Ion Cyclotron Range of Frequency Heating of a Deuterium-Tritium Plasma via the Second-Harmonic Tritium Cyclotron Resonance

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Experiments have been performed on the TFTR to study rf wave heating of a D-T plasma by way of the second-harmonic tritium cyclotron resonance. The addition of tritium ions to a deuterium plasma allows for absorption of the rf waves at the tritium cyclotron harmonics and by electron damping of a mode converted ion Bernstein wave. Competing mechanisms include direct electron damping and damping at the fundamental cyclotron resonance of deuterium, α particles, and ^{3}He ions. The contribution of each is estimated from a series of plasma discharges where various plasma parameters are varied. The majority of the rf power is found to damp on the tritium ions.

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To reach the temperatures required for sustained thermonuclear burn in a tokamak plasma some form of auxiliary heating is required. The use of rf waves in the ion cyclotron range of frequencies (ICRF) to heat plasmas has a long tradition in fusion research. Absorption of rf wave energy at the ion cyclotron frequency and its harmonics has proven to be an efficient method of heating hydrogen and deuterium plasmas. The introduction of tritium ions into the plasma adds further complexity to the dielectric properties of the magnetized plasma. Heating via the second-harmonic cyclotron resonance of the tritium ions was proposed by both Stix [1] and Perkins [2] and is presently a leading candidate for heating the International Test Reactor to ignition. In order to explore, for the first time, the effectiveness of this heating scenario a series of deuterium-tritium (D-T) plasma discharges were carried out on the TFTR. In these discharges the plasma fueling was provided by both tritium and deuterium neutral beam injection (NBI). The concentration of tritium ions was adjusted by varying the number of NBI sources injecting tritium. In addition, the strength of the toroidal magnetic field and the concentration of ^{3}He ions were varied. The amplitude of the applied rf power was square wave modulated to obtain information on the location of the power deposition and the plasma species heated.

Extensive modeling of the ICRF heating of a D-T-^{3}He plasma has been carried out using a variety of numerical codes, including both the PICES [3] and TRANSP [4] 2D codes. A number of absorption mechanisms are expected to compete. For a toroidal field strength of 4.7 T and a frequency of 43 MHz these mechanisms include second-harmonic ion cyclotron absorption on the tritium ions (centrally peaked), Landau damping on the electrons (always peaked on axis), fundamental cyclotron absorption on deuterium ions and alphas (on the high-field side of the plasma axis), and absorption of mode-converted ion Bernstein waves on either ions or electrons (also on the high-field side of the axis). If a minority of ^{3}He ions is also present then absorption at its fundamental cyclotron resonance is degenerate with the tritium second harmonic. When the second-harmonic tritium resonance is placed near the magnetic axis predictions from a simple 1D code (CARDS [5]) indicate that, in the absence of a ^{3}He minority, second-harmonic tritium absorption and direct electron absorption should dominate with negligible deuterium fundamental or mode-conversion absorption taking place. For the parameters of the experiments described below α absorption should be no more than 10% of the input power. Increasing the tritium concentration should increase the fraction of power absorbed by the tritium ions at the expense of the electrons. The addition of even a small amount of ^{3}He ions shifts the absorption to the ^{3}He. Analysis with 2D codes yields a more complicated picture. These codes can predict significant absorption ($\sim$50%) at the deuterium fundamental and/or mode-conversion surfaces on the high-field side ($r/a \sim 0.7$) of the plasma. These predictions, of high edge absorption, are found to a high sensitivity with the edge plasma profiles and the assumed parallel wave number ($k_{\|}$).

The experiments were conducted in a series of discharges [$B_T(2.62) = 4.0-4.8$ T, $I_P = 1.8$ MA, $R = 2.62$ m, $a = 0.99$ m, $f_{\rm rf} = 43$ MHz] where the plasma target density ($n_{\rm el} = 4 \times 10^{19}$ m^{-3} and temperature [$T_e(0) = 8$ keV, $T_i(0) = 26$ keV] were established by NBI. By changing the number of NBI sources using tritium from one to seven the tritium concentration η_T ($\equiv n_T/n_e$) in the plasma was varied between 0.06 and 0.40. The time evolution of the plasma density and the applied NBI and ICRF power is shown in Fig. 1. The NBI commences at $t = 3.0$ s. The density is seen to build up from the NBI in 0.4 s. At $t = 3.2$ s there is sufficient density for the rf power to be coupled efficiently to the plasma. The rf power wave form has a period of constant amplitude having sufficient length (300 ms) to allow the formation of a non-Maxwellian

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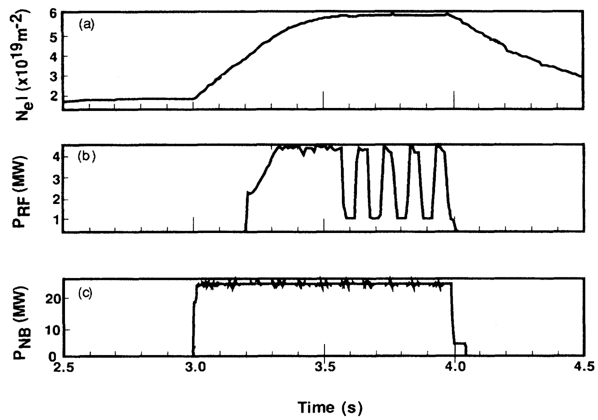

FIG. 1. Time evolution of the plasma density (a), ICRF power (b), and NBI power (c) for the power modulation experiments.

tail in the tritium ion distribution followed by a period of square wave modulation ($f_{\mathrm{mod}} = 5$ or 10 Hz). The response of the plasma to this modulated power is shown in Fig. 2. By Fourier analysis of the temperature and density signals the power flow from the rf waves to the various plasma species can be derived. The radial profile of the power to the electrons (open triangles) and ions (solid circles) is shown in Fig. 3. For the electrons the central peak represents the direct electron absorption via Landau damping of the fast wave while mode-conversion electron heating should appear as off-axis heating. The absence of such a peak indicates that the amount of power absorbed by this mechanism is negligible for the parameters studied. The centrally peaked ion response is due to the second-harmonic tritium absorption. By analyzing the diamagnetic (W_d) and equilibrium magnetic signals a measure of the excess perpendicular plasma stored energy ($W_{\mathrm{tail}} = 3W_d - 2W_T$) can be obtained. This excess represents the tritium tail energy. In addition, the ion temperature modulation is obtained from charge exchange recombination spectroscopy. From this analysis it is found that the power split varies as is shown in Fig. 4. From this we see that the tritium absorption dominates and that the agreement between experiment and modeling is quite good.

The absorption on the high-field side of the plasma at the deuterium fundamental is not evident in the analysis of the temperature profiles. Signals from a series of vertically viewing neutron detectors provide an additional constraint on the magnitude of this absorption. The chords near the location of the deuterium resonance show no indication of modulated neutron emission beyond that from the observed density modulation, indicating no significant heating of deuterium takes place. Since energy confinement at these large radii is poor, a small amount of power flowing to the deuterium ions is still possible. Table I shows a comparison of the experimental power deposition split and that predicted by the PICES and TRANSP codes. The electron heating power is seen to be predicted quite accurately by both codes. Some differences are seen in the predictions for edge absorption due to mode conversion. The predicted amount of power deposited at the edge of the plasma has been found to be quite sensitive to the edge density and magnetic equilibrium profiles assumed. The chief difference between the codes is in their handling of the antenna $k_{\parallel}$ spectrum. For these TRANSP simulations a single k was chosen at the peak of the antenna vacuum spectrum; for PICES a multiple k spectrum was used. The enhanced mode conversion found by

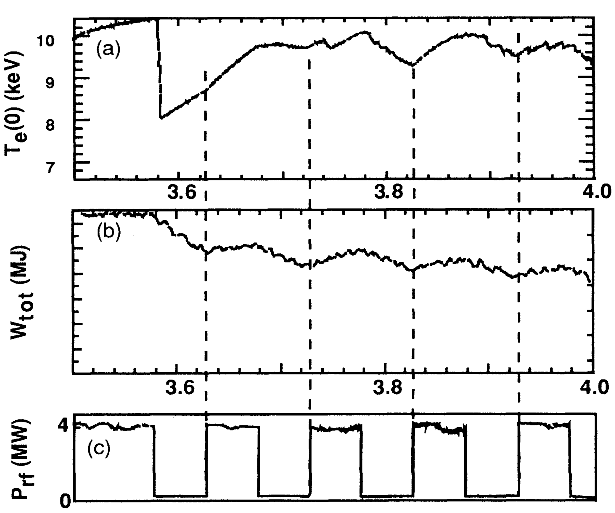

FIG. 2. Time evolution of the central electron temperature from electron cyclotron emission (a) and the total stored energy from magnetic measurements (b), along with the modulated ICRF power wave form (c).

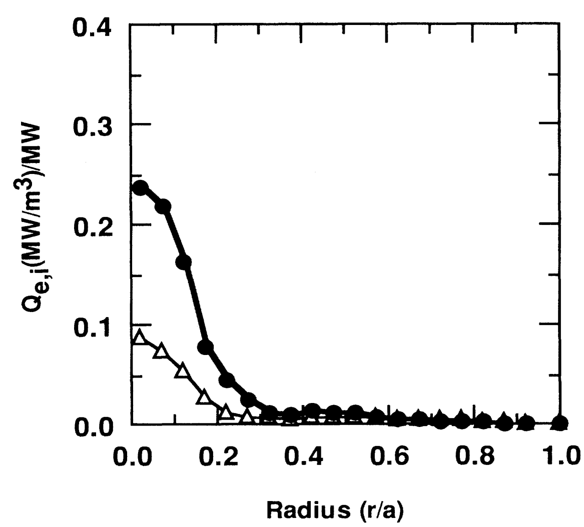

FIG. 3. Power deposition profiles for the ions (●) and electrons (△) as inferred by the power modulation technique.

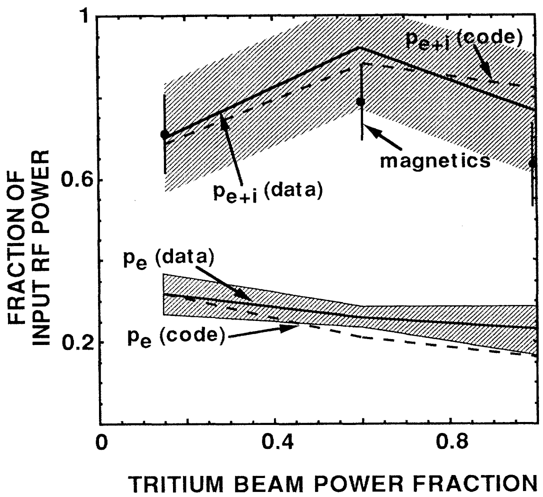

FIG. 4. Fraction of power absorbed by electrons and ions as a function of tritium beam power fraction.

PICES could be the result of an overestimate of the lower wave-number portion of the spectrum. It should be noted that the single pass absorption predicted by both codes is $\leq 20\%$ for these plasmas, indicating that multiple pass absorption is taking place.

Signals from a series of high energy (>300 keV) particle detectors [6] located between the outer midplane and the bottom of the tokamak also demonstrate the presence of an energetic tail. These detectors contain a 2D scintillator which is viewed by both a slow video camera and a fast photomultiplier tube. The geometric structure allows both energy and pitch angle resolution. Figure 5 shows the modulation of the photomultiplier signal with the rf power level. The excess signal during the rf shown in Fig. 5(a) is identified by its gyroradius and poloidal angle as coming from tritium ions of energy ≥ 300 keV. This signal is similar in character but larger in amplitude than that seen in H minority ICRF heating and distinctly different from the signal produced by fusion products. The background signal that commences with the NBI is a combination of neutron induced light and fusion alphas. Since the signal is normalized to the

TABLE I. Comparison of code predictions (PICES and TRANSP) with the experimentally derived power deposition mechanisms.

	PICES	TRANSP	Experiment
Direct electron heating ($r/a < 0.85$)	~26%	~24%	~26 ± 3%
Direct ion heating $2\Omega_T + \Omega_D$ ($r/a < 0.7$)	~43%	~59%	59 ± 10%
Mode conversion ($r/a > 0.7$)	~22%	<10%	<5%

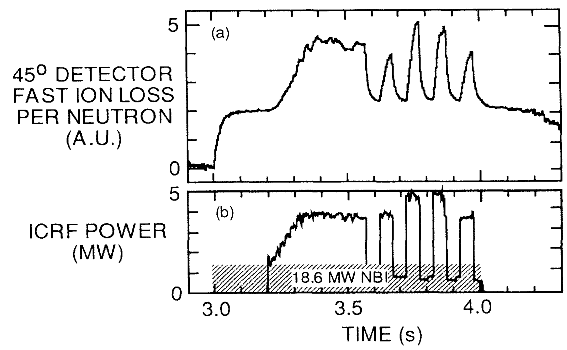

FIG. 5. Accelerated triton loss signal as a function of time (a) and modulated rf power wave form (b).

neutron production rate, this pedestal level is constant during the NBI.

In order to gauge the overall effectiveness of the heating method a small number of discharges were taken without modulating the rf power wave form. This allowed the plasma response to the rf heating to come to steady state. Comparison could then be made to deuterium only by heating. Two shots were taken with a 2% ^{3}He minority present and one shot without. In plasmas with a 2% ^{3}He minority the addition of 5.4 MW of rf power increased the central electron temperature from 8 to 10.5 keV and the central ion temperature from 26 to 36 keV (Fig. 6). The core ion temperature for the shot without ^{3}He reached 32 keV for 4.4 MW of rf heating. This was accompanied by a 10% increase in the D-T neutron production rate to 1.2×10^{18} s^{-1}. While the core electron heating rate was

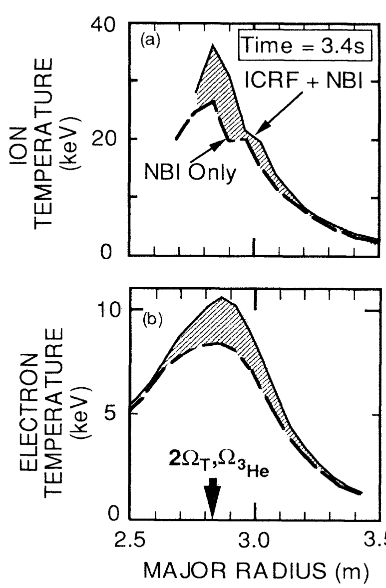

FIG. 6. Ion and electron temperature profiles for discharges with and without nonmodulated rf power showing strong central ion and electron heating.

similar to that observed in D-^{3}He minority supershots, the core ion heating rate was superior in the D-T shots; in fact, no central ion temperature increase is seen in the nontritium case. This is interpreted as being due to the stronger coupling of the heated tritium ions to the background ions than that of the analogous ^{3}He ions in the D-D case. Energy confinement was typically 15% better in the D-T discharges than in corresponding DD discharges.

These experiments have verified that second-harmonic tritium heating provides a strong central power absorption in a D-T tokamak plasma even in competition with numerous other absorption channels and demonstrated good agreement with code predictions. In future, hotter plasmas such as those envisioned for reactors, the codes predict such strong (>50% per pass) absorption that this regime should be even more successful.

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