INVESTIGATION OF THE FORMATION OF A HOLLOW BEAM IN THE PLASMA LENS*

A.Drozdowskiy, N.Alexeev, S.Drozdowskiy, A.Golubev,
A.Kuznetsov, Yu.Novozhilov, S.Savin, B.Sharkov, V.Yanenko. ITEP, Moscow, Russia

Abstract

At ITEP established high-current plasma lens, which carried a strong focus ion beams. However, lens ensures the formation of tubular ion beams in a wide range of parameters. The report presents the results of studies on the ion beam with C^{+6} and Fe +6 to 200 MeV / amu. The analysis of the results.

INTRODUCTION

An experimental facility for investigation of the physics of high energy densities in matter is being created at ITEP on the basis of the accelerator-accumulator complex TWAC (Terawatt accumulator) [1]. A plasma lens is planned to be used as the last stage of the TWAC focusing channel. The focusing properties of plasma lenses depend on the current density distribution along the radius of the plasma discharge. 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. Then the expansion of the plasma column with a current up to full fill the discharge tube. This occurs within a half-cycle current variation in the discharge circuit. The process of discharge depends on the initial gas pressure in the volume of the tube and on speed of the current rise. As seen from these figures, the current distribution changes significantly during the discharge. Therefore, plasma lens, in general, is nonlinear. The uniform distribution is a limited time, so the plasma lens, as a device for sharp focusing, can be used to beams by duration of about 1 microsecond or less. As a non-linear focusing device, a 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].

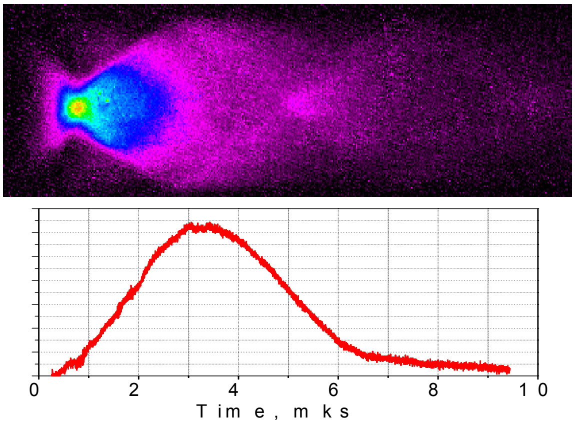
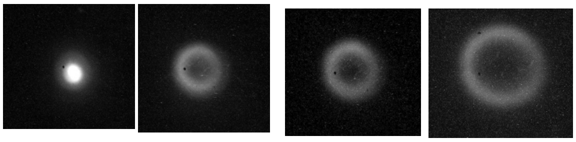


Fig. 1: Time scanning of the discharge luminescence and current.

In the 2007-2008 test for sharp focusing of carbon ions beam of with energy of 200 MeV/a.e.m have been conducted. Then experimental researches the possibility of using the lens for the formation of hollow beams was begun.

FORMATION OF HOLLOW BEAMS

Reality converting conventional ion beam in the tube one has been demonstrated experimentally in the GSI [3]. Research carried out on the plasma lens ITEP, confirmed the possibility of creating such beams in a wide range of operating modes lens. Fig. 2 shows the mapping of C^{+6} ion beam with energy 200 MeV / amu. on the scintillator.



20 см 30 см 35 см 45 см

Fig.2: Ringlike light output from a scintillator for the different distances behind the discharge tube

Numerical studies have shown that a necessary condition for creation of the beam with an internal failure of the density distribution is the presence of a core for distribution of the discharge current in the plasma lens. The question arises: which of the current distribution leads to the formation of tubular ion beam? The problem was solved by us as a thin lens. In this case, the paraxial beam with zero emittance is converted to a tube, if the distribution of azimuthal magnetic field in the plasma lens is given by $B = a + br,$ (1)

where a and b - constants. This distribution is obtained if the distribution of the discharge current density is a superposition of a homogeneous distribution and the singular, decreasing inversely proportional to the distance r from the axis of the lens:

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

Here R - plasma lens aperture, within which there is a homogeneous current Io and the singular I_s. In this notation $B = B_o\,(r/R + I_s/I_o),$ (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

$$Z_O = R\,\Re/B_oL, \qquad (5)$$

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 rotation of the particles on the angle ρ / Z.

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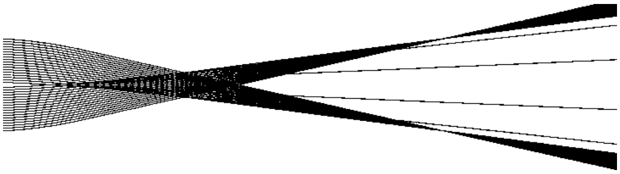
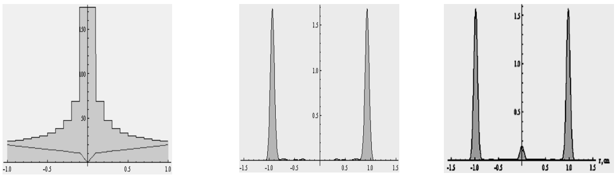
On fig.3 the picture of trajectories of a beam of ions C^{+6} with energy of 200 MeV/a.e.m is shown. For the considered approximation, the thickness of the layer in the plane of the ring is zero.



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

Fig. 3: The picture of trajectories of a beam of ions

Upon receipt of a hollow beam, satisfying the practical requirements, which, of course, admit the nonzero thickness of the annular layer and the nonzero density of particles inside the cavity, the distribution of the discharge current should not be so extreme. For example, if the size of a homogeneous core of the discharge current is much smaller than the beam, and the number of particles inside the cavity is negligible. In Fig.4 presents the current density distribution of ions formed in the tubular beam in the case of stepwise approximation of the theoretical distribution of the discharge current in the lens (2) with core radius 0.1R for zero beam emittance, as well as in the case of the analytical distribution (2) for the real beam emittance (R=1 cm, L=10 cm, z=18 cm, ρ=1 cm, Is / Io=1, Is + Io=100 kA).



a *в* *c*

Fig. 4: Distribution of ion density with a discrete distribution (a) discharge current for the emittance E=0 (b) and the analytic distribution for E=10 mm mrad (c).

As we see, the account of real size of phase volume of a focused beam eliminates the effect of differences between the actual current distribution in the plasma lens from the model of an ideal thin lens. What distribution exists in reality, can be estimate by comparing the characteristics of the beam obtained in the experiment with different variations of the numerical models.

EXPERIMENTAL STUDY

The lens parameters were as follows: capacitance - 24 μF, discharge current - 150 kA, current half-wave - 5 μs, argon pressure – 1-5 mbar. Ion beam current pulse length – 300 ns (fig. 5). The a lens discharge tube has size: R = 1 cm and L = 10 cm. The effect of focusing the beam was detected by the luminescence of a thin quartz scintillator. Fig.6 shows what it looks like a beam of ions at a distance of 30 cm from the lens during the injection of ions into the lens at the time T after its switch.

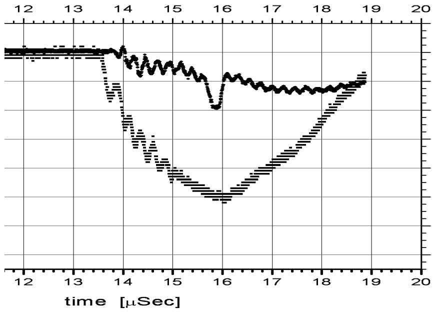
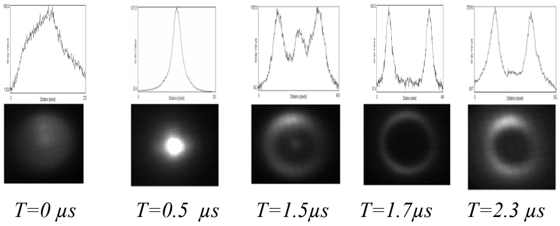


Fig. 5: Oscillograms of the discharge current and the beam current.



T=0 μs *T=0.5 μs* *T=1.5μs* *T=1.7μs* *T=2.3 μs*

Fig. 6: The light output from a scintillator and the distribution of ion Fe^{+26} density for T > 0 behind discharge switch

Fig. 7 shows the dependence of geometrical parameters in cross-section tubular beam of the distance behind of the plasma lens. As seen from these dependences, the beam acquires a distinct tubular structure at a distance from the lens of 35 cm, and a satisfactory quality at a distance of 45 cm.

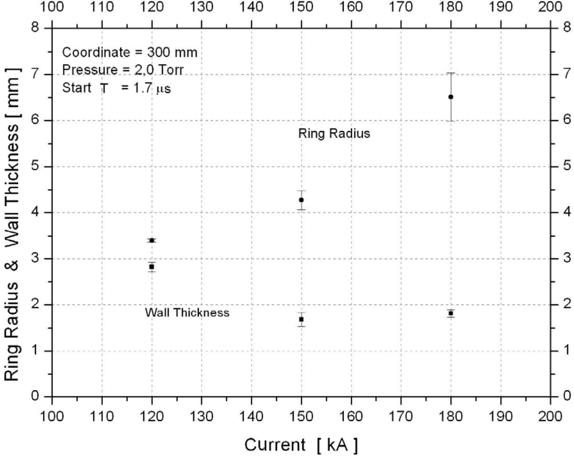


Fig. 7: Dependence of the geometric parameters in cross-section tubular beam of the distance behind the plasma lens

Fig. 8 shows the measured dependence of the geometric parameters of a tubular beam formed from the amplitude of the discharge current. The lens begins to form a tubular structure at the amplitude of the discharge current ≥ 120 kA. For zones of satisfactory tubular beam at a distance of 30 ÷ 40 cm from the lens current amplitude

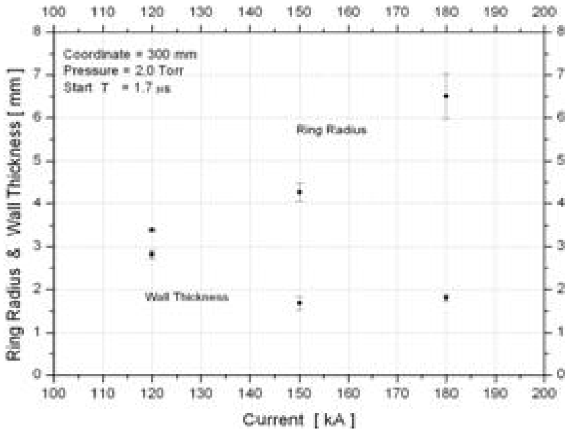


Fig. 8: Dependence of the geometric parameters in cross-section tubular beam of the discharge current.

must be greater than 150 kA (with decreasing amplitude of the current distance increases). Also studied the dependence of the tubular beam quality from the gas pressure in the discharge tube. Best argon pressure is 1.5 - 2 Torr.

SIMULATIONS OF THE PLASMA LENS AND EXPERIMENTAL RESULTS

Numerical calculations of the dynamics of the plasma inside the discharge tube of the plasma lens have been carried out and current distributions in plasma are defined. The calculations were carried out in one-dimensional MHD approximation [1, 4]. The influx of the substance in the plasma due to evaporation of the discharge tube material is taken into account. Calculated density distributions of the discharge current and ions in the focused beam at the time of pinching of the plasma discharge shown in fig. 9. The most appropriate experimental data was the distribution of ion density in the focused beam, corresponding to the time of pinching plasma.

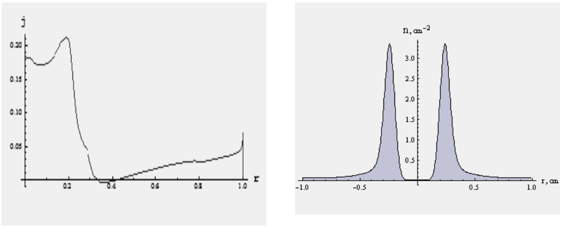


Fig. 9: The current density distribution in the plasma and focused ion distribution at z = 230 mm and T=1.3 ms after the discharge switch, calculated in the MHD approximation.

Fig. 10 shows the experimental results related to the formation of a tubular beam of relatively small diameter, less than 1 cm.

We see good qualitative agreement of numerical calculation and experimental results. At the same time, the calculation of the ideal model with the same value of the discharge current does not give adequate results. This is explained by the presence of the wall current due to evaporation of the discharge tube material.

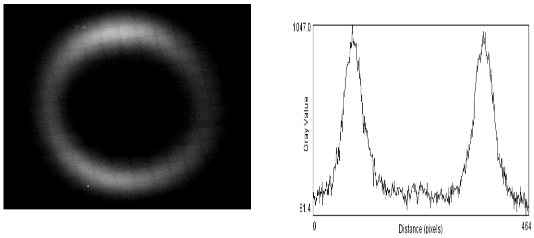


Fig. 10: The light output from a scintillator and the distribution of ion Fe^{+26} density in time 1.7 μs behind discharge switch for distances 30 см and discharge current 150 кА. The ring diameter - 9 мм .

CONCLUSION

The plasma lens ensures provides the formation of tubular ion beams in a wide range of parameters. The plasma lens operates at relatively small currents, $I \geq 100$ kA and allows to create a tubular beam of relatively small diameter (less than 1 cm), corresponding to the size of the cylindrical target for the HIT [2]. That allows us to consider it as an option terminal lens for inertial confinement fusion.

The theoretical dependence of the distribution of the discharge current in a thin lens to form ideal hollow beams with predetermined sizes are received. The plasma lens operates at relatively small currents ($I \sim 100$ kA) and with a good approximation can be regarded as a thin lens.

The technique of numerical simulation allowing on the basis the experimental data about focusing the ion beam in a plasma lens to determine its physical characteristics in detail is developed.

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