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Dynamic Stabilization by Modulated Toroidal Current on the HT-7 Superconducting Tokamak *

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The technique of toroidal current modulation has been successfully used in suppressing magnetohydrodynamic (MHD) perturbations effectively on the HT-7 superconducting tokamak. When the ratio of amplitude of plasma modulated current $\Delta I_{\rm p}$ versus the equilibrium plasma current $I_{\rm p0}$ is about $12-30\%$, the resonance surface is moved outside the island width, and the suppression of MHD perturbations is observed. The disruption induced by tearing mode instability is delayed or avoided. Different formats of frequency modulated are compared.

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The tokamak plasma is subjected to major disruptions when plasma density or current exceeds certain critical values. It is generally believed that major tokamak disruptions are caused by nonlinear growth of the tearing perturbation. The tearing instability and the associated magnetic island can lead to a degradation of the tokamak plasma performance or even to a disruption.[1−3] A large $m = 2$ magnetic perturbation is always observed before the major disruption on the HT-7 tokamak (Hefei, China), and the $m = 2$ tearing mode is generally considered to be the most dangerous mode for disruption. In order to suppress the tearing mode, various methods have been proposed and realized. A mode-lock disruption, caused by the $m = 2$ during the density increase, was avoided by the island heating with electron cyclotron heating (ECH) in JFT-2M (Culham, UK). The suppression of the magnetic island was realized by radio-frequency driven current and by further increase of the plasma current in JIPP T-Ⅱ (NIFS, Japan). In recent years the control of the $m = 2$ tearing mode has attracted more interest. The mechanism for the control is to reduce the magnetic free energy proportional to the tearing stability factor Δ'. One issue of stabilization schemes is based on affecting locally either the current profile or the resistivity. Another stabilization method is based on the control of the boundary condition of the tearing mode using a resonant magnetic perturbation (RMP) or magnetic feedback. An improved confinement phase has been observed with a toroidal modulated current on the HT-6M tokamak[4−6] (Hefei, China). Dynamic stabilization of the $m = 1$ tearing mode by resonance detuning has been investigated theoretically.[7] It was shown that rapidly oscillating the resonant point ($q = 1$ radius) about its mean position would reduce the growth rate even to zero. The oscillation frequency ω of the safety factor $q = 1$ movement must be faster than the classical growth rate of the tearing mode γ. In this letter, we report on some recent experimental results of suppressing magnetohydrodynamic (MHD) perturbations by an oscillating flux current driven (OFCD) on the HT-7 superconducting tokamak.

On the HT-7 superconducting tokamak[8] one feedback system simultaneously controls the plasma current, density and displacement. The HT-7 tokamak has its major radius $R = 1.22$ m, and minor radius $a = 0.26 - 0.28$ m defined by a full circular limiter in the circular cross section. There are two layers of thick copper shells, and between them 24 superconducting coils are located, which can create a toroidal magnetic field ($B_{\rm t}$) up to 2.5 T. The HT-7 ohmic heating transformer has an iron core and can offer a magnetic flux of 1.7 V·s at its maximum. For alternating current (ac) experiments, we feedback the plasma current and horizontal displacement.[9] The feedback control system for the HT-7 tokamak is a multi-variable feedback controller due to the strong coupling between the ohmic heating coil and vertical field coil. The input parameters are: (1) the plasma current; (2) the current of the vertical coil; (3) the centre of the last magnetic surface as measured by four single flux loops. The output parameters are the ohmic heating current and the vertical coil current. The response time of the feedback system is limited by the double copper shells; it is greater than 200 ms. The current waveforms are preset by the operator before the experiment. The main diagnostics for recent experiments on the HT-7 are as follows: the electron density profile measured by a vertical 5-channel far-infrared (FIR) hydrogen cyanide (HCN) laser interferometer, a multi-channel soft x-ray array, a 16-channel XUV bolometer array to measure plasma radiation losses, a 3-channel soft x-ray spectrum analyser, a 7-channel hard x-ray intensity and spectrum analyser, a neutral particle analyser (NPA), an electromagnetic measurement system,

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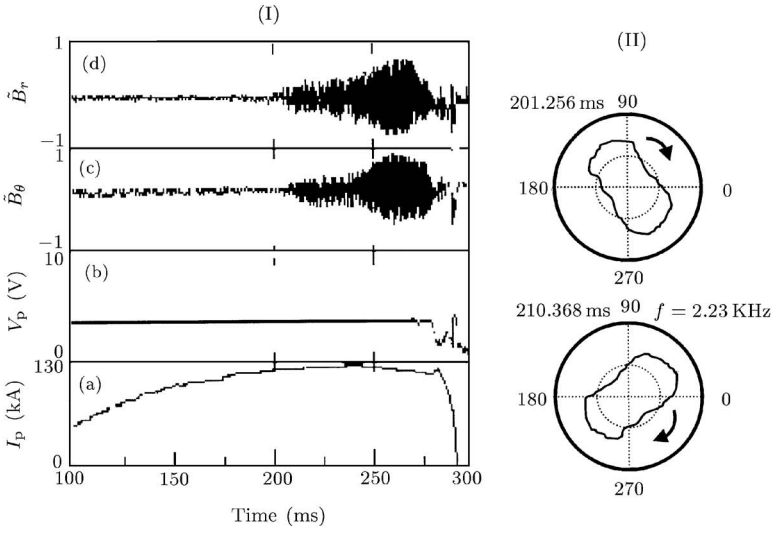

Fig. 1. (I) A typical HT-7 discharge with an MHD disruption: (a) plasma current; (b) loop voltage; (c) poloidal magnetic field perturbation $\tilde{B}_\theta$; (d) radial magnetic field perturbation $\tilde{B}_r$. (II) The MHD model, $m = 2$ for discharge (I).

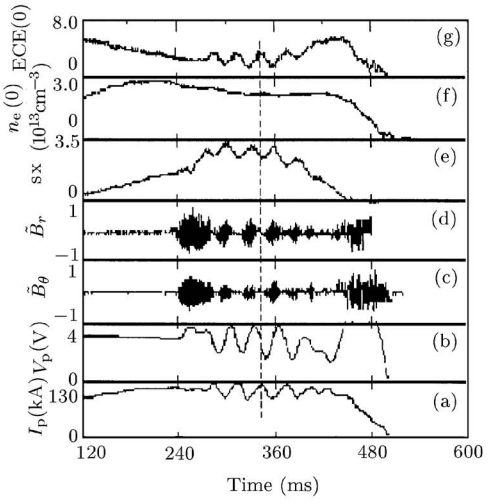

Fig. 2. Suppression of MHD perturbation with OFCD: (a) plasma current I_p; (b) loop voltage V_p; (c) poloidal magnetic perturbation; (d) radial magnetic perturbation; (e) soft x-ray emission; (f) central average electron density; (g) central electron cyclotron emission.

a multi-channel $H_\alpha(D_\alpha)$ radiation array, 4-channel visible bremsstrahlung emission, 10-channel CIII line emission and optical impurity spectrum measurement system, multi-channel fast scanning electron cyclotron emission (ECE) system, multi-point Nd laser Thomson scattering system. During an OFCD experiment, the programming ohmic heating field is modulated. A toroidal frequency modulated current, induced by the modulated loop voltage, is added to the plasma equilibrium current. The ratio of ac amplitude of plasma current ΔI_p versus the equilibrium plasma current I_{p0} is about $12 - 30\%$. The poloidal field B_p varies with plasma current. For simplicity, the model has circular cylindrical geometry. The model is described by

$$I_p = I_{p0} + \Delta I_p \sin(\omega t + \delta),$$
$$B_p = \frac{\mu_0 I_p}{2\pi a} = B_{p0}\left[I_{p0} + \Delta I_p \sin(\omega t)\right],$$

where I_p is the total plasma current, I_{p0} is the equilibrium plasma current, ΔI_p is the ac amplitude of plasma current, ω is the modulation frequency, B_p is the poloidal field, B_{p0} is the average poloidal field, and a is the minor radius. Operation at too high a frequency might yield an adiabatic process, because high-temperature plasma is frozen to the magnetic flux, but the modulation period must be much shorter than the field penetration time.[10] For this reason, we carefully selected the correct modulation amplitudes and frequency in the HT-7 experiments.

Figure 1(I) shows a typical shot where large MHD activity leads to disruptions. MHD activity starts to increase at 200 ms, which then leads to a disruption at 280 ms. Figure 1(II) shows the $m = 2$ modes with a rotation frequency of 2.23 kHz for the MHD activity in Fig. 1(I). Figure 2 shows a typical shot of discharge with OFCD, $I_{p0} = 120$ kA, $B_t = 2.0$ T, $\overline{N}_{e0} \sim 1.9 \times 10^{13}\,\mathrm{cm}^{-3}$), perturbation $\tilde{B}_\theta$ and $\tilde{B}_r$ increase at 240 ms (the disruption usually occurs at 260 ms). The modulated current with sine form was added at 250 ms. During OFCD, the modulated current amplitude $\Delta I_p / I_{p0}$ is about 23%, with a modulated frequency $f = 32$ Hz. The field penetration time

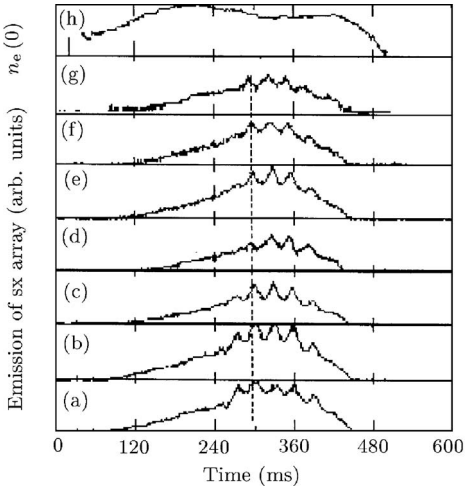

Fig. 3. Emission from the soft x-ray array and electron density: (a) – (g) $r = 0$, 4.5, 7.5, 10.5, 11.5, 13.5, 14.5 cm; (h) central electron density is $10^{13}\,\mathrm{cm}^{-3}$.

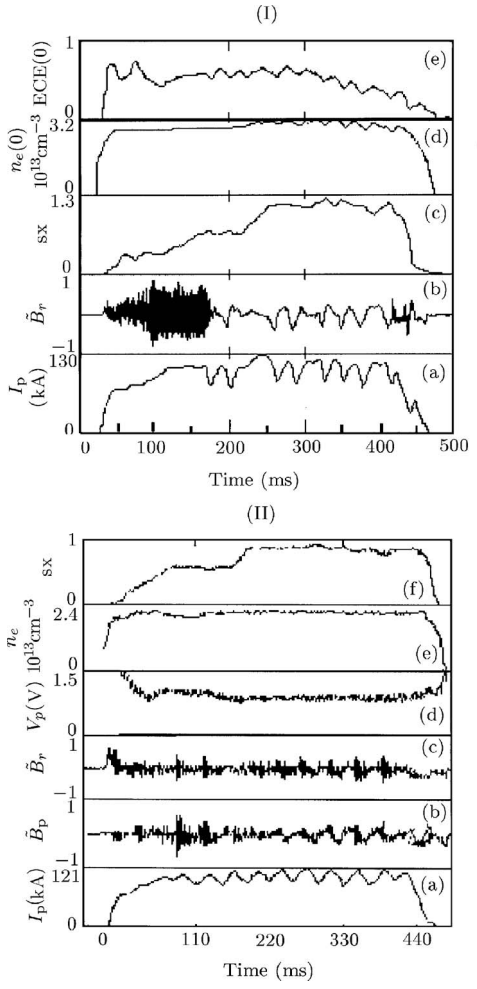

Fig. 4. (I) Discharge with $\overline{N}_{e_0} \approx 2.2 \times 10^{13}\,\mathrm{cm}^{-3}$, $I_\mathrm{p} = 114\,\mathrm{kA}$ with negative pulses modulation: (a) plasma current; (b) poloidal magnetic perturbation; (c) soft x-ray emission; (d) central electron density; (e) central electron cyclotron emission. (II) Discharge with $\overline{N}_{e_0} \approx 2.2 \times 10^{13}\,\mathrm{cm}^{-3}$, $I_\mathrm{p} = 114\,\mathrm{kA}$ with sine current modulation.

of the HT-7 tokamak is typically larger than 100 ms. The MHD perturbations were suppressed effectively (see Figs. 1(c) and 1(d)). The discharge extended to 500 ms and the disruption was avoided. Modulations of both the soft x-ray and ECE signals were observed (see Figs. 2(e) and 2(g)). Figure 3 shows even the innermost soft x-ray channels were modulated. This implies that the plasma parameters n_e and T_e were modulated from the edge to near the centre during current oscillation. Figure 4(I) shows the discharge with the negative pulses modulation $\bar{N}_{\mathrm{e}\,0} \approx 2.2 \times 10^{13}\,\mathrm{cm}^{-3}$, and $I_\mathrm{p} = 114\,\mathrm{kA}$. The MHD perturbations $\tilde{B}_\theta$ and $\tilde{B}_\mathrm{r}$ increase at 100 ms. A toroidal frequency modulated current was induced to add to the plasma equilibrium current at 170 ms. The modulated current is negative multi-pulses with $\Delta I_\mathrm{p}/I_{\mathrm{p}0} = 30\%, -\mathrm{d}I_\mathrm{p}/\mathrm{d}t = 5.43\,\mathrm{MA/s}$, $+\mathrm{d}I_\mathrm{p}/\mathrm{d}t = 2.4\,\mathrm{MA/s}$, $f = 40\,\mathrm{Hz}$. The MHD perturbations were suppressed completely. The discharge delayed to 460 ms, and no disruption occurred. Compared with a sine frequency modulated current (see Figs. 1 and 4(II)), it is found that the negative current pulse is more effective for MHD suppression. In the experiments of OFCD, it is also found that the larger and the faster the modulated current is, the more effective the suppression of MHD perturbations. However, the modulation period must be much shorter than the field penetration time. The MHD activity was suppressed only when the modulation of the plasma current $\Delta I_\mathrm{p}/I_{\mathrm{p}0}$ was greater than 12%. No suppression of MHD activity was observed for modulations with $\Delta I_\mathrm{p}/I_{\mathrm{p}0} < 10\%$ (see Fig. 5).

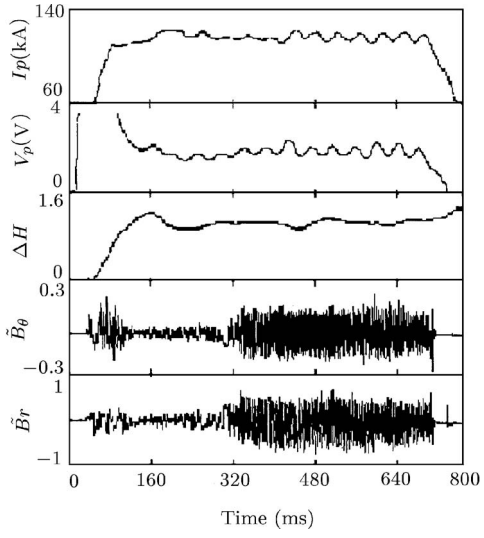

Fig. 5. Discharge with small amplitude current modulation $\Delta I_\mathrm{p}/I_{\mathrm{p}0} < 10\%$.

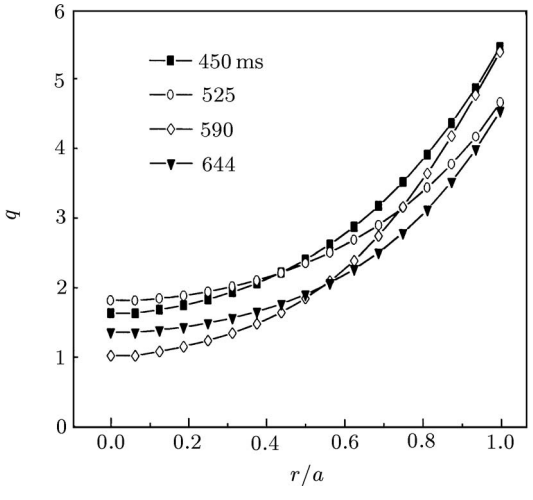

Fig. 6. Safety factor profiles $q(r)$ during OFCD.

The MHD activity observed here can be associated with neoclassical tearing modes. A nonlinear instability with low modes is located at the rational surface with $q = m/n$. By the generalized Rutherford equation describing the dynamics of the island width,[11]

the $m = 2$ island width of the HT-7 tokamak is approximately 2 cm. The current and q profile evolution are computed by solving the poloidal flux diffusion equation for a cylinder using Sptizer resistivity from the experimental profiles of temperature, $Z_{\rm eff}$ and the total plasma current $I_{\rm p}(t)$ as the boundary condition. The code calculates the loop voltage, which is compared with the experimental observations as a consistency check. The change in the location of the $q = 2$ surface during the current oscillations was also calculated and compared with the island widths. The safety factor profiles $q(r)$ during OFCD are shown in Fig. 6. The location changed of $q = 2$ is $\Delta L_{q=2} \sim 2 - 4\,{\rm cm}$ during OFCD. This would indicate that current oscillations move to the resonance location. If the resonance is moved outside the island width, the suppression of MHD perturbations and the delay or avoidance of the major disruption can be observed.

In conclusion, a dynamic stabilization of the plasma disruption precursors for avoiding and softening disruption in our primary experiments has been realized. The technique of the toroidal current modulation has been successfully used in suppressing MHD perturbations on the HT-7 superconducting tokamak. The disruption, which was induced by tearing instability, was delayed or avoided.

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