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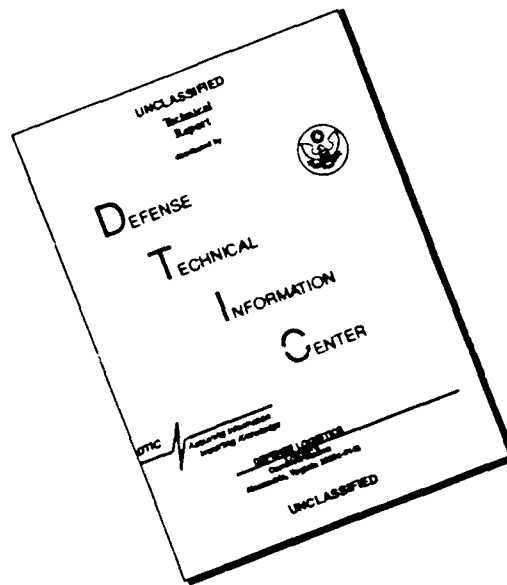
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NINTH INTERNATIONAL CONFERENCE ON  
INFRARED AND MILLIMETER WAVES

TOHOKU UNIVERSITY, JAPAN

OCTOBER 1984

# A SUBMILLIMETER FREE-ELECTRON LASER

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## Introduction

Free-electron lasers (FEL's) are powerful sources of electromagnetic radiation capable of operating efficiently over a broad band of frequencies spanning from the vacuum-ultraviolet to the millimeter region of the spectrum. The first demonstration of short wavelength FEL coherent radiation took place at Stanford University in 1975. Since then, many other research laboratories throughout the world have initiated research programs oriented toward the development of these type of devices. At the University of California, Santa Barbara a major experimental effort is underway to develop low-voltage free-electron lasers operating in: a) the FIR region using a single-stage FEL design and b) the uv-visible-ir region using a two-stage FEL device.

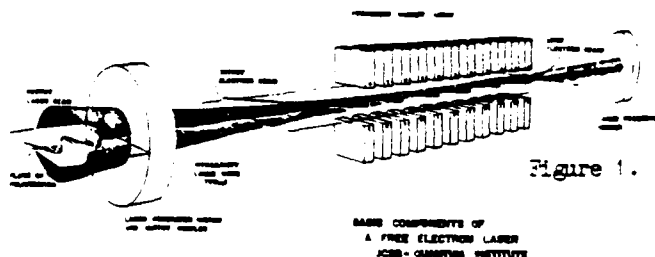
A major portion of this presentation is devoted to examining, in a tutorial manner, the basic single-particle physics of free-electron lasers and discussing in some detail the important design considerations of the UCSB FIR FEL.

## Basic Physics

The operation of a FEL is based on the amplification of electromagnetic radiation by fast electrons moving through a periodic electromagnetic structure. A typical system, as illustrated in figure 1, contains the following three basic components: a) a monochromatic electron beam, b) a periodic static magnetic field generated by either an array of permanent magnets (wiggler or undulator) oriented with alternating magnetic field polarity or by a periodic arrangement of current carrying conductors, and c) an electromagnetic resonator.

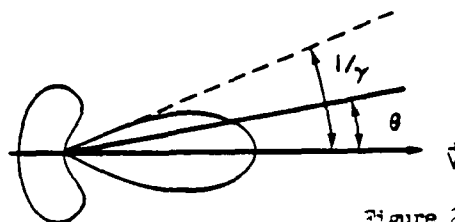
An electron moving through the magnet array will do so describing a classical periodic trajectory in which the orbit plane is perpendicular to the direction of magnetic field as shown in figure 1. As a result of its periodic centripetal acceleration the electron will radiate spontaneously (initially) into the cavity resonator. After the first few bounces inside the cavity, the radiated field will stimulate emission by other electrons. The electromagnetic amplification process will continue until the laser reaches gain saturation.

Assume that the magnetic undulator is N



periods long and that the length of each period is  $\lambda_0$ . Classical Electrodynamics predicts that an electron will, in the absence of an stimulating electromagnetic field, radiate a periodic electromagnetic pulse N periods long. Because of its motion, the radiation fields generated by a single electron have an angular distribution of power peaked along the electrons's direction of motion. For an electron moving with relativistic speed most of the power is radiated within a cone having a half angle value of  $1/\gamma$ , where  $\gamma mc^2$  is the total energy of the electron. This effect is illustrated in figure 2. Also because of its motion an electron in a FEL will radiate over a range of wavelengths whose value depends on angle of observation  $\theta$  and on electron normalized longitudinal speed  $\beta_z$ . It is given by:

$$\lambda = \lambda_0 (1/\beta_z - \cos(\theta)) \quad (1)$$



## SPONTANEOUS RADIATION PATTERN

Figure 3 shows a plot of  $\lambda$  as a function of angle of observation for two different electron energies. Along the direction of motion ( $\theta=0$ ), the radiation wavelength is shortest. At 90 degrees the radiation wavelength is equal to the magnet period and at 180 degrees there is a backward wave with wavelength equal to twice the magnet period.

The spectral purity of the radiation field produced by a single electron is limited by the number of magnet periods. The spectral

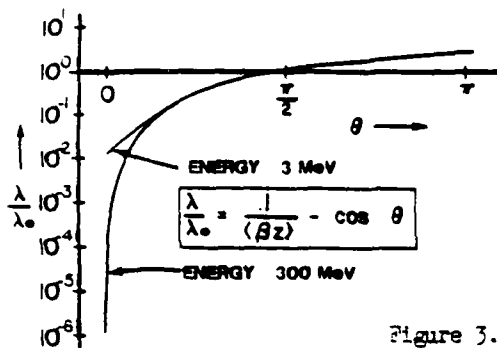


Figure 3.

#### FEL WAVELENGTH

distribution of radiation at a fixed angle of observation is shown in Figure 4. The bandwidth of radiation is given by the following approximate relation:

$$\Delta\lambda/\lambda = 1/2N$$

(2)

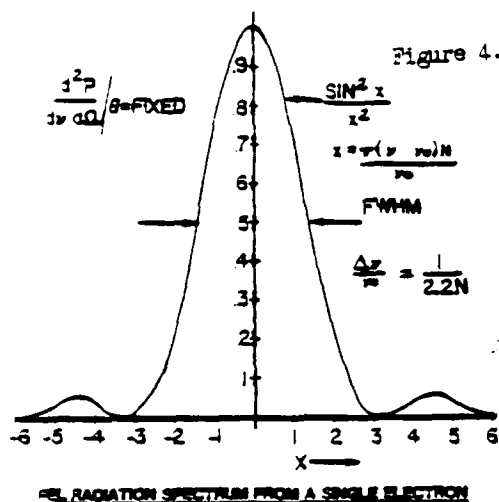


Figure 4.

When a beam of electrons is injected into the undulator, each electron radiates independently. The resultant synchrotron radiation field can be described as a superposition of waves emitted by individual electrons but with random phases. However, in the presence of an input wave having the appropriate resonance wavelength of equation (1) it is possible to exchange energy between the electron beam and the input wave in such a manner that amplification of the input wave can result. This process can be interpreted as a constructive interference of radiation pulses emitted by individual electrons. The correct phasing of the electrons is produced by a net longitudinal force which tends to bunch the electron beam with the periodicity of the input wave. The effect of the bunching process is illustrated in Figure 5 showing the time dependence of the resultant electric field amplitude generated by a short pulse of electrons as observed at a fixed point in space. At the beginning of the trace the resultant electric field is small because the electrons have not had time to bunch. As time

progresses bunching forces the electrons to radiate in phase with each other and in phase with the input wave.

The maximum small signal gain of a free electron laser can be written as follows:

$$G \propto \frac{\text{BEAM CURRENT}}{\text{MODE AREA}} \times B^2 \lambda_0^2 (N/\gamma)^2 \quad (5)$$

where B is the peak amplitude of the undulator magnetic field. For a fixed wavelength the dependence of small signal gain on electron energy is illustrated in Figure 6. The resonance energy  $\gamma_R$  can be calculated from equation (1). Wave amplification (stimulated emission) occurs for energies slightly greater than resonance energy and wave attenuation (stimulated absorption) takes place for

#### COHERENT FEL RADIATION PULSE

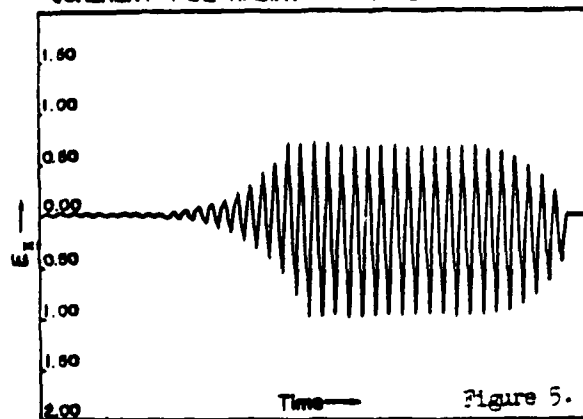


Figure 5.

#### GAIN

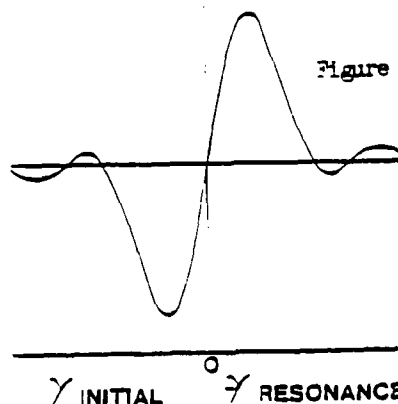


Figure 6.

electron energies slightly lower than resonance energy.

There are some restrictions regarding the optical quality of electron beams required to drive FEL's. In order for electrons to maintain velocity synchronism with the amplified wave it is necessary that their longitudinal velocity spread be smaller than the gain amplification bandwidth. The following relation describes approximately such condition:

$$\beta_2 < 1/2Nv^2$$

(6)

A summary of the range of wavelengths attainable with present electron accelerator technology is shown in figure 7.

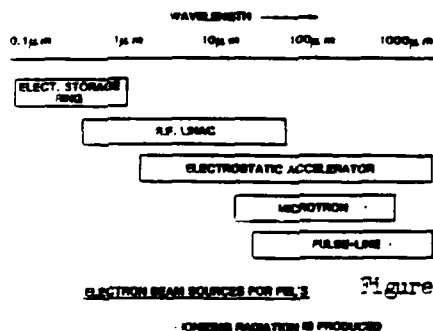


Figure 7.

Finally, the amount of power that can be extracted from electron beam moving through a constant period undulator is approximately given by:

$$P_{\text{LASER}} = P_{\text{E. BEAM}} / 2N$$

(7)

#### The UCSB FEL Project

At the University of California at Santa Barbara a free-electron laser research program is underway to study the operation of FEL's based on electron beams generated by electrostatic accelerators. A conceptual drawing of the system is presented in figure 8. The major features of this device are:

##### - Long wavelength, continuous tunability

75 micron to 2000 micron

##### - High Laser Power

$P = 18 \text{ kw}$        $\langle P \rangle = 200 \text{ watts}$

##### - High Optical Resolution

$< 1.0e-4$

##### - High operating efficiency

$> 10\%$

##### - Low ionizing radiation levels

The UCSB electrostatic-accelerator electron beam system is well suited to drive FEL's in the millimeter-FIR region because: (1) the system covers the proper operating electron energy range, (2) it generates a better than required high quality electron beam and (3) the unused energy of the electron beam can be recovered efficiently.

To optimize net gain amplification, a new type of electromagnetic resonator has been

designed at UCSB. It is a semi-open cavity consisting of two parallel metallic plates which guide the waves in the vertical direction. In the horizontal direction the optical beam is contained by cylindrical mirrors located at each end of the resonator. A conceptual illustration of the resonator is presented in figure 9.

Table I below summarizes the important expected optical characteristics of the FIR-UCSB FEL in its initial configuration.

Table I. Expected UCSB FEL optical characteristics

|                        |             |          |
|------------------------|-------------|----------|
| Wavelength             | 750         | micron   |
| Peak power             | 18          | k-watts  |
| Pulse length           | 4-200       | microsec |
| Pulse rate             | 20          | Hz       |
| Optical mode dimension |             |          |
| vertical               | 2.0         | cm       |
| horizontal             | 4.0         | cm       |
| Optical resolution     | $< 1/10000$ |          |
| Tunability             | 75- 2000    | micron   |

Later on in 1985 the UCSB FEL will be tested as a two-stage device. The range of wavelength that will be covered with this mode of operation is from the vacuum ultraviolet to the near IR.

Finally, a condensed matter research effort using the FIR radiation from the FEL will soon be initiated in collaboration with other scientists at UCSB. If successful, the program will be expanded to allow other US scientists to utilize this unique source in other research areas such as chemistry and biology.

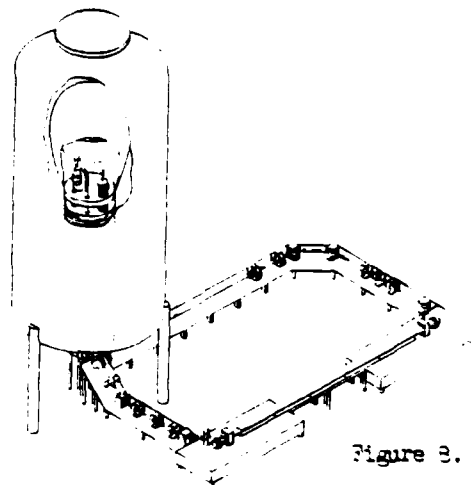


Figure 8.