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ICRF Mode Conversion Flow Drive on Alcator C-Mod

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Flow drive via externally launched electromagnetic waves has been widely identified as a high leverage tool that, if successful, can produce great benefits for ITER and reactors. For the first time in tokamak plasmas, we have demonstrated plasma flow drive, in both toroidal (V_ϕ) and poloidal (V_θ) directions, by ion cyclotron range of frequency (ICRF) mode conversion heating on the Alcator C-Mod tokamak [1, 2].

I. Rotation in ICRF mode conversion and minority heating plasmas

On Alcator C-Mod, the rotation in ICRF minority heated (MH) plasmas has been shown empirically to scale with $\Delta W_p/I_p$, similar to Ohmic heated plasmas, thus it is intrinsic plasma rotation [3, 4]. To identify externally driven flow by mode conversion (MC) heating, we compare the rotation (both toroidal and poloidal) in MC heated plasmas and MH plasmas. In this experiment, MH plasmas are heated by 80 MHz ICRF power with H as the minority in majority D plasmas. For the MC plasmas, we use 50 MHz ICRF power, and at modest ^{3}He levels (n_{3He}/n_e ~ 8-12%). In such a setup, the H cyclotron resonance in MH plasmas is at the same location as the MC surface in MC plasmas. All other parameters are similar, $\bar{n}_e$ ~ 1.3×10^{20} m^{-3}, B_{t0} ~ 5.1 T, and I_p = 800 kA. The plasmas are in up-single-null configuration to avoid entering H-mode and the associated strong intrinsic rotation. In Fig. 1, V_ϕ, T_e, n_e and P_{rf} traces of an MC plasma and an MH plasma are compared. Strong (up to 90 km/s) toroidal rotation in the co-current direction has been observed by high-resolution x-ray spectroscopy in the MC plasma, but the rotation in the MH plasma changed much less (< 30 km/s), consistent with the small ΔW_p in L-mode. In Fig. 2, the change of central V_ϕ in a number of MC plasmas and MH plasmas in this experiment is plotted. ΔV_ϕ in MC plasmas is generally at least a factor of 2 higher than the empirically determined intrinsic plasma rotation scaling (Fig. 2), and scales with the applied rf power (≤ 30 km/s per MW). The rotation rises near the core first and the profile is broadly peaked. Spatially (0.3 ≤ r/a ≤ 0.6) localized poloidal rotation V_θ in the ion diamagnetic drift direction (~2 km/s at 3 MW) is also observed in MC plasmas, and it similarly increases with rf power, while the poloidal rotation in MH plasmas is smaller than the diagnostic sensitivity (Fig. 3). Changing the toroidal phase of the antenna does not affect the rotation direction, and it only weakly affects the rotation magnitude. The rotation is also sensitive to the relative location of the MC layer vs. magnetic axis, and it is largest when both MC and ^{3}He IC layers are near the axis.

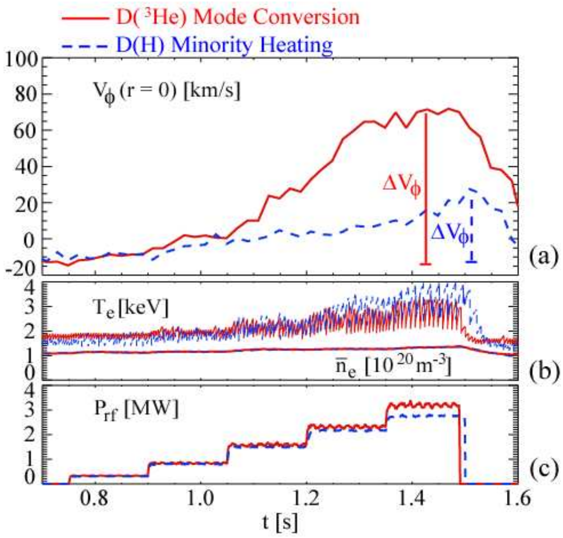

FIG. 1. (a) Central V_ϕ after rf power application at 0.75 sec in an MC plasma (red solid) and an MH plasma (blue dashed); (b) T_e and n_e traces; (c) rf power traces.

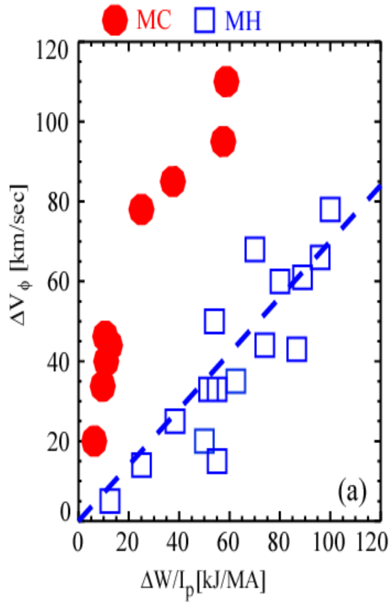

FIG. 2. Rotation scaling vs. empirical intrinsic rotation scaling $\Delta W/I_p$.

II Mode conversion wave detection and 2-dimensional full-wave simulation

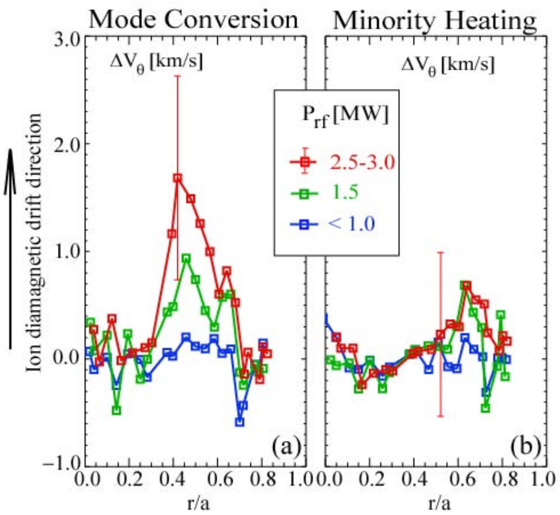

FIG. 3. Poloidal velocity profiles at different RF power levels: (a) MC plasma; (b) MH plasma.

The mode converted ion cyclotron wave (MC ICW) has been detected by a phase contrast imaging system [5]. The spatial location and k_R value (Fig. 4) of the wave agree with those calculated from dispersion relation solution of the wave and previous MC experiments [6]. Using 2-D full wave TORIC code [7], we find that in the scenario of strong flow drive, there is a significant portion of rf power deposition by the MC ICW to the ^{3}He ions via cyclotron resonance (Fig. 5). The power of the MC ICW is deposited on ^{3}He ions in the vicinity of the MC layer, and has a rather broad feature in the region of $0.2 < r/a < 0.6$. The possibility of rf flow drive through the MC ICW to ions is further supported by the similarity of the power deposition and the observed flow drive efficiency vs. the MC layer location [8].

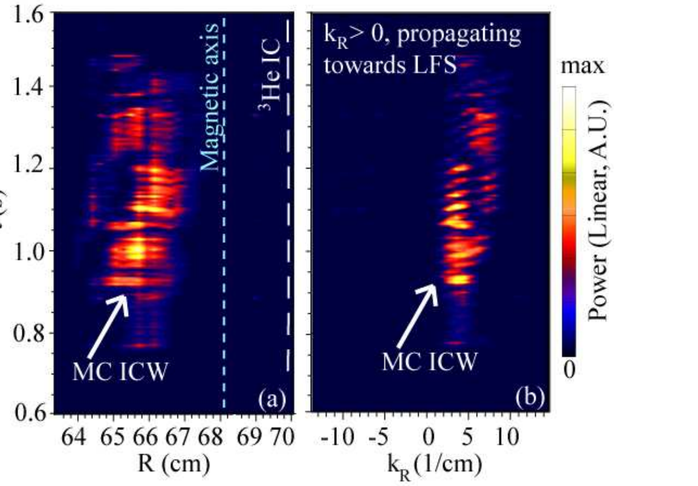

FIG. 4. MC ICW detected by PCI line integrated density fluctuation at the heterodyne RF frequency: (a) vs. R and t. (b) vs. k_R and t.

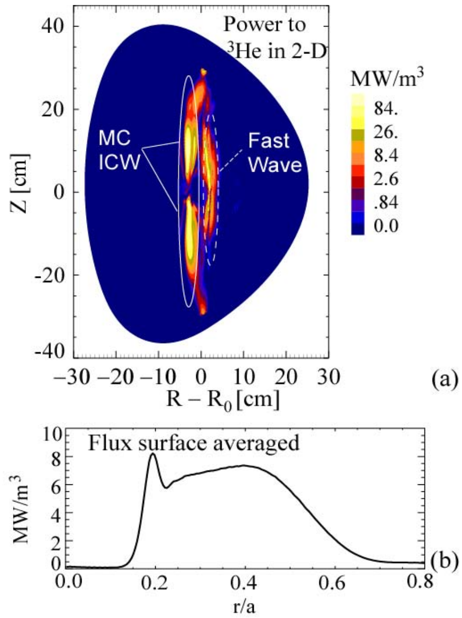

FIG. 5. TORIC simulation on MC ICW power deposition to ^{3}He ions: (a) 2-D plot; (b) flux surface averaged.

III Momentum transport modelling

Assuming a momentum source proportional to the deposition profile shown in Fig. 5, we can reproduce the velocity profile and time evolution by solving the transport equation in cylindrical coordinates including a momentum diffusion coefficient χ_ϕ and a pinch velocity V_{pinch} [8]. In Fig. 6, good agreement is shown between the experimentally measured V_ϕ (same MC discharge as in Fig. 1) and that from transport modelling using $\chi_\phi = 0.1$ m^2/s and $V_{pinch} = -2.0\times(r/a)$ (m/s). Although the modelling cannot unambiguously determine the momentum source because too many unknown parameters are involved, it can estimate the effective driving force to be about 0.03 to 0.05 N per MW rf power to ions through the MC ICW.

IV Discussion

The flow shear observed in our experiment is marginally sufficient for plasma confinement enhancement based on the comparison of the E × B shearing rate and linear gyrokinetic stability analysis [2]. Further experiments will be carried out to explore and develop the MC flow drive as a useful tool for turbulence suppression and ITB creation.

MC flow drive has been numerically studied previously [9]. Further study is required to have detailed comparison with our experimental result, and also understand the generation of the rf force or an equivalent mechanism that transports momentum against the V_ϕ gradient.

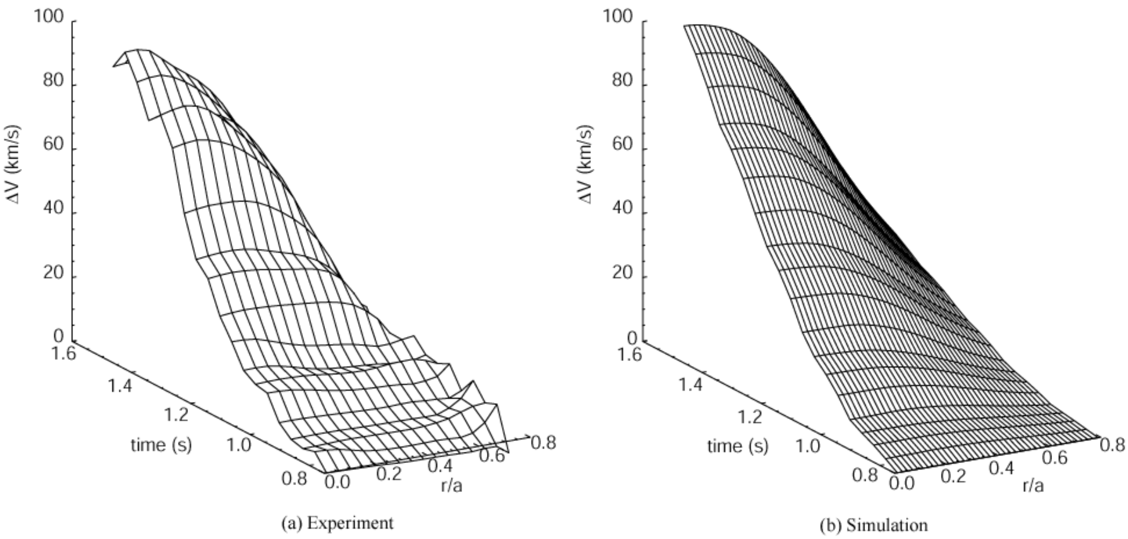

FIG. 6. Surface plots of $\Delta V_\phi = V_\phi - V_\phi (P_{rf} = 0)$ vs. r/a and time for the MC plasma in Fig. 1. (a) Experimental data; (b) Momentum transport modelling.

Acknowledgments

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