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H. Hojo, T. Watanabe, M. Inutake, M. Ichimura
and S. Miyoshi

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Axial Pressure Profile Effects on Flute Interchange Stability in the Tandem Mirror GAMMA 10

Hitoshi HOJO, Tsuguhiro WATANABE+
Masaaki INUTAKE, Makoto ICHIMURA and Syoichi MIYOSHI

Plasma Research Center, University of Tsukuba, Tsukuba 305
+National Institute for Fusion Science, Nagoya 464-01

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Keyword:

MHD stability, tandem mirror, GAMMA 10, interchange mode,
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Synopsis

Flute interchange stability of the tandem mirror GAMMA 10 with a minimum-B MHD anchor is studied numerically. The stability criterion in beta value is obtained and its axial pressure profile-dependence is also analyzed. It is shown that the anchor beta value for stability is reduced when the axial localization of a mirror-trapped hot plasma becomes narrower in the central cell or/and in the anchor cell.

Among thermonuclear fusion researches, the attainment of a high-beta plasma is one of significantly important research subjects. High beta plasmas can supply high fusion power in a reactor and are also interesting from the viewpoint of advanced fusion. In tandem mirrors such as GAMMA 10 and TMX-U, the MHD stability of a plasma is provided by a minimum-B MHD anchor. In the anchor stabilization, the beta value attainable in the central cell strongly depends on that in the anchor cell and increases with the increase of the anchor-cell beta value.

In the previous study[1] on the MHD stability of GAMMA 10 against flute interchange modes, the calculation has been done for a case of a constant central-cell pressure and assumed axial pressure profiles in the anchor and end cells. The assumption of a constant central-cell pressure is reasonable in the absence of ICRF heating in the central cell. But with the ICRF heating, hot ions are produced, which are mirror-trapped and localized in the central cell. Therefore, we have to take account of the axial variation of the central-cell pressure due to the central-cell ICRF heating. The axial variation of the anchor-cell pressure is also important to determine the MHD stability condition, since the good curvature region of the anchor cell which contributes to the stabilization is localized in a relatively narrow region around the midplane.

In this short note, we study numerically how the stability condition of GAMMA 10 against flute interchange modes depends on the axial variation of pressures in the central and anchor cells. The magnetic field configuration of GAMMA 10 is here calculated by using the code developed by refs. 2 and 3. In the code the magnetic field induced by body coil currents is calculated by Biot-Savart's law. When we express the magnetic field as $\underline{B} = B\underline{b} = \nabla\psi \times \nabla\theta$ in the magnetic flux coordinates (ψ, θ, s), where ψ is the flux coordinate, θ is an anglelike ccordinate and s is the distance along a field line, then the curvature of a field line is expressed as $\underline{\kappa} = (\underline{b}\cdot\nabla)\underline{b} = \kappa_\psi \nabla\psi + \kappa_\theta \nabla\theta$, κ_ψ being the normal curvature and κ_θ the geodesic curvature. We here analyze the stability using the long-thin approximation, which is well satisfied for any field lines near the axis of $r = 0$ and then we have $ds \fallingdotseq dz$ and $B \fallingdotseq B_z$. We show the axial profiles of the vacuum magnetic field B(z) and the normal curvature $\kappa_\psi(z)$ in Fig. 1 for the field line passing through the position of r=5cm, $\theta = \pi/4$ at the central-cell midplane (z=0), where $B(-z) = B(z)$ and $\kappa_\psi(-z) = \kappa_\psi(z)$. We note that the long-thin approximation is not used in the the calculation of κ_ψ.

When the finite Larmor radius effect is neglected, the stability condition against flute interchange modes is given by[4]

$$\int_{-L}^{L} \frac{dz}{B} \kappa_\psi \frac{\partial}{\partial \psi}(P_\perp + P_\parallel) \leqq 0 , \tag{1}$$

where $P_\perp$ and $P_\parallel$ are pressures perpendicular and parallel to the magnetic field, respectively, and L(= 10m) is the distance from the central-cell midplane to the outer end-cell throat. Since κ_ψ is expressed as $\kappa_\psi(z) = g_1(z) + g_2(z)\cos(2\theta)$, where $g_1(-z) = g_1(z)$ and $g_2(-z) = -g_2(z)$, the integration range of eq. (1) from $-L$ to L can be replaced to that from 0 to L and the integral is independent of θ. We here assume $P_\perp(\psi, B) = h(\psi)\bar{P}_\perp(B)$, $P_\parallel(\psi, B) = h(\psi)\bar{P}_\parallel(B)$ and

$\partial h/\partial \psi < 0$, and use the following model for $P(z) = \bar{P}_{\perp} + \bar{P}_{\parallel}$:

$$
\begin{aligned}
P(z) &= P_0 + P_C[1-(z/2.8)^2]\exp[-(z/L_C)^2], && 0<|z|<2.8 \\
&= P_0, && 2.8<|z|<4.4 \\
&= P_0 + P_A[1-((z-5.2)/0.8)^2]\exp[-((z-5.2)/L_A)^2], && 4.4<|z|<6.0 \quad (2) \\
&= P_0, && 6.0<|z|<7.6 \\
&= P_0 + P_B[1-((z-8.8)/1.2)^2], && 7.6<|z|<10.0
\end{aligned}
$$

where P_0 expresses a uniform cold-plasma component, and P_A, P_B and P_C express the peak pressures of mirror-trapped hot-plasma components with the axial profiles in the anchor, end and central cells, respectively. L_A and L_C express the axial extent of the hot-plasma components in the anchor and central cells, respectively. The axial pressure profile in the end cell is fixed, for simplicity. The axial distance in eq. (2) is measured in unit of meter.
If we define the beta values in each cell as $\beta_A = 8\pi(P_0 + P_A)/B_A^2$, $\beta_B = 8\pi(P_0 + P_B)/B_B^2$, $\beta_{CC} = 8\pi P_0/B_C^2$, $\beta_{CH} = 8\pi P_C/B_C^2$, where B_A, B_B and B_C are the magnetic field strength at the midplane in the anchor, end and central cells, respectively. And β_{CC} and β_{CH} denote the beta values of cold- and hot-plasma components in the central cell, respectively. The calculation of eq. (1) is performed for the field line shown in Fig. 1.

Since eq. (1) is linear in P_A, P_B and P_C, therefore the stability criterion on the beta value is written as

$$\beta_A \geqq f_B\beta_B + f_C\beta_{CC} + f_H\beta_{CH}, \qquad (3)$$

where the coefficients f_B, f_C and f_H depend on the axial extent of the pressure profile, i.e., f_B and f_C are functions of L_A and f_H is a function of L_A and L_C. We show f_C versus L_A in Fig.2. We see that f_C decreases with decreasing L_A, which is reasonable because the hot-plasma component in the anchor cell can localize well in the good curvature region when L_A decreases. In Fig.3, we show f_B versus L_A for two axial pressure profiles in the end cell. The solid line are obtained for the pressure shown in eq.(2) with $P_E = P_0$ and the dashed line is the result for the end-cell pressure profile of $P(z) = P_0[1-((z-8.8)/1.2)^2]$. We find that both results are almost same and f_B decreases with decreasing L_A since the anchor-cell hot plasma localizes well in the good curvature region. We show f_H versus L_C for different values of L_A in Fig.4. We first note that f_H is much smaller than f_C, and see that f_H decreases with decreasing L_C. In the central cell, the bad curvature region is localized in the end region of the central-cell mirror and there is only a small curvature near the midplane as the magnetic field is almost constant there. Since the decrease in L_C means that the central-cell hot plasma is kept off the bad curvature region, therefore, it leads to the decrease in f_H. The value of f_H becomes smaller also for the smaller L_A for the same reason as that in Figs.2 and 3.

In conclusion, we have shown that the anchor beta value for the flute stability is reduced when the axial localization of a mirror-trapped hot plasma becomes narrower in the central cell or/and in the anchor cell and that f_H is much smaller than f_C.

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Figure Captions

Fig. 1. The magnetic field B(z) and the normal curvature $\kappa_{\psi}(z)$ of the tandem mirror GAMMA 10 for the field line of r = 5cm and $\theta = \pi/4$ at z = 0, where B(−z) = B(z) being in unit of tesla and $\kappa_{\psi}(-z) = \kappa_{\psi}(z)$.

Fig. 2. L_A-dependence of f_C.

Fig. 3. L_A-dependence of f_B. The end-cell pressure is given by eq. (2) with $P_B = P_0$ (solid line) or $P(z) = P_0[1-((z-8.8)/1.2)^2]$ (dashed line).

Fig. 4. L_C-dependence of f_H for L_A(m) = 0.4 and 0.8.

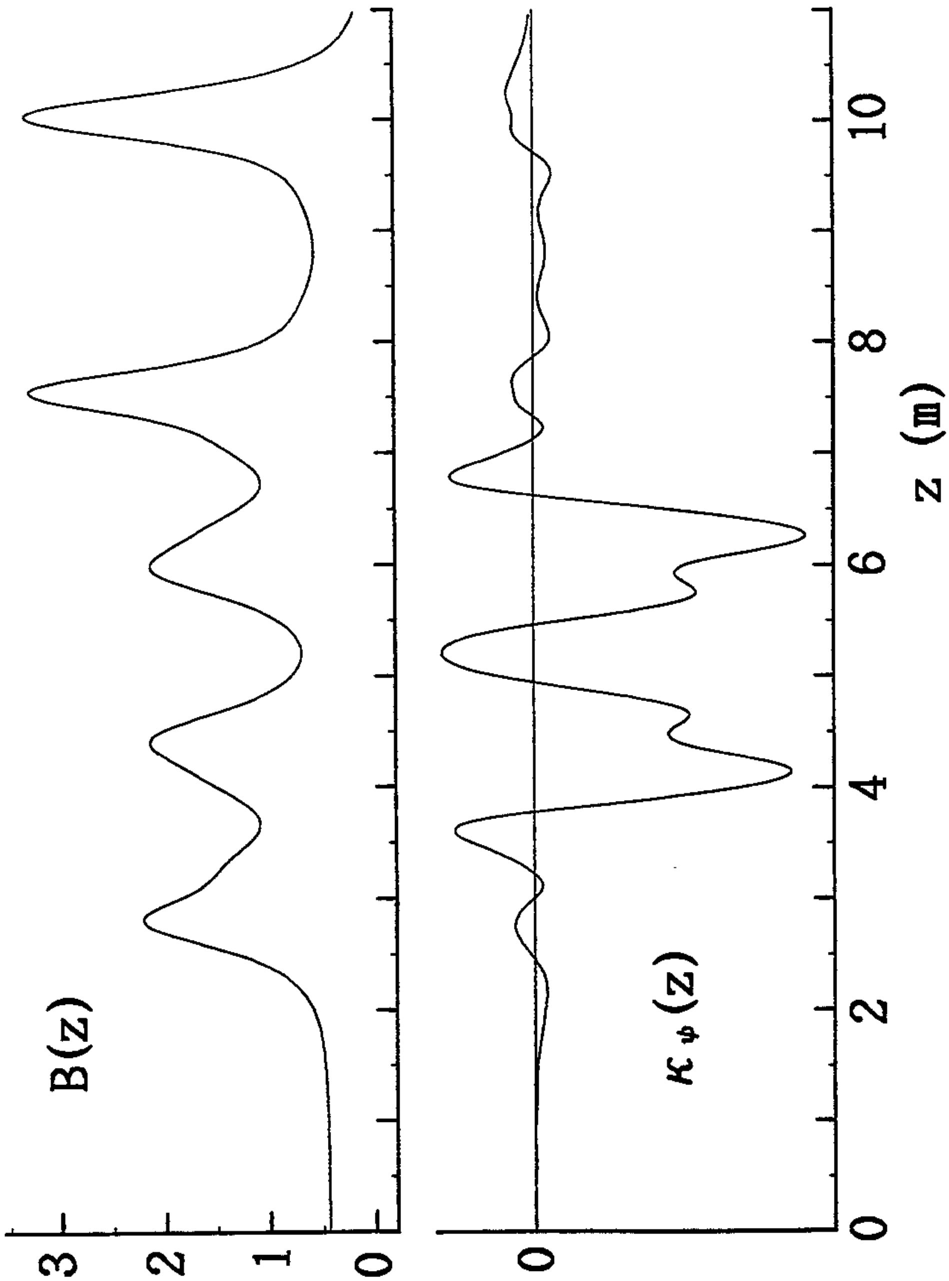

Fig.1

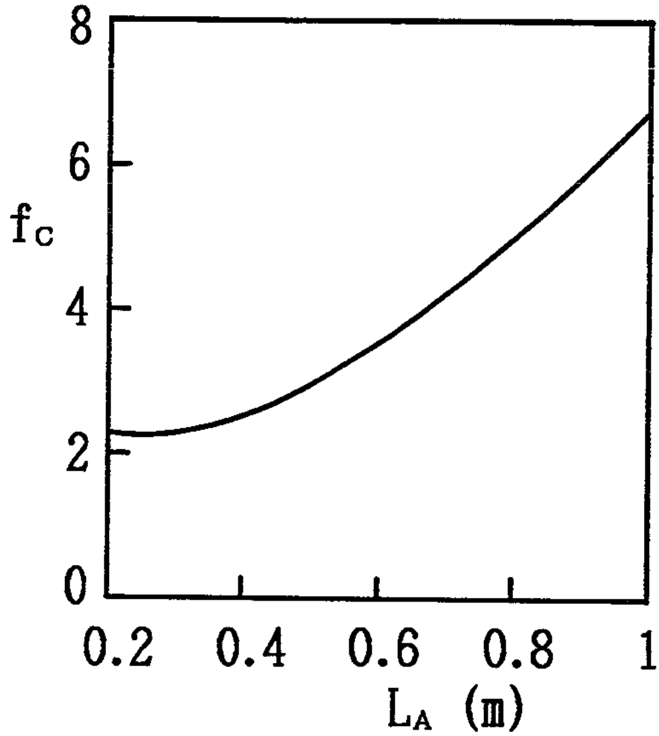

Fig.2

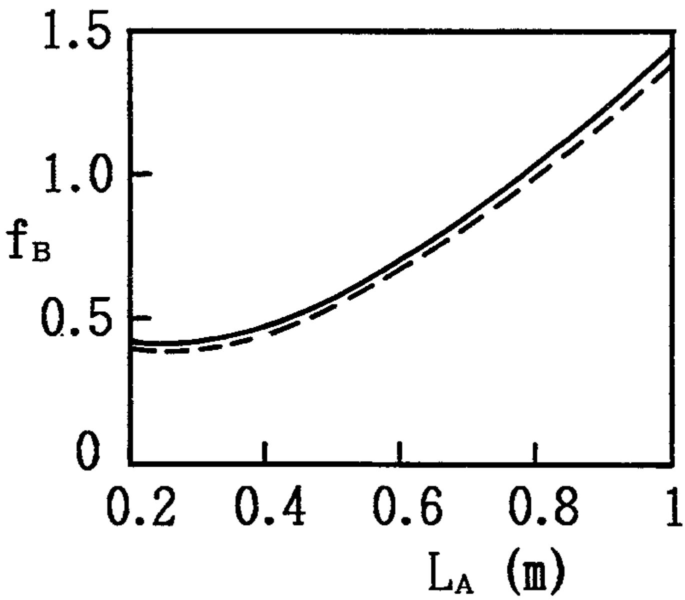

Fig.3

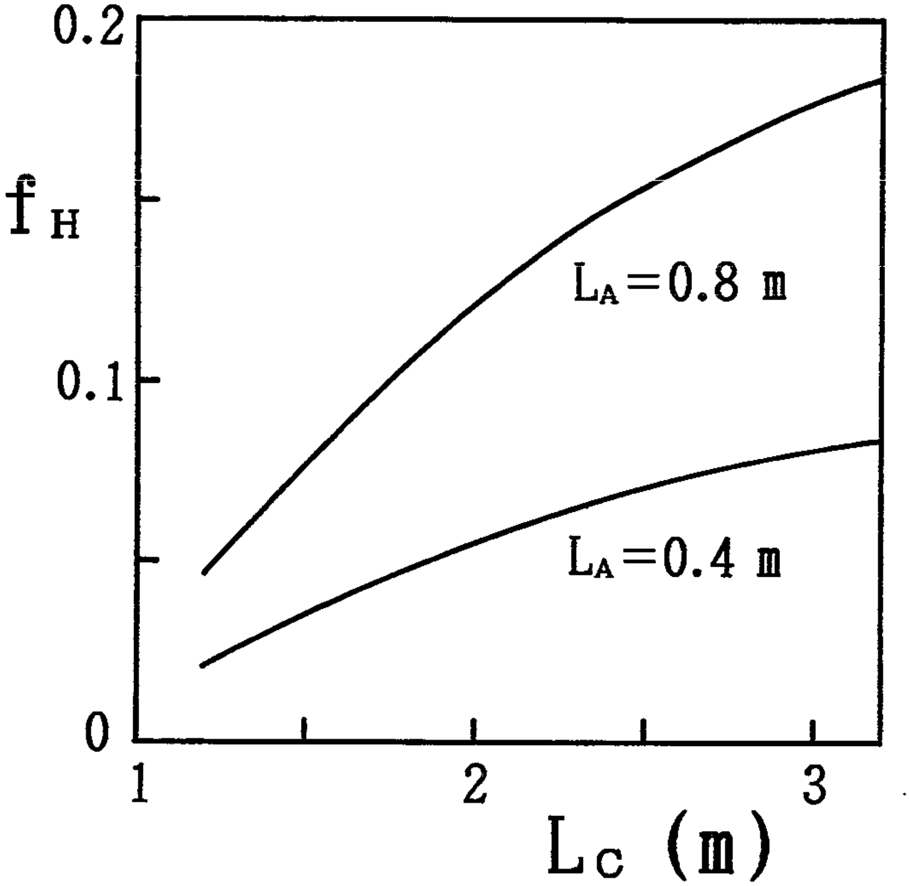

Fig.4

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