Creation of plasma column with different density gradients to generate terahertz radiation during beam-plasma interaction

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Abstract. The system is described for the preliminary plasma creation in the GOL-PET facility. Currently, after this system was considerably reconstructed, it is based on a high-voltage discharge system with pulsed gas injection. The new system was studied on the subject of whether, with its help, it is possible to create preliminary plasma with different longitudinal and transverse density distributions. The results obtained are presented which seem to be encouraging.

1. Introduction
The submillimeter-wave generation during the beam-plasma interaction is being researched in the Budker Institute of Nuclear Physics (BINP). In the course of research, two generation mechanisms were discovered and described [1, 2]. In both cases, the upper-hybrid plasma waves are excited and pumped by the relativistic electron beam (REB). According to the first mechanism, the upper-hybrid plasma wave is scattered by the plasma density gradients and transformed into the electromagnetic wave with the same frequency [1]. According to the second mechanism, the coalescence of two upper-hybrid plasma waves occurs and the electromagnetic wave with the doubled frequency is formed [2]. Currently, the first mechanism is studied in detail in experiments at the GOL-PET facility. The system of the preliminary plasma creation should meet some requirements. Firstly, the preliminary plasma should ensure the REB propagation along entire length of the vacuum chamber and its efficient relaxation in the plasma. Secondly, it should be possible to output the submillimeter wave radiation from the vacuum chamber containing the plasma column in both transverse and longitudinal directions [2]. Thirdly, according to the last experiments, the output electromagnetic flux in the longitudinal direction increases with growing plasma density, and moreover, if there are transverse density gradients inside the plasma column, then the output flux power will increase more than 10 times [3]. Therefore, in order to ensure the radiation output in the longitudinal direction, the system is required that generates plasma with different density distributions in the longitudinal and transverse directions at plasma densities of more than $10^{15}$ cm$^{-3}$.

2. Description of the plasma creation system
To generate the preliminary plasma, we use the high-voltage discharge system shown in Fig. 1. This system is similar to those used in experiments at the GOL-3 [4] and the GOL-3T [5] facilities. The standard operating conditions of the GOL-PET facility are created as follows. At first, using
the pulsed quick-opening valves, the gas puffing into the vacuum chamber is performed. Then the high-voltage discharge system initiates the electrical breakdown in the gas cloud to create the preliminary plasma column. Then, the high-current REB is injected into the plasma.

The gas puffing system includes three pulsed valves. The first valve (valve 4 in Fig. 1) is located at a distance of $z = -38$ cm from the input magnetic mirror of the solenoid and is used to inject krypton (the heavy gas). On the one hand, the krypton cloud provides charge compensation for electrons in the REB compression region; on the other hand, it prevents the diode from hydrogen spreading from the solenoid region. Two other valves (valves 5 in Fig.1) are used for puffing hydrogen into the solenoid region of the vacuum chamber. The valves are located at distances of $z = -22$ and 84 cm, respectively. For each valve, the opening time and the open state duration are determined independently.

After the controlled ignitron triggering, the high-voltage discharge system of the GOL-PET facility supplies a high-voltage pulse of up to 30 kV from the capacitor with a capacitance of $C_1 = 3.2 \mu F$ to three electrodes specially insulated from the metal chamber with zero potential. Two graphite semirings operating as main "discharge" electrodes are installed diametrically opposite to each other inside the quartz tube with a diameter of 8 cm. The semirings are insulated from each other. The quartz tube with an inner diameter of 10 cm insulates the semirings from the chamber and prevents the formation of discharge arcs between the semirings and the chamber walls. The high-voltage pulse causes breakdown in the gas cloud, which occurs along the entire chamber length up to the location of the graphite collector, which captures the electron beam. To initiate discharge near this collector, the metal rod is inserted into the vacuum chamber through the ceramic tube. In the discharge circuit, the rod is the third high-voltage electrode. The pulsed voltage is applied to it simultaneously with the voltages applied to the graphite semirings through the separating capacitor with a capacitance of $C_2 = 0.4 \mu F$.

3. Experimental results
After reconstruction of the high voltage system, two series of experiments were conducted. New high-voltage system was studied on the subject of whether, with its help, it is possible to create preliminary plasma with the different longitudinal and transverse density distributions.

3.1. Experiments with different high-voltage discharge circuits
Different circuits of the semiring voltage supply were tested to study, if it is possible to form different radial plasma density distributions. In order to analyze the obtained radial density distributions,
we used photographs of the plasma column glow (see Figs. 2a, 2b and 2c). The plasma glow intensity distributions, which, in a first approximation, correspond to the plasma density distributions, were calculated for each of the photographs shown in Figs. 2a, 2b and 2c. The calculated distributions are presented in the corresponding Figs. 3a, 3b and 3c. For all circuits of the discharge electrode supply, the igniting electrode was also included in the circuit. This electrode was installed on the left side of the vacuum chamber (if we look along the beam). The results presented in Figs. 2 and 3 demonstrate that, using the different circuits of the discharge electrode supply, we can obtain different radial density distributions in plasma.

**Figure 2.** Photographs of plasma column glow. (a) 20 kV voltage is applied to both semirings; (b) and (c) 26 kV voltage is applied only the left or right semiring (if we look along the beam), respectively.

**Figure 3.** The calculated glow intensity distributions corresponding to the photographs in Figs. 2a, 2b and 2c.

In addition, for the different circuits of the igniting electrode connection, the longitudinal plasma density distributions were studied. For this purpose, three currents were measured by the Rogowski loops: the current flowing into the plasma through the discharge semirings ($I_{\text{charge}}$), the current flowing through the plasma in the direction of the solenoid inlet ($I_{\text{head}}$) and the current flowing through the plasma in the direction of the graphite collector at the chamber end ($I_{\text{end}}$). Waveforms of these currents for three circuits of the igniting electrode connection are shown in Fig. 4. In shot #12962, the igniting electrode is disconnected; in shots #12972 and #12988, it is connected through the capacitors with a capacitances of $C_2 = 0.25$ and 0.4 μF, respectively. In all shots, the applied voltage was 26 kV. The $I_{\text{charge}}$ signal turns out to be the same for all circuits of the igniting electrode connection; the changes in the $I_{\text{head}}$ signal are insignificant. On the contrary, the $I_{\text{end}}$ current considerably increases with increasing $C_2$ capacitance. Thus, we can control the discharge propagation toward the collector located at the chamber end.

**Figure 4.** Waveforms of currents for different circuits of the igniting electrode connection: (a) $I_{\text{charge}}$; (b) $I_{\text{head}}$; and (c) $I_{\text{end}}$. 
3.2. Experiments with different regimes of gas puffing
A series of experiments was conducted at different regimes of gas puffing into the vacuum chamber. We varied opening time of the valve and the open state duration for the valve for hydrogen puffing located at z = 84 cm. When we decreased the valve open state duration \( \tau \) step by step from 10 to 3 ms and then to 1.5 ms we decreased the amount of gas injected. The high voltage discharge currents measured for three gas puffing regimes are shown in Fig. 5. The \( I_{\text{charge}} \) current does not change with decreasing amount of the injected gas; the changes in the \( I_{\text{head}} \) current are insignificant, and the \( I_{\text{end}} \) current strongly decreases with decreasing amount of the injected gas. Also REB transportation through plasma was studied. Current of the beam (\( I_{\text{diod}} \)) was additionally measured in these experiments. The waveforms of currents, measured during the beam injection in 20 \( \mu \)s after the beginning of the high voltage discharge, are presented in Fig. 6. The results presented in Fig. 6 (d) demonstrate there was no beam current neutralisation in the chamber end when the duration \( \tau = 1.5 \) ms. The beam charge was still compensated in this case.

![Waveforms of currents for different regimes of gas puffing](image1)

![Waveforms of currents measured during the electron beam injection for different regimes of gas puffing](image2)

In these experiments, the Michelson interferometer with a wavelength of 10.6 \( \mu \)m was used to measure plasma density averaged over the cross section. The results of measurements are presented in Table 1. The plasma densities measured during beam injection are almost the same when the valve open state duration \( \tau \) is 10 or 3 ms. For \( \tau = 1.5 \) ms, the plasma density at the beam injection was two times higher than for \( \tau = 3 \) ms. In case of \( \tau = 1.5 \) ms, the more efficient beam–plasma interaction and the increase in the power of the output terahertz flux were measured.

**Table 1.** Plasma density in the cross section of the second valve for hydrogen puffing (84 cm).

| Valve open state duration | 10 ms | 3 ms | 1.5 ms |
|---------------------------|-------|------|-------|
| Plasma                    | \( n = 1.2 \cdot 10^{14} \text{ cm}^{-3} \) | \( n = 6.4 \cdot 10^{13} \text{ cm}^{-3} \) | \( n = 6 \cdot 10^{13} \text{ cm}^{-3} \) |
| Plasma and REB            | \( n = 1.7 \cdot 10^{15} \text{ cm}^{-3} \) | \( n = 1.6 \cdot 10^{15} \text{ cm}^{-3} \) | \( n = 3.3 \cdot 10^{15} \text{ cm}^{-3} \) |

4. Conclusions
The high-voltage discharge system for creating preliminary plasma, which can be used in the beam-plasma experiments, has been upgraded and studied at the GOL-PET facility. Creation of different transverse and longitudinal plasma density distributions was realized which is necessary for providing future experiments on the generation of terahertz radiation due to the beam-plasma interaction. In experiments on beam injection, it has been found that to increase the power of the radiation flux along the axis one need to create low plasma density at the column end where the flux goes out.
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