Contribution ID: **1109** Type: **Regular Poster**

Plasma flow suppression in the open magnetic traps by the helical mirror

Wednesday 12 May 2021 18:25 (20 minutes)

New concept of the longitudinal losses suppression for linear magnetic traps have experimentally demonstrated the reduction of the plasma flow by the factor of 2–2.5. This factor is in a good agreement with the theory. Preliminary scalings show the possibility of the further improvement of the suppression efficiency.

High relative pressure (β ≈ 60%), mean energy of hot ions of 12 keV and the electron temperature up to 0.9 keV in quasistationary regime were achieved in linear magnetic traps in the last decade [1]. These parameters in gas-dynamically confined plasma exceed both the design parameters of the GDT (gas-dynamic trap) device and the parameters, which can be obtained in linear plasma with classical longitudinal thermal conductivity [2]. The problems of the MHD stability of the plasma column, kinetic instabilities driven by the anisotropic ion distribution function and high longitudinal particle and energy losses were successfully solved [3]. The challenge of creation of an open trap with the reactor-grade plasma is achievable if such trap will use specialized sections of the magnetic system for suppression of particle and energy losses along the magnetic field. These results made it possible to propose the next generation of the open trap GDMT. This project includes the central gas-dynamic cell (0.3–3 T at midplane, 12–20 T in mirrors) and improved longitudinal confinement [4, 5]. Basic method of suppression of the axial flux for the project is multiple-mirror confinement [6], which can provide effective mirror ratio of the order of 100 and gives fusion gain appropriate for the hybrid reactor driver and, in optimistic case, for pore fusion reactor.
Another way is the helical mirror confinement [8]. That proposal renewed an idea of a plasma control by moving magnetic mirrors. Modulation of the guiding magnetic field travelling in the laboratory reference frame have limitations on corrugation depth and possibility of utilizing superconducting coils [7]. The idea of the helical mirror considers a flow of a rotating plasma through a linear static magnetic system with helical corrugation that looks like a straightened stellarator. Periodical variations of the magnetic field moving upstream in plasma's reference frame transfer momentum to trapped particles and lead to plasma pumping towards the central trap. The helical mirror should have two improvements over the classical multiple-mirrors: the exponential law of the confinement improvement with the system length and the radial pinch of the ions that can counteract the diffusive broadening of the plasma stream.
Concept exploration helical mirror «SMOLA» was put in operation in the end of 2017 in BINP [9, 10]. In this device hydrogen plasma with the density $10^{19} m^{-3}$ and temperature 2 –5 eV is generated by the plasma gun, based on the design of [11]. Ionization is performed by the electrons emitted from heated LaB_6 cathode. Potentials of the anode and cathode are independent and magnetically insulated by the guide field 0.06–0.2 T of each other and of the grounded vacuum chamber. Potential on axis is negative. Plasma passed along the 2.3-m-long transport section with 12 periods of the helical magnetic corrugation. The magnetic system of the transport section consisted of two separately-powered windings, which created the straight and the helical components of the magnetic field. The direction of the axial transport is controlled by the proper choice of direction of magnetic field. Electric field and the helicity are determined by the setup.
Plasma flux suppression by the helical sections was demonstrated in the first experimental campaign [12]. This work presents the dependences of the plasma flow suppression on the essential experimental parameters: guide magnetic field strength, mean corrugation ratio, rotation velocity and initial plasma density. Activation of the helical plug changes the density distribution inside and at the exit from the transport section, while the discharge parameters stay unperturbed. Plasma density at the exit from the transport section is sufficiently suppressed in the case of the helical field. Width of the plasma column, and, therefore, the amount of the particles transported through the mirror, strictly depend on the guide magnetic field and rotation velocity. 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 plasma radially contracts. Dependence does not contradict to the estimations based on eq. (21) from [13] for given B and T_e.
Plasma flow suppression improves with the rise of the mean corrugation ratio. Experimental dependence in the range of the $R_{mean} = 1–1.4$ lies between linear and quadratic. The corrugation and its effects vanish at the magnetic axis and increase with the radius, as required by the theory.
The described measurements show an increase of the suppression efficiency with the rise of the magnetic field, corrugation ratio and the rotation velocity. As on the end of the 2019, the plasma stream width and total number of particles transported to the exit were reduced in helical mirror by the factors of 1.45 and 2–2.5, respectively. The experiments with the more stable plasma source, higher magnetic field and corrugation are being held now. Preliminary scalings show the possibility of the further improvement of the suppression

efficiency in these experiments.
Further campaign on the SMOLA device will be directed to the more precise measurements of the plasma flow suppression at extreme rotation velocities and at the dimensionless parameters of the plasma density relevant to the GDMT program.

Acknowledgements
This work was supported by Russian Science Foundation (project No. 18-72-10080).

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Session Classification: P4 Posters 4

Track Classification: Innovative and Alternative Fusion Concepts