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Plasma Shaping by Control of Plasma Current, Decay Index and Gas Puffing in Non-Circular Tokamak TNT-A

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In the non-circular tokamak TNT-A, we have tried to elongate plasma column by the combined operation of rapid rise of plasma current and rapid decrease in the decay index n $(=-(R/B_z)\cdot(\partial B_z/\partial R))$ with gas puffing after the current establishment. The increase in elongation ratio is obtained without deleterious effects on MHD instabilities. Dependence of elongation ratio on plasma parameters is calculated and compared with measurements. The growth rate of positional instabilities in the vertical direction is measured as a function of the decay index, and has good agreement with a calculation.

Non-circular plasmas are expected to have significant advantages to conventional ones.[1-3] The results from Doublet IIA,[4] Doublet III[5,6] and TOSCA[7,8] showed improvement of plasma parameters, *e.g.*, plasma current, energy confinement time and poloidal beta value, with increasing elongation ratio κ ($=b/a$: ratio of height to horizontal semi axis length).

From the point of the equilibrium, it was shown in TNT-A,[9,10] TOSCA[7] and Doublet III[11] that elongation ratio increases with flatter current profile and the lower decay index $n=-(R/B_z)\cdot(\partial B_z/\partial R)$. But elongation ratio decreases with time due to the current peaking in TNT-A.[12,13]

Since the discharge duration becomes long in a reactor size tokamak, the equilibrium is modified greatly in a long time scale even if the internal structures gradually change. By change of the equilibrium from optimum conditions, the confinement becomes worse and, in some cases, major disruptions may occur. Therefore, it is necessary to control elongation ratio and maintain plasma properties.

In this paper, control of plasma shape is tried by the combined operation of rapid rise of plasma current, rapid decrease in the decay index and additional gas puffing after the current establishment in TNT-A. Positional instabilities are also investigated and compared with a calculation.

The machine and typical plasma parameters are the following: major radius $R_0=40$ cm; plasma current $I_p=20$ kA; toroidal field $B_t=4.2$ kG; safety factor $q_a>2.5$; central electron temperature $T_{e0}=250$ eV; average electron density $\bar{n}_e=5\times10^{12}$ cm^{-3}; elongation ratio of plasma boundary $\kappa=1.4$.

The plasma is limited by a molybdenum limiter with a D-shaped aperture, 36 cm high and 18 cm wide. Eight shaping coils and partial shell elongate plasma cross section vertically. The shape of plasma boundary, and thus κ, is determined by six ψ loops and 14 magnetic probes.[10] Two dimensional measurements of the laser scattering give contour map of the electron temperature and density.

Rapid rise of plasma current with gas puffing after the current establishment[14,15] heats the outer region of plasma column so that plasma current profile becomes flatter and plasma cross section more elongated. We employed this operation and plasma cross section was enlarged. Figure 1 shows vertical profiles of the electron temperature and density with and without this operation. The rise time of plasma current is 1.1 ms, while the skin depth and skin time of the plasma are $\delta=\sqrt{2/\mu_0\sigma\omega}\simeq4.8$ cm and $\tau=\mu_0\sigma\delta^2\simeq1.4$ ms, respectively, where $T_e=100$ eV, $n_e=2\times10^{12}$ cm^{-3} and $Z_{\rm eff}=2.5$ are assumed. The electron temperature and density near plasma boundary

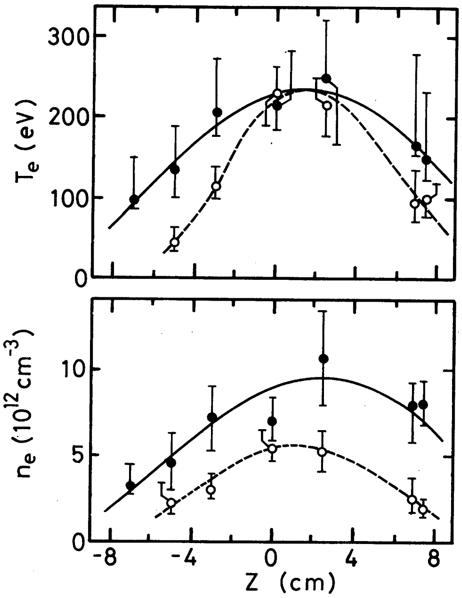

Fig. 1. Vertical profiles of electron temperature T_e and density n_e with (●) and without (○) combined operation of rapid current rise and additional gas putting at $t=6.5$ ms. Rise time of plasma current from $I_p=16$ kA ($t=5.4$ ms) to 23 kA ($t=6.5$ ms) is 1.1 ms. Hydrogen gas is pulsed from $t=3$ ms to 5 ms.

increased and the mean electron density also rose by $\simeq 80\%$, while the central electron temperature was unchanged.

Next, we have tried to elongate plasma cross section by the combined operation of rapid current rise and rapid decrease in the decay index after the current establishment. Figure 2 shows time evolution of plasma parameters with and without this operation. The decay index was lowered by $\simeq 0.2$ with $\bar{n}_e=2-3\times 10^{12}$ cm^{-3}. Elongation ratio κ was found to increase by $\simeq 0.1$ with this operation. MHD activities, mainly $m=2$, $n=1$ mode after $t=4$ ms (m and n are the toroidal and poloidal mode numbers, respectively), were enhanced slightly; relative amplitude of poloidal field fluctuations $\tilde{B}_p/B_p<0.3\%$.

Individual operation of rapid rise of plasma current from $I_p=15$ kA to 23 kA and rapid decrease in the decay index by $\simeq 0.4$ was tried. It was also found that elongation ratio increased by up to 0.1 in both cases.

Figure 3 shows the dependence of elongation ratio on the central decay index in TNT-A, calculated by the equilibrium code EQUCIR.[16] It is shown that elongation ratio increases with flatter current profile (internal inductance l_i is lower) and/or the decrease in the decay index. (The increase in triangularity γ also elongates plasma cross section with the same value of the central decay index.) The increase in elongation by various operations is also shown in Fig. 3, which shows good agreement with the calculation. (The experimental central decay index was derived as the same way in ref. 10.)

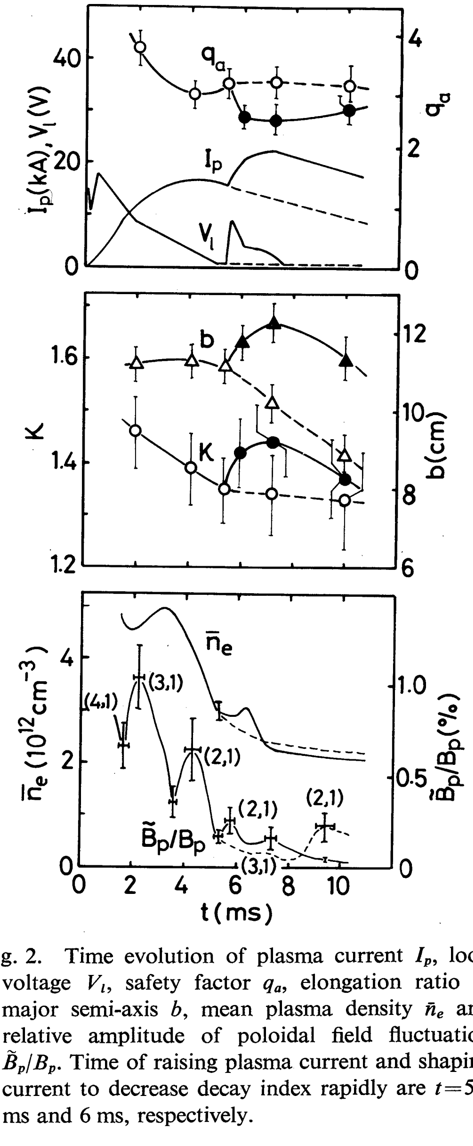

Fig. 2. Time evolution of plasma current I_p, loop voltage V_l, safety factor q_a, elongation ratio κ, major semi-axis b, mean plasma density $\bar{n}_e$ and relative amplitude of poloidal field fluctuation $\tilde{B}_p/B_p$. Time of raising plasma current and shaping current to decrease decay index rapidly are $t=5.4$ ms and 6 ms, respectively.

A comparison of poloidal field fluctuations was also done for the case of same plasma current. The value of $\tilde{B}_p/B_p$ with rapid current

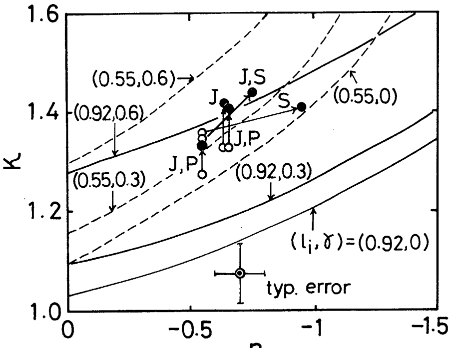

Fig. 3. Dependence of elongation ratio κ on central decay index n_0 by EQUCIR code. Here, l_i and γ are internal inductance and triangularity, respectively. Increase in elongation by various operations is also shown. **J**, **S** and **P** indicate operation of rapid current rise, rapid decrease in decay index and gas puffing, respectively.

rise from $I_p = 18$ kA to 23 kA was smaller than that without current rise ($I_p = 23$ kA) by $\simeq 30\%$. This result is presumably due to the change of plasma current profile, which affects the growth of tearing mode.

The decay index n should be lowered to get highly elongated plasma. However, positional instabilities in the vertical direction limit the allowable decay index. The lower limit of the decay index must be studied in connection with control of plasma shape and plasma position. The growth time of positional instabilities was measured by magnetic probes[7] for the case of rapid decrease in the decay index after the current establishment, as shown in Fig. 4. This figure also shows the calculated growth time τ_g against the central decay index n_0. The growth time has the form of $\tau_g \simeq \tau_e(n_c - n)/n$.[17] $(n_c < n < 0)$: τ_e is the effective skin time of the vacuum vessel or shell; n is the averaged decay index over plasma cross section ($n \simeq n_0 - 0.15$ in TNT-A); n_c is the critical decay index, below which the stabilizing force from the induced current of the vacuum vessel or shell is less than destabilizing force from the vertical field even within the time scale shorter than τ_e. We have (n_c, τ_e(ms)) $\simeq (-1.8, 0.63)$ and $(-1, 33)$ for the case of vacuum vessel and shell, respectively, with $a = 10$ cm, $R_0 = 40$ cm, poloidal beta value $= 0.3$ and $l_i = 0.7$, considering effects of two toroidal gaps of them.

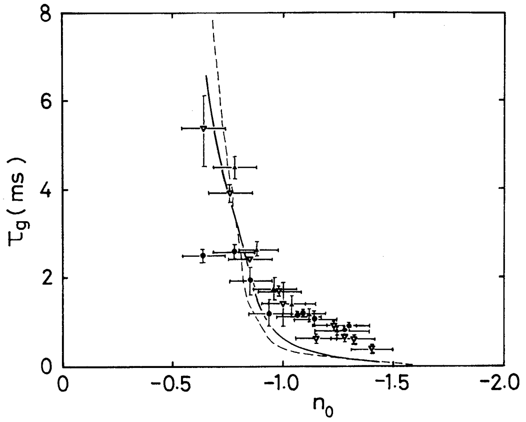

Fig. 4. Experimentally measured growth time τ_g plotted against central decay index n_0. Three symbols stand for different turns of initially excited shaping coils. Solid line shows experimentally determined growth time, considering rise time of second shaping current (1.1 ms). Broken line shows calculated growth time, considering effects of vacuum vessel and shell with two toroidal gaps.

Figure 4 shows good agreement between measurements and calculation. The region $n_0 \lesssim -1$ is the unstable region of $\tau_g \ll \tau_e$, which agrees with the previous result[10] that the plasma discharge could not be initiated.

In conclusion, control of plasma shape was successfully executed without deleterious effects on MHD instabilities, by the combined operation of rapid current rise and rapid decrease in the decay index with gas puffing. The growth time of positional instabilities was measured, and had good agreement with the calculation. The unstable region of $n_0 \lesssim -1$ with $\tau_g \ll \tau_e$ agreed with the previous result.

As for control of current density profile, it is necessary to examine another method such as electron cyclotron heating and lower hybrid heating. In order to control and maintain plasma shape, it is important to study further the combined effect of the decay index, gas puffing and additional heating with feedback control of plasma position.

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