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Electron Cyclotron Resonance Heating in the Microwave Tokamak Experiment

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ELECTRON CYCLOTRON RESONANCE HEATING IN THE MICROWAVE TOKAMAK EXPERIMENT*

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Abstract

ELECTRON CYCLOTRON RESONANCE HEATING IN THE MICROWAVE TOKAMAK EXPERIMENT.

This paper presents the results from a series of Electron Cyclotron Resonance Heating (ECRH) experiments on the Microwave Tokamak Experiment (MTX). On-axis heating at B_T=5T (f_{ce}=140 GHz) has been performed at electron densities up to cutoff (n_e=0.5-2.5 x 10^{20} m^{-3}). We have used both a long-pulse gyrotron (~200 kW, ~0.1s) and a pulsed Free Electron Laser (FEL) (1.4 GW, ~30ns, single pulse) as microwave sources. Gyrotron experiments with power densities corresponding to 4 MW m^{-3} resulted in bulk heating of $\bar{n}_e \Delta T_{eo}$ up to 1x10^{20} keV m^{-3}. A far infrared (FIR) polarimeter measured peaking of plasma current profiles in some discharges during the ECRH pulse. During high-power single-pulse FEL experiments, single-pass microwave transmission measurements show nonlinear effects; i.e., higher transmission than predicted by linear theory. A corrugated-wall duct was used in the tokamak port to increase the gradient of the parallel refractive index $n_{\parallel}$ of the incident wave, and increased absorption was observed. Evidence of electron tail heating during FEL pulses was observed on soft x-ray and ECE diagnostics. These results are in agreement with predictions of nonlinear theory; extrapolation of this theory to reactor-like conditions indicates efficient absorption and heating. A Laser Assisted Particle Probe Spectroscopy (LAPPS) diagnostic provided estimates of

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the vacuum electric field of the FEL which were consistent with the measured power. Multiple pulse (5 kHz, 50 pulse burst) operation of the ETA-II accelerator for the FEL has also been demonstrated, indicating the feasibility of high-average power FEL operation.

1. INTRODUCTION

ECRH will be an important tool in future tokamaks for heating, plasma control, and current drive. Because it is a resonance technique, very localized heating is possible, which in turn enables localized control of plasma profiles and disruptions. Efficient absorption is achieved with launching structures far removed from the plasma edge. Enhanced confinement such as the H-mode has been achieved with ECRH [1,2].

One major issue with the use of ECRH is the efficient and reliable generation and transmission of high power microwaves at the required frequencies. Machines such as the International Thermonuclear Experimental Reactor (ITER) are designed with a toroidal field in the 5 T range, requiring microwave sources with frequencies of ~140 GHz for fundamental heating; we describe here the first ECRH experiments at 140 GHz. Current high power technology uses a fixed-frequency gyrotron coupled with a waveguide system to a transmitting horn near the plasma. The goal of the MTX experiments is to compare this conventional approach with microwaves generated by a FEL. For both systems, we have utilized a new, efficient quasi-optical transport system. When fully developed, the FEL provides several advantages, including the generation of power in the desired mode (e.g., HE_{11}), and the capability to sweep the microwave frequency and thereby the heating zone in the plasma.

The present discussion first describes gyrotron heating experiments on MTX (Section 2). We then discuss in Section 3.1 recent advances in FEL technology that have enabled the generation of ~2 GW single pulses at 140 GHz. Pulses from the FEL were injected into MTX plasmas for transmission measurements, which are discussed in Section 3.2. Recent burst mode operation and a summary are presented in Section 4.

2. GYROTRON HEATING EXPERIMENTS

A 140 GHz gyrotron (one in a series under development by Varian) was used to inject microwaves (~200 kW, 0.1 s) into the MTX plasma at 5T for on-axis fundamental O-mode heating experiments. In Fig. 1, we present on-axis T_e data from a 15-channel ECE polychromator during three different plasma conditions. In Fig. 1a, the T_e increase is due to injection of a 200 kW ECRH pulse into a quiescent discharge ($\bar{n}_e = 0.9\times10^{20}$) with an ohmic input of ~450 kW. The ohmic neo-Alcator τ_E^{na} for this shot is 9 ms; the central T_e increased in 3-6 ms, and the τ_{Ed} decay obtained from a specially-compensated diamagnetic loop is nearly

equal to τ_E^{na}. In Fig. 1b, we present a case where T_e is decreasing prior to the ECRH pulse due to increases in radiated power (presumably due to increases in impurity radiation). On a similar shot without ECRH, the shot disrupted, and FIR polarimetry shows a hollow plasma current density j(r) profile[3]. Injection of ECRH causes a recovery of the discharge to a normal, sawtoothing plasma. In Fig. 1c, the discharge begins in a low temperature (radiation dominated) mode, and application of ECRH causes recovery into a normal sawtoothing shot. FIR polarimetry data show that j(r) (and $\propto T_e(r)^{1.5}$-dotted line) goes from a hollow profile (Fig. 1d) before ECRH to a peaked profile (Fig. 1e). These data demonstrate the bulk heating (Fig. 1a) and plasma control capabilities due to localized heating (Fig. 1b-d) of ECRH at high frequency.

3. MICROWAVE TRANSMISSION MEASUREMENTS WITH THE FEL

3.1. Advances in FEL technology-generation of 2 GW pulses

Initial FEL experiments on MTX [4] were limited to ~200 MW single pulses; no evidence of nonlinear absorption was seen at this power level, as expected. To reach higher power levels (several GW), theoretical models [5] indicated we needed to reduce the corkscrew motion of the electron beam from 1 cm to about 0.1-0.2 cm, with an energy sweep of ±1%

Several accelerator modifications to implement these changes were first done on a 3 MeV section (20 cell modules) of the ETA-II accelerator. After successfully tested, they were added to the remaining 60 cells. The energy regulation was improved with a multi-cable distribution system to the induction cells, resulting in ± 1% energy stability for 35 ns at the ~6 MeV operating point. The corkscrew beam motion, which is due to energy sweep and the magnetic misalignment of the ETA-II solenoidal transport system, required new alignment methods. Better alignment during construction was achieved with a Stretched Wire Alignment Technique (SWAT)[6] in which misalignments cause deflections in a current pulse propagated in a wire stretched on the axis of the accelerator. During electron beam operations (1Hz), a computerized system (MAESTRO) achieves better alignment by minimizes the corkscrew motion directly. The computer scans the current in a pair of magnetic trim coils in each induction cell while the beam motion is measured and the corkscrew is computed. Usually, a minimum is found in the motion as a function of trim coil current for each cell, in agreement with theory[7]. All of the 120 trim coils can be adjusted by the MAESTRO system in a few hours. Once the tuning is completed, the corkscrew motion is reproducible from day to day. The result of the modifications is that the measured beam motion at 6-6.6 MeV, 2.5 kA is 1.5 mm[8], an improvement of an order of magnitude over previous operations. Coupled with the beam energy results, the beam quality required by theory was achieved.

The output of the ETA-II accelerator is coupled to the IMP wiggler with a set of magnetic lenses. The IMP wiggler is a steady-state hybrid laced wiggler; i.e., it uses a combination of permanent and electromagnetic magnets and can be tuned to resonance (matching the beam energy) and tapered (varying the

magnetic field with length to keep the electron beam and wave in resonance). Careful alignment resulted in magnetic errors less than 0.2%, again comparable to requirements based on theoretical models.

The FEL is operated in an amplifier mode. The gyrotron (mentioned above) was reconfigured and used as the master-oscillator driver; the estimated input drive power was 7 kW. The first ~2m of the wiggler is operated at a constant field of ~3 kG, in resonance with the ~6 MeV beam energy. Beyond this point, the wiggler was empirically tapered to maximize the output power.

Efficient tapering resulted in an output power at the FEL of nearly 2 GW, a new high-power achievement at 140 GHz (1 GW was produced at 35 GHz [9]). The microwave power was measured at the FEL output with a calibrated receiver and at the input to MTX with a calorimeter supplied by JAERI. Peak powers as large as 1.4 GW were measured at MTX, implying a transmission of at least 70% compared to a theoretical 89%; detailed comparisons are in progress. Spatial measurements of the FEL output power were consistent with a TE_{11} mode. Estimates of the electric field of the FEL (vacuum-no plasma) were obtained by the LAPPS [10] diagnostic and are consistent with the measured ~1 GW input power.

3.2 High-Power Microwave Transmission Measurements in MTX Plasmas

A single high-power FEL pulse was injected into each MTX discharge. Two diagnostics, mounted on the inside wall of the tokamak, are used to measure the single-pass transmission data: a 48 channel calorimeter which measures transmitted energy and a single channel microwave horn which measures transmitted power versus time. Normalizations (e.g., signals during no-plasma shots) are applied to the data to obtain fractional transmission data.

A complete comparison of the transmission data with theory is beyond the scope of the present discussion. Representative transmission data from the central channels of the calorimeter (± 2 cm) for high power pulses (solid circles) as a function of the central electron density are presented in Fig. 2. The peak input FEL power for these data ranges from 0.8 to 1.3 GW; the energy is 20-30 J per pulse. For reference, low-power (driver only ~5 kW) transmission data (diamonds) from the on-axis microwave horn are also shown; these data agree with linear transmission theory corrected for refraction. Note that the high power transmission is greater than that at low power, as predicted by nonlinear theory [11]. Detailed comparisons of these data with theory are in progress; we present in Fig. 2 one theoretical calculation of on-axis transmission (solid line) for 1GW input power with a correction for refraction. Here, we have performed only semi-quantitative comparisons of this theory curve with data because of several details, including the variation of the power across the calorimeter tiles and off-axis refraction corrections. Detailed code modeling is in progress to address these issues.

The reduced nonlinear opacities, validated by (low T_e ~1 keV) experiments here, are not limiting for future machine applications such as ITER (with much higher T_e). Additionally, the absorption can be increased[12] (in

some cases, even above linear theory) by increasing the gradients in $n_{\parallel}$. To test this theory, a corrugated-wall tapered insert was installed in the MTX port to diffract the microwave beam and thereby increase the microwave beam divergence. These transmission values (open circles) are less than those without the insert, indicating that the absorption is increased. For semi-quantitative comparison, a 1 GW theory curve (dotted line) is included for comparison.

Several diagnostics were used to measure the presence of hot electrons in the plasma: a fast multi-channel (energy and spatial) x-ray system provided by JAERI, several ECE systems (including a heterodyne detection technique), and a Thomson scattering system (emphasizing the spectrum away from the bulk). All of these diagnostics observed increases in signals during operation with the insert(i.e., conditions with better single-pass absorption). Estimates from x-ray measurements indicate electron energies in roughly the 3-30 keV range; signals increased with increasing input power.

4. SUMMARY

We have performed the first ECRH experiments at 140 GHz on MTX using a gyrotron and a high-power (1-2 GW) FEL. Gyrotron experiments demonstrated plasma heating and control. During FEL experiments, the measured microwave transmission was greater than at low power; these results are in semi-quantitative agreement with theory. Nonlinear absorption can be increased by either increasing the electron temperature or increasing the gradient in the parallel index of refraction. Experiments on MTX showed absorption was increased by increasing the divergence of the microwave beam. Detailed comparisons of the transmission data with theory are in progress.

Recently, burst mode operation of the ETA-II accelerator has been demonstrated. Each power supply has been operated independently for 50 pulses at a 5 kHz repetition rate. The whole accelerator has been operated at 1 kA, 3 MeV at 2 kHz with a new timing feedback system. Six-pulse bursts have been achieved at full beam parameters (2 kA, 6 MeV). These results indicate the feasibility of high-average power FEL operation.

We acknowledge the extremely useful collaboration with the JAERI group on MTX. Support by the MTX and ETA-II engineering and technician groups was essential for the overall success of this experiment. This work was performed under the auspices of the US Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

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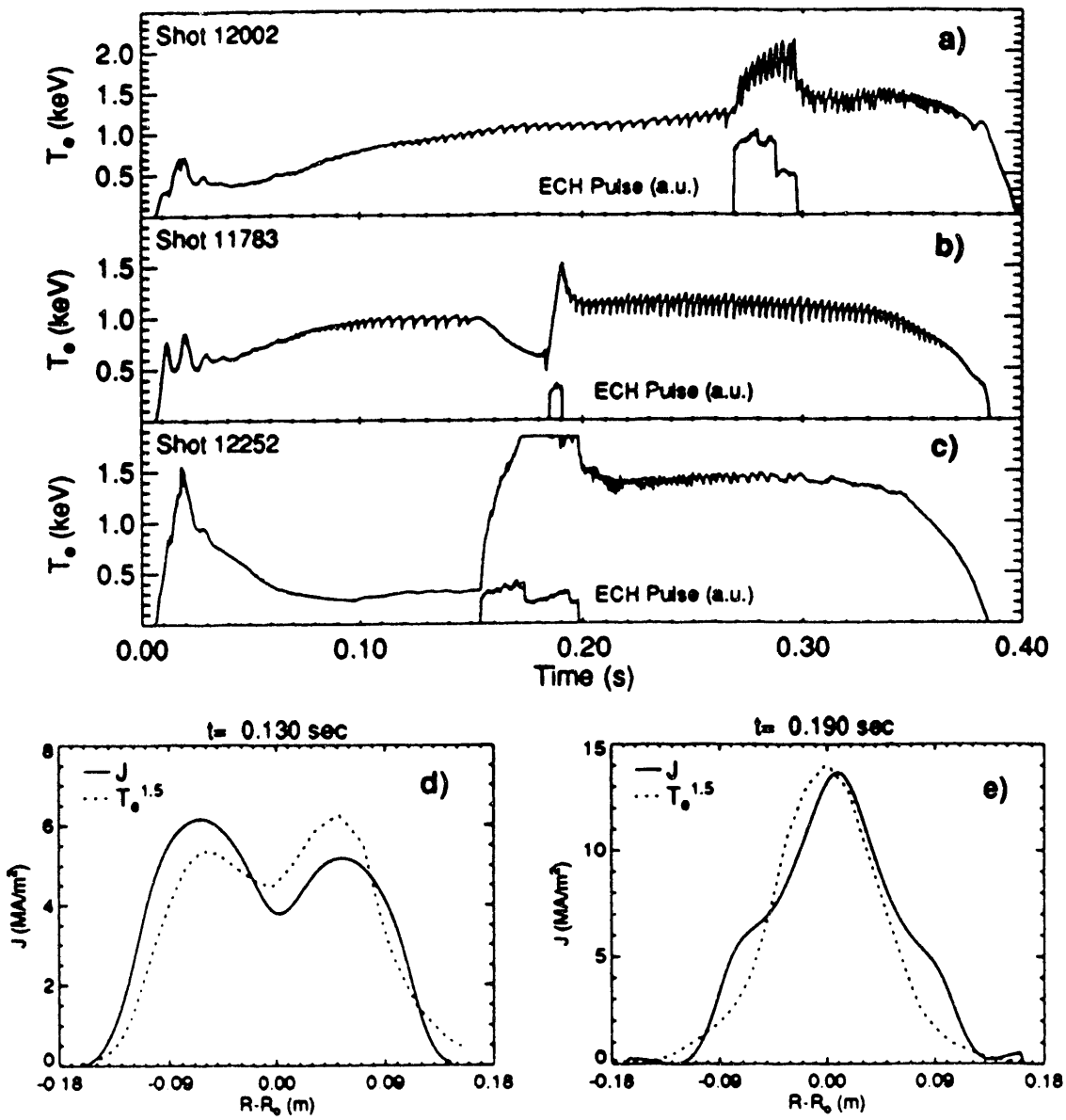
FIGURE CAPTIONS

Figure 1 Electron temperature data from ECE during gyrotron ECRH heating experiments. In a), the temperature rise during a 200 kW injection during a quiescent discharge is shown. In b), increases in radiated power cause a decrease in T_e and sawtoothing stops; injection of ECRH restores the discharge to normal. On similar shots without ECRH, the discharge disrupted, and data from the FIR polarimeter show hollow j(r) profiles. In c), large radiated power at the beginning of the discharge causes low T_e and nearly a disruption; application of ECRH restores the discharge. The j(r)(solid) and $\propto T_e(r)^{1.5}$ (dashed) profiles before d) and after e) ECRH are also shown.

Figure 2 Representative FEL microwave transmission data from the central channels of the calorimeter. Data from high power FEL shots both without (solid circles) and with (open circles) an insert to increase the divergence of the microwave beam are shown. Low power data (from an on-axis microwave horn) are presented (diamonds) for reference; these agree well with linear theory corrected for on-axis refraction. Theoretical calculations of nonlinear absorption at 1 GW with (on-axis) refraction are shown for cases with and without the insert.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Shot 11783
b)
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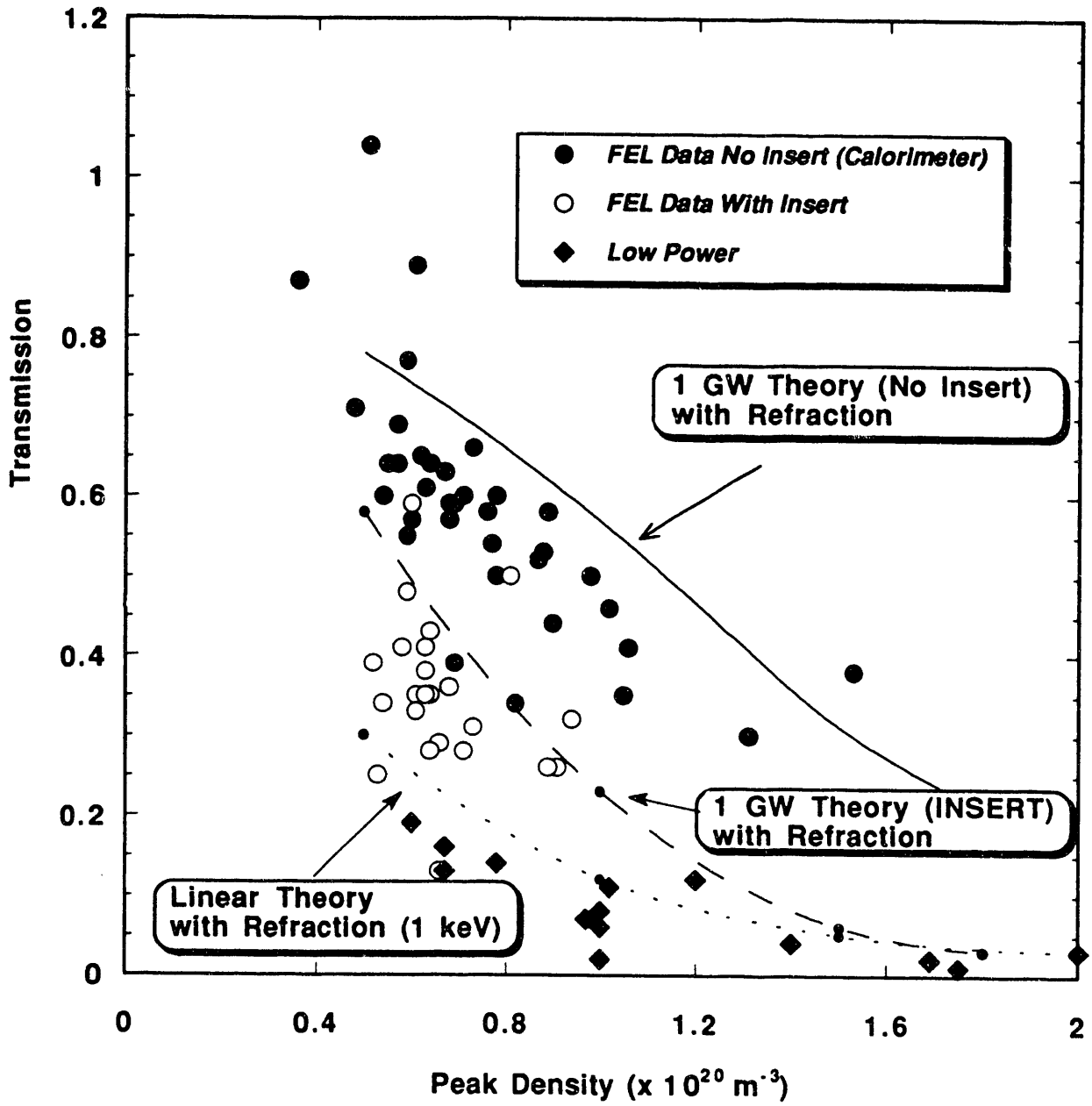
J (MA/m²)
R-R₀ (m)
t= 0.190 sec
e)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0.6
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Transmission
0
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FEL Data With Insert
Low Power
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1 GW Theory (INSERT) with Refraction
Linear Theory with Refraction (1 keV)

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