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RECENT RESULTS FROM THE TFTR ICRF DT PROGRAM

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Abstract

The first experiments to be performed with ICRF heating of DT plasmas are reported. ICRF heating of minority ions, tritium (second harmonic resonance), as well as direct electron heating are being performed during the DT phase of TFTR. RF power modulation and Fourier transform techniques are used to attempt to elucidate the competition between tritium second harmonic, direct electron, and ^{3}He fundamental heating in DT plasmas. A significant fraction of the RF power has been found to couple to the tritium ions via second harmonic heating. Relevant RF coupling physics is investigated using ^{3}He minority heating (43 MHz), H minority heating (64 MHz), and mode conversion (43 MHz, comparable densities of ^{3}He and ^{4}He) at a toroidal field of 4.5T.

I. DT Supershots

ICRF on TFTR has the capability of increasing the DT reaction rate by increasing the ion temperature and by directly accelerating the tritium ions via second harmonic resonance heating. Also, ICRF has been shown to be effective at raising the electron temperature[1] which increases the alpha particle slowing down time; the increased alpha pressure will help verify thresholds for alpha instabilities. Initial DT experiments on TFTR which include both ICRF and neutral beam power have all been with an RF frequency of 43 MHz, which is resonant with second harmonic tritium and ^{3}He minority. Many shots had no ^{3}He injected, so the ICRF power was shared between the tritium second harmonic heating and direct electron heating. In order to estimate the fraction of power going to either the tritium or electrons, the ICRF power was modulated during many of the shots. Figure 1 shows the modulated ICRF waveform along with the variation in electron temperature (measured by ECE) and excess perpendicular energy ($\delta W_\perp - 2\delta W_\parallel$ measured by the magnetics, where modulation of $\delta W_\parallel$ is assumed small) for two different tritium concentrations in which no ^{3}He was added. The variation of the electron temperature (with no phase delay) is characteristic of direct electron heating, while the variation of excess perpendicular energy is characteristic of resonant ion heating. As the number of tritium neutral beams increases, the second harmonic damping on the tritium beam ions increases, and the amount of power going directly to the electrons decreases. In fact, the modulation of the excess perpendicular energy indicates that for high tritium concentrations, about half of the RF power is coupled directly to the tritium ions.

Further evidence of tritium high energy tail formation has been observed with the escaping fast ion probe[2] 45° below the outer midplane of the tokamak. A signal modulated synchronously with the RF is observed on this probe in DT plasmas with no ^{3}He minority (tail ions are usually seen by this probe during ion minority heating). This signal is not due to neutral beam ions, because the probe is only sensitive to ions with energies in excess of 300 keV, and the gyroradius measured is less than those of fusion products. Therefore, it is inferred that the signal is due to accelerated tritium ions.

When unmodulated ICRF was added to DT supershots, the electron temperature, ion temperature, and fusion power were increased. Figure 2 shows a comparison between two shots each with 23 MW of neutral beam power (including 13 MW of tritium neutral beam power) and one in which 5.4 MW of ICRF is added. The recycled gas from the carbon limiters is primarily deuterium, so a net fraction of approximately 30% of the ions are tritium. In this case, a small ^{3}He puff precedes the neutral beam injection, which results in the ^{3}He density of approximately 2% of the electron density. The electron temperature on axis is increased from around 8.5 keV to almost 11 keV by the RF. The ion temperature increases on axis from around 25 keV to 30-35 keV until a carbon bloom develops (probably due to a shift in the limiter strike point due to the increased stored energy). The neutron flux is increased approximately by 10% before the carbon bloom, reaching a peak fusion power of 3.2 MW.

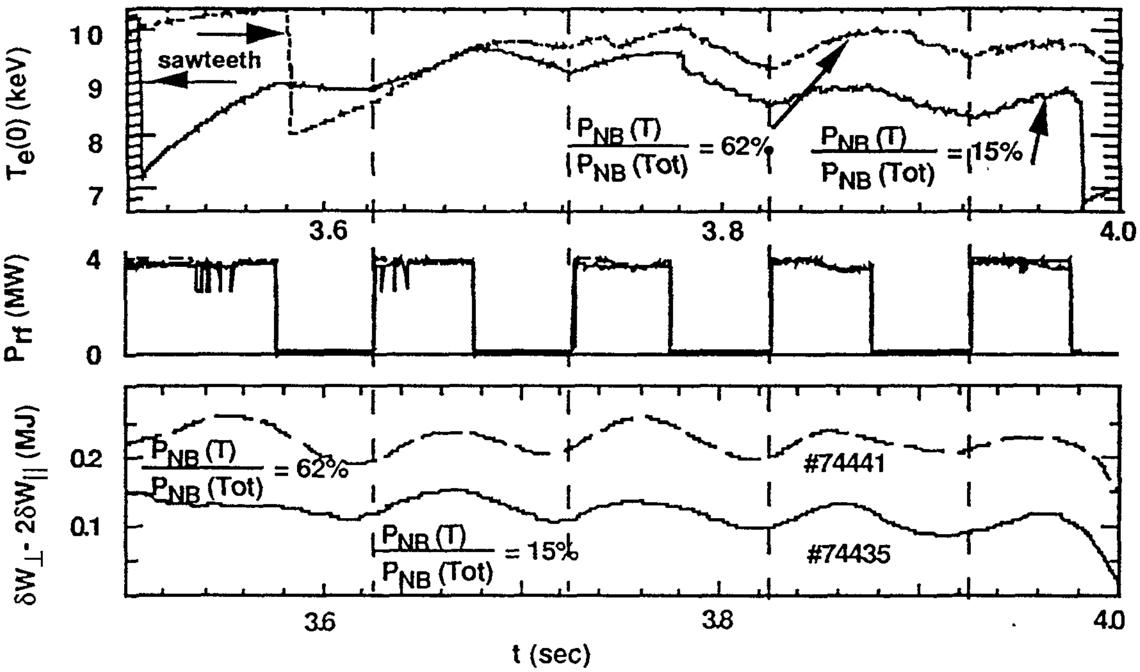

FIG. 1. Time variation of the electron temperature on axis, RF power, and excess perpendicular energy for two shots with different tritium concentrations. The power contained in the tritium beams is 3MW out of 19.5MW in shot #74435 and 11.5MW out of 18.5MW in shot #74441.

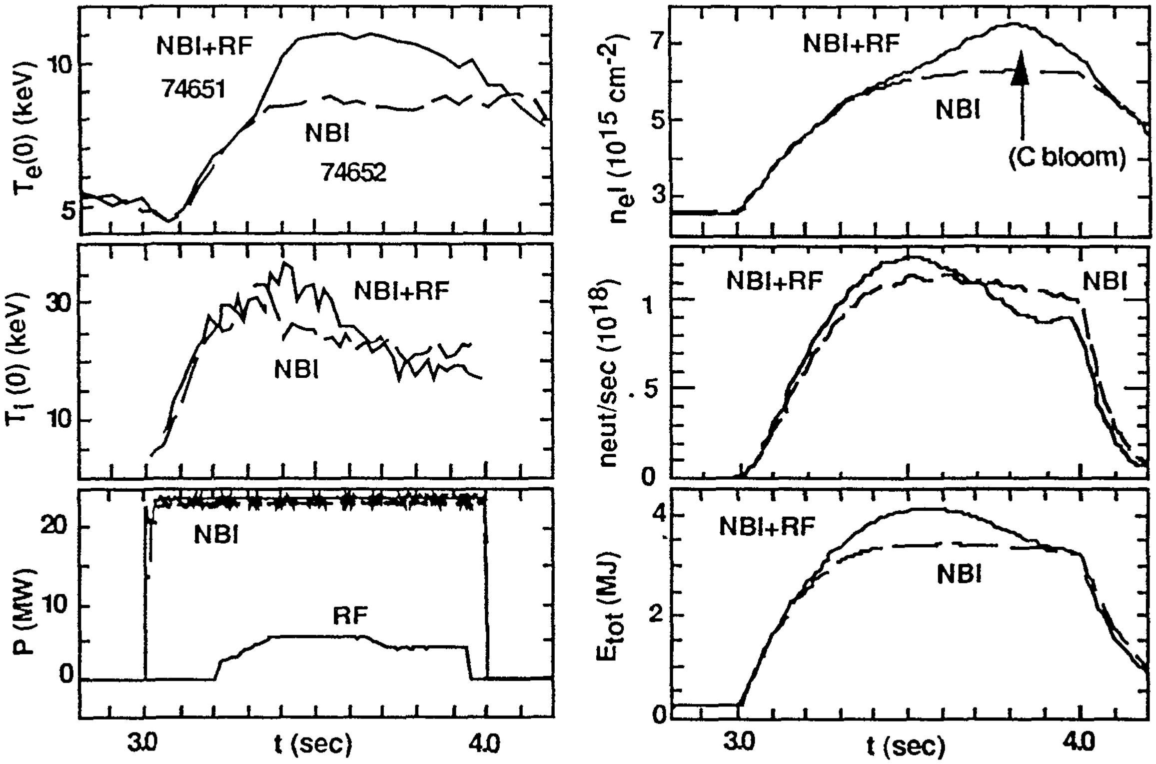

FIG. 2. A comparison of two shots, one with RF (5.4 MW peak) and one without RF. Tritium neutral beams contained 13.5 MW of the 23.5 MW total neutral beam heating. A carbon bloom in the RF shot degraded the performance near the end of the shot.

II. Mode Conversion Current Drive

One method of current drive particularly well suited for ICRF in a DT plasma is mode conversion of the fast wave to an ion Bernstein wave at the ion-ion hybrid resonance between the D and the T cyclotron resonances.[3] Recent experiments in TFTR have successfully tested the capability of this technique to efficiently couple energy to the electrons on or off axis. The experiments were performed in an ohmic plasma with comparable densities of ^{3}He and ^{4}He. In this case, the mode conversion layer is remote from either ion cyclotron resonance layer and ion heating can be avoided.[3] Amplitude modulation of the ICRF power combined with radially resolved ECE measurements are used to determine the power deposition profile for different toroidal fields (i.e. different locations in major radius of the mode conversion layer). Fig. 3a shows the Thomson scattering measurement of the electron temperature profile. With only ohmic heating and 3 MW of ICRF, the central electron temperature was increased to ~ 8 keV. The FWHM of the electron temperature is less than 30 cm, indicating that the electron heating was also very localized. Fig. 3b shows the measured electron absorption profile and the absorption profile calculated by the sixth order 1-D code FELICE[4] for a case in which the mode conversion surface is off axis (B_0=4.4 T, $n_{He\text{-}3}/n_e$=.24, $n_{He\text{-}4}/n_e$=.06, n_D/n_e=.13, n_C/n_e=.045). The small amount of absorption on axis is an indication that the direct electron damping of the fast wave is small compared to the damping due to the mode converted wave (the mode conversion layer is on the high field side of the axis). These results demonstrate that this technique could be a prime candidate for current profile control.

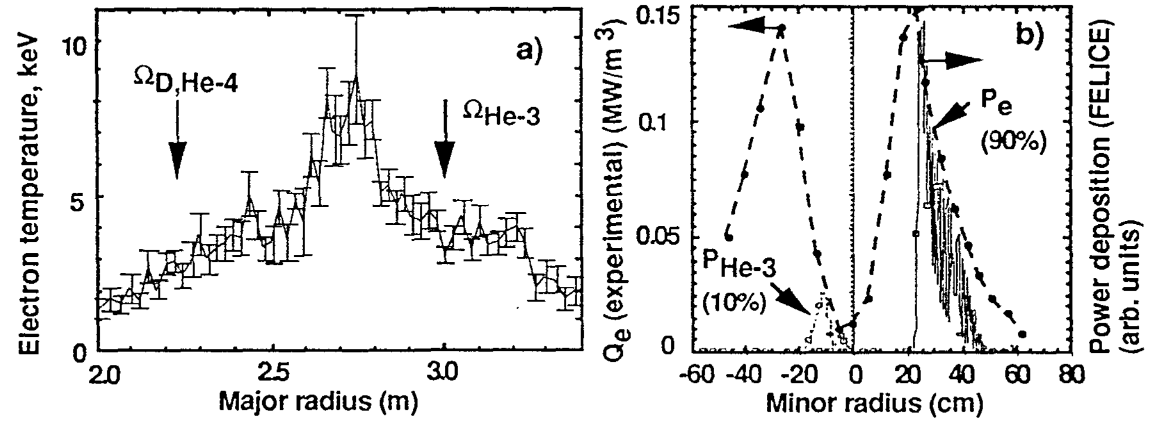

FIG. 3. Electron heating via the fast wave mode converted to a ion Bernstein wave provides localized coupling on or off axis. a) T_e profile with mode conversion layer on axis (3 MW of RF, no neutral beams). b) measured and calculated power deposition profile with mode conversion layer off axis (experimental measurements can not distinguish where on the flux surface the absorption takes place).

III. ICRF coupling to alpha particles

Coupling of the ICRF power to the alpha particles has been observed in the TFTR DT experiments. Fig. 4 shows the signal from the escaping fast ion probe[2] at the bottom of the vessel with a toroidal magnetic field of 4.1 T at the magnetic axis. The observed gyroradius of the alpha particles ejected during the RF implies energies greater than the 3.5 MeV birth energy. When the toroidal magnetic field was raised to 4.2 and 4.5 T, this signal was not present. A possible explanation for the acceleration is doppler broadened fundamental resonance heating of the alphas, i.e. $\omega_{c\alpha} = \omega - k_{\parallel}v_{\parallel}$. If this is the mechanism, it is likely that there are still alphas being

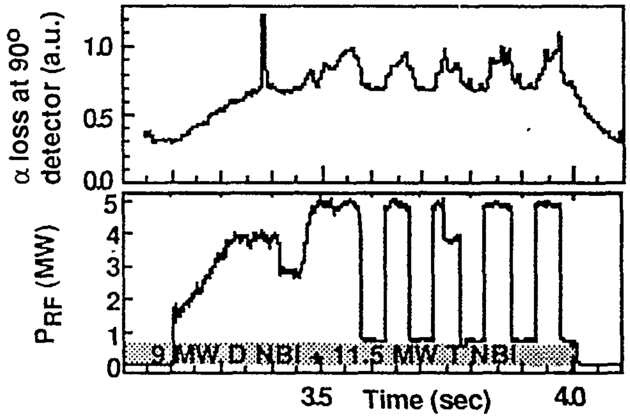

FIG. 4. The lost alpha particle signal and RF power for B_0 = 4.1 T.

accelerated by the ICRF at the higher toroidal magnetic fields, but those alphas which are lost due to the acceleration are no longer striking the wall at the fast ion probe location.

IV. Toroidal Alfven Eigenmodes (TAE)

In a fusion reactor, the energetic alpha particles may drive Toroidal Alfven Eigenmodes (TAE) unstable. TAE modes have been excited in TFTR DT supershots with the aid of an ICRF hydrogen minority. The ICRF power (63.6 MHz, $B_0 = 4.2$ T) was brought up to a level just above the TAE instability threshold (~5 MW) for a deuterium plasma (19.8 MW of neutral beams). Then 14 MW out of a total of 19 MW of neutral beams were supplied by tritium neutral beams, and the TAE signal strength was observed to increase by a large amount. The increase in the signal amplitude could be partially due to the alpha particles present in the DT shot supplying energy to the wave. Unfortunately, the dominant damping of the TAE wave is Landau damping by the beam ions, and because the tritium beam ions are moving at slower velocities than the deuterium beam ions, the damping is reduced in the DT shots. Detailed analysis of this data to determine the relative importance of these two effects is still in progress.

V. Fast Wave Current Drive (FWCD)

Though the current design of ITER relies heavily on FWCD, there have been few experiments demonstrating FWCD, and none in a DT plasma.[5] Recent improvements in the TFTR ICRF hardware have made it possible to launch several megawatts in a toroidally directed ICRF wave. Initial attempts at FWCD on TFTR used 1.5 MW of hydrogen minority heating with 43 MHz ICRF ($B_0 = 2.9$ T) to raise the electron temperature. After 200 ms, when $T_e \sim$ 3.5 keV, an additional 3 MW of 63.6 MHz ICRF was used for FWCD. With the chosen toroidal field, the hydrogen fundamental resonance for 63.6 MHz was inside the plasma near the high field limiter (but the wave polarization is dominantly right handed due to the proximity of the $n_{\|}^2 = R$ cutoff, so there is little energy coupled to the H-minority) and the second harmonic hydrogen resonance is approximately 10 cm beyond the low field limiter. Comparisons between +90 degree phasing between the antenna straps and -90 degree phasing are complicated by the fact that the density and electron temperature evolved differently. Early in the pulse, while the electron temperature and density are still similar, the loop voltage was measured to be ~ 50 mV lower when trying to drive co-current than when trying to drive counter-current. This result is consistent with driving ~ 40-100 kA of current.

VI. Future Plans

During the remainder of the TFTR DT run, a number of experiments will make use of the unique capabilities on TFTR. Mode conversion current drive will be attempted in a DT plasma. The effects of ICRF on toroidal plasma rotation, which are of importance to the ITER design, will also be investigated. Future ICRF heating of supershot experiments will include using lithium pellet conditioning to reduce the carbon influx during the shot, and the simultaneous use of hydrogen minority heating and second harmonic tritium heating (64 and 43 MHz, from different antennas). This use of two simultaneous frequencies is expected to result in the maximum ICRF power coupled into TFTR supershots, and the maximum total auxiliary heating (NBI and ICRF) of DT plasmas to ever be performed on TFTR.

Acknowledgments

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