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MINORITY REGIME

BY

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ICRF HEATING OF TFTR DEUTERIUM SUPERSHOT PLASMAS IN THE ^3He MINORITY REGIME⁺

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Abstract -- The increased core electron temperature produced by ICRF heating of TFTR, D-T neutral-beam-heated supershot plasmas is expected to extend the alpha particle slowing down time and hence enhance the central alpha particle pressure. In preparation for the TFTR D-T operational phase, which is due to start in late 1993, a series of experiments were conducted on TFTR to explore the effect of ICRF heating on the performance and stability of low recycling, deuterium supershot plasmas in the ^3He minority heating regime. The coupling of up to 7.4 MW of 47 MHz ICRF power to full size ($R \sim 2.62$ m, $a \sim 0.96$ m), ^3He minority, deuterium supershots heated with up to 30 MW of deuterium neutral beam injection has resulted in a significant increase in core electron temperature ($\Delta T_e = 3-4$ keV). Simulations of equivalent D-T supershots predict that such ICRF heating should result in approximately a 60% increase in the alpha particle slowing down time and an enhancement of about 30% in the central alpha pressure. Future experiments to be conducted at ICRF powers up to 12.5 MW during the upcoming TFTR D-T campaign may result in even greater enhancements in core alpha parameters. This paper presents results from experiments performed at an axial toroidal magnetic field of ~ 4.8 T, where the minority resonance was within 0.1-0.15 m of the plasma core. Combined ICRF and neutral beam heating powers in these experiments reached TFTR record levels of over 37 MW, which allowed an exploration of the power loading limits on the carbon limiter tiles. The plasma current was operated at 1.85 and 2.2 MA and sawtooth suppression was observed at the higher plasma current.

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I. INTRODUCTION

One of the major objectives of the ion cyclotron range of frequency (ICRF) program (WILSON *et al.*, 1992; TAYLOR *et al.*, 1993a) on TFTR is to enhance the alpha particle parameters in deuterium-tritium (D-T) plasma experiments, which are scheduled to commence later in 1993. The increased core electron temperature produced by ICRF heating (ICRH) of D-T neutral beam injection (NBI) heated plasmas is expected to increase the alpha particle slowing down time and hence enhance the central alpha particle pressure. In preparation for D-T operation, experiments were conducted on TFTR to explore the effect of ICRH on the performance and stability of low recycling, D-D supershot plasmas (STRACHAN *et al.*, 1987) in the ^3He minority heating regime. These experiments also provided an opportunity to investigate ICRH-induced loss of fusion products and the confinement of the ^3He tail ions.

TFTR supershot plasmas are predominantly beam-fueled discharges with low edge recycling, and as such, the plasma density profile evolves significantly throughout the NBI pulse and the edge density is relatively low, particularly at the start of NBI. This is a challenging regime for ICRH since a finite density must be established in front of the antennas for efficient RF coupling. In addition, the antenna loading impedance increases significantly at the start of NBI due to the rapid density rise. The antenna coupling was optimized in experiments which explored a range of plasma major radial positions and ellipticity. Extensive plasma conditioning was employed to minimize the influx of impurities and deuterium gas from the limiter tiles and antennas, Sec. IIA summarizes the results from this plasma optimization phase. Experiments were performed at an axial toroidal magnetic field of $\sim 4.8\text{T}$, at two plasma currents; 1.85 and 2.2 MA. Combined ICRH and NBI powers in these experiments reached levels of over 37 MW, about 15-20% higher than in previous TFTR NBI-only experiments. The exploration of TFTR power handling limits is discussed in Sec. IIB. Sec. IIC summarizes the global plasma performance data. Magneto hydrodynamic (MHD) behavior and fast ion loss measurements are presented in Sec. IID. The equilibrium kinetic analysis of these plasmas is

discussed in Sec. III together with results from a D-T plasma simulation. A summary of our conclusions and plans for future work in this plasma regime are presented in Sec. IV.

II. EXPERIMENT AND RESULTS

A. DISCHARGE OPTIMIZATION

Figure 1 shows a poloidal cross-section through the TFTR vacuum vessel and indicates schematically the position of the ICRH antennas and limiter positions. Since the inner limiter has considerably more power handling capability than the outer limiters (SEVIER *et al.*, 1983; PELESSONE *et al.*, 1983) the plasmas in these experiments were run so that the majority of the power flow was to the inboard bumper limiter. However, to simultaneously bring the outer edge of the plasma close to the four ICRH antennas on the outboard side it was necessary to develop a "full bore" ($R \sim 2.62\text{m}$, $a \sim 0.96\text{m}$) supershot plasma. Prior to the 1991-92 TFTR run period, supershot plasma performance was optimized at $R \sim 2.45\text{m}$, $a \sim 0.83\text{m}$ but with the installation of an upgraded RF limiter in 1991 the supershot performance at the larger major radius was significantly improved (HAWRYLUK *et al.*, 1992).

Supershots are characterized by low edge recycling with all the fueling provided by the beam ions and hence they have a low edge density. However, NBI provides a relatively significant increase in edge density, so that after 100-200 ms sufficient density had built-up in front of the antennas to allow efficient coupling of ICRH power (MAJESKI *et al.*, 1993). The evolution of the electron density at the last closed flux surface on the outboard side ($R \sim 3.6\text{m}$) from Abel-inverted multi-channel far-infrared interferometer data (MANSFIELD *et al.*, 1987; PARK, 1989) is shown in Fig. 2. The rapid rise in edge density throughout the NBI pulse from 3 to 4 s (shown lightly shaded in Fig. 2) is particularly challenging for ICRH in this regime since it can result in a factor of 5 to 6 increase in antenna loading impedance. The start of the ICRH pulse (shown by the darker shading in Fig. 2) was delayed ~ 200 ms from the beginning of NBI to allow time for some NBI fueling to occur and the ICRH pulse shape was

programmed with a modest initial step and ramp to avoid antenna arcs. A 100 ms duration, 1 Torr liter/s, ^3He puff was introduced into the discharge about 0.5 s before the start of the NBI pulse. The increase in edge density due to the ^3He puff at 2.5 s is relatively small, as shown in Fig. 2. The increase in measured electron density at the time of the puff was used to extrapolate the ^3He concentration during NBI. We calculated that this puff was sufficient to produce a ^3He concentration equal to about 1.5-2.5% of the peak electron density 500 ms after the start of NBI. The puff correlated with a degradation in global energy confinement of $\sim 5\%$ [Fig. 3(a)] and a decrease in plasma reactivity $\sim 10\%$ [Fig. 3(b)], presumably due to the high recycling ^3He (ZARNSTORFF *et al.*, 1988; SCOTT *et al.*, 1992).

B. EXPLORATION OF POWER HANDLING LIMITS

Combined ICRH and NBI powers reached levels of over 37 MW during these experiments, about 5 MW higher than previous TFTR plasmas which were heated only by neutral beams. This provided an opportunity to explore the power loading limits for the carbon limiter tiles. Figure 4 shows a plot of the radiated power fraction as a function of the total heating power at the time of maximum stored energy. The radiated power fraction remained below 15% for the 1.85 MA plasmas up to the highest input powers used at this plasma current ($\sim 32\text{MW}$). However, some of the 2.2 MA plasmas which were positioned vertically $\sim 2\text{mm}$ higher exhibited elevated radiation losses at heating powers above $\sim 30\text{ MW}$. The enhanced radiation levels were also accompanied by a significant increase or "bloom" in carbon-II light (RAMSEY *et al.*, 1991). Vertical plasma position shifts of 2-3 mm were found to reduce or eliminate the carbon bloom and enhanced radiation for the same plasma input power. Figure 5 shows the time evolution of major plasma parameters for two similar plasmas, one positioned $\sim 2\text{ mm}$ higher than the other. Although there is no noticeable elevation in $D\alpha$ emission [Fig.5(e)] prior to the bloom, the carbon-II light [Fig.5(f)] is significantly higher throughout the NBI and ICRH pulses in the plasma with the bloom. The extreme sensitivity of the plasma performance to changes in the vertical position could be interpreted as indicating a steep power scrape-off. But a more likely explanation is that the shift in vertical position moves the plasma so that it no

longer interacts with the bottom of the RF limiters. Since this in turn increases the connection length of the outer flux surface it will result in increased power loading at the top of the RF limiters. Furthermore, since the scrape-off length increases as the square root of the connection length some of this power may fall behind the front surface, on the edges of the RF limiters. This effect can increase the power loading significantly since the power falling on the limiter edge is no longer at near-tangential incidence.

C. SUPERSHOT PLASMA PERFORMANCE WITH ICRH

Experiments were performed at plasma currents of 1.85 and 2.2 MA. 22-23 MW of NBI was typically employed in the 1.85 MA plasmas and 28-30 MW of NBI was used in the 2.2 MA plasmas. The plasma current and NBI power were chosen to stay well below the empirical TFTR β limit, β_n was typically <1.5 for these discharges. Up to 5.7 MW and 7.4 MW of 47 MHz ICRH power has been coupled into R~2.62 m, a~0.96 m deuterium discharges at a plasma current of 1.85 MA and 2.2 MA, respectively. The plasmas had an axial toroidal magnetic field of ~4.8 T. The Shafranov shift on axis was 0.2-0.25 m and 0.16-0.2 m for the 1.8 MA and 2.2 MA plasmas, respectively. The ^3He resonance was within 0.1-0.15 m of the plasma core.

Figure 6 shows a comparison between two plasmas heated with 23 MW of NBI between 3 and 4 seconds. Approximately 60% of the NBI power was in the direction of the plasma current in both cases. One of these discharges (solid line) had 5.7 MW of ICRH coupled into it between 3.2 and 4 seconds, the other plasma (dashed line) had no ICRH power but both plasmas had a similar size ^3He puff at 2.5 s. The central electron temperature measured by electron cyclotron emission (ECE) (STAUFFER *et al.*, 1985) increased by 40% [Fig.6(b)] and the diamagnetically measured global stored energy increased by 20% [Fig.6(c)] with the addition of ICRH. With the application of ICRH the core ion temperature at 3.7 seconds measured by charge exchange recombination spectroscopy (FONCK *et al.*, 1989) increased from 20 to 24 keV. The confinement time [Fig.6(f)] and central electron density evolution

from 20 to 24 keV. The confinement time [Fig.6(f)] and central electron density evolution [Fig.6(g)] were similar in both discharges, however there was ~10% increase in Z_{eff} [Fig.6(h)] with the application of ICRH heating. Although there was an increase in titanium concentration during the ICRH pulse, consistent with some impurities coming from the antennas, it was insufficient to account for the rise in Z_{eff} . The increased Z_{eff} probably results from a combination of impurity influx from the limiter and the antennas. The relatively small increase in impurities results from the beneficial effect of the extensive antenna conditioning which preceded these experiments. The neutron production rate [Fig.6(e)] is very similar for both plasmas. Since the critical energy for the beam ions is ~200keV within 200 ms of the start of NBI, the beam ions predominantly slow down on the plasma ions, not the electrons. The D-D neutron production rate is therefore only expected to increase ~10-15% due to the enhanced core electron temperature. The calculated slowing down time for the ~100 keV neutral beam full-energy component [Fig.6(d)] is ~150 msec at 3.7 sec for both plasmas. The fact that the plasma reactivity shows no improvement is probably due to the combination of increased impurity content and reduced central electron density with the addition of ICRH.

Figure 7 summarizes the results, at the time of peak stored energy, for an ICRH power scan of 1.85 MA supershot plasmas with 22-23 MW of NBI. The fraction of NBI power in the direction of the plasma current was kept relatively constant at a value of ~60% and the ^3He puff size was similar for these plasmas. The maximum ICRH power coupled into a 1.85 MA supershot plasma was 5.7 MW. Core electron temperature [Fig. 7(a)] measured from ECE was increased ~40% with the application of the maximum ICRH power. Thomson scattering measurements (JOHNSON *et al.*, 1986) of electron temperature were generally not taken at the time of peaked stored energy. Temperature profile comparisons with ECE measurements (at other times in the pulse) gave core Thomson scattering electron temperatures which were systematically ~10% lower when the ECE temperature was ~9keV, and 15-20% lower when the ECE temperature was ~11.5 keV. For example, Fig. 6(b) shows the change in core electron temperature with the addition of ICRH measured by Thomson scattering. A systematic disagreement between Thomson scattering and ECE electron temperature measurements has

several years ago. This empirical observation remains an unresolved issue and is the subject of an ongoing study (TAYLOR *et al.*, 1993b). The change in central ion temperature [Fig. 7(b)] was of the same order as the $\pm 10\%$ measurement errors of the charge exchange recombination spectroscopy diagnostic. There was an $\sim 4\%$ drop in the core electron density (Fig. 7(c)) and $\sim 10\%$ drop in density profile peakedness ($n_e(0)/\langle n_e \rangle$) determined from far-infrared interferometry data. The peakedness degradation was due in part to an increase in edge density, this was correlated with a small increase in Z_{eff} measured by visible bremsstrahlung (RAMSEY and TURNER, 1987) from approximately 3.1 to 3.4 with the addition of 5.7 MW of ICRH. The decreased core electron density could result from reduced beam penetration due to the higher edge density and/or Z_{eff} . τ_E decreased 5-10% as the ICRH power was increased [Fig. 7(d)], although this is comparable to the degradation expected for Goldston empirical L-mode scaling (GOLDSTON *et al.*, 1984) it is also of the same order as the uncertainty in the τ_E measurement. The relatively large scatter in τ_E with no ICRH is due to variations in wall conditioning. The enhancement over the Goldston empirical L-mode was typically 1.7-2.3 for the 1.85 MA dataset. The measured plasma reactivity [Fig. 7(e)] remained unchanged with the addition of ICRH. Figure 7(f) shows the projected core alpha energy slowing down time calculated for D-T equivalent plasmas, with the same central density and temperature measured during the D-D experiments. A 60% enhancement in the core alpha particle energy slowing down time was calculated for equivalent D-T plasmas at the highest ICRH powers.

Operation at 2.2 MA was attempted at higher NBI power (~ 28 -30 MW) and higher ICRH power (up to 7.4 MW). At these higher input powers, plasma performance was relatively poor and unreliable as has already been indicated in the previous section on power handling limits. Global energy confinement times were 15-20% lower in the 2.2 MA plasmas compared to the 1.85 MA discharges. the enhancement over the Goldston empirical L-mode scaling was only 1.2-1.7 for the 2.2 MA plasmas. Figure 8 provides an overview of the general features of these discharges; the evolution of major plasma parameters for two 2.2 MA plasmas is shown. Discharges that could be directly compared with and without ICRF were difficult to obtain due to variations in plasma conditioning. The two shots of Fig. 8 are generally similar and have the

same NBI powers but some differences remain which tend to complicate the analysis. The discharge shown by the solid lines had an additional 5.8 MW of ICRH power during NBI starting at 3.2 s and it is somewhat better conditioned before the NBI pulse starts. About 100 ms after the beginning of the NBI pulse in the shot without ICRH (dashed lines) the electron density peakedness [Fig.8(i)] suddenly drops, and there is a 10-15% enhancement in radiated power [Fig.8(g)] and carbon-II light [Fig.8(h)] early in the NBI pulse. In the shot with ICRH the density peakedness continues to rise until 3.2 s. This behavior complicates interpretation of the plasma evolution immediately following turn on of the ICRH, however during the last 400 ms of NBI there is a significant enhancement in the central electron temperature [Fig.8(c)] and a suppression of sawteeth in the shot with ICRH. Although the neutron production rate [Fig.8(b)] falls towards the end of NBI it remains at over twice the level of the shot without ICRH, despite a significant increase in carbon-II light. Figure 9 summarizes data analyzed at the time of peak stored energy from an ICRH power scan of 2.2 MA plasmas heated with 28-30 MW of NBI. With the addition of 6-7 MW of ICRH the central electron temperature [Fig.9(a)] measured by ECE increases 40-50% and the projected alpha particle energy slowing down time [Fig.9(d)] is enhanced ~50%. However, the neutron production rate [Fig.9(b)] and global confinement [Fig.9(c)] data show considerable variability due to variations in impurity in-flux.

D. MHD AND FAST ION LOSSES

The addition of ICRH resulted in somewhat higher levels of MHD activity in the 1.85 MA discharges. The irreproducible nature of the 2.2 MA plasmas precluded any systematic study of MHD at the higher current. In Fig.10 the evolution of the amplitude of Mirnov coil fluctuations is plotted for the two 1.85 MA plasmas shown in Fig. 6. The plasma with 5.7 MW of ICRH (solid line) exhibits an increased level of MHD activity during the ICRH pulse. MHD fluctuations above 25 kHz were only enhanced ~10% over the level measured for the plasma with neutral beams alone (dashed line). The most noticeable enhancement in MHD activity was seen between 5 and 25 kHz, in particular a bursting, $m=1$, $n=1$ mode was observed at ~10 kHz

by an ECE Grating polychromator (CAVALLO *et al.*, 1988). Measurements of MeV ion loss (ZWEBEN *et al.*, 1990) were also made for these discharges. Escaping MeV ions were measured by detectors at 90° , 60° and 45° below the outer midplane just outside the limiter radius. The results are shown in Fig.11, where the time at which the ICRH power first steps up is indicated by the vertical dashed line. Although the evolution of the D-D neutron rates for these two plasmas are very similar [Fig.11(b)] the fast ion loss for all three detector locations is considerably enhanced for the plasma with ICRH (solid line) and in particular the signal at the 45° detector during ICRH is approximately five times that at the 90° detector [Fig.11(e)]. These observations are qualitatively similar to earlier MeV ion loss measurements during ^3He minority ICRH experiments (ZWEBEN *et al.*, 1992). The time evolution of the signal at all three detectors was examined for evidence of a 10 kHz modulation coincident with the $m=1$, $n=1$ MHD mode seen on the ECE signal, but none was seen. It would appear therefore that the enhancement in fast ion losses is not due predominantly to the presence of the MHD mode. The enhancement in the fast ion loss at the 90° detector for the shot with ICRH occurs coincident with the turn-on of the ICRH consistent with the first-orbit loss of D- ^3He fusion product alpha particles, however the enhancement appears to be delayed by 50-100 ms at the 45° detector, consistent with either ICRH-induced loss of previously confined D-D or D- ^3He fusion products, or direct ICRH tail ion losses. Figure 12 shows the dependence of the measured MeV ion loss on the coupled ICRH power for the plasmas shown in Fig. 7. The signal at the 90° detector rises relatively little with increasing ICRH power, but the signal at the 45° detector increases rapidly above 2-3 MW. The 45° detector signal with 6MW of ICRH is about an order of magnitude greater than the D-D fusion product signal seen with NBI alone and is probably only due to $<1\%$ of the ICRH tail ion population being lost to the walls. For the same ICRH power scan D-D neutron collimator measurements (JOHNSON, 1992) indicate no apparent broadening of the neutron emissivity profile with increasing ICRH power, consistent with relatively little RF-induced beam ion spreading.

III. EQUILIBRIUM ANALYSIS AND D-T PROJECTIONS

The SNAP time independent equilibrium code (MURPHY *et al.*, 1992) was used to model approximately 90 of the 1.85 and 2.2 MA plasmas at the time of peak stored energy. The calculation used a 2% ^3He concentration, and the measured profiles of ion temperature (from charge exchange recombination spectroscopy), electron temperature (from ECE) and electron density (from far-infrared interferometry). Figure 13 shows a plot of the ratio of the SNAP calculated neutron production rate to the measured value versus the ratio of the SNAP calculated global stored energy to the diamagnetically measured energy. The calculated global stored energy agreed within 5-10% with the diamagnetically measured values. However, the calculated neutron production rate was typically 30-40% lower than the measured value, well outside the $\sim 15\%$ uncertainty in the measured neutron rate. Initial kinetic equilibrium analysis of these same discharges had indicated that the SNAP calculated neutron rate was within 15% of the measured rate (TAYLOR *et al.*, 1993c), the SNAP calculated neutron rate decreased in large part due to a subsequent recalibration of the visible bremsstrahlung viewing window which resulted in an $\sim 45\%$ increase in the deduced Z_{eff} for these plasmas. For the 1.85 MA ICRH power scan shown earlier in Fig. 7 the calculated neutron rate was 25-35% lower than the measurement. The calculated neutron production rate came 55-60% from beam-beam reactions, 35-40% from beam-target reactions and $<5\%$ came from thermonuclear reactions.

Figure 14(a) shows the dependence of the ^3He RF tail stored energy calculated by SNAP (SMITHE *et al.*, 1987; SMITHE *et al.*, 1989) as a function of coupled ICRH power for the 1.85 MA ICRH power scan of Fig. 7. To assess the effect of uncertainties in the estimated ^3He concentration which was used in the experiment, $^3\text{He}/n_e$ concentrations of 1.5% (open squares), as well as 2% (closed circles), were employed in the SNAP modeling of the 1.85 MA ICRH power scan. The calculated RF tail stored energy reached ~ 400 kJ at 5.7 MW. Typically the calculated stored energy was 10-15% lower when the $^3\text{He}/n_e$ concentration was dropped from 2% to 1.5%. The calculated RF tail energy corresponds to a tail temperature of

0.8-1 MeV with 5.7 MW of ICRH. In the SNAP computer model the ^3He is assumed to have a flat radial concentration profile so that its profile shape is similar to the electron density profile, however recent charge exchange recombination spectroscopy data analysis of ^4He transport in supershots (SYNAKOWSKI *et al.*, 1993) suggest a more peaked ^3He concentration profile may exist in these discharges. In some ($\sim 10\%$) of shots analyzed by SNAP with a 2% $^3\text{He}/n_e$ concentration, there was insufficient measured electron density to satisfy quasi-neutrality in the calculation. This problem was obviated for most of these shots by reducing the $^3\text{He}/n_e$ concentration in the model to 1.5%. This reduced $^3\text{He}/n_e$ concentration had little effect on the calculated stored energy and increased the predicted neutron production rate by only 1-2%. The anisotropy in the diamagnetically measured stored energy as a function of ICRH power is shown in Fig. 14(b). The energy distribution has a residual parallel component due to the beam ion population which is ~ 600 kJ without ICRH. As the ICRH power is increased to ~ 6 MW the parallel anisotropy drops to ~ 200 kJ. If this behavior is interpreted as being due entirely to the presence of the perpendicular energy in the RF tail then it implies a tail stored energy, which is consistent with the model results. (The uncertainty in the diamagnetic determination of the tail stored energy is typically 50-100 kJ.) Figure 14(c) shows the calculated fraction of RF power to the electrons as a function of applied RF power. At 5.7 MW just under 50% of the RF power is calculated to go to electron heating. As the ^3He tail slows down it increasingly damps on the ion population near the plasma core, this process accounts for a further $\sim 30\%$ of the power coupled to the plasma at 5.7 MW. The code indicates that the remainder of the RF power ($\sim 20\%$) is deposited along the fundamental deuterium and carbon resonance layer on the small major radius side of the discharge, with a distribution which moderately peaks where these resonances intersect the shear Alfvén mode conversion layer. At lower ICRH powers (≤ 2 MW) this damping mechanism is even more significant and the calculated ICRH power fraction to the fundamental deuterium and carbon resonance layer rises to $\sim 60\%$. Since the region where these layers intersect is comparable to the poloidal resolution limits in the code, there is some concern that large errors in the predicted RF damping may result. Furthermore, the accuracy of the reduced order approximation which forms the basis for the RF model in the

code has not been verified for the region involving the deuterium and shear Alfvén layers. These problems are presently being investigated.

Figure 15 shows profiles of various measured and calculated plasma parameters near the time of peaked stored energy for the two plasmas of Fig. 6. The plasma with 5.7 MW of ICRH is indicated by the solid line. The ^3He tail energy, as calculated by the SNAP code, is located within 0.3m of the magnetic axis [Fig.15(d)], the calculated tail stored energy in this case was ~ 440 kJ. The RF power deposition to the electrons peaks at $\sim 1\text{MW/m}^3$ on axis [Fig.15(e)], electron heating is largely due to damping of the ^3He tail but about 25% of the heating occurs directly through electron Landau damping or transit-time magnetic pumping near the core. The RF power deposition to the ions is much broader [Fig.15(f)]. The core ion heating is the result of the ^3He tail slowing down, while the off-axis peak in the heating profile is due to the calculated damping at the fundamental deuterium and carbon resonance. The total heating power to the electrons, including beam heating, peaks significantly on-axis with the addition of ICRH [Fig.15(g)], while the ion power deposition profile shape remains relatively unchanged with the addition of ICRH [Fig.15(h)].

The effect of the observed increase in core electron temperature [Fig. 6(b)] on alpha particle slowing down time and central alpha pressure has been investigated for equivalent D-T plasmas with a time-dependent equilibrium code, TRANSP (HAMMETT, 1986). The results from one of these D-T plasma simulations are summarized in Fig.16. The simulation used measured D-D plasma parameters up to 3.7s. After that, an extrapolation was made to a steady state condition. The time evolution of the central electron temperature used in the model is shown in Fig.14(a). The central electron temperature, and hence the alpha energy slowing down time is enhanced early in the ICRH pulse [Fig.16(b)]. However, the central alpha pressure does not increase until ~ 0.5 s after the start of the ICRH pulse. The central alpha pressure was enhanced by $\sim 30\%$ in this simulation.

IV. SUMMARY AND CONCLUSIONS

Coupling of up to 7.4 MW of ICRH to deuterium supershot plasmas in the ^3He minority regime has resulted in significant core electron heating ($\Delta T_e \sim 40\%$). The enhancement in projected core alpha slowing down time for the 1.85 MA ICRH power scan appears linear with increasing ICRH power [Fig.7(f)] up to the ICRH power levels explored so far (~ 5.7 MW). The projected alpha particle slowing down time was enhanced $\sim 60\%$ as a result of the increased core electron temperature. A time dependent D-T simulation indicated the need for longer heating pulses (~ 1.4 s) than were used in these experiments, this would provide sufficient time for the increased alpha slowing down time to result in enhanced alpha pressure.

It was apparent that the plasma performance was being degraded as the ICRH power was increased, largely as a result of increased edge density and Z_{eff} . It may be possible to further improve performance with additional plasma conditioning. Operation at 2.2 MA, at higher total heating powers (~ 37 MW) proved problematic; plasma performance was found to be critically dependent on the vertical position of the plasma, however relatively low radiated power fraction ($< 15\%$) and carbon in-flux was obtained with up to 35 MW of heating power.

Calculated RF tail energies were found to be consistent with diamagnetic measurements of the residual anisotropy in the energy distribution. RF tail temperatures were calculated to be 0.8-1 MeV near the magnetic axis. There was an order of magnitude enhancement in MeV ion losses with the addition of 5.7 MW of ICRH, although this represents $< 1\%$ of the tail ion population there is some concern that with increased ICRH power fast ion losses could become significant. Although the fraction of RF power calculated to go to the core electron population via ^3He tail damping and direct electron heating increased to $\sim 45\%$ as the RF power was increased there appears to be a saturation in the fraction of RF power to the electrons above ~ 4 MW. Also, modeling indicates that $\sim 20\%$ of the RF power is deposited on the high field side, along the fundamental deuterium and carbon resonance. Because of concerns regarding

the validity of these model results, experiments will be conducted in the near future to test the accuracy of the computer model.

Future ICRH experiments on TFTR in the supershot regime will attempt to extend the results presented here to the full design capability of the TFTR ICRH system, which is ~12 MW for two seconds. These experiments will be performed in both D-D and D-T plasmas and will utilize a lower operating frequency of 43 MHz which will allow coupling to the ^3He minority and second harmonic tritium resonance at the magnetic axis even where Shafranov shifts are $\geq 0.25m$. These D-T ICRH experiments will provide the first opportunity to study second harmonic tritium damping both with and without a resonant minority species. Other planned experiments will combine 43 and 64 MHz operation to simultaneously heat hydrogen and ^3He minority species.

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FIGURE CAPTIONS

Fig.1 Schematic diagram showing a poloidal cross-section of the TFTR vacuum vessel.

Fig.2 Evolution of the density at the outer closed flux surface. NBI from 3-4 s (lighter shading) results in a rapid rise in edge density. The ICRH pulse (darker shading) was delayed from the start of NBI to allow time for density to build in from of the antennas. Also a modest step and ramp were programmed into the start of the ICRH pulse in order to avoid antenna arcs.

Fig.3 Comparison of the evolution of (a) the diamagnetically determined stored energy and (b) neutron reactivity for two similar plasmas heated with 23 MW of NBI. One plasma (thicker line) had a 1 torr.liter/s, 100 ms ^3He puff at 2.5 s, the other plasma had no ^3He puff. The helium-3 puff was observed to degrade the stored energy by ~5% and the neutron reactivity by ~10%.

Fig.4 Radiated power fraction versus total heating power for ^3He minority, deuterium supershots at 1.85 and 2.2 MA. Data are at the time of maximum stored energy. For most plasmas the radiated power fraction was 10-15%.

Fig.5 Evolution of plasmas parameters for two plasmas, one centered vertically (thin line) the other positioned ~2 mm higher (thicker line). Both plasmas had ~36 MW of input heating power, with similar NBI and ICRH power waveforms. The time dependence of (a) the NBI power, (b) the ICRH power, (c) the plasma stored energy, (d) the total radiated power, (e) the C-II light and (f) the D_α light is shown. A significant increase in radiation and a carbon "bloom" is seen for the plasma with the 2mm vertical shift.

Fig.6 Evolution of (a) ICRH power, (b) the central electron temperature, (c) the total stored energy, (d) the beam ion slowing down time, (e) the plasma stored energy, (f) the global energy confinement time, (g) the central electron density and h) the plasma Z_{eff} for two $I_p = 1.85$ MA, $B_T(0) = 4.8$ T, $R = 2.62$ m, $a = 0.96$ m ^3He minority, deuterium Supershot plasmas. One had NBI only (dashed line) the other had an additional 5.7 MW of ICRH (solid line). The fundamental resonant field location for ^3He was at $R = 2.75$ m. A 3-4 keV electron temperature rise is measured in the plasma core with no change in neutron reactivity .

Fig.7 Plasma performance during an ICRH power scan of 1.85 MA D-D supershots with 22-23 MW of NBI. Data were obtained at the time of maximum stored energy. (a) the central electron temperature, (b) the central ion temperature, (c) the central density, (d) the global energy confinement time, (e) the neutron production rate and (f) the projected alpha energy slowing down time for an equivalent D-T plasma are plotted versus coupled ICRH power. A linear fit has been made to the data for each plot, the error bars represent typical uncertainties on the data points. (The open square and circle indicate the shots used for the discharge evolution comparison of Fig. 6.)

Fig.8 Evolution of (a) the plasma stored energy, (b) the plasma reactivity, (c) the central electron temperature (d) the central electron density, (e) the NBI power, (f) the ICRH power, (g) the radiated power, h) the carbon-II signal and (i) electron density profile peakedness for two $I_p = 2.2$ MA, $B_T(0) = 4.8$ T, $R = 2.62$ m, $a = 0.96$ m ^3He minority, deuterium Supershot plasmas. One had NBI only (dashed line) the other had an additional 5.8 MW of ICRH (solid line). The fundamental resonant field location for ^3He was at $R = 2.75$ m.

Fig.9 Plasma performance during an ICRH power scan of 2.2 MA D-D supershots with 28-30 MW of NBI. Data were obtained at the time of maximum stored energy. (a) the central electron temperature, (b) the neutron production rate, (c) the global energy confinement time, and (d) the projected alpha energy slowing down time for an equivalent D-T plasma are plotted versus coupled ICRH power. A linear fit has been made to the data for each plot, the error bars represent typical uncertainties on the data points. Although the observed trends are similar to the 1.85 MA data there is considerable variability in plasma performance. (The open square and circle indicate the shots used for the discharge evolution comparison of Fig. 8.)

Fig.10 The amplitude of Mirnov coil MHD fluctuation data is shown for the two plasmas in Fig. 6. One plasma (solid line) had 5.7 MW of ICRH coupled into it at the time indicated the other (dashed line) had no ICRH. Data are shown for (a) the $m=2$ monitor signal and the amplitude of fluctuations with frequencies in the range (b) 5-15 kHz, (c) 15-25 kHz, (d) 25-35 kHz, (e) 35-45 kHz, (f) 45-55 kHz, (g) 55-65 kHz and (h) 65-75 kHz.

Fig.11 Time evolution of the MeV ion losses for the two plasmas shown in Fig.6. (a) The timing of the ICRH and NBI pulses, (b) the D-D fusion rate, (c) the 90° fast ion loss, (d) the 60° fast ion loss and (e) the 45° fast ion loss. The plasma with ICRH coupled is indicated by the solid line. The neutron production rate is similar for the two discharges however the fast ion losses are enhanced significantly in the plasma with ICRH. The 45° detector signal shows a delayed turn on relative to the initial step in ICRH power (vertical dashed line).

Fig.12 Dependence of the relative fast ion loss versus coupled ICRH power for the 1.85 MA ICRH power scan of Fig.7.

Fig.13 Plot of the ratio of the calculated neutron rate from SNAP to the measured neutron rate versus the ratio of the calculated global stored energy from SNAP to the measured value.

Fig.14 (a) the calculated ^3He tail stored energy, (b) the anisotropy in the diamagnetically measured energy and (c) the calculated fraction of ICRH power to the electrons as a function of coupled ICRH power, for the 1.85 MA ICRH power scan of Fig.7. Analysis results are shown for a 1.5% (open squares) and 2% (solid circles) $^3\text{He}/n_e$ concentration.

Fig.15 Comparison of various measured and calculated plasma profiles, near the time of peaked stored energy for the two plasmas in Fig.6. The plasma with ICRH is represented by the solid line. Profiles of (a) the measured electron temperature, (b) the measured ion temperature, (c) the measured electron density, (d) the calculated RF tail stored energy density, (e) the calculated RF power to the electron and (f) the calculated RF power to the ions, the calculated beam + RF heating power to (g) the electrons and (h) the ions plotted versus minor radius.

Fig.16 D-T simulation using measured D-D plasma parameters up to 3.7s and an extrapolation to steady state after that. (a) the enhancement of the central electron temperature with application of ICRH. (b) this results in a 60% increase in projected central alpha energy slowing down time and (c) a 30% increase central alpha pressure.

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