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PHYSICS AND TECHNIQUE OF ACCELERATORS

Plasma Lens for the Heavy Ion Accelerator at ITEP[1]

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Abstract—Efficient focusing of intense heavy ion beams is an important issue for heavy-ion driven inertial confinement fusion and for investigations of high energy densities in matter produced by heavy ion beams. Here, the description and the results of performance investigation of a plasma lens designed for the heavy-ion accelerator–accumulator facility TWAC-ITEP are presented.

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INTRODUCTION

The main advantage that a plasma lens has over a quadrupole one is that the focusing forces correspond to the magnetic field strength in the first order of its magnitude along both coordinates, and there is no limitation for the field strength due to the magnetic saturation of iron; inside the lens, there is a neutralization of the spatial beam charge, and the magnetic beam rigidity is significantly reduced in the process of focusing due to the ionization of the beam ions in the lens plasma. Plasma lenses started being intensively developed in the middle of 1970's. Direct experiments with focusing heavy ions were conducted in 1994–1997 at GSI on the SIS-18 accelerator [1]. A 300 MeV/u beam of neon ions (Ne^{10+}) and a beam current of up to 350 kA were focused onto a 300 μm spot.

On the bases of the TWAC-ITEP (Terawatt Accumulator) complex, a new facility is being built at ITEP to conduct research at high energy densities in matter [2, 3]. As a performance goal, heavy ions should be accelerated to ~0.7 GeV/u and accumulated in the amount of up to ~10^{13} particles per pulse for ~10^{-7} s. At the last stage of beam focusing, a plasma lens is supposed to be used.

In accordance with the principal goals of this project, the following activities have been undertaken:

• a pulse-power generator of unipolar current was developed;

• a stable unipolar discharge with a current of up to 250 kA and duration of 5 μs was achieved in the discharge tube of the plasma lens;

• an experimental investigation of the plasma lens performance was conducted and a range of parameters was determined where it is possible to obtain a uniform current density with a linear dependence on the focusing forces;

• numerical simulations of the plasma lens performance have been conducted and a conceptual model has been formulated, providing an adequate interpretation of the experimental results.

THE DESIGN OF A PULSE-POWER GENERATOR WITH UNIPOLAR CURRENT

Ion beam focusing in a plasma lens is achieved as follows (see Fig. 1). The discharge current J produces an azimuthal magnetic field H, which exerts a radial Lorentz force on beam ions injected along the lens axis; as a result, the ion beam is focused towards the axis. Usually, an LC-circuit with a high-current commutator is used as a current generator.

Then the time dependence of the plasma lens current takes the form of attenuating oscillations. The oscillating character of the current reduces the resource of the lens commutator and of the discharge unit. The generator scheme adopted here is distinguished by inclusion of a permalloy inductor to obtain unipolar current pulses (see Fig. 2).

In the final scheme of the generator, TGI-150k/25 thyratrons with a cold cathode are used as commutating elements.

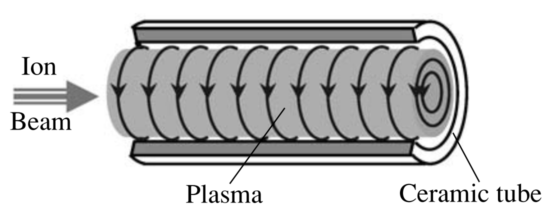

Fig. 1. Ion focusing in a plasma lens.

[1] The text was submitted by the authors in English.

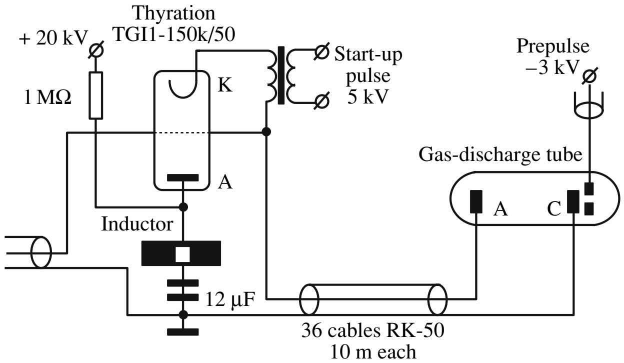

Fig. 2. Functional scheme of the current generator for the plasma lens.

PLASMA LENS DESIGN

Figures 3 and 4 show pictures of the constructed plasma lens. Figure 3 gives a general view of the installation. The principal supporting element is a solid disk of stainless steel.

It is adjoined on one side by a current receiving unit (left part of Fig. 4), which collects the current-carrying cables. On the opposite side is the cathode unit, which has a gas-discharge tube placed between two graphite electrodes (right part of Fig. 4).

In the first series of experiments, gas discharges (in a z-pinch mode) were performed in a quartz tube that could withstand discharge loads of up to 100 kA. For higher currents, thick-wall ceramic tubes with an inner diameter of 20 mm were used. A Rogovskii coil, placed between the supporting disk and the current receiving unit (central part of Fig. 4), was used to measure the current amplitude.

Besides the Rogovskii coil, one clearly sees the anode cup attached to the disk by a caprolon insulator. Vacuum pumping was done with a forevacuum pump. The high pumping rate allowed the working gas to be let into the vacuum cavity continuously through the inlet, which ensured steady conditions for gas discharges.

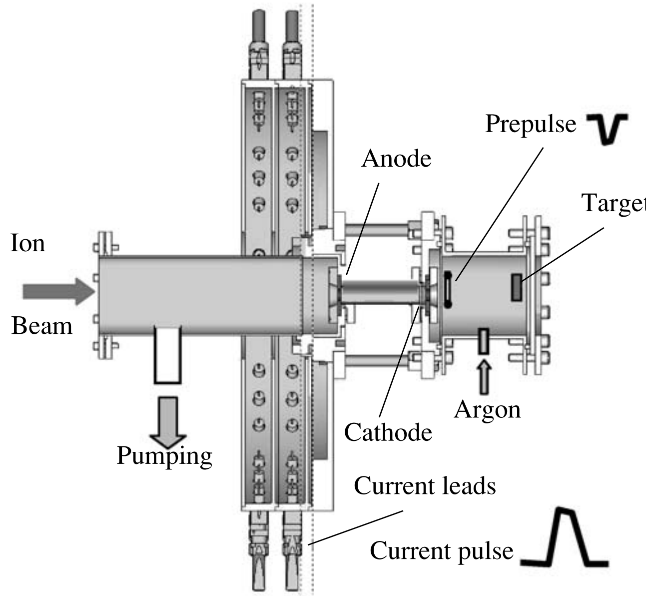

Fig. 3. Scheme of plasma lens.

To stabilize the discharge process, the working gas has to be pre-ionized. To this end, an additional short (shorter than 5 mm) discharge tube has been mounted behind the cathode, followed by a ring electrode which receives a 3 kV negative voltage pulse 5 μs before the main discharge. As a result, an axially symmetric preliminary discharge supplies plasma into the main tube, which ensures the stable performance of the entire plasma lens.

EXPERIMENTAL STUDY OF THE LENS PERFORMANCE

Experimental testing of the plasma lens at this stage was aimed primarily at achieving the stable performance of all systems. By varying the working gas (argon) pressure and generator voltage, the parameter range of stable lens performance was determined. Tem-

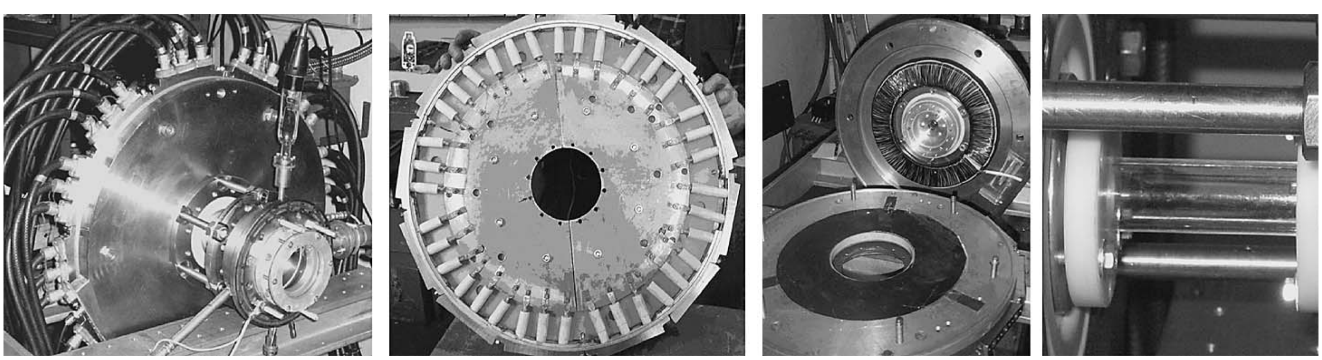

Fig. 4. Plasma lens units: general view of the plasma lens on its test bed (on the left), the current receiving section, the inner part (Rogovskii coil around the anode cup), the cathode unit with the gas-discharge tube (on the right).

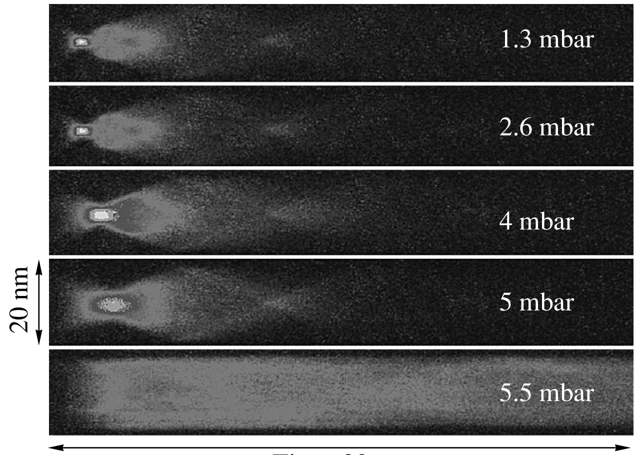

Fig. 5. Plasma pinch dynamics at different argon pressures, J = 80 kA.

Fig. 6. Temporal scan of the plasma emission for the initial argon pressure of 3.5 mbar and the discharge current of 200 kA; the total scan duration is 6 μs, the transverse size is 2 cm.

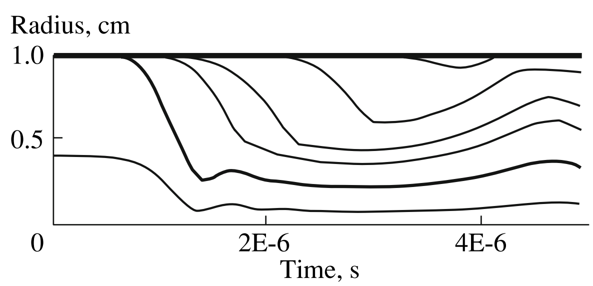

Fig. 7. Trajectories of radial plasma motion. The interface between the argon and the wall-material plasma parts is shown as a thick blue line.

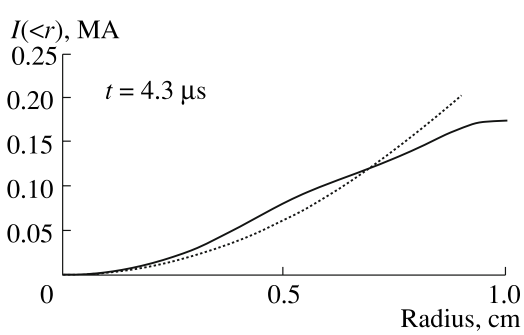

Fig. 8. Total current inside a radius as a function of this radius. Dashed curve corresponds to a uniform current-density distribution.

poral and spatial discharge dynamics have been investigated by measuring the plasma optical self-emission in the transverse direction with the electron-optical converter in the slit-scan regime.

Figure 5 shows the temporal dependence of the plasma emission at different gas pressures. Argon was used as a working gas; the electric current value was fixed at 80 kA. Figure 6 shows the temporal scan of the transverse plasma size and luminosity at a discharge current of 200 kA.

As a result of tuning all the lens components, a quasi-uniform current density distribution has been achieved near the maximum of the discharge current for the initial gas pressure of 3.5 mbar and the peak current value of 200 kA, which is confirmed by a quasi-uniform light emission from the plasma volume shown in Fig. 6.

NUMERICAL SIMULATIONS OF THE PLASMA LENS PERFORMANCE AND A CONCEPTUAL MODEL OF THE DISCHARGE PLASMA DYNAMICS

To elucidate the key physical processes which govern the plasma dynamics and the current density distribution inside the discharge tube, a series of model numerical simulations with the one-dimensional MHD code NPINCH [4] have been carried out.

Different models for plasma interaction with the ceramic walls of the discharge tube have been tried. It was found that a qualitative agreement with the experimental data can only be achieved when the evaporation of the wall material is taken into account. Visible expansion of the discharge region can be explained as a result of the wall plasma colliding with the central argon pinch; simulations show that the two plasma parts carry over comparable portions of the total discharge current. The following discharge parameters have been used in simulations: an initial argon pressure of 2.7 Torr, a discharge tube radius of 1 cm, a discharge-current pulse with a half-period of 7.5 μs, and a current amplitude of 180 kA. The calculated trajectories of plasma motion and the radial distribution of the discharge current at $t = 4.3$ μs are shown in Figs. 7 and 8. These curves have been obtained under the assumption that the evaporation energy threshold for ceramic is significantly surpassed.

General conclusions from the conducted simulations can be formulated as follows: when properly accounted for, wall evaporation allows the adequate interpretation of the discharge plasma dynamics; the evaporated wall material contributes substantially to the overall amount of plasma and plays an important role for current-density redistribution over the discharge volume. These conclusions were not initially expected and require further experimental verification.

CONCLUSIONS

The key elements of the plasma lens have been designed and fabricated. Investigating the plasma discharge formation confirmed the functionality of the original physical and technical solutions implemented in the high-current generator and the plasma lens. Testing the principal technological units was completed, and a discharge current of 200 kA was achieved with spatial distribution suitable for ion beam focusing.

These accomplished tasks allow us to move on to the next stage of optimizing the discharge parameters aimed at reaching the required focusing ability of the plasma lens. A plasma lens is planned to be installed in the exit channel of the TWAC accelerator complex by the end of 2007, when it will begin to be tested for focusing a carbon ion beam.

ACKNOWLEDGMENTS

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