Helical Mirrors for Active Plasma Flow Suppression in Linear Magnetic Traps

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Introduction

Recent advances in physics and technology of linear magnetic traps led to the achievement of relatively high plasma parameters. In a quasistationary collisional regime, the relative plasma pressure up to $\beta \approx 60\%$ was demonstrated in GDT device [1] at mean energy of hot ions of 12 keV. The electron temperature up to 0.9 keV was obtained recently with an additional ECR heating [2]. A simple interpolation of GDT parameters to higher NBI injection energy and D-T fuel resulted in a project of GDT-based neutron source with Q = 0.02 that is sufficient for a material test facility with neutron flux of 2 MW/m^2 [3].

Suppression of the longitudinal losses is the key issue in increasing plasma parameters. Multiple-mirror [4] or ambipolar [5] passive barriers are used to suppress axial plasma flow. Recently, a new idea of active plasma counterflow pumping with the combination of helicoidal magnetic and radial electric fields was proposed [6]. Plasma rotates due to $\boldsymbol{E}\times\boldsymbol{B}$ drift. Periodical variations of magnetic field move along the flow in its reference frame, inducing longitudinal force acting on the trapped particles. Velocity could be estimated as

$$V_z \approx \frac{hcE_r}{2\pi r B_z},$$

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. Up- or downstream direction of this force depends on the directions of the electric and the magnetic fields and on the helical structure. Theory predicts exponential dependence of the flow suppression on the magnetic structure length, that is more favorable than the linear dependence in passive confinement systems.

This paper describes the layout of an experiment for the verification for this theory, namely the required plasma parameters and the optimization of the helicoidal magnetic field.

Plasma parameters

The most effective suppression of the longitudinal plasma flow corresponds to the conditions when mean free path of the ion λ is of the order of the period of the helicity:

$$h \sim \lambda \sim \frac{T_i^2}{4\pi\Lambda e^4 Z^4 n_i} \qquad\qquad n_i \sim \frac{T_i^2}{4\pi\Lambda e^4 Z^4 h}$$

Plasma should be magnetized to suppress the transversal conductivity:

$$\rho_B \ll r,\ \rho_B \ll \frac{\lambda}{2\pi} \sim \frac{h}{2\pi},\ r \sim \frac{h}{2\pi} \qquad\qquad B_z[T] \gg \frac{2\sqrt{2}\pi c}{e\sqrt{m_i}} \frac{\sqrt{T_i}}{h}$$

Velocity of the magnetic perturbation V_z should be greater than the thermal velocity V_i, therefore the radial electric field:

$$E_r > B_z \frac{2\pi r}{h} \frac{V_i}{c} \gg \frac{2}{em_i} \frac{T_i}{r}$$

To achieve an appropriate concentration of the trapped particles the mean corrugation of the magnetic field along the field line in the plasma cross-section should be $R \sim 1.5$–2.

Duration of the experiment τ should be greater than the ion transit time to achieve the steady state. Length of the device is $N\times h$, where $N \sim 10$ is the number of periods, therefore:

$$\tau \gg \frac{N \times h}{V_i} \sim \frac{\sqrt{m_i}}{4\sqrt{2}\pi\Lambda e^4 Z^4} \frac{T_i^{\frac{3}{2}}}{n_i} N$$

Summarizing the estimations above the required plasma parameters are:

$$n_i \sim 10^{19}\ m^{-3} \qquad E_r \sim 100\ V/cm \qquad h \sim 20\ cm$$
$$T_i \sim 10 - 100\ eV \qquad \tau \sim 0.1\ s \qquad N = 12$$
$$B_{max} = 0.1 - 0.3\ T \qquad r \sim 5\ cm \qquad R_{mean} \sim 1.5 - 2$$

Magnetic field structure

Magnetic system of the device includes the plasma gun coils, entrance and exit expander coils, solenoid with helicoidal field and interconnections between these parts — see Fig. 1. The main goal of the optimization is to maximize the variation of the magnetic field along the field line in the cross-section of the plasma. We note that the mirror ratio R is equal to unity on the magnetic axis in a helically symmetric magnetic system. Plasma

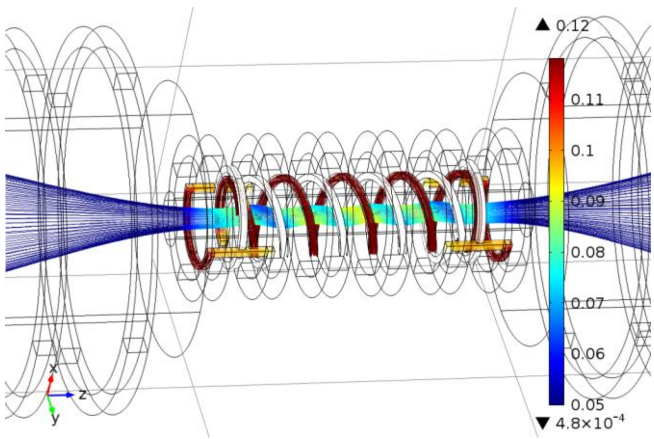

Fig. 1. Configuration of the magnetic system with a helicoidal section for control of the axial plasma flow.

gun and expander coils are axisymmetric and therefore need no complicated optimization. Combined solenoid is composed of two parts: strait axial component of the helicoidal field is created by the set of the flat coils; helicity is induced by the even number of spiral bars with counter-flowing currents. Two bars provide the most favorable distribution of the magnetic field variation along the radius [7]. The free variables are the period of the helicity to the diameter of the spiral bars ratio h/d and helical to strait magnetic field ratio B_{hel}/B_{str}. The range of variables where detailed calculations were performed was $h/d = 0.6$–1.2, $B_{hel}/B_{str} = 0.4$–0.8. Field lines were assumed to be lost if they cross the cylinder with the diameter $d_c = 0.8\ d$.

Optimal values of the parameters were $B_{hel}/B_{str} \sim 0.75$–$0.8$, $h/d \sim 0.8$–0.9 (Fig. 2).

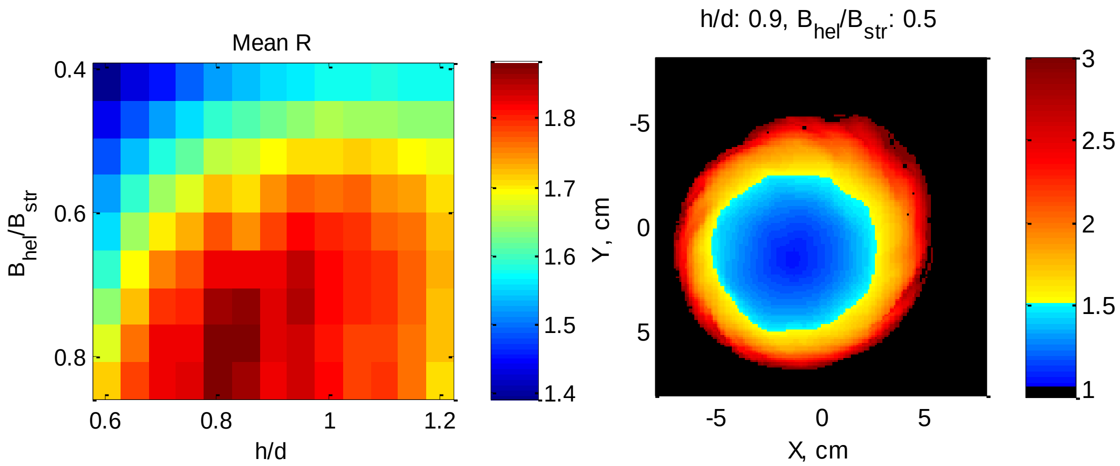

Fig. 2. Left: mean variation of the magnetic field along the field line R in parameter space. Right: distribution of the R value along the cross-section near the optimal parameters.

Magnetic axis in helical magnetic field is sufficiently 3-dimensional. Saddle-like correction coils were used in interconnections between the combined solenoid and expanders to match it with the geometrical axis and, therefore, plasma gun and radial electric field source. Axes match when the current in the correction coil is proportional to the current in spiral bars, $I_{corr} = 0.23\ I_{spiral}$. (Fig. 3). The ends of the helicoidal winding create parasite mirrors at the ends of the combined solenoid. The mirrors are eliminated by the additional planar error correction coil with the current $I_{planar} = 0.57\ I_{spiral}$.

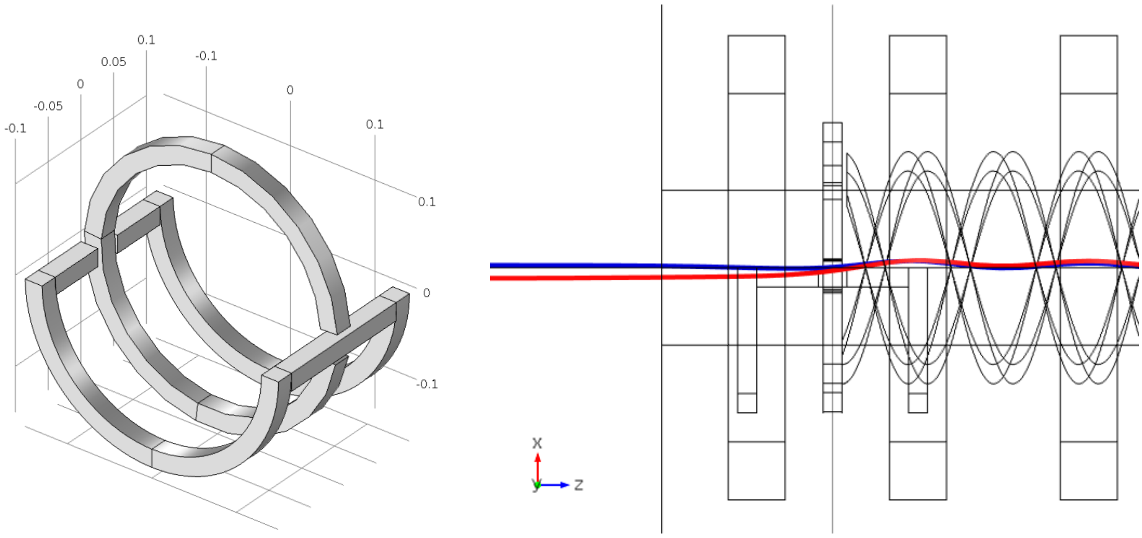

Fig. 3. Left: correction coil layout. Right: magnetic axis before (red) and after (blue) correction.

Summary

Plasma parameters and magnetic field configuration that are required to verify the helicoidal confinement theory are appropriate for a moderate-scale experimental device of the concept exploration category. Such a device is now planned in BINP.

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, *Plasma Phys. Control. Fusion* **55**, 063001 (2013)

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

[5] T. Imai et al, *Fusion Sci. Technol.* **63** (No. 1T), 8 (2013)

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

[7] Masahiro Wakatani, *Stellarator and heliotron devices*, Oxford: Clarendon Press, 27 (1998)