FREE-ELECTRON LASERS AND RELATED TOPICS*

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Summary

This past year has been very exciting for the experimental free-electron laser (FEL) programs. At three Laboratories, oscillator experiments were performed with wavelengths from the visible to far infrared. The output powers are steadily advancing. The status of these programs will be discussed. As shorter wavelengths and higher powers are pursued, higher currents with improved beam quality will be required. Advanced electron linacs should be developed to meet these demands.

Introduction

FELs are being actively developed at many Laboratories because of several highly desirable properties. They span the wavelength range from centimeters to tenths of microns and are typically continuously tunable over an order of magnitude by varying the electron beam energy, the wiggler wavelength, or both. Recent experiments indicate that the optical quality is excellent at modest power levels. FELs are scalable to high average power because the lasing medium is the electron beam itself and is removed from the cavity at nearly the speed of light, thus avoiding the cooling problems associated with using solid or gaseous lasing media. Finally, it appears that FELs can be quite efficient through the use of tapered wigglers and the recovery of most of the kinetic energy left in the beam.

Recent studies have identified potential scientific,[1] industrial,[2] and medical applications of FELs. Chemistry and surface chemistry would benefit particularly from (1) a pulsed tunable infrared source with an energy comparable to that of laboratory CO_2 lasers and (2) a pulsed tunable laser of substantial energy below 200 nm. High-power sources at centimeter wavelengths could lead to shorter high-energy accelerators either by providing high-power tube replacements or through reverse operation of an FEL. High-power millimeter sources could find applications in radar and plasma heating in fusion reactors. Their biggest impact very likely will be in industry where reliable, tunable, inexpensive sources of photons can open up new photochemistry applications. High average powers would allow production and separation of molecules from large volumes of chemical feedstock. As these machines are more fully developed, many now unforeseen applications will probably arise.

Basic Principles

The basic components of an FEL are an electron beam, an external oscillatory field, and a radiation field. The external oscillatory field causes the moving electrons to oscillate ("wiggle") transversely so that the transverse electric field of the imposed photons can bunch and decelerate the electrons. The deceleration energy of the electrons appears as a coherent enhancement of the radiation field. If the beams are very intense so that collective plasma effects are important, the FEL is described as operating in the "Raman regime." Such FELs are typically driven by induction linear accelerators or pulsed transmission-line accelerators. The beam quality limits these to infrared and longer wavelengths, but the very high currents produce large single-pass gains. FELs based on lower current sources, such as rf linacs, microtrons, or storage rings, operate in the "Compton regime." At these currents, there are primarily single-particle interactions, and collective and space-charge effects can be neglected. The lower currents also mean smaller gains and lower efficiencies unless enhancement schemes are introduced. With high-energy beams of low emittance and small energy spread, FELs in the Compton regime can operate at optical or ultraviolet wavelengths.

FELs are configured as amplifiers or oscillators. An amplifier increases the power of an external radiation source during a single pass through the wiggler. This configuration is best suited to the high-gain FELs operating in the Raman regime. An FEL oscillator employs an optical resonator around the wiggler that allows the radiation field to build up with time through many synchronous passes with multiple electron pulses through the wiggler. If the pulse train is long enough and the small-signal gain is adequate, an FEL oscillator should start up from spontaneous emission without an externally injected radiation field.

The remainder of this overview will concentrate on short-wavelength ($\leq$10-μm) FEL oscillators operating in the Compton regime where there has been substantial progress lately. A recent excellent review[3] by Sprangle and Coffey lists most of the FEL experiments and their wide range of parameters.

The basic elements of a Compton-regime FEL oscillator are shown in fig. 1. The FEL consists of a pulsed beam of relativistic electrons from an rf linac directed through a static, periodic, transverse magnetic field, called a wiggler, and an optical resonator with one mirror slightly transmitting for output coupling. The electrons oscillate transversely and emit polarized radiation at a wavelength λ_s determined by the resonance condition,

$$\lambda_s = \frac{\lambda_w}{2\gamma^2}(1 + K^2/2) \quad ,$$

where λ_w is the wiggler period, γ is the electron energy in units of its rest mass, and $K = e\lambda_w B/2\pi mc^2$ with B being the peak magnetic field at the wiggler midplane. The emission from the initial electron

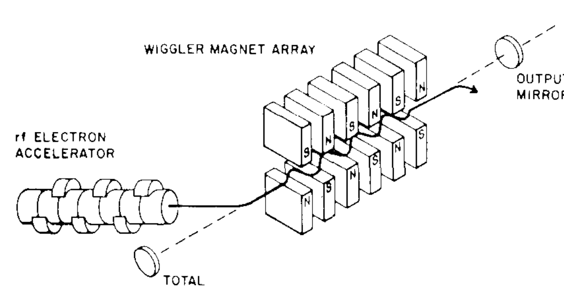

Fig. 1. The basic elements of a Compton-regime FEL oscillator: relativistic electron beam, magnetic wiggler, and optical resonator.

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pulses passing through the wiggler is primarily spontaneous. The precisely spaced mirrors provide a round-trip time for the light that matches the period of the electron bunches. As the captured radiation field increases, the transverse electric field of the light causes longitudinal bunching on an optical wavelength spatial scale. When the average electron energy is above the resonant energy defined in the equation, the radiation field causes a net deceleration accompanied by "stimulated emission." If the optical gain of the wiggler at low power levels exceeds the mirror and diffraction losses, there will be a rapid build-up of this stimulated radiation until the power losses (including outcoupling) equal the power produced.

The extraction efficiency of a constant-period wiggler is limited to 1/2N, where N is the number of wiggler periods. For a 50-period wiggler, for example, a maximum of 1% efficiency would be attainable. This limitation occurs when the average electron energy reaches the resonance energy. Efficiencies greater than 5% should be attainable with "tapered" wigglers. A tapered wiggler is designed to have either its period or magnetic field continuously decrease along its length so as to maintain the electron energy at resonance for the desired wavelength.

FEL Oscillator Experiments

Since the first operation of an FEL oscillator at Stanford University in 1977,[4] FEL theory and simulations have advanced substantially. The introduction of an accelerator-based description that led to the tapered wiggler[5] is resulting in higher efficiencies. FEL amplifier experiments at Los Alamos[6] and Math Sciences/Boeing[7] have demonstrated 4% efficiencies. During the summer of 1983, a team from TRW and Stanford University attained 1.1% efficiency with a 1% tapered wiggler in an oscillator.[8]

In 1983, three oscillators were demonstrated, as listed in table I. These experiments used a conventional linac, a superconducting linac, and a storage ring and spanned a wide range of powers and wavelengths.

TABLE I

SUMMARY OF SHORT-WAVELENGTH FEL OSCILLATORS

Year	Institution	Accelerator	Beam Energy (Mev)	Wave-length	Peak Power	Average Power[a]
1977	Stanford[4]	sc linac	43	3.4 μm	135 kW	5 W
1983	U Paris/ Stanford[9]	ACO	160	640-655 nm	60 mW	75 μW
1983	TRW/ Stanford[8]	sc linac	66	1.6 μm	1 MW	4 W
1983	Los Alamos[10]	rf linac	20-23	9-11 μm	1 MW	1 kW

[a]Average power during each beam macropulse.

The University of Paris/Stanford experiment at Orsay represents the first operation of a visible wavelength FEL on a storage ring. They used a 1.3-m permanent-magnet optical-klystron wiggler (contains magnetic bunching). With a 50-mA ring current, a net gain per pass of ∿0.001 was achieved. The oscillations grew for 200 μs and then stabilized at 2-kW intracavity peak power during the 1-ns electron bunches. The primary problem they encountered was the degradation of the mirror coatings by the ultraviolet radiation from the ring and wiggler. With such a small gain, practically any degradation could prevent oscillation build-up.

The TRW/Stanford experiment was performed at Stanford on their superconducting linac. This experiment represents the first oscillator with a tapered wiggler. The accelerator was operated at 66 MeV with peak currents from 0.5 to 2.5 A with very low emittance and small energy spread. They used a 5.4-m permanent-magnet wiggler that contained two 0.5-m constant-period sections, a magnetic bunching section, and a 3.2-m adjustable tapered section. With a taper of 1% in γ, they achieved 7% gain per pass, reaching saturation in 25 μs. The peak cavity power was 1.2 MW and the average output power was 4 W at 1.6 μm. The efficiency obtained was 1.1%, which was a factor of 3 greater than the performance of their wiggler with no taper.

Operation of several more FEL oscillators is expected in 1984 and 1985. The oscillators are listed in table II. The initial operating results and the increase in the number and diversity of experiments are very encouraging.

TABLE II

ANTICIPATED FEL OSCILLATORS IN 1984-1985

Institution	Accelerator	Beam Energy (MeV)	Wavelength
Los Alamos	rf linac	10-28	5-50 μm
TRW/Stanford	sc linac	120	0.5-0.8 μm
United Kingdom[11]	rf linac	30-100	10-20 μm
UC-Santa Barbara[12]	electrostatic	6	0.1-1 mm
ENEA at Frascati[13]	ADONE	600	0.5 μm

Los Alamos FEL Oscillator Experiment

The schematic layout of the Los Alamos FEL oscillator experiment is shown in fig. 2 and the initial operating parameters are listed in table III. The electron gun produces a train of 2000 micropulses, spaced 46 ns apart, for a macropulse of 100 μs. These are bunched and accelerated to approximately 21 MeV. The train of high-current pulses then passes through the wiggler generating spontaneous emission and, if the gain exceeds the losses, stimulated emission, which grows exponentially to a saturated level of optical power.

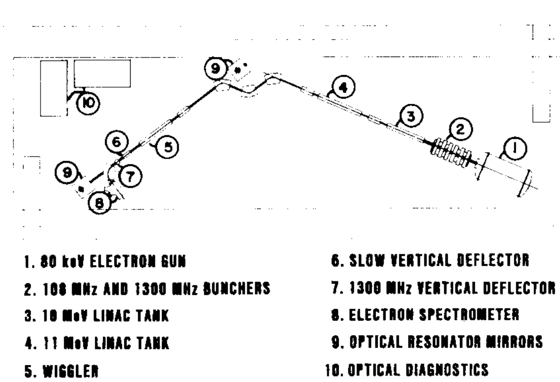

Fig. 2. Layout of Los Alamos FEL oscillator experiment.

TABLE III

FEL OSCILLATOR PARAMETERS

Electron Beam	
Electron energy	20-23 MeV
Accelerator frequency	1.3 GHz
Micropulse width, estimated	30 ps
Peak current, estimated	25 A
Micropulse repetition time	46.15 ns
Macropulse length	100 μs
Energy spread	∿2% (FWHM)
Emittance	∿2π mm•mrad
Diameter at waist	2.0 mm
Wiggler	
Length	100 cm
Period	2.73 cm
Gap between magnets	0.88 cm
Field strength	0.31 T
Optical	
Cavity length	6.92 m
Rayleigh range	63.2 cm
Diameter at waist	2.8 mm
Wavelength	9-11 μm
Round-trip losses	3.3%
Output coupler	3.0%

During the initial tests, the subharmonic bunchers were not used because of multipactoring and control problems, limiting the peak currents to 25 A during the 30-ps bunches. With only the fundamental buncher operating, the 3-ns pulse from the gun usually filled about five of the 1.3-GHz buckets. This limited the peak currents that could be achieved, but provided a means of measuring gain as a function of current under identical conditions. The temporal build-up of laser oscillation for the different intensity bunches can be seen in fig. 3. The maximum growth shown corresponds to 20% per pass with 3% cavity loss. The smaller gains of the lower intensity pulses are also apparent.

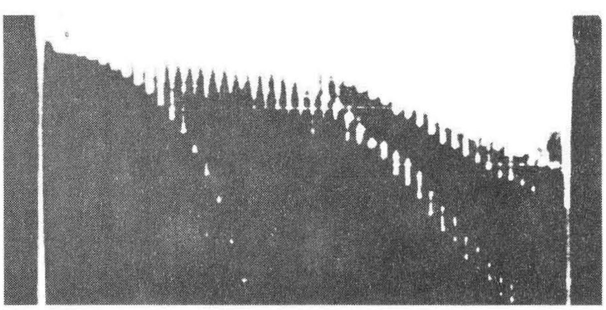

Fig. 3. Temporal build-up of laser oscillations. Slower rise times are from lower current electron bunches in micropulse.

The mirrors of the optical resonator were curved for a stable, fundamental mode of the correct size to maximize the gain of the wiggler. The mirrors were composed of multiple dielectric layers deposited on ZnSe substrates transparent to visible light. This combination allowed use of a HeNe laser for mirror alignment and for alignment of the electron beam with the resonator. The respective reflectances of the end mirror and output coupler were 99.7 and 97.0%. The mirrors were remotely tilted for optimum alignment, and the end mirror was translated longitudinally to achieve the correct spacing. A separate HeNe interferometer monitored the mirror spacing continuously.

When the cavity length was optimized, the intracavity power grew quickly to saturation in 10-20 μs and continued to lase for the remainder of the macropulse. A typical measurement of the output power is shown in fig. 4. Superimposed on fig. 4 is shown the optical power that theoretically would develop if the optical gain were 4, 8, and 16%. The observed behavior agrees qualitatively with these curves in time to saturation and saturated power, but the large modulations are not explained. At this point we feel most of the modulation is due to phase noise from the klystrons or their driving electronics. The optical cavity acts as a very precise clock whose frequency must be matched by the electron bunch repetition rate to continue maximum efficiency.

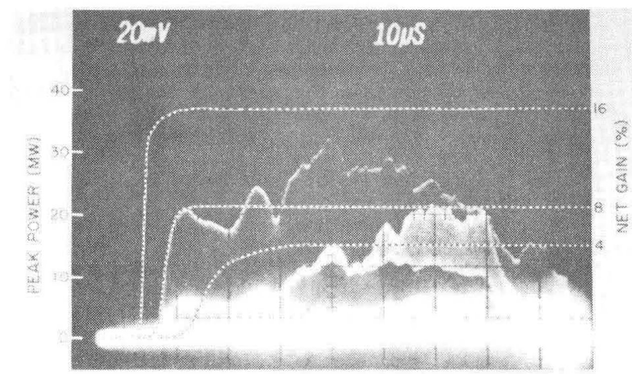

Fig. 4. Optical power within Los Alamos FEL oscillator during one macropulse.

The trailing edge of the saturated macropulse is shown in fig. 5. This display is a good diagnostic for final alignment of the resonator mirrors. When the system is properly aligned, the decay constant of the optical pulse agrees with the 3% cavity loss that is due to the output mirror. When the mirrors are grossly misaligned, the second-lowest-order cavity mode appears and mixes in to cause a modulation to appear on the exponential decay.

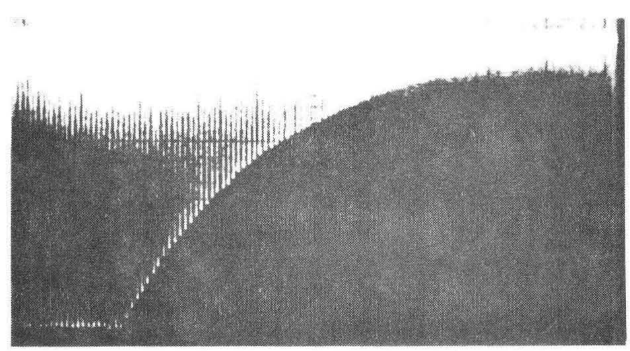

Fig. 5. Decay of oscillator power at end of macropulse provides a measurement of resonator losses.

The spatial profile was in good agreement with a Gaussian shape--another indication that only the lowest order mode was enhanced. If this is true, the optical quality should be limited only by diffraction.

The high-reflectivity region of the present mirrors extends from 9 to 11 µm. Oscillation throughout this range was easily accomplished by varying the electron beam energy ±5%.

Future Requirements

As shorter wavelengths and higher average power are pursued, substantial development effort will be required in several accelerator areas. These include injectors with improved beam quality, high-current accelerators, and energy-recovery concepts.

Improved Injectors

Most of the emittance growth in conventional electron linacs occurs during the bunching and acceleration up to relativistic energy (a few MeV). For bunches with several nanocoulombs, the growth in the normalized transverse emittance is usually more than an order of magnitude above the gun emittance. High-current optical-wavelength FELs will require normalized emittances smaller than 40π mm•mrad. To achieve this beam quality, most of the conventional injector emittance growth must be avoided.

Several approaches are being considered for an improved injector. The first would consist of many buncher cavities so the bunching can proceed adiabatically, analogous to an RFQ for ions. In our simulations so far, this approach is disappointing because of the large space-charge forces. The second approach being considered is a high-voltage (1-MeV) pulsed gun with magnetic bunching at higher energies. The large current densities require such high fields in the gun that this approach is difficult. The third, and perhaps most promising approach, is the use of a photocathode gun mounted within an rf cavity that is shaped to provide a Pierce field configuration at peak field. A mode-locked laser would illuminate the photocathode to produce the already short bunches that could then be accelerated very quickly in the rf cavity. This cavity could even be the first cell of the injector linac. Photocathodes such as GaAs and Cs_3Sb are being investigated. These are capable of current densities exceeding 100 A/cm^2 with modest laser illumination.

High-Current Accelerators

The maximum current limit in most electron accelerators occurs at an average current of a few hundred milliamperes because of beam-breakup instabilities. These instabilities are the result of higher order dipole modes that are excited by the passage of the beam slightly off-axis. For operation at average currents approaching 1 A, improvements in electron accelerators will be necessary. We have found that ramping the beam up slowly (∿1 µs) and using more focusing helps to avoid the transient phenomena. However, it will probably be necessary to develop cells that will not support these modes, or that have Q-damping posts or slots for these unwanted modes without affecting the accelerating mode appreciably.

Energy-Recovery Concepts

After passing through a high-efficiency FEL, the beam has more than 90% of its initial power; it still has good microbunch structure and emittance, but it will have several per cent energy spread that makes it unsuitable for recirculation through the wiggler. For a linac-based FEL, it appears that the most efficient energy-recovery scheme is to recirculate the beam through the accelerator, but at the deceleration phase, thus converting the kinetic energy back into rf power within the linac at its fundamental mode. In high-power FELs, it appears that energy recovery could enhance the efficiency by up to a factor of 5. This approach will be tested at Los Alamos in the future. A similar idea of energy-recovery on an electrostatic machine is being developed on the UC-Santa Barbara FEL.

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