Helical Mirror Concept Exploration: Design and Status

A. V. Sudnikov[1,2,a)], A. D. Beklemishev[1,2], V. V. Postupaev[1,2], A. V. Burdakov[1,3], I. A. Ivanov[1,2], N. G. Vasilyeva[1], K. N. Kuklin[1], A. G. Makarov[1], E. N Sidorov[1]

[1] *Budker Institute of Nuclear Physics, Novosibirsk, Russia*
[2] *Novosibirsk State University, Novosibirsk, Russia*
[3] *Novosibirsk State Technical University, Novosibirsk, Russia*

[a)]Corresponding author: A.V.Sudnikov@inp.nsk.su

Abstract. Technical solutions of the concept exploration device SMOLA for longitudinal plasma flow suppression in linear plasma trap by active plasma pumping in helicoidal magnetic field are described in the article. Vacuum system, magnetic system, plasma source and the source of the radial electric field are discussed.

INTRODUCTION

In the last years, linear magnetic traps for plasma confinement have shown rapid progress in plasma parameters, including electron temperature up to 0.9 keV at mean energy of hot ions of 12 keV [1] and relative plasma pressure up to $\beta \approx 60\%$ [2]. Highly conservative extrapolation of GDT parameters to higher NBI injection energy and D-T fuel combined with technology of multiple-mirror confinement that was developed in GOL-3 [3,4] resulted in a GDMT project with $Q_{DT} = 0.1$ [5]. Improved configuration leads to even more attractive plasma parameters and fusion gain in a material test neutron source with $Q \approx 0.5$ and neutron flux of 2 MW/m^2 [6]. All current projects including the GOL-NB device [7] rely on passive multiple-mirrors for confinement improvement.

Recently, a new method of active plasma flow suppression in a helical magnetic field was proposed [8]. Periodical variations of the magnetic field moving upstream in the plasma's reference frame transfer momentum to trapped particles. In collisional regime, this momentum transfer leads to the pumping of the plasma inside the central cell of the trap. Plasma acceleration can also be achieved [9].

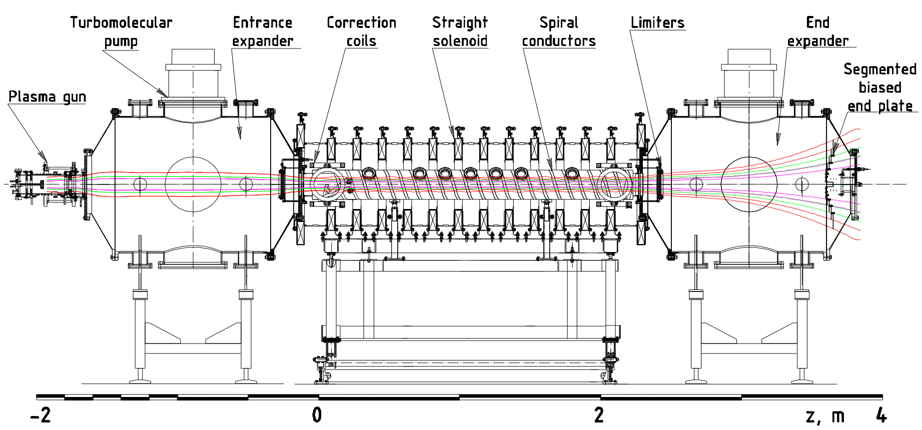


FIGURE 1. SMOLA device. The plasma source, the vacuum vessel, the magnetic system and the biased limiters are shown. Magenta field line: edge of the cathode, green: edge of the anode, red: touching grounded vessel.

Magnetic corrugation travelling in laboratory frame of reference needs excessive energetics. The most attainable configuration of the travelling corrugation involves plasma rotation in helical magnetic field. The rotation is induced by ***E***×***B*** drift in the way similar to vortex confinement [10]. In the rotating reference frame longitudinal corrugation velocity is

$$V_z = \frac{hcE_r}{2\pi r B_z} \tag{1}$$

where h is the helicity period, r is the plasma radius, E_r is the radial electric field and B_z is the longitudinal magnetic field. Direction of this force depends on the directions of the electric and the magnetic fields and its helicity.

Concept exploration device SMOLA (abbreviation from Russian "Spiral Magnetic Open Trap") is now being constructed in BINP (Fig. 1). The main parameters are as follows [11]: maximal ion density $n_i \sim 10^{19}$ m^{-3}, ion temperature T_i = 10–100 eV, magnetic field B_{max} = 0.1–0.3 T, radial electric field E_r ~ 100 V/cm, plasma radius a ~ 5 cm, period of the helicity h ~ 18 cm (12 turns are used), mean corrugation (i.e. ratio of highest to lowest magnetic field along the field line averaged over plasma's cross-section) R_{mean} = 1.5–2, experiment duration τ = 0.01–0.1 s.

This paper describes the main parts and the basic idea of the experiment. The device consists of long helical section, plasma gun and two expanders. Plasma is trapped in the entrance expander between high-field region of the plasma gun and the helical section. Vacuum and magnetic systems, plasma source and the source of the radial electric field have the main importance for the first experiments.

VACUUM AND MAGNETIC SYSTEMS

Vacuum requirements are determined by the minimization of the charge exchange losses. Charge exchange of the ion at the energy ~10–100 eV is negligible if pressure is much less than 4×10^{-3} Pa:

$$\mathrm{L} \ll \lambda = \frac{1}{n_0 \sigma_{ce}}, \qquad p \ll \frac{T}{\sigma_{ce} L} \tag{2}$$

where n_0, p and T — concentration, pressure and temperature of the neutral gas, σ_{ce} — charge-exchange cross-section, L — length of the device.

Operating pressure of 10^{-4} Pa will be attained by the turbomolecular pumps. Neutral gas is generated during the experiment mostly by the plasma gun. Expanders have the volume of ~1 m^3 each and serve as receivers for neutral gas generated by the plasma source. Gas flow will reach ~10^{20} s^{-1}. Vacuum chamber of ~1 m^3 will be filled to a critical concentration in ~0.01 s, defining maximal duration of the plasma gun discharge at maximal density.

Optimization of the magnetic system is described in [9]. Magnetic system includes a plasma gun coils, an entrance and exit expander coils, a solenoid with helicoidal field and transitions between these parts. The solenoid is composed of two windings. The uniform axial component of the magnetic field is created by a set of flat circular coils; the helicity is induced by two spiral conductors with counter-flowing currents.

We mention the magnetic field line without corrugation (R = 1) as the magnetic axis. In our configuration the magnetic axis has a form of 3D spiral with a radius ~ 1.5 cm. Magnetic corrugation scales square of the distance from

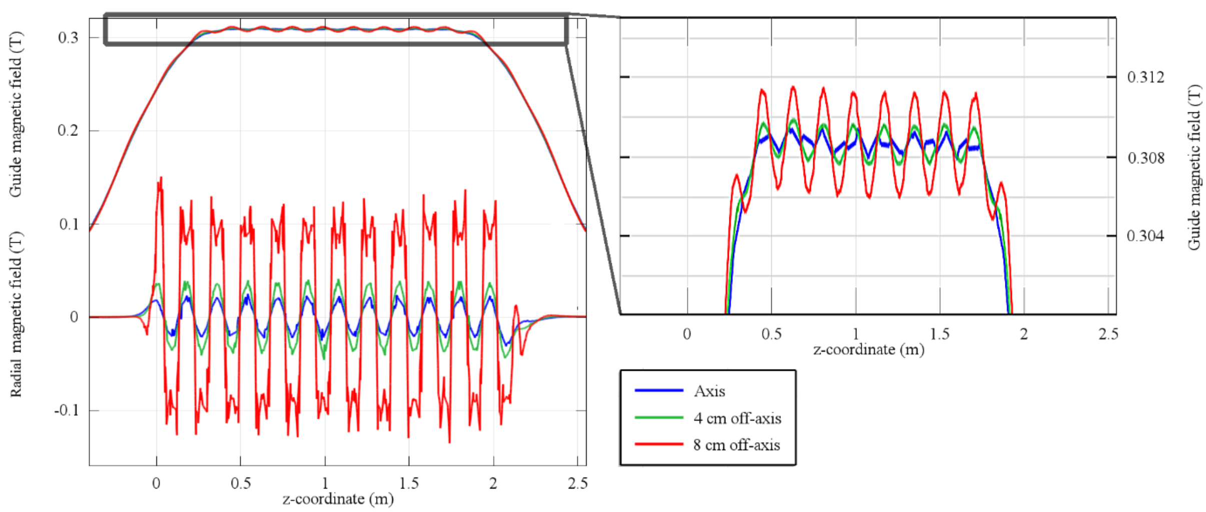


FIGURE 2. Magnetic field in the helical section

the magnetic axis to the edge. Maximal mean corrugation is achieved if the distance between plasma and helical strands is minimized. Placing of the winding inside the vacuum chamber was considered inappropriate in view of the complexity of the heat sink. Therefore the internal diameter of the spiral conductors was set almost equal to the external diameter of the chamber (17.2 cm and 16.8 cm correspondingly). Helical winding has 26 conductors with the maximal operating current of 500 A. Maximal mean corrugation up to R_{mean} ~ 1.8 could be achieved with the straight field $B_{sol} \leq 0.1$ T.

Straight solenoid with the internal diameter of 37.5 cm and period of 18 cm provides the uniform magnetic field inside the operating volume. Coils consist of 90 turns each with the maximal operating current of 500 A. Operating magnetic field up to 0.3 T could be achieved in the 1.3-m-long region (Fig. 2). Variations of the magnetic field are below 1% in 4 cm off-axis and 2% in 8 cm off-axis. Expanders' magnetic field up to 0.05 T do not have special requirements. The plasma gun has its own independent set of magnetic coils.

Three-dimensional magnetic axis of the helical section should be merged with the geometrical axis of the expanders for correct potential distribution in plasma gun and radial electric field source. Another problem is the parasitic mirror, which depends on the ratio of the straight and helical components of the magnetic field [11]. Direct comparison of the experimental results for all achievable parameters requires compensation of these effects. Magnetic axis correction is achieved by two perpendicular pairs of planar coils. In each direction magnetic axis could be shifted by 1.5 cm, which corresponds to its own radius. Parasitic mirror is compensated by the planar coil with two separated windings. High-current winding is connected in series with the helical one and therefore provides equal mirror suppression for any spiral current. Auxiliary winding allows fine tuning of the magnetic field in the range corresponding to the magnetic field of one turn of high-current winding.

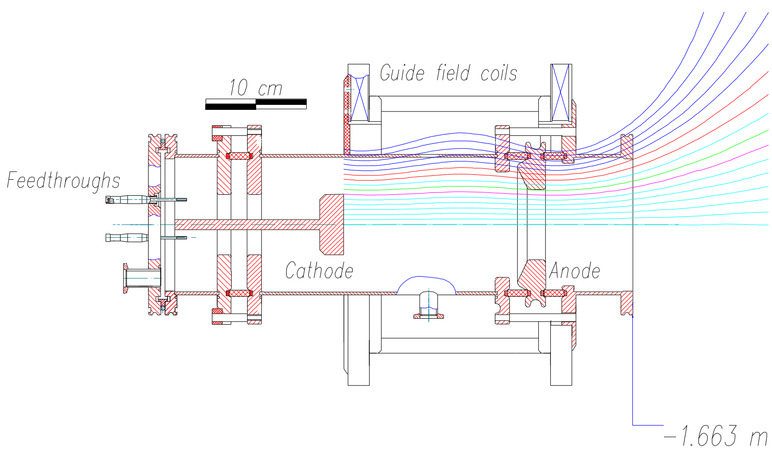
PLASMA SOURCE AND RADIAL ELECTRIC FIELD FORMATION

Plasma source should provide maximal plasma density of up to 10^{19} m^{-3} and controllable radial electric field distribution. The proposed plasma gun is based on the previously developed plasma source [12] with plasma density n ~ 2×10^{19} m^{-3} and temperature T ~ 5 eV. Ionization is performed by the electrons emitted from preheated LaB_6 cathode like in [13]. The plasma gun is schematically shown in Fig. 3a. Potentials of the anode and cathode are independent. Guiding magnetic of 0.1–0.2 T suppresses transverse conductivity in plasma gun volume, therefore current closes in the expanders. Expander magnetic field doesn't affect guide field of the gun. Arc discharges are suppressed by a set of the floating diaphragms.

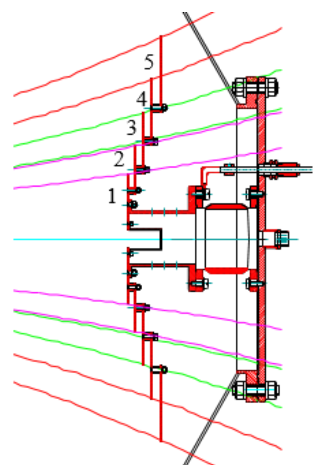
Neutral gas flux is approximately equal to the longitudinal plasma flux in plasma gun outlet (marked as $z = -1.663$ m on Fig. 3a) and is estimated as:

$$N = \langle n \rangle S \sqrt{2T_e/m_i}$$

where $\langle n \rangle$ — plasma density averaged over the transverse cross-section S, T_e — electron temperature.



(a)



(b)

FIGURE 3. (a) Plasma gun design (simplified). Longitudinal coordinate matches Fig. 1. Expander magnetic field is off. (b) Radially segmented end plate. Each segment is insulated and has independent potential. Magenta field lines: edge of the cathode, green: edge of the anode, red: touching grounded vessel.

Concept exploration requires controlled profile of the radial electric field, which is induced inside the plasma by the individually controlled anode and cathode biases and radially segmented biased end plate. Similar radially segmented plate is used in GDT for vortex confinement [10]. Equal effectiveness of the flow suppression on any plasma radius requires the radial electric field profile depending on the radial distributions of the plasma density and field line inclination [14]. In the first experiments simple GDT-like field, mostly affecting broad plasma edge region, will be used.

Asymmetry of the magnetic field in the helical section causes plasma's cross section deformation proportional to the straight-to-helical components ratio. At any ratio, magnetic surfaces starting on the outer edge of the cathode and on the inner edge of the anode end on the sections 2 and 3 correspondingly (Fig. 3b). Geometry with section overlapping is chosen to avoid plasma formation in the gaps. Field lines starting on the chamber strike section 5.

Supercapacitor-based recuperative current source will be used for magnetic and plasma systems. Current ramps up in $\tau \sim 0.5$ s. Sawteeth-like current pulsation with symmetric slopes is less than 1% of the amplitude.

An important question of plasma diagnostics is beyond the scope of this paper.

BASIC EXPERIMENTAL SCENARIO

With rotating plasma, a helical mirror presumably leads to the appearance of the longitudinal force and radial drift of ions in the electric field direction [8]. At constant initial plasma density, it leads to exponential density decay along the trap until $h \sim \lambda$ and to pinching of ions to central region with low R. The critical experiment excludes all effects except the helical confinement. It requires an identical regimes of the plasma gun, end-plates biasing and a magnitude of the magnetic field in quasi-steady state. Magnetic fields of the opposite directions cause different signs of the longitudinal force, changing axial dependence of plasma density and velocity. Changes in the longitudinal plasma profile in different regimes allow finding the essential scalings of the helical mirrors performance.

In our experiment we have a system with only one helical plug; the plasma is trapped between it and the high-field zone of the gun. Mirror ratio of the high-field zone is ~3–4 and do not provide high flow suppression. At constant plasma flow from the gun this system models one end of the infinitely long central section of GDMT-like trap.

The following basic scenario is proposed. The plasma gun initiation is taken as $t = 0$. Heating of the cathode starts in advance due to its high thermal inertia. Magnetic field is powered at $t = -0.5$ s to provide current ramp-up. Neutral gas injection starts at $t = -0.05$ ms. By the zero time hydrogen fills the entire plasma gun volume at appropriate density. After the start of the discharge plasma travels along the field lines and reaches helical section at $t \sim +0.05$ ms and end plate at $t \sim +0.2$ ms. These times relate to the basic experiment without additional plasma heating. Before $t \sim +0.2$ ms, radial electric field distribution is determined by the plasma gun solely, after that the end plates potentials become important. At $t = +10$ ms (or later for lower densities) gas injection will be stopped to avoid excessive neutral gas density inside the vacuum chamber. After this moment plasma will be generated from the background gas.

SUMMARY

This paper describes the proposed technical solutions of the SMOLA concept exploration helical mirror device. Choice of the solutions is determined by the required plasma parameters and existing experience of the Budker INP. 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 suitable for fusion applications.

ACKNOWLEDGMENTS

This work was supported by Russian Science Foundation (project 14-50-00080).

REFERENCES

[1] P. A. Bagryansky, et al., Nuclear Fusion **55**, 053009 (2015)
[2] T. C. Simonen, et al., J. Fusion Energy **29**, 558-560 (2010)
[3] A. Burdakov, et al., Fusion Sci. Technol. **51** (No. 2T), 106-111 (2007)
[4] A.V. Burdakov, et al. Fusion Sci. Technol. **59** (No. 1T), 9-16 (2011).
[5] A. D. Beklemishev, et al., Fusion Sci. Technol. **63** (No. 1T), 46-51 (2013)

[6] A. V. Anikeev, et al., Materials **8**, 8452–8459 (2015)
[7] V. V. Postupaev, et al. Fusion Sci. Technol. **68**, 92-98 (2015)
[8] A. D. Beklemishev, Fusion Sci. Technol. **63** (No. 1T), 355-357 (2013)
[9] A. D. Beklemishev, Phys. Plasmas **22**, 103506 (2015)
[10] A. D. Beklemishev, et al., Fusion Sci. Technol. **57**, 351-360 (2010)
[11] V. V. Postupaev, et al., Fusion Eng. Design, **106**, 29-33 (2016)
[12] T. D. Akhmetov, et al., Rev. Sci. Instrum. **87**, 056106 (2016)
[13] V. I. Davydenko, et al., Plasma Phys. Reports **41,** 930–933 (2015)
[14] A. D. Beklemishev, "Radial and Axial Transport in Trap Sections with Helical Corrugation", AIP Conf. Proc. (these proceedings).