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ФИЗИКА И ТЕХНИКА УСКОРИТЕЛЕЙ

THE NONLINEAR TRANSFORMATION OF AN ION BEAM IN THE PLASMA LENS

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The plasma lens can carry out not only sharp focusing of ion beam. At those stages at which the magnetic field is nonlinear, formation of other interesting configurations of beams is possible. Plasma lens provides formation of hollow beams of ions. Application of several plasma lenses allows one to get a conic and a cylindrical beams. The plasma lens can be used for obtaining beams with homogeneous spatial distribution. Calculations and measurements were performed for C^{+6} and Fe^{+26} beams of 200–300 MeV/a.u.m. energy. The obtained results and analysis are reported.

Плазменные линзы могут осуществлять не только острую фокусировку ионного пучка со значительным сокращением размера фокусного пятна. На тех этапах плазменного разряда, на которых магнитное поле является нелинейным, возможно формирование других интересных конфигураций ионного пучка. Плазменная линза обеспечивает формирование полых пучков ионов. Применение нескольких плазменных линз позволяет получать конические и цилиндрические пучки. Плазменные линзы могут быть использованы для получения пучков с однородным пространственным распределением. Расчеты и измерения проводились для пучков C^{+6} и Fe^{+26} с энергией 200–300 МэВ/нуклон. Приведен анализ полученных результатов.

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INTRODUCTION

The ion beam focusing in the plasma lens is carried out as shown in Fig. 1. The discharge current produces an azimuthal magnetic field. The ions are injected along the lens axis, and the radial Lorentz force focuses the ion beam [1].

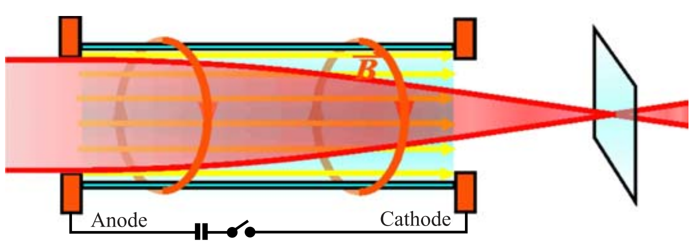


Fig. 1. Ion focusing in a plasma lens

In the current generator (see table) cold-hollow cathode thyratrons (pseudospark switches) TDI1-200k/25H [2] are employed to form a stable discharge with peak current up to 250 kA. TDI-thyratrons in plasma lens generator avail to operate in a mode of long energy-intensive pulse. The time sweep of the luminosity of the plasma and the discharge current for short pulse mode and long pulse mode are shown in Figs. 2 and 3.

Hamped shape of the long current is due to the fact that part of the capacity (25 μF) has low self-inductance. The focusing properties of plasma lenses depend on the current density distribution along the radius of the plasma discharge. The current distribution across the tube changes significantly during the discharge. Therefore, plasma lens, in general, is nonlinear.

Features of discharge current generator

Parameter	Short pulse mode	Long pulse mode
Switch (2 ps)	Thyratron TDI1-150/25	Thyratron TDI1-200k/25H
Discharge current pulse duration	$T = 5$ μs at $C = 25$ μF	$T = 20$ μs at $C = 160$ μF
Max. discharge current	$I = 200$ kA at $T = 5$ μs	$I = 400$ kA at $T = 20$ μs

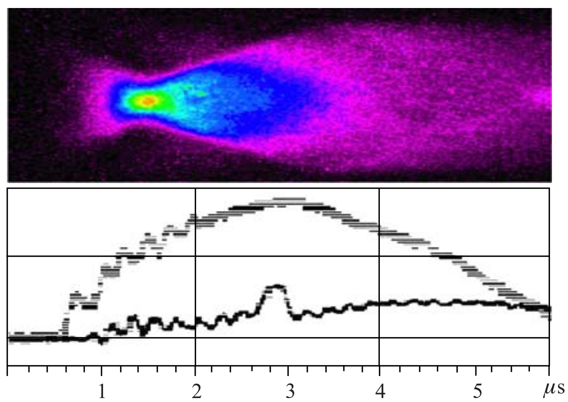


Fig. 2. Time scanning of a discharge luminescence and a discharge and beam currents for short pulse mode

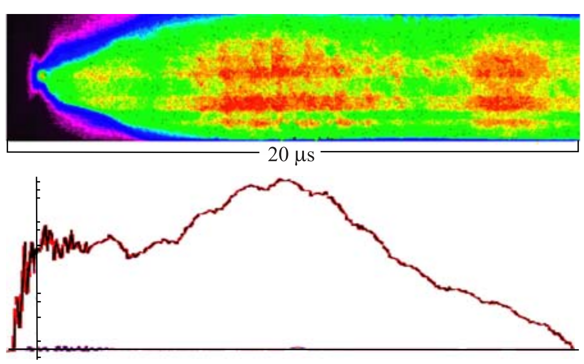


Fig. 3. Time scanning of the discharge luminescence and current for long pulse mode

Uniform current distribution exists for a limited time, so the plasma lens, as a device for sharp focusing, operates for about 1 μs or less. As a nonlinear focusing device, the plasma lens can be used to produce beams of special shape. The research was conducted at the following parameters: the discharge tube radius $R = 1$ cm and its length $L = 10$ cm, argon pressure 1–8 mbar, the ion beam duration 300 ns.

FORMATION OF THE HOMOGENEOUS BEAM

Usage of ions beams for irradiation of various objects, in particular, for medical purposes, demands creation of a homogeneous field of an irradiation. The initial beam, as a rule, has the Gaussian distribution. For alignment irradiation fields use the special filters-absorbers. This solution spoils however the quality of irradiation fields and essentially reduces the efficiency of beams. The solution of this problem is possible by means of the nonlinear focusing device. A simulation was conducted for research into opportunities of plasma lenses to solve this problem. It appears that it is possible to get homogeneous distribution of ion density for a case of equilibrium distribution of a discharge current. At enough large duration of a current pulse of > 10 μs, current distribution is tending to equilibrium one. A similar distribution is the «quasi-Bennett» distribution, which was applied in the study of a high-current arc discharge [3]:

$$j = \frac{I(1+\tilde{A})}{\pi R^2}\left(1+\tilde{A}\left(\frac{r}{R}\right)^2\right)^2, \tag{1}$$

where R — plasma lens aperture, I — discharge current. The value $\tilde{A}$ is a function of the discharge current, the plasma temperature and the plasma conductivity.

The results of the first experiments (beam of C^{+6} ions with energy 300 MeV/u, current half-wave — 20 μs) are presented in Fig. 4 The ion density distribution was obtained by averaging of the scintillator luminosity over the angle around the beam axis.

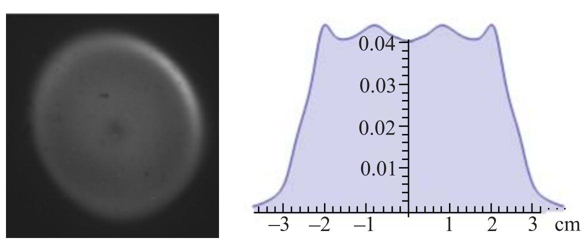


Fig. 4. The light output from the scintillator and the density distribution of the ion C^{+6} at 8.5 μs after beginning of discharge at a distance of 110 cm for a current of 80 kA. The spot rms diameter is 40 mm

The calculated distributions of density of ions in a beam of C^{+6} (300 MeV/u, $z = 150$ cm) are shown in Fig. 5.

The initial distribution is adequate to the beam injected into the plasma lens. The transformed distribution was obtained in the plasma discharge which has the «quasi-Bennett» distribution (1) where $\tilde{A} = 0.85$.

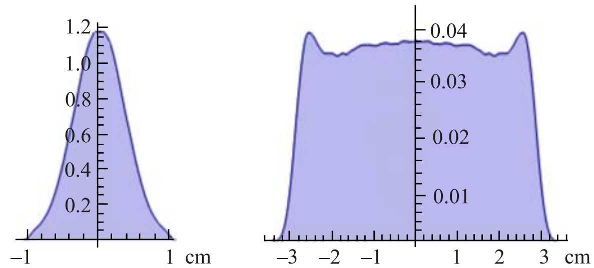


Fig. 5. The initial and transformed distributions

As we can see, transformation of a Gaussian beam into a homogeneous one can be carried out effectively, and with observance of the geometrical sizes demanded at a medical irradiation: the size of a beam spot and drift distance behind the lens.

FORMATION OF HOLLOW BEAMS

Hollow beams can be used for the implosion of thermonuclear targets [4]. Possibility of that transformation of ion beams has been demonstrated experimentally in GSI [5]. Researches carried out on the ITEP plasma lenses confirmed these opportunities in a wide range of operating modes of lenses [6, 7].

Experimental results concerning formation of a hollow beam of small diameter, less than 1 cm, are shown in Fig. 6.

The paraxial beam with zero emittance is converted to a tube beam, when the distribution of azimuthal magnetic field in the plasma lens is as follows:

$$B = a + br, \tag{2}$$

where a and b are constants. This distribution takes place when distribution of the discharge current density is a superposition of a homogeneous distribution and a singular one, inversely proportional to radius r:

$$j = I_0 \pi R^2 + I_s. \tag{3}$$

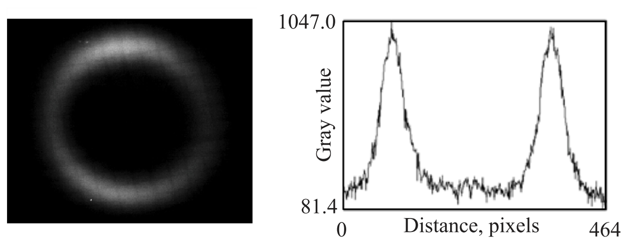
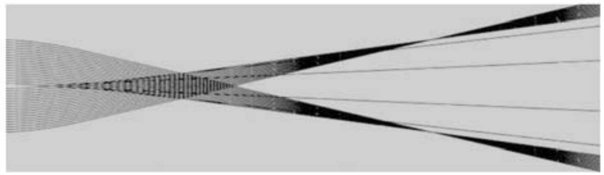


Fig. 6. Light output from scintillator and the density distribution of ion Fe^{+26} at 1.7 μs after beginning of discharge at a distance of 30 cm for a current of 150 kA. The ring diameter is 9 mm



|-*L*-|----------------------------*Z*--------------------------------|

Fig. 7. The picture of trajectories of a beam of ions

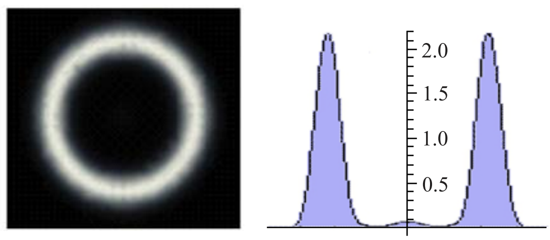


Fig. 8. The light output from a scintillator and the distribution of ion Fe^{+26} density calculated in the model approximation for the experimental condition

Here R is plasma lens aperture, within which there are a homogeneous current I_0 and a singular one I_s. In this lens the ion beam is focused into a ring of radius

$$\rho = \frac{RI_s}{I_0} \tag{4}$$

at a distance

$$Z_0 = \frac{RP}{B_0 L}, \tag{5}$$

where L is length of the lens and P is rigidity of the beam of ions. Note that Z_0 is equal to the focal length of the lens in the absence of a singular component of the current. The role of the latter is to create an r-independent component of the field, which causes the coherent deflection of ion trajectories through the angle ρ/Z. The picture of ions trajectories is shown in Fig. 7.

Our mathematical model gives (Fig. 8) adequate ion beam distribution for the described experiment, if $I_s/I_0 = 0.3$.

TWO-STAGE BEAM TRANSFORMATION

Another possible application of a plasma lens is formation of a converging conic beam by means of two plasma lenses. In this case the problem of an irradiation of certain area is solved in such a way as to not affect the previous adjacent zone. The results of calculations for C^{+6} (200 MeV/u) beam focused by two lenses are shown in Fig. 9.

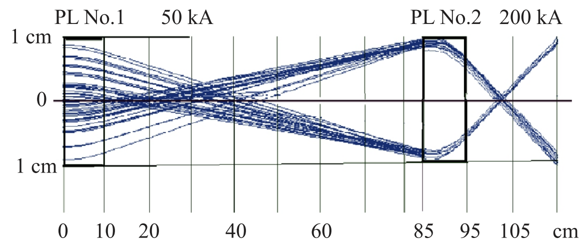


Fig. 9. Formation of a converging conic beam by means of two plasma lenses

In this case we used the distributions of discharge currents close to real ones. We can see that it is possible to get a conic beam and, as a special case, cylindrical one.

CONCLUSION

The plasma lens can carry out not only sharp focusing of ion beam with considerable reduction of sizes of focal spot. At those stages of the plasma discharge at which the magnetic field is nonlinear, formation of other interesting configurations of beams is possible.

The plasma lens can be used for transformation of beams with Gaussian distribution of particles density in beams with homogeneous spatial distribution.

The plasma lens provides formation of hollow beams in a wide range of parameters which allows one to consider it as a possible variant of a terminal lens for realization of inertial thermonuclear synthesis.

Application of several plasma lenses which are in different stages of the plasma discharge presumes to create some special spatial configurations of ion beams.

Thus, the plasma lens essentially represents the universal device able to form beams for scientific and technical applications.

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