UDC 533.9

INTENSE PROTON BEAM FOCUSING BY PLASMA LENS

V. Belan, V. Butenko, B. Ivanov, V. Kiselev, A. Kitsenko, A. Linnik, V. Maslov,
I. Onishchenko, V. Ognivenko, V. Prishchepov, and A. Yegorov
National Science Center "Kharkov Institute of Physics & Technology"

1. Introduction

Plasma is an attractive object for using as a plasma lens to focus efficiently electron and ion beams. Due to the compensation of space charge, the high intensity electric and/or magnetic fields arising in plasma at charge polarization and/or current passage plasma lens (PL) provides high luminosity beams at the target in high energy physics, high current and large focusing force for the technological ion beams.

For the ultrarelativistic electron bunch when space charge repulsion is compensated by magnetic compression (γ^2 times, γ is relativistic factor) the "passive" PL is elaborated. If beam rise time is more than plasma response ($\tau_b > \omega_p^{-1}$) the focusing processes is mainly concluded to charge neutralization in overdense plasma ($n_p > n_b$) or underdense ($n_p < n_b$). If beam rise time is less than plasma response ($\tau_b < \omega_p^{-1}$) the focusing processes is predominantly provided by plasma wake-field excited in plasma by moving relativistic bunch. So for the SLAC electron bunch with parameters: charge 1 nC, longitudinal size 1.2 mm, radial size 2 μm the focusing gradient is 250 MG/cm, four orders more of the conventional lens. In the future TeV colliders extremely small spot sizes (1nm×200nm) are required at the interaction point [1]. This goal can be achieved only with PL focusing. PL is also considering as a possible focusing tool in the nuclear microprobe development [2]. Ion beams use for scientific and technological goals involves their focusing and transportation. For this some non-traditional schemes of ion focusing with plasma were considered [3-9]. For the ion beam of moderate energy applied in material modification and semiconductor technology the electric field of electron cloud [3] or charged plasma in magnetic field with electrodes for the electric potential tapering [4-7] are used. The focusing gradient is about several hundreds G/m. In nuclear physics and inertial fusion plasma current lenses are used for high-energy heavy ion beams focusing. Their focusing gradient of order several tens kG/cm is achieved due to the azimuth magnetic field of the longitudinal current in plasma [8-10].

In the present work theoretical and experimental investigations of the high-energy intense ion beam by means of PL have been carried out. Some aspects of this problem have been considered and published elsewhere [11-14]. In Sec. 2 the possible models of PL related to the experiment are considered. Theoretical study and macroparticles simulation was performed to evaluate the focusing properties of the plasma injected from plasma gun into the external magnetic field. The role of the electric and magnetic fields excited in the plasma column on the focusing processes were considered. The influences of HF instabilities and polarization phenomena on ion focusing were estimated. In Sec. 3 the experimental setup and applied diagnostics is described. Proton beam of 5 MeV energy, 100 mA current, and 30 μsec time duration was produced at the proton accelerator "Ural-5" with radio frequency quadruple (RFQ) radial-phase focusing. PL consisted of a coaxial plasma gun for plasma column formation and a short coil for nonuniform magnetic field creation. The parameters of the plasma flow were the followings: plasma density 10^{11} – 10^{15} cm^{-3}, temperature 1 – 3 eV, velocity 10^7 cm/sec, and time duration 500 μsec. The magnetic field value of a short coil was 500 – 1000 Oe. The experimental results are represented in Sec. 4. In the performed experiments the focusing coefficient was ten times the compression at the length of 30 cm obtained. It was revealed that the main focusing effect was caused by the azimuth magnetic field of the currents carried in the plasma column. The dependencies of ion beam size upon various parameters of the PL were investigated. In Sec. 5 the results are concluded and the perspective and some applications are discussed.

2. Theoretical models of PL

The considered models are based on the physical phenomena occurred during plasma injection from plasma gun into magnetic field of the short coil. Two cases are possible. Firstly assuming the absence of any electric and/or magnetic fields in plasma it should be considered induced polarization electric fields and induced magnetic fields at the entrance of coil. Besides due to the HF-frequency instability of ion beam moving in plasma the separation of electrons and ions can lead to electric field arising. In the second case we should consider the focusing role of electric and magnetic fields originating just in the plasma gun or magnetic field of the electric current in plasma from the gun to the collector. Because the magnetic focusing is closer to the experiment results it is represented in details while the other mechanisms are discussed shortly.

2.1 Proton beam focusing by magnetic fields of plasma currents

Focusing by means of the azimuth magnetic field of plasma stream currents

It has been found experimentally that longitudinal currents of the order of some hundreds amperes can arise in the plasma stream produced by a coaxial plasma gun and then used for 5 MeV proton beam focusing. Below we shall discuss the possibility of proton beam focusing by the azimuth magnetic field of such a current. Azimuth magnetic field that is linear respect to the radius can be successfully used for high-energy ion beam focusing [10]. The formula for the focal length f of the PL with the longitudinal current density j_z has been derived in the paper [15]:

$$f = \frac{1}{\sqrt{K}\,\sin\left(\sqrt{K}\,l\right)} \qquad (1)$$

where $K = e\mu_0 j / 2p$, p is the proton momentum, l is the PL length (the system of the units SI is used in the expression (1)). The focal length in the relation (1) is counted from the main plane of the PL. We are going to investigate ion focusing inside of the plasma stream. In connection with this problem let us study the ion motion inside the plasma stream and calculate the distance from the initial point of the magnetic field region to the focus. We shall consider the azimuthally symmetric configuration where the azimuth magnetic field component is given by the expression

$$H_\varphi = \frac{2\pi}{c} j_z r \qquad (2)$$

where j_z is the constant longitudinal current density. If at the beginning of the region where H_φ is different from zero(i.e. at z = 0) the proton velocity is $V_z = V_0$ and the azimuth velocity component $V_\varphi(z = 0)$ is equal to zero then the following conservation laws are valid:

$$V_z - \frac{e\pi}{m_p c^2} j_z r^2 = V_0 , \tag{3}$$

$$V_\varphi = 0 \tag{4}$$

where e and m_p are respectively the charge and the mass of the proton. The proton distance from the system axis r is determined by the equation

$$\ddot r + \frac{2\pi \cdot e j_z}{m_p c^2} \dot z r = 0 \cdot \tag{5}$$

If $$\frac{1}{2}\omega_{c\varphi}(r) r / V_0 << 1 , \tag{6}$$

where $\omega_{c\varphi} = eH_\varphi(r)/m_p c$ then we approximately have $V_z \approx V_0$. Let us note that for 5 MeV protons we have $V_0 = 3 \cdot 10^9$cm/s. In the case when $j_z > 0$, $V_0 > 0$ and the inequality (6) is true, the equation (5) can be written in the form

$$\ddot r + \Omega^2 r = 0 , \tag{7}$$

where the radial oscillation frequency of protons is introduced

$$\Omega = \left(\frac{eH_\varphi(r) V_0}{m_p c r} \right)^{\frac{1}{2}} \tag{8}$$

Since $H_\varphi \sim r$ then the frequency Ω does not depend on the radius. It is possible to get from (7)

$$r = r_0 \cos(\Omega t) , \tag{9}$$

or $$r = r_0 \cos\left(\frac{\Omega}{V_0} z \right) \tag{10}$$

where r_0 is the initial proton radius at z = 0 (or at the initial moment t = 0 when the proton penetrates into the focusing region).

If the focusing region length is l then we get for the focal length F that is counted from the end of the focusing region

$$F = V_0 \frac{r(l)}{|\dot r(l)|} = \frac{l}{\xi \cdot tg\xi} \tag{11}$$

where $\xi = \Omega l / V_0$. The focal distance F_t being counted from the beginning of the lens is determined by the relation

$$F_t = l + F . \tag{12}$$

For the main plane coordinate of the lens $z = z_H$ we have the formula $$z_H = l\left(1 + \frac{\cos\xi - 1}{\xi \sin\xi} \right). \tag{13}$$

It is easy to see from (1), (13) and (11), (12) that obvious identity takes place: $z_H + f = F_t$.

As it can be seen from the relation (10) the proton beam will be focused inside the plasma stream if the following inequality is valid $$\frac{\Omega z_c}{V_0} > \frac{\pi}{2} , \tag{14}$$

where z_c is the plasma stream length. The minimum current density $j_z^{(min)}$ that is necessary for proton focusing at the distance z_c can be found from the relation

$$\frac{\Omega z_c}{V_0} = \frac{\pi}{2} , \tag{15}$$

so that $$j_z^{(min)} = \frac{\pi}{8} \cdot \frac{m_p c^2 V_0}{e z_c^2} . \tag{16}$$

Assuming that z_c =100 cm and $V_0 = 3 \cdot 10^9$cm/s we get from the expression (16) $j_z^{(min)} \approx 3.7 \cdot 10^{11}$ CGSE or $j_z^{(min)} \approx 120$ A/cm^2. If we put the plasma stream radius to be equal to 1cm then the minimum current value is about 390A and it allows obtaining the focal length approximately equal to 1 m.

Proton beam focusing by the azimuth magnetic field of currents carried out from the plasma gun (the short lens model)

As it has been mentioned the azimuth 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. The compressed plasma configuration has been studied theoretically and it has been shown [16] that the plasma formation becomes extended along z-axis and acquires the almost cylindrical form. Its mean radius $\bar r$ increases due to the diffusion processes:

$$\bar r^{2} \sim \frac{c^2}{4\pi\sigma} t \tag{17}$$

where σ is the plasma conductivity. The linear dependence of H_φ on the radius r takes place at $r < \bar r$. For $\bar r \sim 1$ cm and $T_e \sim 20$ eV the time of the diffusion spreading is of the order 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 $$V_z \sim \frac{cH_\varphi}{enr} \tag{18}$$

where n is the plasma density. For $H_\varphi \sim 1$ 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

$$F = \frac{l}{\xi^2} \tag{19}$$

where $\xi = \frac{\Omega l}{v_0}, \Omega = \left(\frac{eH_\varphi(r) v_0}{m_p c r} \right)^{1/2}$. 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. For the proton beam radius equal to 1cm the current value is of the order 1.5 kA that provides proton beam focusing at the distance approximately equal to 1 m. The mentioned current value is only the small part of a total current flowing to the external gun electrode. The experimental estimation of total current gives the value about 200÷300 kA.

Proton beam focusing in the inhomogeneous magnetic field, focal distance calculation in the momentum approximation

The proton beam can be focused inside the plasma system at the focal distance given by the relation

$$f = \frac{\pi}{2} \frac{v_0}{\Omega} , \tag{20}$$

where v_0 is the proton beam velocity, $\Omega = \sqrt{\frac{eB_\varphi v_0}{m_p c r}}$ and $B_\varphi = \frac{2\pi}{c} r j_z$. It follows from the relation (20) that the focal distance decreases, as the current density becomes lager (f ~ $1/\sqrt{j_z}$). Accordingly as the plasma stream cross section becomes less then the focal distance decreases proportionally to the average plasma diameter. The size of the plasma stream cross section depends on the external magnetic field strength that is responsible for the plasma column constriction. The equation of the proton radial motion is of the form

$$\ddot r + \frac{2\pi e v_0 I_0}{m_p c^2 S(z)} r = 0 \tag{21}$$

where V_0 is the proton longitudinal velocity, I_0 is the plasma current, S(z) is the plasma stream cross-section. The Gaussian system of units is used in the equation (21). If the proton beam is focused inside the plasma at all plasma column length (the long lens model) then the minimum focal distance decreases in $\sqrt{K}$ times. The external magnetic field of the coil can lead to decreasing of a plasma column cross-section. For the conditions of experiments carried out at NSC KPTI the plasma column radius can decrease due to the coil approximately in three-five times.

If the longitudinal magnetic field is zero the compression can be caused by the pinch instability of the constriction type.

It should be noted also that for the short PL the focal distance decreases in K times if the plasma cross-section becomes K times less (see Eq. (19)).

It is necessary to take into account that in the plasma stream that moves in the inhomogeneous magnetic field there appear the azimuth current. This effect causes the coil magnetic field expelling from the plasma volume that does not allow in many cases to use the value of the coil magnetic field for the plasma column diameter and current density estimation. To consider such a situation the dependence of magnetic field of the PL on the current density distribution has been studied. This investigation has been carried out for the region near the system axis. If the longitudinal current density is expanded in powers of radius r

$$j_z(z,r)=\sum_{n=0}^{\infty} r^n j_z^{(n)}(z), \tag{22}$$

then we get for the azimuth component of the magnetic field

$$H_\varphi(z,r)=\frac{2\pi}{c} j_z^{(0)}(z)r+\frac{4\pi}{3c} j_z^{(1)}(z)r^2+... \tag{23}$$

The longitudinal magnetic field depends on the azimuth current density

$$H_z(z,r)\approx H_z^{(0)}(z)-\frac{4\pi}{c} j_\varphi^{(0)}(z)r+... \tag{24}$$

In the expression (4) $H_z^{(0)}(z)$ can be considerably different from the coil magnetic field strength as far as the azimuth plasma current causes the external magnetic field expelling from the plasma volume. The magnetic surface equation for the region near the axis $r^2 H_z^{(0)}(z)\approx const$ is determined rather by the total magnetic field arising in the plasma medium than that one of the magnetic coil.

Focusing of the proton beam by the PL has been considered for the case when the plasma is compressed under the coil and the azimuth magnetic field becomes rather large. Assuming that the radial proton momentum appreciably changes just in this region (i.e. using the momentum approximation) we get for the focal distance

$$f=\frac{m_p v_0 c^2}{2\pi \quad e\int\limits_{-\infty}^{\infty} j_z^{(0)}(z)dz}, \tag{25}$$

here the integration of the longitudinal current is carried out over the interval of z where the compression of the plasma stream is important and the azimuth magnetic field is rather large. The expression (25) can be used also for focal distance calculating is the case of the short inhomogeneous PL that is created near the edge of the plasma gun.

Plasma magnetostatic 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:

$$a^2(z)=\frac{a^2(0)B_z(0)}{B_z(z)} \tag{26}$$

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.(26) 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:

$$r''+k^2\frac{B_z(z)}{B_z(0)}r=0,\ k^2=\frac{2IZe}{Mc^2vb^2} \tag{27}$$

where I is the current in plasma, Ze and M are the charge and mass of the ion, c is the light velocity, *and* v is the ion velocity. For our installation the relation $\frac{B_z(z)}{B_z(0)}$ 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. 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 has 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 has the form

$$r''+\frac{\kappa}{r}=0 \quad \kappa=\frac{2ZeI}{c^2Mv} \quad \text{for } r=r_{ms}. \tag{28}$$

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 (26) 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 . With the help of the A.N.Tikhonov regularization method [17], the parameters of the solenoid have been successfully calculated, and the required magnetic field is formed.

2.2 HF-plasma lens [18]

Let us consider the PL where the charged plasma with uncompensated electron charge is confined in the external magnetic field by means of high frequency (HF) methods.

The ac electromagnetic fields that are necessary for creating HF plasma trap with an excess of electrons can be launched from outside or can appear selfconsistently due to an interaction of the plasma with ion beam to be focused. In the latter case the ion beam excites potential oscillations in the region of inhomogeneous plasma under the magnetic coil. If the frequency of unstable oscillations is less than the cyclotron frequency of electrons and more than that one of ions then the ponderomotive forces acting respectively on electrons and ions can be of opposite sings. The region of HF localized oscillations becomes the potential well for electrons and it accumulates an excess of an electron space charge. It should be noted that the ion ponderomotive potential push out plasma ions from the region of large amplitude oscillations. As a result the plasma configuration is created with the large value of the radial electric field that causes ion beam focusing. Theoretical estimates well agree with the preliminary results of experiments carried out at NSC KPTI. Let us consider at first the linear mechanism of oscillations excitation in the frequency range $\omega_{ci} < \omega < \omega_{ce}$, where ω_{ci} and ω_{ce} are respectively the cyclotron frequencies of plasma ions and electrons. For estimates, let us use the values of the experimental parameters on high energy ($5MeV$) ion beam focusing. In connection with this, let us take for the plasma density $n_{pe} \approx 10^{13}$ cm^{-3}, for the magnetic field strength $H_0 \approx 500\ Oe$, the ion beam density equals $n_{bi} = 1.7 \cdot 10^7\ cm^{-3}$ and the beam velocity is $v_0 = 3 \cdot 10^9\ cm/s$. The plasma supposed to be created by injecting of bunches by means of the plasma gun. Under the magnetic coil the plasma stream is of the cylindrical form with the longitudinal size of about $1m$ and the cross-section radius approximately equal $2cm$.

At the frequency range $\omega << \omega_{ce}$ the dispersion properties of potential oscillations in the homogeneous plasma are determined by the relationship

$$\omega = \sqrt{\omega_{ci}\omega_{ce}}\sqrt{1 + \frac{m_i}{m_b}\cos^2\theta}\ , \tag{29}$$

where $\cos\theta << 1, \theta$ is the angle between the wave vector $\vec{k}$ and $\vec{H}_0$. For the drift branch of oscillations we have in the case of almost transverse propagation ($\sin\theta \approx 1$)

$$\omega = \frac{\kappa k_\varphi}{k^2}\omega_{ce}\ , \tag{30}$$

where κ is the reciprocal of the characteristic length for the radial distribution of the plasma density l_n, i.e. $\kappa \sim 1/l_n$; k_φ - the azimuth component of the wave vector. The growth rate of oscillations γ under conditions of the Cherenkov resonance ($\omega \approx k_z v_0$) is defined by the formula

$$\frac{\gamma}{\omega} \sim \frac{\sqrt{3}}{2} \cdot \left(\frac{n_{bi}}{n_{pe}}\right)^{\frac{1}{3}} \cdot \left(\frac{\Omega_{\hbar}}{\omega}\right)^{\frac{2}{3}}\ , \tag{31}$$

where Ω_k is the Kerper frequency ($\Omega_k = \sqrt{\omega_{ci}\omega_{ce}}$).

The oscillations with frequencies (29) and (30) exist only for the case when the external magnetic field is different from zero. It is easy to see that the localization of HF oscillations under the magnetic coil can be achieved in the case when the magnetic field strength has the point of a minimum. The decrease of the magnetic field strength just at the central region under the coil can be available as a result of the coil design choice, so due to peculiarities of the plasma stream (bunch) interaction with the axially symmetric magnetic field. Indeed, the azimuth current arises in the plasma bunch that leads to the decrease of the total magnetic field and the minimum of the magnetic field becomes possible at some point of z - axis under the coil.

In the case of the excitation of the localized along z - axis HF oscillations it is possible to find the ac electric field maximum amplitude with the help of the estimate proposed in [19]:

$$\Omega_{tr}\frac{L}{v_0} \approx 0.2\pi\ , \tag{32}$$

where Ω_{tr} - the bounce frequency of ions trapped by the wave, L is the longitudinal size of the region under the coil where HF oscillations are localized.

The HF oscillations potential amplitude $\tilde{\varphi}$ at $k_z = \frac{\pi}{L}$ for the above given values of the plasma and beam parameters is determined by the estimate $\tilde{\varphi} \approx 24200V$.

If frequencies of excited oscillations are of the order of the Kerper frequency then the ion beam motion is substantially affected by the radial component of the electric field. In this case radial focusing of the ion beam is hardly probable.

For the homogeneous plasma oscillations with the frequency $\omega = \omega_{ce}\cos\theta$ the excitation conditions are satisfied only for a rather rarefied plasma. For the experimental conditions under consideration we get criterion $n_{pe} < 6.5 \cdot 10^{11}\ cm^{-3}$.

If the plasma density is $n_{pe} \sim 10^{13}\ cm^{-3}$, then ion beam focusing can be realized as a result of the drift branch excitation in the inhomogeneous plasma.

It should be noted that the preliminary experiments with high energy ($5MeV$) ion beam focusing have been carried out in the conditions when the ion beam was modulated at the frequency $\omega \sim 10^9\ s^{-1}$. Such a circumstance could contribute to the development of the drift branch instability at this frequency value. For the case under consideration $\Omega_k << \omega << \omega_{ce}$, $k_z << k_\perp$ and the ponderomotive potential acting on the plasma electrons is determined by the relation

$$\phi_e \approx -\frac{e^2}{4m_e^2\omega_{ce}^2} \cdot \left|E_\perp\right|^2\ , \tag{33}$$

where $E_\perp$ is the perpendicular (respect to $\vec{H}_0$) component of the oscillating electric field. At the steady state the ponderomotive force acting on the plasma electrons is balanced by the electrostatic force and we obtain for the electrostatic potential φ_{st}:

$$\varphi_{st} = \frac{m_e}{e}\phi_e\ . \tag{34}$$

The ponderomotive potential for the plasma ions is small in comparison with $\left|\varphi_{st}\right|$, that is why the kinetic energy of plasma ions can become rather large when they move in the negative potential created by surplus electrons. From the Poisson's equation we can find the excess electron density at the steady state $n_e - n_i \sim 10^{10}\ cm^{-3}$. It follows from the equation (34) that $\left|\varphi_{st}\right| \approx 30$ kV and in the focusing region (r<1cm) the radial electric field strength is of the order of $E_r \approx 30$ kV/cm. It should be noted that for effective focusing it is preferable to use the oscillation mode with the azimuth numbers equal ± 1. Let us assume that the longitudinal size of the region with uncompensated electron space charge is approximately equal 10 cm. Using Gabor's formula [3] we get for the focal length the estimate f ≈ 30 cm.

2.3 Polarization fields

The polarization model for compensated ion bunches

Experiments [20] have shown the charge and current neutralization of 5 MeV proton beam by plasma electrons or electrons produced at ion beam bombardment of the lavsan film. At the coil entrance electrons are compressed by the magnetic field, that leads to the radial electric field arising. Thus in the central region of the coil the beam protons get the momentum directed to the system axis that causes proton focusing.

The estimations of the radial compression rate for the electron component of the radius r_0 for the experimental parameters give:

$$r_{min} \approx 0.17 r_0 \,. \tag{35}$$

The focal length can be obtained from the relation:

$$F \approx v_0 \frac{\rho_{0i}}{v_{ri}} \,, \tag{36}$$

where ρ_{0i} is the ion beam radius. It is easy to determine the electrostatic potential of electrons uniformly distributed inside the cylindrical region of radius $\rho_{0e} \approx r_{min}$ and ion velocity v_{ri}. Resulting we get:

$$F = \frac{1}{2} v_0 \rho_{0i} \sqrt{\frac{m_i}{e_i Q \alpha}} \,, \tag{37}$$

where $\alpha = 1 + 2\ln(\frac{\rho_{0i}}{\rho_{0e}})$. To estimate the linear charge density of electrons Q we assume that in the region of weak magnetic field (far from the coil) the electron density is close to that one of ions $\sim 1.7 \cdot 10^7$ cm^{-3} and the proton bunch radius is equal 1 cm. From the relationship (37) we get the focal length F=250 cm. This length exceeds the experimentally observed value approximately 5 times. So the theoretical consideration has shown that the polarization model that takes into account trapping of electrons by the proton bunches and the further radial separation of electrons and protons under the coil fails to explain the experimental data.

Plasma polarization

A dynamical PL is created by a plasma flow propagating with energy ε_p=100eV from a plasma source to a nonhomogeneous magnetic field of a comparatively short coil ($R_k \approx L_k \approx$ 15cm, here R_k, L_k are radius and length of the coil). Plasma density near the source is $n_p=10^{16}$ cm^{-3} and decreases along the axis.

Ion beam is injected in the system with a time delay when the plasma is not already generated by the source. The plasma flow is polarized in the region of the magnetic barrier because the electron cyclotron radius is less than the ion cyclotron radius. The measurements of transversal compressing of plasma bunch, its longitudinal and transversal polarization are represented in [21]. Theoretical description of short plasma bunch interaction with magnetic field was made in [22-23]. The radial electric field appears due to the radial polarization of the plasma as well as due to the longitudinal polarization. The nonhomogeneous distribution of plasma electrons relative to the ions in the region of the coil forms the PL.

The maximum focusing fields is considered, then we assume the cyclotron radius of electrons $r_{ce} = eE_r/m_e\omega^2_{ce}$ less than plasma radius but not very small in comparable with the plasma radius r_i. In the first approximation let us assume the plasma ion and electron clouds to be cylinders of different radii with the densities that are independent on radius.

Mechanisms of focusing

We consider the case when the plasma flow propagates in the region of the magnetic field from the region where the magnetic field is absent. At first, we are interested in values of transversal fields, which arise due to longitudinal and transversal polarizations of plasma flow at its entrance in the region of cylindrically symmetrical magnetic barrier. In [24] the estimation of the maximum focusing field was evaluated. For the experiment it equals 100 kV/cm, i.e. the formation of large focusing fields in PL is possible. The energy for creation of polarization fields is taken from the kinetic energy of plasma flow. Because the plasma flow from the gun is nonmagnetized the current is induced in the plasma at the entrance of the magnetic field. Thus the induced magnetic field can corrugate the external magnetic field.

Focusing in the field of longitudinal polarization

At the ion beam propagation through the region of longitudinally polarized plasma the beam is focused in the region of noncompansated negative charge and focusing intensity decreases in the region of noncompansated positive charge. As far as in the region of noncompansated positive charge the ion beam propagates on smaller radius, where the defocusing force is smaller, the focusing continues. Focusing continues also after leaving from the region of focusing fields due to radial velocity obtained by ion beam. It has shown that at the plasma density longitudinal polarization, approximately equal $\delta n \approx 10^{12}$ cm^{-3}, the focusing of ion beam with energy 5 MeV is achieved on the distance 30 cm.

Focusing in the field of transversal polarization

In accordance with experiments, we assume that the magnetic field penetrates with some rate into the plasma. The plasma ions are not magnetized and electrons are magnetized in magnetic field of coil. The radius of the electron trajectory r_{ce} in the magnetic field is inversely proportional to $\sqrt{H}$. Moving in the region of stronger magnetic field the electrons are slowed down in the longitudinal direction because the longitudinal velocity transforms into the transversal one according to $V_\perp^2 \propto$ H. But the longitudinal field of polarization of plasma flow appears which provides the plasma electrons carrying away by ions. Thus the plasma electrons, exchanging by energy with ions, propagate into the field of stronger magnetic field. At the same time the plasma electrons, moving along the magnetic field, propagates to the axis of the coil. Thus the radial polarization of plasma appears. Then the electron cyclotron radius becomes proportional to $r_{ce} \propto E_r/H^2$. As far as we consider the maximum focusing fields, then we assume $r_{ce} < r_i$, i.e. the radius of the region, occupied by electrons, is less than the radius of the region, occupied by ions (but is not very small in comparison with the radius of the region, occupied by ions).

Let us consider the possibility of the ion beam focusing with energy 5 MeV in the collective fields on the distance of nonhomogenous magnetic field 30 cm. Hence on this space interval the plasma ions with energy 100 eV many times oscillate in the radial fields during the time interval of filling of the region of the magnetic coil by plasma. It means that the kinetic energy of the plasma flow transforms into the energy of radial oscillations of the plasma ions. Also the longitudinal velocity of the plasma flow decreases, leading to the increasing of the plasma density. Thus the plasma electrons and ions may be presented in the type of two cylinders of different radii. Inside one cylinder, with radius r_i, the ions oscillate in the radial polarization field, having the effective temperature approximately equal $T_\perp \approx e\overline{E}_r r_i$. $\overline{E}_r$ is the average electric field of transversal polarization. The electrons occupy the second cylinder of smaller radius r_e. Such structure of the particle density distribution provides at the plasma density 10^{11} cm^{-3} the radial electric field E_{ar} =25 kV/cm, sufficient for the ion beam focusing with energy 5 MeV on the space interval of the nonhomogeneous magnetic field.

2.4 Focusing due to the charge deposition on the dielectric walls

The plasma is isolated from the walls by the magnetic fields. Hence the bombarding of walls by ion beam leads to the accumulation on them the noncompansated positive charge. This leads to the formation of additional focusing field for ion beam of order of 10 kV/cm. It should be noted that in experiment [25] the better focusing has been observed without the external electric field. The focusing field appeared due to the drop of the beam part on the electrodes.

3. EXPERIMENTAL SETUP

PL installation and accelerator Ural-5

The stand of PL (Fig.1) 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 PL 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 $v = 6\cdot10^6$ cm/s to 10^7 cm/s. Optimal quantity of injected gas was $V \sim 2$—3 cm^3. 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.

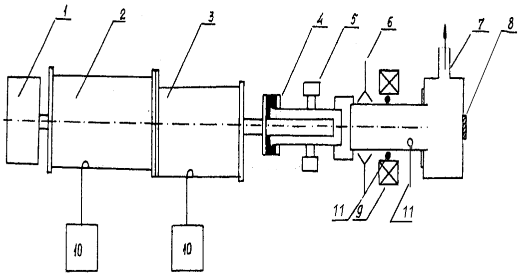

Fig.1. Scheme of the installation. (1) proton injector; (2) initial stage of accelerator; (3) final stage; (4) plasma gun; (5) gas valve; (6) horn antenna; (7) chamber; (8) luminescence screen; (9) solenoid; (10) RF sources; (11) magnetic field probes

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 [26]. For successful working with the PL, 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: 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 30 mA, pulse duration is 30 μs); 10 - RF power amplifiers (RF power is about 1 MW, pulse duration is 100 μs).

Diagnostics

In experiments the following diagnostic equipment was used. For determination of plasma diameter on the end of the plasma source and propagation velocity of plasma formation the magnetic probes of 3 mm diameter and the spectrograph ICP-51 were used. Longitudinal and radial distributions of azimuth magnetic field of plasma source current were measured by magnetic probes. The amplitude of proton beam current and changing of its diameter were measured by double Faraday cylinder (the diameter of outer cylinder is 4 cm, diameter of inner cylinder is 1.6 cm) and by luminescent screen. The screen was covered by thin aluminum foil, which was transparent for high energy proton beam and protected screen against plasma.

4. EXPERIMENTAL RESULTS

Plasma current lens is considered that is placed in the non-uniform longitudinal magnetic field which can change the radius of the current channel, the current density, and the focusing azimuth 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.

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 [11]. Besides radial electric fields that can arise in plasma, the azimuth 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 for 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 [9]. Here more complicated non-uniform case is considered.

In addition to the experiments [11] 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. 2. 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 G (115 G).

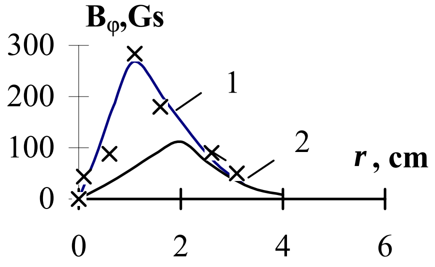

Fig. 2. Distributions of the azimuth magnetic field versus radius (curve 1 or 2 corresponds to the solenoid switching on or off)

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 maximum 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. (27-28) and measured values of the current channel radius 1.3 cm, 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.3), that agree with the experiments.

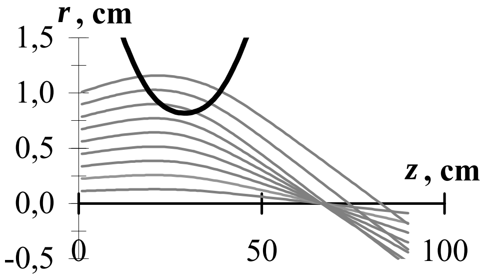

Fig. 3. Simulation of the 5 MeV proton trajectories for the experimental parameters

In Fig.3 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 PL of this type the efficiency can be increased by the simultaneous decreasing of the current channel radius and the focused beam one.

3.1.2. FOCUSING OF HIGH-ENERGY ION BEAMS BY PLASMA FOCUS OF COAXIAL PLASMA SOURCE

We have also investigated the focusing of ion beams with wide range of energies and currents by plasma focus of the coaxial plasma source (CPS).It is known [7-9] the current layer of width 5 cm is formed under discharge between electrodes of CPS. This layer propagates with velocity $\sim 10^7$cm/sec up to the end of the plasma source. Current between inner and outer electrodes leads to creation of large azimuth magnetic field. This field provides plasma focusing to axis of the system and formation so called plasma focus. Azimuth magnetic field of the current in this plasma formation may be used for focusing of ion beams of high energy. The experimental results will be published elsewhere. Here we represent only beam portraits in dependence on plasma parameters caused by the values of gun voltage (Fig.4).

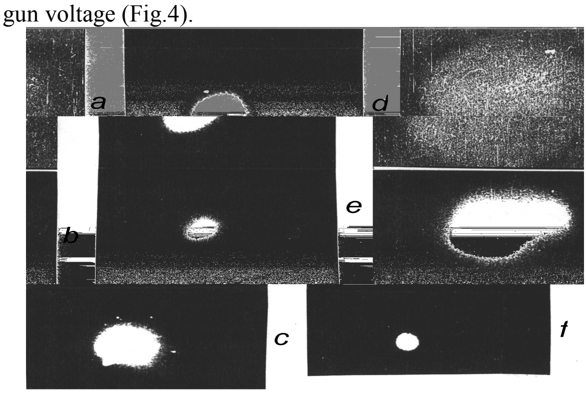

Fig. 4. Photos of beam diameter in absent of plasma (a) and after passing through the plasma at different voltages on electrodes of plasma source: b - U = 5 kV, c - U = 6 kV, d - U = 7 kV, e- U = 8 kV, f - U = 9 kV

5. SUMMARY

It was fulfilled complex of theoretical investigations, computer simulations, and experimental studies of possible physical mechanisms of ion beam focusing by plasma formations. As a result, the preference is given to the magneto-static (current) PL. They are of two types: the PL with ion beam focusing by plasma source focus in which pulse current of tens kA flows and azimuth magnetic field of hundreds kOe is created on the distance about 10 cm (compression of ion beam reaches ten times) and the adiabatic PL. The latter is considered that is placed in the tapered longitudinal magnetic field which changes the radius of the current channel, the current density, and the focusing azimuth magnetic field. For these plasma lenses the efficiency can be increased by the synchronous decreasing of the current channel radius and the focused beam one.

Besides the further investigation should be directed on using of cooled charged plasma [27] for nuclear microprobe developing [2] and plasma focus for efficient focusing of heavy ion beams [12,28].

This work was supported by STCU (Project No. 298).

REFERENCES

1. K. Oide // *Phys. Rev. Lett.* 1988, 61, p.1713.
2. H.Lefevre, //*Nucl. Instrum.Methods Phys. Res.* ***B,*** 1985, № 10/11, p.707.
3. D. Gabor // *Nature (London),* 1947, v.160, p. 89.
4. A. Morozov // *Doklady Akad. Nauk SSSR,* 1965, v. 36, p. 1363
5. A. Goncharov, I. Protsenko // *Ukr. Fiz. Zh.,* 1991, v. 36, p. 1720.
6. A. Goncharov, I.Protsenko, and A. Zatyugan // *IEEE Trans. Plasma Sci.* 1993, v. 21, p.578.
7. A. Goncharov, // *Rev. Sci. Instr.*. 1998, v. 69, № 2, p. 150.
8. F. Dathan et al // *J. Appl. Phys.* 1987, v. 62, p. 3585.
9. E. Boggach et al., // *Appl. Phys. Lett.* 1992, v. 60, p. 2475.
10. G. Hairapetian, // *Proc of 5th Workshop on Advanced Acceleration Concepts. Woodbury, NY,* 1994, p.174.
11. V.N. Belan, V.I. Butenko, B.I. Ivanov, et al. //*.Rev. Sci. Instrum.*. 1998, v. 69, № 2, p. 1110.
12. B.P. Il'enko, I.M. Nekludov, and I.N. Onishchenko // *Rev. Sci. Instrum.*. 1998, v. 69, № 2, p. 849.
13. V.N. Belan et al. //*.Problems of Atomic Sci.and Technology, series: Plasma Phys.* 1999, v, 3-4, p.224.
14. V.N. Belan et al. //*.Problems of Atomic Sci.and Technology, series: Plasma Phys. Rep. 2000*, v, 26, № 4 p.351.
15. B. Autin, H. Riege, E. Boggasch, K. Frank, L. De Menna, and G. Miano, // *IEEE Trans. Plasma Sci.* 1987, v. 15, p.226.
16. A.I. Morozov, L.S. Solovyev. // *Voprosy teoriyi plazmy. Sb. statey.* . Atomizdat, 1974, No. 8, p. 3-87.
17. A.N.Tikhonov, V.Ya.Arsenin, // *Methods of incorrect problems solution*. Moscow, "Nauka", 1988 (in Russian).
18. I. Onishchenko, A. Kitsenko HF Plasma Lens// *Bulletin of the APS*, May 1997, v. 42, No. 3 , 4V. 43, p. 1256.
19. V.I.Kurilko // Sov. *ZETP* 1969, v. 57, p. 885.
20. V.A.Kiselev et al.// *Preprint KFTI 89-21, Kharkov,* 1989, 8 p.
21. K.D.Sinelnikov et al., // *Proc. of 2nd Intern. Conf. on Peaceful Using of Atomic Energy. Nuclear Physics,* 1959, v. 1, p.110.
22. K.D.Sinelnikov, N.A.Khiznyak, B.G.Safronov, // *Sov. Plasma Physics,* 1962, v. 1, p.93.
23. N.A.Khiznyak, // *Plasma Physics and Problems of Nuclear Fusion* 1965, v. 5.
24. M.D.Gabovich, I.E.Gasanov, I.M.Protsenko, // *Preprint. Kiev. IF AN UkrSSR* 8(1982).
25. M.D.Gabovich, I.E.Gasanov, I.M.Protsenko, // *Pis'ma ZTF* 1977, v. 3, p.1153.
26. I.M. Kapchinsky, V.A. Teplyakov, // *Pribory i Tekhnika Exper.*, 1970, №4, p.17 (in Russian).
27. T.O'Neil, // *Proc. of Int.Conf on Plasma Physics*, Nagoya, 1996.
28. I.N.Onishchenko, // *STCU Project No. 298 "Plasma Lens for Ion Beam Focusing"* 1996-1998