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ABSTRACT

Microwave pulses have been injected from a free electron-laser (FEL) into the Microwave Tokamak Experiment (MTX) at up to 0.2 GW at 140 GHz in short pulses (10-ns duration) with O-mode polarization. The power transmitted through the plasma was measured in a first experimental study of high power pulse propagation in the plasma; no nonlinear effects were found at this power level. Calculations indicate that nonlinear effects may be found at the higher power densities expected in future experiments.

1. INTRODUCTION

The primary goal of MTX [1] is to study electron-cyclotron resonance heating and control of a high-density tokamak (Alcator C) by microwaves from an FEL or a gyrotron. Here we report the first measurements of high peaked-power microwave absorption in the plasma. Microwaves were generated by the FEL, and their transmission and absorption in MTX were experimentally evaluated. In agreement with theory, nonlinear effects [2] were not found at these power levels (0.2 GW) but are predicted at higher levels.

2. FREE-ELECTRON LASER OPERATIONS: MICROWAVE GENERATION AND TRANSMISSION TO MTX

For the microwave transmission and absorption experiments, the ELF-II wiggler (9.8 cm wiggler wavelength and 4 m total length) was used [3]. With nontapered operation of the wiggler, peak power levels up to 0.2 GW and pulse lengths up to 10 ns were achieved at 140 GHz. Figure 1 shows an experimental gain curve for the wiggler, obtained by varying the wiggler length (number of energized magnets). At the available drive power and electron beam current, the FEL interaction just reached saturation. Operation with the wiggler tapered achieved 0.4 GW, but this power level was not used during tokamak experiments.

The FEL microwave pulse was injected into the windowless, quasi-optical transport system [4] for transmission to the tokamak. This system consists of an evacuated, stainless steel pipe of 50 cm diameter; six aluminum mirrors transmit the beam 33.3 m. Measurements outside the tokamak port demonstrated that the transmitted microwave beam envelope was well approximated by a Gaussian curve, in good agreement with theory.

3. ABSORPTION PHYSICS EXPERIMENTS

FEL-produced microwave pulses were injected into the tokamak for a variety of plasma parameters. Local measurement of the transmitted fraction of injected power was made using a microwave horn located just below the midplane on the inside wall of the tokamak. At toroidal magnetic fields sufficiently high (6.5 T) that there was no electron-cyclotron resonance in the plasma, the transmitted power showed the expected drop to negligible levels as the peak density approached cutoff. Ray-tracing calculations [5] based on measured density profiles qualitatively reproduced the observed falloff in transmitted power vs. density, indicating that refraction was strong enough to be the dominant mechanism for the measured result.

Experiments were also performed with a central magnetic field of 5.0 T so that the cyclotron resonance passed through the plasma center. Figure 2 shows the data from these experiments compared to ray-tracing calculations of refraction effects and of the additional effects of linear absorption. Analysis indicates that the FEL power levels were below that at which nonlinear absorption [2], Brillouin backscatter instabilities [6], and pondermotive self-focusing [7,8] are important.

The transmitted power fraction data from the FEL experiments are shown by solid circles. For comparison, the upper hatched region shows the calculated effect of refraction alone. This region spans the range o plasma density profiles ($\alpha_n = 0.5$–1.0, where $n(r) = n(0)\,[1-(r/a)^2]^{\alpha_n}$) measured in the experiments. The lower hatched region shows the combined effects of refraction and linear absorption. This band spans the range of density profiles and electron temperatures (0.5–1.0 keV) observed. Within the variation, there is no evidence that non-linear saturation of the absorption plays a role in these experiments, in agreement with theory [2].

Data from 5.0-T experiments at low power (1 W) and long pulselength (1-2 μs) are shown as squares in Fig. 2. The bars on the data points represent the RMS variation in the amplitude of the microwave horn signal during the pulse. These variations also occurred in the high power experiments. Ray tracing calculations with edge-density fluctuations predicted scattering of 10–15% of the power through angles of about 20°, insufficient to explain the observed signal variations. The timescale of the variations is also much shorter than for edge turbulence periods. Multiple spatial modes (generated by wall interaction in the narrow MTX access duct) together with time varying, multipath transmission of power through the plasma (due to edge turbulence) could produce a rapidly varying interference pattern on the tokamak inside wall. This might account for the variations in the observed signals. Experiments are planned to quantify these effects.

4. INTENSE WAVE ISSUES

4.1. Ponderomotive self-focusing

Ponderomotive self-focusing calculations are relevant for future high-power microwave propagation experiments in MTX. Numerical solutions of a scaled, paraxial self-focusing equation for ordinary modes perpendicularly incident to an applied magnetic field show qualitative differences from theories in which the laser beam remains Gaussian: self-focusing occurs in a shotrer distance and the beam does not remain Gaussian [8]. In the limit that ion inertia is neglected, calculations for $T_e = T_i = 1$ keV, 3-cm beam radius, $\omega_{pe}^2/\omega^2 = 0.5$, f = 140 GHz, and $v_o/v_e = 0.24$ (0.1 GW/cm^2 at 1 keV core temperature) show that self-focusing would occur near the magnetic axis in 3–5 ns. The numerical studies further indicate that the self-focusing time and distance increase approximately as $(v_o/v_e)^{-1}$ for powers above threshold for self-focusing in agreement with a self-similar analysis [7]. Thus, self-focusing is less severe for higher plasma temperatures and larger beam cross sections, which will make FEL heating applications in CIT less susceptible to self-focusing than in MTX.

Our numerical calculations overestimate the degree of self-focusing because they do not include several effects that significantly delay or prevent the focusing: ion inertia [7], scattering by edge fluctuations that increase the effective beam divergence, and absorption. Analytical and numerical calculations including ion inertia [7] and additional numerical calculations including absorption, plasma profiles, and beam divergence with ion inertia omitted [8] have shown that these effects greatly reduce the amount of self-focusing expected in MTX. These calculations also indicate how self-focusing can be avoided; e.g., increasing the beam divergence in the plasma.

4.2. Microinstability

Microinstability of the FEL-heated electrons could rapidly relax the distribution function, thus affecting nonlinear physics. We have developed a new computer code that solves the electromagnetic linear dispersion for a relativistic plasma with an arbitrary distribution [9]; and we have analyzed distributions predicted by a particle-orbit code for whistler, upper-hybrid loss-cone (UHLC) and cyclotron-maser instabilities in an infinite homogeneous geometry. For a representative distribution we chose the one generated by injecting into an MTX plasma (at 5 T) 2 GW of power at 140 HHz in a beam with cross section of 6 x 8 cm. At a typical density given by $\omega_{pe}/\omega_{ce} = 0.6$, the whistler mode has a maximum growth rate of $\gamma/\omega_{ce} = 7 \times 10^{-3}$, the UHLC mode has $\gamma/\omega_{ce} = 5.6 \times 10^{-3}$, and the cyclotron-maser mode is stable. The UHLC mode is unstable for a range of wave numbers $0.3<k_{\parallel}c/\omega_{ce}<1.5$ and $12<k_{\perp}c/\omega_{ce}<22$. The cyclotron-maser mode becomes unstable at a lower density, $\omega_{pe}/\omega_{ce} \approx 0.3$. The maximum growth rates for the whistler and UHLC modes increase monotonically with density in ranges of interest. Thus, high frequency linear microinstabilities should be observable in the operating regime of MTX and could enhance the relaxation of the heated distribution.

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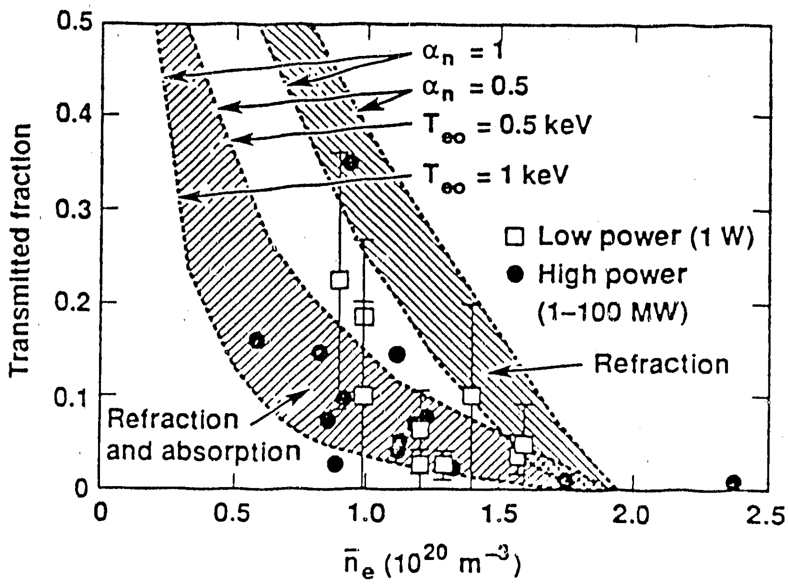
FIGURE CAPTIONS

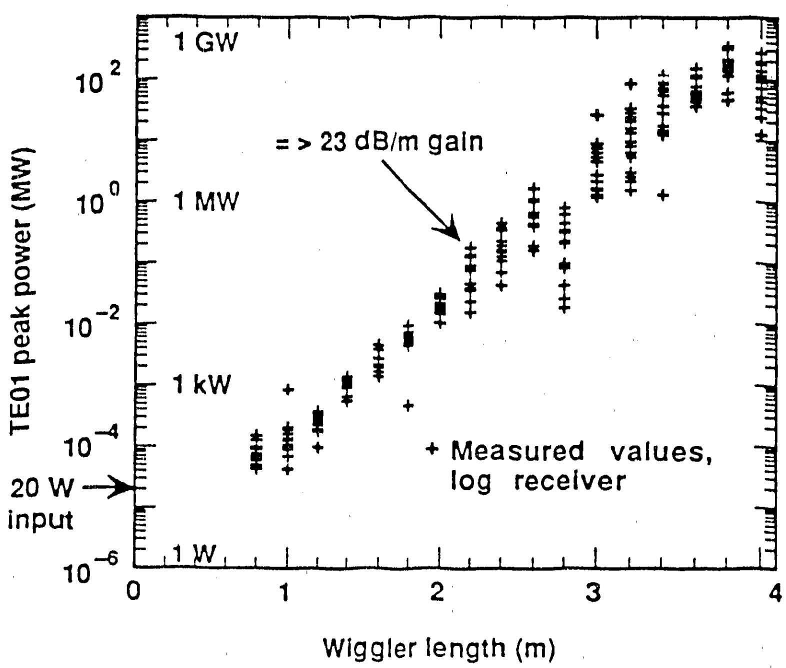
FIG. 1. Measured Gain curve for nontapered FEL operation at 139.9 GHz. The electron beam parameters were 6 MeV, 2 kA, and 50 ns pulse length. The input drive power was 20 W from an extended interaction oscillator (EIO) source, injected into the wiggler waveguide co-linear with the electron beam.

FIG. 2. Measured plasma transmission for FEL and EIO power for resonance at plasma center. See text for discussion.



0.5
0.4
0.3
0.2
0.1
0
Transmitted fraction
α_n = 1
α_n = 0.5
T_{eo} = 0.5 keV
T_{eo} = 1 keV
Low power (1 W)
High power
(1–100 MW)
Refraction
Refraction
and absorption
0
0.5
1.0
1.5
2.0
2.5
$\bar{n}_e$ (10^{20} m^{-3})

Fig. 1



1 GW
10^2
=> 23 dB/m gain
10^0
1 MW
10^{-2}
1 kW
10^{-4}
20 W input
1 W
10^{-6}
+ Measured values, log receiver
TE01 peak power (MW)
0
1
2
3
4
Wiggler length (m)

Fig. 2

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