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ICRF HEATING OF DEUTERIUM-TRITIUM PLASMAS IN TFTR

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ABSTRACT

The first experiments to heat D-T plasmas in the ion cyclotron range of frequencies (ICRF) have been performed on the Tokamak Fusion Test Reactor (TFTR). These experiments have two major objectives: to study the RF physics of ICRF-heated D-T plasmas and to enhance the performance of D-T discharges. Experiments have been conducted at 43 MHz with out-of-phase current strap excitation to explore n_T/n_e concentrations up to approximately 40%. In these experiments n_T/n_e was limited by D recycling from the carbon walls. The location of the T resonance was varied by changing the toroidal magnetic field, and the RF power was modulated (f_{mod}=5-10 Hz) to elucidate competing heating mechanisms. Up to 5.8 MW of ICRF heating has been coupled into D-T plasmas. The addition of 5.5 MW of ICRF heating to a D-T supershot resulted in an increase in central ion temperature from 26 to 36 keV and an increase in central electron temperature from 8 to 10.5 keV. Up to 80% of the absorbed ICRF power was coupled directly to ions, in good agreement with computer code predictions. These results extrapolate to efficient T heating in future devices such as ITER.

1. INTRODUCTION

Future D-T fusion devices, such as the International Thermonuclear Experimental Reactor (ITER), emphasize ion cyclotron range of frequency (ICRF) heating, but until now no experimental database has been available to provide a benchmark for the RF computer codes which predict performance in plasmas containing tritium. The Tokamak Fusion Test Reactor (TFTR) has performed the first experiments which combine ICRF heating with tritium plasmas.

The D-T ICRF program on TFTR has two major objectives: first to study D-T RF physics and second to enhance the performance of D-T supershots [1], and eventually L-mode plasmas. Plasma reactivity can be increased by directly heating tritium ions via second harmonic ICRF. Significant increases in the central electron temperature of supershots via heating by collisions with minority tail ions [2] or direct electron heating may result in lengthened alpha particle slowing times and increased alpha particle pressure in D-T plasmas.

Initial experiments on TFTR were directed primarily towards investigating the RF physics of ICRF-heated plasmas containing tritium. These experiments were conducted at 43 MHz with out-of-phase current strap excitation into D-T plasmas fueled by 18-24 MW of ~100 keV neutral-beam-injection. This paper presents results from 21 ICRF-heated D-T plasmas which have explored n_T/n_e concentrations from approximately 6% to 40%. In addition, the toroidal field was scanned to vary the location of the second harmonic T resonance from R = 2.6 m to 3.0 m in full bore (R = 2.62 m, a = 0.96 m) plasmas with the Shafranov-shifted magnetic axis at R ~ 2.8 m. Of these D-T plasmas, 16 discharges utilized 90% power modulation (f_{mod}=5-10 Hz) to investigate the relative strength of the possible heating mechanisms.

2. PLASMA PERFORMANCE

The maximum ICRF power coupled thus far into a D-T plasma has been 5.8 MW with a 2% ^{3}He minority species and 4.9 MW without a ^{3}He minority. ^{3}He was added to some plasmas to avoid eigenmode effects on the ICRF coupling. The RF power was launched by up to four antennas [3] at the midplane, on the low field side of the plasma. Figure 1 shows the evolution of two D-T plasmas heated by 23.5 MW of neutral beam injection. The discharge shown by the solid line had an additional 5.5 MW of ICRF heating [Fig.1 (a)]. Both plasmas had a 2% ^{3}He minority, and 60% of the beam-injected power was in T. Based on comparisons of the measured D-T neutron production rate with the rate calculated by the SNAP time-independent equilibrium code [4], the tritium fraction at the center of the plasma, $n_T/(n_T+n_D+n_H)$, appears to be only 25-30% due to significant D (and minimal T) recycling from the carbon limiters on the inner and outer walls. In the core, $n_H/(n_T+n_D+n_H)$ is assumed to be ~ 5%, half the edge value measured by spectroscopy. For the two plasmas in Fig. 1, the magnetic field at the Shafranov-shifted magnetic axis was 4.2 T, placing the second harmonic T (and fundamental ^{3}He minority) resonance at the axis. With the addition of ICRF, the central electron temperature, measured by electron cyclotron emission (ECE), increased from 8 to 10.5 keV at 3.4 s [Fig.1(b)], due to fast wave direct electron heating (via Landau damping and transit time magnetic pumping) and heating by collisions with minority tail ions. The central ion temperature, measured by charge-exchange recombination spectroscopy, initially increased from 26 to 36 keV at 3.4s [Fig.1(c)]. However, it later decreased as an enhanced carbon influx [5] developed. This carbon influx also resulted in increased line average density [Fig.1 (d)] approximately 400 ms after the start of ICRF heating. Prior to this influx, the stored energy (E_{tot}) increased from 3.4 to 4.1 MJ [Fig. 1(f)] with the addition of RF, and the excess perpendicular component of the stored energy ($E_{ex\perp} = 3E_{\perp} - 2E_{tot}$) increased by 200 - 250 kJ due to the presence of an RF tail. There was also a 10% enhancement in the D-T neutron production rate to approximately 1.2×10^{18} s^{-1}. Figure 2 shows the ion and electron temperature profiles at 3.4s (the time of peak performance). A significant increase in temperature is seen out to r/a ~ 0.3. The core ion heating observed is consistent with $2\Omega_T$ heating, since an analogous increase in core heating was noticeably absent in D-^{3}He minority experiments [2]. A D-T plasma which was essentially identical to the ICRF-heated discharge shown in Fig. 2, but with no ^{3}He minority and only 4.4 MW of ICRF, reached a core ion temperature of 32 keV.

3. RF PHYSICS

RF power modulation [6] provides a technique for studying the power deposition directly. Sixteen of the ICRF-heated D-T discharges utilized 90% power modulation (f_{mod}=5-10 Hz). The changes in the electron temperature and density profiles were measured by ECE and multi-chord, far-infrared interferometry, respectively. The electron temperature response showed no delay, consistent with direct electron heating. Density modulation contributed up to 10% to the calculated power absorbed directly by electrons.

Figure 3 shows the fraction of power absorbed by ions and electrons during RF modulation as a function of the fraction of neutral beam power in tritium for three plasmas with the $2\Omega_T$ resonance at the magnetic axis. Although no ^{3}He minority was added to these plasmas there may have been ~0.2% ^{3}He concentration remaining from prior D-^{3}He discharges. The neutral-beam-injection and RF powers for this scan were 17-20 MW and 3.6-3.8 MW, respectively. The absorbed power fraction is calculated noting that ~10% of the RF power is lost in the antennas. The total power absorbed by the plasma, determined from the modulation in the magnetic measurement, was typically 80% ± 15% of the power leaving the antenna. The electron absorbed power fraction decreased from 25% to 15% when the T beam fraction increased from 15% to 100% (the corresponding estimated increase in n_T/n_e was from ~6% to ~40%). This behavior is expected as a result of the competition between direct electron heating and $2\Omega_T$ heating of the tritium beam ions. There is also possibly some mode conversion, although because of the limited T fraction and magnetic field, the mode conversion around the two-ion hybrid resonance did not move far enough into the core to enable detection in the present experiments.

The RF modulation results for the plasma with a 60% T beam fraction in Fig. 3 were compared in detail with two independent computer codes. In the first, a single time point analysis was done with the PICES code [7], a 2-D, reduced order, full wave code, using multiple toroidal mode numbers weighted by the antenna spectrum. The predicted power deposition profiles were calculated using the experimental temperature and density profiles (including beam ions with an effective temperature of ~60 keV on axis). Of the RF power leaving the antenna (~10% antenna loss), 36% was absorbed at the $2\Omega_T$ resonance near the core (26% going to T beams and 10% to thermal T) and 7% was absorbed at the D (and carbon) fundamental resonance located at r/a~0.8. 26% of the RF power was absorbed directly by electron Landau damping and transit time magnetic pumping near the core, in good agreement with the RF modulation data. This code also calculates that approximately 30% of the RF power is absorbed at the intersection of deuterium ion fundamental resonance (R ~ 2.1 m) and the mode conversion layer near the last closed flux surface. There is so far no experimental evidence supporting or refuting this effect. A time-dependent analysis of the power deposition profiles was also obtained for the same plasma with the TRANSP transport analysis code [8]. The RF package in TRANSP consists of the 2D reduced order wave solver, SPRUCE [9], combined with the bounce-averaged Fokker-Planck solver, FPP [10]. Power deposition was computed for a single toroidal mode number representative of the peak of the launched antenna spectrum. Experimental density and temperature profiles were used for the thermal ions and electrons, while the beam density and effective temperature profiles were obtained using the Monte Carlo beam deposition subroutines. From this analysis, the ratio of the ion to electron power absorption is about 3.3, with 80% of the ion heating occurring within r/a = 0.6. These results are in relatively close agreement with the data.

Figure 4 shows the result of varying the toroidal magnetic field to scan the location of the $2\Omega_T$ resonance from R = 2.5 m to R = 3.0 m (the Shafranov-shifted axis was at approximately R = 2.8 m). Data are shown for four D-T plasmas with 60% of the neutral beam power in T. The neutral beam injection and RF powers for this scan were 18.5-21 MW and 3.7-4.9 MW, respectively. The plasma current was adjusted to maintain a relatively constant edge safety factor. The RF power fraction absorbed directly by electrons increased from 15% to 25% as the $2\Omega_T$ resonance was moved from the low to the high field side of the plasma column. Since the direct electron heating peaks on axis, placing the $2\Omega_T$ resonance between the antenna and the core would be expected to reduce the direct electron heating fraction as observed.

4. RF-INDUCED FAST ION LOSSES

During ICRF heating of D-T plasmas with no ^{3}He, the detectors which measure escaping fast ions [11] indicated two sorts of fast ion losses, in addition to first orbit loss of alpha particles. The first of these, illustrated in Fig. 5, was the loss, at the detectors 45° and 60° below the outer midplane, of ~ 600 keV tritium ions accelerated by the ICRF waves. The magnitude of the loss was modulated synchronously with the applied ICRF power. The characteristic interval for these losses to reach a steady level was ~50ms, significantly shorter than the 100ms required to produce a proton tail in H-minority heating. This is consistent with 100 keV beam-injected tritons being heated at their second harmonic, since a tail can be created more rapidly from hot ions than from bulk ions and furthermore $2\Omega_T$ heating preferentially heats hotter ions. This unambiguous observation of tritium tail ions confirms that $2\Omega_T$ heating occurred in these discharges.

The second type of fast ion loss was the ICRF-induced loss of alpha particles to the detector at 90° below the midplane. As depicted in Fig. 6, the ICRF-induced loss is modulated with the RF power and can be as much as 50% of the first orbit loss rate, with only 4 MW of applied power. The RF-induced loss appears in the detector at the pitch angle of the fattest banana orbit. We conclude that the loss is caused by marginally-passing alphas being heated by the waves and converted into marginally-trapped particles which then strike the vessel wall [12]. To date, only birth energy alphas have been expelled by this process, and so it is unlikely to be useful as an ash removal technique.

5. SUMMARY AND FUTURE PLANS

ICRF-heated D-T plasmas with n_T/n_e concentrations up to ~40% have been studied in TFTR. RF power modulation was employed to measure the ICRF power deposition. Up to 80% of the RF power was absorbed directly by ions. In addition, a lost fast ion diagnostic confirms the presence of a tritium tail.

Future TFTR D-T experiments will be focused on utilizing ICRF-heating to significantly enhance the alpha pressure and plasma reactivity. Two RF frequencies, 43 and 64 MHz, will be combined to allow simultaneous H-minority and $2\Omega_T$ heating, thereby minimizing effects associated with energetic tails. ICRF-heating of L-mode D-T plasmas will directly test the preferred heating scheme for ITER. Finally, the effect of the high field side mode-conversion layer will be explored in more detail both theoretically, and in future TFTR experiments at higher toroidal field [13].

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FIGURES

Fig. 1: Time evolution of (a) the neutral-beam-injection and ICRF power, (b) central electron temperature, (c) central ion temperature, (d) line average density, (e) D-T neutron production rate and (f) magnetically measured stored energy for two plasmas with 23.5 MW of neutral-beam-injection (60% in tritium). The plasma indicated by the solid line had 5.5 MW of 43 MHz ICRF heating. Both plasmas had a 2% ^{3}He minority, the ^{3}He fundamental resonance is degenerate with the $2\Omega_T$ resonance.

Fig. 2: Comparison of (a) ion and (b) electron temperature profiles for the two D-T plasmas in Fig. 1 at the time shown by the vertical dashed line. The discharge indicated by the bold solid line had 5.5 MW of ICRF heating.

Fig. 3: Fraction of RF power delivered directly to electrons and ions as a function of tritium beam power fraction during RF modulation. Data are for plasmas with no ^{3}He minority, 3.6-3.8 MW of RF power input to the antenna, 17-20 MW of neutral-beam-injection and with the $2\Omega_T$ resonance at the magnetic axis.

Fig. 4: Fraction of RF power delivered directly to electrons and ions as a function of the distance of the $2\Omega_T$ resonance from the magnetic axis. Data are for plasmas with no ^{3}He minority, 3.7-4.9 MW of RF power input to the antenna, 18.5-21 MW of neutral-beam-injection and approximately 60% of the injected power in T.

Fig. 5: (a) Neutron-normalized fast ion loss rate to a detector 45^o below the midplane as a function of time and (b) the corresponding RF power evolution. 7.1 MW of D and 11.5 MW of T neutral beam power were injected during the time indicated by the shaded region. The portion of the loss which is synchronous with the ICRF power waveform is due to the loss of T tail ions.

Fig. 6: (a) Neutron-normalized alpha loss rate to a detector 90^o below the midplane as a function of time and (b) the corresponding RF power evolution. 9.1 MW of D and 11.6 MW of T neutral beam power were injected during the time indicated by the shaded region.

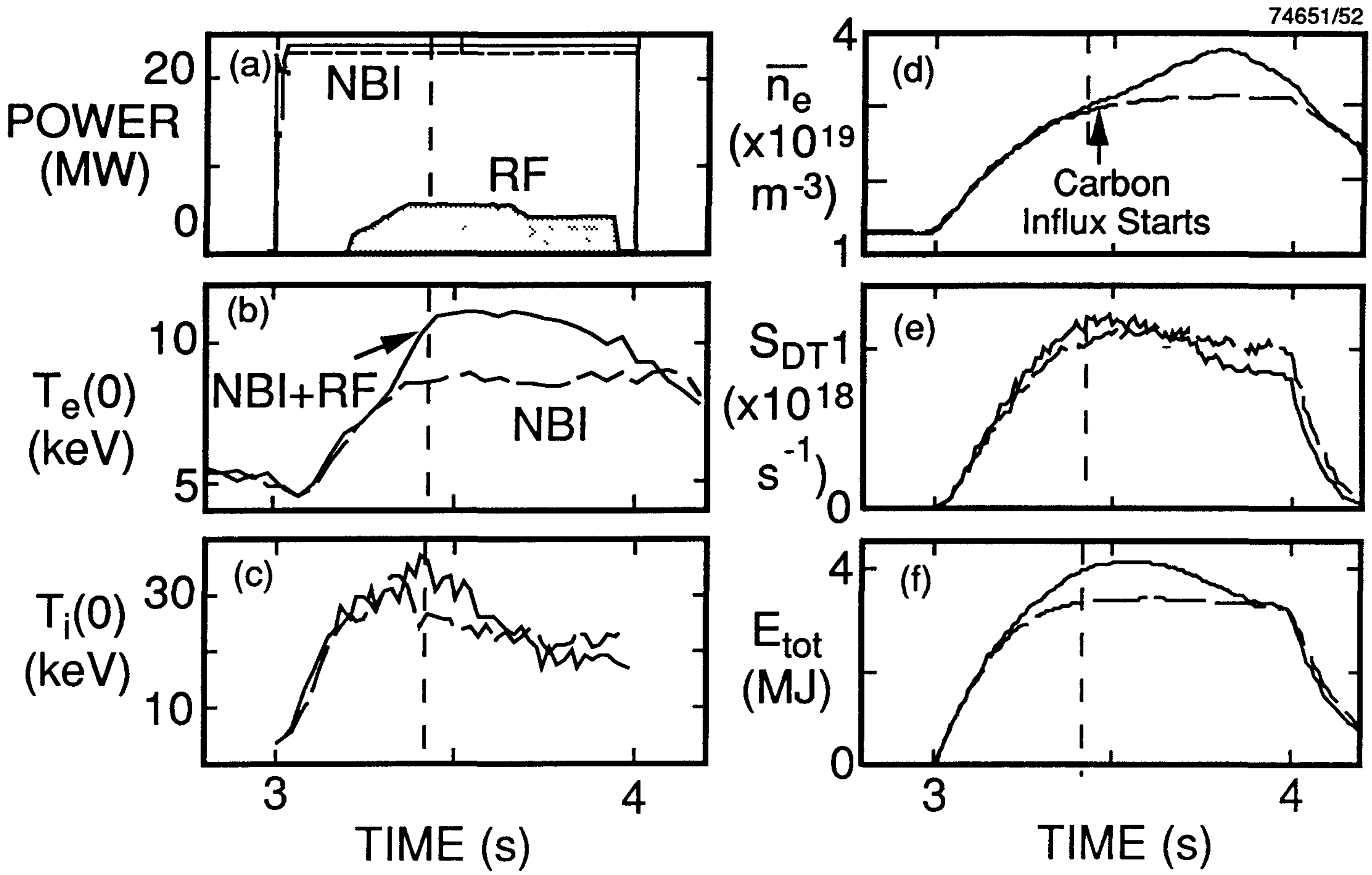
74651/52
(a)
POWER (MW)
20
0
NBI
RF
(b)
$T_e(0)$ (keV)
10
5
NBI+RF
NBI
(c)
$T_i(0)$ (keV)
30
10
3
4
TIME (s)
(d)
$\overline{n}_e$ ($\times10^{19}$ m^{-3})
4
1
Carbon Influx Starts
(e)
S_{DT} ($\times10^{18}$ s^{-1})
1
0
(f)
E_{tot} (MJ)
4
0
3
4
TIME (s)

Figure 1

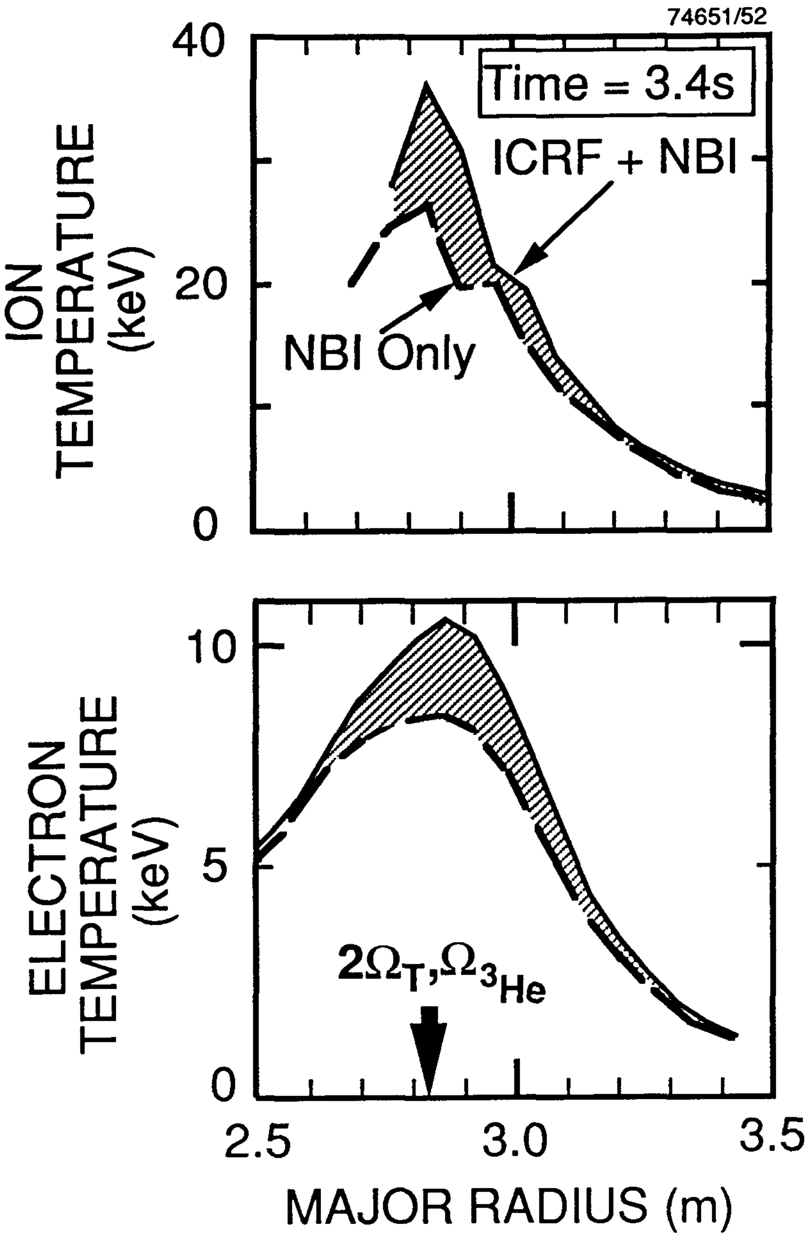
74651/52
ION TEMPERATURE (keV)
40
20
0
Time = 3.4s
ICRF + NBI
NBI Only
ELECTRON TEMPERATURE (keV)
10
5
0
$2\Omega_T, \Omega_{^3He}$
2.5
3.0
3.5
MAJOR RADIUS (m)

Figure 2

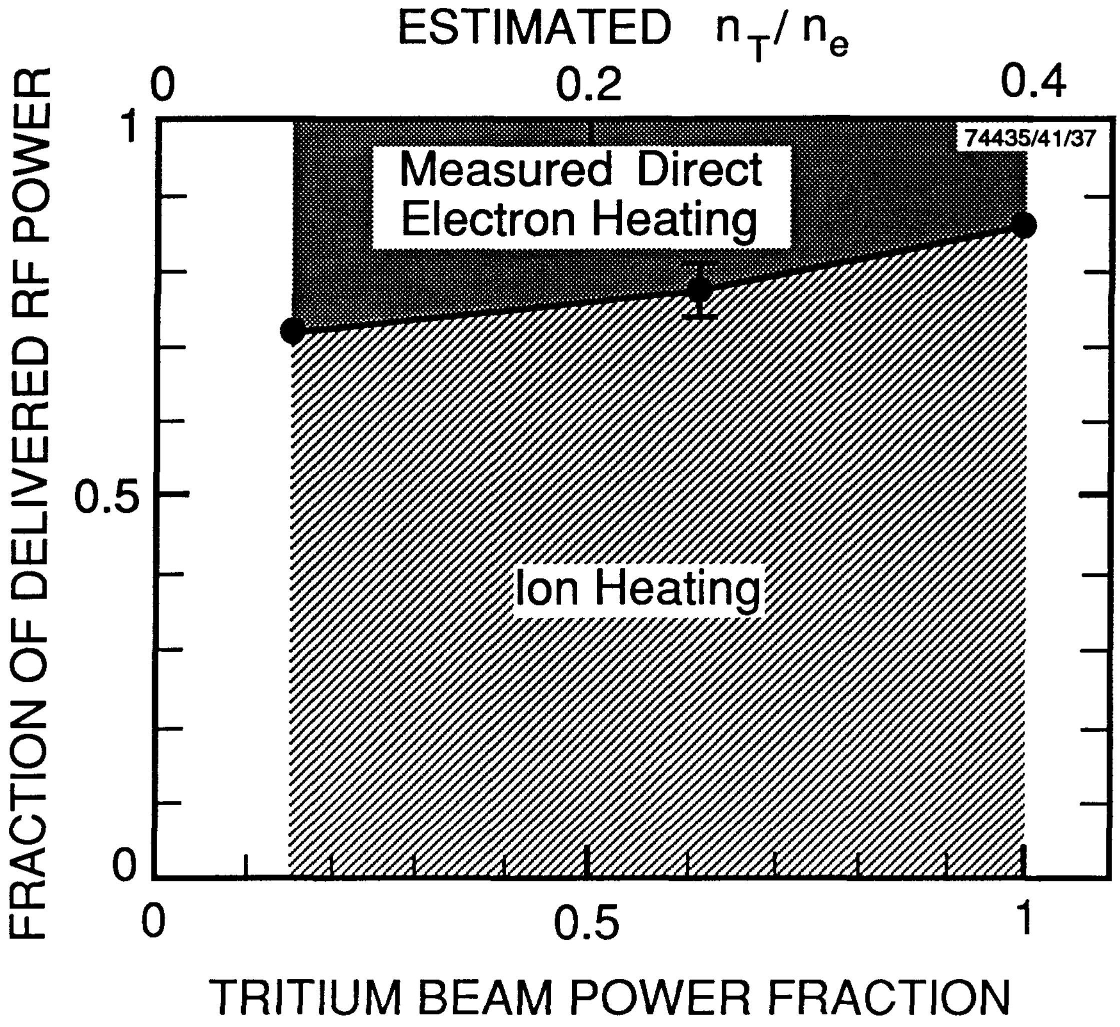
ESTIMATED n_T/n_e
0
0.2
0.4
74435/41/37
Measured Direct Electron Heating
Ion Heating
FRACTION OF DELIVERED RF POWER
1
0.5
0
0
0.5
1
TRITIUM BEAM POWER FRACTION

Figure 3

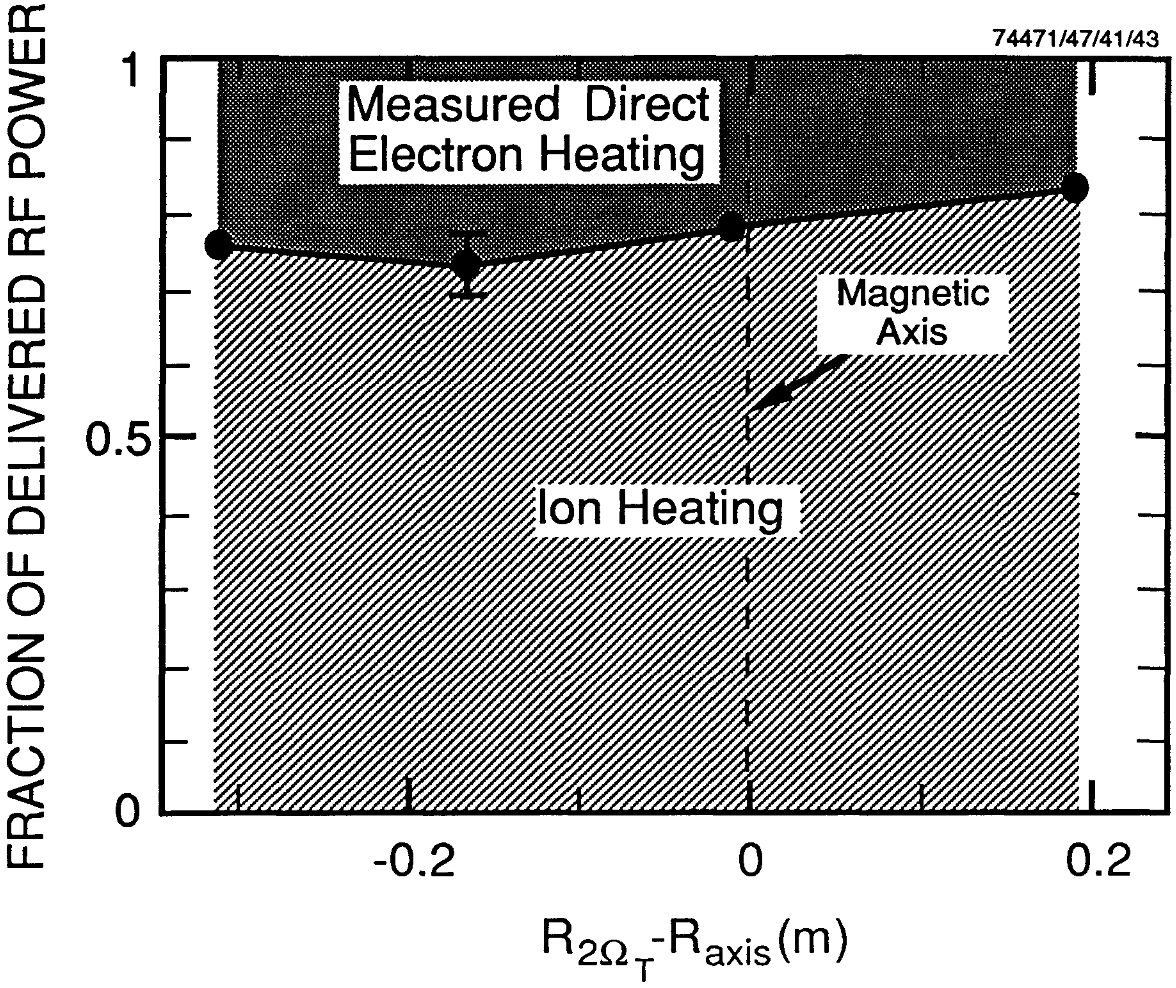
74471/47/41/43
FRACTION OF DELIVERED RF POWER
1
0.5
0
Measured Direct Electron Heating
Magnetic Axis
Ion Heating
-0.2
0
0.2
$R_{2\Omega_T}$-R_{axis}(m)

Figure 4

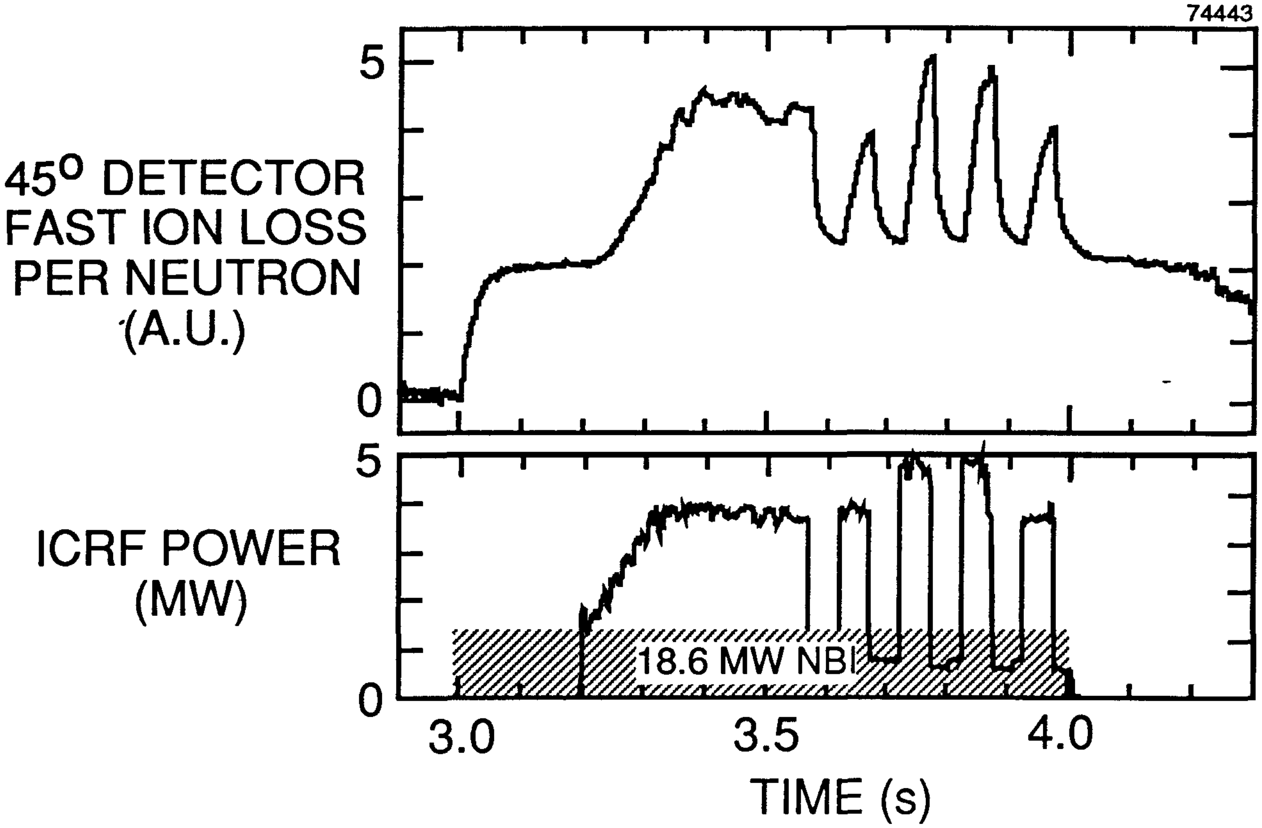74443
45° DETECTOR FAST ION LOSS PER NEUTRON (A.U.)
5
0
ICRF POWER (MW)
5
0
18.6 MW NBI
3.0
3.5
4.0
TIME (s)

Figure 5

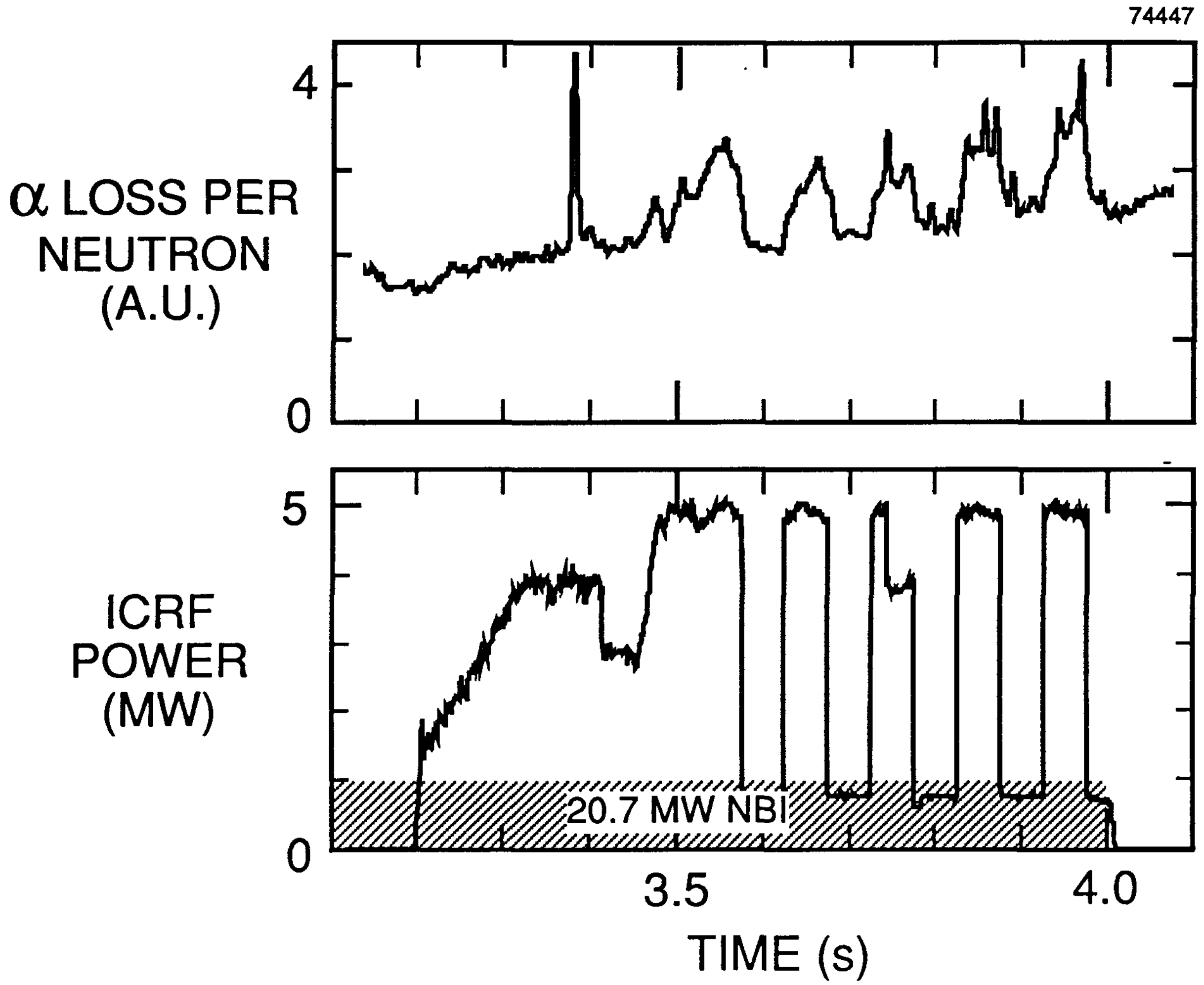
74447
α LOSS PER NEUTRON (A.U.)
4
0
ICRF POWER (MW)
5
0
20.7 MW NBI
3.5
4.0
TIME (s)

Figure 6