ICRF HEATING AND PROFILE CONTROL TECHNIQUES IN TFTR*

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Abstract

In fast wave to ion Bernstein wave mode conversion experiments in DT supershot plasmas, localized efficient ion heating rather than electron heating was observed, due to Doppler-broadened tritium cyclotron resonance overlap into the mode conversion region. The ion temperature heat pulse associated with RF power modulation in this regime could provide a diagnostic tool for measuring the local ion thermal conductivity in various confinement regimes. In direct-launch ion Bernstein wave heating experiments, core power coupling was limited by the excitation of parasitic edge modes. However, a sheared poloidal flow was observed that is consistent in both magnitude and direction with theoretical models based on RF-driven Reynolds stress. With the modest power coupled to the core (~ 360 kW), the magnitude of the observed flow was estimated to be a factor of 3-4 too low to trigger transport barrier formation through localized shear suppression of turbulence.

1. INTRODUCTION

The Tokamak Fusion Test Reactor (TFTR) recently completed 14 years of operation, the last decade of which included detailed studies of the physics of wave-plasma interactions in the ion cyclotron range of frequencies (ICRF). Many of the experiments in the final year of operations focused on the development of techniques for localized current and pressure profile control that are relevant to deuterium-tritium (DT) high-performance plasmas. In this paper, results from the final experiments on DT mode conversion (MC), tritium minority heating, and poloidal sheared flow drive with both off-axis fast wave heating and direct-launch ion Bernstein wave (IBW) heating will be presented.

2. MODE CONVERSION EXPERIMENTS IN DT PLASMAS

Steady-state operation in advanced tokamak regimes will require auxiliary means of controlling both the current and pressure profiles. Noninductive currents driven by mode converted ion Bernstein waves had previously been demonstrated in TFTR with non-DT plasmas [1]. Initial mode conversion experiments in DT plasmas were hampered by significant parasitic ion cyclotron resonance absorption on a dilute lithium-7 minority present in the plasma due to wall conditioning processes [2]. After switching to the use of isotopically pure lithium-6 (same charge-to-mass ratio as D) for the final run period, mode conversion heating at the DT ion-ion hybrid resonance was explored in supershot plasmas fueled with a mix of deuterium and tritium neutral beam injection (NBI). For ion temperatures above 20 keV, significant Doppler broadening of the tritium cyclotron harmonic layer occurs, leading to tritium ion absorption rather than electron absorption near the mode conversion layer where the E_+ wave field peaks. Figure 1 shows the temporal evolution of the ion temperature in a DT supershot plasma fueled with 18 MW of tritium NBI heating and 1.2 MW of mode conversion heating at 30 MHz. The magnetic field was 4.7 T on the magnetic axis at 2.84 m, the central electron density was 4.7×10^{19} m^{-3} and the central electron temperature was 6.8 keV. The tritium concentration was estimated to be 42% relative to the electron density, based on spectroscopic measurements of the hydrogenic Balmer

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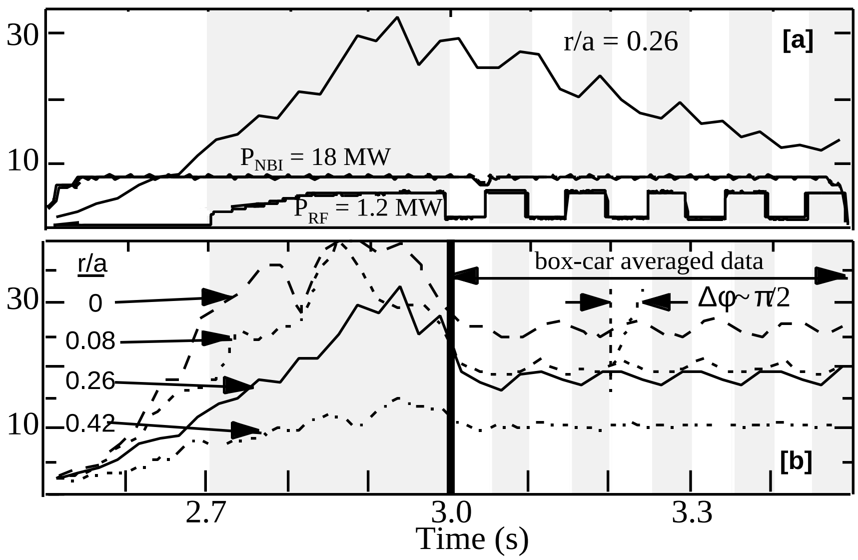

FIG. 1. (a *) Ion temperature evolution in a DT supershot with 18 MW of TNB and 1.2 MW of modulated ICRF mode conversion heating at the radius of maximum temperature modulation; (b) $T_i(t)$ at different core minor radii, with the data box-car averaged in the time period 3-3.5s.*

lines at the plasma edge and the measured neutron emission. The RF power was modulated at 10 Hz between 3.0 and 3.5 s, resulting in an ion temperature modulation of about 4 keV peaked near R ~ 3.0 m, corresponding to r/a ~ 0.26. The measured ion temperature at this radius is displayed in Fig. 1a, while the box-car averaged temperature response over the rf modulation periods for selected radii in the plasma core is displayed in Fig.1b. The inferred power deposition profile obtained from analysis with the 1D kinetic wave code, METS [3], is shown in Fig. 2a. METS solves for the wave fields and absorption profiles without assuming the small Larmor radius limit, as has been done commonly in the past. The analysis indicates that the mode conversion layer was located near R ~ 2.78 m, as shown in Fig. 2b. Tritium ions absorbed most of the power, with the deposition peaked off-axis to the high field side of the mode conversion layer in the region of propagation for the mode converted ion Bernstein wave. The absorption profile is predicted to have been broadly peaked near R ~ 2.58 m, mapping to r/a ~ 0.22, consistent with the location at which the measured ion temperature modulation peaked.

Propagation of the heat pulse resulting from the modulated localized mode conversion heating is evident in the ion temperature evolution in Fig. 1b. The ion temperature response was in phase with the RF power modulation near r/a ~ 0.26, with a phase change of about $\pi/2$ accumulated by the time the heat pulse reached the magnetic axis. According to the analysis, no direct ion heating from the RF is predicted to have occurred at the magnetic axis. Assuming a simplified model with radial plasma homogeneity in the local power balance, a Fourier transform

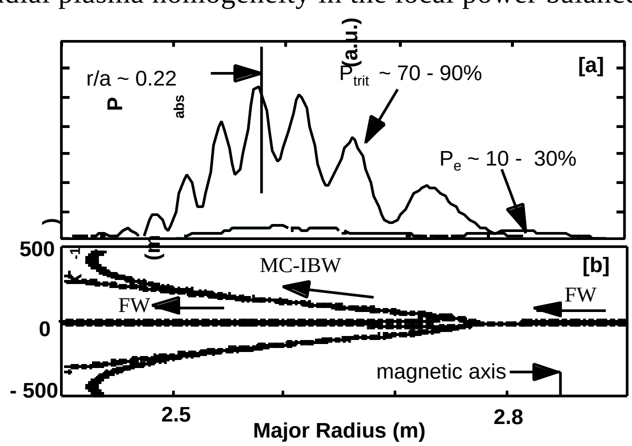

Fig. 2. (a) *Power deposition profile obtained from the 1D kinetic wave code METS; (b) corresponding real part of the dispersion relation for k .*

in time leads to an expression for the local thermal ion conductivity, χ:

$$\left(\frac{\Delta\varphi}{\Delta r}\right)^2 = \frac{3\omega}{4\chi} \tag{1}$$

where $\Delta\varphi$ is the change in relative phase over radial distance Δr, and ω is the angular frequency of the modulation. For the plasma shown in Fig 1b, the value of χ inferred from the temperature heat pulse is ~ 1 m^2/s. According to TRANSP analysis of the ion stored energy evolution, the spatial average of χ ranges from 0.7 m^2/s near the start of the ICRF power modulation at 3.05 s, up to 1.9 m^2/s near the end of the modulation phase at 3.45 s, with a time-averaged value of ~1 m^2/s during the 0.5 s of RF power modulation. Thus, the heat pulse associated with localized mode conversion ion heating could provide a means of measuring the local ion thermal conductivity in various confinement regimes.

In related experiments with lower tritium concentrations (≤ 20%), tritium minority heating occurred and an energetic tritium tail population was formed. Direct tail temperature measurements obtained with the Pellet Charge Exchange (PCX) diagnostic indicate that T_{tail} ~ 130 ± 10 keV in this regime.

3. DIRECT-LAUNCH ION BERNSTEIN WAVE HEATING EXPERIMENTS

In previous experiments on PBX-M, the combination of off-axis direct-launch IBW heating and core NBI fueling and heating led to the formation of an internal transport barrier (ITB) and consequently, an enhanced core confinement regime (CH mode) [4]. It has been suggested that the formation of the internal transport barrier was due to localized sheared poloidal flow driven by the IBW absorption [5,6]. Since, in this model, the location of the ITB is controlled by the location of the IBW absorption layer, IBW may provide a means of controlling the local pressure profile in tokamaks. A new IBW antenna was installed and direct-launch IBW heating experiments were conducted on TFTR in 1997. Though core heating was observed, coupling was limited by parasitic surface mode excitation [2]. Improved core absorption, but lower loading, was obtained on TFTR with out-of-phase, as opposed to in-phase, poloidal launch. Hence, poloidal launch control may contribute to achieving sufficient core power absorption to meet the modest power requirements for turbulence suppression and transport barrier control in future tokamaks. Despite the limited power coupled to the plasma, a localized sheared poloidal flow was observed with a new poloidal rotation diagnostic, as illustrated in Fig. 3 for a plasma with about 360 kW of core power absorption. In a companion plasma without applied IBW heating, no analogous change in the poloidal rotation was detected. The change in poloidal rotation, relative to the average poloidal rotation observed in the 0.5 s prior to the start of IBW heating, is displayed. Positive Δv_θ corresponds to the ion diamagnetic drift direction. The radial profile of the measured poloidal rotation has been found to depend on the amount of tritium in the plasma. In discharges with significant tritium concentrations on the order of 10%, a positive change in the poloidal rotation localized around the $5\Omega_T$ layer was observed, with a negative change found in the region away from the $5\Omega_T$ layer towards the $3\Omega_D$ layer. In plasmas with negligible tritium content, only the negative poloidal rotation feature was observed. These features are reproduced, both in direction and magnitude of the predicted poloidal rotation, by including finite $k_{//}$ effects in the ray-tracing analysis of the power deposition and Reynolds-stress induced rotation profiles [7]. The flow produced by the IBW was insufficient by a factor of 3-4 relative to that expected to be required to suppress local turbulence [2] and create a local transport barrier. A simple measure of the amount of power required for transport barrier formation may be obtained by requiring the shear in the poloidal flow, $\partial V_\theta / \partial r$, to exceed the linear growth rate of the turbulence, C_s / L_s , where C_s is the sound speed and L_s is the connection length [6]. Assuming a linear dependence of induced sheared flow on input power, the estimated power required for turbulence suppression is 1 - 2 MW in TFTR, whereas the power coupled in the discharge shown in Fig. 3 is ~ 360 kW.

Experiments with off-axis fast wave heating were also conducted in D-^{4}He-^{3}He plasmas to investigate whether sheared poloidal rotation could be driven efficiently with mode converted ion Bernstein waves as well as with direct-launch IBW. As in the direct-launch case, a localized sheared

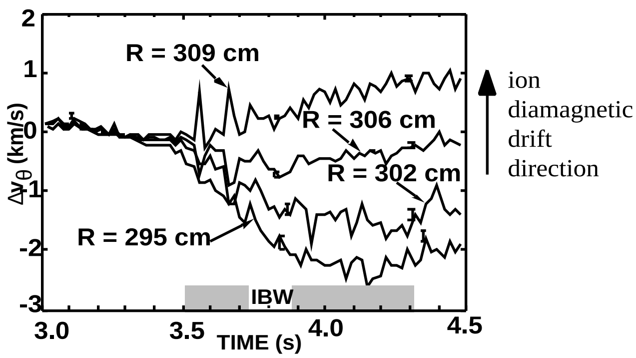

FIG. 3. *The change in poloidal speed resulting from direct-launch IBW for different major radii.*

poloidal flow was detected, as shown in Fig. 4 where the chordal average of Δv_θ is plotted for a discharge with 2 MW of RF power and 5 MW of DNB. The temporal evolution of the observed Δv_θ correlates with the time dependence of the applied ICRF power. However, the location of the peak flow occurred on the low field side of the mode conversion layer and may have been associated with minority ^{3}He ion absorption rather than mode conversion heating of electrons. Measurements of the diamagnetic stored energy and the plasma inductance imply that a small perpendicular anisotropic energy component of about 20 kJ is present in the plasma, suggesting that the amount of ^{3}He in the discharge was too low for efficient mode conversion. Power deposition modeling with the METS code, assuming a 5% ^{3}He concentration, indicates that localized ^{3}He ion and electron absorption occurs in the region of the plasma where the poloidal rotation is observed. However, the power split between the ^{3}He ions and the electrons depends sensitively on the exact ^{3}He concentration which is not accurately known. Further experiments will be required to determine whether mode conversion or minority heating is the source of the measured poloidal rotation. Nevertheless, the observation of sheared poloidal flows during both direct-launch IBW heating experiments and off-axis fast wave heating experiments on TFTR, coupled with the previous confinement enhancement observed with direct IBW heating on PBX-M, indicates that sheared rotational suppression of turbulence via RF-driven Reynolds stress [5] may provide a viable means of improved performance in tokamak plasmas.

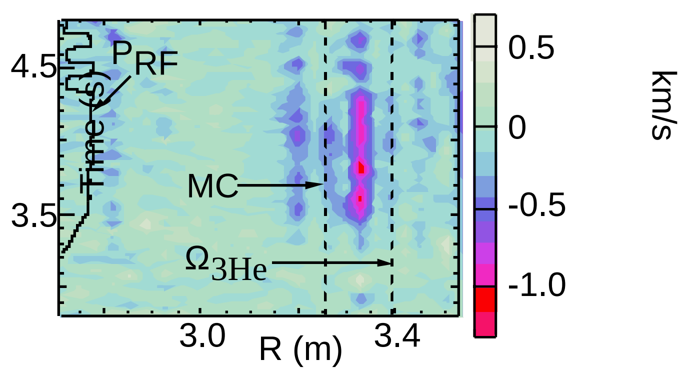

Fig. 4. *Chordal-averaged Δv_θ for a discharge with 2 MW of applied ICRF heating.*

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