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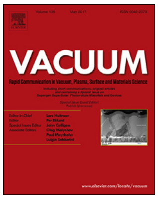

Generation and transport of submillisecond intense electron beams in plasma cathode vacuum diodes

V.T. Astrelin [a, c], I.V. Kandaurov [a], M.S. Vorobyov [b, *], N.N. Koval [b, d], V.V. Kurkuchekov [a, c], S.A. Sulakshin [b], Yu A. Trunev [a]

[a] Institute of Nuclear Physics, Siberian Branch of Russian Academy of Sciences, 11, Akademika Lavrentieva Prospect, Novosibirsk, 630090, Russia
[b] Institute of High Current Electronics, Siberian Branch of Russian Academy of Sciences, 2/3, Academichesky Ave., Tomsk, 634055, Russia
[c] Novosibirsk State University, 2, Pirogova Str., 630090, Novosibirsk, Russia
[d] National Research Tomsk State University, 30 Lenin Ave., Tomsk, 634050, Russia

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ABSTRACT

The paper reports on a comparative study of two different types of diode system for producing intense submillisecond electron beam in a source with low-pressure arc plasma emitter. The first is a planar multi-aperture diode comprising cathode and anode performed as molybdenum grids with 241 round openings of few millimeters in diameter. In the second system electrons are accelerated in a sheath between the grid-stabilized cathode plasma and the open boundary of beam-generated anode plasma. It was demonstrated in experiments that latter system should be advantageous in terms of maximally achievable beam current and total beam energy content, but there are drawbacks connected with slow anode plasma build-up that require further study.

1. Introduction

The injection of a high-power electron beam into linear plasma systems has long been studied at the Budker Institute of Nuclear Physics (BINP SB RAS, Novosibirsk, Russia). When injected into the plasma, the beam produces Langmuir turbulence which increases the plasma electron temperature, suppresses the longitudinal electron thermal conductivity of the plasma and causes emission of sub-terahertz electromagnetic radiation [1,2]. Electron beam injection is also considered as an instrument for MHD stabilization of a plasma in an open trap due to the effect of on-axis negative charge injection which provides azimuthal drift rotation of the plasma column in radial electric and longitudinal magnetic fields [3]. Recently, interest has been shown in the use of linear beam plasma systems for studying the interaction of high-power particle and plasma flows with material surfaces [4,5] and specifically for modeling the high heat loads on tokamak divertor plates during fast transient plasma events. For type I ELMs and major disruption, such heat loads can reach an energy density of 5–80 MJ m^{-2} and a power density of 5–25 GW m^{-2} in a time of 0.3–3 ms.

These tasks require submillisecond (and longer) beams with an energy of the electrons up to 100 keV and power of 5–20 MW. To reduce the energy density in a plasma back-flow to the beam source from experimental chamber, the source should be placed in the expander vacuum tank of a linear plasma system where the magnetic field is about 100 times lower than the field in the solenoid part of the facility. Thus, on injection, the electron beam having a comparatively low current density (~10^4 A m^{-2}) will be adiabatically compressed in the increasing magnetic field, reaching the desired current density in the solenoid and at the irradiated target.

At BINP, in view of the foregoing, it was decided to apply an electron beam source with a plasma emitter based on a low-pressure arc discharge. The use of an arc plasma emitter looks expedient and promising because of its obvious advantages such as engineering simplicity, relative insensitivity to vacuum conditions, possibility to independently vary emission current and accelerated

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* Corresponding author. Tel.: +7(3822) 492 683; fax: +7(3822) 492 410.
E-mail addresses: astrelin@inp.nsk.su (V.T. Astrelin), i.v.kandaurov@inp.nsk.su (I.V. Kandaurov), vorobyovms@yandex.ru (M.S. Vorobyov), koval@hcei.tsc.ru (N.N. Koval), kurkuchekov.victor@gmail.com (V.V. Kurkuchekov), sulakshinsa@yandex.ru (S.A. Sulakshin), yu.a.trunev@gmail.com (Y.A. Trunev).

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electron energy, and attainability of high emission currents. For electron extraction and acceleration, a diode-type multi-aperture electron optical system (EOS) was used in which the cathode and the anode are made of molybdenum in the form of flat hexagonal grids with a large number of coaxial openings several millimeters in diameter. This design easily provides the large area beams with small pitch angles of electrons in an elementary beamlet, allowing magnetic compression of the beam current density up to about 100 times. Experiments have shown maximum achievable beam parameters with this EOS as follow: an electron energy of up to 110 keV, an emission current of up to 100 A and pulse duration of up to 1 ms. The beam can be transported in a mirror magnetic field with a flow compression ratio of $R = (30–60)$ to the target or into a Faraday cup (FC) to measure transmitted beam current.

The experiments also demonstrate that injection of the electron beam into a mirror magnetic field along with intense beam exposure on a target can greatly decrease the beam duration due to a breakdown of the diode gap. One of the major causes of breakdown is likely a backward stream of high-energy electrons in the system due to partial reflection of the beam from the magnetic mirror and from the irradiated metal target. The back-streaming electrons bombard the backside of the anode, producing plasma at its surface, and penetrate to the acceleration gap through the anode openings, distorting the electron optics and enhancing the beam current onto the anode. Along with such reflected electrons, backflow ions enter the diode gap from the plasma formed in a drift space through residual gas ionization by the beam and from the plasma arising at the target and at the anode. The accelerated ions bombard the cathode at the edges of emission openings and initiate emission of secondary electrons which in turn are accelerated in the gap, increasing the beam load onto the anode. Thus, at a high electric field strength in the diode gap ($E \sim 10^7$ V m^{-1}), these particle flows can initiate avalanche particle multiplication processes in the diode, eventually leading to its breakdown. In terms of lengthening the beam current pulse, it is reasonable to try alternative plasma emission systems in which the probability of multiplicative interelectrode processes initiated by back-streaming particles would be decreased and the formation of anode plasma would not be so critical for operation of the diode.

This kind of approach has been successfully developed in recent years at the Institute of High Current Electronics (HCEI SB RAS, Tomsk, Russia), demonstrating the possibility to obtain a submillisecond beam in an electron source based on an arc plasma cathode and plasma anode [6,7]. Electrons are accelerated in a the Langmuir sheath between the cathode plasma with a boundary stabilized by a fine metal mesh and the open boundary of anode plasma formed by the beam itself. Thus, the source operates without a multi-aperture metal anode. However, the specific conditions are needed to form the plasma anode, in particular, an operating gas pressure of no less than a certain level (about $2\cdot10^{-2}$ Pa for argon) in the drift chamber. The source provides stable operation and produces a beam with a current of up to 180 A at the accelerating voltage of up to 30 kV in a moderate ($B < 0.03$ T) weakly inhomogeneous ($R < 5$) guiding magnetic field. With a multi-arc fine mesh cathode (six plasma generators), the source produces an emission current of up to 1 kA at an accelerating voltage of up to 70 kV, the beam duration of up to 0.1 ms and an energy content in the beam of up to 4 kJ in a magnetic field of about 0.015 T [8]. Experiments exploring the possibility of magnetic compression of such beams at $R > 5$ have not been conducted so far.

In this paper we report on the first comparative study of two foregoing approaches to the generation of an electron beam under identical experimental conditions. The main criterion for the comparison is the ability of the specific system to generate an electron beam with a maximum pulse duration and energy content. A discussion is presented for characteristic modes of the beam operation together with the results of measurements of the current density distribution over the beam cross-section.

2. Experimental setup

The schematic layout of the electron beam test facility is shown in Fig. 1. The beam source was placed in a vacuum tank evacuated to a typical residual pressure of ~$6\cdot10^{-4}$ Pa. A quasi-uniform guiding magnetic field of about 0.01 T at the beam source location was produced using the coils (*1*) arranged on the outer side of the vacuum tank. The magnetic field in the experimental chamber attached to the tank is produced by a solenoid (*2*) and reached a maximum value of 0.4 T. A negative accelerating voltage of up to 100 kV was applied between the high-voltage electrode (*3*) and extracting electrode (*4*) placed at ground potential. The high-voltage electrode (*3*) was mounted on a plexiglass bushing, (*5*) and was performed as a hollow stainless steel cylinder with an arc generator (*6*) placed on its axis inside the cavity. The generator employed a cold Al cathode and pulsed gas supply, its design is similar to that described elsewhere [9,10]. The gas (argon) injected by a fast solenoid valve in the amount of ca. $4\cdot10^{18}$ molecules per injection pulse of less than 1 ms duration. The arc discharge was ignited with a delay of 0.4 ms after valve actuation. When an arc discharge arose, it first developed in a channel of diameter ca.

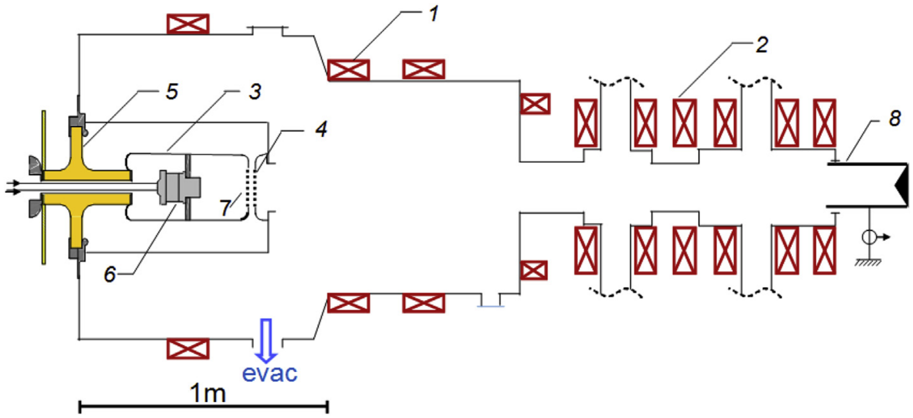

Fig. 1. Schematic layout of the electron beam facility: *1* – magnetic coils; *2* – solenoid; *3* – high-voltage electrode; *4* – extracting electrode; *5* – PMMA bushing insulator; *6* – arc generator; *7* – emission electrode; *8* – Faraday cup.

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