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AXISYMMETRIC MIRROR STABILIZED BY A SHAPED END WALL

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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.

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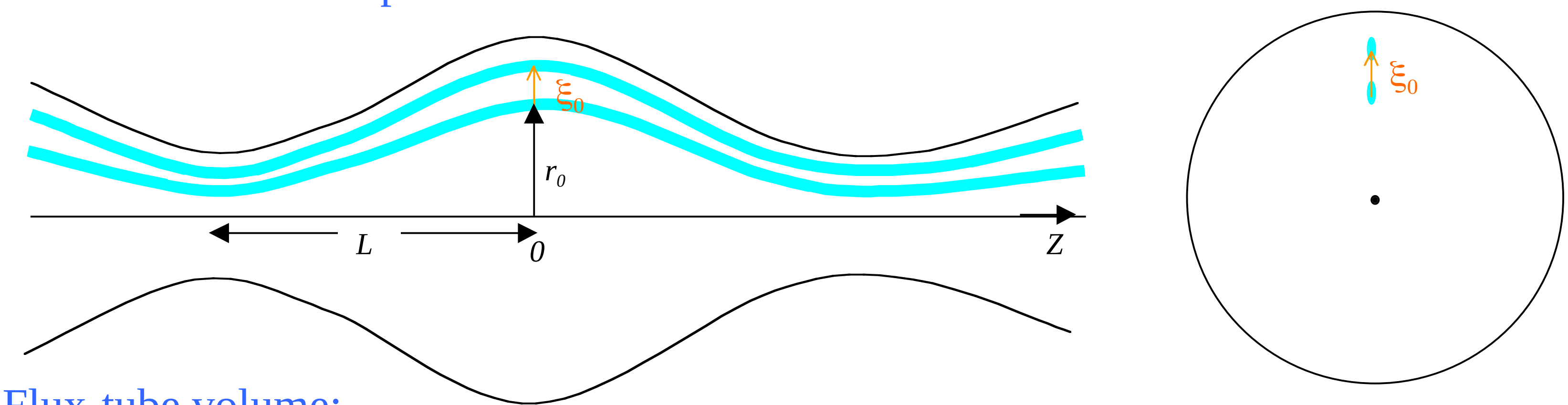
An axisymmetric mirror is usually unstable (the energy principle)

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:

$$\int \kappa dl / B^{3/2} < 0$$

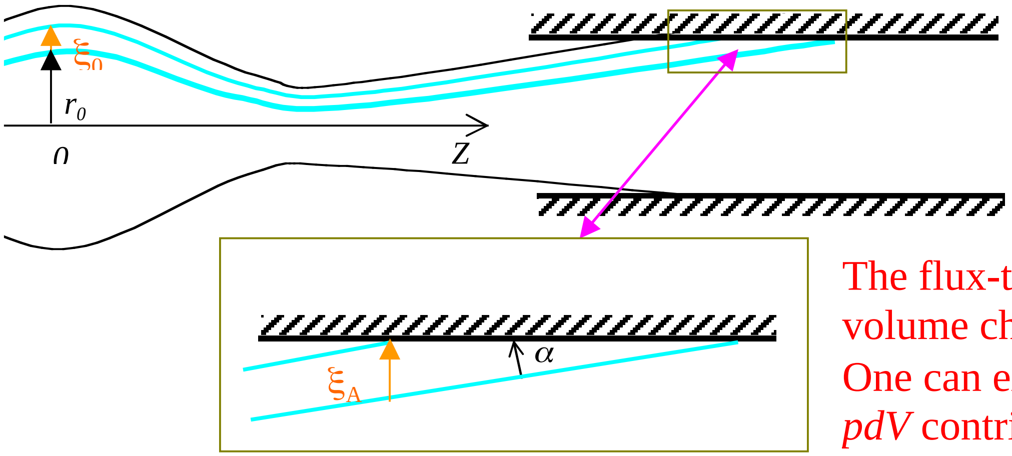
(unstable)

Pressure-weighted version (Rosenbluth, Longmire):

$$\int (p_\parallel + p_\perp) \kappa dl / B^{3/2} < 0$$

(unstable)

Contribution of the end wall to the stability integral



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

$$\delta l = \xi_A \cot\alpha; \quad \delta V = \Phi \frac{\xi_A}{B_A} \cot\alpha \qquad (\text{“A”=absorber})$$

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:

$$\int (p_{\parallel} + p_{\perp}) \frac{\kappa dl}{B^{3/2}} + \frac{2 p_{eA} \cot\alpha}{B_A^{3/2}} > 0 \qquad \text{(stable)}$$

Is there anything more than a curiosity in all this?

$$\underbrace{\int (p_{\parallel} + p_{\perp}) \frac{\kappa dl}{B^{3/2}}}_{\sim -\frac{p_0 r_0}{L B_0^{3/2}}} + \frac{2 p_{eA} \cot \alpha}{B_A^{3/2}} > 0 \qquad \text{(stable)}$$

$$\frac{p_{eA}}{p_0} > \underbrace{\alpha}_{\frac{1}{30}} \cdot \underbrace{\frac{r_0}{L}}_{\frac{1}{30}} \cdot \underbrace{\left(\frac{B_A}{B_0} \right)^{3/2}}_{\frac{1}{30}} \sim 3 \cdot 10^{-5} \quad (!!)$$

(No problem with the heat load)

Note that direct contact of the plasma with a conducting wall *does not mean that the line-tying is present!* (Kunkel and Guillory, 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)

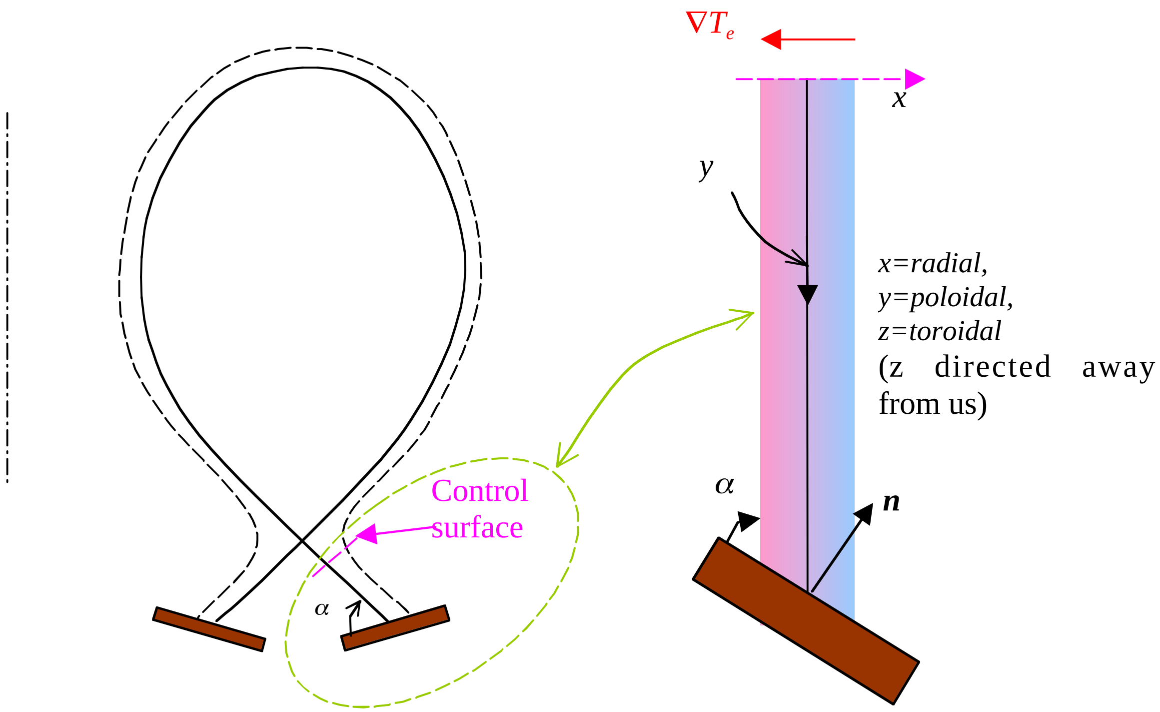
This stabilization technique can be used in Q~1 mirror facility for the nuclear waste burning

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)

inertia — *Kunkel-Guillory sheath resistivity* — *Effect of the x-point* — *the BRT term*

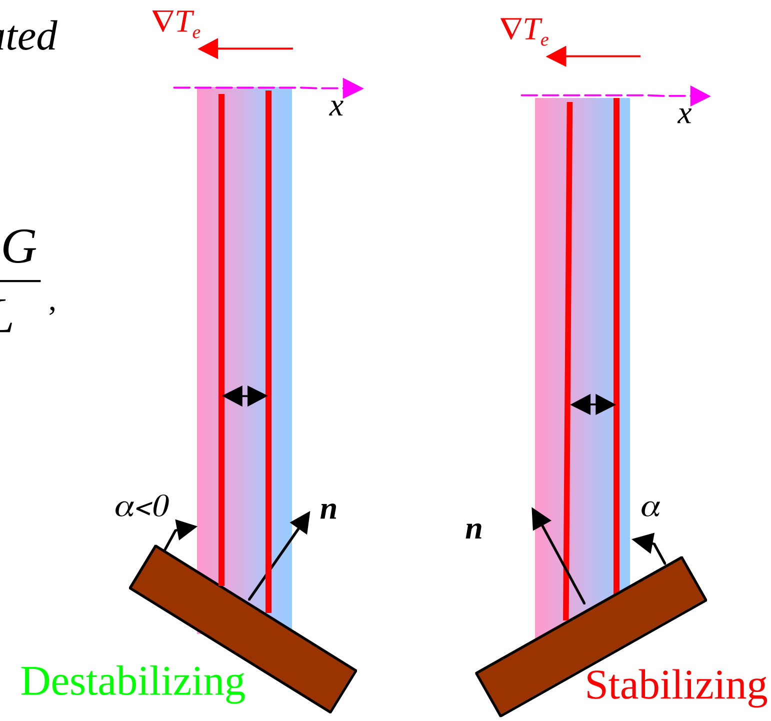
$$\Omega^2 + \Omega\left(i\Omega_1 + \Omega_2 + i\Omega_3\right) - i\Gamma_1^2 + \Gamma_2^2 = 0$$

Effects associated with radial tilt

$$\Omega_1 = \frac{\omega_{Ci}^2 Mu}{Lk^2 T_e}, \qquad \Omega_2 = \frac{\omega_{Ci}}{kl}\cot\alpha, \quad \Omega_3 = \frac{\omega_{Ci} G}{kL},$$

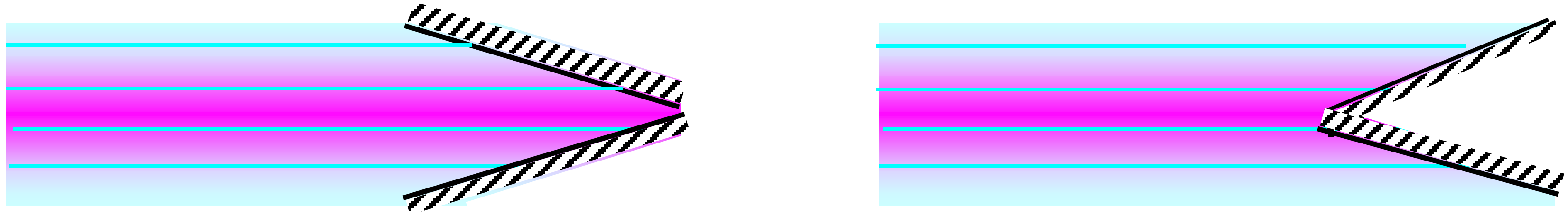
$$\Gamma_1^2 = \left(\Lambda + \frac{1}{2}\right)\frac{\omega_{Ci} u}{kL}\frac{T_e'}{T_e}, \quad \Gamma_2^2 = \frac{T_e'}{ML}\cot\alpha.$$

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



Stabilizing Destabilizing

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.

[1] D.D. Ryutov. "Axisymmetric MHD stable mirrors." In: Physics of Mirrors, Reversed Field Pinches and Compact Tori (Proc. of the Course and Workshop, Intern. School of Plasma Physics, Varenna, Italy, Sept. 1-11, 1987, S. Ortolani and E. Sindoni, Eds.) v.2, p. 791, Editrici Compositori, Bologna, 1988.

Relevant references:

D.D. Ryutov. “Axisymmetric MHD stable mirrors.” In: Physics of Mirrors, Reversed Field Pinches and Compact Tori (Proc. of the Course and Workshop, Intern. School of Plasma Physics, Varenna, Italy, Sept. 1-11, 1987, S. Ortolani and E. Sindoni, Eds.) v.2, p. 791, Editrici Compositori, Bologna, 1988.

W. Kunkel, J. Guillory. In: “Phenomena in Ionized Gases” (Proc. &th Conf. Belgrade, 1965) Vol. 2, p. 702, Belgrade, 1966

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

H.Berk, D. D. Ryutov, Yu. A.Tsidulko JETP Lett., **52**, 23 (1990).

D.Farina, R.Pozzoli, D. Ryutov. Plasma Phys. Contr. Fusion, **35**, 1271 (1993).

D.Farina, R.Pozzoli, D.D. Ryutov. Phys.Fluids, **B5**, p.4055 (1993).

R.H.Cohen, D.D. Ryutov. Phys. Plasmas, **2**, 2011 (1995).

D.Farina, R.Pozzoli, D. Ryutov. Nuclear Fusion, **33**, 1315 (1993).

D.D. Ryutov, R.H. Cohen. Contributions to Plasma Physics, **44**, 168 (2004).