IAEA-CN-64/EP-2

ICRF HEATING AND CURRENT DRIVE EXPERIMENTS ON TFTR

J. H. ROGERS, J. C. HOSEA, B. LEBLANC, R. MAJESKI, C. K. PHILLIPS,
G. SCHILLING, J. R. WILSON, S. H. BATHA[1], M. G. BELL,
D. S. DARROW, H. DUONG[2], K. W. HILL, F. M. LEVINTON[1],
S. S. MEDLEY, M. PETROV[3], E. J. SYNAKOWSKI, G. TAYLOR,
M. C. ZARNSTORFF, S. J. ZWEBEN, AND THE TFTR GROUP

Princeton Plasma Physics Laboratory
Princeton University
Princeton, New Jersey 08543
USA

---

[1] Fusion Physics and Technologies, Torrance, California, USA.

[2] General Atomics, San Diego, California, USA.

[3] A. F. Ioffe Physical-Technical Institute, St. Petersburg, Russian Federation.

ABSTRACT

ICRF HEATING AND CURRENT DRIVE EXPERIMENTS ON TFTR

Recent experiments in the Ion Cyclotron Range of Frequencies (ICRF) at TFTR have focused on the RF physics relevant to advanced tokamak D-T reactors. Experiments performed either tested confinement in reactor relevant plasmas or tested specific ICRF heating scenarios under consideration for reactors. H-minority heating was used to supply identical heating sources for matched D-T and D only L-mode plasmas to determine the species scaling for energy confinement. Second harmonic tritium heating was performed with only thermal tritium ions in an L-mode target plasma, verifying a possible start-up scenario for the International Thermonuclear Experimental Reactor (ITER). Direct electron heating in Enhanced Reverse Shear (ERS) plasmas has been found to delay the back transition out of the ERS state. D-T mode conversion of the fast magnetosonic wave to an Ion Berstein Wave (IBW) for off-axis heating and current drive has been successfully demonstrated for the first time. Parasitic Li^7 cyclotron damping limited the fraction of the power going to the electrons to less than 30%. Similar parasitic damping by Be^9 could be problematic in ITER. Doppler shifted fundamental resonance heating of beam ions and alpha particles has also been observed.

1. INTRODUCTION

ICRF has been used extensively on TFTR to explore a variety of important topics relevant to the D-T reactor regime. The focus of this paper is confinement, heating, current drive, and wave interactions with alpha particles for extrapolation to ITER. Second harmonic tritium heating of the low density start-up plasma in ITER is expected to bring the plasma to an H-mode transition. On TFTR, a favorable isotope scaling of the confinement time has been demonstrated going from D to D-T, and the second harmonic tritium heating scenario has been verified. Advanced tokamak scenarios with improved confinement and stability will require pressure and current profile control. Direct heating of electrons with RF power is therefore another important application of ICRF. On TFTR, efficient core heating of ERS plasmas has been demonstrated with direct electron heating from the fast wave which, in addition, was observed to sustain the ERS mode. Strongly localized electron heating and current drive have also been achieved in multi-ion species plasmas via mode conversion of the fast wave to an Ion Bernstein Wave (IBW). The efficiency of a tokamak reactor may be greatly enhanced if the IBW properties are properly controlled so that the wave interaction with the alpha particles channels energy from the alpha particles to the thermal ions [1]. During mode conversion experiments, coupling of the RF power to energetic beam ions and alpha particles has been observed.

2. SPECIES SCALING OF TRANSPORT IN L-MODE

H-minority heating in deuterium (D) plasmas and deuterium-tritium (D-T) plasmas has been used to provide a heating mechanism which is independent of the majority ion species, giving a good test of confinement time scaling with species. Such identical heating profiles for different species are not possible with neutral beam heating, because of the velocity dependence of the energy deposition profile. Similarly, it is not possible to utilize the same RF heating scheme in hydrogen and deuterium plasmas, making TFTR uniquely qualified for this experiment.

Density feedback gas puffing was used to maintain closely matched densities ($n_e(0) \sim 5.5 - 6.0 \times 10^{19}\ m^{-3}$). The H-minority absorption profile was the same for all the plasmas, and the energy distribution in the hydrogen minority ion tail was measured to be the same for a given RF power in D and D-T plasmas.

Figure 1 shows that the total stored energy increased when going from a deuterium plasma (8% H, 2-3% C, 1% T) to a plasma with 35-40% tritium and 40% deuterium (5% H, 2-3% C). The increase in stored energy is consistent with the energy confinement time improving proportional to the average atomic number of the ions to the power of 0.35-0.50 (Fig. 2). These measurements are consistent with other isotope experiments on TFTR [2,3], but they contradict gyro-Bohm diffusion scaling which predicts a decrease in the confinement time as the effective ion mass increases. The positive isotope effect observed in this experiment supports the enhancement of the performance of ITER in D-T.

3. ITER STARTUP SCENARIO: SECOND HARMONIC TRITIUM HEATING IN L-MODE

One possible ITER startup scenario would feature second harmonic tritium heating of the L-mode plasma to heat it to the H-mode transition threshold and on to ignition. Because of the low single pass absorption by low temperature tritium, this scenario might prove to be too inefficient. On TFTR, second harmonic tritium heating of an L-mode plasma with only thermal low temperature tritium (no tritium neutral beams) has been demonstrated to be an effective means of heating the plasma. An energetic tritium tail distribution was formed quickly (T_{tail}~ 0.5 MeV in ~100 ms), thereby significantly enhancing the RF damping. The increase in total stored energy per MW was the same as that for neutral beams with identical target plasmas (Fig. 3). These experiments used 43 MHz RF to heat an approximately 50:50 mix of D:T with 1.8 MA plasma current, 4.7 T toroidal magnetic field and peak density of $5x10^{19}$ m^{-3}.

4. DIRECT ELECTRON HEATING IN ERS PLASMAS

Much attention has been focused recently on the Enhanced Reverse Shear (ERS) mode in TFTR [4]. The distinguishing characteristic of this mode is that the particle and energy diffusivity are dramatically reduced in the core of the plasma. The resulting discharges have a very high central density (~ $1x10^{20}$ m^{-3}) but more modest ion and electron temperatures than the typical TFTR supershot. Direct fast wave electron heating with ICRF was used to provide additional heating of the ERS plasma in order to investigate the effect of the higher electron temperature on the evolution of the ERS mode. The RF electron heating is found to delay the transition out of the ERS state.

The target plasma is based on a reproducible ERS shot in which low power neutral beam heating (~ 7.5 MW) starts at 0.7 sec during the current ramp up. The plasma current reaches 1.6 MA by 2.0 sec, at which time (usually) a lithium pellet is injected. The ERS transition is triggered during a high power neutral beam heating phase which occurs from 2.5 to 2.9 seconds. The central density remains high during the low power "postlude" (2.9-3.5 sec, 7.5 - 10 MW neutral beam heating) until the plasma has a back-transition out of the ERS mode [5].

Direct electron heating was performed with 43 MHz RF and a toroidal magnetic field of 4.57 T at the machine major radius (2.62 m). The only ion heating competition for the fast wave was second harmonic tritium heating of the recycled tritium. From the D-T neutron rate, the tritium density could be estimated as ~ .3 % of the deuterium density and should not have absorbed much of the RF power.

When the RF power changes abruptly during square wave modulation, there is a discontinuity in the time derivative of the electron stored energy density which is equal to the local power density going to the electrons (assuming a time scale short compared to the transport times). The power deposition profile to the electrons can then be estimated by using the measured quantities n_e and T_e.

Figure 4 shows profiles of RF power deposition, T_e, and n_e during the postlude with and without 2 MW of RF.

With co-only injection of the neutral beams, the back transition occurs ~100 ms into the postlude without RF heating, and ~200 ms into the postlude with the addition of ~ 2 MW of electron heating (see Fig. 5). The addition of another co-directed neutral beam (2.5 MW) did not change the time of the back-transition (with or without the RF power). At the end of the high power phase, 2.9 sec, the density and ion temperature with and without RF are the same. The cause of the delay of the back transition is still under investigation but may be due to the additional electron pressure gradient or a slower q-profile evolution caused by the increase in electron temperature or an RF induced change in the toroidal plasma rotation.

5. MODE CONVERSION HEATING AND CURRENT DRIVE

Recent experiments on TFTR have measured current profile modifications resulting from mode conversion current drive (MCCD) with 43 MHz RF in D-He^4-He^3 plasmas [6]. When co- and counter-current drive antenna phasing (± 90^o) are compared, the difference in loop voltage after ~1 s is consistent with the current drive expected from theory. The current density profile measured by the Motional Stark Effect (MSE) diagnostic for co- and counter-current drive phasing with the mode conversion surface at r/a = .17 is shown in Fig. 6. During off axis current drive, the inductive current opposing the driven current appears to be predominately on axis, which allows a change in the current profile in a time less than the usual current diffusion time, L/R. A dramatic example of the capability for localized off axis mode conversion power deposition is shown in Fig. 7, where a hollow electron temperature profile persists for approximately two energy confinement times (τ_E ~ 160 ms).

The frequency of a pair of transmitters driving two antennas was lowered to 30 MHz for TFTR operation in 1996 to allow mode conversion at the D-T ion-ion hybrid resonance at full toroidal field on TFTR. The fraction of RF heating power going to the electrons was found to be less than 30%. This low efficiency is believed to be due to competition with Li^7 minority heating. The mass to charge ratio for Li^7 is 2.33, placing the Li^7 cyclotron resonance between D and T, generally on the low field side of the D-T mode conversion layer in TFTR. Though fundamental resonance heating of the tritium beam ions is also expected, it has been minimized by arranging the tritium beam and directed ICRF to be counter propagating with respect to each other.

Because use of lithium pellets has become common on TFTR to reduce the recycling rate, lithium has now become an unavoidable impurity. Even after several hours of high power (> 10 MJ/shot, H-minority heated) helium conditioning discharges, the ratio of lithium ions to carbon ions is estimated spectroscopically to be approximately 0.1, corresponding to a lithium density of typically 0.5% of the electron density in the plasma core. This small amount of Li^7 can be an efficient absorber with sufficient tritium in the plasma such that the Li^7 ion becomes a "light" minority ion. Figure 8 shows the expected and measured fraction of RF power going to the electrons as a function of tritium fraction with 0.5% Li^7 and no Li^7. With low tritium fractions, most of the wave energy goes to the tritium ions; at high tritium fractions significant energy goes to the lithium ions, if Li^7 is present in sufficient quantity.

In 1997, Li^6 will be used for wall conditioning to avoid the complication of lithium absorption (Li^6 constitutes 7.5% of naturally occurring Li). Since the charge to mass ratio for Li^6 is 1/2 (as it is for D and C^{12}), it is equivalent to deuterium in the wave dispersion relation. For tokamaks in which beryllium

(Be^9) is used for wall conditioning, as proposed for ITER, comparable minority Be^9 ion heating will arise in D-T plasmas because the charge to mass ratio is between that of tritium and deuterium. However, unlike lithium, there is no stable isotope of beryllium which has a charge to mass ratio of 1/2. Therefore, electron heating in the frequency range $\omega_{cT} < \omega < \omega_{cD}$ will not be consistent with using Be on plasma facing components in ITER unless the level of Be entering the plasma can be held to very low values.

6. FUNDAMENTAL CYCLOTRON RESONANCE HEATING

Ions with sufficient energy can be heated because of Doppler broadening. The resonance condition for fundamental cyclotron resonance heating is $\omega = \vec{k} \cdot \vec{v} + \omega_{ci}$. In general, during 30 MHz operation in TFTR, both the deuterium and tritium resonances are in the plasma. The fast wave field is predominately right circularly polarized near the deuterium resonance because of the high fraction of deuterium in the plasma. However, energetic particles such as deuterium or tritium beam ions or alpha particles can have large enough values of $\vec{k} \cdot \vec{v}$ to be resonant far from the cyclotron layers. In reactor plasmas where there is a significant fraction of alpha particles and ion temperatures are high, fundamental resonance absorption can become important.

Alpha particle heating due to fundamental ICRF auxiliary heating has been observed with the pellet charge exchange (PCX) diagnostic [7] during D-T mode conversion experiments. It has not been determined whether the fast wave or the mode converted IBW wave is responsible for the wave-alpha interaction.

Deuterium and tritium neutral beam ion wave absorption has also been detected. Heating of deuterium beam ions was measured with the lost fast ion probe [8] during D-He^3 mode conversion heating experiments. Only a small fraction of the RF power was absorbed by the energetic ions in this case (T_e measurements indicate ~ 80% of the power going to the electrons). Because the lost fast ion probe signal is sensitive to the location of the mode conversion layer, it is most likely that the mode converted IBW is heating the deuterium beam ions (because the IBW is very spatially localized, whereas the fast wave is not).

7. SUMMARY

ICRF experiments on TFTR have verified a number of reactor relevant physics issues and auxiliary heating scenarios. In L-mode plasmas with T_i~T_e, a favorable isotope scaling was demonstrated going from D plasmas to D-T plasmas. Second harmonic tritium heating was verified as an efficient means of heating the ITER start-up plasma. Electron heating in ERS plasmas was found to sustain the ERS mode. Current profile control has been demonstrated using strongly localized electron heating with MCCD. D-T mode conversion heating and heating of fusion alpha particles has been performed for the first time.

8. FUTURE PLANS

For the 1997 operation of TFTR, three two strap fast wave ICRF antennas will be replaced with new antennas. A four strap direct launch IBW antenna will be used to explore development of a transport barrier and access to high confinement modes using the poloidal sheared flow generated by the IBW (4 MW source power) [9]. Two four strap fast wave antennas in adjacent bays will be used to test D-T mode conversion current drive at higher RF driven current to levels that may assist ERS optimization and wave coupling to the alpha particles (8 MW source power, 30 MHz).

ACKNOWLEDGMENTS

The authors express their appreciation to the technical, engineering, and scientific staff of TFTR, and to R. J. Hawryluk for his support. This work is supported by US Department of Energy contract No. DE-AC02-76CH03073.

REFERENCES

[1] N. J. FISCH, et al., IAEA-CN-64/A2-3 these Proceedings.
[2] S. D. SCOTT, et al., Phys. Plasmas, **2** (1995) 2299.
[3] S. D. SCOTT, et al., IAEA-CN-64/A6-6 these Proceedings
[4] F. M. LEVINTON, et al., Phys. Rev. Lett. **75** (1995) 4417.
[5] F. M. LEVINTON, et al., IAEA-CN-64/A1-3 these Proceedings.
[6] R. MAJESKI, et al., Phys. Rev. Lett. **76** (1996) 764.
[7] S. S. MEDLEY, et al., Rev. Sci. Instrm. **67** (1996) 1-14.
[8] S. J. ZWEBEN, et al., Nucl. Fusion **30** (1990) 1551.
[9] M. ONO, et al., Plasma Physics and Controlled Nuclear Fusion Research 1994 (Proc. 20th Int. Conf. Seville, 1994) Vol. 1, IAEA, Vienna (1995) 469-480.

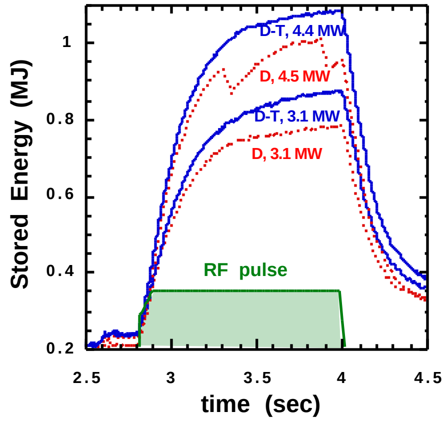

FIG. 1. Stored energy in D (dashed line) and D-T (solid line) plasmas with two levels of ICRF H-minority heating.

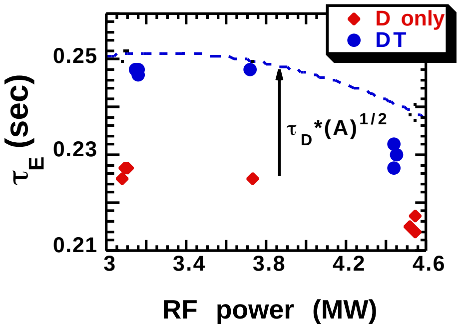

Fig. 2. Measured energy confinement time vs RF power for D only plasmas (diamonds) D-T plasmas (circle). The dashed line is the D only value times the square root of the effective mass ratio.

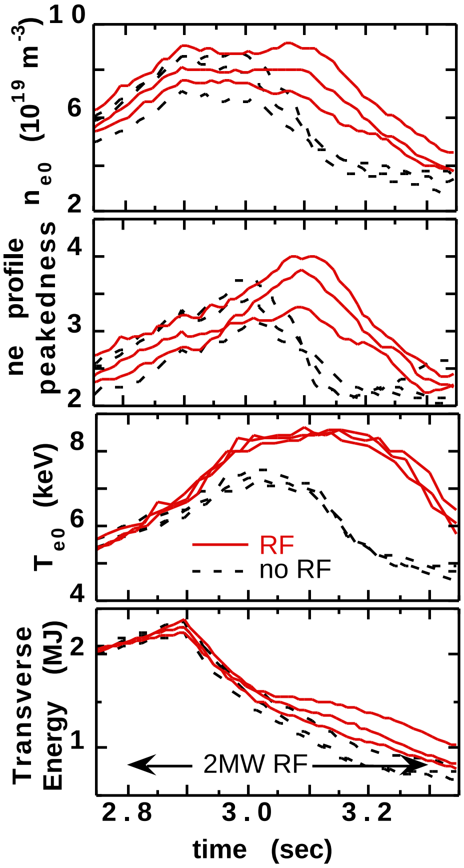

FIG. 4. ERS plasmas: 3 shots with no RF (2 with 3 co-beam postlude, 1 with 4 co-postlude) and 3 RF heated shots (2 with 3 co-beam postlude, 1 with 4 co-postlude).

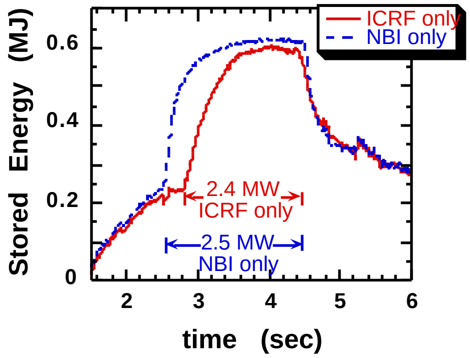

FIG. 3. Stored energy for 2.5 MW neutral beam injection and 2.4 MW of 2nd harmonic tritium heating in 50/50 D/T L-mode plasma.

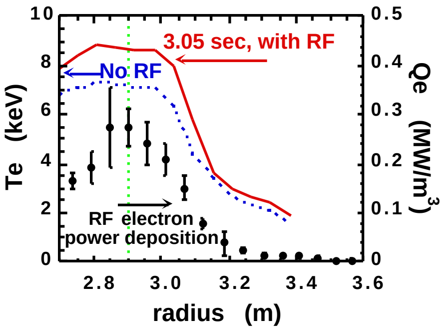

FIG. 5. Electron temperature profile at 3.05 sec in ERS plasma with RF (solid line) and without RF (dashed line). Symbols show RF electron heat deposition (right vertical axis).

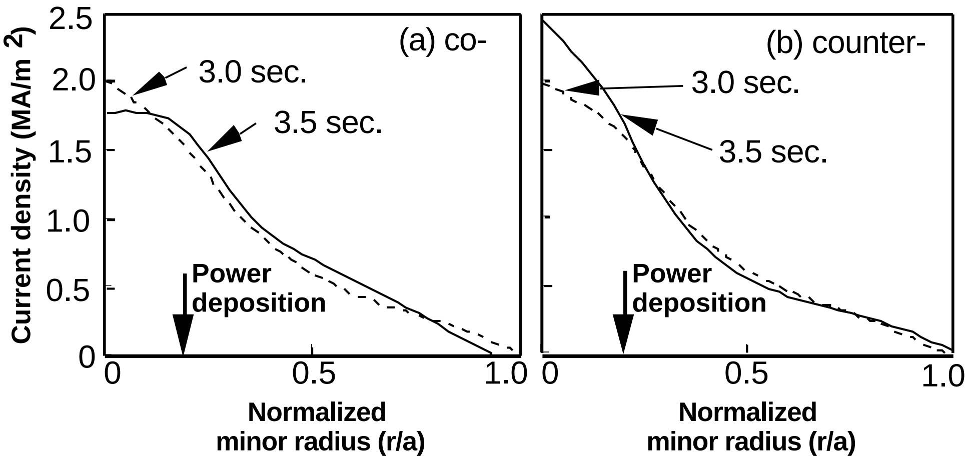

FIG. 6. Current density profile at the start of the RF pulse (3.0 sec) and 0.5 sec later for co-current antenna phasing (a), and counter-current antenna phasing (b) with mode conversion layer at r/a ~ .17.

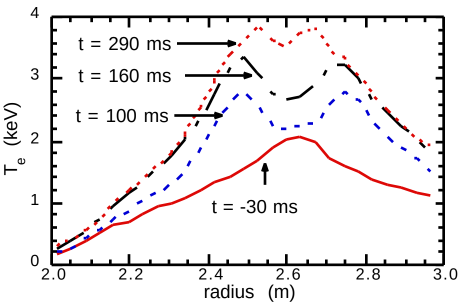

FIG. 7. Hollow T_e profile from off axis mode conversion heating in a D-He^3 plasma. Times are relative to the start of the RF pulse.

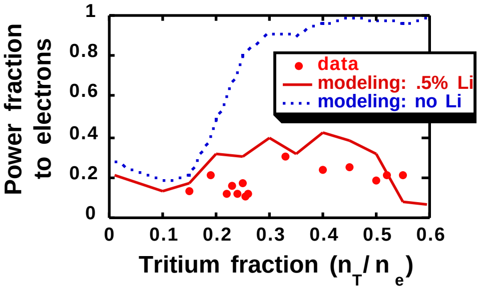

FIG. 8. Calculated power split of the RF power with 0.5% Li^7 (solid line) and no Li^7 (dashed line) and measured fraction heating electrons (symbols).