PLASMA LENS WITH A CURRENT DENSITY DEPENDED ON EXTERNAL MAGNETIC FIELD

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Abstract

Plasma current lenses are concidered that are placed in the non-uniform (can be programmed) longitudinal magnetic field which can change the radius of the current channel, the current density, and the focusing azimuthal magnetic field. For these plasma lenses the efficiency can be increased by the simultaneous decreasing of the current channel radius and the focused beam one.

1 INTRODUCTION

In our studies the focusing electromagnetic fields created by the coaxial plasma gun during injection of plasma into the magnetic field of the short solenoid is being investigated [1,2]. In this processes, besides radial electric fields that can arise in plasma, the asimuth magnetic field of the longitudinal current passing through the plasma resulting in the discharge of the capacitors battery can focusing the 5 MeV energy proton beam. The measurements of the longitudinal current with the help of the Rogovsky coil show that its amplitude comes up to several kA that enough four explanation of the focusing if to consider the compression of the current channel in the plasma by the outer non-uniform magnetic field which is created by the short solenoid. The focusing by the uniform (along the length) current lens was investigated elsewhere (e.g.,[3]). Here more complicated non-uniform (in z-direction) case is considered.

2 CALCULATION OF FOCUSING IN NON-UNIFORM PLASMA LENSES

1.Plasma current lens with arbitrary solenoid. Let us consider the problem of ion beam focusing by an azimuth magnetic field of longitudinal current in plasma. We investigate the case in that the current radius is determined by the outer nonhomogeneous longitudinal magnetic field. The problem is being solved at the paraxial approximation. In this case the equation of the magnetic surfaces is as follows:

$$a^2(z) = \frac{a^2(0)B_z(0)}{B_z(z)} \qquad (1)$$

where $a(z)$ is variable radius of the magnetic surface, $B_z(z)$ is longitudinal magnetic field on the axis, $B_z(0)$ and $a(0)$ are determined by the boundary conditions at $z = 0$.

We assume that in the case of the strong magnetic field the electrons which transport the current in plasma are moving along cylindrical magnetic surfaces enclosed one into another. The 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 (e.g., it is the inner electrode of the plasma gun). From Eq.(1) it is follows: if the equidistance of the magnetic surfaces is set in some cross-section, so it conserves in any other one. As a result, if the current density is homogeneous in the electron emitter region, so it will be homogeneous in any other current channel cross-section. It is necessary (and, as a rule, sufficiently) for a good ion focusing without spherical aberration. The equation of the focusing ions trajectories has the form:

$$r'' + k^2 \frac{B_z(z)}{B_z(0)} r = 0, \quad k^2 = \frac{2I\,Ze}{Mc^2 vb^2} \qquad (2)$$

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 $\dfrac{B_z(z)}{B_z(0)}$ is defined from the specific parameters of the magnetic system, i.e. the short magnetic solenoid; $B_z(0)$ is the magnetic field induction in the region of the plasma gun face.

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:

$$r'' + \frac{\kappa}{r} = 0, \quad \kappa = \frac{2ZeI}{c^2 Mv} \qquad (3)$$

The example of computations of the 5 MeV proton trajectories is presented below, comparing with the experiments.

2.Plasma current lens with the optimized solenoid. To put together all ions in the focus, it is needed the optimization of the outer 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 ions trajectories.

The calculation have been carried out for paraxial ion trajectories and paraxial magnetic surfaces. For the outer ion that defined the "boundary" magnetic surface (*ms*), the motion equation have the form (3) for $r = r_{ms}$.

This equation have 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. From the relation for paraxial magnetic surface (1) 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 parameters of our experiments (see Fig.1).
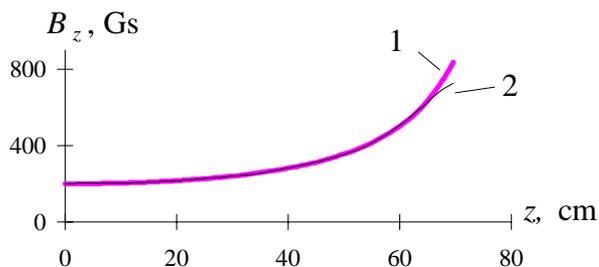
Fig.1. The distribution of the outer magnetic field (1 is the required field, 2 is the field formed by the optimized solenoid).

With the help of the A.N.Tikhonov regularization method [4], the parameters of the solenoid have been successfully 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. (2) were $b=r_{ms}(0)=1$ cm.

The results of the protons focusing simulation are represented on Fig.2. By the bold line the current channel boundary is painted that formed by the calculated non-uniform solenoid. The vertical line at $z=z_c$ represents the position of the "cathode" 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.
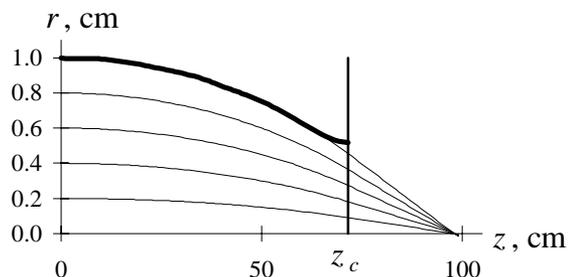
Fig. 2. The trajectories of the focused protons.

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 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 \sim$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 = $6 \cdot 10^6$ cm/s to 10^7 cm/s. Opimal quantity of injected gas was V~2-3 cm³. The plasma density achieved the value $n_p \sim 10^{16}$ cm⁻³ and decreased to $n_p \sim 10^{11}$ 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.
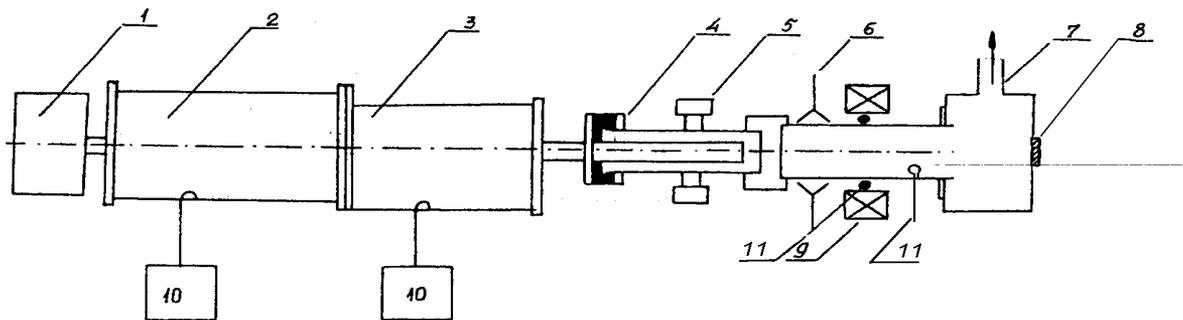
Fig.3. Scheme of the installation. (1) proton injector; (2) initial stage of accelerator; (3) final stage; (4) plasma gun; (5) gas valve; (6) horn antenna; (7) chamber; (8) luminescence screen; (9) solenoid; (10) RF sources; (11) magnetic field probes.

Teplyakov (e.g., see [5,6]). 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); 3 - the initial part of the accelerator (energy is 700 keV, proton current is about 100 mA, pulse duration is 30 μs); 4 - 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 Refs.[1,2], measurements of the azimuth 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 face 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 to displace the probe in the cross-section. The results are given in Fig.4. As one can see from the measurements, at the solenoid switching on (off), the current channel radius is ≈ 1 cm (2 cm) and magnetic field ≈ 270 Gs (115 Gs).
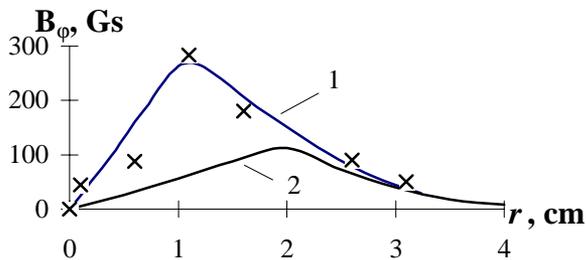
Fig.4. Distributions of the azimuth magnetic field along the radius (curve 1 or 2 corresponds to the solenoid switching on or off).

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 face. 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 intervals $\tau_1 = 12$ 16   μs and $\tau_2 =$

24   28 μs respectively to the gun discharge start. It was coincided with the maximima of the plasma current measured by the Rogovsky 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. Without focusing, this radius is equal to 2.5 cm. Using Eqs. (1,2) and measured values of the current channel radius 1.3cm, magnetic field 270 Gs, and initial beam divergence 0.015 rad, we compute the beam radius of 0.6 cm at the screen coordinate (see Fig.5), that agree with the experiments.
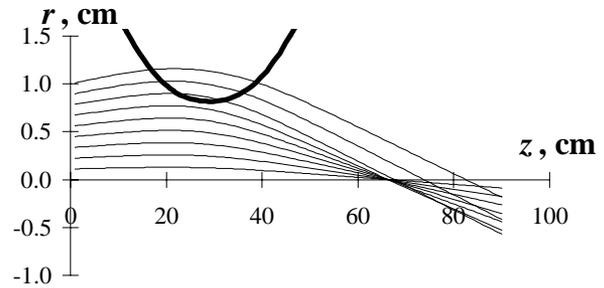
Fig.5. Simulation of the 5 MeV proton trajectories for the experimental parameters.

In Fig.5 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 gauze) was at 60 cm. Protons injected at $r \leq 0.7$ cm are focused at z=70 cm. Other protons partly go out from the current channel and not reach the focus. 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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