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FUSION PERSPECTIVES*

LLNL Fusion Energy Sciences Program

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This talk consists of 2 parts:

I. Fusion perspectives

II. Two specific plasma physics problems

PART I: FUSION PERSPECTIVES

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1. Controlling the interaction of fusion plasmas with external structures

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   - High neutron fluxes
   - Electromagnetic and mechanical interactions with external structures

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2. Gradual shift of the “center of gravity” to China and India

   They really need fusion energy!

3. Much stronger emphasis on the projects with a short turn-around time

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5. Possible pleasant surprises in physics and technology

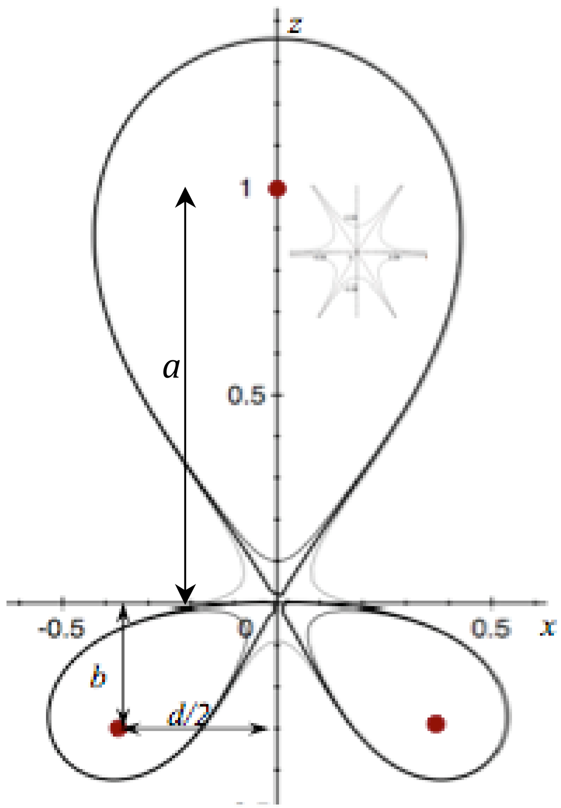
   We need them!

PART II: TWO SPECIFIC PLASMA PHYSICS PROBLEMS

PART II.1

Snowflake divertor: an attempt to mitigate the tokamak heat load problems

A snowflake divertor is a divertor with the second-order null of the poloidal field



Snowflake divertor in symmetric 3-wire configuration.

- Larger flux-expansion ratio
- Increased magnetic shear in the pedestal region (potentially better control of ELMs)
- Reduced blob transport (stronger flux-tube squeezing near the null-point)
- Increased connection length
- Increased non-quasineutral ion transport, leading to stronger shear flows in the pedestal region
- Possibility to create this configuration with existing set of PF coils on some of the existing devices (DIII-D, NSTX, ….)
- Possibility to create “snowflake” in ITER-scale machines with PF coils situated outside TF coils

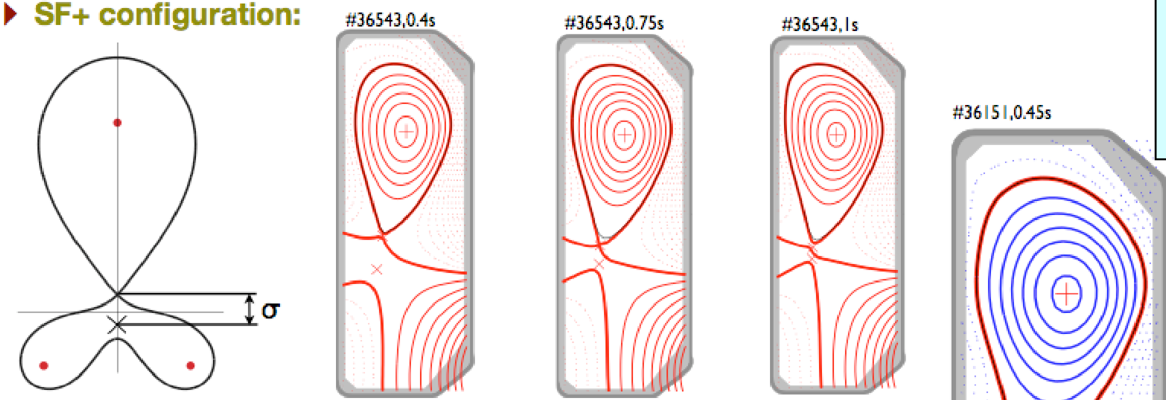
*D. Ryutov. Phys. Plas, **14**, 064502, 2007*

SF configurations on TCV

- **Equilibrium reconstruction**
  - **Different SF configurations have been created in TCV and reconstructed using the LIUQE code**

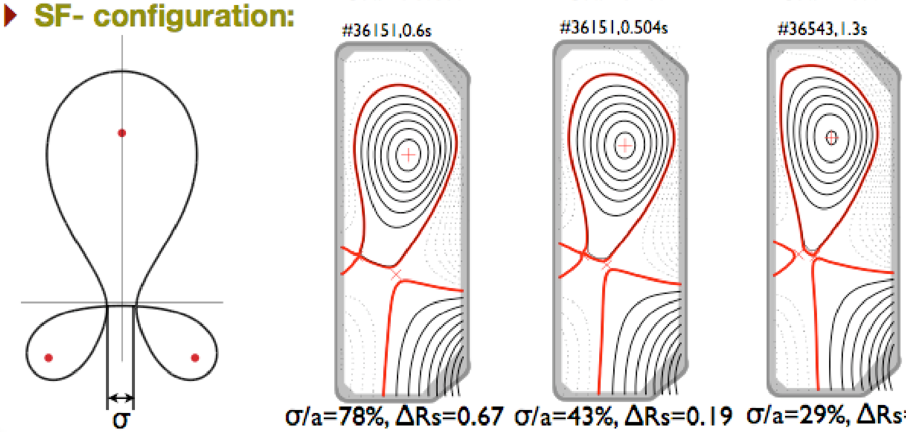
F. Piras et al, Lausanne, 2009

- **SF+ configuration:**



σ/a=58.8% σ/a=32% σ/a=20%

- **SF- configuration:**



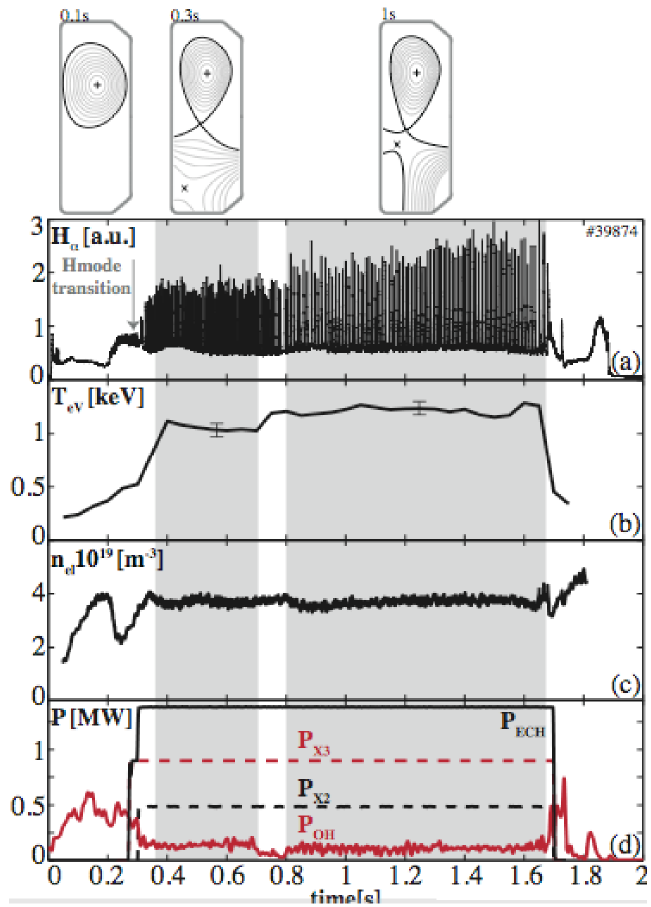
σ/a=78%, ΔRs=0.67 σ/a=43%, ΔRs=0.19 σ/a=29%, ΔRs=0.1

σ/a=15%

TCV SOL:

W=2-3cm
B_T=1.25T
T_e=7-40eV
n_e=0.3-30×$10^{18}m^{-3}$
ρ_e=10-20μm
ρ_i=0.5-1mm
λ_D=3-30μm

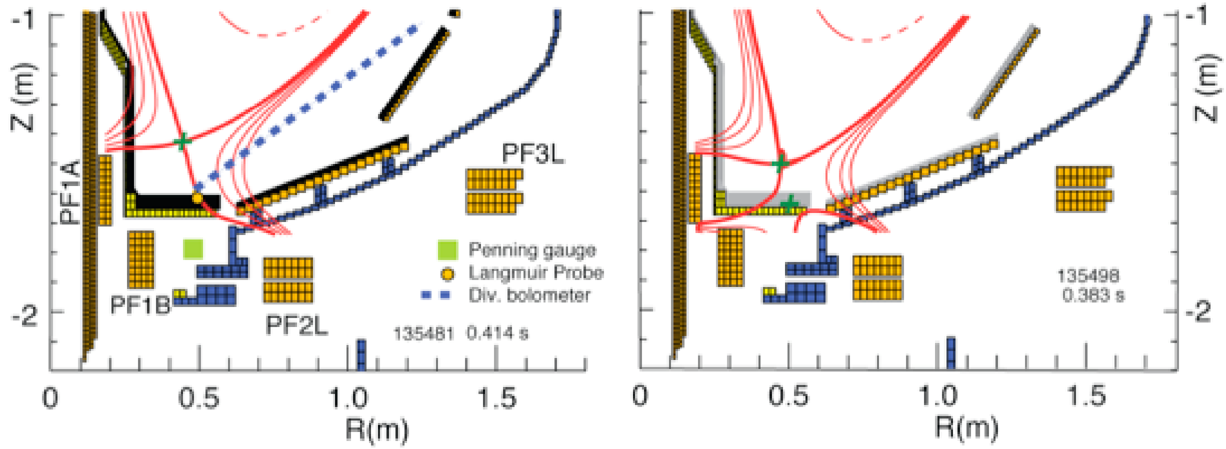
Strong effect of a SF+ divertor on the ELM activity was observed on the TCV tokamak in Lausanne



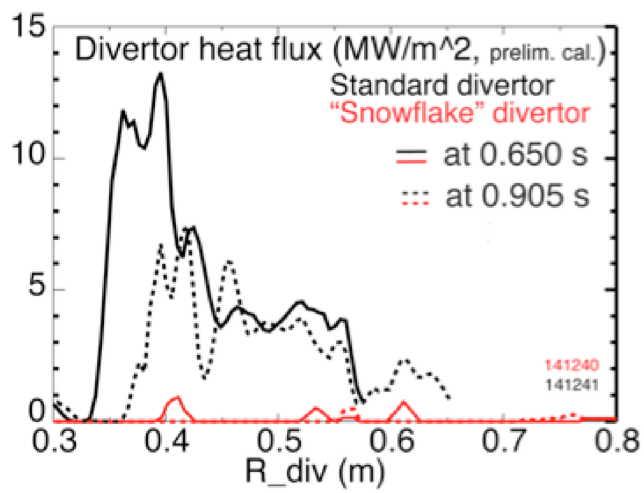
Courtesy F. Piras;

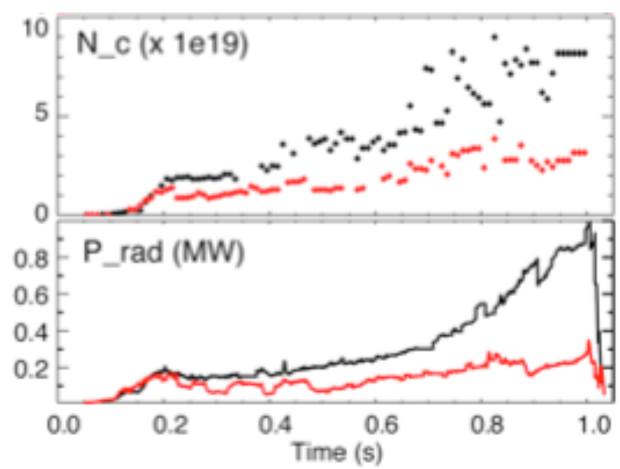
PRL, **105**, 155003 (2010)

Transition to SF- on NSTX caused dramatic reduction of the heat flux



Standard divertor configuration (δ ~0.55-0.60) is transformed into "Snowflake" divertor with **two coils**





Courtesy
V. Soukhanovskii
(IAEA
presentation,
2010)

SUMMARY: SF divertor is an inexpensive and versatile approach for controlling ELM activity and divertor heat loads

PART II.2

Comeback of (axisymmetric) mirrors?

Attractive features of mirrors as fusion devices

- High beta
- Natural divertors (no problems with wall heat loads)
- Fusion occurs in a simple linear solenoid
- Inherently steady-state
- No axial currents, no disruptions

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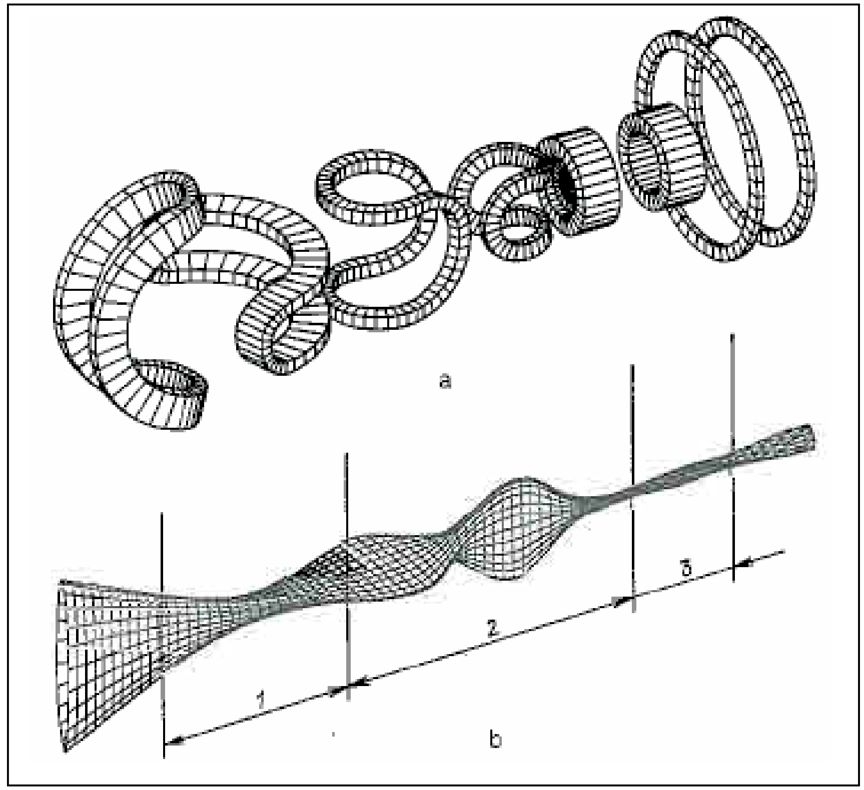

Stability by the set of quadrupole coils (MFTF-B, Livermore, 1980s)

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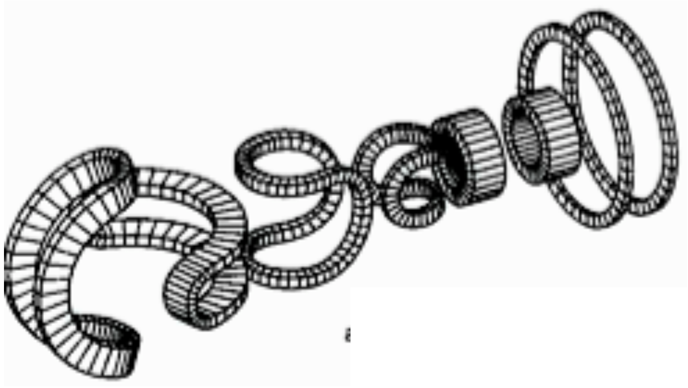
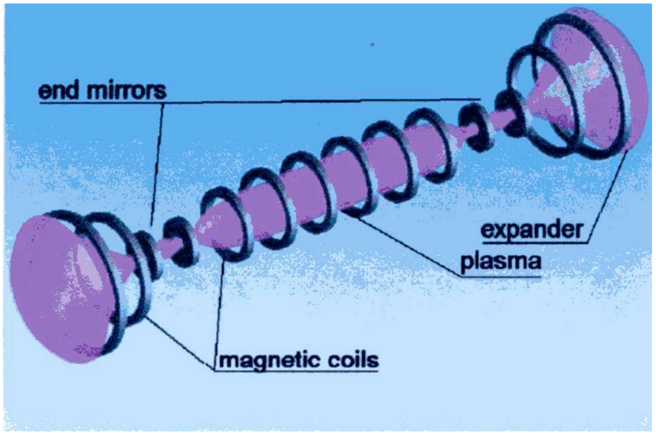
Axial symmetry adds a lot:

- Higher magnetic field strength in mirror throats (!)
- Construction and maintenance simplicity
- No neoclassical transport
- Remarkable flexibility

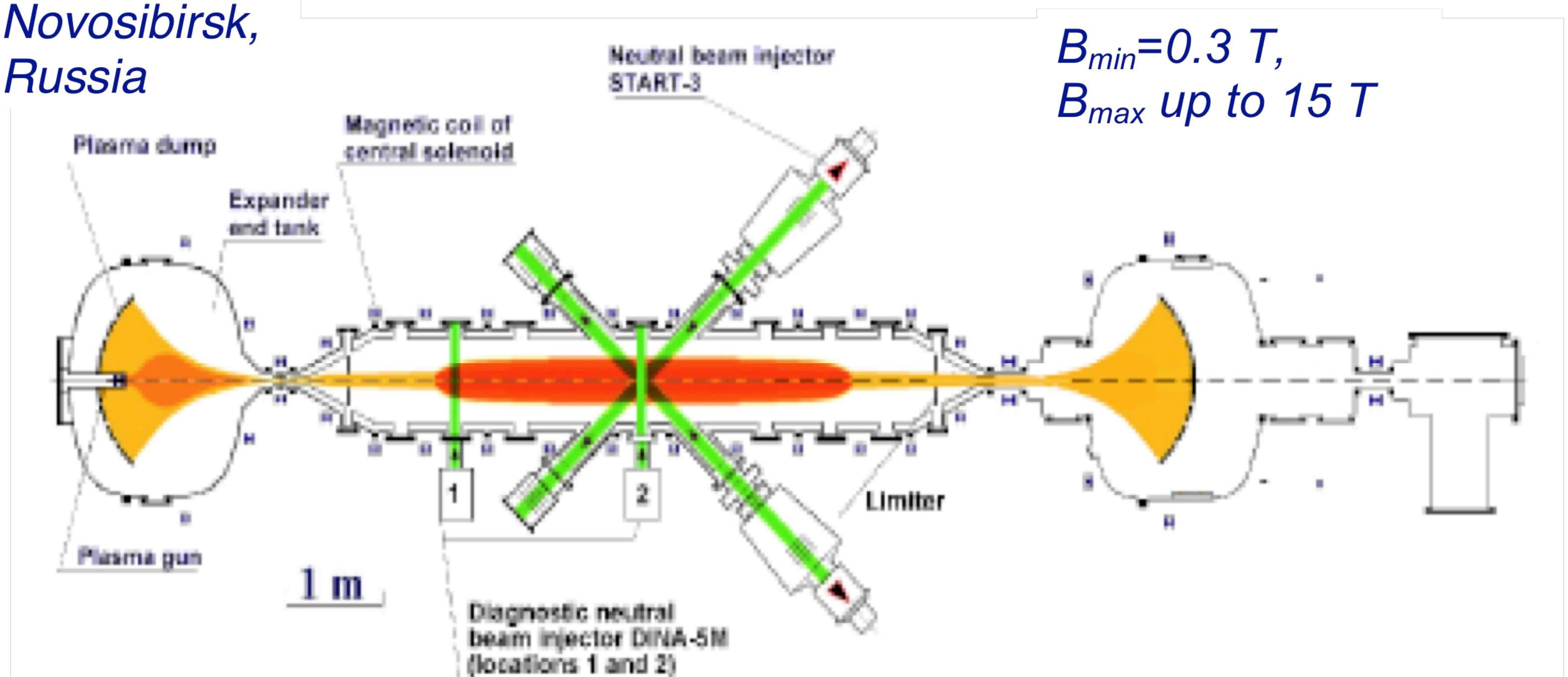




GDT (Gas-Dynamic Trap) Experimental Results

Novosibirsk, Russia

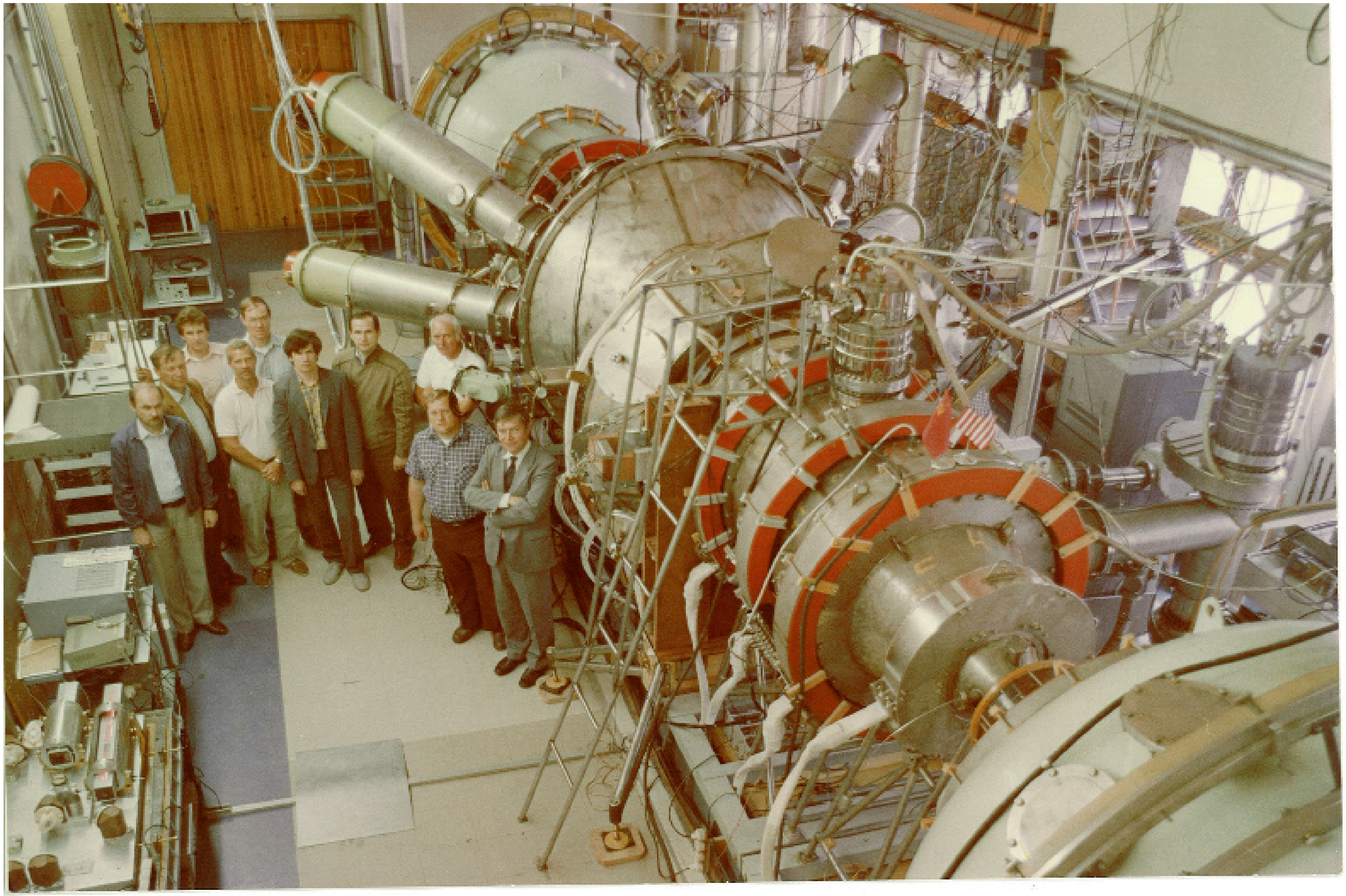
B_{min}=0.3 T, B_{max} up to 15 T



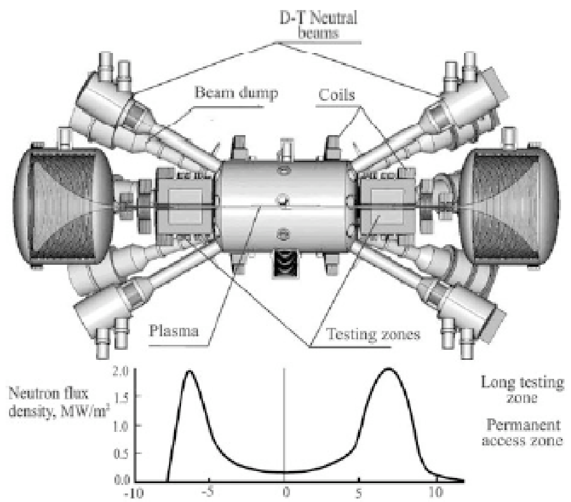
Fully axisymmetric plasma, MHD stable for beta 0.6 (60%), average ion energy 10 keV, average ion density 5×10^{13} cm^{-3}, no signs of the ion microinstabilities, electron temperature 200 eV, classical energy and particle confinement.

MHD stability by favorable curvature in the expansion tanks; can be enhanced by controlling the radial potential distribution.

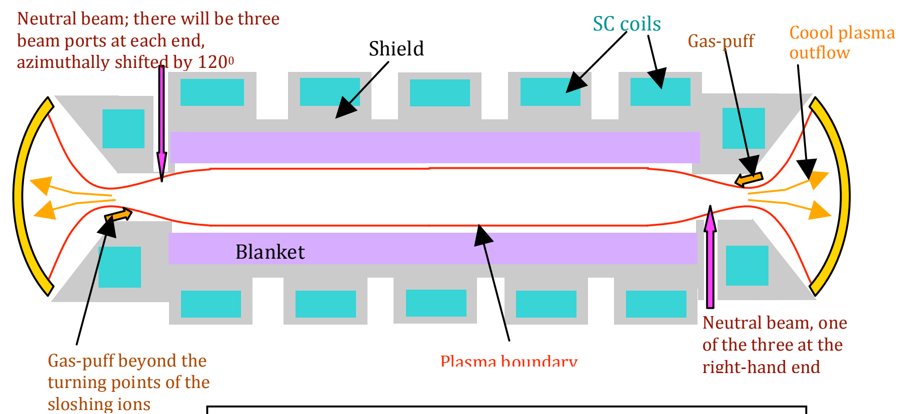
GDT at the Budker Institute of Nuclear Physics, Novosibirsk, July 1988: working together with the LLNL team



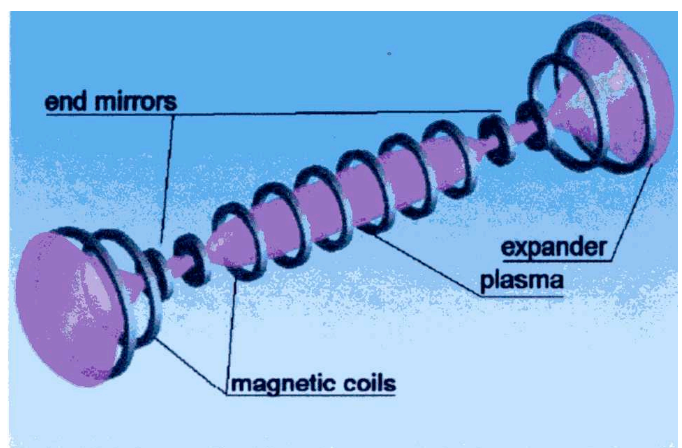
Axisymmetric mirrors can serve as a basis for several types of fusion devices



14 MeV neutron source for material and subcomponent testing



Q~1 driver for a fusion-fission hybrid



Pure fusion tandem mirror reactor

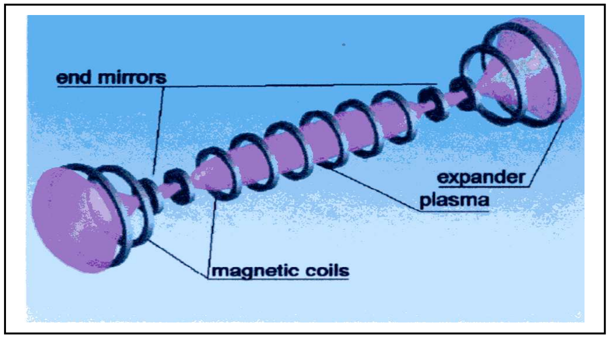
Due to the engineering simplicity and remarkable flexibility of axisymmetric mirrors, the turn-around time for testing various approaches and choosing the best one is short (it is in the range of a few years, not many decades!)

AXISYMMETRIC MIRROR IS A GAME-CHANGER IN FUSION RESEARCH

Very elegant “architecture”

Significant experimental backing

A variety of applications



We have here a very exciting opportunity

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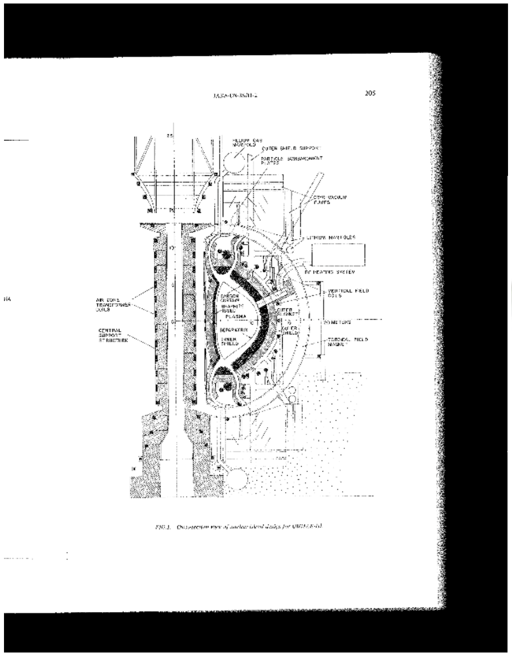
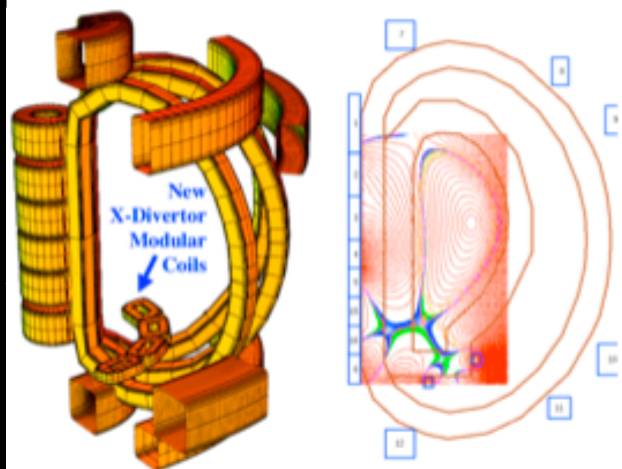
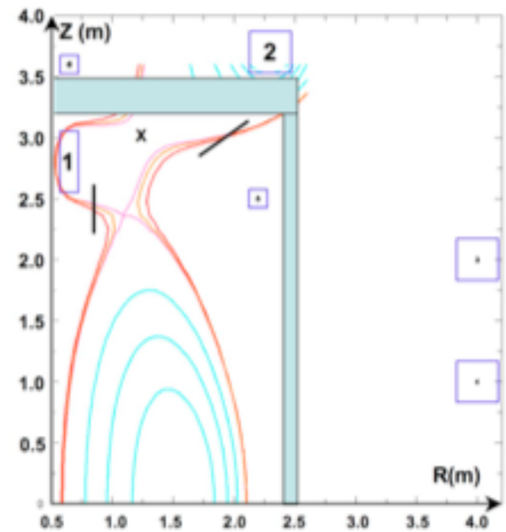
BACKUP VGs

SEVERAL POTENTIAL SOLUTIONS BASED ON THE MODIFICATIONS OF THE DIVERTOR GEOMETRY HAVE BEEN PROPOSED







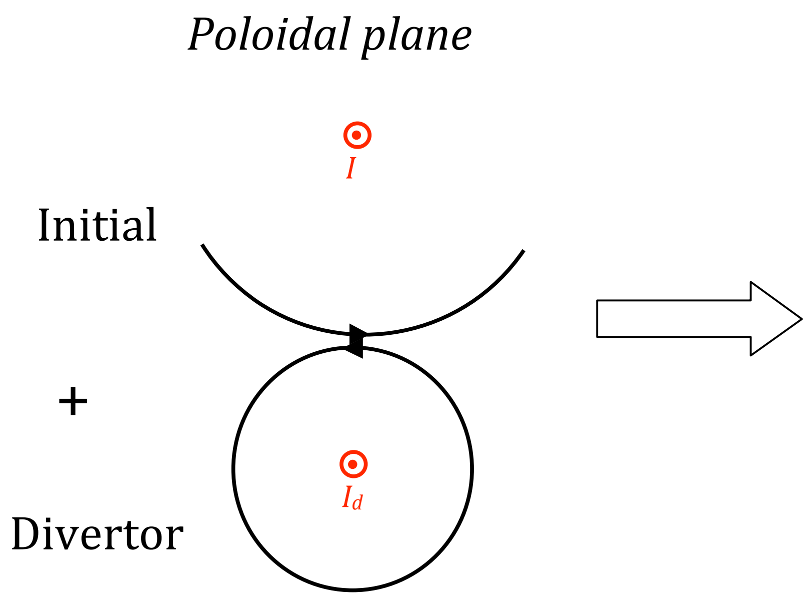
Long-legged divertor (pulling the flux out of the TF coils) R.W. Conn et al, Nucl. Fusion Suppl., v. 3, p. 203, 1977

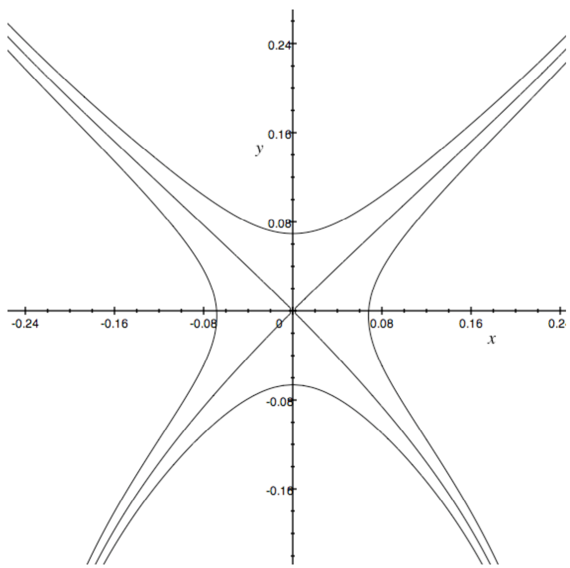
X-divertor (expanding magnetic field in the divertor legs by adding additional coils) M. Kotschenreuther et al, Proc. 2006 IAEA Fusion Energy Conf, Paper IC/P7-12

Super-X divertor (pulling the outer strike point as far as possible along the major radius) P.M. Valanju et al, Phys. Plasmas, **16**, 056110, 2009

All these solutions are interesting and are worth further studies

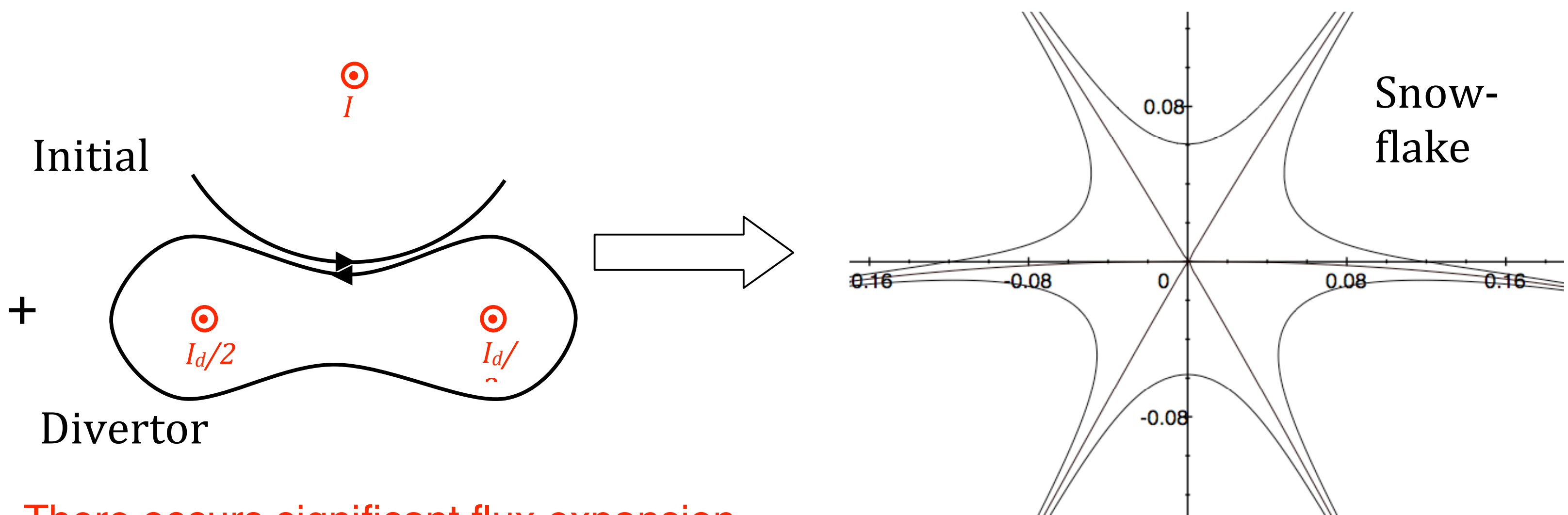
A “standard” X-point divertor is based on a first-order null of the poloidal magnetic field





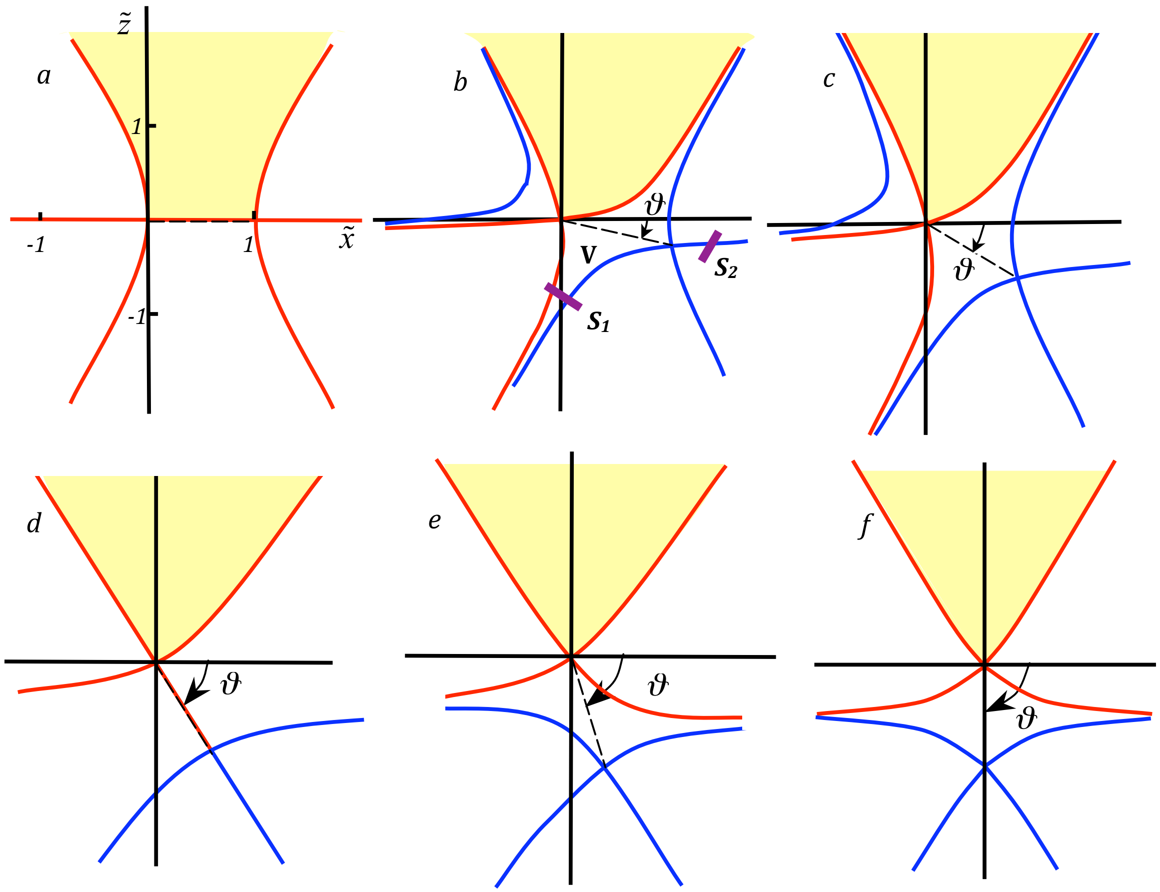
If one wants to make a second-order null of the poloidal magnetic field at a chosen point, one should design the divertor coils in such a way as to satisfy two conditions:

1. The magnetic field of divertor coils at the chosen point is equal in magnitude and directed oppositely to the “initial” field
2. The curvature of the field lines generated by the divertor coils in the chosen point is equal to the curvature of the field lines of the initial field



There occurs significant flux expansion

In addition to an exact snowflake, there exists a broad variety of “near-snowflake” configurations



Axial electron heat loss is small in a properly designed mirror

- 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 is large and/or the gas pressure in the expander is too high – but these issues are solved by a proper design.
- Large expansion ratios ($A_{wall} > (m_i/m_e)^{1/2} A_{mirror}$; A= surface area) solve the problem of the secondary emission; large end tanks and adequate pumping system solve the problem of gas ionization. [Theory and experiment; an interesting feature: at large expansions, the hight of the Debye sheath near the wall becomes small compared to T_e/e.]

Additional favorable features of axisymmetric mirrors:

- If the flute stabilization is robust, the critical beta for ballooning modes is ~ 1
- Due to accessibility of higher mirror ratios, the loss cone becomes small and the microstability improves

There are many ideas of axisymmetric, stable systems. We need an experimental platform for testing these ideas

This platform must:

- be axisymmetric from the outset
- have a reference stable configuration
- have a NBI system
- have a flexible, "easy-to-modify" magnetic system

A good candidate: a device of the type of GDT (or GDT itself)

Due to the engineering simplicity and remarkable flexibility of axisymmetric mirrors, the turn-around time for testing various approaches and choosing the best one is short (it is in the range of a few years, not many decades!)