laser handbook

edited by
W. B. COLSON
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free electron lasers

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LASER HANDBOOK

VOLUME 6

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Preface

After more than a decade of experimental and theoretical activity, the basic physical principles of the Free Electron Laser (FEL) can be stated clearly and accurately. Many different FEL configurations have been successfully explored, and a diverse range of experimental details have been reproduced by theoretical analysis. Furthermore, the theory has been confidently used to design and predict the performance of new devices.

Attaining this high level of maturity has not meant saturation. FELs are being proposed in the USA, Europe, USSR, Japan, and China. These projects use novel schemes to increase the FEL's power, efficiency, spectral resolution, and range of tunability. In addition, efforts are being made to reduce the FEL's large size and cost. FEL development has always benefited from the contributions of a broad range of physicists from different fields, and this tradition is continuing as scientists enter the field each year.

This is an opportune time for a comprehensive textbook on the entire subject. The FEL Handbook contains the essential concepts of the FEL mechanism, as well as many of the most advanced ideas. It can be used by both graduate students and scientists beginning work in the field, yet should provide a comprehensive resource for the experienced professional. The range and depth of FEL topics has grown to such an extent that a handbook would benefit researchers at all levels of familiarity with FEL development. The goal of the handbook is to consolidate the research within the FEL community, to extend the FEL scientific base to others who may make future contributions, and to encourage the use of FELs for applications.

The fundamental physics of the FEL also makes it an attractive area of research. Physical issues intersect particle beam physics, plasma physics, quantum and classical optics, and laser physics. It is truly an inter-disciplinary area of science that is able to reflect the progress in each of these separate fields. In our opinion, this is what makes the FEL field so attractive to so many physicists. New applications have continued to raise interesting questions that extend our present understanding of the fundamental FEL physics.

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The free electron laser (FEL) uses a beam of relativistic electrons passing through a transverse, periodic magnetic field, called an "undulator", to exchange energy with an electromagnetic radiation field (Madey, 1971). Efficient energy exchange requires that the electrons experience nearly resonant forces from the radiation and undulator fields. This resonance is achieved when the radiation wavelength λ, the beam energy γmc^2, and the undulator period λ_u approximately satisfy $\lambda \approx \lambda_u/2\gamma^2$, where γ is the Lorentz factor, m is the electron mass, and c is the speed of light in vacuum. The resonance relationship shows that the FEL wavelength can be continuously tuned by changing the electron beam energy, and that the FEL mechanism can be designed to operate over a large region, from centimeters to nanometers.

Most often, the FEL is operated so that the net energy transfer is from the electron beam to the radiation field, in order to amplify it. But, it is also possible to operate the FEL so that the net energy transfer is from the radiation field to the electrons making an accelerator, or an inverse FEL. Since the radiation pulse structure reflects that of the electron beam, it is easy to produce pulse lengths ranging from picoseconds, using an rf linac, to almost cw using a recirculating electrostatic accelerator. The FEL is also able to obtain large peak power, on the order of a few GWs, because of the high power density carried by the relativistic electron beam. Unlike atomic lasers or microwave tubes, the energy that is not transferred to the radiation field remains in the form of a relativistic particle beam that can be transported out of the undulator at near the speed of light, or even recovered to improve overall efficiency. The FEL has become an exciting conceptual and practical alternative to other radiation sources, like microwave tubes and lasers, and can extend the operational range of both. Because of its flexibility the FEL can find applications in many diverse areas, such as lithography, plasma heating, particle acceleration, as well as material, biological, medical and solid state research.

Microwave tubes were the first generators of coherent radiation from free electron beams, and their development received a strong impulse from the radar development during World War II. They relied on slow-wave structures which limited their operation to long wavelengths. FELs have developed from the work on free electron radiation sources. Motz (Motz and Nakamura 1959, Motz 1951, Motz et al. 1953) showed in 1951 that an electron beam propagating through an undulator magnet can be used to amplify radiation. A particular microwave tube developed in 1960 by Phillips called the ubitron (Phillips 1960) was quite similar to the FEL in design and operation. Other researchers (Palmer 1972, Robinson

1985, Csonka 1978) were exploring concepts along the lines of the FEL mechanism, but their ideas did not result in experiments.

After 1960, research on short wavelength sources has been dominated by lasers, which require an atomic or molecular medium to operate, resulting in a limitation on tunability. The optical resonator (Schawlow and Townes 1958) with macroscopic dimensions that could store significant optical power at optical wavelengths was crucial to the invention of the laser, and is also used in the FEL oscillator. The FEL, using free electrons, and not needing a slow-wave structure, is a natural alternative as a radiation source where lasers and microwave tubes are limited.

An important step in FEL development came in 1976 (Elias et al. 1976) when Madey and his co-workers at Stanford University measured 7% gain from an FEL configured as an amplifier at 10 μm wavelength. This experiment, and the successful operation of the same FEL configured as an oscillator in 1977 (Deacon et al. 1977) created a large interest in FEL research. In the following years, many experimental groups around the world have built FELs that operate at frequencies ranging from microwaves to the UV. The science and technology used has been a blend of plasma physics, laser physics, and accelerator physics. Each of these communities has made significant contributions to the development of FELs, and the FEL remains a cross-disciplinary device.

In the following years, technology of the undulator magnet has seen important developments with the introduction of permanent magnets and hybrid magnet systems (Halbach 1983). A typical undulator length is $L_u \approx 5$ m, but can range from 1 m to more than 25 m. Each period of a typical undulator is about $\lambda_u \approx 5$ cm long, but can range from 1 cm to 10 cm. The resulting number of periods is typically $N_u \approx 10^2$. Within each period the peak field strength is $B_u \approx 2 \rightarrow 5$ kG, which is sufficient to cause slight deflections in the path of relativistic electrons while they travel through the undulator length. If the undulator field is circularly polarized along the undulator axis, the electron path is helical in shape and the FEL amplifies circularly polarized radiation. If the undulator field is linearly polarized, the FEL radiation is linearly polarized. The field geometry can be constructed from current-carrying coils as well as permanent-magnet material. There is now a push toward the production of short-period undulators in order to reduce the size of the accelerator and undulator that are needed for a fixed-wavelength application.

The characteristics of the electron beam from the accelerator are crucial in determining the ultimate potential of an FEL. The need for high beam current and high beam quality is pushing the accelerator designers to develop new and better electron sources and accelerators. While the beam energies can range from 1 MeV to 1 GeV, the typical FEL uses a beam around $\gamma mc^2 \approx 50$ MeV. The current can be from 1 A to 1000 A, but the most FELs fall into the range from $I \approx 10$ A to $I \approx 100$ A. The typical power carried along by the electron beam is therefore $\approx$5 GW, so that even a small conversion efficiency leads to a laser with high peak power. The small duty cycle of most accelerators provides the limit to the average FEL power. The FEL interaction volume contains only light, the undulator magnetic field, and the electron beam, so that unwanted nonlinear effects common in conventional lasers using gases, liquids, or solids are absent. The efficiency of the FEL has been demonstrated to be as high as 35% at long wavelengths, but most FELs will operate at a lower efficiency of just a few percent. Five percent efficiency could be considered feasible for a typical FEL with good beam quality in the future. The resonant FEL wavelength with $\lambda_u \approx 5$ cm and $\gamma \approx 10^2$ is then $\lambda \approx 3$ μm.

The transverse size of the electron beam is usually about 0.1 mm to 5 mm, depending on the accelerator and transport system. The FEL beam quality must be sufficient to maintain coherent bunching over a characteristic gain-length that may cover many undulator periods. Both the electron beam's energy spread and angular spread (emittance) must be sufficiently narrow to preserve a coherent bunch in each section of the electron beam that is one radiation wavelength in length.

Theory has played an important role in the progress of FEL technology and concepts. The original FEL theory used quantum analysis in the frame of the relativistic electrons (Madey 1971), and later, quantum electrodynamics. Now, the phase-space motion of FEL electrons has been described in terms of the simple pendulum equation coupled to the self-consistent wave equation. There are new important effects like the exponential growth of the high-gain regime, the evolution of short pulses, efficiency enhancement with tapered undulators, optical guiding, and the trapped-particle sideband instability that have been studied. Agreement between theory and experiment is generally excellent, and the design of proposed FELs is most often carried out with analytical and numerical calculations. The same theoretical formalism works from cm wavelengths to 0.1 nm wavelengths, and only depends on the FEL design, the electron mass m, the electron charge magnitude e, the speed of light c, and possibly Planck's constant $\hbar$.

The classical gain in the low-gain FEL oscillator develops from coherent electron bunching on the scale of the radiation wavelength. As the electrons travel through the undulator, they accelerate from side to side and radiate in the forward direction. On the first few passes through the FEL oscillator, some of this radiation is stored in the resonator. Subsequent electrons enter the undulator and move from side to side in the presence of the transverse radiation field. In each λ-section of the electron beam, some of the electrons lose energy to the radiation field, while other electrons gain energy from the wave. As the faster electrons move ahead of the average and the slower electrons move back, the beam is periodically bunched on the radiation wavelength scale. The bunched beam then radiates coherently and amplifies the existing radiation. On each pass, there may be only a 10% increase in radiation power at the wavelength with maximum gain, but over many hundreds of passes, this process results in substantial power at that wavelength.

In the classical, high-gain FEL amplifier, the high current of the electron beam accelerates the same series of steps described above so that coherent bunching develops in one pass through a long undulator. The amplified wavelength is selected by the external master oscillator laser. In the super-radiant FEL, there is no initial light wave so that radiation must first grow from spontaneous emission.

For either high or low gain, the relativistic electrons "see" each rapidly advancing undulator period Lorentz contracted to a shorter wavelength $\lambda_u' = \lambda_u/\gamma$. Also, the electrons "see" the radiation field passing over them, Doppler shifted to longer wavelengths $\lambda' = (1+\beta_z)\gamma\lambda \approx 2\gamma\lambda$. The condition of resonance between the undulator and radiation forces in the beam frame, $\lambda_u' \approx \lambda'$, gives the FEL resonance condition in the laboratory frame, $\lambda \approx \lambda_u/2\gamma^2$.

The expression for the resonant FEL wavelength above shows one of the FEL's most important attributes, continuous tunability. As the electron energy from the accelerator is varied the resonant wavelength is changed. A factor of 10 tunable frequency range has already been demonstrated. This is a greater tunable range for a given machine than any other laser of any kind. It appears possible that a factor of a 10^2 is possible in the future. When an FEL facility is tuned over such a large range, some of the components such as resonator mirrors must be changed because they are designed to operate in a limited frequency range.

All this work is now opening the possibility of extending the FEL to new levels of peak and average power, and to shorter X-ray wavelengths. There are an increased number of applications in research and industry. Possibly more important than tunability is the "designable" feature of the FEL. FEL sources can be made from 1 cm to 10 nm radiation wavelength without a significant change in the basic mechanism. New wavelength ranges where there are no other powerful sources of radiation are now being explored. From $\lambda = 1$ cm to 20 μm, the FEL is providing a new source of coherent radiation for scientific applications using low-energy accelerators like the pulse-line accelerator, the microtron, the induction linac, and the electrostatic accelerator. Another new range is from $\lambda \approx 100$ nm to 10 nm, where there may soon be an FEL providing a source of X-ray radiation for studying materials and biological organisms. The high-energy accelerators that can be used for short-wavelength FELs are the rf linac and the electron storage-ring.

The reliability of the technology used in the FEL is similar to facilities like SLAC or CERN in high-energy physics, or synchrotron sources using electron storage rings. These large machines operate 24 hours a day for a large fraction of a year in order to provide particle beams or light to users ready for experiments. It is anticipated that the FEL will eventually be used as a facility as well. While the attributes of the FEL as a radiation source are impressive, at present, the FEL remains too large and expensive for individual experimenters. This drawback need not be too discouraging, however, because synchrotron facilities operate as an extremely successful physics tool. The FEL may become a part of some synchrotron facilities, but there are now several FELs that are beginning to provide users with a unique new source of photons for science. Current research is attempting to make FELs smaller and less expensive as a radiation source.

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