Excitation of Stable MHD Mode Using Electrodes on the Compact Helical System Plasmas

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Stable MHD modes have been externally excited by electrode exciters placed at the edge of the CHS heliotron/torsatron plasma. The excited modes are related to the rational surface $m = 3/n = 2$ (m, n : poloidal and toroidal mode number, respectively) near the edge. These stability margins can be estimated based on the plasma response to externally applied small magnetic field perturbations. This experiment suggests a possibility that the stability margin of MHD modes can be investigated by applying small magnetic field perturbations externally.

Keywords:

heliotron/torsatron, electrode excitor, stability margin, interchange-like perturbations

A promising prospect for nuclear fusion research is supported by the realization of high performance plasmas based on the high confinement mode (H-mode) and/or the internal transport barrier (ITB) mode. In these high performance plasmas, however, the pressure gradient sometimes becomes too steep, and often excites MHD instabilities. Therefore, it is important to cope with both high plasma confinement and improved MHD stability. For this reason, the MHD stability margin should be examined in real-time manner for maintaining high confinement and securing MHD stability. In the JET and DIII-D tokamak, experiments were performed to develop a method to monitor their distance from the present plasma state to the marginal stability boundary using external coils installed inside the vacuum vessel [1,2].

In the Compact Helical System (CHS) heliotron/torsatron with poloidal and toroidal field periods $l = 2$ and $N = 8$, of which major and minor radii are $R \approx 1$ m and $\langle a \rangle \approx 0.2$ m, respectively [3], we have performed experiments to determine the distance of the plasma state from the marginal stability boundary by applying small magnetic field perturbations externally. The magnetic field perturbations with the specified toroidal mode number n have been applied by using a set of

Fig. 1 Schematic drawing of electrode system with a simplified electrical circuit and electrode structure together with the predicted current paths in a CHS plasma.

electrodes shown in Fig. 1. For this electrode arrangement, n is even and is dominated by $n = 2$. The same system was also employed for Alfvén-eigenmode spectroscopy [4,5]. In this experiment, the electrodes were inserted beyond the last closed flux surface

Fig. 2 External excitation of the stable mode ($f_{\text{ex}} = 25$ kHz). (a) Amplitude and (b) phase of the plasma response. (c) Radial integration of plasma response for several electrode positions $\rho_{\text{EL}} = 0.65, 0.83$ and 0.90 . (d) Radial profile of the rotational transform in CHS.

(LCFS) in a tenuous low temperature plasma where this new idea could easily be tested. The plasma was produced by 2.45 GHz electron cyclotron waves up to 1 kW at a low magnetic field (~ 0.1 T). The electron density and electron temperature of the plasma are in the range of $\sim 3 \times 10^{16} \text{ m}^{-3}$ and ~ 4 eV, respectively.

Oscillatory voltage is applied between each electrode and the vacuum vessel wall, where the oscillatory current is induced along a specified magnetic field line as an electron or ion saturation current, depending on the polarity of the applied voltage. The length of the current path along the equilibrium magnetic field line is determined based on a so-called free streaming length [6]. The frequency of the applied voltage f_{ex} is swept over the range of 10 kHz to 200 kHz in order to measure the plasma response. This plasma response G_{θ} is defined as a complex function $G_{\theta}(f_{\text{ex}}) = b_{\theta}(f_{\text{ex}})/I(f_{\text{ex}})$, where b_{θ} and I are the poloidal component of the magnetic perturbations and the oscillatory current, respectively. The magnetic fluctuations are measured by

Fig. 3 Frequency response to externally applied perturbations. $|G_{\theta}|$, $\text{Re}[G_{\theta}]$, and $\text{Im}[G_{\theta}]$ are absolute, real, and imaginary part of the excited stable MHD mode, respectively. Stability margin can be estimated from the width of $|G_{\theta}|$.

a magnetic probe array inserted into a plasma.

In this experiment, the amplitude of the plasma response rapidly increases when the electrodes are inserted around the normalized radial position $\rho_{\text{EL}} = r/\langle a \rangle \simeq 0.83$. The radial profiles of the amplitude and phase of the plasma response $G_{\theta}(f_{\text{ex}})$ are shown in Figs. 2(a) and (b). The eigenfunction as the radial displacement ξ_r is roughly derived by $\mathbf{b} = \nabla \times (\xi \times \mathbf{B}_0)$ assuming a cylindrical configuration for simplicity, where $\mathbf{b}$, ξ , and $\mathbf{B}_0$ are the magnetic perturbation, the displacement, and the equilibrium magnetic field vector, respectively. Thus, the radial displacement ξ_r is evaluated as

$$\xi_r \simeq -\frac{1}{B_p} \int_0^r b_{\theta} dr' \propto \int_0^r G_{\theta}(r') dr'.$$

The eigenfunctions of the radial displacement are respectively derived from the real and imaginary part of G_{θ} using an approximate equation of

$$\int_0^r G_{\theta}(r') dr',$$

and these eigenfunctions are almost the same except for the polarity. As shown in Fig. 2(c), the eigenfunction has a peak at the particular radial position ($\rho_{\text{EL}} \sim 0.8$), where the phase of the plasma response is reversed as shown in Fig. 2(b). The radial profile of the rotational transform $t (= 1/q; q$ is a safety factor) is shown in Fig. 2(d). The radial position where the eigenfunction reaches its maximum agrees well with the position of the $t = 2/3$ rational surface; that is, $\rho \simeq 0.77$. The plasma response was investigated by changing the electrode position ρ_{EL} from 1.05 up to 0.65. Thus the derived ξ_r at the $t = 2/3$ rational surface reaches the maximum when the electrode is placed at the position near this rational surface. This shows that this wave number parallel to the magnetic field is almost zero, thus this excited mode is thought to be an interchange or flute-like mode. It

should be noted that the eigenfunction is fairly broad compared with that in an ideal plasma with very low beta. This broadening of the eigenfunction may be due to non-ideal effects such as high resistivity.

Figure 3 shows that the frequency response of this mode increases toward the zero, where in this low temperature tenuous plasma the Doppler frequency is expected to be almost zero. The damping rate γ_d of the excited perturbation, which corresponds to the stability margin, can be derived from the shape of the frequency response shown in Fig. 3. The damping rate γ_d of the $m = 3/n = 2$ mode is estimated to be $\gamma_d \sim 0.1 v_A/R$, where v_A is the Alfvén, velocity.

In conclusion, stable $m = 3/n = 2$ interchange-like modes localized near the $r = 2/3$ rational surface have been excited by applying external magnetic perturbations. The plasma response to these perturbations gives the damping rate of the mode corresponding to the distance from the marginal stability boundary. This experiment demonstrates the possibility of searching for the stability margin of stable MHD modes in a toroidal

plasma.

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