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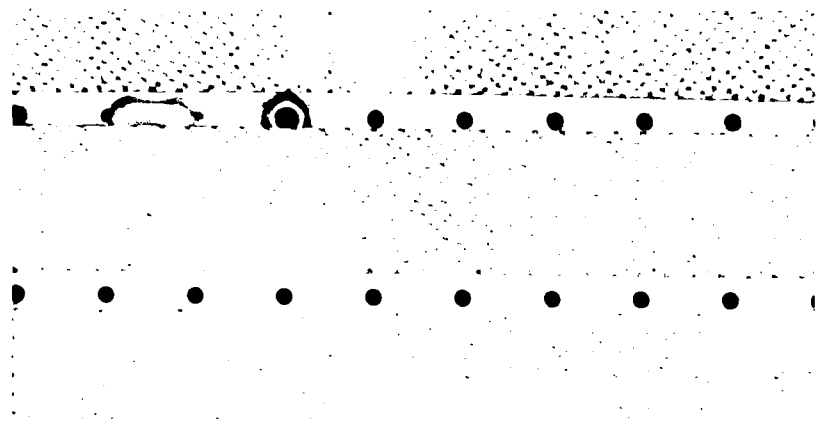
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FREE ELECTRON LASER PROJECT

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The operation of a Free Electron Laser (FEL) is based on the amplification of electromagnetic radiation by relativistic electrons moving through a periodic electromagnetic structure. A typical system 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 of by a periodic arrangement of current carrying conductors, and c) an electromagnetic resonator.

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Free Electron Lasers

Luis Elias

The Future of Lightwave Technology
NSF Workshop Concerning Quantum Electronics, 1984

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FREE ELECTRON LASERS

Luis R. Elias

University of California at Santa Barbara

BASIC PHYSICS

The operation of a Free Electron Laser (FEL) is based on the amplification of electromagnetic radiation by relativistic 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.
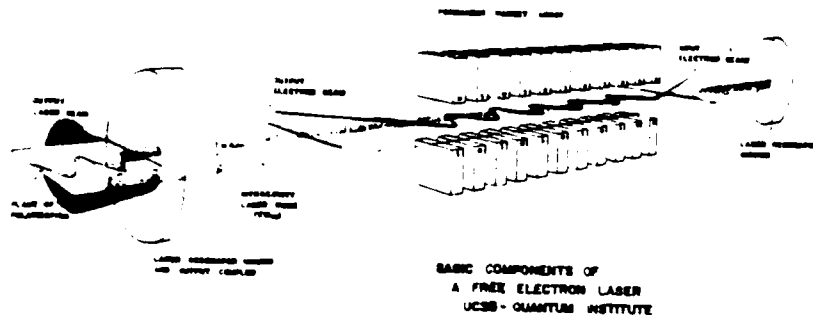

BASIC COMPONENTS OF
A FREE ELECTRON LASER
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Figure1. Basic components of a FEL.

In the absence of an input stimulating electromagnetic field , a single electron describes a periodic trajectory through the magnetic undulator as shown in the figure. Assume for the moment that the magnetic undulator is N periods long and that the length of each period is λ_0. Clasical Electrodynamics predicts that ,as a result of the periodic centripetal acceleration received by the electron, it will radiate a sinusoidal electromagnetic pulse N periods long and because of relativistic effects its free space wavelength will depend on electron average speed $\langle \beta_z \rangle$ and angle of observation θ as follows:

$$\lambda = \lambda_0 \left(1/\langle \beta_z \rangle - \cos(\theta) \right)$$

where the relation shown on the right describes the radiation wavelength for small angles of observation. Illustration of the above relation can be seen in figure 2b. Note from the figure that a large range of wavelengths can be obtained using existing accelerator energies. Spatially, the radiation is emitted in a narrow relativistic cone symmetrically distributed along the direction of electron motion as shown in figure 2b. Most of the power emitted is radiated within a half angle of $1/\gamma$. In the frequency domain an observer will detect a relatively narrow power spectrum of 1/2N fractional spectral width as shown in figure 3a (Fourier transform of a finite length sinusoidal pulse).
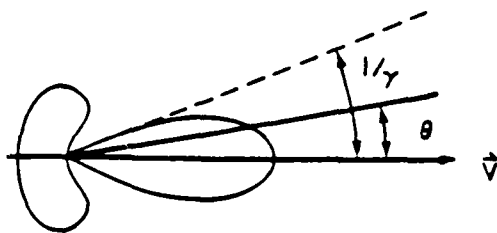
SPONTANEOUS RADIATION PATTERN

FEL WAVELENGTH

$$\frac{\lambda}{\lambda_e} = \frac{1}{(\beta z)} - \cos\theta$$
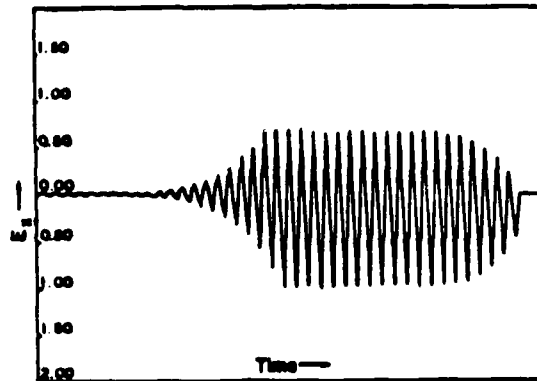
ENERGY 3 MeV

ENERGY 300 MeV
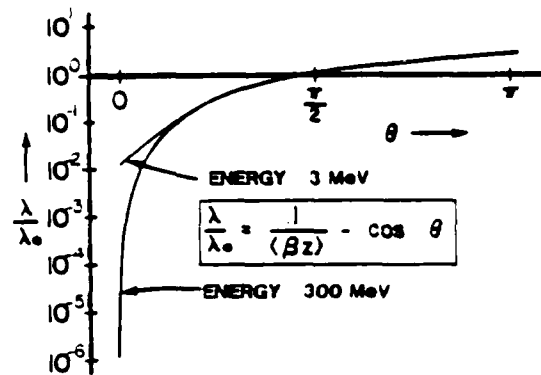
a) Radiation cone b) Wavelength vs. angle

Figure 2.

In the presence of an input wave of wavelength ___ propagating in the same direction as the electron, an interaction takes place between the input wave and the undulating electron. A net resulting force (the so called ponderomotive force) accelerates the electron along its direction of motion and forces it to radiate in phase with the input wave. Thus, the input wave is "stimulating" the radiation process.

$$\frac{d^2P}{d\omega\,d\Omega}\Big/_{\theta=FIXED}$$

$$\frac{SIN^2 x}{x^2}$$

FWHM

$$\frac{\Delta\omega}{\omega} = \frac{1}{2.2N}$$
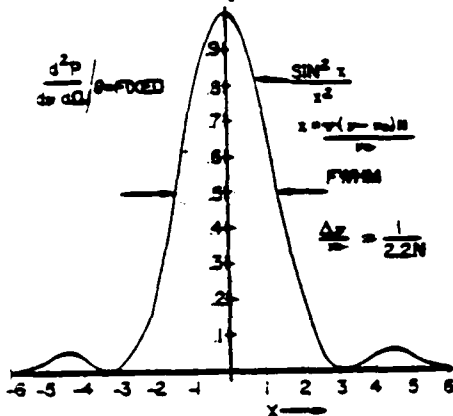
a) Spectral distribution b) FEL radiation pulse

Figure 3.

When a beam of electrons is considered, the effect of the ponderomotive force is to bunch the electrons with the periodicity of the input wave and force them to radiate in phase with the input wave. This is the basic mechanism of FEL operation. The electron bunching process manifests istself as a phase foccusing effect in the resultant radiated wave. Figure 3b illustrated in figure 3b. It shows how the stimulated radiation process takes place as a function of time as seen by an observer located at some fixed distance from the interaction region. At the beggining of the process the electrons are radiating with random phases and the resulting radiation power is negligible. As the bunching process takes place the electrons radiate in phase with each other and with the input wave and as a result the resulting electromagnetic field amplitude increases reaching a maximum near the end of the pulse. If the phase of the radiated wave is near the phase of the input wave, wave amplification process takes place. If the phase of the resultant radiation pulse is out of phase by 180 degrees with respect to the input wave, wave attenuation (i.e., stimulated absorption) takes place.

The process of FEL gain saturation originates in the bunching process. For strong input fields electron bunching introduces a longitudinal velocity spread in the beam. As a result of this, radiation pulses originating from different electrons in a bunch do not radiate at the same wavelength . Consequently signal gain will diminish as a result of incomplete constructive interference effects.

The amount of electron beam power that can be converted to laser radiation at gain saturation is approximattely given by (Laser Power)= (Electron Beam Power)/2N.

POTENTIAL CAPABILITIES OF FEL'S.

The following are some of the important features of FEL's.

- ### HIGH AVERAGE POWER

   Magnetic wigglers can be designed to extract more than 5 % of the electron beam power. Accelerators can provide beam powe in excess of 100 Megawatts. Therefore the average power of FEL's can be greater than 1 Megawatt.

- ### BROADBAND CONTINUOUS TUNABILITY

   With present accelerator technology it is possible to drive FEL'sfrom the millimeter to the X-ray region of the spectrum. Continuous tunability can be achieved readily by changing the energy of the accelerator.

- ### HIGH OPTICAL RESOLUTION

   Using continuous electron beams, such as the ones produced with electrostatic accelerator at UC Santa Barbara, laser operation at high optical resolution can be achieved.

- ### SHORT PULSE OPERATION

   The first high energy FEL was operated at Stanford University an optical pulse length of 1.3 picoseconds. All RF acceleratorswill produce short FEL optical pulses.

- ### HIGH EFFICIENCY OPERATION

   Using high single pass energy extraction undulators, such as the one constructed for the FEL project at Los Alamos National Laboratory and TRW, or utilizing the electron beam energy recovery features of the UCSBelectrostatic accelerator, overall laser operating efficiency in excess of 10 % can be achieved.

ACCELERATORS FOR FEL'S

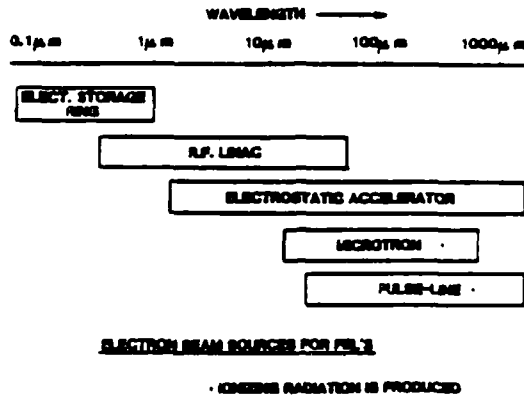A summary of of the range of wavelength attainable with present electron accelerators is listed in figure 4 below.

Figure 4. Accelerators for FEL's

Also, a table of ongoing FEL experimental research is presented below.

Type of accelerator	Country	Wavelength range
Electron Storage Ring		
- Stanford University	US	X-Ray
- Orsay	FRANCE	Visible
- Brookhaven	US	Visible-UV
RF Linac		
- Stanford University	US	IR
- Los Alamos	US	IR
- University of Edinburgh	UK	IR
Microtron		
- Bell Laboratories	US	FIR
- Frascati	Italy	FIR
Electrostatic		
- UC Santa Barbara	US	FIR-IR-UV

FACILITIES REQUIRED FOR UTILIZATION OF FEL RADIATION

A FEL operating in the Far-Infrared (FIR-IR) region of the electromagnetic spectrum will be a powerful tool for research in solid state physics, surface science, chemistry and biology. As such, there will be required specific auxiliary instrumentation and facilities for its effective utilization. These could cost in excess of $2 - $4 million, depending on the variety of in-house capabilities one would think appropriate to provide.

Rather than generalize these needs, we briefly mention the tentative planning that has been given for expanding the UCSB FEL laboratory to make possible a user-ready facility. A separate laboratory building of approximately 4000 sq. ft. of floor space would be attached to the present FEL structure. It would have all standard laboratory needs (e.g. vacuum, gases, recirculating deionized water LHe and LN2). A variety of special lasers and optical and I-R detection equipment would be available along with signal processing and computing equipment. Estimated cost for new laboratory plus an office wing to house visiting scientists is approximately $2.5 million and the necessary basis equipment for user-compatibility approximately $ 1.5 million.

Condensed Matter Science Program

As a first stage toward realization of the full utilization of the UCSB FEL, initial condensed matter science program has been planned. In this it has been proposed to study the generation and propagation of magnons and phonons throughout the Brillouin Zone, nonlinear phenomena involving two-photon spectroscopy, excitations of 2-dimensional electronic systems, pinned charge density waves in 1-dimensional metals and homogeneous spectroscopy in inhomogeneous systems.

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