Beam-produced plasma generated by the pulsed large-radius electron beam in the forevacuum pressure range

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Abstract. The research of plasma produced by a pulsed low-energy large-radius electron beam generated by the plasma-cathode electron source in the forevacuum pressure range 4-13 Pa is presented. The beam-produced plasma has been generated in nitrogen by the electron beam with energy of 8 keV and pulse duration of 1.5 ms. The emission spectrum analysis and probe measurements have been used to investigate plasma parameters. Density of beam-produced plasma increases linearly with increasing electron beam current. The probe measurements have demonstrated almost linear dependence of plasma density on gas pressure in the pressure range 4-13 Pa, while intensities of spectral lines came from exited plasma ions are linear dependent on beam current only in pressure range 6-13 Pa. These spectral lines have low intensities at gas pressure below 6 Pa.

1. Introduction
Electron beams are widely used for direct processing of materials. For example, continuous electron beams are used for welding of metals [1, 2], surface activation [3]; pulsed wide-area (large-radius) electron beams are used to modify the material surfaces [4, 5]. Compared to thermionic (hot) cathode electron sources, plasma-cathode sources provide electron beam generation in more "heavy" vacuum conditions, i.e. in the presence of active gases (nitrogen, oxygen, etc.) and at higher working gas pressures (10⁻³–10⁻¹ Pa) [6]. These features of the plasma-cathode sources have made it possible to use electron beams to efficiently generate beam-produced plasmas [7–9]. These plasmas can be use to process different materials [10, 11]. The one of the features of the beam-produced plasma is lower electron temperature of plasma compared to plasmas generated by common gas discharges (e.g., glow discharges, arc etc.) [8, 9]. The electron temperature of plasma determines the plasma potential, and consequently it determines the minimum energy of the ions extracted from the plasma. The low ion energy provides to decrease of the spread in ion energies in ion beam (or in accelerated ion stream), which is important for the precision processing of materials, in particular in the manufacture of semiconductor devices [12]. Also, low ion energy provides to treat sensitive materials (for example, polymers) [10]. In order to increase the efficiency of beam-produced plasma generation, it seems justified to increase the working gas pressure, since with increasing pressure the number of ionization events of atoms and molecules of the plasma-forming medium increases.
The further development of the features of plasma-cathode sources, such as generation of electron beams at higher gas pressure and in active gases, has led to the development of forevacuum plasma electron sources [13–15]. The forevacuum plasma e-beam sources provide generation of continuous and pulsed electron beams at pressures from 3 to 100 Pa. In particular, currently the pulsed forevacuum plasma electron source provides generation of low-energy (up to 10 keV) large-radius electron beam with current of up to tens of amperes and pulse duration of up to several milliseconds at pressure of up to 30 Pa [14, 15]. The generation of the beam-produced plasma by the continuous and pulsed electron beams with currents of up to hundreds of mA has been studied rather well in the forevacuum pressure range [9, 17]. In case of use the pulsed electron beam, the energy of accelerated beam electrons was not exceeded 3 keV, and the beam-produced plasma has been generated in rather strong external magnetic field (up to 100 G) [9].

However, investigations of beam-produced plasma generation by the pulsed electron beam with currents of up to tens of amperes and energies more than 3 keV without external magnetic field have not been previously carried out in the forevacuum pressure range. Therefore, investigation of beam-produced plasma generation at these conditions is relevant for development of application of beam-produced plasmas.

2. Experimental setup and techniques
The experimental setup for researching of the plasma generated by pulsed electron beam is shown in figure 1. The pulsed low-energy large-radius electron beam has been generated by the pulsed forevacuum plasma-cathode electron source based on a cathodic arc. This plasma electron source is described in [15]. The plasma electron source has been placed on a flange of the vacuum chamber. The vacuum chamber has been pumped out by a roughing pump to pressure \( p_{\text{min}} = 2.5 \text{ Pa} \). The operating pressure \( p \) in the range of 4–13 Pa has been regulated by the flow rate of the working gas into the chamber at constant pumping speed. Nitrogen (N\(_2\) purity - 99.99%) has been used as the working gas. The plasma-cathode electron source has been powered and controlled by a power supply unit. The source has operated in isobaric mode, i.e. the pressure in the chamber and in the source has been the same. The electron beam has propagated in the vacuum chamber with dimensions of \( 50 \times 60 \times 50 \text{ cm}^3 \), which are much larger than cross-sectional dimension of the electron beam (average beam’s diameter is 7 cm). The emission current \( I_e \) has been measured by a current transformer installed in the corresponding circuit of the power unit. The electron beam current \( I_b \) is less than the emission current \( I_e \) due to losses mainly on an accelerating electrode of the plasma-cathode source. Therefore, to measure the beam current \( I_b \) a Faraday cup has been installed at the distance of 35 cm from the accelerating electrode. The current \( I_b \) in the circuit of the Faraday cup has been measured by a current transformer. The beam current \( I_b \) in the range 11–23 A has been regulated by varying the emission current \( I_e \), which controlled by arc discharge current \( I_a \). In all experiments, the DC accelerating voltage \( U_a \) has been 8 kV, the pulse duration has been 1.5 ms, and the pulse repetition rate has been 1 – 2 Hz.

The density \( n \) of the beam-produced plasma has been measured by a single flat probe with a guard ring. The working part (collecting surface) of the probe is made of stainless steel. The diameter of the collecting surface of the probe is 5 mm. The insulation of the working part of the probe is provided by a ceramic insulator. The guard ring, made of stainless steel, has been grounded. To measure radial distribution of the density \( n \) the probe has been mounted on a manipulator. The radial distance \( r \) has been counted from the symmetry axis of electron beam. The plasma density \( n \) has been determined from the ion saturation current \( I_s \) to the probe. Negative DC bias voltage \( U_{\text{bias}} = -100 \text{ V} \) has been applied to the probe to provide saturation of \( I_s \). The current \( I_s \) to the probe has been obtained by measuring the voltage \( U_p \) on the non-inductive resistance \( R_p \) (500 \( \Omega \)). Voltage \( U_p \) has been measured by a compensated oscilloscope voltage probe.

The optical spectrometer (Ocean Optics HR4000CG-UV-NIR) has been used to investigate radiation spectra of the beam-produced plasma. The spectrometer provides registration of optical radiation in the range of 200–1100 nm. To output optical radiation from the vacuum chamber, a special vacuum input with a quartz window (with known bandwidth) has been used. Optical radiation has been transmitted to the spectrometer using optical fiber. The input aperture of the optical fiber has
been directed perpendicular to the propagation path of the electron beam. Distance between beam’s symmetry axis and the input aperture of the fiber has been about 14 cm. The emission spectrum of beam-produced plasma has been obtained by subtracting the background radiation spectrum (without plasma generation) from the spectrum recorded during generation of beam-produced plasma. The identification of the emission lines observed in the experiment has been carried out with [9, 18–20].

Figure 2 shows the optical emission spectra of beam-produced plasma generated by the pulsed electron beam in the forevacuum pressure range. In the optical spectra of beam-produced plasma emission came mainly from the excited nitrogen molecules N\textsubscript{2} of the second-positive system (SPS) (337.1 nm, 357.7 nm and 380.5 nm), the excited molecular ions of the first-negative nitrogen system N\textsubscript{2}+ (FNS) (391.4 nm, 427.8 nm and 470.8 nm), the excited nitrogen molecules of the first-positive system N\textsubscript{2} (FPS) (528 – 890 nm), the excited atomic nitrogen ion N\textsuperscript{+} (641.3 nm) and the excited nitrogen atoms of N (746.9 nm). Among the spectral lines of ions, the emission of molecular ions N\textsubscript{2}+ of the first-negative system with wavelength \(\lambda = 391.4\) nm, caused by the transition
\[
(B^2 \Sigma^+_u \rightarrow X^2 \Sigma^+_g),
\]
is the most intense. The second intense ion line is produced by radiation of the atomic nitrogen ion N\textsuperscript{+} with wavelength of \(\lambda = 641.3\) nm, caused by the transition
\[
(3d^3F^0_i \rightarrow 3p^1D_2).
\]
The spectral line of this atomic nitrogen ion N\textsuperscript{+} lies in the range of the FPS. The intensity of the emission bands of the SPS is higher than the radiation intensity of the FPS. The line intensity of the nitrogen molecular ion \(\lambda = 391.4\) nm from the FNS is higher than the intensity of the lines of the SPS. Probably, under our experimental conditions, this is due to the cross section \(\sigma_i\) for ionization of nitrogen molecules by the direct electron impact from the ground state of the molecule N\textsubscript{2} with the occupation density of the \(B^2 \Sigma^+_u\) level of the molecular nitrogen ion significantly exceeds the cross section \(\sigma_{exc}\) for the excitation of the \(C^1\Pi_u\) level by the direct electron impact from the ground state of N\textsubscript{2} [19]. Several lines with low intensity can be attributed to the radiation of atomic nitrogen N\textsuperscript{+} [18]. Also, we have observed emission lines came from the exited molecule OH (lines lay in the range 305–320 nm), caused by the transition
\[
(A^2\Sigma^+) \rightarrow (X^2\Pi_i),
\]
the exited atomic oxygen O (777.4 nm), caused by the transition
\[
(4s(\overset{3}{D})4d) \rightarrow (4p(3P^o)),
\]

3. Experimental results and discussion

Figure 1. Scheme of the experimental setup: 1 – electron beam; 2 – plasma e-beam source; 3 – vacuum chamber; 4 – vacuum pump; 5 – power supply unit; 6 – Faraday cup; 7 – probe; 8 – DC voltage source; 9 – optical spectrometer; 10 – vacuum input; 11 – optical fiber; \(L\) – distance from the accelerating electrode.
and the exited (Balmer series) of hydrogen atoms H_α (656.2 nm) and H_β (486.3 nm). The observed lines from the exited OH, O, H_α and H_β indicate the dissociation of water vapor H_2O and hydrogen H_2 molecules [20]. The presence of water vapor H_2O and hydrogen H_2 in the vacuum chamber is due to the used pumping system. In addition, due to vacuum chamber walls have not been heated, the presence of water vapor and hydrogen are also caused by the gas desorption from the walls of the vacuum chamber [21].

In case of beam plasma generation in nitrogen, the lines emitted from the excited molecular ions of the first-negative nitrogen system N_2^+ with \( \lambda = 391.4 \) nm and the excited atomic nitrogen ion N^+ with \( \lambda = 661.3 \) nm are rather often used to characterize parameters of plasmas (e.g. plasma density) [9]. Therefore, we have also selected these lines to observe changes of density of the beam-produced plasma. An increase in the beam current \( I_b \), as expected, has led to increase in the radiation intensity of the beam-produced plasma and, consequently, to increase in line intensities of N_2^+ and N^+ (figure 3). The linear increase of intensities of lines 391.4 nm and 661.3 nm indicates the linear increase of density \( n \) of the beam-produced plasma. The linear increase of \( n \) is confirmed by the probe measurements. Increase of gas pressure \( p \) has led to increase of the radiation intensity of the beam-produced plasma (figure 2, b). Previously, has been shown, that an increase in gas pressure induces the effect of “switching” the discharge current into emission in the forevacuum pressure range [22]. Thus, an increase in gas pressure leads to an increase in the emission current \( I_e \) and, consequently, to an increase in the electron beam current \( I_b \) at invariable discharge current \( I_d \). Therefore, the dependencies of the emission intensities normalized to beam current \( I/I_b \) on gas pressure \( p \) (figure 4) and the dependence of the density \( n \) normalized to beam current \( n/I_b \) on gas pressure \( p \) (figure 5) have been plotted to demonstrate influence only gas pressure on plasma density. An increase in pressure \( p \) leads to an increase in the density \( n \) of the beam plasma, which is confirmed by both spectral measurements and probe measurements. The probe measurements have demonstrated almost linear dependence \( n/I_b \) on \( p \) in full investigated pressure range 4 – 13 Pa (figure 5), while dependencies \( I/I_b \) on \( p \) are linear in pressure range 6–13 Pa (figure 4). Ion spectral lines have decreased rapidly as \( p \) decreasing at gas pressure below 6 Pa. The decrease of intensities of molecular nitrogen ion line and atomic nitrogen ion

Figure 2. Emission spectrum of the beam-produced plasma, \( L = 15 \) cm, \( I_b = 23 \) A:

a) \( p = 8 \) Pa; b) \( p = 13 \) Pa.
line at gas pressure below 6 Pa requires more detailed research. The linear dependences of the beam-produced plasma density on the current $I_b$ and on the pressure $p$ indicate absence of beam-plasma instabilities, which could create RF fields and provide beam-plasma discharge. The linear dependencies of the spectral lines presented on figures 3 and 4 are due to the optical radiation of the beam-produced plasma is caused only by spontaneous emission for our experimental conditions.

Figure 6 shows the radial distribution of the density $n$ of the beam-produced plasma at the distance of 15 cm from the electron source extractor. The density distribution $n$ has a shape close to the normal distribution, which is mainly due to the distribution of current density over the electron beam cross section has had a shape close to normal. For the fixed distance $r$ from the electron beam axis, the beam-produced plasma density $n$ has depended linearly on the beam current (current density).

**Figure 3.** Dependences of the radiation intensities $I$ of nitrogen ions with wavelengths of 391.4 nm (1) and 661.3 nm (2) on the electron beam current $I_b$ at pressure $p = 8$ Pa ($L = 15$ cm).

**Figure 4.** Dependencies of the emission intensities normalized to beam current $I/I_b$ on $p$ ($L = 15$ cm): 1 – 391.4 nm; 2 – 661.3 nm.

**Figure 5.** Dependence of the plasma density $n$ normalized to beam current $n/I_b$ on gas pressure $p$ ($L = 15$ cm; $r = 0$).

4. Conclusion
The research of generation of the beam-produced plasma by the pulsed low-energy (8 keV) large radius electron beam in the forevacuum pressure range is presented. Increase of beam current and increase of gas pressure have provided increase of density of beam-produced plasma. This increase has been confirmed by the emission spectrum analysis and by the probe measurements. The plasma density increases linearly with increasing beam current. The probe measurements have demonstrated almost linear dependence of plasma density on gas pressure, while emission spectrum measurements have demonstrated linear dependence only in pressure range 6–13 Pa. The low intensities of spectral lines of plasma ions at pressure below 6 Pa require more detailed research.
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Figure 6. Radial distribution of the density $n$ of the beam-produced plasma. The distance from the electron source extractor to the probe is 15 cm.