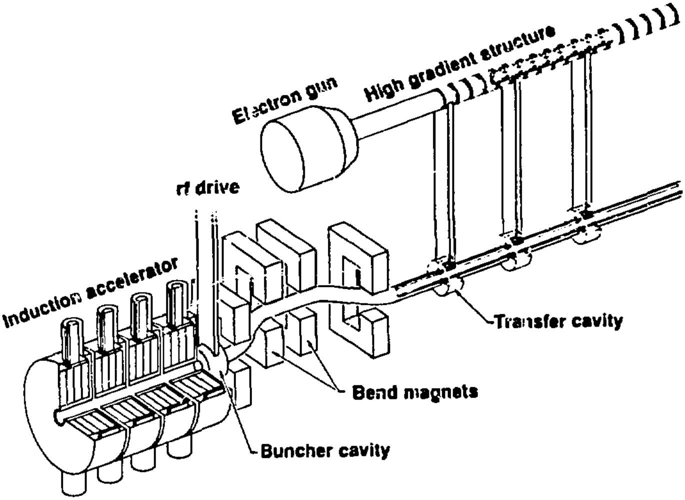
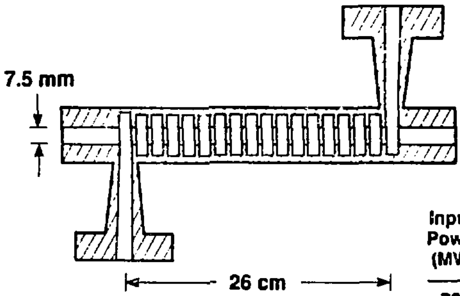


Figure 5. Schematic of a relativistic klystron.



Frequency 11.4 GHz
Filling time 26 ns
Number of cavities 30

Input Power (MW)	Energy (MeV)	Accelerating Field (MV/m)
70	20	80
100	25	100
200	35	130
500	50	200

Figure 6. High gradient waveguide structure.

Table 2. Characteristics of compact accelerator drive for laboratory x-ray laser.

Beam parameters		**Accelerator**	
Beam energy (GeV)	1	Frequency (GHz)	11.49
Peak current (A)	1000	rf efficiency	50%
Pulse length (ps)	1.2	Iris a (mm)	4.35
Pulse length (mm)	0.4	Fill T/atten . T	0.15
Norm Emit (mm-rad)	0.001	Bunch (°full phase)	5.1
N-part	7.2×10^9	v-group/c	0.049
Size in linac (μm)	24.1	Energy/m (J/m)	28.9
Δp/p (%)	0.1	E-max (MV/m)	375
n bunches	5	Grad (MeV/m)	155.1
bunch space (ns)	0.26	Length (m)	6.59
rep rate	200	Cavity size (mm)	10.7
		Fill length (m)	0.44
Induction drive		Fill fraction	0.95
I-induction (A)	3000	rf P (MW/m)	1128
Overall length (m)	9.5	loading %	0.8
V-induction (MeV)	5.4	Beam efficiency (%)	3.1
Length induction drive	7.1	rf supply (ns)	28

Recombination X-Ray Lasers

The beams that can be produced from the accelerators suitable for driving x-ray FELs can also be focused into low density dielectrics such as aerogels or compressed gases as shown in Fig. 7. In that case the beam will rapidly achieve charge neutralization and propagate in a self-focused mode. The relationships among beam radius, energy, current, normalized emittance ε_n, and betatron wavelength and mean betatron angle, $<\Theta^2>^{1/2}$, for self-focused beams are well known [14]:

$$a = (\varepsilon_n / \gamma)\,(17\gamma / f_c I)^{1/2}\,, \tag{13}$$

$$<\Theta^2>^{1/2} = (17\gamma / f_c I)^{-1/2}\,, \tag{14}$$

and

$$\lambda_\beta = 2\pi a / <\Theta^2>^{1/2}\,. \tag{15}$$

As the beam passes through the medium, it will deposit energy via direct collisions. These scattering events also degrade the emittance of the beam, causing it to expand. The e-folding length for beam expansion of a self-focused beam is known as the Nordseick length [14], L_N:

$$L_N = 0.135\ (E / 1\ \mathrm{GeV})\,(I / 1\ \mathrm{kA})\, X_R\, (1.3 \times 10^{-3} / \rho_m)\,, \tag{16}$$

where E is the beam energy, I is the beam current, ρ_m is the density of the medium in g/cm^3, and X_R is the radiation length. The Nordseick length sets a scale length for the deposition of extremely high energy densities into the dielectric. Examples of the depositions and scale length for beams of diverse characteristics are given in Table 3.

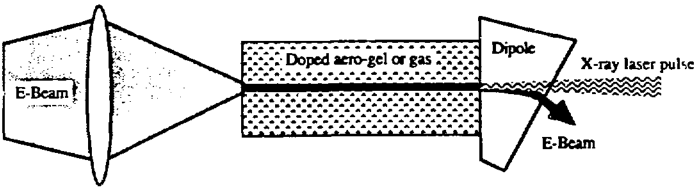


Figure 7. Schematic of fine beam pumping a recombination x-ray laser.

Table 3. Energy deposition with fine beams for pumping recombination x-ray lasers.[a]

Emittance (mm-mrad)	Beam energy (GeV)	Beam radius (μm)	Deposition (MJ/g)	Laser length (m)	Deposit time (ps)
10	1	1.5	0.1	>>1	<3
1	1	0.5	1	≈1	<3
10	50	0.15	10	>>0.1	<3
10	50	0.05[b]	100	≈0.01	<3

[a]Average current = 1 kA.
[b]Not self-focused.

The energy deposition rates implied by the examples in Table 3 suggest that fine beams produced with compact 1-GeV linacs may be able to pump recombination x-ray lasers with lengths ≈1 m. The actual deposition processes and laser kinetics are presently under study at LLNL to determine the potential of this deposition mechanism. The final two examples indicate the very large depositions that would be available in the "final focus facility" proposed for the Stanford Linear Collider. In the 50-GeV cases, the dominant energy loss process for the beam will be the production of extremely hard gamma radiation via synchrotron radiation in the multi-megagauss self-field of the beam [15]. This process, "beamstrahlung," will cause the beam to lose energy over a scale length

$$L_R = 25 \text{ meters } (a / 1\ \mu m)^2 (1\ kA / f_c I)^2 (10\ GeV / E)\,, \qquad (17)$$

where f_c is the charge neutralization fraction. During the radiation process the beam will remain in quasi-static equilibrium if $L_R >> \lambda_\beta$. In the last two cases of Table 3, L_R will set the scale length of the potential laser medium. Of particular interest is the last case, in which the material is hit by a 50-nm-radius beam (much smaller than the self-focused radius); the matter may be brought to > 10 keV on the picosecond time scale.

Critical Issues and Conclusions

The electron-beam driven x-ray laser relies on the performance of many components that have been shown to operate well, although not necessarily in the required parameter range. The ultimate performance of the laser will depend not just on the component-level performance, but also on the integrated system of high precision beam generation, guidance, and control. The issues most critical to the extension of accelerator and free electron laser technology to the x-ray regime can be summarized as

1. Reliable generation of extremely high brightness electron beams and preservation of beam quality during the acceleration and energy conversion process.
2. Reproducibility and stability of accelerating the electron beam to high energy while maintaining the beam quality.

Both these areas must be studied in the laboratory at the component level and eventually in integrated subscale tests at longer wavelengths.

Compact x-ray FELs will require precise mechanical alignment of the cavities, beam tube, magnetic centerline, and optical axis. A key to the success of this program will be the development of fast beam position monitors with an accuracy of ≈20 μm.

Industrial applications of compact sources of coherent x rays with very high time average brilliance include integrated circuit lithography using imaging masks and soft x-ray (4–5 nm) reflective optics. This technique offers ultimate feature size of about 50–150 nm, well below that currently achieved (0.75–1 μm).

X-ray FELs driven by compact linacs could also provide sources of extremely high peak brilliance. Imaging of biological samples with x rays in the wavelength range of 4–5 nm will allow resolution of cellular substructures in the natural state without dehydration or staining. This wavelength regime is also the most suitable for holographic imaging of proteins *in vivo* . Moreover, the picosecond duration exposures at multi-gigahertz rates, obtainable with linear light sources, will allow dynamic measurements of specimens. Such studies of samples in a normal physiological environment would be complementary to ordinary scanning electron microscopy. X-ray spectroscopy in the range of 2–4 keV accesses the K-edges of P, S, Na, K, Ca, and Cl, which are all elements of considerable biological significance. Based on the cost algorithm of Ref. 11, the expected cost of such high brilliance x-ray instruments is expected to be under $10 million.

Acknowledgments

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