29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. ***26B****, P-1.058 (2002)*

Phase Contrast Imaging of Mode-Converted Ion Cyclotron Waves in the Alcator C-Mod tokamak

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Introduction

The Alcator C-Mod tokamak uses electromagnetic waves in the ion cyclotron range of frequencies (ICRF) for auxiliary plasma heating. When there is more than one ion species present in the plasma, an ion-ion hybrid resonance layer can exist. If the long wavelength fast wave (FW) launched from the low-field side encounters this resonance, it can mode-convert into a short wavelength wave which can subsequently heat electrons. This type of situation has been studied experimentally [1–3] and theoretically [4–7]. The short wavelength wave excited in the hot core of the plasma in this manner has usually been identified as an ion Bernstein wave (IBW). However, very recently it was realized that the dominant mode conversion process for the FW in Alcator C-Mod (and in any hot tokamak with significant plasma current) is into an electromagnetic ion cyclotron wave (ICW) as predicted by Perkins in 1977 [8]. This wave propagates to the low-field side along a magnetic flux surface, and damps by electron Landau damping before reaching the cyclotron resonance layer.

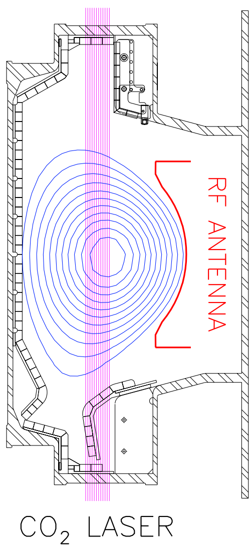

Figure 1: The Alcator C-Mod tokamak, with PCI laser path shown.

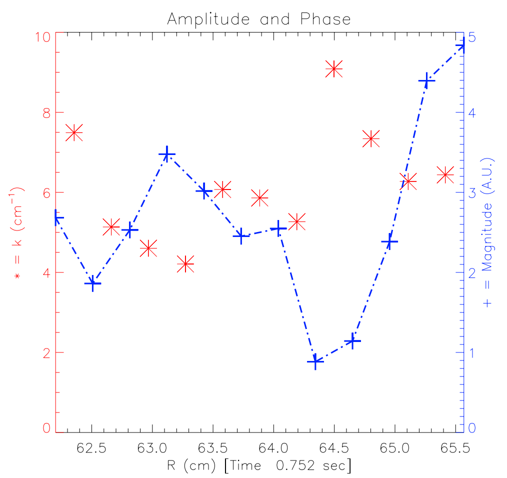

Figure 2: Amplitude (+) and Phase (*) (represented by an effective k number) for the Fourier-transformed PCI signal.

Experimental Observations

Phase Contrast Imaging (PCI) [9], combined with an optical heterodyne technique [10], has been used to detect electron density fluctuations at the launched RF frequency of 80 MHz. Figure 1 is a cross-section of the Alcator C-Mod tokamak (major radius 67 cm, minor radius

22 cm) showing the path of the PCI laser through the plasma, and the position of the RF antenna. Line integrated signal levels as small as 1×10^{15} m^{-2} (with a steady-state electron density of $2 - 4 \times 10^{20}$ m^{-3}) can be distinguished from the background noise. Figure 2 shows measurements near the core of the plasma during a discharge with a mode conversion layer present in the plasma. The plasma consisted of H, D and ^{3}He in a background toroidal field of 5.8 Tesla and plasma current of 800 kA. The plasma density was 2×10^{20} m^{-3} and the temperature was 1.2 keV. The spatial structure shows peaks and troughs in amplitude across the PCI laser beam, with 1-2 cm separating the peaks. From the phase of adjacent PCI channels, and assuming a plane wave with a single wavevector passing from one channel to the next, an effective wavenumber k can also be deduced. This is shown in Fig. 2 by the asterisks (*). Note the major radial wavenumbers are all positive, indicating that the phase velocity of this wave is towards the antenna. The magnitude of the wavenumbers thus measured are between those of the FW and typically expected IBW wavenumbers. This is consistent with ICW wavenumbers [8].

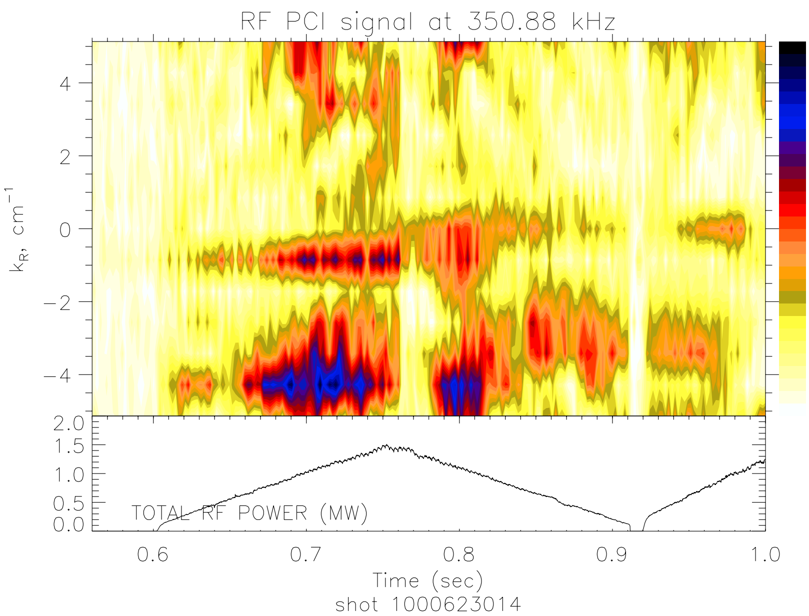

Figure 3: Simultaneous observation of FW and ICW in the k spectrum.

Figure 3 shows the wavenumber spectrum and RF power as a function of time for a plasma discharge where both the FW and mode-converted ICW were observed in the same view. The FW appears at $k \simeq -1$ cm^{-1}. The ICW appears as the larger spread of wavenumbers around -4 cm^{-1}. For this measurement, the laser beam was expanded to a greater width than that used for Fig. 2, thus the large positive wavenumbers usually observed are aliased and appear mostly as negative wavenumbers of approximately -4 cm^{-1}. After detailed analysis of the ion species concentrations [11], it was determined that in all these experiments, the ion-ion hybrid layer was several centimeters to the high-field side of the PCI viewing range. Thus the PCI is detecting the FW travelling away from the antenna (negative k number), and also the ICW travelling back towards the antenna and away from the mode-conversion region (positive k number). Thus the ICW phase and group velocities are in the same direction. This is contrary to what would be expected for an IBW, which is a backward wave. An IBW travelling away from the mode-conversion region towards the antenna would have a negative phase velocity (negative k number).

Numerical Modelling of the Electromagnetic Ion Cyclotron Wave

The full-wave ICRF code TORIC [5] was used to simulate the expected electron density fluctuation pattern in the plasma. The parallel electric field component $E_{||}$ was found to contribute most to the electron density fluctuation, and the ICW was particularly strong in $E_{||}$. An IBW did appear in some simulations to the high-field side of the mode conversion layer, but with much smaller amplitude than the ICW.

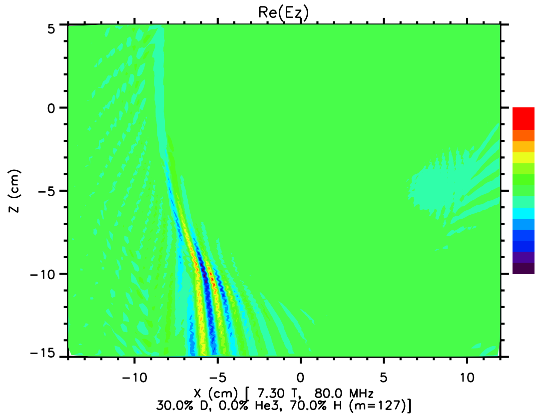

Figure 4: $E_{||}$ for $I_p = 400$ kA

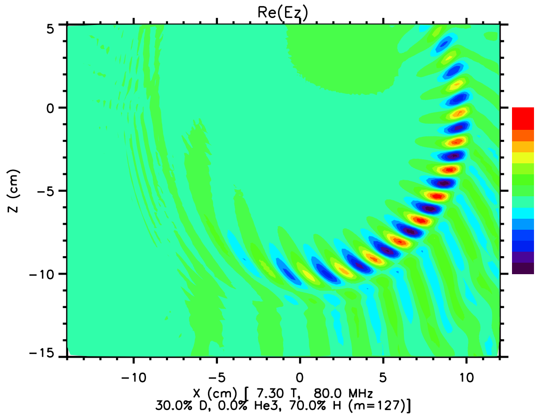

Figure 5: $E_{||}$ for $I_p = 1600$ kA

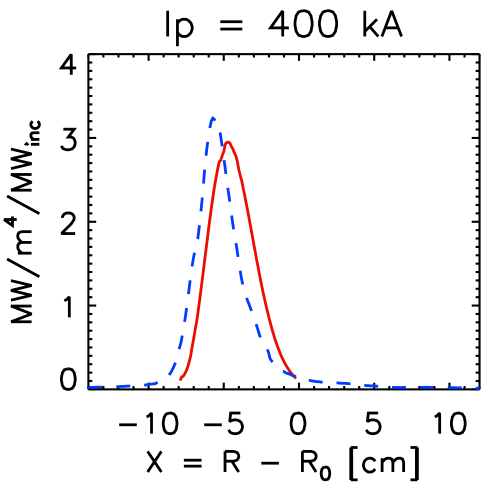

Figure 6: Power deposition profile for I_p 400 kA (MW/m^3 per m per MW incident).

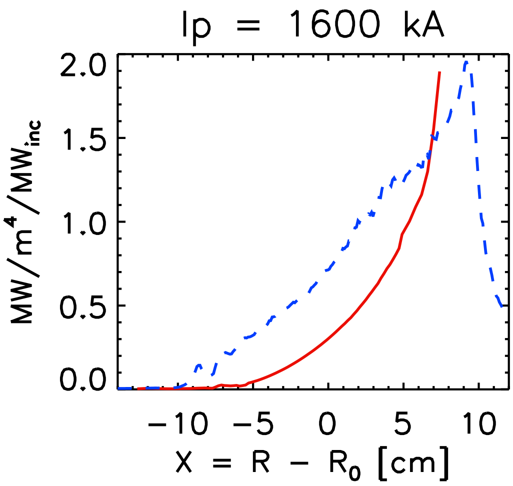

Figure 7: Power deposition profile for I_p 1600 kA (MW/m^3 per m per MW incident).

Figures 4 and 5 are the results of TORIC simulations of D-H plasmas (30% deuterium, 70%

hydrogen, 7.3 Tesla, 2.4×10^{20} m^{-3}, 1.5 keV) where the electromagnetic ICW also appears to the low-field side of the ion-ion hybrid layer. The real part of the parallel electric field near the center of the plasma is shown for toroidal mode number 10 (TORIC solves for the RF electric field by decomposing into toroidal and poloidal mode numbers — Figs. 4 and 5 are the results of combining 127 poloidal mode numbers). Note that the ICW propagates much farther at higher current (the amplitude is also larger). Perkins noted that the mode-converted ICW required the presence of a poloidal magnetic field. This has been verified by simulations with very low plasma current, in which there was hardly any ICW excited. Figures 6 and 7 show the power deposition profiles for the ICW. The dashed lines are those predicted from TORIC (power damped to electrons), and the solid lines are from integrating the imaginary part of the perpendicular wavenumber as obtained from solving the full electromagnetic hot plasma dispersion relation for fixed frequency, but with complex $k_\perp$ and $k_\parallel$, the two being related by the (approximate) relation

$$k_\parallel = \frac{n_\phi}{R}\frac{B_\phi}{B} + k_\perp \frac{B_\theta}{B}, \qquad (1)$$

where B_ϕ is the toroidal and B_θ the poloidal magnetic field components (B is the total magnetic field), R is the major radius, and n_ϕ is the toroidal mode number.

Conclusions

The mode conversion of fast waves into electromagnetic ion cyclotron waves in multiple ion species plasmas predicted by Perkins 25 years ago has been observed and identified for the first time by the PCI diagnostic in the Alcator C-Mod tokamak. The strong magnetic shear off the midplane in tokamak geometry is responsible for this mode conversion, instead of conversion into the IBW. The full-wave ICRF code TORIC has been used to study these waves and the predicted electron density fluctuation pattern, and compares favorably with the PCI measurements. This FW to ICW mode conversion process should also play a role in future D-T plasmas with near equal mixtures of deuterium and tritium, if ICRF waves are used as an auxiliary heating source. These results indicate that localized electron heating along a flux surface should be possible, which could lead to current drive and improved confinement.

Work Supported by D.o.E. Coop. Agreement DE-FC02-99ER54512.

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