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Recent ICRF Results in Alcator C-Mod

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One of the main goals of the ICRF research program on C-Mod is to provide first principle understanding of ICRF physics such that ICRF can be reliably utilized as an actuator to optimize overall plasma performance with minimum negative impact on the plasma. Development of an RF flow drive actuator has been long sought because it potentially offers an external tool for potentially manipulating transport via flow shear and stabilizing macro- and micro-instabilities. Here we report the first demonstration of efficient, 15-30 km/s/MW, RF toroidal flow drive by mode converted waves (mode conversion flow drive - MCFD). We also emphasize validating the physics and computational models through comparison of experiments and advanced simulations over a wide range of regimes including direct fast wave absorption regimes. For the first time in C-Mod, we have observed evidence of direct fast wave (FW) electron heating despite low single pass absorption. We also investigate and develop solutions to technological and physics issues associated with the antenna/coupler and operations to enable successful RF operation. One challenge for ICRF utilization is mitigation and control of impurities associated with ICRF operation attributed to RF sheaths. We have measured the sheath potential in the presence of ICRF and identified their dependence on linkage to antenna, confinement mode, boronization, and insulating limiters.

Mode Conversion Flow Drive Experiments

Plasma rotation or flow has long been identified as an effective means of improving plasma stability and confinement that can result in significant improvement of the economic attractiveness of the tokamak concept.[1,2] Identification of an RF scenario that results in significant and efficient rotation has been sought and earlier efforts have focused on ion Bernstein wave.[3,4,5] Difficulty coupling significant power via IBWs spurred investigation into utilizing a fast wave mode conversion scenario (fast wave converts to IBW and ion cyclotron waves) and poloidal flow drive has been reported.[6] Simulations of mode conversion flow drive suggested the importance of ion damping and indicated that the resulting flow would be sheared poloidal flow.[7]

In C-Mod, the experimental focus has been on utilizing mode conversion in deuterium plasmas with a ^{3}He minority. In this scenario, a relatively long wavelength fast wave is launched from the low field side, largely passes through with minimum damping at the ^{3}He resonance, and mode converts to two short wavelength modes, IBW and ion cyclotron wave (ICW).[8,9,10] For these experiments, the plasma current was 0.8 MA, line averaged density was 1.2-1.5 x10^{20} m^{-3}, and the magnetic field ~5.1T. For minority heating, the H minority resonance at 80 MHz is ~0.65 m, on the high field side of the magnetic axis (~0.68 m) and the 50 MHz ^{3}He resonance is ~0.71 m. The mode conversion layer is located ~0.63 m based on estimated ^{3}He concentration and power deposition measurements. A comparison of discharge parameters for minority H and mode conversion absorption is shown in Figure 1. The central rotation is significantly higher for the mode conversion case than minority H. The rotation observed in the minority H heated discharge is consistent with the intrinsic spontaneous rotation scaling with stored energy that has been observed in the past, independent of heating method, ICRF or ohmic.[11] Furthermore the increase in toroidal rotation mode conversion absorption scales with ICRF power, 15-30 km/s/MW, as shown in Figure 2 and in excess of the spontaneous rotation with minority heating, or with the normal increase in plasma stored energy, as shown in Figure 3. We found that the toroidal flow drive was largest for counter-current drive phasing of the antenna and weakest for co-current drive phasing. For current drive, we seek scenarios where the majority of the mode converted power is damped on electrons and we have yet to observe significant flow drive when electron absorption is dominant. In discharges with strong toroidal rotation, the measured power deposited on electrons was ~15% suggesting the remaining power was being absorbed on ions. Initial full-wave simulations show the mode converted waves propagate to the ^{3}He cyclotron resonance layer.

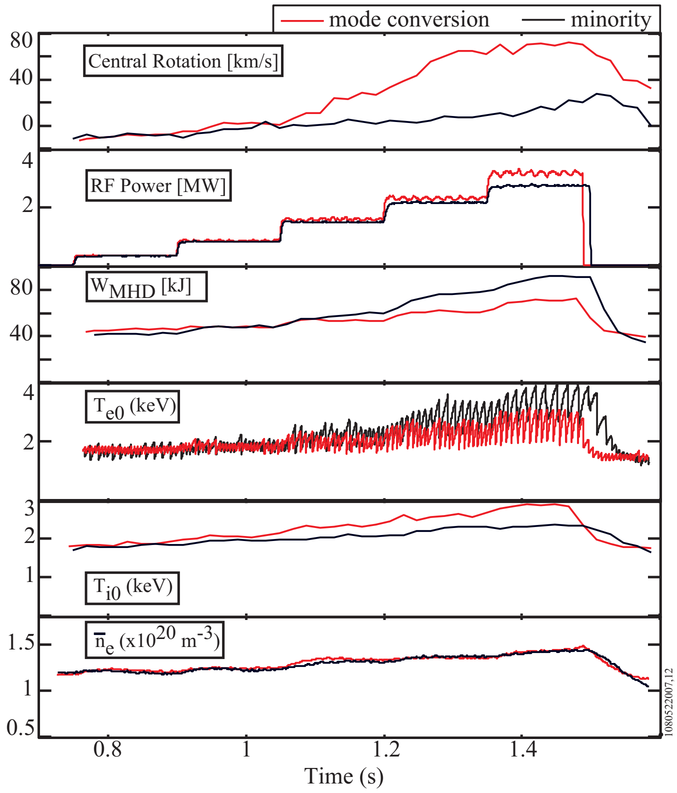

Figure 1: Comparison of central rotation for mode conversion and minority H absorption scenarios. The mode conversion discharge has significantly higher central toroidal rotation.

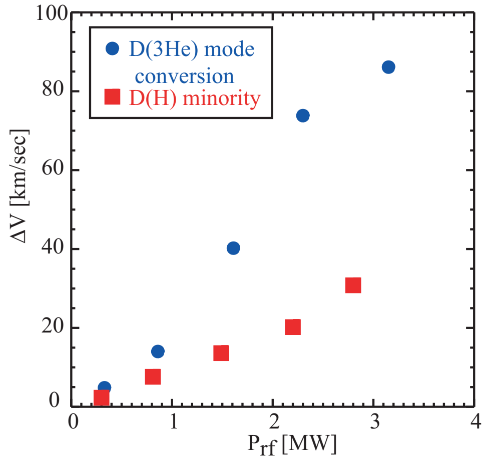

Figure 2: Increase in central rotation for mode conversion and minority absorption scenarios where mode conversion case scales more strongly than minority case.

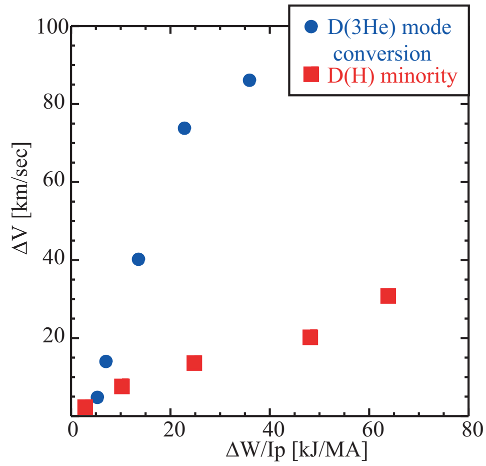

Figure 3: Increase in central rotation for mode conversion and minority absorption scenarios where the minority is following the typical spontaneous intrinsic rotation scaling with stored energy.

Direct Fast Wave Absorption Experiments

In C-Mod, direct fast wave (FW) absorption on electrons is typically weak. The absorption is nonlinearly dependent on electron temperature and electron beta.[12] The goal of these experiments was to evaluate FW electron heating for future use in experiments to validate full wave simulations, particularly TORIC, and use for central current drive for optimizing current profile in advanced tokamak operation. In the discharges investigated, the estimated single pass absorption was 1-2% in the target discharge for heating phase, toroidal mode number, n_ϕ,~10, and <1% for current drive phase, n_ϕ =7. These L-mode discharges were 1 MA, USN discharges at 5.2 T. The RF frequency was 50 MHz; thus no fundamental cyclotron resonances were in the plasma cross-section but the fundamental deuterium resonance was at r/a~0.5 to the high field side of the magnetic axis.

As shown in Figure 4, the target discharge was pre-heated with H minority heating at 80 MHz to raise the target plasma temperature >4 keV at the top of the sawteeth and the FW heating at 50 MHz is applied at 0.8 s. For the discharge utilizing heating phase (red trace in Figure 4), the plasma stored energy, central temperature, and neutrons increase significantly. The radiated power increases significantly during the FW heating phase. Using ITER-89P confinement scaling, the effective absorbed power fraction of the FW heating is >0.5. To discriminate the importance of FW versus fundamental D absorption, we utilized similar target discharge and lowered the FW absorption, to <1%, by changing the antenna phasing to current drive and the expected fundamental harmonic absorption would be unchanged. In this case (blue trace in Figure 4), no evidence of plasma heating is observed suggesting FW absorption dominates in these discharges when the single pass absorption is 1-2%.

Characterization of RF sheaths

Using emissive probes, plasma potential measurements confirm the presence of an enhanced sheath with ICRF when the probe is magnetically linked to the active antenna. Plasma potentials were typically 100-200 V for ~1.25 MW injected ICRF power. In L-mode, the plasma potential scales with the square root of RF power as expected, see Figure 5. However, an RF sheath was unexpectedly present with insulating limiters and the scaling in H-mode deviated from expected scaling. Furthermore, the increase in plasma potential in H-mode compared to L-mode was larger than expected. These dependencies suggest that other scrape-off layer and plasma-surface characteristics are influencing the RF sheaths.

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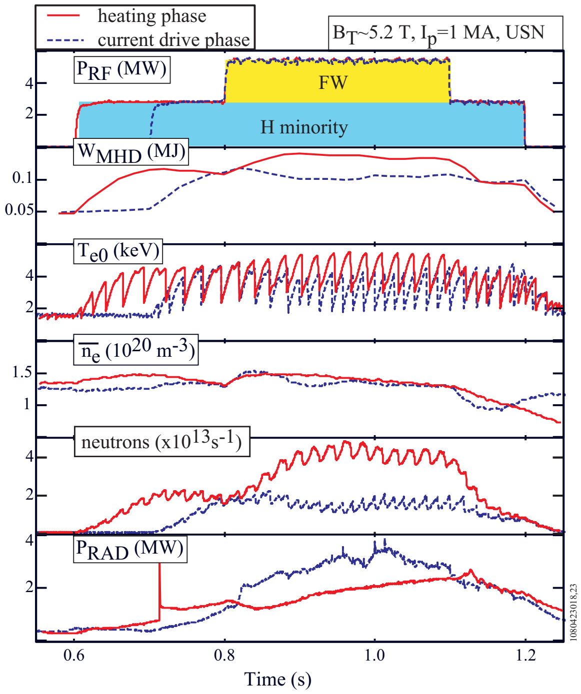

Figure 4: Comparison of two FW electron absorption cases. In red, a discharge utilizing heating phase and a discharge utilizing current drive phase is shown in blue.

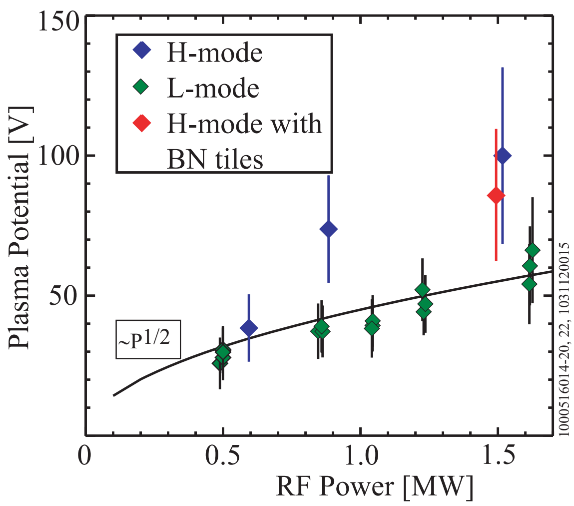

Figure 5: Plasma potential measured on flux tube magnetically linked to the antenna in L-mode, H-mode and for an antenna armored with insulating limiters.