Measurement of the phase relationship of coupled *n* = 1 tearing modes in J-TEXT

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Introduction

Tearing mode (TM) is a common magnetohydrodynamics instability in tokamaks. Coupled tearing modes lead to confinement degradation, and may cause major disruption. Near the onset of partial thermal quenches, locked island O-points are observed to align with each other on the low field side (LFS) midplane[1]. However, recent experiments in AUG show that phase difference of 2/1 and 3/1 mode varies significantly with plasma pressure and rotation velocity[2]. The observation of phase difference and its parameter dependence helps to understand the evolution of coupled tearing modes. Based on the model for ASDEX-U [2,3], a fitting model of magnetic measurements in J-TEXT is developed to determine the phase difference of 2/1 and 3/1 modes in J-TEXT.

Analytical Model

For coupled tearing modes with the same toroidal mode number *n* and rotation frequency *f*, the poloidal mode number *m* can be distinguished by a poloidal array of Mirnov coils. The perturbed magnetic field generated by the tearing mode can be measured by the Mirnov probes, and the poloidal variation of the perturbed field δB_θ depends on the amplitudes and phase difference of coupled modes.

The source of the perturbed field is the perturbed current in the vicinity of the resonant surface. To simplify the calculation of the perturbed current, it is assumed the perturbed current is on the resonant surface and flows force-free along the equilibrium field line. The amplitudes and phases of the surface currents can be fitted by measured data of Mirnov coils, representing the amplitude and phase of the tearing modes.

The perturbed current representing the *m/n* mode can be expressed as $j = j_m \cos(m\theta^* + n\varphi + \omega t + \varphi_m)$, where φ is the toroidal angle of the Mirnov array, φ_m is the phase, $\theta^*(\theta)$ is the poloidal angle in straight field line coordinate, defined by the condition $d\varphi/d\theta^* = q$. The position of resonant surfaces and the poloidal angle θ^* are determined by EFIT. The value

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of θ^* in this model can also be expressed as $\theta^* = \theta - \lambda \sin\theta$ for the circular J-TEXT plasma, where λ is a function of the minor radius r.

The surface currents in the model are represented as filaments, which are arranged at equal intervals by θ^*. The current of each filament is

$$I_i = |I_{m/n}| \cos\left(m\theta_i^* + \xi_{m/n}(t)\right)$$

$$\xi_{m/n}(t) = \omega t + \varphi_{m/n}$$

$$\theta_i^* = \frac{2\pi i}{N_{\text{filament}}} (i = 1,2, \dots, N_{\text{filament}}, N_{\text{filament}} = 720)$$

Where $|I_{m/n}|$ is the maximum current of filaments, $\xi_{m/n}(t)$ is the phase of the *m/n* mode, ω is the mode frequency, $\varphi_{m/n}$ is the initial phase, θ_i^* is the poloidal position of a filament, N_{filament} is the number of filaments on a resonant surface. The perturbed current on the *m/n* resonant surface can be expressed as a complex number $I_{m/n}(t) = |I_{m/n}(t)|\angle\xi_{m/n}(t)$.

The poloidal array in J-TEXT consists of 46 Mirnov coils, measuring the poloidal magnetic perturbation dB_θ/dt. The perturbed field at each Mirnov coil can be expressed as

$$B_{\theta,i\text{coil}}^{\text{exp}}(t) = \left|B_{\theta,i\text{coil}}^{\text{exp}}(t)\right| \cos(\xi_{i\text{coil}}(t)) \ (i_{\text{coil}} = 1,2, \dots, N_{\text{coil}}, N_{\text{coil}} = 46)$$

Where N_{coil} is the number of Mirnov coils in the array. The amplitude and phase of B_θ can be obtained using Hilbert transform. The experimental measurements of B_θ can be expressed as a complex matrix $B_\theta^{\text{exp}}(t)$, which consists of 46 complex numbers $\left|B_{\theta,i\text{coil}}^{\text{exp}}(t)\right|\angle\xi_{i\text{coil}}(t)$.

Assuming that only one mode exists, the perturbed magnetic field at the poloidal array for a unit perturbed surface current can be calculated, expressed as a complex matrix $B_{\theta,m/n}^{\text{cal}}(t)$. Considering the coupling of 2/1 and 3/1 modes (*m*≥4 modes not exist at q_a<4), the total B_θ at the poloidal array (the experimental data) can be expressed as

$$B_\theta^{\text{exp}}(t) = \left[B_{\theta,2/1}^{\text{cal}}(t), B_{\theta,3/1}^{\text{cal}}(t)\right] * \begin{bmatrix} I_{2/1}(t) \\ I_{3/1}(t) \end{bmatrix}$$

The amplitudes and phases of the perturbed surface currents at $q = 2$ and $q = 3$ surfaces can be obtained by least square fitting, and the phase difference of 2/1 and 3/1 tearing modes is defined by $\Delta\varphi = \varphi_{2/1} - \varphi_{3/1}$ is determined. $\Delta\varphi = 0°$ means two modes are in phase coupled on the LFS midplane.

Experimental Results

The coupling of 2/1 and 3/1 modes is often observed in the J-TEXT discharges. In discharge #1069542, the parameters are $R = 1.05$ m, $a = 0.255$ m, $B_{\text{t}} = 1.7$ T, $I_{\text{p}} =$

170 kA, $q_a = 3.1$. There exist saturated tearing modes, and the Mirnov signal on the LFS is much stronger than that on the high field side (HFS), as shown in Figure 1(a). Fitting the Mirnov signal to obtain the amplitudes and phase difference of the 2/1 and 3/1 perturbed currents, as shown in Figure 1(b). The amplitudes of 2/1 and 3/1 perturbed currents are similar. The phase difference is $\Delta\varphi = 0°$, proved that two modes are coupled in phase. Figure 1(c) shows the comparison of the perturbed magnetic field at the poloidal Mirnov array calculated by perturbed current filaments (B_θ^{cal}) and measured in the experiment (B_θ^{exp}), the calculated and experimental values are in good agreement at all poloidal positions.

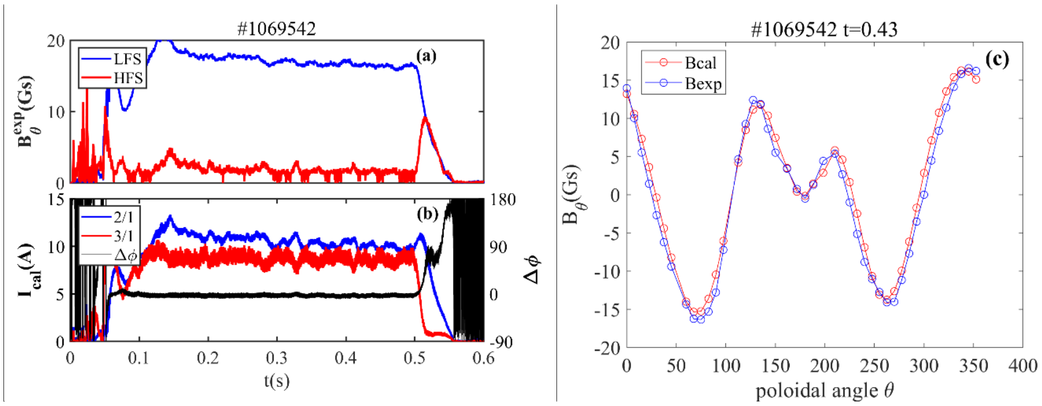

Fig 1. (a) Time evolutions of Mirnov signal (b) Time evolution of the amplitudes and phase difference of 2/1 and 3/1 mode (c) comparison of calculated and experimental data

In discharge #1074404, the parameters are $B_{\mathrm{t}} = 1.7$ T, $I_{\mathrm{p}} = 140$ kA, $q_a = 3.75$. There is only an 8 kHz small magnetic oscillation (SMO) before 0.25 s without large saturated tearing modes, ECRH is turned on at 0.25 s. The power of ECRH is 300kW, and the deposition position of ECRH is at r=-8.5 cm (close to the q=1 surface). Horizontal displacement dx is disturbed at 0.38 s, the frequency of SMO decrease from 8 kHz to 4 kHz. Then a minor disruption happens, excites tearing modes.

After t=0.4 s, the Mirnov signal on the HFS is slightly stronger than that on the LFS. The amplitude of the perturbed magnetic field is not as large as that shown in Fig. 1. Assuming that the asymmetry of the signal is caused by the coupling of 2/1 and 3/1 modes, the perturbed currents are obtained by the fitting model, as shown in Figure 2. The amplitude of the 3/1 mode is smaller than the 2/1 mode, especially the phase difference $\Delta\varphi = 180°$.

After ECRH turns off at 0.55 s, the amplitude of 2/1 perturbed current increases. The frequency of tearing modes increases from 4 kHz to about 6 kHz, and the phase difference jumps from $\Delta\varphi = 180°$ to $\Delta\varphi = 0°$. The phase difference of the tearing modes may be related to the plasma pressure β according to the observation from AUG [2]. Further study is required to understand this observation.

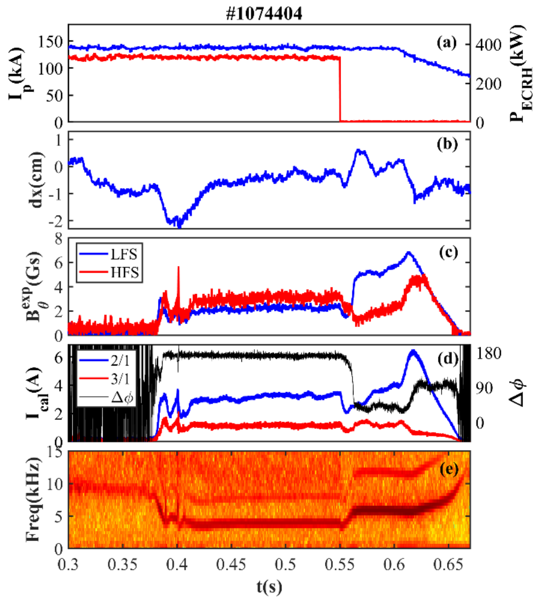

Fig 2. Influence of ECRH on the phase difference of 2/1 and 3/1 modes. (a) plasma current I_p and ECRH power (b) horizontal displacement dx (c) Mirnov signal B_θ on the Hand HFS (d) amplitudes and phase difference of 2/1 and 3/1 perturbed surface current (e) spectrum of the Mirnov signal

Summary and Acknowledgement

In this paper, a model for the phase relationship of the coupled n=1 modes in J-TEXT is developed. The amplitude and phase of the perturbed surface currents at q = 2 and q = 3 surfaces are obtained by least squares fitting, so the time evolutions of the amplitude and phase difference of 2/1 and 3/1 modes are obtained.

The coupling of 2/1 and 3/1 modes is often observed to be in phase in the low field side (LFS) midplane. However, with the application of ECRH, the 2/1 and 3/1 modes are observed to be off phase in the LFS midplane. And the phase difference jumps from 180° to 0° once the ECRH is turned off, meanwhile the amplitudes of the 2/1 mode increase.

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Reference

[1] R. Sweeney et al, Nucl. Fusion 58, 056022 (2018)

[2] A Gude et al, Plasma Phys. Control. Fusion 63, 045018 (2021)

[3] M. Schittenhelm, H. Zohm and ASDEX Upgrade Team, Nucl. Fusion 37, 1255 (1997)