Plasma flow from vacuum surface flashover initiated by 70-kV 20-ns pulses

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Abstract. In this work we study plasma beams generated by vacuum surface flashover discharge. We measured ionic current, velocity of ions at values of discharge current 2.8 kA and 5.5 kA for polymethylmethacrylate (PMMA), polytetrafluorethylene (PTFE) and polyethylene (PE). The aim of the work is to compare parameters of particle flows at different values of discharge current and unchanged voltage. We used generators with coaxial and disk-shaped glycerol-filled pulse-forming lines. Maximum voltage is 70 kV; voltage pulse duration is 20 ns; width of a current pulse first half wave is 30 ns. Average velocity of the ions for all materials is within the range $\sim 100 - 150$ km/s and doesn’t change significantly as the current increases from 2.8 kA to 5.5 kA. Ion current of the beam increase approximately linearly at higher discharge current. We estimate the density of electrons in plasma as a function of distance from the discharge. The applicability of this type of discharge for creating plasma for neutralizing high-power ion beams in inertial confinement fusion facilities is discussed.

1. Introduction
Pulsed plasma beams are widely used in technology like thin film deposition, pulsed plasma thrusters, laser pumping, ion implantation, and other pulsed power applications. Among other things, some properties of pulsed plasma beams have provided application of such beams in devices for neutralization high-power heavy elements ion beams which are used in facilities for inertial confinement fusion (ICF) [1, 2].

Plasma flow is a good instrument for ion beam neutralization, however, there are a lot of technical and physical problems to be solved. A lot of efforts are done to homogeneously fill the drift space in focusing magnetic fields with plasma. The requirement of plasma homogeneity plays a key role in the choice of plasma source location and plasma generation moment [3]. Various electrode systems and propellant materials are used to achieve specific spatial distributions of electron and ion concentration in technological volume. For example, in works [4, 5] a metal grid attached to an inner surface of a cylindrical BaTiO$_3$ shell is used to create plasma. In work [6] plasma is formed between the metal electrodes by a high-current vacuum arc in which the electrons flow from the cathode craters.

An alternative method of generation of dense particle beams for neutralization issues using vacuum discharges is a high-voltage vacuum surface flashover.

Some of our earlier works [7, 8] were devoted to the design of compact high-voltage low-joule generators and improving their performance in creating plasma beams by means of nanosecond (10 – 80 ns) vacuum dielectric surface flashover. We have shown that nanosecond discharges
initiate plasma beams with maximum ion velocities of $\sim 150 - 200$ km/s, and a full ion current of $\sim 1$ A in case of a generator based on semiconductor opening switches with a working voltage of $\sim 120$ kV and energy storage of $\sim 0.2$ J [7], as well as in the case of a generator based on a coaxial forming line with a capacity of $\sim 1$ nF, working voltage of $\sim 80$ kV, and energy storage of $\sim 2$ J [8]. We found that a discharge in a linear electrode configuration results in an anisotropy of the plasma flow in the plane perpendicular to the discharge, where the particle flow is concentrated in a narrow region having distinct angular orientation [7, 8]. This specific feature allows to form a narrow plasma flow with an electron concentration of more than $10^{10}$ cm$^{-3}$ at a distance of 10 cm from the discharge which is sufficient for ion beam neutralization [3]. Thus, using low-joule pulsed generators allows to form plasma flows suitable for neutralization of heavy ion beams in ICF experiments.

The potential new applications of such compact generators motivate research on how discharge plasma parameters depend on discharge current and energy input. Furthermore, the promising results we obtained gave us a reason for further improvement of the generators, in particular, increasing the discharge current and stored energy, which will allow us to achieve a concentration $\sim 10^{12}$ cm$^{-3}$ for electrons and $\sim 10^{15}$ cm$^{-3}$ for neutrals.

In this work, we present the results of measurements of full ion current of the beams generated by 2.8-kA and 5.5-kA discharges with durations of current pulse of $\sim 30$ ns on the surfaces of several polymer materials. These results will be used for calculating the values of stored energy and discharge current which provide optimal electron concentration in neutralizing plasma.

2. Experimental

The experimental apparatus includes a 2.5-m$^3$ vacuum chamber, pulsed generators, Tektronix TDS644B oscilloscope and a Faraday cup.

Two generators were used for the experiments (figure 1). The generators have 3 main units: a pulse transformer (1), a forming line (2), and a discharge unit (3). Both generators have a similar design of the pulse transformer, which is shown in figure 2. The difference between the generators is in the design of the forming lines (figure 3). The coaxial forming line (figure 3-a) has an impedance of 25 Ω providing discharge current of 2.8 kA, whereas the disk-based forming line (figure 3-b) has an impedance of 10 Ω and provides a current of 5.5 kA. The coaxial forming line consists of two 10-cm-long coaxial cylinders (11 and 7 cm in diameter). The line is capable of storing $\sim 1.2$ J of energy. The disk-based forming line contains an aluminum 16-cm-

Figure 1. Pulsed generators with coaxial (a) and disk-based (b) forming lines and discharge unit (c): 1 – pulse transformer; 2 – pulse forming line; 3 – discharge unit outlet.
Figure 2. Circuit layout of the pulsed generator: $L1$, $VD1$, $VD2$, $C1$ are the voltage doubler; $VS$ is the thyristor; $L2$ is the inductor of the energy recovery circuit; $Tr1$ is the microsecond pulse transformer; $Div1$, $Div2$ are the voltage dividers.

diameter disk within a cylindrical 20-cm-diameter 7-cm-long volume. The capacity of the line is 1 nF which corresponds to $\sim 3$ J of stored energy. Both lines are filled with glycerol. Current switching is controlled by a nitrogen-filled spark gap. The working voltage of the spark gap is 70 kV for both generators, and the maximum pulse repetition rate is 100 pps.

In our previous work [8] we used polyethylene (PE), polymethylmetacrylate (PMMA), and polytetrafluorethylene (PTFE) as model samples. Particularly, experimental data on polyethylene was used for theoretical calculations concerning the surface heating process. In this work, we use the same samples for the purpose of further development of the theoretical model using new numerical data on the plasma beam parameters at higher discharge currents.

We put the samples in the discharge unit so that the electrodes are firmly attached to the surface of the sample with a gap of 20 mm. During the breakdown process, the propagation of the ionization front across the surface of the sample starts from the sharpened anode (the cathode is smoothened and polished). A strong electric field $\sim 10^7 - 10^8$ V/cm around the sharpened anode pulls the electrons out of the subsurface layer and accelerates them. This process leads to the formation of a conductive subsurface layer of positive charge and further propagation of the ionization front towards the cathode. As the ionization front spans the whole gap, the high current stage (arc discharge) follows. According to the measurements of erosion tracks on the surface of the sample, the diameter of the arc is 0.5 mm.

The waveforms of the current and voltage during the discharge are presented in figure 4. The figure shows that the duration of the discharge current pulse at half height is $\sim 30$ ns.

To measure the ion current of the plasma flow, we use a Faraday cup. Aperture area of the cup is 100 cm$^2$, and the resistive load is 60 $\Omega$. The signal from secondary electron emission in the Faraday cup is suppressed by means of two permanent magnets.
Figure 4. Waveforms of the discharge current (a) and voltage (b) for coaxial (2.8 kA) and disk-based (5.5 kA) pulse forming lines (polyethylene as sample).

3. Results and Discussion

Time-dependent waveforms of the ion current for two values of discharge current are presented in figures 5-a and 5-c. Values of the maximum ion current ($I_{\text{max}}$) obtained from the corresponding waveforms and calculated values of ion charge ($Q_{\text{ion}}$), full ion charge ($Q_{\Sigma}$) and average ion velocity ($V_{\text{ion}}$, ion velocity at maximum value of ion current) are presented in table 1. The ion charge in the normal direction is calculated via integration of ion current over time (see figures 5-a and 5-c). The full ion charge is calculated via integration of ion current by polar and azimuth angles using the data on the angular distribution of the ion charge in these conditions [8].

Table 1. Parameters of the plasma flow for 2.8-kA and 5.5-kA discharges.

| Polymer | $I_{\text{max}}$, A | $Q_{\text{ion}}$, $\mu$C | $Q_{\Sigma}$, $\mu$C | $V_{\text{ion}}$, km/s |
|---------|---------------------|-------------------------|---------------------|----------------------|
| PTFE    | 0.95                | 11                      | 13                  | 85                   |
| PMMA    | 1                   | 8.7                     | 10                  | 66                   |
| PE      | 1                   | 7.5                     | 11                  | 58                   |

As can be seen from the table, average velocity of ion doesn’t change significantly ($\sim$10%) as the current grow twice (from 2.8 kA to 5.5 kA). This fact indicates that the acceleration of the ions occurs mainly at the high-voltage stage of the breakdown process.

The possibility of application of a plasma generator as a part of a high-power ion beam neutralization facility is defined by the electron density which might be achieved in the produced plasma at certain distance. In the beam of neutral plasma, the electron concentration is equal to the ion charge concentration, which we can approximately estimate from the waveform of the ion current. Following this, we calculate the concentration of electrons at the position of the Faraday cup, averaged over the Faraday cup aperture (10×10 cm) from the density of the ion current ($I_{\text{max}}/S$) and ion velocity at the maximum values of current according with the expression:

$$n_e \approx \frac{I_{\text{max}}}{e S V_{\text{ion}}}$$

where $I_{\text{max}}$ is the maximum ion current, $e$ is electron charge, $S$ is the aperture of the Faraday cup, and $V_{\text{ion}}$ is the velocity of ions at maximum value of current.
Figure 5. Time dependence of the ion current registered by the Faraday cup and velocity distribution of ion current for 2.8-kA (a, b) and 5.5-kA (c, d) discharge currents (time-of-flight base 60 cm).

In order to obtain the dependence of electron density on distance from the discharge, we carried out measurements of the ion current at different distances using additional diaphragms without changing the solid angle of particle collection. We obtained the dependence of maximum ion current (electron density) on distance from the discharge area for PMMA in the case of a 2.8-kA discharge (see figure 6-a). For this case, the electron density accounts for $0.5 \times 10^{10}$ cm$^{-3}$ at a distance of 60 cm from the discharge, and $2 \times 10^{11}$ cm$^{-3}$ at 10 cm, according to (1). This dependence is well approximated by the expression:

$$n_e = \frac{1.2 \times 10^{13}}{1 + x^2} \text{ cm}^{-3},$$

(2)

where $x$ is the distance from the discharge, which allow us to estimate the density of electrons in discharge plasma at $x = 0$ as $1.2 \times 10^{13}$ cm$^{-3}$.

The ion charge for all three materials increases as the discharge current increases (see table 1), so we may expect increasing of electron concentration during the 5.5-kA discharge. Actually, in the case of PMMA, it rises from $0.5 \times 10^{10}$ cm$^{-3}$ to $0.7 \times 10^{10}$ cm$^{-3}$ at a distance of 60 cm from the discharge.

The concentration of electrons necessary for ion beam neutralization in real ICF facilities is up to $10^{12}$ cm$^{-3}$ and higher [3, 6]. Figure 6-b shows the dependence of electron density on discharge current for all the tested materials (at a distance of 60 cm). As can be seen from the figure, the electron density increases approximately linearly as the discharge current increases. This linear dependence leads to an approximate preliminary estimation of the discharge current,
which is needed to raise the electron concentration in the plasma beam up to $10^{12}$ cm$^{-3}$. It is about 20 kA for a distance of 10 cm.

The concentration of the charged components of the plasma depends on the distance from the discharge, voltage, discharge current and other parameters. For example, in experiments earlier [8] on measuring the directional pattern of the particle flow obtained by the linear surface nanosecond flashover, we observed distinct anisotropy of the plasma flow. This anisotropy results in high electron concentration within a narrow disk-shaped region above the discharge area. The lifetime of this region is defined by the velocity of ionic component of the plasma (figures 5-b and 5-d). As can be seen from figure 5, this time is $\sim 5-10$ µs for the tested materials. These features of the directional pattern, along with the features of the ion velocity distribution, might be taken into account in development of an ion beam neutralizing system based on a linear array of discharge gaps of similar design.

4. Conclusion

The measurements of parameters of plasma beams initiated by vacuum surface discharges at currents of 2.8 kA and 5.5 kA for three polymer materials demonstrate that ion current and electron density grow approximately linearly as the discharge current increases. At the same time, we found that the influence of discharge current on velocity of high-speed component of the plasma flow is weak. The ion velocity distributions for 2.8 kA and 5.5 kA might be used for calculation of the travelling time of the plasma bunch within the high-power ion beam transportation region.

Acknowledgments

This work was supported in part by the Russian Foundation for Basic Research under grant 18–08–000185.

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