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ICRF HEATING ON TFTR-EFFECT ON STABILITY AND PERFORMANCE

BY

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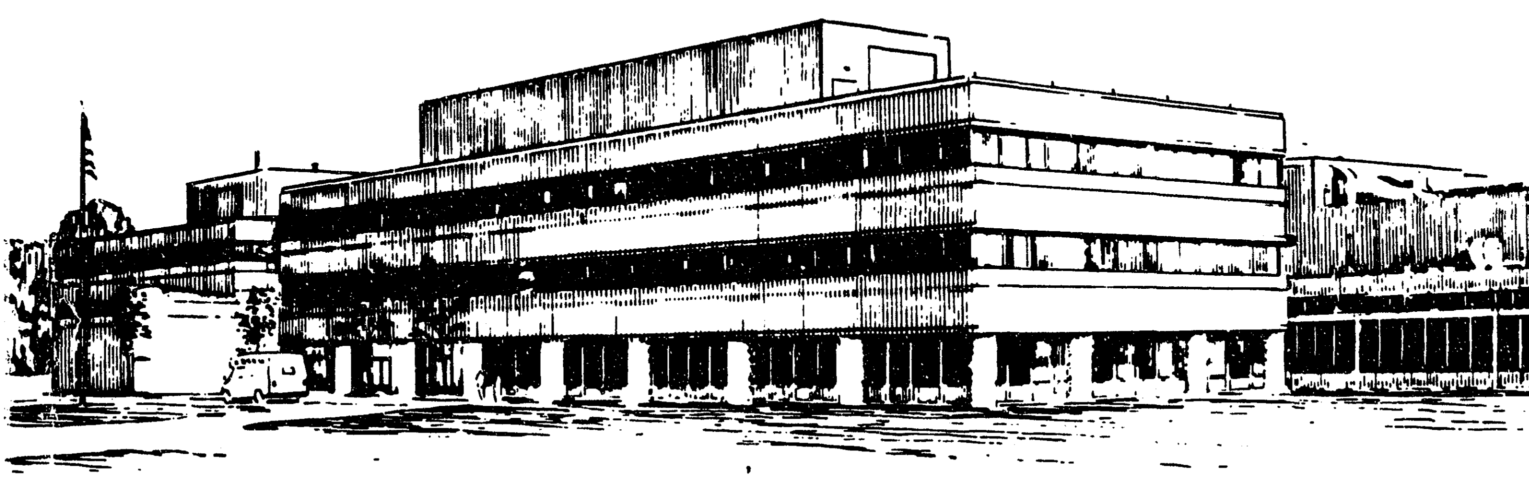

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ICRF HEATING ON TFTR - EFFECT ON STABILITY AND PERFORMANCE

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ICRF Heating on TFTR- Effect on Stability and Performance

Abstract

With the addition of two new antennas and two radiofrequency (RF) generators, the TFTR ICRF system is complete. The total complement of four antennas and six generators is designed for 12.5 MW operation. Experiments with this system have been performed recently on TFTR in the low recycling regime to increase the performance of supershot plasmas, in a non-resonant regime to explore electron heating, and in high recycling discharges with energetic ion tails to simulate fusion alpha particles. Noteworthy results include: direct electron heating observed with absorption rates in agreement with theory; electron heating of supershot plasmas ($\Delta Te0 \sim 2$ keV) via energetic ion tails that would increase the pressure of the alpha particles in DT plasmas; and the first observation of the toroidal Alfven eigenmode (TAE) instability driven by the energetic ion tail in hydrogen minority heating.

1. TFTR ICRF Research Program

ICRF heating is employed on TFTR in support of its goal to explore alpha physics in two ways: first, by increasing β_α during DT operations either through electron heating (to increase the α slowing down time) or by improving MHD stability properties of NBI driven supershot plasmas; second, to simulate α particle physics in DD plasmas through energetic ion tails. In addition, the program explores ICRF heating regimes, such as direct electron heating, of relevance to future devices. To pursue these objectives an ICRF system consisting of four antenna boxes has been installed on TFTR. Each box contains two radiating poloidal current elements. The elements have been used with the currents either in-phase (monopole) or out-of-phase (dipole). The antennas are fed by six RF generators, two of the antennas with a generator per element and the other two with a single generator feeding both elements. A fixed frequency of 47 MHz has been employed to date at power levels up to 7.8 MW in L-mode plasmas. At this frequency, allowed heating regimes include He-3 minority fundamental or T second harmonic at the full magnetic field value of 5.2 T (R=2.45 m) and H minority heating at 3.4 T. Heating of NBI fueled supershot plasmas in the He-3 minority regime is presented in section 3. Experiments have been performed utilizing direct electron heating at 2.4 T and at 4.8 T. Direct electron heating provides an alternative to minority ion heating in the DT experiments that does not require a diluting minority ion species. ICRF heating has also been utilized to study possible alpha particle driven instabilities. In these experiments an energetic hydrogen minority tail has been observed to drive the toroidal Alfven eigenmode (TAE) instability.

2. Antenna Configuration and Performance

The original configuration of TFTR antennas consisted of two antennas of significantly different design[1,2]. A considerable difference in antenna loading impedance and hence operating power level was found[3]. There were several possible explanations for this difference, including the different k_z spectra, toroidal location (particularly with respect to limiters), and radial build of the antennas. One of the antennas was rebuilt to resemble the other as closely as possible and the resulting system performed well at power levels up to 7 MW. Remaining differences in antenna performance could be attributed to the differences in the k_z spectrum[4]. The design of the two new antennas added for this last run period built on this experience, but small changes in design were incorporated. Since radial build appeared to be an important variable, the Faraday shield designs were modified to further reduce the separation between plasma and radiating element, including on one antenna the elimination of one Faraday screen layer[5]. To improve the k_z spectrum of the antennas, the slots in the side walls were doubled in width and the internal septum used to mechanically support the Faraday screen was reduced to a skeleton consisting only of a series of radial rods. This change, while improving the purity of the k_z spectrum, led to a factor of three increase in the mutual coupling between radiating elements, which renders it more difficult to phase these antennas other than in monopole or dipole. Finally, the Faraday screen elements are slanted at an angle of six degrees to align with the total magnetic field for typical operating conditions.

Since only six RF sources are available, each of the new antennas is fed from a single generator with the power division and phasing being accomplished with external resonant transmission line sections. This fixes these antennas in the dipole phasing configuration. In the limited operating time to date, both of the new antennas have performed at power levels of over 2 MW with peak antenna voltages of 25 kV. In comparison, the original antenna with the same toroidal width, operated at the same power level, has a peak voltage of 32 kV, leading to the conclusion that the reduced radial build of the antennas has increased antenna plasma coupling. A total power of 7.8 MW has been delivered to a TFTR plasma by the four antennas.

3. ICRF Heating of Supershot Plasmas

The principal goal of ICRF heating on TFTR is to enhance performance of plasmas during the DT physics phase of operations. Since the highest reactivity discharges are obtained in the NBI fueled supershot regime, ICRF heating was combined with these discharges. Supershots were first achieved by intense NBI heating of a low density target plasma with major radius of 2.45 m and minor radius of 0.8 m[6]. To couple the ICRF power, it has been necessary to develop supershot plasmas at larger major and minor radius (R= 2.6m, a= 0.99 m) so that the outer plasma boundary is within 1-2 cm of the ICRF antennas. Though initially supershot performance in these large plasmas was not as good as in the smaller plasmas, good supershot performance (in terms of plasma reactivity) has now been achieved in large plasmas[7]. The target plasma for supershots is fueled only by recycling from the limiter. Upon injection of the beams, the density rises rapidly and reaches a plateau in ~0.3 s. During the density rise, it is difficult to couple RF power because of the change in loading impedance (the average level of which changes by a factor of five to six) and the eigenmodes observed during He-3 minority heating. RF power is applied during the flat top portion of the discharge to increase the electron temperature, which will, in DT plasmas, increase the α slowing down time and hence β_α, and to stabilize the sawtooth instability. Though ordinarily sawteeth do not limit supershot performance, operation at the highest power levels of NBI and with a significant amount of alpha energy may require larger values of plasma current to avoid the observed β limit[8]. In Fig. 1, the effect of efficient rf heating of the electrons in the core of the discharge is shown. The addition of 4.5 MW of ICRF power in the He-3 minority regime is seen to increase the central electron temperature by 2 keV. In comparison, the overlay shot with 5 MW of additional NBI power is 1 keV lower in central electron temperature. While the DD neutron emission for the two discharges is comparable, in a DT plasma the central β_α will be higher with the ICRF heating, thereby allowing study of alpha particle physics over a wider range of β_α. When ICRF heating is applied in the H minority mode to a deuterium plasma, an increase in neutron emission is observed. TRANSP simulations and Fokker-Planck calculations indicate that this increase is due to second harmonic heating of the deuterium beam ions. This increase would not be as pronounced in a DT plasma where the beam injection takes place near the peak of the DT fusion cross section. It must be noted that the effect of ICRF heating on DT supershot plasma performance cannot be inferred from just the behavior of the DD neutrons since, while the alpha particle slowing down time depends strongly on the electron temperature in high power discharges where the electron temperature is near 10 keV, the deuterium beam particle slowing down time is nearly insensitive to the electron temperature in this range. Therefore, simulations such as those provided by TRANSP are required to fully evaluate the expected DT performance with added ICRF heating.

4. Direct Electron Heating Experiments

Direct electron heating offers an alternative to the normal ion resonant methods. It can be particularly attractive in DT experiments on TFTR since it does not require the addition to the plasma of a minority species which can deplete the reactive ion species, and furthermore, in the case of He-3 minority heating, the presence of energetic He-3 ions can make alpha diagnostic measurements difficult. In addition, direct electron damping may lead to a viable current drive scenario for future steady-state operation. Direct electron heating experiments have been carried out in two regimes of operation. Results are comparable to those seen in previous work[9,10]. In order to maximize the electron heating, which is relatively weak, it is necessary to avoid ion cyclotron resonances in the plasma. In the low field regime, B_T= 2.3 T, the competing ion resonances include the fundamental hydrogen resonance at the high field edge, the second harmonic He-3 resonance at the center, and the third harmonic deuterium resonance, 0.4 m to the low field side of the plasma center. In the high field regime, B_T= 4.8 T, the competing resonances include the deuterium fundamental and shear Alfven resonances near the high field edge and the He-3 fundamental resonance at the plasma center.

Experiments were conducted in the low field regime with He-3 as the majority ion species. The RF power was 100% modulated with a 4 Hz square wave. The time evolution of the electron temperature indicated that significant direct electron heating was taking place. This heating was analyzed by two methods. First the power deposition profile was inferred from using the equation $q_e = 1.5 n_e \Delta(dT_e/dt)$ where $\Delta(dT_e/dt)$ is the change in the electron temperature slope at the time of RF power transition, assuming that at these times the electron heat transport does not change and that there is no discontinuity in the electron density. The second technique involves a Fourier Transform (FT) of the electron temperature data. Good agreement between the two methods indicates that the time scale of the modulation is faster than the characteristic times of energy transport. The results are consistent with the superposition of a broad profile and a centrally peaked profile from transit-time magnetic pumping (TTMP) and electron Landau damping (ELD). Measurements of the ion temperature evolution using charge exchange recombination from carbon ions shows only a small response to the RF modulation, indicating that the second harmonic He-3 cyclotron absorption is weak. Measurements with a vertically viewing neutron collimator indicate that some third harmonic deuterium absorption is taking place on the doping beam used for the ion temperature measurement at a minor radius of 0.3 m. The measured volume integrated power absorbed by the electrons is found to be 30%-50% of the modulated power. The remaining power is presumed to flow to the ion resonances, especially the hydrogen fundamental layer near the inner plasma edge.

High field experiments, $B_T = 4.8$ T, were conducted in the He-3 minority regime with no He-3 present. In this case, the only ion resonance present is the deuterium majority resonance on the high field side, where damping is expected to be weak, so the electron damping should totally dominate the results. A 5 Hz square wave modulated 1.5 MW RF pulse was applied to a 24 MW NBI preheated supershot plasma (Fig. 2). The time evolution of the central electron temperature (R = 2.82 m) shows a strong modulation. At these high toroidal fields, theory predicts that a large target β_e is required for good absorption. This is provided by the NBI heating. The electron temperature response was again analyzed by the two methods described above and the results are shown in Fig. 3. Again, a strong centrally peaked electron absorption is observed. Both calculations indicate that 60% of the power is absorbed centrally on electrons. The FT analysis has insufficient signal to calculate deposition further out in radius while the discontinuity analysis implies that an additional 20% of the power is absorbed in the outer half of the plasma. Central electron temperature increases of up to 1.5 keV were observed in this mode indicating that, since no diluting minority is required, it may be a viable alternative to He-3 minority heating for DT experiments.

5. Observation of MHD Modes Driven by RF Tail Ions

Energetic ICRF minority tail ions are a good candidate to simulate alpha particle physics. In particular, alpha particle driven instabilities which require MeV energies can be approximated by ICRF heated tails which can reach the MeV range. One class of alpha driven instabilities that is of particular interest is the TAE instability. This instability has been observed at low toroidal field strength, driven by passing NBI ions in the 100 keV range[11,12]. This instability has also been predicted to be driven by energetic trapped ions as well[13]. Experiments have been conducted in gas fueled L-mode discharges with ICRF heating of a hydrogen minority at B_T= 3.4 T, I_p= 1.4 MA, and $<n_e> = 1.5 - 3 \times 10^{19}$ m^{-3}. An instability is observed with the Mirnov coils and microwave reflectometer, shown in Fig. 4, at an RF power level of 5.2 MW. Several closely spaced frequencies are observed. For power levels near the threshold of 3 MW the instability appears ~100 ms after the RF power is applied. This is consistent with the time needed to build up the energetic ion tail to exceed the instability threshold. As expected, this time lag shortens at higher RF power levels. Detailed magnetic measurements suggest that the threshold can, alternatively, be characterized by requiring that the stored tail energy exceed ~100 kJ. The frequency spectrum of the instability is quite narrow. The frequencies are consistent with the TAE mode frequency $\omega = v_A/2qR$ for n_e evaluated near q=1.5. The instability frequency varies inversely with the square root of density as expected. The multiple frequencies are assumed to be due to multiple poloidal and toroidal modes being simultaneously present. The inability to uniquely determine a mode number from the Mirnov coils supports this conjecture. The fast ion loss probes measure an increased signal whose envelope corresponds to the envelope of the Mirnov oscillations (Fig. 5). Note the clear threshold as the power level is increased from 2 to 3 MW. Estimates of the power lost in fast ions indicate that only an insignificant amount (~50 kW) is required to agree with the probe signals. This is in agreement with the global energy balance which shows no additional degradation in energy confinement over the normal L-mode power dependence. The oscillation can be modulated by other MHD modes present, such as sawtooth and m=1 oscillations. This modulation may be due to the variation of the energetic ion pressure gradient. All of these features are similar to the NBI driven TAE modes previously observed in TFTR[11]. Based on our current knowledge of the wave damping physics, collisional damping due to electrons near the trapped/passing boundary should be the dominant damping mechanism for our experiment. If this is correct, then theory predicts that at full magnetic field ~500 kJ of tail energy would be required to destabilize the mode. This level should be achievable in He-3 minority heating experiments, allowing an even closer simulation of DT alpha parameters. It should be pointed out, however, that as the background ion beta is increased, ion Landau damping may become important and further damp the mode.

6. Summary

ICRF experiments on TFTR have been extended by utilizing two new antennas and additional RF power. A new maximum power level of 7.8 MW has been achieved. ICRF heating of supershot plasmas has efficiently increased the electron temperature in DD plasmas. These increases extrapolate to increases in β_α in DT plasmas. Direct electron heating has been observed in low and high toroidal field regimes where ion resonances have been placed only in the periphery of the plasma. In this regime, as much as 80% of the RF power can be damped directly on the electrons. Excitation of the TAE mode has been observed in L-mode discharges in minority heating experiments which produce an energetic trapped ion population.

Acknowledgments

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Figure Captions

Figure 1 ICRF heating of supershot plasmas shows a stronger central $T_e(0)$ increase than with similar power NBI. Time evolution of, (a) $T_e(0)$, (b) NBI power, (c) neutron emission, and (d) ICRF power. (— NBI alone, - - - NBI + ICRF)

Figure 2 Direct electron heating of a supershot plasma is observed with modulated rf power in a D plasma with no minority species present. ($B_T(0) \sim 4.7$ T, $f_{rf} = 47$ MHz, R = 2.82 m)

Figure 3 Power deposition profile analysis and volume integrated power at time 3.6 s of Fig. 2.

Figure 4 Observation of TAE mode at 170 kHz driven by RF tail ions. (a) time evolution of Mirnov signal data (b) frequency spectrum of density fluctuations near plasma center (r ~ 10 cm), as measured by a microwave reflectometer.

Figure 5 Correlation between lost energetic particles and TAE mode amplitude. A clear threshold is seen as the power level is increased above 3 MW (a) Signal from lost particle probe located 45° below outer midplane (b) Amplitude of Mirnov oscillations between 150 and 200 kHz (c) central soft x-ray signal (d) ICRF power waveform

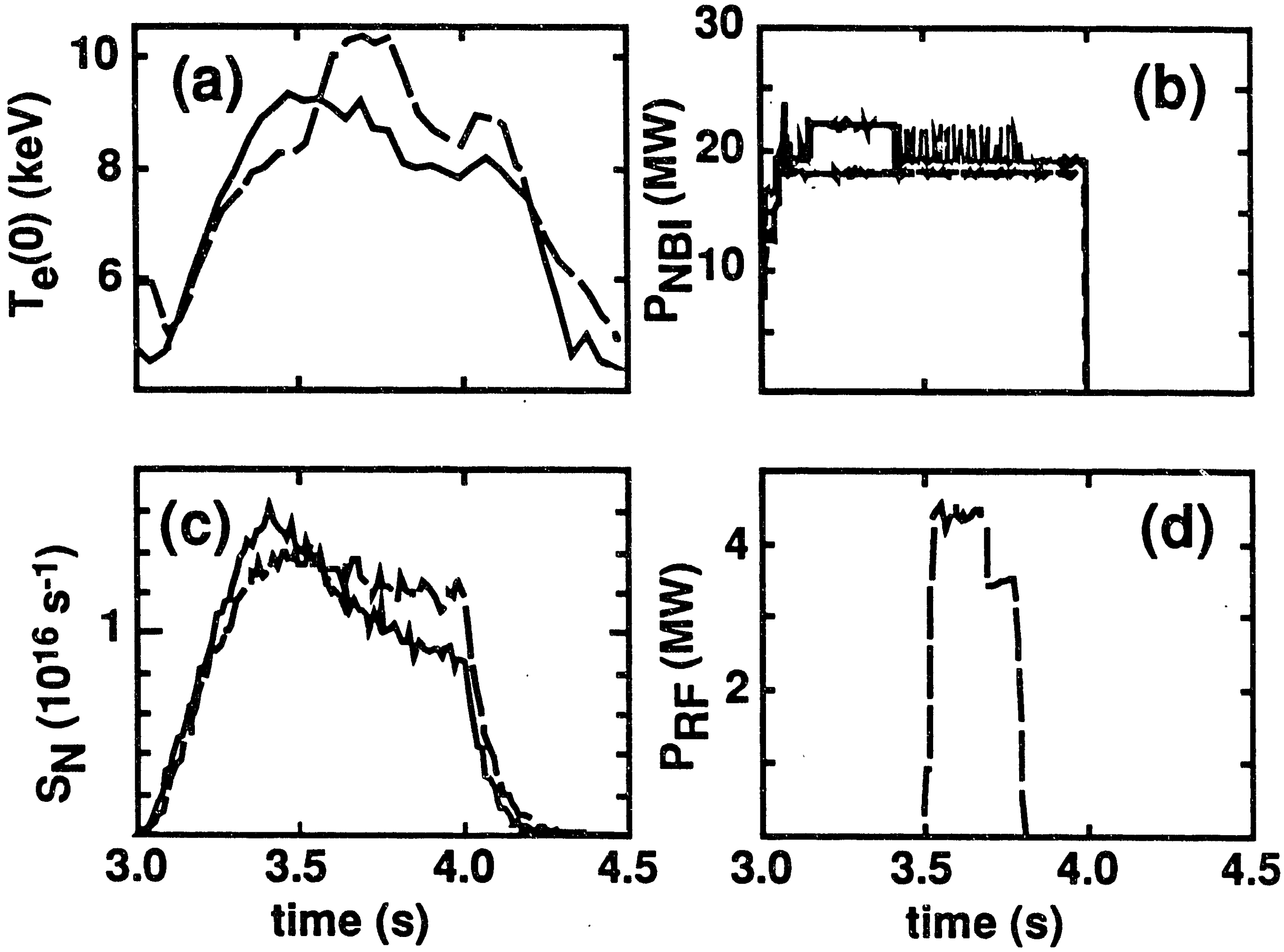
(a)
(b)
(c)
(d)
$T_e(0)$ (keV)
P_{NBI} (MW)
S_N (10^{16} s^{-1})
P_{RF} (MW)
10
8
6
30
20
10
1
4
2
3.0
3.5
4.0
4.5
time (s)
time (s)

Fig. 1

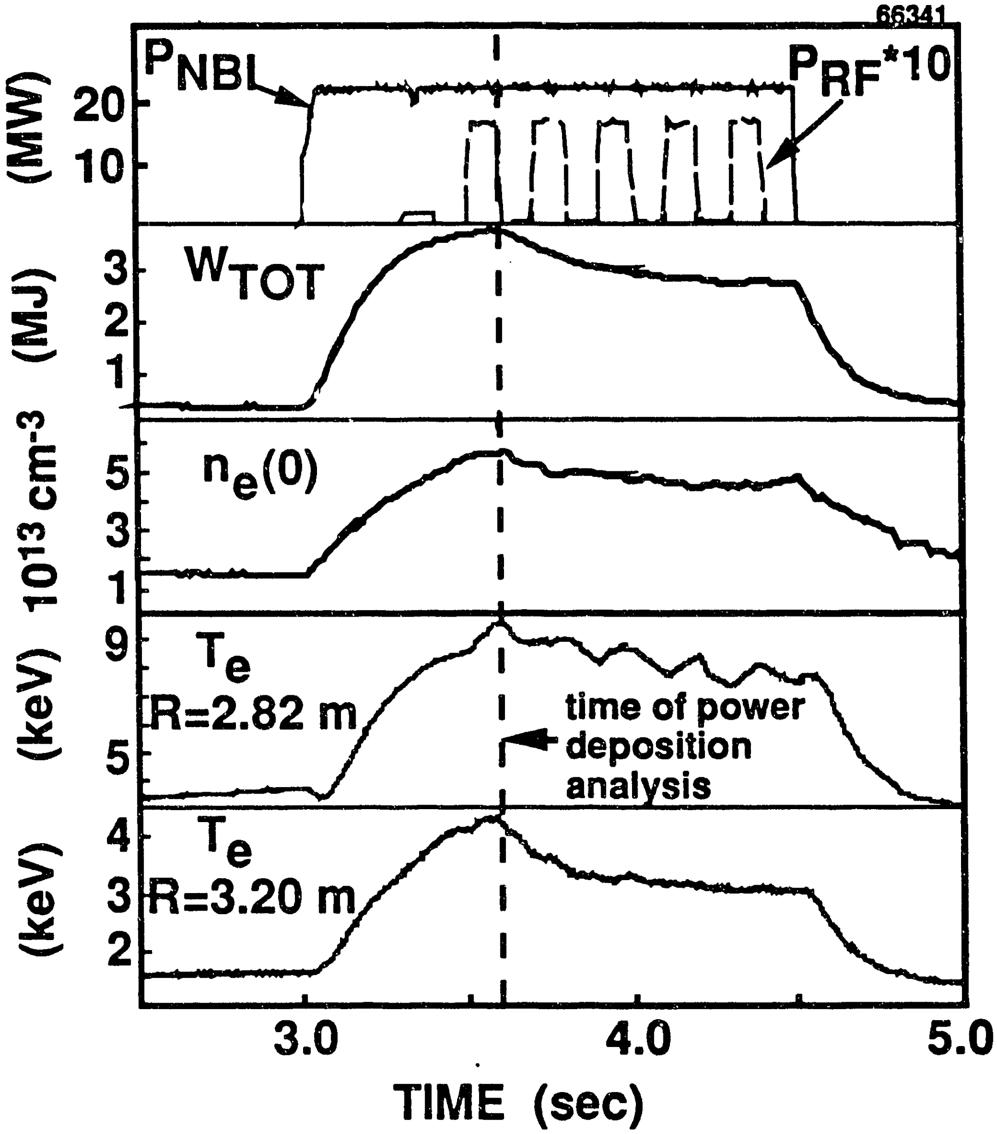
66341
PNBL
PRF*10
(MW)
20
10
WTOT
(MJ)
3
2
1
ne(0)
10^13 cm^-3
5
3
1
Te
R=2.82 m
(keV)
9
5
time of power deposition analysis
Te
R=3.20 m
(keV)
4
3
2
3.0
4.0
5.0
TIME (sec)

Fig. 2

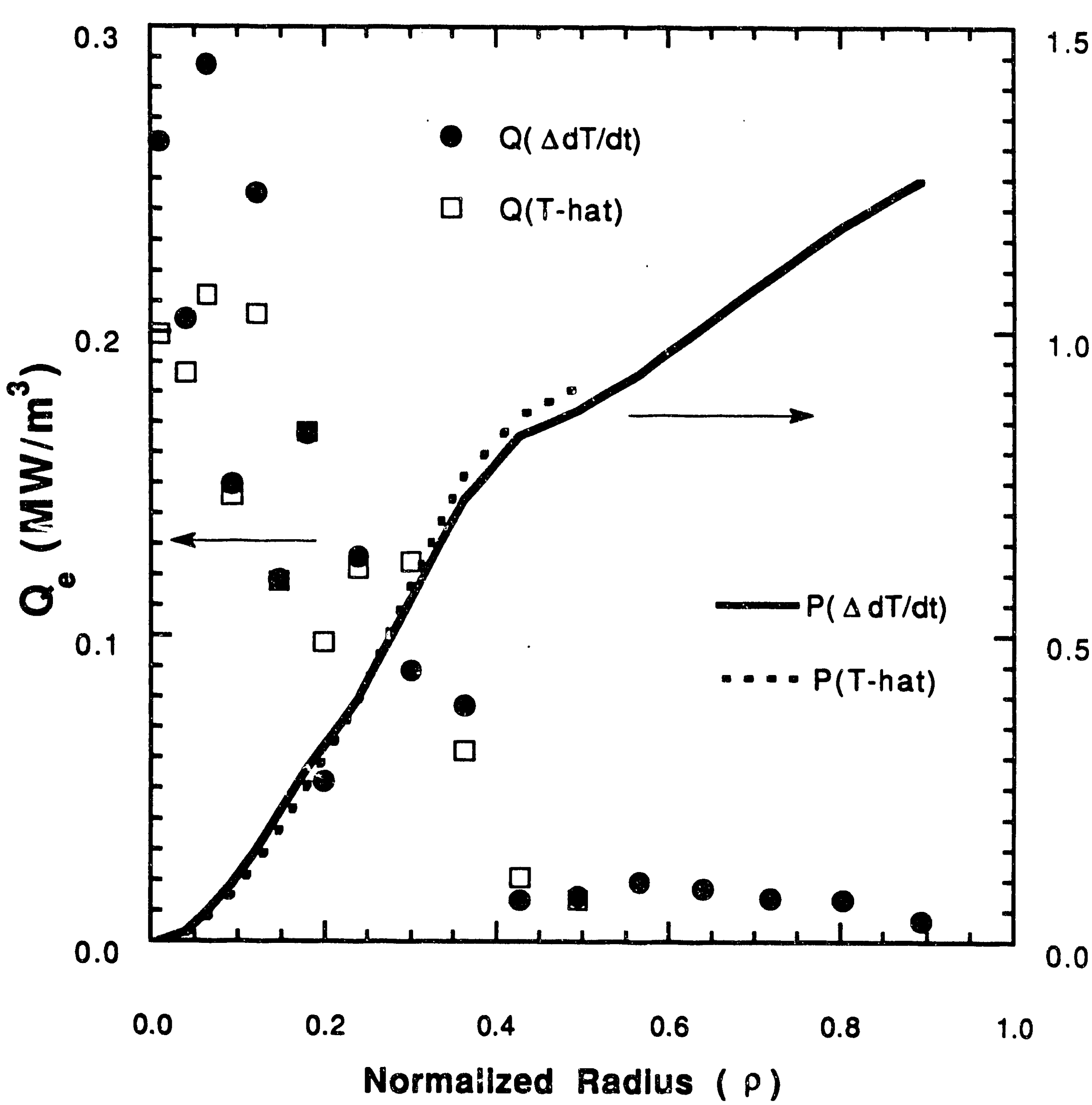
0.3
0.2
0.1
0.0
1.5
1.0
0.5
0.0
Q(ΔdT/dt)
Q(T-hat)
P(Δ dT/dt)
P(T-hat)
Q_e (MW/m^3)
P_e (ρ) (MW)
0.0
0.2
0.4
0.6
0.8
1.0
Normalized Radius (ρ)

Fig. 3

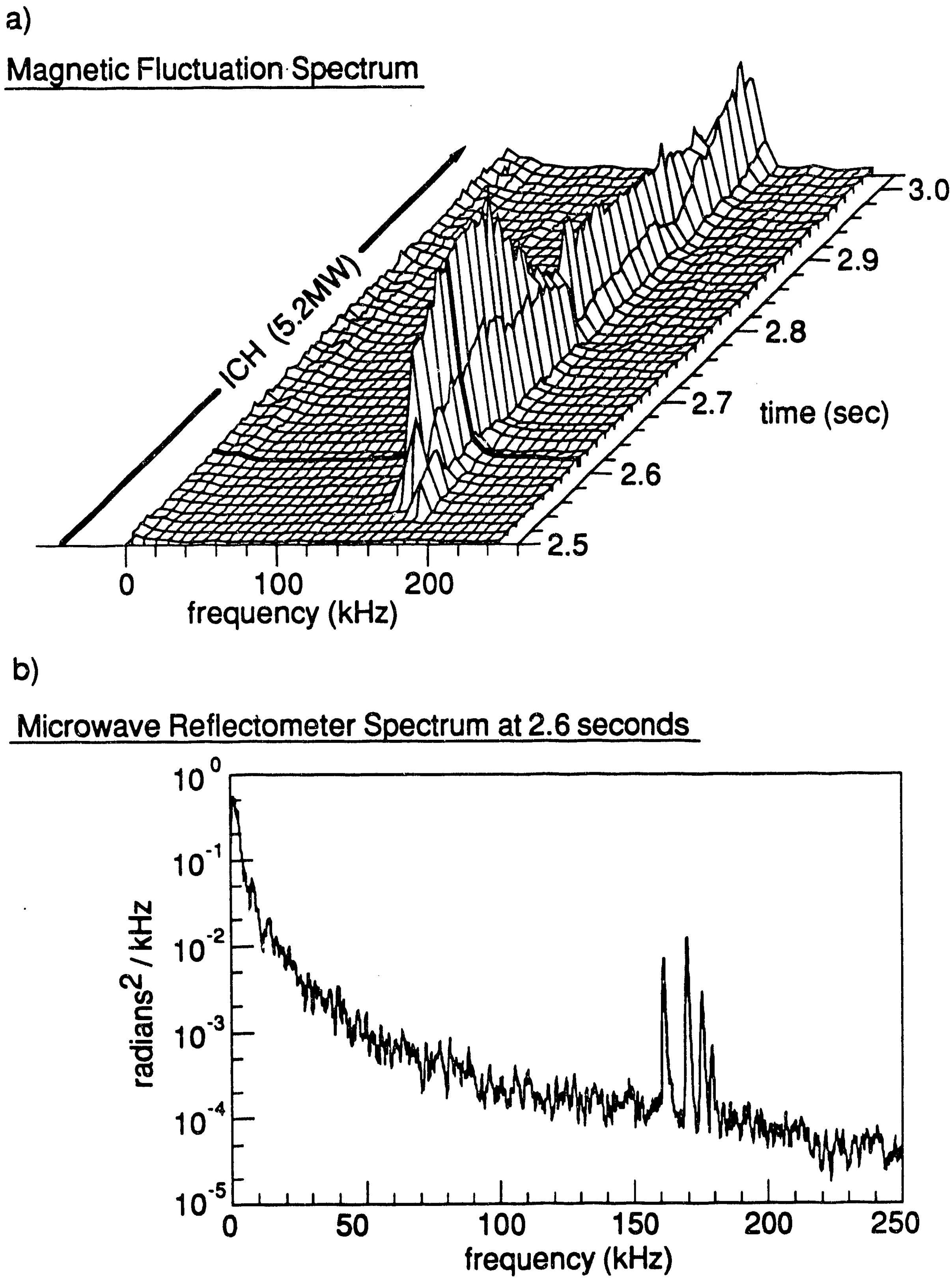
a)
Magnetic Fluctuation Spectrum
ICH (5.2MW)
3.0
2.9
2.8
2.7
time (sec)
2.6
2.5
0
100
200
frequency (kHz)
b)
Microwave Reflectometer Spectrum at 2.6 seconds
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
radians^2 / kHz
0
50
100
150
200
250
frequency (kHz)

Fig. 4

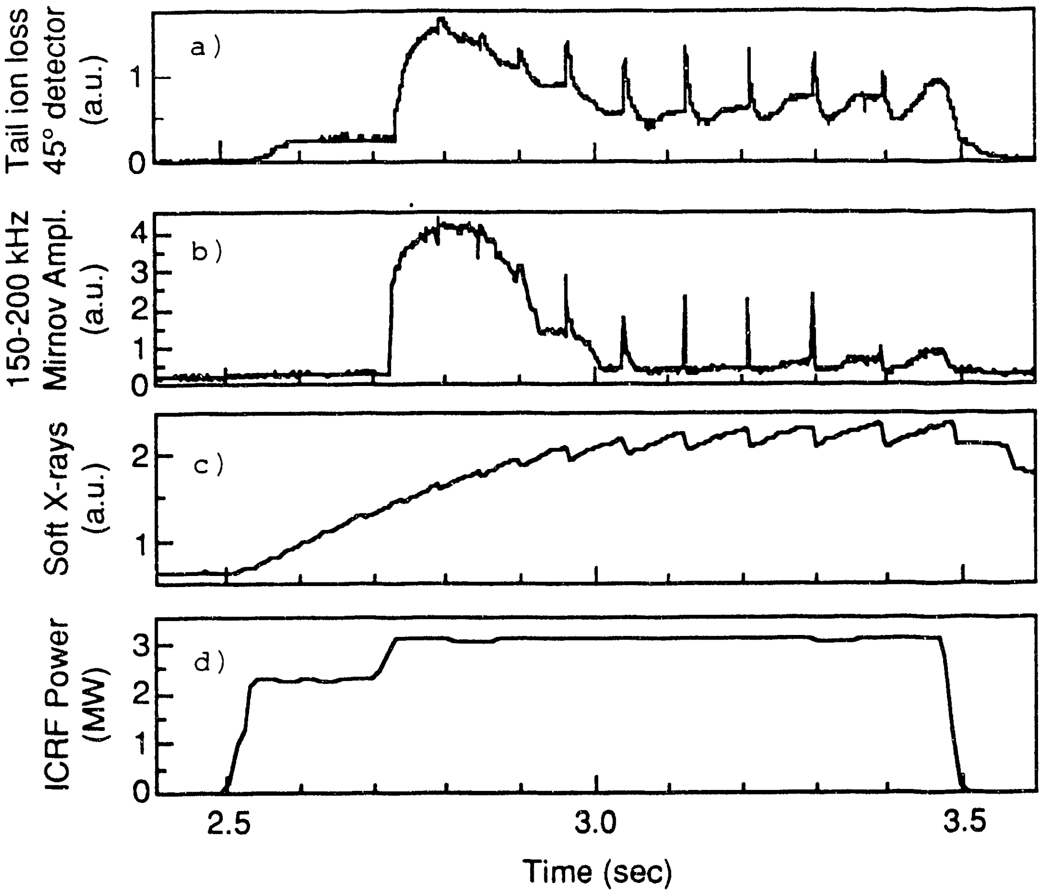
Tail ion loss
45° detector
(a.u.)
a)
150-200 kHz
Mirnov Ampl.
(a.u.)
b)
Soft X-rays
(a.u.)
c)
ICRF Power
(MW)
d)
2.5
3.0
3.5
Time (sec)

Fig. 5

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