Preliminary Experimental Scaling of the Helical Mirror Confinement Effectiveness

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Introduction

Advanced plasma confinement in magnetic mirrors features high relative pressure ($\beta \approx 60\%$), mean energy of the hot ions of 12 keV and electron temperature of up to 0.9 keV in stable regime today [1-3]. In modern concepts mirror ratio of ~15–20 and improved longitudinal confinement are proposed [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.

New idea of the helical mirror confinement was suggested in [8]. That proposal renewed the idea of a plasma flow control with moving magnetic mirrors. Periodical variations of helicoidal magnetic field moving upstream in plasma's frame of reference transfer momentum to trapped particles and lead to plasma pumping towards the central trap. Plasma rotation in $\boldsymbol{E}\times\boldsymbol{B}$ fields similar to vortex confinement [9] can be utilized to create periodical variations of helicoidal magnetic field moving upstream in plasma's frame of reference. Variations transfer momentum to trapped particles [10] and lead to plasma pumping towards the central trap. The helical mirror traps should have two improvements over the classical multiple-mirrors: the exponential (instead of the quadratic) law of the confinement improvement with the system length and the radial pinch of ions that can counteract the diffusive broadening of the plasma [11].

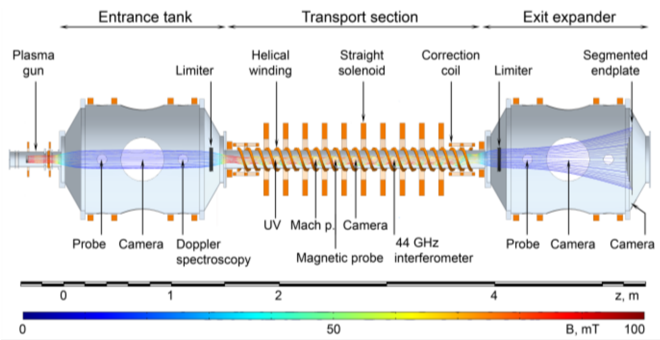

Fig. 1. SMOLA device. The plasma source, the vacuum and the magnetic systems, the limiters and the diagnostics are shown. Calculated field lines start on the edge of the cathode.

Concept exploration device «SMOLA» with a helical mirror system was put in operation in the end of 2017 in BINP [12, 13]. Plasma flux suppression by the helical sections was demonstrated in the first experimental campaign [14]. Here we report the preliminary experimental scalings of the flow suppression in a helical mirror on the magnetic field and corrugation ratio.

Experimental setup and parameters

In these experiments, the scalings of the suppression efficiency on the magnetic configuration at low values of the magnetic field (B_z = 25–70 mT, project limit 300 mT) and corrugation depth (R = 1–1.4, project limit R ~ 2–2.5) were studied. Magnetic configuration correspond to the weak trap in the entrance tank with the mirror ratios to the transport section R = 3 and to the plasma gun R = 6. Hydrogen plasma with the density ~1–5×10^{18} m^{-3} (project range 10^{18}–3×10^{19} m^{-3}) and temperatures T_i ~ 2 eV, T_e ~ 7 eV was generated by the plasma gun, based on the design of [15]. Plasma parameters were stable during any series of the experiments, providing the same flow. Average values on the flattop of the discharge were used to build up the radial profiles of the plasma parameters.

Potentials of the anode, cathode and coaxial rings of the endplate were intended to drive the rotation of the plasma. Potential on axis is negative. Unlike the previous experiments [16], rotation velocity was lower and didn't depend strongly on the experimental parameters. The velocity of the edge of the plasma was limited to v_φ ~ 1.2×10^4 m/s, which is comparable to the ion thermal velocity or the rotation velocity in ambipolar potential for given electron temperature. The stability of the rotational velocity made it possible to measure the dependences on the magnetic configuration without the influence of the changing of the corrugation velocity v_z; although, the definite reason of the slower rotation requires further investigations.

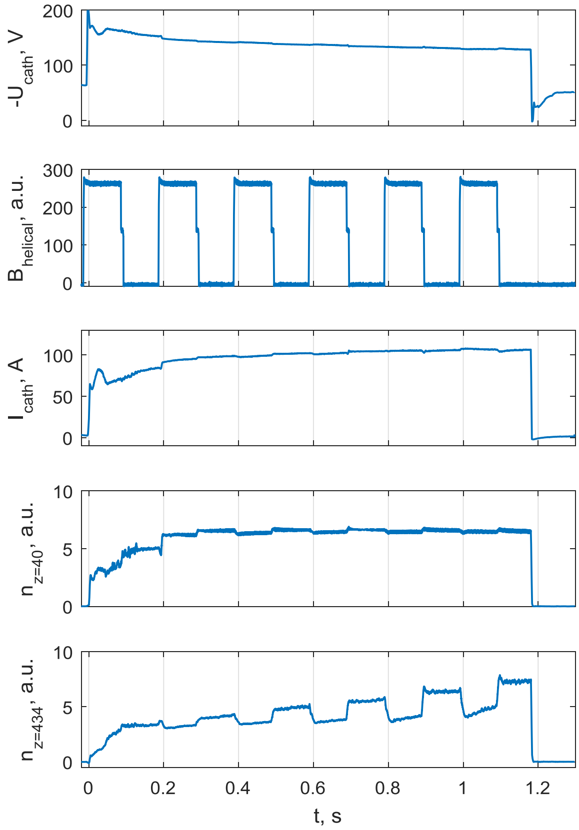

Fig. 2. Typical waveforms in a shot with the repetitive switching between straight solenoidal (R=1) and helical (R=1.3) magnetic field.

From top to bottom: a) voltage between the cathode and the anode, b) amplitude of the helical component of the magnetic field, c) discharge current, d) the ion saturation current on the axis at z = 0.4 m, e) the same at z = 4.34 m.

Results and discussion

Activation of the helical plug changes the density profiles, while the discharge parameters stay unperturbed (Fig. 2). At the described magnetic configuration, plasma density in the entrance expander becomes ~10% higher and plasma column broadens by ~10% when the transport section is in the helical configuration (Fig. 3, 4). The significance of this effect depends mainly on the mirror ratio between the trap region and the plasma gun.

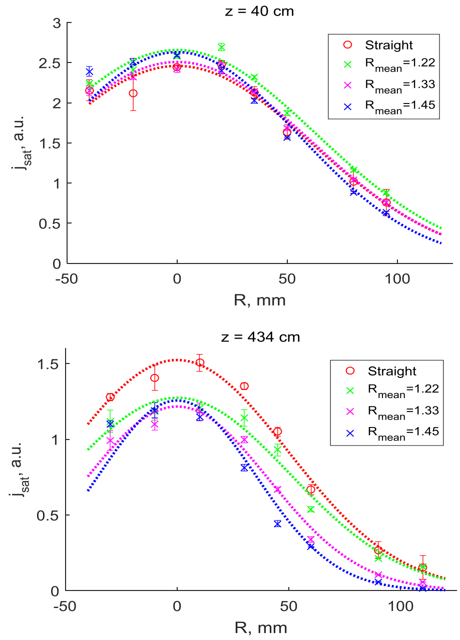

Fig. 3. Density profiles before (above) and after (below) the transport section at different corrugation. Rotation velocity $\omega \sim 3\times10^5$ s^{-1}.

Plasma density at the exit from the transport section is sufficiently suppressed in the case of the helical field. Width of the profile, and, therefore, the amount of the particles transported through the mirror, strictly depend on the guide magnetic field and rotation velocity. Presumably, in the regime of the slow rotation velocity radial pinching is insufficient to counteract diffusion. At lower magnetic fields radial diffusion prevails, causing stronger plasma column broadening and less effectiveness. Increase of the magnetic field leads to the significant improvement of the suppression effectiveness. At higher rotation velocity, pinching become significant, and

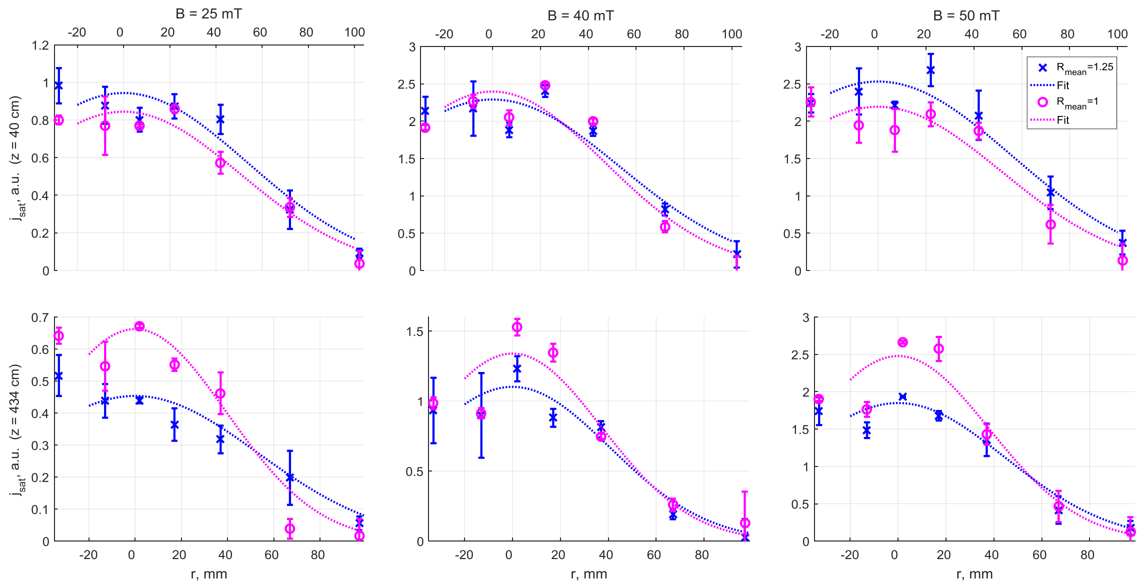

Fig. 4. Density profiles before (above) and after (below) the transport section at different magnetic field. Rotation velocity $\omega \sim 3\times10^5$ s^{-1}. Straight to helical component ratio is equal at different fields, configuration is not changed during the discharge. Circles: straight field, crosses: helical field

plasma radially contracts. Dependence does not contradict to the estimations based on eq. (21) from [11] for given B and T_e.

Scaling of the suppression efficiency on the corrugation ratio averaged over the plasma cross-section was measured at high guide magnetic field and high rotation velocity. Experimental dependence lies between linear and quadratic, it does not conflict with the theory.

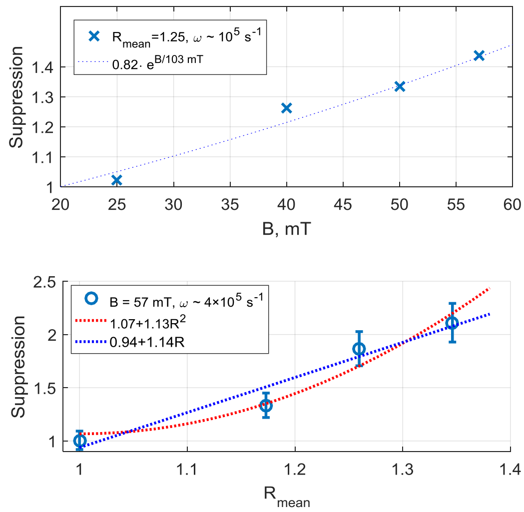

Fig. 5. Suppression dependences on the guide magnetic field (above) and corrugation ratio averaged over the plasma cross-section (below).

Line averaged plasma density at the exit of the transport section, measured by the microwave interferometer, and particle flux to the exit expander, estimated by the ionizing pressure gauges, matches the profiles obtained by the probes. The described measurements show an increase of the suppression efficiency with the increase of the magnetic field, corrugation ratio and the rotation velocity. Further experiments on the SMOLA device will be directed to the raising of these parameters.

Acknowledgements

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