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# Free Electron Lasers

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Free electron lasers (FELs) comprise a class of potentially efficient devices capable of generating high quality coherent radiation, continuously tunable from the microwave region to the x-ray region, at high average and/or high peak power. A short description of the physics of the FEL and its applications are described in this paper. The FEL is now becoming a research tool rather than a pure research topic. The light properties at the currently funded FEL user facilities are listed.

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# FREE ELECTRON LASERS

Free electron lasers (FELs) comprise a class of potentially efficient devices capable of generating high quality coherent radiation, continuously tunable from the microwave region to the x-ray region, at high average and/or high peak power. The essential FEL physics have been demonstrated. The FEL is now becoming a research tool rather than a pure research topic.

FEL Physics The FEL is characterized by a relativistic electron beam co-propagating through an undulator field (or wiggler field) with an input radiation field. The undulator field, which gives electrons a periodic transverse motion, is typically a static periodic magnetic field. If the electron beam is of good quality and has a sufficiently high current density, input radiation at the appropriate frequency will grow, as in the case of an FEL amplifier. When the gain per pass through the undulator is low, many passes are required for the radiation to reach saturation, as in an FEL oscillator. A schematic of the FEL oscillator is shown in Fig. 1. Here, the end mirrors reflect the radiation between the exit and the entrance of the undulator.

The FEL has major differences relative to conventional lasers. The active medium in the FEL is not atoms or molecules but free electrons. The radiation frequency of the FEL is continuously tunable and is not limited to the discrete allowed quantum transitions. The FEL mechanism is a stimulated process, differing from the incoherent, low power spontaneous radiation due to electron acceleration in the undulator field. In the FEL, the electron kinetic energy is converted into radiation. Some electrons may lose kinetic energy, while others may gain kinetic energy. Under the appropriate resonance conditions, coherent radiation is generated as electrons on the average lose kinetic energy. Since each electron can gain or lose many photons, the physics can be understood in terms of classical mechanics.

The detailed electron trajectory through the undulator is complicated. The net effect of the electron dynamics, however, can be summarized by an interaction between the electrons and a wave traveling at a phase velocity slightly less than the electrons. This wave is called the "ponderomotive potential wave", which is generated by the beating of the radiation field (frequency $\omega$, wavelength $\lambda = 2\pi/k$ and wavenumber $k = \omega/c$) and the undulator fields (wavelength $\lambda_u$ and wavenumber $k_u = 2\pi/\lambda_u$), where $c$ is the speed of light. The beat wave has the same frequency as the radiation, but its wavenumber is $k + k_u$. The phase velocity of the beat wave $v_{ph} = \omega/(k + k_u)$ is slower than the speed of light. When the axial electron beam velocity $v_{z0}$ is approximately equal to the phase velocity of the ponderomotive potential wave, the electrons see an approximately constant axial field. Hence, the ponderomotive beat wave may interact strongly with the electron beam. Since some electrons see an accelerating field while others see a decelerating field, the initially uniformly distributed electrons become bunched at the ponderomotive wavelength. If the initial beam velocity

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is slightly larger than the phase velocity of the beat wave, the beam, on average, will lose energy during the bunching process. The stimulated radiation thus emitted from the periodic beam bunches is coherent and is many orders of magnitude higher in power than the spontaneous radiation.

The wavelength of the radiation $\lambda$ is tunable because it is a function of the energy of the electron beam and the magnetic field of the undulator,

$$\lambda[cm] \simeq \frac{1 + (5.6 \times 10^{-5} B_u[G]\lambda_u[cm])^2}{2\gamma^2} \lambda_u[cm],$$

where $B_u$ is the magnetic field of the undulator on axis (for planar undulator fields as shown in Fig. 1), [illegible] $1 + 1.96E[MeV]$ and $E$ is the energy of the electron beam. This radiation wavelength relation is a consequence of requiring $v_{z0} \simeq v_{ph}$. Since the period of the undulator is hard to change, the wavelength of the radiation can be decreased/increased by increasing/decreasing the energy of the electron beam or by opening/closing the gap separating the top and bottom arrays of undulator magnets leading to a decrease/increase of the magnetic field of the undulator on axis.

For an FEL to be a practical device, the percentage of the electron energy converted to radiation must be large, i.e., high efficiency is required. The intrinsic efficiency of the FEL drops as the wavelength of the radiation decreases. At any particular wavelength, efficiency can be increased by a gradual decrease in the period or the amplitude of the magnetic field of the undulator among other schemes. Decreasing the period of the undulator decreases the phase velocity of the ponderomotive wave, forcing the trapped electrons to decelerate axially and give up kinetic energy associated with their axial motion. Decreasing the amplitude of the magnetic field of the undulator decreases the kinetic energy associated with the transverse wiggling motion. The additional energy lost by the electrons as the result of such tapering of the undulator is converted to radiation energy leading to an increase of the efficiency. Experiments at Lawrence Livermore National Laboratory (LLNL) have demonstrated efficiency of 35% at millimeter wavelength with tapered undulator, whereas a uniform undulator in the same system gives only 6% efficiency.

The FEL can provide very high peak and/or average power, because high power electron beams can be generated with high efficiency. In addition, the electron beam differs from a conventional laser medium in that it can support high power radiation without being damaged.

The implementation of the FEL is critically dependent on having an electron beam with a small effective axial velocity spread. Sources of effective axial velocity spread are the energy spread and emittance (a measure of the transverse velocity spread and beam size) of the electron beam and the undulator field errors (difference between the actual undulator field and a pure sinusoid). The condition for effective axial velocity spread of the beam not to degrade the performance of the FEL is that electrons with different axial velocities do not significantly separate over some relevant interaction length. This separation distance must be less than some fraction of the ponderomotive potential wavelength $2\pi/(k + k_u)$, which is approximately the radiation wavelength for high energy beams. The relevant interaction lengths are: i) undulator length for low gain regime, ii) e-folding length in the high gain, low current (no space charge effect) regime and iii) plasma wavelength in the high gain, high current (space charge dominated) regime. The limits on the effective axial velocity spread of the electron beam are more stringent for shorter radiation wavelengths. A large effective axial velocity spread will significantly reduce electron bunching in the ponderomotive potential wave, leading to significant degradation of the FEL growth rate, gain and efficiency. Thus, FELs require electron beams of good quality, i.e., an electron beam with small energy spread and small transverse emittance.

FEL Experiments Electron beam sources vary widely in energy, beam quality, current, pulse length and repetition rate. Radio frequency (rf) driven accelerators, such as rf linacs (linear accelerators), microtrons, and storage rings, have peak currents from a few Amperes to hundreds of Amperes, electron energies up to hundreds of MeVs and electron micro-pulse lengths much shorter than the rf wavelength. Induction accelerators can have many kilo-Amperes of currents and, currently, have energies up to tens of MeVs and pulse lengths of a few tens of nanoseconds to a few microseconds. Electrostatic accelerators usually have low current and low energy, but good beam quality. Lumped parameter modulators usually can provide relatively inexpensive electron beams in the low energy range with pulse durations up to several microseconds and hundreds of Amperes of current. Electron beams from pulsed power sources can have very high currents, but they have low energies and pulse durations of tens of nanoseconds. Each of these electron beam sources have been applied to the generation of FEL radiation. The output radiation characteristics are diverse as a result of this diverse variation of electron beam sources.

Although FEL concepts have been known since the original article by H. Motz in 1951 and the successful experiments by Robert M. Phillips in the mm wavelength regime in 1960, it is the work by John M. J. Madey in the infrared wavelength regime in the 1970s that has made the FEL a serious candidate for a new powerful radiation source.

Free electron laser experiments are conducted all over the world. Although the conceptual configuration of the FEL is simple, the implementation was arduous because existing electron beam sources were not designed with FELs in mind. The basic FEL theory has mostly been verified. All the experiments have demonstrated the importance of high quality electron beams. Research efforts are underway to develop FELs in the direction of user-oriented and practical devices.

Applications of FELs Many applications have been envisioned for FELs. Due to the current complexity and the cost of the FEL, applications are in the area of research rather than as consumer products, and centers of FEL user facilities are being developed. Table I lists the output light properties at the currently funded user facilities. Many additional user facilities are being proposed. Proposed accelerators are being designed for specific user needs. Important criteria for FEL user facilities are electron beam stability, reliability, ease of frequency tuning and ease of operation.

In the microwave regime, the high power and high efficiency nature of the FEL dominates FEL applications. FELs have been constructed for plasma heating in tokamaks and as rf sources for conventional rf accelerators.

In the infrared and visible wavelength regime, there exists a wide range of applications in spectroscopy, chemistry, biology, medicine, isotope separation, condensed matter studies, material sciences and national defense. In addition to the tunability and high peak and/or average power, FELs also have other desirable characteristics. FELs driven by rf accelerators in this range can deliver laser pulses of pico-second durations. This short pulse duration, and the corresponding wide frequency range in the IR provides new spectroscopic capabilities. The micro pulse nature also facilitates the pump-probe type experiments, which can provide quantitative studies of many surface phenomena.

Applications in the UV and x-ray range are exciting, but FELs become more difficult and more expensive as wavelength decreases. The energy in UV radiation is high enough to cause ionization and bond breaking in DNA and proteins. Radiation can also be absorbed and redistributed to vibrational states. Radiation within the "water window" between 24 Å and 44 Å will allow biologies to study living matter in their natural aqueous environment. Coherent x-ray sources can be used for holography. Three-dimensional imaging of atomic structures may be feasible in the future. The criteria limiting the ultimate wavelength for the FEL are electron beam quality and laser optics.

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Table Ia: Radiation Characteristics
of Medical and Material Science FEL User Facilities
(Driven by rf Linacs)

| | Duke | Stanford[a] | Stanford[a] | Vanderbilt |
|---|---|---|---|---|
| **Accelerator** | MK III | Super Conducting | Super Conducting | MK III clone |
| **Status** | 1990 | 1990 | 1991 | 1991 |
| **Electron Energy** | 27–44 MeV | 20–200 MeV | 20–200 MeV | 20–45 MeV |
| **Current** | 30 A | 5 A | 35 A | 35 A |
| **Wavelength** | 2–9 $\mu$m | 0.5–5 $\mu$m | 0.2–15 $\mu$m | 1–8 $\mu$m |
| **Lasing Pulse Duration** | | | | |
| Micropulse | 1–4 ps | 3 ps | 2.2 ps | 0.5–3 ps |
| Macropulse | 1-8 $\mu$s | 10 ms | 20 ms | 1–8 $\mu$s |
| **Rep Rate** | | | | |
| Micropulse | 2.856 GHz | 12 MHz | 12 MHz | 2.856 GHz |
| Macropulse | 30 Hz | 10 Hz | 20 Hz | 60 Hz |
| **Energy per Pulse** | | | | |
| Extracted | 5–10 $\mu$J | 3 $\mu$J | 15 $\mu$J | 4 $\mu$J |
| Q–switched | 500 $\mu$J | | 500 $\mu$J | — |
| **Power** | | | | |
| Peak(extracted) | 1.25–10 MW | 1 MW | 7 MW | 2 MW |
| Peak(Q–switched) | 125–500 MW | | 230 MW | — |
| Avg.(extracted) | 6 W | 3.6 W | 36 W | 12 W |
| **Bandwidth** (Transform Limited) | yes | yes | yes | yes |
| **Radiation Mode** | | | | |
| Linearly Polarized | yes | yes | yes | yes |
| $TEM_{00}$ | yes | yes | yes | yes |
| Diffraction Limited | yes | yes | yes | yes |

[a] Energy and power are based on radiation at 4 $\mu$m.

Table Ib: Radiation Characteristics
of Medical and Material Science FEL User Facilities
(Driven by Other Than rf Linacs)

| | Duke[a] | NIST/NRL | UCSB |
|---|---|---|---|
| **Accelerator** | Storage ring | race–track microtron | Electrostatic Van de Graaf |
| **Status** | 1993 | 1992[h] | 1990 |
| **Electron Energy** | 0.5–1 GeV | 17–185 MeV | 2–6 MeV |
| **Current** | | | |
| Peak | 300 A | 2–4 A | 2 A |
| Average | 150 mA | 0.5 mA[b] | |
| **Wavelength** | 500–4000 Å | 0.2–10 $\mu$m | 63–400 $\mu$m<br>1.34 mm - 193 $\mu$m<br>30.6-100 $\mu$m[c] |
| **Pulse Duration** | 30 ps | 3 ps | 1-3 $\mu$s[d]<br>3-20 $\mu$s[e] |
| **Rep Rate** | 2.7624 MHz | 66.111 MHz | 1 Hz |
| **Energy per Pulse** | | | |
| (extracted) | 3 $\mu$J | 0.1-3 $\mu$J | 1.4-4.2 mJ |
| (Q-switched) | 300 $\mu$J | | 3-280 |
| **Power** | | | |
| Peak(extracted) | 100 kW | 40-1000 kW | 1-1.4 kW |
| Peak(Q-switched) | 10 MW | | $\sim$ 6–8 kW[f] |
| Avg.(extracted) | 0.037 W | 10–200 W | 0.0014–0.014 W |
| **Bandwidth $\Delta\lambda/\lambda$** | transform limited | transform limited | $(10^{-7})$[d]<br>0.05 %[g] |
| **Radiation Mode** | | | |
| Linearly Polarized | yes | yes | yes |
| Coupled Out | $TEM_{00}$ | $TEM_{00}$ | mirror |
| Diffraction Limited | yes | yes | yes |

[a] Single bunch. Energy and power are based on radiation at 1000 Å.

[b] At full energy.

[c] Third harmonic operation, with beam energy 3–6 MeV, to be operational by 1991.

[d] Single pulse mode operation.

[e] Multiple longitudinal mode operation.

[f] 40 ns pulse.

[g] Averaged over many pulses

[h] Project will be terminated before completion.

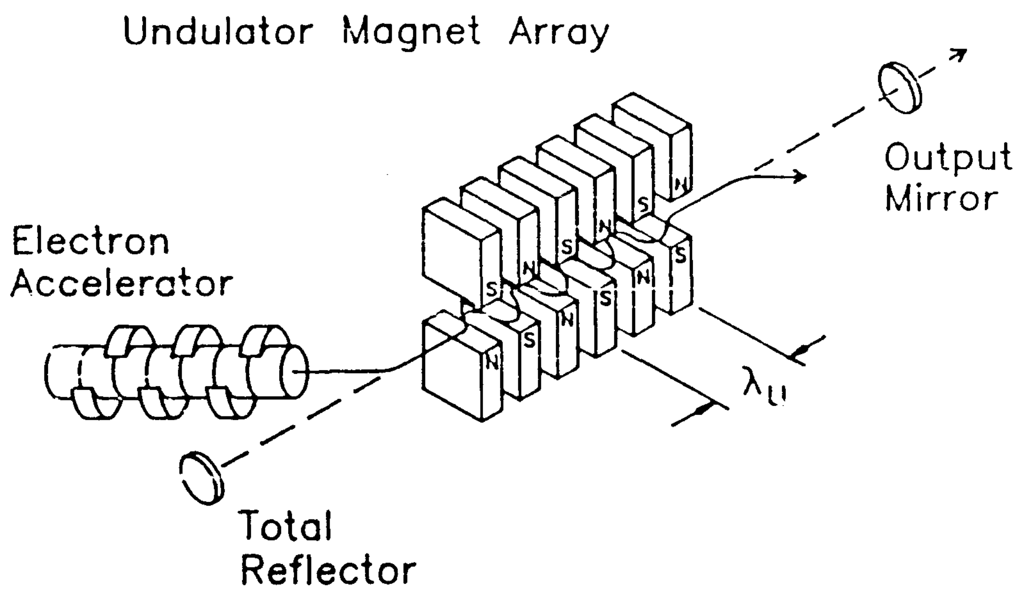


Fig. 1 — Schematic of a free electron laser in an oscillator configuration