THE NONLINEAR TRANSFORMATION OF A IONS BEAM IN THE PLASMA LENS

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Abstract

The focusing capabilities of a plasma lens depend on the stage of plasma development. Under certain conditions a magnetic field is linear, that allow focusing the beam to a very small spot. In other conditions, the magnetic field is nonlinear, that allow formation of hollow and others beam structures. Calculations and measurements were performed for a C+6 and Fe+26 beams of 200 MeV/a.u.m. energy. The obtained results and analysis are reported.

INTRODUCTION

The focusing properties of plasma lenses depend on the current density distribution along the radius of the

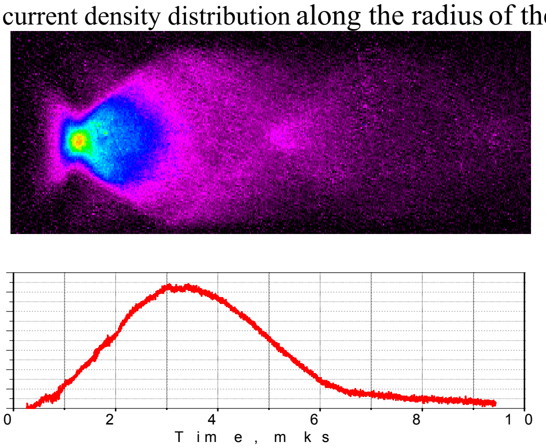


Fig. 1: Time scanning of the discharge luminescence and current.

plasma discharge [1]. Fig. 1 shows the time sweep of the luminosity of the plasma and the discharge current. The created magnetic field compresses the plasma-current cylinder. Expansion of the plasma column with a current takes place later and the discharge fills the whole tube. Current distribution across the tube changes significantly during the discharge. Therefore, plasma lens, in general, is nonlinear. Uniform current distribution longs for a limited time, so the plasma lens, as a device for sharp focusing, operates for about 1 microsecond or less. As a non-linear focusing device, the plasma lens can be used to produce beams of special shape. In particular, to create hollow beams, which can be used for the implosion of thermonuclear targets [2].

Test for sharp focusing of carbon ions has been conducted at ITEP in 2007-2008 [3]. These researches were continued in [4] to investigate possibilities of hollow beams formation. Lens parameters were as follows: capacitance - 24 µF; discharge current - 150 kA; current half-wave - 5 µs; argon pressure – 1-5 mbar; ion beam duration – 300 ns (fig. 2). The discharge tube has radius of R = 1 cm and length of L = 10 cm. The effect of beam focusing was detected by the luminescence of a thin quartz scintillator. Fig. 3 shows crossections of the beam at position of 30 cm behind the lens as function of time during injection of the beam.

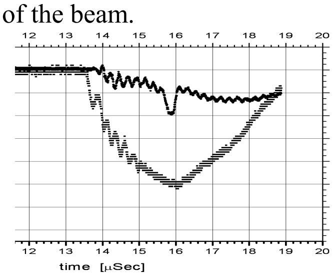


Fig. 2: Oscillograms of the discharge and the beam current.

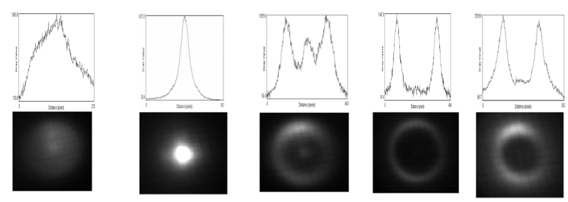


Fig. 3: The light output from a scintillator and the distribution of ion Fe^{+26} density for T > 0 behind discharge switch

FORMATION OF HOLLOW BEAMS

Possibility of transformation of ion beams with such plasma lenses has been demonstrated experimentally in GSI [5]. Researches carried out on the ITEP plasma lens confirmed this opportunities in a wide range of operating modes lens.

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

$$B = a + br, \qquad (1)$$

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

$$j = I_o/\pi R^2 + I_s/2\pi Rr. \qquad (2)$$

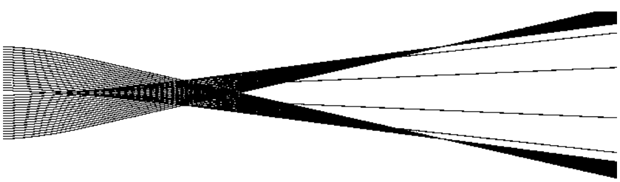
Here R - plasma lens aperture, within which there are a homogeneous current, Io and a singular one, I_s. In this notations $B = B_o (r/R + I_s/I_o),$ (3)

where *Bo* - the field strength due to uniform current Io of the discharge radius *R*. In this lens the ion beam is focused into a ring of radius

$$\rho = R\, I_s / I_o \qquad (4)$$

at a distance $Z_o = R\, \Re / B_o L,$
(5)

where *L* - length of the lens and $\Re$ – rigidity of the beam of ions. Note that Z_o is equal to the focal length of the same plasma lens in the absence of a singular component of the current. The role of the latter is to create a independent from *r* component of the field, which causes the coherent deflection of ion trajectories on the angle ρ / *Z*. The picture of trajectories of ions C^{+6} with energy of 200 MeV/a.e.m is shown in fig. 4. Radial thickness of the hollow beam at the position of the ring vanishes in this approximation.



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

Fig. 4: The picture of trajectories of a beam of ions

It is not necessary to have the extreme electric current distribution to obtain a hollow beam, satisfying the practical requirements. For real electric current distributions the annular ring will have finite thickness, and a nonzero density of particles will be inside the cavity. If real core size of the `singular' component is much smaller, than the beam diameter, then number of particles inside the cavity is negligible. Taking into account real beam phase volume leads to considerably weaker differences between the actual current distribution in the plasma lens and the ideal model introduced above. What distribution exists in reality can be estimated by comparing the characteristics of the beam obtained in the experiment with different variations of the numerical models.

Fig. 5 shows the experimental results about formation of a hollow beam of relatively small diameter, less than 1 cm.

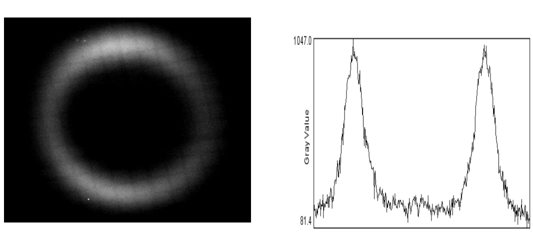


Fig. 5: Light output from scintillator and distribution of ion Fe^{+26} density at 1.7 μs after beginning of discharge at distances of 30 cm for discharge current of 150 кА. The ring diameter is 9 мм .

Our mathematical model describing the experiment gives quite similar ion beam distribution, when *Is/Io* = 0.3 (fig. 6).

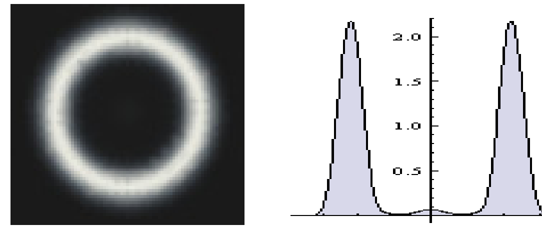


Fig. 6. The light output from a scintillator and the distribution of ion Fe^{+26} density calculated in the model approximation for the experimental condition.

FORMATION OF THE HOMOGENEOUS BEAM

Usage of ions beams for irradiation of various objects, in particular, in medical purposes, demands creation of a uniform field of an irradiation. The initial beam, as a rule, has the gaussian distribution. For alignment irradiation fields use special filters-absorbers [6]. This solution spoils however quality of irradiation fields and essentially reduces efficiency of beam. Solution of this problem is possible by means of the nonlinear focusing device. A simulation were conducted for to research opportunities of plasma lenses to solve this problem. It appears that it is possible to get uniform distribution of ion density for a case of so called ‘equilibrium distribution’ of a discharge current. At enough long, but quite real duration of a current pulse of <10 μs, current distribution is believed to tend to so called Bennet's distribution [7]:

$$j = I_o / \pi R^2 \,(1 + (r/R)^2)^2. \qquad (8)$$

Fig. 7 shows distributions of density of ions in a beam of C^{+6} (200 MeV/n): the initial distribution and the distribution received as a result of the beam transformation in a plasma lens.

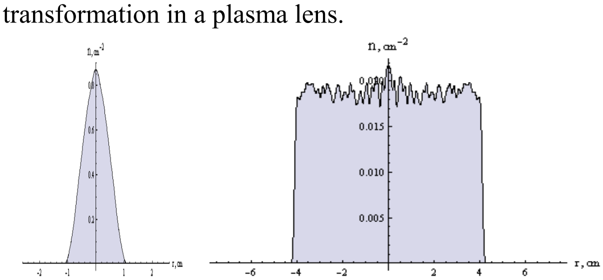


Fig. 7. The initial and transformed distributions.

Apparently, transformation can be carried out effectively, and with observance of the geometrical sizes demanded at a medical irradiation: the size of a stain and distance to it.

TWO-DIMENSIONAL TRANSFORMATION OF THE BEAM

Other possible application of a plasma lens is formation a converging conic beam by means of two plasma lens. In this case the problem of an irradiation of certain area is solved without influence in the previous zone. Fig. 8

shows results of calculations for C^{+6} (200 MeV/n) beam focused by two lenses with distributions of a discharge currents that are close to the real ones. We can see that it is possible to get a conic bunch and, as a special case, cylindrical one.

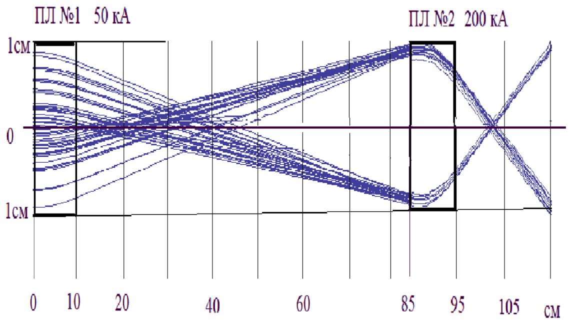


Fig. 8. Formation a converging conic beam by means of two plasma lens.

CONCLUSION

The plasma lens can carry out not only sharp focusing of ions beam with considerable reduction of their sizes. 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 provides formation of hollow beams of ions in a wide range of parameters that allows to consider it as a possible variant of a terminal lens for realization of inertial thermonuclear synthesis.

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

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

Thus, the plasma lens essentially represents the universal tool for preparation of a beams for the decision of scientific and applied technical problems.

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