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ECH Propagation and Absorption Experiments at 140 GHz in MTX*

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ABSTRACT

Single pass absorption experiments using fundamental, O-mode ECH waves have been performed in the Microwave Tokamak Experiment (MTX) and found to be consistent with linear absorption theory, as predicted for the ECH source which is a 140 GHz, 400 kW CW gyrotron. These experiments provide the basis for comparison with future Free Electron Laser (FEL) experiments in which the absorption is predicted to be in the non-linear regime for $P_{FEL} \geq 1$ GW. The gyrotron power is coupled into a quasi-optical transmission line to the tokamak by a Vlasov antenna. The input power is measured by calorimeters located just outside the injection port and on the vacuum wall opposite the port. For plasma shots, the total transmitted power and its profile are measured. Temporal analysis of the thermistor signals compared with a heat diffusion model for the tiles gives the spatial profile of transmitted power. These measurements are compared with the stored energy increase by diamagnetism measurements, 3-D vacuum fields calculations and ray-tracing calculations of the transmitted power.

INTRODUCTION

For the most recent run of MTX a 140 GHz, 400 kW, gyrotron was used in single pass linear absorption and bulk heating experiments. The plasma conditions were similar to those required for the non-linear heating experiments with the ETA-II/IMP FEL planned for the Spring of 1992. A direct comparison of linear vs. non-linear absorption will then be made. The diagnostics used to analyze these experiments and compare with linear theory include two highly absorbing microwave calorimeters (1) mounted outside the injection port, and (2) mounted on the vessel wall opposite the injection port, for measuring injected and single pass transmitted power, respectively; a fast ECE polychromator for electron temperature measurements; and a 15-channel FIR interferometer/polarimeter to measure the electron and current density profiles. The plasma stored energy is measured with diamagnetic loops.

ECH POWER SYSTEM FOR MTX

The ECH power system for MTX consists of: (1) a 400 kW, 140 GHz gyrotron producing power nominally in the $TE_{15,2}$ mode, (2) a Vlasov-type coupler with two double-curved focusing optics illuminated by a spiral cut waveguide, and (3) a four mirror, quasi-optical transmission line of 0.5 m diameter and 35 m total length. Microwave power values at the gyrotron output and at the MTX input port are measured calorimetrically. The microwave beam profile was measured at several locations by small movable waveguide probes. The microwave power measured at the MTX input is typically ≤ 200 kW for gyrotron output of approximately 400 kW. Losses in the system arise from: (1) ECH power in modes other than the $TE_{15,2}$ mode, (2) transport loss of side lobe power in the output beam of the Vlasov coupler, (3) small waveguide losses from the gyrotron to the Vlasov, and (4) small transport loss of the quasi-optical transmission line.

Figure 1 shows the microwave profiles at the transmission line output. The high frequency spatial ripples are sensitive to alignment and are believed to arise from interference between the main beam and beam "edge power" reflected from the transmission pipe walls. The beam was

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aligned into MTX using an IR camera viewing microwave absorbers surrounding the 4 cm wide, 30 cm high port. The diameter of the nearly circular beam at the port was about 3 cm.

THEORETICAL MODEL

The propagation of the microwave beam through the 35 m transmission line is calculated with a 3-D vacuum fields (Huygens integral) code.¹ Transmission of the beam through the tall, narrow MTX access duct, including duct waveguide effects, is calculated as described in Ref. 2.

For the present experiments, the final focussing mirror produces a nearly circular beam waist at the entrance to the MTX duct. This reduces the vertical spreading of the beam as compared with previous experiments.³ The microwave transmission calculations show that the beam waist dimension, w_0 , is about 1 cm. This means that the propagation lengths are of order 1-2 Rayleigh lengths, $Z_R \equiv \pi w_0^2 / \lambda \approx 15$ cm for $\lambda = 2.1$ mm, so that diffraction is important. In addition, for the smooth wall duct used in these experiments, a mixture of modes is launched from the duct which interfere in the plasma.

Ray-tracing for electron cyclotron wave propagation in MTX is done with the TORCH code.⁴ To determine the launch angles and locations of the rays, the microwave beam launched from the MTX port is modeled as an elliptical Gaussian beam.⁵ The beam interference effects are modeled by launching rays perpendicular to a wavefront such that in the absence of plasma refraction effects, the ray propagation to the center would yield a Gaussian approximation to the wavefront calculated by the Huygens integral code (horizontal and vertical radii of curvature, $R_c^h = 33.7$ cm and $R_c^v = 28$ cm, respectively).

The ray launch locations are calculated such that each ray represents the same fraction of the total beam power. Power represented on the tokamak calorimeter by ray hit locations is smoothed onto a regular grid from which power density contours can be generated.⁵ These contours and the calculated fractional absorption over the beam are compared with the measured power density profile and total absorbed energy on the calorimeter.

ELECTRON TEMPERATURE MEASUREMENTS

The electron temperature in MTX is measured with three diagnostics; a single-point Thompson scattering system, a Michelson interferometer, and a fast grating polychromator. The rapid-scanning Michelson interferometer is calibrated using a liquid-nitrogen temperature blackbody to give relative calibrations between different frequencies. Thomson scattering data from the same plasma discharge is used to set the overall scale factor. The signals for the nine channels of the ECE grating polychromator are then scaled to agree with the intensities measured at the corresponding frequencies by the Michelson. The polychromator has sufficient time resolution (down to 2-3 microseconds; 300 microseconds as processed in the data shown) to track the fast temperature changes occurring in the plasma. The Michelson interferometer has 15-millisecond time resolution.

ANALYSIS OF ABSORPTION AND HEATING

Initial analysis indicates that theoretical predictions of plasma refraction and single pass absorption are consistent with experimental measurements. Shot 11656, chosen primarily because a measurable stored energy increase was observed during the rf pulse and a sufficient number of the diagnostics were working to allow a complete ray-tracing analysis to be done, is used as an example. Individual shots with higher observed stored energy increase (up to 1 kJ or 15% of the pre-rf stored energy) and larger central electron temperature increase (up to 800 eV, approximately an 80% increase in $T_e(0)$) have been obtained. Analysis of these and other shots, including any effects of ECH on current profiles measured by the polarimeter, is underway.

The time history of Shot 11656 is shown in Fig. 2. The gyrotron pulse came on at about 135 ms and lasted for 30 ms. The line averaged density during this period was about $\bar{n}_{20} = 1.15$ (peak

density, $n_{20}(0) \approx 1.7$), well below the cutoff density, $n_{c,20} = 2.45$ for 140 GHz, fundamental, O-mode ECH waves at $B_0 = 5$ T ($n_{20} \equiv n/10^{20} \text{ m}^{-3}$). The sawtooth averaged, central electron temperature prior to the shot was approximately 1.1 keV. The temperature profiles are shown in Fig. 3 at the time of central sawtooth peaks, before gyrotron turn-on and at the time of peak temperature increase. The heating resonance is at the center, and the heating is also strongly peaked about the center.

The ECH power level during the pulse was monitored with a waveguide horn inserted into the edge of the beam just outside the tokamak entrance duct. The uncalibrated signal from this horn showing considerable time variation, is given in Fig. 2d. The time evolution of the central electron temperature measured with the fast ECE polychromator showing the same temporal behavior is shown in Fig. 2c. Previous calibrations of the gyrotron power were made for short pulses (3 ms) by firing into the tokamak calorimeter without plasma. Spline fits to the thermistor data and an independent analysis based on a model for heat diffusion in the calorimeter tiles agreed to within 10% that the power reaching the tokamak far wall was about 120 kW for typical gyrotron operation. Normalizing the initial flat-top power level in Fig. 2d to this value gives an average power over the 30 ms duration of the pulse of about 60 kW.

The average stored energy increase during the pulse, measured with diamagnetic loops, was about $\Delta W = 800$ J. Integration of the product of the density and temperature profiles gives a similar ΔW . The inferred ohmic energy confinement time over this period was in the range 12-15 ms (in good agreement with Neo-Alcator scaling), implying, if one assumes no change during ECH, an absorbed power in the range 50-65 kW.

A ray-tracing calculation for this shot was done to determine the fractional transmission through the plasma including the effects of refraction. For the code model, a cylindrical plasma is assumed with radial density and temperature profiles of the form $X(r) = X(0) * [1 - \{(r - d)/(a_0 - |d|)\}^{\beta_n}]^{\alpha_n}$, where $X \equiv (n, T)$, $X(0)$ is the peak value, α is a profile parameter, d is the plasma offset and a_0 is the minor radius of the circular limiter. For the density fits $\beta_n = 2$ is used. Typically $\alpha_n \approx 0.5 - 1.0$, $\beta_T \approx 2$, $\alpha_T \approx 2$ and $d \leq \pm 1.0$ cm. The electron temperature profile from the Michelson interferometer at 150 ms (effectively averaged from 143 to 158 ms) was used as a representative mean value during the heating. The electron density was nearly constant, $n_{20}(0) = 1.6$ during the pulse, although the small decrease may indicate pumpout. Using these average values, the integrated fractional absorption of the beam was predicted to be 93%. For a 30 ms pulse with average power of 60 kW, this implied that about 120 J should reach the tokamak calorimeter. The error in this value is large, perhaps $\pm 50\%$ due to the combination of using the averaged values of plasma temperature and ECH power during the pulse and the low transmission regime, $f_{trans} \leq 10\%$, in MTX. Future analysis will include the time evolution of the temperature and power to reduce this uncertainty.

Contours of the energy density on the tokamak calorimeter, 2.5 sec after the end of the tokamak shot, are shown in Fig. 4. This time delay is sufficient to allow equilibration of heat in the calorimeter tiles. Previous detailed comparisons of the signals from the thermistors mounted on the tiles with a heat diffusion model have shown that they are consistent with insulating boundary conditions at the ends of and between adjacent tiles on a 3 sec time scale. By allowing the energy to equilibrate in the tiles, errors in the 2-D spline fits of the energy deposition profile, introduced by inoperative thermistors (squares indicate working thermistors in Fig. 4) are reduced. The integrated energy measured for Shot 11656 was 93 J, within the error bars of the theoretical prediction.

CONCLUSIONS

Initial analysis of recent ECH heating experiments in the MTX tokamak indicates that the measured transmitted power (inferred absorption) is consistent with theoretical calculations. The calculations used averaged plasma quantities over the heating pulse and included the effect of plasma refraction (significant in MTX) with a geometrical optics, ray-tracing code and absorption computed in the linear, Doppler regime. These experiments demonstrate the ability

in MTX to determine the single pass absorption of fundamental O-mode ECH waves. Also demonstrated was significant plasma heating (80% increase in central electron temperature) in a high density plasma, $\omega_{pe}^2/\omega_{ce}^2 \approx 0.7$. Future experiments in MTX will measure the non-linear absorption of short (50 ns), high power (≥ 1 GW) pulses from an FEL for similar plasma conditions. The present experiments have established the basis for linear ECH absorption from which comparisons can be made of the non-linear absorption data in the FEL experiments.

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Fig. 1. Horizontal (a) and vertical (b) beam profiles from scanning probe measurements.

Fig. 2. Evolution of Shot 11656.

Fig. 3. T_e profiles before and during ECH.

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