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Interchange Stability Criteria for Anisotropic Central-Cell Plasmas in the Tandem Mirror GAMMA 10

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MHD stability, tandem mirror, GAMMA 10, interchange mode, beta value,
temperature anisotropy

ABSTRACT

Flute interchange stability of anisotropic central-cell plasmas in the tandem mirror GAMMA 10 is studied numerically. The stability criteria on the beta value is obtained as a function of axial localization length of the pressure in both central and anchor cells. The temperature anisotropy of the plasma is also discussed.

In tandem mirrors with a minimum-B anchor for magnetohydrodynamic (MHD) stability such as GAMMA 10 and TMX-U, the beta value attainable in the central cell strongly depends on the axial profile of plasma pressure in each cell as well as the beta value in the anchor cell. Recently, the temperature anisotropy of the central-cell plasma has been observed with use of ion cyclotron range of frequencies (ICRF) heating in the GAMMA 10 experiment.[1,2] The anisotropy is due to the ICRF-heated hot ions trapped in the central-cell mirror and causes axial variation of the central-cell pressure. Together with central-cell ICRF heating, anchor-cell ion heating for the MHD-anchor stabilization has been also observed, which is caused by the mode conversion of the m=1 fast wave excited in the central cell to the m=−1 slow wave via a spatial modulation of the nonaxisymmetric quadrupole field.[3]

In this short note, we study numerically the flute interchange stability of anisotropic central-cell hot plasmas in the tandem mirror GAMMA 10. We neglect the effect of the plug/barrier cell, since the plug/barrier-cell beta value is much smaller than the central-cell beta value for the ICRF-heated plasma. The magnetic field configuration of GAMMA 10 is calculated using Biot-Savart's law and shown in Fig.1. In the figure, κ_ψ is the normal curvature defined by $\boldsymbol{\kappa}=(\mathbf{b}\cdot\nabla)\mathbf{b}=\kappa_\psi\nabla\psi+\kappa_\theta\nabla\theta$, where the magnetic field is expressed as $\mathbf{B}=B\mathbf{b}=\nabla\psi\times\nabla\theta$ in the magnetic flux coordinates (ψ,θ,s), ψ is the flux coordinate, θ is an anglelike coordinate and s is the distance along a field line. The magnetic field B and normal curvature κ_ψ are calculated for the field line passing through the position of $r=5\text{cm}$ and $\theta=\pi/4$ at the central-cell midplane $(z=0)$, where the long-thin approximation $(B\cong B_z, ds\cong dz)$ is well satisfied and $B(-z)=B(z)$ and

$\kappa_\psi(-z) = \kappa_\psi(z)$. We here neglect the finite beta effect on the magnetic field, for simplicity.

If $P_\perp$ and $P_\parallel$, pressures perpendicular and parallel to the magnetic field, are expressed as $P_\perp(\psi,z) = h(\psi)\hat{P}_\perp(z)$ and $P_\parallel(\psi,z) = h(\psi)\hat{P}_\parallel(z)$ with $dh/d\psi < 0$, the stability condition against the flute interchange mode is then given by[4)]

$$\int_{-l}^{l} \frac{dz}{B}\kappa_\psi(\hat{P}_\perp + \hat{P}_\parallel) \geq 0, \tag{1}$$

where $l(=7.6\text{m})$ is chosen to be the position of the inner barrier-cell throat, as we neglect here the contribution of a plug/barrier-cell plasma. The integration is independent of θ. We here assume, for $\hat{P} = \hat{P}_\perp + \hat{P}_\parallel$ (z: in unit of m),

$$\begin{aligned}
\hat{P}(z) &= P_0 + P_C[1-(\frac{z}{2.8})^2]\exp[-(\frac{z}{L_C})^2] \ , & 0 \leq |z| \leq 2.8, \\
&= P_0 \ , & 2.8 \leq |z| \leq 4.4, \\
&= P_0 + P_A[1-(\frac{z-5.2}{0.8})^2]\exp[-(\frac{z-5.2}{L_A})^2] \ , & 4.4 \leq |z| \leq 6.0, \\
&= P_0 \ , & 6.0 \leq |z| \leq 7.6,
\end{aligned} \tag{2}$$

where P_0 is a cold-plasma component which is assumed to be distributed uniformly in $|z| \leq 7.6\text{m}$, P_C is the peak pressure of a central-cell-trapped hot plasma and P_A the peak pressure of an anchor-cell-trapped hot plasma. The parameters L_C and L_A characterize the axial localization of the pressures.

When we define the midplane beta values in each cell as $\beta_A = 8\pi(P_0 + P_A)/B_A^2$, $\beta_{CC} = 8\pi P_0 / B_C^2$ and $\beta_{CH} = 8\pi P_C / B_C^2$, the stability condition is then given by

$$\beta_A \geq f_C \beta_{CC} + f_H \beta_{CH} \ , \tag{3}$$

where $f_C = f_C(L_A)$ and $f_H = f_H(L_A, L_C)$. We show f_H and f_C versus L_A in Fig.2. The symbols shown in the figure denote the calculated data. The value of f_H is smaller than the value of f_C by more than one order of magnitude. This is because the axially localized hot plasma in the central cell is kept off the bad curvature region and then is much less unstable than the axially uniform cold plasma, since the bad curvature of the central-cell mirror is localized only near the throat as shown in Fig.1. Therefore, f_H is smaller for the smaller L_C, and also f_H and f_C become smaller for the smaller L_A for a similar reason. We note that the MHD anchoring almost saturates at $L_A \approx 0.2\text{m}$, and f_H and f_C conversely become larger for $L_A < 0.2\text{m}$.

We next consider the anisotropy of the mirror-trapped hot plasma in the central cell.[2)] The anisotropy is calculated from the equilibrium relationship between $\overline{P}_\perp$ and $\overline{P}_\parallel$ satisfying $\overline{P}_\perp + \overline{P}_\parallel = \hat{P} - P_0 \equiv \overline{P}$ given by

$$\frac{d\overline{P}_\parallel}{dz} = \frac{\overline{P}_\parallel - \overline{P}_\perp}{B} \frac{dB}{dz} \ . \tag{4}$$

Using eq.(4), we can express $\overline{P}_\parallel$ for $0 \leq z \leq l_0$ ($l_0 = 2.8\text{m}$) as,

$$\overline{P}_\parallel(z) = B^2 \int_z^{l_0} dz' \frac{\overline{P}}{B^3} \frac{dB}{dz'} \ , \tag{5}$$

and then the temperature anisotropy at the central-cell midplane is given by

$$\frac{T_{\perp i}}{T_{\parallel i}} = \frac{P_C}{B_C^2}\left(\int_0^{l_0} dz \frac{\overline{P}}{B^3}\frac{dB}{dz}\right)^{-1} - 1 \,. \tag{6}$$

We show f_H and $T_{\perp i}/T_{\parallel i}$ versus L_C in Fig.3. The symbols in the figure show the calculated data for f_H. We see that f_H becomes smaller for the smaller L_C, which yields the larger temperature anisotropy of the central-cell hot plasma.

In conclusion, we have obtained the criteria on the beta value for the flute interchange stability of anisotropic central-cell plasmas in the tandem mirror GAMMA 10 and have shown that the stability criteria are reduced for the axially-localized anisotropic plasma as compared with the uniform plasma.

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REFERENCES

1) M.Ichimura, M.Inutake, E.Asari, S.Adachi, R.Katsumata, Y.Kimura and S.Miyoshi: Jpn. J. Appl. Phys. **30** (1991) 854.

2) R.Katsumata, M.Inutake, M.Ichimura, N.Hino, H.Onda, I.Katanuma, H.Hojo, A.Mase and S.Miyoshi: Jpn. J. Appl. Phys. **31** (1992) 2249.

3) M.Inutake, M.Ichimura, H.Hojo, Y.Kimura, R.Katsumata, S.Adachi, Y.Nakashima, A.Itakura, A.Mase and S.Miyoshi: Phys. Rev. Lett. 65 (1991) 3397.

4) W.A.Newcomb: J. Plasma Phys. **26** (1981) 529.

FIGURE CAPTIONS

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

Fig.2. The values of f_H and f_C as a function of L_A(m), where the symbols denote the calculated data.

Fig.3. The values of f_H (symbols) and the anisotropy $T_{\perp i} / T_{\parallel i}$ (thick line) as a function of L_C(m).

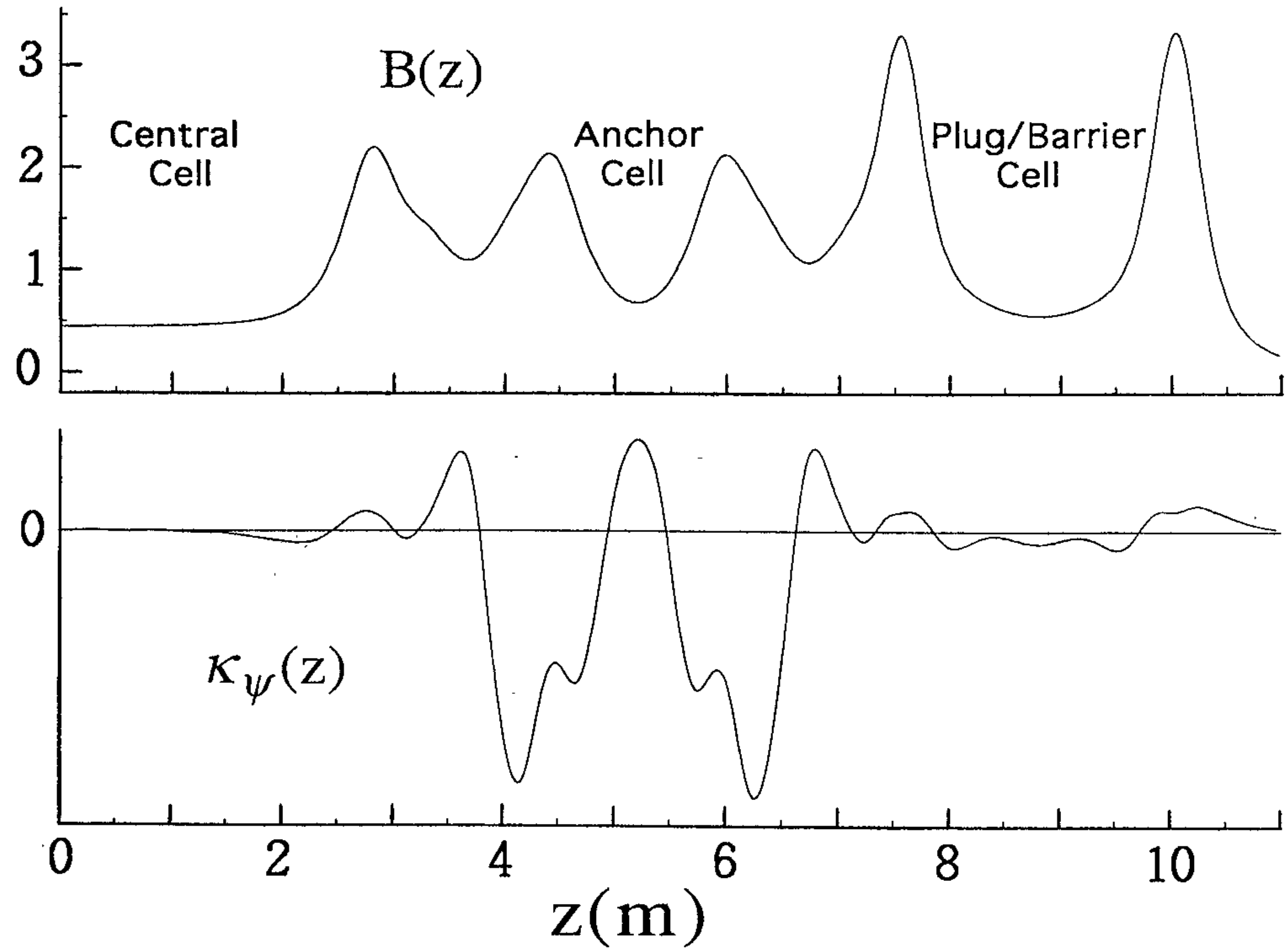
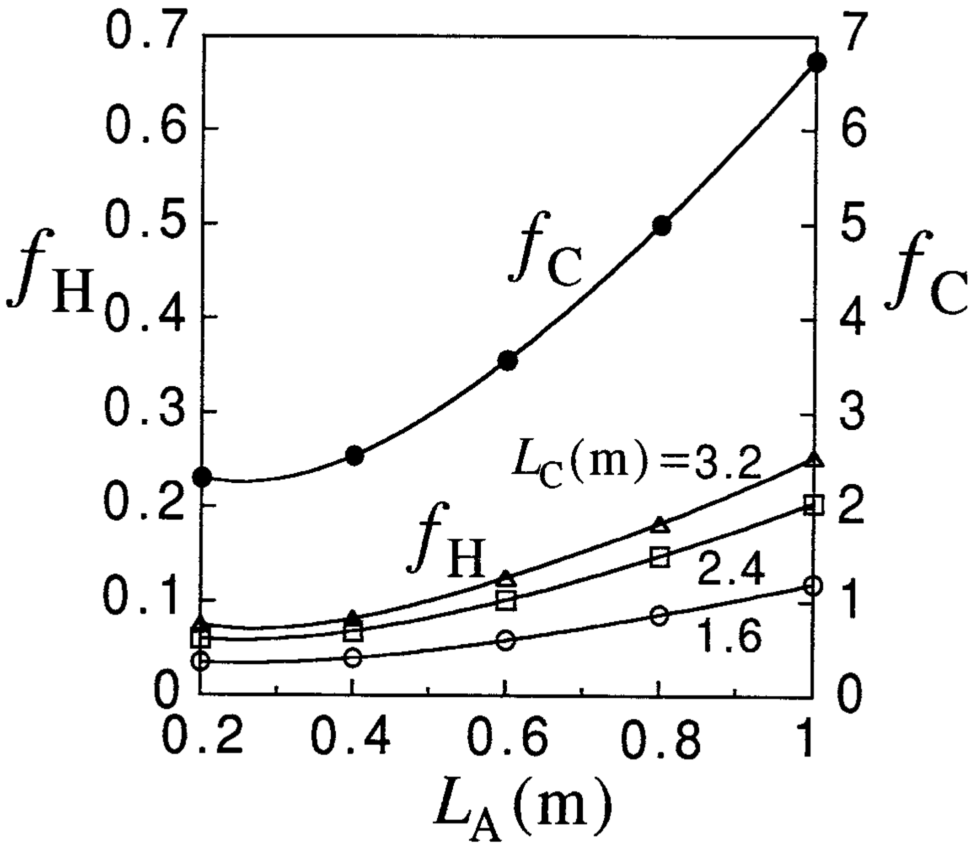

3
2
1
0
B(z)
Central Cell
Anchor Cell
Plug/Barrier Cell
0
$\kappa_\psi(z)$
0
2
4
6
8
10
z(m)

Fig.1



0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
f_H
7
6
5
4
3
2
1
0
f_C
f_C
L_C(m)=3.2
f_H
2.4
1.6
0.2
0.4
0.6
0.8
1
L_A(m)

Fig.2

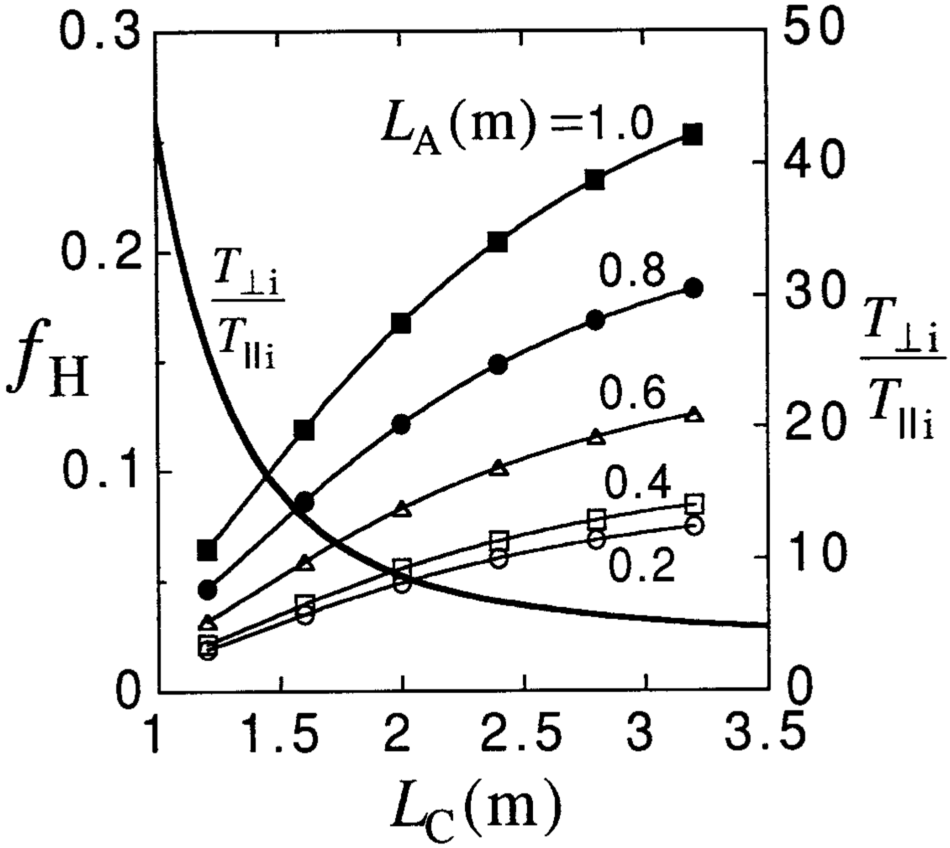

0.3
0.2
0.1
0
50
40
30
20
10
0
1
1.5
2
2.5
3
3.5
L_A(m) =1.0
0.8
0.6
0.4
0.2
f_H
$\frac{T_{\perp i}}{T_{\parallel i}}$
$\frac{T_{\perp i}}{T_{\parallel i}}$
L_C(m)

Fig.3

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