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Experiments on Ion Cyclotron Damping at the Deuterium Fourth Harmonic in DIII–D

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Abstract. Absorption of fast Alfvén waves by the energetic ions of an injected beam is evaluated in the DIII–D tokamak. Ion cyclotron resonance absorption at the fourth harmonic of the deuteron cyclotron frequency is observed with deuterium neutral beam injection (f = 60 MHz, B_T = 1.9 T). Enhanced D-D neutron rates are evidence of absorption at the Doppler-shifted cyclotron resonance. Characteristics of global energy confinement provide further proof of substantial beam acceleration by the rf. In many cases, the accelerated deuterons cause temporary stabilization of the sawtooth ("monster sawteeth"), at relatively low rf power levels of ~1 MW.

INTRODUCTION

Previous DIII–D experiments have demonstrated efficient fast wave electron heating [1] and current drive with either electron cyclotron preheating [2,3] or neutral beam preheating [4]. The fast wave power is absorbed directly on electrons by Landau damping and TTMP. Later experiments showed that a fraction of the power can be absorbed at high cyclotron harmonics of the preheating neutral beam [5] when a cyclotron harmonic layer is near the magnetic axis. In current drive experiments, this ion absorption constitutes an undesirable loss process. The purpose of the experiments discussed here was to *maximize* the ion cyclotron absorption, to further the understanding of the physics of high harmonic damping [6,7] and to develop another scenario for rf heating applicable to DIII–D discharges with deuterium neutral beam heating. In particular, a method of sawtooth stabilization may be required for some projected advanced tokamak scenarios ("high ℓ_i"), and the DIII–D rf systems are not optimized for fundamental heating of a hydrogen minority, the previously best-characterized scheme for sawtooth stabilization.

EXPERIMENTAL SETUP

The four-element array of loop antennas used to launch 60 MHz fast waves and the associated transmission line system have been described in detail [8]. This tunerless system applies either co-current or counter-current toroidal phasing ([0,π/2,π,3π/2] or the reverse) to the array. The peak in the vacuum spectrum occurs at $n_{||} = k_{||}c/\omega \approx 5$. To maximize the coupled rf power in the presence of an empirical antenna voltage limit, in these experiments the antenna was operated at a feedback-controlled peak voltage of 20–25 kV. In this operating scenario, the coupled power is proportional to the resistive antenna loading. At an L–H transition, for example, when the antenna loading resistance drops by about a factor of two, the coupled power drops correspondingly. Under high loading resistance conditions (e.g., L–mode), the coupled 60 MHz power was typically about 1.0–1.5 MW.

Deuterium (D) neutral beam injection (NBI) was used to provide a fast ion population in the target plasma and for diagnostics (active neutral particle charge exchange analysis, MSE measurements of the plasma current profile, and charge exchange recombination spectroscopy). The beams were all injected in the co-current direction, and the 60–90 keV beams form an angle of 48° ("Left sources") or 64° ("Right sources") with the magnetic axis. The layout of the plasma, antenna, and ion cyclotron resonance layers is shown in Fig. 1. In typical discharges, NBI begins several hundred ms after the start of the steady-state portion of the discharge (B_T = 1.9 T, I_p = 1.2 MA, $n_e = 3 \times 10^{19}$ m^{-3}); after the plasma parameters reach new steady-state values, 60 MHz rf power is added for a 1 to 2 s long pulse.

In D discharges with D NBI, the neutron rate is dominated by beam-target reactions under the plasma conditions studied here. The neutron rate thus provides a sensitive diagnostic for rf acceleration of the beam. The reaction rate in purely beam heated discharges is well predicted by a simple O-D model [9]. The ratio of the measured neutron rate to the prediction of the model is referred to here as the "neutron enhancement." In cases of strong cyclotron harmonic absorption, this ratio exceeds 2.

RESULTS

The combination of unidirectional beam injection and a highly directional wave spectrum leads to a particularly clear manifestation of the Doppler-shifted cyclotron resonance. Ion cyclotron harmonic absorption occurs where $\omega - k_{||}v_{ib} = n\Omega_{ib}$. Accounting for both the toroidal upshift of the launched wave spectrum ($k_{||}R$ is constant) and the beam injection geometry, the absorption occurs where

$$\frac{\omega}{n\Omega_{ib}} = \left[1 - n_{||}\big|_{ant} \frac{R_{ant}\,R_{tan}}{R_o^2}\left(\frac{v_{ib}}{c}\right)\right]^{-1} \qquad (1)$$

in which $n_{||}\big|_{ant}$ is the parallel index of refraction of the coupled wave at major radius R_{ant}, R_{tan} is the beam tangency radius, R_o is the major radius at which $\omega = n\Omega_{ib}$ and the speed of the injected beams ions is v_{ib}. In the DIII–D setup, positive $n_{||}\big|_{ant}$ in Eq. (1) corresponds to counter-current phasing of the four-element array. This resonance condition shows that absorption of counter-phased waves on the beam should occur at a slightly larger major radius than the radius where $\omega = n\Omega_{ib}$.

Even in the linear limit, the shape of the rf deposition profile is a complicated function of the beam deposition profile, the slowing down distribution of the beam ions, and the coupled rf spectrum. A rough idea of the location of and a lower limit on the width of the rf deposition profile may be obtained under the assumption that the rf deposition profile is narrow compared to that of the beam. Since the absorption occurs predominantly on the highest energy ions present (largest $k_\perp \rho_i$), it is reasonable to use v_{ib} corresponding to the beam injection energy in Eq. (1). The coupled antenna spectrum $P(n_{||})$ can be estimated with a simple model, and Eq. (1) used to map $n_{||}$ to $\omega/(n\Omega_{ib})$; the

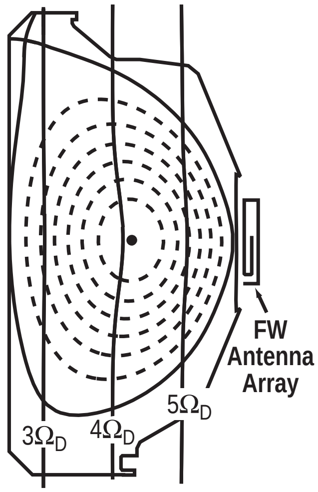

Figure 1. The optimal location of the resonance layer is about 5 cm inboard of the magnetic axis.

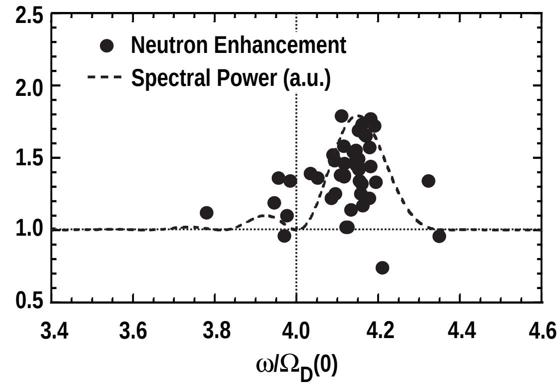

Figure 2. Comparison of simple model for absorption profile (dotted curve) with measured neutron enhancement (dots).

resulting estimate of the absorption profile is indicated by the dashed line in Fig. 2. The experimental neutron enhancement from a number of discharges with different toroidal fields is also plotted in the figure, where Ω_D is evaluated at the magnetic axis. The neutron enhancement peaks at a value of $\omega/\Omega_D = 4.15$ in agreement with the model, which corresponds to a coupled $n_{||} = 4.5$. This shift amounts to a displacement of the absorption location from the $\omega=4\Omega_D$ contour by 5 cm radially outwards, as illustrated in Fig. 1.

The global confinement in a series of discharges with deuterium beam injection and 60 MHz rf power is summarized in Fig. 3. The measured energy confinement time is normalized to the (L–mode) ITER89P scaling relation. The fact that the L–mode confinement in discharges with NBI alone and in those with combined $4\Omega_D$ and beam heating is generally well predicted by the scaling law is evidence of strong central absorption of the rf power [1] in the latter case. However, the addition of rf power to the NBI heated discharge consistently improves the global confinement, as is shown by the positive slope of the lines joining the points with and without rf in the same discharges. This is presumably a result of the increased fast ion content caused by the acceleration of the beam. The most striking effects of the increased fast ion content due to $4\Omega_D$ heating are the increased neutron rate, already discussed, and the temporary stabilization of the sawtooth instability. An example of both of these phenomena is exhibited in Fig. 4. D NBI (2.7 MW, 80 keV) establishes a steady-state with a sawtooth period of 0.080 s. The addition of 1.2 MW of rf at 60.1 MHz causes the sawtooth period to increase to 0.27 s. During the long sawtooth period, the fast ion content builds up near the magnetic axis, causing the increase in total stored energy and of the neutron enhancement, as well as exciting toroidal Alfvén eigenmode (TAE) instabilities (not shown). When the sawtooth crash occurs, the resultant heat pulse through the plasma edge triggers an L-H transition, as signaled by the drop in recycling light, the decrease in antenna loading, and the sudden increase in plasma stored energy. Each of the H–mode points in Fig. 3 resulted from the crash of a "monster" sawtooth, which accounts for the drop in total heating power due to the accompanying drop in antenna loading. Further discussion of the sawtooth stabilization phenomenon and the correlated Alfvénic instabilities can be found in Ref. [10].

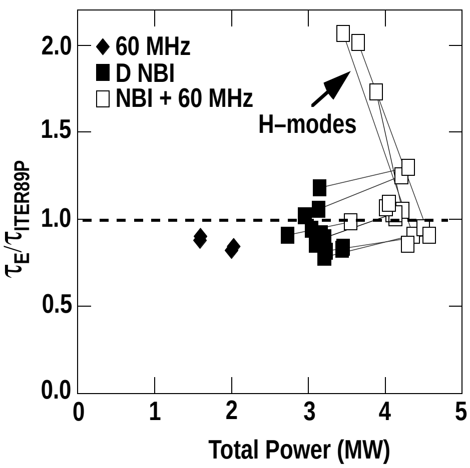

Figure 3. Confinement time normalized to ITER89P scaling relation (I_p = 1.2 MA, B_T = 1.9 T).

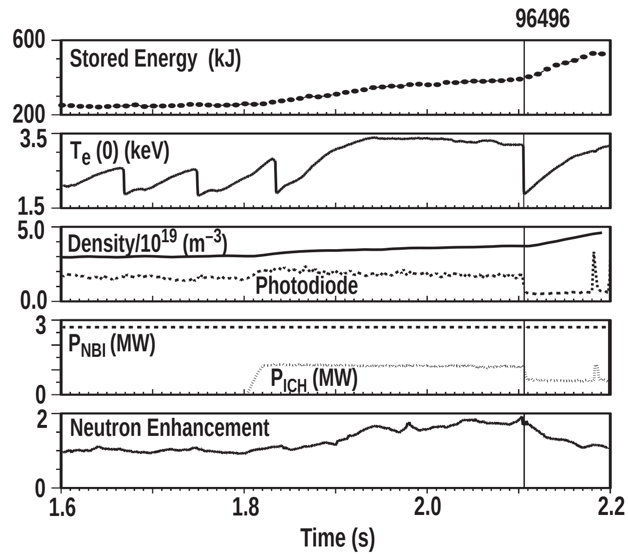

Figure 4. Time history of discharge with stabilized sawtooth (I_p = 1.2 MA, B_T = 1.9 T). Vertical line shows time of L/H transition.

In summary, efficient absorption of fast wave power at $4\Omega_D$ by energetic ions of an injected beam has been observed, and been found to be effective for stabilizing sawteeth at a remarkably low power of around 1 MW in a narrow range of plasma parameters. Future experiments will double the 60 MHz power by adding two more transmitters and antenna arrays; this will permit extension of the range of parameters for which this heating technique is useful (higher density, etc.)

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