

Helical Mirror Concept Exploration: Design and Status

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Outline

1. Bases: multimirror confinement
2. Bases: vortex confinement
3. Motivation
4. Helical mirror conception
5. Required plasma parameters
6. Experimental device layout
7. Critical experiment features

Multimirror confinement

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

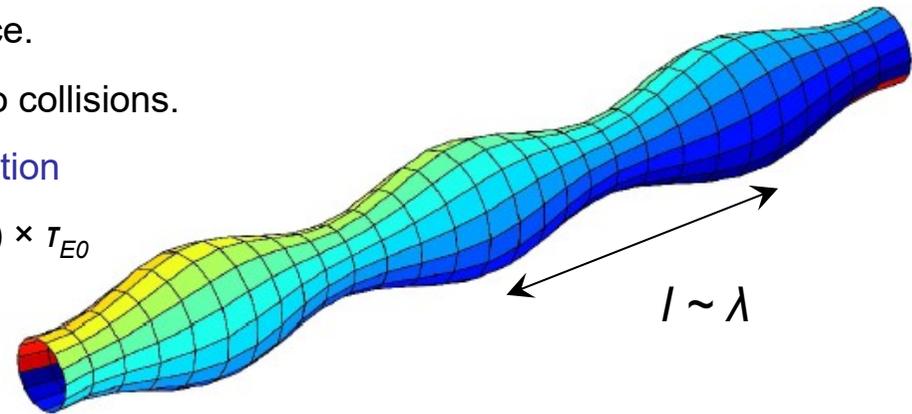
$\lambda \sim l$ due to high density or high turbulence.

Transiting particles can be trapped due to collisions.

Trapped particles scatter in **random direction**

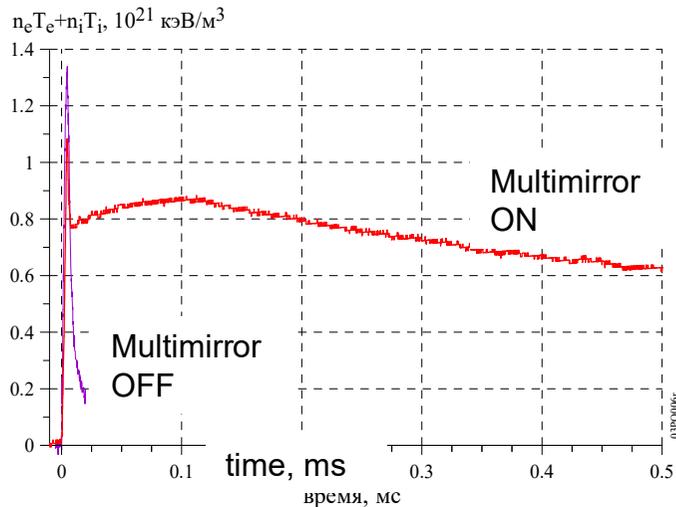
Plasma **flow** become **diffusive**. $\tau_E \sim (\text{Number of cells}) \times \tau_{E0}$

$$\tau \sim R^2 \frac{L}{\lambda_i} \frac{L}{V_{Ti}}$$



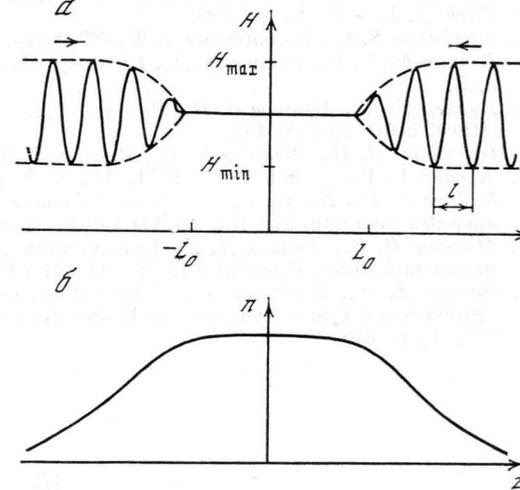
A. V. Burdakov, *Multiple Mirror Trap: Milestones and Future*, **Thursday Aug. 11, 09:00**

In experiment:



A. V. Burdakov, et al., *Fusion Sci. Technol.*, 59 (No 1T), 9 (2011).

Early concept: moving mirrors



G. I. Budker. *International Conference on Plasma Theory*, Kiev, 1971

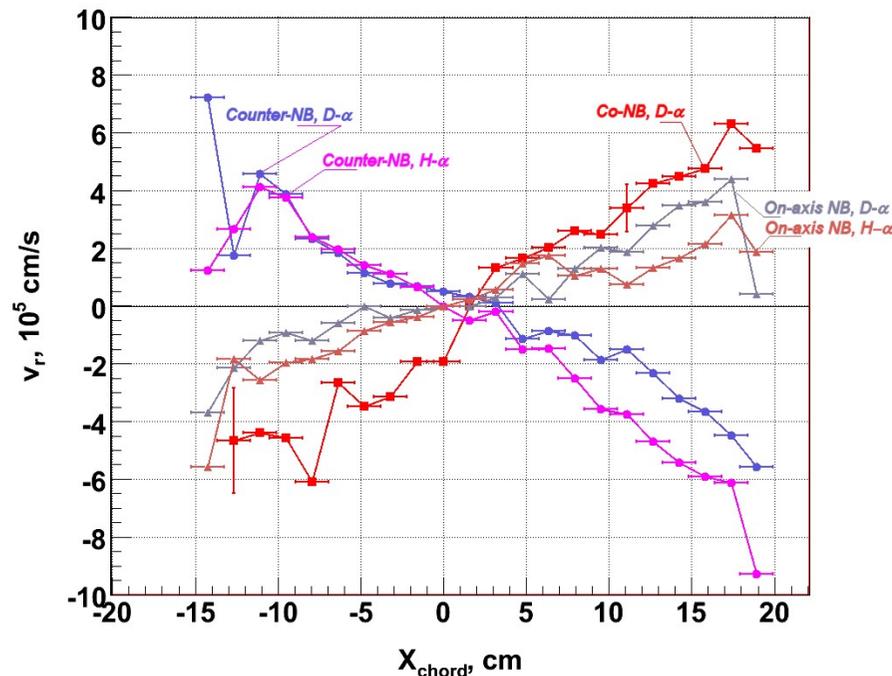
Vortex confinement

The confinement time for Co-NB is almost twice better than that for on-axis NB.

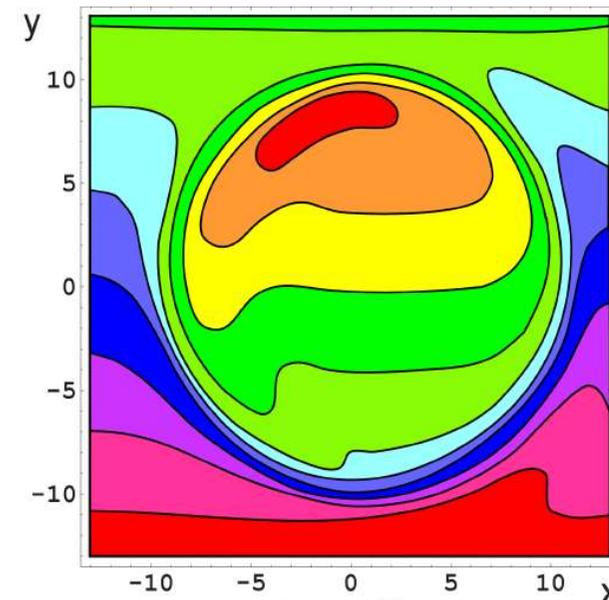
Momentum injection controls the *axial* fluxes via the potential well.

A. D. Beklemishev, et al., Fusion Sci. Technol. 57, 351-360 (2010)

	On-axis NB	Co-NB	Counter-NB
Electron temperature, eV	220	260	150
Energy content kJ	1.8	1.8	0.8
Beta	0.6	0.6	No data

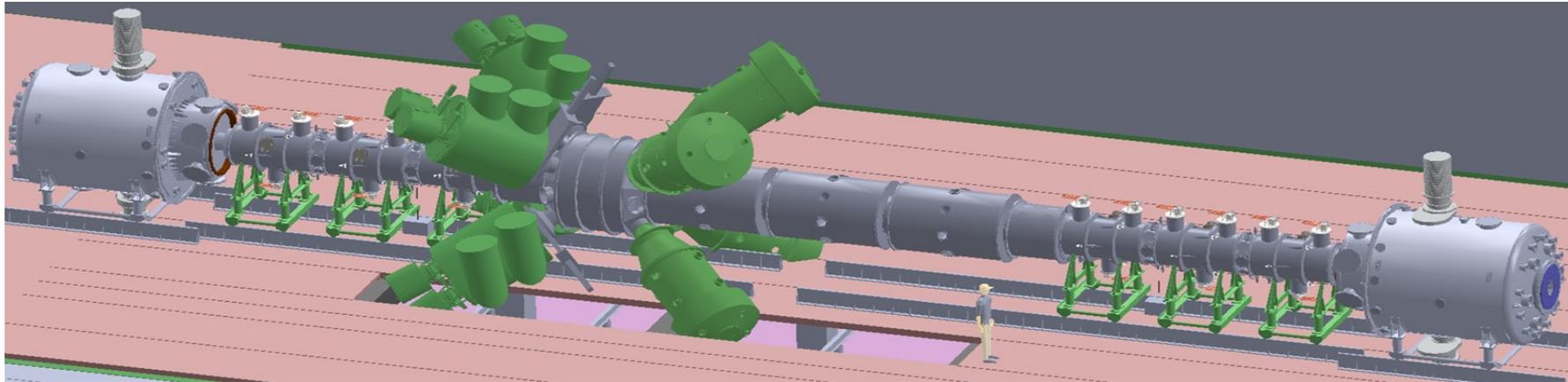


Velocity profiles indicate change of sign of rotation with momentum injection

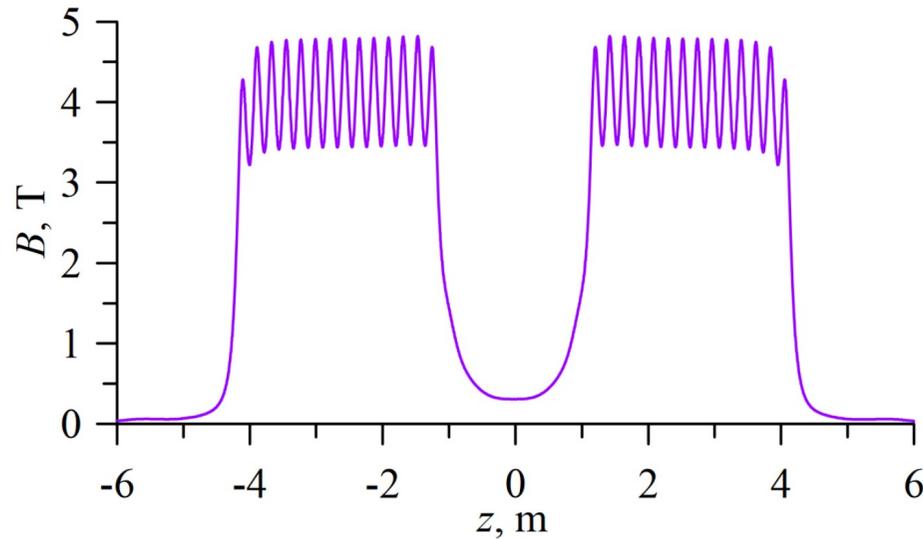


Plasma flow lines become closed
 $E \times B$ may be used to create rotation

Gas-Dynamic Multiple-mirror Trap



Combination of a central GDT-like vortex-confined mirror with multiple-mirror axial plugs.



To the left: guide field in the concept-exploration device GOL-NB (in construction)

Smaller-scale GDMT-like experiment.

*V. V. Postupaev, Status of GOL-NB Project,
Tuesday Aug. 9, 12:30*

Motivation

What if multiple mirrors move only in plasma's frame of reference?

Plasma rotates due to $E \times B$ as in vortex confinement.

Guide magnetic field is helical, corrugated along each field line.

High corrugation velocity is achieved easily:

$$V_z = \frac{hcE_r}{2\pi r B_z}$$

Plasma is actively pumped inside the trap

Classical mirror: $\tau_E \sim L$

Multimirror $\tau_E \sim L^2$

Helical mirror $\tau_E \sim \exp(L) ?$

A. D. Beklemishev, *Transport in Trap Sections with Helical Corrugation*, **Wednesday, Aug. 10, Poster #32.**

Motivation

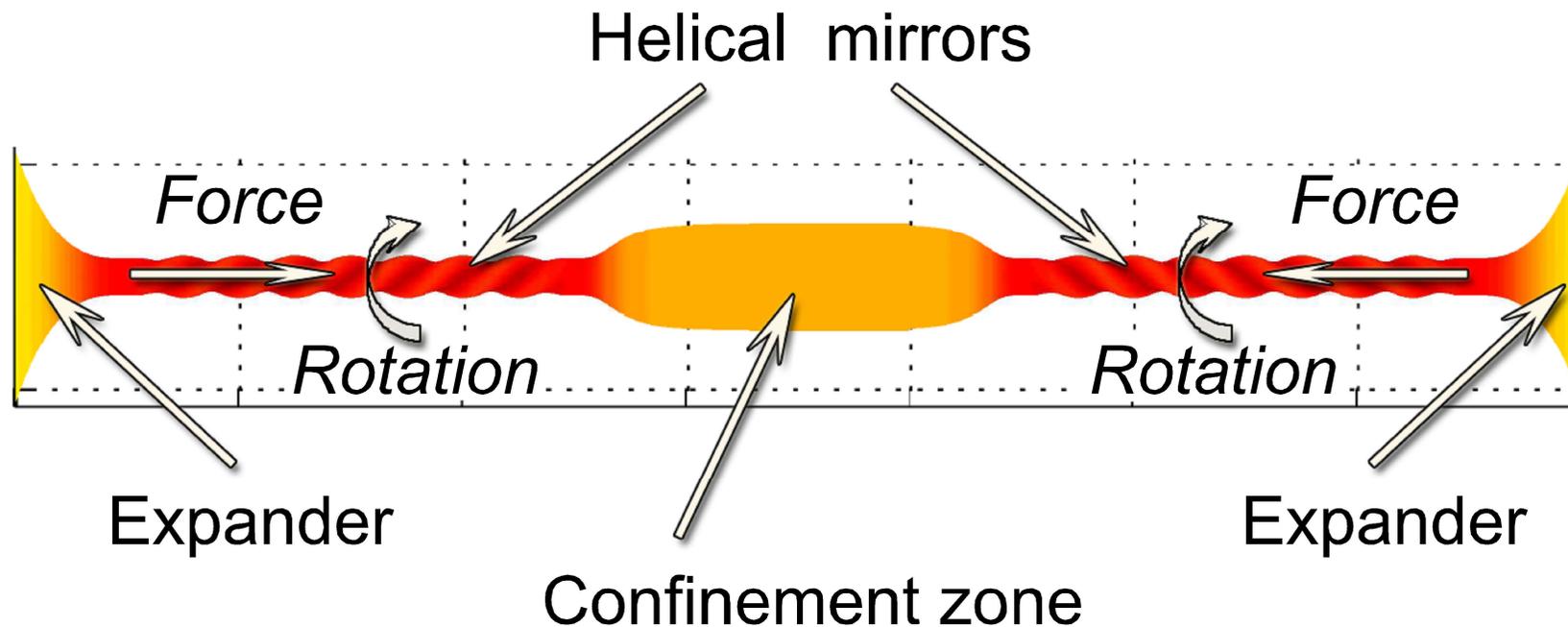
Direction of the force depends on the directions of the electric and the magnetic fields and its helicity

1. Helical confinement demonstration (*needed for future GDMT-like trap*)

Counter-flow force

Task 1: Demonstration of plasma flow suppression

Task 2: Optimal confinement regimes



Motivation

2. Plasma flow acceleration (needed for **plasma thruster**)

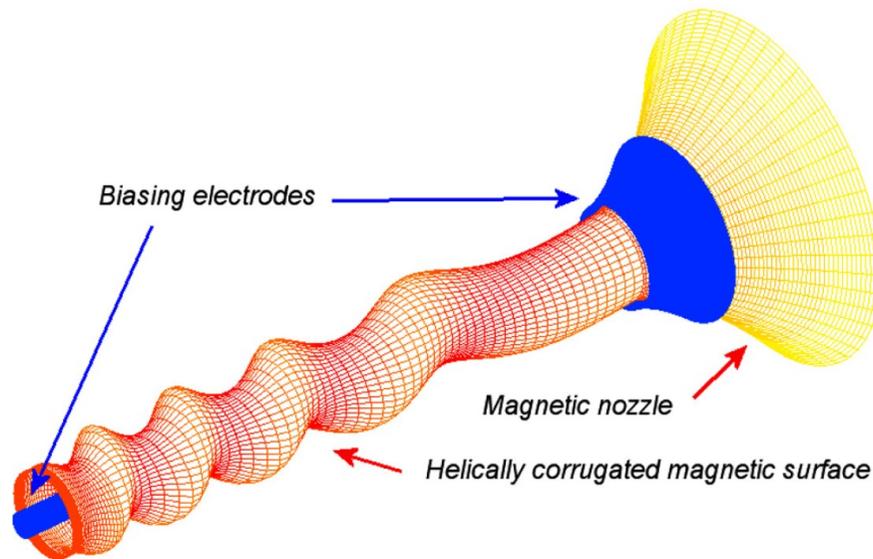
Co-flow force

Task 1: Demonstration of the acceleration

Task 2: Plasma detachment

Both motivations require plasma stream in helical magnetic field

Phys. Plasmas **22**, 103506 (2015)



1. A. D. Beklemishev. Helicoidal System for Axial Plasma Pumping in Linear Traps // Fusion Science and Technology, V.63, N.1T, May 2013. P.355
 2. A. D. Beklemishev. Helical plasma thruster // Physics of Plasmas **22**, 103506 (2015); doi: 10.1063/1.4932075
- A. D. Beklemishev, *Design Optimization of a Helical Plasma Thruster*, **Wednesday, Aug. 10, Poster #34.**

Required plasma parameters

$h \sim \lambda:$

$$n_i \sim \frac{T_i^2}{4\pi\Lambda e^4 Z^4 h}, n_i [10^{13} \text{ cm}^{-3}] \sim \frac{2 T_i [\text{eV}]^2}{\Lambda h [\text{cm}]}$$

Magnetized plasma:

$$\rho_B \propto r, \rho_B \propto \frac{\lambda}{2\pi} \sim \frac{h}{2\pi}, r \sim \frac{h}{2\pi}$$

$$B_z \propto \frac{2\sqrt{2}\pi c \sqrt{T_i}}{e\sqrt{m_i} h} = 2\pi \cdot 10^{-2} \frac{\sqrt{T_i [\text{eV}]}}{h [\text{cm}]}$$

Superthermal velocity:

$$E_r > B_z \frac{2\pi r V_i}{h c} \propto \frac{2 T_i [\text{eV}]}{e m_i r [\text{cm}]}$$

Stationary:

$$\tau \propto \frac{N \times h}{V_i} \sim \frac{\sqrt{m_i}}{4\sqrt{2}\pi\Lambda e^4 Z^4} \frac{T_e^{\frac{3}{2}}}{n_i} N \sim \frac{2 \cdot 10^{-6}}{\Lambda} \frac{T_e [\text{eV}]^{\frac{3}{2}}}{n_i [10^{13} \text{ cm}^{-3}]} N$$

List of parameters:

$$n_i \sim 10^{19} \text{ m}^{-3}$$

$$T_i \sim 10 - 100 \text{ eV}$$

$$B_{max} = 0.1 - 0.3 \text{ T}$$

$$E_r \sim 100 \text{ V/cm}$$

$$\tau \sim 0.1 \text{ s}$$

$$r \sim 5 \text{ cm}$$

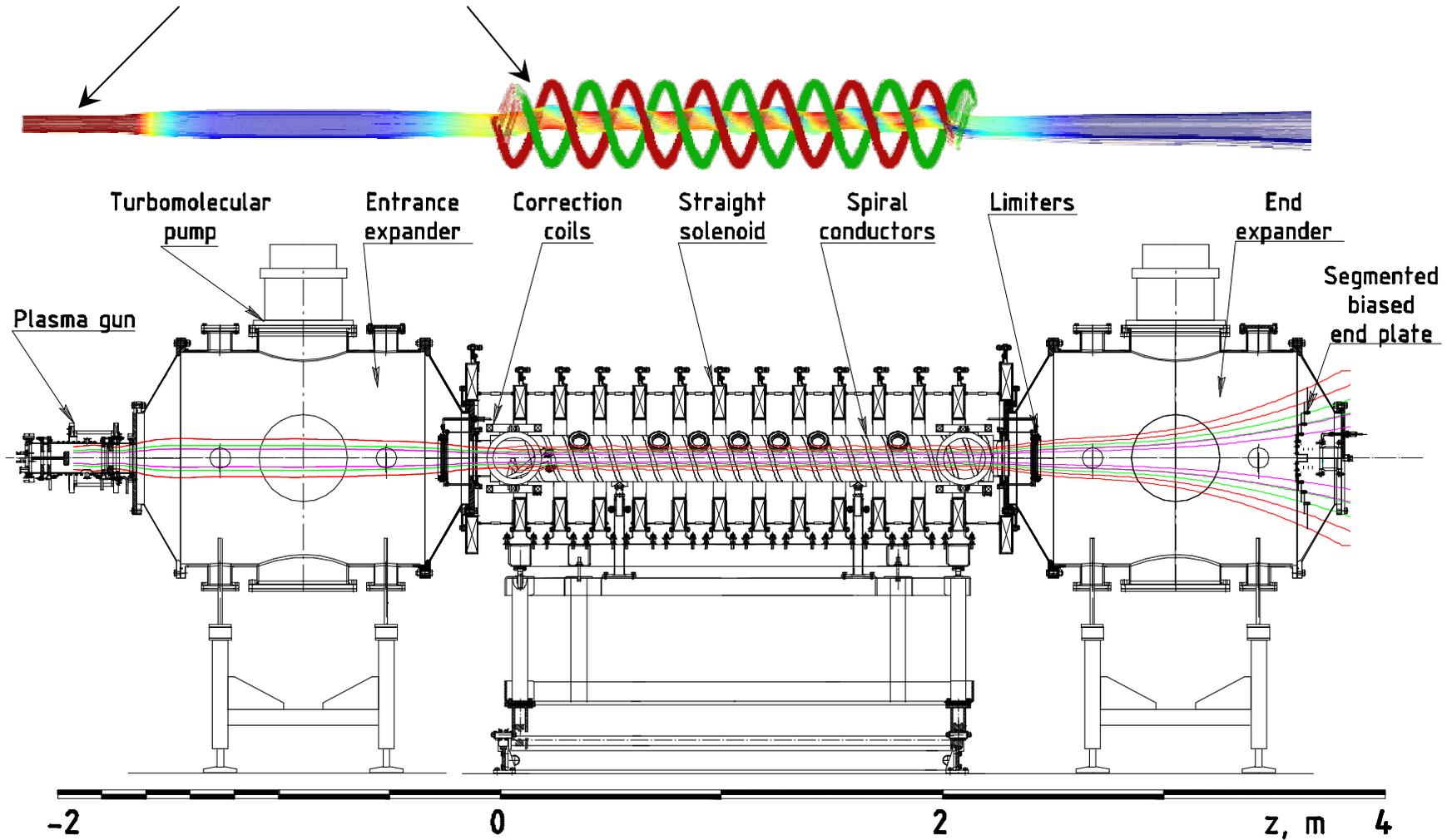
$$h \sim 18 \text{ cm}$$

$$N = 12$$

$$R_{mean} \sim 1.5 - 2$$

SMOLA concept exploration device

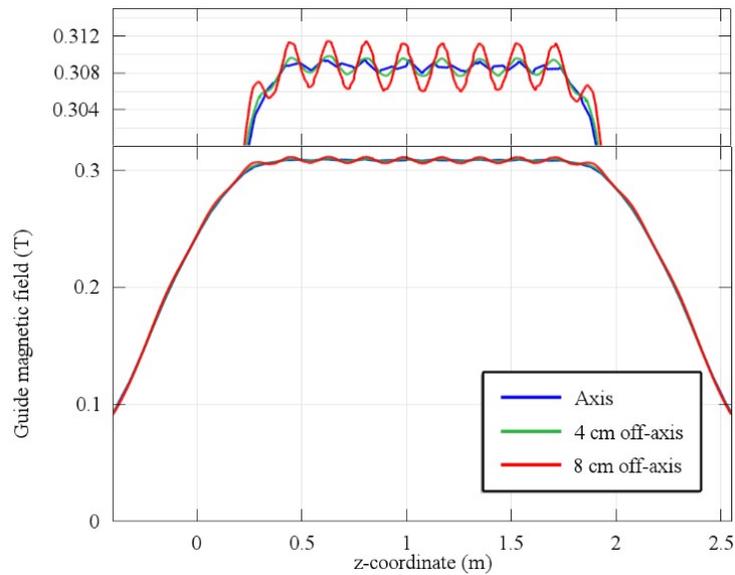
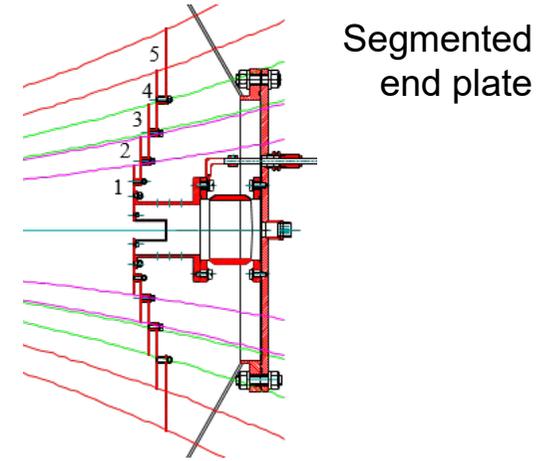
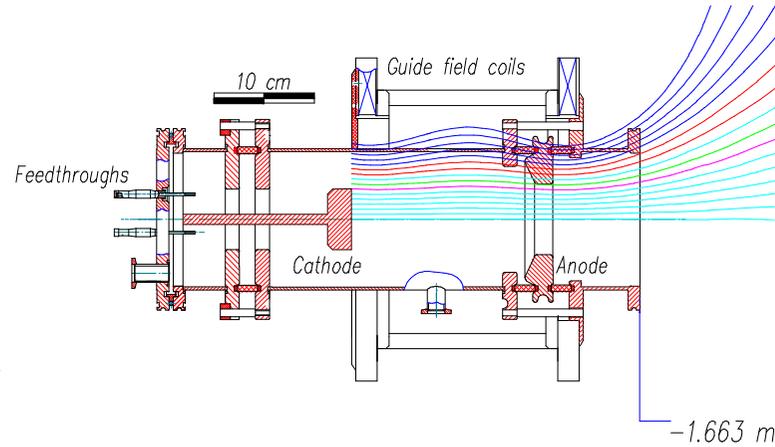
Plasma is trapped between high-field region of the plasma gun and the helical section.



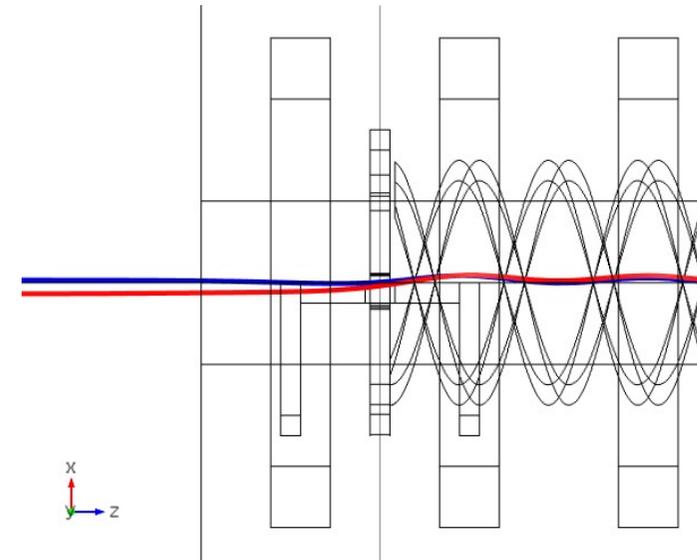
SMOLA device: important parts

Plasma gun. Similar to

G. Shulzhenko, Studies of plasma production in a linear device with plane LaB_6 cathode and hollow anode, Wednesday, Aug. 10, Poster #75.



Guide magnetic field. Straight component.



Correction coils. Magnetic axis before (red) and after (blue) correction.

Critical experiment features

Main effects:

- longitudinal transport depending on corrugation velocity;
- radial drift of ions in the electric field direction

*A. D. Beklemishev, Transport in Trap Sections with Helical Corrugation, **Wednesday, Aug. 10, Poster #32.***

Plasma density modifications:

- exponential density decay along the trap until $h \sim \lambda$;
- pinching of ions to central region with low R .

The critical experiment excludes all effects except the helical confinement:

- identical regimes of the plasma gun;
- identical end-plates biasing;
- identical magnitude of the magnetic field;
- quasi-steady state;
- magnetic fields of the opposite directions;
- different signs of the longitudinal force.
- plasma should be trapped at one magnetic field direction and pumped out at another

Conclusion

SMOLA: only **one helical plug**;

- the plasma is trapped between it and the high-field zone of the gun;
- constant plasma flow from the gun;
- models **one end** of the infinitely **long central section** of GDMT-like trap.

Helical mirrors could expand the existing set of the axial losses suppression methods in linear traps.

Even at moderate efficiency with an enhancement factor of **5–10**, they will significantly improve the prospects of the open traps making them more suitable for **fusion applications**.

Thank you for your attention!

