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Axisymmetric MHD-stable mirror as a neutron source and a fusion reactor

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Significant progress with the GDT facility has raised interest in mirrors in USA

General coordination: *Tom Simonen*

Mirror Calendar

September 2008: Berkeley workshop on mirrors

March 2009: Berkeley workshop on technical feasibility of GDT-based neutron source

March 2009: First meeting of biweekly Mirror Forum

May 2009: Brookings Institute workshop on hybrids

September 2009: DoE-sponsored workshop on hybrids

November 2009: Mini-Conference on mirrors at the APS DPP meeting

Conceptually, mirror is a very simple system

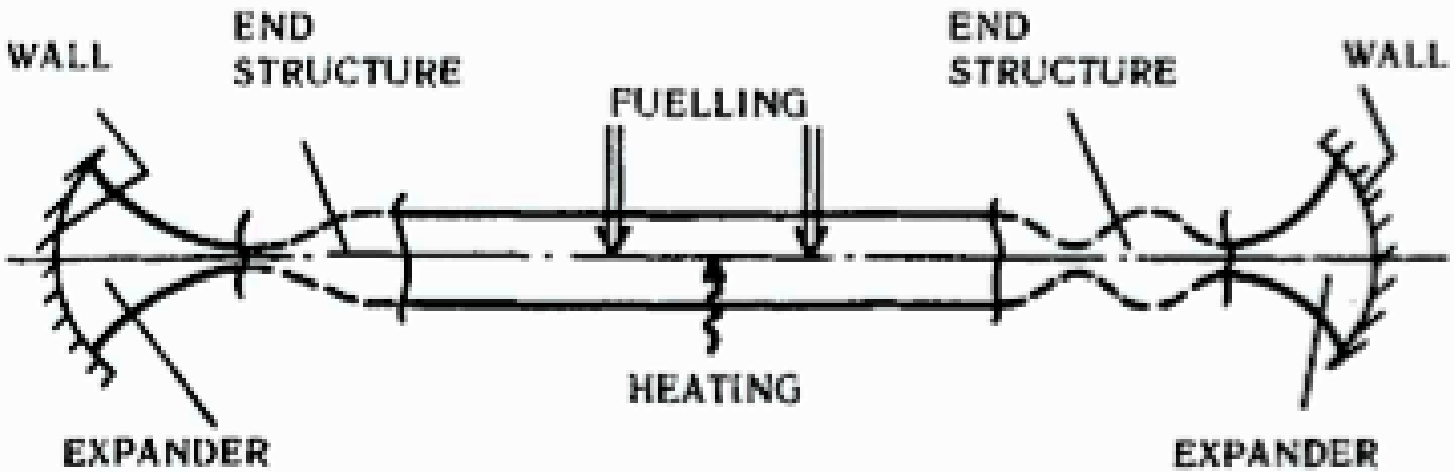


FIGURE 1 Schematic of a generic mirror reactor. In order to emphasize that there exists more than one option for end plugging and MHD anchoring, the end structures (each incorporating the plug and the anchor) are shown different and in dashed lines.

D.D. Ryutov. "Plasma Devices and Operations," **1**, 79 (1990)

Advantages of mirrors as fusion devices

Inherently steady-state

High beta

Natural divertors (no problems with wall heat loads)

Simplicity of the energy-releasing element (simple solenoid)

No axial currents

These advantages would be amplified if mirrors could be made *fully axisymmetric* and, at the same time, MHD stable

No neoclassical or resonant transport

Availability of high-beta equilibria in long systems

Higher magnetic field strengths in mirror throats (!)

Engineering simplicity

Remarkable flexibility

There exists at least one experimentally-proven technique for stabilizing axisymmetric mirrors: the GDT

Gas-Dynamic Trap is a mirror machine with large mirror ratio *R* and length *L* exceeding the mean free path with respect to the particle scattering into the loss cone

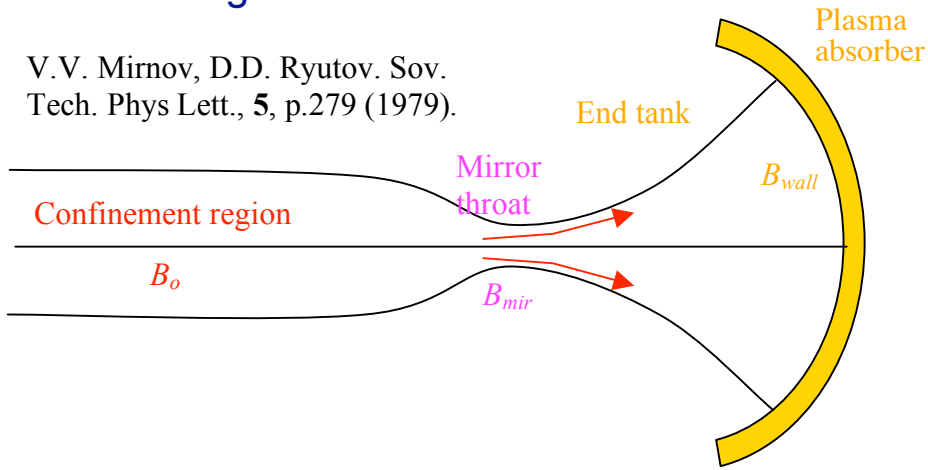
$$L > \frac{\lambda \ln R}{R},$$

The confinement time is then the same as for a gas leaking from a vessel with a small hole in the wall:

$$\tau \approx \frac{LR}{2c_s}$$

The plasma in such a mirror machine can be made MHD-stable in axisymmetric geometry, via stabilizing effect of the favorable field line curvature in the end tanks

V.V. Mirnov, D.D. Ryutov. Sov. Tech. Phys Lett., **5**, p.279 (1979).



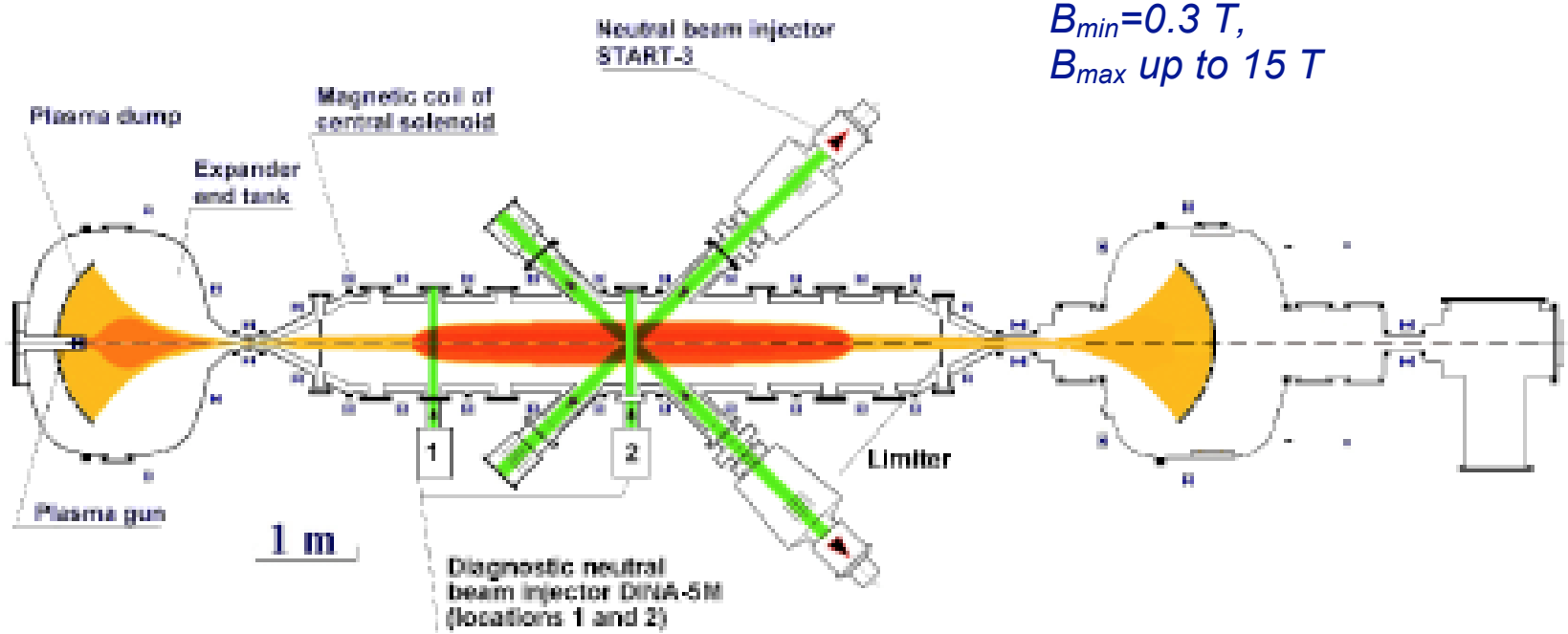
Field line curvature

$$\int dl \frac{\kappa}{B^{3/2}} (p_{\parallel} + p_{\perp} + \rho v^2) > 0$$

M.N. Rosenbluth, C.L. Longmire. Ann. Phys., **1**, 120 (1957)

GDT Experimental Results

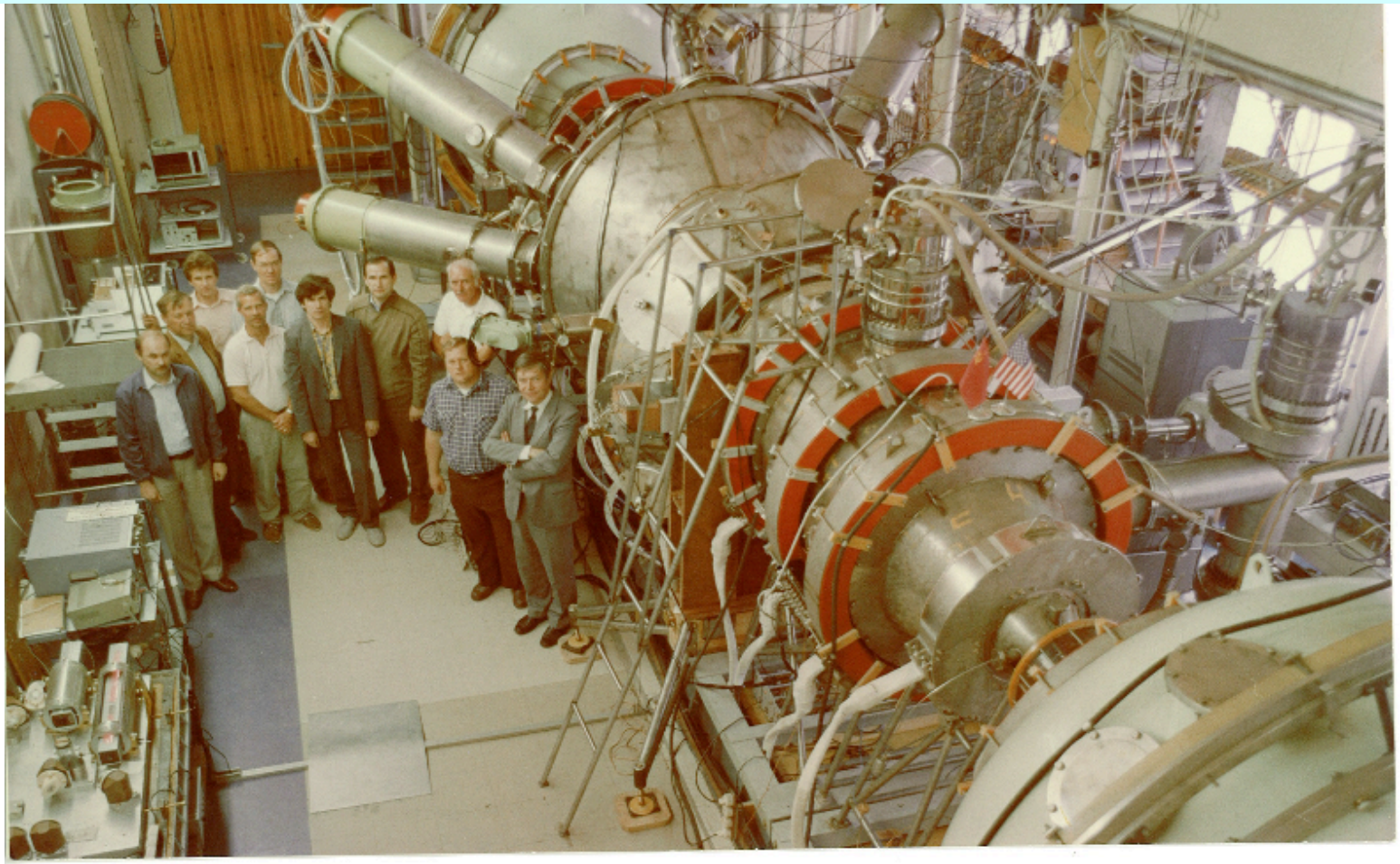
B_{min}=0.3 T,
B_{max} up to 15 T



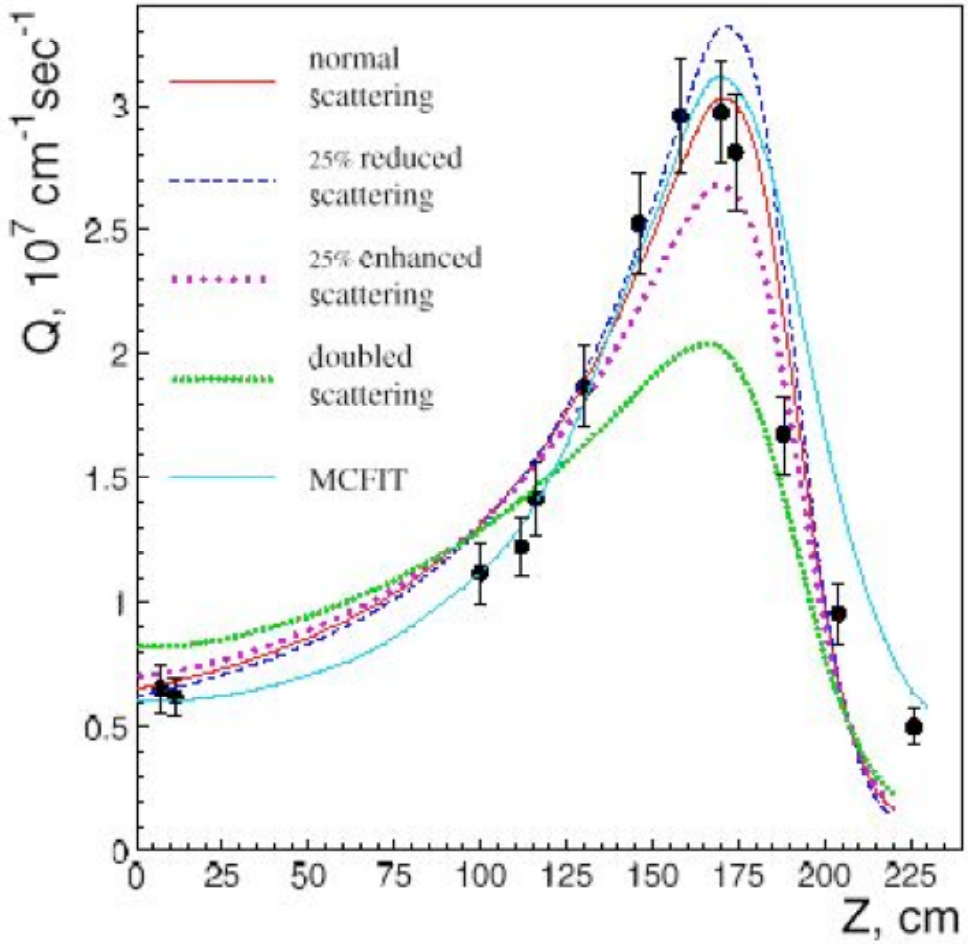
Fully axisymmetric plasma, MHD stable for beta 0.6 (60%), average ion energy 10 keV, average ion density 5×10^{13} cm^{-3}, no signs of the ion microinstabilities, electron temperature 200 eV, classical energy and particle confinement.

MHD stability by favorable curvature in the expansion tanks; can be enhanced by sheared rotation

GDT at the Budker Institute of Nuclear Physics, Novosibirsk, July 1988: working together with the LLNL team



Measured profile of DD-reaction intensity



Axial electron heat loss

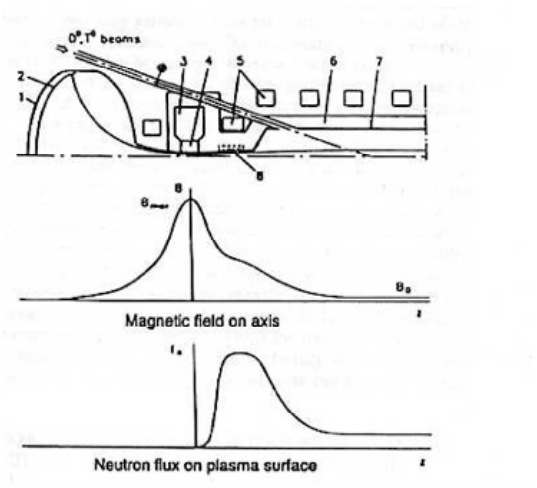
The issue of the parallel heat losses is still often quoted as a “show-stopper” for open confinement systems.

However, it is obvious that, for a small secondary emission from end plates and low neutral gas pressure in the end tanks, the quasineutrality constraint limits the electron losses to one electron per one ion; this leads to quite a favorable energy balance of a mirror device.

Problems may appear if the secondary emission coefficient of the end-plates *h* exceeds 1 and/or the gas pressure in the expander is too high.

Large expansion ratios ($S_{wall} > 60\ S_{mirror}$) solve the problem of the secondary emission; large end tanks and adequate pumping system solve the problem of gas ionization. [Theory and experiment.]

Possible parameters of a GDT-based neutron source*



- 2 MW/m2 Neutron Flux
  - L/a = 11 m / 14 cm
  - B = 28 T / 1.8 T
  - Slosh Ion = 4e20 m-3
  - NBI = 80 keV
  - Te = 0.8 keV
  - Test area = 70x60 cm
  - Tritium consumption = 1 kg for 20 MWy/m2

A number of other versions, from quite ambitious, with neutron flux up to 4-5 MW/m^2 (beam-target version), to those which do not require any significant extrapolation from the existing GDT results, with neutron flux of 0.1-0.3 MW/m^2, have been considered (see references below and references therein)

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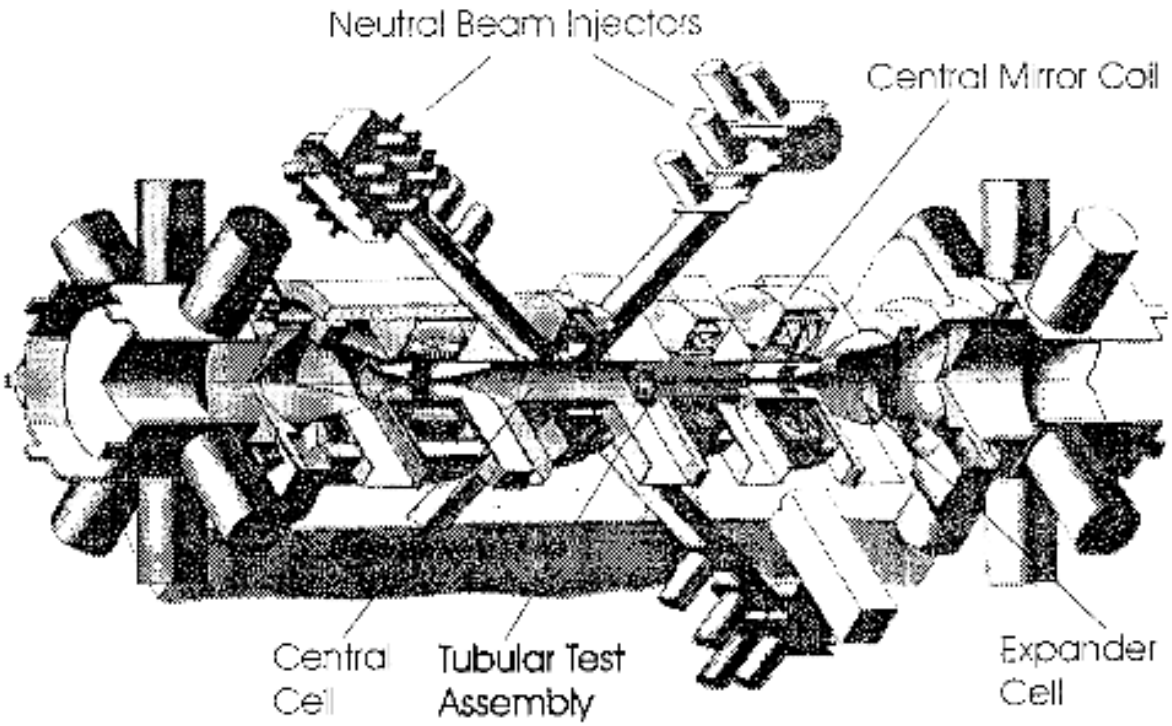
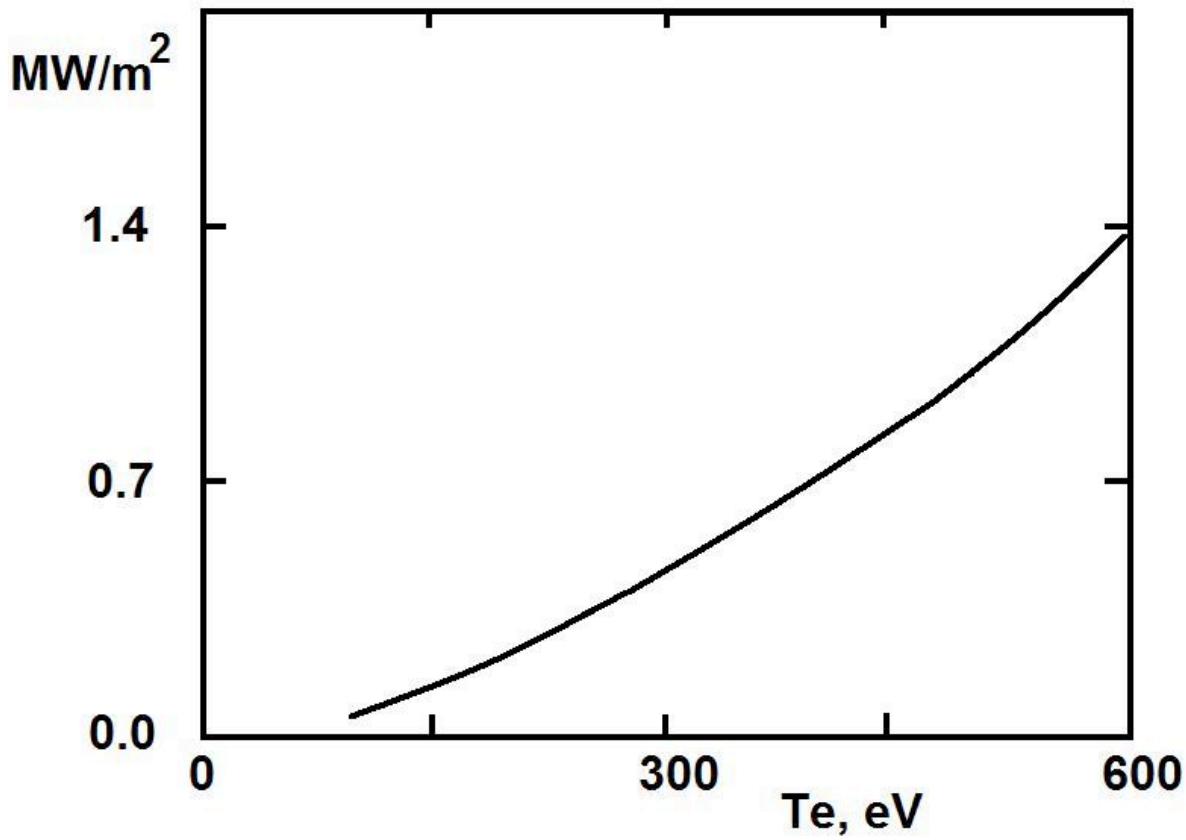
*V.V. Mirnov et al., Rep. 1984-40, Budker Inst. Nucl. Phys, 1984; D.D. Ryutov. Plasma Phys. Contr. Fusion, **32**, p.999 (1990); I.A. Kotelnikov et al. Rep. 1990-105, Budker Inst. Nucl. Phys, 1990; A.A. Ivanov et al. J. Nucl. Mater., **307-311** (2002); E.P. Kruglyakov et al. Trans. Fus. Sci. Technol., **43**, 315 (2003); P.A. Bagryanski et al, Fus. Eng. Design, **70**, 13 (2004).

Isometric view of one of the versions of the neutron source*



*U. Fischer, A. Moslang, A.A. Ivanov. Trans. of Fusion Techn., 35, 160 (1999)

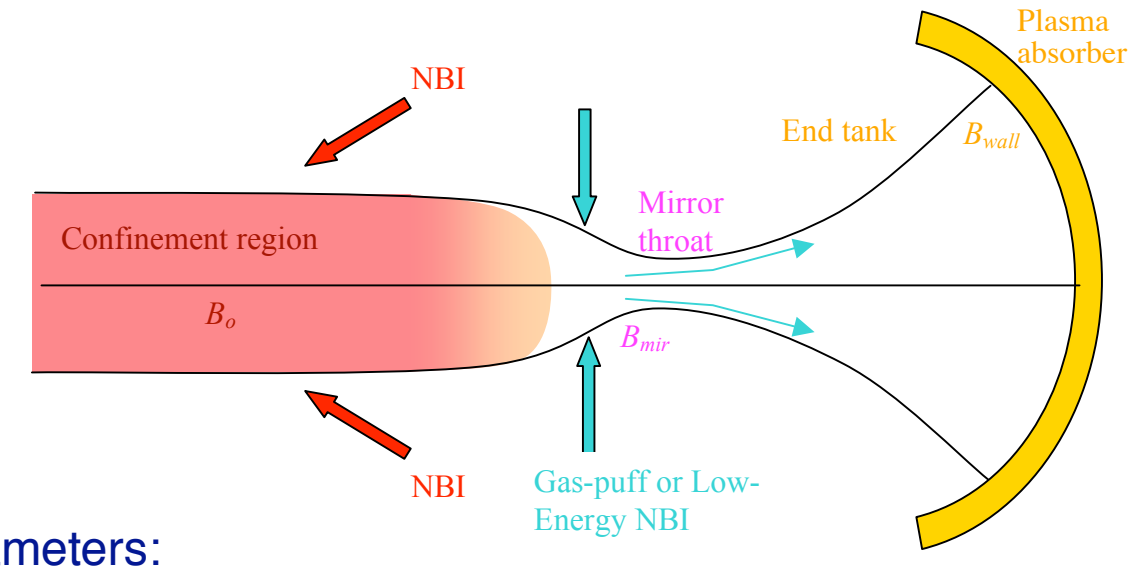
Neutron Flux *vs* Plasma Temperature



Main technology issue: steady-state operation (including NBI)

Consider mirror as an "engine" for a hybrid/waste burner

Axisymmetric mirror with sloshing ions, artificially cooled electrons, and end-tank stabilization



Device parameters:

Injection energy W_0=70 keV; absorbed beam power 200 MW; plasma radius a=0.5 m; mirror-to-mirror length L=30 m; plasma density n=10^{14} cm^{-3}; plasma beta = 0.25; neutron wall load 1 MW/m^2; electron temperature T_e=3 keV; cold plasma outflow 3 kA (Eq) per end. Magnetic field (superconducting) B_0= 2.5 T, B_{mir}= 15 T, B_{wall}=0.08T.

We want to keep the electron temperature low in order to make the system more stable for both velocity-space modes and MHD modes

Without gas-puff near the ends, we would approach a standard simple-mirror power and particle balance, with electrons heated to $\sim 0.3\,T_i$ and a large “hole” formed in the ion velocity space

Most probably, the system without gas-puff near the ends would “fall apart” due to both velocity-space and micro-instabilities

One has to pay for the good plasma stability by a relatively low Q value of 0.5

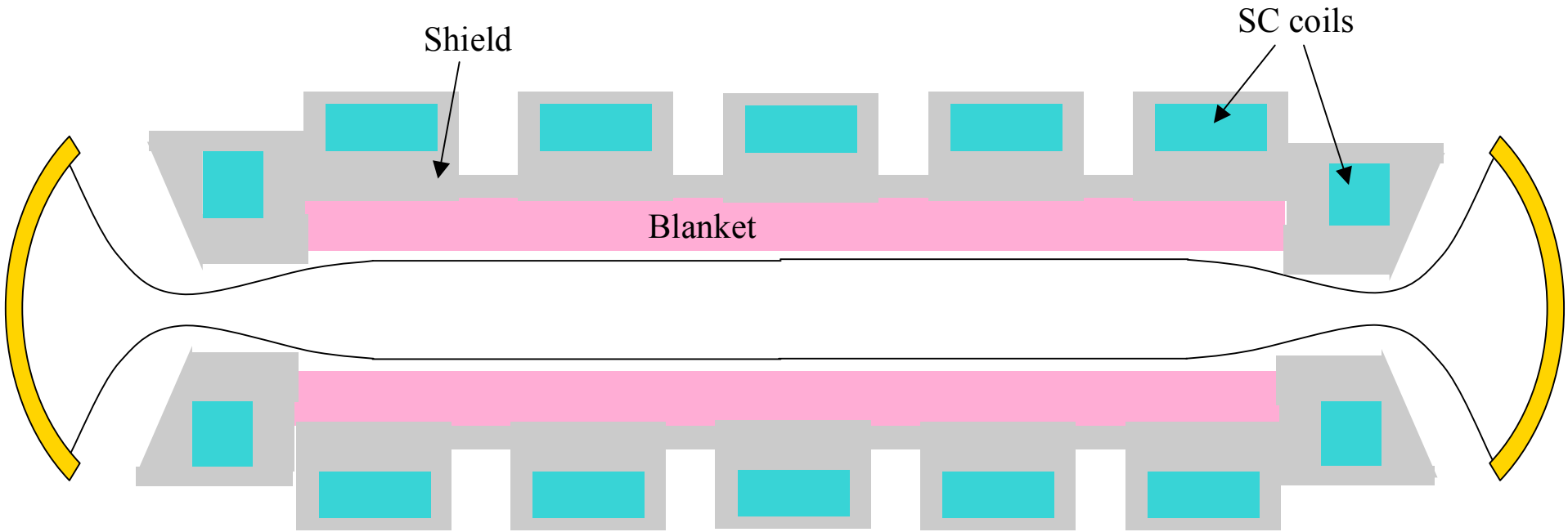
SLOSHING IONS ARE REMARKABLY STABLE WITH RESPECT TO THE MICROINSTABILITIES

This general observation has been made in 1980s, during experiments with TMX-U

It served as a basis for the GDT neutron source proposal at Novosibirsk, where the sloshing ions are one of key ingredients for making the neutron source attractive

Sloshing ions in GDT are remarkably stable (no “anomalous” scattering)

Schematic of a fusion "engine" based on the axisymmetric mirror device (not to scale)



Fusion power 100 MW

Q_{fus}=0.5, $\eta_{heating}$=0.4 (plug-to-plasma)

Required power amplification in the blanket ~ 10-15 (power to the grid ~ 200 - 500 MW)

Length 50 m (mirror-to-mirror 30 m)

Plasma diameter 1 m

B_0=2.5 T, B_{mir}=15 T (SC)

Overall energy balance in the system

For the 50-70-keV DT beams, one can expect the plug-to-plasma efficiency of 50%

As the magnetic system is superconducting, the engineering Q ($Q_{eng}=\eta_{inj}Q$) of our system is Q_{eng}~0.2-0.3

The condition for the net power output:

$\eta_{inj}QA\eta_{thermal}>1$ (A = blanket power amplification)

Assuming $\eta_{inj}=0.5$, $Q=0.5$, $\eta_{thermal}=0.4$, one sees that the blanket power amplification A has to be 10 - 15, to make the system a net energy producer

Pure-fusion (Q=10-20) reactor of an acceptable length (most probably) cannot rely on stabilization with the end-tank plasma: end losses must be small

Scheme of the GDT End-Plug Experiment

End Plug:

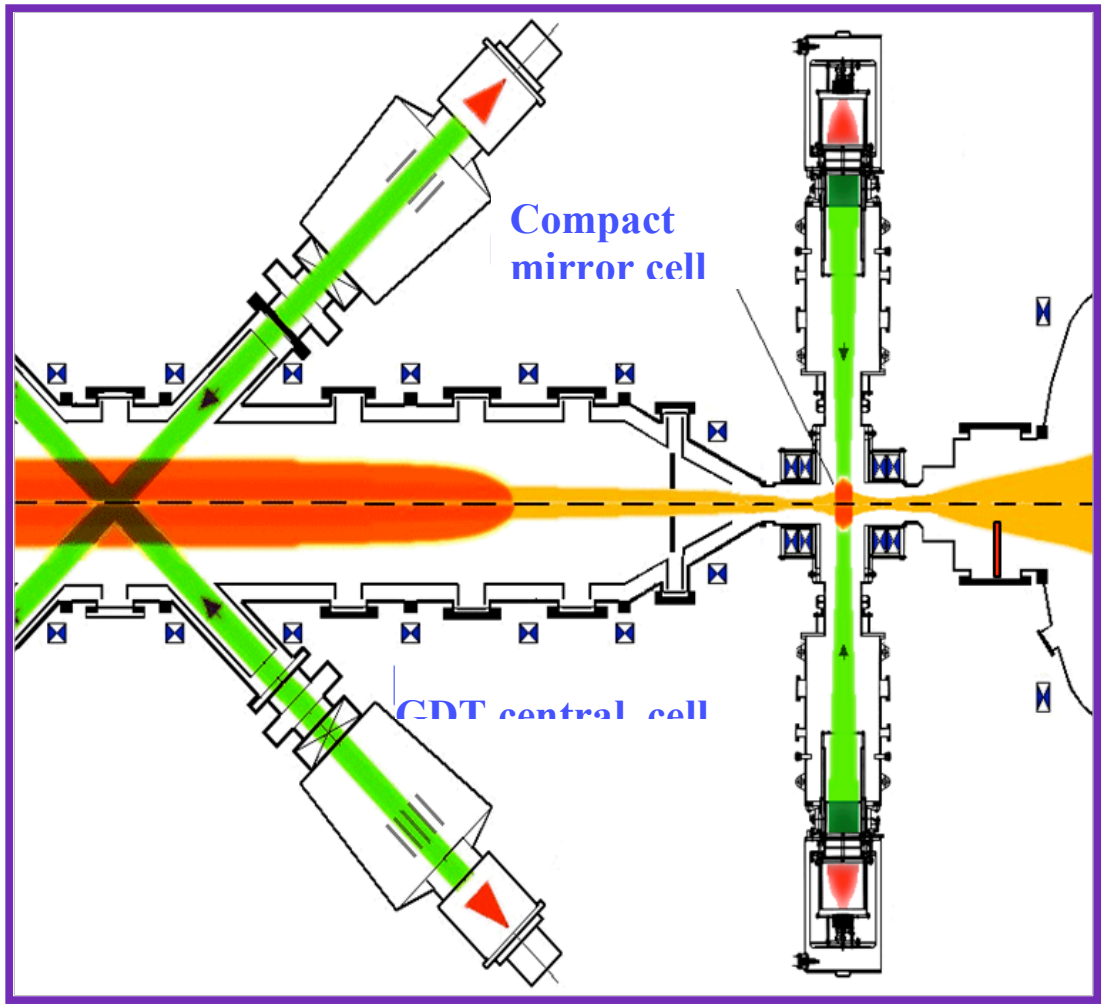
L=30 cm, d =70 cm.

Magnetic field:

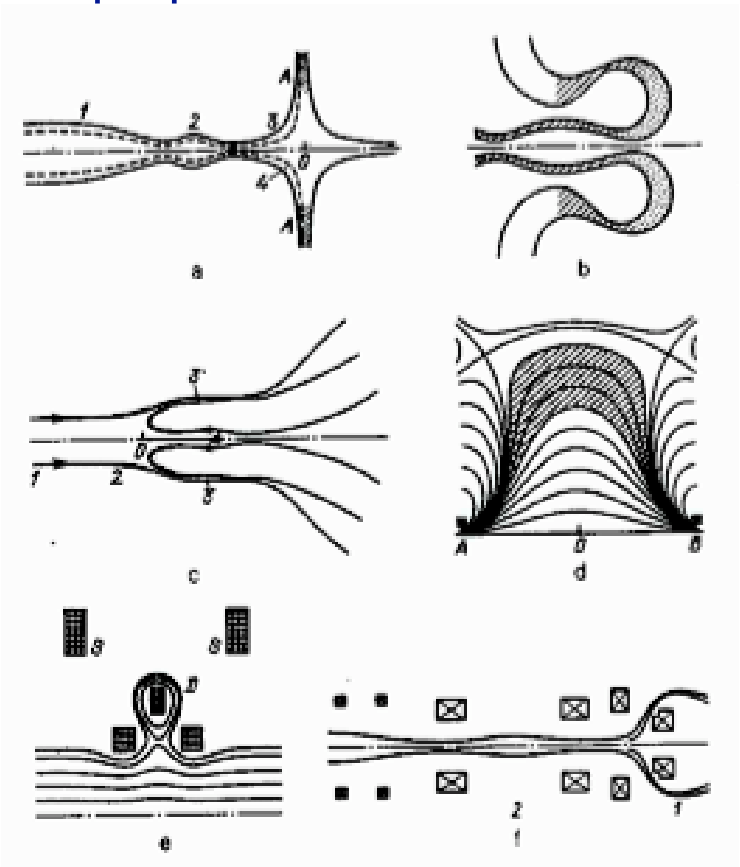
B_0=2.4 T, B_m=5.2 T

Background plasma:
hydrogen, $n_0 \approx 10^{13}$ cm^{-3},
$T_e \approx$ 70 eV, a =9 cm.

NBI system:
H^0 or D^0
E_0=20 keV, θ=90º,
$P_{inj} \approx$ 1 MW, τ_{inj}=4 ms



A number of versions of axisymmetric stabilizers not relying on the plasma outflow have been proposed



See a summary in: D.D. Ryutov, Proc. 1987 Varenna School, v. 2, p. 791; Sov. Phys. Usp., **31**, 300, 1988.

Also:

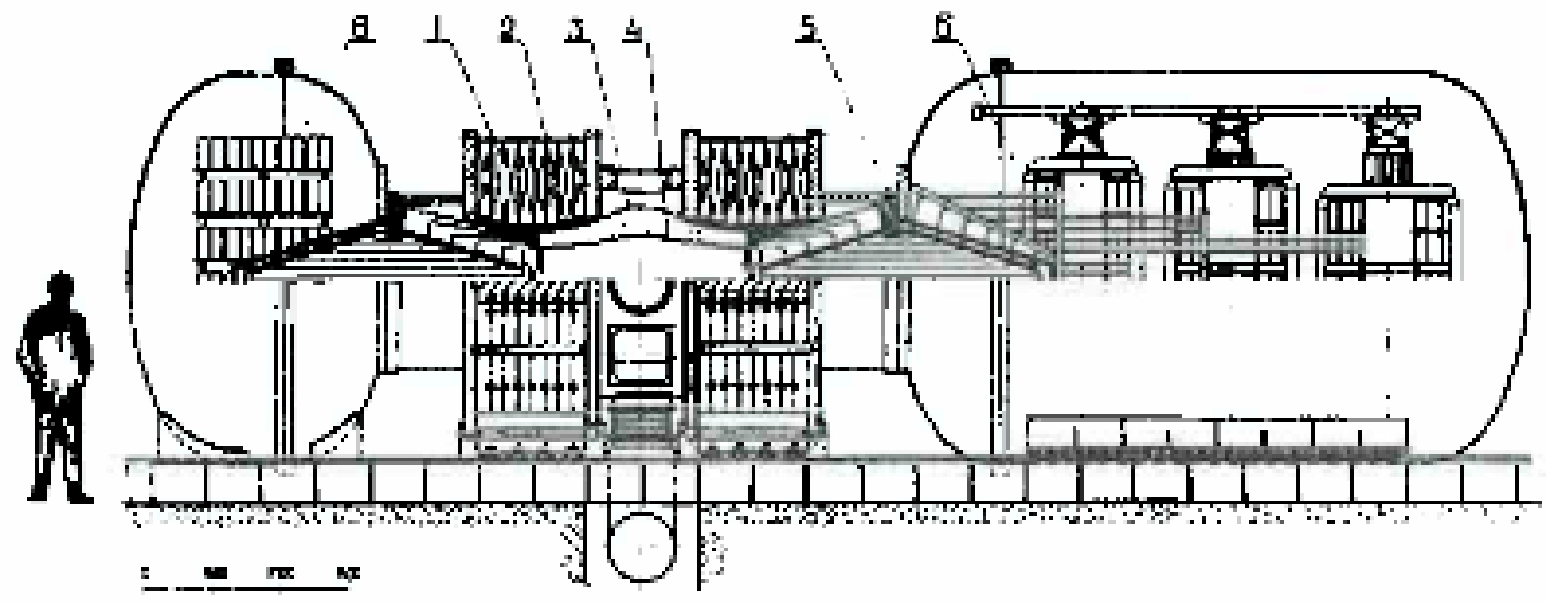
Using sloshing ions with turning points in the zone of favorable curvature
M.N. Rosenbluth, C.L.Longmire. Ann.Phys., **1**, 120 (1957); F. Hinton, M.N. Rosenbluth. Nucl. Fus., **22**, 1547 (1982).

Using stabilization by outflowing plasma and favorable curvature in the expansion tanks (gas-dynamic trap)
V.V. Mirnov, D.D. Ryutov. Techn. Phys. Lett., **5**, 678, 1979

Using ions injected from the ends and with turning points in the zone of favorable curvature in expansion tanks ("kinetic stabilizer")
R.F. Post et al, Fusion Sci. Technol., **47,** 49 (2005).

Also: recent revival of interest to stabilization by sheared rotation

(successfully exploited with the PSP device at Novosibirsk)



Most recent analysis and further references at: A.D. Beklemishev, M.S. Chaschin, Plasma Physics Reports, 34, 422 (2008).

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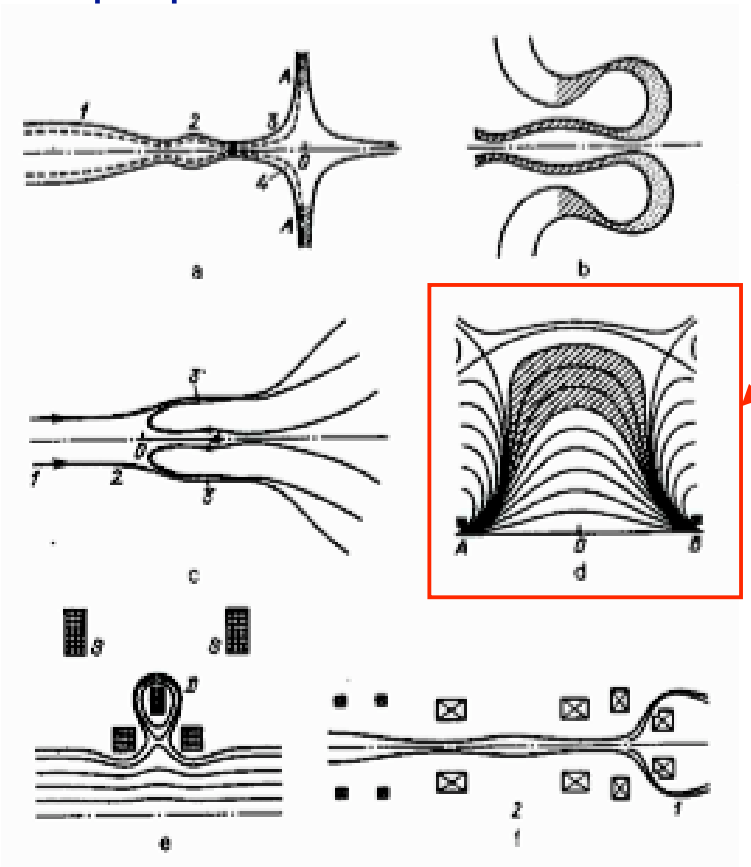

My favorite

See a summary in: D.D. Ryutov, Proc. 1987 Varenna School, v. 2, p. 791; Sov. Phys. Usp., **31**, 300, 1988.

Summary

Significant progress in both mirror theory and experiments has been made during the last decade

Time has come to seriously discuss how to use these developments in the interests of the broader fusion program

Final quotation:

"The tremendous importance of the ultimate goal and the enormous difficulties that lie in the way combine to stamp the problem of thermonuclear fusion with a quite distinctive character. For the time being we find ourselves as it were on the dividing line between dream and reality…"

L. A. Artsimovich
20th September 1962