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FREE ELECTRON LASER RESEARCH

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1. Introduction

There have already been several introductory talks given to the accelerator community explaining the various operating modes of the "free electron laser." C. Pellegrini gave one of the earliest talks back in 1979 at the National Accelerator conference[1]; another talk, which utilized accelerator jargon was given at the 1981 National Accelerator Conference.[2] At that time, the only successful operation of the "free electron laser" was by the group at Stanford, directed by John Madey, which used an electron beam from the superconducting linac.[3,4] In addition, there have been many other descriptions of the operation of the "free electron laser" FEL given in the various FEL conferences.[5] One of the most recent talks was given by C. Brau at the last National Accelerator Conference. It will be assumed that most of the audience is already familiar with the way an FEL works; therefore, only a brief explanation will be given here. The remainder of the report will describe the current plans and status of the FEL work.

2. Simple Description of a FEL

A free electron laser consists of a wiggler field through which a beam of electrons passes, together with a plane electromagnetic wave as shown in Fig. 1. The wiggler field may be either a periodic magnetic bending field or a different electromagnetic wave traveling in the opposite direction. Laser people refer to this wiggler field as the pump field. For simplicity we will restrict our consideration only to periodic magnetic wiggler fields.

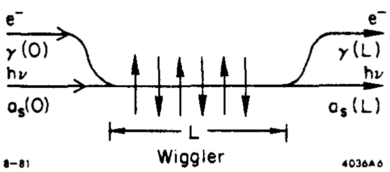

Fig. 1. Schematic representation of free-electron-laser.

The electrons enter the wiggler at $\gamma(0)$ and leave the wiggler with energy $\gamma(L)$, while the intensity of the electromagnetic radiation enters with an initial value $a_s(0)$ and exits with a value $a_s(L)$. For FEL operation it is important that energy from the electron beam be transferred to the electromagnetic radiation, i.e.,

$$\gamma(L) < \gamma(0) \quad \text{and} \quad a_s(L) > a_s(0) \ .$$

The FEL is classified as an amplifier if the electromagnetic wave passes through the FEL only once. For this mode of operation to be useful it is necessary to have a high gain, i.e., $a_s(L) \gg a_s(0)$. If mirrors are used to recirculate the photons then the FEL is classified as an oscillator and low gain devices in which $a_s(L) \gtrsim a_s(0)$ are useful.

Similarly we can use a linac to produce a beam of electrons which pass through the FEL only once or use a storage ring to recirculate the electron beam so the same electrons pass through the FEL many times.

In order for the electron and the optical electromagnetic field to exchange energy it is necessary for the electron to have a velocity in the same direction as the transverse electric field of the optical wave. One method of obtaining this transverse velocity is by the use of a wiggler magnetic field. A wiggler magnet is one with a transverse magnetic field which oscillates in amplitude as a function of the longitudinal coordinate. There are two types of wigglers; the helical type as originally used by Madey to amplify circularly polarized light and the linear wiggler which amplifies linearly polarized light. An example of a linear wiggler and the transverse particle motion is shown at the top of Fig. 2. The magnetic field is given by

$$B_y = \sqrt{2}\ B_0 \sin k_w z \tag{1}$$

with B_0 the rms magnetic field strength and $\lambda_w = 2\pi/k_w$ the wiggler wavelength. The transverse angle of the oscillation in such a wiggler is given by

$$x' = \frac{v_x}{v_z} = \frac{a_w}{\gamma} \cos k_w z \tag{2}$$

where a_w is the reduced wiggler vector potential

$$a_w = \frac{e\ B_0}{k_w\ mc^2} \tag{3}$$

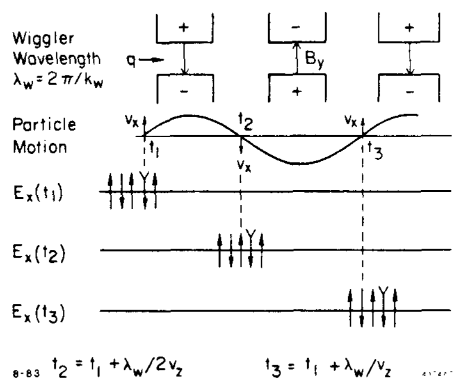

Fig. 2. Interaction of electron transverse velocity with transverse electric force of optical electromagnetic wave at various times and positions in FEL.

In Fig. 2 we display the mechanism for the transfer of energy between the electron and the transverse electric field of the optical plane wave. We consider an electron in the wiggler at time t_1 with its transverse velocity v_x positive as shown in Fig. 2. At time $t_2 = t_1 + \lambda_w/2v_z$ the electron has traveled along the wiggler one-half of a wiggler period and the sign of v_x has changed, while at time $t_3 = t_1 + \lambda_w/v_z$ the electron has traveled one full wiggler period and v_x is positive. The electric force from the optical wave is represented by arrows displayed in Fig. 2 labeled E_x for the various times. Notice that at time t_1 the electric force from the optical wave opposes the transverse velocity v_x of the electron. This electric force arrow is marked with a large tail. We consider the case where the optical wavelength is chosen such that at time t_2 the optical wave has traveled one-half

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of an optical wave further in the longitudinal direction than the electron beam. The new electric force vector is now one-half wavelength behind the original electric force vector (with the tail) and opposes the new transverse electron velocity. Similarly at time t_3 the optical wave has moved ahead of the electron by one full optical wavelength and again the electric force opposes the transverse electron velocity. For the transverse electron velocity to remain in phase with the optical force the electron slips behind the optical wave by one optical wavelength in traveling one wiggler period. The net rate of change in the phase between the transverse electron velocity and the optical electric force is given by

$$\frac{d\psi}{dz} = k_w - \frac{k_s}{2\gamma^2}(1 + a_w^2) \tag{4}$$

where k_s is the optical wave number $= 2\pi/\lambda_s$.

The resonance condition is given by $d\psi/dz = 0$ or

$$\lambda_s = \frac{\lambda_w}{2\gamma_r^2}(1 + a_w^2) \tag{5}$$

with γ_r the resonant energy. This definition may be used to obtain (to first order in $\delta\gamma - \gamma - \gamma_r$) the equation of motion for the phase

$$\frac{d\psi}{dz} = 2k_w\left(\frac{\delta\gamma}{\gamma}\right) \tag{6}$$

The change in the energy of the electron is proportional to the transverse velocity of the electron, the transverse electric field of the wave, and the sine of the relative phase ψ, so we can write the equation of motion for this energy change as

$$\frac{d\gamma}{dz} = \gamma' = -\frac{k_s a_s a_w}{\gamma}\sin\psi \tag{7}$$

where

$$a_s = \frac{e(E_x)_{rms}}{k_s mc^2} \tag{8}$$

Equations (6) and (7) describe the same type of motion as the synchrotron motion in accelerators. The phase plane motion of the electron in FEL may therefore be described by the type of phase plane curve shown in Fig. 3.

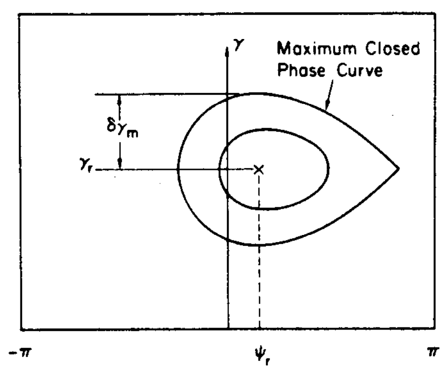

Fig. 3. Stable phase plane trajectories.

The "standard operational mode" of the FEL, which was the mode used in the Madey experiment, is one in which the wiggler wave number k_w and field amplitude a_w are constant. The resonant energy γ_r is therefore also constant, and the resonant phase $\psi_r = 0$. In this mode the buckets are nonaccelerating or stationary. At first glance it is a little difficult to understand how such a device can work since the energies of electrons injected near the resonant energy with a uniform phase distribution will oscillate about the resonant energy (which remains constant). The key to successful operation of the FEL in this mode is to inject the electrons above the resonant energy and to allow them to complete only a fraction of an oscillation, as shown in Fig. 4.

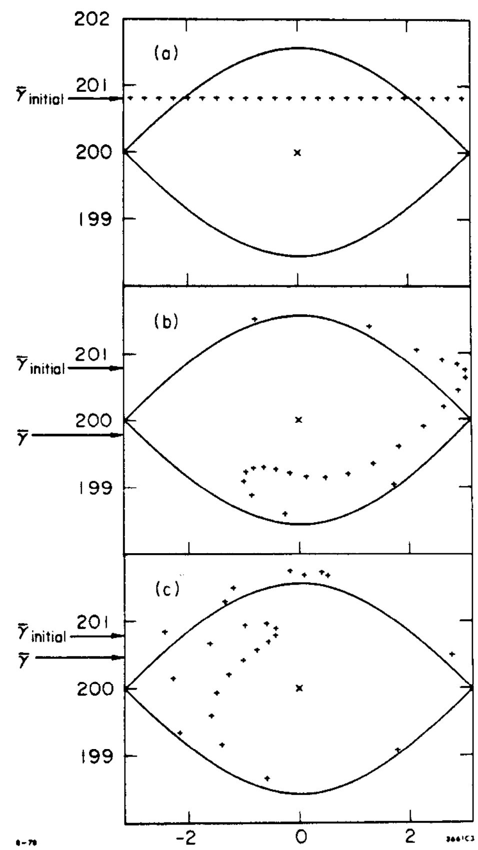

Fig. 4. Evolution of the electron energy distribution: (a) initial distribution; (b) after one-half oscillation; and (c) after nearly one-oscillation.

3. More Exotic FEL Schemes

We see from Fig. 4 that the maximum energy transferred from the electron to the optical wave is roughly equal to the bucket half-height which results in an equivalent energy spread in the electrons. This places severe restrictions on the power and efficiency of this type of FEL. Several schemes have been devised to overcome these limitations.

Deacon[6] has analyzed the operation of a constant parameter FEL in an isochromous storage ring. As a electron travels around the ring, such a device maintains the phase relationship between the electron and the optical wave. The electron is trapped in the optical bucket and can transfer energy from the low frequency rf cavity to the high frequency optical cavity. He discusses the design of a storage ring capable of restricting the spread in the longitudinal position of the electrons to be less than a fraction of the optical wavelength. This requires of the storage ring a very low momentum compaction factor, and consequently the longitudinal focusing is very weak in the absence of the optical wave.

Another scheme[7] designated as a gain-expanded wiggler was proposed by the Stanford Group to reduce the sensitivity of the optical gain to the electron energy. The equations of motion were presented by Madey and Taber[8] and a complete review was presented by Kroll.[9] In addition, Madey and Ekstein have obtained new results[10] on the excitation-canceling FEL with a gain-expanded wiggler.

The gain-expanded FEL utilizes a transverse gradient in the wiggler magnetic field which has the property that the average value of the dispersion in the wiggler is constant and non-zero. Thus different energy electrons will have different trajectories. For the gain-expanded wiggler the gradient of the wiggler field is chosen so that the increase in the path length, due to the increased magnetic field, seen by the higher energy electrons, just compensates for the increase in the electron speed. In this case the change in the phase ψ is proportional to the averaged betatron oscillation displacement and the energy transfer leads to an excitation of the betatron motion. By utilizing the coupling between the transverse and longitudinal motion it is possible to have a transfer of electron energy to the optical wave even for electric beams with a large energy spread. At the present time a storage ring to be built at Stanford has been authorized so that these schemes may be investigated.

Another scheme called the tapered wiggler has been devised which allows the resonant energy to decrease by allowing the wiggler field and period to decrease with longitudinal position. This corresponds to having a resonant phase $\psi_r > 0$ or a moving bucket. In this scheme electrons trapped in the bucket will have their average energy decreased by an amount equal to the decrease in the resonant energy. This scheme, which allows a much larger transfer of energy from the electrons to the optical wave, is shown in Fig. 5.

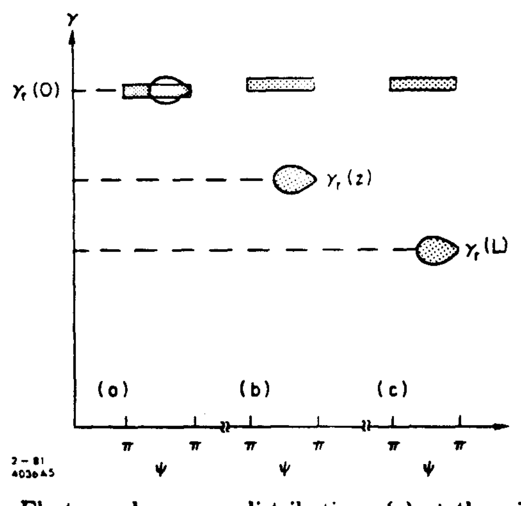

Fig. 5. Electron phase area distribution: (a) at the wiggler entrance; (b) at the wiggler center; and (c) at the wiggler exit.

As we see from Fig. 5, only a portion of the electrons are trapped in the bucket and hence decelerated. The remaining untrapped electrons actually have their energy increased slightly so that the electrons will exit the FEL with a large spread in the energy. This large energy spread in the beam makes it difficult to reuse the electrons in the FEL again. This scheme is most useful in single pass FEL's where a linear accelerator is used as the electron source.

Several experiments have been completed and several others are now being performed using a taper wiggler FEL.

Two amplifier experiments have been very successful, one at Boeing and Math. Sci. N.W. and one at LANL. Both use linacs with electron energies of 20 MeV and measured energy extraction from the electrons of approximately 4%. In Fig. 6 we have a schematic of the amplifier experiment at LANL, and in Fig. 7 we have a comparison of the experimental results with the theory for the energy of the electrons after interacting with the laser beam. The extraction efficiency as a function of input optical power is shown in Fig. 8. The group from Boeing and Math. Sci. N.W. have obtained similar results.

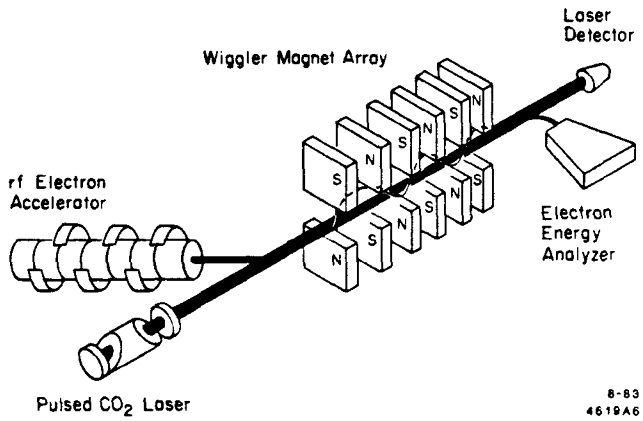

Fig. 6. Schematic of amplifier experiment at LANL.

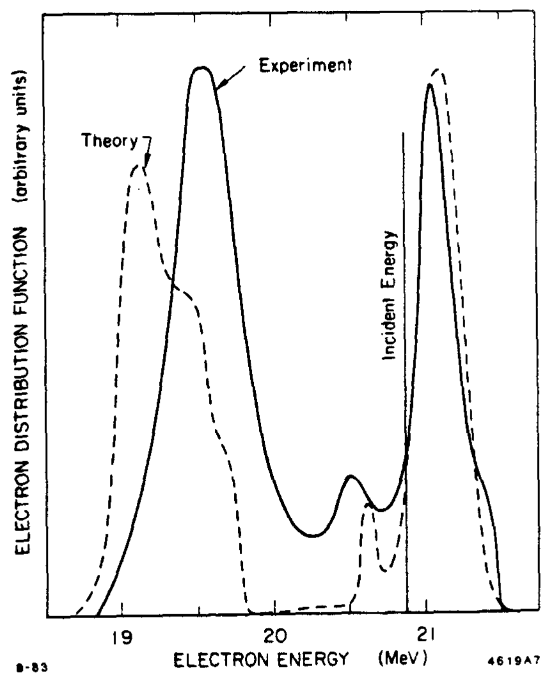

Fig. 7. Energy of electron at output of LANL amplifier experiment. At 0.75 GW over 50% of the electrons were trapped.

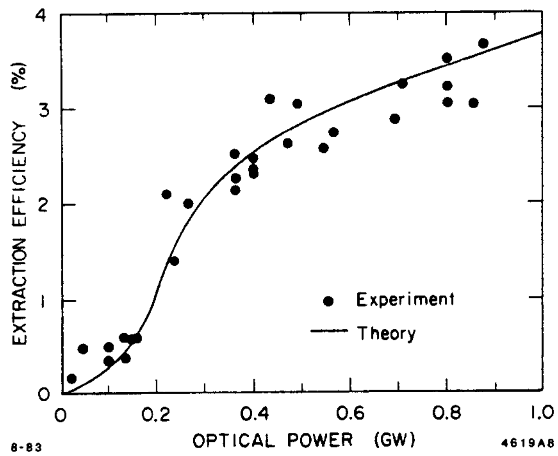

Fig. 8. Extraction efficiency as function of optical power. Saturation shows onset of electron trapping.

4. Most Recent Results

In June of this year a "free electron laser" was made to oscillate in the ACO storage ring by a group from LURE and Stanford. The gain of the FEL was quite small so that obtaining very low losses in the mirrors were an important factor in lowering the gain threshold. The group has reported on the results of an amplifier experiment in 1981. The group was faced with several difficult problems. As the average current in the storage ring is increased above a threshold value the bunch exhibits anomalous bunch lengthening which lowers the peak current and hence lowers the gain. Also at higher energies for the storage ring where the current limits are higher it is necessary to use larger values of a_w to obtain the desired values of λ_s for a given value of λ_w. The energy in the higher harmonics of the optical radiation was found to damage the mirrors which also then raised the threshold value for the necessary gain. Nevertheless, the group was able to find an energy where the oscillator would work. This was a very difficult experiment and the group should be congratulated on their success.

Even more recently, in the end of July a group from TRW operated the first FEL oscillator with a tapered wiggler. They used the Stanford super-conducting linac and the FEL lased as the electron beam was tuned up without the need to adjust the optical cavity length. The main reasons for their quick success were:

1. the use of a very stable-low-emittance electron beam,
2. the large amount of diagnostics that they had designed into the experiment,
3. the great care that they had put into the alignment of their experiment, and
4. the fact that the people supplying the electron beam were an integral part of the experiment.

5. Summary

The present situation with free electron laser research is very encouraging. After the initial experiments by Madey there was a long time where most of the research was theoretical. Now we are getting a lot of experimental results to feed back into the theory and no major inconsistencies have been found. The main restriction seems to be the need for very good quality electron beams. This has promoted research on achieving such electron beams, and accelerator technology is being advanced at the laboratories engaged in FEL research.

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