RF LINACS FOR FELs *

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Abstract

There are twenty rf linac driven Free Electron Lasers (FELs) existing or under construction throughout the world and proposals for several more. A number of these FELs have recently been established as facilities to produce coherent optical beams for Materials and Biomedical Research. Both short pulse low duty factor and long pulse high duty factor linac driven FELs will be discussed. Accelerator issues that influence the performance of an FEL as a scientific instrument will be indicated.

Introduction

The Landmark Free Electron Laser (FEL) Oscillator Experiment is now 15 years of age [1]. Although potential applications of the FEL have been discussed for many years, it is only recently that FEL technology has advanced to a stage that will support serious programs of scientific research. In scientific applications FELs provide a number of significant advantages. Perhaps the most important advantage is that FELs can operate at wavelengths previously inaccessible and that this wavelength can be scanned readily. Simple wavelength agility, however, is not sufficient. If one hopes to produce "world class" science with FELs, one must match or better the performance of conventional lasers independent of wavelength. Potentially, FELs can provide excellent optical beam quality and beam stability and FEL systems can provide great flexibility in operation, including variation of the optical micropulse length, variation in the optical pulse repetition rate and production of multiple-color synchronized optical beams. In industrial and defense applications FELs additionally offer the potential for high power and high efficiency operation. It is important that all of these capabilities be realized.

In 1991 a Directory of Free Electron Lasers was compiled [2] listing eighteen rf linac driven FELs existing or under construction throughout the world and proposals for several more. The list has grown modestly in the past year. In Tables 1 and 2 below, these FELs have been segregated into short pulse linac-driven FELs and superconducting linac-driven FELs. The short pulse linac systems in Table 1 produce an optical pulse train that lasts from a few microseconds to twenty microseconds. This pulse train is referred to as the macropulse (Tm) and is repeated at a frequency (fm) that ranges from 10 Hz to 360 Hz. Typically every rf bucket is filled in these machines which means that individual optical micropulses (within the macropulse) are separated by approximately 300 ps. The superconducting linac-driven FELs are listed in Table 2 and it is immediately evident from the micropulse repetition frequencies (fμ) that only a few rf buckets of the linac are filled. Even for the highest repetition frequency (50 MHz) the separation between micropulses is 20 ns. Since optical pulse switching at 20 ns is rather easy and switching at 300 ps is rather difficult, this is an important distinction between the two classes of FEL systems. Many of the FELs listed in Tables 1 and 2 will evolve into facilities for materials and biomedical research.

TABLE 1
Short Pulse Linac-Driven FELs

Operating FEL Facilities:

	f(MHz)	E(MeV)	Tm(μs)	fm(Hz)
Orsay (CLIO)	3000	70	10	50
Duke	2856	45	9	15
FOM (FELIX)	3000	45	20	10
Vanderbilt	2856	45	7	30

FELs in Construction:

	f(MHz)	E(MeV)	Tm(μs)	fm(Hz)
BNL(ATF)	2856	50	--	--
LANL (AFEL)	1300	20	20	30
Osaka(1)	2856	6	10	10
Osaka(2)	1300	38	2.5	360
Rockwell	2856	78	3.7	360
Stanford (3)	2856	3.5	3	10
Tokyo	2856	15	6	50
Twente	1300	25	10	10
UCLA	2856	20	4	5

FEL Proposals:

	f(MHz)	E(MeV)	Tm(μs)	fm(Hz)
SSRL/SLAC	2856	6000	--	--

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(2) Institute of Scientific and Industrial Research
(3) Department of Electrical Engineering

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TABLE 2
Superconducting Linac-Driven FELs

	f(MHz)	E(MeV)	fμ(MHz)
Operating FEL Facilities:			
Stanford	1300	70	11.8
FELs in Construction:			
Darmstadt	3000	50	10
Frascati	500	25	50
JAERI	500	13	10.4
FEL Proposals:			
BNL(1)	500	250	0.01
CEBAF(2)	1500	85/445	2.5-7.5
LBL	500	50	6

(1)BNL proposal is for an XUV amplifier
(2)CEBAF proposal is for both an IR and UV oscillator

Excluded from the two lists of linac driven FELs are the APEX facility at Los Alamos, the APLE facility at Boeing and the ELSA facility at Bruyeers-le-Chatel. All these FELs are high power systems of greatest interest in industrial and defense applications. Since the focus of this paper is FELs for research facilities, they will not be discussed further.

Characteristics of RF Linac-driven FELs

In an FEL the optical wave is amplified by extracting energy from a co-propagating electron beam. Transverse motion of this electron beam, that couples to the transverse electric field of the wave, is induced by a magnetic wiggler system as shown in Fig. 1. To maintain a constant phase relation between the transverse motion of the electron and the transverse electric field, the electrons must slip behind the wave by one optical period each wiggler period. This synchronism condition is satisfied if:

$$\lambda = \frac{\lambda n}{2\gamma^2}(1+k^2)$$

where λ is the optical period (or wavelength),λn is the wiggler period, γ is the relativistic energy of the electron beam, and k^2 depends solely on parameters of the wiggler. As in a klystron, bunching of the electrons by the optical field is required for net energy extraction.

For a Van de Graaff-driven FEL the electron beam is continuous and the resulting optical wave is likewise continuous. For an rf linac-driven FEL, however, the electron beam consists of a train of electron bunches each a few picoseconds in length and the optical beam exhibits the same pulse format. This is an important feature of the linac-driven FEL that makes it particularly well matched, for instance, to studies of molecular dynamics on the picosecond time scale.

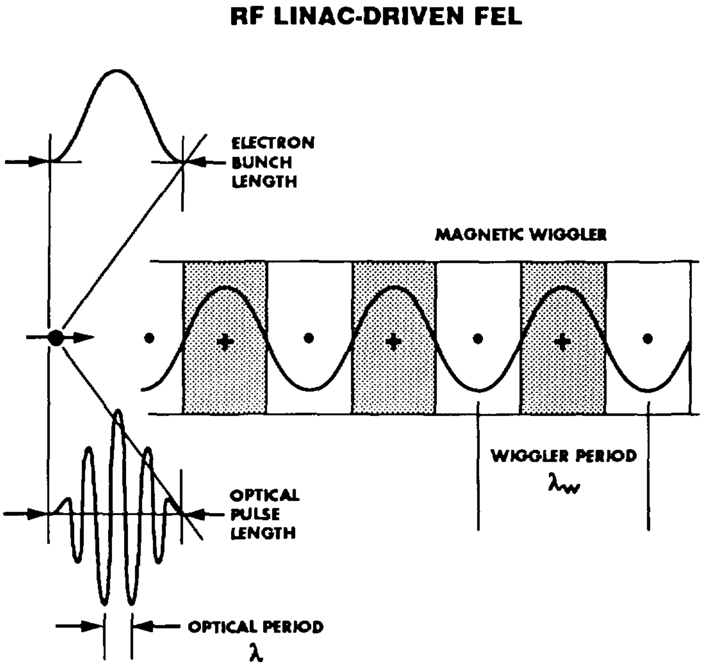

Fig. 1 Overlapping electron bunch and optical pulse propagating through a magnetic wiggler.

Linac-driven FELs are most often configured as oscillators, with the wiggler enclosed in an optical cavity, as shown in Fig. 2. Typically, the optical cavity is a few meters to a few tens of meters in length and therefore if every rf bucket of the linac is filled, there will be many optical bunches in the optical cavity. One can reduce the number of optical bunches in the cavity, however, by selectively filling rf buckets in the linac.

Adjusting and stabilizing the length of the FEL optical cavity is critically important. For the Stanford machine the optical cavity is 12.7 meters in length, providing a photon round trip time equal to 110 rf periods of the linac, and a change in length of 1 micron will produce observable changes in the optical wave. A change in cavity length by 20 microns will stop lasing completely.

A notable exception to the usual FEL oscillator configuration can be found in the Los Alamos and more recently the Brookhaven and the SSRL/SLAC proposals for XUV lasers. At these wavelength mirrors suitable for optical cavities do not exist and thus an amplifier configuration is required.

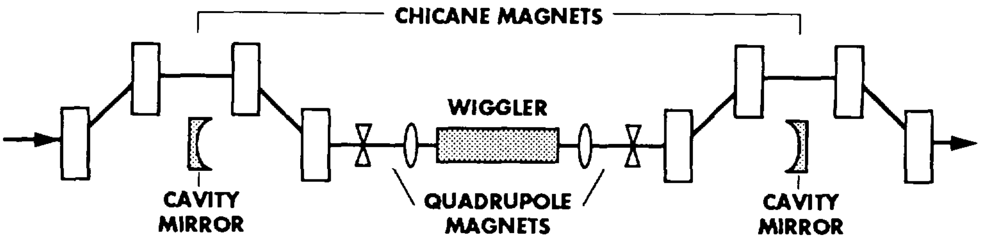

Fig. 2 Schematic of the FEL optical cavity and wiggler together with the electron beam transport system. Magnetic chicanes are used to transport the electron beam around the cavity mirrors.

Experimental Facilities

It must be remembered that a laser by itself is not sufficient to make a meaningful physical measurement. An FEL application will involve an experimental apparatus whose complexity may approach that of the FEL. Furthermore, to exploit fully the scientific potential of the FEL one will need experimental apparatus for several classes of experiment. This raises a number of questions. First, for what class of experiment should "permanent" optical set-ups be established? Second, what complementary instrumentation is appropriate? The need for "permanent" optical set-ups and complementary instrumentation raise important questions about the experimental laboratory space required and suggests it might be desirable to provide the FEL optical beam to several experiments simultaneously.

A good example of the laboratory space that is appropriate for an FEL facility is provided by the Medical FEL facilities at Vanderbilt University. A plan view of the Vanderbilt facility is shown in Fig. 3.

The FEL optical beam enters a laser diagnostic lab which is adjacent to the FEL control room and from there proceeds to the experimental area . There are five target rooms for experiments and two animal operating rooms complete with an animal-care facility. The operating rooms are equipped with hand-held beam delivery systems to allow surgeons to manipulate the beam. The rooms will be supported by wet lab and a tissue culture lab for biological tests, and by shop facilities for the construction and test of equipment to be used in the experiments. Users are able to control the FEL through two slave computers which can be moved to any of the labs. Total experimental laboratory space is 600 m^2.

Complementary facilities or instruments will represent an important component of each FEL facility. At Vanderbilt there is a high resolution Bruker IFS-113 FTIR spectrometer for experiments involving hole burning, IR multiphoton dissociation, and radiation damage in biomaterials and molecular systems, and a Raman spectrometer system for time-resolved studies of vibrational energy transfer, and FEL induced material modification processing using the Raman spectrum as a probe.

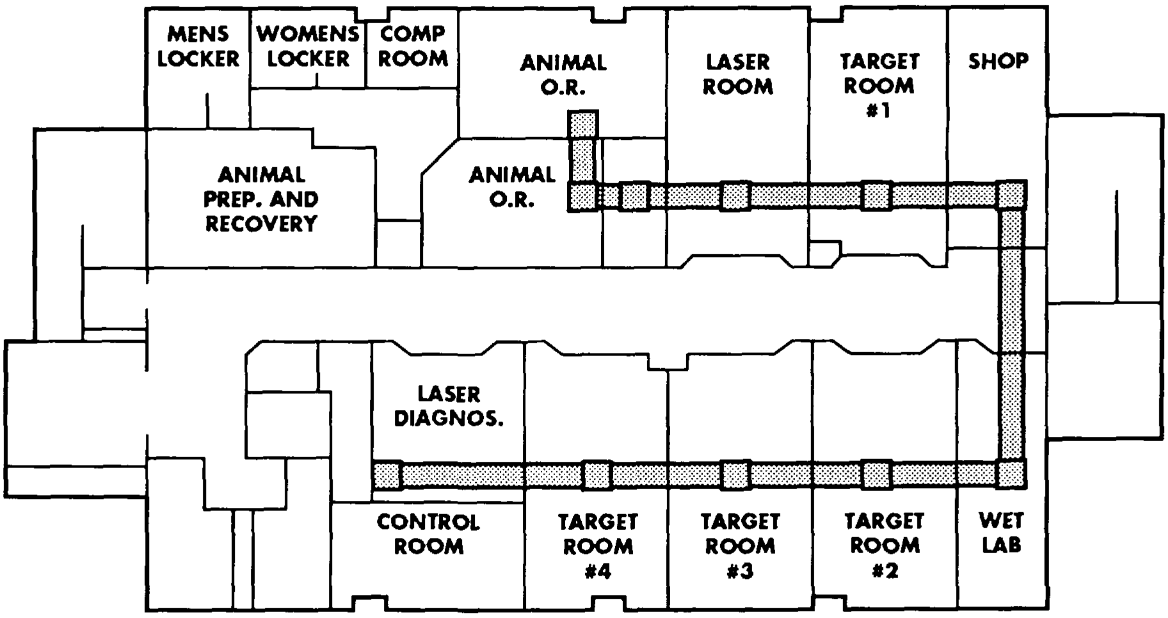

Fig. 3 Plan view of the Vanderbilt MFEL Program experimental labs. The FEL beam enters at the diagnostic room and proceeds to the target rooms. The optical beam transport system is shaded in the diagram.

At Stanford there is a tunable picosecond dye laser system synchronized to the FEL for two color experiments involving studies of vibrational energy transfer, photo chemistry, time-resolved fluorescence and Raman spectroscopy of non-equilibrium carriers in semiconductors, and a Zeiss axiovert microscope for experiments on single living cells. At Duke, synchrotron radiation, synchronized to the FEL, will soon be available.

"Permanent" optical set-ups will also be an essential part of each FEL facility. At Stanford an optical set-up that provides two (or three) beams crossed in space and time is available for single color pump probe, photon echo, and transient grating experiments. This set-up also provides a capability for single pulse selection to match the optical pulse repetition rate to the requirements of the experiment at hand. At Vanderbilt a beamline is being established for monochromatic (incoherent) X-ray photons tunable from 300 eV to 18 KeV [3]. The photons are produced by Compton scattering of the FEL beam by the electron beam. Many other complementary facilities and "permanent" optical set-ups are being established at FELs throughout the world.

Optical Beam Quality and Beam Stability

The optical beam quality and beam stability that can be achieved in an rf linac driven FEL is exceptional. Within 10% the FEL optical pulse is transform limited and is a single diffraction limited TEM$_{00}$ mode. The FEL optical beam stability is also very good, but requires more extensive discussion.

Although one can expect the FEL optical pulse shape to be stable, one must expect significant fluctuations in the central wavelength and the optical pulse amplitude during operation. Central wavelength fluctuations in the Stanford SCA/FEL [4] are shown in Fig. 4. Over the time span shown (>20,000 micropulses) the fractional variation is $\pm 2\times10^{-4}$. This is nearly two orders of magnitude better than achieved in short pulse linac-driven FELs, and it is nearly one order of magnitude better than the transform limited band width of the optical pulse, but it is still greater than that required for some experiments. Inspection of the data in Fig. 4 reveals an interesting fact. Significant fluctuations exist at surprisingly high frequencies. The large amplitude fluctuation occurs at approximately 3 kHz and the small amplitude fluctuation at approximately 30 kHz.

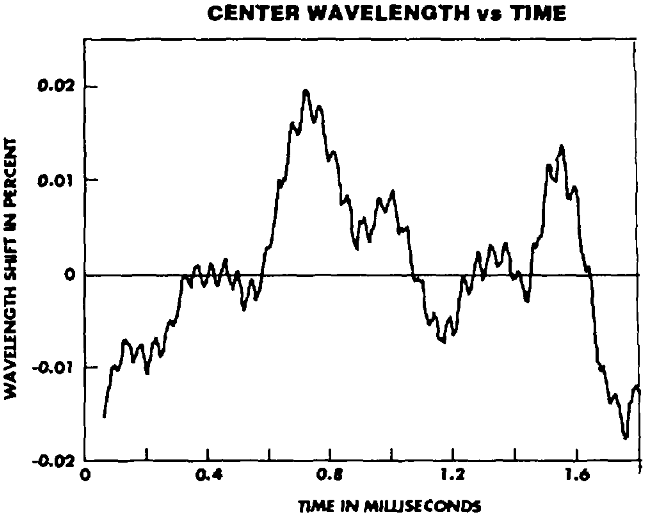

Fig. 4 Center wavelength of the Stanford FEL beam as a function of time: largest fluctuations occur at 3 kHz, but small fluctuations occur at 30 kHz.

Relatively large fluctuations are observed in the amplitude of the FEL optical micropulses. It is not unusual to observe fluctuations of ±10% and it is not unusual for these fluctuations to extend to frequencies of many kHz. At Stanford, some success has been achieved in reducing both wavelength and amplitude fluctuations by feedback control. In the case of wavelength stabilization, feedback is provided to the electron beam energy [5].In the case of amplitude stabilization, feedback is provided to an AOM that diffracts away part of the incident pulse energy. In both cases the high frequency components are the most difficult to deal with.

Pointing and position stability of the FEL optical beam is also an important issue. At Stanford, despite the fact that the optical beam is transported 100 meters from the FEL to the experimental area, the fluctuations in beam position are measured to be less than 10% of the optical beam size.

Considerable interest has been expressed in the timing stability of the train of optical pulses delivered by the FEL. We have recently measured this timing stability by coupling the FEL beam into an external optical cavity that is identical to the FEL cavity. The build-up of optical energy in the external cavity provides a measure of the timing stability of the incident pulses. The optical power transmitted through the external cavity (lower trace) and the power reflected from the cavity (upper trace) are shown in Fig. 5. For the measured[6] optical cavity Q of 15, the observed optical energy stored in the external cavity was 19 times the incident FEL micropulse energy, in agreement with calculations. These measurements hold promise that one can deliver giant optical pulses by cavity dumping and indicate that the principal timing error is an oscillation of ± two femtoseconds at a frequency of approximately 100 Hz. This is remarkable timing stability.

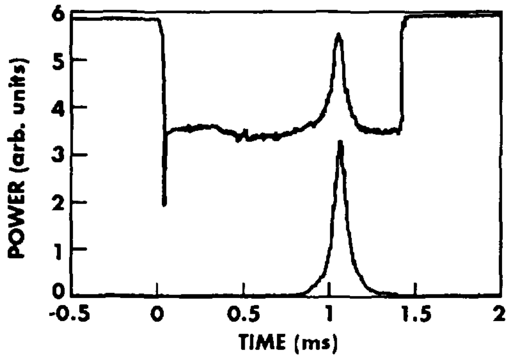

Fig. 5 Transmitted (lower trace) and reflected (upper trace) power from the external cavity. The reflected power decreases at resonance since the wave transmitted out of the coupling mirror and the wave directly reflected from the coupling mirror are out of phase.

It is clear that fluctuations in electron beam energy and electron bunch charge, fluctuations in electron beam pointing and position, and fluctuations in electron bunch timing can all influence the optical beam in the FEL. While some of these fluctuations can be compensated by feedback, it is most desirable to eliminate them at the source. This is a challenge for accelerator physics, particularly for the higher frequency contributions.

FEL System Flexibility

Operation of an FEL can be remarkably flexible. The system for feedback control of the FEL wavelength includes a dipole detector located at the output of an optical spectrometer. The error signal from this detector is used to change the electron beam energy, and thus if we simply scan the spectrometer, the feedback control system will automatically scan the FEL wavelength. By adjusting the phases and amplitudes of the injector cavities in the linac, one can vary the electron bunch length and thereby the FEL optical pulse length. At Stanford we have varied the optical pulse length from 1 ps to 5 ps in this way.

An example of quite a different sort is beam sharing by macropulse switching. As illustrated schematically in Fig. 6, if the electron beam energy is changed from one macropulse to the next, then the optical wavelength will also be changed. For interesting changes in wavelength this modulation can easily proceed at 30 Hz. The optical macropulses of different wavelength can be delivered to the appropriate experiment either by optical switching in time or by use of dichroic mirrors to enable an experimenter to pick out his wavelength component of the beam. Many other examples of system flexibility could be cited.

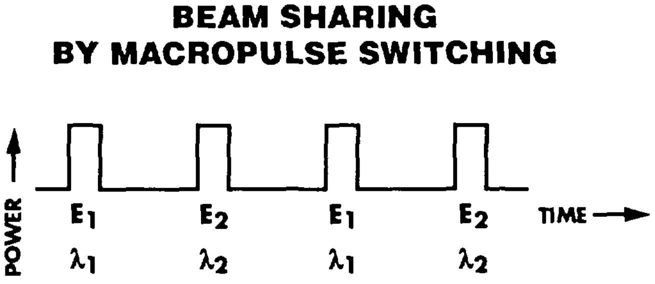

Fig. 6 Beam sharing by macropulse switching. Switching the electron beam energy from one macropulse to the next results in switching of the optical wavelength. In this way, optical beams of two or more wavelengths can be delivered.

Conclusions

If the full potential of FEL systems can be realized, then one has a unique opportunity to develop an "FEL Analog" of a Synchrotron Radiation Facility. One can imagine delivering optical beams of exceptional quality to sophisticated optical set-ups that are analogous to synchrotron radiation beam lines and one can imagine perfecting techniques for beam sharing to expand utilization of the facility. Achieving this potential will require careful design of accelerator systems and extensive diagnostics.

References

[1] D. A. Deacon, L.R. Elias, J.M. J. Madey, G. R. Ramian, H.A. Schwettman, T. I. Smith, "First Operation of a Free Electron Laser", Phys. Rev. Lett., 38 #16, pp 892-894, 1977.

[2] Directory of Free Electron Laser Experiments, Compilation by R. Dei-Cas, Service de Physique et Techniques Nucleaires, B.P.N

[3] F. E. Carroll et al., Investigative Radiology 25 (1990) 465.

[4] J. C. Frisch, "Time Dependent Measurements on the Superconducting Accelerator Free Electron Laser", Stanford University Ph.D. Thesis, 1990.

[5] A. Marziali, T. I. Smith, "Feedback Stabilization of the SCA/FEL Wavelength". Presented at the XIVth International Free Electron Laser Conference, Kobe, Japan, August, 1992.

[6] P. Haar, H.A. Schwettman, T.I. Smith, "Experimental Test of the SCA/FEL External Cavity". Presented at the XIVth International Free Electron Laser Conference, Kobe, Japan, August, 1992.