ICRF mode conversion flow drive on Alcator C-Mod∗

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Abstract
We have carried out a detailed study of ion cyclotron range of frequency (ICRF) mode conversion (MC) flow drive on the Alcator C-Mod tokamak including its dependence on plasma and RF parameters. The flow drive efficiency is found to strongly depend on the 3He concentration in D(3He) plasmas, a key parameter separating the ICRF minority heating regime and MC regime. At +90° antenna phasing (waves in co-Ip direction) and dipole phasing (waves symmetrical in both directions), we find that ∆V0, the change in the core toroidal rotation velocity, is in the co-Ip direction, increases with RF power and with Ip (opposite to the 1/Ip intrinsic rotation scaling). The flow drive efficiency decreases at higher plasma density and also at higher antenna frequency. The observed flow drive efficiency in H-mode has been small due to the unfavourable density scaling. The flow drive effect at −90° phasing appears to be saturated or decrease at high RF power. The up–down asymmetry in the MC to the ion cyclotron wave may be the key to understand the flow drive mechanism.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Plasma rotation (flow) and velocity shear can be important in stabilizing micro- and macro-instabilities in tokamak plasmas, and plasma rotation has been shown to be beneficial for tokamak plasma performance. Experimentally, shear flow has been demonstrated to improve plasma confinement [1–3], and a large toroidal rotation can help stabilize MHD modes [4, 5], but the issue of plasma rotation drive and control on ITER is far from being resolved. The study of plasma rotation is currently a very active research field (see, e.g., [6–11]). In present tokamaks, externally driven rotation is mainly from neutral beam injection as a by-product of beam heating with direct angular momentum input to the plasma. However, for ITER, the neutral beam energy will be significantly higher in order to penetrate the expected higher density plasma and larger machine size, and this requirement will result in a much lower torque per MW beam power. Beam driven rotation is thus presumed to be small in ITER. Intrinsic rotation has been observed on many tokamaks [6, 7, 11, 12], and it exists independent of the external momentum input or auxiliary heating method. For ITER and future reactors, active intrinsic rotation and rotation profile control will be difficult due to its correlation with plasma pressure. Considerable effort has been made on present tokamaks in search of an efficient RF flow drive method that may also be applicable on ITER and beyond. A potential ITER-applicable flow drive method—ion cyclotron range of frequency (ICRF) mode conversion (MC) flow drive—has been observed on Alcator C-Mod [13–16] and also recently on JET [17–19]. This paper reports the results from a detailed study on Alcator C-Mod on this flow drive method.

The application of ICRF power in multiple-species tokamak plasmas, for example, D(3He) plasmas, where 3He is a minority and D is majority, usually involves two heating regimes: minority heating (MH) and MC heating. In D(3He) plasmas, when the minority concentration X[3He] (≡n3He/n) is small (e.g. a few per cent on Alcator C-Mod), MH is dominant, where most of the launched fast magnetosonic wave (fast wave) is absorbed by the minority 3He ions through the ion cyclotron (IC) resonance interaction [20]. When X[3He] is larger (e.g. 10% and above), the fast wave undergoes MC near the D–3He hybrid layer (also called the MC layer), and evolves into slower and shorter-wavelength waves: the MC ion Bernstein wave (IBW) and ion cyclotron wave (ICW) [21–23]. To illustrate the difference between these two scenarios, in figure 1, we compare the electric field of E− contours of a MH and a MC case from TORIC simulations. TORIC is a...
2D full wave ICRF simulation code [24, 25]. The $E^+$ field is the electric field with right-handed polarization, in the same direction as the Larmor gyration of electrons. In figure 1(a), at $X[3\text{He}] = 2\%$, only fast waves can be seen, and the RF power is absorbed at the $^{3}\text{He}$ resonance layer. In figure 1(b), at $X[3\text{He}] = 20\%$, near the MC layer, there are features of short wavelength waves. On the mid-plane and on the high-field side (HFS) of the MC layer, the short-wavelength MC IBW can be identified. Above and below mid-plane, the MC ICW can be seen on the low-field side (LFS) of the MC layer. In this MC scenario, the MC IBW is mostly absorbed by the electrons, while the MC ICW can interact with both electrons and the $^{3}\text{He}$ ions along its propagating path towards the LFS and to the $^{3}\text{He}$ IC layer. ICRF MH is the main heating scheme in Alcator C-Mod, but MC has also been used for many interesting applications, for example direct electron heating and sawtooth modification via local current drive [26]. Flow drive is one of the recently demonstrated applications of this ICRF heating scheme.

Experimentally, ICRF minority heated plasmas show no evidence of direct RF driven rotation. The rotation in ICRF minority heated plasmas on Alcator C-Mod has the same trend versus plasma stored energy and plasma current as the rotation in Ohmic plasmas [27, 28]. Results from JET [29–31], Tore-Supra [32, 33] and ASDEX-Upgrade [34] all show that the contribution of ICRF MH to rotation is intrinsic, i.e. not directly from the RF power absorption but rather indirectly due to the change in the plasma temperature or plasma pressure. In the previous Alcator C-Mod studies, we showed that ICRF MC in D($^{3}\text{He}$) L-mode plasmas can drive significantly higher plasma rotation than that from the empirical intrinsic rotation scaling. In a recent study on JET, plasma rotation driven by ICRF MC has also been observed [18, 19].

In this paper, we present results from a further study of the MC flow drive method on Alcator C-Mod. The experimental setup is described in section 2. In sections 3 to 6, we show the parametric dependence of the driven flow on a number of plasma parameters, including D(H) versus D($^{3}\text{He}$), He$^{3}$ concentration in D($^{3}\text{He}$) plasmas, magnetic field, plasma current, plasma density, plasma shape and confinement mode (L-mode versus H-mode), and also dependence on RF parameters such as RF power, frequency and antenna phasing. In section 7, we show an empirical scaling law obtained from the parametric dependence study. Discussion and summary are in sections 8 and 9, respectively.

2. Experimental setup and main diagnostics

Alcator C-Mod [35] is a compact high field tokamak ($R = 0.67\text{ m}, a = 0.22\text{ m}, I_p \leq 2\text{ MA} \text{ and } B_{\phi} \leq 8.1\text{ T}$). There are three ICRF antennas on Alcator C-Mod [36]. The 4-strap antenna at J-port (J antenna) is phase variable ($+90^\circ$, $-90^\circ$ or $180^\circ$) and also frequency tuneable (50, 70 or 78 MHz). It is capable of coupling $\leq 3\text{ MW}$ power to the plasma. The other two antennas (D-port and E-port) are operated at a fixed frequency (80.5 MHz and 80 MHz) and fixed phasing ($180^\circ$). Each of D and E antennas is capable of coupling $\leq 1.7\text{ MW}$ to the plasma. At $+90^\circ$ phasing, the launched RF wave from J antenna is preferentially in the same direction as the plasma current (co-$I_p$), while $-90^\circ$ phasing is counter-$I_p$ and $180^\circ$ phasing (dipole) is toroidally symmetric. The flexibility of the antenna system and the range of toroidal magnetic field of the tokamak provide us with a number of heating combinations (table 1), and allow us to explore the parametric dependence of ICRF MC flow drive under multiple scenarios. In this study, we ran plasmas with toroidal field as high as 8.0 T, plasma current up to 1.35 MA, and central density $n_e$ ranging from 1 to $5 \times 10^{20} \text{ m}^{-3}$. Central electron temperatures up to 9 keV have also been achieved via high power ICRF heating. The plasma rotation velocity is measured by observing the Doppler shift of the H-like and He-like argon line emissions in the wavelength range 3.7–4.0 Å. A trace amount of argon is
introduced by gas puffing in the early part of plasma pulses. The spectra of the line emission are obtained from a spatially resolving high resolution x-ray crystal spectrometer [37]. The instrument utilizes a spherically bent quartz crystal and a set of two-dimensional x-ray detectors to image the entire plasma cross section with a spatial resolution about 1 cm and frame rate up to 200 Hz. Observations of poloidal rotation have been reported in previous MCFD experiments [14, 15], but unfortunately such measurements are not available in this study. The absolute value of the toroidal rotation velocity is routinely calibrated against plasmas with artificially induced locked-modes, where the rotation is presumed zero in the lab frame. The rotation velocity can also be inferred from the frequency change of the MHD modes and we can use such changes as corroborative evidence of flow drive. In figure 2, an L-mode plasma ($B_0 = 8.0\, T$, $I_p = 1.2\, MA$, upper-single-null (USN) shape) heated with stepped-up ICRF power to 5 MW (78 and 80 MHz combined) is shown. The central rotation velocity from the x-ray spectroscopy, shown in figure 2(a), increases from $-20\, km\, s^{-1}$ to $100\, km\, s^{-1}$ following the step-ups of the input RF power. Positive velocity values in this paper correspond to rotation in the same direction as the plasma current ($co-I_p$). This observation in figure 2(a) is independently verified by the change of frequencies of the magnetic perturbations associated with sawtooth oscillations. The frequency changes are shown in the signals of a magnetic coil in figure 2(b) and those from an AXUV diode array in figure 2(c). The propagating velocity of these MHD modes has been studied previously and shown to approximate the plasma ion rotation velocity near the q = 1 surface ($R \sim 0.75\, m$ for this plasma) [28]. Therefore, the frequency change up to 20 kHz shown in figures 2(b) and (c) corresponds to a plasma rotation velocity of $2\pi R \times \Delta f \sim 95\, km\, s^{-1}$ at $R \sim 0.75\, m$. $^3$He is introduced to the plasma via gas puff in the early part of the discharge. The concentration of $^3$He is varied, shot by shot, by changing the duration time of valve opening. No real-time feedback is available. In the discharge shown in figure 2, $^3$He is puffed from $t = 0.2-0.35\, s$. Typically, the VUV spectroscopic measurement, monitoring a $^3$He line at the edge, peaks approximately 0.1 s after the end of puff, then slowly decays as shown in figure 2(d). The RF waves are measured by a phase contrast imaging (PCI) system, using the heterodyne scheme as detailed in [23, 38]. The PCI detects the line-integrated density fluctuations induced by the ICRF waves. The spatial distribution of such fluctuations, via a synthetic diagnostic simulation based on ICRF codes such as TORIC, can help us understand the ICRF physics, and reveal the possible flow drive mechanism. The absolute level of $X(^3$He) in the core plasma is estimated and corroborated from the location of the MC waves by PCI, TORIC simulations and the responses of $T_e$ signals at RF power transitions, which can also be used to calculate the direct RF power deposition profile to electrons.

**Figure 2.** (a) Central toroidal velocity from x-ray spectroscopy; (b) and (c) frequencies of magnetic perturbation from a magnetic coil and an AXUV diode; (d) VUV signal monitoring a helium line at the edge; (e) total RF power trace (78 and 80 MHz). $B_0 = 8.0\, T$, $I_p = 1.2\, MA$, $n_{e0} = 1.6 \times 10^{19} \, m^{-3}$, L-mode, D($^3$He) plasma.

The toroidal rotation profiles from the MCFD experiment are typically peaked at the magnetic axis, as shown previously in [15]. The central rotation tends to rise first after RF power is applied. In figure 3, we show the time traces of the rotation velocities (inverted from line-integrated measurement) in a discharge with 2.7 MW RF. To show the trend more clearly, the values at $t = 0.59\, s$ (just prior to the RF pulse) have been subtracted. Within the temporal resolution of the spectroscopy data (10 ms), the velocity at $r/a = 0$ starts to rise as soon as the RF power is applied, while the delay of the response at $r/a = 0.44$ is no less than one data point. The dynamic of the rotation profile evolution will be addressed by future studies. In the following sections, we only show the parametric dependence of the change of central rotation velocity $\Delta V_0$.
For L-mode plasmas, $\Delta V_0$ is defined as the difference with RF power and without RF power (Ohmic), and for H-mode plasmas, $\Delta V_0$ is defined as the additional change of rotation velocity after applying RF power for MC (see section 5 for details).

3. MC heating versus MH

In D($^3$He) plasmas, the concentration of $^3$He, $X[^3{\text{He}}] = n_{^3{\text{He}}}/n_e$, determines whether the fast wave launched by the antenna is heating via MH or MC heating. A larger $X[^3{\text{He}}]$ also moves the MC layer further away from the IC resonance layer towards the HFS. The distance between the MC layer and the IC layer strongly affects how the RF wave power is deposited. The flow drive efficiency is found to be sensitive to $X[^3{\text{He}}]$. In figure 4(a), $\Delta V_0$ is plotted versus $X[^3{\text{He}}]$ from a series of plasmas with a $^3$He scan. All the plasmas have $I_p = 0.8$ MA, $B_t = 5.1$ T, $n_{eo} = 2.0 \times 10^{20}$ m$^{-3}$, and steady $P_{RF} = 2.5$ MW at 50 MHz and at +90° phasing. $X[^3{\text{He}}]$ is estimated from PCI measurement. Figure 4(a) shows that the maximum rotation can be obtained at $X[^3{\text{He}}] \sim 10\%$. As shown in figure 4(b), in this case both the MC layer and the IC resonance are near the axis. This result suggests that an intermediate level of $^3$He is conducive for flow drive. At low $X[^3{\text{He}}]$, the heating scenario is $^3$He MH, and at high $X[^3{\text{He}}]$ (>20%), the heating is mostly MC electron heating. In both cases of low and high $^3$He concentration, $\Delta V_0$ is smaller than the intermediate $^3$He concentration level.

We have also compared the rotation from the usual D($^3$He) flow drive scenario with the routinely used D(H) MH scenario on Alcator C-Mod. In the D(H) heating scenario, we typically use the residual H ions for MH, where $X[\text{H}] = n_H/n_e$ is nominally in the range 4–6%. In figure 5(a), we compare two L-mode USN plasmas that have the same $B_t$, $I_p$ and $n_e$, but one is heated with D($^3$He) MC at 50 MHz and the other one heated with the D(H) minority scenario at 80 MHz. In this setup, the H IC layer in the D(H) plasma is nearly at the same position as the $^3$He IC layer in the D($^3$He) plasma. At the same RF power the D($^3$He) MC heated plasma shows a much larger change of rotation. The difference also becomes more significant at higher RF power. The dependence of rotation versus RF power will be discussed in the next section. Two different RF frequencies are used in this comparison in figure 5(a), and as discussed later in this paper, RF frequency may also affect the flow drive efficiency. In figure 5(b), we compare two plasmas with D($^3$He) MC and D(H) MH at the same $f_{RF} = 70$ MHz, but at different $\phi$ fields so that they have the same IC resonance position. Again, the plasma at D($^3$He) MC shows a larger increase in rotation. In both figures 5(a) and (b), the change in rotation velocity in the MH plasmas follows the well-established empirical $\Delta W/I_p$ scaling [27] (where $\Delta W$ is the change in plasma stored energy). On the other hand, $\Delta V_0$ in the MC plasmas increases versus the level of the applied RF power. For the cases shown in figure 5, the antenna is in +90° phasing, and the MC flow is larger than that from the intrinsic rotation, even at smaller $\Delta W$.

4. Dependence on RF power, plasma current and antenna phasing

The flow drive effect is found to increase with RF power as shown in figure 5. The flow drive effect also depends on plasma current at the same RF power. In figure 6, we plot the results of plasmas at different $I_p$ using +90° phasing of RF power, which has four steps from 1 to 2.8 MW. Other parameters are $B_{t0} = 5.1$ T, $n_{eo} = 2.0 \times 10^{20}$ m$^{-3}$, $f_{RF} = 50$ MHz. The trend that $\Delta V_0$ increases versus $P_{RF}$ holds for all plasma currents. The effect of $P_{RF}$ appears to be nonlinear, and the rotation seems to increase more significantly above a certain RF power level (also shown in figure 5(a)). This may suggest a positive dependence versus electron temperature. For the same $P_{RF}$, $\Delta V_0$ is generally larger at higher plasma current. The $I_p$ dependence is in the opposite direction to the intrinsic rotation observed in ICRF minority heated plasmas.

At 180° (dipole) phasing, the net ICRF wave momentum is approximately zero, while at +90° and −90° phasings, the fast wave carries toroidal momentum. The dependence of antenna phasings has been studied in detail. In figure 7, we show the frequency of the magnetic perturbation and rotation velocity from x-ray spectroscopy of two discharges with different antenna phasings, but otherwise identical plasma parameters (L-mode, $I_p = 1.2$ MA, $B_{t0} = 7.9$ T, $n_{eo} = 1.9 \times 10^{20}$ m$^{-3}$, $P_{RF} = 2.5$ MW, $f_{RF} = 78$ MHz). The plasma with +90° phasing has larger rotation than that from −90° phasing. This result suggests that the antenna phasing can affect the rotation in the MC flow drive.

Further experiments show that the effect of the antenna phasing is complicated, and $I_p$ and $P_{RF}$ also play a role. In figure 8, we compare the rotation of comparable plasmas at different antenna phasings. In figure 8(a), the plasmas are all with $I_p = 1.2$ MA. We note that the rotation velocities at all three phasings are similar for $P_{RF} < 2$ MW, while at the higher RF power, the flow drive effect diverges: increasing ICRF power at +90° phasing drives larger co-$I_p$ rotation, and the rotation from dipole phasing also increases albeit at a slower...
rate, while at $-90^\circ$ phasing, the rotation actually decreases. A similar conclusion can be made from figure 8(b) where the flow drive effect diverges at $P_{\text{RF}} > 2.3$ MW for $I_p = 0.8$ MA.

Since the fast wave carries a net counter-$I_p$ momentum at $-90^\circ$ phasing and co-$I_p$ momentum at $+90^\circ$ phasing, the divergence seen in the flow drive effect may be due to the difference in the wave momentum, and also suggests that the direct RF momentum input can affect the magnitude of the flow drive. Following the increase of plasma stored energy due to RF heating, the intrinsic rotation in the co-$I_p$ direction would also increase. At $-90^\circ$ phasing and high RF power, the rotation slows down to below the expected intrinsic rotation. This observation indicates that the flow drive torque might be counter-$I_p$ in this case. More experiments will be required to obtain firmer evidence of counter-$I_p$ flow drive.

5. Dependence on plasma density, L- and H-modes

The flow drive efficiency is sensitive to plasma density. In figure 9, we show the results from a shot by shot plasma
density scan of the MC flow drive. All the plasmas are in L-mode, and have \( I_p = 1 \text{ MA}, B_t = 5.1 \text{ T}, P_{RF} = 2.5 \text{ MW}, f_{RF} = 50 \text{ MHz} \) and at +90° phasing. In figure 9(a), \( \Delta V_0 \) are as high as 100 km s\(^{-1}\) at low density and as low as 20 km s\(^{-1}\) at high density. Such strong dependence on density clearly shows that lower density is favoured for the flow drive. In figure 9(b), the product of central rotation and the central density, \( \Delta V_0 n_{e0} \), is plotted versus \( n_{e0} \). The vertical axis is approximately proportional to the total gain of the plasma angular momentum. For \( n_{e0} \lesssim 2 \times 10^{20} \text{ m}^{-3} \), \( \Delta V_0 n_{e0} \) appears to be approximately
constant versus \( n_{e0} \), and the rotation scaling versus density in figure 9(a) is mostly likely a power (or momentum) per particle scaling. However, a precipitous drop in \( \Delta V_0(n_{e0}) \) at higher density indicates a more complicated mechanism.

This density scan was carried out for the USN plasmas in normal toroidal field direction, where the power threshold for the L-mode to H-mode transition is much higher than the typical lower-single-null (LSN) plasmas. Unlike the intrinsic rotation, the flow drive effect in LSN plasmas is shown to be very similar to that in USN plasmas for RF power levels below the L–H transition power threshold, thus we can rule out that plasma shape or plasma edge conditions play a significant role. After an L–H transition, the rotation velocity increases significantly following the intrinsic rotation scaling. In our experiment, launching RF power into plasmas that are already in H-mode does not drive significant rotation in addition to the intrinsic rotation. One such H-mode plasma is shown in figure 10. In this plasma, 2 MW RF power at 80 MHz for D(H) MH is applied from \( t = 0.6 \) to 1.4 s. The L–H transition occurs at 0.7 s, and the plasma density shown in figure 10(c) and stored energy shown in figure 10(d) rise significantly after the transition. The H-mode is enhanced D\(_{a}\) (EDA) H-mode, which does not have discrete ELMs but characterized with a quasi-coherent mode in the pedestal region [39]. The rotation velocity in figure 10(a) increases following the rise in the stored energy, which is typical behaviour for intrinsic rotation. To study the MC flow drive capability, at \( t = 0.8 \) s, an additional 2.6 MW RF power at 50 MHz is applied. As seen in figure 10(d), the additional power gives the stored energy a rather large boost from \( \sim 100 \) to \( \sim 140 \) kJ, but the change in the central rotation shown in figure 10(a) is only about 10 km s\(^{-1}\), much smaller than that arising from the intrinsic rotation.

**Figure 8.** Central rotation velocity, RF power and stored energy trace versus antenna phasing. (a1)–(a3) \( I_p = 1.2 \) MA; (b1)–(b3) \( I_p = 0.8 \) MA. \( B_{0} = 5.1 \) T and \( f_{RF} = 50 \) MHz, \( n_{e0} = 2.0 \times 10^{20} \) m\(^{-3}\).

**Figure 9.** Density dependence: (a) \( \Delta V_0 \) versus plasma density \( n_{e0} \); (b) \( \Delta V_0(n_{e0}) \) versus plasma density \( n_{e0} \). Other parameters \( P_{RF} = 2.6 \) MW, \( f_{RF} = 50 \) MHz, +90\(^{\circ}\) phasing, \( B_{0} = 5.1 \) T, \( I_p = 1 \) MA.
rotation alone. Note that the central density in the H-mode period of this discharge is as high as $4.5 \times 10^{20} \text{m}^{-3}$, beyond the maximum density studied in L-mode (figure 9). Thus the weak flow drive effect in H-mode is likely due to the much higher density. Because it is difficult to control H-mode density on Alcator C-Mod, we have not been able to identify the potential positive contribution to flow drive from improved momentum confinement. The obtained flow drive efficiency in H-mode, using the additional rotation velocity from the intrinsic rotation, appears to follow the same empirical scaling (see section 6) as that in L-mode plasmas. Further study of flow drive in other high confinement modes that have small or no density rise, for example, the so-called I-mode [40], will help us study whether possibly better momentum confinement can improve the flow drive efficiency.

6. Dependence on toroidal magnetic field and RF frequency

For a fixed antenna frequency, changing the toroidal magnetic field moves the location of both the MC layer and IC resonance in the plasma, and it appears to also affect the flow drive efficiency. In figure 11, we show the result of a series of identical plasmas ($I_p = 0.8 \text{MA}$, $n_{e0} = 1.8 \times 10^{20} \text{m}^{-3}$) at different magnetic fields while heated with $P_{RF} = 2.6 \text{MW}$, $f_{RF} = 50 \text{MHz}$ and $+90^{\circ}$ phasing. The largest rotation is obtained for $B_{fo} \sim 5.0 - 5.1 \text{T}$ as shown in figure 11(a). At this magnetic field, the $^3\text{He}$ cyclotron resonance is a few cm on the LFS of the magnetic axis, and the MC layer (D–$^3\text{He}$ hybrid layer) is also a few cm on the HFS of the axis. When both the resonance and MC layer are on one side of the plasma axis (e.g. $B_{fo} = 4.5 \text{T}$ and 5.6 T), the flow drive is not as effective.

Magnetic field scans have also been carried out at $f_{RF} = 70 \text{MHz}$ ($B \sim 7 \text{T}$) and $f_{RF} = 78 \text{MHz}$ ($B \sim 8 \text{T}$), and similar to the result in figure 11, the largest central toroidal rotation is found when both the MC layer and IC resonance layers are close to the plasma axis. However, the flow drive efficiency at different frequencies (and magnetic fields) is different even at the, respectively, optimized $B_{fo}$. In figure 12, we show two plasmas having the same $I_p = 1 \text{MA}$, $^3\text{He}$ concentration, $n_{e0} = 1.4 \times 10^{20} \text{m}^{-3}$ and $P_{RF} = 2.5 \text{MW}$ at $+90^{\circ}$ phasing, but one is at 70 MHz/7.2 T and the other one at 50 MHz/5.1 T. These two plasmas show very similar changes of plasma stored energy (and presumably similar change in intrinsic rotation), but $\Delta V_0$ in the 50 MHz plasma, $\sim 80 \text{km} \text{s}^{-1}$, is significantly larger than that from the 70 MHz plasma, $\sim 55 \text{km} \text{s}^{-1}$. The ratio of $\Delta V_0$ is approximately the inverse ratio of the frequencies (or equivalently, $B_{fo}$). Since the momentum carried by the RF waves is inversely proportional to the frequency for the same toroidal antenna structure, the dependence on RF frequency indicates the RF momentum input may play an important role in flow drive. However, we cannot simply exclude the effect of different $q$ profiles of these two plasmas, which may also affect the momentum confinement and transport.

7. Empirical scaling law of the flow drive efficiency

Our detailed experimental study has revealed the dependence of the flow drive efficiency versus $X[^3\text{He}]$, plasma current, plasma density, and RF power, frequency and antenna phasing. The result from $-90^{\circ}$ antenna phasing is complicated, but the flow drive efficiency at $+90^{\circ}$ and $180^{\circ}$ appears to have simple parametric dependences. Using all the data from dedicated experiments, we have carried out a multiple-parameter regression and obtained an empirical scaling law for the $+90^{\circ}$ and $180^{\circ}$ phasings (with $X[^3\text{He}] \sim 10\%$ and optimal $B_{fo}$ for chosen RF frequencies). The resulting scaling law is $\Delta V_0 (\text{km} \text{s}^{-1}) \approx 7.5 \times 10^5 P_{RF} (\text{MW})^{1.3} I_p (\text{MA})^{0.6} n_{e0} (10^{20} \text{m}^{-3})^{-0.9} f (\text{MHz})^{-0.8}$. Data from different antenna frequencies and confinement modes are separately plotted in figure 13. For L-mode data, $\Delta V_0$ is defined as the difference of rotation velocity after the RF application and the Ohmic part before RF; and for H-mode, $\Delta V_0$ is the difference of rotation after the application of RF for MC heating and that in H-mode heated by MH only, like that labelled in figure 10(a).

Note the intrinsic rotation on Alcator C-Mod (Ohmic and ICRF minority heated plasmas) approximately follows an empirical $\Delta W/I_p$ scaling. In figure 14, we compare the MC flow drive data (L-mode) to the intrinsic rotation scaling. H-mode data are not included in figure 14. For H-mode, the intrinsic rotation is usually rather large and the change in rotation from MCFD is much smaller than the
Figure 11. $B$ field dependence: (a) $\Delta V_0$ versus $B$ field; (b) the MC layer and IC resonance locations at three $B$ fields. $I_p = 0.8$ MA, $n_{e0} = 1.8 \times 10^{20}$ m$^{-3}$, $P_{RF} = 2.6$ MW, $f_{RF} = 50$ MHz and +90° phasing.

Figure 12. Central rotation velocity at two different antenna frequencies (solid blue lines: 50 MHz and $B_{10} = 5.1$ T; dashed red lines: 70 MHz and $B_{10} = 7.2$ T): (a) $V_0$; (b) $P_{RF}$; (c) stored energy. $I_p = 1$ MA, +90° phasing, $n_{e0} = 1.4 \times 10^{20}$ m$^{-3}$.

Figure 13. Empirical scaling law for all the data from 180° and +90° antenna phasing. Data are grouped by antenna frequency ($B$ field) and plasma confinement mode.

actual rotation change from L-mode to H-mode. Because with RF heating the stored energy generally rises, it is no surprise that a general trend of $\Delta V_0$ versus $\Delta W$ exists for all the L-mode data. However, the experimental data are much more scattered to be fitted with this simple $\Delta W/I_p$ scaling. While the rotation velocities from 78 MHz are not significantly different than that from this intrinsic scaling, those from 50 and 70 MHz are much larger (note that both axes of the graph are logarithmic). For the cases of 50 MHz, since the observed rotation is significantly above the intrinsic scaling, we have studied the velocity gained due to MC flow drive alone. In figure 15, we subtract 0.8 $\Delta W$(kJ)/$I_p$(MA) from the data of
the L-mode plasmas at 50 MHz RF frequency, and plot them versus a scaling formula from regression analysis. Like that shown in figure 13, strong dependences on $P_{RF}$, $I_p$ and $n_{e0}$ can be clearly seen. However, we need to be cautious because plasma rotation velocity involves many processes, including torque, sink and transport, and more sophisticated modelling is require to separate the effects of MC flow drive and the intrinsic rotation.

8. Discussion

In this study, we have determined the parametric dependence of the efficiency of MC flow drive, and obtained an empirical scaling law based on the parameter scans. $X^{[3}\text{He}]$ is one of the most important factors that determines the RF physics, whether it is in MH or MC heating. The dependence of the rotation versus $X^{[3}\text{He}]$ suggests that MC plays an important role. As shown in previous studies [15], in the region of intermediate $X^{[3}\text{He}]$, the mode converted ICWs deposit power to both ions and electrons, and we proposed that the RF power via the MC ICW to ions may be a key. Here we show some more detailed discussion on the MC process and the possibility of rotation torque from this process.

In figure 16, we show the RF power deposition to $^{3}\text{He}$ ions from TORIC simulation for three $^{3}\text{He}$ concentration levels. In figure 16(a), $X^{[3}\text{He}] = 2\%$ corresponds to the MH scenario (no MC), and most ion interaction occurs with the launched fast wave on the IC resonance location. Figure 16(b) shows the case of $X^{[3}\text{He}] = 10\%$. In this case, some RF power to ions via the fast wave is apparent, but there is also a significant amount to ions via the MC ICW above and below mid-plane. In figure 16(c), in the case of $X^{[3}\text{He}] = 20\%$, there is some power to ions via FW and the MC ICW, but the total level is much smaller. Note all three plots have the same logarithmic colour scale. Experimentally, we have observed that the scenario of figure 16(b) has the most flow drive effect. In figure 17, the RF power to ions via the MC ICW is plotted versus $X^{[3}\text{He}]$. This result is obtained from a single toroidal mode, $n_{\phi} = +6$, the peak antenna spectrum. As a result, the trend is only qualitative. Interestingly, the peak in the figure is rather similar to figure 4.

The MC to the ICW is up–down asymmetric. This can be clearly seen in the power deposition contours in figures 16(b) and (c) and it can also be seen in the field contours of figure 16(b). Because of the requirement of an up-shift of $k_z$ for the MC ICW to exist, the waves above and below the mid-plane have different wavelengths (opposite sign of $k_z$), and they are generally at different vertical locations and flux surfaces. A detailed description and experimental study of this up–down asymmetry can be found in [38]. Although the total canonical momentum of the system, RF waves and plasma, is conserved, the mode converted waves have larger momentum content per MW than the launched fast wave, by gaining momentum via non-resonance process [41]. The MC ICWs then carry the momentum to differential spatial locations, and deposit their momentum to ions via the IC resonance interaction. A detailed mechanism that may transfer this asymmetry to plasma rotation needs more theoretical and experimental work. In typical ICRF MH scenario, there does not exist such up–down asymmetry in wave–particle interaction. Directionally launched fast waves in MH have been shown to contribute to plasma rotation on JET [42], but its effect is much smaller than the recently observed rotation change in D$^{[3}\text{He}$ plasmas via MC on JET [19].

The empirical scaling law of MC flow drive indicates that the ICRF power (or momentum) per particle plays an important role. The positive dependence on $I_p$ may suggest a momentum confinement scaling (similar to energy scaling). In addition, $I_p$ can also affect the MC to the ICW by varying the poloidal magnetic field. The interaction between the mode converted ICWs and the $^{3}\text{He}$ ions, and its associated momentum asymmetry has been thought to be the key to generate the flow [14, 15, 19]. The experimental observation for $+90^\circ$ phasing is consistent with this conjecture. But the complicated $P_{RF}$ and $I_p$ dependence for $-90^\circ$ antenna
phasing indicates that possibly two mechanisms are involved in determining the total torque: one is RF power dependent (i.e. independent of the antenna phasing), which generates a torque in the co-$I_p$ direction on Alcator C-Mod; the other is wave momentum dependent, i.e. the torque changes direction versus antenna phasing. Other plasma parameters, such as $I_p$ and $n_e$, can affect both the MC process and momentum confinement and transport. The density effect on MC is complicated, for example, [43]. And the approximately inverse density scaling in the empirical scaling law indicates that the power or momentum per particle is the dominant role played by the density. The steep drop-off of the flow drive effect at very high density in L-mode (figure 9) and in H-mode (figure 10) is not yet understood. Larger plasma current generally increases the total power to the MC ICW by introducing larger poloidal field, and it also affects the momentum confinement. This is consistent with the experimental observations.

The intrinsic rotation, which exists independent of RF heating, complicates our study to some extent. The intrinsic rotation has been found to rise from the plasma edge, while the rotation driven by the MC seems to increase first in the core (figure 3). The scaling law shown in figure 13 refers to the combined effect of intrinsic rotation and flow drive from MC. In cases that the flow drive is much larger than that from the intrinsic rotation, we may subtract the intrinsic rotation and the result is shown in figure 15, but more modelling will be required to separate their effects. Detailed dynamic of the rotation profile evolution in the MC flow drive experiment will be addressed in future work.

9. Summary
ICRF mode conversion flow drive has been studied in detail on Alcator C-Mod. The flow drive efficiency has been shown to depend on the ICRF power, frequency and antenna phasing, the level of $^3$He concentration in D($^3$He) plasmas, plasma density, plasma current and magnetic field. An empirical scaling law has been obtained for the $+90^\circ$ phasing and dipole phasing. At $-90^\circ$ phasing, the parametric dependence is more complicated, and in general, the co-$I_p$ rotation velocity is smaller. The experimental evidence suggests that both the ICRF heating and
momentum carried by the wave play roles in driving the flow, and the asymmetry associated with the mode conversion process may be the key to understand the flow drive mechanism.

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