CONVERSION OF BEAMS IN THE PLASMA LENS AND INVESTIGATION OF Z-PINCH DYNAMICS

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The plasma lens can carry out sharp focusing of ion beam. At stages of the plasma discharge at which the magnetic field is nonlinear, formation of other configurations of beams is possible. The discharge current distributions obtained by calculation ensure the experiment. Possibility of the research of the plasma discharge dynamics by means of relativistic ions beams is shown.

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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, 2].

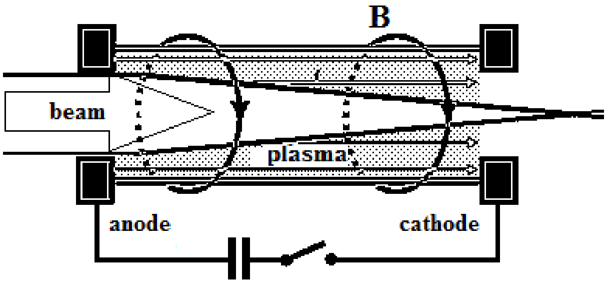

Fig. 1. Ion focusing in a plasma lens

The studies of possibility of use of a plasma lens were carried out at ITEP both for sharp focusing, and for formation of tubular beams and beams with homogeneous distribution of density [3 - 5]. In the current generator (Table) cold-hollow cathode thyratrons (pseudospark switches) TDI are employed to form a stable discharge. Researches were carried out of ion beams of carbon and iron with energy 200…300 Mev/a.e.m. Duration of an impulse of a current of the plasma was 5 and 20 μs, and the duration of an impulse of a current of an ion beam – 0.3 μs. Sizes of a discharge tube: length – 10 cm, diameter – 2 cm. Pressure of gas (argon) before a discharge impulse was of 0.5…10 mbar.

Features of discharge current generator

Short pulse mode	
Switch (2 pcs) Discharge current pulse duration Max discharge current	Thyratron TDI1-150/25 T = 5 μs at C = 25 μF I = 200 kA at T = 5 μs
Long pulse mode	
Switch (2 pcs) Discharge current pulse duration Max. discharge current	ThyratronTDI1-200 k/25H T = 20 μs at C = 160 μF I = 400 kA at T = 20 μs

The time sweep of the plasma luminosity for short and long pulse mode are shown on Figs. 2 and 3.

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

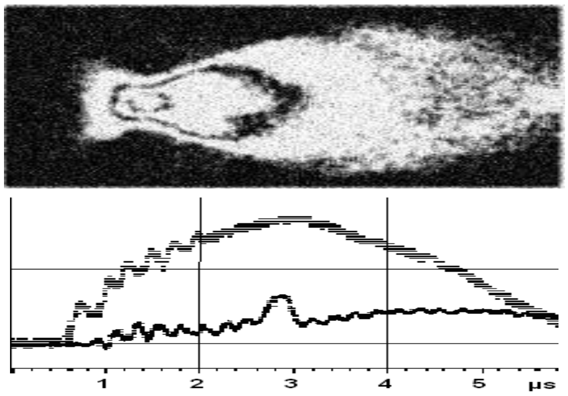

Fig. 2. Time scanning of discharge luminescence and discharge and beam currents for short pulse mode

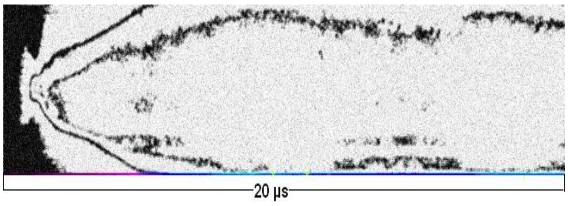

Fig. 3. Time scanning of discharge luminescence for long pulse mode

The current distribution across the tube changes significantly during the discharge. Therefore, plasma lens, in general, is nonlinear. 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 non-linear focusing device, the plasma lens can be used to produce beams of special shape.

1. Z-PINCHS DYNAMIC RESEARCH

Research of that implosion of plasma and mechanisms of penetration into it a magnetic field is a fundamental scientific problem. The understanding of the mechanisms defining distribution of a current in plasma is absolutely necessary for thermonuclear synthesis, lasers in the field of XUV and soft X-ray, powerful beams of ions, transportation of powerful laser beams, focusing of powerful beams of ions, etc.

Active corpuscular diagnostics, based on application of special beams of atoms and ions, have considerable development. The principal problem for using that technique is a limited transparency of plasma for beams. Therefore the relativistic energy beams are necessary for plasma research. Meanwhile in plasma lens creation Z-pinches for a wide interval of parameters is possible: with a current to 0.5 MA at duration of impulses of 1…30 μs.

We developed a numerical technique of receiving distribution of currents and self magnetic fields in the plasma lens, adequate to the configurations of an ion beams received experimentally. Finding of distribution of discharge current at which the focusing magnetic field of a lens will transform an ion beam to a look received in experiment, is carried out in the following way. The discharge current distributions in z-pinch is represented in the form of a quasipower series:

$$j = \frac{I}{\pi R^2}\left(\frac{s_b\,(1+b)^2}{(1+bx^2)^2} + s_{-1}x^{-1} + s_0 + s_1x^1 + s_2x^2 + s_3x^3 + \ldots \right),$$

where $I = \Sigma I_x = I \Sigma s_x$.

The first term corresponds to a stationary distribution of a discharge current. A similar distribution is the “quasibennett” distribution, was applied in the study of a high-current arc discharge [6]. The special case of this distribution is Bennett's distribution:

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

The third term correspond the uniform distribution which for a beam is a linear lens which allows to carry out ideal sharp focusing. The combination of the second and third terms is responsible for the ideal transformation of a beam into tubular structure [4]. Terms of a high order are responsible for current which is closer to wall.

Based on the experimental distribution of the beam focused by a lens and considering noted above property of terms of our approximation, distribution for the first iteration gets out. Thus it is possible to find the distribution of discharge current adequate to experiment rather small amount (<10) iterations.

The results of experimental researches of influence of a plasma lens on a beam of ions with Gaussian distribution of density at various stages of development of the plasma discharge are shown on Fig. 4. The each column of the figure corresponds to a certain moment of time after the beginning of the plasma discharge: 0.5, 1.7 and 8.5 μs. The light output from the scintillator behind lens is shown on the first line of the figure. The experimental distributions of ion beam density are shown on the second line. The correspondence self-magnetic field distributions are shown on the third line. The modeling self-magnetic field z-pinch distributions are shown on the fourth line.

2. COMPARISON OF THE EXPERIMENTAL RESULTS AND MHD-SIMULATIONS

The beam diagnostics gives important information concerning spatial distribution of electric current across the discharge of the investigated type. This causes a question about correspondence of these data with the theory of z-pinches as well as with results of MHD simulations. To clarify this question we used the one-dimensional MHD code NPINCH. It adopts all dissipative processes in plasma and was successfully used for simulation of capillary discharges of different types. See refs [7, 8].

One of the main questions that should be answered concerns a role of evaporation from inner wall of the discharge insulator tube, which interacts with discharge plasma, ionization of these vapours and engaging of this new plasma in the discharge. Preliminary very rough estimations show that the present discharges are close to the threshold of the evaporation. The method of inner wall evaporation description, used in refs. [7, 8], was tested there and in other publications for fast capillary discharges with typical current rise time of the order of 0.1 μs, when the evaporation threshold was surely overcame. In the present case the typical discharge time is 10…100 times longer. For this reason it is not so obvious in advance that the same simplified method can be applicable for these discharges also.

Let us consider at first discharges with the typical current ~ 150 kA and its half period ~ 5 μs. Under assumption that there is no evaporation, dynamics of plasma in such discharge would be characterized by detachment of plasma from the discharge tube inside wall at the very beginning of the discharge and to unreal strong compression of the plasma at the axis. Such strong compression would lead to strong implosion of the whole current to a very thin pinch. This contradicts apparently to experimental data and, in particular, to the data about field distribution across the discharge. See Fig. 4.3 for t = 7 μs. This apparent and strong contradiction means that more or less smooth distribution of the current over the whole discharge including the outermost parts of it is possible only if there is a significant evaporation from inner walls of the discharge tube. Mass of plasma formed from the vapors that joints the discharge should be comparable with the initial mass of argon inside the tube. Our next step is to include evaporation of inner wall material and plasma formation from these vapors in MHD-simulation. We use the same method for description of this evaporation as previously in publications mentioned above. We assume that the whole heat flux from the discharge plasma toward the walls is spent for formation of new plasma. Thus we neglect completely initial period of the discharge when the wall surface is heated up to sufficiently high temperature ~1000 K and the energy of the discharge that was spent to this latent heating. Results of such simulations are presented in Fig. 4.4 (col. 1, 2).

Our simulations show that radial current distribution changes dramatically after taking into account stays in outer parts of the discharge including very close vicinity of the wall. Magnetic field distribution becomes qualitatively similar to that takes place in the experiment. About 60% of the total current flows in the central region of the discharge that occupies about 15% of its cross-section. The remaining current flows in outer discharge region. As a result we may conclude that the experimental data indicate to a considerable role of new plasma formed from evaporated material of the walls.

Turn now to the longer discharges with ~ 20 μs half-periods and about ~ 60 kA peak currents (Fig. 4.4, column 3). In this case there is no plasma detachment from the walls even, if we neglect evaporation from the walls. As a result current is distributed across the whole cross-section more or less uniformly even without taking into account wall evaporation. As a result there is no rough contradiction of our simulations without the evaporation with the experiment. It is in contrast to the previous case. Thus there are no apparent arguments for existence of evaporation in this case. Nevertheless more detailed analysis of radial current density distributions says that there is a bump of experimental current density that does not correspond to simulations. We may conclude that wall evaporation plays probably some role in this case also. It appears however we cannot simulate unlimited evaporation with the Lagrange code NPINCH for such long lived discharges. The reason of this situation is that this hydro-code cannot to take into account kinetics of phase transitions that is necessary to describe considerable discontinuity of electric conductivity between hot dielectric and plasma. However we have presently no suitable code without this disadvantage. Such code should be likely an Euler one.

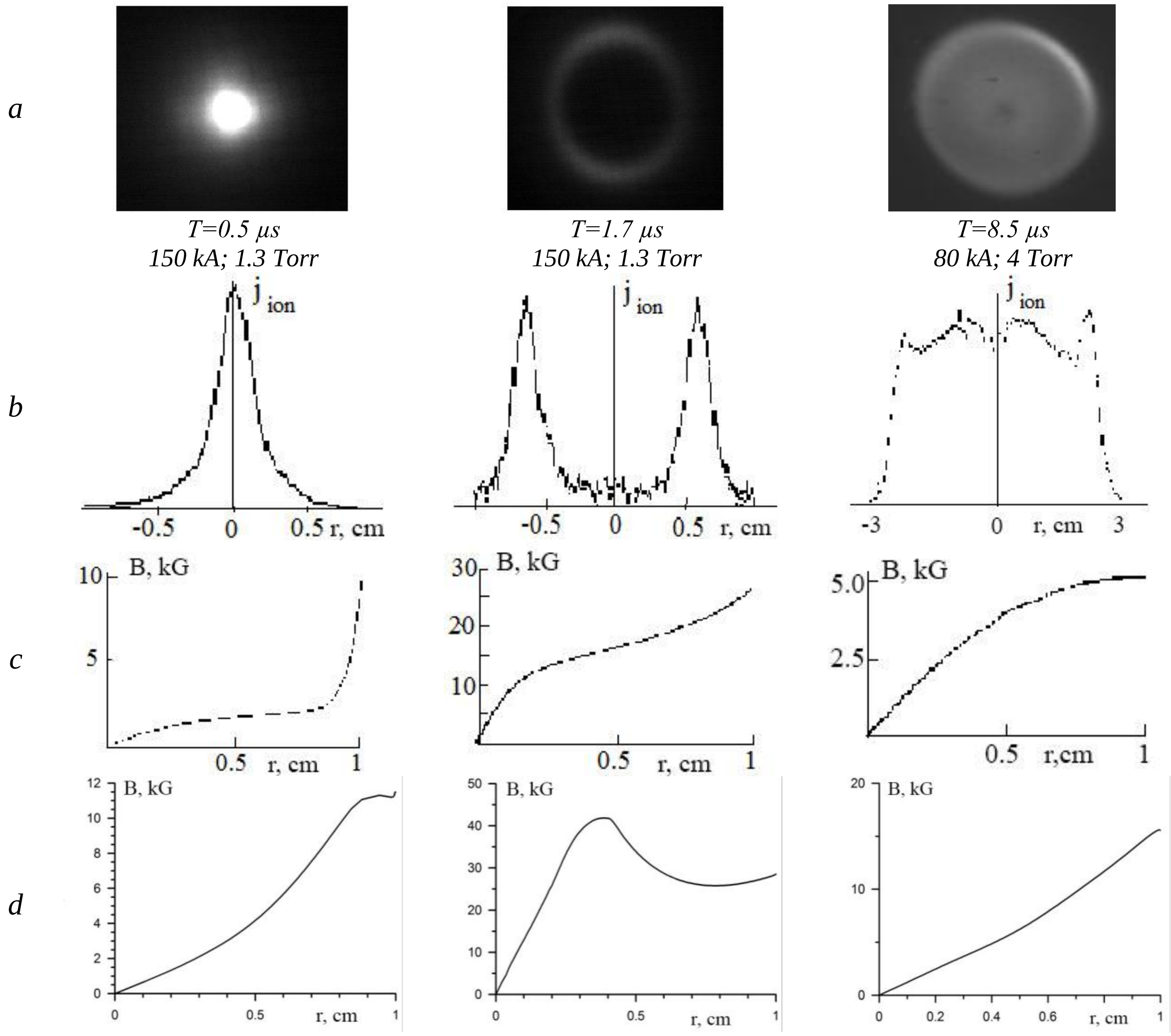

Fig. 4. The results of experimental researches of plasma lens influence on ion beams and comparison of selfmagnetic field B z-pinch, defined from experimental data and MHD theoretical modeling: light output from scintillator (time after the beginning of the plasma discharge) (a); density ions distribution was obtained from the scintillator luminosity (b); magnetic field strength obtained by mathematical processing of experimental data (c); magnetic field strength obtained by MHD simulations (d)

CONCLUSIONS

The plasma lens can carry out not only sharp focusing of ion beam with considerable reduction of focusing spot. At those stages of the plasma discharge at which the magnetic field is nonlinear, formation of other special configurations of beams is possible. The plasma lens provides transformation the Gaussian beam into hollow one and into beam with homogeneous spatial distribution. The plasma lens essentially represents the universal tool for preparation of beams for the decision of scientific and applied technical problems, in particular for irradiation of medical objects and as a possible variant of a terminal lens for realization of inertial thermonuclear synthesis [9].

The discharge current distributions obtained by numerical calculation ensure the experimental beam transformations. Thus possibility of the research of the plasma discharge dynamics by means of relativistic ions beams is shown.

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ПРЕОБРАЗОВАНИЕ ИОННЫХ ПУЧКОВ ПЛАЗМЕННОЙ ЛИНЗОЙ И ИССЛЕДОВАНИЕ ДИНАМИКИ Z-ПИНЧЕЙ

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Плазменные линзы могут осуществлять не только острую фокусировку ионного пучка на тех этапах плазменного разряда, на которых магнитное поле является нелинейным, возможно формирование других интересных конфигураций ионного пучка. Разработана численная методика получения распределения тока в плазменной линзе, адекватная фокусирующим свойствам линзы. Продемонстрирована возможность исследования динамики плазменного разряда с помощью релятивистских пучков ионов.

ПЕРЕТВОРЕННЯ ІОННИХ ПУЧКІВ ПЛАЗМОВОЮ ЛІНЗОЮ І ДОСЛІДЖЕННЯ ДИНАМІКИ Z-ПІНЧЕЙ

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Плазмові лінзи можуть здійснювати не тільки гостре фокусування іонного пучка на тих етапах плазмового розряду, на яких магнітне поле є нелінійним, можливе формування інших цікавих конфігурацій іонного пучка. Розроблено чисельну методику отримання розподілу струму в плазмовій лінзі, адекватну фокусуючим властивостям лінзи. Продемонстрована можливість дослідження динаміки плазмового розряду за допомогою релятивістських пучків іонів.