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ABSTRACT

Free electron lasers represent a radical alternative to conventional lasers, being potentially the most flexible, high power and efficient generators of coherent radiation from the ultraviolet to the far infra-red. In this review the properties of free electron lasers are discussed from both a theoretical and an experimental viewpoint, and some likely areas of application for these devices are outlined.

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1. INTRODUCTION

Although the first operation of a Free Electron Laser (FEL) was achieved relatively recently$^{(1)}$, in 1975, the development of this device can be traced back to 1951, to the generation of narrow-band synchrotron radiation using a magnetically modulated relativistic electron beam$^{(2)}$. Experiments have proved both difficult and expensive, yet are currently being well funded world-wide, principally because theoretical predictions (rather than experimental results) are so encouraging. These predictions include high efficiency, high power (both peak and average) and a range of operating wavelengths from the millimetre to vacuum UV.

In a conventional laser the gain mechanism involves electrons making radiative transitions between bound states of atoms or molecules. In an FEL the electrons are unbound, and travel in an almost monoenergetic beam. In such a beam a population inversion exists with respect to the entire energy spectrum with lower energy, and as such FEL's are freed from such restrictions as operating wavelength, which are imposed on conventional lasers by the properties of atomic particles. Nevertheless, the operating parameters of an FEL are constrained by a phase matching requirement which must be satisfied if a strong interaction between the electrons and the laser field is to take place.

Microwave devices also rely on the interaction of free electrons with electromagnetic radiation$^{(3)}$ and it is the advanced microwave devices such as Ubitrons and gyrotrons, rather than conventional lasers that are the forerunners of the FEL$^{(4)}$. In these devices, which can generate powerful radiation at millmetre wavelengths, the phase matching condition is satisfied by inducing an oscillatory motion in an intense relativistic electron beam$^{(5)}$. Conventional microwave devices are limited to longer wavelength operation since in order to satisfy the phase matching requirement a cavity (with dimensions small compared to the operating wavelength) is required to reduce the phase velocity of the radiation to approximately that of the electrons. The only basic difference between FEL's and some of the advanced millimetre wave generators is that the former employ 'open' optical resonators whereas the latter make use of 'closed' waveguide resonator structures. However, to date, only the Ubitron$^{(6)}$ has been successfully transformed into a working FEL.

The emphasis of the paper is on the properties of FEL's and possible areas of application. These are covered in sections 4 and 5, and include references to current experimental programmes. This is preceded by a review of the basics of FEL operation in section 2 and a discussion of some recent experimental results in section 3.

2. OPTICAL GAIN IN THE FEL

2.1 Spontaneous Emission

J.M.J. Madley's group at Stanford University were the first to successfully operate an FEL(1). Figure 1 shows the salient features of this device, which will be discussed in detail in section 3. The laser comprises a nearly monoenergetic, low divergence beam of relativistic electrons (generated by a linear accelerator), a spatially periodic magnetic field called 'wiggler' and two cavity mirrors. A solenoid (not shown) wrapped around the wiggler provides an axial guiding field.

In the field of the wiggler each electron describes a helical trajectory in which the perpendicular component of its velocity $v_\perp$ remains constant with a magnitude(7)

$$\beta_\perp = \frac{v_\perp}{c} = \frac{K}{\gamma} \qquad (1)$$

where c is the speed of light, γ is the electron energy divided by its rest mass $m_o c^2$, and K is the (dimensionless) wiggler parameter given by

$$K = \frac{eB_\omega \lambda_\omega}{2\pi m_o c^2} \qquad (2)$$

where B_ω is amplitude of the wiggler magnetic field, λ_ω is the period of the field, and e is the electronic charge. It is difficult in practice to achieve values of K much in excess of unity.

The transverse acceleration of the electrons produces some circularly polarised light which is emitted in the forward direction, in a narrow spectral band ($\lambda/\Delta\lambda \sim 2N$, with N the number of periods in the wiggler) centred on the wavelength

$$\lambda_s = \frac{\lambda_\omega}{2\gamma^2}(1 + K^2) \qquad (3)$$

An important interpretation of equation (3) follows from the realisation that in terms of its effect on the electron beam, the wiggler can be replaced by an equivalent electromagnetic field (Weizsacker-Williams approximation). This equivalent field has a wavelength λ_i given by

$$\lambda_i = 2\lambda_\omega \qquad (4)$$

and propagates in the opposite direction to the electrons. A wiggler with $B_\omega = 1$ kG becomes equivalent to a 300 MW cm^{-2} pump wave, and equation (3) simply expresses the change in wavelength of radiation of wavelength λ_i which is backscattered by the electron beam and which therefore suffers a double Doppler shift$^{(8,9)}$. It follows from equation (3) that for $\gamma \sim 100$, wavelengths in the visible region can be produced in a wiggler with $\lambda_\omega \sim 1$ cm. It is shown below that λ_s is approximately (but slightly less than) the operating wavelength of the FEL.

2.2 Gain Mechanism in the Stanford FEL

In an FEL the electron beam moves in the combined field of the wiggler and an axial electromagnetic field of wavelength λ_L. The energy exchange between an electron and this wave, with electric field $\underline{E}$ is

$$\dot{\gamma} = \frac{e}{m_o c}\,\underline{E}.\underline{\beta} \qquad (5)$$

which is finite only by virture of the transverse component of $\underline{\beta}$ (i.e. $\underline{\beta}_\perp$) induced by the wiggler (equation 1). In the rest frame of the electron beam the electric field vector $\underline{E}$ rotates at frequency ω_L', while the vector $\underline{\beta}_\perp$ induced by the wiggler rotates at frequency ω_i'. Unless $\omega_i' \approx \omega_L'$, the sign of $\dot{\gamma}$ in equation 5 oscillates very rapidly, i.e. there is no net energy exchange. The condition $\omega_i' = \omega_L'$ becomes the phase matching condition and ensures that the sign of $\dot{\gamma}$ remains the same over many oscillations of $\underline{\beta}_\perp$$^{(10)}$. But since the sign of $\dot{\gamma}$ for any one electron depends on the relative phase of $\underline{E}$ and $\underline{\beta}$, which varies at random between the electrons (from zero to 2π over a distance λ_L), half the electrons in the beam gain energy ($\dot{\gamma}$ positive) and half lose energy. This gives rise to a splitting of the electron energy distribution, with electrons undergoing 'slow' synchrotron oscillations about nodal points at which

$\underline{\beta}$ and $\underline{E}$ are always orthogonal. These nodal points are separated by a distance λ_L. The condition $\omega_i' = \omega_L'$ corresponds to $\lambda_L = \lambda_s$ (given by equation 3) and it follows that there is no net gain at this wavelength.

For $\lambda_L > \lambda_s$, then $\omega_L' < \omega_i'$ and the nodal points move backwards in the rest frame of the beam, in the same way as decelerating electrons (i.e. those losing energy to the radiation field). It follows that for a time $\tau = 2\pi/(\omega_L' - \omega_i')$ inside the wiggler, the sign of $\dot{\gamma}$ will change more slowly for those electrons losing energy (in the form of stimulated emission) than for those absorbing energy from the radiation field. Thus, radiation of wavelength $\lambda_L > \lambda_s$ will experience a net optical gain for a period τ, followed by an equal period of absorption. The converse holds for radiation of wavelength $\lambda_L < \lambda_s$. Consequently, for net optical gain the period τ should not be smaller than the transit time of the electron beam in the wiggler (10).

Because of the nature of the gain mechanism, a gain per pass G at wavelength λ_L, rather than a gain coefficient, must be specified. Analysis yields (7)

$$G = 2.66\ 10^{-3}\ \lambda_L^{3/2}\ \lambda_\omega^{\frac{1}{2}}\ \frac{K^2}{(1 + K^2)^{3/2}}\ \frac{I}{\Sigma}\ N^3\ f(x) \qquad (6)$$

where I is the current (Amps) in the electron beam, Σ is the transverse cross section of the electromagnetic wave (assumed to be greater or equal to that of the electron beam) and f(x) is the gain function which is plotted in Figure 2 (7), with

$$x = 4\pi N\ (\gamma - \gamma_r)/\gamma_r\ . \qquad (7)$$

In equation 7, γ_r is the resonance energy defined by (cf. equation 3)

$$\gamma_r^{\ 2} = \frac{\lambda_\omega}{2\lambda_L}\ (1 + K^2)\ . \qquad (8)$$

It follows from Figure 2 that for maximum gain, K = 2 and

$$\gamma = \gamma_r\ (1 + \frac{0.2}{N})\ . \qquad (9)$$

It also follows from this figure and equation 7 that the energy spread $(\delta\gamma/\gamma)$ in the electron beam must be $\lesssim 1/2N$, and that the angular divergence of the beam must be less than $1/\gamma\sqrt{2N}$ (7) if the gain is not to be seriously reduced.

The FEL gain mechanism described above assumes that all the electrons move independently through the wiggler (10). The corresponding backscattering process is termed Compton (i.e. single particle) scattering.

It follows from equation 6 that Compton FEL's differ in many respects from a conventional laser. In particular, the small signal gain does not increase exponentially with the wiggler length L (but as L^3, since $N = L/\lambda_\omega$), and the gain curve (Figure 2) looks more like the derivative of the gain curve of a conventional laser.

2.3 Compton and Raman FEL's

In general, backscattering of radiation by an electron beam involves both single particle and collective processes. In an electron beam the Debye length D is a measure of the distance over which deviations from charge uniformity can occur before space-charge (i.e. collective) effects need be considered, and for an electron beam in an FEL this is to be compared with the separation of nodes (where $\underline{\beta} \cdot \underline{E} = 0$) in the electron beam i.e. the points about which the electrons tend to 'bunch' (as discussed in section 2.2). Thus, a necessary condition for Compton scattering is (11,12)

$$\lambda_L \gamma \ll D . \tag{10}$$

When the inequality in equation 10 does not hold, the possibility of collective oscillations in the electron beam needs to be considered.

It was implied in section 2.2 that the combined effect of the wiggler and backscattered radiation of wavelength λ_L is to generate an axial wave of frequency $\omega_L' - \omega_i'$ in the beam. This wave is driven by the beating of the pondermotive forces of the wiggler and electromagnetic wave (i.e. the $\underline{\beta} \times \underline{B}$ forces arising from the interaction of the moving electron with the transverse magnetic fields of the wiggler and backscattered radiation.) It follows that a convective instability can be set up in the beam, since an increase in the amplitude of the axial wave increases the intensity of backscattered radiation which in turn can reinforce the axial wave through the influence of the ponderomotive force. This convective instability becomes particularly strong when

$$\omega_L' - \omega_i' \simeq \omega_p \tag{11}$$

where ω_p is the plasma frequency for the beam$^{(8)}$. This collective scattering process described above is otherwise known a stimulated Raman scattering.

Thus the inequality in equation (10) distinguishes two types of laser, the Compton FEL and the Raman FEL. This distinction is exaggerated by accelerator technology, with pulse line accelerators (induction linacs, IREB accelerators, radial line accelerators) generating electron beams which are simultaneously of higher density and lower energy (i.e. larger D/γ) than the electron beams generated by r.f. accelerators (linacs, microtrons, storage rings).

2.4 The Raman FEL

In the gain mechanism described in section 2.3, an axial beam wave and the laser radiation both feed on the energy of the electron beam. In this three-wave interaction the laser radiation and the axial wave undergo exponential growth$^{(12,13,14,15)}$, with a gain coefficient (g)$^{(12,14)}$ given by

$$g = \frac{K}{\gamma} \left(\frac{\pi \ \Gamma \ \omega_p \ \gamma^{\frac{1}{2}}}{2c(1 + K^2)^{\frac{1}{2}} \ \lambda_\omega} \right)^{\frac{1}{2}} \qquad (12)$$

occurring at a wavelength λ_L given by$^{(16)}$

$$\frac{2\pi c}{\lambda_L} = \frac{2\pi c}{\lambda_s} - \frac{\omega_p}{\gamma(1 - \beta)} \qquad (13)$$

where

$$\omega_p{}^2 = 4\pi n e^2/\gamma m_o \qquad (14)$$

with n the electron density in the beam.

In common with the gain spectrum for the Compton FEL (Figure 2), there is Raman gain for $\lambda_L > \lambda_s$ and absorption (stimulated Raman absorption) for $\lambda_L < \lambda_s$. The requirements of energy spread ($\delta\gamma/\gamma$) and angular divergence in the beam is not as severe in this case as in the Compton FEL (see section 2.2), but if large can invalidate the condition for collective scattering (equation (10)) since

$$D = \frac{2\pi c}{\omega_p} \left(\frac{\delta\gamma}{\gamma}\right) . \qquad (15)$$

In practice the gain spectrum is not as simple as the above discussion would suggest because there are other collective modes of the plasma which can be excited and give rise to gain. In particular the guiding magnetic field (B) in an FEL gives rise to a cyclotron resonance(9) of frequency

$$\omega_c = eB/mc \ . \qquad (16)$$

This transverse wave is driven by the pondermotive forces of the wiggler and scattered waves by virtue of whatever transverse inhomogeneity exists in the magnetic field(9,17).

Finally, when the wiggler field is very strong the natural frequencies of collective oscillations in the electron beam are modified by the ponderomotive forces, and equation 11 no longer holds. To date, this situation has not arisen in FEL operation, but is discussed in detail elsewhere(18).

3. EXPERIMENTAL RESULTS

To date, the Stanford FEL shown in Figure 1 is the only Compton FEL to have been operated(1). The electron beam was generated by the Stanford superconducting linac (SCA) in the form of a train of pulses of 4.3 ps duration. The beam was directed through a 5.2 m long wiggler of period 3.2 cm. Initially, gain was measured using a 10.6 μm CO_2 laser(19), and for these measurements the electron beam energy was adjusted to 24 MeV (i.e. $\gamma = 47$) as predicted by equations 8 and 9. With a peak electron current of 70 mA, a maximum gain (G) of 7% was measured, in close agreement with theoretical predictions.

The first FEL operation produced a train of pulses of 3.4 μm radiation with a peak power of 7 kW and average power 360 mW(1). To achieve this, the SCA produced a beam of energy 43.5 MeV and peak current 2.5A. The corresponding peak gain was 12% per pass. Because the gain was low, the round trip time for the intracavity laser pulse had to be accurately synchronised to the 85 ns separation of pulses for a large number of pulses, requiring control of the 12.7 m cavity length to within 5 μm. An 8.10^{-3} μm laser bandwidth was measured, representing the Fourier transform limit imposed by the 4.3 ps duration of the electron beam pulses.

In contrast to Compton FEL's, Raman FEL's are high gain devices, capable of operation in an amplified spontaneous emission (ASE) mode. The equivalent effects of a magnetic wiggler and an electromagnetic pump wave was demonstrated in the first results from NRL. In the absence of a wiggler, an intense (> 100 MW) pulse of 2 cm^{-1} radiation produced a gain of $\sim 0.3\ cm^{-1}$ at a wavelength of 400 μm in a 2 MeV, 30 kA electron beam(15). About 1 MW of 400 μm ASE radiated was generated. Later experiments at NRL and Columbia University produced intense ASE using a magnetic wiggler(9,17), and were followed in 1978 by a joint NRL - Columbia report of the first Raman FEL operation(16). Raman FEL operation has also been achieved at TRW(20).

This first Raman FEL is shown in Figure 3, including the guiding magnetic field. An annular electron beam of 1.2 MeV, 25 kA and 40 ns duration from the NRL 'VEBA' accelerator was adabatically expanded into a 5 cm diameter drift tube in which was located a 50 cm long wiggler with $\lambda_\omega = 0.8$ cm. The FEL cavity is defined by two annular mirrors 1.5 m apart, and since the pulses from the VEBA machine were of 40 ns duration only four round trips of the cavity could be made. The laser output was enhanced by resonance effects near the cyclotron frequency(21) (equation 16), and a maximum power of 1 MW at 400 μm was produced. A gain length product of 1.7 for these operating conditions was calculated using equation (11),(16) and so it was concluded that the 40 ns duration of the electron beam was insufficient time for the intracavity laser power to reach saturation.

One important difference between the operating parameters of the Raman and Compton FEL's which is not revealed in the above descriptions, is in the quality of the electron beam. The energy spread ($\delta\gamma/\gamma$) in the Stanford SCA was $\leq 0.05\%$(1) whereas from the NRL VEBA machine voltage variations alone produced a $\frac{\delta\gamma}{\gamma}$ of $\sim 5\%$(16). Although the long length of wiggler and narrowness of the gain spectrum in a Compton FEL places a premium on a small angular divergence (see section 2.2), the relatively large energy spread of the VEBA beam was sufficient to account for the orders of magnitude discrepancy between the calculated efficiency of 5% and that measured experimentally(16).

The above example illustrates the importance of beam quality; its improvement lies at the heart of FEL development. The principal quantity of interest is the emittance (ε) of the electron beam, defined as the product of the radius of the electron beam and its RMS angular divergence. The smaller this quantity, the smaller can be made the cross section of the electron beam, which in turn reduces beam instabilities and inhomogeneous broadening due to magnetic effects (22) (see section 4.3). Small beam cross sections are also important for short wavelength generation (see section 4.2). However, the requirement for a small emittance conflicts with the generation of high current beams. The Lawson-Penner relationship states that the ratio I/ε cannot exceed a value proportional to the square root of the emissivity of the electron source. This has inspired efforts to develop new high-emissivity cathode materials e.g. laser irradiated cathodes.

Other areas of current experimental investigation include energy recycling and recovery, high power, high efficiency amplifiers, and short wavelength (visible and UV) FEL's. This work will be referred to in section (4).

4. PREDICTED PROPERTIES OF FEL's

4.1 Wavelength Tunability

It follows directly from equations 2 and 3 that the operating wavelength of an FEL can be tuned continuously by varying the electron beam energy or (where electromagnets are used in the wiggler) the magnetic field of the wiggler.

4.2 Wavelength Range

Even within the parameters of accelerators presently in operation, FEL's have the capability of covering the wavelength range from ∿ 1 mm to ∿ 100 nm. Raman lasers have already demonstrated their capability in the 400 μm region, a region of some interest (see section 5.3) and one which is relatively devoid of laser sources.

In conventional gas lasers it is argued (23) that the laser power requirements for constant gain increase as the laser wavelength decreases, as λ^{-4}. In an FEL the situation is completely different. The power in the electron beam is

$$P = 0.51\ \gamma I \text{ MW} \tag{17}$$

with I in amps, and (from equations 3, 6 and 9) it follows that for constant gain, P increases only as λ_L^{-1} in a Compton FEL, assuming that the electron beam diameter can always be made smaller than that of the laser field in the resonator. Unfortunately, this assumption is valid only for $\lambda_L \gtrsim 1$ μm for existing r.f. linacs, because of the finite emittance of the beams they produce(24).

Storage rings are presently capable of generating beams of peak current of up to 100 A, at energies of several hundred MeV, and with a very low emittance. They offer the best prospects as electron beam sources for short wavelength FEL's. Experiments are now being undertaken at Brookhaven, Frascati and Saclay to demonstrate FEL operation in a storage ring.

For short wavelength laser generation it is also important to consider the two stage FEL(25). The principle, which follows from equations (3) and (4), is to make the laser radiation generated at $\sim \lambda_\omega/2\gamma^2$ itself act as an electromagnetic pump wave to generate radiation at $\sim \lambda_\omega/8\gamma^2$. In this way an electron beam of relatively low energy could be used to generate short wavelength laser radiation, provided the laser cavity could maintain a sufficiently high intra-cavity power ($\gtrsim 100$ MW cm^{-2}) at the wavelength $\lambda_\omega/2\gamma^2$.

4.3 Laser Bandwidth

The homogeneous contribution to the gain bandwidth $\Delta\lambda/\lambda$ in a Compton FEL is limited to $\sim \frac{1}{2}N$ by the finite interaction time of an electron in the wiggler. In a Raman FEL the three-wave resonance has a homogeneous bandwidth which increases in proportion to the gain coefficient. Under certain conditions secondary gain maxima due to the excitation of other beam instabilities (e.g. the cyclotron resonance) can appear. Although the laser output bandwidth can be much less than the gain bandwidth, intracavity dispersive elements could in theory be used in either type of FEL to further reduce the laser bandwidth. However, line narrowing without adversely affecting laser performance is only possible for laser bandwidths greater than the inhomogeneous contribution to the total gain bandwidth.

Inhomogeneous broadening of the gain is primarily associated with the finite dimensions, angular and energy spread of the electron beam. For a Compton FEL, Figure 2 and equation (7) give the energy spread contribution as $\Delta\lambda/\lambda \simeq \delta\gamma/\gamma$ (i.e. 10^{-3} for the Stanford SCA). The contributions due to inhomogeneities in the transverse magnetic field of the wiggler(22) and the finite emittance of the electron beam are of similar magnitude.

Preliminary attempts have been made at Columbia University to reduce the FEL output linewidth by using a distributive feedback technique, and further work is planned at NRL and Stanford. However, it must be noted that since the output from an r.f. accelerator is bunched (with individual electron beam pulses of $\lesssim$ 10ps duration) a similar temporal structure will be imposed on the FEL output. Consequently, the laser bandwidth in this case is Fourier transform limited to

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda_L}{\ell_e} \quad . \qquad (17)$$

where ℓ_e is the bunch length. For the Stanford SCA, the bunch length was ∿ 1.3 mm(1), and this totally accounts for the measured 8.10^{-3} μm laser linewidth at the 3.4 μm FEL operating wavelength.

4.4 Efficiency

In a simple Compton FEL the efficiency η_c for transfer of electron beam energy into laser energy(26) is limited by the width of the resonance (Figure 2) to a value(7)

$$\eta_c \lesssim 1/2N \cdot \qquad (18)$$

Thus the efficiency limit is typically $\lesssim$ 0.5%. Since the gain is proportional to N^3 (equation 6) it is unrealistic to attempt to increase η_c by decreasing N.

In the simple Raman FEL the efficiency is limited by non-linear saturation of the axial plasma wave to a value(13)

$$\eta_R \leq \frac{\omega_p \lambda_\omega}{4\pi c(\gamma-1)} \approx 2\gamma \left(\frac{\omega_p}{\omega_L}\right) \quad . \qquad (19)$$

The theoretical efficiency of the Raman FEL is typically much greater than for the Compton FEL; but whereas the measured Stanford FEL efficiency of 0.14% came close to the theoretical limit, the NRL - Columbia Raman FEL efficiency was only ∿ 0.003%(16) (cf. 5% given by equation 19). Even so, theoretical efficiencies are low; but there have been several important developments designed to improve this situation.

4.4.1 Modifications to the Wiggler Design

In a uniform wiggler, maximum energy extraction has occurred when the mean electron energy has decreased to γ_R (equation 8). The efficiency may in theory be improved by using a 'tapered' wiggler(27). In this device, λ_ω decreases slowly along the length of the wiggler, and this has the effect of reducing the value of γ_R and so allowing more of the electron beam energy to be extracted. The technique only appears feasible however, for very high power (∿ 1.5 GW) laser fields(24), and small-signal gains are estimated to be typically an order of magnitude lower than for equivalent uniform wigglers(28). Nevertheless, efficiencies of up to 10% for a Compton FEL and 20% for a Raman FEL might be achieved in this way. The tapered wiggler has yet to be demonstrated experimentally. Gain measurements in such a device at the 10.6 µm CO_2 laser wavelength are planned at LASL(29) and elsewhere in an effort to develop high efficiency, high power single pass amplifiers.

An alternative to the 'tapered' wiggler is the 'gain-expanded' wiggler in which λ_ω is held constant but opposing magnetic poles are wedged so as to produce a transverse gradient in the magnetic field(30). In this way the acceptable energy spread in the electron beam may be greatly increased, and such a device may be particularly relevant in the use of storage rings for FEL's as discussed below.

4.4.2 Recycling of the Electron Beam(7,30,31,32,33)

Ideally, by recycling the electrons in a storage ring an r.f. cavity would make good all the electron energy lost to radiation. The principal problem is how to reconstitute the original electron energy distribution after passage through the FEL. The problem is severe since the electron beam energy distribution is split into two components in the FEL, separated by an amount much greater than the change in mean energy(10).

4.4.3 Collection of the Electron Beam

The problems associated with recycling of the electrons can be largely overcome by recovering the electrons without re-using them. One such scheme employs a Van de Graff electrostatic accelerator to provide the input electron beam, and an electrostatic decelerator to collect the unused beam at a high negative potential(34). A relatively low voltage generator makes up the difference in potential due to energy loss in the FEL. If beam losses can be kept sufficiently small, such a system could provide a cw laser output. Experimental development of such a system is presently underway at the University of California at Santa Barbara. Unfortunately, the beams produced by electrostatic accelerators are presently limited to $\gamma \lesssim 50$.

For short wavelength generations an energy recovery system based on r.f. linacs is being undertaken at LASL(29). By inserting the electron bunches leaving the wiggler into a linac with the correct phase, their energy can be returned to the r.f. field. The same linac can also be used to provide a fresh electron beam for the FEL.

4.5 Power

In an FEL there is no fundamental limit set by the gain medium to the power that can be generated, and intense optical fields can propagate without being influenced by the non-linear effects (e.g. self-focusing, gas breakdown) occurring in denser media.

The saturation power P_{sat} of an FEL is simply

$$P_{sat} = P \times \eta_{sat} \tag{20}$$

where P is given by equation 16 and η_{sat} is the FEL efficiency at saturation such as given by equations 18 or 19. Using equation 16 and the data given in section 3, beam powers of 113 MW and 30 GW are estimated to have been used to generate the first Compton and Raman FEL's, respectively. It follows that even for modest values of η_{sat} the peak power from an FEL can be large. Average powers can also be high, with high power (up to 200 kW) high reliability accelerators already in existence.

4.6 Pulse Duration

Because the gain requirements in FEL's require electron beams of high peak power (see section 4.5), overall 'wall-plug' efficiencies(26) need to be high in all except short pulse operation. To date the electrostatic accelerator with recovery (discussed in section 4.4.3) offers the best prospects for long pulse or cw operation.

4.7 Repetition Rate

Electron accelerators generally have a high repetition rate capability e.g. the microtron for the FEL being developed at Frascati has a power supply limited repetition rate of 400 Hz. But whereas the problem of high voltage switching at high repetition rates is common to all lasers, the FEL has the advantage of not requiring cooling or recirculation of the gain media.

5. APPLICATIONS OF FEL's

The uniqueness of the FEL lies in the fact that the laser parameters are determined entirely by external variables, and that the technology of these devices differs radically from that of conventional lasers.

As summarised in section 4, FEL's offer the capability of high overall efficiency ($\gtrsim 25\%$) and high power from the UV to FIR regions of the spectrum. Consequently, possible applications are in such fields as plasma heating, isotope separation / photochemistry, FIR solid state spectroscopy and diagnostics, radar, lidar, heat treatment / welding / cutting of metals, and space transmission / communications. And while it may be many years before FEL's made a significant contribution in any of these fields, it is of interest to examine some of the more likely areas of applications in more detail.

5.1 Photochemistry

Photochemical applications generally require specific laser wavelengths and impose strict bandwidth restrictions. However, in section 4.3 it was shown that FEL emission bandwidths ($\Delta\lambda/\lambda$) of better than 10^{-3} appear impractical at present. This may exclude the use of FEL's for infrared (molecular) isotope separation of the heavier elements. Fortunately, laser bandwidth restrictions are not so severe in such areas as the laser initiation of chemical reactions and the isotope separation of lighter elements (e.g. deuterium). Detailed calculations at LASL indicate that FEL's could have low capital and operating costs, and so could find applications in the large scale photochemical production of a wide range of materials(29).

5.2 Laser Fusion

Theoretical studies have been made at Lawrence Livermore Laboratories which indicate that single-pass FEL amplifiers using tapered wigglers could meet the ever increasing laser requirements (presently $\sim 10^6$ MW at < 300 nm) for inertial confinement fusion. Experimental work at LASL, TRW and Mathematical Sciences North-West is aimed at developing very high power CO_2 laser amplifiers for this and other applications.

5.3 FIR Spectroscopy

Very little work has previously been possible in FIR spectroscopy due to a shortage of coherent sources operating in this region (20-1000 μm). Raman FEL's offer an immediate solution to this problem and Bell Laboratories are presently building an FEL for use as a spectroscopic tool. The laser is designed to deliver pulses of 10^{-11}s duration, 500 kW peak power (10W average power) in the 100-400 μm region(35). Areas of application include the electronic structure of semiconductors, molecular motion in liquids and polymers, and time resolved spectroscopy in solids, liquids and gases.

5.4 Plasma Heating

The present generation of magnetic confinement machines (such as the JET machine at Culham(36) require plasmas with densities of 10^{13}-10^{14} cm^{-3} to be heated to high temperatures. Such heating might be accomplished by matching the operating frequency of an FEL to a characteristic frequency of the plasma. Wavelengths in the mm region would typically be required to match the electron cyclotron frequency ($\sim$ 80 GHz for JET). FEL's may also be used for FIR plasma diagnostics.

6. CONCLUSIONS

Experimental results to date have already demonstrated the ability of FEL's to provide short, high power pulses of continuously tunable wavelength in the infrared region of the spectrum. Theoretical predictions also indicate that FEL's could be developed to exceed the performance of conventional lasers in terms of efficiency, peak and average power capability and range of operating wavelengths.

There is undoubtedly a healthy scepticism within the laser community towards the impressive theoretical predictions of FEL performance. Such scepticism is based largely on past experience with conventional lasers, where theoretical predictions have so often greatly exceeded experimental results. Such large discrepancies can generally be attributed to a lack of good numerical data on atomic parameters and collisional processes, coupled with the necessity of making over simplifying assumptions (in order to avoid the overwhelming numerical complexity involved in constructing a quantum mechanical model of the processes taking place in a system of excited atoms or molecules). Such discrepancies between theory and experiment should not occur in the case of the FEL where the simplicity of the gain medium allows accurate theoretical modelling with the minimum number of simplifying assumptions. Interestingly, classical physics can be used to describe operation of an FEL(7,10). But it remains to be seen to what extent technological constraints will conspire to limit the performance of these devices.

It should also be pointed out that there are other mechanisms involving relativistic electron beams which could also lead to FEL operation(37). While none of these alternatives has proven successful to date, it is too early to draw any definite conclusions.

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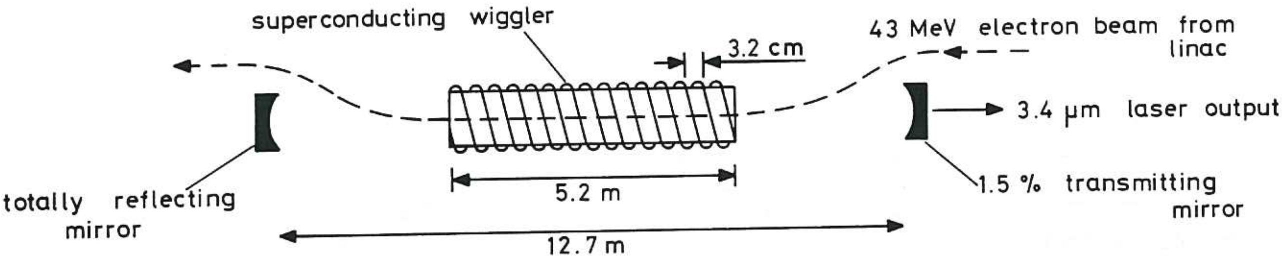

Fig.1 The Stanford free electron laser.

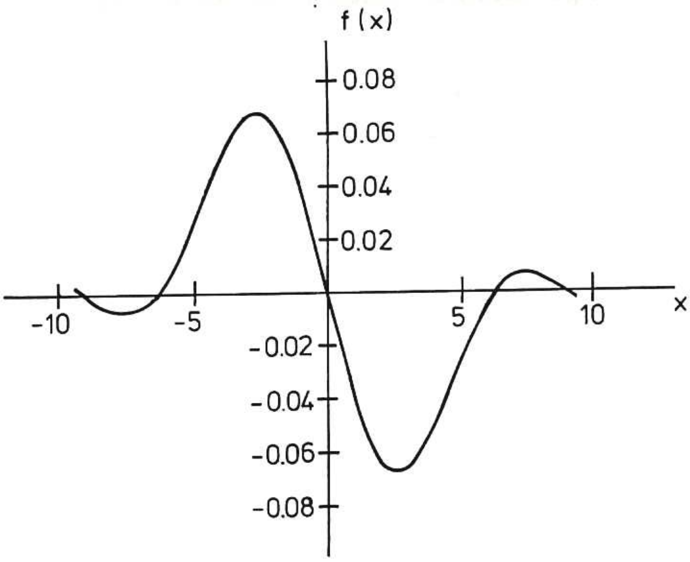

Fig.2 The gain function f(x).

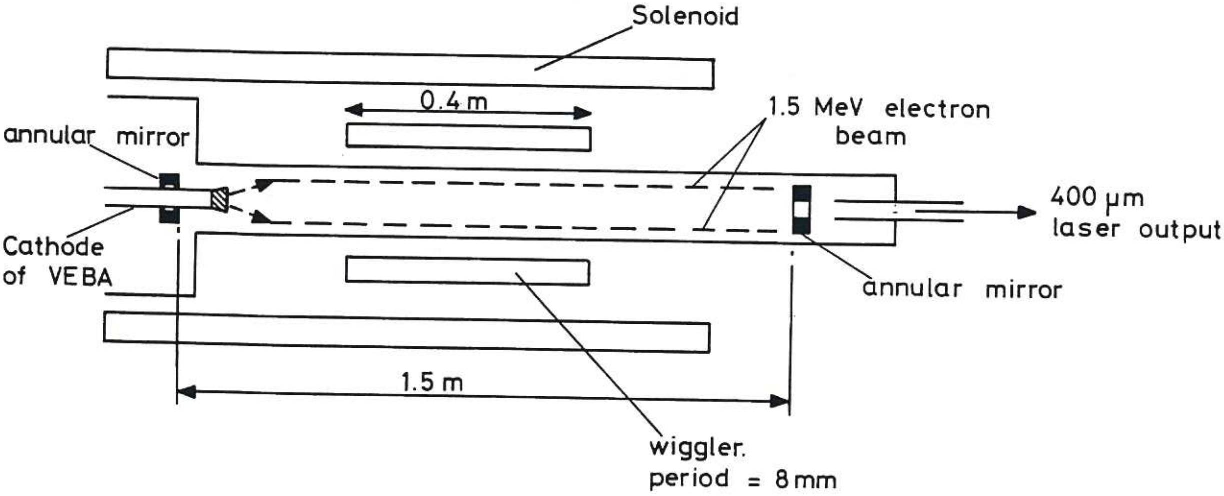

Fig.3 The NRL – Columbia free electron laser.