MODE CONVERSION STUDIES IN TFTR

BY

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ABSTRACT

Mode converted Ion Bernstein Waves (IBW) have important potential applications in tokamak reactors. These applications include on or off axis electron heating and current drive[1] and the channeling of alpha particle power for both current drive and increased reactivity[2]. Efficient mode conversion electron heating with a low field side antenna, with both on and off axis power deposition, has been demonstrated for the first time in TFTR in D-^{3}He-^{4}He plasmas. Up to 80% of the Ion Cyclotron Range of Frequency (ICRF) power is coupled to electrons at the mode conversion surface. Experiments during deuterium and tritium neutral beam injection (NBI) indicate that good mode conversion efficiency can be maintained during NBI if sufficient ^{3}He is present. No evidence of strong alpha particle heating by the IBW is seen. Recent modelling indicates that if the mode converted IBW is preferentially excited off the horizontal midplane then the resultant high poloidal mode number wave may channel alpha particle power to either electrons or ions[2]. In TFTR both the propagation of the IBW and its effect on the alpha particle population is being investigated. Experiments with 2 MW of ICRF power launched with $\pm$ 90^o antenna phasing for current drive show that electron heating and sawtooth activity depend strongly on the direction of the launched wave. The noninductively driven current could not be experimentally determined in these relatively high plasma current (1.2 MA), short pulse discharges. Experiments at higher RF power and lower plasma current are planned to determine on and off axis current drive efficiency.

1. INTRODUCTION

An increasing emphasis is being placed on control of the q-profile in order to access advanced tokamak operating regimes. Enhanced plasma performance in the Tokamak Fusion Test Reactor (TFTR)[3], in the Joint European Torus[4], and in the DIII-D device[5] has been attributed to reversed shear operation. Reversed shear operating scenarios are planned for the Tokamak Physics Experiment[6] and the International Thermonuclear Experimental Reactor. The ability to drive off-axis currents noninductively is a key requirement for such scenarios.

We present here the initial experimental demonstration of a technique which can provide either on or off axis electron heating and current drive. A fast magnetosonic wave is launched using low field side Ion Cyclotron Range of Frequency (ICRF) antennas in a multiple ion species plasma with parameters chosen to yield efficient mode conversion to a low parallel phase velocity, strongly damped Ion Bernstein Wave (IBW)[1]. Ion species mixes which maximize mode conversion include D (or ^{4}He)-^{3}He, D-T-^{3}He, and D-T, where the fractional ion densities of the species are comparable. In TFTR, the present range of toroidal field and ICRF generator frequencies do not permit mode conversion studies in D-T. Heating has been demonstrated in TFTR with D-^{4}He-^{3}He and D-T-^{3}He plasmas. Experiments in mode conversion current drive have also begun. Previous theoretical studies of the ray trajectory of the mode converted IBW in the case of high parallel phase velocities have indicated that no net directivity would be obtained[7]. Here, where the mode converted IBW has a low parallel phase velocity, the electron response is experimentally found to be sensitive to the direction of the launched wave.

The use of a high poloidal mode number IBW to "channel" power directly from the alpha particles to ion heating has also been recently discussed

[2]. In TFTR the effect of the mode converted IBW on the small population of alpha particles in an L-mode plasma with neutral beam fueled D-T and puffed ^3He is under investigation. Simulations predict that the IBW will diffuse the alpha particle population in both space and energy. This quasilinear diffusion is expected to depend on the toroidal direction of IBW propagation. The alpha particle current to the lost alpha detectors [8] should therefore be dependent on the toroidal direction of the IBW and hence the launched fast wave.

2. EFFICIENT MODE CONVERSION HEATING AND CURRENT DRIVE.

Efficient single-pass mode conversion in a multiple ion species plasma, such as D-T, has been discussed in detail elsewhere[1,9]. Briefly, the fast wave is cutoff at surfaces defined by the conditions $n_{\|}{}^2=L$, R; where $n_{\|}=ck_{\|}/\omega$, and $k_{\|}$ is the parallel wavenumber. Mode conversion occurs at the ion-ion hybrid resonance defined by $n_{\|}{}^2=S$. The functions R, L, and S are defined by Stix[10]. Previous treatments have neglected the $n_{\|}{}^2=R$ cutoff, considering mode conversion at a cutoff - resonance pair. However, if the ion species mix, central density, and toroidal magnetic field are correctly chosen, these surfaces form a closely spaced cutoff - resonance - cutoff triplet for some value of $k_{\|}$. An increase in the "single pass" mode conversion efficiency of up to a factor of four over the cutoff-resonance pair case results. Numerical modelling of the D - or ^4He - ^3He and D - T - ^3He ion systems indicates that single pass mode conversion efficiencies in excess of 90% can be achieved. Efficient mode conversion is obtained at the mode conversion triplet for high $n_{\|}$, so that the resultant IBW is excited with $v_\phi/v_{Te} < 1$ and is rapidly damped on electrons. If the mode converted Bernstein wave is directional then current drive will result. Unlike direct fast wave current drive which is always localized to the plasma axis, the radial location of the mode conversion surface and hence the driven current can be varied by the species mix or magnetic field strength. Current drive efficiency is expected to be comparable to fast wave current drive.

3. MODE CONVERSION HEATING EXPERIMENTS.

Experiments using ^3He, ^4He, D ohmic target plasmas in TFTR have demonstrated mode conversion electron heating. The electron temperature rise with near-axis mode conversion is shown in Fig. 1(a). A Thomson scattering electron temperature profile taken at 2.8 seconds during this discharge is shown in Fig. 1(b). Heating occurs at the mode conversion layer, remote from the ion cyclotron resonances. In Fig. 2 the measured electron power deposition profile is shown for off-axis mode conversion, for an ohmic target plasma and for plasmas with 4.6, 7.6, and 10.6 MW of NBI. The power deposition profile was measured using Fourier transform techniques with 10 Hz RF power modulation[11]. Power deposition is localized to the mode conversion layer on the high field side of the axis for both the ohmic and NBI heated discharges. Peak ion temperature in the neutral-beam fueled L-mode target discharges was measured to be 5 - 7 keV by Charge-Exchange Recombination Spectroscopy (CHERS). Modelling of the RF-heated ohmic discharge with the FELICE code[12] predicts that the fraction of ICRF power coupled to electrons should be 0.86, while the experimentally observed fraction is 0.7. The predicted and observed power deposition radii are in agreement to < 5 centimeters. The modelling used parabolic density and temperature profiles with $n_e(0)=4 \times 10^{19}$

m^{-3}, n_{He3}/n_e=0.2, $T_e(0)$=5 keV, where the electron temperature is obtained from electron cyclotron emission measurements, and $T_i(0)$=4 keV, based on x-ray crystal spectrometry and CHERS results for similiar discharges. The experimentally measured central electron power deposition is small for the ohmic target case, indicating that the single pass mode conversion efficiency is larger by an order of magnitude than the single pass absorption for direct fast wave electron heating. Single pass direct fast wave electron absorption is calculated to be ~5%, from which we infer that the single pass mode conversion efficiency is ~50%. The fraction of power absorbed near the axis for the NBI heated discharges is difficult to estimate due to strong sawtooth mixing.

The location of the mode conversion layer can be controlled by adjusting either the toroidal magnetic field (B_T) or the ion species ratio. In Fig. 3 the measured radius of electron power deposition as a function of the toroidal field is shown for constant density ($n_e(0)=4 \times 10^{19}$ m^{-3}) and ^{3}He fraction (0.14). The power deposition radius occurs within a few cm of the $n_{\|}{}^2$=S layer. In Fig. 4 the measured fraction of the RF power coupled to electrons at the mode conversion surface is shown for discharges in which the mode conversion radius is varied through either the species fraction or the toroidal field. Discharges with 4.0 T<B_T<4.8 T and 0.1 < n_{He3}/n_e <0.3 are included. The central density was $n_e(0)=4\text{-}5 \times 10^{19}$ m^{-3}, and the central ion temperature was 4 - 7 keV. Up to 80% of the ICRF power is mode converted, with >50% typical for a wide range of deposition radii. The fraction of power mode converted and coupled to electrons rises with ^{3}He concentration, as shown in Fig. 5. Here B_T = 4.5 T, while other plasma conditions were as noted for Fig. 4. Relatively little mode conversion electron heating is found for NBI heated discharges with low ^{3}He fractions (<0.1), where minority ion heating of the ^{3}He population becomes significant.

4. MODE CONVERSION CURRENT DRIVE.

Initial mode conversion current drive experiments used ohmic D-^{4}He-^{3}He target plasmas, with two of the two-strap TFTR antennas each phased at 90° to provide a directional fast wave launch at $k_{\|}$ (antenna)=7 m^{-1}. The mode conversion layer was located near the plasma axis, with $n_{He\text{-}3}/n_e$ =0.12, B_T=4.5 T, and $n_e(0)=4 \times 10^{19}$ m^{-3}. The electron temperature response depended on the antenna phasing, and hence the direction of the fast wave launch, as shown in Fig. 6. This result indicates that the IBW directivity depends on the directivity of the fast wave. However, the surface loop voltage was substantially the same during the 0.8 sec. RF pulse with co- (i. e. parallel to the electron current) and counter fast wave launches. Subsequent TRANSP modelling of these 1.2 MA discharges indicates that centrally driven currents in the expected 100 - 200 kA range would not be reflected in the surface voltage on these time scales. Future current drive experiments will be performed in lower current discharges with on and off axis electron coupling, 2 sec. RF pulses, and measurement of the current profile by motional Stark effect, to permit a more direct observation of noninductive currents.

5. RESULTS IN D-T-^{3}He PLASMAS.

IBW - alpha particle interactions were investigated in an L-mode D-T-^{3}He plasma with D-T supplied via neutral beam injection while ^{3}He was supplied by gas puffing. Five discharges with 2.3 MW of deuterium neutral beam injection and 2.9 MW of tritium neutral beam injection into a 1.6 MA plasma have been produced as mode conversion targets. The mode conversion layer was located near the plasma axis, and the RF power was modulated at 10 Hz. No corresponding modulation in the lost alpha signal, normalized to the neutron rate, was seen. Hence at the power levels employed for these initial experiments (2 MW), IBW heating of the alpha particles is not discernable relative to collisional pitch angle scattering into the alpha particle loss cone. It should be noted that the mode converted power fraction in these experiments was low (~0.2), probably due to low on-axis ^{3}He concentration (<0.1) with a resultant onset of minority ion heating (see Fig. 5). During these experiments significant levels of $\langle|\delta n_e(k_r, \omega = \omega_{rf})|\rangle$ were observed with microwave scattering [13] at $k \sim 5\text{-}11\ \mathrm{cm}^{-1}$ in the horizontal midplane near the location of the mode conversion layer. A precise determination of the peak mode wavenumber and correlation with the expected IBW dispersion will be attempted in future experiments at higher toroidal field and ^{3}He concentrations.

6. CHANNELING OF ALPHA PARTICLE POWER.

Poloidally propagating waves with small phase velocities [14] are required for effective alpha channeling. Such waves extract power from energetic alpha particles, while diffusing them radially. The mode-converted IBW has the necessary wave properties[2]. If alpha particle power can be channeled effectively to ions, the power density can be doubled in a fusion reactor[15]. Ray tracing studies for TFTR parameters, with T_e=10 keV, T_i=20 keV, predict that with suitable toroidal phasing and a frequency of 35 MHz, high poloidal wavenumber ion Bernstein waves could be excited off the horizontal midplane of the plasma by mode conversion[16].

The present TFTR range of operating frequencies and toroidal fields do not permit near-axis excitation of an IBW in a D-T plasma. However, microwave scattering and reflectometry in D and D-T-^{3}He plasmas will be used to investigate the propagation of the IBW. Preliminary evidence of high wavenumber modes in the midplane has already been obtained. With toroidal phasing of the ICRF antennas, such as is already utilized in the current drive experiments, the prediction of up-down asymmetries in the poloidal wavenumber will be investigated with microwave scattering. Mode conversion in a D-T-^{3}He L-mode plasma provides a small population of alpha particles to test the interaction. Because of the up-down asymmetry in IBW propagation, reversal of the toroidal launch direction should produce observable differences in the energy of the outwardly diffused alpha particles detected with the lost-alpha probes.

7. SUMMARY AND FUTURE PLANS.

Efficient on and off axis mode conversion electron heating has been demonstrated with ohmic D-^{4}He-^{3}He and neutral beam fueled D-T-^{3}He plasmas. The effects of directional propagation of the mode converted IBW have been observed. Future experiments will seek to demonstrate on and off axis mode conversion current drive. In D-T-^{3}He systems, key ingredients of the physics of IBW - alpha particle interactions are being investigated.

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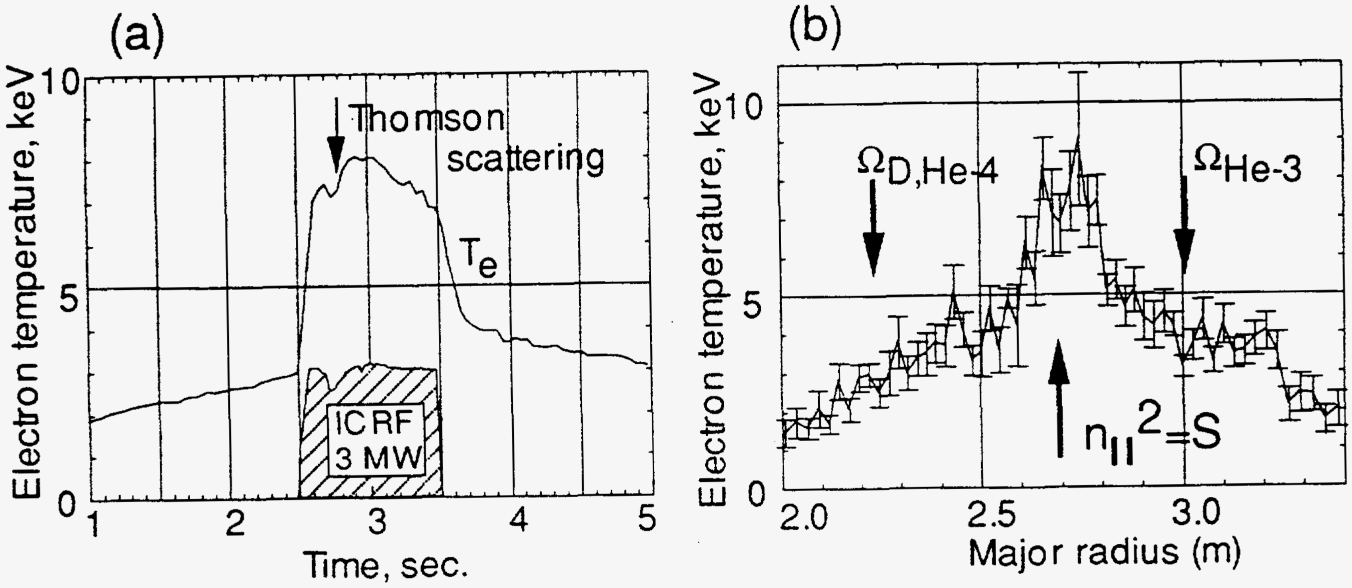

Fig. 1. (a)Time evolution of the central electron temperature for on-axis mode conversion heating, derived from electron cyclotron emission measurements, and (b) radial profile of the electron temperature from Thomson scattering at 2.8 seconds.

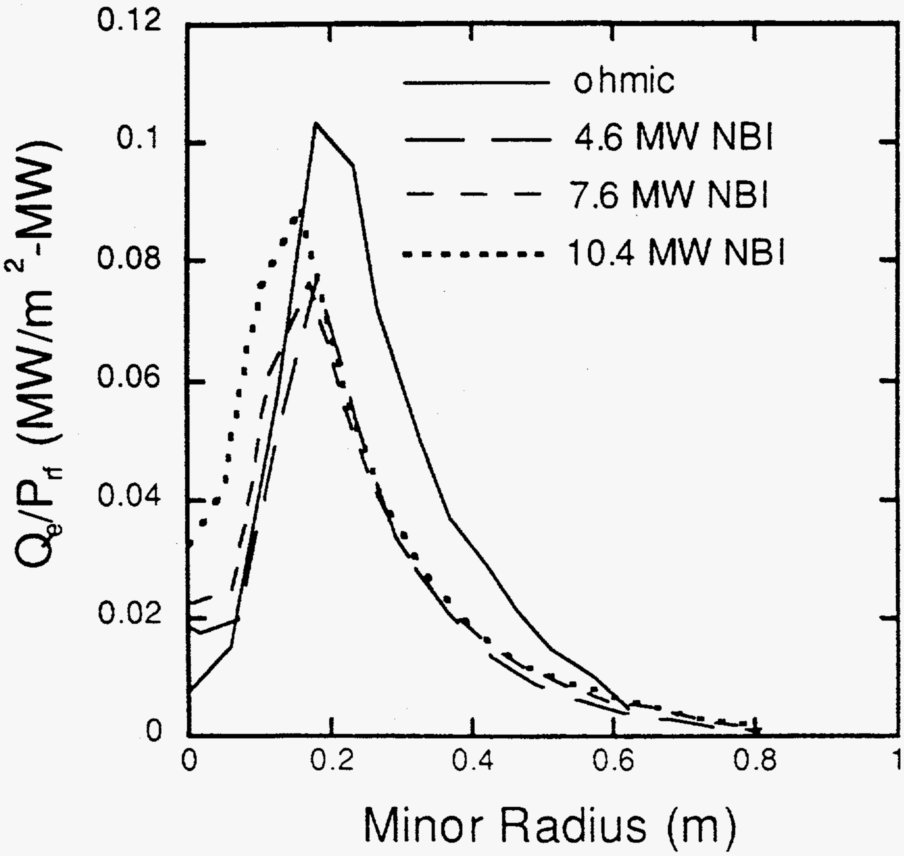

Fig. 2. Electron power deposition profile, derived from power modulation techniques, for off-axis mode conversion, for ohmic and NBI heated target plasmas with $n_e(0) = 4\text{-}5 \times 10^{19}$ m^{-3}, n_{He3}/n_e=0.12.

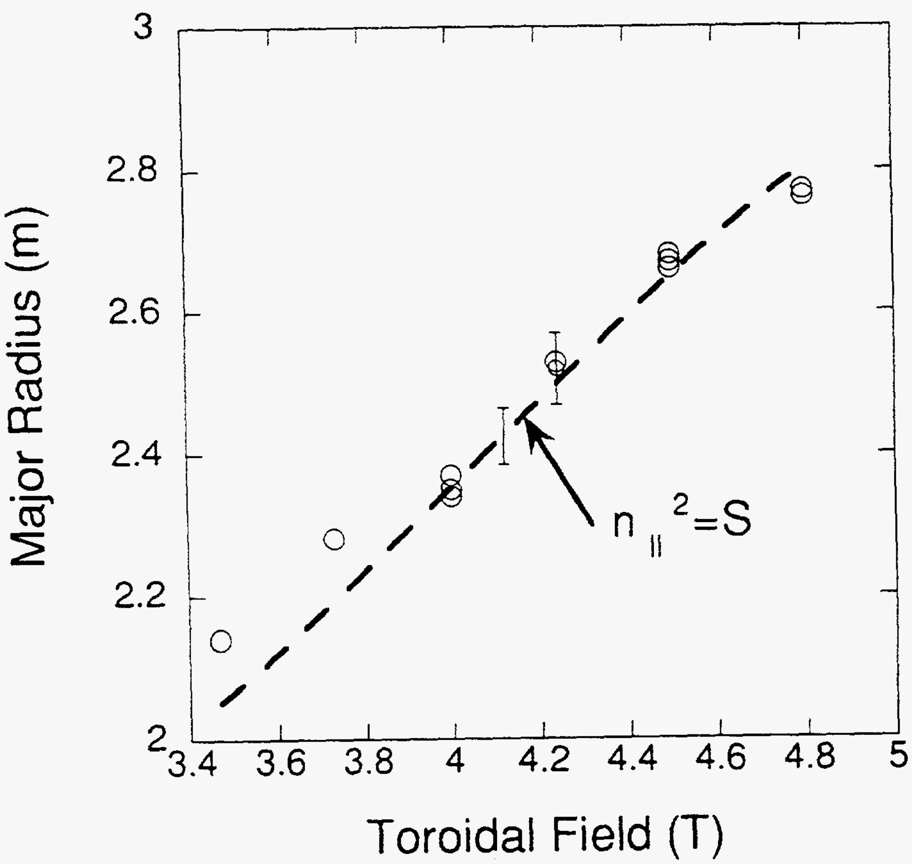

Fig. 3. Observed radius of electron power deposition as a function of the toroidal field, for constant helium-3 fraction (n_{He3}/n_e=0.14) and constant density ($n_e(0) = 4 \times 10^{19}$ m^{-3}). The open circles indicate the experimentally observed radii of deposition; the dashed line denotes the calculated position of the mode conversion surface.

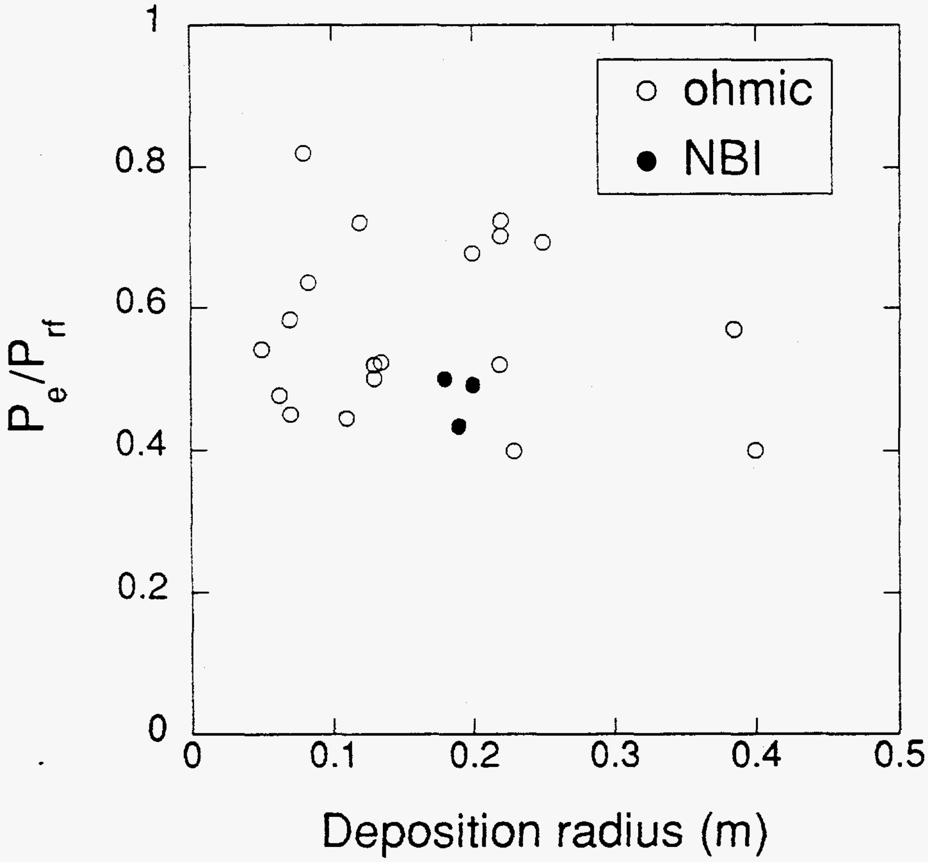

Fig. 4. Fraction of power coupled to electrons at the mode conversion surface as a function of the radius of the mode conversion surface. For these discharges 4.0 T<B_T<4.8 T, 0.1 < $n_{He\text{-}3}/n_e$ <0.3, and $n_e(0)$ = 4-5 × 10^{19} m^{-3}. The solid circles indicate NBI heated discharges.

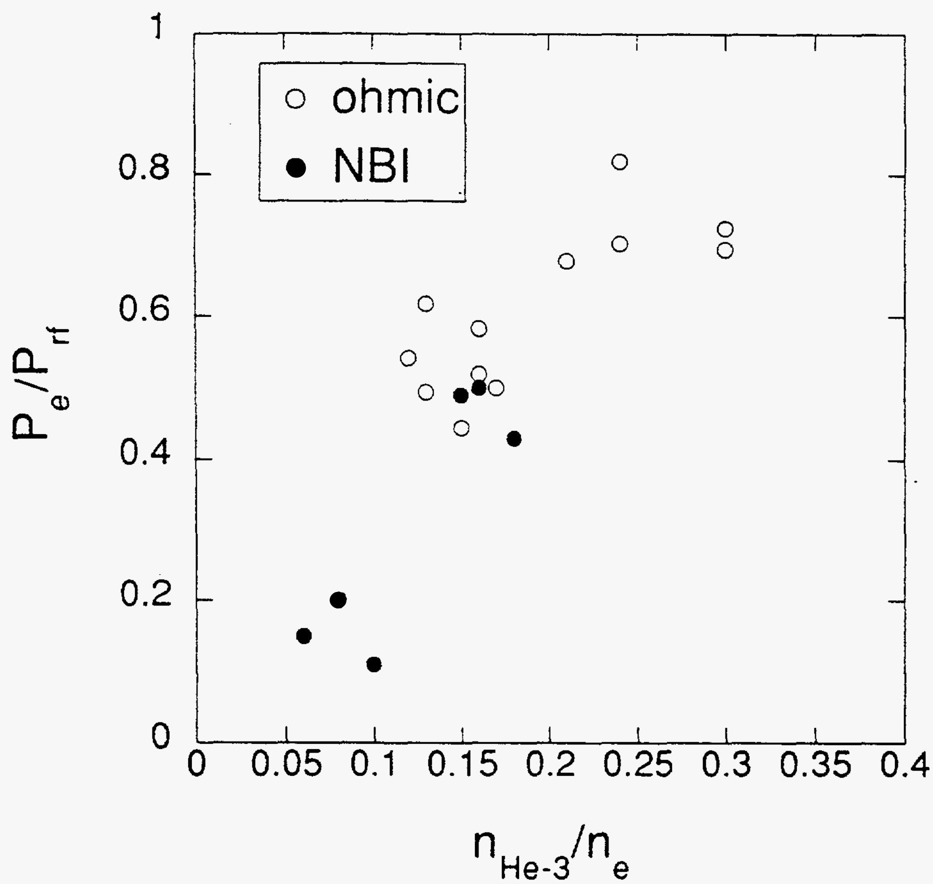

Fig. 5. Fraction of power coupled to electrons at the mode conversion surface as a function of the helium-3 fraction, for constant toroidal field (4.5 T) and density ($n_e(0) = 4 \times 10^{19}$ m^{-3}). The solid circles indicate NBI heated discharges.

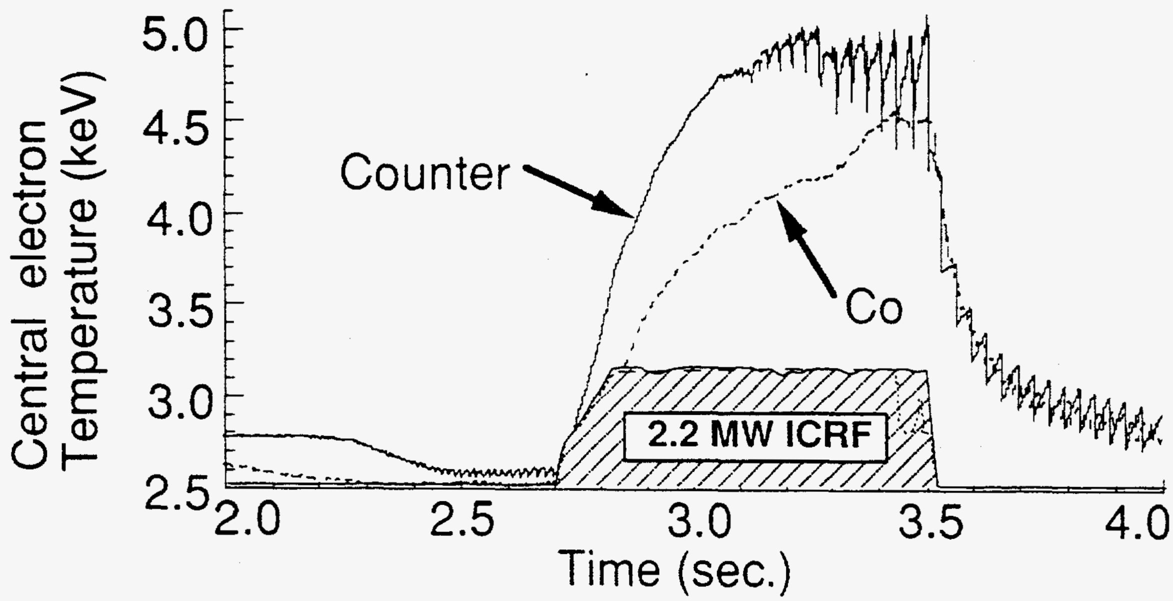

Fig. 6. Electron temperature evolution during directional (90^o) fast wave launch parallel to the ohmic current (co) and antiparallel to the ohmic current (counter). Here $n_e(0) = 4 \times 10^{19}$ m^{-3}, $B_T = 4.5$ T, and I_p=1.2 MA.