Angular distribution of mass and charge flows in far zone of plasma beams generated by nanosecond vacuum surface flashover at 70 kV

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Abstract. In this work, we measure directional patterns of charge flow of ions and mass flow of neutrals in particle beam generated by vacuum surface flashover in linear configuration at voltage of 70 kV. We used a generator, which provide a discharge current of 2.8 kA. The samples used are polymethylmethacrylate, polytetrafluorethylene and polyethylene. We found that the directional patterns of mass and charge flows in linear configuration have distinct axial asymmetry. The corresponding angular distributions are significantly wider in the plane which is normal to the discharge than in the plane which contains the discharge. Angular distributions of charge flow are wider than distributions of neutral mass flow in the same planes. Besides, the asymmetry in ion current amplitudes at the cathode side and at the anode side is observed. We found that the share of low-velocity ions in ion current drops drastically in the plane which contains the discharge at the angles of 15 degrees and larger for all the tested materials.

1. Introduction

Various plasma beams applications were and remain the main driver of thorough fundamental investigation of plasma generation methods and plasma characteristics. During the last decades, a lot of work has been done concerning measurements of velocity spectra of plasma beams, ion and electron density, intensity of plasma impact, ionization degree and many other parameters. However, there are applications where it is necessary to know not only the concentrations and velocities of ions, but their angular distributions, which are defined by the directional patterns in different discharge configurations. Directional pattern of the plasma flow seriously influences the efficiency of some plasma-beams related devices. In particular, in pulsed plasma thrusters (PPT) angular scattering has to be reduced to increase thrust [1]. In technology of thin films deposition and in neutralization of high-power ion beams in ICF facilities, highly homogeneous filling of technological volume with plasma is required [2]. Some special applications require the measurements of angular distribution of mass and charge flows [3–5]. From the fundamental point of view, directional pattern is interesting because its structure may reveal the features of how the plasma is accelerated.

There are few works devoted to measurement of directional patterns of plasma flows from the surface flashover area. In particular, there are works on spatial distribution of mass [1], temperature and density [6]. In our previous works, we measured specific features of angular distribution of charge flow in coaxial and linear configurations [7] and distributions of mass and charge flows [8]. In this work, we complement the earlier results by the measurements of angular distributions of intensities of...
mass and charge flows by the mutually complementary methods. They include mapping of relative intensity of the particle flow deposited on mica and copper targets and measurement of ion charge flow using Faraday cup in the far zone of the particle beam.

2. Experimental setup and methods
To initiate the discharge, we use a pulsed generator. It has a coaxial pulse forming line with an impedance of 25 Ω and a stored energy of 1.5 J. The design of the forming line is presented in figure 1. The maximum voltage of the generator is 70 kV, voltage pulse width is 20 ns, discharge current is 2.8 kA, and the width of current pulse is 30 ns (see figure 2).

![Figure 1](image1.png)  
**Figure 1.** Design of the pulse forming line: housing (1); inner cylinder (2); insulators (3); input electrode (4); nitrogen-filled spark gap (5); glycerol (6); high-voltage output electrode (7).

![Figure 2](image2.png)  
**Figure 2.** Waveforms of voltage across the gap (black solid line) and discharge current (red dashed line) in the case of polyethylene.

The discharge gap is formed by the two plane electrodes attached to the dielectric sample at distance of 20 mm one from another. High electric field near the sharpened anode leads to the initiation of the flashover and following high-current discharge.

The samples used are polymethylmethacrylate (PMMA), polytetrafluorethylene (PTFE) and polyethylene (PE). These materials have been chosen because they are widely used in pulsed power applications. In addition, relatively large difference in masses of atoms in these materials (varying from 1 to 40 a.m.u.) facilitates the analysis of ion velocity spectra.

To retrieve the angular distribution of the neutrals, we mount the witness plates within a hemispherical volume above the discharge. Doing so, we plot the directional pattern by the two independent methods: recovery of the distribution of the relative opacity of the deposited film (1) and weighing of the witness plates before and after the deposition (2).

In the first case we used thin transparent mica plates with dimensions of 160 mm×28 mm, which were mounted in a metal holder forming 2 arcs with radius of 10 cm (see figure 3a). Relative thickness (relative opacity) of the deposited film is estimated from the scanned images of the plates. Using the expression for absorption of light:

\[
I = I_o (1 - R)^2 e^{(-kd)} ,
\]

and considering that the absorption coefficient \( k \) of the deposited material is constant, we can estimate the relative thickness (relative opacity) of the film as a function of angle:

\[
\frac{d(\theta)}{d(0)} = \ln \left( \frac{I_o}{I(\theta)} \right) / \ln \left( \frac{I_o}{I(0)} \right) ,
\]

and
where $d(0)$ and $d(\theta)$ are the thicknesses of the film deposited in the normal direction and at $\theta$ degrees, $I_0$ is the intensity of incident light, $I(0)$ and $I(\theta)$ are the intensities of the transmitted light at the point corresponding to the normal deposition and to the deposition at $\theta$ degrees.

**Figure 3.** Gear for measuring of the angular distribution of neutral mass in the flow from the linear discharge: four 160 mm×28 mm mica plates forming two mutually perpendicular arcs with radius of 100 mm (a) and a set of 25 mm×20 mm copper sheets mounted on arcs with radius of 150 mm (b).

Another method is the measuring of mass of the material deposited on 25×20 mm copper foil sheets. The sheets were mounted on metal arcs with radius of 15 cm by step of 10 degrees (see figure 3b).

In both cases (mica plates and copper sheets) ~ 15 000 shots were made, so that mass loss of the sample achieved 40 mg and the weight gain by a single copper sheet achieved 600 $\mu$g.

**Figure 4.** Ion velocity spectra for PMMA at different positions of the Faraday cup.

To measure the ion current of the plasma flow, we use a Faraday cup with an aperture of 10 cm×10 cm. Two permanent magnets and an iron yoke around the cup’s collector reduce the influence of secondary electron emission in the collector. We measure the ion current at the distance of 60 cm from the discharge. The choice of this time-of-flight base is caused by the several advantages, which the far zone of plasma beam gives. Firstly, this length is less than the mean ion free
path at the pressure of $10^{-4}$ mm Hg, so the distortion of the velocity spectrum is still insignificant, whereas the density of plasma is already low which facilitates the separation of ions. Secondly, it is a way to separate in time the ion peaks, which have close velocities. The ions having velocities in range of 50–250 km/s spend 2–10 μs to cover the distance of 50 cm, which allow us to obtain the well-resolved waveforms of the ionic current. Thirdly, the relatively long time-of-flight base allows to shift the starting point of the ionic current in the region of larger times in order to avoid the overlaying of the ionic current with the cross-talk signal (~100–200 ns) following the high-current discharge. Finally, at this distance (60 cm) the solid angle of particles collecting is about 0.03 sr, which give us a possibility to shrink the angle step down to 15° and increase the angular resolution. A resistive load of the Faraday cup (~ 60 Ω) served as an independent instrument for time resolution control, providing the resolution of ~ 30 ns.

Firstly, we measured the ion current for PMMA at different distances from the discharge (from 20 to 60 cm) keeping the solid angle (0.03 sr) unchanged by means of diaphragms. The ion velocity spectra obtained from the waveforms of the ion current are presented in figure 4. As can be seen from the figure, they demonstrate minor changes in form, which are due to statistical variation of flashover conditions. In general, the spectra match very well, which indicates relatively high reliability of measurements in the far zone of the beam (at distance of 60 cm).

3. Results and discussion

The normalized angular distributions of the mass flow in equatorial plane (normal to the discharge) and meridional plane (which contains the discharge channel and is perpendicular to the equatorial plane) for PTFE are presented in figure 5. The results obtained via measuring of relative thickness of the film deposited on the transparent mica plates and via weighing of the copper witness plates before and after the deposition are in good agreement with each other. As it can be seen from the figure, the directional pattern of the mass flow is asymmetric. The angular distribution in meridional plane is much narrower (12° at the half-height) than in the equatorial plane (60° at the half-height). The similar asymmetry of the flow was reported in work [1] devoted to pulsed plasma thruster performance.

![Figure 5](image)

**Figure 5.** Angular distribution of the mass flow in equatorial plane (a) and meridional plane (b) for PTFE obtained by measuring of weight gain and relative thickness (opacity) of the witness plates.

The normalized angular distributions of the charge flow in equatorial and meridional plane for all three materials are presented in figure 6. The directional pattern of the charge flow, which these angular distributions represent, is spatially asymmetric, similarly to the pattern of the mass flow. The width of the directional pattern in the meridional plane (see figure 6a) is almost 3 times less than in the equatorial plane (figure 6b).
Figure 6. Angular distribution of the ion charge flow in equatorial plane (a) and meridional plane (b) for PTFE, PMMA and PE.

The pattern is plotted using the measured values of the ion charge captured by the Faraday cup. The ion charge is calculated via integration of the ion current waveforms over time from the moment of breakdown until the moment, when the amplitude of the current signal accounts for about 0.5% of its maximum. Absolute values of the ion charge and maximum ion current of the plasma flow measured in normal direction (θ = 0°) are presented in table 1.

Table 1. Parameters of the ion flow in normal direction.

|            | PMMA | PTFE | PE  |
|------------|------|------|-----|
| Q (μC)     | 8.7  | 11   | 7.5 |
| I_{max} (A)| 1    | 0.95 | 1   |

Figure 6 demonstrates broadening of the angular distribution of charge for materials with lighter ions, which are influenced by Coulomb scattering to a greater extent. Particularly, the distribution at half-height for PE is 1.5 times wider than for PTFE. Probably, these ions are accelerated at the high-voltage stage of the surface discharge by the electrostatic field of the charged surface.

It is interesting to compare the directional patterns of mass and charge flows (see figure 7). It is seen from the figure that the patterns are similar in general. However, the pattern of the charge flow is wider than that of the mass flow. The narrowness of the directional pattern of the mass flow in meridional plane indicates that anisotropy of acceleration is specific not only for charged component of the particle flow, but also for the neutral.

We assume that the observed anisotropies of the mass and charge flows are related with the specific features of plasma density distribution along the discharge arc. Probably, the density of plasma near the electrodes is higher than in between, which results in the occurrence of density gradient in plasma along the discharge. Thus, plasma is squeezed in the gap because of this gradient during the expansion, which defines the narrow angular scattering of ions in meridional plane (see figure 8).

In addition to the spatial asymmetry, we observe the asymmetry of the ion current in the meridional plane as the Faraday cup moves either towards the cathode or towards the anode along the arc (see figure 9). The figures show, that the asymmetry of the directional pattern in meridional plane is peculiar for PE. The ion current measured in the meridional plane for PE accounts for about 700 mA at 15° and 80 mA at 30° on the anode side, whereas on the cathode side its only 250 mA and 33 mA at the same angles. Thus, the anode-side and cathode-side flows differ twice or more. The difference in anode-side and cathode-side parts of the ion current for PTFE is less significant. They are 110 and 90 mA at 15°, and 25 and 35 mA at 30°, respectively. Visually, the plasma plume for PTFE sample seems to be more symmetric in meridional plane.
Figure 7. Comparison of the angular distributions of mass and charge flows for PTFE in equatorial (a) and meridional (b) planes.

Figure 8. Typical plasma plume in linear configuration of high-voltage surface flashover.

As it is seen from the figure 9, the ion current for PE at 15° is 5 times higher than for PTFE. Probably, the dissimilarity in anode and cathode influence on the directional pattern is due to the ionic composition of the beams. In the case of PE, in meridional plane, the light hydrogen ions are accelerated in predominantly repulsive electric field at the anode side and are decelerated in predominantly attracting electric field at the cathode side. In the case of PTFE, relatively heavy fluorine ions are influenced by the electric field of the electrodes to a lesser extent. Thus, the ions in PE plasma in average move ~ 2 times faster than those in PTFE plasma.

From the waveforms of the ion current for PE and PTFE at 15° and 30° (figure 9) we see that as the angle increases, the slow ions vanish in the spectra very rapidly, whereas the fast ions with velocities of more than 60 km·s⁻¹ for PTFE and more than 100 km·s⁻¹ for PE remain in the spectra. Probably, these ions are accelerated at the high-voltage stage of the surface flashover, when the electrostatic forces prevail over the others in near-anode region of the sample surface.
Figure 9. Waveforms of the anode-side and cathode-side parts of ion flow for PE and PTFE at 15° and 30° (from the normal): PE at 15° (a), PE at 30° (b), PTFE at 15° (c), PTFE at 30° (d).

4. Conclusion
The results show, that the directional patterns of charge and mass flows are spatially heterogeneous. The angular distributions of mass and charge flows are significantly wider in the plane, which is normal to the discharge. The fact that directional pattern of charge flow is wider than the pattern of mass flow, probably, it is due to the Coulomb interaction of ions in the ion beam. The asymmetry of the charge flow in the plane which contains the discharge and the normal to the sample is caused by the different acceleration conditions near anode and cathode. The sharp reduction of the share of low-velocity ions in spectra measured at the angles other than normal (15° and larger) indicates the great difference in formation of directional pattern of charged particles flow at the high-voltage and high-current stages.

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