Title
PROSPECTS FOR THE FEL

Author
Sessler, A.M.

Publication Date
2008-09-17

LBL-27034 c.2

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

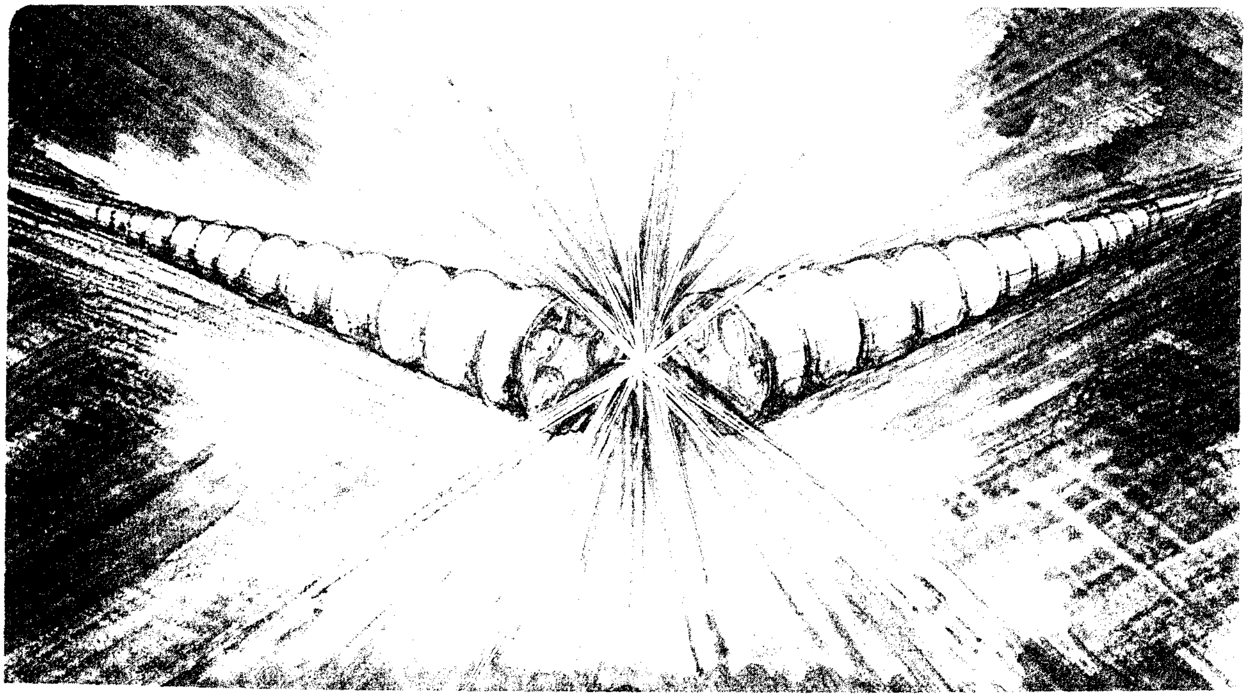
Accelerator & Fusion Research Division

Presented at the CERN Accelerator School,
Chester, U.K., April 6–13, 1989

Prospects for the FEL

A.M. Sessler

April 1989



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

PROSPECTS FOR THE FEL

Andrew M. Sessler
Accelerator and Fusion Research Division, Lawrence Berkeley Laboratory,
University of California, 1 Cyclotron Road, Berkeley, CA 94720, USA*

April , 1989

---

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Berkeley Laboratory under contract No. DE-AC03-76SF00098.

LBL-27034

PROSPECTS FOR THE FEL

Andrew M. Sessler
**Accelerator and Fusion Research Division, Lawrence Berkeley Laboratory,
1 Cyclotron Road, Berkeley, CA 94720, USA***

ABSTRACT

The future for FELs depends upon the very large number of applications which is envisioned for them. These grow out of the FEL extensive range of wavelengths, tunability, and high power capability. High power requires demonstration of optical guiding. Tunability has already been demonstrated. And the effort to extend the range of wavelengths is ever on going. The future will also bring more work on gas-loaded FELs, on electromagnetic wigglers, and on harmonic generation. We can, also, look forward to observation of various new effects, a few of which will be described. Finally, a list of various FEL projects around the world will be given.

1. INTRODUCTION

Unencumbered by equations, unfettered by the facts, callous towards any calculations, and oblivious of the observations, in short quite unrestricted by reality, it would be quite easy to address the prospects for Free Electron Lasers. Tied by the theory, dominated by details, and engrossed by the present state of experiments, one would take a very different view of the future of FELs. Clearly a proper picture of the future lies somewhere between these two extremes and, quite naturally, I will present here a balanced picture of FEL prospects. Just how successful I am in that regard, you can--and will--judge for yourself! A different worker's view of the future, this time by Colson, is given in a recent book on FELs which covers in much more detail the material of this article; I recommend it to the reader [1].

Turning first to various applications, which in the last analysis has to be the motivating force for continued work on FELs, I propose to list them, make some comments, but certainly not expound upon the science of each application, for such effort would quickly take me far afield.

I then propose to take some of the features of FELs which are most exciting, such as high power operation, or short wavelength generation, and go into the problems and the prospects of achieving these features in some detail. In fact, this will take up most of the paper.

In the last Section, I list the FEL projects, of which I am aware, around the world. Such a list, if referenced and documented with beam properties, would be most exhaustive (of me especially), and will not be presented here. I am hopeful that a list alone will be of some value;

---

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Berkeley Laboratory under contract No. DE-AC03-76SF00098.

those desiring more information should be able to obtain it using the list to point them in the right direction. In any case, the list shows the range of activity and, most importantly, where we can expect to see realization of some of the "prospects" for FELs.

2. APPLICATIONS

Applications are based upon the extensive range of wavelengths, tunability, and high power capability expected for FELs. This can be seen in Fig 1 which shows sources of radiation and the expected range of operation of FELs. The expected range is, quite naturally, dictated to some degree, by the "competition", i.e., the range where other sources are not available.

In Fig 2 we show the range of wavelengths in which FELs have already operated. One can see that the enthusiasm for a wide operating range is not without basis. In Fig. 3 is an expanded view of the Soft-X-Ray range. We show various sources of radiation and the expected intensity of an FEL. The graph is based upon a particular design so in that sense it is "real". Although the FEL is not designed to be a "high power" device, it produces very intense radiation compared to all other sources. The intensity of FELs, compared to other sources, is even more dramatic in the infra-red. In the microwave range, FELs have already produced radiation of an intensity exceeding all other sources.

Various applications of FELs are given in Table 1. A little more detail on the applications in basic science and in medicine is given in Tables 2 and 3. One can give more details about some of the other applications as well, but perhaps this is unnecessary for our purposes. It should suffice to note that there are a wealth of potential applications.

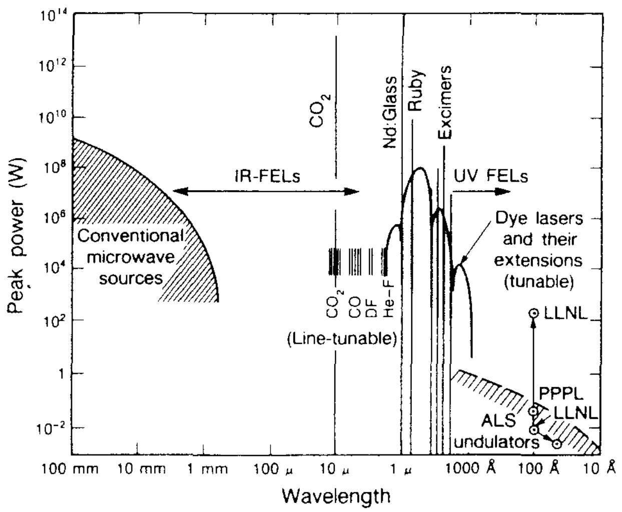


Fig. 1. FELs may provide tunable, coherent radiation in the IR and UV spectral regions (Figure courtesy of K-J. Kim)

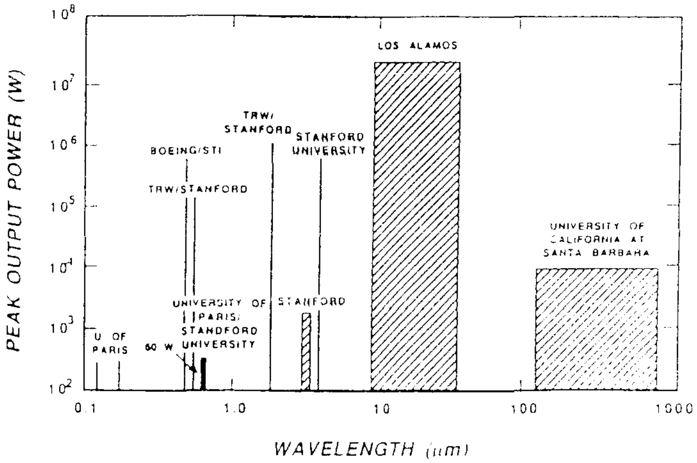


Fig. 2. FEL oscillators span a broad wavelength range.
(Figure courtesy of K-J. Kim)

As can be seen, the many applications can all be characterized as growing out of the extensive range, tunability and high power of FELs. In subsequent sections we shall explore the problems which need to be overcome before the various applications can be achieved. We shall also explore some of the innovative techniques which are proposed to extend the operating range of FELs and, in particular, methods for making FELs less expensive and/or more convenient.

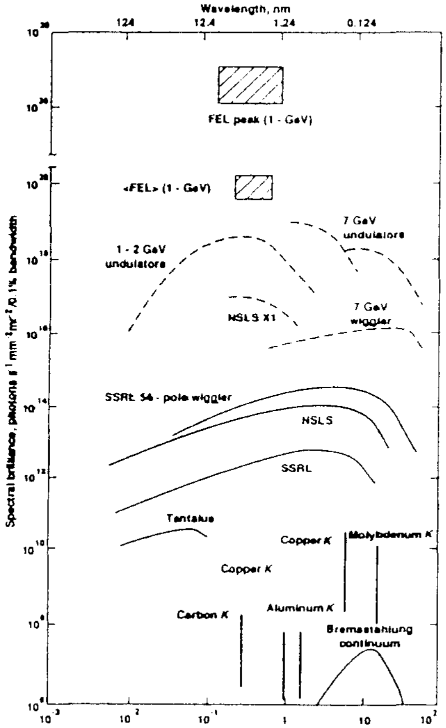


Fig. 3. Comparison of radiation sources.
(Figure courtesy of K-J. Kim)

Table 1 FEL Applications

1. Condensed Matter Studies
    - Surface science (IR)
    - Semiconductors (IR)
    - Superconductors (IR)
    - Magnetic properties (IR)
2. Non Linear Plasma Studies
    - Heating (μ-wave)
    - Current drive in tokamaks (μ-wave)
3. Non-Linear QED Studies
    - (1 μm or 10 μm)
4. Non-Linear Optics and Microwaves
5. Inertial Fusion (~ 1/2 μm)
6. Chemistry
    - Molecular excitations (IR)
    - Dynamic reactions (1-10 μm) [Pump-Probe]
    - Crossed photon-molecular beams (1000-2000 Å)
7. Biology
    - Microscopy
    - DNA studies
    - Cell response
8. Medicine
    - Surgery (1-10 μm)
    - Photo-reactions (IR)
    - Angiography
9. Accelerators
    - IFEL
    - TBA (1-10 mm)
10. Photo-reactions
    - Fixing polymers
    - Making drugs
11. Isotope separation (ENEA)
12. Military uses (LLNL, LANL, Boeing/ST)

3. HIGH-POWER AND HIGH-EFFICIENCY FELs

Quite a number of the envisioned applications for FELs require high power, high efficiency operation. Of course, even a "regular FEL" has rather high power and would, because of this feature alone, be very valuable in basic science and medicine. However, I want in this section to differentiate between "normal FELs" and really high power FELs and focus upon the latter.

Table 2. Applications in Basic Science

1. In Infra-Red:

   10 μm to 1 mm: of interest to solid state physicists
   - rotational and vibrational relaxation mechanism
     - phonons, plasmons, quasi-particles
     - pump-probe
     - surface catysis

   2.5 μm to 50 μm: "fingerprint region"
   - multiphoton absorption enhanced
   - thin film deposition
   - photo-chemistry

2. In Ultra-Violet:

   of interest to chemist
   ≤ 250 mm electronic excitations
   Raman spectroscopy
   Crossed beams
   Large area deposition of dielectric
   and metallic films

Really high power FELs are needed for the applications listed in Table 1 as (#2) plasma heating and current drive, (#3) non-linear QED studies, (#4) non-linear optics studies, (#5) inertial fusion, (#9) acceleration of particles, (#10) military uses, and (#11) isotope separation. One can see that there are many applications requiring high power operation.

Not all of the applications are equally difficult to achieve. The acceleration of particles requires radiation in the wavelength range of 1 cm, where high power, high efficiency has

Table 3. Applications in Medicine

0.7 μm - 3.0 μm
"therapeutic window"

1. Surgery
   Tissue ablation ~ 3 μm (water absorption so clean cut)
   High $\hat{p}$ Low $< p >$
   (10-50W)
2. Phototherapy
   Selective absorption in pigmented structures,
   cells, organelles

   Want variable pulse length to limit thermal damage

   Release singlet Oxygen ~ 0.7 μm

---

already been demonstrated. Thus, the application requires demonstration of cost saving and ease of operation. The application to microwave heating of plasmas and current drive in tokamacs requires radiation with wavelength in the range of 1 mm. Demonstration is now underway, in a rather large program at Livermore, thus the necessary FEL performance, if not yet demonstrated, is close to being in hand.

The other listed applications require radiation in the range of 1 μm. In order to achieve this performance requires control of sidebands and realization of optical guiding. The physics of this has been described earlier in this School, so I need not go into it here. A large effort, both on the theory and on experimental realization, is underway, as was described earlier in this School, but the required work is large and it will be quite some time, I believe, before high power operation is achieved in the optical range.

4. SHORT WAVELENGTH FELs

The efforts to extend the operating range of FELs to ever shorter wavelengths have been extensive. The work is described in the Proceedings of two whole workshops devoted to the topic [2,3]. One method is to employ storage rings, and I assume that this has been covered in the School. The original work, by the Orsay Group, was in the visible, but I hear that recent Novosibirsk work has been able to extend the range down to 2400 Å.

The use of linacs has been championed for many years by Newnam and by Pellegrini [4]. The use of a linac depends upon having a source of electrons which is very bright. Recently very great progress has been made with a photo-cathode [5]. Prior to this work, the best normalized emittance of an intense beam, i.e., a beam suitable for an FEL, was the beam coming out of the SLAC damping ring and then sent down the 2 mile accelerator, where the root mean square normalized, emittance is $3*10^{-5}$ m-rad. (Within the damping ring the emittance is smaller by a factor of two.) The LANL gun has an emittance of $0.5\text{-}1*10^{-5}$ m-rad. The Brookhaven Group, using this same photo-cathode method, but with various modifications hope to achieve an emittance of $7*10^{-6}$ m-rad. Other groups have been doing paper studies and hope, soon, to be doing real hardware development (UCLA, LBL, LLNL, CERN). This field is rapidly developing, and most likely in the future, the achieved emittances will be even smaller. (The LBL design is for a normalized emittance of $2*10^{-5}$.)

The design of a short wavelength FEL can be done, at least initially, using a 1D analysis. After, of course, one should make 2D and 3D simulations and worry about all sorts of other things such as diffraction, mirror damage, wiggler imperfections, quantum mechanical effects, etc. Some of the effects of three dimensions can be incorporated into a 1D model. The design, then, in this simplistic approach, can be based upon the following equations:

1) The usual free electron laser resonance condition:

$$\lambda = (\lambda_w/2\gamma^2)\,(1+a_w^2), \tag{1}$$

where λ_w is the wavelength of the wiggler, λ is the wavelength of the radiation, and a_w is the dimensionless vector potential of the wiggler with peak magnetic field strength, B,

$$a_w = \frac{eB\lambda_w}{2\sqrt{2}\,\pi m_e c^2} . \tag{2}$$

2) The wiggler provides natural focusing in the plane transverse to the wiggle plane. By appropriately shaping the pole face this natural focusing can be extended to the wiggle plane. Then the betatron wavelength, λ_β, will be given by

$$\lambda_\beta = \frac{\sqrt{2}\,\gamma\lambda_w}{a_w} . \tag{3}$$

3) It is useful to introduce the relativistic plasma frequency, ω_p, where

$$\omega_p^2 = \frac{4\pi\, n_e r_o c^2}{\gamma^3} , \tag{4}$$

where r_o is the classical radius of the electron. The beam density, n_e, is given in terms of the beam current, I, and the beam radius, r_b, by the relation

$$I = \pi\, c\, e\, n_e\, r_b^2 . \tag{5}$$

4) The radius of the electron beam is related to the normalized emittance, ε_n, of the beam by

$$\varepsilon_n = \frac{2\pi\gamma\, r_b^2}{\lambda_\beta} . \tag{6}$$

5) According to the one dimensional theory in the cold beam limit, the performance of the FEL is given in terms of the Pierce parameter, ρ, which is defined by

$$\rho = \left(\frac{a_w\, \omega_p\, \lambda_w}{8\,\pi\, c}\right)^{2/3} . \tag{7}$$

The power in the FEL grows exponentially with a gain length of

$$L_G = \frac{\lambda_w}{4\,\pi\,\rho} . \tag{8}$$

The amplifier will saturate in a length $L_u \sim \lambda_w/\rho$ at which point the power in the radiation field will be $P_{FEL} = \rho\, P_{beam}$.

6) To observe the conditions for proper FEL operation one must augment the one dimensional theory with conditions that account for two dimensional effects. The first condition is

$$\varepsilon_n = \frac{\lambda\gamma}{2\pi} f_1 , \tag{9}$$

where $f_1 \leq 1$.

7) A condition for coherence over a gain length is

$$\frac{1}{2}\frac{\varepsilon_n^2}{r_b^2(1+a_w^2)}=\frac{\rho}{4}f_2\,, \tag{10}$$

where $f_2 \leq 1$.

8) A third design condition comes from requiring that diffraction does not remove radiation from the vicinity of the electron beam in a distance shorter than a gain length. The Rayleigh length, Z_R, should be comparable to the gain length; that is,

$$L_G = Z_R\, f_3\,, \tag{11}$$

where

$$Z_R = \frac{\pi\, r_b^2}{\lambda} \tag{12}$$

and $f_3 \leq 1$.

The resonance condition and constraints (15), (16), and (17) are not all independent. One can easily show that

$$f_2 = f_1^2 f_3\,. \tag{13}$$

Studies with two dimensional particle simulation codes indicate that the f_i can exceed unity by factors of 2 or 3 without appreciable degradation of the FEL performance.

Based upon these (simplistic) equations a large number of designs for X-Ray FELs have been produced. The interested reader will want to consult Refs. 2 and 3. A typical example of parameters and performance can be found displayed in Table 4.

5. HARMONIC GENERATION

The use of an FEL to generate harmonics has been pioneered by the Orsay Group[6]. Efforts have also been made, and are being made, by a Bell Labs/ Brookhaven Group.

The principle is rather simple: fundamental radiation comes from an external laser, causes bunching of the electron beam, which acts like a non-linear medium and emits radiation at harmonics. The optical klystron, which is the name by which this is called, is depicted in Figure 4. Note that the system does not use an optical cavity and it does not use mirrors, and hence it can be expected to work in the extreme ultra-violet.

One should differentiate between an FEL oscillating, or amplifying spontaneous emission, at a harmonic of the resonant frequency, and harmonic generation by the mechanism described

Table 4. An FEL for Generating X-rays at 50 Å

$I =$ 1kA

$E =$ 2.1 GeV

$\varepsilon_n =$ 6×10^{-6} π m-rad

$\lambda =$ 5nm

$a_w =$ 2.1

No ions

$r_b =$ 144 µm

$\lambda_\beta =$ 91.2 m

$\lambda_w =$ 3.2 cm

$B =$ 1.0T

$n =$ 3.2×10^{14} cm^{-3}

$\omega_p =$ 3.7×10^6 sec^{-1}

$\rho =$ 1.1×10^{-3}

$L_{Ray} =$ 13.1 m

$L_G =$ 2.31 m

$P_{sat} =$ 2.3 GW

$f_1 =$ 1.80

$f_2 =$ 0.57

$f_3 =$ 0.18

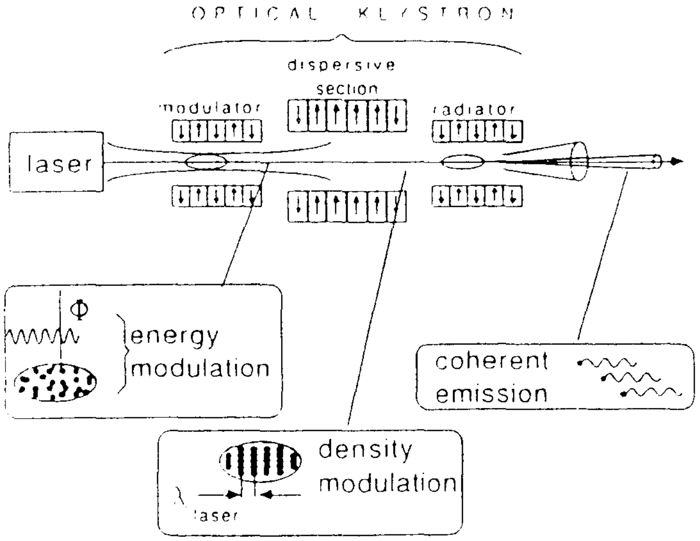


Fig. 4. Coherent harmonic generation process, showing of an electron beam passing through the three parts of an optical klystron.

above. Clearly they are closely related, but different. And clearly, the laser bunching mechanism requires a less intense electron beam.

The Orsay work resulted, in 1984, using the storage ring ACO, in third harmonic generation (3547 Å) of a Nd-YAG laser. In 1987, and using the same machine, they were able to obtain the 3rd and 5th harmonics of a doubled Nd-YAG laser. Their results are exhibited in Table 5.

The efficient generation of harmonics depends upon very small errors in the wiggler and upon a very small energy spread in the electron beam. Using the new storage ring, Super-ACO, the Orsay Group expects to be able to reach 300-2000 Å. Subsequently, they hope to set up a real user facility working on a tunable dye laser in the 2000-4000 Å range with a peak power of 100 MW.

6. GAS -LOADED FELs

Work on gas-loaded FELs has been done by Pantell's Group [7]. The synchronism condition, if an FEL is operated with gas having an index of refraction, n, inside the wiggler is:

$$(n-1) + \frac{\lambda}{\lambda_w} = \frac{1 + a_w^2}{2\gamma^2} \; . \tag{14}$$

Equation (14) shows that a given wavelength can be produced with a lower beam energy when a gas is used. The effect is significant, even when the index of refraction is close to unity, because all of the three terms in Eq. (1) are small. Tuning of the FEL can be simply accomplished by changing the index of refraction, i.e., by changing the gas pressure.

Using the parameters given in Table 6 the Stanford Group, with gas pressure ranging up to 200 Torr of H_2 were able to operate an FEL over the range from 4.2 µm to 3.4 µm.

The workers have plans for further exploitation of the concept, and point out that they should be able to go down to 0.3 µm with the Mark-III Accelerator with parameters of Table 6.

Table 5. Experimental Results on ACO (1987)

Observed harmonic	3	5
Corresponding wavelength [Å]	1773	1064
Integrated ratio R_n^{int}	350	3-4
monochromator bandwidth [Å]	2	2
monochromator angular aperture [mrad^2]	1.4	3
Spectral ratio $R_n(\lambda,\Omega)$	6000	1000
Number of coherent photons/pulse	1.5×10^7	10^5
in spectral width [Å]	0.1	0.07
in angular aperture [mrad]	0.2	0.1

Table 6. FEL Operating Parameters Used in the Gas-loaded FEL Experiment

Wiggler length	108 cm
Wiggler period, λ_w	2.3 cm
Optical wavelength (in vacuum)	4.18 µm
Wiggler parameter, a_w	0.98
Electron energy, γ	73.6
Normalized beam emittance	7π mm mrad
Electron beam diameter	1 mm
Peak current	25-100 A
Micropulse duration	0.5-2 psec
Micropulse repetition period	350 psec
Macropulse duration	2.7 µsec
Macropulse repetition rate	15 Hz

7. ELECTROMAGNETIC WIGGLERS

The use of an electromagnetic wiggler was first proposed by Elias and has, subsequently, received a good deal of attention [8]. The motivation, of course, is to obtain short wavelength FELs without needing high energy electron beams, i.e., the electromagnetic wiggler (EMW) can have a shorter wavelength than a conventional wiggler. This is shown in Fig 5.

There are a number of different ways which have been considered for making an EMW. They include backward wave oscillators, high powered Nd or CO_2 lasers, or FELs themselves. The last is the two-staged FEL pushed by the Santa Barbara Group.

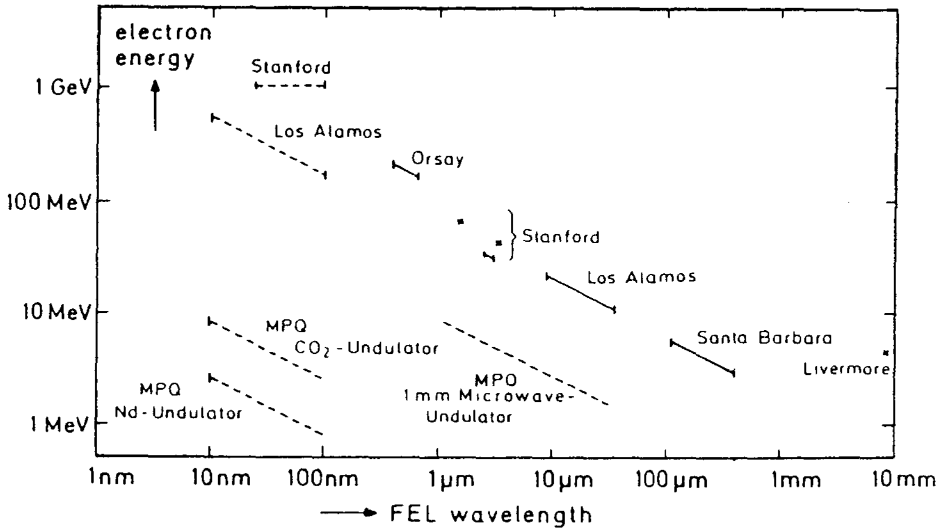


Fig. 5. Relationship between electron energy and wavelength for different FELs. All FELs with magnetic undulators lie approximately on a straight line. The proposed FELs with electromagnetic wave undulators lie far below this line and require only a small accelerator. Solid lines: operating FELs;dashed lines: proposed FELs.

Work to date, has has shown that an EMW, through which electrons have been sent, creates spontaneous radiation. Further work has shown that there is some (small) amount of stimulated radiation, i.e., some FEL action [8].

The undulator parameter for an EMW tends to be smaller than that for a conventional wiggler, and hence the gain per period is smaller. Consequently the electrons must traverse many periods for the FEL to be interesting. As a result, the requirement on electron beam energy spread and emittance is very high.

A proper analysis of the various effects in an EMW-FEL has been carried out [8]. Perhaps it suffices, here, to remark that the dotted lines in Fig 5 are based upon realistic designs. First work will probably be done using an intense microwave undulator field of the order of 1 mm wavelength, to show that one can build an infra-red FEL. The real motivation, however, is to get on to the ultra-violet.

8. NEW EFFECTS

There are an untoward number of new effects. Thus, it is very arbitrary which I mention here. For various reasons I shall discuss superradiance [9], plasma self-focusing [10], chirping [11], and quantum mechanical phenomena [12].

8.1 Superradiance

Supperradiance is a phenomena which is predicted to occur under special circumstances in FELs [9]. The phenomena is one of many which occur in a real FEL where the electron bunches are of finite length. In other words, a proper FEL theory needs to be invoked when studying finite length bunches; it does not suffice to employ the Kroll, Morton, Rosenbluth (KMR) equations.

It does suffice to employ the formalism which has been developed for studying sidebands; and these PDEs describe a wealth of physical phenomena, only a tiny fraction of which has so far been explored, and of which supperradiance is one (and the observed pulsed behavior of an oscillator is presumably another).

It is well-known that for every period of the wiggler that the electrons move through, the light advances one optical wave length; this is the very principle of an FEL. Let us introduce a number of different lengths, whose ratios will characterize various regimes of operation. The first length is the electron bunch length L_b. The second is the length of the wiggler L_w. A third length is the slippage distance L_s, i.e., the distance light moves ahead of an average electron while the electron traverses the wiggler. A fourth distance is the distance an electron must travel, L_{syn}, while experiencing one synchrotron oscillation. A fifth distance is the distance corresponding to one gain length of the FEL, L_g. And a sixth distance, the cooperation distance, L_c, is the slippage in a gain length.

It is quite clear that there are a large number of regimes of operation of an FEL, and the physics is quite different as one goes from one regime to another. For a real pulse there is always a back end, and the behavior in a slippage distance, or more precisely in a cooperation distance, from the back is always different than one would deduce from the KMR equations. In particular, if $L_c << L_b$ then a large pulse, dependent upon the current I as I^2, rather than the more usual dependence of $I^{3/2}$ is predicted. This pulse is called "superradiant" as the dependence upon particle number is just the same as in superradiant conventional laser operation [9].

The phenomena of superradiance has not yet been observed. It is only one, as I have emphasized, of many very interesting phenomena resulting from the slippage phenomena. Much work remains to be done in observing and analyzing this rich behavior so as to better understand FEL physics and, possibly, because other than "usual" operation may be advantageous for various applications.

8.2 Plasma Self-Focusing

If the electron beam in an FEL is subject to more focusing than "naturally" occurs in an FEL, the the performance of the FEL can be improved [4]. One way of achieving enhanced focusing is by means of an ion channel [10]. The equations governing motion by a beam of electrons in such a channel are:

$$\begin{aligned} a &= \left(\frac{\epsilon_n}{\gamma}\right)\left(\frac{17\,\gamma}{f_c I}\right)^{1/2} , \\ \lambda_\beta &= 2\pi a \left(\frac{17\,\gamma}{f_c I}\right)^{1/2} , \end{aligned} \tag{15}$$

where f_c is the fraction of beam electrons for which there are ions, the current I is in kilo-amps, λ_β is the betatron wavelength, a is the beam radius. The betatron wavelength can easily (i.e., for a small fraction of neutralization) be made quite small. In Table 7 is shown the same FEL as is shown in Table 4, but now with ions. It can be seen that the performance is improved by a factor of two.

The enhanced performance of an FEL operated with a plasma has not yet been attempted. It would seem to be worth exploring.

8.3 Chirping

It has been pointed out that a highly chirped pulse (i.e., frequency varying along the photon pulse) would have a number of interesting applications [11]. Firstly, such pulses propagating in a dispersive media can be made of short duration, i.e., undergo pulse compression. Secondly, intense chirped FEL pulses can be propagated through the atmosphere, i.e., tend to suppress stimulated Raman scattering. Thirdly, chirped intense FEL pulse can be advantageous for confined plasma heating, i.e., the absorption layer will shift through the plasma.

Table 7. A 50 Å FEL with Ion Focusing.

With Ions

$\lambda_b =$	46 μm
$\lambda_\beta =$	9.1 m
$\lambda_w =$	3.2 cm
$B =$	1.0 T
$n =$	3.2×10^{15} cm^{-3}
$\omega_p =$	1.2×10^{7} sec^{-1}
$\zeta =$	2.4×10^{-3}
$L_{Ray} =$	1.3
$L_G =$	1.1 m
$P_{sat} =$	5.04 GW
$f_1 =$	1.80
$f_2 =$	2.68
$f_3 =$	0.82

Chirped pulses can be produced by varying the energy of the electrons entering the FEL as a function of time. It would seem, in principle, possible to arrange the accelerator, be it an induction accelerator or an rf linac, to provide such a beam. The analysis of the performance of the FEL when the input electron energy varies, especially if it is tapered, is rather involved. Questions such as efficiency must be addressed, which probably requires numerical simulation studies.

There are many technical problems (as contrasted with questions of principle) in producing and transporting a beam of varying energy. Nevertheless, it would seem to be worth exploring the idea of producing high intensity chirped FEL pulse.

8.4 Quantum Mechanical Phenomena

Quantum Mechanical behavior of an FEL can be expected as one moves into the ultraviolet regime [12]. One should differentiate classical vs. quantum mechanical behavior for the electrons and for the photons. Thus there are four different regimes. We have been thinking classically all through the School (although the original theory of an FEL was quantum mechanical). In contrast, to remind us, ordinary lasers treat the electrons quantum mechanically, but the radiation classically.

We can ask when do we have to treat the electrons quantum mechanically? Clearly, when the spread in an electron's wave function in traversing a wiggler is of the order of a wavelength of light. One finds

$$\lambda \geq \pi \sqrt{\frac{\bar{\lambda}_c L_w}{\gamma^3}} \tag{16}$$

where $\lambda\!\!\!^{-}_c$ is the Compton wavelength, and L_W is the wiggler length.
Electromagnetic wigglers (because γ is quite small) can get into this range and it will be most interesting to observe quantum mechanical electron behavior in them.

In order to estimate what is required to be in the range where the radiation is quantum mechanical, all that is required is that we determine when the number of photons in a characteristic volume be small. The characteristic volume is given by a mode transverse area times the slippage length in traversing the wiggler:

$$V = w^2 \left(\frac{L_w}{\lambda_w} \lambda\right) \quad . \tag{17}$$

Since the Rayleigh length can be employed to relate the mode area to the wiggler length,

$$L_w = \frac{\pi w^2}{\lambda} \tag{18}$$

we obtain:

$$V = \frac{L^2 \lambda^2}{\lambda_w} \, . \tag{19}$$

Notice the λ^2 dependence which, once again, shows the importance of short wavelengths for observing quantum mechanical effects.

The number of photons emitted can be estimated by Compton back scattering the wiggler energy density times the volume swept out by one electron, divided by the energy of one wiggler photon. One finds:

$$\begin{aligned} \frac{\#\text{photons}}{\text{pass}} &= \left(\frac{B^2}{8\pi}\right) \left(\frac{1}{\hbar k_w c}\right) (\pi \, r_e^2 \, L) \\ &= \frac{\pi}{4} N \, \alpha \, a_w^2 \; , \end{aligned} \tag{20}$$

where α is the fine structure constant.

Thus one electron limits about 1-10 photons per pass, but not all of these photons go into the coherent mode. In fact a large numerical reduction of the order of L_W/λ_W is appropriate. For usual FEL operation the number of photons per characteristic volume is large and Poisson statistics are appropriate. However, it is possible to imagine operation where quantum mechanical behavior of the photons (Bose statistics) is neccessary. No observations have yet been made in this regime, but it would be most interesting.

9. RESEARCH FACILITIES AROUND THE WORLD

Various authors have generated lists of world-wide FEL projects. Perhaps the most recent is by Colson.[1] An even more up to date list, but a list with very much less detail, is given in Table 8.

It might be good to take a different "cut" of the FEL development. That is, to look at the work in a different manner. There is a lot of work on wiggler development. This includes work on reducing errors, developing shorter wavelengths, and on the use of superconductors. There is work on electromagnetic wigglers and on related devices (such as CARMs and on Wiggler-Free FELs). There is work on compact FELs and on harmonic generation from FELs. There are optical guiding studies and sideband studies. There is work on the development of high power FELs.

Table 8. WORLD-WIDE FEL PROJECTS

China	Shanghai (pulsed)
	Beijing (rf)
	Chengdu (rf)
Japan	JAERI 4+2 projects (rf)
	Osaka (induction linac)
Germany	Darmstadt (superconducting)
	Dortmund DELTA (storage ring)
Israel	Technion
	Weizmann (DC)
France	ACO (sr)
	Super ACO (sr)
	CLIO (rf)
	1 project (induction linac)
Holland	FOM Institute, Nieuwegein FELIX (rf)
Italy	ENEA (microtron)
	INFN (sc)
	Milan ARES (sc), ELFA(sc)
	Padua (DC)
England	Oxford (DC)
	Liverpool
USSR	Novosibirsk
USA	UCSB 2 projects (DC)
	Vanderbilt (rf)
	LLNL Palladin (induction)
	LLNL MTX (induction)
	BNL (TOK) (sr)
	BNL (rf)
	Stanford Mark III (rf)
	Stanford (sc)
	Stanford (sr)
	LASL (rf)
	Boeing/ Spectra Physics (rf)
	Hughes
	Florida (DC)
	NBS (microtron)
	MIT
	Columbia (induction)
	Duke (rf)

Projects Terminated: UK and Bell Labs

There is study of slippage and superradiance effects. There is work on pulse compression and, always, efforts to extend the operating range of FELs. Finally, physicists are always on the lookout for new effects such as photon statistics, squeezed states, and temporal correlations.

10. CONCLUSION

We have seen that FELs have been operated in many places in the world and from 1/2 μm to 1 cm. Further, the operation is in agreement with the theory, i.e., FEL performance can be predicted.

Applications of FELs are only just starting, although the first operation of an FEL was about a decade ago. Nevertheless, it is the potential applications which fuel the efforts on FELs.

Looking to the future, we note that there are a very large number of FELs under contemplation and/or construction. From these we can expect to learn a great deal. In particular, we should learn about optical guiding, sideband control, superradiance, harmonic generation, electromagnetic wigglers, and gas-loaded devices. We can be confident that we shall learn it is quite something else to be confident that all of our hopes will be realized.

The diversity and depth of behavior of FELs has provided, and can be expected to provide, continued interest to physicists. The attention of physicists to FELs is essential to their continued development; in no sense are FELs at the "engineering stage".

Continuing to look ahead, I think we can expect to see ever new forms of FELs, as physicists attempt to make them cheaper, simpler, and more reliable. Work can be expected on gas-loaded and plasma-loaded devices, as well as on closely related devices (such as CARMs).

Finally, with out any risk, I think, I can predict that the next ten years (that is as far ahead as even I attempt to see) will be interesting times for FEL physicists, and produce considerable advance in FELs. Now, we'd better get down to work.

REFERENCES

[1] W. B. Colson, "Fundamental FEL Theory and New Principles for Advanced Devices", in *Free Electron Lasers*, Critical Review of Optical Science and Technology, B.E. Newnam, Editor, SPIE Vol. 738, (1988) 2.

[2] J.M.J. Madey and C. Pellegrini, Editors, *Free Electron Generation of Extreme Ultraviolet Coherent Radiation*, AIP Conference Proceedings No. 118, American Institute of Physics, New York (1984).

[3] R. Bonifacio, F. Casagrande, and C. Pellegrini, Editors, *Coherent and Collective Properties in the Interaction of Relativistic Electrons and Electromagnetic Radiation*, North-Holland, Amsterdam (1985).

[4] B.E. Newnam, "Extension of FELs into the Extreme Ultraviolet", Ref.1, p. 155; C. Pellegrini, "Progress Towards a Soft X-Ray FEL", Nucl. Instr. and Methods in Phys. Res. A272, (1988) 364.

[5] J. S. Fraser, R.L. Sheffield, E.R. Gray, and P.M. Giles, "Photocathodes in Accelerator Applications", Proc. of the 1987 IEEE Particle Accelerator Conference, IEEE 87CH2387-9,1705 (1987).

[6] R. Prazeres, et al, "Coherent Harmonic Generation in the Vacuum Ultraviolet Spectral Range on the Storage Ring ACO", Nucl. Instr. and Methods in Phys. Res. A272, (1988) 68

[7] M.B. Reid, et al, Phys. Rev. Lett. 62, (1989) 249.

[8] L.R. Elias, Phys. Rev. Lett. 42, (1979) 977 ; J. Gea-Banacloche et al, "Proposal for a Compact FEL With Electromagnetic Wave Undulator", Nucl. Instr. and Methods in Phys. Res. A272, (1988) 199 ; K. Mima et al, "Experiment and Theory on CO_2 Laser Powered Wiggler, ibid p.106.

[9] R. Bonifacio and B.W.J. McNeil, Slippage and Superradiance in the High-Gain FEL, Nucl. Instr. and Methods in Phys. Res. A272, (1988) 280 ; W. Sharp et. al., "Simulation of Superradiant FELs", Proc. of the 10th Inter. FEL Conference, Lawrence Livermore National Laboratory Report UCRL-98676 (1989).

[10] W.A. Barletta and A.M. Sessler, "Radiation from Fine, Intense, Self-Focused Beams at High Energy", Nucl. Instr. and Methods in Phys. Res. (to be published), Lawrence Livermore National Laboratory Report UCRL-98767, Rev.1 (1989).

[11] G.T. Moore, "The Chirped Pulse Free Electron Laser", Nucl. Instr. and Methods in Phys. Res. A272 (1988) 302.

[12] W.B. Colson,"Theoretical Aspects of XUV FELs", Ref. 2, p.260; A Reneiri, "Free Electron Generation of Extreme Ultraviolet Coherent Radiation: Theoretical Aspects", Ref. 2, p.1.