CREMLIN PLUS
Connecting Russian and European Measures for Large-scale Research Infrastructures

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Magnetic mirrors in Budker INP

Scientific goals and research infrastructure

CREMLINplus WP8 Kick-off web-conference #4

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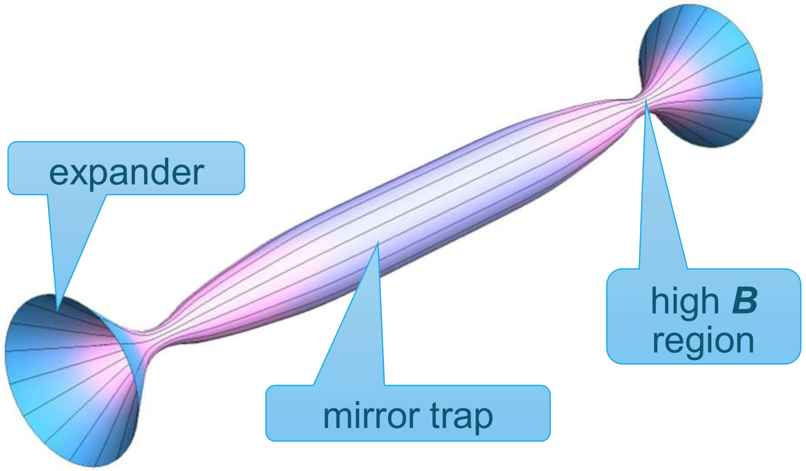
Budker INP Plasma laboratories

Magnetic mirrors for fusion



- Hot plasma is confined between two regions with high magnetic field (*«magnetic mirrors»*).
- Transverse particle and energy losses are low.
- Axial losses can be suppressed in different ways.
- Mirror traps are proposed as fusion neutron source or fusion reactor.

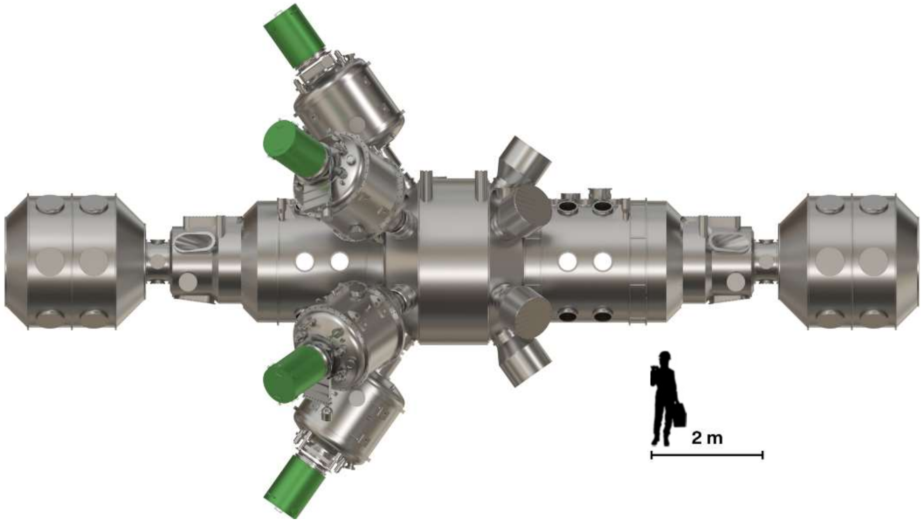
Pros:

- Simplicity of design (in axially symmetric form);
- Proven capability of high plasma pressure;
- Inherently steady-state operation;
- Intrinsic mechanism of removing impurities and products of fusion reactions;
- Relatively low and easily controllable wall loading by plasma heat flux and radiation;
- Possibility of direct conversion of plasma "exhaust" to electricity.

Cons:

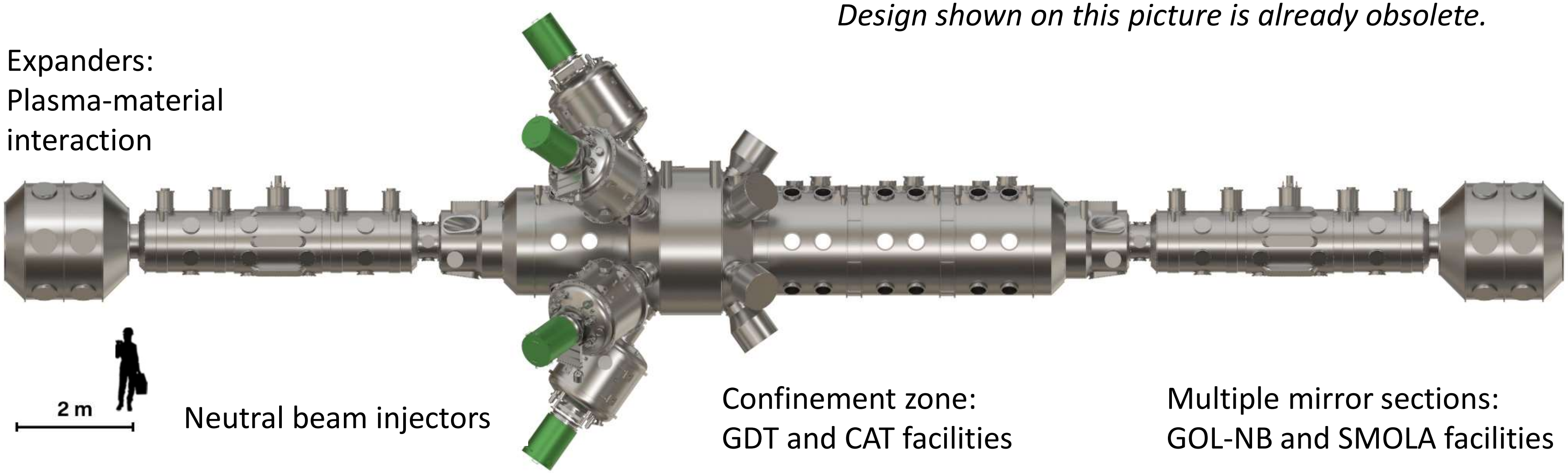
- High axial thermal conductivity.
- Plasma is plagued with micro-instabilities.
  (The natural anisotropy of the ion distribution function in the velocity space causes unlimited increasing of several types of electromagnetic waves in the plasma, which leads to the ion scattering rate increasing and degradation of the confinement time)

GDMT project

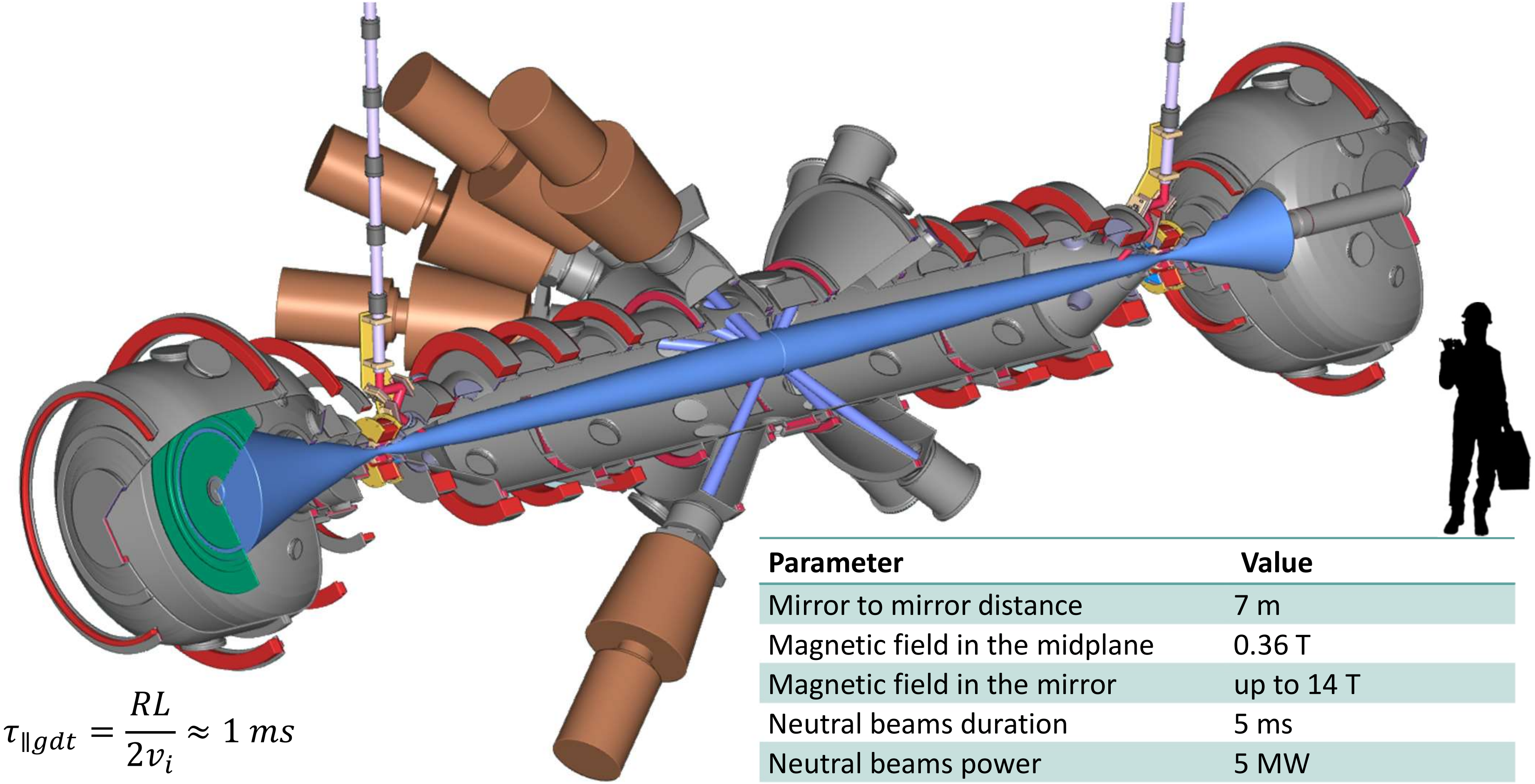


- Plasma laboratories of the Budker INP are focused on the next generation of the linear machine for fusion.
- GDMT: stationary gas-dynamic multiple mirror trap. Includes all recent advances in physics of the mirror plasma.
- The project is the prototype of neutron source for various purposes.
- GDMT project is also intended for development of the technologies for plasma confinement methods
- The conceptual design of the GDMT is in progress.
- Major physical topics are supported by the existing devices.

Design shown on this picture is already obsolete.



Gas Dynamic Trap (GDT)



$$\tau_{\parallel gdt} = \frac{RL}{2v_i} \approx 1\ ms$$

$$\tau_{\parallel adiab} = \tau_{ii} \cdot \ln R$$

$$\tau_{\parallel fast} = \tau_{ie} \cdot \ln\left(\frac{E_{inj}}{10\ T_e}\right) \approx 1\ ms$$

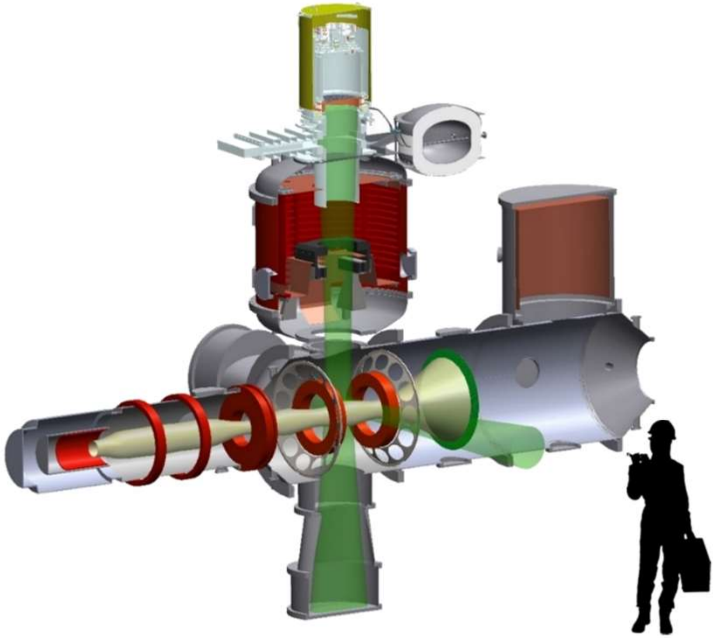
Parameter	Value
Mirror to mirror distance	7 m
Magnetic field in the midplane	0.36 T
Magnetic field in the mirror	up to 14 T
Neutral beams duration	5 ms
Neutral beams power	5 MW
ECRH power	700 kW
Plasma density	up to $5\cdot10^{19}$ m^{-3}
Fast ions energy	10 keV
Plasma beta	up to 60%
Electron temperature	from 250 to **900** eV

GDT main achievements

Key problem	Solution
Transverse transport caused by MHD instabilities	Stable high energy density plasma can be confined with simple circular magnets: SIMONEN, Tom, et al., J. Fusion Energ. 29, (2010) 558.
Micro-instabilities which lead to the fast ions loss	Micro-instabilities can be tamed: ZAYTSEV, Konstantin, et al., Physica Scripta 2014, (2014) 014004.
Low values of the electron temperature	Electron temperatures reaching keV range have been measured: BAGRYANSKY, Petr, et al., PRL 114, (2015) 205001.

These three accomplishments provide a basis to reconsider the mirror concept as a neutron source for materials development, nuclear fuel production, and fusion energy production

CAT experiment: plasma pressure increasing



CAT = compact axisymmetric toroid

Length – 6 m
Height – 5 m
B_0 – 0.2 T
B_0 /B_{max} – 2

Plasma:
n_0 – $3{\cdot}10^{19}$ m^{-3}
r_0 – 10 cm
T_e – 50 eV

NBI:
2 × 2 MW at 15 keV, 8 ms

First plasma is planned in 2020

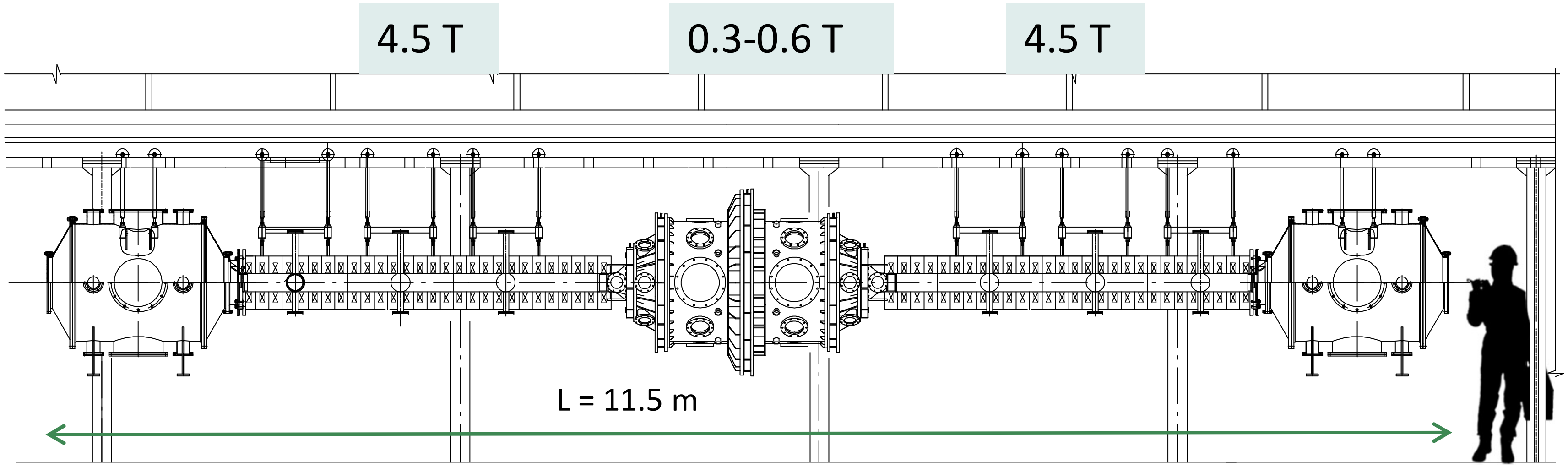
Idea: equilibrium with the maximum attainable value of relative relative plasma pressure β ≈ 1, where $\beta = p \times (B^2/8\pi)^{-1}$

Plasma is diamagnetic. At β ≈ 1 magnetic field is almost completely displaced from the plasma.

Formally, for β → 1 the mirror ratio tends to infinity (but in fact the confinement time in this limits defined by the "sheath": $\tau_E \propto \sqrt{\tau_\perp \tau_\parallel}$)

This scaling of the confinement is sufficient to fulfill Lawson's criterion in a trap of 30 m long, with a plasma radius of 1 m for a field of 10T

GOL-NB – stationary multiple mirror confinement



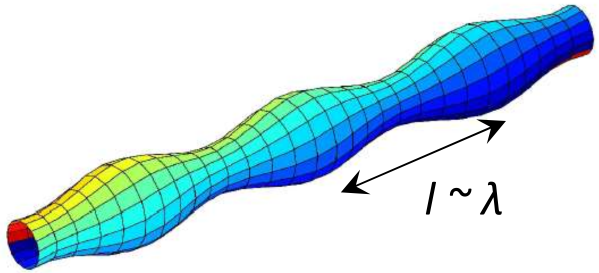
Chain of the mirrors ($R \sim 1.5$–2)

$\lambda \sim l$ due to high density or high turbulence.

Transiting particles can be trapped due to collisions.

Trapped particles scatter in random direction

Plasma flow become diffusive. $\tau_E \sim$ (Number of cells) × τ_{E0}



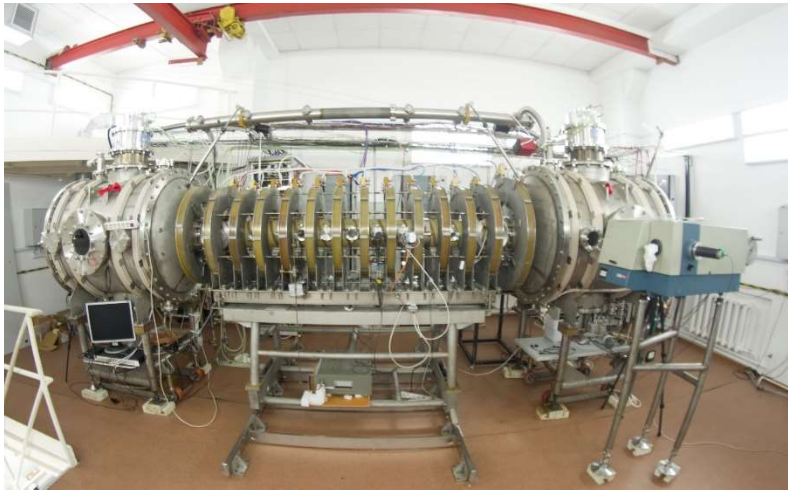
Research objective: Demonstration of multimirror plugs effectiveness

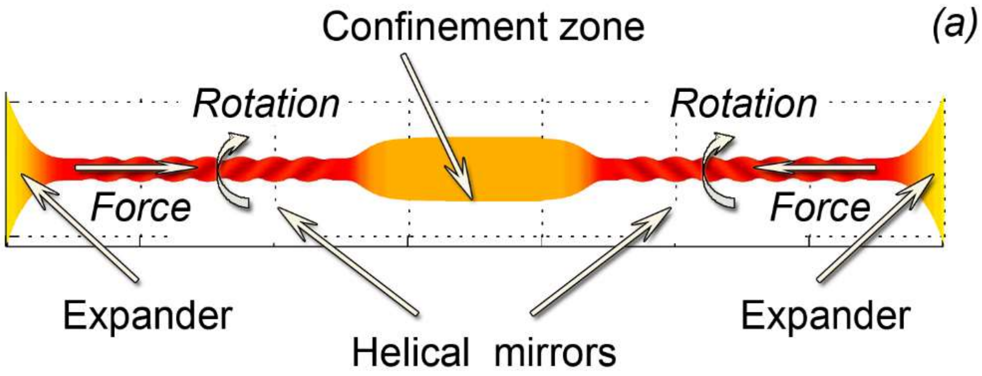
Plasma heating: NBI 2 × 0.75 MW at 25 keV

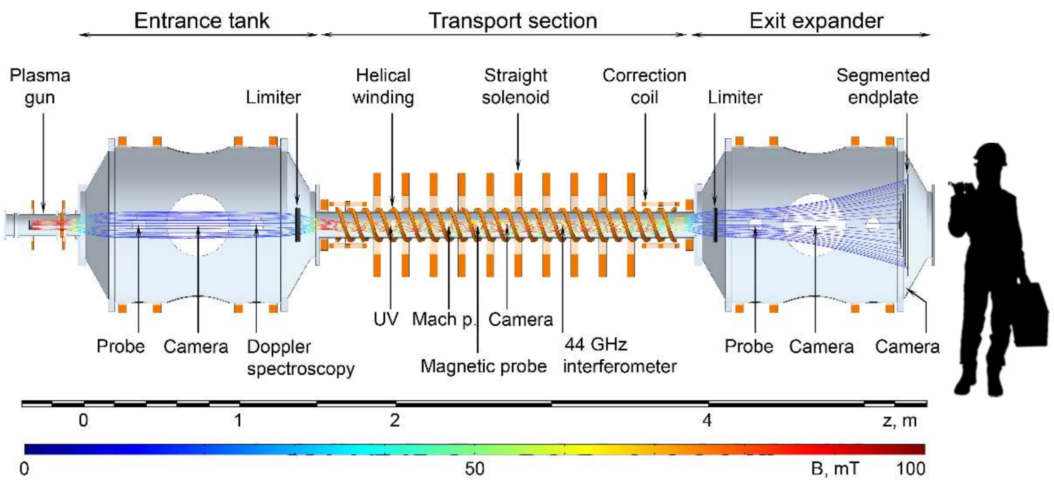
Plasma parameters: density 3×10^{19} m^{-3}, temperature **30** – **100** eV

V. Postupaev, Nuclear Fusion 57, 036012 (2017)

SMOLA – dynamic multiple mirror confinement







Helical magnetic field is corrugated along any field line.

Plasma rotates in ***E*×*B***. Magnetic mirrors move in plasma's frame of reference.

Looks like multiple mirrors, moving along the axis

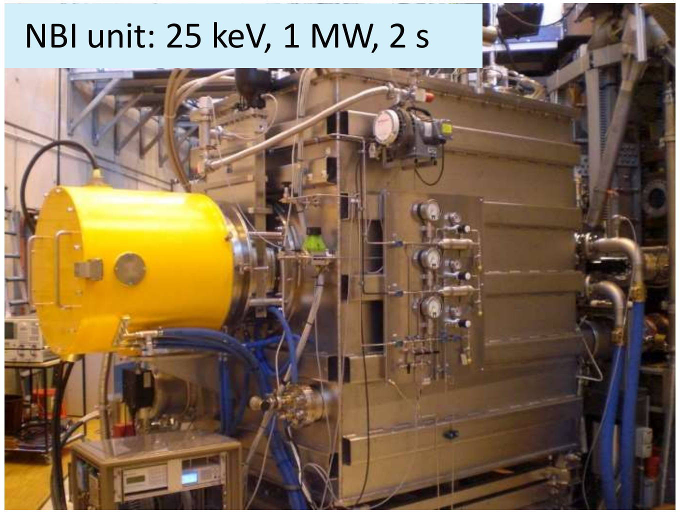
Momentum is transferred from magnetic field to trapped particles.

SMOLA device models one side of helical fusion device

$$\boldsymbol{q_{\parallel} \propto exp\left(-\frac{L}{kl}\right)}$$

A. Sudnikov, Fus. Eng. Des. 122, 85 (2017)

Neutral beam injectors



NBI unit: 25 keV, 1 MW, 2 s

Wide range of NBIs was developed for plasma heating and diagnostics.

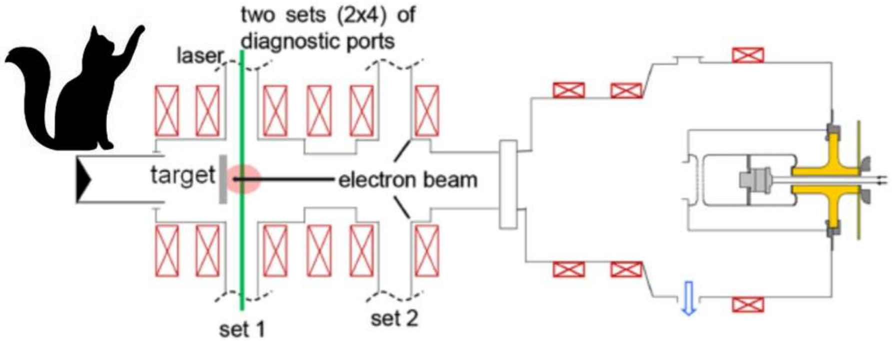
- **Positive ion source based NBIs**:
  - Energy **E** = 20–80 keV
  - Beam power **P** up to 3.5 MW (in short pulses)
  - Pulse duration **t** up to 10 s.
- **Negative ion source based NBIs**:
  - Energy **E** up to 1 MeV
  - Beam power **P** up to 2 MW

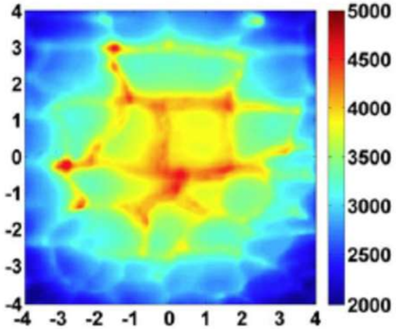
HV platform, electrostatic accelerator and dipole magnet

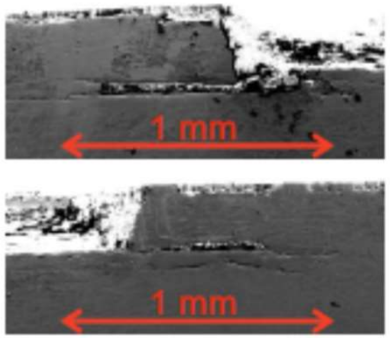
High power HV transformer

Energy recuperation unit

Plasma-material interaction







← BETA facility:

ITER-relevant heat load to materials (mainly, tungsten) by the electron beam

Energy: 30–110 keV

Current: up to 80 A

Pulse duration: 0.1–1 ms

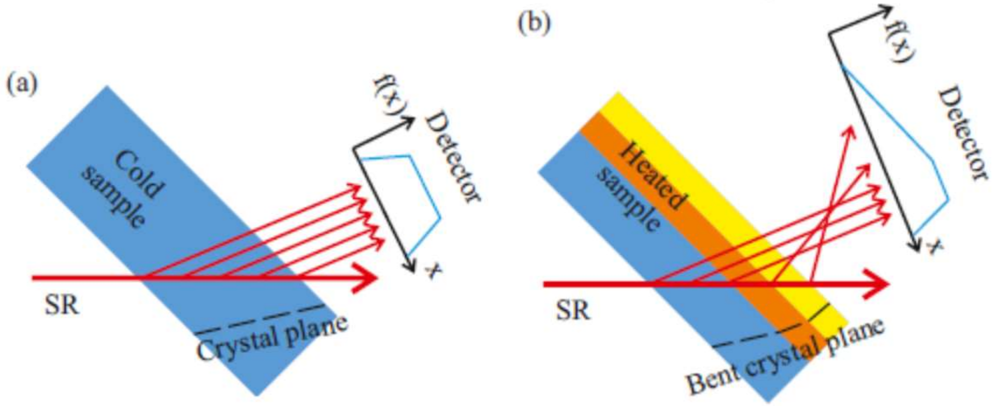
Exposure area: 1–6 cm²

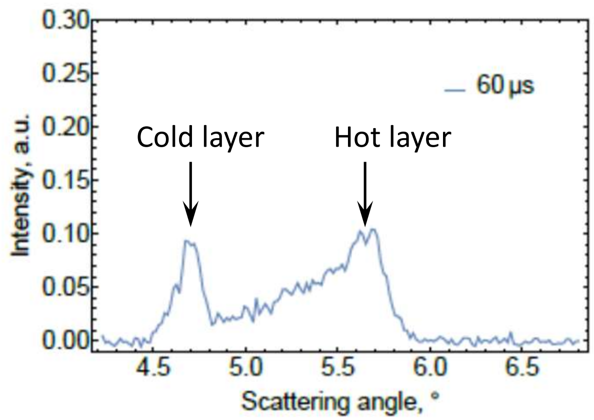
Heat flux factor: up to 250 MW·s$^{0.5}$·m^{-2} (cracking at 8–15 MW·s$^{0.5}$·m^{-2}, melting at 60 MW·s$^{0.5}$·m^{-2})

↓ Synchrotron radiation scattering station «Plasma»:

Fast *in-situ* diffractometry of the mechanical stress in heated material.

ND:YAG laser (50 J, 140 us) simulates pulsed heat loads.

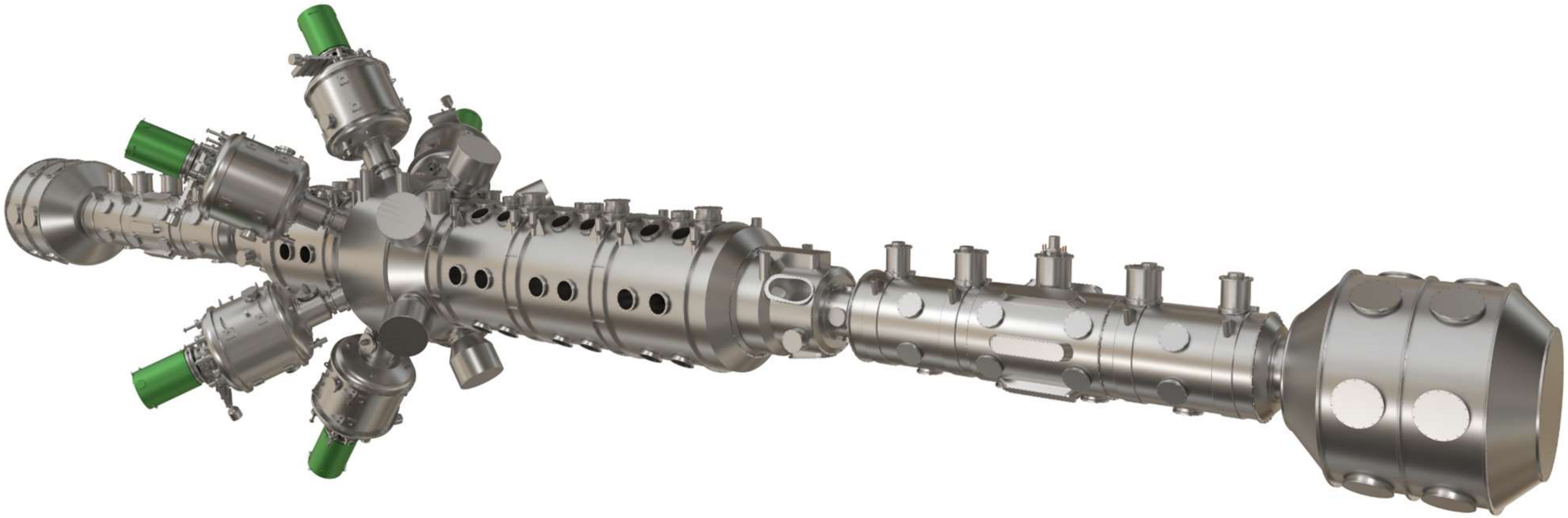




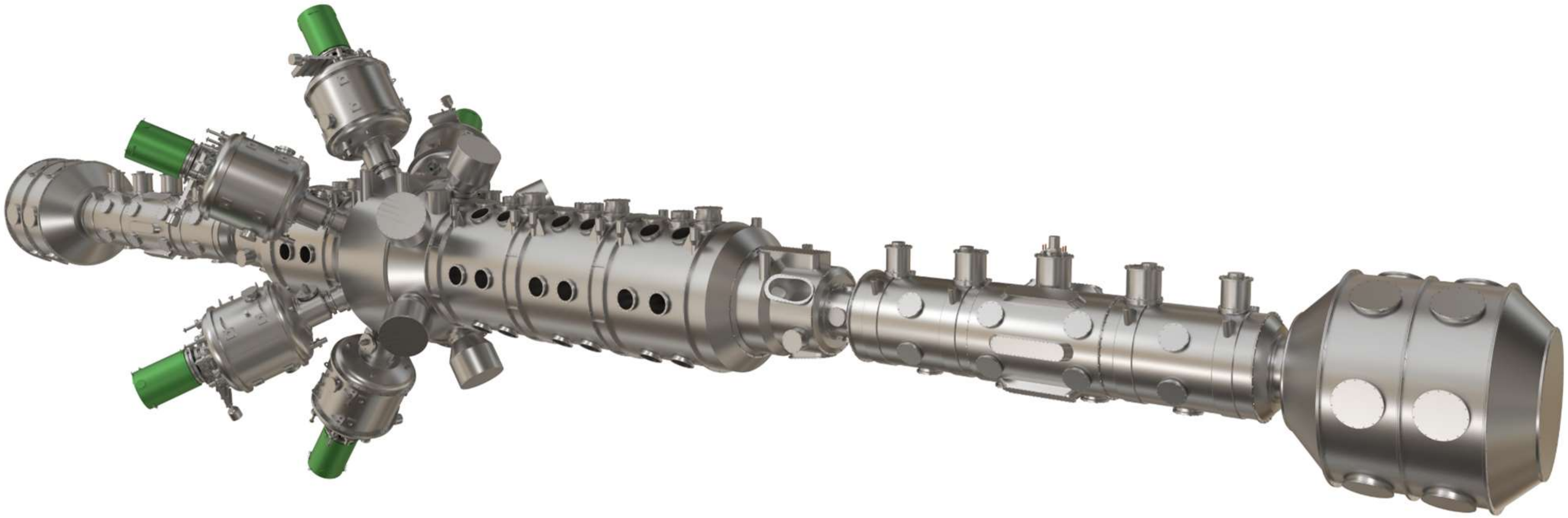
Summary

- **The development of the conceptual design of the GDMT installation is in progress**
  - The project is the prototype of neutron source for various purposes (testing nuclear and thermonuclear materials, processing radioactive waste, and control of fission reactors operating in subcritical mode);
  - GDMT project is also intended for development of technologies for new plasma confinement methods: diamagnetic, multi-mirror and helical, which potentially open the way to the compact fusion reactor capable of working with fuels that do not contain tritium and even fuels that do not produce neutrons. Numerical calculations show the possibility of $Q_{DT} > 1$.
- **Experiments plasma devices in BINP are basically aimed at supporting the GDMT project:**
  - GDT: fast ions confinement, expander physics, ECR heating
  - GOL-NB: multiple mirror confinement
  - SMOLA: dynamic multiple mirror confinement
  - CAT: diamagnetic confinement
  - NBIs: plasma heating
  - Different stations for plasma-material interaction.

Thank you for your attention!



Supplementary materials



What for?

- Neutron sources (DT) for:
  - Material testing $\rightarrow$ $j \sim 2$ MW/m^2, $S \sim 1$ m^2;
  - The reprocessing of minor actinides from spent nuclear fuel by the transmutation method $\rightarrow$ $J_\Sigma \geq 10^{18}$ s^{-1};
  - Control of fission reactors operating in subcritical mode $\rightarrow$ $J_\Sigma \geq 10^{19}$ s^{-1};
  - …
- Relatively compact fusion reactors capable of operating with alternative types of fuels: those that do not contain tritium (DD, D^3He) and even do not produce neutrons (p-^{11}B);
- Experimental devices for researches on PSI.

GDT axial losses

Plasma in open trap faces the end absorbers directly

Classic (collisional) axial Spitzer conductivity

Valu... usion

parar... $\propto T_e^{7/2}$)

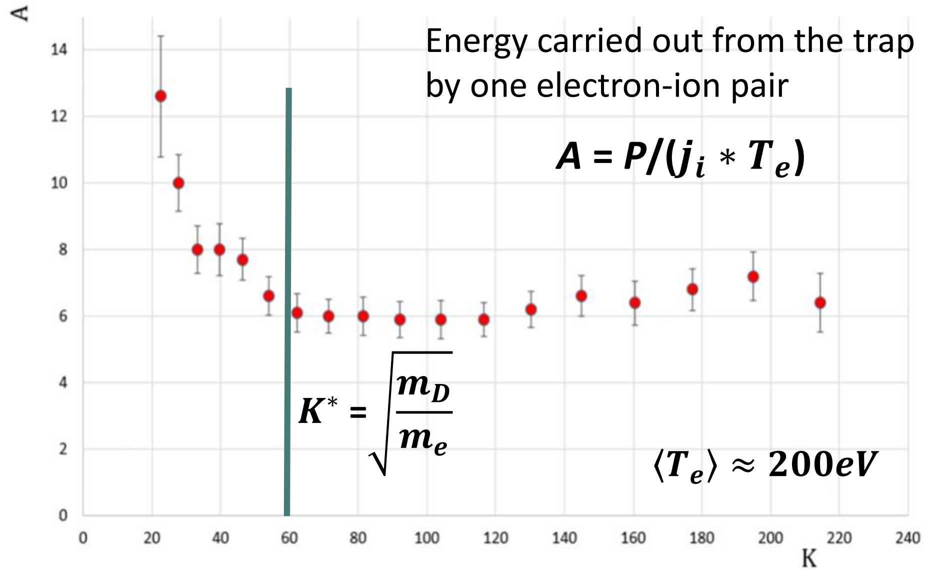
Due to its simplicity it can consume a lot of electricity

Solution: collisionless regime behind the mirror ($q \propto T_e^{3/2}$)

Expanding magnetic field

Danger: cold electrons in the expander – will they penetrate to the trap?

Where in expander should we place plasma absorber for future open reactor or NS?

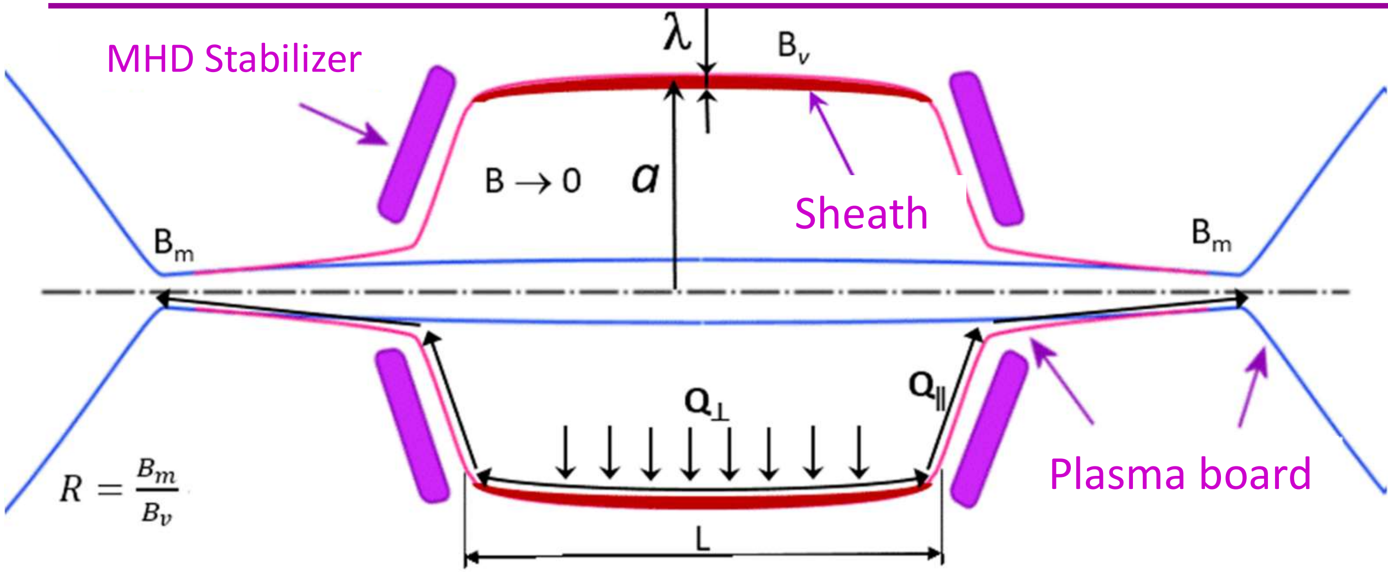


Theory prediction: A ~ 8T_e

D. Ryutov Fusion Science and Technology 47, 148 (2005)

Energy losses of this scale are designed in the projects of future fusion machines based on an open trap

Diamagnetic trap idea



$$\sqrt{\tau_\perp . \tau_{||}} = \sqrt{\frac{4\pi\sigma a^2}{c^2} \cdot \tau_\parallel}$$

σ - transverse plasma conductivity

$$\tau_{\parallel gdt} = \frac{RL}{2v_i}$$

$$\tau_{\parallel adiab} = \tau_{ii} \cdot \ln R$$

Idea: equilibrium with the maximum attainable value of relative pressure β ≈ 1

A quasi homogeneous field at the center requires

Formally, for β → 1 the mirror ratio tends to infinity (but in fact the confinement time in this limits defined by the "sheath": $\tau_E \propto \sqrt{\tau_\perp \tau_\parallel}$)

This scaling of the confinement is sufficient to fulfill Lawson's criterion in a trap of 30 m long, with a plasma radius of 1 m for a field of 10T

With classical transverse losses and adiabatic confinement in the sheath, this scaling predicts a positive energy output when using alternative fuels: DD, D^3He and even p-^{11}B, with the same trap parameters

A. Beklemishev, Phys. Plasmas 23, 082506 (2016)