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Evaluation of plasma optics reality for proton therapy beams

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The possibility of using plasma as an optical element for controlling non-relativistic proton beams with energies of the order of 250 MeV used in proton beam therapy is investigated numerically using the particle-in-cell method taking into account collisions. Such optics would allow a significant reduction in secondary radiation in the processes of collimation, scattering or rotation of a standard proton beam, and would also become an important part of controlling ion beams accelerated in plasma formed by short powerful laser pulses. Passive plasma optics for non-relativistic beams of proton beam therapy is possible only in plasma formed by optical ionization of the medium by short-pulse laser radiation. Optical ionization of the gas medium allows the formation of significant plasma gradients with an electron temperature depending on the intensity of the ionizing laser radiation. The transverse electric field generated in this case can have a strength sufficient to seriously affect proton and even ion beams. In experiments, this manifests itself as a rapid (explosive) formation of plasma channels even at relatively low intensities of short laser pulses. The structure of explosive plasma channels depends on the focusing and polarization of laser radiation and its power. When passing along such a channel, even non-relativistic proton beams can be focused, scattered or deviated from the original trajectory.

Keywords: proton beam therapy, medical physics, beams in plasma, plasma channels.

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Introduction

The proton beam therapy as well as the ion beam therapy are actively developed fields of medicine, which have proven their efficiency [1,2]. Presently, along with improvement of accelerators and gantry of the traditional systems of proton beam therapy (PBT) [1–4], there is active research of both laser PBT [5,6] and its combination with the traditional systems of acceleration of heavy charged particles. Thus, for example, according to the paper [7], there is initiation of active designing of a ring carbon accelerator with injection of carbon ions that are accelerated by femtosecond laser radiation in plasma. Nevertheless, issues of radiation safety are still one of key PBT elements [8]. A possible field that allows improving radiation safety can be plasma optics, which in principle can allow substantial reduction of secondary radiation when controlling beams of the charged particles.

The plasma optics means a plasma object that can change spatial characteristics of the beam of the charged particles, which is transmitted therethrough, by focusing, scattering or diverting this beam. Presently, the plasma optics is seriously studied in relation to relativistic electron beams and powerful laser radiation. It is primarily related to designing new principles of formation of the relativistic beams of the charged particles [9–11]. Particular interest to the plasma optics was manifested when short-pulse and powerful lasers appeared, whose radiation can create a plasma of arbitrary configuration by optical ionization of a medium [12–15]. The plasma optics of the means is conditionally divided into passive optics and active optics. In the passive optics, the beam affecting the plasma changes its characteristics [11,14]. In the active plasma optics, fields changing the characteristics of the beam are created by an additional external effect. One of the examples of the active plasma optics is a plasma of the z-pinch, wherein a magnetic field is regulated by a plasma current and has a structure that is similar to a structure of the system of quadrupole magnets [16–18]. Short laser pulses can also form the fields which are sufficient, for example, for collimation of relativistic electrons [11,14]. However, for nonrelativistic heavy particles, such as protons and multicharged ions, the plasma optics is not deemed as somewhat promising.

The present study is numerically investigating principle applicability of the plasma optics for the nonrelativistic proton beams, which is based on using the plasma formed by optical ionization. For this purpose, it adapted a multi-dimensional code FPlaser [19] and using the particle-in-cell method modelled dynamics of the proton beams which are typical for PBT in the variously-configured plasma with an initial electron temperature that is equal to a ponderomotive potential of the laser pulse. This temperature is achieved in a wakefield wave of the laser pulse usually after its decomposition [20,21].

1. Passive and active plasma optics of the beams

It is traditionally assumed that the plasma optics is possible only for the relativistic beams of the charged particles,

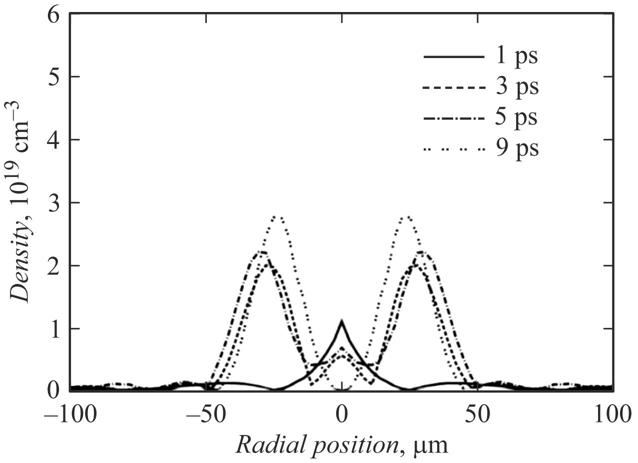

Figure 1. Dynamics of transverse distribution of the argon plasma density in the channel created by the laser pulse with the energy of 90 mJ, the pulse duration of 0.3 ns, while the laser wavelength is 0.8 μm [22].

for which the Bennett-Budker equation is valid [22–24], which in a frame of reference of the beam rest is as follows:

$$\frac{\partial E_\perp}{\partial r} = 4\pi e\left[\pm\frac{N_B}{\gamma_B} - \gamma_B(N_e - N_i)\right],$$

where $E_\perp, r$ — the transverse electric field and the coordinate, N_B — the density of the beam, N_e, N_i — the densities of electrons and ions of the plasma, γ_B — the relativistic beam factor, the plus sign is for the ion beam and the minus sign is for the electron beam. Since the signs of the right hand terms of the equation are always different, even a slight difference of the electron density from the ion density results in focusing of the beam irrespective of the charge sign. If γ_B is about unity (a nonrelativistic case), then the focusing conditions seem rather strict $N_B < |N_e - N_i|$. In the passive case, fulfilment of this condition can not be checked analytically and focusability of the beam requires numerical calculations by the particle-in-cell method.

In the active case, fulfilment of this condition begins to depend on an external factor and can be achieved at its certain parameters. But in this situation, too, the final result can be studied only numerically. It should be noted that the active optics can be more flexible and along with beam focusing it can scatter or even divert the beam. For relativistic electrons, along with a discharge plasma and a low-temperature plasma formed by optical ionization [25–30], there is another candidate for the active plasma optics, which is „explosive" plasma channels that are created by femto- or pico-second laser pulses [25,30]. Unlike the discharge plasma, in the optical plasma the electron temperature can achieve relativistic values. However, for the proton beams the plasma optics is possible only when using „explosive" plasma channels.

The „explosive" plasma channels were formed and studied in order to create waveguides for powerful laser pulses and to accelerate electrons in the wakefield wave of the laser pulse [25–30]. Fig. 1 shows a typical plasma dynamics that is measured in a laser channel of the argon gas jet [25]. Despite a high density of the gas, a nonoptimal ratio of the mass of to the charge of the argon ions, the ion velocity achieves substantial values, $v \sim 10^9$ cm/s. Certainly, after several nanoseconds this channel relaxes and turns into an area of the heated plasma and the plasma ions practically remain stationary. However, if the charged particle comes from outside, then having a longitudinal velocity, upon exit from the plasma area this particle can keep a significant transverse component of the velocity. Thus, the protons with the energy of 250 MeV in the beam transmitted through the plasma in Fig. 1, would be diverted by a solid angle 0.16−0.3 rad. The high velocity of transverse motion of the ions is related to the fact that electrons in the plasma created by optical ionization have a high temperature T_e. It is estimated to be close to the ponderomotive potential [21] $U = mc^2\left(\sqrt{1 + a_0^2/n} - 1\right)$, where $a_0 = eE_L/mc\omega$, E_L — the strength of the laser electric field, ω — the frequency of laser radiation, $n = 1$ or 2 depending on polarization of laser radiation. The a_0 becomes about unity with intensity of laser radiation 10^{18} Wt/cm2. This temperature can be achieved after decomposition of the wakefield plasma wave.

In turn, as known, the velocity of ion motion is determined by the temperature of electrons, the charge and mass of the ions: $V_i = (2kZT_e/M)^{0.5}$, where Z, M — the charge and mass of the ion. This velocity of the ions is formed by the plasma field $E = -\nabla_\perp(N_eT_e)/eN_e$ [31] and directed from a plasma symmetry axis, thereby resulting in formation of a plasma channel. Therefore, the beam of the protons will also take a transverse component of the velocity, whose value depends on duration of exposure of protons to the field. However, unlike the plasma ions, the charged particle that moves along the channel will be exposed to a qualitatively different field. For example, in the plasma channel formed in the initially homogeneous gas, where the density of the positive charge at the periphery is higher than in the center, the positively-charged proton will shift towards the center. In case of using the plasma created by the radially-polarized laser pulse [32], whose transverse distribution of intensity is toroidal, the formed plasma will have a density minimum in the center, while the beam transmitted through the torus center must be focused more effectively. And, for example, plasma formation at a gradient of the density of the gas flow shall result in diversion of the beam proton along the gradient of the density. Thus, the laser plasma channels could have been a good tool both for focusing, scattering the ion beam and for it diversion to a pre-defined angle. These estimates can be checked only numerically.

2. Modeling of dynamics of the proton beam in the plasma

Dynamics of the proton beam must be modelled using the particle-in-cell method [33]. For this purpose, the modified code FPlaser is used [19]. At this, two equations are solved in a self-consistent manner: the field equation as

$$\frac{\partial \mathbf{E}}{c\partial t} = \mathrm{rot}\mathbf{B} - \frac{4\pi}{c}[\mathbf{j}_e + \mathbf{j}_i + \mathbf{j}_p], \tag{1}$$

$$\frac{\partial \mathbf{B}}{c\partial t} = -\mathrm{rot}\mathbf{E} \tag{2}$$

and the continuity equation

$$\frac{\partial \rho_{e,i,p}}{\partial t} + \mathrm{div}\mathbf{j}_{e,i,p} = 0. \tag{3}$$

Here $\mathbf{j}_e, \mathbf{j}_i, \mathbf{j}_p$ are electron, ion and proton currents in the plasma, and $\rho_{e,i,p}$ is a density of the particle charge. The Buneman method [34] is used for weighing the currents, wherein the equation (3) is automatically solved both in a two- and three-dimensional variant of calculation by means of an accurate numerical method of weighing. Movement of protons, ions and electrons of the plasma is solved in a relativistic approximation for each sort of the particles, thereby making it possible to expand capabilities of the used code. Since movement of the ions in this problem is a key one, their movement shall be taken into account in the calculations. The equation of motion has the standard form:

$$\frac{d\mathbf{p}}{dt} = q\Big[\mathbf{E} + \mathbf{p} \times \frac{\mathbf{B}}{Mc\gamma}\Big] - \mathbf{F}, \tag{4}$$

where q and M — the charge and mass of the particle, $\mathbf{p}$ — the momentum of the particle, γ — the relativistic factor. Movement of the plasma ions is often neglected in these calculations, but in this problem the movement of the ions can substantially affect formation of the plasma channels and, respectively, motion of the proton beam. In the equation (4) $\mathbf{F}$ is a friction force that is determined by the Langevin equation [35]. These calculations have used only a part of the force, which is responsible for elastic collisions of plasma electrons with neutral atoms and ions and has the following form [35]:

$$\mathbf{F} = -\frac{m}{M}v\mathbf{v}\left[\sigma_1 N_{gas} + 4\pi\Lambda N_i\left(\frac{e^2}{mv^2}\right)^2\right] + \frac{e^2}{m}\sqrt{\frac{4\pi\Lambda N_i}{v}}\left(\boldsymbol{\xi} - \frac{v(\xi v)}{v^2}\right) + \sqrt{\frac{\sigma_2 v^3 N_{gas}}{8}}\left(\boldsymbol{\xi} + \boldsymbol{\eta} - \frac{v(\boldsymbol{\xi} + \boldsymbol{\eta}, v)}{v^2}\right) + \sqrt{\frac{2\sigma_1 - \sigma_2)v^3 N_{gas}}{8}}\,\frac{\mathbf{v}(\boldsymbol{\xi} - \boldsymbol{\eta}, \mathbf{v})}{v^2}. \tag{5}$$

Here Λ — the Coulomb logarithm; N_{gas}, N_i — the densities of the neutral gas and the plasma ions; $\mathbf{v}$ — the velocity of the plasma electron, M — the mass of the ions; σ_1, σ_2 — the transport sections of collisions of electrons with the gas atoms [36]; $\boldsymbol{\xi}+, \boldsymbol{\eta}$ — the three-component random Gaussian processes with the characteristics:

$$\xi_i(t) \le 0,\ < \xi_i(t)\xi_k(t+\tau) \ge \delta_{ik}\delta(\tau),\ \int_t^{t+\Delta t} \xi_i(t')dt' = p_i\sqrt{\Delta t},$$

where p_i — the random number from normal distribution with an average equal to unity and dispersion equal to zero. If required, the system can be supplemented with a force for collision of identical particles [35]. The collisions of the identical particles are performed in the frame of reference, where the particles are at rest. If required, a neutral component is added at the plasma periphery without ionization. Influence of this component is insignificant in this specific study and therefore was neglected. However, in some cases this component can affect formation of the plasma channel and it shall be taken into account in the code.

Since it is necessary to know the density and often the temperature and the average velocity of the particles for taking into account the collisions, a kinetic grid that includes several cells of the finer grid of the „particle-in-cell" method is additionally introduced. For each such kinetic cell the average values are calculated

$$N = \sum \rho_i;\ u = \sum \rho_i v_i / N;\ T = \sum \rho_i (v_i - u)^2 / 3N,$$

where ρ_i — the density of the i-th particle, v_i — its velocity, N — the density of the particles, T and u — their temperature and average velocity.

Weighing of the currents and the field in the two-dimensional variant is linear and this is quadratic in the three-dimensional variant [19,34]. The boundary conditions are standard and mean introduction of an absorbing layer [37]. The initial values of strength of the fields were in a standard manner selected to be zero. The beam field was taken into account by using a compensation model, wherein along with the beam there is motion a similar beam of pseudo-particles that have an opposite charge equal to the beam charge. The charge of the pseudo-particles quickly decreases with time and in a short time the beam field becomes equal to its field in vacuum. This method works well both with nonrelativistic and relativistic beams.

3. Dynamics of the proton beam in the plasma channel

The calculations were performed in a two-dimensional approximation for the hydrogen plasma of the length of up to 10 cm and the transverse size of 1 cm, with spatial resolution of $\Delta x^{-1} \sim 3000$/cm. The calculations were performed with 4 particles in each cell for each sort thereof. The plasma density was taken within the range $N_e \sim 10^{15}\,\mathrm{cm}^{-3}$. This low plasma density was selected to avoid a noticeable change of characteristics of the proton beam with its propagation at centimeter lengths. At the same time, the value of strength of the transverse field should weakly depend on the plasma density. The proton beam with the charge 50–200 pC, of the length of 3 mm and of the transverse size of 1 mm propagated from left to right along the plasma. The beam sizes were selected to be close to the typical parameters of the beams of the standard

PBT. The transverse sizes of the beams that are accelerated by laser radiation are usually noticeably less than $100\,\mu$m and the respective pressure gradients are less. As a result, the values of the electric fields can be higher by orders because it is possible to better focus the laser pulse and to respectively have the higher ponderomotive potential, but substantially lesser channel sizes are required.

The calculations were performed for the beam energy of 250 MeV without transverse pulses, the ideal beam. The plasma profile when $t = 0$, where $t = 0$ is a time of entry of the proton beam into the plasma, was selected to simulate transmission of the laser pulse and pre-defined in three kinds: the homogeneous plasma, the plasma with a density maximum in the center and the plasma with a density minimum in the center — the latter is for simulating the plasma that is created by radially-polarized laser radiation. With transmission of the proton beam, the plasma profile will substantially vary to affect the characteristics of the proton beam. It is technically difficult to simulate propagation of ionizing radiation and subsequent decomposition of the wakefield wave at the studied distances. For this reason, the initial conditions for the velocities of electrons in the plasma were pre-defined based on their initial energy of 9 keV (the relation of this temperature with the parameters of the laser pules is discussed below) and in dependence on the density profile. Thus, for the initially homogeneous plasma and the initially pre-defined plasma with the maximum in the center, the electrons got the equal energy and velocities for motion from the center; for the plasma that simulates effects of the radially-polarized laser pulse, the distribution was: the electrons symmetrically moved sideways from each maximum of the density. Initially, the plasma ions were at rest. In order to study a possibility of scattering, the center of the proton beam was shifted from the plasma maximum; in order to study focusing and scattering, the beam was placed in a center of an extremum of the plasma density.

Fig. 2 shows the dynamics of the proton beam in the low-dense plasma. Since propagation of the beam is slightly affected by such plasma, then it moves in a straight line. However, the plasma effect is noticeable and manifested in beam focusing. It density increases with the distance traveled. As noted, this effect is related to formation of the plasma channel with the positive charge that has a minimum in the center. Respectively, a force acting on the beam protons shifts them into the center. It is valid for a moderately large beam charge, when the plasma field is still larger than the field of the beam itself. In these calculations, the beam density is significantly less than the plasma density and this condition can be easily achieved. When the protons are accelerated by laser radiation, the density of the beam charge can be noticeably higher and compensation of the beam field may require increase of the plasma density and intensity of ionizing radiation. It is also noticeable that a small portion of the protons is decelerated during propagation of the beam, which is related to formation a longitudinal wakefield wave of the beam itself, and with increase of the plasma density the portion of the decelerated protons increases.

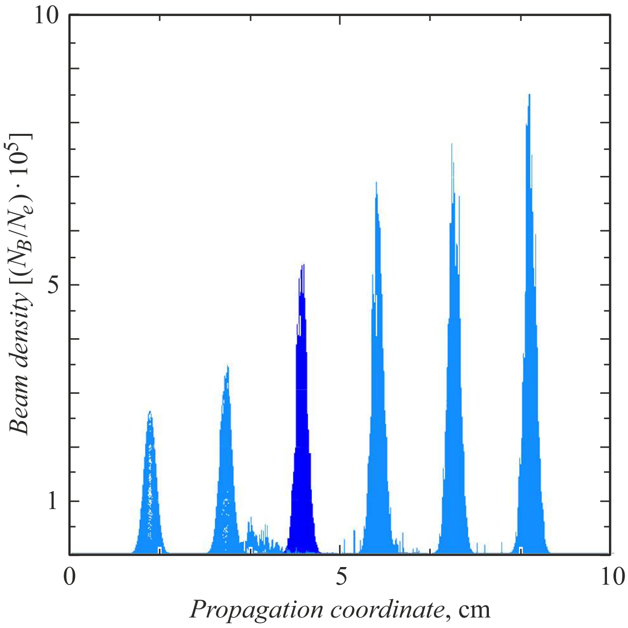

Figure 2. Propagation of the proton beam with the charge of 50 pC, the energy of 250 MeV in the plasma with the density of $N_e = 10^{15}\,\mathrm{cm}^{-3}$ and the initial electron temperature of 9 keV.

In order to find out how the plasma affects the characteristics of the beam, calculations were performed for the various profiles and a value of the plasma density within a small range. Fig. 3, *a* shows results of calculations of the profile of the proton beam after traveling for 10 cm in the plasma with initially homogeneous distribution of the density (the parameters of the plasma are given in Fig. 3, *b*). It can be seen that the density of the proton beam in the center has noticeably increases. It is a result of both beam focusing in the „explosive“ channel being formed and modulation of the proton beam by the transverse plasma wave. The modulation effect is manifested in that the distance between the density peaks is close to the length of the plasma wave, $\lambda_p = (\pi mc^2/e^2N_e)^{1/2}$. Fig. 3, *c* shows the momentums of all the beam protons, including distribution wings, so an area of the basic density of the beam is selected within the sigma that corresponds to normal distribution. Strong oscillations of the transverse momentum of the protons can be seen in the figure. As a result, after exit of the plasma the proton beam will be scattered with the transverse velocity $v \sim (2-3)m_e c/M_p$, where m_e — the mass of the electron and M_p — the mass of the proton. However, if the distance to the target is small, then the beam will be focused. It is interesting that proton collimation may be also affected by an increased density of electrons in the beam center. It is a purely plasmic process, since the density of the proton beam is by orders less than the plasma density. The similar pattern is observed in case of the plasma that is created by the radially-

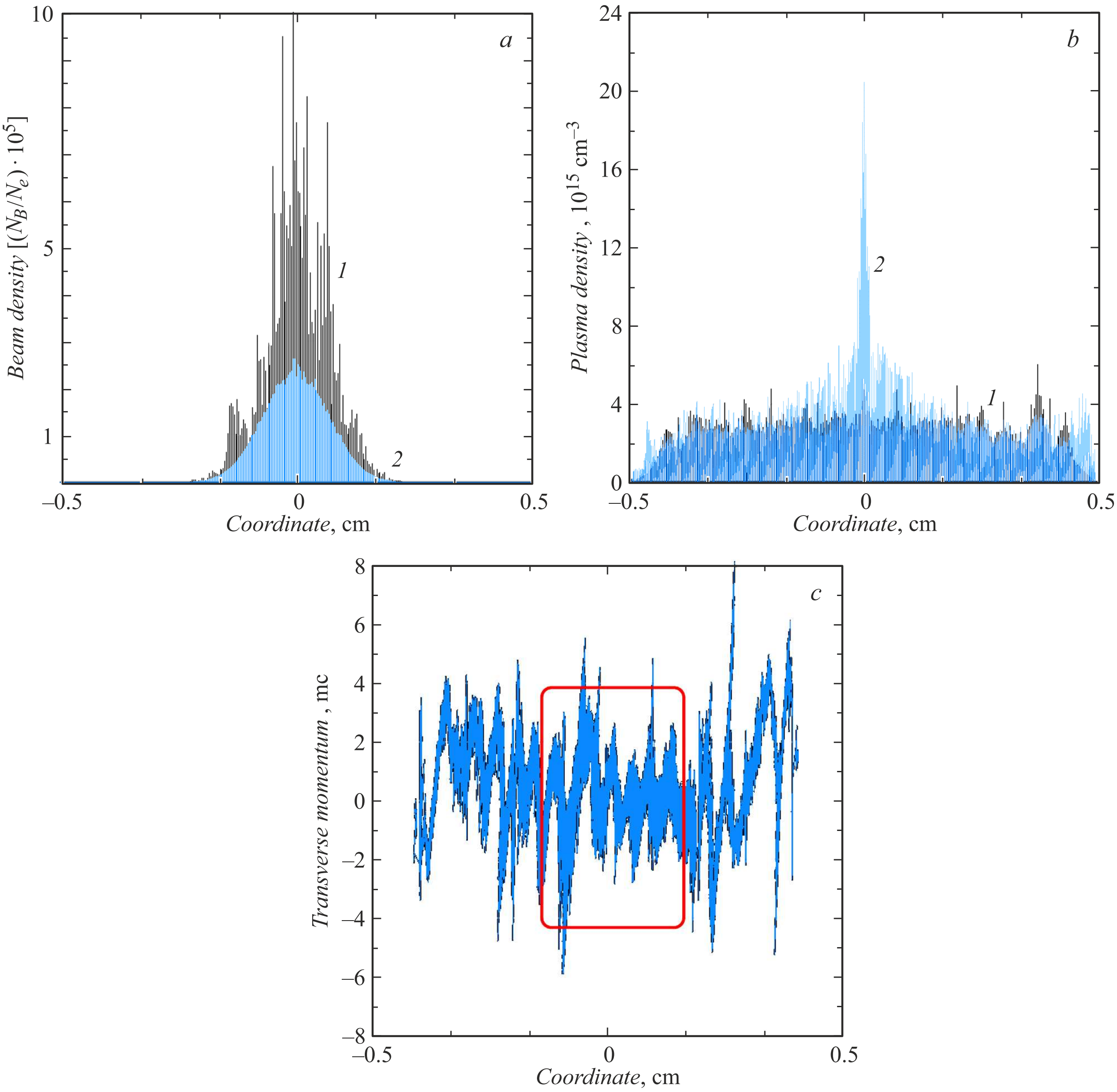

Figure 3. Parameters of the proton beam with the charge of 50 pC and the energy of 250 MeV after transmission of the distance of 10 cm in the homogeneous plasma with the density of $N_e = 10^{15}\,\mathrm{cm}^{-3}$ at the time $t = 0$; *a* — the profile of the proton beam after transmission of the plasma (*1*) and at entry into the plasma (*2*); *b* — the profile of electrons and ions of the plasma formed by the laser pulse with the ponderomotive potential ~ 9 keV; *c* — the distribution of the transverse momentum of the protons in the beam after transmission of the plasma; a selected area shows arrangement of the proton beam within the sigma, i.e. within the area of the maximum density of the beam.

polarized laser pulse (Fig. 4). Availability of the minimum of the plasma density and noticeable electron collimation in the beam center resulted in the proton focusing that is significantly increased by an order of the magnitude. At the same time, the transverse momentum of the protons is also increased (Fig. 4, *c*). It can be seen from Fig. 4, *c* that the typical velocity is $v \sim 8m_e c/M_p$. It is also noted that the velocity sign in the beam center is changed, which indicates direct focusing of the proton beam by the plasma.

Behavior of the beam of the protons that are shifted in relation to the plasma center is illustrated in Fig. 5. The figure shows the profiles of the beam densities (Fig. 5, *a, b*) with its various shifts from the center of the plasma with the profile shown in Fig. 5, *c*. You can see a dependence of the beam profile on a shift value that is determined by decreasing strength of the electric field when removing from the plasma center. Not only focusing of the beam of the protons is visible, but their noticeable shift to the plasma periphery is visible, too. At this, the value of the

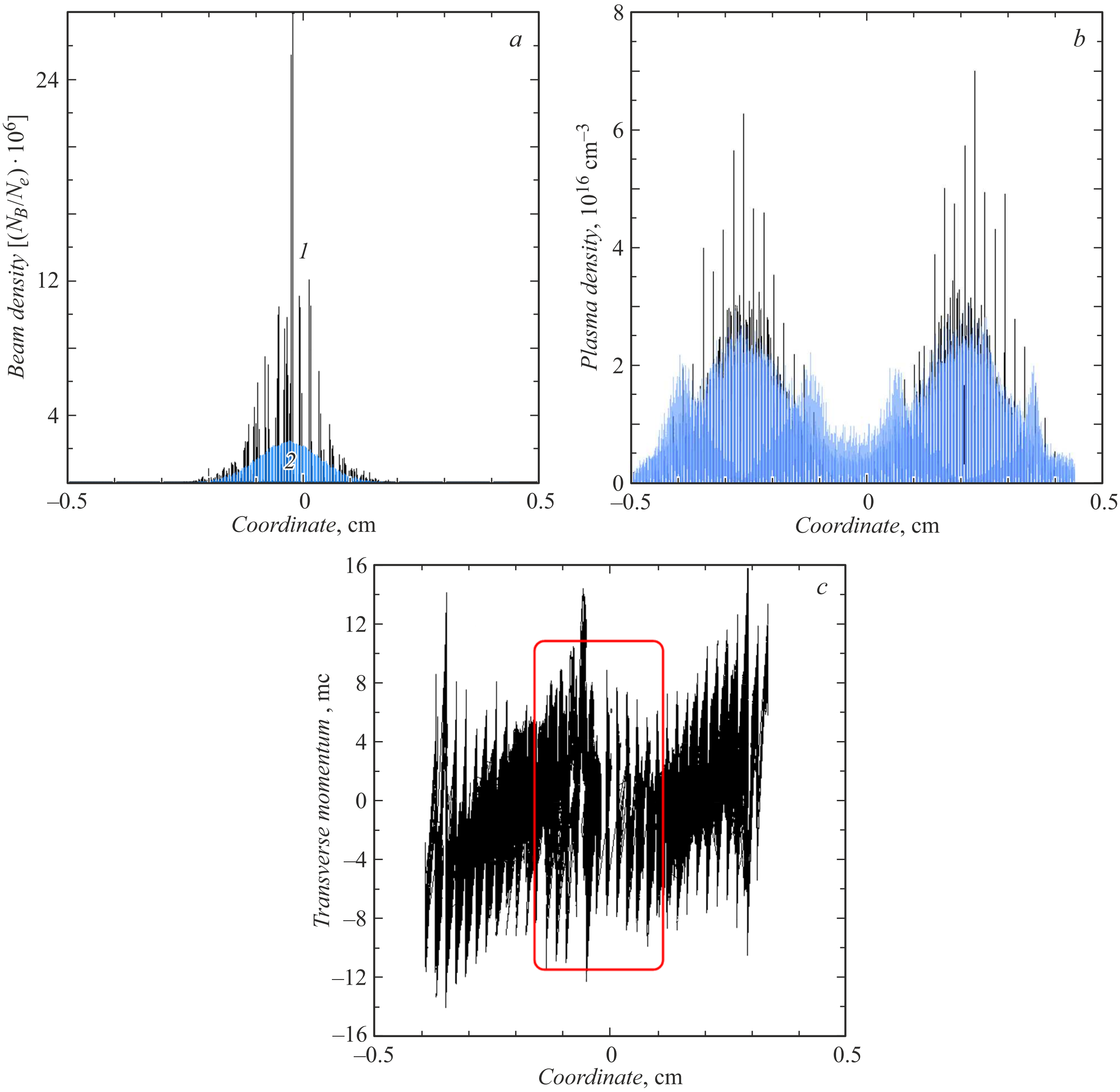

Figure 4. Parameters of the proton beam with the charge of 50 pC and the energy of 250 MeV after transmission of the distance of 10 cm in the plasma with the density of $N_e = 10^{15}\,\text{cm}^{-3}$, which is formed by the radially-polarized laser pulse; *a* — the profile of the proton beam after transmission of the plasma (*1*) and at entry into the plasma (*2*); *b* — the profiles of electrons and ions of the plasma formed by the ponderomotive potential of 9 keV; *c* — the distribution of the transverse momentum of the protons in the beam after transmission of the plasma; a selected area shows arrangement of the proton beam within the sigma.

transverse velocity of the beam reaches $v \sim 20 m_e c/M_p$ or $v \sim 4 \cdot 10^8$ cm/s (Fig. 5, *d*). We note that reduction of a diameter of the beam and the plasma can increase strength of the electric field by an order of the magnitude, but these parameters are only applicable for the beams of the protons that are accelerated by laser radiation from dense targets [6]. The important characteristic is the behavior of the plasma (Fig. 5, *b*). As you can see, relaxation of the low-density plasma requires significant time, thereby meaning that it is possible to use the plasma optics for long proton beams of an order of ten nanoseconds. However, for the continuous beams this technique may be inapplicable. A change of the plasma pressure in calculation within a magnitude order did not change significantly the behavior of the proton beams in transmission of 8–10 cm of the plasma. However, the increase of the plasma density to $N_e = 10^{17}\,\text{cm}^{-3}$ at these lengths resulted in noticeable increase of beam duration by deceleration of the protons by the longitudinal laser field. Increase of the protons of the beam by 1–2 orders of the magnitude did not result in a noticeable change of the

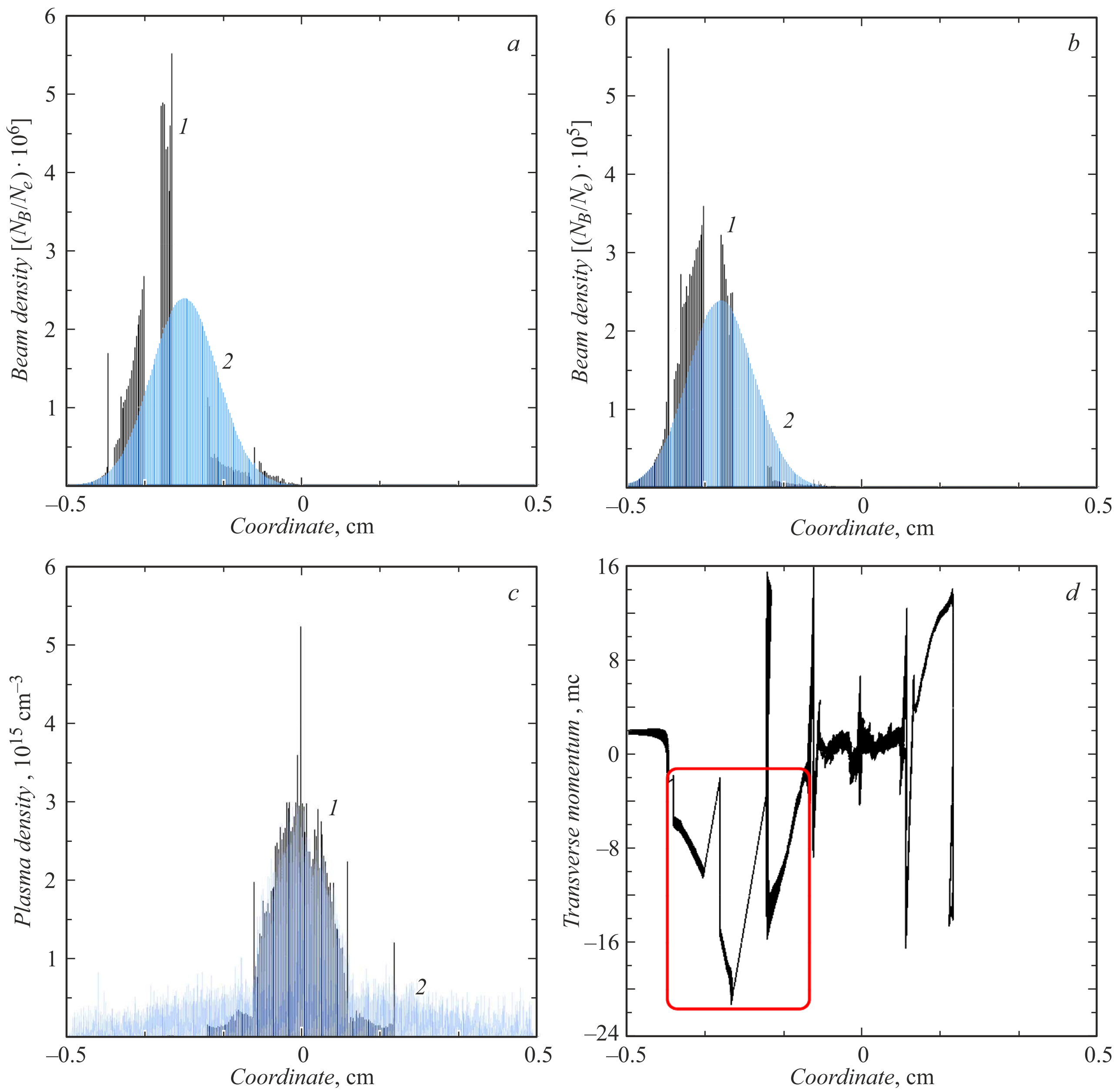

Figure 5. Parameters of the proton beam with the charge of 50 pC and the energy of 250 MeV after transmission of the distance of 10 cm in the plasma with the density of $N_e = 10^{15}$ cm^{-3} with a transverse size that is comparable to the transverse size of the beam; *a, b* — the profiles of the proton beam shifted in relation to the plasma center by 2, 5 and 3 mm, after transmission of the plasma (*1*) and at entry into the plasma (*2*); *c* — the profile of electrons and ions of the plasma formed by the ponderomotive potential of 9 keV; *d* — the distribution of the transverse momentum of the protons in the beam after transmission of the plasma with parameters as shown in Fig. 5, *b*, a selected area shows arrangement of the proton beam within the sigma, i.e. within the area of the basic density of the beam.

process dynamics, since in all the cases it was significantly lower than the plasma density. It should be noted that in case of the beams of the protons accelerated by laser radiation influence of the protons of the beam can be significant due to its high initial density.

Conclusion

This study is the first to have considered usability of superstrong transverse electric fields in the plasma that is created by optical ionization by means of laser pulses to affect a trajectory of motion of nonrelativistic proton beams. For this purpose, the particle-in-cell method was taken to calculation motion of the nonrelativistic proton beams in the „explosive" plasma channel that was formed as a result of optical ionization of the gas by the short laser pulse. The results show that in principle it is possible to use such plasma channels for controlling and correcting the proton beams for beam therapy. The maximum effect of focusing is achieved primarily in the plasma that is created by radially-polarized laser pulses which form the plasma with the density minimum at the beam propagation axis. At the same time, scattering of the proton beam requires the plasma with the density maximum in the axis center. The focusing process weakly depends on the plasma density in the considered range and the full charge of the beam. This result may be violated for the beams of the protons that are formed by laser radiation due to the high initial density of the beam.

Since the electron temperature is determined by intensity of the laser pulse, then strength of the field and, the transverse velocity of the protons, respectively, also depend on its intensity. The maximum momentums of the plasma electrons nonlinearly depend on intensity of laser radiation. The transverse velocities of the protons can be up to 10^9 cm/s and significantly affect subsequent dynamics of the beams. However, real application of this technique depends on transverse sizes of the beam. Although, the density of the proton beam is usually low, its formation of the wakefield wave at the large lengths results in energy losses. The calculations show that the field strengths weakly depend on the plasma density as it should be as per the known expression $E_\perp = -\nabla_\perp[N_e T_e(a_0)]/eN_e$. It largely determines selection of the density of an optical element. Formation of the initial electron temperature of about 10 keV at the plasma length ~ 10 cm and at the transverse sizes of about $1-2$ mm that are typical for the beams of conventional accelerators requires the energy of about $0.2(N_e/10^{15}\,\mathrm{cm}^{-3})$ J. Whence, it is clear that the low plasma densities seem to be more preferable. Besides, increase of the plasma density affects th energy parameters of the ion beam. However, creation of this temperature requires a high ponderomotive potential or a quite large value of a_0. It may present certain difficulties for large transverse sizes. Thus, when judging by the above-mentioned estimate of the ponderomotive potential, it is required that $a_0 \sim 0.3$ for the temperature of about $10-20$ keV . For the Ti-Sph-laser with the wavelength of $\lambda = 0.8\,\mu$m, the required power approaches a petawatt level. Although these lasers are already widely used, their application may be economically unjustified. However, the magnitude a_0 is indirectly related to power of the laser pulse. Thus, for the pulse of the CO_2-laser (the powerful short-pulse CO_2-laser are actively designed [38,39]), with the same value of a_0 as for the pulse of the Ti-Sph-laser, the intensity is requried to be in 150 times less with the same focusing spot. The CO_2-lasers can turn out to be a good candidate for forming the plasma optics for the heavy particles. The low plasma density makes it impossible to use waveguide capabilities of the plasma, thereby limiting the longitudinal size of the plasma channel by a Rayleigh length of the pulse — $L_R \sim \pi D^2/4\lambda$, where D is a diameter of focusing of the laser beam, λ a wavelength of its radiation. For example, for the pulse with the wavelength of1 μm and the channel length of about 10 cm, the diameter of the laser beam shall not be less than 200 μm, while for the CO_2-laser it shall be at least 0.5 mm. The transverse sizes of the ion beams that are formed during laser acceleration are significantly smaller and, therefore, it is possible to use higher intensities of laser radiation and stronger fields, respectively, in the plasma channels, possibly, of the higher density. But even for the wide-aperture proton beams it is possible to affect a small part of the beam in the plasma when using low-power laser pulses.

Although formation of the „explosive“ plasma channels, even of meter-long sizes [30], is well established [25,40], the performed calculations are still preliminary. The dependences of the plasma optics parameters, such as the optimal density, duration and intensity of the laser pulses require more detailed calculations, which, however, are relevant after experimental check of influence of the „explosive“ plasma channels on dynamics of the nonrelativistic proton beams.

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Conflict of interest

The author declares that he has no conflict of interest.

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