Plasma Rotation Behavior of RF-Heated H-mode Discharges on EAST

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Plasma rotation driven by RF waves such as lower hybrid current driven (LHCD) and ion cyclotron range of frequencies (ICRF) heating is considered to be able to provide the sufficient rotation for suppressing RWM instability on ITER. Substantial rotation has been recorded on major MCF devices without external momentum input. Recent experimental rotation observations of H-mode plasmas on EAST under LHCD and ICRF were presented in this paper. It was found that co-current core rotation increase was induced for H-mode discharges. For stationary type-III H-mode, core plasma rotation was constant. Type-I ELM decreases the rotation over each burst while ion temperatures remain unchanged. Rotation increase in H-mode plasmas scales proportionally to the increase in plasma stored energy normalized by the plasma current.

1. Introduction

The origin of spontaneous plasma rotation and its characteristics are currently being widely investigated on many tokamaks, since it is considered to be capable of providing the sufficient rotation required for steady-state operations of ITER and future fusion devices, on which neutral beam may not provide enough torque input due to high density and large machine size [1]. This was based on the extrapolation from the scaling derived from the current experiment data of H-mode discharges on several major devices with varying sizes and operating conditions. Currently, LHCD and ICRF are the only auxiliary heating schemes on EAST, which can deliver a maximum power of 4MW and 6MW, respectively. Steady-state long pulse H-mode plasmas have been obtained in the recent campaigns [2]. EAST provides the unique capability of studying spontaneous rotation behaviour under auxiliary heating and current drive without perturbations from external momentum source. During the latest EAST campaigns, plasma rotation profiles were measured for a wide range of plasma conditions and related physics experiments were carried out on EAST.

EAST is a fully superconducting tokomak (R~1.85m, a~0.45m, B_t<3.5T, I_p~1MA) with flexible magnetic configuration and wall conditioning techniques, which is aimed at long-pulse steady-state high performance plasma operations [4]. Since the 2010 campaign, several major upgrades have been carried out, including the replacement of first wall material with molybdenum tiles and upgrade of ICRF and LHW system with a total power of 6MW and 4MW, respectively. Lithium wall conditioning techniques were also improved and several new fueling techniques (pellet injection, supersonic molecular beam injection) were added. These upgrades have greatly extended the EAST's operation regimes. Long-pulse steady-state H-mode plasmas have been readily achieved in the recent EAST campaign [2]. Ion temperature and plasma rotation were reliably measured with two imaging X-ray crystal spectrometers for the core plasma [3]. Recently, the spectrometer was upgraded to improve the time and spatial resolution (~10ms and ~1cm) using new X-ray detecting technology [3]. This passive spectrometer is capable of providing measurements for nearly all kinds of discharges with auxiliary heating schemes. The rotation measurements presented in this paper were entirely from the tangential X-ray crystal spectrometer on EAST.

2. Rotation characteristics of steady-state ELMy H-mode discharges

Figure 1 plots the time histories of plasma parameters for a stationary LSN H-mode discharge with H-mode duration of ~5.9s. Lower hybrid wave (f=2.45GHz, $n_{//}$=2.1) and ICRF wave (f=27MHz) are applied at 1.5 and 1.2 MW, respectively.. On-axis ICRF heating occurs for the toroidal field of ~2.0T. Lower hybrid wave was injected at as early as 0.75s during the current ramp-up phase to suppress the runaway generation at the beginning of the discharge. L-H at 3.1s shortly after the application of ICRF wave, as could been seen in the density increase, the sudden drop in the divertor Dα signal, and the abrupt increase in central electron density, central plasma temperatures and stored energy, and the co-current increase in the central toroidal rotation. The plasma exited H-mode following the withdrawal of ICRF wave at ~9.0s, after which the stored energy, electron density and rotation velocity, plasma temperatures all returned to their previous L-mode values.

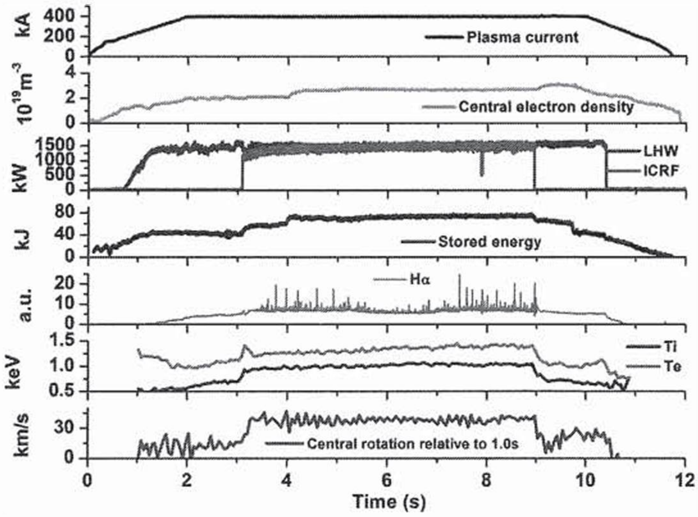

Figure 1 Time histories of plasma parameters for a LHW/ICRF steady-state H-mode discharge (#43251)

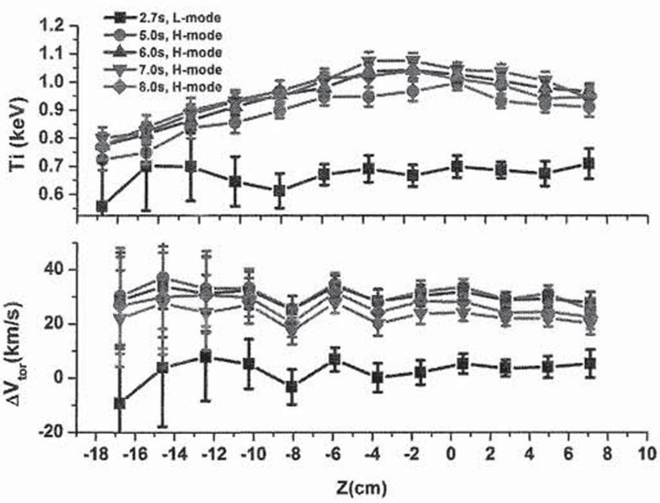

Figure 2 Profile of ion temperature and plasma rotation (#43251)

After L-H transition, central electron density increases from 2.0×10^{19} to $3.0\times10^{19}m^{-3}$. Plasma stored energy increased from 40kJ to 70kJ. Ion temperature increases from 0.6keV before L-H transition to about 1.0keV in the H-mode phase, while electron temperature increases from 1.2keV to 1.4keV in the H-mode phase. Central rotation increase of 40km/s relative to the L-mode phase was induced due to L-H transition, which takes about ~300ms to reach steady-state. All these parameters remain nearly unchanged during the H-mode phase.

Profiles of ion temperature and plasma rotation were also measured. Figure 2 plots the profile of ion temperature and plasma rotation of the core plasma relative to the L-mode phase at 1.0s for five different moments. It can be seen that ion temperatures are centrally peaked on the magnetic axis. Ion temperature increases over L-H transition and the profiles remain nearly unchanged during the H-mode period. The rotation profiles were also elevated following L-H transition during the entire H-mode phase. For the region covered by the tangential XCS, the rotation profile is very flat. Different from the C-Mod results, the increase in the central rotation is already in the co-current direction before the injection of ICRF, which was induced by LHCD [7]. Although the rotation velocity remains very stable, it could be seen that rotation does change slightly when ELMs burst.

Since other parameters were kept constant, ELM bursts might be the source of the change in rotation, which is more prominent in type-I ELMy discharges.

3. Rotation characteristics of steady-state type-I ELMy H-mode discharges

Type-I ELMy H-mode was also obtained with high-power auxiliary heating. Figure 3 plotted time histories of plasma parameters for a discharge with type-I ELMs. The current was lowered to 0.3MA to reduce the power threshold. LHCD (f=2.45GHz, $n_{//}$=2.1) and ICRF (f=27MHz) are injected at 1.2 and 1.8 MW, respectively. L-H transition occurs at 2.77s, first followed by a period of ELM-free phase and then type-I phase before back transition to the L-mode again. The frequency of ELM ranges from 6Hz to 25Hz.

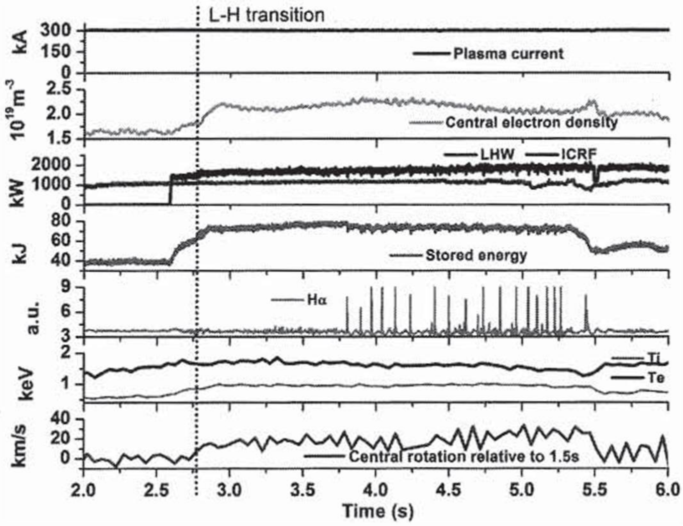

Figure 3 Time histories of plasma parameters for a LHW/ICRF type-I ELMy H-mode discharge (#42556).

For each type-I ELM burst, there is simultaneous drop in the stored energy (3-6 kJ per burst). Between two consecutive bursts, the stored energy tends to recover. ELM also changes the central rotation velocity. On JET, the effect on rotation for type-I ELM of NBI H-mode plasmas was only seen for the outer region up to $r/a \sim 0.65$, with no effect on the core region [8]. The difference may be due to the different heating mechanism between NBI and RF. Figure 4 plots the profiles of ion temperature and rotation velocity at three different times with t=3.77s close to and before the first ELM burst, t=3.85s between the first and second bursts, and t=3.93s between the second and third bursts. For T_i, there was nearly no noticeable change caused by the ELM burst; while the rotation profile was different at pre- and post- ELM burst, with different magnitude of change for each burst. For example, for the first two bursts presented here, the maximum change in rotation velocity is about 9.0 and 13.0 km/s, respectively.

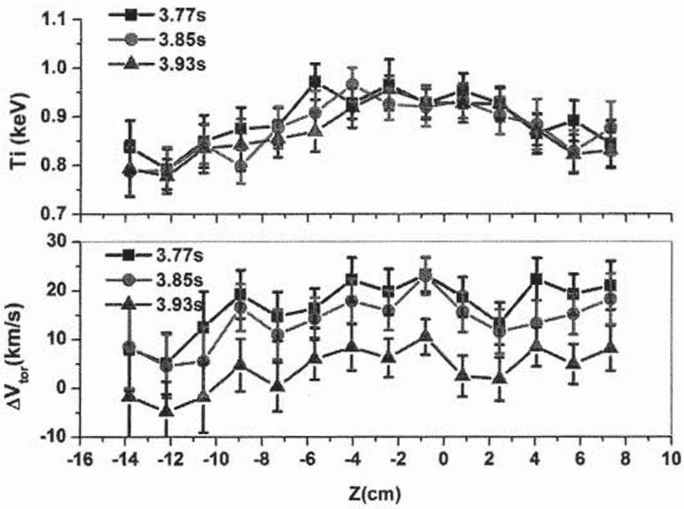

Figure 4 Profile of ion temperature and plasma rotation (#42556)

4. Global scaling of rotation

The effort to unify the rotation measurement on various devices has led to global Rice scaling law for H-mode plasmas, i.e. the core rotation change is proportional to the change in the stored energy divided by the plasma current [1]. The scaling works on various devices for Ohmic H-mode plasmas or plasmas with different auxiliary heating methods Experimental observations for

LHCD/ICRF H-mode plasmas on EAST were also collected. Figure 5 showed the rotation increase over L-H transition as a function of the change in plasma stored energy normalized by plasma current. Two groups of data were included: one for LHW/ICRF H-mode with I_p=0.4MA and the other for ICRF H-mode discharges with I_p=0.5MA. It can been that there is a clear linear trend between the rotation change and plasma stored energy change normalized by the plasma current.

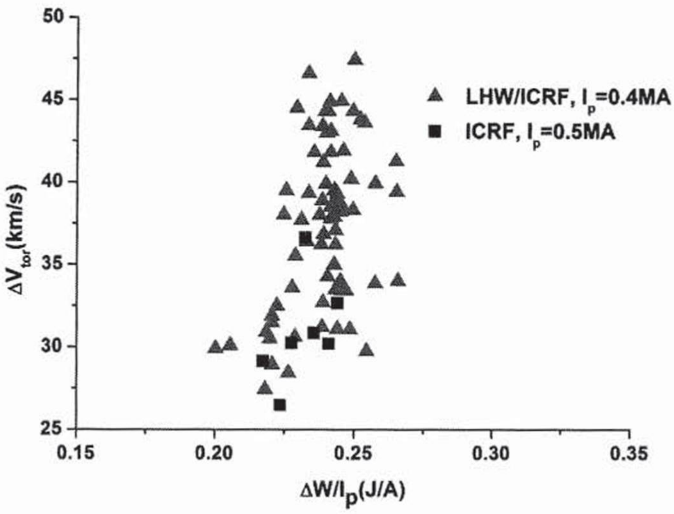

Figure 5 The change in central rotation as a function of the change in stored energy

5. Conclusions

Profiles of H-mode plasma rotation and ion temperature under LHCD and ICRF heating were measured using high-resolution X-ray crystal spectrometer on the EAST tokamak. Strong co-current rotation increase over L-H transition was effectively driven by the two waves. For steady-state ELMy H-mode discharges, plasma rotation is also very stable and the profiles remain nearly constant during the H-mode phase. Type-I ELM H-modes were also obtained with lowered plasma current. Rotation was found to be reduced by the ELM burst. H-mode rotation change on EAST also follows consistently the Rice scaling.

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References

[1] Rice, J.E, et al.,Nucl. Fusion **47** (2007) 1618.

[2] Wan, B.N., et al., Proceeding of 24th IAEA FEC (2012).

[3] Lu, B., et al., Rev. Sci. Instrum. **83** (2012) 10E130.

[4] Wan, B.N., et al., Nucl. Fusion **49** (2009) 104011.

[5] Shi, Y.J., et al, Plasma Phys., Control. Fusion **52** (2010) 085014.

[6] Wang, F.D., et al., J. Korean Phys. Soc. **59** (2011) 2734.

[7] Shi, Y.J., et al., Phys. Rev. Lett. **106** (2011) 235001.

[8] Versloot, T.W., et al., in JET", Plasma Phys. Control. Fusion **52** (2010) 045014.