Fusion Engineering and Design 106 (2016) 29–33

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Helical mirrors for active plasma flow suppression in linear magnetic traps

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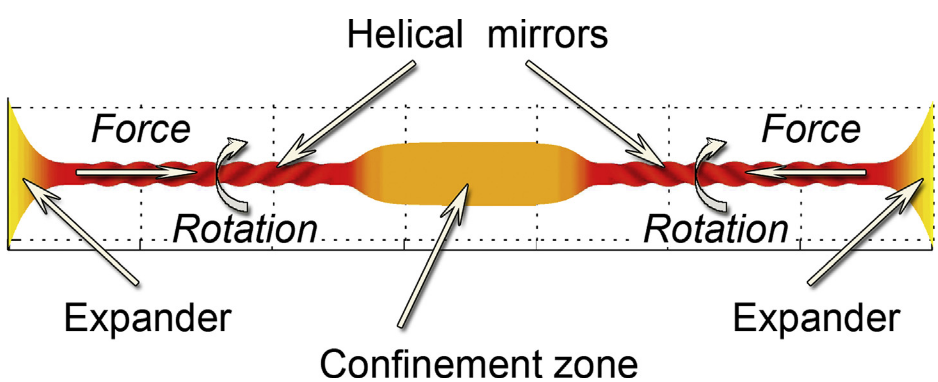
HIGHLIGHTS

- The recently-suggested helical mirror confinement concept is discussed.
- Active suppression of axial particle and energy losses.
- Parameter space for the first experiment is discussed.
- Details of magnetic system of the SMOLA project are presented.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 6 November 2015
Received in revised form 4 February 2016
Accepted 5 March 2016

Keywords:
Helical mirror
SMOLA device
Plasma rotation
Open traps

ABSTRACT

A novel concept of helical mirror confinement with active axial and radial plasma flow control is discussed. The idea relies on the retarding force that appears when biased plasma experiences rotation in crossed electrical and helical mirror magnetic fields. Preparations for its experimental study started in Budker Institute of Nuclear Physics, Novosibirsk. Possible parameter space for a concept-exploration-class device SMOLA is identified. Details of numerical optimization of the magnetic structure of the device are presented. The main physical task for the SMOLA experiment will be direct demonstration of the helical mirror performance in simple experimental conditions at reasonably low plasma parameters.

1. Introduction

Open magnetic systems for plasma confinement (also referred to as magnetic mirrors) are considered as candidate configurations for a thermonuclear reactor since the early days of fusion research. Though such systems are not the mainstream in fusion research programs, the progress in physical understanding of open magnetic configurations and in the achieved plasma parameters is steady. An extensive review of research activities in magnetic mirrors can be found in Ref. [1]. Recently, a significant breakthrough was reported by GDT team. [2] The electron temperature up to 0.9 keV was obtained in an advanced scenario with a combination of neutral beam (NBI) and electron cyclotron (ECR) heating. Earlier, the relative plasma pressure up to $\beta \approx 60\%$ was demonstrated [3] in the same GDT device at mean energy of hot ions of 12 keV in a quasistationary collisional regime. A simple interpolation of current GDT parameters to higher NBI injection energy and D-T fuel resulted in a project of GDT-based neutron source [4] with the

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http://dx.doi.org/10.1016/j.fusengdes.2016.03.029
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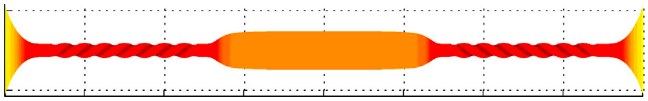

Fig. 1. A mirror trap with a GDT-like central section for plasma confinement, two sections with a helicoidal magnetic field that decrease axial plasma flow, and two exit expanders of the magnetic flux. Color intensity corresponds to magnetic field strength.

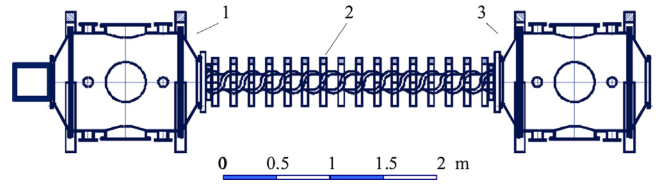

Fig. 2. Configuration of the proposed experiment: 1 is the plasma source tank, 2 is the helical magnetic mirror section, 3 is the plasma receiver tank.

fusion energy gain factor $Q = 0.02$ that is sufficient for a material test facility with a neutron flux of 2 MW/m^2 in a test zone.

Physics and technology for the next-step open trap is under development in the framework of the GDMT project [5] in Novosibirsk. This device should demonstrate in a non-tritium experiment the main plasma parameters directly relevant to a fusion neutron source. The key physical issue in increasing the plasma parameters is the suppression of the longitudinal power and particle losses. For this purpose, multiple-mirror [6–8] or ambipolar [9–11] passive barriers were proposed and experimentally tested. Recently, a new idea of active plasma counterflow pumping with the combination of helicoidal magnetic and radial electric fields was proposed in Ref. [12]. In this proposal, special magnetic sections with helicoidal magnetic field are connected to the outer sides of magnetic mirrors of a GDT-like central confinement section—see Fig. 1.

In this system, plasma is confined in the central section that operates as a classical gas-dynamic trap with the well-established physics [4]. Plasma escapes the trap through the magnetic mirrors along the magnetic field. The plasma acquires some negative electric potential that balances electron and ion flows. The end magnetic expanders with high expansion ratio prevent the back flux of cold electrons from plasma receivers into the confinement zone. In such conditions, no classical thermal conductivity exists. The energy losses along the magnetic field are much more favorable; the mean energy of an electron-ion pair that escapes the trap is $\varepsilon \approx 8T_e$. The role of the proposed sections with a helical magnetic field is to decrease particle losses along the magnetic field and therefore to decrease energy losses as well.

Magnetohydrodynamical (MHD) stability in the GDT device is currently provided with the so-called vortex confinement technique [13]. Plasma is biased by a special electrode system, therefore it rotates due to $E \times B$ drift. In a magnetic system with a helical field component, rotating plasma will see axially moving magnetic hills and wells in its reference frame. Velocity of the magnetic perturbations V_z could be estimated as

$$V_z \approx \frac{hcE_r}{2\pi rB_z} \qquad (1)$$

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. Plasma interaction with the rotating magnetic field creates an average force that acts on the plasma flow. The simplest (though not completely correct) analogy of this system is the well-known Archimedes' screw. Up- or downstream direction of the acting 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.

In this paper we briefly introduce the theory of helical mirror confinement. Then we discuss possible parameters of an experiment that can validate the theory predictions and finally we present results of a numerical optimization of a chosen magnetic configuration.

2. Helical mirror confinement

The main idea of the helical mirror confinement is the active pumping of plasma into the trap along field lines by means of its interaction with the corrugated magnetic field. If the plasma rotates and the corrugation is helical, the axial interaction occurs in the moving reference frame, so that any form of friction between the plasma and the magnetic structure will suffice [12]. To estimate such friction we can recall main results of the theory of multiple-mirror confinement [14]. We will give a brief introduction into the idea in several paragraphs below; the more detailed and accurate theoretical analysis can be found in Ref. [15].

The slowest-moving plasma component is always the ion component, so that we need to consider the motion of ions. If the electron temperature is greater or comparable to the ion temperature, the presence of electrons, no matter collisional or not, will then affect the motion of ions essentially through the "ambipolar" potential. Conversely, the outflow and the heat flux of electrons will be limited by the same ambipolar barrier. In GDT this barrier occurs in expander, while in multiple-mirror traps the plasma density is supposed to fall off along the corrugated section. Thus, for magnetized ions, sections with corrugated magnetic field look like a series of Yushmanov-potential [16] wells sitting on a downhill slope toward the endplate (the slope is due to the ambipolar potential and the pressure of electrons). One can consider several distinct cases of the motion of ions. If their mean free path, λ_i, along the slope is greater than the trap length, L, the presence of ions trapped in potential wells will not affect the motion of passing ions, and the multiple-mirror system will not work. If it is less than that, but greater than the corrugation length, h, $h < \lambda_i < L$, sequential trapping and detrapping of ions provides a channel of momentum transfer between ions and the magnetic structure that peaks around $h \approx \lambda_i$. If the mean free path continues to decrease, the effectiveness of interaction is reduced due to shorter life-times of trapped ions that have less opportunity to transfer momentum to the magnetic well. In the MHD limit the interaction can be described in terms of the parallel plasma viscosity, which goes to zero in an ideal fluid.

Thus, the multiple-mirror confinement theory predicts an optimal relation between the corrugation period and the mean free path, namely, $h = \lambda_i$, when the ion outflow through multiple-mirror field looks like diffusion with $D = hv_{Ti}$. Note that in the case of helical corrugation (with active pumping) it becomes diffusion with the background flow velocity

$$F = \rho V + D d\rho/dz \qquad (2)$$

where F is the flow density of the mass density ρ, and V is the effective velocity of the corrugation. If V is directed into the trap, the ion confinement problem can be solved.

Finally, we should note important differences between the simple picture of multiple-mirror confinement in a shifted reference frame that we used above and the more complicated reality. First, any ion experiencing collisional friction in non-axisymmetric magnetic field will drift radially. This is also obvious from the energy conservation law, namely, if the axial ion energy is changed due to