ICRF HEATING AND TRANSPORT OF DEUTERIUM-TRITIUM PLASMAS IN TFTR

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ABSTRACT

This paper describes results of the first experiments utilizing high-power ion cyclotron range of frequency (ICRF) to heat deuterium-tritium (D-T) plasmas in reactor-relevant regimes on the Tokamak Fusion Test Reactor (TFTR). Results from these experiments have demonstrated efficient core, second harmonic, tritium heating of D-T supershot plasmas with tritium concentrations ranging from 6%-40%. Significant direct ion heating on the order of 60% of the input radio frequency (rf) power has been observed. The measured deposition profiles are in good agreement with two-dimensional modeling code predictions. Energy confinement in an rf-heated supershot is at least similar to that without rf, and possibly better in the electron channel. Efficient electron heating via mode conversion of fast waves to ion Bernstein waves (IBW) has been demonstrated in ohmic, deuterium-deuterium and DT-neutral beam injection plasmas with high concentrations of minority ^{3}He ($n_{^3He}/n_e$ = 15% - 30%). By changing the ^{3}He concentration or the toroidal field strength, the location of the mode-conversion radius was varied. The power deposition profile measured with rf power modulation indicated that up to 70% of the power can be deposited on electrons at an off-axis position. Preliminary results with up to 4 MW coupled into the plasma by 90-degree phased antennas showed directional propagation of the mode-converted IBW. Analysis of heat wave propagation showed no strong inward thermal pinch in off-axis heating of an ohmically-heated target plasma in TFTR.

I. INTRODUCTION

Future fusion devices, such as the International Thermonuclear Experimental Reactor (ITER), emphasize ion cyclotron range of frequency (ICRF) heating and current drive (CD). Tritium second harmonic cyclotron resonance ($2\Omega_T$) is the proposed heating scenario in ITER operation, but until now, no experimental data have been available. The Tokamak Fusion Test Reactor (TFTR) has performed the first experiments on ICRF heating of D-T plasmas showing significant ion heating in the $2\Omega_T$ regime.[1,2] An increasing emphasis is being placed on control of the plasma current profile in order to access the Advanced Tokamak operating regime in future devices, such as the Tokamak Physics Experiment (TPX). Mode conversion to ion Bernstein waves (IBW) has been proposed for the profile control, and, in particular, off-axis heating and CD. The efficient mode conversion scheme recently proposed[3] has been demonstrated for the first time in TFTR in ^{3}He-^{4}He plasmas.[4] Benchmarking of the rf computer codes, which are needed for designing future devices, with these experimental data has been facilitated by rf power modulation.

This paper gives an overview of the recent TFTR ICRF experiments. Section II describes ICRF heating in D-T plasmas, demonstrating second harmonic tritium heating, the benchmarking of rf modeling, and comparison of confinement of rf-heated D-T supershots with those heated by neutral beam injection (NBI) alone. Section III describes experiments on mode conversion of fast waves to IBWs, demonstrating the efficient on- and off-axis mode conversion, and testing for an inward thermal pinch by the use of off-axis heating. Section IV conclude the discussion with future plans.

II. ICRF HEATING IN D-T PLASMAS

The initial series of ICRF heating experiments with D-T plasmas had two main experimental objectives: to investigate the physics of ICRF-heated plasmas in the $2\Omega_T$ regime and to enhance the performance of D-T supershots. Plasma reactivity can be increased by directly heating tritium ions via second harmonic ICRF. Significant increases in the central electron heating of supershots via direct electron heating or collisional heating with minority tail ions may result in the lengthening of the alpha particle slowing time and an

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enhancement of the alpha particle pressure in D-T plasmas, facilitating the investigation of alpha-particle effects in TFTR. Transport in these rf-heated D-T discharges is of significant interest.

A total of 21 D-T supershot target plasmas driven by 18 to 24 MW of $\approx$100-keV NBI were heated with ICRF power launched by up to four antennas located at the midplane on the low-field side of the torus.[5] Input power of up to 5.8 MW was coupled to full-size (major radius, R_0, of 2.62 m, and minor radius, a, of 0.96 m) D-T plasmas at an rf frequency of 43 MHz with out-of-phase current strap excitation. To elucidate heating mechanisms, two systematic scans were conducted: (1) a tritium concentration scan with η_T ($\equiv n_T/n_e$) ranging from 6%–40% by varying the ratio of injected tritium to deuterium neutral beams, and (2) a toroidal field scan to vary the location of the $2\Omega_T$ layer relative to the magnetic axis.

The rf power modulation provides a technique for directly measuring the ICRF power absorption profiles by examining the time response of the measured ion- and electron-stored energies to the rf power modulation.[6,7] The electron and ion heating power per unit volume can be inferred from either: (1) the change in the time-derivative of the electron and ion energy density when the rf power was turned on or off, or (2) the Fourier transform analysis carried out over several cycles of modulation. The electron-stored energy was computed from the electron temperature profile, measured by electron cyclotron emission (ECE), combined with the electron density profile, obtained by a multi-channel far infrared interferometer (MIRI). The ion stored energy was computed from the charge exchange recombination spectroscopy (CHERS) measurement of T_i combined with the thermal ion density calculated by the TRANSP code which was in turn based on the electron density, Z_{eff} (obtained from visible bremstrahlung) and a Monte Carlo beam deposition model. Figure 1 shows the local ion and electron power deposition profiles (for a 1-MW power input to the antenna) obtained from the modulation analysis for a plasma where the $2\Omega_T$ layer was located at the magnetic axis and with 60% tritium NBI [$B_T = 4.6$ T, $R_{axis} = 2.82$ m, $P_{bT}/(P_{bD}+P_{bT}) = 0.6$]. The central portion of the ion and electron local power deposition profiles can be expressed as Gaussians, $\exp[-(\rho/\alpha)^2]$, with $\alpha = 0.17$ and 0.16, respectively, where ρ is the normalized minor radius r/a. The volume integrated values of the curves give the power absorption (within r = a with uncertainties in the analysis) of 59 ± 10% for ions and 26 ± 3% for electrons. The total absorption, 85 ± 10%, is consistent with the value, 80 ± 10%, estimated by magnetic analysis.

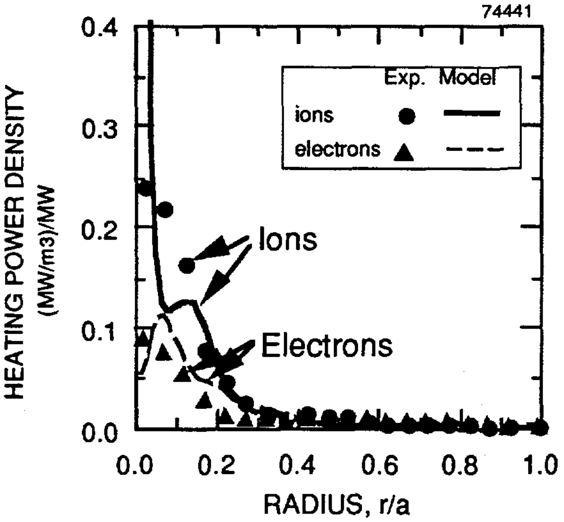

Fig. 1. Ion and electron heating power density as a function of radius measured (solid circles and triangles) with the modulation technique with the $2\Omega_T$ layer on the magnetic axis with 60% tritium NBI. The continuous curves are the heating power density profiles predicted by the PICES code.

The rf modeling predictions compare favorably with the experimental results determined by rf modulation. The curves overlaying the experimental points in Figure 1 are the ion and electron heating power deposition profiles predicted by the PICES code.[8] PICES is a two-dimensional (2-D), reduced-order, full wave code, with multiple (80) toroidal modes for representation of the launched antenna spectrum. The PICES analysis is based on the experimental temperature and density profiles (including beam ions with an effective temperature of ~60 keV on axis). The calculated heating power density profiles are similar to the experimental measurements. Of the total rf power, 26% was absorbed directly by electrons via Landau damping and transit time magnetic pumping near the core, in good agreement with rf modulation data. Of the 49% ion absorption, 43% was absorbed at the $2\Omega_T$ resonance in the core and 6% near the D (and carbon) fundamental resonance located at r/a ≈ 0.7. This code also predicts that ~16% of the rf power was absorbed at the intersection of deuterium ion fundamental resonance (R ≈ 2.1 m) and the mode conversion layer near the last closed flux surface. So far there is no experimental evidence to support (or refute) this effect. Power deposition profiles were also calculated for the same plasma with the rf package in TRANSP, consisting of a 2-D reduced-order wave solver, SPRUCE,[9] combined with the bounce-averaged Fokker-Planck solver, FPP.[10] From this analysis, 24% of the power was absorbed by electrons and 63% by ions within r/a = 0.85. The differences between the results of PICES and TRANSP stem primarily from the difference in the multiple and single mode calculations. The power splits predicted by both codes are in relatively close agreement with the data.

Similar agreement between the experimental power splits and the model predictions are found for the data from the tritium concentration scan with the $2\Omega_T$ layer on axis, as shown in Figure 2. The observed trends in the data are consistent with the theoretical prediction that the

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$2\Omega_T$ heating efficiency increases with the tritium beta. Up to 59 ± 10% of the rf power was observed to be absorbed by ions. The core $2\Omega_T$ heating is strong even for η_T as low as ~ 6% (15% of NBI power in T) primarily due to the presence of hot tritium beam ions. Further experimental evidence supports the core $2\Omega_T$ absorption: (1) the B_T scan showed that the ion heating peaks at the $2\Omega_T$ layer on axis, which is in agreement with the models[2]; and (2) the fast ion loss detectors observed escaping tritium tail ions (of ~600 keV) synchronously with rf modulation.[11]

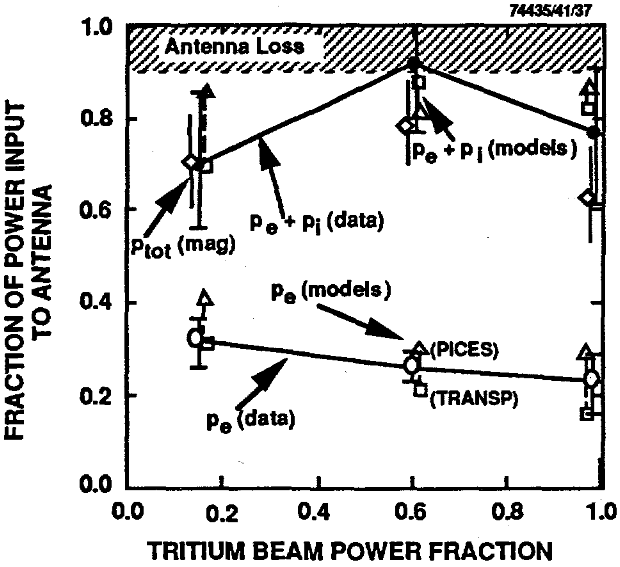

Fig. 2. Dependence of the measured power fraction absorbed directly by electrons and ions is shown as a function of tritium beam power fraction during rf modulation. Also shown are the total absorbed power fraction (open diamonds) determined from the magnetic analysis, and the electron and ion power splits predicted by rf modeling codes, PICES (open triangles) and TRANSP (open square).

The addition of 5.8 MW of ICRF power to a D-T supershot resulted in a significant increase in the core ion and electron temperatures[1], as shown in Figures 3a and 3b. A plasma line average density of about 4×10^{19} m^{-3} was established by NBI, and 2% ^{3}He gas was added to minimize effects of rf eigenmode excitation. The 43-MHz ICRF waves were resonant with both the minority ^{3}He ($\omega \sim \Omega_{^3He}$) and the majority tritium ($\omega \sim 2\Omega_T$) near the Shafranov-shifted magnetic axis ($B_T = 4.2$ T at R = 2.83 m). The central ion temperature, measured by CHERS, increased from 26 to 36 keV. The central electron temperature, as measured by ECE, increased from 8 to 10.5 keV, due to a combination of direct electron heating via Landau damping and collisions with minority tail ions. There was also a 10% increase in the D-T neutron production rate to $\sim 1.2 \times 10^{18}$ s^{-1} during the early part of the discharge. However, the performance was spoiled by an enhanced carbon influx that began at about 3.4 s due to the plasma moving to an unconditioned portion of the limiter. Figures 3c and 3d show the measured ICRF heating power density added to the underlying heating power calculated for neutral beam, ohmic, and α-particles to ions and electrons. The ICRF additions are significant out to r/a ~ 0.3, leading to the increase in T_i and T_e there. The observed core ion heating is consistent with $2\Omega_T$ heating, because an analogous increase was not evident in the earlier D (^{3}He) experiments.[12] Furthermore, a core ion temperature of 32 keV was obtained with only 4.4 MW of ICRF power during a companion discharge that was essentially identical to the present case without ^{3}He added.

Measurements of the ion and electron and heating power density allow the examination of the effects of transport in rf-heated plasmas relative to that with NBI alone. Figures 3e and 3f show the total effective heat diffusivity for ions and electrons as a function of radius with the measured rf power deposition profiles (rather than the predicted rf deposition profiles by the model) incorporated in the post-TRANSP analysis. To avoid prescribing a particular convective multiplier (3/2 or 5/2), the local transport is characterized by the total (conductive and convective) effective diffusivity χ_i^{tot} and χ_e^{tot} which are the ratio of the total radial ion and electron heat flux to the corresponding temperature gradient. The same conclusions, however, can be drawn from the usual ion and electron thermal diffusivity analysis. There is no significant difference between the χ_i^{tot} profile with and without rf, indicating that $T_i(r)$ increases with rf power while maintaining χ_i. Electron transport is even more favorable with rf. It showed a reduction in χ_e^{tot} by almost factor of 2 in the radii outside $\rho = 0.4$. So confinement of rf-heated D-T plasmas is at least similar to that with NBI alone, and possibly better in the electron channel. Inclusion of rf-driven ripple loss tends to indicate more favorable confinement for rf-heated shots.[13]

III. MODE CONVERSION EXPERIMENTS

Recently, a novel technique for localized electron heating and CD utilizing efficient mode conversion of fast magnetosonic waves into IBW at two-ion hybrid layers has been suggested by Majeski et al.[3] This technique is D-T compatible, uses no extra hardware, and may provide off-axis CD to access the advanced tokamak operating regime. In contrast to mode conversion[14] in the conventional minority heating scheme utilizing a small minority ion concentration, the proposed scheme enhances the mode conversion efficiency (and thereby the electron heating efficiency) by: (1) separating the mode conversion layer (at the two-ion hybrid layer $n_{//}^2 = S$) from the cyclotron layer; and (2) forming a closely spaced "cutoff-resonance-cutoff" triplet.

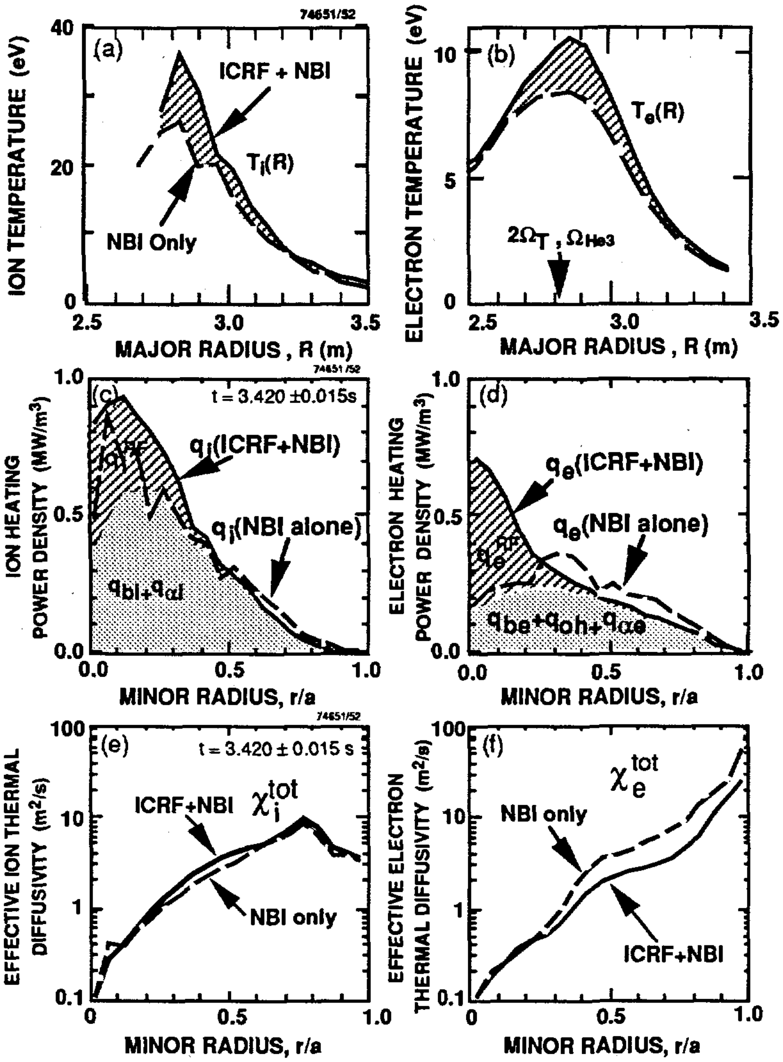

Fig. 3. Comparison of (a) ion and (b) electron temperature profiles; (c) ion and (d) electron heating power density profiles; and (e) ion and (f) electron total effective thermal diffusivity profiles for two plasmas with 23.5 MW of neutral beam injection (60% in tritium). The plasma indicated by the solid line had 5.5 MW of 43-MHz ICRF heating resonant with the $2\Omega_T$ cyclotron layer on the magnetic axis at R = 2.82 m. Both plasmas had a 2% ^{3}He minority, the fundamental resonance of which is degenerate with the $2\Omega_T$ resonance.

The efficient mode conversion was demonstrated for the first time with plasmas with ^{3}He "minority" ions on TFTR.[2,4] Experiments performed in D-^{4}He plasmas with a high ^{3}He concentration (n_{3He}/n_e = 15 - 30%) have demonstrated efficient mode conversion electron heating on and off axis. With the mode conversion layer located on axis and far away from the cyclotron resonance (Ω_{3He} at $\rho = 0.3$ on the low-field side), highly peaked electron temperature profiles have been observed with central temperatures reaching the 8 to 10 keV range (as measured by Thomson scattering and ECE diagnostics) heated by only 2 to 3 MW of incident rf power. The fraction of the power mode converted and coupled to electrons rises with increasing ^{3}He concentration, from 0.2 at $n_{3He}/n_e < 10\%$ (close to the conventional minority heating regime) to >50% typical (as high as 80%) for n_{3He}/n_e = 15% to 30%. Figure 4 shows the measured major radius of the peak of the electron power deposition profile as a function of the toroidal field for a constant density [$n_e(0) = 4 \times 10^{19}$ m^3] and constant ^{3}He fraction (0.14). The power deposition radius is located within a few centimeters of the two-ion hybrid layer ($n_{//}^2 = S$) which is separated from the cyclotron resonance (Ω_{3He}) and whose distance from the magnetic axis increases with decreasing magnetic field (i.e., more off-axis).

Figure 5 shows the rf heating profile measured by the modulation technique for a discharge in which the mode conversion surface was located at r/a ≈ 0.2 on the high-field side of the magnetic axis. This plasma had a central electron density of ~4 × 10^{19} m^{-3}, a central electron temperature of 5 keV, and profiles that were approximately

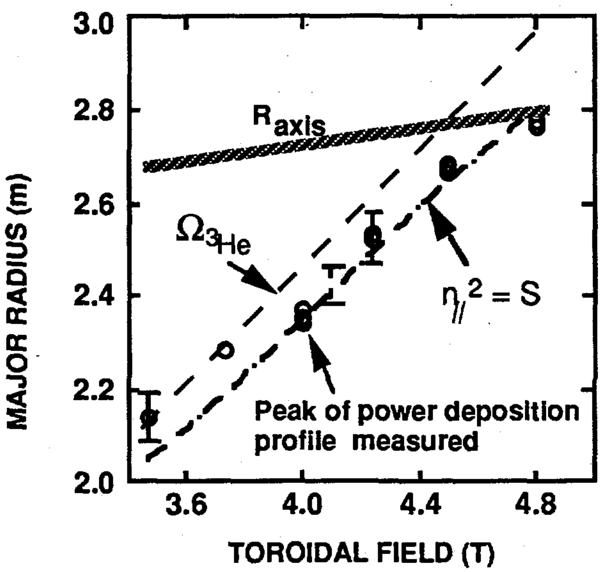

Fig. 4. Dependence of the major radius (open circles) of the peak of electron absorbed power determined by power modulation techniques as a function of toroidal magnetic field intensity for constant ^{3}He fraction ($n_{^3He}/n_e = 0.14$) and constant density ($n_e(0) = 4 \times 10^{19}$ m^{-3}). The chained line denotes the calculated position of the mode conversion layer, the dashed line the ^{3}He cyclotron layer, and the shaded thick line the approximate position of the magnetic axis in the discharges shown.

parabolic. CHERS measurements from similar discharges imply a central ion temperature of about 4 keV for this plasma. The measured net power coupled to the electrons is observed to be about 70% of the total rf input power, with only a small amount, ~5%, deposited near the magnetic axis via direct electron Landau damping. The measured power absorption by electrons is compared with model calculations in Figure 5. The analyses obtained with the 1-D kinetic wave codes, FELICE[15] and GLOSI[16], show good agreement with the observed deposition radius, although the predicted profiles are substantially narrower than the experimental profiles, probably due to neglecting poloidal variations in the equilibrium and wave focusing. The GLOSI code result is based on an average of multiple $k_{\parallel}$ calculations with a power weighting function of a Gaussian form, $\exp[-((k_{\parallel} - 9)/2)^2]$ to average out the standing wave pattern in the rf field within the triplet.[3] The FELICE code result is based on multiple (40) toroidal and (5) poloidal modes representing the launched antenna spectrum. The electron absorption fraction predicted by FELICE is 85% and 82% by GLOSI.

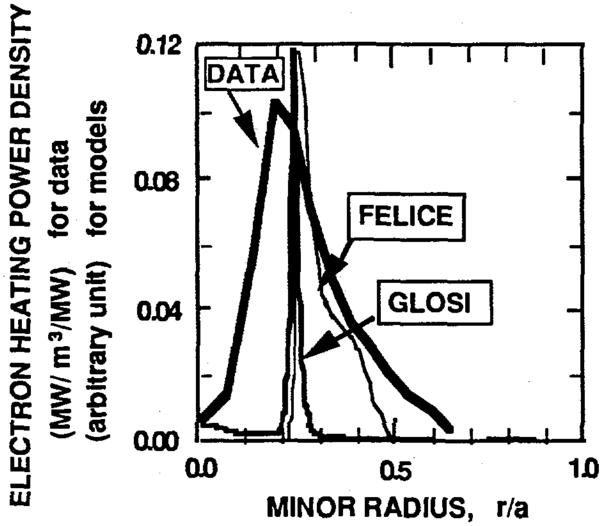

Fig. 5. The ICRF power deposition profile of the electrons, derived from power modulation techniques, is compared with model predictions of 1-D codes (FELICE and GLOSI) for off-axis mode conversion on the high field side of the magnetic axis.

Crucial to the application of this technique to current drive is the question of directivity of the mode converted IBW. Initial tests were performed in D-^{4}He-^{3}He plasmas with 2.2 MW of ICRF power launched with ± 90° antenna phasing to provide a directional fast wave with $k_{//} \sim 6$ m^{-1} at the antenna. The mode conversion layer was placed near the magnetic axis for the rf frequency of 43 MHz, $B_T = 4.5$T, $\eta_{^3He} \sim 12\%$, and $n_e(0) = 4 \times 10^{19}$ m^{-3}. The observed electron temperature response was distinctly different for +90° and -90° launch. However, the measured surface voltage was essentially the same for these two cases in spite of expectation of rf-driven currents in the range of 100 to 200 kA. Subsequent TRANSP modeling indicated that centrally rf-driven currents of this magnitude are insufficient to modify the surface voltage on the time scale of the rf pulse (0.8 s). Nevertheless, the heating results indicate that the mode converted IBW is directional. Future CD experiments will be performed with longer rf pulses and more direct measurements of the current profile by the motional Stark effect.

Off-axis mode conversion electron heating was used to study the inward thermal pinch, transport phenomena that is currently under active discussion for the toroidal confinement research. A strong inward thermal pinch was observed with off-axis electron cyclotron heated (ECH)-plasmas in DIII-D.[17] On the other hand, no strong inward pinch was observed in Wendelstein VII-Advanced Stellarator (WVII-AS) ECH off-axis experiments[18], raising the possibility that the strong inward pinch and related the profile resilience are specific to tokamaks. Also during the Toki conference, Dr. Kadomtsev [19] offered an explanation for the phenomena via a trapped particle effect of ECH electrons primarily heated in the perpendicular direction. Since the present heating tends to increase the parallel energy component, it is interesting to see how transport behavior with this heating contrasts with that of ECH. Analysis of the electron temperature response at turn-off showed sharp off-axis heating at $\rho = 0.24$ with Δ_ρ(FWHM) of 0.17 at $B_T = 4.2$ T. Radial variations of the Fourier-transformed electron temperature $(\tilde{T}_e)$ response (Figure 6) shows that heat pulses propagate simultaneously inward and outward with similar velocities $(d\phi/dr)$. Furthermore, the thermal diffusivity estimated from the slope of the $\tilde{T}_e$ amplitude (on a semi-logarithmic scale) and that from the phase are nearly equal, implying that there is no substantial (inward) thermal pinch.[20] These studies will be extended to rf powers substantially larger than the ohmic power in the future.

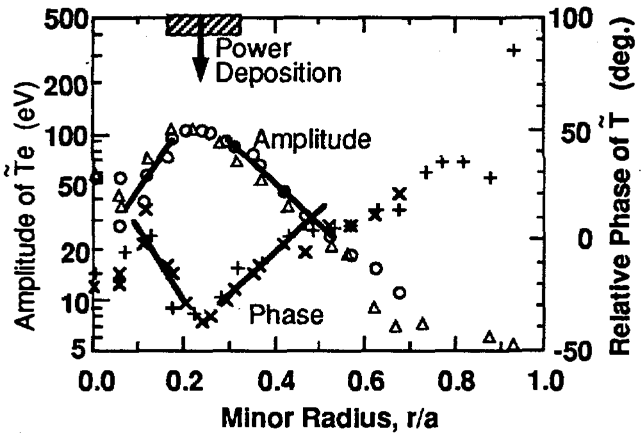

Fig. 6. Dependence of the heat pulse phase (linear scale) and amplitude (semi-logarithmic scale) vs. normalized minor radius for off-axis power deposition with mode conversion electron heating in an rf-heated ^{3}He-^{4}He plasma. Data are included from two separated ECE diagnostics.

IV. CONCLUSIONS

The first experiments utilizing high-power ICRF to heat D-T plasmas in reactor-relevant regimes have been completed on TFTR. Results from these experiments have demonstrated efficient core, second harmonic tritium heating in D-T supershot plasmas with tritium concentrations ranging from 6%-40%. Significant direct ion heating on the order of 60% of the input rf power has been observed. The measured deposition profiles are in good agreement with 2-D code analyses of these discharges. Based on these observations and models, efficient core $2\Omega_T$ ICRF heating is anticipated in the higher density plasmas projected for ITER. Energy confinement in an rf-heated supershot is at least similar to that without rf, and possibly better in the electron channel.

Efficient, localized electron heating via mode conversion of incident fast waves to IBWs at the two-ion hybrid layer has been documented with a relatively large concentration of minority ^{3}He ions in D-^{4}He and D-T-^{4}He plasmas. By varying the relative concentration of the ion species as well as the toroidal magnetic field for a fixed rf frequency of 43 MHz, the location of the hybrid layer was scanned between the magnetic axis out to about 40% of the minor radius on the high-field side of the discharge. The rf power modulation studies indicate that 50% or more of the input ICRF power was damped on electrons near the mode conversion layer, consistent with theoretical predictions. The direction of propagation of the mode converted IBW was shown to depend on the propagation of the launched waves, as controlled by the antenna phasing. Analysis of heat wave propagation with off-axis heating shows no strong inward pinch in ohmically-heated target plasmas in TFTR.

Future TFTR experiments utilizing ICRF heating will focus on both supershot and L-mode regimes (ITER relevant) and increasing the pressure in D-T supershots. We will also explore Ω_D and mode conversion heating at higher B_T and continue to develop current profile control via mode conversion CD.

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