Technical Options for High Average Power Free Electron Millimeter-Wave and Laser Devices

James C. Swingle
Lawrence Livermore National Laboratory

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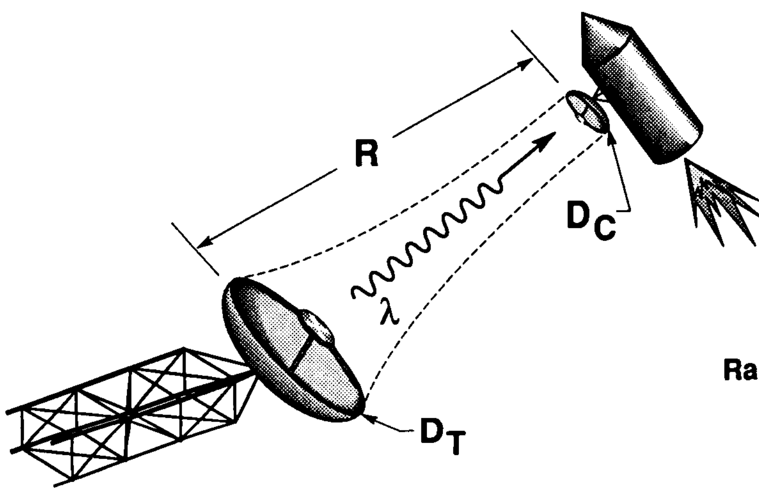
Many of the potential space power beaming applications require the generation of directed energy beams with respectable amounts of average power (MWs). A somewhat tutorial summary is provided here on recent advances in the laboratory aimed at producing direct conversion of electrical energy to electromagnetic radiation over a wide spectral regime from microwaves to the ultraviolet.

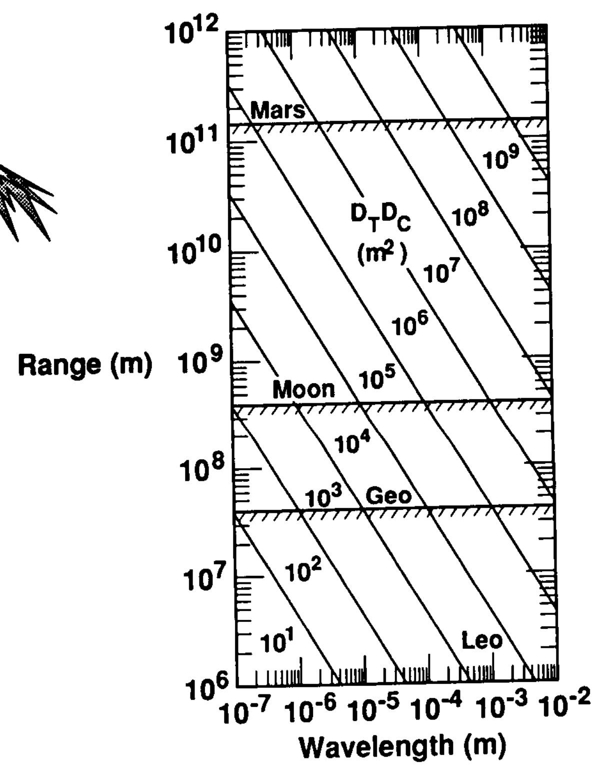
The space power beaming problem

A broad range of wavelength options is needed to thoroughly investigate power beaming scenarios over characteristic ranges for NASA's missions spanning at least 5 orders of magnitude. A simple calculation of the size of the Airy disk produced in the focal plane of a uniformly illuminated transmitter aperture motivates the need to push toward shorter wavelength as the characteristic range increases. The microwave and mm-wave beams suitable for beaming to low earth orbit (LEO) and requiring apertures with sizes of order hundreds of meters become impractical for beaming to geosynchronous orbit (GEO) or to the earth's moon. Infrared or visible beams allow aperture sizes in the tens of meters over these distances. At ranges associated with beaming to Mars from the earth (or its moon), even shorter wavelengths would appear to be worth examining.

It is important to remember that the benefits of reduced aperture size at shorter wavelength are accompanied by the need to maintain surface figure and jitter at levels permitting nearly diffraction-limited performance for the design wavelength. The sophistication and cost of the transmitter technology (at least on a per unit area basis) increases as the wavelength is reduced. Detailed trades must therefore be performed for any particular application.



$$D_T D_C = 2.44\ \lambda R$$



Energy and directed energy weapons programs have extended technical options

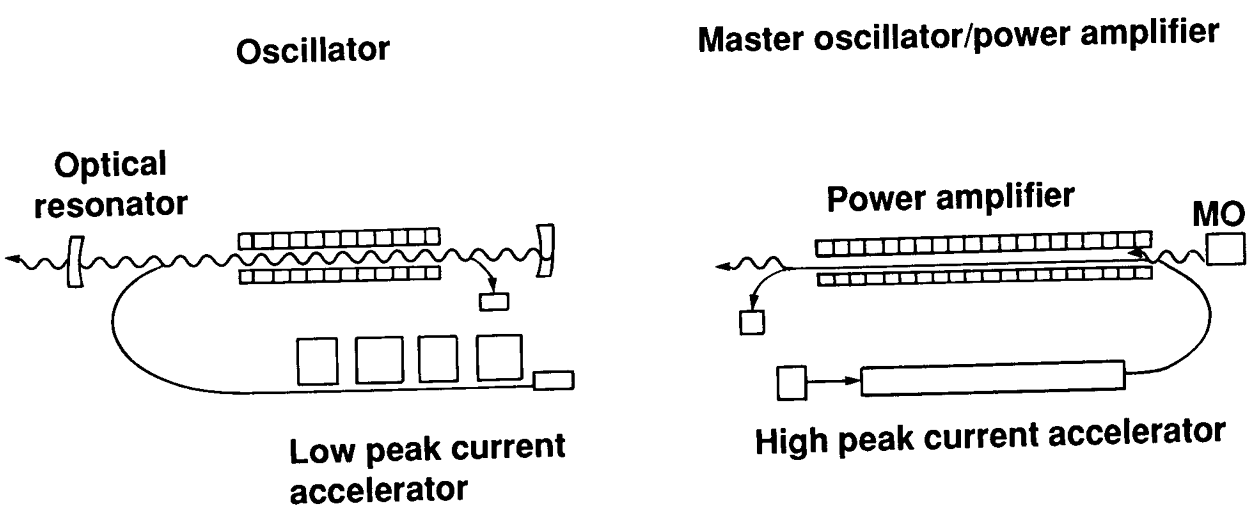
Programs aimed at inertial fusion, magnetic fusion, and directed energy weapons have advanced the technologies that may contribute to the generation of very high power beams with good mode quality. For example, the tokamak programs around the world have begun to focus on the use of high average power mm-wave sources (140 - 250 GHz) to drive electron cyclotron heating in confined plasmas. This technique is seen as a way to promote stabilization of the plasma and to enhance the fusion energy gain of these devices.

The inertial fusion and laser weapons programs have produced advances in the technologies of carbon dioxide, chemical (HF, DF, iodine), excimer (ArF, KrF, XeF, etc.), and free electron lasers. The free electron devices are newcomers in the high energy laser business, and thus will be the focus of this brief tutorial summary.

- **Multi-MW microwave and mm-wave sources**
  - **— Gyrotrons**
  - **— Free electron masers**
- **Infrared, visible, and ultraviolet lasers scalable to high average power**
  - **— Carbon dioxide (10.6 μm)**
  - **— Chemical lasers (1.3 — 4 μm)**
  - **— Excimer (.2 — .4 μm)**
  - **— Free electron lasers (.1 — 100 μm)**

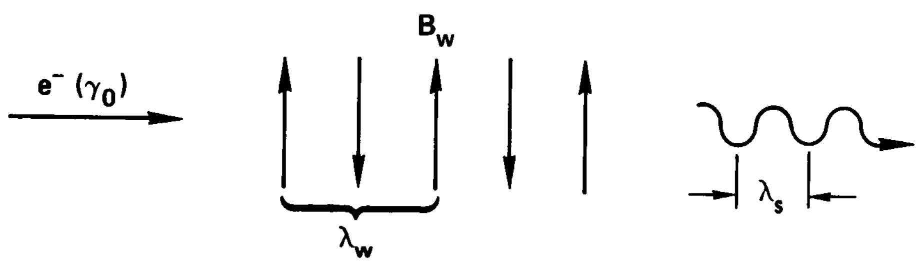
Compton FELs in the near infrared have been envisioned as oscillators and MOPAs.

The majority of the free electron laser work performed around the world has been done in regimes of electron energy and current density where collective effects do not dominate the electron interaction with the electromagnetic field: the so-called Compton regime. A high quality electron beam is injected into a wiggler which produces an alternating magnetic field along the direction of propagation. Since the electrons are relativistic, this field undulation that occurs on scale lengths of many centimeters in the laboratory reference frame becomes equivalent to optical wavlengths in the electron frame of reference, thus allowing for conditions of resonance between the wiggler field and an electromagnetic field. Depending on the gain of the electromagnetic field in a single pass through the wiggler (which depends on many variables including the peak current of the e-beam, the e-beam quality, and the detailed configuration of the wiggler), the FEL can be configured as an oscillator or a single pass amplifier. In the oscillator configuration, which is typical of devices using low peak current accelerators (10s to 100s of Amperes), a resonator cavity is established around the wiggler to allow the build-up of the electromagnetic field as many electron pulses propagate through the device. In the single pass schemes typical of high peak current accelerators (100s to 1000s of Amperes), efficient extraction of energy occurs in a single pass through the wiggler without the use of optics. A master oscillator pulse at the appropriate wavelength is usually injected into the wiggler with the electron pulse in order to facilitate initial coupling of the electrons to the electromagnetic field.



Wavelength scaling

The condition for resonance between the magnetic field of the wiggler and the electromagnetic radiation produced by the electrons is established through the Lorentz contraction of the wiggler period into the frame of reference of the electron and the Doppler shift of the radiation. If the resonance condition is not met for an FEL design at a given wavelength, it is possible (even likely) that no net energy will be extracted from the electron beam or that the electron beam will actually extract energy from the injected signal applied to the wiggler. In general, a wiggler of a given period and magnetic field will be resonant with shorter wavelengths as the energy of the electrons is increased, scaling as the inverse square of the energy.

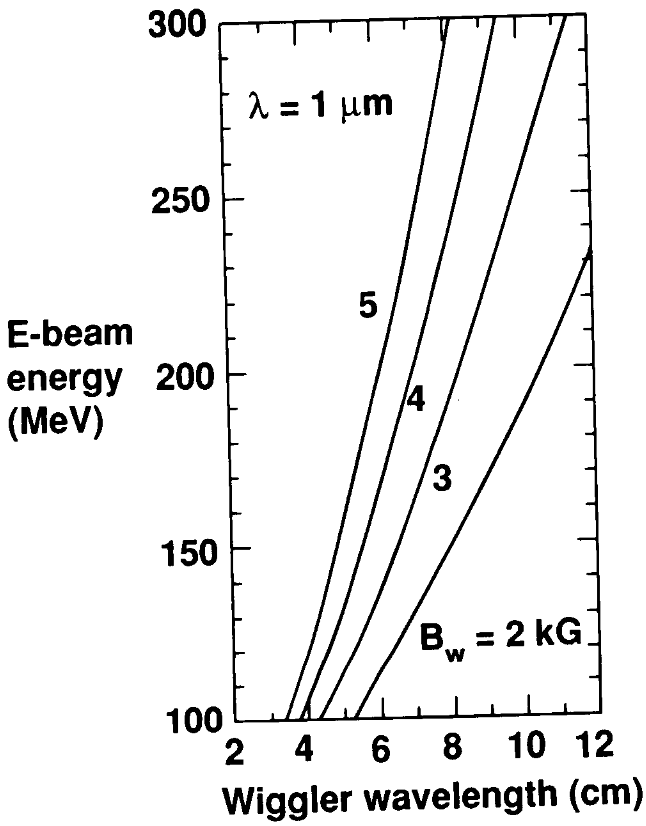


The output frequency of the FEL is the result of a Lorentz contraction (of the wiggler period) followed by a Doppler shift.

$$\lambda_s = \frac{\lambda_w}{2\gamma_{||}^2} = \frac{\lambda_w}{2\gamma_0^2}\left[1+\frac{1}{2}\left(\frac{e\,B_w\,\lambda_w}{2\pi mc}\right)^2\right]$$

FEL resonance condition in the near infrared

Design trades are illustrated in this figure for a wavelength of 1 um. Current state of the art on wiggler technology for the near infrared makes use of wiggler periods in the range 4 - 10 cm and peak fields in the range 2 - 5 kG. Permanent magnet, electromagnet, and hybrid designs have been constructed. It can be seen that e-beam energies in the range 100 - 200 MeV are prescribed by the resonance condition. Other constraints must be applied to the choice of wiggler parameters. The Halbach limit deals with constraints on delivering the requisite peak field to the wiggler axis as the wiggler takes on different values of period and gap between the pole tips.



Resonance condition

$$\lambda = \frac{\lambda_w}{2\gamma^2}(1 + a_w^2)$$

$$\gamma \simeq \frac{E\ (\mathrm{MeV})}{0.511}$$

$$a_w \simeq 0.0661\ B_w(\mathrm{kG})\ \lambda_w\ (\mathrm{cm})$$

Halbach limit*

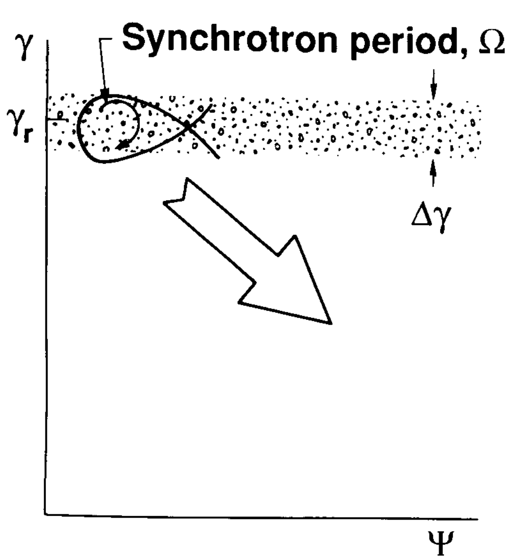
$$B_w \leq 33.4 \exp\left[-\frac{g}{\lambda_w}\left(5.47 - 1.8\frac{g}{\lambda_w}\right)\right]$$

g = gap between poles

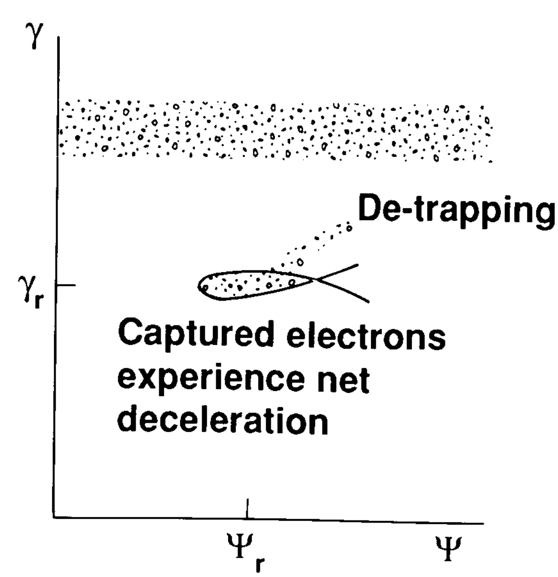
* hybrid undulator, electromagnet with steel core assisted by permanent magnets

Electron capture and deceleration

Establishing conditions for the initial resonance is only part of the problem associated with achieving high extraction efficiency from the FEL. Resonance between the electromagnetic field and wiggle motion must be considered for the ensemble of electrons making up the beam. These electrons are spread out uniformly along the axis and have some instantaneous energy distribution for a real beam. The phase space plot on the left illustrates the initial conditions, where the vertical axis is electron energy and the horizontal axis is equivalent to axial position expressed as a relative phase angle between some idealized single resonant electron and every other electron in the beam. Initial conditions at the entrance to the wiggler promote axial bunching of the electrons on scale lengths of the wavelength of the electromagnetic field injected at the entrance to the wiggler. For a MOPA configuration, this initial EM field would be that of the master oscillator. A region of the electron phase space is defined (a ponderomotive well) such that electrons confined to this region will be decelerated. Electrons that are not trapped in this well remain relatively unaffected by the FEL interaction. The schematic at right illustrates the situation after propagation through some portion of the wiggler, where the phase space viewed is now associated with one electron bunch of spatial extent equal to the wavelength of the light. The trapped particles have now been decelerated by some amount, producing gain in the light wave. In order to maintain resonance as the deceleration takes place, adjustment of wiggler parameters must occur. The magnetic field or the wiggler period can be reduced to maintain resonance as the electrons lose energy. This technique is called tapering. Several real world effects can cause electrons to spill out of the ponderomotive well (often called a "bucket") as propagation proceeds down the wiggler. Field errors in the wiggler can provide discreet kicks to the beam that destroy resonance or the electron beam may be misaligned with respect to the magnetic axis of the wiggler so that its betatron motion eventually results in partial decoupling of the electron distribution in the transverse plane from the propagating EM spatial mode.



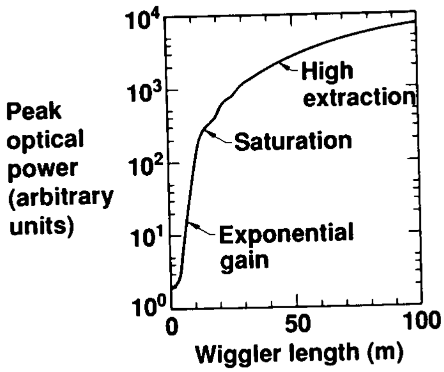
- **Ponderomotive well defines stable phase space orbits**

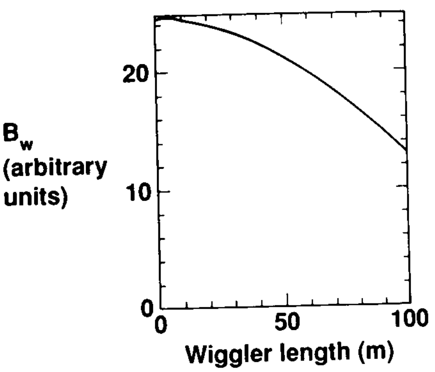


- **De-trapping mechanisms reduce gain**

Typical FEL amplifier performance and B-field tapering in the near-infrared

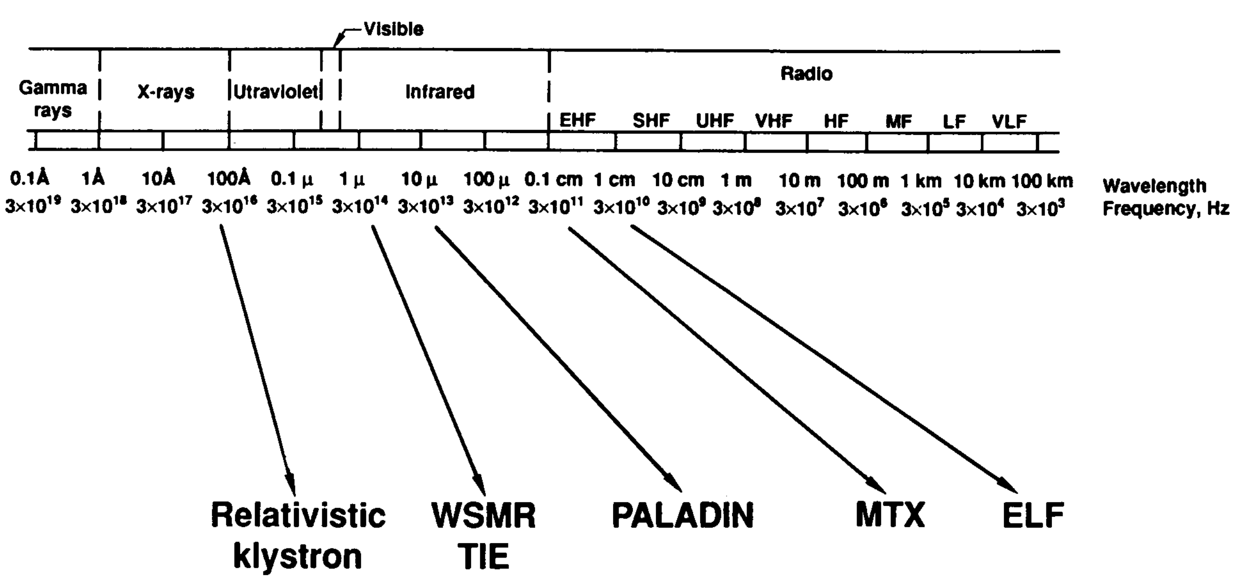
For a high gain (typically high peak current) FEL amplifier, a typical tapered wiggler B-field profile along the axial coordinate of the wiggler is shown. The corresponding laser intensity as a function of position is shown at left. The amplifier produces extremely high exponential gain in the initial stages until saturation occurs. At this point, significant tapering must begin in order to maintain resonance. Beyond saturation, significant energy extraction occurs from the electron beam.





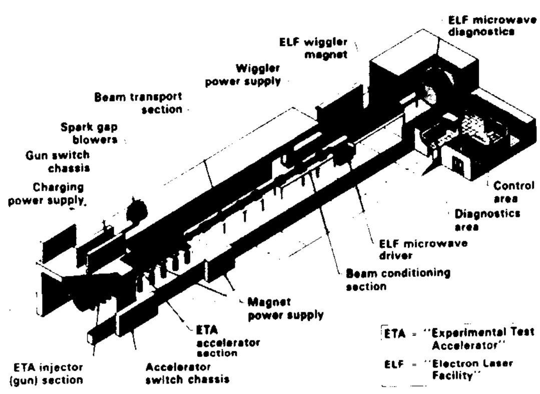
Induction FEL technology will provide sources over a broad spectrum

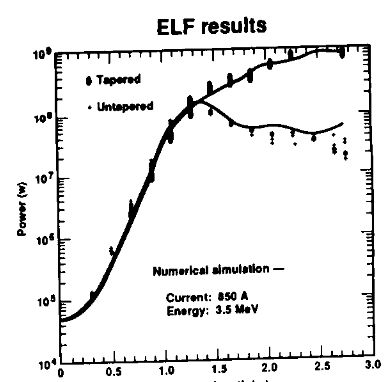
The possibility of producing FEL design concepts over a large region of the electromagnetic spectrum has prompted FEL research groups around the world to study and propose a multitude of experiments. Many of these experiments are now underway and some have achieved remarkable success. As an example of the wide range of technology options that any given program may be pursuing, the array of FEL devices under study at Livermore is illustrated. The Electron Laser Facility (ELF) was used to conduct an experiment at a wavelength of 8 mm that showed high extraction efficiency in a MOPA configuration. The Microwave Tokamak Experiment (MTX) is now under construction and will supply mm-waves and multi-megawatts of average power to the Alcator-C tokamak. The PALADIN experiment is currently operating at a wavelength of 10.6 um using a 25 meter long hybrid wiggler with extremely low field errors. High single pass gain has been observed on this experiment. Detailed computational studies have been conducted over the last two years on a 1 um FEL which is being offered to the U.S. Army Strategic Defense Command as an option for use in its Technology Integration Experiment at the White Sands Missile Range. Finally, some high gradient accelerator research being conducted in collaboration with LBL and SLAC has produced encouraging results on a relativistic klystron that could be used to drive traveling wave accelerators at average gradients of order 100 MeV/meter. Access to the high e-beam energy regime with a compact accelerator has spawned computational studies of single pass vacuum ultraviolet and soft x-ray FELs for a variety of applications (e.g. holography and x-ray lithography).



Experiments at the Electron Laser Facility (ELF) produced 1 GW of peak power at 35 GHz

High single pass extraction efficiency in an FEL device was first observed at Livermore in 1984. The ELF device made use of the existing Experimental Test Accelerator, a 3.5 MeV induction accelerator. The multi-kA beam of the accelerator was passed through an emittance filter to obtain a beam of sufficient quality for an FEL experiment. Typical peak currents delivered to the wiggler were in the range 800 - 1000 Amperes in a pulse lasting 15 - 20 ns. The wiggler was a pulsed electromagnet and was assembled from 1 meter long modules. Experiments involved wiggler lengths of 3 - 4 meters. A conventional magnetron was used as the master oscillator source, producing 40 - 50 kW of peak power. The experiment typically ran at repetition rates of 0.5 - 1 Hz. A schematic diagram is shown of the experimental layout. Experimental results are shown at right. It can be seen that exponential gain of ~ 30 dB/meter was observed in the front end of the wiggler. Upon gain saturation, the performance of an untapered wiggler was observed to degrade rapidly, in good agreement with the predictions of a particle simulation code that treated the electron motion in 3 dimensions and the electromagnetic field in two dimensions (upgraded since then to 3-D). The tapered wiggler continued to extract energy from the e-beam, producing 1 GW of peak power at a single pass extraction efficiency of 35 - 40 %.





IMP is designed to deliver high peak and high average power radiation

Since 1986, the accelerator used on ELF has been upgraded to produce a much higher quality e-beam at high repetition rate (5 kHz). The new accelerator is undergoing initial activation and testing this year. By 1991, the goal is to couple the output of this accelerator to a new wiggler based on the parameters shown in this chart. The device will operate at 250 GHz and will produce peak power of 12 GW and average power of 2 MW for delivery to the Alcator C tokamak located adjacent to the facility. The extraction efficiency in the mm-wave regime is calculated to be quite high. Typical of these MOPA devices, the mm-wave beam quality is expected to be very good, featuring virtually single transverse mode operation. This device, and others of its generation, will begin the demonstration of efficient, high average power mm-wave operation in the laboratory during the 1990s, with mode quality suitable for convenient phased array operation for power beaming applications.

IMP design parameters:

E_{beam}	10 MeV
I_{beam}	3 kA
f	250 GHz
P (peak)	12 GW
% extraction	40%
P (ave)	2 MW
PRF	5 kHz

IMP wiggler

L_w	5.5 m
λ_w	0.1 m
B_w (max)	4.5 kG

Experimental Test Accelerator II (ELF II/IMP microwave facility)

A schematic of the IMP facility is shown in this chart. The induction accelerator is shown in the shielded tunnel with the pulse power units located directly above. Magnetic modulators are used for pulse compression on this system, thus avoiding the use of spark gaps for operation at 5 kHz. These devices have been operated into dummy loads at this repetition frequency. The FEL beamline is shown extending to the right. In initial tests this year, the ELF wiggler will be driven by the beam to produce 140 GHz pulses in short bursts for initial tokamak experiments. The facility will reach full high average power capability at 250 GHz in 1991.

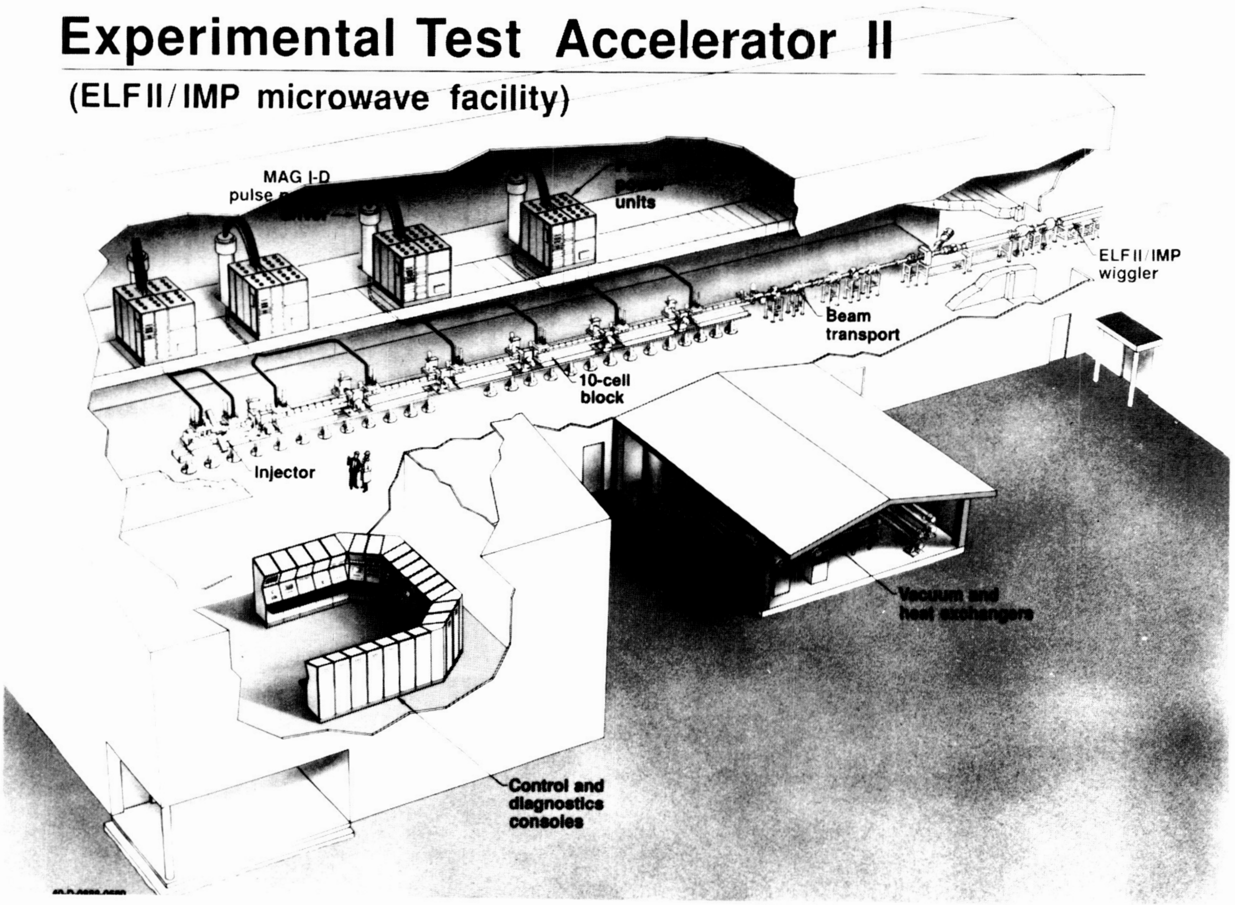


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Photo of ETA II induction accelerator

The existing configuration of the ETA II accelerator that will be used to drive IMP is shown. The electron injector is seen in the foreground. It currently produces a 1.5 MeV, 1.6 kA beam with a pulse length of 70 ns FWHM at a brightness of > 3×10^9 A/(m-rad)^2, which greatly exceeds the brightness requirement for the IMP experiment. The output of the injector is currently being accelerated in the modules extending to the left up to an energy of ~ 5 MeV.

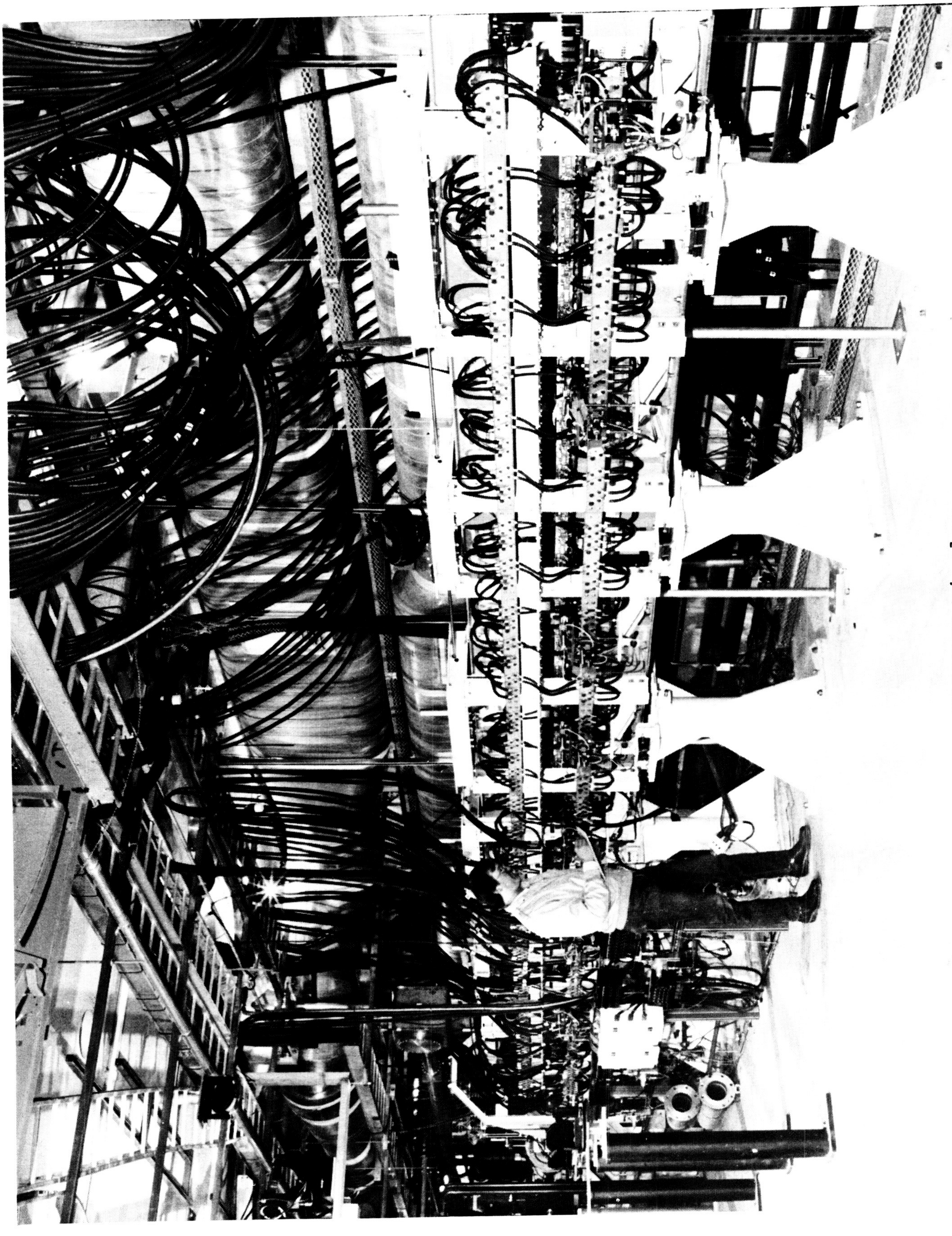
(See figure on next page.)

Induction Accelerator

Photo of the PALADIN wiggler

As a representative example of the maturity of wiggler technology being fielded in laboratories around the world, this photo shows a view of the 25 meter long wiggler operating as part of the 10.6 um FEL experiment underway at Livermore. The 45 MeV, 500 Ampere beam from the Advanced Test accelerator makes a single pass through this device. Very high single pass gain has been observed to date with the wiggler being seeded by a conventional CO_2 laser located above the tunnel. The PALADIN wiggler has a period of 8 cm and a peak field of ~ 3 kG. It is a DC electromagnet that is operated for many hours at a time and has field errors of 2 parts in 1000. The electron beam has been routinely propagated through this device without application of external steering.

(See figure on next page.)



PALADIN Wiggler

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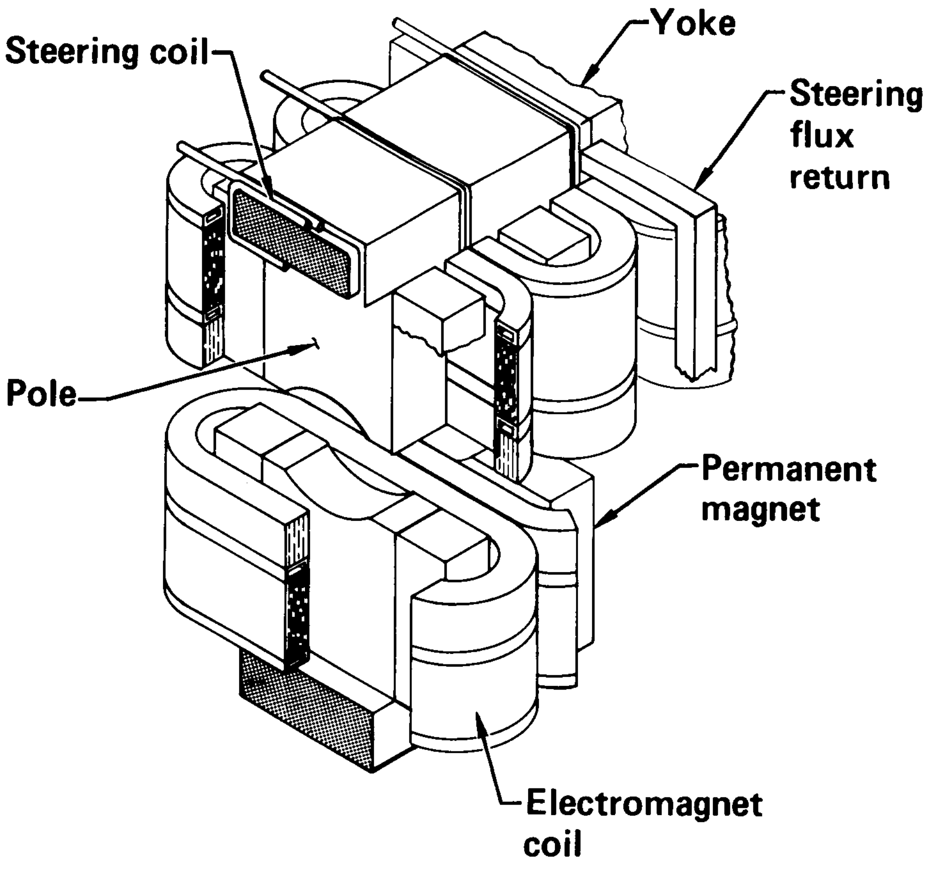
PALADIN Wiggler Schematic

The PALADIN wiggler is a hybrid wiggler in the sense that it is an electromagnetic device with permanent magnet assist. The wiggler is segmented into 5 meter long modules and is currently operating at a total length of 25 meters. Each module separates into top and bottom halves, where each side consists of cast iron pole pieces that are precisely machined on the tips after attachment to rigid structural beams. The curved shape produced on the pole tips provides gentle focusing of the e-beam in the horizontal plane. A water cooled coil is fitted over each pole piece to provide excitation and permanent magnets are attached to the sides of each pole piece to retard saturation in the iron, especially near the roots of each pole piece. The top half of each module is lowered onto the bottom half after assembly and the gap between pole pieces in the vertical direction is precisely controlled via gage blocks.



Artist's rendering of the Army's Technology Integration Experiment site at the White Sands Missile Range

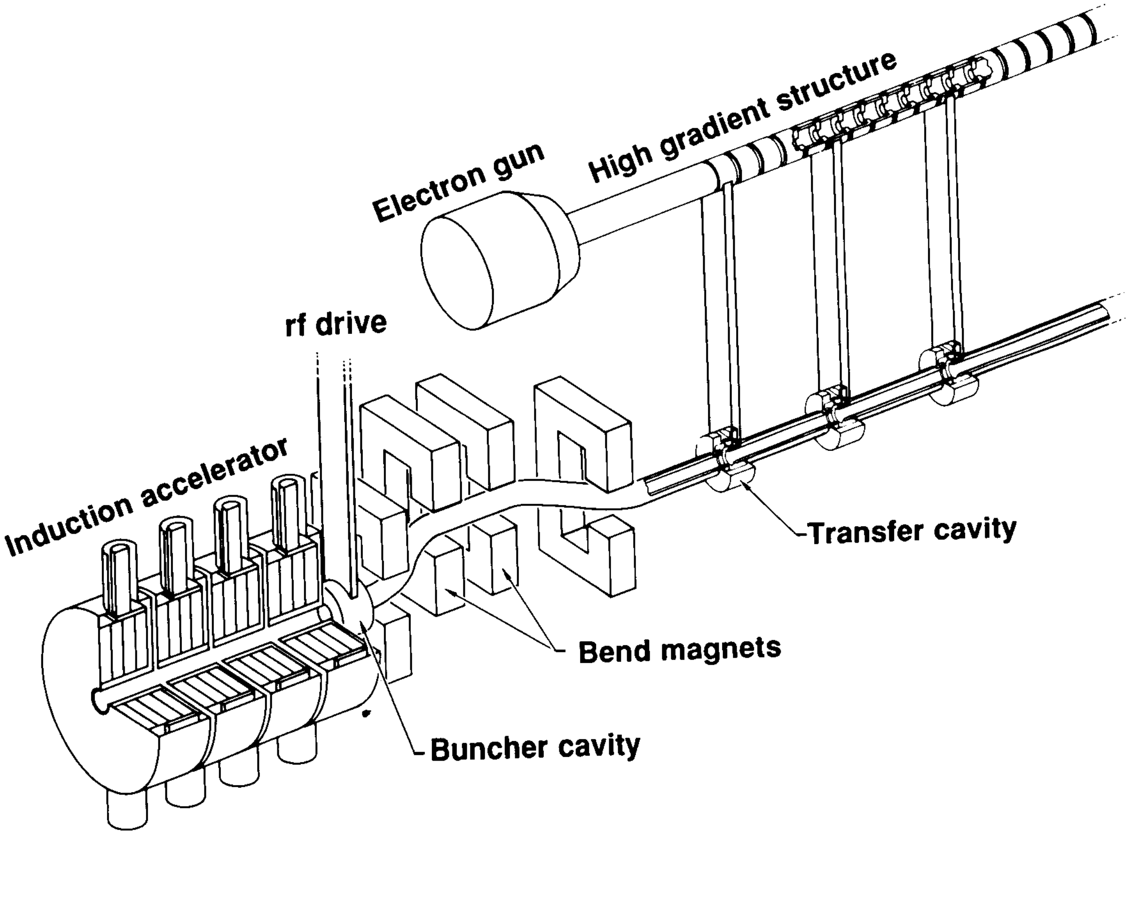
Significant focus in the optical FEL program has been on the development of design concepts for a moderate power free electron laser which would be integrated with an optical transmitter at the White Sands Missile Range in the mid-1990s at a wavelength near 1 um. The U.S. Army Strategic Defense Command is conducting a technology selection process for the type of FEL to be incorporated in the facility. FELs driven by RF linacs and induction machines are being offered by Boeing and TRW, respectively.

(See figure on next page.)

Artist's rendering of the Army's Technology Integration Experiment site at the White Sands Missile Range

Schematic of a relativistic klystron

Various research groups around the world are examining advanced concepts for high gradient accelerators that could be used for TeV colliders and short wavelength FELs. The FEL resonance condition requires that the e-beam energy be increased as the design wavelength is reduced. Operation of FELs in the wavelength regime from the vacuum ultraviolet to soft x-rays requires 500 - 1500 MeV beams. In order to have reasonable overall size for these accelerators, the average gradient must be increased by an order of magnitude compared to the state-of-the-art. In this schematic, one approach being studied at Livermore is shown. A low energy induction accelerator is used to drive a series of relativistic klystron cavities that produce high peak power microwave pulses for insertion into a traveling wave high gradient beamline. The high peak power, short pulse and somewhat higher frequency of the relativistic klystron drive compared to conventional microwave tubes allow the high gradient beamline to sustain electric fields on its surfaces that are well above those used in conventional RF accelerators (10s to 100s of MV/m). Klystron tests at Livermore have demonstrated efficient conversion (~50%) of induction accelerator beam power to microwaves at 11.4 GHz. Peak power of 200 MW has been observed from a single extraction cavity. This microwave power was used to drive a prototype traveling wave structure (built by SLAC) up to field levels near 100 MV/m without observation of dark current or breakdown. The possibility of compact .5 - 1 GeV accelerators operating at peak currents of kiloamps could, in the future, allow the development of efficient single pass vacuum ultraviolet lasers that could be used for power beaming over very large distances within the solar system.



Photograph of relativistic klystron experiment

A 1.5 MeV induction accelerator shown in the foreground is used to drive the relativistic klystron device at the top of the picture. Peak power in the range 200 MW at 11.4 GHz has been observed at this facility. The length of this apparatus is approximately 4 meters.

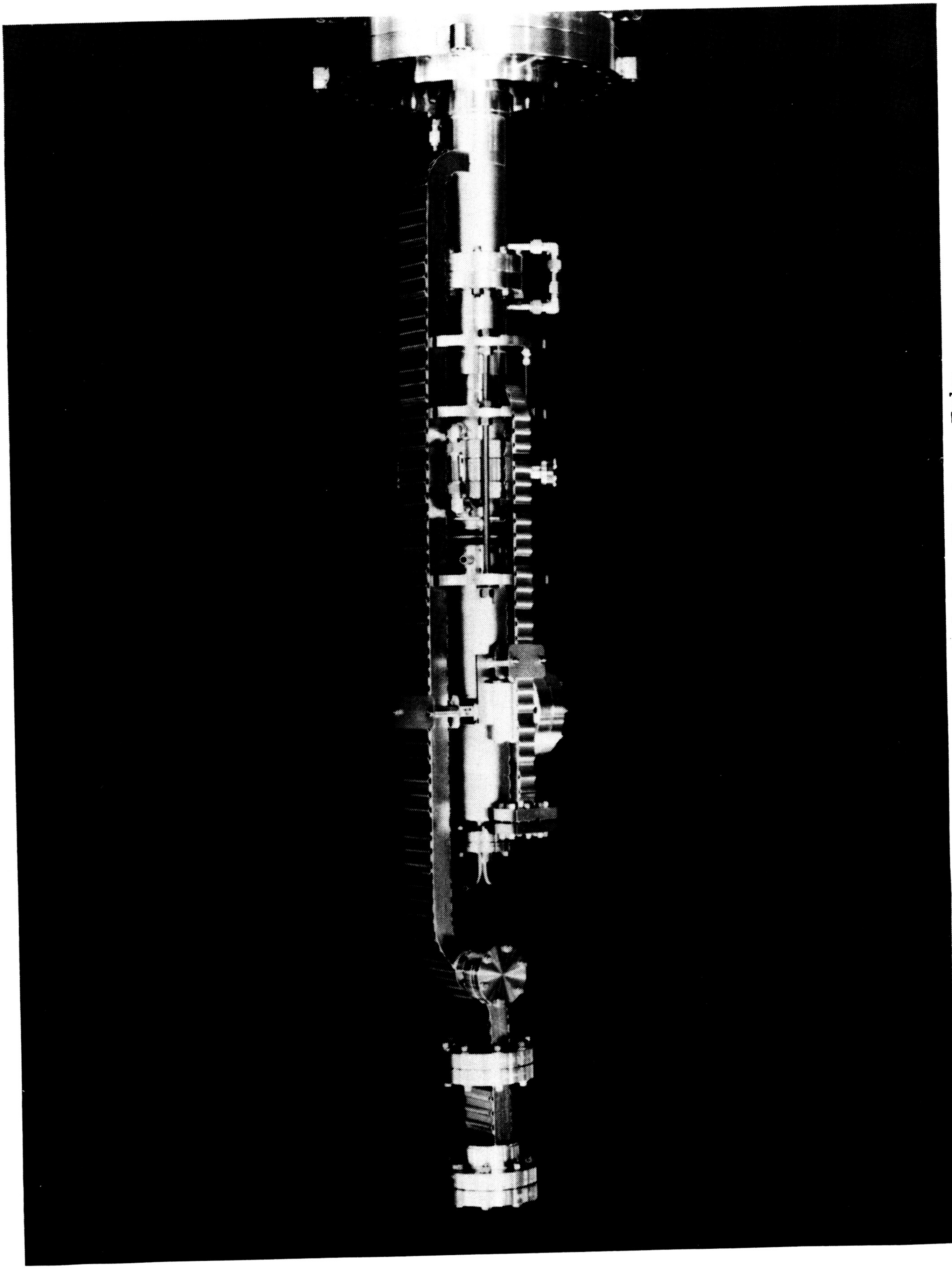
(See figure on next page.)

Photograph of a Relativistic Klystron Experiment

Photograph of relativistic klystron tube

This 11.4 GHz tube is driven subharmonically through the larger waveguide at 5.7 GHz. The electron beam propagates from right to left in the picture. The subharmonic drive initiates bunching of the electron beam. In some of the designs tested, several bunching cavities are used to increase the gain of the device until extraction of the high power microwaves is performed in a cavity coupled to the smaller waveguide. These devices operate as wideband amplifiers which can be configured as injection-locked arrays.

(See figure on next page.)



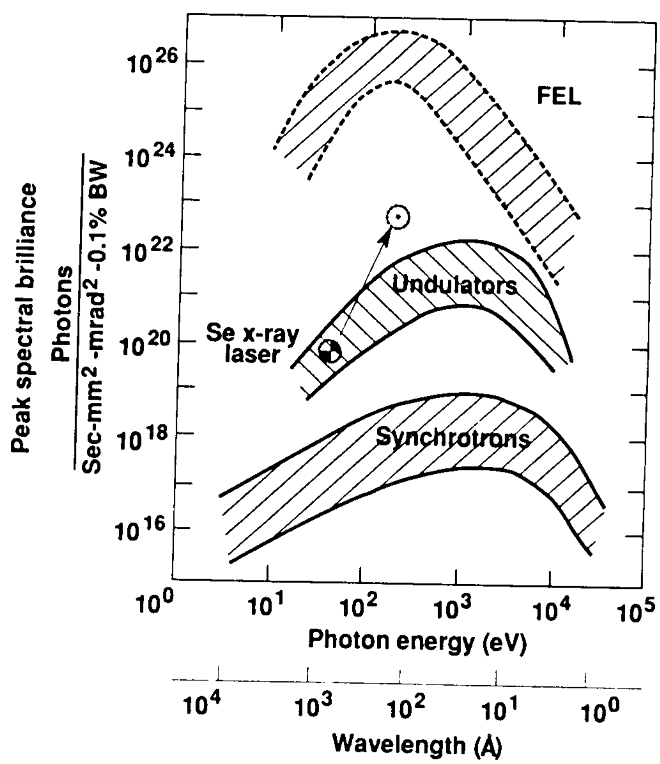
Photograph of Relativistic Klystron Tube

Soft x-ray FELs, if they work, will exceed competing sources in peak spectral brilliance.

Particle simulation codes are now being used to estimate the conditions under which soft x-ray FELs can be made to work. Preliminary results indicate that it is possible to obtain coherent x-ray beams from single pass amplifiers. For applications such as semiconductor lithography and holography of biological materials, these sources could substantially increase the peak spectral brilliance of the source compared to conventional undulators and synchrotrons. In order to obtain this result, it will be necessary to improve the brightness of electron beams by 1 to 2 orders of magnitude while still maintaining high peak current. Wiggler technology will also need to be advanced in order to obtain very short wavelengths. Uncorrelated pole-to-pole wiggler field errors will have to be reduced by a factor of 10 compared to the current state-of-the-art. MOPA configurations are desirable in the very short wavelength regime because of the lack of suitable optics. In general, extraction efficiency will be quite low in the soft x-ray regime (perhaps 1% at best). Therefore, recirculation of the e-beam energy will be required for efficient operation. At Los Alamos, experiments have shown that the e-beam energy emerging from the wiggler can be converted into microwaves and delivered through bridge couplers back into the RF accelerating structure. At very low extraction efficiency, direct electron recirculation may be possible in ring geometries.

Key Issues

1. **Bright electron beams (10^{11} - 10^{12} A/(m-rad)^2)**
2. **High peak current (300 - 1000A)**
3. **Accurate wigglers ($\delta a_w/a_w < 10^{-4}$)**



Key questions for short wavelength FEL technology development

Much of the practical experience in operating FELs in the world exists in the infrared and microwave regimes. Highly developed particle simulation codes, which have been validated at these longer wavelengths, are being used to predict the design requirements for shorter wavelength devices. It is important to remember that some key physics issues remain to be resolved for short wavelength operation. One example concerns the propagation of the electromagnetic wave through long wigglers as it interacts with the electron beam. As the wavelength becomes short, the wiggler can be many Rayleigh ranges long. (The Rayleigh range is the scale length over which diffraction is expanding the beam). Two processes tend to work against diffraction to confine the power in the optical mode to a transverse dimension comparable to the e-beam size. The first is gain guiding, which puts the power where gain exists (i.e. near the electron beam). This effect has been easily observed on PALADIN. The second effect is that of refractive guiding, where the non-uniform refractive index of the electron beam provides gentle focusing of the optical mode. Tentative indications of this effect have been seen in some experiments and computational studies have indicated that the effect should be present. Further validation is needed.

The drive toward shorter wavelength must also be accompanied by large improvements in e-beam quality in terms of brightness, energy uniformity (both instantaneous and throughout the electron pulse), and spatial jitter with respect to the axis of the magnetic transport system. Furthermore, these conditions must be reproducible at high repetition rate as the device is driven up in average power. The accelerator must be able to meet the requirements for high FEL extraction efficiency while coming to steady state conditions both electrically and thermally. Component reliability must be extremely high under these conditions.

- **Can the short wavelength FELs be made to work at all?**
  - **Are we modeling the right physics?**
  - **Do computational models compare well with experiment?**

- **Can high quality electron beams be produced (and reproduced)?**
  - **High brightness**
  - **Low energy sweep**
  - **Small transverse jitter**

E-beam requirements become more stressing as wavelength becomes shorter.

This chart ilustrates the general trend toward more advanced accelerator capabilities as wavelength is reduced. The electron energy requirements prescribed by the resonance condition increase. Technical options supporting higher gradient accelerators become important as one proceeds to shorter wavelength. Brightness requirements, which can currently be met down into the near infrared, must be improved by factors of 10 to 100 in order to produce efficient FELs in the visible and ultraviolet. Finally, the tolerances on the variation of electron energy become much tighter.

Parameter \ Wavelength	Millimeter Wave	Mid-Infrared	Near IR/ Visible	Ultraviolet
Electron beam energy (MeV)	2 — 10	30 — 70	15 — 400	400 — 1000
E-beam brightness $(A/(m\text{-}rad)^2)$	1 — 10 x 10^7	1 — 10 x 10^8	1 — 10 x 10^9	1 — 10 x 10^{10}
E-beam energy sweep (%)	5 — 10	1 — 3	.3 — 1	.1 — .3

Summary

A brief update was presented on the current trends in the development of FEL technology that could potentially support future power beaming applications. Concepts exist at this time that could allow efficient conversion of electrical power to directed energy beams over an extremely large spectral range. Component technology is beginning to mature to the point where high average power operation is possible, although the current generation of prototype devices is rather large and expensive. Realization of the need for compactness, light weight, and affordability has begun to spawn some advanced concepts that could move the technology toward practical applications over the next decade.

- **Concepts for efficient conversion to directed energy are being developed over a broad spectral range**
- **Some schemes are beginning to address need for compactness and light weight**
  - **— must maintain favorable high power scaling**
- **In general, current generation of technology is inadequate**
  - **— too large**
  - **— too expensive**