Observation of Central Toroidal Rotation Induced by ICRF on EAST

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Core plasma rotation of both L-mode and H-mode discharges with ion cyclotron range of frequency (ICRF) minority heating (MH) scheme were measured with a tangential X-ray imaging crystal spectrometer on EAST. Co-current central impurity toroidal rotation change was observed in ICRF-heated L- and H-mode plasmas. Rotation increment as high as 30 km/s was generated at ~ 1.7 MW ICRF power. Scaling results showed similar trend as the Rice scaling but with significant scattering especially in L-mode plasmas. We varied plasma current, toroidal field and magnetic configuration separately to study their effect on L-mode plasma rotation, while keeping other major plasma parameters and heating unchanged during the scanning. It was found that larger plasma current could induce plasma rotation more efficiently. A scan of toroidal magnetic field indicated that the largest rotation was obtained for on-axis ICRF heating. The comparison between lower-single-null (LSN) than (double-null) DN configurations showed that LSN discharges rendered larger rotation change for the same power input and plasma parameters.

1. Introduction

Plasma rotation and velocity shear have been shown to be beneficial for tokamak plasma performance. Strong rotation can significantly affect the transition from L to H mode [1-3], help the formation of internal transport barriers (ITBs) [4], and stabilize destructive magneto-hydrodynamic (MHD) instabilities (i.e. resistive wall modes (RWMs)) [5-7], while rotation gradients can improve plasma confinement by suppressing turbulence [8, 9]. In the current generation of tokamak devices, neutral bean injection (NBI) is the most effective method to produce plasma rotation. However, for International Thermonuclear Experimental Reactor (ITER) and future reactors, this approach may be impractical due to the large machine size and high plasma density. Other alternative rotation drive methods were widely examined without external momentum input. One potential rotation driving scheme was to use ion cyclotron range of frequency (ICRF) heating, and substantial intrinsic rotation induced by ICRF waves has been observed on a number of tokamaks. On JET, co-current toroidal rotation was first observed to be induced by ICRF waves and the driving mechanism was considered to be fast ion pressure gradient [10]. ICRF driven co-current rotation was also observed on Alcator C-Mod for both minority heating (MH) and mode conversion (MC) regimes [11-15], and the mechanism driving rotation was thought to be the edge temperature gradient [16]. On Tore Supra, ICRF-heated plasma toroidal rotation was accelerated in both co- and counter-current direction. A close relationship between rotation change and ion pressure was found and the driving source might be due to the improved confinement [17]. On EAST, ICRF was used as one of the major auxiliary heating schemes and self-generated co-current flows were induced in both L-mode and H-mode plasmas with ICRF heating. These experiment results implied that ICRF heating might be an applicable flow drive method for ITER, which requires significant rotation level for RWM stabilization in typical operation regimes [18]. This paper presents experimental results of the toroidal plasma rotation produced by ICRF as the only auxiliary heating on EAST. ICRF were typically used to deuterium-hydrogen (D-H) plasmas via MH scheme, where the H-minority concentration was typically around 5%.

2. Experimental Description

Rotation measurements were performed on EAST, which is a fully superconducting tokamak (major radius R ~ 1.85 m, minor radius a = 0.45 m, toroidal magnetic field Bt < 3.5 T, plasma current Ip < 1MA) with flexible magnetic configurations (diverted and limited) and advanced wall conditioning techniques for long-pulse (1000s) high-performance steady-state operation [19]. All of these experiments were performed with a molybdenum first wall and lithium wall conditioning. ICRF with a total source power of 12MW was used to heat deuterium plasmas. During the normal ICRF experiments, the antenna was powered at predominantly symmetric spectrum for heating purposes. Both 2D TORIC full-wave simulation and ECE imaging measurement indicated that the ICRF power deposition profile was normally peaked near the magnetic axis for on-axis heating (ϱ ~ 0.1) for Bt ~ 2.0 T and ICRF frequency of 27 MHz [20].

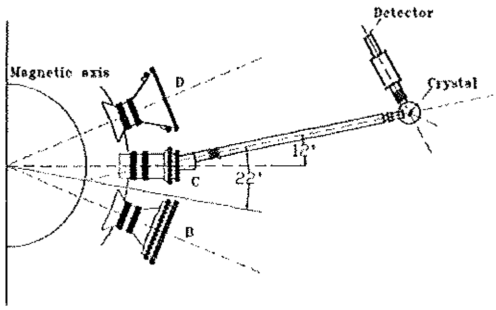

Figure 1. Layout of tangential X-ray crystal spectrometer on EAST

The rotation measurements presented in this paper were all derived from the tangential X-ray crystal spectrometer (TXCS) on EAST (Figure 1). Due to the unavailable absolute wavelength calibration, rotation measurements in this paper were presented in the form of relative velocity increment (ΔV0), i.e. the rotation velocity magnitude was subtracted by the average pre-ICRF value, which was presumed to be nearly zero. The positive sign of rotation velocity means that the rotation increases in the co-current direction, while the negative sign of rotation velocity means the opposite increasing direction.

3. Plasma rotation characteristics for ICRF heated discharges

H-mode plasmas with only ICRF heating were recently obtained with double-null (DN) magnetic shape. The ICRF heated H-mode plasmas were generally characterized by type-III edge localized mode (ELM). Figure 2 shows an ELMy ICRF H-mode discharge (B_t = 2.0 T, I_p = 0.5 MA). The deuterium DN plasma was heated on axis by 27 MHz ICRF. As shown in Figure 2, the pre-ICRF plasma line-averaged density was about 2.0×10^{19} m^{-3} and ICRF power of 1.6 MW was coupled to the plasma from 3.1 to 6.8 s. The L-H transition took place at 3.4 s as indicated by a sudden drop of Dα emission and a successive increase in electron density and stored energy, which occurred at ~ 300 ms after ICRF power was applied and the duration of H-mode was about 3.4 s. After the application of ICRF power, substantial changes in plasma parameters were observed. Electron density rise to ~ 3.54×10^{19} m^{-3}, stored energy increment was about 55 kJ, core ion and electron temperature showed an increase

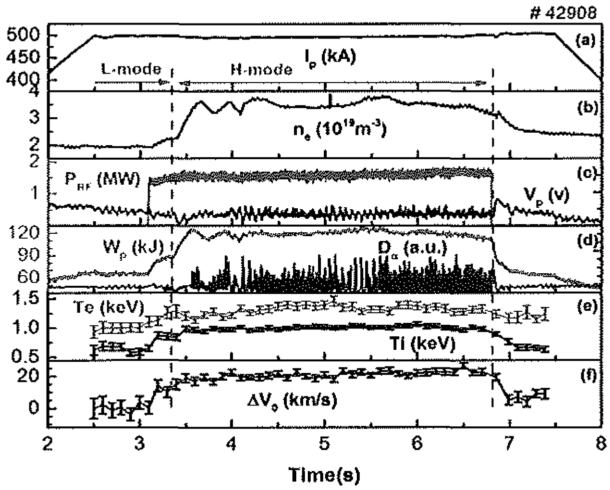

Figure 2. Time histories of plasma parameters for an ICRF heated H-mode discharge: (a) plasma current; (b) electron density; (c) ICRF injection power (red) and loop voltage; (d) stored energy (red) and Dα emission; (e) electron (red) and ion temperature; (f) central toroidal rotation.

of 370 eV and 330 eV, respectively. The increase in core plasma toroidal rotation was about 20.0 km/s relative to pre-ICRF phase and remained elevated during the entire H-mode phase.

Toroidal rotation generally increases with stored energy consistently, which showed close relationship between rotation and confinement [11, 12]. Figure 3 showed a scatter plot of central toroidal rotation increase versus the change of stored energy normalized to plasma current for ICRF-heated plasmas. The dataset included both H- and L-mode discharges with ICRF minority heating covering plasma parameters from I_p = 0.3-0.6 MA, n_e = 1.5-3.6×10^{19} m^{-3}, 1.0 MW < P_{ICRF} < 2.0 MW, DN H-mode and LSN and DN L-mode. As shown in Figure 3, these points fell into two groups: plasmas with the normalized stored energy increases below 0.8 J/A were of L-mode, while plasmas with the normalized stored energy increases above 0.8 J/A were of H-mode. The general trend of rotation increase versus stored energy increase was obvious for a wide range of plasma parameters, implying again the close relation between energy and momentum confinement as summarized by Rice et al [21]. Rice scaling is a global scaling between global plasma parameters, it doesn't include too much physics. When looking at L-mode data alone, the data scattering was not small, and the rotation increase even faster than a linear rate over ΔW/Ip, while H-mode data were more closely grouped. To further investigate plasma rotation behaviour in L-mode cases, plasma current, toroidal field and magnetic configurations were scanned during a sequence of deuterium discharges on EAST with only ICRF minority heating to study their effect on the rotation change. The experimental results were summarized in the follow section

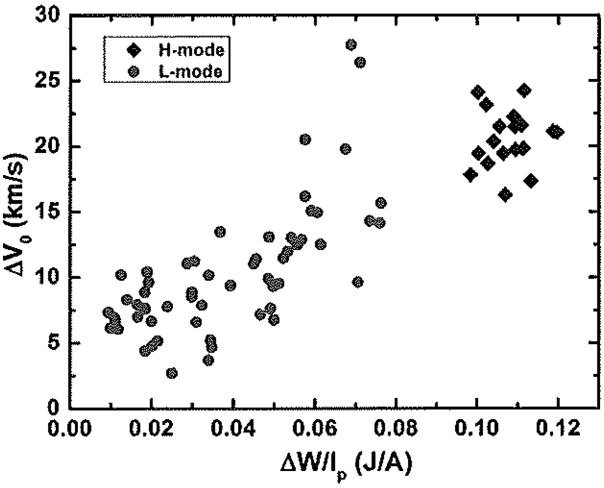

Figure 3. Rotation change as a function of the change in the stored energy normalized to the plasma current.

4. Effect of plasma current, toroidal magnetic field and magnetic configuration on the ICRF-heated plasma rotation

To study the effect of plasma current, toroidal magnetic field, electron density and ICRF power were also fixed at the same value while Ip was varied from 0.3 MA to 0.5 MA. Figure 4 plots the waveforms of several representative plasma parameters for deuterium LSN L-mode discharges (B_t = 2.0 T) at different plasma current (0.3 MA, 0.4 MA and 0.5 MA). The line-averaged densities were ~ 1.7×10^{19} m^{-3}. It could be seen that the rotation change depended on plasma current, where larger Ip generated larger rotation. For I_p ~ 0.3 MA, 0.4 MA and 0.5 MA, the stored energy increment was ~ 20 kJ, ~ 30 kJ and ~ 40 kJ, and toroidal rotation increment were ~ 10 km/s, ~ 16 km/s and ~ 30 km/s, respectively. For these three cases, the change of stored energy increased with plasma current,

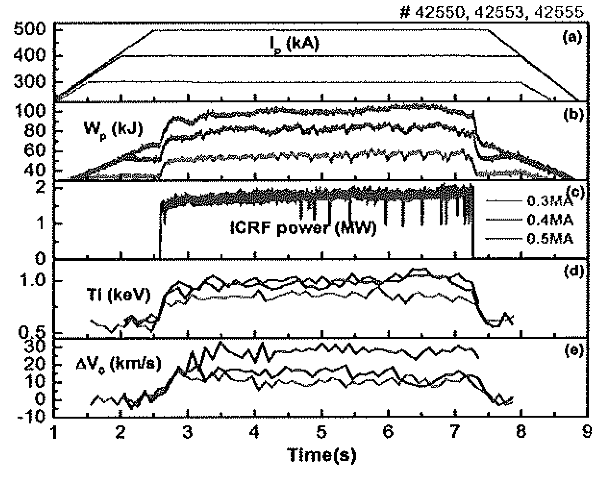

Figure 4. Time histories of several parameters for ICRF heated discharges with different Ip: (a) plasma current; (b) stored energy; (c) ICRF injection power; (d) ion temperature; (e) central toroidal rotation.

resulting in similar values of $\Delta W/I_p$. In this case, larger plasma current generated larger toroidal rotation, it may be due to the better coupling efficiency between ICRF power and plasmas with larger current. Although the global scaling law showed a general trend of rotation increase versus $\Delta W/I_p$, the rotation change did not increase with $\Delta W/I_p$ linearly. The result showed that for the same ICRF power, change in target plasma parameters affected the resulting rotation, but could still be roughly described by Rice scaling

The effect of ICRF resonance location on the rotation was also investigated by changing the toroidal magnetic field at fixed ICRF frequency (27 MHz) and plasma current (0.4 MA). Figure 5 showed the results of toroidal magnetic field scan for a series of deuterium DN L-mode discharges. The plasma densities were ~ 2.0×10^{19} m^{-3}, and ICRF at ~ 1.5 MW was delivered to the plasma. It could be seen that the largest core rotation increment was obtained for B_{t0} ~ 1.9-2.0 T, for which on-axis ICRF heating was occurred. Off-axis heating generally resulted in less rotation increment in the core. At fixed frequency, the H ion cyclotron (IC) resonance was on the magnetic axis for B_{t0} ~ 1.9-2.0 T, while the IC resonance was on the high-field side (HFS) of the axis for B_{t0} = 1.8 T and on the low-field side (LFS) of the axis for B_{t0} = 2.13 T, 2.26 T. When the ion cyclotron resonance was away from the magnetic axis, the flow drive was not as effective as on-axis heating in the core region. Due to limited diagnostic capabilities, it was hard to evaluate the rotation changes in off-axis positions, but from JET results it was showed that varying resonance location did not change off-axis rotation substantially and the most change was still in the core [19].

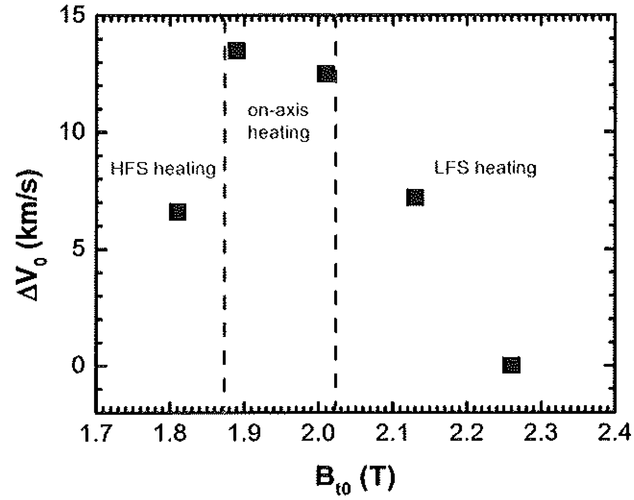

Figure 5. Dependence of rotation increment on toroidal magnetic field: ΔV_0 versus B field.

The flow drive efficiency was also found to be affected by the plasma shape. Figure 6 compared time traces of plasma parameters for an LSN plasma (red) and DN plasma (blue) on EAST. Both discharges were heated by 27 MHz ICRF with the same Ip = 0.5 MA, same density (ne ~ 1.75×10^{19} m^{-3}), toroidal magnetic field (B_t = 2.0 T), similar RF power (P_{RF} = 1.75 MW). After the application of ICRF, both stored energy and ion temperature increased significantly at similar magnitude, however, the driven rotation velocities were very different for LSN and DN plasmas: LSN plasma rotation increase was much higher than plasma rotation increase in DN plasma. Core rotation increases were 30 km/s and 15 km/s, both in the co-current direction.

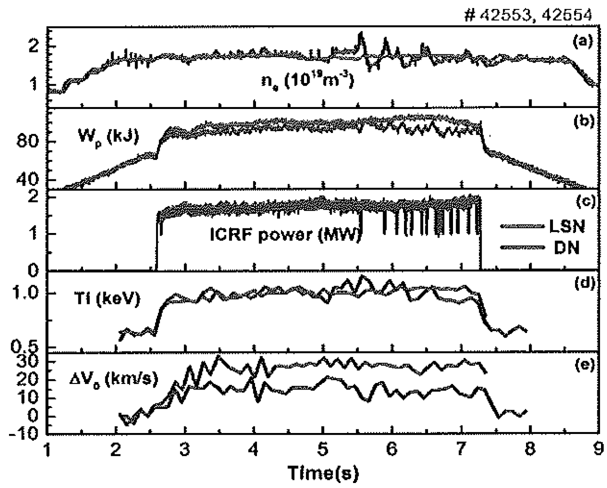

Figure 6. Time histories of several parameters for LSN and DN L-mode discharges: (a) electron density; (b) stored energy; (c) ICRF injection power; (d) ion temperature; (e) central toroidal rotation.

5. Conclusions

Core plasma rotation and ion temperature in both H-mode and L-mode discharges with 27 MHz ICRF minority heating alone were measured using a high-resolution X-ray imaging crystal spectrometer on the EAST. Significant co-current toroidal rotation increases in both H-mode and L-mode plasmas were observed. The flow drive was found to be sensitive to plasma current, toroidal field and plasma shape. The toroidal rotation was higher in plasmas with larger current. For a fixed RF frequency, the largest core rotation increase was obtained at an optimized toroidal field which makes the IC resonance on the magnetic axis. Additionally, LSN plasma produced larger rotation increase than DN shape while keeping other parameters the same plasmas

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References

[1] Shaing K C, Crume E C. 1989, Phys. Rev. Lett., 63: 2369
[2] Groebner R J, Burrell K H, Seraydarian R P. 1990, Phys. Rev. Lett., 64: 3015
[3] Ida K, Hidekuma S, Miura Y, et al. 1990, Phys. Rev. Lett., 65: 1364
[4] Wolf R C 2003, Plasma Phys. Control. Fusion 45: R1
[5] Bondeson A, Ward D J. 1994, Phys. Rev. Lett., 72: 2709
[6] Betti R, Freidberg J P. 1995, Phys. Rev. Lett., 74: 2949
[7] Strait E J, Taylor T S, Turnbull A D, et al. 1995, Phys. Rev. Lett., 74: 2483
[8] Hahm T S, Burrell K H. 1995, Phys. Plasmas, 2: 1648
[9] Burrell K H. 1997, Phys. Plasmas, 4: 1499
[10] Eriksson L G, Righi E, Zastrow K-D. 1997, Plasma Phys. Control. Fusion, 39: 27
[11] Rice J E, Bonoli P T, Goetz J A, et al. 1999, Nucl. Fusion, 39: 1175
[12] Rice J E, Lee W D, Marmar E S, et al. 2004, Phys. Plasmas, 11: 2427
[13] Rice J E, Lee W D, Marmar E S, et al. 2004, Nucl. Fusion, 44: 379
[14] Lin Y, Rice J E, Wukitch S J, et al. 2008, Phys. Rev. Lett., 101: 235002
[15] Lin Y, Rice J E, Wukitch S J, et al. 2011, Nucl. Fusion, 51: 063002
[16] Rice J, Hughes J W, Diamond P H, et al. 2011, Phys. Rev. Lett., 106: 215001
[17] Eriksson L G, Hoang G T, Bergeaud V. 2001, Nucl. Fusion 41: 91
[18] Liu Y, Bondeson A, Gribov Y, et al. 2004, Nucl. Fusion, 44: 232
[19] Wan B Y, Li J G, Guo H Y, et al. 2013 Nucl. Fusion, 53: 1040006
[20] Zhang X J, Zhao Y P, Wan B N, et al. 2013, Nucl. Fusion, 53: 023004
[21] Rice J E, Ince-Cushman A, deGrassie J S, et al. 2007, Nucl. Fusion, 47: 1618