HIGH-AVERAGE-POWER MILLIMETER-WAVE FEL FOR PLASMA HEATING USING THE ETA-II ACCELERATOR*

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Abstract

The Microwave Tokamak Experiment (MTX) is under construction at LLNL to investigate the feasibility of intense, pulsed microwave radiation for plasma heating on future ignition tokamaks. A high-average-power free-electron laser (FEL) will use the Experimental Test Accelerator (ETA-II), a linear induction accelerator, in combination with an advanced high-field wiggler, to produce 1-2 MW of power at 1-2-mm wavelengths for periods of up to 0.5 s. The design of the FEL, termed the intense microwave prototype (IMP), is described, along with the status and major issues associated with the experiment.

Introduction

Electron cyclotron heating (ECH) has become an important option for achieving and sustaining ignition in the next generation of tokamaks, such as the Compact Ignition Tokamak (CIT) and the International Thermonuclear Engineering Reactor (ITER).[1] Table 1 lists the major requirements of an ECH source.

Table 1. ECH source requirements.

Frequency (GHz)	140 - 600
Total average power (MW)	10 - 30
Overall efficiency (%)	15-30
Center frequency adjustment(%)	± 25
Rapid frequency tuning over 100 ms(%)	± 3-5

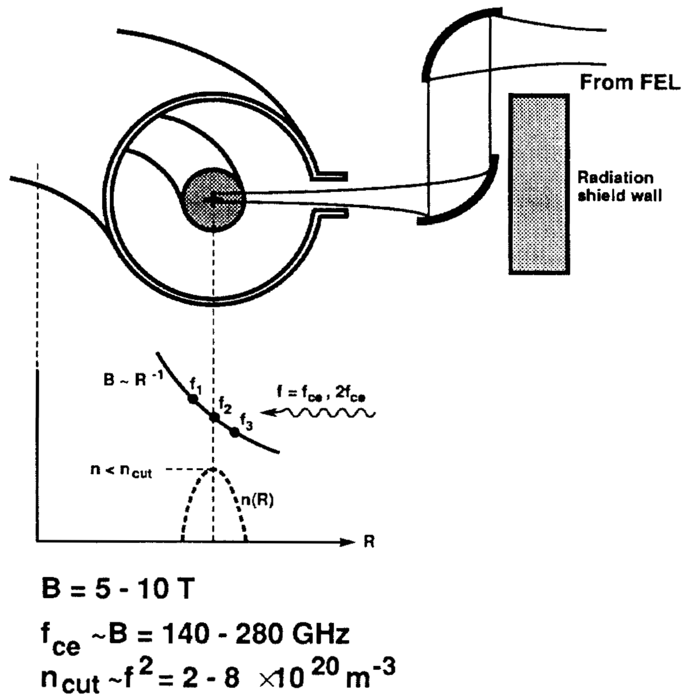

Figure 1. Geometry for ECH heating.

Figure 1 illustrates the geometry of ECH. The coupling structure consists of simple mirrors, which are removed from the plasma edge, thereby reducing impurity influx and minimizing neutron activation issues. High flux densities (100 kW/cm^2) can be achieved with ECH, requiring small port access. The ECH resonance is also highly localized so that by frequency-tuning the source (5% over 100 ms), one can adjust the heating location to improve confinement time and to suppress disruption processes.

There has been considerable interest in using the induction-linac driven FEL (IFEL) for ECH over the past two years. Previous experiments using the ETA and ELF facilities demonstrated peak powers of over 1 GW and conversion efficiencies of over 35% at 35 GHz using a tapered wiggler.[2] The same facility operated at 140 GHz in an untapered configuration and produced peak powers of over 50 MW and total gains of 63 dB.[3] Simulation codes showed good agreement with the measurements. While these experiments operated at low repetition rate (PRF) and, thereby, low average power, the recent developments in high-brightness, high-repetition-rate technology have made a high-average-power IFEL feasible.[4]

For ECH applications, the relativistic beam energies and high currents of the IFEL are well suited for operation at high frequencies and high powers. The high-gain amplifier configuration of the IFEL allows the low-power master oscillator to be frequency swept for rapid tuning. The short pulse length mitigates electrical breakdown issues. The intense nature of the output pulses also offers the unique opportunity for using nonlinear mechanisms for efficient current drive and other applications.[5]

Overview and FEL Simulations

Figure 2 shows the layout of the MTX experiment.[6] Figure 2(a) shows the ETA-II facility, consisting of a nominal 1-MeV injector and 6 to 8 accelerating sections to achieve 6 to 10 MeV of beam energy.[7] The IMP wiggler is located in the ETA-II vault along with FEL microwave diagnostics. An optical train of six mirrors is used to transport the FEL output power to the tokamak, as shown in Fig. 2(b). The MTX uses the Alcator-C tokamak, which has been relocated to LLNL from MIT. Alcator-C produces a high-field (> 9-T), high-density ($n > 4 \times 10^{20} m^{-3}$) target plasma that is relevant to future machines. The toroidal field coils are cooled by liquid nitrogen and can operate at a maximum rate of about twelve shots per hour. The design objectives for the MTX FEL are to produce 1-2 MW of average power at a frequency of 140 or 250 GHz for durations of up to 0.5 s.

Figure 3 shows the results of simulation codes for the IMP FEL operating at 250 GHz where the axial variation of the wiggler magnetic field and the

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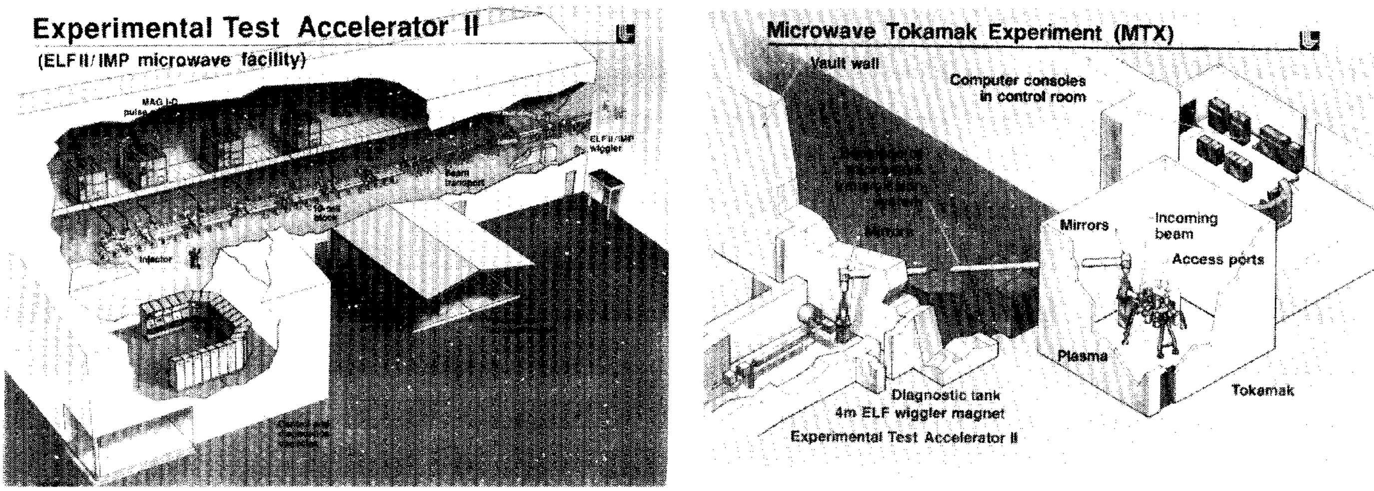

Figure 2. (a) ETA-II accelerator and wiggler for FEL. (b) Schematic of MTX experiment.

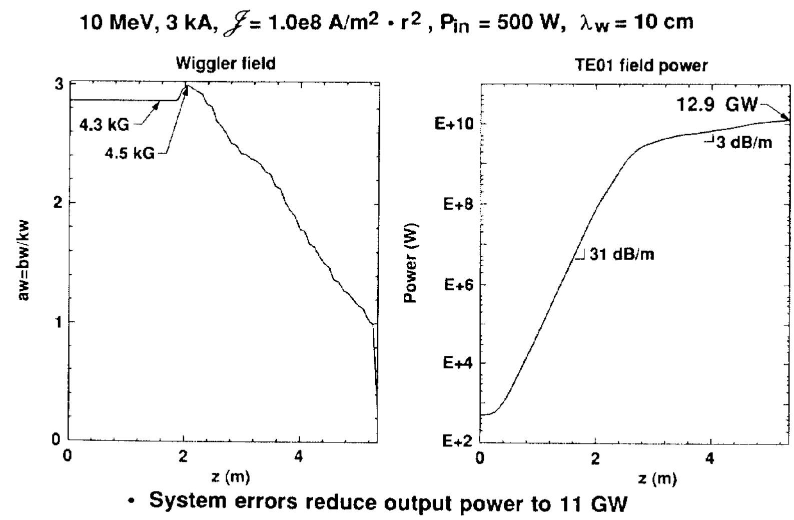

Figure 3. Axial field profile and output power for 250-GHz FEL.

corresponding microwave output for tapered operation are plotted.[8] Exponential gain and saturation occurs over the first 2 m of the wiggler, while an additional 3 m is required for tapering and high extraction efficiency. Table 2 lists the performance predicted at 250 GHz. Over 10 GW of peak power and 2.5 MW of average power is predicted, providing a design margin over the MTX requirements. High mode purity is predicted for tapered operation, along with a wide amplifier bandwidth.

Table 2. Summary of simulation results for 250-GHZ FEL.

Peak TE_{01} output power (GW)	> 12 (11)*
TE_{01} mode fraction (%)	> 97
Extraction efficiency (%)	> 40 (37)*
Peak noise power (MW)	3
3-dB amplifier bandwidth (%)	10
Average TE_{01} power (MW)	2.7*

* with system errors: 0.1% wiggler error, 1 mm offset, ± 1% energy sweep; pulse format = 5 kHz, 50 ns.

ETA-II Accelerator and Beam Transport

Table 3 lists the beam parameters required to operate the FEL and compares them with the ETA-II design objectives and present status. The ETA-II is designed to deliver a bright beam at high average power. The brightness required for microwave FELs is 20 to 40 times less than the value measured on ETA-II.[9] Similarly, the energy variation and macropulse length are within the ETA-II design objectives. For higher-current operation, an anode-cathode design will be used that produces 3 kA, but at a predicted brightness of over 1×10^8 A/(rad-m)^2.

Figure 4 shows the beamline transport for the FEL. Solenoidal lenses are used to transport and match the electron beam from the accelerator to the wiggler. The design results in less than 10% variation in the diameter of the beam envelope and predicts only small emittance growth. The transport section contains a section for accelerator diagnostics as well as periodic graphite limiters to scatter and remove any halo electrons with a large transverse velocity component.

Table 3. Summary of ETA-II objectives and FEL requirements

Parameter	High-brightness objectives	Microwave FEL 250 (140) GHz	Initial measurements*
Energy (MeV)	6 - 20	9 - 10* (6-7.4)	2.3 - 5.2
Current (kA)	1.5	3.0	1.5 - 2.0
Brightness [x 10^9 A/m^2·r^2]	2.0	0.1	2.0 - 4.0
Pulse width (ns)			
- FWHM	70	70	70
- "Flat top"	50	50	50
Energy variation (%)	±0.4	±1	--
PRF, burst (Hz)	5000	5000	1 - 3 †
Burst length (s)	30	0.5	-

* See paper M24: W.C. Turner et al., this conference.
† Operation up to 5 kHz demonstrated on offline facility.

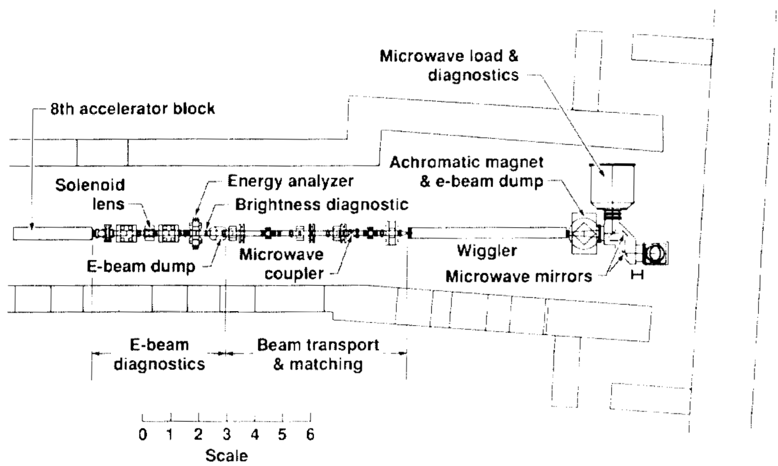

Figure 4. Plan view of beamline for 250-GHz FEL.

The input master oscillator microwave signal is coupled into the wiggler collinearly with the electron beam using a 45-degree mirror in the beamline. The mirror contains an aperture through which the electron beam is focused and couples the input signal with an expected 10-16 dB insertion loss. Except for the graphite limiters, the linear beam fill factor (beam radius / wall radius) has been kept at less than about 50% to avoid potential wall loading. At the output of the FEL, the microwave radiation can either be deflected into an anechoic diagnostic chamber using a movable mirror or it can be allowed to continue into the microwave transmission system to the tokamak.

The FEL interaction causes the electron beam exiting the wiggler to have a large energy spread. An achromatic magnet reimages the beam at nearly right angles to the beamline, where the beam is expanded to reduce the power density. The beam absorber is a simple graphite slab that uses thermal inertia during the 0.5-s macropulse and is cooled between shots.

IMP Wiggler

For operation at millimeter wavelengths and high average powers, the FEL wiggler must operate with steady-state fields (to accommodate high PRF accelerator operation), must allow the wiggler field to be arbitrarily tapered, and must achieve high magnetic fields with small transverse error fields to avoid beam steering. Table 4 lists the wiggler requirements. The wiggler design uses iron electromagnet pole pieces in conjunction with permanent magnets to achieve the required field strength and tunability. A similar design, operating at a lower field, is presently in use in a 25-m wiggler that is part of a 10-µm FEL experiment at LLNL.

Table 4. Requirements for IMP wiggler.

Period (cm)	10
Gap (cm)	3.7
Length (m)	5.5
Peak field (kG)	4.7
RMS field error (%)	0.1
B-field tuning range (%)	>37

Figure 5 illustrates the basis of the high-field design, and Fig. 6 shows the pole piece configuration. The permanent magnets are placed adjacent to the iron pole pieces to bias the B-H curve of the iron to higher field strengths. In the process, the linear range of operation is reduced as indicated in the figure. For the IMP design, the maximum field is operated at an acceptable value of about 85% of the Halbach limit, and a 50% tuning range is achieved. The IMP wiggler is presently in fabrication. Assembly and testing will occur this summer, with installation planned for this fall.

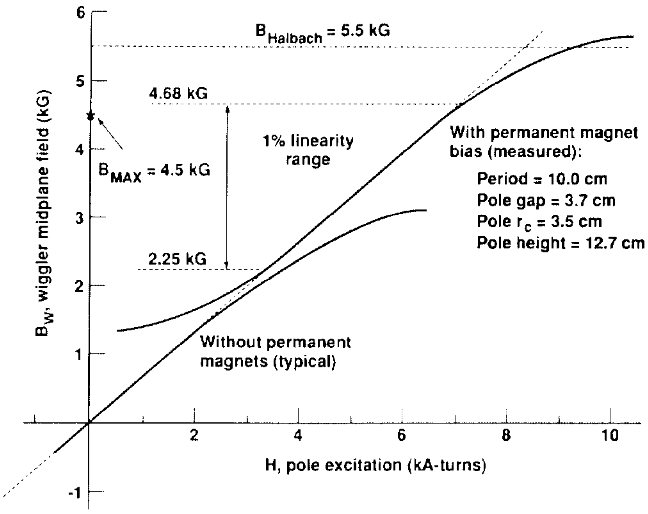

Figure 5. B-H curves for IMP wiggler with and without permanent magnets.

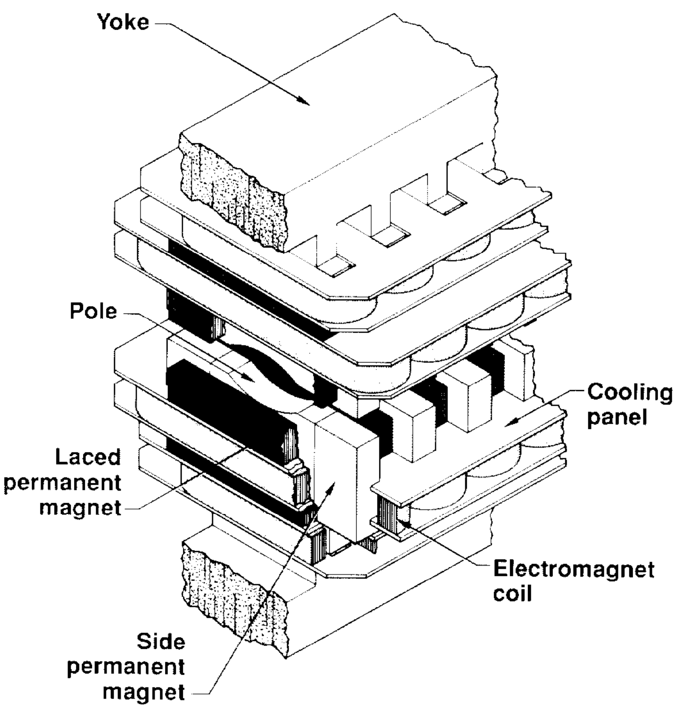

Figure 6. Pole piece design for laced electromagnetic wiggler.

Microwave System

Figure 7 shows an elevation view of the microwave system for the 250-GHz FEL. A 5-kW gyrotron is used as the master oscillator and has been tested off line. A Vlasov coupler is used to launch a free-space Gaussian beam, which is then coupled into the wiggler using the mirror coupler described above.

Four primary mirrors transmit the FEL output to the tokamak over a 20-m distance in a 20-in.-diam evacuated pipe. At millimeter wavelengths and for high peak powers, quasi-optical transport is favored over waveguide methods due to attenuation and surface heating. The transmission system for the IFEL is windowless, thereby avoiding thermal and bandwidth issues associated with using a window at high average power and with a tunable source. The mirrors are approximately 44 x 58 cm in diameter and are being fabricated with a 5-μin. finish. Alignment tolerances are not severe - about ± 3 mm at each mirror. Simulations predict an overall transmission loss of less than 8% at 250 GHz, with most of the loss (4%) occurring at the first mirror due to loss of sidelobe power in the antenna pattern from the FEL waveguide.

Two major issues in a high-power microwave FEL are surface breakdown and thermal heating in the interaction waveguide.[10] Figure 8 shows the waveguide geometry. The waveguide is highly overmoded (d/λ = 30) and operates in the TE_{11} mode, as determined by the FEL resonance condition. An elliptical waveguide is shown since it provides additional margin to keep the beam fill factor at less than 50%. The first experiments to be conducted will use a circular waveguide of equivalent area for ease of fabrication.

At millimeter wavelengths, surface heating, rather than surface breakdown, determines the maximum power limit in the waveguide. With 10 GW of peak power, the maximum surface fields will be about 140 MV/m. Based on an extrapolation of Stanford Linear Accelerator Center data for 3-10-GHz, 2.5-μs-wide pulses, the threshold for surface breakdown for a 250-GHz, 50-ns pulse is over 5000 MV/m. A threshold of 360 MV/m measured using the 35-GHz FEL and an unconditioned cavity, extrapolates to a threshold of 1000 MW/m. Thus, surface breakdown is not expected. Multipacting is also of concern, but the experiment operates outside of the range for multipacting in either a field-free region ($0.07 < fd < 10$ GHz·cm; IMP = 750 GHz·cm) or in the presence of the wiggler field ($0.2 < f_c/f < 1$; IMP = 0.04). In addition, the 50-ns pulse length is much less than the volume ionizaton time for the vacuum quality of interest (10^{-6} Torr).

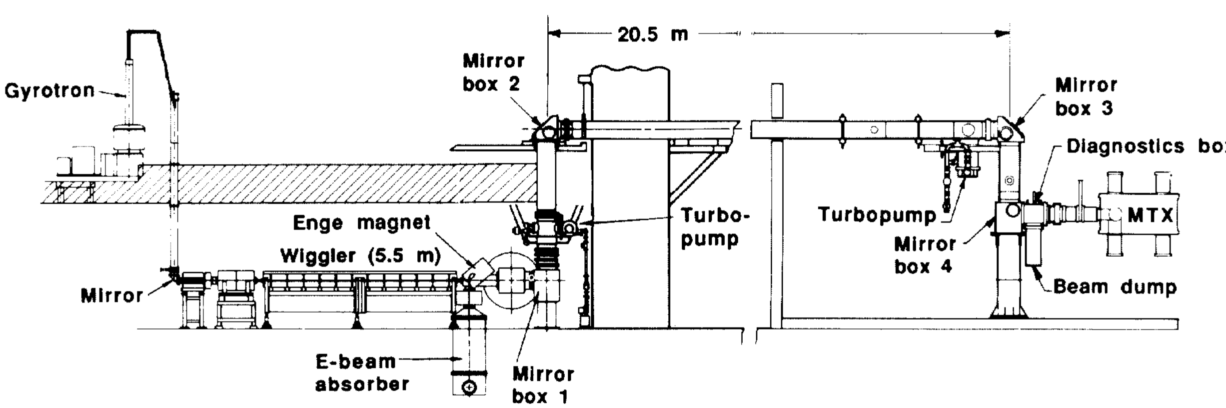

Figure 7. Elevation view of microwave system for 250-GHz FEL.

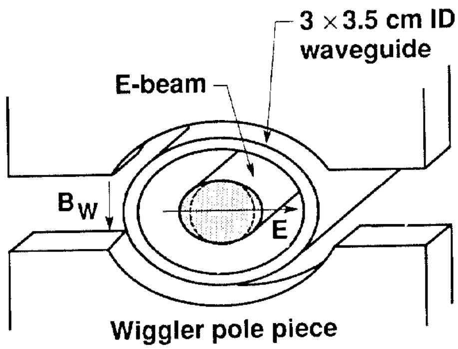

Figure 8. Interaction waveguide geometry.

The peak surface-wall load is a unique issue for the IFEL because of the intense field strengths that occur over the last 1-2 m of the interaction waveguide. At 10 GW of peak power, the peak wall loads are 0.07 J/cm^2 per pulse, which is about 10% of the damage threshold measured for an uncoated copper surface. In general the temperature rise is kept to less than 30°C during the 50-ns pulse to avoid surface fatigue. Thus, for the MTX experiment, the peak wall loads are not expected to be a major issue. For operation at higher average powers in ignition tokamaks, a corrugated waveguide that operates in the low-loss HE_{11} mode will be used.

At 2 MW of average power, the peak wall loading is 300 W/cm^2 near the end of the interaction waveguide. For the 0.5-s shot duration of the MTX experiment, thermal inertia will limit the temperature rise of the wall to less than 80°C so that only low levels of cooling between shots will be required. Again, for higher power devices and long-pulse operation, the use of a corrugated waveguide will reduce the average wall loading to a tractable value.

Plans for Experiments

The first series of FEL and plasma heating experiments is planned for this summer. While the IMP wiggler is in fabrication, the air core wiggler used in the previous ELF experiments will be used for early "single-pulse" experiments at 140 GHz. This will require ETA-II to operate at 6 MeV and 2.5 kA and is expected to produce up to 2 GW of peak power. These experiments will allow first evaluation of the ETA-II beam for driving an FEL, will test the microwave transmission system, and will allow preliminary studies of the coupling of intense microwave pulses to the plasma.

During FY90, after installation of the IMP wiggler, experiments will continue at 140 GHz but with 5-kHz pulse trains of up to 10-ms duration. This pulse train will deliver over 6 kJ of energy to the plasma for bulk heating experiments, and will begin to address issues of high average-power transport of both the electron and microwave beams.

Operation at 250 GHz for 0.5 s will require an upgrade in ETA-II power conditioning and energy as well as changes in the master oscillator and microwave diagnostics. This is expected to be completed during FY91, allowing ECH experiments at higher tokamak fields and densities, near to those of interest to CIT and ITER.

Summary

The technology for constructing a multi-megawatt FEL operating at millimeter wavelengths appears feasible using the induction linac. The ability to transport and use bright, high-power electron beams for an FEL will be developed on the ETA-II and IMP Facilities. The MTX experiment will investigate the ability to transport intense microwave beams, to couple them efficiently to the tokamak plasma, and to use predicted nonlinear effects for current drive and other advanced concepts.

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