ICRF mode conversion flow drive in JET D(^{3}He) plasmas and comparison with results from Alcator C-Mod

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Following a recent Alcator C-Mod experiment on ICRF mode conversion flow drive [1, 2, 3], we have carried out a similar experiment in JET D(^{3}He) plasmas (Fig. 1): B_{t0} = 3.45 T at R_0 = 2.97 m, I_p = 2.8 and 1.8 MA, central density $n_{e0} \sim 3\times10^{19}$ m^{-3} during flat top, and in L-mode confinement. The plasma current was in the same direction as the toroidal B field. All the plasmas were in D majority with external ^{3}He puffing. The ^{3}He concentration $X[^3He] \equiv n_{He3}/n_e$, was feedback controlled in real-time (Fig. 1-(c)), and scanned pulse by pulse. $X[^3He]$ was estimated from visible spectroscopy light in the divertor, linking relative light intensities to relative concentrations. The ICRF power was at 33 MHz from the A2 antennas. At B_{t0} = 3.45 T, the ^{3}He ion cyclotron resonance layer was about 20 cm to the low field side of the magnetic axis. For $X[^3He] \sim 13\%$, the D-^{3}He hybrid layer was about 10 cm to the high-field-side of the magnetic axis. The ICRF antennas were at -90^0 phasing, i.e., the launched fast waves were toroidally asymmetric predominantly in the counter-I_p direction. The toroidal angular velocity ω_ϕ of C^{6+} is measured by the core CXRS system during beam blips. As shown in Fig. 1-(e), for pulse 78845, counter-I_p rotation ($\omega_\phi < 0$) was observed during all the blips for t < 11 sec, and the rotation only became co-I_p later in the pulse with continuous neutral beam injection. A scintillator probe measured the energy and pitch angle of lost fast ions [4]. As shown in Fig. 1-(h), the detection of 3.7 MeV α-particles, born from the nuclear reaction between D and ^{3}He, indicates a hot ^{3}He ion population near the plasma centre.

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*See Appendix of F.R. Romanelli et al., Fusion Energy Conference 2008 (Proc. 22nd Int. Conf. Geneva 2008), IAEA Vienna (2008)

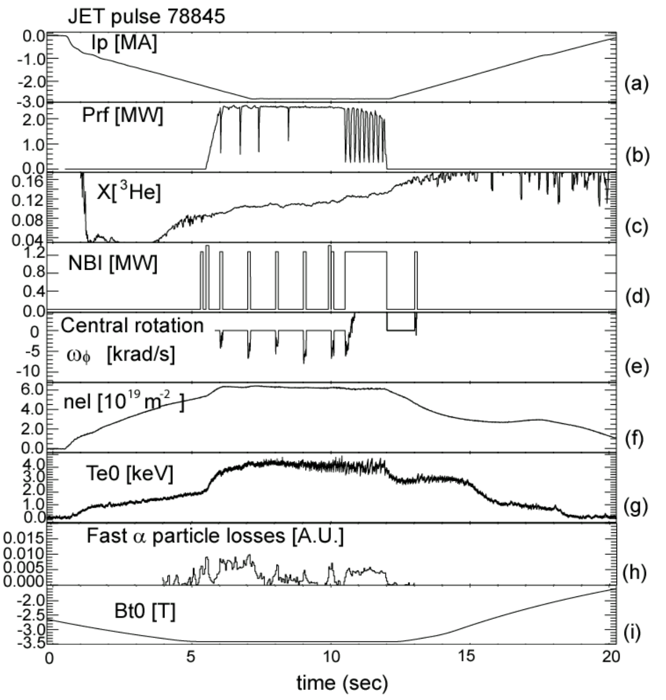


FIG. 1 Data traces for JET pulse 78845. Rotation in the counter- I_p direction ($\omega_\phi < 0$) shown in panel (e).

The observed rotation profiles are sensitive to X[^{3}He]. For X[^{3}He] ≤ 5%, the rotation is in the co-I_p direction, ω_ϕ ~ 1-4 krad/sec, with a nearly flat profile, similar to those previously reported in minority heated plasmas that have high I_p and near-axis heating [5, 6]. The result for X[^{3}He] ≥ 25% is similar. For X[^{3}He] ~ 10%-17%, the rotation is ~ 0 for the outer half of the plasma, but is in the counter I_p direction for r/a < 0.4 and peaked near the plasma centre. In Fig. 2, the central rotation (R = 3.04 m) is plotted vs. X[^{3}He]. On Alcator C-Mod, the flow drive is also sensitive to X[^{3}He], largest flow drive at X[^{3}He] ~ 10-12%, but the driven flow is in the co-I_p direction [3].

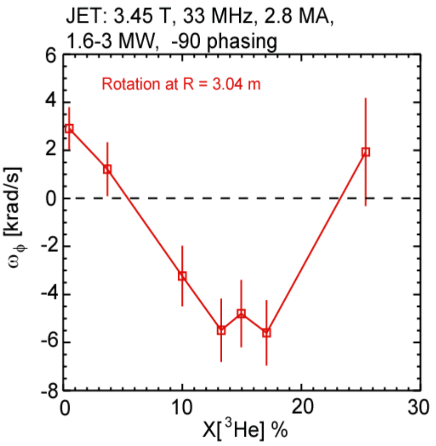


FIG. 2 Central rotation vs. X[^{3}He].

In Fig. 3-(a), we show the central rotation from all the beam blips in this experiment vs. RF power level. There is no P_{RF} dependence for X[^{3}He] ≤ 5%, but for X[^{3}He] ~ 6%-18%, we have larger counter-I_p rotation at higher RF power. The rotation change at ~ 2 krad/sec per MW ICRF power is about a factor of 4 larger than the observed rotation difference in a previous study on direct momentum input from the directional fast waves in the ICRF minority heating scenario [7]. A pulse at 1.8 MA indicates a larger counter-I_p rotation. Note ω_ϕ ~ -10 krad/s corresponds to thermal Mach number M_{th} (0) ~ -0.07 and Alfven Mach number M_A (0) ~ -0.003. The approximately linear RF power dependence is similar to the result from Alcator C-Mod as shown in Fig. 3-(b), which also shows an I_p dependence (details discussed in Ref. [3]).

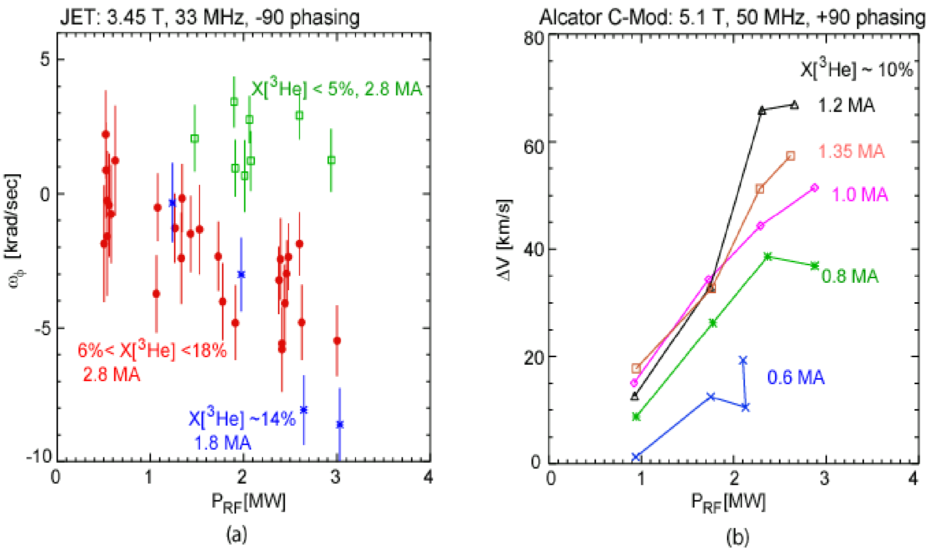
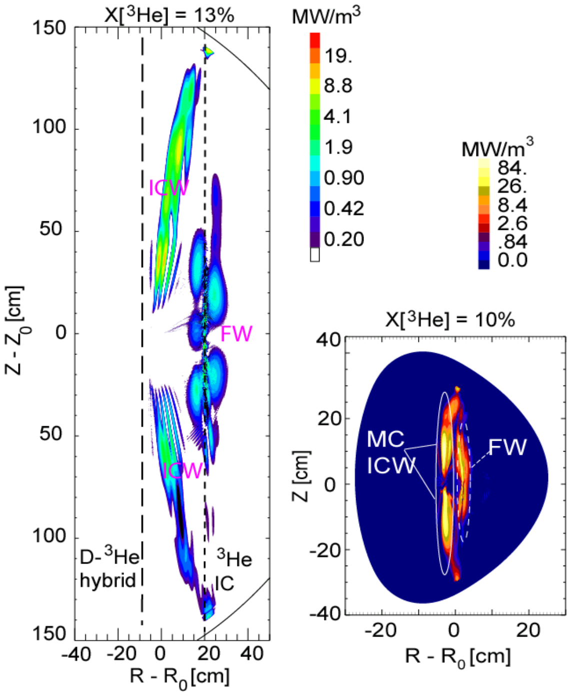


FIG. 3 (a) JET rotation at different X[^{3}He]and I_p vs. ICRF powe; (b):Alcator C-Mod rotation at different I_p vs. ICRF power..

At low X[^{3}He], the ICRF power is in the minority heating regime, and fast waves directly interact with the ^{3}He ions. At large X[^{3}He], e.g., ≥ 25% in this JET experiment, almost all the RF power is deposited on electrons via mode converted waves, and wave-^{3}He ion interaction is weak. In the intermediary regime where we observed large flow drive effect on both JET and Alcator C-Mod, the launched fast waves from the antenna undergo mode conversion, and the resulted MC ion cyclotron waves interact with both electrons and the ^{3}He ions. The 2-D power deposition contours from TORIC simulation [8] are shown in Fig. 4 (a) for JET and 4-(b) for Alcator C-Mod, with the wave branches labelled. This mode conversion scenario and interaction between the MC waves with the ^{3}He ions and electrons and associated transport may be key for flow drive, but the detailed physical mechanism is not yet understood.

The trend in the wave particle interactions vs. X[^{3}He] is also confirmed by the scintillator probe (SP) measurement of fast α-particle (3.7 MeV) losses and gamma-ray spectrometry. For X[^{3}He] < 0.5%, SP shows a large amount of fast α-particle loss, suggesting high energy ^{3}He ions created by the fast wave minority heating on the IC resonance with effective temperature ~ 200 keV. For X[^{3}He] ~ 13%, the fast α-particle loss becomes much smaller but is still significant. Together with gamma-ray observations and the temperature dependence of the D-^{3}He reaction rate, the result indicates a population of hot ^{3}He ions (effective temperature ~ 20-40 keV) near the plasma centre, created by the interaction between the MC ICW and ^{3}He ions. In our experiment, the pulses with larger counter-I_p rotation have less ^{3}He ion loss than those in the minority heating regime, where no flow drive effect is observed. As a result, we can reasonably exclude the contribution of fast ion losses to the observed counter-I_p rotation.



(a) JET (b) Alcator C-Mod

FIG. 4 TORIC simulation on RF powers to ^{3}He ions in the cases with strong flow drive effect: (a) JET; (b) Alcator C-Mod.

Similar rotation in the counter-I_p direction has also been observed in a (H)-^{3}He inverted mode conversion plasmas (with dipole phasing) [9]. Counter-I_p rotation has been observed in low I_p minority heating [5], ripple experiment [10], and low I_p (1.4 MA) 2nd harmonic ^{3}He heating [9], thus mode conversion is not the only effective method to drive counter rotation on JET. Further experiments on JET and other tokamaks are needed in order to understand the direction and magnitude of the rotation in these mode conversion flow drive experiments.

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