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Initial Results from an Upgraded ICRF System on Alcator C-Mod

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Introduction

In Alcator C-Mod (a compact, high field tokamak [1], a=0.21 m, R_0=0.67 m, κ<1.8), ion cyclotron range frequencies (ICRF) power is the only auxiliary heating source. In addition to providing auxiliary heating power, we have sought to develop capabilities for pressure profile control, current drive, and flow drive. This effort has been facilitated by an upgraded ICRF system, an improved ICRF full-wave code TORIC, and the development of a core plasma RF wave diagnostic.

Recently we have added 4 MW, 40-80 MHz tunable RF power to the original ICRF system (4 MW, 80 MHz RF system), for a total power of 8 MW. In the experiments discussed here, the source frequencies are 80/80.5 MHz and 78 MHz for the fixed and tunable sources, respectively, and the 4-strap antenna (J-port) is configured for [0,π,0,π] heating phase. This configuration produces a symmetric spectrum with peaks at n=±13 as compared to n=±10 of the original antennas (where n is the toroidal mode number). Using a standard D(H) (minority species in parenthesis) minority heating scenario for B_T=4.1-6 T, we present initial observations from: (a) internal transport barriers (ITB) formed with off-axis ICRF heating experiments; (b) initial results from a new plasma core RF wave diagnostic; (c) results from improved TORIC simulations; (d) and progress on the 4-strap performance.

Internal Transport Barrier Experiments

Recently, an internal transport barrier (ITB) mode has been identified in which the core plasma density is observed to become highly peaked ($n_e(0)$ ~5-6 x 10^{20} m^{-3}) relative to the region outside the barrier where n_e ~2 x 10^{20} m^{-3}. These barriers were produced in H-mode plasmas by applying 2.0 - 2.8 MW of off-axis ICRF heating power. A typical 4.5 T, 0.8 kA plasma discharge is shown in Fig. 1. The ICRF power was absorbed at the H cyclotron resonance layer located 9.4 cm to the tokamak high field side. Interestingly, the ITB was not observed in similar plasmas for B_T = 4.6 -5.75 T, where the H resonance layer is located closer to the plasma center or on the low-field side. The density profile before and after the barrier formation is plotted in Fig. 2. As the core density rises, the toroidal plasma rotation (co-current direction) decreased and finally reversed direction. In H-mode discharges where the ITB did not form, the rotation remained co-current.[2] The central Z_{eff} is also found to increase to ~3 during the density rise, as a consequence of impurity accumulation inside the

ITB. Many of these ITB phases of the discharge end after the sawteeth have stabilized and the temperature profile has become hollow.

Phase Contrast Imaging Results

In these experiments, the phase contrast imaging (PCI) diagnostic was used to measure electron density fluctuations associated with the RF wave propagation for the first time.[3] To measure these high-frequency density fluctuations, the intensity of the laser beam is modulated at a frequency within a few hundred kilohertz of the RF source (80 MHz) and the signal is then detected at the beat frequency. This is done by combining two beams modulated at 40.1MHz each. There are 12 vertical PCI chord views covering from 0.59-0.70 m (the magnetic axis is typically at 0.67 m) with 0.2-10 cm resolution at the location of the E-port antenna. For these experiments, the resolution was 0.6 cm. Before each discharge, a relative calibration is performed via sound wave measurements. Shown in Fig. 3 is a typical PCI signal observed with peak density profile due to ITB formation at 4.5 T (see Figs. 1,2). The maximum signal is ~5 times larger than the background noise. In addition, one leg of the beam modulation circuitry was blocked for an identical shot to verify that there was no measured signal above background noise level at the beat frequency. The measured radial wavenumber, $k_r \sim 2.0$ cm^{-1} is in excellent agreement with predictions of both the cold plasma dispersion relation and TORIC.[4] In addition both positive and negative wave number components are detected, suggesting a standing wave pattern.

TORIC Simulations

Another important potential ICRF application is to use localized RF driven flows to induce flow shears to trigger and control transport barrier formation. Recently, direct launch ion Bernstein waves have been reported to drive poloidal flow.[5] In the near future we will explore the possibility of using mode-converted IBW for producing flow drive. In support of these experiments we have performed numerical simulations of mode converted ion Bernstein waves (IBW) using the full-wave, poloidal mode code TORIC. Up to 161 modes ($-80 \leq m \leq 80$) were retained in these simulations in order to resolve mode converted waves with $k_\perp \rho_i \sim 1$. These computations are seminal in that for the first time mode converted IBW at $k_\perp \rho_i \sim 1$ have been accurately resolved in toroidal geometry using a full-wave approach. Such a model calculation is shown in Fig. 4 using H(^{3}He) with $n_H / n_e = 0.50$, $n_{3He} / n_e = 0.24$, and $n_D / n_e = 0.02$. Other parameters used in Fig.4 were $B_0 = 5.8$ T, $n_e(0) = 2.0 \times 10^{20}$ m^{-3}, $T_e(0) = 3.0$ keV, $T_i(0) = 2.8$ keV, $f = 80$ MHz, and n = 10. The total electron absorption in Fig.4 (fast wave plus IBW) is 69% with the remaining power absorbed via fundamental H cyclotron resonance damping. The predicted profile of electron damping is quite narrow with a full width at half-maximum of $\Delta(r/a) \sim 0.10$. It is important to note that if fewer poloidal modes are used (< 50), the Fourier reconstruction of the wave electric field is not accurate on flux surfaces which pass through both the mode conversion and H cyclotron resonance layers, leading to spurious fundamental cyclotron damping.[6]

J-port Antenna Performance

In the 1999 campaign, a new 4-strap antenna was commissioned at 78 MHz allowing for a direct antenna performance comparison with the original 2-strap D and E-port antennas. Results indicated that the J-port antenna had an impurity generation problem. In discharges with ~1 MW ohmic input power, the radiated power associated with 1 MW of ICRF power from the J-port antenna was ~ 1.7 MW compared to 0.7 MW from the D and E-port antennas. Furthermore, the J-port antenna had dramatic impurity injections when the injected power exceeded 1.2 MW total from all four straps, or 0.6 MW per antenna strap pair. The antenna also performed poorly at high target density plasmas. In a post-campaign inspection, significant arc damage to the top and bottom protection tiles and the ceramic insulators was found. This suggested that significant RF voltages were present during operation.

In the current campaign, J-port antenna modifications were made to address these issues. A low impedance short to prevent voltage buildup between the protection tiles was implemented. The ceramic washer assemblies, important for the faraday screen design, had an additional stainless steel shield installed to protect the washer assemblies from damage.

In initial experiments in the present campaign, we have successfully coupled 2.8 MW into the plasma without an excessive negative impact on the discharge. This suggests that the impurity problem has been significantly reduced. Measurement of Mo core density is approximately an order of magnitude less than the previous campaign and the radiated power is also reduced. Although reduced, both the Mo core density and radiated power are still higher than that observed from D-port antenna. In addition, regular impurity injections for power levels >1.2 MW have been eliminated. The J-port operational density limit has not been fully explored this campaign thus far, but J-port has operated in discharges with 30% higher target densities than the previous campaign. The heating efficiency however appears to be ~50% of the other antennas. Its loading appears nearly independent of the plasma position and power between 0.2-2 MW. This suggests a parasitic load is absorbing a significant fraction of the delivered power.

Acknowledgements

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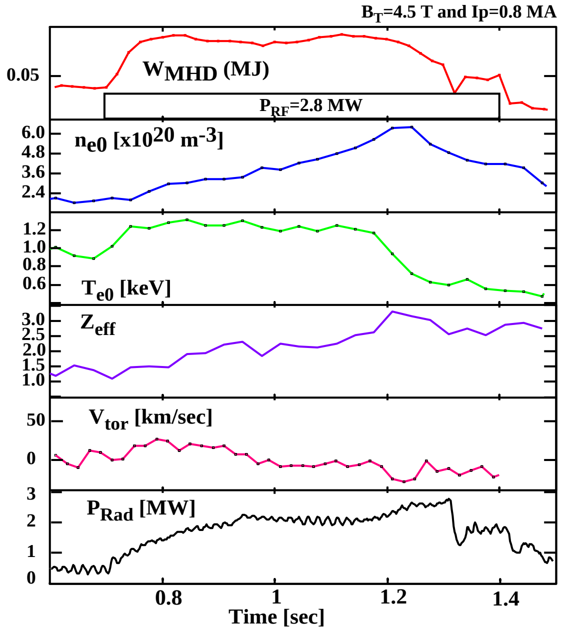

Figure 1: Time history of internal transport barrier discharge.

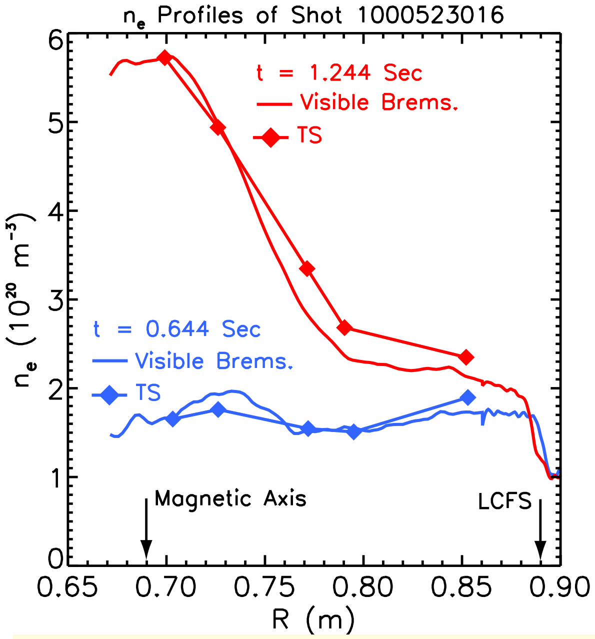

Figure 2: Comparison of peaked density profile to H-mode density profile.

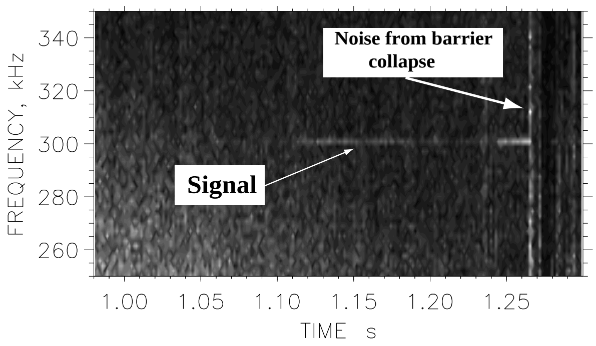

Figure 3: RF signal detected by single PCI channel for peaked density discharge.

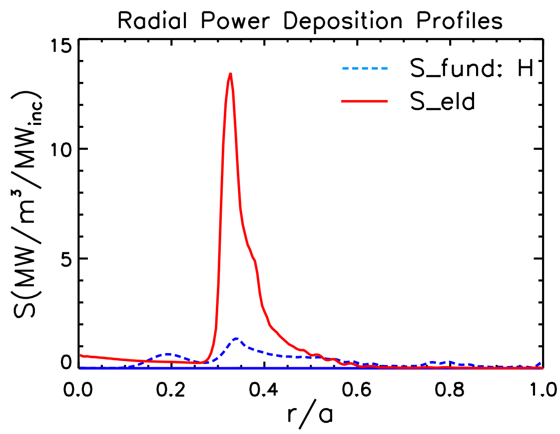

Figure 4: TORIC prediction for mode conversion electron heating in H(^{3}He).