First Experiments on Helical Mirror Device SMOLA

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Introduction

Advances plasma confinement in open magnetic mirrors features high relative pressure ($\beta \approx 60\%$), mean energy of hot ions of 12 keV and the electron temperature up to 0.9 keV in quasistationary regime [1-3]. At the same time, the mirror ratio in a simple open trap is limited by the achievable magnetic field and is supposed to be 15–20 in neutron source concepts [4]. Higher fusion gain in linear plasma devices is possible with improved longitudinal confinement [5]. Existing method of multiple-mirror suppression of the axial heat flux combined with gas-dynamic central cell [6, 7] can provide effective mirror ratios of the order of 100, which gives feasible fusion gain appropriate for hybrid systems.

Recently, a new method of active plasma flow suppression in a helical magnetic field was proposed [8, 9]. That proposal renewed the idea of a plasma flow control with moving magnetic mirrors. Modulation of the guiding magnetic field travelling in the laboratory reference frame requires excessive energetics. Plasma rotation in $\boldsymbol{E}\times\boldsymbol{B}$ fields similar to vortex confinement [10] can be utilized to create periodical variations of helicoidal magnetic field moving upstream in plasma's frame of reference. These variations transfer momentum to trapped particles [11] and lead to plasma pumping towards the central trap. Theory predicts exponential dependence of the flow suppression on the magnetic structure length, that is more favorable then the power dependence in passive magnetic systems. Plasma biasing or natural ambipolar potential can drive the rotation. The first case also leads to plasma pinching [12]. Plasma acceleration can also be achieved [13].

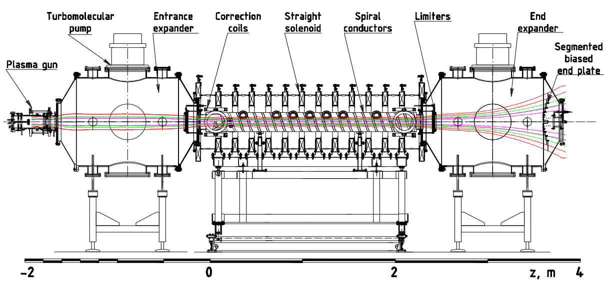

Fig. 1. SMOLA device. The plasma source, the vacuum vessel, the magnetic system and the biased limiters are shown. Magenta field line: edge of the cathode, green: edge of the anode, red: touching grounded vessel.

Concept exploration device SMOLA with a helical mirror started operation in the end of 2017 in BINP [14]. The main parameters were discussed in [9]. Here we report the experimental observation of the rotating plasma flow suppression in a helical magnetic mirror from the first plasma campaign. The aim of the first experiments was to prove the concept itself, regardless of the efficiency. Some of subsystems were not installed yet or was operating in interim configurations.

Experimental setup and parameters

In these experiments, the influence of the magnetic configuration on the plasma stream parameters was studeied. Hydrogen plasma with the density ~10^{19} m^{-3} and temperature 2 – 5 eV was generated by the plasma gun, based on the design of [15]. The plasma source always operated at the same parameters, providing the same plasma flow.

The plasma rotation was driven by the radial electric field of the plasma gun; external sources were not used to form the special profile of the radial electric field. Electric field of the gun corresponds to the negative charge on the plasma axis.

Significant dimensionless parameters were the following:

— pitch of the helical field to the ion mean free path $h / \lambda \sim 0.5 - 1$,

— mean corrugation $R_{mean} \sim 1.5 - 2$,

— ion gyroradius to the plasma radius $\rho / r \sim 0.1$,

— longitudinal velocity of the magnetic corrugation in the plasma's

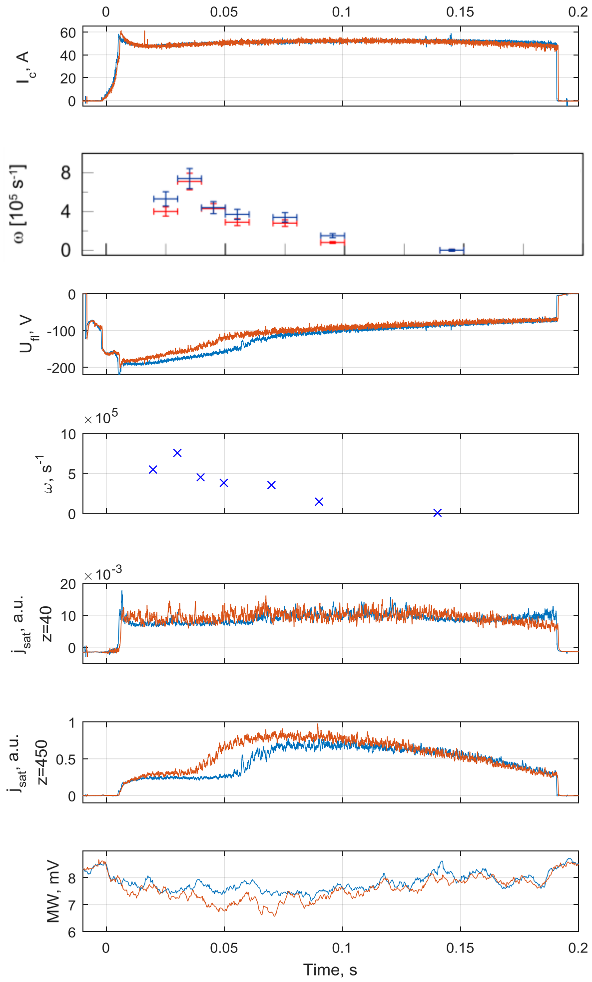

Fig. 2. Typical waveforms in shots with the solenoidal field (SM1936, red) and with the helical component (SM1937, blue) magnetic field.

From top to bottom: a) discharge current, b) the voltage between the cathode and the anode, c) the potential of the central ring of the endplate, d) the rotation velocity in the entrance tank, e) the ion saturation current on the axis at z = 0.85 m, f) the same at z = 4.79 m, g) raw signal of the 50 GHz interferometer at z = 3.93 m.

frame of reference to the ion thermal velocity $v_z / v_T \sim 1$.

The magnetic corrugations moved oppositely the plasma flow. Two significant effects were expected in this case: flow suppression at the plasma periphery with higher magnetic corrugation along the field line, and radial plasma pinchng [12]. Both of these effects lead to the radial contraction of the discharge.

An experiment with the opposite direction of the rotation was also performed to exclude an effect of the static multiple mirror confinement. Due to $v_z / v_{Ti} \sim 1$, the helical field component should not have influenced the flow significantly.

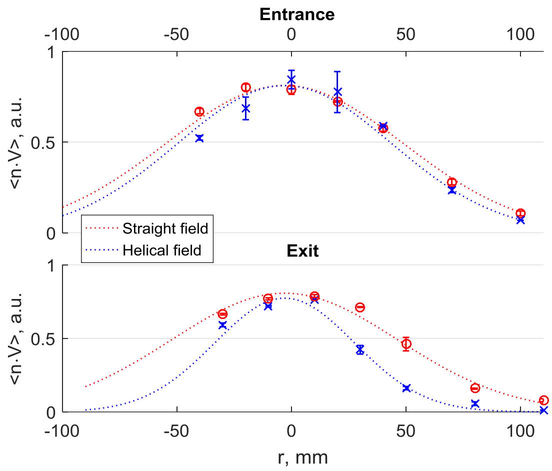

Fig. 3. Density profiles averaged for 0.07 – 0.1 s interval before (a) and after (b) the transport section shown for configurations with (crosses) and without (circles) the helical field component.

Results and discussion

Main discharge parameters (Fig. 2a, 2b), plasma density, its shape, and visible spectrum of the plasma before helical mirror (Fig. 2e) do not depend on the presence of the helical component of the magnetic field. Density profile in the entrance expander also does not significantly change by the configuration of the magnetic field in helical plug (Fig. 3b).

At the same time, direct comparison of the experimental signals show significant difference between plasma parameters at the exit from the helical section with and without helical field (Fig. 2c, 2f, 2g) in quasi-stationary phase. Difference become negligible when rotation velocity drops to zero. We observed minor changes at the axis and large decrease of the density in the periphery. This is consistent with theory predictions of the helical mirror confinement and inwards pinching. The plasma stream width at the half-maximum at the exit from the helical mirror was 70±5 mm in the solenoidal configuration, whereas it decreased to 43±8 mm with the helical field in the deceleration regime – see Fig. 3(b). Changes of the plasma radius in the entrance tank were within the measurement accuracy (73±4 mm vs. 66±5 mm), albeit this difference is in the correct direction.

The interferometry data was averaged over ~25 discharges in each regime. Line averaged plasma density at the exit is suppressed by the factor of 1.25 compared to the regime with straight field lines (Fig. 4).

In the series with the reversal of the magnetic field direction in all coils, the magnetic mirrors moved with the plasma flow at approximately the same velocity. No influence of the helical field was expected for our set of experimental paremeters, exactly as we got from the experiment.

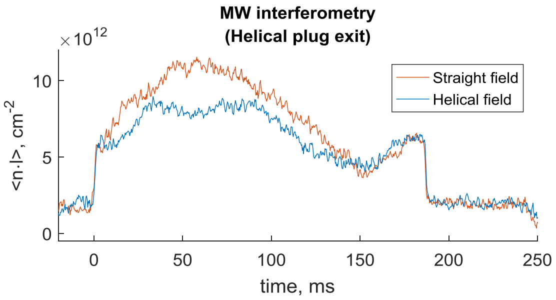

Fig. 4. Line averaged plasma densities at z = 3.48 m with (blue line) and without (red line) the helical field.

Experiments in the first plasma campaign evidently demonstrated the flow suppression with the helical mirror in the flow reduction mode.

In the current configuration, the axial modulation of the magnetic field introduces some effects of the multiple mirrors, which may slow down the plasma even without the helical component. This complicates the comparison of the reported experiment with the theory. Even at these conditions, we observed two main effects predicted by the theory: decrease of the plasma flow through the transport section and its radial pinching. We expect stronger and more controllable effect in the final configuration of SMOLA.

Acknowledgements

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[1] T.C. Simonen, et al., *J. Fusion Energy* **29**, 558 (2010)

[2] P.A. Bagryansky, et al., *Nuclear Fusion* **55**, 053009 (2015)

[3] A A Ivanov and V V Prikhodko, *Physics-Uspekhi* **60** (5),509 (2017)

[4] A.V. Anikeev et al. *Materials* **8**, 8452 (2015)

[5] A. D. Beklemishev et al. *Fusion Sci. Technol.* **63 (No. 1T)**, 46 (2013)

[6] V.V. Postupaev, et al., *Nuclear Fusion*, **57**, 036012 (2017).

[7] A.V. Burdakov and V.V. Postupaev, *AIP Conf. Proc.*, **1771**, 080002 (2016);

[8] A. D. Beklemishev, *Fusion Sci. Technol*, **63 (No. 1T)**, 355 (2013).

[9] V.V. Postupaev et al., *Fusion Eng. Design,* **106**, 29 (May 2016).

[10] A.D. Beklemishev et al., *Fusion Sci. Technol*. **57**, 351 (2010):

[11] A. Burdakov et al., *Fusion Sci. Technol*. **51 (No. 2T)**, 106 (2007).

[12] A. D. Beklemishev, AIP Conference Proceedings. 1771, 040006 (2016).

[13] A.D. Beklemishev, *Phys. Plasmas*, **22, Iss.10**, 103506 (2015);

[14] A. V. Sudnikov, *Fusion Engineering and Design*. **122**, 85 (2017);

[15]V. I. Davydenko, A. A. Ivanov, and G. I. Shul'zhenko. Plasma Phys. Rep., **41** (11), 930 (2015).