Experimental study of effect of poloidal flow on stability of magnetic island in LHD and TJ-II

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1. Introduction

In toroidal plasmas, nested flux surfaces are required for good plasma confinement because a magnetic island brings degradation of confinement and/or MHD instabilities such as NTM. On the other hand, it has been reported that the magnetic island might play a key role to improve the confinement and/or MHD stabilities [1-3]. Furthermore, they are found to pose no problem for confinement as long as the magnetic shear is not zero [4,5] and have been found to be able to trigger Core Electron Root Confinement (CERC) in TJ-II [6]. It is thought that the control of magnetic islands enables us to obtain high-performance plasmas. Therefore, the study of the dynamics of magnetic islands is a critical issue. To study the dynamics of magnetic island, experimental observations of two kinds of experimental devices are shown here. The Large Helical Device (LHD) [7] and TJ-II [8] are illustrated in Fig.1. The LHD (Fig.1(a)) is the largest Heliotron-type plasma confinement device with poloidal/toroidal period numbers of 2/10, and is equipped with superconducting helical and poloidal coils. Typical plasma major and average minor radii are R = 3.6 and a = 0.6 m, respectively. The perturbation-coils, which are made of normal conductor, are placed on the top and bottom of LHD at intervals of 0.2π[rad] in the toroidal circumference. The perturbation-coils can make a seed magnetic island [9]. The TJ-II (Fig.1(b)) coil set is composed of 32 toroidal field coils, whose centres describe a circular helix, a central conductor made of two coils, circular and helical ones. There are two pairs of vertical field coils that control the radial position of the plasma, and two OH coils. It is possible to induce an Ohmic current in the plasma using these coils, which can modify the rotational transform ($\iota/2\pi$) profile.

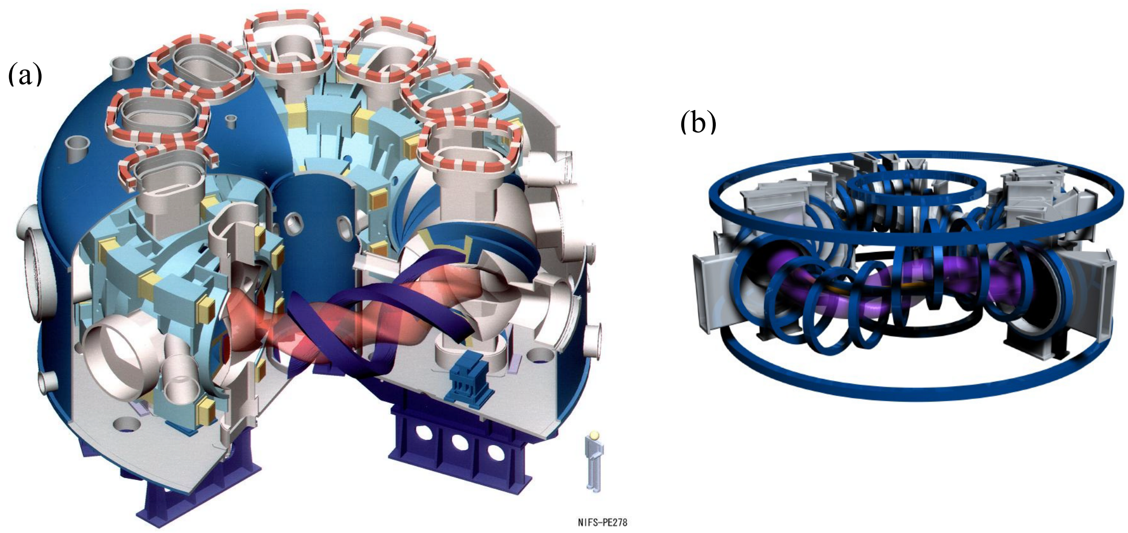

Fig.1 Figure of LHD (a) and TJ-II (b). (not in scale.)

2. Experimental results

In the LHD experiment, the magnetic island produced by the perturbation field coils shows a dynamic behaviour depending on beta (β) and collisionality (ν_h*) [10]. Figure 2 shows the region of the growth and healing of the magnetic island. The magnetic island grows in the lower-β and higher- ν_h* regime (closed circles) while it disappears in the higher- β and lower- ν_h* regime (open circles). The boundary indicated by a black solid line can be clearly drawn in the β - ν_h* space. To investigate the effect of the change of direction of the bootstrap current on the magnetic island, the dependence on the bootstrap current by the finite beta effect via the change of the magnetic configuration is calculated [11]. The boundary where the bootstrap current reverses is indicated by a grey solid line. The direction is ctr- in the high-ν_h* regime and co- in the low-ν_h* regime. Its dependence of the beta on the direction of the bootstrap current is small whereas the dependency of collisionality is weak in experiment. The island healing properties cannot be explained by the dependence of the sign of bootstrap current on beta effects due to the equilibrium change. The dependence of the structure of the magnetic island on beta shows a nonlinear behavior as shown in Fig.3. The resonant field amplitude ($\delta b_{pl}^{n=1}/\delta b_{ext}^{n=1}$) and difference of toroidal angle ($\Delta\phi_{n=1}$) correspond to the square of the width of the magnetic island and the difference of the toroidal angle of X-point from the seed island, respectively. The $\delta b_{pl}^{n=1}/\delta b_{ext}^{n=1}$ increases with beta until a certain critical beta $\beta_c = 0.28\%$. At the same time, the $\Delta\phi_{n=1}$ stays around 0. They discontinuously change at the critical beta. Beyond the critical beta, the magnetic island shows the healing, in which the $\delta b_{pl}^{n=1}/\delta b_{ext}^{n=1}$ is unity and $\Delta\phi_{n=1}$ is $\Delta\phi_{n=1} \sim \pi$[rad]. The numerical study of the dynamics of the magnetic island is also done by using the 3-D MHD equilibrium code HINT/HINT2 [12], in which the net (bootstrap current) current free condition is adopted and the Pfirsch-Schlüter current is allowed to flow in the plasma. The calculation results are shown by solid lines with

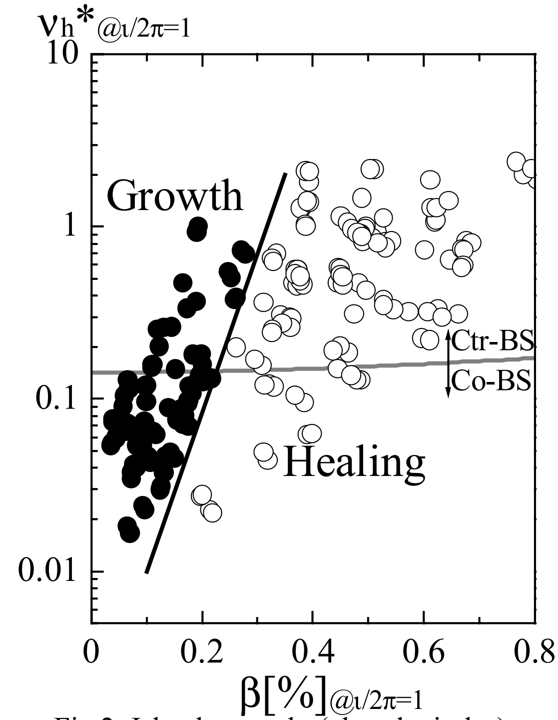

Fig.2 Island growth (closed circles) and healing (open circles) in β - ν_h^* space [10].

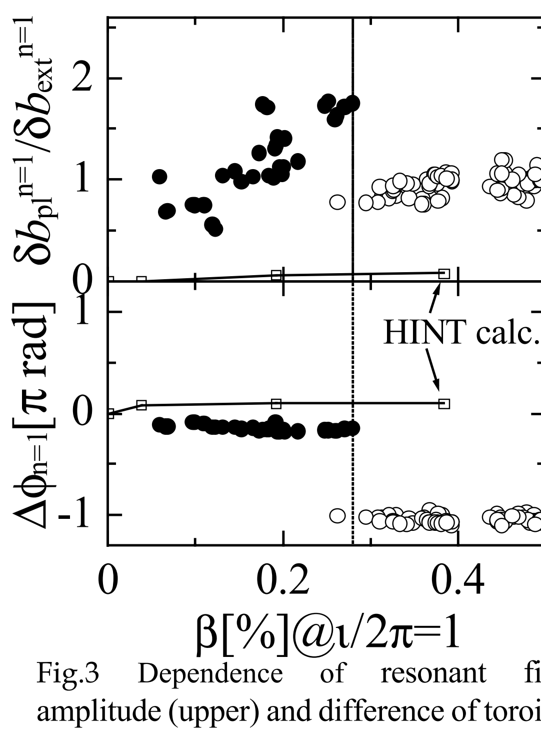

Fig.3 Dependence of resonant field amplitude (upper) and difference of toroidal angle on beta

open squares in Fig.3. The $\delta b_{pl}^{n=1}/\delta b_{ext}^{n=1}$ increases with averaged beta and the $\Delta\phi_{n=1}$ is constant. This behaviour has two differences from the experimental result. First, the value of $\delta b_{pl}^{n=1}/\delta b_{ext}^{n=1}$ is one order or more smaller than that of the experimental observation. Second, self-healing does not appear beyond the critical beta $\beta_c = 0.28\%$. These results mean it cannot explain the experimental observation in the effect of the Pfirsch-Schlüter current alone.

The magnetic island in the core electron root confinement (CERC) [13] in TJ-II shows healing. The CERC is produced by locating a low order rational in the core of TJ-II plasmas. The rational increases the positive electric field which improves the heat confinement. The TJ-II stellarator has a set of coils that can be used to induce an Ohmic current in the plasma. It is possible to change dynamically the current during the discharge and to modify the $\iota/2\pi$ profile. Figure 4 shows the time sequence of the CERC formation with $\iota/2\pi$ scan [6]. When the plasma current reaches $I_p \sim -1\ 6$ [kA], the core electron temperature rapidly increases, showing a clear increase in heat confinement coincident with the presence of the $n/m = 3/2$ resonance near the plasma core. In case of $n/m = 4/2$, the healing of the magnetic island has been observed [14]. As shown in Fig.5, island healing is produced simultaneously to the CERC onset. In the time slice of $t = 1117$[ms] and 1120[ms], the local flattening of soft X-ray (SXR) profiles at $\rho = 0.4$ appears. This shows the existence of a magnetic island. The fact that this

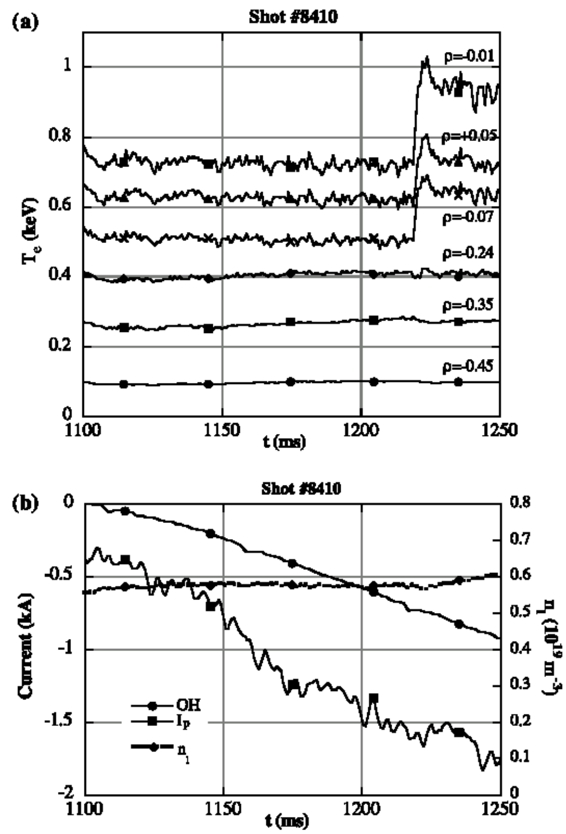

Fig.4 Time evolution of (a) temperature and (b) line density, OH coil current and plasma current for the case of Ohmic current induction [6].

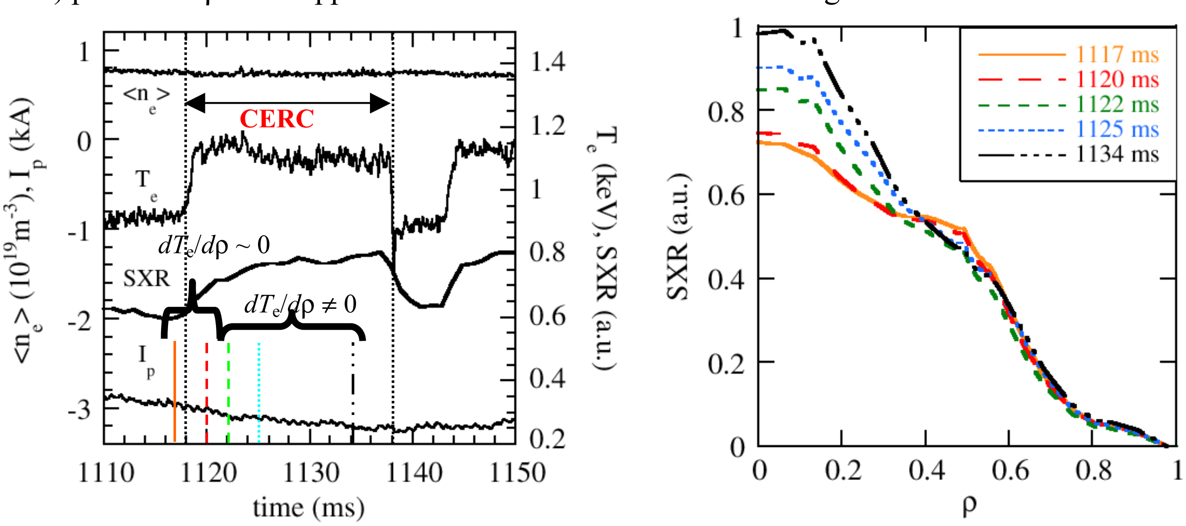

Fig.5 Time evolution of electron density, electron temperature, SXR and plasma current in CERC formation (Left). SXR profiles (Right) [14].

magnetic island does not rotate has been confirmed by the SXR tomography diagnostic. Just after the formation of the CERC, the local flattening of SXR profiles disappears at $t > 1122$[ms]. These experimental observations mean that the magnetic island is in the healing-state during the CERC formation. Castejón, et al. have shown that the time scale can be estimated by following equation [15], which has been extracted from the modified Rutherford equation and is in rough agreement with the experimental data.

$$\Delta t \approx \frac{w^2}{\eta\left(w\Delta' - 6\sqrt{\varepsilon}\,\frac{|\Delta p|\iota}{B_p \Delta\iota}\right)} \tag{1}$$

When the CERC without temperature flattening is formed, mode stabilization is observed, nevertheless as shown in Fig.6 [16]. It is the opposite sense to the MHD characteristics. Namely, in the CERC formation, fluctuation is suppressed in case of a finite pressure gradient whereas the fluctuation appears when the pressure gradient goes down.

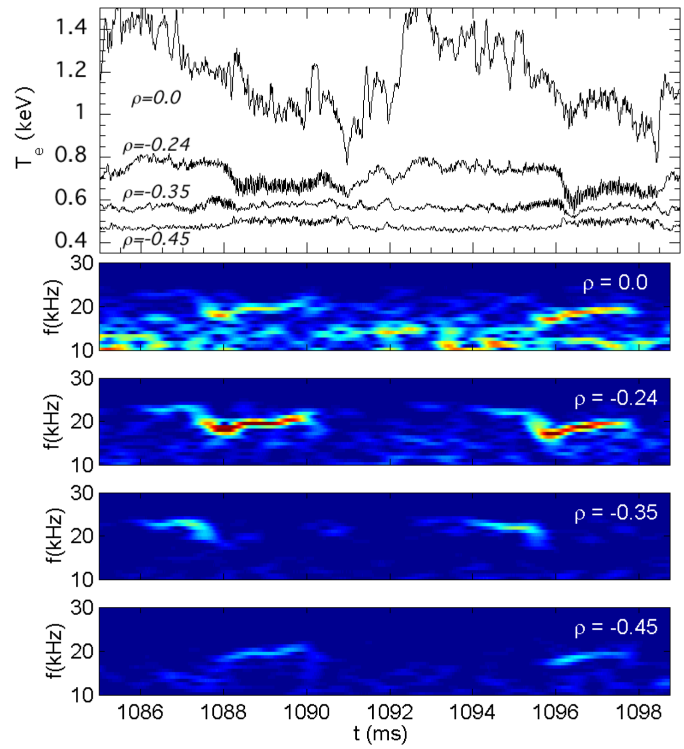

Fig.6 Time evolution of electron temperature (Upper) and spectrum of ECE (Lower) [16]. CERC is formed from t = 1092[ms] to t = 1096[ms].

3. Discussion

From the above experiments, it is thought that the radial electric field is important to clarify the dynamics of the magnetic island, since it is a common ingredient of LHD and TJ-II, provided the right sign of magnetic shear (negative) is given. In the LHD experiment, BS current and PS current cannot explain the healing of the magnetic island. In a TJ-II experiment, the increase of the radial electric field is important to trigger CERC formation in which the magnetic island shows healing. Here, we pay attention to the radial electric field. In other words, the relationship between poloidal flow and island are discussed.

The role of the ion polarization current on the stability of the magnetic island is written in Ref.[17]. A coefficient of a_{pc} denotes the sign of the effect of ion-polarization current, $a_{pc} = \omega(\omega - \omega_{*pi})\omega_{*pi}^{-2}$, where ω and ω_{*pi} are the relative angular velocity of the island to the $\boldsymbol{E}\times\boldsymbol{B}$ drift and that of the ion diamagnetic drift, respectively. When the plasma is in the electron-root ($E_r > 0$), the effect is stabilizing. In contrast, in the case of an ion-root ($E_r < 0$), the relation between the magnitudes of the $\boldsymbol{E}\times\boldsymbol{B}$ drift ($\omega_{\boldsymbol{E}\times\boldsymbol{B}}$) and the ion diamagnetic drift (ω_{*pi}) is important. The relationship of $|\omega_{\boldsymbol{E}\times\boldsymbol{B}}| >(<) |\omega_{*pi}|$ indicates the island is stabilized (destabilized). In the condition of the electron-root ($E_r > 0$), in which the ion polarization current effect is stabilizing, the experimental observation of the CERC in TJ-II plasmas shows that the magnetic island is healed (See Fig.5), which is in agreement with the theoretical prediction. The positive E_r can be created in the neighbourhood of magnetic resonances, which will be able to heal them under certain conditions. In the LHD experiment, on the other hand, the radial electric field calculated by GSRAKE [18] in the case that the magnetic island is stabilized shows the ion-root ($E_r < 0$) in the whole region of the plasma. Therefore, the relation between $|\omega_{\boldsymbol{E}\times\boldsymbol{B}}|$ and $|\omega_{*pi}|$ is important. Figure 7 shows the profile of $\omega_{\boldsymbol{E}\times\boldsymbol{B}}$ and ω_{*pi} assuming n_i (p_i) = n_e (p_e), in which the $\omega_{\boldsymbol{E}\times\boldsymbol{B}}$ ~ -5[krad/s] and ω_{*pi} < 5[krad/s]. The relationship of $|\omega_{\boldsymbol{E}\times\boldsymbol{B}}| > |\omega_{*pi}|$ corresponds to stabilization of the island, which is consistent with the experimental observation. The mechanism of the transition of the magnetic island (See Fig.3) is left as an unsolved problem. Further progress of theoretical studies is expected to explain that phenomena.

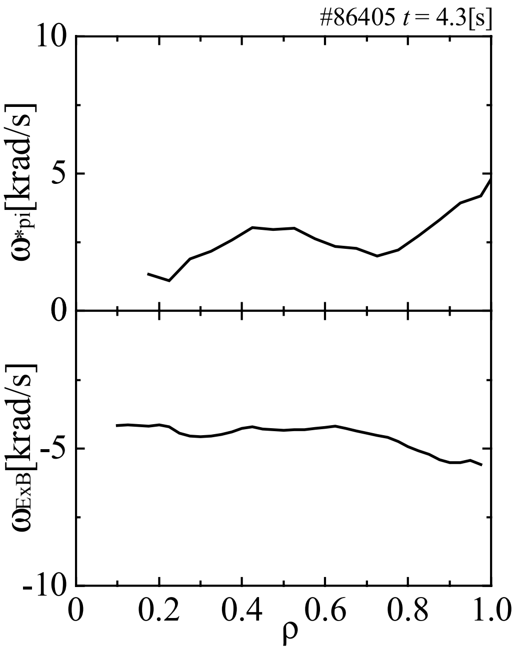

Fig.7 Minor radius profile of ion diamagnetic angular velocity ω_{*pi} (a) and $\boldsymbol{E}\times\boldsymbol{B}$ drift angular velocity $\omega_{\boldsymbol{E}\times\boldsymbol{B}}$ (b).

4. Summary

In LHD, the dynamics of the magnetic island depending on β and ν show non-linear behaviour. The poloidal flow might affect island stabilization in the ion-root ($E_r < 0$) regime. In TJ-II, the magnetic island is present with the ambient electron-root ($E_r > 0$) before the CERC formation. When the CERC onsets, the E_r becomes more intense and the magnetic island is stabilized. The suppression of the associated coherent oscillation is also observed. For further studies, the detailed investigation of the transition of the magnetic island is required in LHD as well as studies on the island width and time scale of growing and healing dependences on collisionality etc. in TJ-II.

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