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Preparation for Propagation and Absorption Experiments in MTX

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ABSTRACT

Preparatory calculations of microwave transmission through the MTX access duct, propagation of the waves through the plasma and the resulting power deposition profile on a calorimeter located on the tokamak inside wall have been performed. The microwave transmission calculations include the relative phase slippage of waveguide modes in the duct to determine the spatial structure of the wavefront at the duct exit. Ray-tracing calculations show substantial spreading of the beam in the poloidal direction at densities above $1.5 \times 10^{20} \text{ m}^{-3}$, well within the range of the experiments. Initial experiments with low or high toroidal field (cyclotron resonance outside the plasma) will investigate both diffraction and refraction effects, without absorption. Estimates of the fractional absorption of the beam in the initial experiments with the cyclotron resonance at the plasma axis have also been made.

INTRODUCTION

The initial ECH absorption experiments in MTX will be done during the summer of 1989. The nominal major and minor radii in these experiments will be $R_0 = 64 \text{ cm}$ and $a = 16.5 \text{ cm}$, respectively, and the field on axis will be $B_0 = 5 \text{ T}$. A single pulse of 140 GHz microwave radiation from the ETA-II/ELF free electron laser (FEL) will be used per tokamak shot. The primary diagnostic for determining the fractional absorption of the FEL power by the plasma is a microwave calorimeter mounted on the inner wall of the vacuum vessel opposite the FEL access port. To calculate the fractional absorption, comparisons of the power absorbed by the calorimeter for shots without plasma, shots with plasma but with the cyclotron resonance outside the tokamak, and shots with the resonance in the plasma will be made. To interpret these experiments and to predict results for various plasma conditions, several theoretical tools have been developed which analyze the propagation and absorption of the beam through the MTX access port and the plasma. The tools and results described below include wave propagation with a Huygens integral code¹ to determine the effects of diffraction, non-linear absorption calculations at the resonance plane with an orbit code, and ray-tracing with the TORCH code² to determine the plasma refraction effects on the beam.

MICROWAVE TRANSMISSION THROUGH THE MTX DUCT

The access duct to the MTX plasma through the toroidal field coils is a tall, narrow rectangular opening 4 cm wide by 25 cm high by 22 cm deep. To calculate the transmission of the microwave beam through this duct, the field impinging onto the entrance of the duct is represented as a set of duct waveguide modes, which then are transported to the end of the duct with the phase shifts appropriate for each mode. The transverse variations of both the incident amplitude $E_x(x, y)$ and phase $\phi(x, y)$ are obtained from the Huygens integral code MTH.¹ This code calculates the transport of the microwave beam from the FEL output through a system of several mirrors up to the duct. Two dimensional Fourier decompositions of an in-phase piece, $E_R = E_x(x, y) \cos \phi(x, y)$, and an out-of-phase piece, $E_I = E_x(x, y) \sin \phi(x, y)$, are required. The Fourier coefficients for even modes are given by

$$A_{Rmn} = \frac{\int_{-a}^a dx \int_{-b}^b dy E_R(x, y) \cos \frac{m\pi x}{2a} \cos \frac{n\pi y}{2b}}{ab}$$

¹ Work performed for the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

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and similarly for A_{lmn} in terms of E_l . Each index mn is associated with a waveguide mode with a transverse wavenumber given by $k_{\perp}^2 = (\frac{m\pi}{2a})^2 + (\frac{n\pi}{2b})^2$ and a corresponding axial wavenumber given by $k_z^2 = k^2 - k_{\perp}^2$.

The net phase at the end of the duct is the sum of the initial phase and the phase shift through the duct Δ_{mn} . For each mode, the real and imaginary mode coefficients at the end of the duct can be expressed in terms of the real and imaginary mode coefficients at the beginning of the duct and the differential phase shift for each mode. The total real and imaginary fields at any point x, y at $z = L$ are given by summing the Fourier series for E_R and E_I . Then the total field amplitude and phase at $z = L$ are $E(x, y) = \sqrt{E_R^2(x, y) + E_I^2(x, y)}$ and $\phi(x, y) = \tan^{-1} \frac{E_I(x, y)}{E_R(x, y)}$. Using the MTH code this field is propagated another 18 cm to the plasma absorption region.

For the beam and duct parameters of the initial FEL experiments, the magnitude of the electric field exiting the duct on the horizontal midplane at the duct wall is 42% of the central field of the beam. This produces a mixture of launched modes which interfere as they propagate through the plasma. The horizontal field pattern at the plasma center is shown in Fig. 1. The electric field at the duct wall in the vertical midplane is only a few percent of the central field. The vertical field pattern in the plasma is nearly Gaussian.

The structure in the horizontal field pattern may complicate the interpretation of the initial experiments. Corrugated inserts along the duct walls may be used in later experiments to reduce the wall fields and smooth the field pattern to a nearly Gaussian shape. Tapering of the duct may also be used to spread the beam out toroidally in the plasma and thereby increase the nonlinear absorption.

CALCULATION OF NONLINEAR ABSORPTION

The nonlinear absorption of the FEL is calculated using a computer code ORPAT which solves reduced relativistic equations of motion⁴ for a Maxwellian ensemble of electrons streaming through the rf beam along the static magnetic field, B . The electric field as seen by an electron is expanded into a Bessel function series where one term is resonant for each cyclotron harmonic number l defined by the resonance condition $\omega - \omega_c - \gamma k_{\parallel} v = 0$. Here $\gamma = (1 + p^2/m^2c^2)^{1/2}$ is the relativistic mass factor. Only one such harmonic is included for a typical calculation ($l = 1$ for MTX). The effect of the rf on the energy, magnetic moment, and gyrophase is calculated for each particle passing through the beam. The power absorbed is determined by taking the net change in the energy content of the ensemble. The reduced equations allow an economical evaluation of the absorption and the results have been checked with a code which solves the full relativistic equations of motion.

The nonlinear absorption is sensitive to the variation of the wavenumber $k_{\parallel}$ across the rf beam. This variation arises from the divergence of the beam and from the curvature of the toroidal field line, and causes the resonant energy to increase as the electrons stream across the beam. Thus, electrons trapped about the resonance are lifted to higher energy; for MTX, this process is the major contributor to the power absorption⁴.

We use the variation of $k_{\parallel}$ and $E_{\parallel}$ calculated just in front of the absorption region by the MTH code. The ORPAT code then calculates the absorption on a series of flux surfaces (usually 50) as the microwave beam propagates through the resonance layer. The parallel electric field, $E_{\parallel}$, is attenuated according to the equation $dP_{\parallel}/dR = -W_{rf}(s, R)$, where $P_{\parallel}(s, R) = \epsilon_0 c N E_{\parallel}^2/2$ is the parallel Poynting flux in MKS units, N is the refractive index, and W_{rf} is the power absorbed per unit volume. Also, s and R are the directions along the magnetic field and the major radius, respectively. The value of $k_{\parallel}$ is assumed unaltered by the nonlinear interaction.

The calculated absorption for 140 GHz in MTX is shown in Fig. 2 at several densities. Without enhancing the spread in $k_{\parallel}$ by tapering the transmission duct, the absorption of a 2 GW pulse is predicted to be about 40% at $n_e = 1.8 \times 10^{21} \text{ m}^{-3}$ and $T_e = 1 \text{ keV}$. The absorption is nearly proportional to T_e . The scaling of the total absorbed power with incident power is $P_{\text{abs}} = 0.62 - 0.23 \ln P_{\text{inc}}$ for $0.5 \text{ GW} < P_{\text{inc}} < 4 \text{ GW}$.

RAY-TRACING CALCULATIONS

Ray-tracing for electron cyclotron wave propagation in MTX is done with the TORCH code³ using the cold plasma approximation. For the purposes of determining the launch angles and locations of the rays, the microwave beam launched from the MTX port is modeled as an elliptical Gaussian beam.

The microwave transmission calculations show that in the horizontal direction the beam waist dimension, w_0 , is about 1 cm. This means that the propagation lengths are of order 1-2 Rayleigh lengths, $Z_R = \pi w_0^2 / \lambda \approx 15$ cm for $\lambda = 2.1$ mm, so that diffraction will be important. In addition, a mixture of modes are launched from the duct which interfere in the plasma. These effects are modeled crudely in the ray-tracing calculation by launching rays perpendicular to a wavefront shaped 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. The horizontal radius of curvature of this launched wavefront at the duct exit is 33.7 cm.

The Rayleigh length for the vertical direction, $Z_R \approx 4$ m, is much larger than the minor radius so that the plasma is in the near field of the duct for this direction. With $Z_R \gg 2a$ and small fields on the duct walls, diffraction effects are negligible in this direction. The launched vertical wavefront at the duct exit, as calculated by the MTH code, is concave towards the plasma with a radius of curvature of 275 cm.

The ray launch locations are calculated such that each ray represents the same fraction of the total beam power. This assures that calculational time is not wasted on rays which do not represent significant beam power. The beam is subdivided into elliptical zones with minor and major semi-axes a_i and b_i respectively. Each annular zone i is further sub-divided into azimuthal sectors. A ray is launched from the center of each of these wedge-shaped areas of the beam. The zone radii a_i and b_i , and the azimuthal angles of the sector edges are determined by solving multiple integral equations such that the integral of the beam power in each wedge-shaped region is the same.

The target plasma for the initial experiments has a central electron density and temperature, $n_e(0) = 1.5 \times 10^{21} \text{ m}^{-3}$ and $T_e(0) = 1.0 \text{ keV}$ respectively. The density profile is of the form $n_e(r) = n_e(0) [1 - (r/a)^2]^{\alpha_n}$ with $\alpha_n = 1.0$. A poloidal projection of the ray trajectories in this target plasma is shown in Fig. 3. Ray tracing calculations without absorption have been done for plasma densities in the range $1.0 \leq n_e(0) \leq 2.4 \times 10^{21} \text{ m}^{-3}$ and profiles in the range $0.5 \leq \alpha_n \leq 2.0$. The cut-off density for these experiments at 140 GHz is $n_c = 2.45 \times 10^{21} \text{ m}^{-3}$. For $n_e(0)$ less than the target density the fraction of the beam which misses the calorimeter is less than 10%. As the density is increased toward n_c , poloidal refraction of the beam center increases rapidly and a vertical cut of the power profile on the calorimeter begins to show a depression near the calorimeter center and maxima near the top and bottom.

The power profile on the calorimeter is only weakly sensitive to changes in the plasma density profile for central densities less than the target density. Calculations using the target density on axis and profiles in the range $0.5 \leq \alpha_n \leq 2.0$ show a slight increase in the bunching of the power at the extremes of the calorimeter for more peaked profiles. The power fraction missing the calorimeter did not exceed 20% in any of these cases.

SUMMARY

Tools for calculating wave propagation, refraction and diffraction effects, and nonlinear absorption in the MTX experiments have been developed. Calculations of microwave transmission through the duct show that with the smooth walled duct the wave pattern in the plasma will have a complicated spatial structure. Nonlinear absorption calculations indicate that approximately 40% of a 2 GW beam pulse with this spatial structure will be absorbed with the resonance on axis. Calculations are in progress using corrugated duct walls to produce a smooth Gaussian wave pattern in the plasma and tapering in the duct which should increase the absorption by increasing the spread in k_z of the beam in the plasma.

Refraction of the beam by the plasma, as calculated by TORCH, produces a reduction in the power density on the inside of the torus compared with the outside. By moving the location of the resonance (by varying B) from outside to inside, an asymmetry in the nonlinear absorption, which would be absent for linear absorption, may be measurable. Experiments at fixed resonance location with various FEL powers will also be used to determine the nonlinear characteristics of the absorption.

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Figure 1. Parallel refractive index (solid) and parallel electric field (dashed) vs. toroidal distance within the beam.

Figure 2. Fractional absorption vs. central density for linear theory ($\circ$), and non-linear theory with 1 GW ($\circ$) and 2 GW ($\square$) pulses.

Figure 3. Poloidal projection of ray trajectories in the MTX target plasma.