AXISYMMETRIC MIRROR STABILIZED BY A SHAPED END WALL

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(Presented at the ICC Workshop, Madison, WI, May 25-28 2004)

* Work performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No.W-7405-Eng-48.
MOTIVATION / SUMMARY

• Axisymmetric mirrors have a number of advantages (no neoclassical losses; very high magnetic field in the mirror throats; higher critical betas for ballooning modes; engineering simplicity).

• The particular stabilization scheme* does not require introducing any specific sub-systems and naturally fits into the overall design.

• It may substantially improve performance of high-beta, $Q \sim 1$ mirrors suitable for burning the radioactive waste.

• The physics involved may favorably affect the tokamak divertor design, and FRC confinement (plasma stability on the open field lines).

• This physics can be tested with existing small-scale open-ended systems.

An axisymmetric mirror is usually unstable (the energy principle)
Consider a radial displacement of the flux tube

Flux-tube volume:
\[ V = \int S\,dl = \Phi \int \frac{dl}{B} \equiv \Phi U(r_0) \]

The plasma thermal energy is released if the volume \( V \) increases for the outward displacement: \( \partial U/\partial r_0 > 0 \) (unstable). We use a paraxial approximation (very accurate).

Another version: Pressure-weighted version (Rosenbluth, Longmire):

\[ \int \kappa \frac{dl}{B^{3/2}} < 0 \]

(unstable) \hspace{2cm} \int (p_\parallel + p_\perp) \kappa \frac{dl}{B^{3/2}} < 0 

(unstable)
Contribution of the end wall to the stability integral

The flux-tube length and volume change at $\alpha \approx \pi/2$! One can expect a stabilizing $pdV$ contribution to emerge.

\[ \delta l = \xi_A \cot \alpha; \quad \delta V = \Phi \frac{\xi_A}{B_A} \cot \alpha \quad \text{("A"=absorber)} \]

The $pdV$ work is done only in the case if plasma is reflected by the wall (this is why the wall effect may look as a curiosity).

However, 98% of the electrons are reflected by the Debye sheath. This leads to the following modification of the stability integral:

\[ \int (p_{\parallel} + p_{\perp}) \frac{k dl}{B^{3/2}} + \frac{2 p e_{A} \cot \alpha}{B_A^{3/2}} > 0 \quad \text{(stable)} \]
Is there anything more than a curiosity in all this?

\[
\int (p_{||} + p_{\perp}) \frac{\kappa dl}{B^{3/2}} + \frac{2p_{eA} \cot \alpha}{B_A^{3/2}} > 0 \quad \text{(stable)}
\]

\[
\sim - \frac{p_0 r_0}{L B_0^{3/2}}
\]

\[
\frac{p_{eA}}{p_0} > \alpha \cdot \frac{r_0}{L} \left( \frac{B_A}{B_0} \right)^{3/2} \sim 3 \cdot 10^{-5} \quad \text{(!)}
\]

Note that direct contact of the plasma with a conducting wall does not mean that the line-tying is present! (Kunkel and Guillery, 1965; Kadomtsev, 1965). For the plasma parameters of interest for fusion research, the sheath voltage effectively decouples the plasma from the conducting wall (Ryutov, 1987).

For a complete description of the wall effect, one needs to formulate BC’s for the sheath in the tilted field (Farina, Pozzoli, Ryutov, 1993; Cohen, Ryutov, 1995).
This stabilization technique can be used in $Q \sim 1$ mirror facility for the nuclear waste burning.

The natural plasma loss is sufficient to maintain a required amount of a stabilizing plasma.

No specific additional systems are needed – just a properly shaped plasma absorber.
Although this study was primarily motivated by mirror physics, it may have an impact on the other fusion systems

- Plasma on open field lines in FRCs
- Divertors (one of possible ICC contributions to the main-line research)
Dispersion relation (Ryutov, Cohen, 2004)

\[
\Omega^2 + \Omega \left( i\Omega_1 + \Omega_2 + i\Omega_3 \right) - i\Gamma_1^2 + \Gamma_2^2 = 0
\]

\[
\Omega_1 = \frac{\omega_{ci}^2 Mu}{Lk^2 T_e}, \quad \Omega_2 = \frac{\omega_{ci}}{kl} \cot \alpha, \quad \Omega_3 = \frac{\omega_{ci} G}{kL},
\]

\[
\Gamma_1^2 = \left( \Lambda + \frac{1}{2} \right) \frac{\omega_{ci} u T_e'}{kL} \quad \Gamma_2^2 = \frac{T_e'}{ML} \cot \alpha.
\]

Destabilizing is good in the context of reducing the divertor heat load (spreading the heat over a larger area)
This is an interesting subject for basic research

Depending on the shape of the plasma receiver in a linear device, the plasma may be more or less stable

LAPD, other devices with open field lines...
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ABSTRACT

We consider a possibility of stabilizing a mirror device by the proper shaping of the end walls. The idea is that the sheath at the wall would reflect the majority of the impinging electrons; then, by the proper shaping of the wall, one can achieve the situation where a flute sliding along the wall in the radially-outward direction, would get shorter and the corresponding PdV work over the electron gas would overweigh the effect of the unfavorable field-line curvature. This general idea was described more than 15 years ago [1] but was thought to be impractical because of a very low electron pressure in the end tank of a mirror device. We have recently revisited this issue and found that, by making the end-wall of a conical shape, with a small opening angle and the apex pointing away from the mirror, one can reach a robust stabilization without compromising the plasma confinement. The axial dependence of the magnetic field near the field maximum should be properly tailored. We consider a possible impact of this improvement on the prospects of a mirror facility for the burning of the nuclear waste of fission reactors and conclude that such a facility may become feasible.

Relevant references:


B.B. Kadomtsev, ibid, p. 610.


