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Intense Microwave Generation Using **Free-Electron Lasers**

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This article is being prepared for the Workshop on Strong Microwaves in Plasmas September 18-25, 1990 Suzdal, U.S.S.R.

September 1990

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INTENSE MICROWAVE GENERATION USING FREE-ELECTRON LASERS*

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I. INTRODUCTION

Free-electron lasers (FELs) have demonstrated their ability to generate coherent radiation over a large region of the electromagnetic spectrum ranging from the microwave regime down to the visible regime [1]. In this device, the relativistic electron beam is coupled to the radiation using a periodic, transverse magnetic field called an undulator or wiggler. The coherence of the radiation results from the bunching of the electron beam by a ponderomotive well generated by the wiggler field and the electromagnetic radiation [2]. The wavelength of the emitted radiation is determined by a Lorentz contraction followed by a Doppler shift of the wiggler period. This wavelength scaling is given in by

$$\lambda_{s} = \frac{\lambda_{w}}{2\gamma^{2}} = \frac{\lambda_{w}}{2\gamma_{0}^{2}} \left[1 + \frac{1}{2} \left(\frac{eB_{w}\lambda_{w}}{2\pi mc} \right)^{2} \right]$$
(1)

Here, γ_0 is the energy of the electron in units of the electron rest mass $(\gamma_0 = 1 + eV/mc^2)$, λ_W is the wiggler period, and B_W is the peak wiggler magnetic field. This expression describes the wavelength scaling for a device using a plane polarized wiggler field. The FEL is shown schematically in Fig. 1. The electron beam passes through the wiggler where its transverse motion couples to the transverse electric field of the electromagnetic wave. If the proper resonance condition is maintained, the electrons lose energy to the radiation. This process continues until the electrons have lost sufficient energy that the resonance condition is no longer satisfied.

FELs can be configured either as oscillators or amplifiers. An oscillator is formed by installing mirrors on either end of the wiggler magnet. The radiation builds up in the cavity while a small amount is extracted. In such a device, the pulse length of the

^{*} Performed jointly under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No.W-7405-ENG-48 and for the Department of Defense under Contract No. SDIO/SDC MIPR No. W31RPD 3-D4074.

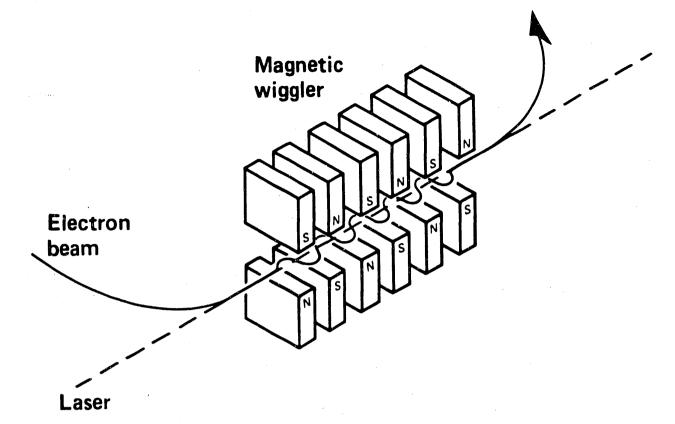


Figure 1. Schematic of a single pass free-electron laser amplifier.

electron beam must be of sufficient duration for the fields in the cavity to saturate. Alternatively, the FEL can be configured as an amplifier in which a "seed" signal is introduced into the interaction region and grows exponentially to saturation. This seed signal can either be introduced from an external source or it can arise from the noise on the electron beam.

Perhaps the most critical part of the FEL is the electron beam. The quality of the beam is measured by its instantaneous energy spread and its emittance, which characterizes its area in transverse phase space. This parameter is a measure of the electron beam's transverse random motion. If the emittance or energy spread is too large, then the random motion of the electrons dominates the coherent transverse motior. and the gain is reduced. Space charge of the electron beam can also become an important factor to the performance of the FEL. As the electron beam bunches in the ponderomotive well, the space charge forces tend to debunch the electrons, again reducing the gain of the system. If the electron beam density is sufficiently high, then plasma waves on the electron beam must be taken into consideration [3]. In this case, the FEL is characterized by Raman scattering and the FEL is said to be operating in the Raman regime. For the type of FEL described in this paper, the interaction can be described by studying the single particle equations of motion. Here, the FEL can be characterized by Compton scattering and the device is said to be operating in the high gain Compton regime.

The wiggler for the FEL can be either plane polarized, as depicted in Fig. 1, or helically polarized. This latter device is fabricated by winding a conductor in a helical pattern. This helical wiggler has the advantage of focusing the electron beam in both transverse dimensions while the plane polarized wiggler focuses the electron beam only in the direction of the wiggler field. One advantage of the plane polarized wiggler is the relative ease with which the wiggler field can be varied along the length of the wiggler. This ability, called tapering, is an important part of the single pass amplifier.

In this paper, I will describe a free-electron laser amplifier which operated in the microwave regime. This device, called the Electron Laser Facility (ELF), used an electron beam generated by a Linear Induction Accelerator (LIA). ELF operated as a single pass amplifier at 35 and 140 GHz. Because the device had no cavity, we could study the FEL physics independent of cavity considerations (i.e., longitudinal mode competition and cavity filltime). With a sufficiently large input signal, growth of the signal from noise on the beam did not influence the performance. This device demonstrated significant gain and allowed us to investigate such FEL phenomenon as saturation and synchrotron oscillation of the electrons trapped in the ponderomotive well. We were also able to study the phase shift of the radiation due to the real part of complex gain of the FEL. Because the interaction takes place in a waveguide, the FEL can couple to several spatial modes at a given frequency. The bunched electrons can radiate at harmonics of the fundamental and in this experiment we studied the evolution of the third harmonic. In Part II of this paper, I will describe the Electron Laser Facility. I will discuss the FEL performance with regard to gain, saturation, phase evolution, mode coupling and harmonic generation. In Part III, I will briefly discuss a switching technique which allows the LIA to run at high average power. When driven by such a device, an FEL can produce high average power radiation. We will present the design for such a device which can be used to heat a Tokamak plasma. This device is designed to operate at 250 GHz and produce an average power of 2 MW [4].

II. The Electron Laser Facility

ELF was a single pass FEL amplifier operating in the microwave regime [5]. This facility was operational from 1982 to 1987. This device was decommissioned to provide for the construction of a new, high repetition rate LIA. ELF used a 3.5 MeV electron beam generated by the Experimental Test Accelerator (ETA) [6]. While the accelerator was capable of producing a 10-kA peak current with a 30-ns duration once per second, we typically accelerated 3kA. Of this, ELF used only a fraction of this current (800 to 1200 A) and operated at 1/2 Hz. ELF is shown schematically in Fig. 2. The 3 kA electron beam passed through an emittance filter which comprised a 2.5-cm diameter, 2-m long pipe immersed in an axial magnetic field. The acceptance of this device could be varied by changing the magnitude of the axial magnetic field. Only electrons whose emittance was less than or equal to the acceptance of this device passed through the

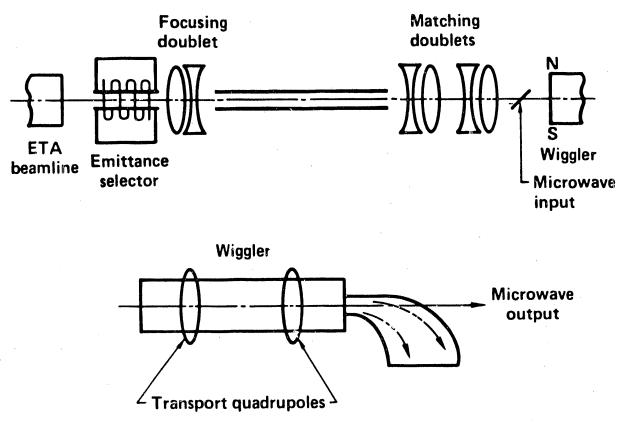


Figure 2. Schematic of the Electron Laser Facility.

filter. We typically discarded 2/3 of the electron beam in this device. This was important for two reasons. First, as mentioned above, electrons whose emittance is too large do not contribute to the gain and, in some circumstances can actually reduce the gain of the device. Second, since we know the maximum emittance of the transmitted beam (and since we passed only a small fraction of the original beam, we could assume a fairly uniform distribution in phase space of the transmitted beam) we can accurately model the FEL. After the emittance filter, three quadrupole doublets were used to transport and match the electron beam into the wiggler. Because the transport from the end of the accelerator to the entrance of the wiggler was fairly chromatic (±1% energy acceptance), the electron beam pulse length was reduced from 30 ns to 15 or 20 ns. The wiggler magnets comprised two rows of rectangular, air core solenoids: one row above and one below the interaction region. The wiggler was 3-m long for the 35-GHz experiments and was extended to 4 m for the 140-GHz experiment. The wiggler period was 10 cm and the solenoids were 16-cm wide. The two rows of solenoids were separated by 3 cm to allow for the waveguide which served as the beam transport line through the wiggler. The wiggler magnet was pulsed with a rise time of about 600 μ s. The wiggler field was essentially flat for the 30 ns duration of the electron beam. Heating of the wiggler magnet itself limited the pulse repetition frequency to one pulse every two seconds. In addition, each two periods of the wiggler (with the exception of the first and last period) was energized by a separate power supply. Thus, we could

vary the resonant length of the wiggler or taper the wiggler field in two period steps. The wiggler field provided focusing for the electron beam in the direction of the wiggler field (vertical). Continuous horizontal focusing quadrupoles focused the beam in the horizontal direction. The focusing of the wiggler and the quadrupoles was not the same and therefore the electron beam had an elliptical transverse spatial profile ($k\beta_V \simeq 19.2 \text{ m}^{-1}$ and $k\beta_H \simeq 6.8 \text{ m}^{-1}$). With a normalized edge emittance of 3×10^{-3} m-rad, the beam had an elliptical shape 2.4 cm wide by 1.3 cm high. Prior to the wiggler, a fine meshed screen was used to match the input microwave signal into the waveguide. The waveguide in the interaction region was made of thin walled stainless steel to ensure good penetration of the pulsed wiggler field. The waveguide dimensions were 3 cm high by 10 cm wide. The wide dimension lies in the wiggle plane. Gentle tapers were used to match the fundamental TE₁₀ mode of the input signal source (either a magnetron at 35 GHz or an Extended Interaction Oscillator at 140 GHz) to the TE₀₁ mode of the interaction region. The resonance condition for the FEL which accounts for the waveguide modification to the electromagnetic wave propagation is:

$$2\gamma^{2} = \frac{\omega/c}{[k_{w} + (k - \omega/c)]} \left[1 + \frac{1}{2} \left(\frac{eB_{w}\lambda_{w}}{2\pi mc} \right)^{2} \right]$$
(2)

where the frequency and wavenumber are related by the waveguide dispersion which is given by:

$$\omega^2 = k^2 c^2 + \omega_{c0}^2 \tag{3}$$

and where w_{co} is the cutoff frequency of the waveguide. For a rectangular waveguide

$$\omega_{\rm c0} = \pi c \, \sqrt{\frac{m^2}{a^2} + \frac{n^2}{b^2}} \tag{4}$$

where *a* is the narrow dimension of the guide, *b* is the wide dimension, and *m* and *n* are the mode numbers. Table I lists the resonant energies for various modes in the waveguide (at 34.6 GHz). The TE₂₁ and TM₂₁ modes can couple to the electromagnetic wave. In the experiments discussed here, as much as half of the radiated power could reside in these higher modes (except in the tapered wiggler case). At the end of the

 Table I: Resonant Energy Shift for Higher Order Modes

Mode	$\gamma_{r}(m, 1) / \gamma_{r}(0, 1)$
TE ₀₁	1
TE ₂₁ , TM ₂₁	1.02
TE41, TM41	1.11

wiggler, the electron beam was deflected into the waveguide wall and the electromagnetic radiation was injected into an evacuated diffraction tank. The radiated signal was monitored in the far field. By proper location of the receiving antennas we could determine the waveguide mode to which the signal coupled.

The FEL resonance was determined by varying the wiggler field for a 1-m long uniform wiggler (the remainder of the wiggler was tuned far from resonance). When the peak of the resonance was determined, the wiggler length was varied from 20 cm to 3 m. Figure 3 shows the results of this gain measurement. The two curves correspond to a tapered and untapered wiggler. These curves show the power only in the TE₀₁ mode, which is the fundamental design mode. In the linear regime, the signal grew exponentially at a rate of 34 dB/m and saturated 1.2 m into the wiggler. In the uniform wiggler case, the signal actually decreased beyond the saturation point and the power oscillated corresponding to the synchrotron motion of the electrons in the ponderomotive well. This syncrotron motion had a period of about 1 meter. The solid line in this figure corresponds to the results from a 2-D simulation code, FRED. There is a slight discrepancy between the theory and the experiment beyond saturation. The theory predicts a shorter period synchrotron oscillation with a more pronounced amplitude.

The deleterious effect of saturation can be eliminated by tapering the wiggler. In the experiment, this was be accomplished by tuning the wiggler in two period increments starting near saturation and maximizing the output perver at each step. In this manner, the radiated power increased from 200 MW to 1 GW. The wiggler field dropped to 40% of its peak value. This corresponded to an extraction efficiency of about 35% and a trapping fraction (of electrons in the ponderomotive well) of about 60%. We repeated this experiment at 140 GHz using a 4-m long wiggler. In this case, a 50 W signal from a conventional EIO was injected into the interaction region. Because the energy of the electron beam was still 3.5 MeV, the wiggler magnetic field had to be reduced to match the resonance condition. For this case the resonant wiggler field was 1.7 kG. Because the wiggler field was reduced by a factor 0.46, the gain per unit length was reduced by

 $\left(\frac{B_{w,res}(140 \text{ GHz})}{B_{w,res}(35 \text{ GHz})}\right)^{2/3}$

or 0.6 (22 dB/m as opposed to 34 dB/m at 35 GHz). In this experiment the signal saturated at 70 MW 3.4 m into the wiggler. However, saturation occurred too far into the wiggler to allow for any meaningful tapering studies. The amplification of the input signal is shown in Fig. 4. Again, the solid line is the result of the numerical simulation.

The complex gain of the FEL produces both an amplification of the electromagnetic wave as well as a phase shift of the radiation [8]. We measured the

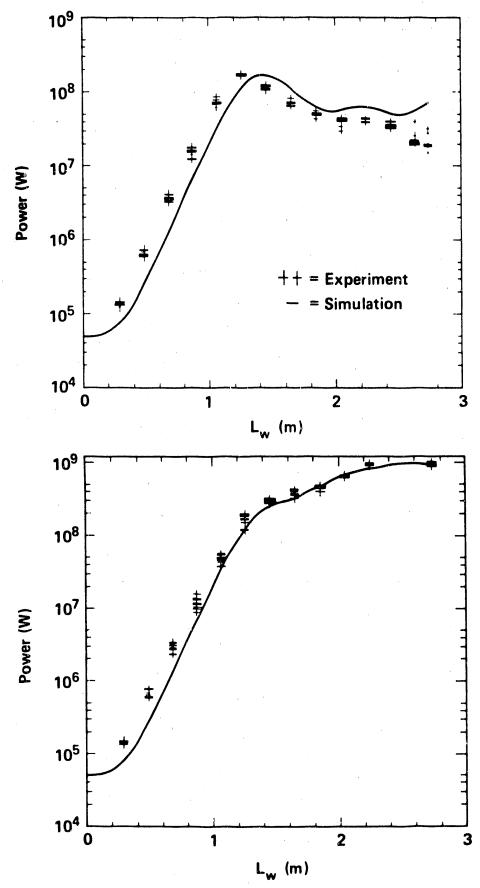


Figure 3. Gain measurement of 35 GHz input signal. Bresonant = 3.7 kG. Top: 3-m uniform wiggler. Bottom: optimized apered wiggler. For both cases the beam current is 850 A.

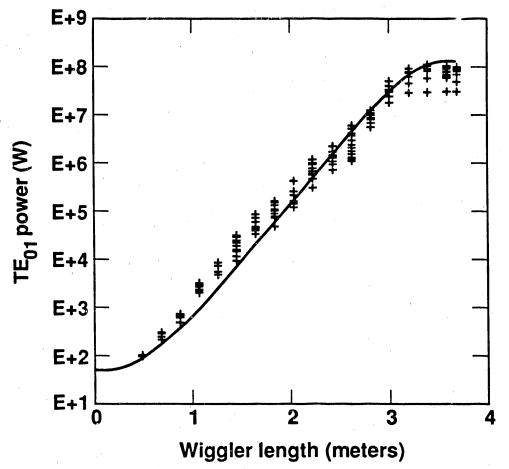


Figure 4. Gain measurement of 140 GHz input signal. Bresonant = 1.7 kG, 4-m uniform wiggler, Ibeam = 950 A.

progressive shift in phase as the radiation grew in the FEL using a homodyne technique. With a microwave interferometer, we measured the phase shift of the amplified radiation relative to the input signal as a function of length through the wiggler as well as a function of wiggler field. We have plotted the results of this measurement in Fig. 5 for the 35 GHz experiment. The three curves correspond to the wiggler field at resonance, 5% above resonance, and 5% below resonance. These data correspond to the tapered wiggler case. Again, the solid line corresponds to the results of the two dimensional simulation of this device. Our ability to accurately model the FEL's performance is crucial to designing future devices. Successfully modeling the real and imaginary parts of the complex gain gives us great confidence in other FEL designs.

We had previously discussed the effect of the waveguide on mode competition in the microwave FEL. Table I shows the shift in energy required for the electron beam to couple to modes other than the fundamental design mode (TE₀₁). We considered only modes which have a non-zero electric field on the axis of the intraction region—the TE_{m1} and TM_{m1} modes where m is even. As indicated in Table I, the TE₂₁ (TM₂₁) mode has a resonant energy only 2% from the resonant energy for the TE₀₁ mode. The resonant energy for all other higher order modes is significantly further away from the

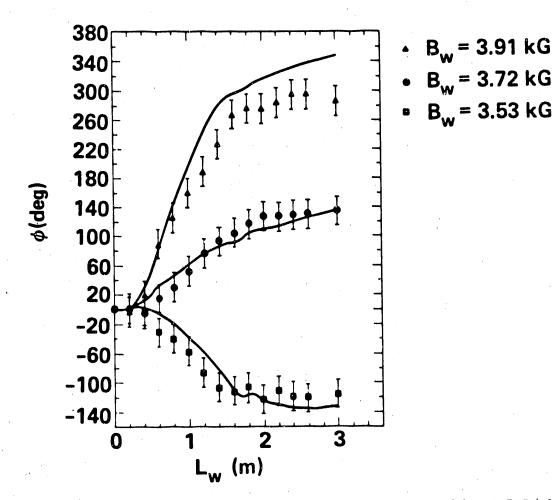
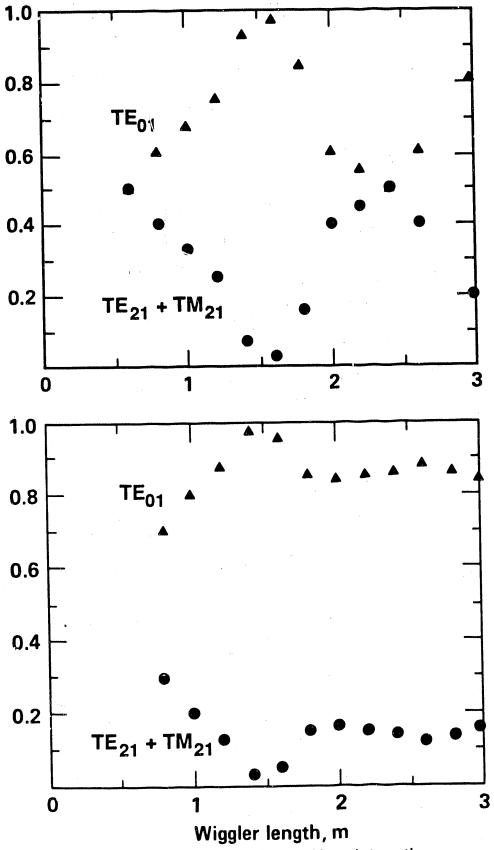
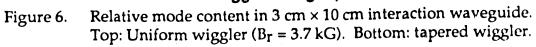


Figure 5. Phase shift of amplified signal relative to input signal (at 35 GHz) for tapered wiggler at resonance, 5% above resonance and 5% below resonance.

energy corresponding to the fundamental design mode. We probed the radiation pattern in the far field assuming that only the TE₀₁, TE₂₁, and TM₂₁ modes were present. Figure 6 shows the power in the fundamental mode and the TE₂₁ + TM₂₁ modes for both the tapered and untapered wiggler. In the uniform wiggler case, the power is distributed in the two modes with half of the total power at times residing in the higher order mode. In the tapered wiggler case, most of the power (85%) remains in the fundamental design mode. As the electrons lose energy, the longitudinal momentum of the electrons is forced to track this particular mode in the tapered wiggler.

The electrons' motion in the wiggler field results in radiation not only at the fundamental frequency, but also in harmonics of this frequency. Although the FEL is resonant with one particular mode at one particular frequency, the electrons which are bunched by this mechanism can radiate coherently at the harmonics. For the plane polarized wiggler, only the odd harmonics radiate on axis. Figure 7 shows the fundamental and third harmonic power for both the tapered and the untapered wiggler case. Although there is almost a factor of five difference in the power radiated at the





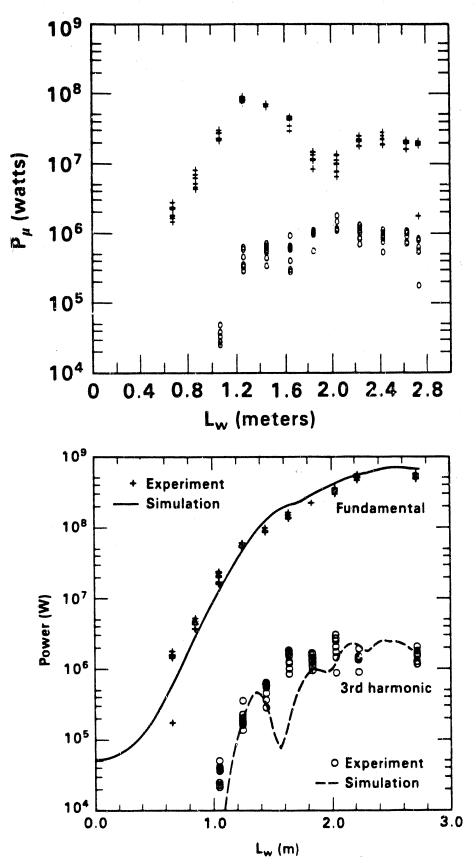


Figure 7. Power at fundamental (FEL) frequency (35 GHz) and at third harmonic (105 GHz). Top: uniform wiggler. Bottom: tapered wiggler.

fundamental for the two cases shown, there is only a slight difference in the third harmonic emission. The explanation for this is simple. The electrons are bunched by the action of the FEL. These bunches remain resonant with the FEL frequency at 35 GHz. The bunches, however, radiate at the harmonics as an array of small dipole antennas. The FEL action simply maintains the bunches. The slight improvement in harmonic emission in the tapered wiggler case is due to the fact that the tapered wiggler maintains a tighter bunch. Again, the lines in these graphs correspond to the results of a simulation code designed to study harmonic emission in the FEL.

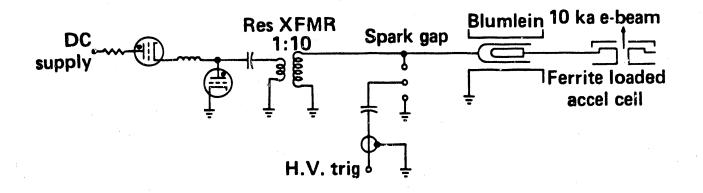
III. Intense Microwave Prototype

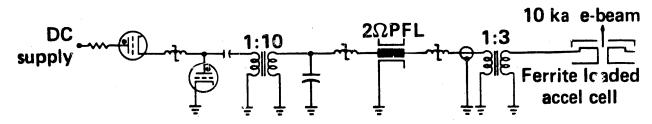
Based on our previous experiments with LIA driven FEL amplifiers and advances in LIA technology, we have designed a free electron laser to heat a tokamak plasma. This device is referred to as the Intense Microwave Prototype (IMP) [4], and the design parameters for this device are given in Table II. In particular, this device is designed to operate at 250 GHz to match the electron cyclotron resonance in the Alcator tokamak which has a main toroidal field of 10 T. This experiment is referred to as the Microwave Tokamak Experiment (MTX) [9]. The FEL is designed to deliver 2 MW of average power for a period of 1 second. In order to achieve this high average power, the accelerator must run at a relatively high duty factor.

Previous LIAs used Blumleins which were discharged through pressurized sparkgaps to energize the induction accelerator cells [10]. The development of new high power pulse compression techniques allowed us to consider systems which could operate at several kHz [11]. Both of these pulse power chains are illustrated in Fig. 8. The problem with the sparkgap is erosion of the electrodes. The magnetic switch (Mag 1-D) relies on saturable reactors to transfer the energy from one energy storage stage to another at successively faster rates. Since there are no electrodes to degrade gasses which need to recover, these switches can in principle achieve high pulse repetition frequencies. The Mag 1-D was designed to operate at high average PRF.

Because this FEL operates at a high duty factor, we cannot rely on a pulsed electromagnet to generate the wiggler field An iron core electromagnet is available to generate the required wiggler field. The parameters for this wiggler are given in Table III. One notable feature about this wiggler is the large range of magnetic field

Table II: IMP Design Pa	rameters
Ebeam	10 MeV
Ibeam	3 kA
fμ	250 GHz
Ρ _μ (peak)	12 GW
% extraction	4 0%
Ρ _μ (ave)	2 MW





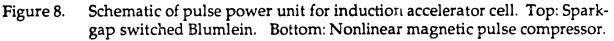
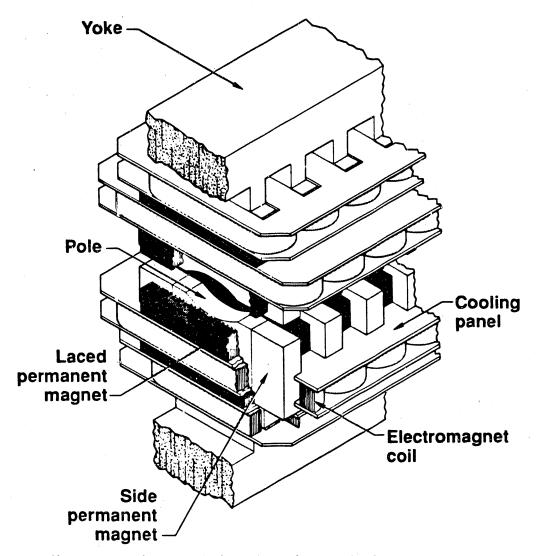
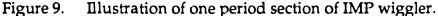


Table III: IMP Wiggler Requirements Period = 10 cm Gap = 4.0 cm Length = 5.5 m Peak field = 4.7 kG RMS wiggler errors < 0.1% B-field tuning range > 37%

which must be covered in the taper. The overall length of the wiggler is 5.4 m and the period is 10 cm. Unlike the aircore, pulsed electromagnet in the ELF experiment which used external quadrupoles to provide horizontal focusing, this wiggler has specially shaped poles to provide the horizontal focusing [12]. The pole tips are curved in such a manner that the wiggler field increases away from the axis in the wiggle plane. The shape of these poles is such that the focusing in the horizontal direction is equal to the focusing in the vertical direction. This results in a round electron beam in the interaction region. Figure 9 illustrates a one period section of the IMP wiggler.

When designing high a grage power systems, care must be exercised to avoid thermal stress in any of the componenets. Clearly, this is an issue in the pulsed power systems as well as the accelerator. The waveguide which passes through the wiggler and defines the FEL interaction region is also subjected to thermal stress due to the absorption of radiation on the walls of the beam tube. In order to achieve a high wiggler field, the poles above and below the interaction region want to be as close





together as possible. To provide the focusing as described above, the transverse dimensions of the interaction region must also be kept small—on the order of the vertical dimensions. Hence, the transverse profile of the interaction region must be kept as small as possible. However, the attenuation losses for the rf in passing through a waveguide increase as the inverse of the cross-sectional area. This implies high thermal loading on the waveguide walls. A possible solution to this problem is to propagate the intense radiation in the HE11 mode, which has substantially reduced attenuation in the waveguide [13].

Another consideration regarding thermal loading on waveguide wall has to do with the size of the electron beam in the waveguide. As the wiggler field is reduced according to the required taper, the transverse focusing of the electron beam is relaxed and the radial size of the beam is increased. At some point, the beam stikes the waveguide wall. To prevent this happening, the waveguide radius must be increased or the wiggler field must be kept above a certain minimum value. We arbitrarily impose the restriction that the beam diameter must not get larger than the one-half waveguide diameter. Clearly, there are a great number of engineering details which must be addressed to ensure reliability of this device. We have not addressed the technical issues of the accelerator. The performance of the accelerator is crucial to the performance of the FEL. At present, the accelerator for IMP is being upgraded to provide a beam of sufficient quality to drive the FEL.

SUMMARY

We have demonstrated the ability to achieve high peak power in an FEL amplifier operating at 35 and 140 GHz. In addition, we have successfully modeled the performance of this device with respect to the complex gain and harmonic generation. We have designed a high average power FEL for the purpose of heating a tokamak plasma. For this device, the accelerator performance must be improved in order to demonstrate the high average power capability of the FEL.

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DATE FILMED 02/26/91