SUBMILLISECOND ELECTRON BEAM FOR PLASMA HEATING IN MULTI-MIRROR TRAP GOL-3

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Experiments on plasma heating in open magnetic traps require a powerful electron beam with pulse length of 0.1 – 1 ms. Such a beam is expected to obtain in the source with a plasma cathode and high perveance multi-aperture electron optical system. An appropriate technology is being developed at Budker Institute of Nuclear Physics (BINP), Novosibirsk. Here we introduce a prototype electron beam injector with the following design parameters: energy of electrons up to 150 keV, pulse duration of > 0.1 ms and beam current up to a few hundred amperes. The injector is intended to operate in an external axial magnetic field of ~ 0.1 T. In this paper, the design of injector prototype is described and the first test experiments are presented.

I. INTRODUCTION

Significant plasma parameters (T_e ~ 1 – 3 keV, T_i ~ 1 – 2 keV, n ~ 10^{15} cm^{-3}) have been achieved over the past few years in the experiments on deuterium plasma heating with high power relativistic electron beam (REB) in multi-mirror trap GOL-3 at BINP[1]. Energy lifetime of the plasma in these experiments has reached the level of ~ 1 ms. However, the suppression of longitudinal electron heat loss due to electron scattering on strong plasma turbulence excited by REB exists only during the REB injection, which is of ~ 10 μs now. To improve the plasma parameters in GOL-3, a powerful electron beam with a duration up to one millisecond, with the retention of high current density and high brightness of the beam is needed. The physical ground for the use of long-pulse electron beam and rationale for the choice of beam parameters are given in Ref. 2. For the first-stage experiment at GOL-3, the beam parameters should be as follows: energy of electrons is 100 – 200 keV, total beam current is up to 1 kA, current density in the plasma is 0.5 – 1 kA/cm^2 with electron pitch-angles less than 0.2 rad. The beam duration should be at least 0.1 ms (one order of magnitude higher than currently available at GOL-3). An external axial magnetic field is a prerequisite, so the high current density injection can be obtained by magnetic compression of the beam with a relatively low initial current density, generated within a moderate magnetic field of ~ 0.1 T.

The key issues related to the design of the beam injector are the cathode capable to emit a current density of the order of tens of A/cm^2 and the required total current of ~1 kA with a pulse duration in the millisecond range, and an electrode structure that enables the extraction and acceleration of high current high brightness electron beam. Among different types of cathodes suitable for producing such a beam, the plasma cathode looks promising because it can provide a long beam extraction, high current density and survival at poor vacuum conditions. It seems rather natural decision to use a plasma cathode for the electron beam injection into a plasma trap. The extraction and acceleration of high perveance electron beam with required brightness can be achieved in multiple aperture electron optic system (EOS), where the total beam current is the sum of the currents of many beamlets.

These concepts were studied on a test-bed electron beam source with plasma emitter[3] at accelerating voltage of 25 kV. In test-bed experiments the diode-type EOS with 37 circular apertures was used. In axial magnetic field of 0.1 T, an electron beam current of 120 A have been obtained that corresponds to emission current density of 28 A/cm^2, with a pulse duration of 0.25 ms. The efficiency of the discharge current utilization into the beam current was more than 80%.

In our report, we introduce a prototype electron beam injector with acceleration voltage up to 150 kV, based on a hydrogen arc discharge plasma emitter and multiaperture diode-type EOS. The injector was designed, manufactured and installed for the test experiments into the end vacuum tank of GOL-3.

II. INJECTOR DESIGN

Design of electron beam injector is basically the same as described in Ref. 3. The schematic of the injector is shown in Fig. 1(a). The device is consists of the following

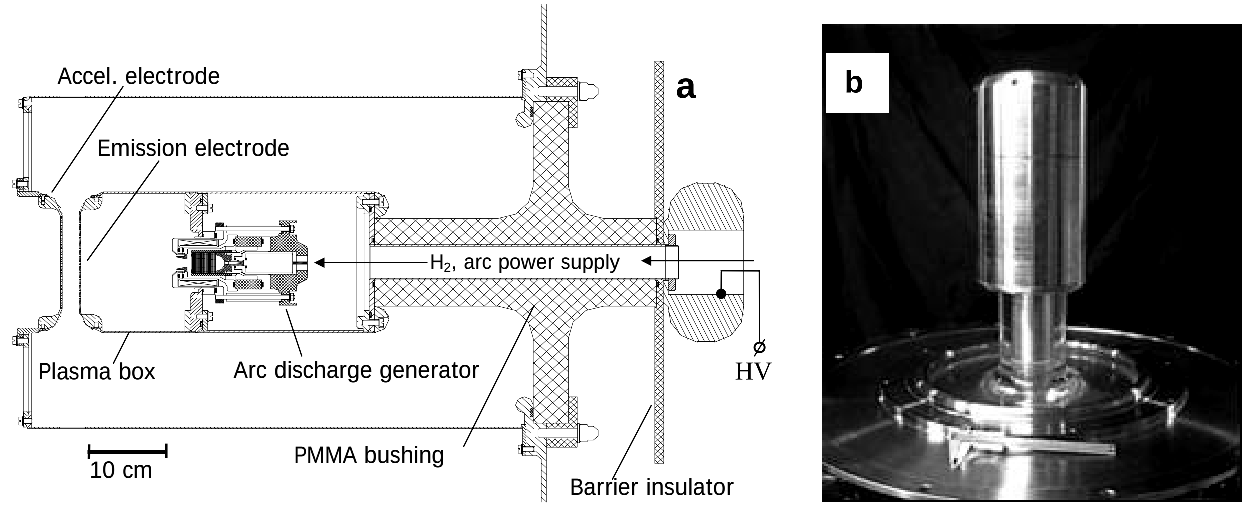

Fig. 1. (a) Schematic layout of electron beam injector with arc plasma emitter, (b) Photo of high-voltage electrode (plasma box) mounted on lead-in PMMA bushing.

parts: a stainless steel plasma box with emission electrode on the face plate, mounted on a PMMA bushing, and the accelerating electrode, which is under the ground potential. A plasma emitter for the electron extraction is produced with an arc discharge in hydrogen gas. An arc plasma generator is installed inside the plasma box and comprises a cold aluminium cathode, a stack of insulated copper washers with a central bore that forms the 30 mm length arc channel, and an exit copper nozzle, which serves as auxiliary anode to aid an arc ignition. Hydrogen as a plasma-forming gas is puffed through the central bore in the arc cathode by the pulse valve. A sharp H_2 pressure drop between the arc channel and the plasma box exists at the moment of arc ignition. An arc discharge occurs between the cold cathode and the inner wall of a plasma box which serves as a hollow anode of the arc discharge. Axial magnetic field, formed in the arc channel by the coil, stabilizes the discharge and enhances the production of a plasma.

The frontal plate of the plasma box constitutes the emission electrode (cathode of the diode) with 36 circular emission openings (Fig. 2) aligned precisely with the openings in the accelerating electrode (anode of EOS). Diameter of the openings in the cathode and in the anode was 4.0 mm and 4.6 mm, correspondingly.

The plasma box with arc generator is mounted on a PMMA bushing, as it is shown in the Fig. 1(b). Power supply lines to the arc generator and a plastic pipeline for hydrogen supply are laid in a metal tube through the bushing. Power and control electronics of the arc generator was mounted inside a Faraday cage located near the injector vacuum tank and floated under accelerating potential. An arc discharge power supply system was built on a modular principle. Each module includes two series-connected electrolytic capacitors (4700 μF, 400 V) with ballast resistor, and turns on and off by IGBT. At maximum current of 200 A per module, the required arc discharge current can be obtained with parallel connection of a suitable number of the modules. This solution makes it easy to change in a wide range an arc current and a pulse duration. All arc-related equipment was powered by a rechargeable battery and controlled via fiber optic lines.

Fig. 2. Emission electrode with 36 openings.

Accelerating voltage was supplied to plasma box with high-voltage modulator which main elements are capacitor bank with maximum capacity of 1.2 μF at 200 kV and two multi-gap spark switches. The second switch forms the trailing edge of high-voltage pulse and serves as a crowbar to prevent arching in the accelerating gap at breakdowns. All control and triggering signals were applied through fiber optic lines.

Geometry of injector have been optimized using FEM-code computer modelling in order to reduce the electric field strength on the metal and bushing surfaces to the safe levels at accelerating voltage of 160 kV.

III. TEST RESULTS

Injector was installed into the exit vacuum tank of GOL-3 for the test experimental run. Residual pressure in the tank was about $6\cdot10^{-3}$ Pa. The «cold» high-voltage trials of injector were carried out, in which the device held static voltage of 140 kV and pulse voltage up to 180 kV (upper limit of the available high-voltage rectifier). The first test shots with an electron beam were performed using a single-aperture electrode system. The diode gap was 11.5 mm. A beam with current of 3 A at accelerating voltage of 110 kV was demonstrated at 0.5 ms pulse duration. During the experiments, the beam emission current was measured with a current transformer, and the beam current loss on the anode was measured with a shunt. Accelerating voltage was measured with the resistive divider.

After the successful initial trials the single-aperture EOS was replaced with the multiaperture one. An accelerated beam propagates in the vacuum tank and stopped at the target at 1 meter from the beam source. After a number of conditioning shots, the total emission current up to 70 A was obtained at a pulse duration of 0.17 ms. Typical emission current and diode voltage waveforms are shown in Fig. 3. The voltage declines due to a small capacity of the high-voltage bank, which was 0.6 μF in these test experiments. An arc discharge current was 250 A.

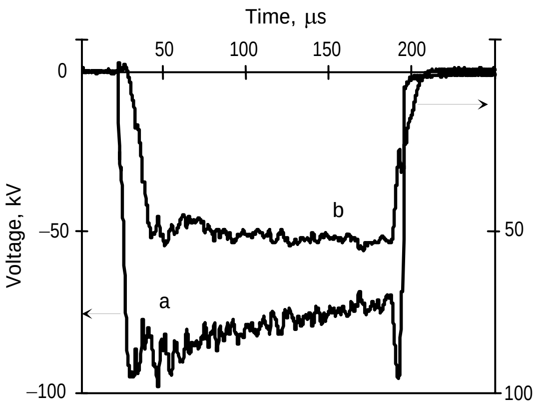

Fig.3 Typical waveforms of the beam voltage (a) and emission current (b) with 36-aperture EOS.

IV. CONCLUSIONS

A prototype electron beam injector on a base of hydrogen arc plasma emitter and multiaperture diode-type EOS was developed. The injector is intended for the experiments on long-pulse electron beam injection into a plasma of multi-mirror trap GOL-3. The first test experiments with the injector were performed and reliable operation was demonstrated. The beam with the energy of electrons of up to 100 keV and total current of 70 A have been achieved (not simultaneously) with 36-aperture diode system at a pulse duration of 0.17 ms.

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