CONF-880904--11
BNL-42393

A COMPACT X-RAY FREE ELECTRON LASER

W. Barletta, M. Atac, A. Bhowmik, B. Bobbs, D.B. Cline,
R.A. Cover, F.P. Dixon, J. Gallardo, J. Kolonko,
C. Pellegrini, G. Rakowsky, X. Wang, G. Westenskow

September 9th, 1988

CENTER FOR ACCELERATOR PHYSICS

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
Under Contract No. DE-AC02-76CH00016 with the
UNITED STATES DEPARTMENT OF ENERGY

DISCLAIMER

Submitted to the American Optical Society Meeting, Cape Cod, September 9, 1988.

BNL-42393

A COMPACT X-RAY FREE ELECTRON LASER

W. Barletta[1,3], M. Atac[1], A. Bhowmik[4], B. Bobbs[4], D.B. Cline[1], R.A. Cover[4], F.P. Dixon[4], J. Gallardo[2], J. Kolonko[1], C. Pellegrini[2], G. Rakowsky[4], X. Wang[1,2], G. Westenskow[3]

BNL--42393

DE89 017236

1 Center for Advanced Accelerators
Univeristy of California, Los Angeles

2 Brookhaven National Laboratory

3 Lawrence Livermore National Laboratory

4 Rockwell International Corporation
Rocketdyne Division, Canoga Park, California

ABSTRACT

We present a design concept and simulation of the performance of a compact x-ray, free electron laser driven by ultra-high gradient rf-linacs. The accelerator design is based on recent advances in high gradient technology by a LLNL/SLAC/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 from 2 – 10 nm by passage through short period, high field strength wigglers as are being designed at Rocketdyne. Linear light sources of this type 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.

I. Introduction

Over the past decade the material, chemical, and biological science research communities have demonstrated an ever increasing interest in using sources of radiation of XUV and soft x-ray radiation. The most important sources in this spectral region are storage ring facilities which produce broad band, 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 density. Moreover, the minimum pulse lengths available exceed 20 ps.

†Work performed under the auspices of the U.S. Dept. of Energy by LLNL under contract W-7405-ENG-48.

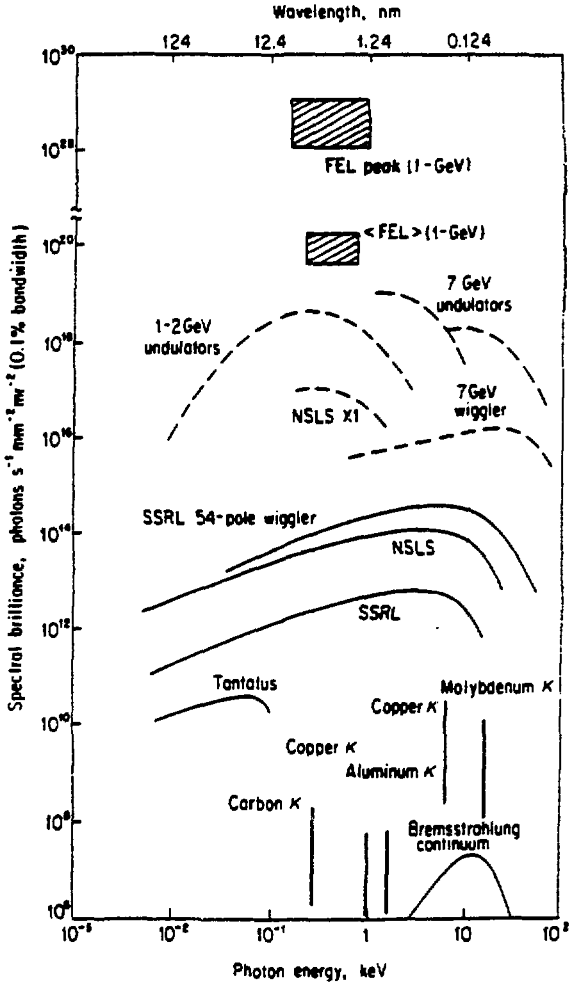

Figure 1

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 (Figure 1), very short pulse duration (picosecond or less), and broad frequency tunability. The x-rays are generated by self-amplified spontanteous emission from an intense electron beam traversing a wiggler in a single-pass free electron laser (FEL) architecture. X-ray FEL's driven by ultra-high gradient, rf-linacs, should find a wide range of uses due to 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 Figure 2 are, 1) a laser driven, high gradient r.f. electron gun plus a conventional S-band post accelerator, 2) an ultra-high gradient linac to produce a GeV beam, 3) and a high field strength, short wavelength wiggler with a precision beam control system.

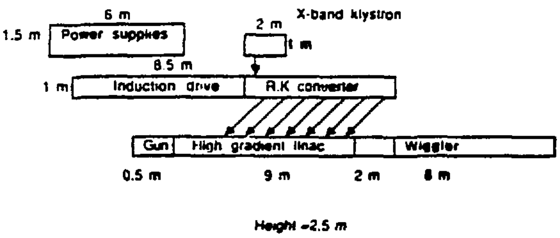

Figure 2

This report describes the prospects for the design of a compact, X-ray FEL and of the various component sub-systems. It includes recent simultations plus rules for scaling the FEL performance to other wavelengths. Finally, the critical issues for the construction of an instrument in the near future are addressed.

II. Scaling Basis For the X – Ray FEL Design

Building a compact, soft x-ray FEL presents two main design difficulties: a) producing a high energy electron beam with sufficiently high density and sufficiently small momentum spread as required to generate high gain, b) producing high precision, high field strength wigglers. The architecture for the FEL relies on single pass growth from self-amplified spontaneous emission (SASE) starting from beam noise in a long undulator[1,2]. This process can be viewed as the 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 in a quasi-optical experiment with 2 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 signal wavelength, λ, is

$$\lambda = \left(\frac{\lambda_W}{2\lambda^2}\right)(1 + a_W{}^2) \qquad (1)$$

where a_W is the dimensionless vector potential of the planar wiggler,

$$a_W = \frac{e\lambda_W B_o}{2\sqrt{2}\pi m_e c^2} \qquad (2)$$

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

$$L_g = \frac{\lambda_W}{4\pi\rho}, \qquad (3)$$

where

$$\rho = \left(\frac{a_W \omega_p}{4\omega_W}\right)^{\frac{2}{3}}. \qquad (4)$$

In Equation (4), ω_p is the beam plasma frequency divided by γ^3 and ω_W is the wiggler frequency. The power at saturation 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,

$$\frac{\Delta\gamma}{\gamma} = \frac{\rho}{4}, \qquad (5)$$

and

$$\epsilon_n \leq \frac{\lambda\gamma}{2\pi}. \qquad (6)$$

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

$$Z_R = \frac{\pi a^2}{\lambda_s}. \quad (7)$$

Hence,

$$a^2 > \frac{\lambda_s \lambda_W}{4\pi^2 \rho}, \quad (8)$$

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

$$\lambda_\beta = \frac{\lambda_W \gamma \sqrt{2}}{a_W} \quad (9)$$

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

$$\rho \sim \gamma \lambda^{\frac{1}{3}}, \quad (10)$$

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

III. Simulation of the X – Ray FEL Performance & Undulator Design

To go beyond the estimate of FEL performance based on scaling laws, the Rocketdyne simulation code, FELOPT, was used to calculate the performance of a 2.5 nm SASE amplifier and to assess the sensitivity of the gain to energy spread, emittance, and wiggler errors. Two sets of parameters, listed in Table I, were chosen that differ in the assumed electron beam energy and in the wiggler magnetic field strength and period. In both cases, the wiggler poles are assumed to be curved so as to provide natural focussing in both transverse planes. The electron beam has a parabolic radial distribution of charge and is uniformly distributed in transverse phase space with 90 % of the electrons in the energy interval ±0.05 %.

As illustrated in Figures 3 and 4, both amplifiers saturate in ≈ 800 wiggler periods to yield powers of a few hundred megawatts. The sensitivity of the performance to increase in energy spread or emittance is indicated in Table II. Doubling ϵ_n or $\Delta\gamma$ significantly decreases the saturated output. Still, the output is adequate for most purposes. Sensitivity to wiggler phase errors is presented in Table III. Steering errors are neglected; i.e., perfected corrections to the trajectory are assumed. The results indicate that an rms field error of ≈ 0.1 % is adequate.

PARAMETERS		
	CASE I	CASE II
Wavelength (Å)	25	25
Energy (GeV)	1.02	1.44
Wiggler Wavelength (cm)	1.0	2.0
Magnetic Field (T)	1.514	0.757
Wiggler Length (m)	8.1	11.5
Current (A)	400	400
Energy Spread (%)	0.1	0.1
Normalized Emittance (mm-mrad)	1.0	1.0

Table I

As the simulations show, efficient conversion of the high energy electron beam to soft x-rays requires the fabrication of long, high accuracy, high field strength wigglers with precision beam control. Considerable progress in precision wiggler design 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[4] and 8 cm period – has ≈ 300 periods with a measured uncorrelated field error of < 0.1 %. An alternative approach, especially attractive for wigglers with a periodicity shorter than 4 cm, is a pure permanent magnet (PPM) structure.

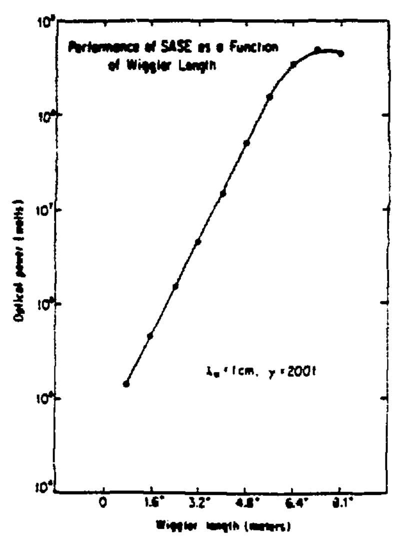

Figure 3

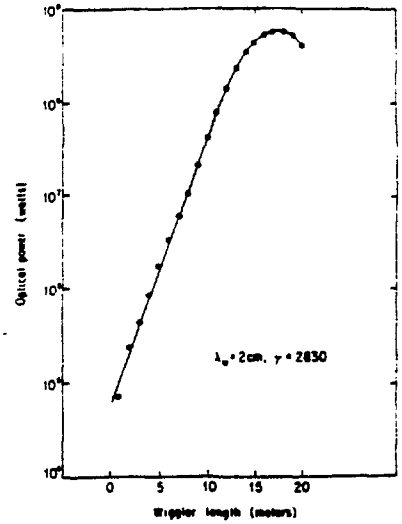

Figure 4

An 80 period, 2 m long, PPM wiggler built by Rocketdyne for experiments at the Stanford Mark III accelerator[5] has demonstrated precision control of electron trajectories equivalent to an uncorrelated field error of 0.055 %. A photograph of the functioning wiggler is given in Figure 5.

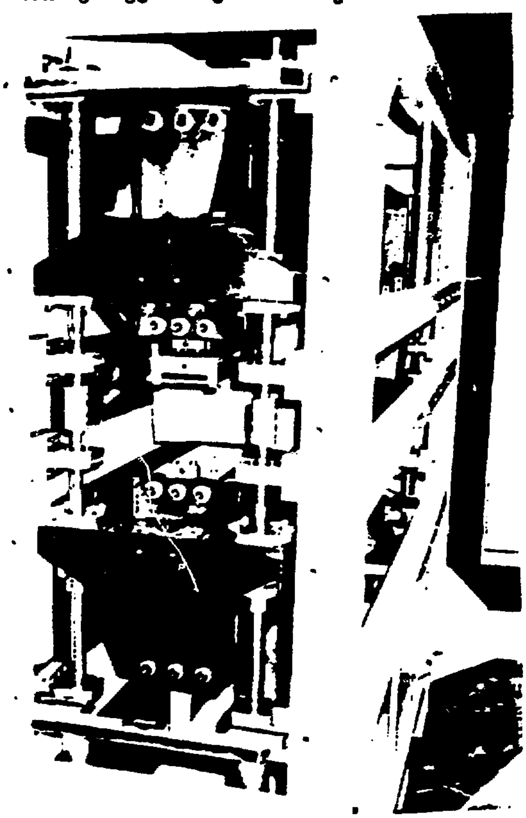

Figure 5

The design used an innovative optimization algorithm, "simulated annealing"[6], to compensate for normal production tolerances in the field strength and polarization angle of individual magnets.

Rocketdyne is now extending this technique to minimize phase errors between the electrons and the optical field in the design of new higher field PPM arrays for retrofit into the 2-m wiggler.

SENSITIVITY TO CHANGES IN ELECTRON EMITTANCE AND ENERGY SPREAD		
$\gamma = 2830$, WIGGLER LENGTH, $L_w = 20$ m		
ENERGY SPREAD (%)	NORMALIZED EMITTANCE (mm – mr)	POWER OUT (W)
0.1	1	5.8×10^8
0.1	2	3.0×10^8
0.2	1	3.8×10^7

Table II

The high field wiggler design has been validated in full-scale laboratory models. Special magnet module assembly fixtures and insertion/extraction tools have been developed for safe handling and accurate positioning of magnets in the presence of strong magnetic forces. Improved magnet measurement procedures have in turn lead to improved field models and improved wiggler optimization algorithms.

EFFECT OF PHASE ERRORS RESULTING FROM WIGGLER FIELD ERRORS				
Power at Peak of Gain Curve (8 m & 17 m, Respectively)				
WFE (%)	0	0.3	0.5	1.0
Case 1 ($\gamma = 2001$) ($\times 10^8$ W)	4.9	4.2	3.6	
Case 2 ($\gamma = 2830$) ($\times 10^8$ W)	5.8	5.7	5.5	4.0

Table III

The basic PPM wiggler design is readily scalable subject to some practical limitations. First, all magnet dimensions scale directly with λ_W. Hence, the minimum period is limited to ≈ 1 cm by the difficulties in handling, assembling, and clamping fragile wafers of powerful $SmCo_5$ magnets. The replacement arrays for the 2-m wiggler have a period of 2.4 cm. This high field configuration has been extended in a detailed design to even shorter periods (1.2 cm). Another critical dimension, the minimum gap, g, between the poles may be set by optical aperture requirements or by mechanical limitations in the vacuum chamber design. Since $B_o \sim \exp(-g/\lambda_W)$, the minimum practical gap height constrains the choice of B_o and λ_W for a given beam energy.

The PPM wiggler for the x-ray FEL will have several hundred periods and an overall length from several to twenty meters. The wiggler could be built in sections to be assembled and aligned on site. The structure will consist of a series of linked, kinematically mounted space frames (Figure 6) or tables depending on the desired orientation of the wiggle plane (and consequent polarization of the x-rays).

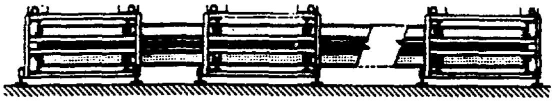

Figure 6

The magnet arrays themselves will also be built in optimized sections of 100 periods and joined in a way that maintains the prescribed periodicity and field strength across each joint. Mechanical support and gap adjustment are also provided at each joint. Beam position monitors and steering correction coils are also provided at 100 period internals. Since the PPM array is iron-free and the relative permeability of $SmCo_5$ is near unity, fields superimpose linearly. Therefore, steering coils and additional distributed quadrupole focusing coils can be mounted externally along the wiggler.

The separate aluminum vacuum chamber will consist of extruded segments in the shape of an I-beam with an elliptical beam aperture through the center of the web. The I-beam shape is sufficiently strong that the chamber can be supported independently of the magnet arrays. Wigglers longer than a few meters will require vacuum joints in the beam tube welded in situ. Access ports drilled through the web to the beam aperture allow for diagnostic access and provide vacuum ports.

IV. 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 pre-requisite for such high gains is the generation of extremely bright, high current electron beams. Recent advances at LANL, BNL, and other laboratories in 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 photo-cathodes (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 $\sim$ 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 $\approx$ 50 ps.

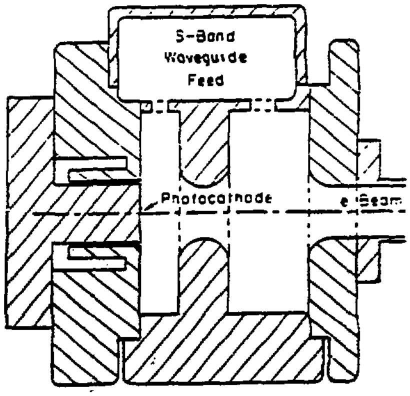

Figure 7

Limitations on the emittance of an electron gun are imposed by several physical effects: the maximum current density available from the cathode, non-linear electro-magnetic 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. The BNL gun, illustrated in Figure 7, 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 with 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 ($1\frac{1}{2}$ 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 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 from 5 – 10 nm. 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 ultra-high gradient structures now under investigation by a

SLAC/LLNL/LBL collaboration for a linear collider at TeV energies. The performance goals[8] for these structures are gradients exceeding 200 MeV/m and cost < 1 M$/GeV. The peak currents will be ~ 1 kA at a normalized brightness of about 10^{12} A/(m^2-rad^2) in a train of ~ 20 micro-pulses each of ~ 1 ps duration and spaced by 0.1 to 1 ns. The pulse train is repeated at a frequency of 100 – 1000 Hz; the rms energy spread through the macro-pulse must be < 0.1 %.

The physical phenomenon which forms the basis for scaling the gradient in rf-linacs from the 17 MeV/m of the Stanford Linear Colider to the desired ≈ 200 MeV/m for compact linear light sources, is the increase in peak electric field that can be sustained without breakdown[9] 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

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

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

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

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[10] driven by an induction linac, as illustrated in Figure 8.

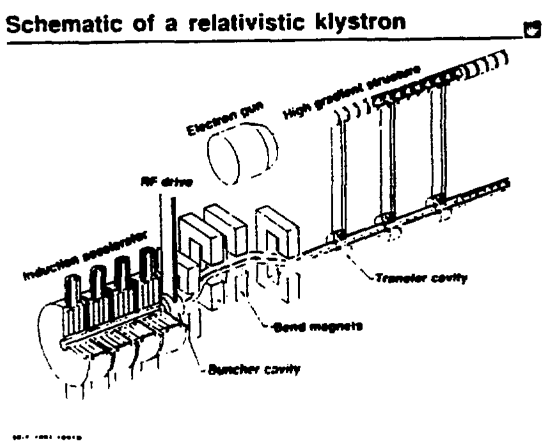

Figure 8

In the relativistic klystron a multi-kA, multi-MeV beam produced with a linear induction accelerator (LIA) is modulated at the desired rf-frequency (10 to 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[11] 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 to obtain an accelerating gradient exceeding 135 MeV/m in a demonstration earlier this year.

Characteristics of drive for x-ray FEL			
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
$\Delta\gamma/\gamma$ (%)	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

Table IV

For the 1 GeV linac needed to drive the FEL described by the FELOPT simulation, one injects the beam from a photo-cathode 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[8,12] and are listed in Table IV. This linac would produce a train of five micropulses spaced by 0.46 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 ≈ 3×10^{28} (photons-sec^{-1}-mm^2-mrad^{-2}) per 0.1 % bandwidth. The time average brilliance for this design is ≈ 4×10^{19}.

V. Critical Issues and Conclusions

The x-ray FEL relies on the performance of 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 issue most critical to the extension of free electron laser technology to the x-ray regime can be summarized as

0) generation of extremely high brightness electron beams and preservation of beam quality during the acceleration and energy conversion process

In addition to the difficulties of beam generation, the following four areas will be critical to the ultimate performance of the FEL in that they profoundly affect beam quality:

1) pulse-to-pulse reproducibility and stability of the electron beam
2) phase and amplitude stability of the relativistic klystron power drive with respect to the electron pulses from the photo-injector
3) beam transport into and through the wiggler
4) wake-field suppression in the high gradient rf-linac

Each of these areas must be studied in the laboratory at the component level and eventually in integrated sub-scale tests at longer wavelengths.

Compact x-ray FELs will require precise mechanical alignment of the cavities, beam tube, magnetic centerline, and optical axis. Laser alignment techniques used for large optical systems may be useful. Insertable screens and steering correction may provide initial alignment of magnetic mechanical axes. In the wiggler, the beam should not deviate from the centerline by more than a fraction of the beam size. A key to the success of this program will be the development of fast beam position monitors with an accuracy of $\approx$ 20 microns.

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 ($\frac{3}{4}$ to 1 microns).

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 sub-structures 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-GHz 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 – all elements of considerable biological significance. Based on the cost algorithm of Reference 11, the expected cost of such high brilliance x-ray instruments is expected to be under 10 M$.

References

1. R. Bonifacio, C. Pellegrini, L. M. Narducci, Opt. Comm., 50, 373 (1984)
2 J.B. Murphy and C. Pellegrini, J. Opt. Soc. Am., B2, 259 (1985)
3 A.L. Throop, et al.; "Experimental results of a high-gain microwave FEL operating at 140 GHz"; LLNL, UCRL-97706, presented at the Ninth International FEL Conference, Williamsburg, VA, Sept 14 – 18, 1987; to be published in Nuclear Instrumentation Methods.
4 G. Deis, et al, "A Long Electromagnetic Wiggler for the Paladin Free-Electron Laser Experiments", IEEE Transactions on Magnetics, Vol 24, No. 2, March 1988.
5 A. Bohwmik, et. al., "First Operation of the Rocketdyne/Stanford Free Electron Laser", Proc. IX International Free Electron Laser Conference, Williamsburg, VA, Sept 1987.
6 A.D. Cox and B.P. Youngman, Proc. SPIE, Vol. 582, pp 91 – 97, 1985.
7 J.S. Fraser and R.L. Sheffield, J. Quantum Electronics QE-23, 1489 (1987)
8 R. Palmer, Interdependence of Parameters for TeV Colliders, SLAC-4295.
9 J.W. Wang, V.Nguyen-Tuong, and G.A.Loew, RF Breakdown Studies in a SLAC Disk-loaded Structure, Proceedings of the 1986 Linear Accelerator Conference, SLAC-303 (1986)
10 A.M. Sessler and S.S. Yu, Phys. Rev. Lett. 58, 2439 (1987)
11 M. Allen, et al, Proceedings of the European Particle Accelerator Conference, (1988)
12 W.A. Barletta, High Gradient Accelerators for Linear Light Sources, LLNL report UCRL-99268, Rev I, to be published in Nuc. Instruments and Methods, (1988)