HALL ION SOURCE WITH BALLISTIC AND MAGNETIC BEAM FOCUSING

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Reversible magnetic system for the circular Hall ion source with ion beam ballistic focusing was contrived and then investigated both theoretically and experimentally. It was shown that simultaneous application of ballistic and reversible magnetic focusing systems allows achieving ion beam compression from initial diameter of *100 mm* to the *1 mm* diameter in a plane of the crossover.

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1. INTRODUCTION

Gas discharge plasma is widely used in scientific research, technique and technology as a source of intense flows of charged particles [1, 2].

The problem of enhancing the density of electric current in compact sources of ion flows always was of an interest for the further development of plasma technologies. One kind of such type modifications is application of focusing.

Objective of this paper is designing and studying the Hall ion source with ballistic focusing and achieving high density of beam current and high power density within the crossover plane. This problem is urgent, e.g., for modeling the plasma-wall interaction in fusion devices.

2. BALLISTIC FOCUSING OF ION BEAM

2.1. MODIFICATION OF HALL ACCELERATOR DESIGN FOR BALLISTIC FOCUSING OF ION BEAM

If the method of ballistic focusing is used for enhancing the beam current density then the geometric coefficient of compression is equal (see Fig.1):

$$G_j = \frac{8R\sin^2\alpha}{a}. \qquad (1)$$

For the geometrical values which are typical for our experimental conditions the coefficient of compression is equal $G_j=171$.

Square of the crossover is expected to be $S(crossover) = 3{,}45\ mm^2$. In the Hall ion source, the beam current uses to be up to *200 mA* while the average ion energy is 1 keV. Due to decreasing the square of the beam we expect to get the beam density $j_{crossover}=5{,}79\ A/cm^2$. The latter is rather high power per unit of square $P=j\ \varepsilon_{ib}=116\ MW/m^2$.

To realize the ballistic focusing, usual plane cathode and anode were replaced by the new ones of special shape (Fig.1(d)) with channels which provided the producing of cone-like beam (Fig.2).

The experiments were carried out under the discharge voltage $(1{,}5 \div 5)$ *kV*. Electric current in the magnetic coils was varied from *0,7* up to *3 A*, what corresponded to maximum of magnetic field strength in the discharge gap 900 – 3300 Oe. The pressure in the work chamber was $(4 \div 5)10^{-4}$ *Torr*. Argon was used as a working gas.

The experiments showed that the beam diameter in crossover *d* increased with increase in the magnetic field strength and decrease in the discharge voltage, and it did not depend on the gas pressure and the beam current (Fig.3.).

Analysis of the experimental data gives the value of power *n* by *U* that in average is close to (*–1/2*).

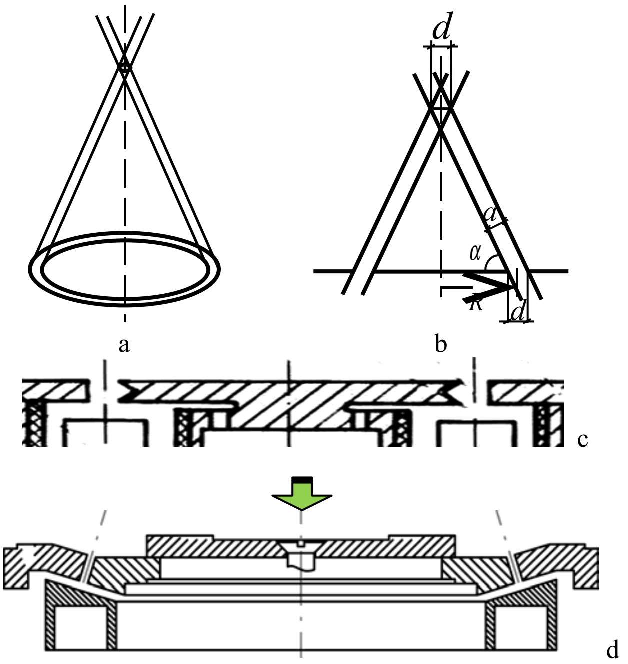

Fig. 1. Model of the beam ballistic focusing (a), its geometric parameters (b), original hardware (c), developed hardware (d)

Minimum diameter of the beam in the plane of crossover obtained due to the utilization of ballistic focusing reached *1.5 cm*. Thus the ballistic focusing itself does not produce ideal cone-like beam in Hall source (Fig. 2).

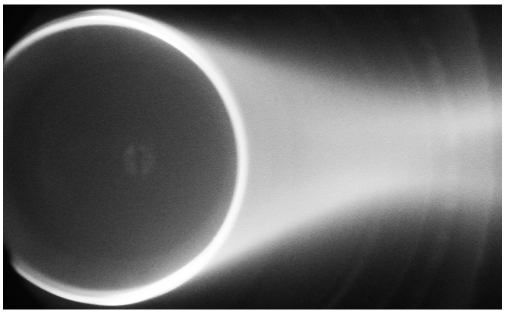

Fig.2. Conditions of weak magnetic field and high discharge voltage

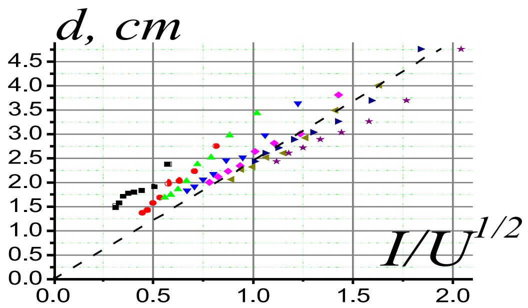

Fig.3. The beam internal diameter in the plane of crossover versus the electric current in the coils of the source magnetic system and the discharge voltage

3. ESTIMATION OF ION DYNAMICS

Stages of ion motion in the system were considered. Ion produced in the discharge gap finds itself in the gap of the magnetic circuit with the velocity caused by the discharge voltage. In the gap of the magnetic circuit, the ion moves in the transversal radial magnetic field (Fig.4)

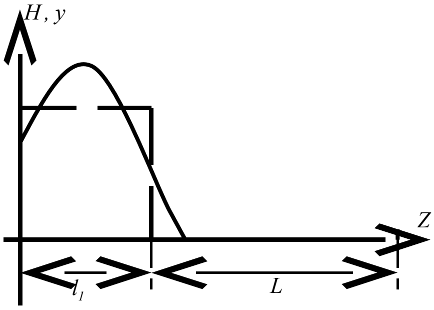

Fig.4. Qualitative distribution of the magnetic field strength in the Hall source

and gets azimuthal acceleration caused by Lorentz force. After leaving the zone where the magnetic field exists, the ion keeps the transverse velocity that can prevent successful ion flow convergence. Typical length of the magnetic field zone is $l_1 \approx 2$ *cm* and Larmor radius is $\rho_L = 10$ *cm*. Note that

$$\rho_L >> l_1. \tag{2}$$

Overall deviation of the ion trajectory from the point of focus is given by the following expression:

$$y_\Sigma = \frac{\omega_{Hi} l_1^2}{2\upsilon_Z} + \frac{\omega_{Hi} l_1 L}{\upsilon_Z} = \frac{l_1 L}{\rho_L} \sim \frac{H}{\sqrt{U}}. \tag{3}$$

The expression (3) shows the main problem, viz, the transversal pulse obtained by the ion at the short distance l_1 retains the same at the long distance L. To improve the focusing, it was proposed to compensate the transversal pulse by the magnetic field of opposite direction (sign), i.e. to use the magnetic system with reversible magnetic field in the Hall ion source (Fig.5). In this case, after leaving the zone of the magnetic field the beam has the deviation along y:

$$y(l_2) = \frac{\omega_{Hi1} l_1^2}{2\upsilon_Z} + \omega_{Hi1} l_1 \frac{l_2}{\upsilon_Z} - \frac{\omega_{Hi2} l_2^2}{2\upsilon_Z}. \tag{4}$$

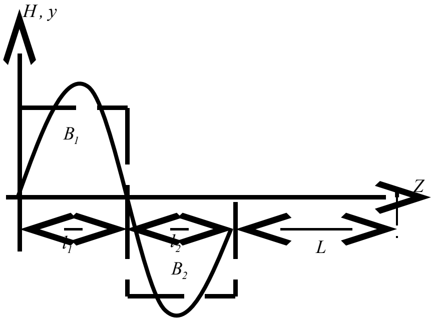

Fig.5. Qualitative distribution of the magnetic field strength in the reversible system

For our purposes, it would be ideally if $\upsilon_{y2}(l_2)=0$, i.e. $\omega_{Hi1} l_1 = \omega_{Hi2} l_2$. From physical point of view this means the equality of magnetic fluxes, i.e. symmetric reversible magnetic configuration. In this case the beam deviation takes the form:

$$y(l_2) = \frac{\omega_{Hi1} l_1 l_2}{\upsilon_Z} = \frac{l_1 l_2}{\rho_{L1}}. \tag{5}$$

To get maximum focusing of the ion beam one needs minimum typical lengths of the zones of the reversible magnetic field.

4. HALL SOURCE WITH REVERSIBLE MAGNETIC SYSTEM AND BALLISTIC FOCUSING OF ION BEAM

Design of the source with both ballistic and magnetic focusing is presented in the Fig.6.

Calculations of the ion deviation from the ballistic trajectory for the conditions of our experiment (Fig.7) give *0,1 cm*. We succeeded in reaching the best results in focusing the ion beam in the case of optimal magnetic field in the coils. For our steady magnets which produce the reversible magnetic field *I(coil)=0.4 A* and the highest discharge voltage $U_{dischrge}=6$ *kV*.

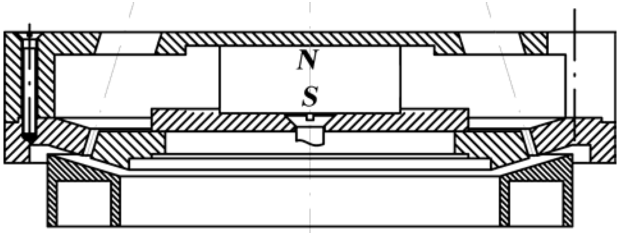

Fig.6. Hall ion source with ballistic and magnetic beam focusing

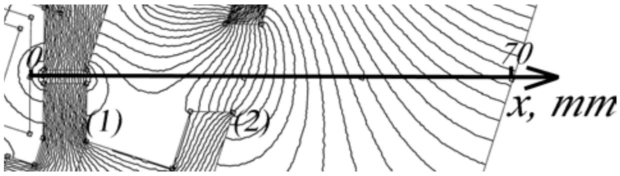

Fig.7. Ion trajectory along which the magnetic field strength distribution was found. In the figure:
(1) – first magnetic circuit for ballistic focusing,
(2) – second magnetic circuit for magnetic focusing

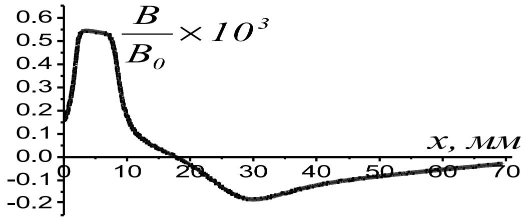

Fig. 8

The magnetic field distribution along the ion trajectory is presented in Fig. 8.

For such limiting conditions the ion beam has internal diameter in the plane of crossover less than the width of the Hall source gap. (Fig. 9) For the parameters of high discharge voltage and low current magnetic field coil the coefficient of compression is equal $G_J=33$ and the power density is equal $P=21\ MW/m^2$.

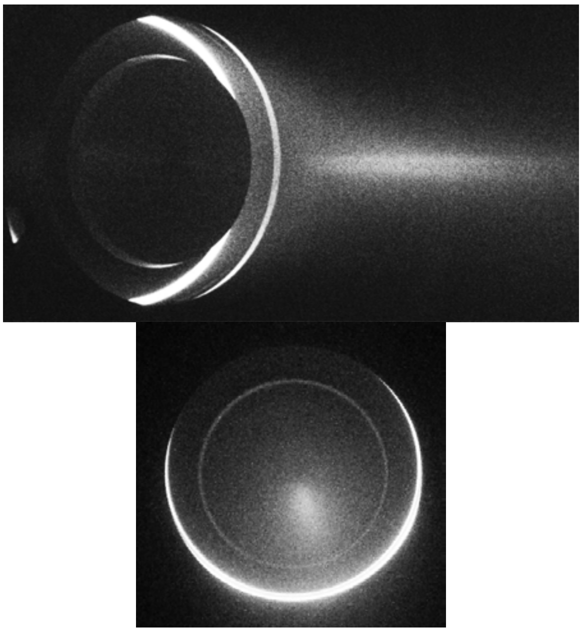

Fig.9.

The dependence of the ion beam internal diameter in the plane of crossover on the given variable is presented in the Fig.10. With taking into account the saturation of the magnetic circuit this curve corresponds to theoretical predictions good.

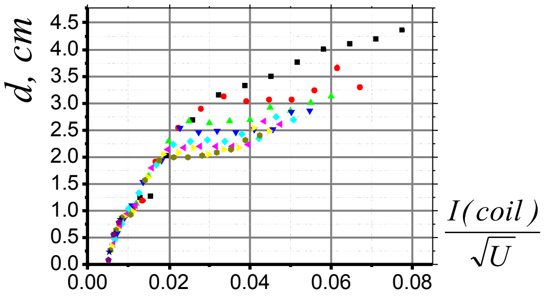

Fig. 10

CONCLUSIONS

In this paper, it is shown both experimentally and theoretically, that eigen magnetic field of the annular Hall ion source prevents the ballistic formation of the cone beam with high density of the current in the plane of crossover.

Reversible magnetic system is proposed and studied both theoretically and experimentally for Hall source with ballistic focusing of ion beam. Joint utilization of ballistic and reversible magnetic focusing of ion beam is shown to allow reaching the compression of ion annular beam with the thickness of *2 mm* from initial diameter *100 mm* to the circle with internal diameter about *1 mm* in the plane of crossover.

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ХОЛЛОВСКИЙ ИСТОЧНИК ИОНОВ С БАЛЛИСТИЧЕСКОЙ И МАГНИТНОЙ ФОКУСИРОВКОЙ ПУЧКА

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Предложена, теоретически и экспериментально исследована реверсивная магнитная система для холловского источника с баллистической фокусировкой ионного пучка. Показано, что совместное применение баллистической и реверсивной магнитной фокусировки ионного пучка позволяет достичь компрессии ионного пучка с начального диаметра *100 мм* до диаметра в плоскости кроссовера *1 мм*.

ХОЛІВСЬКЕ ДЖЕРЕЛО ІОНІВ З БАЛІСТИЧНИМ І МАГНІТНИМ ФОКУСУВАННЯМ ПУЧКА

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Запропоновано, теоретично й експериментально досліджено реверсивну магнітну систему для холівського джерела з балістичним фокусуванням іонного пучка. Показано, що одночасне застосування балістичного й реверсивного магнітного фокусування іонного пучка дозволяє досягти компресії іонного пучка з початкового діаметра *100 мм* до діаметра в площині кросовера *1 мм*.