Rapid Communications

Direct Evaluation of Spatio-Temporal Change in Current Density Profile Applied to a Discharge with Neo-Classical Tearing Mode

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An analytical method to evaluate spatio-temporal change in the current density profile directly from the motional Stark effect (MSE) diagnostic is applied to a discharge, where a neo-classical tearing mode (NTM) appeared and was stabilized by electron cyclotron current drive (ECCD). The analysis clearly shows a spatially localized decrease in current density at the magnetic island location, implying a decrease in bootstrap current due to a flattening of the pressure profile within the island. When the NTM is stabilized after the start of the ECCD application, an increase in current density at the island location is observed.

Keywords:

motional Stark effect (MSE), neo-classical tearing mode (NTM), magnetic island, bootstrap current, electron cyclotron current drive (ECCD).

A method to analyze small changes in current profile by far off-axis ECCD [1] using the MSE diagnostic [2] was developed. The method is applied to the JT-60U discharge where the m/n = 3/2 NTM was stabilized by ECCD [3]. A spatially localized decrease in current density at the magnetic island location is clearly observed, implying a decrease in bootstrap current density due to a flattening of pressure profile within the island, as was reported for a larger island for the m/n = 2/1 NTM by equilibrium reconstruction [4]. We also see compensation for the missing bootstrap current by ECCD.

Here we describe the analysis; the accuracy of the analysis here has been improved from the one in ref. [1], taking into account of an elongation κ of the plasma shape. The MSE diagnostic (spatial channel i) measures the temporal evolution of pitch angle $\gamma_i \equiv \tan^{-1}(B_{p,i}/B_{t,i})$ of the magnetic field in a plasma, where $B_{p,i}$ and $B_{t,i}$ are the poloidal and toroidal magnetic fields at the location of the i-th channel. Integration of Ampere's law gives $\bar{B}_{p,i} = \mu_0 I_i / C\rho_i$, where I_i is the current enclosed in a magnetic surface at the channel i. An overbar means an average along the magnetic surface, and $C \equiv 2\pi a\sqrt{(1+\kappa^2)/2}$ is the perimeter of the last closed flux surface, where a is the horizontal minor radius. Equilibrium reconstruction determines the normalized minor radius ρ_i for each channel. In typical JT-60U discharges, $B_{p,i}$ agrees with $\bar{B}_{p,i}$ within 30%, so that we have

$$I_i \sim \frac{C\rho_i}{\mu_0} B_{p,i} = \frac{(B_t R)}{\mu_0}\frac{C\rho_i}{R_i}\tan(\gamma_i),$$

where R_i is the major radius of channel i. Subtracting each side for channels i and $i + 1$, the current enclosed between the two magnetic surfaces is

$$\delta I_i(t) \equiv I_i(t) - I_{i+1}(t) = \frac{B_t R}{\mu_0} C\left\{\frac{\rho_i}{R_i}\tan\gamma_i(t) - \frac{\rho_{i+1}}{R_{i+1}}\tan\gamma_{i+1}(t)\right\};$$

I_i is larger than I_{i+1}, since the MSE channels in JT-60U are located near the outboard mid-plane, and the channel order satisfies $R_{i+1} < R_i$. Since the plasma configuration is fixed, ρ_i hardly changes in time. The major radius R_i of the measurement point is constant in time. Therefore an increment of $\delta I_i(t)$ from that at a time $t = t_0$ is expressed as

$$\delta I_i(t;t_0) \equiv \delta I_i(t) - \delta I_i(t_0) \sim \frac{B_t R}{\mu_0} C\left\{\frac{\rho_i}{R_i}\tan\gamma_i(t;t_0) - \frac{\rho_{i+1}}{R_{i+1}}\tan\gamma_{i+1}(t;t_0)\right\} \quad (1),$$

where we used $\tan(\gamma_i(t))\tan(\gamma_i(t_0)) << 1$ that is valid under the large aspect ratio approximation. The corresponding change in the current density is given by $\delta j_i = \delta I_i/(\pi\kappa a^2(\rho_i^2 - \rho_{i+1}^2))$. The equilibrium determining ρ_i is reconstructed only at the reference time $t = t_0$, not at every time step, under a condition that ρ_i is constant in time. When the configuration parameters (C and ρ_i) are determined at $t = t_0$, the equation (1) directly gives $\delta I_i(t;t_0)$. The most important point is that $\delta j_i(t;t_0)$ is sensitive only to the spatio(i)-temporal(t) change in measured pitch angle $\gamma_i(t)$. A change in $\delta j_i(t;t_0)$ is a direct consequence of change in the measured $\gamma_i(t)$. When obtaining such temporal evolution of current density profile with repetitive equilibrium reconstructions, the equilibria are affected by parameterizations of $FF'(\psi)$ and $p'(\psi)$ in solving the Grad-Shafranov equation. The parameterizations can smooth out changes in the current density profile with a small-scale length close to the spatial resolution of the MSE diagnostic.

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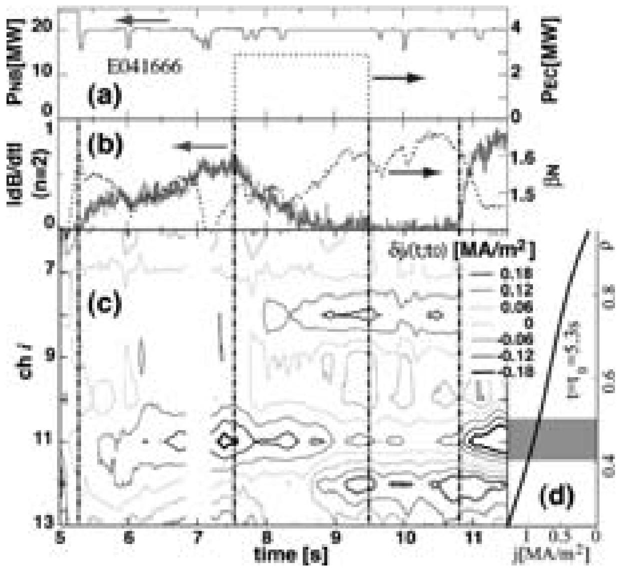

Fig. 1 (a) Injection power by NB and EC waves. (b) Amplitude of magnetic fluctuation ($|dB/dt|$) for n = 2 mode and normalized beta. (c) Temporal evolution of $\delta j_i(t;t_0)$. (d) Current density profile at $t = t_0$ for the normalized minor radius corresponding to the MSE channel i.

Such difficulty does not appear in this method.

The analysis is applied to a discharge shown in Fig. 1. The plasma configuration was fixed. During the constant neutral beam (NB) injection power phase (t < 7.6 s as shown in Fig. 1(a)), increase of the magnetic fluctuation is observed (Fig. 1(b)) due to appearance of an NTM (m/n = 3/2). When ECCD of 2.9 MW at the NTM-induced islands was applied from t = 7.6 s, the mode amplitude decreased, and the NTM was completely stabilized at t = 9.0 s. After the stabilization of the NTM, normalized beta (β_N) increased (Fig. 1(b)) as a result of the NTM stabilization, even if EC heating was stopped after t = 9.5 s. Figure 1(c) shows a contour plot of $\delta j_i(t;t_0)$ on the $t - i$ plane, that is, changes in the current density between magnetic surfaces at MSE channels i and i + 1 from the reference (t_0 = 5.3 s). The current density profile at $t = t_0$ is shown in Fig. 1(d) for the ρ corresponding to the MSE channel i in Fig. 1(c). We see decrease in $\delta j_i(t;t_0)$ near i = 11 (ρ = 0.41–0.51) after the appearance of the NTM (t = 5.3 s) until the ECCD starts at t = 7.6 s. The location matches the location of the magnetic island center (ρ = 0.46±0.03 at t = 7.5 s) identified by fluctuation in electron temperature measured by the electron cyclotron emission (ECE) diagnostic. This location also agrees with the location of the q = 1.5 magnetic surface resonant to the m/n = 3/2 mode. The radial width of the island seems to be close to the spatial separation of the MSE (~8 cm). After the start of the ECCD (t > 7.6 s), the decreased $\delta j_i(t;t_0)$ gradually disappeared, and the n = 2 mode amplitude simultaneously decreased, showing stabilization of the NTM. After the NTM stabilization, when β_N reached 1.67, again, an NTM appeared (t = 10.8 s) at the same location (i = 11; ρ = 0.41–0.50) and a decrease in $\delta j_i(t;t_0)$ was also observed.

A decrease in current density at i = 8 after the start of the EC injection is seen in Fig. 1(c). This decrease is considered due to the central peaking of the current density profile under the fixed plasma current, that is, the decrease in current density at i = 8 and the increase in current density inside the location ($i \geq 9$) by (1) additional EC driven current and (2) bootstrap current increased by the increased injection power and by the NTM stabilization.

The amount of the EC driven current, and hence the ECCD efficiency, under the existence of the magnetic islands will be discussed elsewhere, since change in the current $\delta I_i(t;t_0)$ includes not only the EC driven current but also the bootstrap current. Careful separation of both components is necessary.

The new method reported here is effective in analyzing a spatially localized change in current. Although the temporal resolution of the MSE diagnostic is restricted to several tens of ms (presently in JT-60U), this analysis can be applied to various phenomena that evolve in a time scale of local resistive diffusion of the magnetic field (typically longer than 0.1 s in JT-60U); e.g., non-inductive current drive such as the ECCD described in ref. [1], resistive instabilities affected by current profile (NTM here), and current hole [5]. For the last example, the temporal evolution of bootstrap current at an internal transport barrier has been considered to play an important role in the production of the current hole.

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