Experimental installation for studying cathode plasma processes in vacuum gap of pulsed electron accelerator with gas or liquid injection

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Abstract. One of the directions of using plasma sources is the formation of plasma emitters for electron beams as part of direct-action charged particle accelerators. The parameters of the accelerator generators require mutual matching with the characteristics of the plasma emitters. The paper describes the design, composition and diagnostic equipment of an experimental stand based on a vacuum chamber of a pulsed electron accelerator for testing plasma sources of pulsed electron beams. The stand includes a vacuum volume with a high-voltage bushing, pumping out pipes, diagnostic windows along the perimeter and a mounting flange of a complex device for diagnosing the characteristics of pulsed electron beams. The stand provides the possibility of controlled supply of gas and liquid to the formation region of the plasma emitter of electrons under the influence of an accelerating voltage pulse. The location of the diagnostic windows and flanges of the stand allows direct optical observations of the plasma formation region in the frontal and profile directions. The use of the stand will make it possible to determine the characteristics of the tested plasma emitters for their operation as part of a vacuum diode of pulsed electron accelerator.

1. Introduction

An expansion of radiation technologies [1, 2] stimulates the improvement and development of new electron beam sources based on plasma emitters. A promising research direction is the development of pulsed sources based on emitters with substance injection for plasma formation. Hollow cathodes filled with a gaseous plasma [3, 4] have been developed for a low-pulse-power electron beam sources and liquid-metal cathodes [5] are known for high-power machines. The paper [6] describes a cathode with liquid injection into the accelerating gap for creating a plasma emitting surface. Potentially, such cathodes can provide high resource of the accelerator diode unit, which is critically important for practical use of radiation technologies. Understanding the operation principles of vacuum diodes with such cathodes is necessary for designing and configuring of vacuum diodes for existing and new accelerators. The study of the plasma formation mechanism is necessary to know the influence of accelerating gap geometry, parameters of the injected liquid and its supply, vacuum conditions, and etc. to vacuum diode characteristics. In this work, we describe the experimental installation built for testing plasma cathodes in a vacuum electron diode of a pulsed accelerator with parameters 475 kV, 1.5 kA, 0.25 µs (FWHM) [7].
2. Experimental installation

The design of the experimental installation based on vacuum diode of pulsed electron accelerator (figure 1) was developed taking into account the following provisions: compatibility with the output of the high-voltage generator of the pulse accelerator [7]; compatibility with ISO40 fore vacuum pumping system and ISO200 high vacuum pumping system; the possibility to install viewing (diagnostic) windows that provide illumination and registration of optical signals from different projections in the area of liquid injection; compatibility with previously developed electron beam diagnostic equipment [8–11] and designs of exit windows [12, 13]; providing an external supply of liquid to the potential electrode; wide range regulating the supplied liquid flow rate; adjustment of the accelerating gap (average electric field strength); adjustable electrostatic shielding of the emitting surface (electric field strength at the cathode surface, liquid injection area).

The design of the stand vacuum chamber provides the allocation of 11 viewing windows, placed with a step of 30° around the chamber axis relative to each other and relative to the high-vacuum pump nozzle. Such construction provides straight, sharp and obtuse angles of illumination and registration of the observed area (injection area) in different projections relative to the direction of high-vacuum pumping. Each of the viewing windows can be used for atmosphere evacuation by installing a KF40 compatible adapter. The height of the viewing windows, with the lower boundary of the diameter, coincides with the plane of the anode flange, which has installation dimensions similar to the used exit windows of the accelerator.

For the experimental stand, a liquid injector (figure 1) supplied from an external volume located at atmospheric pressure was developed. The design provides a repetition of the electron emitter configuration developed and tested by the authors earlier [6], which provides a larger number and range of adjustable geometric parameters: the distance from the injector to the potential grid \(D_I\), the depth of electrostatic screening of the potential grid surface \(D_S\), and the size of the accelerating gap \(D_A\). The liquid is supplied through the tube \(\Omega 1 \times 0.25 \text{ mm}\) connected with a volume outside of the accelerator installation.

![Figure 1](image_url)

**Figure 1.** Structure of the cathode assembly and diagnostic window in CAD: vacuum chamber (1), diagnostic window flange (2), diagnostic window glass (3), diagnostic window glass clamp (4), anode flange (5), fluid injector retainer sleeve (6), shielding electrode (7), potential electrode of the generator (8), tube for supplying liquid to the cathode (9).

The design of the diagnostic windows allows observing of the accelerating gap in the entire range of its adjustable value (figure 1). The sealing and clamping system is designed for the installation of cylindrical glasses \(\Omega 50 \text{ mm}\) made of CaF\(_2\) and KCl.

For external supply of liquid (or gas) to the cathode (figure 1, pos. 9) a simple flow control scheme has been developed and implemented (figure 2). The flow rate is adjusted by the pressure...
(underpressure) level in the receiver (Figure 2, pos. 3) The supply circuit confirmed operability at atmospheric pressure, providing the required liquid flow rate of 1.5 μg/s at an overpressure of 0.4 bar in the receiver. The liquid flow rate at the adjusted pressure difference is determined by the rate of change of the liquid level (scale) in the receiver in the channel of a known diameter.

Figure 2 Cathode supply circuit with liquid injection: cathode in the vacuum chamber of the accelerator diode (1), cathode supply pipeline (2), supply receiver case (3), liquid level scale in supply receiver (4), pressure gauge (5), buffer tank with rarefied atmosphere (6), buffer tank with compressed gas (7), liquid supply-discharge valve (8).

3. Diagnostics
The design of the stand allows the installation of previously developed devices for studying beam characteristics and operating modes of a vacuum electron diode.

For the evaluation of the charge and energy distribution in the cross section of the beam, a sectioned calorimeter combined with a detector of the total electron beam current [8] was developed on the basis of the previously developed sectioned calorimeter [10]. The characteristics of the calorimeter make it possible to measure the energy distribution in the cross section of pulsed electron beams with a kinetic energy of electrons up to 700 keV, an energy density of up to 3.6 J/cm² and total beam energy of up to 50 J/pulse. The calorimeter current detector records the total electron beam current through the electrical connection of the sectioned collector with a common shunt. The signal is detected by an oscilloscope for the beam charge calculating. Thus, the charge distribution can be estimated in proportion to the electron beam energy distribution.

For studying the operation modes of vacuum electron diodes with an explosive-emission cathode, the authors have also created an original diagnostic device that combines the functionality of a submicrosecond Faraday cup and a system for capturing an image of the cathode surface [9].

A special task for which the installation was created is the studying the propagation of a liquid in the area of plasma formation. It is assumed that liquid (water) can be in two states in the injection region. To reconstruct the trajectory of movement of water aerosol and/or ice particles, methods of laser sensing and high-speed imaging are provided. Aerosol registration by the emission of its laser-induced fluorescence is widely used in remote laser sensing [14–23], as well as registration by scattering. Registration of fluorescence emission is provided by a spectral device, the distribution of particles - by a video camera.

The placement of the diagnostic equipment corresponds to the diagram shown in Figure 3. The input of radiation and the registration of the scattered signal and the fluorescence signal are carried out using diagnostic windows made of CaF₂, located with a step of 30° around the axis of the chamber.

The registration procedure of particles in the chamber, as well as evaluating their concentration in the plasma formation region, is described below. The radiation of the laser 3 is introduced into the chamber 1 (Figure 3) through one of the optical windows 2. The second harmonic (532 nm) of the Lotis LS-2134UTF-HG-Fifth Nd: YAG laser with pulse energy of 170 mJ is used as a radiation source. Laser radiation, passing through the chamber, is partially scattered by water particles and
output through the opposite optical window. Registration of both the transmitted signal and the scattered one is carried out. The radiation scattered on the particles through the optical windows is recorded by the photodetector 6 (an LFD-2 photodiode with a lens is used as an optical radiation detector).

**Figure 3.** Scheme of optical diagnostic equipment: vacuum chamber (1), optical window (2), diagnostic laser (3), rotary mirror (4), laser beam expander (5), photodetector (6), polarizer (7), spectrometer (8), video camera (9).

For the polarization degree determination, a polarizer 7 can be installed in front of the photodetector. To determine the scattering indicatrix and the dependence of the depolarization degree on the scattering angle, the experiment is carried out with a change in the position of the photodetector at different optical windows. If it is necessary to register backscattered radiation, it is possible to introduce a rotary mirror 4 into the optical scheme, which removes radiation to the photodetector.

In order to register particles by fluorescence, laser-induced fluorescence emission of a dye in a particle (a fluorone dye of the rhodamine family - rhodamine 6G - C_{28}H_{31}N_2O_3Cl is used as a dye) enters spectral device 8 through the optical window (spectrometer APE AA160.00.200.10 is used as a spectral device - Spectrometer 200-540 nm, wavelength resolution < 0.05 nm.). Since the fluorescence emission of rhodamine 6G is located in the visible region of the spectrum, the control of the distribution of fluorescent particles can be carried out with a video camera. To increase the volume of the particles interaction with laser radiation, the possibility of introducing a laser beam expander 5 into the optical scheme in place of the rotating mirror 4 is provided.

High-speed visualization of the discharge formation process, as well as the dynamics of movement and changes in the aggregate state of an aqueous solution during operation, is available using high-speed cameras AOS Q-PRI and MegaSpeed 103. Registration by video camera 9 in vertical planes is carried out through one of the optical windows 2. To register the distribution particles in the horizontal plane, the same video camera and optical window are used in the lower part of the installation.

To increase the temporal resolution of visualization, it is proposed to use the method of laser illumination [24, 25]. Illumination will be carried out by a synchronized pulse CuBr laser with pulse repetition rate up to 20 kHz, illumination pulse duration 40 ns. The radiation parameters will ensure the formation of a frame in one pulse. Due to this, temporary filtering of the image from the discharge plasma will be achieved. Spectral filtering will be carried out using narrow-band and color filters (SZS-22). Due to high-speed capturing, it is proposed to study the process of the plasma formation region when a liquid is supplied to a vacuum volume.
4. Conclusion
Thus, the experimental installation was developed to study the mechanisms of plasma formation that affect the operational characteristics of vacuum electron diodes with gas or liquid injection. The installation includes a vacuum chamber with a high-voltage bushing, pumping out pipes, diagnostic windows along the perimeter and a mounting flange for the equipment monitoring the characteristics of pulsed electron beams.

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References
[1] Chmielewski A G and Haji-Saeid M 2004 Radiat. Phys. Chem. 71 17–21
[2] Pillai S D and Shayanfar S 2017 Top. Curr. Chem. 375 1–20
[3] Vorobyov M S, Koval N N and Sulakshin S A 2015 J. Phys. Conf. Ser. 652 012067
[4] Krasik Y E, Yarmolich D, Gleizer J Z, Vekselman V, Hadas Y, Gurovich V T and Felsteiner J 2009 Phys. Plasmas 16 057103
[5] Proskurovsky D I 2008 23rd International Symposium on Discharges and Electrical Insulation in Vacuum (New Jersey: IEEE)
[6] Egorov I, Poloskov A, Serebrennikov M and Remnev G 2019 Nucl. Instrum. Meth. A 943 162459
[7] Poloskov A, Egorov I, Nashilevskiy A, Ezov V, Smolyanskiy E, Serebrennikov M and Remnev G 2020 Nucl. Instrum. Meth. A 969 163951
[8] Serebrennikov M, Adamov E, Poloskov A, Yu X and Egorov I 2021 Radiat. Meas. 143 106569
[9] Egorov I and Poloskov A 2018 Nucl. Instrum. Meth. A. 911 10–4
[10] Egorov I, Serebrennikov M, Isakova Y and Poloskov A 2017 Nucl. Instrum. Meth. A 875 132–6
[11] Egorov I, Xiao Y and Poloskov A 2017 J. Phys. Conf. Ser. 830 012044
[12] Egorov I, Poloskov A, Serebrennikov M and Remnev G 2020 S Vacuum 173 109111
[13] Egorov I, Yu X, Poloskov A, Serebrennikov M, Le X and Remnev G 2021 Vacuum 187 110149
[14] Gritsuta A N, Klimkin A V, Kokhanenko G P, Kuryak A N, Osipov K Y, Ponomarev Y N and Simonova G V. 2018 Int. J. Remote Sens. 39 9400–14
[15] Veselovskii I, Whiteman D N, Kolgotin A, Andrews E and Korenskii M 2009 J. Atmos. Ocean. Tech. 26 1543–57
[16] Warren R E, Vanderbeek R G, Ben-David A and Ahl J L 2008 Appl. Optics 47 4309
[17] Aristipini P, Del Bugaro D, Fiorani L, Lcreti S and Palucci A 2005 Proc. SPIE 5850 190–5
[18] Pan Y-L, Hill S C, Pinnick R G, Huang H, Bottiger J R and Chang R K 2010 Opt. Express 18 12436
[19] Pinnick R G, Hill S C, Nachman P, Pendleton J D, Fernandez G L, Mayo M W and Bruno J G 1995 Aerosol Sci. Tech. 23 653–64
[20] Chen Q, Ikemori F and Mochida M 2016 Light Environ. Sci. Technol. 50 10859–68
[21] Kaye P H, Stanley W R, Hirst E, Foot E V, Baxter K L and Barrington S J 2005 Opt. Express 13 3583
[22] Reyes F L, Jeys T H, Newbury N R, Primmerman C A, Rowe G S and Sanchez A 1999 Field Anal. Chem. Tech. 3 240–8
[23] Eversole J D, Hardgrove J J, Cary W K, Choulas D P and Seaver M 1999 Field Anal. Chem. Tech. 3 249–59
[24] Trigub M V, Evtushenko G S, Torgaev S N, Shiyanov D V and Evtushenko T G 2016 Opt. Commun. 376 81–5
[25] Trigub M V, Platnov V V, Evtushenko G S, Osipov V V and Evtushenko T G 2017 Vacuum 143 486–90