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Modeling of Fast Wave Absorption by Beam Ions in DIII-D Discharges

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Abstract. In recent discharges on DIII-D, neutron measurements indicated absorption of the fast wave by energetic deuterium beam ions when the fourth harmonic resonance is on axis, but little or no interaction for the fifth harmonic. In this work, a geometric optics code is used to quantify the beam ion absorption of fast waves as the frequency (or on-axis harmonic resonance) is varied. Isotropic and anisotropic Maxwellians are used to model the beam ion distribution. Wave power flow in this harmonic range has been found to exhibit a strong poloidal and toroidal behavior in its initial transits across the plasma. Absorption along the rays is calculated using the fully thermal and magnetized treatment. Competing with the beam ions for absorption are the minority hydrogen and background electrons. The modeling results are only in partial agreement with experimental observations, indicating that more detailed physics may need to be included.

INTRODUCTION

Fast magnetosonic waves have been studied extensively on DIII-D for electron heating, current drive and profile control. In neutral beam heated discharges, it was observed that application of fast wave power could result in the delay of sawtooth onset and, in some cases, enhanced neutron flux from D-D reactions, indicating wave interaction with energetic beam ions. [1] More recently, two nearly identical discharges have been analyzed in detail, (A) one with $4f_{cD}$ resonance on axis, and (B) one with $5f_{cD}$ resonance on axis. Signs of sawtooth stabilization were detected in the 4th harmonic case (A) where a 30% increase in neutron flux was measured when RF power was applied. On the other hand, for the 5th harmonic case (B), no similar activities have been observed. It is the purpose of this paper to evaluate the strength of beam-wave interactions in these discharges using a model that can be easily incorporated into the ONETWO predictive and time-dependent transport code.

BEAM ION ABSORPTION MODELS IN CURRAY

In this paper, the CURRAY ray tracing code [2] is used to analyze fast wave propagation and absorption in the plasma. Since the wave frequencies of interest cover the 2nd to 7th ion harmonics, a fully kinetic and magnetized approach is used in calculating the thermal and energetic ion damping. The ray equations are solved using the cold ion approximation, i.e., the finite Larmor orbit factor $\lambda_i = \frac{1}{2}k_{\perp}^2\rho_i^2 \ll 1$. The local $k_{\perp}$ is re-evaluated with an order reduction algorithm and substituted into the wave electric field polarization terms used in the ion damping calculations at the harmonics.

Two relatively simple Maxwellian models have been used to model the beam ion slowing down distribution. In the isotropic model, the beam ions are characterized by the temperature $\bar{T}$ on each flux surface, while the anisotropic model is represented by $(T_{\perp}, T_{\parallel})$.

The NFREYA code (via ONETWO) is used to calculate n_B (energetic beam ion density) and $\bar{T}$ on each flux surface, while the TRANSP code computes n_B , $T_\perp$, and $T_\parallel$. The local absorbed power density is given by $P_{abs} = \frac{\omega}{8\pi} |\vec{E}|^2 \gamma$ where $\gamma = \hat{e} \cdot \vec{K}_a \cdot \hat{e}$ with $\vec{K}_a$ being the anti-Hermitian part of the dielectric tensor and $\hat{e} \equiv \vec{E}/|\vec{E}|$. The factor γ is related to the wave damping decrement along the ray, and is given for the ℓ th ion harmonic as

$$\gamma_\ell = \text{Im}(K_{xx}^i) |e_x|^2 + 2\text{Re}(K_{xy}^i) \text{Im}(e_x^* e_y) + \text{Im}(K_{yy}^i) |e_y|^2. \quad (1)$$

With Z being the plasma dispersion function, $\zeta_\ell = (\omega - \ell\Omega_i)/k_\parallel v_{i\parallel}$, and defining

$$Q = \frac{\omega_{pi}^2}{\omega^2} \zeta_0 e^{-\lambda_i} \text{Im}[Z(\zeta_\ell)] \left\{ \frac{\ell\Omega_i}{\omega} + \frac{T_\perp}{T_\parallel} \left(1 - \frac{\ell\Omega_i}{\omega} \right) \right\} \quad (2)$$

the various dielectric elements in Eq. 1 are

$$\begin{aligned} \text{Im}(K_{xx}^i) &= Q \frac{\ell^2 I_\ell(\lambda_i)}{\lambda_i} \\ \text{Im}(K_{yy}^i) &= \text{Im}(K_{xx}^i) + 2Q\lambda_i [I_\ell(\lambda_i) - I'_\ell(\lambda_i)] \\ \text{Re}(K_{xy}^i) &= Q\ell [I_\ell(\lambda_i) - I'_\ell(\lambda_i)]. \end{aligned}$$

MODELING RESULTS FOR DIII-D DISCHARGES

A DIII-D equilibrium for discharge A has been used, with $R = 1.7$ m, $a = 0.63$ m, $I_p = 1.2$ MA, $B_0 = 1.9$ T, and $\beta = 0.8\%$. The plasma parameters are $T_{e0} = 3.3$ keV, $T_{i0} = 2.5$ keV, $n_{e0} = 4.8 \times 10^{13} \text{ cm}^{-3}$, $T_{e0}/\bar{T}_e = 3.9$, $n_{e0}/\bar{n}_e = 1.6$, and deuterium is the majority ion species with a 2% residual hydrogen concentration. With a tangentially injected beam energy of 80 keV at 2 MW of power, the calculated beam ion density is $n_{B0} = 0.4 \times 10^{13} \text{ cm}^{-3}$, and the anisotropic temperature profile is shown in Fig. 1(a) as a function of $\rho(\propto \sqrt{\Phi})$. A frequency of 60 MHz is used that corresponds to $4f_{cD}$ on the magnetic axis, and the main antenna spectrum is peaked at $N_\phi = -4.7$ and $N_\theta = -1.7$. The wave power, represented by 15 rays, is launched from the outboard midplane with an antenna poloidal length of ~ 0.8 m. Shown in Fig. 1(b) are the calculated flux-surface averaged power deposition profiles to the various plasma species, including electrons, after many radial passes of the rays. The absorption profiles for beam ions (B) and electrons (e) are peaked on axis, $\rho \ll 0.1$, while that of hydrogen is peaked at $\rho \approx 0.1$. All absorption takes place within the $\rho = 0.3$ surface.

It is interesting to note that, in this harmonic frequency range, the fast wave rays exhibit a highly poloidal and toroidal path, with a corresponding strong upshift in $|N_\parallel|$ in their initial radial transits. Shown as an example in Fig. 2(a) is a ray for discharge A launched from the outboard midplane, which propagates to the bottom of the minor cross section in its first pass, and specularly reflects into a nearly vertical path to the top. Simultaneously, the ray group velocity also has a strong toroidal component so that at the end of two radial passes the ray has reached half way around the torus. In Fig. 2(b), the strong evolution in $|N_\parallel|$ for the ray is plotted versus ρ . As a check, it is found that lowering the frequency and/or initial $k_\parallel = N_\parallel \omega/c$ for the same plasma conditions results in the ray path becoming more radial and staying closer to the midplane, as expected.

The wave propagation characteristics, as shown in Fig. 2, largely determine the absorption for each pass and the partition of power among the various species. Absorption calculations have been carried out for both isotropic and anisotropic Maxwellian beam ion approximations. A comparison of the fractions of power absorbed in discharge A are given in Table 1. The beam ions dominate the wave absorption because of their higher energy and,

Figure 1: (a) Calculated anisotropic beam ion temperature profile, and (b) wave power deposition profiles to various plasma species, for discharge A.

thus, stronger finite Larmor orbit effect even though the resonance is at the 4th harmonic. Electron damping is significant mainly because of the upshift in $N_{||}$, while the minority hydrogen absorption is relatively strong due to the $2f_{cD}$ resonance on axis. The results between the two cases are very close, since the beam ions have an essentially isotropic distribution in the plasma core (see Fig. 1(a)) where most of the beam ion damping occurs. Thus, when using a thermal beam model, the isotropic approximation appears quite adequate for these DIII-D discharges.

Table 1:
Species Absorption Fractions for Discharge A

Beam Model	Beam Ions	Electrons	Hydrogen	Thermal D
Isotropic	0.423	0.280	0.292	0.004
Anisotropic	0.439	0.273	0.283	0.004

Calculation of beam ion absorption for discharge B has also been carried out. In this case, a frequency of 83 MHz at $B_0 = 2.06$ T is used to locate the $5f_{cD}$ resonance on axis, and the plasma parameters are: $T_{e0} = 2.8$ keV, $n_{e0} = 4.9 \times 10^{13}$ cm⁻³, and $\beta = 0.6\%$. The launched wave spectrum is centered at $N_\phi = -4.4$ and $N_\theta = -1.3$. The ray tracing results using isotropic beam ions are shown in Table 2 together with those of discharge A for two and many (~ 10) radial passes of the rays. It is noted that for discharge B, beam ion absorption appears much stronger than indicated by experiment. One plausible explanation lies in the observation that sawteeth stabilization is dependent on strong ion absorption close to the magnetic axis. In discharge B, the beam absorption profile is peaked at $\rho < 0.15$ for 2 passes, but spreads to beyond $\rho = 0.4$ in subsequent passes as the rays become defocused from the axis, whereas for discharge A, beam absorption is always very peaked on axis ($\rho < 0.1$). In addition, the single-pass absorption fraction in discharge B is much smaller than in discharge A, e.g., 0.19 for B vs. 0.58 for A after two passes. These results together imply that more power is absorbed by beam ions within $\rho = 0.1$ for discharge A than for discharge B, which appear to explain the difference in the sawteeth response. [3]

Figure 2: (a) Projection of ray path in minor cross section, and (b) $N_{\parallel}$ evolution along ray path, for discharge A.

Table 2:
Species Absorption Fractions for Discharges A and B

Passes/Discharge	2/A	$\sim 10/A$	2/B	$\sim 10/B$
Electron	0.283	0.280	0.645	0.458
Beam Ions	0.439	0.423	0.316	0.483
Hydrogen	0.273	0.292	0.036	0.055
Deuterium	0.005	0.004	0.001	0.001

It is noted that the calculations reported here are based on approximate beam models and, as such, beam ion kinetic effects and RF-induced diffusion are not included. To address these issues, a 2-D beam distribution, $f_B(E, \lambda)$, has been obtained using TRANSP, where E is energy and λ is velocity pitch. Absorption calculations based on this distribution, which is asymmetric in the parallel velocity direction, will be performed.

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REFERENCES

- [1] C. C. Petty, C. B. Forest, R. I. Pinsker, et al., "Fast Wave Current Drive in Neutral Beam Heated Plasmas on DIII-D," Proc. 12th Top. Conf. on *Radio Frequency Power in Plasmas*, Savannah, GA (1997) 225.
- [2] T. K. Mau, S. C. Chiu, R. W. Harvey, EPS Top. Conf. on *RF Heating and Current Drive of Fusion Devices*, Brussels (1992) 181.
- [3] W. W. Heidbrink, E. Frederickson, T. K. Mau, et al., submitted to *Nucl. Fusion* (1999).