ICRF Mode Conversion Flow Drive on Alcator C-Mod and Projections to Other Tokamaks


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Abstract. Plasma flow drive via ICRF mode conversion (MC) has been demonstrated on Alcator C-Mod. The toroidal rotation in these D(He) MC plasmas is typically more than twice above the empirically determined intrinsic rotation scaling in ICRF minority heated plasmas. In L-mode plasmas at 3 MW ICRF power input, up to 90 km/s toroidal rotation and 2 km/s localized (r/a ~ 0.4) poloidal rotation has been observed. The MC ion cyclotron wave (ICW) was detected by a phase contrast imaging system in heterodyne setup. Through TORIC 2-D full wave simulation, and comparison with other experimental evidence, we hypothesize that the interaction between the MC ICW and the He ions may be the mechanism for the observed MC flow drive. TORIC simulation suggests that similar flow drive scenario may be realized on JET D(He) plasmas. The promising scenarios on ITER are the inverted minority scenario (T)D and high field launch for T-D-(He) plasma. In non-radioactive phase, these correspond to (He)-H and He(He) plasmas respectively.

Keywords: ICRF, flow drive, rotation, mode conversion, Alcator C-Mod, JET, ITER

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INTRODUCTION

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. Flow drive using ICRF waves, both fast waves and slow waves, have been studied previously. Fast magnetosonic wave (fast wave, or FW) flow drive has been studied on JET [1], but the effect was weak. Because of the momentum of RF waves is inversely proportional to the wave propagation velocity at the same power, slow waves are preferred for flow drive. Slow waves can be launched directly from the plasma edge for flow drive, for example, Alfven wave in Phaedrus-T tokamak [2], direct-launch ion Bernstein wave (IBW) experiments on PBX-M and TFTR [3, 4]. However, because the interaction between antenna and edge plasma can cause serious impurity problems, direct launch of slow ICRF wave is generally not a practical option for high power experiments. To utilize high power fast wave antenna for flow drive, we can generate slow wave inside the plasma using the mode conversion (MC) scheme. In a multi-species plasma, mode conversion occurs near the so-called ion-ion hybrid surface (MC surface), n_p^2 = S, where n_p is the parallel index of refraction of the wave, and S is a Stix' parameter [5]. When the fraction of the
minority species is small, the MC surface is very close to the ion cyclotron (IC) resonance layer of the minority species, and the fast wave is absorbed completely at the IC resonance. When the fraction is large, two slow waves may appear near the MC surface [6, 7]: the MC IBW appears near the mid-plane propagates towards the high field side and deposits power to electrons through Landau damping; the MC ion cyclotron wave (ICW) propagates towards the low field side and deposits power to electrons through Landau damping and to the minority ions through IC resonance absorption. Previously, preliminary evidence of MC poloidal flow drive has been reported on TFTR [8] and JET [9]. In this paper, we report the first detailed observation of MC flow drive in both toroidal ($V_\phi$) and poloidal ($V_\theta$) directions in tokamaks [10, 11, 12].

![Graph](image)

**FIGURE 1.** (a) Central $V_\phi$ 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.

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

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**EXPERIMENTAL OBSERVATION**

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 thought to be intrinsic plasma rotation [13, 14]. To identify externally driven flow by 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 used 50 MHz ICRF power, and at modest $^3$He fraction ($n_{^3He}/n_e \sim 8-12\%$) in D majority plasmas. All other plasma parameters are similar, line averaged density $n_e \sim 1.3 \times 10^{20} \text{ m}^{-3}$, $B_{\text{tor}} \sim 5.1 \text{ T}$ and $I_p = 800 \text{ kA}$. In such a setup, the H cyclotron resonance in MH plasmas is at the same location as the MC surface in MC plasmas. The plasmas are in up-single-null L-mode, with VB drift in unfavourable direction for H-mode, to avoid strong intrinsic rotation associated with H-mode. In Fig. 1, $V_\phi$, $T_e$, $n_e$ and $P_{rf}$ traces of
an MC plasma and an MH plasma are compared. Strong (up to 90 km/s) toroidal rotation of impurity ions (Ar$^{17+}$ and Ar$^{16+}$) in the co-current direction has been observed by high-resolution x-ray spectroscopy [15] in the MC plasma, but the rotation change in the MH plasma is much smaller (< 30 km/s), consistent with the empirical scaling of small $\Delta V_0$ in L-mode. In Fig. 2, the change of central $V_0$ in a number of MC plasmas and MH plasmas in this experiment are plotted. $\Delta V_0$ 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 $V_\theta$ in the ion diamagnetic drift direction (∼2 km/s at 3 MW) is also observed in MC plasmas, and similarly increases with rf power, while the poloidal rotation in MH plasmas is smaller than the diagnostic sensitivity (Fig. 3). The rotation also exists in the main ions, as shown in the Doppler broadening of the turbulence spectra measured by a phase contrast imaging system [16] (Fig. 4). 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.

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

FIGURE 4. (a) Main ion rotation indicated Doppler broadening of PCI fluctuations. (b) Trace of impurity $\Delta V_0$. (c) RF power.

MC WAVE DETECTION, TORIC SIMULATION AND MOMENTUM TRANSPORT MODELING

In the MC plasmas, the MC ICW has been detected by the PCI system in heterodyne setup (Fig. 5) [6]. The spatial location of the wave (∼4 cm on the high field side (HFS) of the $^3$He IC layer) and the $k_R$ value (3-7 cm$^{-1}$) agree with those calculated from dispersion equation and previous MC experiments in D($^3$He) at the same frequency and similar B field [7]. We calculate the RF power deposition using 2-D full wave TORIC code [17,18] with experimental parameters and equilibrium. The
direct electron heating profile agrees with break-in-slope analysis of $T_e$ signals from ECE measurement. In the plasmas with strong flow drive, we find that there is a significant portion of rf power deposition by the MC ICW to the $^3$He ions via cyclotron resonance (Fig. 6-(a)). 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 $0.2 < r/a < 0.6$ after integrated along flux surfaces (Fig. 6-(b)). Because of the MC ICW has a parallel wavenumber $k_{\parallel}$ much larger than that of fast wave (a factor of 4-5 in this case), such strong ion interaction of the MC ICW is expected due to a much broader Doppler width. We hypothesize that the interaction between the MC ICW with the $^3$He ions is the main cause of the observed toroidal and poloidal flow.

**FIGURE 5.** 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.

**FIGURE 6.** TORIC simulation on MC ICW power deposition to $^3$He ions: (a) 2-D plot; (b) flux surface averaged.

**FIGURE 7.** Surface plots of $\Delta V_{\phi} = V_{\phi} - V_{\phi}(P_{rf} = 0)$ vs. $r/a$ and time. (a) Experimental data; (b) Momentum transport modelling.
However, the toroidal rotation depends on many closely related parameters including momentum transport. Assuming a toroidal force proportional to the deposition profile shown in Fig. 6-(b), we can reproduce the velocity profile and temporal evolution by solving the transport equation in cylindrical coordinates including a momentum diffusion coefficient $\chi_\phi$ and a pinch velocity $V_{\text{pinch}}$. In Fig. 7, good agreement is shown between the experimentally measured $V_\phi$ (same MC discharge as in Fig. 1) and that from transport modelling using $\chi_\phi = 0.1 \text{ m}^2/\text{s}$ and inward $V_{\text{pinch}} = -2.0 \times (r/a) \text{ (m/s)}$. Although the modelling cannot unambiguously determine the force term, we can estimate the effective driving force to be about 0.03 to 0.05 N per MW ICW power in order to match the experimentally measured rotation evolution.

The MC ICW-$^3$He interaction flow drive hypothesis is consistent with our experimental observation of $^3$He dependence of flow drive: At either low $^3$He (< 4%) fraction (FW minority heating) or high $^3$He (> 20%) fraction (MC electron heating), the rotation is no more than the intrinsic rotation. The hypothesis is also consistent with the similarity of the power deposition and the observed flow drive efficiency vs. the MC layer location shown in Fig. 8. In this figure, we compare the B field dependence of the TORIC calculated fraction of RF power to MC ICW to $^3$He ions and the experimental measured flow drive efficiency. The dependence in the power deposition can be interpreted by the $B_{\text{pol}}$ and $T_i$ contribution that is required by the mode conversion to ICW [19, 20, 21]. Both data show a peak when the MC surface and IC resonance are near the axis. A detailed scan of $^3$He fraction and B field scan will help clarify the role of the MC ICW in flow drive.

**PROJECTION TO OTHER TOKAMAKS AND ITER**

One of the parameters that affect the ICRF physics is the ratio of perpendicular wavelength and the machine size, i.e., $k_z R \sim \omega R/V_A \propto n_e^{1/2} R$. This ratio determines the amount of RF power available for mode conversion by tunneling the evanescent layer between the L-cutoff layer and the MC surface. The MC physics on ITER is expected to be very different because the major radius of ITER is roughly 9 times of that of C-Mod while plasma densities are similar. The high temperature (~20 keV) of ITER plasma will significantly increase the fast wave absorption on electrons independent of minority or MC heating [22]. Therefore, it is critical to verify the MC flow drive method on other tokamaks, especially existing larger tokamaks, in order to establish its applicability on ITER.

We have studied the MC scenarios on JET D($^3$He) plasmas using TORIC, and performed parameters scans including $B_t$, $I_p$, and $^3$He fraction. $^3$He fraction has been shown to be the most sensitive parameter, and our study suggests at $n_{^3\text{He}}/n_e \sim 10$-15%, more than 30% of total RF power can be deposited to ions through the MC ICW. Data-mining of previous JET experiments has indeed found similar dependence of plasma toroidal rotation vs. $^3$He fraction in internal transport barrier (ITB) reversed shear plasmas with both neutral beam heating and ICRF heating [23, 24]. Figure 9 shows the TORIC simulation on the fraction of the MC ICW power to the $^3$He ions vs. the $^3$He fraction from TORIC simulation of one of these ITB plasmas. Future experiment on JET will help understand the likely RF effect on toroidal rotation.
Some preliminary evidence of poloidal flow drive has also been observed on TFTR, where RF power correlated poloidal flow was observed between the MC layer and the \(^3\)He IC resonance in D-\(^4\)He-(\(^3\)He) plasmas \[8\]. In hindsight, it was possible that the flow was caused by the MC ICW, similar mechanism as our observation.

The large size and much higher temperature on ITER create a very different regime in terms of mode conversion physics. TORIC simulation shows that launching fast wave from the low field side of the tokamak, like that planned on ITER, will result in insignificant mode conversion in D-T-(\(^3\)He) and \(^4\)He(\(^3\)He) plasmas (Fig. 10-(a)). On the other hand, if an ITER ICRF antenna were built to launch power from the high field side, a substantial portion of power can be mode converted to slow waves, and deposited directly to \(^3\)He ions, potentially driving plasma rotation (Fig. 10-(b)).

For the normal LFS launch on ITER, mode conversion in inverted minority heating plasmas may be good candidates for MC flow drive. Except some preliminary evidence of sheared poloidal flow drive near the edge in (D)-\(^3\)He plasma on JET (MC IBW interaction with ions) \[9\], MC flow drive in the inverted minority heating scenario has not been well studied. As shown in JET (\(^3\)He)-H inverted minority heating experiments, electron heating becomes dominant even at rather low \(^3\)He fraction at 2.5% \[25\]. The situation on ITER may be different due to its much higher temperature and wider Doppler broadening of the IC resonance. In Fig. 11-(a), the inverted minority case of a (T)-D plasma is shown. By moving the D IC layer out of the plasma, a significant amount of RF power is deposited to the T ions through the MC ICW and IBW. With 70% RF power being deposited to the T ions via the slow waves, this seems to be a promising scenario for flow drive. Another scenario involves

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**FIGURE 8.** B\(_t\) dependence on C-Mod data and comparison to TORIC simulation. The MC and IC locations are also indicated.

**FIGURE 9.** TORIC simulation on a JET plasmas \((B_t = 3.45T , f = 33 \text{ MHz, } I_p = 2.8 \text{ MA})\). Plotted are power of the MC ICW to \(^3\)He ions as a percentage of total power vs. \(^3\)He fraction.
the seeding of $^7$Li to create ($^7$Li)-D inverted minority heating in 50-50 D-T burning plasma (Fig. 11-(b)). In this case, as much as 10% of total RF power may be deposited to the $^7$Li ions. In order to extrapolate this method to ITER, experimental study of MC flow drive will be required in such inverted minority scenario, e.g., ($^3$He)-H plasma, by finding the small window of strong ion interaction of the MC waves.

FIGURE 10. ITER simulation on normal MC scenarios. Contours are RF power to $^3$He ions in D-T-(He3) plasmas. (a) LFS launch, (b) HFS launch.

FIGURE 11. ITER simulation on inverse minority heating plasmas. Contours are RF power to minority ions. (a) (T)-D plasma, (b) T-($^7$Li)-D plasma.
DISCUSSION

Since slow waves carry larger momentum than fast waves at the same power density, slow waves, like direct launched IBW and MC wave have long been predicted to be potentially able to drive plasma flows. Our experimental observation seems to be higher than a previous simulation on flow drive with MC ICW [26], but in reasonable agreement with analytical approximation in Ref. [27]. Theories indicate RF drive rotation would show clear antenna phase (wave toroidal direction) dependence. This is inconsistent with our preliminary experimental evidence. Both experimental and theoretical work will be required in order to further understand the RF force, or an equivalent mechanism that transports momentum against the $V_\phi$ gradient, and extrapolate to other tokamaks and ITER.

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REFERENCES


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