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Suppression of Tearing Modes by Modulated Toroidal Current in the HT-7 Superconducting Tokamak*

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I. INTRODUCTION

The tokamak disruption is a dramatic event in which the plasma confinement is suddenly destroyed. In a major disruption, the onset of the initial thermal energy loss is mainly triggered by an internal MHD instability. It results in rapid redistribution of the initial thermal energy within the plasma core, followed by rapid loss of thermal energy to the plasma-facing components (thermal quench) and rapid decay of the plasma current (current quench). In order to suppress the tearing mode in a tokamak, the various ways have been proposed and realized, such as resonant helical field, ECH to heat m=2 magnetic island and so on. The plasma equilibrium current modulated by a frequency current has been successful used in suppressing MHD perturbations effectively. The role on suppressing the MHD perturbation has been analyzed theoretically and proved numerically[1]. A toroidal frequency modulated current (TFMC), induced by modulated loop voltage, was added on the plasma equilibrium current of HT-7 superconducting tokamak. The suppression of MHD perturbations and the delay of the major disruption are observed.

2. PHYSICAL MODEL OF AC TOROIDAL CURRENT DRIVE

When an AC current is added to plasma current, because the driven current is alternative with time, the resonant surfaces of the modes also vary with time, therefore, it is difficult for the perturbation modes to develop in some fixed locations. The plasma torus is regarded as a conductive toroidal conductor, an ac toroidal current can be induced by modulated loop voltage. The electrical field E is governed by the wave equation,

$$\nabla^2 \vec{E} + \frac{\omega^2}{C^2}\vec{E} = -i\mu_0\omega\vec{j}^{\,*} \qquad (1)$$

The linear motion equation, the low frequency Ohmic equations and Maxwell equation:

$$m_i n_i \frac{\partial \vec{V}}{\partial t} = \vec{j} \times \vec{B} \qquad (2)$$

$$\vec{E} + \vec{V}\times\vec{B} = \frac{m_e}{n_e e^2}\left(\nu_{ei}\vec{j} + \frac{\partial\vec{j}}{\partial t}\right) + \frac{\vec{j}\times\vec{B}}{n_e e} \qquad (3)$$

$$\nabla\times\nabla\times\vec{E} = i\mu_0\omega\vec{j} + \frac{\omega^2}{c^2}\vec{E}$$

The equilibrium magnetic field, $\vec{B} = \hat{\theta} B_\theta + \hat{Z} B_z$ and $B_z >> B_\theta$, $\vec{E}, \vec{V}, \vec{j}, \vec{b}$ are electric field, velocity, current and magnetic field induced by the coils. Suppose the induced quantities have components which vary with time as $e^{-i\omega t}$ then from eqs.(2),(3),the r-component of V can

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$$V_r = \frac{-i\omega_{ci}^2 B_\theta}{\omega\omega_{pi}^2 \varepsilon_0 B^2} j^{\bullet}, \quad V_r = -\frac{B_\theta}{B^2}(E - \eta j)$$

3. ROLE OF THE AC CURRENT IN SUPPRESSING TEARING MODES

When the AC current is introduced, the discontinuous derivative, A', can change favoring stability of the modes. For any mode, A'„ can be written,

$$\Delta'_0 = \lim_{\varepsilon \to 0}\left(\frac{\partial\psi(r_s + \varepsilon)}{\partial r} - \frac{\partial\psi(r_s - \varepsilon)}{\partial r}\right) / \psi(r_s)$$

Where ε is the half width of tearing layer, r_s the resonant surface radius
Outside the tearing layer, the perturbation helical magnetic flux ψ satisfies:

$$\frac{d}{dr}\left(r\frac{d\psi}{dr}\right) - \left(\frac{m^2}{r} + \frac{\frac{dj_0}{dr}}{\left(\frac{1}{q} - \frac{n}{m}\right)}\right)\psi = 0$$

Where m, n are poloidal and toroidal mode number, respectively.
When the AC current is introduced, in same amplitude of $\psi(x)$, then we have

$$\Delta' = \Delta'_0 + \Delta'_1 \qquad \text{A'}, = -s / r_s \psi(0) \qquad s = \int_{-\infty}^{\infty} \psi(x) \frac{\frac{d\tilde{\delta} j}{dx}}{\left(\frac{1}{q} - \frac{n}{m}\right)} dx$$

An integration circuit C_t is properly selected to solve this integration[2]. The A', can be given by

$$\Delta'_1 = 2\left[\frac{d\tilde{\delta} j}{dr} \frac{L_s}{r_s}\right]_{r=r_s}$$

The condition A', <0 can always been hold. Selecting the amplitude of the AC current, the condition A' = Δ'_0 + A', <0 can be satisfied , therefore , MHD perturbations can keep in the zero-or negative growing state .

If there is not ac current modulation, the temperature contraction leads to a rapid growth of MI-ID perturbations and to a current disruption finally, when the amplitudes of MHD perturbations grow to a level at which the overlapping of the islands starts and the role of the coupling between modes becomes important, the evaluations of the magnetic energy growth rates for modes are showed in Fig . 1.

The Figure 1 shows the magnetic energy growth rates remain in the zero-growth state. The MHD perturbations disappear completely, when selecting the amplitude and frequency properly.

4.EXPERIMENT AND RESULDS

HT-7 is a superconducting tokamak with circular configuration limiter. The figure 2 shows when a toroidal frequency modulated current(TFMC), induced by modulated loop voltage, was added on the plasma equilibrium current (Ip=100KA, Bt=1.9T, Ne-2.0 x 10^{13}/cm^{-3}, the modulated current amplitude is about 30KA,ΔIp /Ip ~ 20 - 30%, the modulated frequency >40 Hz), The MHD perturbations (m=2 and m=3) was suppressed effectively. The edge safety factor q(a) was modulated, the signals from the multi-HCN interferometer, Soft X- Ray array, ECE and H_α were modulated obviously, it is indicated that the electron density profile n_e(r) and electron temperature profile T,(r) were modulated. It is also indicated that the electron density profile changed to more peak, the hard x-ray radiation was suppressed, the average electron temperature $\bar{T}_e$ was increased, the impurity radiation was not changed during the TFMC. The rotation velocity of m/n=2/1 and m/n=3/1 magnetic islands were reduced. The disruption, which was induced by tearing mode instability, was avoided.(See Fig.6)

5. CONCLUSION

Numerical results indicated that when a controlled AC current was induced and added to the equilibrium current, the modulated current can make the discontinuous derivative, A', more favorable for the tearing mode stability as long as the parameters of the applied AC current are selected suitably. According to the theoretically analyses and experimental results, the tearing mode stability is much affected by modulation of current density and plasma resistivity near the resonant surfaces of the modes.

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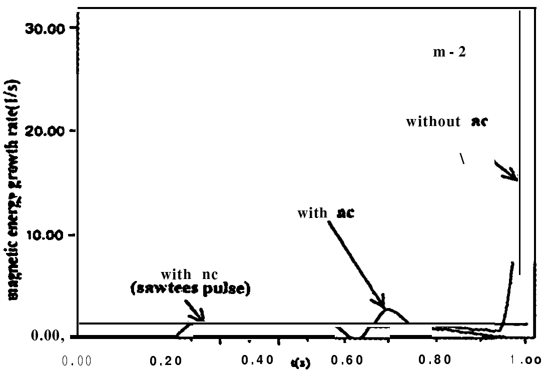

Fig. 1 magnetic energy growth rates

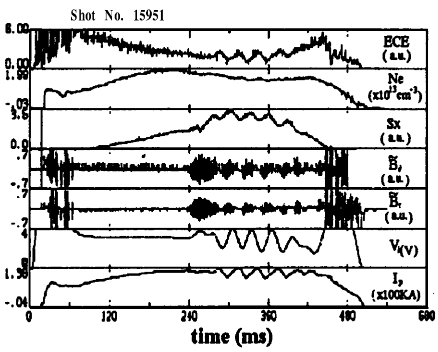

Fig. 2 Typical discharge with TFMC

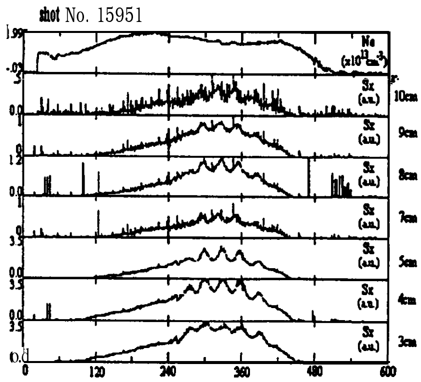

Fig.3 Waveforms of SX array

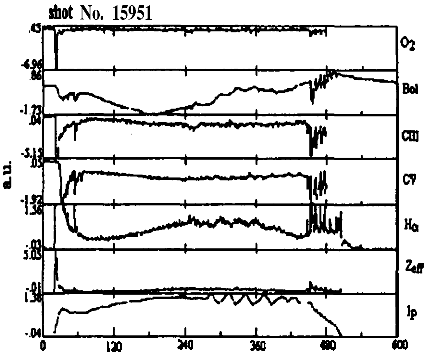

Fig.4 Impurity line emissions and Zeff

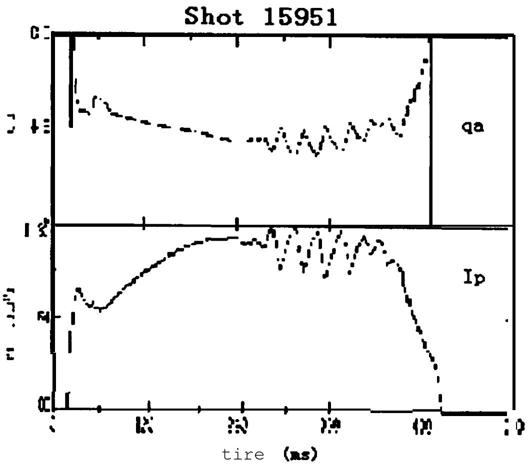

Fig. 5 The edge safety factor q(a)

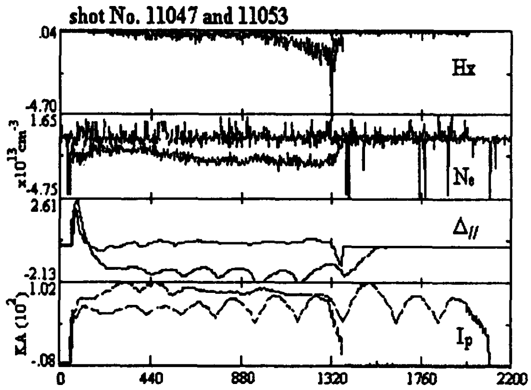

Fig. 6 Compare with and without AC current