Doppler Spectroscopy System for the Plasma Velocity Measurements in SMOLA Helical Mirror*)

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The measurements of the plasma velocity in the SMOLA helical mirror by observation of the Doppler shift of the Hα spectral lines emission were done by high spatial resolution spectrometer. A set of experiments was carried out with the different configuration and amplitude of the magnetic field. Potential is driven by plasma gun potentials. The radial distribution of the Doppler shift of the Hα line is used to calculate the velocity of neutral hydrogen, which gives the estimate of the plasma rotation velocity $\omega \approx 10^6\,\mathrm{s}^{-1}$. The indicated velocity corresponds to the presence of the radial electric field $E \sim 70$ V/cm. The dependence of the plasma rotation velocity on the radial profile of the electrostatic potential is discussed.

Keywords: plasma confinement, helical mirror, optical diagnostics, Doppler spectroscopy, plasma rotation velocity

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1. Introduction

One of the key scientific and technical problems is the ecologically safe generation of the energy [1]. A possible solution of this problem is the mastering of the energy of fusion. The open magnetic systems for plasma confinement, which allow controlling plasma with higher relative pressures, can provide significant advantages, including the possibility of non-tritium and non-deuterium fusion fuels [2]. The main problem of the plasma confinement in such traps is the suppression of the particle and energy losses from the ends of the device. The method of multiple mirror suppression of the axial flux combined with gas-dynamic central cell was proposed to solve this problem [3].

One of the possible improvements of the multiple mirror is the dynamic multimirror confinement, where the magnetic plugs move in the plasma's frame of reference (Fig. 1). The main aim of the SMOLA device (Fig. 2) is to prove the concept of the helical confinement [4].

The motion of the magnetic mirror is created by the plasma rotation in crossed radial electric and helical magnetic fields. Appropriate profile of the radial electric field depends on the required flow suppression and radial diffusion [5,6]. The plasma rotates due to **E**×**B** drift those magnetic mirrors move axially in the plasma reference frame with the velocity V_z:

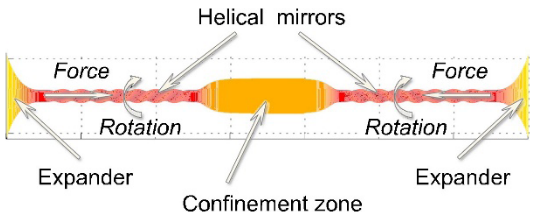

Fig. 1 (Color online) Sketch of the prospected fusion system with helical plugs [3].

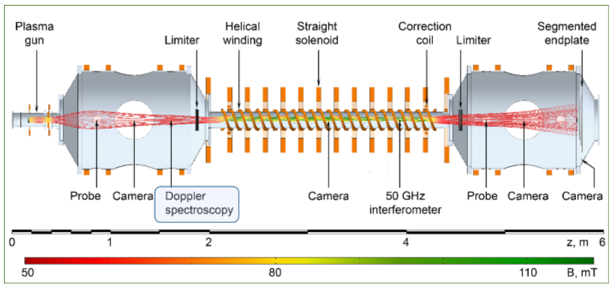

Fig. 2 (Color online) SMOLA helical mirror layout [11].

$$v_z = \frac{h}{2\pi r}\frac{E_r}{B_z}c,$$

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.

The direction of V_z depends on the direction of the

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E×**B** drift and on the helicity of the magnetic corrugation. Thus, the plasma flow can be either decelerated [4] or accelerated [7].

The magnetic system of the device provides fully individual control of the gun field, straight component and helical component of the helical mirror section. End-plate has 5 concentric electrodes with independently controlled potentials. Diameter of the end-plate is ∼0.65 m. Anode of the plasma gun is projected by the magnetic field lines to the outermost electrode of the end-plate. Magnetic field expansion ratio is $R \sim 45$. The main parameters of SMOLA device and its magnetic system were presented in [8]. The positions of the diagnostics are shown on Fig. 2.

The plasma rotation in the discussed experiments was driven by the own radial electric field of the plasma gun projected along the magnetic field lines by axial currents; no special profile of the radial electric field was formed externally. The electric field of the gun always corresponded to the negative potential at the plasma axis, while the direction of plasma rotation was controlled by the inversion of the magnetic field.

The determination of the spatial distribution of the plasma velocity is necessary for constructing a model describing the motion of the plasma flow in a helical trap. The measurements of the plasma velocity by observation of the Doppler shift of the emission spectral lines Hα are provided by high spatial resolution spectrometer [9].

This report demonstrates the diagnosis of the Doppler shift of spectral plasma lines with spatial resolution in the open trap with helical sections to prove the presence of plasma rotation in SMOLA.

2. Diagnostic Setup

The measurements of the plasma velocity by observation of the Doppler shift of the emission spectral lines Hα are provided by high spatial resolution spectrometer (Fig. 3), which is similar to [9].

The optical system, which is located at a distance of 80 cm from the plasma axis, consists of an objective (1) and a long-focus thick lens (2). Behind this, the monochromator MDR-12 is placed. It has an entrance slit (3), parabolic mirrors (4, 6), a diffraction grating (5) and CCD-camera (7) with an exposure of 7 us.

Thus, the image of spectral line is focused on the entrance slit of the spectrometer, and then it is decomposed into a spectrum by a diffraction grating and recorded by the CCD camera as a two-dimensional image.

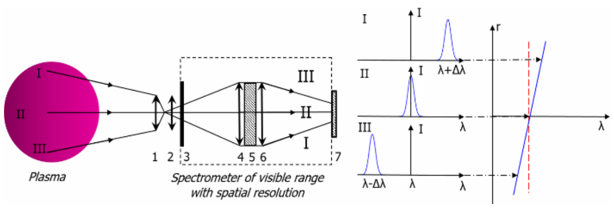

Fig. 3 (Color online) The scheme of the high spatial resolution Doppler spectrometer.

The spectral characteristics of the optical device were determined by the calibration procedure using the radiation of a standard deuterium lamp. The calibration was provided using the Dα (656,106 nm) and Hα (656,278 nm) emission lines. In addition, the difference between the image of the spectral line and the straight line helps to correct the distortion of the spectral device and to determine the basic slope of the spectral calibration line.

In the spectrometric system based on the focusing spectrometer with a reciprocal linear dispersion of 0.1 nm/mm, a spatial resolution of 1.2 mm was attained. The accuracy of the plasma rotation velocity determination is $\Delta\omega \sim 10^5\ \mathrm{s}^{-1}$.

3. Observation of the Plasma Rotation Velocity

3.1 The first experiments

In the reported experiments, hydrogen plasma with the density $\sim 10^{19}\ \mathrm{m}^{-3}$ and temperature 2 - 5 eV was generated by the plasma gun, based on the design of [10].

The lifetime of the excited state 3p of the hydrogen atom is $\tau \sim 10^{-10}$ s, therefore the distance passed by the neutral atom produced by charge exchange before it emits light is estimated as $L = \tau \cdot v \sim 10^{-9}\ \mathrm{s} \cdot 10^{6}\ \mathrm{cm/s} = 10^{-3}$ cm. This length is negligible compared to the plasma radius $r \sim 5$ cm and the Larmor radius $\rho \sim 1$ cm.

Therefore, the recorded velocity of the neutral atom matches to the ion velocity before charge exchange. Shift of the center of the spectral line corresponds to the average velocity of the ion flow.

The first experiments were carried out in the regime when the plasma was deposited on the end of the expander. In this case, the plasma rotation velocity, and hence the radial electric field, depend strongly on the applied magnetic field. A plasma jet and calculated magnetic field lines are shown in Fig. 4 where the number is the radius of the cathode from which the line of force exits.

A set of experiments was carried out with the same configuration but with a different amplitude and direction of the magnetic field. These experiments were performed mostly to verify the ability of the diagnostic system to detect the rotation.

The dependence of the plasma rotation velocity on the amplitude of the magnetic field is demonstrated (Fig. 5). This dependence is explained by the modification of the potential distribution at different diameters of the spot of plasma contact with grounded vacuum chamber.

It could be expected that the plasma rotation velocity is inversely proportional to the magnetic field. However, the experiment demonstrated another result due to the direct contact and short distance between the plasma and the grounded vacuum chamber. Therefore in further experi-

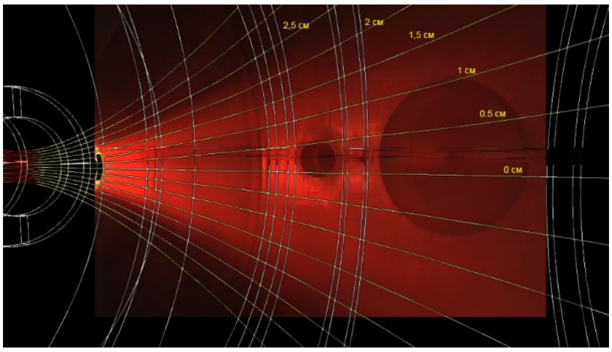

Fig. 4 (Color online) A plasma jet and calculated magnetic lines of force, obtained in the experiments without helical section [6].

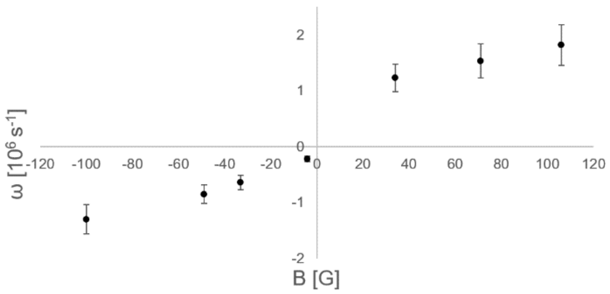

Fig. 5 Dependence of the plasma rotation velocity on the magnetic field in entrance expander without the helical section. Plasma contacts grounded vacuum chamber.

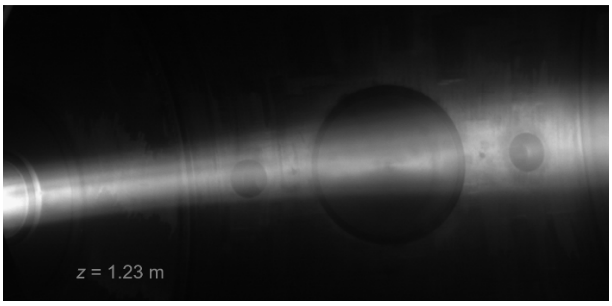

Fig. 6 A typical plasma jet entering the helical section in entrance of in expander of SMOLA.

ments a plasma receiver located on a sufficiently large distance was used.

This measured data was also important as a methodological research, which have shown an appropriate operation of the spectral system.

In main experimental series the plasma jet passed through the helical section (Fig. 6).

The plasma emission spectra in the vicinity of the Hα line (Fig. 7), were obtained at different geometries and directions of the magnetic field.

The difference between the Doppler shifts of the spec-

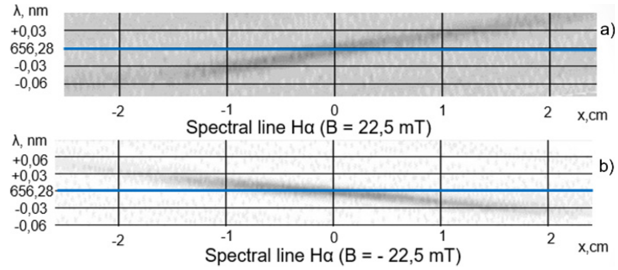

Fig. 7 (Color online) The shift of the Hα line with the different directions of magnetic field.

tral lines in the space is observed which indicates the presence of plasma rotation in the expander of SMOLA.

The spatial distribution of the Doppler shift of the Hα line is used to calculate the velocity of neutral hydrogen, which gives an estimate of the plasma angular velocity $\omega \sim 10^6\,\mathrm{s}^{-1}$. The electric field is directed toward the plasma axis, the direction of plasma rotation velocity coincides with the direction of the ions current.

The magnetic field in the field of observation can be estimated as ~ 0.1 of the magnitude of the magnetic field in the anode region. The indicated angular velocity in this case corresponds to the presence of a radial electric field $E \sim 70$ V/cm.

3.2 Observation of the rotation velocity dynamics

A series of experiments was carried out to observe the change in the plasma rotation velocity at different times relative to the discharge initiation by the hydrogen flow start.

In this operation regime the straight or helical magnetic field were powered on at 12 ms and 60 ms, respectively; the voltage between anode and cathode and gas injection starts at 60 ms. The gas injection stop at 300 ms; the magnetic fields and the gun voltage powered off at 320 ms. Thus, the duration of the discharge is about 250 ms.

The above dependence was constructed for 4 operation regimes of the device (Fig. 8): plasma confinement (straight magnetic field), plasma confinement (helical magnetic field) and plasma acceleration (straight magnetic field), plasma acceleration (helical magnetic field). The exposure of the camera in each shot was the same (10 ms).

In contrast to the first experiments, a differential plasma rotation in this series is detected. In this case, the central part of the plasma rotates faster than the periphery.

We observed that the plasma rotation velocity decreases with time. Probably, this is caused by the growth of neutral gas pressure, which leads to a friction-like force due to charge-exchange processes. As a result, the maximum of rotation velocity for each regime was registered at about 30 ms after the start of plasma injection.

It is noted, when operating in the plasma flow accel-

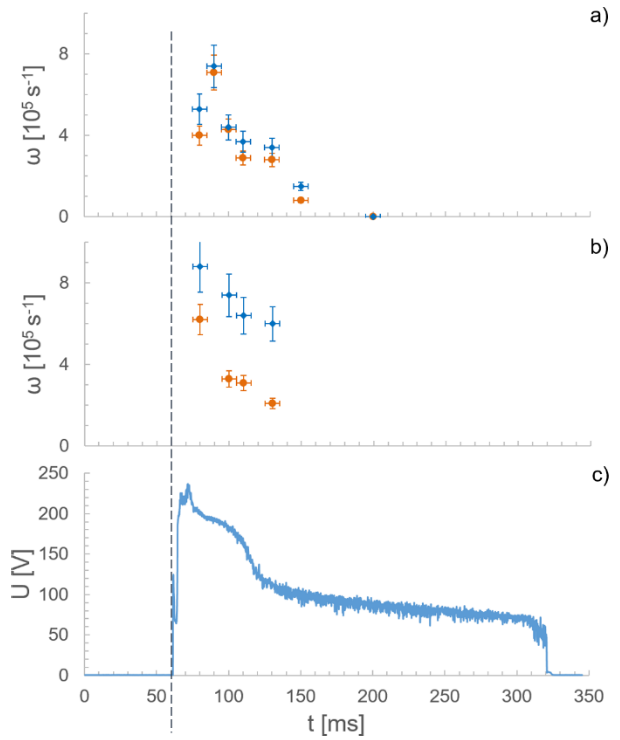

Fig. 8 (Color online) Dynamic velocity of plasma rotation in: a) regime of plasma confinement: straight (red) and helical (blue) magnetic field, b) regime of plasma acceleration: straight (red) and helical (blue) magnetic field, and potential on the plasma receiver (c). Dotted Timeline corresponds to the discharge initiation by the hydrogen flow start.

eration regime, the rotation velocity is higher than in the confinement regime. Considering the velocities for various configurations of the magnetic field, the rotation velocity of the plasma in the helical magnetic field is approximately 30% higher than in a straight field.

The dependence of the rotation velocity of the plasma on the radial profile of the electrostatic potential is presented below. The potential is due to the displacements of the radially segmented end plates. Currently, the plasma receiver can work in 3 basic regimes which are presented in the Table 1: all plates was grounded, each plate had the same floating potential and each plate had different potentials. Experiments with the straight and helical configuration of the magnetic field were carried out in the last of the above plasma receiver regime. At different potentials of the plasma receiver, a noticeable change of the plasma rotation velocity is observed.

The plasma rotation velocity is 20 - 25% higher in the case when each plate of the plasma receiver has itself floating potential.

Table 1 The dependence of the plasma rotation velocity on the potential of the plasma receiver.

Operating regime of the plasma receiver	Plasma rotation velocity
all plates are grounded	$\omega = (7{,}9\pm0{,}9)\cdot10^5\ s^{-1}$
each plate has the same floating potential	$\omega = (8{,}7\pm1)\cdot10^5\ s^{-1}$
each plate has different potentials (straight magnetic field)	$\omega =(10{,}5\pm1{,}2)\cdot10^5\ s^{-1}$
each plate has different potentials (helical magnetic field)	$\omega = (10{,}5\pm1{,}2)\cdot10^5\ s^{-1}$

4. Conclusion

The existence of plasma rotation in the entrance expander was experimentally proved. Comparison of the plasma confinement in straight and helical magnetic field was performed in the regime where each electrode of the end-plate was floating, because this regime provides highest velocity. The time dependence of the plasma rotation velocity was calculated in straight and helical configurations of the magnetic field. The Doppler diagnostics with spatial resolution to determine rotation velocity in the case of a controlled potential on the plasma receiver will be used. We plan to measure the longitudinal and transverse velocities of plasma rotation using a compact spectrometer that registers the spectra of two points in space. The plasma rotation velocity in the helical section will be measured later.

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