ION BEAM FOCUSING BY PLASMA GUN

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Abstract

Focusing of proton beam of energy 5 MeV, current 10 mA, pulse duration 30 μs, obtained on the accelerator «Ural-5» by means of plasma has been investigated. The parameters of the plasma flow produced by a coaxial plasma gun are the followings: plasma density 10^{11}-10^{15} cm^{-3}, temperature 1-3 eV, velocity 10^7 cm/s, time duration 500 μs. Magnetic field value of a short coil is 500-1000 Oe. The focusing coefficient of compression up to 10 times at the length 30 cm is obtained. The dependence of ion beam size upon various parameters of the plasma lens is investigated. Theoretically several models of ion beam focusing in the plasma have been considered.

1 THEORY

1.1 Polarization model

The excitation of low frequency waves in current-carrying plasma in external electrical field and trapping of plasma electrons by the waves have been investigated. The electrons propagate along the magnetic field lines of the coil. It leads to the appearance of radial plasma polarization and to excitation of radial electric field which can focus ion beam.

1.2 HF-plasma lens

The possibility of HF plasma lens creating has been considered[1]. The ion beam excites potential oscillations in the region of an inhomogeneous plasma. If the frequency of unstable oscillations is lower than the cyclotron electron frequency and higher than the ion cyclotron frequency then the ponderomotive forces acting on electrons and ions have the opposite signs. The localization of HF oscillations forms the potential well for electrons in which the excess of an electron space charge is accumulated. As a result the plasma configuration is created with the large value of the radial electric field that causes proton beam focusing.

1.3 Plasmaoptics model.

The plasma lens model proposed by Morozov [2] is considered. We assumed that the potential of gun electrodes is transferred along the external magnetic field lines in plasma. The numerical simulation of proton motion has been carried out for the case when at the entrance of plasma lens potential is proportional to the square of radius. The parameters of proton beam and plasma lens are the following: the potential on axis of plasma lens is -4 kV, proton energy is 5 MeV, beam radius is 1 cm, the length of cylindrical solenoid is 19 cm, inside and outside radius are 8 cm and 16.5 cm accordingly, the distance from proton gun to the solenoid is 24 cm. It is shown that the proton beam is focused without aberration at the distance 69 cm.

1.4 Electron ring model

Ion beam focusing by the electron ring(cloud) with uncompensated electron space charge [3].The possibility of the electron selfconsistent ring creating in the inhomogeneous magnetic field has been considered. Azimuthal currents are induced in the plasma bunch that enters into the region of the axially-symmetric magnetic field under the coil. Resulting magnetic field distribution can be of the magnetic mirror configuration type. Electrons are captured by the magnetic trap while ions cannot be retained in it. It has been estimated that the radial electric field strength can be sufficient for high energy proton beam focusing.

1.5 Pinch current model

Proton beam focusing by the azimuthal magnetic field of currents carried out from the plasma gun. The azimuthal magnetic field with the linear dependence of its strength on the radius is suitable for high energy ion beam focusing. Such a distribution of the magnetic field can arise in the compression region of the plasma stream injected from the plasma gun [2]. In this region the plasma configuration becomes extended along z-axis and acquires the almost cylindrical form. Its mean radius $\bar{r}$ increases due to the diffusion processes:

$$\bar{r}^2 \sim \frac{c^2}{4\pi\sigma} t \qquad (1)$$

where σ is the plasma conductivity. The linear dependence of H_φ on the radius r takes place at r<$\bar{r}$. For $\bar{r}$ ~1 cm and T_e~20 eV the time of the diffusion spreading is of the order of 2 μs. It should be noted that one of the edges of the pinch plasma formation is connected with the central electrode of the plasma gun and another one moves along the chamber with the characteristic velocity

$$V_z \approx \frac{cH_\varphi}{enr} \qquad (2)$$

where n is the plasma density. For H_φ~1 kOe, r=1 cm and $n=10^{15}$ cm^{-3} we get the estimate $V_z \approx 5 \cdot 10^6$ cm/s.

Taking into account that the compressed plasma formation has almost cylindrical form we can apply the expression for the focal length of the short lens

$$F = \frac{l}{\xi^2} \qquad (3)$$

where $\xi = \frac{\Omega l}{v_0}, \Omega = \left(\frac{eH_\varphi(r) v_0}{m_p cr} \right)^{1/2}$. Assuming that the characteristic longitudinal dimension l of the region with currents is about 10 cm and $j_z \approx 0{,}5$ kA/cm^2, $v_0 = 3 \cdot 10^9$ cm/s we get the focal distance F≈100 cm.

Parameters of the compressed plasma formation can depend on the longitudinal coordinate z. In this case we can use the momentum approximation to derive following expression for the focal distance

$$F = \frac{m_p v_0 c^2}{2\pi e \int_{z_1}^{z_2} j_z^{(0)}(z) dz} \qquad (4)$$

where the integration of the longitudinal current density $j_z^{(0)}(z)$ is carried out over the interval of z where the compressed plasma is localized.

2 EXPEIMENTAL SET-UP

2.1 Proton accelerator

The proton accelerator «Ural-5» is one among first high frequency quadrupole focusing (RFQ) proposed by I.M.Kapchinskii and V.A.Teplyakov. For successful working with the plasma lens, the accelerator «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: 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 30 µs); 4-RF power amplifiers (RF power is about 1 MW, pulse duration is 100 µs).

2.2 Plasma lens device

The stand of the plasma lens consists of a coaxial plasma gun with electrodes: length 40 cm, diameters 3cm and 7 cm. The inner electrode is tubular with a hole of 2.5 cm diameter, through which a proton beam of 5 MeV energy enters into the plasma lens chamber. The chamber is a glass tube of 1 m length and 10 cm diameter. Around the tube, the coil of the magnetic field was mounted. Its length is 15 cm, and the inner diameter is 15 cm. The magnetic field can be changed from 200 to 800 Oe. The plasma gun was supplied by a capacitance battery of 30 µF, charged to 10 kV. The gas (hydrogen) filled the space of the gun by means of a pulse electromagnetic gas valve. The volume of gas, injected into the gun was 1-3 cm^3.

3 EXPERIMENTAL RESULTS

The possibility of proton beam focusing with energy 5 MeV and current 20 mA by currents produced by the coaxial plasma gun (CPG) has been investigated experimentally.

It is known that the dense plasma formation with finite dimensions are formed near the electrodes of CPG out of it due to azimuthal magnetic field B_φ generated by currents produced during discharge of battery. The hollow internal electrode is used for proton beam injection into the plasma formation. This leads to the certain structure of the plasma near the gun mouth. Namely the plasma is similar to hollow cylinder and on the distance larger than 4 cm from the end of the gun the plasma is similar to continuous cylinder. The magnetic field B_φ in dependence on voltage on the electrodes can reach up to $2kG$. Magnetic field radial distribution at the distance 4 cm from the gun mouth, measured by a small magnetic probe of diameter 3 mm, is shown in Fig.1. The voltage on the electrodes of the gun is 6 kV.

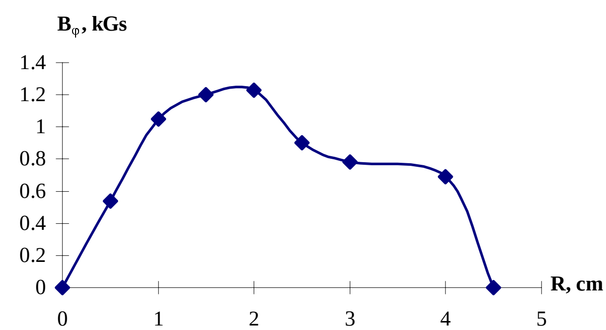

Figure 1: The distribution of azimuthal magnetic field B_φ on radius $(U_n = 6\,kV,\ l = 4\,cm)$.

Ion beam current with plasma and without one was measured by Faraday cup of diameter 1.7 cm and by luminescent screen placed at the distance 40 cm from the gun mouth. Oscillograms of the beam current, obtained by Faraday cup, and transverse dimension of the beam on dependence of the voltage on the gun electrodes, obtained from the screen, are represented in Fig. 2. It has been determined from the photo that the efficiency of proton beam focusing, determined by ratio of beam diameter without plasma d_1 and after passing through the plasma d_2, was equal $k = d_1/d_2 \cong 10$ (at the voltage on the gun electrodes equals $U_n = 9\,kV$.

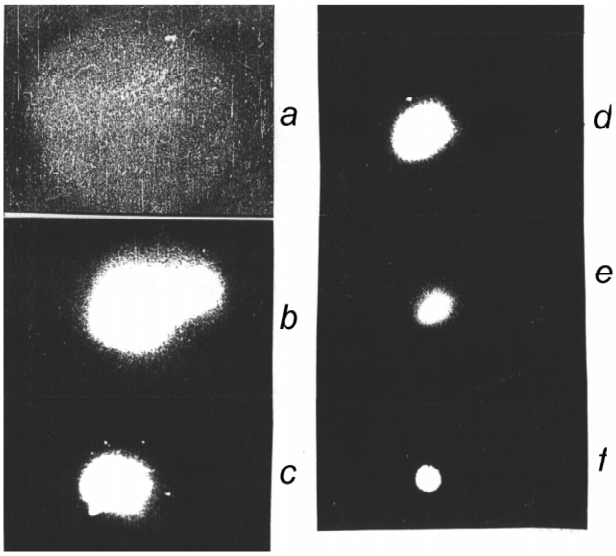

Figure 2: The transversal beam dimension in dependence on the voltage on the electrodes of CPG: a - without plasma; b - $U_n = \mathbf{5}\,kV$; c - $U_n = \mathbf{6}\,kV$; d - $U_n = \mathbf{7}\,kV$; e - $U_n = \mathbf{8}\,kV$; f - $U_n = \mathbf{9}\,kV$

Trajectories of focused protons, calculated on the computer, are shown on Fig. 3. The proton beam is focused by azimuthal magnetic field of CPG currents. In the region of beam injection its protons are distributed on radius homogeneously. The trajectories have been calculated with taking into account the fact that near the gun mouth and near the end of the plasma the current distribution is similar to hollow cylinder with internal radius which depends on longitudinal coordinate.

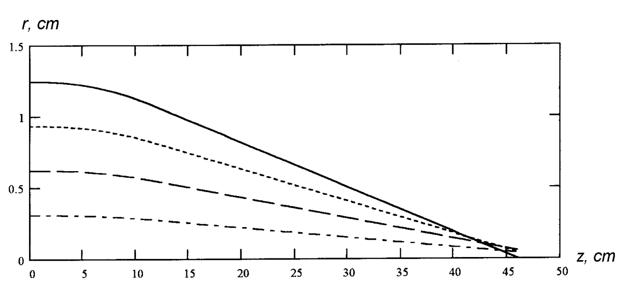

Figure 3: Trajectories of focused protons calculated on the computer

The calculated focusing distance is longer than the length of the plasma approximately 4 times. The results of calculations have shown that trajectories are not crossed in one point due to mentioned above current distribution. The smallest radial dimension of focused beam is smaller than 0.1 R_o. R_o is the initial beam radius.

4 CONCLUSION

The theoretical and experimental investigations presented above have shown that the main mechanism of 5 MeV proton beam focusing with plasma gun is due to the azimutal magnetic field of current-carrying plasma. The regulation of the plasma gun parameters permit to use this mechanism for effective focusing of high energy ion beam.

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REFERENCES

[1] I.N. Onishchenko, A.B. Kitsenko, HF Plasma Lens. Bulletin of the APS. May 1997, Vol. 42, p. 1256. Plasma Acceleration Conference, Canada, Vancouver, report 4V 43, 1997.

[2] A.I. Morozov, L.S. Solovjev, Statsionarnie techeniya plasmy v magnitnom pole. -Voprosy teorii plasmy. Sb. statey. Vyp. 8. Pod red. acad. M.A, Leontovicha. - M.: Atomizdat, 1974, p. 3-87.

[3] B.I. Ivanov, A.B. Kitsenko, V.I. Maslov, I.N. Onishcenko,- VANT, ser.: Yaderno-Fisicheskie issledovaniya, 1997, N 4, 5 (31, 32), p. 111-113.