A Prototype Long-Pulse Electron Beam Injector for GOL-3 Multimirror-Plasma Trap


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Abstract — An electron beam injector based on high current arc plasma emitter and two-electrode multi-aperture electron optical system was developed at BINP, Novosibirsk. This prototype injector is designed to prove a novel concept for plasma maintaining in the multi-mirror trap GOL-3. The project parameters of prototype are as follows: energy of electrons up to 150 keV, pulse duration 0.1 ms and beam current up to hundreds of amperes. The distinctive feature of this injector is the performance in an axial magnetic field ~ 0.1 T, for successive magnetic compression of the electron beam and its injection in a strong magnetic mirror of GOL-3 machine. This report presented the design of the injector device and the results of the first experiments. An electron beam of 90 keV, 50 A and 0.17 ms pulse length, with 12 A/cm² emission current density was obtained. Stable operation in an axial magnetic field with more than 80% of the discharge current utilization into the beam current was demonstrated. A possibility of up to 0.5 ms pulse duration was shown in special experiments with a low-current beam in mono-aperture accelerating system.

1. Introduction

Significant plasma parameters ($T_e \sim 2–3$ keV, $n \sim 10^{14–10^{15}}$ cm$^{-3}$) were achieved over the past few years in experiments on dense plasma heating with high power relativistic electron beam (REB) in the multi-mirror magnetic trap GOL-3 [1] at Budker Institute of Nuclear Physics, Novosibirsk (BINP). Energy lifetime of the hot plasma in these experiments has reached the level of 1 ms. However, suppression of the longitudinal electron heat losses by Langmuir turbulence, excited with the REB, is required during all the time of plasma decay, which is now significantly longer than the REB duration (~ 0.01 ms). To overcome this problem, an electron beam with the pulse duration at least in a submillisecond range with the retention of the high current density and high brightness of the beam is required. For the first-step demonstration of this approach, an electron beam source should have the parameters as follows: energy of electrons 100–200 keV, pulse duration more than 0.1 ms (an order of magnitude higher than currently available) and the beam current up to hundreds of amperes. Moreover, the distinctive features of the required beam source are:

1. Work in an axial magnetic field about 0.1 T.
2. Emission current density of the beam at the level of several tens of amperes per sq. cm.
3. Beam angle characteristics are satisfactory to 50-fold magnetic compression (from ~ 0.1 T in the injector to ~ 5 T in the magnetic trap).

Such a set of the beam parameters in the presence of magnetic field of 0.1 T is rather challenging and, to date, unprecedented.

Key issue in solving of this problem is the development of suitable electron emitter. It should satisfy all requirements for current density, total current and pulse duration of the beam and be workable at moderate axial magnetic field. Among different types of emitters, the plasma emitter looks promising because of its relative technical simplicity and ability of operation in poor vacuum conditions [2]. It seems natural to use the plasma cathode for the electron beam injection into a plasma trap. To extract high-current beam from the plasma emitter, one should provide the discharge with high current in an electron component such as an arc discharge. For this reason, we use an original gas-discharge arc plasma generator with cold cathode [3]. It has been used for long time at BINP to produce a plasma emitter in high-perveance neutral beam injectors [4]. Different modification of such generators produces a stable arc discharge with current up to 1 kA and duration from 0.1 ms to 1 s.

For extraction and acceleration of beam electrons we employed a grid-like electron optical system (EOS) with a set of circular apertures arranged in a hexagonal order.
These concepts were tested on the experimental stand [5] at accelerating voltage of 25 kV. In test-bed experiments we used multi-aperture diode-type EOS and plasma emitter based on high-current hydrogen arc discharge, as it was mentioned above. Electron beam was generated in 37-aperture EOS with 4 mm diameter of openings. The diode gap was 2.3 mm. In axial magnetic field 0.1 T, it was obtained an electron beam current of 120 A that corresponds to the current density about 30 A/cm$^2$. The efficiency of the discharge current utilization into the beam current was up to 80%.

In this paper, we report the development of a prototype beam source with acceleration voltage up to 150 kV, designed for the first-step experiments on long-pulse electron beam injection in the GOL-3 multi-mirror trap.

2. Injector design

Schematic layout of the electron beam injector is shown in Fig. 1, a. Basically the source is similar to that described earlier in Ref. 5. The plasma box (hollow anode of the arc discharge) with arc generator is installed on a plexiglass bushing insulator, as it is shown in Fig. 1, b. Power leads to arc generator and plastic pipe for a hydrogen supply are laid inside a metal tube, passing through the insulator. Power and control electronics of the arc generator was mounted inside a Faraday cage near the injector and floats under accelerating potential. All arc generator related equipment was powered by a rechargeable battery and controlled via fiber optic lines. Accelerating voltage was provided with high voltage modulator which main elements are capacitor bank of 1.2 \( \mu \)F, 200 kV and two multi-gap spark switches. The second switch forms the trailing edge of the high-voltage pulse and serves as crowbar to prevent arching in the accelerating gap at breakdowns. All control and triggering signals were transferred via fiber optic lines.

Arc discharge power system was built on a modular principle. Each unit includes two series-connected electrolytic capacitors (4700 \( \mu \)F, 400 V) with ballast resistor, and turns on and off by IGBT module. At maximum current of 200 A per unit, the required arc discharge current can be obtained with parallel connection of a suitable number of the units. This solution allows to change easy in a wide range the discharge current and pulse duration.

The diode-type EOS with 36 circular apertures was used. Diameters of the openings in the cathode (emission electrode) and in the anode (extractor electrode) were 4.0 and 4.6 millimeters, correspondingly. The openings in the extractor were aligned precisely with the openings in the emission electrode. The design of the extractor is shown in Fig. 2.

Geometry of injector has been optimized using FEM code COMSOL 3.2. In order to reduce the electric field strength on metal and insulator surfaces to a safe level at a voltage of 160 kV.

3. Experimental results

Injector was installed into the exit tank of the GOL-3 facility (see Fig. 3). Residual pressure in the tank was not higher than \( 5 \times 10^{-3} \) Pa. The “cold” high-voltage tests 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 used high-voltage rectifier). The first test shots with an electron beam were performed using a single-aperture electrode system. A beam with current of 3 A at accelerating voltage of 110 kV was demonstrated at 0.5 ms pulse duration. The diode gap was 11 mm.

After the successful initial trials the single-aperture EOS was replaced by the multi-aperture one with 36 emission openings, as shown in Fig. 2. An accelerated electron beam propagates in a stainless steel drift tube 350 mm long with a collector-plug at the end. After a number of conditioning shots, the total emission

![Fig. 1. Schematic layout of electron injector with arc plasma emitter (a); photo of high-voltage electrode (plasma box) mounted on plexiglass insulator (b)](image)
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Fig. 2. Extractor electrode with central 36-aperture molybdenum insert. The diameter of openings is 4.6 mm, thickness of Mo insert is 3 mm

Fig. 3. Exit tank of the GOL-3 facility with electron beam injector installed for “cold” HV testing

Fig. 4. Typical waveforms of the beam voltage (a) and emission current (b) with 36-aperture EOS. An arc current was 250 A current up to 70 A was obtained at the pulse duration of 0.17 ms. The typical emission current and voltage waveforms are shown in Fig. 4. The voltage decline occurs due to a small capacity of the high-voltage bank, which was 0.6 μF in these experiments. An arc discharge current was 250 A.

Along with this, experiments are being started on the generation of electron beam in a guiding magnetic field. An axial field in the range from 0 to 0.1 T is produced with a solenoidal coil wound around the exit tank. The very first shots, illustrating the effect of the magnetic field on beam generation is shown in Fig. 5.

Fig. 5. Waveforms of the beam voltage (a) and emission current (b) without magnetic field and in the field of 0.015 T (a*, b* correspondingly). An arc discharge current was about 50 A

4. Conclusion

A prototype electron beam source on a base of arc plasma emitter and multi-aperture EOS was developed. The source is intended for the experiments on long-pulse electron beam injection into the plasma of multi-mirror magnetic trap GOL-3. The very first experiments with the injector were performed and the beam with the energy of electrons about 100 keV and total current of 70 A have been achieved (not simultaneously) at a pulse duration of 0.17 ms. A reliable operation of the injector was demonstrated, also in the experiments with magnetic field.

References