EXPERIMENTAL INVESTIGATION OF THE CURRENT PLASMA LENS IN THE NON-UNIFORM MAGNETIC FIELD

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1. INTRODUCTION

In our previous studies the focusing electromagnetic fields created by the coaxial plasma gun during injection of plasma into the magnetic field of the short solenoid has been investigated [1, 2]. In this processes, besides radial electric fields that can arise in plasma, the azimuthal magnetic field of the longitudinal current (passing through the plasma due to discharge of the capacitor battery) can focuse the 5 MeV energy proton beam. The ion focusing by the uniform (along the radius and length) current lens was investigated elsewhere (e.g., [3]). In this work the more complicated, strongly non-uniform (in z-direction) case is considered when parameters of the focusing channel (the current channel radius, current density, focusing azimuthal magnetic field) are changed sufficiently on the focusing distance by the external magnetic field. Theoretically the problem is being solved in details in Ref. [4]. In this work the numerical calculations and experimental investigations are presented.

2. CALCULATIONS OF ION FOCUSING IN THE NON-UNIFORM CASE

We consider the problem of ion beam focusing by an azimuthal magnetic field of longitudinal current in plasma where the current radius is determined by the external non-uniform longitudinal magnetic field. It is supposed that in the strong magnetic field the electrons, which transport the current in plasma, are moving along cylindrical magnetic surfaces enclosed one into another. If the current density is homogeneous in the current channel cross-section, the equation of the focusing ions' trajectories has the form [4]:

$$r'' + k^2 \frac{B_z(z)}{B_z(0)} r = 0 , \quad k^2 = \frac{2IZe}{Mc^2 v b^2} , \qquad (1)$$

where I is the current in plasma, Ze and M are the charge and mass of the ion, c is the light velocity, v is the ion velocity. For our «Plasma lens» installation (see below) the relation (1) is defined for the short magnetic solenoid, with $B_z(0)$ at the plasma gun outlet. The other boundary conditions are defined as it follows: at z=0, $a(0) = b$, where b is the radius of an electrode that supply the current in the plasma (in this case, it is the inner electrode of the plasma gun). Particularly, in approximation of thin solenoid with radius R and coordinates of the ends z_1 and z_2 , we can substitute in (1):

$$\frac{B_z(z)}{B_z(0)} = \frac{(z_2 - z)(R^2 + (z_2 - z)^2)^{-0.5} - (z_1 - z)(R^2 + (z_1 - z)^2)^{-0.5}}{z_2 (R^2 + z_2{}^2)^{-0.5} - z_1 (R^2 + z_1{}^2)^{-0.5}}$$

During the ion focusing and compression of the current channel in the plasma by the magnetic field of the short solenoid, some ions (with large injection radius) can move partly out of the current channel. They also deflected to the axis but not get to the common focus. The moving equation for them has the form of Eq. (8) in Ref. [4]. The example of calculated ion trajectories is presented below in comparison with experimental results (see Fig.6).

To put together all ions in the focus, it is needed the optimization of the external magnetic field distribution. For this aim we have determined the form of the magnetic surface that limit the current channel. Then we have calculated the parameters of the solenoid (for producing such magnetic surface) and determined the focusing ion trajectories.

For the outer ion that defined the "boundary" magnetic surface (*ms*), the motion equation have the form of Eq. (8) in Ref.[4] for $r = r_{ms} \equiv R$. This equation has been solved by the Runge – Kutta method. As a result, the function $r_{ms}(z)$ defining the magnetic surface on the uniform mesh have been found. At the boundary conditions $H_{z0}(0)$ = 200 Oe, $r_{ms}(0)$ = 1 cm, the distribution of the longitudinal magnetic field on the axis have been found for our experimental parameters (see Fig.1).

With the help of A.N.Tikhonov regularization method [5, 6], the parameters of the solenoid have been calculated, and the required magnetic field is formed (see Fig.1, curve 2).

The trajectories of the focusing protons propagating inside the current channel are described by the Eq. (1) with the optimized magnetic field. The results of the protons focusing simulation are represented on Fig.2. By the bold line the current channel boundary is marked that formed by the calculated non-uniform solenoid. The vertical line at z=z_c represents the position of the "cathode" (e.g., wire mesh) of the current in the plasma. Whereas in this case, the protons are moving inside the channel with uniform (along the radius) density current, all of them are focusing at the same point.

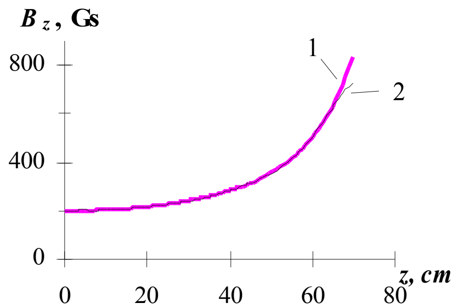

Fig.1. The distribution of the external magnetic field (1 is the required field, 2 is the field formed by the optimized solenoid).

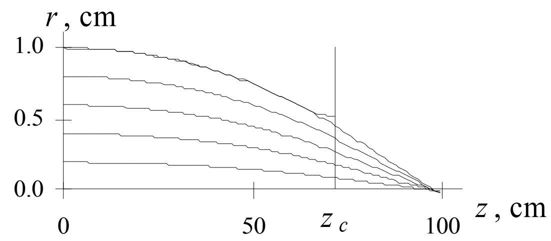

Fig. 2. The trajectories of the focused protons in the optimized magnetic field.

3. PLASMA LENS INSTALLATION AND ACCELERATOR "URAL-5"

The stand of plasma lens (Fig.3) consists of coaxial plasma gun (4) with electrodes of length 40 cm, diameter 3 cm and 7 cm. Inner electrode is tubular with hole of 2.5 cm diameter, through which the proton beam of 5 MeV energy entered into the plasma lens chamber. This chamber is a glass tube of 70 cm length and 10 cm diameter. Around the tube the short solenoid (9) was mounted. Its length is 19 cm, inner diameter is 15 cm. Magnetic field can be changed up to 1 kOe. The plasma gun was supplied by capacity battery of 30 μF, charged up to 10 kV. The gas (hydrogen) filled the space of the gun by means of pulse electromagnetic gas valve (5). The plasma temperature T_e~1-3 eV was measured by broadening of spectral lines of hydrogen H_β and H_γ due to Stark effect.

For the gun voltage 4÷8 kV the plasma flow velocity was changed from $v = 6\cdot10^6$ cm/s to 10^7 cm/s. Optimal quantity of injected gas was V~2-3 cm^3. The plasma density achieved the value n_p~10^{16} cm^{-3} and decreased to n_p~10^{11} during 100-200 μs.

The proton accelerator «Ural-5» is one among first accelerators with high frequency quadruple focusing (RFQ) proposed by I.M. Kapchinskii and V.A. Teplyakov (e.g., see [7,8]). For successful working with the plasma lens, the «Ural-5» was subjected to special modernization in order to improve its parameters and increase reliability and stability of working.

The accelerator consist of the following main parts (see Fig.3): 1 - the proton injector unit (energy is 100 keV, proton current is of order of 100 mA, pulse duration is 50 μs); 2 - the initial part of the accelerator (energy is 700 keV, proton current is about 100 mA, pulse duration is 30 μs); 3 - the final (exit) part of the accelerator (energy is 5 MeV, proton current is up to 30mA, pulse duration is 30μs); 10 - RF power amplifiers (RF power is about 1 MW, pulse duration is 100μs).

4. EXPERIMENTS ON 5 MEV PROTON BEAM FOCUSING

In addition to the experiments of Ref.[1], measurements of the azimuthal magnetic fields in the plasma along the radius of the interaction chamber in the cross-sections at the distance 42 cm from the plasma gun outlet were performed by the magnetic probe of diameter 3 mm. It was introduced into the chamber by means of glass tube of diameter 5 mm that allowed one to displace the probe in the cross-section. The results are given in Fig.4. As one can see from the measurements, for the solenoid switching on, the current channel radius is ≈ 1 cm and azimuthal magnetic field ≈ 270 Gs; for the solenoid switching off, the current channel radius is ≈ 2 cm and azimuthal magnetic field ≈ 115 Gs.

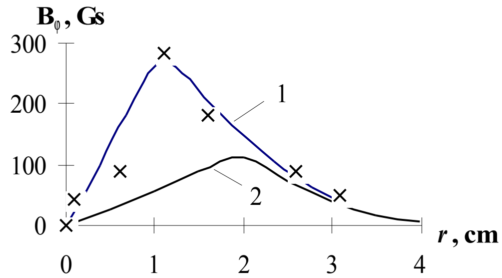

Fig.4. Distributions of the azimuthal magnetic field along the radius (curve 1 or 2 corresponds to the solenoid switching on or off).

The experiments on focusing were carried out by measuring of the diameter of the 5 MeV proton beam passing through the plasma at various time moments respectively to the start of the discharge in the plasma gun. The measurements were performed by using luminescence screen, made from polystyrene plate of thickness 8 mm and diameter 6 cm. The screen was placed at the distance 90 cm from the plasma gun outlet. To avoid the plasma lightning, it was closed by thin aluminum foil of thickness 12 μm transparent for protons of 5 MeV energy. In all experiments at the initial moment the central gun electrode polarity was positive. The gun electrode voltage was 6 kV. The focusing effect was observed at the time delay in

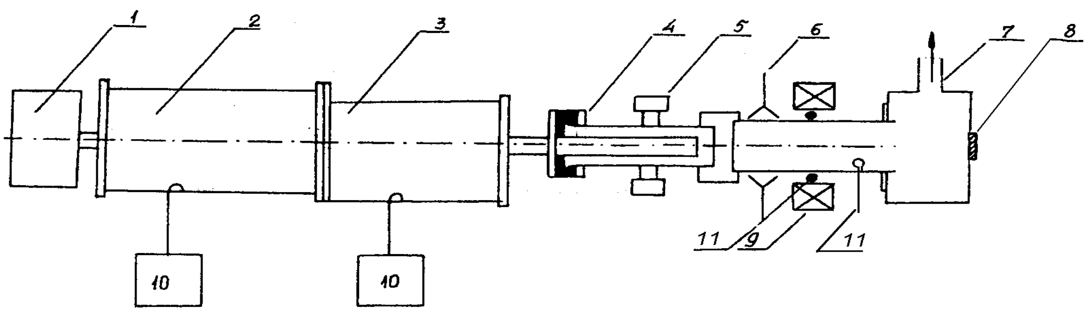

Fig.3. Scheme of the installation. (1) proton injector; (2) initial stage of accelerator; (3) final stage; (4) plasma gun; (5) gas valve; (6) horn antenna; (7) chamber; (8) luminescence screen; (9) solenoid; (10) RF sources; (11) magnetic field probes.

intervals $\tau_1 = 12$ — 16 μs and $\tau_2 = 24$ — 28 μs respectively to the gun discharge start. It was coincided with the maxima of the plasma current measured by the Rogowski coil. The focused proton beam image on the screen was registered by the digital video camera. From these measurements the mean beam radius can be determined as 0.7 cm (Fig.5, bottom). Without focusing (i.e., without plasma), this radius is equal to 2.5 cm (Fig.5, top). Using Eq. (1) and measured values of the current channel radius 1.3 cm, magnetic field 270 Gs (at z=42 cm), and initial beam divergence 0.015 rad, we compute the beam radius of 0.6 cm at the screen coordinate (see Fig.6), that agree with the experiments. In Fig.6 the upper curve (of parabola type) presents the current channel radius. The screen was at 90 cm, and the 2nd electrode of the current channel (a copper wire mesh) was at 60 cm. Protons injected at radii $r \le 0.7$ cm are focused at z=70 cm. Other protons partly go out from the current channel and not reach the focus.

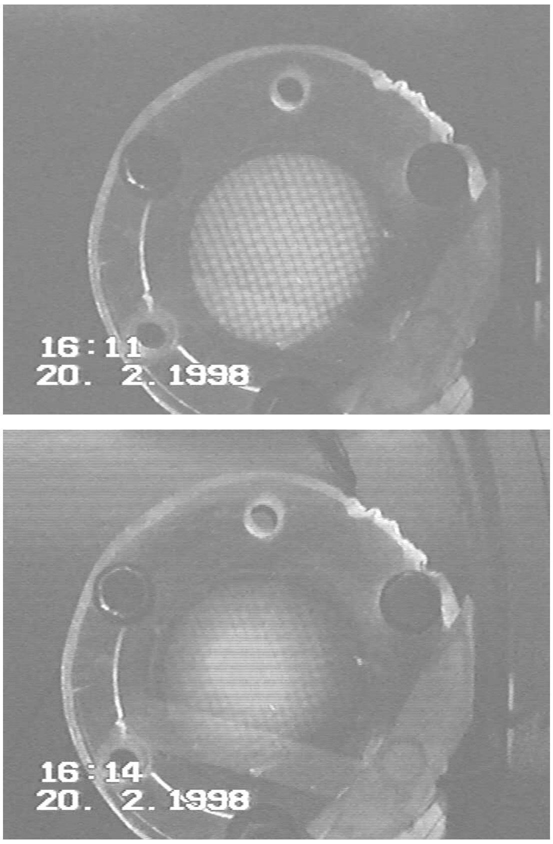

Fig.5.

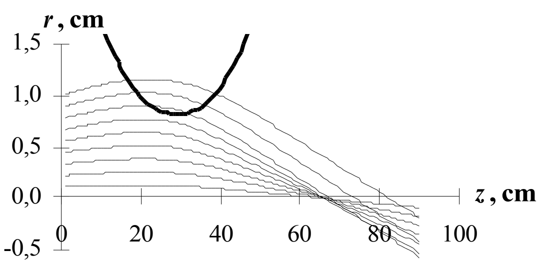

Fig.6. Simulation of the 5 MeV proton trajectories for the experimental parameters.

By analogy with Ch.2, we have calculated the solenoid for the case of divergent proton beam with small emittance. Dependence of the angular divergence versus radius was supposed as $\alpha(r) = \alpha_0 r/r_0$, where $\alpha = 0.015$ rad cooresponds to deviation of the outer protons from the axis at z = 0.

In this case, the parameters of the solenoid were determined for which the outer protons' trajectories coinside with the current channel bondary that formed by the calculated magnetic surface (see Figs. 5, 6 in [6]).

In Fig.7 are presented the proton trajectories in the current channel formed by the magnetic field of the optimized solenoid. The bold line marks the current channel bondary. The vertical line at z = 72 cm represent the position of the cathode that creates the current in the plasma. It is supposed that the cathode (a metal mesh) is transparent for the proton beam.

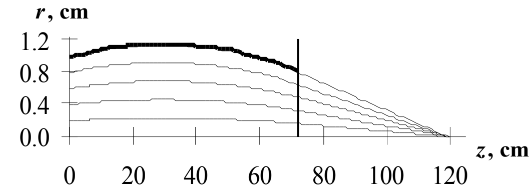

Fig.7.

Whereas the protons are moving inside the channel with uniform (along the radius) density current, all of them are focusing at the same point.

Next experimental study will be devoted to the proton focusing in the optimized magnetic field. For plasma lenses of this type the efficiency can be increased by the simultaneous decreasing of the current channel radius and the focused beam one.

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