New Light : What is Free Electron Laser FEL?

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Abstract: Free electrons are to be distinguished from electrons which are bound in atoms or molecules. The electrons in a Free Electron Laser (FEL) have the form of an electron beam in a vacuum, for example, like as the beam in Braun tube of TV. Electrons bound in atoms and molecules vibrate only at specific frequencies. Thus, the laser light from conventional lasers, which make use of bound electrons, appears only at these specific frequencies. On the other hand, the electrons in FEL are forced to vibrate by their passage through an alternating magnetic field. Thus, the vibration frequency can be adjusted by altering the construction of the magnetic field or by changing the speed of the electrons passing through the magnetic field. This changes the laser frequency or, equivalently, the wavelength. The broad tunability of FEL from the far infrared to the visible and beyond was the origin of the great interest in these lasers. More recently it has been recognized that free electron lasers have unique advantages for operation at high average power levels, and this has made them attractive for medical and industrial applications.

Introduction

FEL as we know them today actually developed independently, synchrotron radiation research. Synchrotron radiation is the very short wavelength radiation which is given off by electron in synchrotrons and storage rings. This radiation can be enhanced by adding magnets to a storage ring to wiggle the electron, with the magnet arranged in the same configuration now used for FEL. The synchrotron radiation from such wigglers (or undulators) is identical to the incoherent, spontaneous radiations observed from FEL before they begin to lase.

The earliest work on wiggler radiation dates back to 1951, when Hans Motz proposed the wiggler magnet configuration now used in FEL. Then, in 1970, John M. J. Madey1), of Stanford University, proposed what he called the free electron laser(FEL). In 1976, Madey at Stanford succeed in demonstrating gain with a FEL, using a 24MeV electron beam and a 5m long wiggler to amplify the beam from a CO_2 laser. In 1978, they added mirror to the system and operated the accelerator at 43MeV to demonstrate laser oscillation2) at a wavelength of 3.5μm, in the near-infrared part of the optical spectrum. Although the power (300mW) and efficiency (0.01%) were small, there could be no doubt that the device had lased, because of the obvious potential of the device for high power and broad tunability, these results immediately attracted a great deal of interest. Theoretical work on FEL expand rapidly, and experimental work began at several laboratories which had suitable accelerators. In 1983, the storage ring (ACO)3) in Orsay was successful in lasing in the visible, and the superconducting accelerator of Stanford University and the electron linear accelerator at Los Alamos succeeded in lasing in the near infrared and the mid-infrared, respectively. In Japan, the storage ring (TERAS) in Electrotechnical Laboratory(ETL) achieved lasing at 0.59μm in 1991, the storage ring (UVSOR) at Molecular Science Laboratory also achieved lasing at 0.49μm4) in 1992. Further, the electron linear accelerator at Laboratory for FEL was successful in lasing a wide range of 5-13μm5), in 1993. Afterward, Nihon University was succeeded in lasing at 1.5 μm6), by using the conventional electron linear accelerator, in 2001.

Now, in Osaka University (FEL Lab.), Science University of Tokyo (FEL-SUT), and Nihon University (LEBRA), the application experiments by use of FEL are performed usefully.

Basic Principle

Conceptually, free electron lasers are simple, consisting of an electron beam in a magnetic field. Because of this essential simplicity, the theoretical description of free electron lasers has often, especially in the early days, preceded the experimental development of these devices. This is significant departure from the mode of development of conventional lasers, and is quite fortunate in view the expense of building and operating high energy electron accelerators for free electron laser (FEL) experiments.

The configuration of the electron beam and wiggler magnets in a free electron laser is shown in Fig. 1. The magnets are arranged with their poles alternating so that the magnetic field reverses every few centimeters. The overall length of wiggler is typically a few meters, which corresponds to about from 50 to 100 periods. The electron beam is injected into the end of the wiggler, and travels down its length. As the electrons proceed down the wiggler they are deflected alternatively left and right by the magnetic field and follow a wiggly path. The motions are simple forced oscillations; no subtle resonant effects are involved. If we place ourselves in a frame of reference moving down the wiggler at the mean velocity of the electrons, we observe the electrons to oscillate back and forth in a straight line perpendicular to the wiggler axis. Observed in the moving frame, the radiation from the electrons goes in all directions, like the radiation from the antenna. However, in the stationary frame of the laboratory the electrons are moving at nearly the speed of light, and radiation directed toward the sides cannot move very far from the wiggler axis before the electron and its radiation field have moved down the wiggler. As a result, the radiation appears to be moving almost entirely in the forward direction, parallel to the electron beam. This phenomenon is well known in high energy particle physics, where Bremsstrahlung (the radiation from the electrons in the wiggler corresponds to magnetic Bremsstrahlung) is observed to be confined within a small cone around the direction of motion of the electron. To an observer standing in the laboratory, then, looking at the radiation produced by a source moving toward them, the frequency is Doppler shifted to a higher frequency, which corresponds to a shorter wavelength.

Fundamental theory

The wavelength of radiation from a single electron traveling down the wiggler with a velocity v=âc is calculated by following procedure, where c is the velocity of light. As shown in Fig.2, the electron executes N_w wiggles as it passes through wiggler in a time $t=L_w/v$, where $L_w= N_w$ë$_w$ is the length of the wiggler, and ë$_w$ the length of one period of the wiggler. By the time the electron has reached the end of the wiggler, the front of the wave packet, which was emitted by the electron at the beginning of the wiggler, has moved a distance ct. But the back of the wave packet is just at the end of the wiggler, so the total length of the wave packet is (c-v)t. Since the wave packet, like the wiggler, contains N_w oscillations, the laser wavelength λ_p is given by the expression $\lambda_p=(c-v)t/N_w=\lambda_w(1-\beta)/\beta$. This expression is simplified by recognizing that for relativistic electrons the velocity is nearly that of light, βR"1, so that $(1-\beta)/\beta=(1-\beta^2)/2$. The energy of a relativistic electron is evaluated by the Einstein formula, $\gamma^2=1/(1-\beta^2)$, where γ is just the energy of electron expressed in units of its rest energy. The rest energy an electron is $mc^2/e=0.511$MeV, where m is the electron rest mass and e the electron charge. The wavelength is then given by the formula $\lambda_p=\lambda_w/2\gamma^2$. Actually, the effect of the wiggler motions on velocity of the electron through the wiggler takes no account for the wavelength. For moderate to strong magnetic fields, the wiggles can significantly through the wiggler. This slows the average velocity of the electrons through the wiggler and increases the wavelength of the light. When this effect properly accounted for the formula, FEL wavelength is given by the expression, $\lambda_p=\lambda_w(1+K^2/2)/2\gamma^2$ (1) Where, K is the wiggler parameter expressed as $K=e\lambda_w B_w/2\pi mc$. The B_w is the rms average magnetic induction. This formula is quite accurate for all cases of interest. It implies that in a frame of reference moving with the mean motion of the electrons the frequency of oscillation of the electrons is the same as that of the optical field.

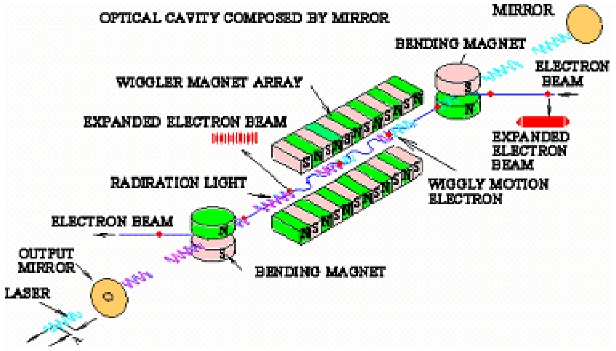

Fig.1. the radiation from FEL is created by electrons which are forced to execute a wiggly motion as they pass through a series of magnets which form an alternating magnetic field called the wiggler.

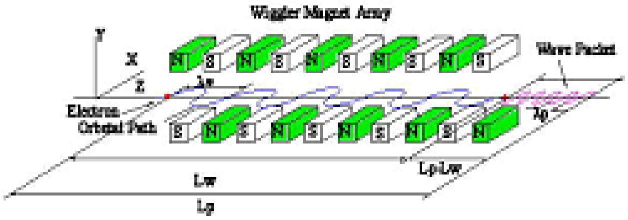

Fig.2. the radiation light from a wiggly electron.

Conclusion

FEL represent a complete departure from conventional lasers, and they offer performance not available from other source. By varying the electron energy it is possible to tune the wavelength over a broad range, and to operate at wavelengths where no other lasers exist. Equally important, by avoiding the cooling problems associated with conventional lasers and using high power accelerator technology, it is possible to operate FEL at extreme power levels. Unfortunately, FEL are expensive, especially in small sizes, and until cheaper FEL are developed only a limited subset of all the possible applications can be addressed.

Nevertheless, it is clear that FEL are developing in the future. As they do so, they will play an increasingly important role in a broad variety of field.

References

1. John M, Madey J. J. Appl. Phys. , 42, 1906 (1970)
2. Deeacon GAG, et al. Phys. Rev. Lett., 38, 892 (1977)
3. Billardon M, et al. SPIE 453 (1984)
4. Takano S, et al. Nucl. Instr. Meth., A331, 20 (1993)
5. Tomimasu T, et al. Proc.PAC’95, Dallas,May 1-5,1995, p.FAA30
6. Hayakawa Y, et al. Nucl. Instr. Math., A8, 483, 1-2, (2002) p29-33