

COMMENT

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Comment

High fusion power gain in a tandem mirror

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Abstract

Comment on ‘A new simpler way to obtain high fusion power gain in tandem mirrors’ by Fowler, Moir and Simonen’

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The article titled ‘A new simpler way to obtain high fusion power gain in tandem mirrors’ by Fowler, Moir and Simonen [1] contains an interesting development of an axisymmetric tandem mirror. The proposed arrangement contains a long axisymmetric mirror with a mirror ratio of $R \sim 10$ that contains the fusing plasma bounded and at both ends by axisymmetric plugging cells which are themselves bounded at each end by the axisymmetric kinetic stabilizers [2–4]. The axisymmetry of the central cell eliminates resonant transport [5] and the expanded fan that exits the kinetic stabilizers eliminates secondary electron energy losses [6].

This configuration is similar to the axicell approach [7], which was embodied in the Tara tandem mirror experiment [8]. In the Tara configuration the axisymmetric central cell and plugs were bounded by quadrupole mirrors rather than kinetic stabilizers. The axisymmetry of the central cell and plug were similarly proposed to eliminate resonant transport. The axisymmetric plugging cells contained angled neutral beam injection which served to stabilize ion cyclotron frequency modes [7, 9].

During the construction of Tara it was found that axisymmetric configurations with outboard magnetohydrodynamic (MHD) stabilizers can be unstable to fast growing trapped particle modes that can be localized to the unstable axisymmetric mirror cells. They are present as electrostatic modes at low beta and can grow at close to the MHD growth rate [10]. Theoretical studies developed a quadratic minimizing energy form which permits the use of simple trial functions that represent modes that are localized in the unstable axisymmetric cells (the central cell or the axisymmetric plugging cells).

Beginning with the gyro kinetic equation, assuming electrostatic modes, we can obtain a quadratic form that is

variational with respect to the electrostatic potential, ϕ as follows [10, 11]:

$$\gamma^2 = -\omega^2 = \frac{-\sum_q q^2 \frac{2\pi}{m_q} \int d\epsilon d\mu \tau_B \bar{\phi}^2 \left[\left(\frac{\underline{b} \times \underline{k}_\perp \cdot \nabla F_0}{m\Omega_q} \right) \left(\frac{\underline{b} \times \underline{k}_\perp \cdot (m v_\parallel^2 \underline{b} \cdot \nabla \underline{b} + \mu \nabla B)}{m\Omega_q} \right) \right]}{\sum_q q^2 \frac{2\pi}{m_q} \int d\epsilon d\mu \tau_B (-F_{0\epsilon}) \left[(\bar{\phi}^2 - \bar{\phi}^2) + \bar{\phi}^2 k_\perp^2 \rho_i^2 \right]}, \quad (1)$$

with $F_0(\epsilon, \psi)$ the equilibrium distribution function and $F_{0\epsilon} = \partial F_0 / \partial \epsilon$. The sum is over electrons and ions, m_q is the respective species mass, ϵ and μ the particle energy and adiabatic invariant, \underline{b} the field direction, $\underline{b} = \underline{B}/B$, Ω_q the cyclotron frequency. The overbar indicates a bounce-time average, i.e. $\bar{\phi} = (1/\tau_B) \oint \phi d\ell / |v_\parallel|$ and $\tau_B = \oint d\ell / |v_\parallel|$.

For example, for a trial function ϕ that is only present in the central cell (or plugging cell) and avoids the outboard anchor or kinetic stabilizer, the growth rate γ , would be as follows [11]:

$$\gamma^2 = \frac{\gamma_{\text{MHD}}^2}{1 + \left(\frac{L_s}{L_{\text{cc}}} \frac{n_{\text{pass}}}{n_{\text{cc}}} \right) \left(\frac{1}{k_\perp^2 \rho_s^2} \right)}. \quad (2)$$

with γ_{MHD} the MHD growth rate, $\gamma_{\text{MHD}}^2 \sim v_i^2 / a \bar{\mathcal{R}}$, L_s the length of the stabilizer, L_{cc} the length of the unstable cell (central or plugging cell), n_{pass} the density of the unstable cell passing (loss cone) particles, n_{cc} the total unstable cell density, a the cell radius, $k_\perp \sim m/a$ the wave number for mode m , v_i the ion thermal speed and $\bar{\mathcal{R}}$ the mean radius of curvature.

An axisymmetric mirror cell like the central cell and the plugging cells have average ‘bad’ curvature and would be MHD unstable in isolation, i.e. if they were not connected to

stabilizing cells. However, for finite mirror ratio cells, these potentially unstable cells can be stabilized by the passing (loss cone) particles that pass through stable field regions along their bounce orbit. When the unstable cell is bounded by a high field magnet $n_{\text{pass}}/n_{\text{cc}} \ll 1$ and the instability growth rate can approach the MHD growth rate. The proposed design utilizes high field plugging cells to minimize their volume and the associated heating power but the high fields that bound the central cell reduce the passing fraction and therefore are destabilizing to trapped particle modes. In the proposed reactor design the mirror ratio of the plugging cell is relatively low ($R_p = 2$) but the mirror ratio of the central cell is high ($R_{\text{cc}} = 10$). A high mirror ratio for an axisymmetric mirror cell means that few particles pass to the stabilizer and the resulting stabilization is weak.

For the parameters in table 2 of [1] $L_S/L_{\text{cc}} \sim 0.01$, $n_{\text{pass}}/n_{\text{cc}} \sim 0.05$, and $k_{\perp}\rho \sim 0.01$ for an $m = 1$ mode, which leads to $\gamma^2 \sim 0.7\gamma_{\text{MHD}}^2$. We have assumed $m > 1$ modes are stabilized by finite Larmor radius (FLR) effects and only the $m = 1$ mode is present. Some stabilization occurs because the electrons and ions reflect in different axial locations (the ions reflect in the plugging cell while the electrons reflect in the kinetic stabilizer). This typically represents a small effect when $L_{\text{cc}} \gg L_S$.

In the Tara experiment the central cell was stable due to ponderomotive [12, 13] effects related to the ion cyclotron heating fields as had been observed in the Phaedrus experiment [12]. Ponderomotive stabilization would not be present in the reactor regime. Additionally the Tara central cell was stabilized by a divertor due to both the short circuiting of the azimuthal wave field [14] and the plasma compressibility. Stability was similarly demonstrated in the Lamex experiment [15] which used multiple divertors to form a ‘picket fence’ arrangement in a large mirror ratio axisymmetric mirror. However, Tara observed trapped particle modes that were localized to the axisymmetric plugging cells [16] which follow from an analysis similar to that given in equation (2). These modes were driven by the particles trapped in the plug cell but were partially stabilized by charge separation combined with a smaller trapped fraction and a reduced FLR stabilization as compared with a central cell localized mode.

In summary, this article resurrects an important approach to fusion energy research. It includes recent advances for preventing cooling of the electron channel by secondary emission electrons, utilizes an axisymmetric ‘kinetic stabilizer’ as an anchor and it introduces a novel approach to enhancing the plugging potential.

However it does not sufficiently address the potentially deleterious instability of trapped particle modes that were studied theoretically and experimentally in the Tara experiment, which had a similar magnetic geometry to that proposed in [1]. Trapped particle modes were observed in the Tara axisymmetric plugging cells; however, they were not observed in the central cells due to the ponderomotive self stabilizing effects associated with ion cyclotron heating which would not be present in a reactor grade plasma. Importantly, theory predicts that when the central cell is long compared to the stabilizing cell and when the central cell trapped particle fraction is large, a central cell localized mode has a growth rate that can approach the MHD growth rate. Additionally the axisymmetric plugs can also be unstable to trapped particle modes. Thus, with outboard stabilizing elements, it becomes necessary to stabilize both the central and plug cells as for example by the application of feedback as suggested in [1]. We note that if the central cell and plugging cells are stabilized there is no need for an outboard stabilizing anchor cell.

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