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GENERAL EXPERIMENTAL TECHNIQUES

A Radial Injection Plasma Source

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Abstract—A plasma source and a new method for filling a mirror magnetic trap with plasma are described. Experimental results on target plasma generation are presented.

To obtain a hot plasma in open magnetic systems with conventional methods, a trap is preliminarily filled with a relatively cold target plasma, which is subsequently irradiated with atomic beams or RF radiation. A gas-discharge plasma source positioned outside the trap is usually used for generating a target plasma, and the plasma flows into the trap along the lines of force of the magnetic field. Unfortunately, there is an obvious contradiction between the necessity of placing the source as far from the trap as possible (i.e., in a weaker magnetic field) to decrease the main high-temperature plasma flow to the source and the desire to increase the source employment efficiency, which abruptly decreases with the distance to the trap because of the plasma-filled parasitic volume between the trap and the source and as a result of instabilities developing in an inhomogeneous transporting magnetic field.

Here, we describe a new method for filling magnetic traps with a target plasma. The method consists in direct filling of a trap with a plasma from a circular gas-discharge source, which encompasses the middle part of the trap, in a changed (injecting) magnetic field with a fast subsequent reset of the initial field geometry. The injecting field has geometry such that the plasma jet injection to the trap can be considered radial. However, this technique is not a method for transverse plasma injection, when a dense plasma bunch is injected transverse to the magnetic field as a result of arising polarization electric field [1]. This method is suggested to be used for generating a target plasma in the central solenoid of the AMBAL-M ambipolar adiabatic trap. The plasma source design was adapted (Fig. 1) to the geometry of the MAL installation (a small adiabatic trap), where experiments were performed. The injecting magnetic field is created by four coils *1*. Lines of force of the mirror-trap magnetic field are shown with dotted lines, and the lines modified by switching on the source coils are shown with dashed lines. An arc plasma source with a discharge channel of circular geometry is placed outside the region of target plasma generation. The source consists of two parts symmetrical with respect to the mirror-trap midplane. The discharge channel bounded with insulated diaphragms *3* reproduces the shape of the lines of force of the injecting magnetic field. The initial discharge is initiated between circular duralumin cathode *4* and copper electrode *5* positioned inside cathode cavity *8*. The initial discharge penetrating the chamber through the holes *9* initiates the principal discharge between the cathode and anode *2* simultaneously in both parts of the source. The plasma generated in the discharge flows along the magnetic lines of force and fills the trap. Then, the current in the source coils is quickly switched off, and the initial nondisturbed magnetic field geometry is reset.

The main difficulties of realizing this method are associated with fulfilling the following conditions: the time of resetting the initial magnetic field geometry must be smaller than the plasma lifetime in the trap, and the gas parameters in the trap must be preserved after the gas is preliminarily admitted to the source.

Coils *1* producing the magnetic field were powered with current from an *LC*-line. For fast switching off of the current, a counter connection of the coils positioned close to each other was used. Each coil had an inductance of 18 μH, and the total inductance of all four coils connected in parallel was $L = 3$ μH. For the necessary current $I = 10$ kA and voltage at the capacitors of several kilovolts, the switch-off time is $\tau = \sqrt{LC} = LI/U \approx$ 10 μs, which is much shorter than the typical plasma lifetime in the mirror trap (of the order of 1 ms).

Since a gas must be admitted to the source beforehand, it is desirable to place shutters as close to the source discharge channel as possible, to create the best gas conditions. Therefore, it is impossible to use conventional shutters because of the strong magnetic field at the source location. Piezoceramic valves, the operation of which is unaffected by the magnetic field, were taken for such valves. To form an azimuthally uniform discharge, hydrogen was admitted to the circular cathode cavity through four valves positioned at equal distances over the external cathode edge.

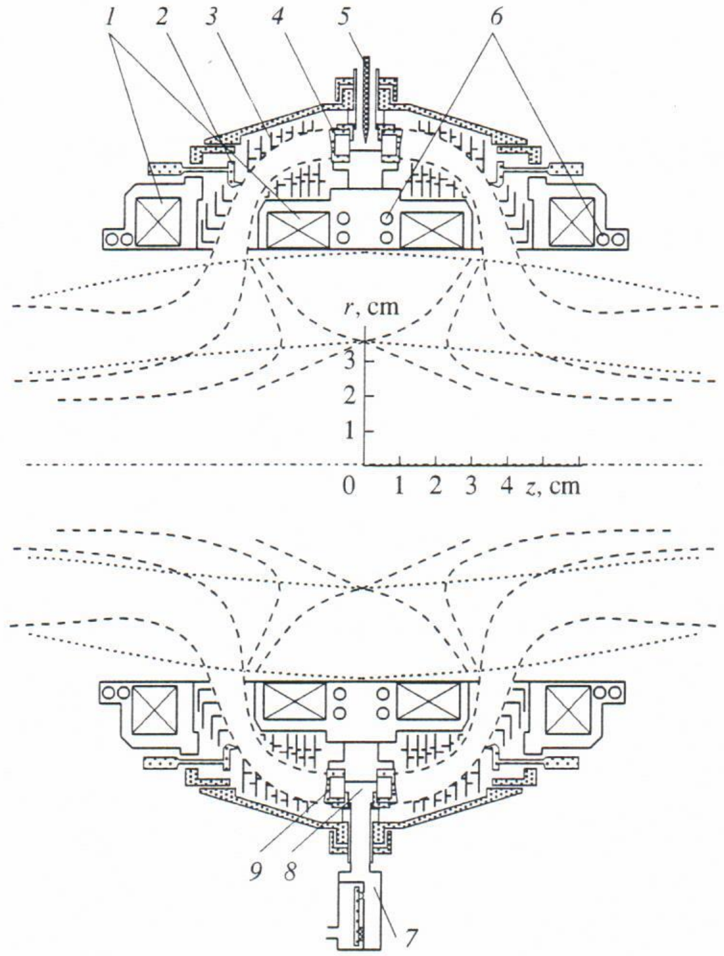

Fig. 1. Schematic diagram of a radial plasma source: *(1)* magnetic field coils; *(2)* anode; *(3)* diaphragms; *(4)* cathode; *(5)* ignitor electrode; *(6)* cooling tubes; *(7)* valve; *(8)* gas-distributing cathode cavity; and *(9)* holes for gas admission to the discharge channels. Nondisturbed magnetic lines of force and magnetic lines of force disturbed by switching on the source coils are shown with dotted and dashed lines, respectively.

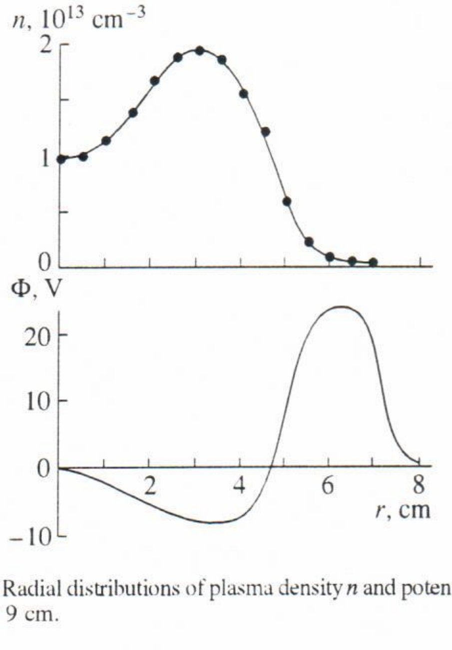

Fig. 2. Radial distributions of plasma density n and potential Φ for $z = 9$ cm.

The piezoceramic valve is of traditional design. A piezoceramic plate with a sealing rubber tightly covers the outlet hole of the volume containing the gas under a pressure of up to 10 atm. The valve opens when voltage is applied to the plate. It was found experimentally that, at a fast change in the magnetic field, the valves may open spontaneously because of accompanying mechanical vibrations, resulting in undesirable gas admission. To eliminate this effect, the duration of the voltage pulse opening the valve was set equal to a half-period of free vibrations of the piezoceramic plate (1.1 ms), and a constant blocking voltage was added to the valve-control circuit.

When designing the mechanical components of the source, forces (up to 2×10^4 N) arising in the alternating magnetic field and heating of the coils (3°C in a shot) were taken into consideration. A bayonet connector was used, allowing easy disconnection of the external coils and providing prompt access to the discharge channel.

A MAL axially symmetrical mirror trap has a mirror ratio of 2, a 40-cm distance between the mirrors, and a magnetic field at the trap center of 6 kG. The initial vacuum is maintained at a level of 10^{-6} Torr. The plasma source with its own coils is placed directly at the mirror-trap center. Only one-half of the plasma source was operated in our experiments.

Hydrogen (6×10^{18} molecules) is admitted 2 ms before the discharge initiation. The arc discharge lasts 600 μs, the discharge voltage is 150 V, and the arc current is up to 3 kA. The plasma generated by one-half of the plasma source has the following parameters: the flow current is 500 A, the density reaches 2×10^{13} cm^{-3}, and the electron temperature is 16 eV. Figure 2 shows the radial distributions of the plasma density and potential at the stage of filling the trap measured by a Langmuir probe near the source end. The inner hollow of the jet is being filled with the diffusion coefficient exceeding the Bohm coefficient. A nonequilibrium radial electric field determined by the potentials at the plasma source electrodes is present in the jet. It may lead to the development of the Kelvin–Helmholtz instability and additional stochastic heating of ions (energy is transferred to the transverse degree of freedom), improving their containment in the mirror trap [2]. Activity at frequencies of tens of kilohertz typical for this instability was registered in our experiments. The plasma obtained is stable, and the presence of a circular region with the zero magnetic field in the mirror-trap midplane is a favorable factor at the filling stage.

The source described makes it possible to significantly increase the efficiency of filling the trap with a target plasma and to avoid contact between the plasma in the trap and the construction components positioned along the magnetic field. Such plasma sources are attractive for use in closed magnetic traps and in long open ones.

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REFERENCES

1. Asano, S., Ihara, M., and Fukao, M., *J. Phys. Soc. Japan*, 1989, vol. 58, p. 1265.
2. Kabantsev, A.A. and Taskaev, S.Yu., *Fiz. Plazmy*, 1992, vol. 18, p. 635.