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A mass-charge measurment of main plasma components generated by the dielectric flashover

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The results of measuring the velocities and mass-charge composition of the main plasma fractions of high-voltage surface discharge of sulfur, potassium chloride and in vacuum polyethylene. Pulsed nanosecond generator with voltage to 60 kV was used. Discharge current amplitude is 3−6 kA with duration of 0.1 μs. When using a mass analyzer with a pulsed magnetic field up to 0.3 T, it was found that at a current density across the discharge channel up to $6 \cdot 10^5$ A/cm^2, the proportion of single-atom ions in the beam does not exceed 10–15%, and the bulk of the ion charge is carried by single ionized molecules (S2, KCl and complexes of 2−4 monomers of polyethylene). The technique is developed to characterize the composition and velocity spectrum of plasma beam components generated in models of low-thrust electric jet ablation engines with various working substances.

Keywords: surface flashover, plasma beams, mass analyzers, macroions.

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Introduction

Papers [1–4] informed about the performed tests of models of low-thrust frequency electric jet ablation engines (EJE) with energy supply in the capacitor about 0.1−0.5 J, and dischsrges frequency 30−100 Hz. In these engines under vacuum conditions with applied high voltage (3−20 kV) the surface dischsrges develops between the electrodes over dielectric. This phenomena is sometimes called as dielectric surface flashover by electric spark or arc. In these studies the low-thrust EJE the current pulse width was about 0.1 μs, and amplitude — in range 1−5 kA. If different working substancies were used we measured the recoil pulse for working substancies of different composition, velocity spectra of charged component of plasma beams were obtained, as well as characteristics of the directional diagram of escaping flow. At that there is large difference in the achieved thrust for various working substancies, it is associated with difference of contributions of the mechanisms of ablation and ionization of components escaping the surface, and their features for substances of various chemical classes.

Besides, when measuring the ion current an full charge carried by these plasma beams we obtained that degree of ionization of the beam substance was low, i.e. below 10% [2]. Such low values can be attributed to large number of neutral atoms and molecules presence in these plasma, or to presence of relatively large single ionized molecular complexes. One of the possible ways of this problem solution is the mass-charge measurement of charged components of the plasma beam, at least their main fractions, and determination of its relationship with features of formations mechanisms of these beams at submicrosecond width of discharge current pulses. This problem is especially serious when scaling EJE for various applications, such as, when designing engines for nanosatellites, where mass of capacitors is limited, and some work parameters, e.g. dischsrges gap, input energy, voltage and current of dischsrges, shall be optimized. At such relatively low values of input energy the processes of substance release from the dielectric surface have own features, and plasma components composition can differ from those obtained during single discharges with frequency of 1−2 Hz and energy supply in capacitors of 10−50 J [6,7].

When selecting the optimal working substance for use in the engines with specific thrust level there is need to identify the molecular masses and velocity spectra of main beam components generated at various power density of the input energy in the dischsrgess by working substances with various types of chemical bonds, including different polymers. In applications where for the required effect all plasma generated during dischsrges is used (plasma flow switches [5], EJE [6,7], film sputtering processes), the information is required on composition and velocity spectra of its components, of main at least of the main ones. In case of EJE this is especially valid, as during their operation a significant portion of escaping substance is deposited on surfaces of the space vehicle reducing thrust efficiency, contaminating work surfaces of solar cells and optical devices [8]. It is considered that reason of plasma flow deposition is scattering of particles and temperature diffusion which are most evident at the beam periphery (at angles from axis over 60°), and phenomenon of late ablation [9]. Paper [8] shows measurement data of

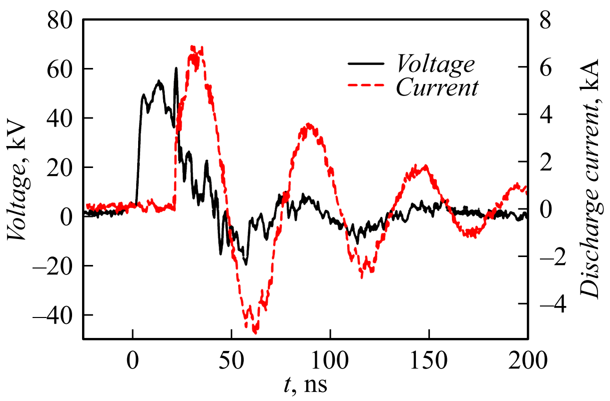

Figure 1. Oscillograms of voltage and current of dischsrges in mode of flashover from the anode.

layers deposited on surface of optical mirrors, the layers comprise substance components of the working fluid, their thickness during $1.4 \cdot 10^6$ dischsrgess of EJE achieved units of microns reducing transmission by almost one and a half times. But atomic composition analysis of these layers does not provide information on the molecular composition of the components in the beam. In paper [10] in microjet engines the authors used mixtures based on ammonium hydroxyl nitrate and polyvinyl alcohol as the working fluid, they stated that when calculating the ions concentration in the plasma beam based on measurements with Langmuir probes the molecular mass of ions should be known. So, the problem of availability of authentic information on the molecular masses and ratio of concentrations of ionized components in these beams is actual. For its solution a magnetic mass analyzer of ions was developed, and procedure and results of executed mass-charge measurements of prevailing components of beam emitted during the vacuum surface flashover and further arc dischsrges of submicrosecond duration were described for several dielectric materials of various chemical classes in mode of testing and calibration.

1. Experimental technique

For measurements the magnetic mass analyzer was manufactured based on Helmholtz coils, positioned in the vacuum chamber in the plasma beam path, and substances with large range of molecular masses were used to test the set-up: sulfur, KCl, polyethylene. The main feature of this procedure is the possibility to determine the parameters of beam not distorted by the dampening devices to obtain the most reliable quantitative data on the actual ratio of main charge and mass fractions. The plasma beam is created in dischsrges during the surface flashover of samples made of dielectric materials of several classes: sulfur, ionic crystals (KCl) and high density polyethylene in current range 3–6 kA. It simulates the parameters of dischsrges occurred in studied models of EJE. We used an oscillator generating pulses of voltage below 60 kV and oscillating damped current below 6 kA with total duration 120 ns (Fig. 1). In dischsrges cell (Fig. 2, *a*) the cathode is oval in shape, and the anode edge is a sharp linear section 2–4 mm long. Such configuration corresponds to the beginning of development of dischsrges conductive channel from anode. The observed delay in the beginning of large discharge current relative to the leading front of the applied voltage corresponds to time of front movement of the conductive channel of the surface dischsrges with high velocity (about $2 \cdot 10^6$ m/s) from anode to contact with cathode.

The ion current and mass-charge characteristics of ionized fractions of plasma beam were measured on the developed small-size mass analyzer with pulsed magnetic field below 0.3 T. The field is created by two Helmholtz coils with inner diameter of 16 cm wound on frame made of stainless steel. The beam directed to the analyzer is formed by two slot diaphragms. The first one is 4 mm wide and located at distance 40 mm from the dischsrges (Fig. 2, *b*, below). The second diaphragm is 3 mm wide and located at the magnetic field entrance. As the effect of field with opposite direction on the beam trajectory outside the solenoid can significantly decrease the effective field, i.e. increases the value of the calculated Larmor radius relatively to its actual value, and can provide the overestimated atomic mass of particles, a screen of steel sheets is installed around the solenoids. All elements of the mass analyzer, including solenoids, are positioned in the vacuum chamber with volume of 2.5 m^3. High vacuum evacuation stage — oil diffusion pump (working fluid — oil VM-5S) creates vacuum $1.2 \cdot 10^{-4}$ Torr, measured by the ionization pressure gauge. During the plasma beams generation the pressure increased to maximum $1.8 \cdot 10^{-4}$ Torr. Pulse width of the magnetic field is 24 ms, and dischsrges voltage pulses are applied to the sample at the moment of field beginning (reference signal) and at the moment of maximum $B(t)$, i.e. after 10 ms (Fig. 3).

The ion currents are registered by three detectors-Faraday cylinders with collectors area of 5 cm^2, the collectors are positioned at distance of 0.47 m from the sample in directions corresponding to several Larmor orbits with fixed radiuses (0.7 and 0.5 m). Ballast resistor 1 kΩ in collector circuit of the Faraday cylinder ensures time constant of the input circuit about 0.2 μs for good resolution of the observed peaks. Fig. 4–6 shows the oscillograms of time-of-flight dependence of ion current entering the detectors, they were obtained by re-calculation from voltage on ballast resistors of the Faraday cylinders. As all used ion current detectors were identical, the measured currents provide rather definite quantitative information on ratio of densities of various ionized components at various Larmor orbits, and integration over time provides good ratio of their total charges. Due to low duration of the plasma emission process (0.12 μs) as compared to the its time of flight to detectors ($3 - 10\,\mu$s) velocities of ions can be directly calculated knowing distance to traps, and determining by oscillograms the movement time of this group of ions.

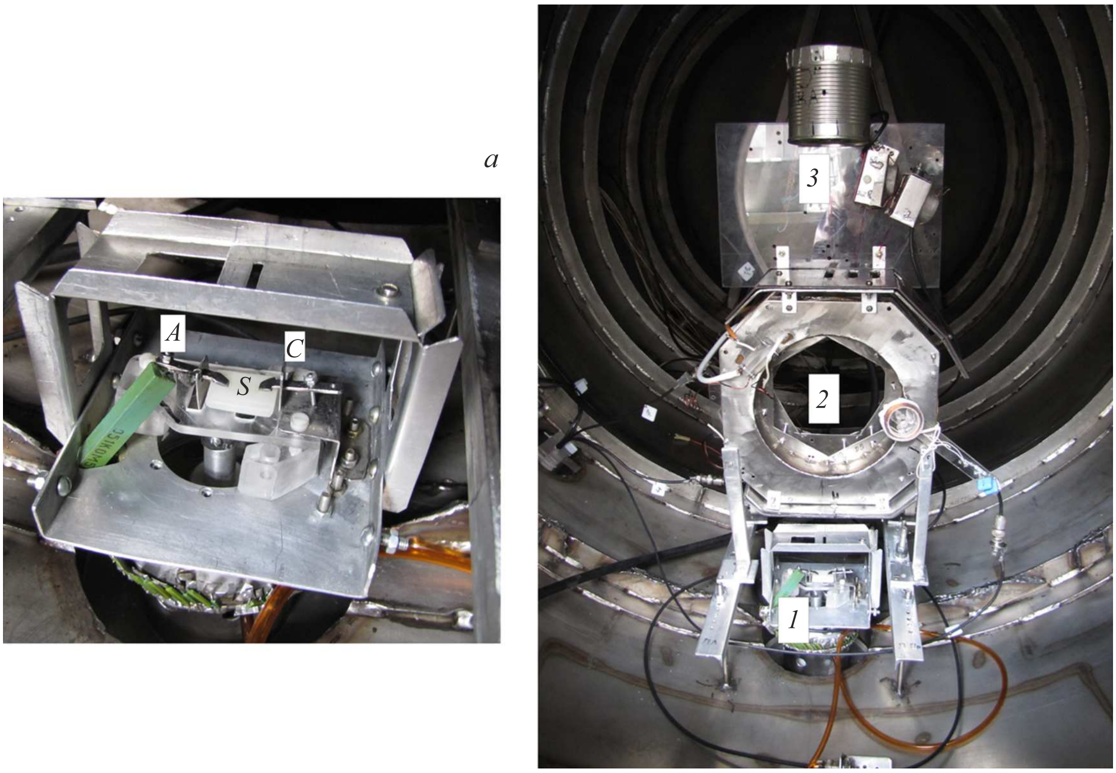

Figure 2. Experimental set-up: *a* — dischsrges gap: A — anode, C — cathode, O — dielectric; *b* — general view: *1* — dischsrges gap, *2* — frame with Helmholtz coils, *3* — ion current sensors (Faraday cylinders).

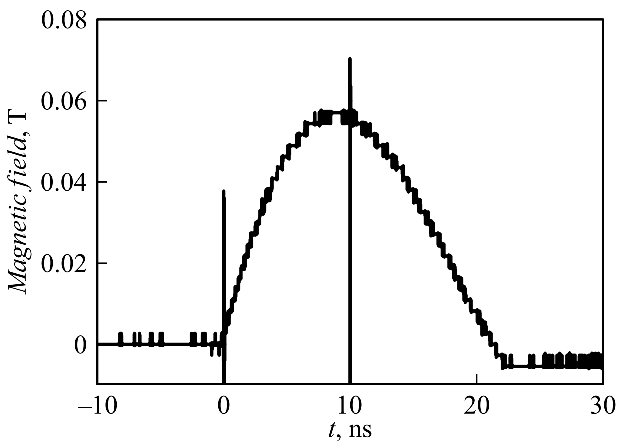

Figure 3. Oscillogram of magnetic field of analyzer with marks of start pulse of high-voltage oscillator.

Varying value of deflecting magnetic field we determine its values at which signal in detectors positioned on these Larmor orbits have maxima, and mass of particles in atomic mass units (a. m. u.) is determined by formula $M = 0.95 \cdot 10^8 \cdot L \cdot B/V$, where L — Larmor radius [m], B — magnetic induction [T], V — velocity [m/s]. Due to the observed large scattering (about 20%) of signal amplitude in the ion current oscillograms we averaged over 4−6 dischsrgess to obtain stable result. To a large extent such scattering is associated also with the fact that on each sensor the plasma flow is gathered only from very narrow solid angle of the directional pattern, and with insufficient reproducibility of the dischsrges path on sample.

2. Measurement results

2.1. Sulfur

As a simple substance with relatively weak interatomic interaction the sulfur was used for testing the set-up registering single- and double-charged ions and evaluation of measurements inaccuracy. Fig. 4 showed oscillograms of current of beam ion component from two detectors after passage through the magnetic field. The first auxiliary sensor registers the residual current of the undeflected beam portion ($\alpha = 0$), and the second one — beam current on the Larmor orbit with radius $L = 0.7$ m. As discharge current duration is below 0.1 μs and signal of the electromagnetic cross talk from this powerful dischsrges corresponds to the time moment of ions departure, then with low inaccuracy the velocity of these ions can be determined by the known time-of-flight base $s = 0.47$ m.

Oscillograms in Fig. 4 show that in field 0.025 T more than half of full ion current (these fractions are lighter than 60 a.m.u) leave the central receiver ($\alpha = 0$) due to the beam deflection in the magnetic field. The residual portion comprises heavier ions. In field 0.04 T almost

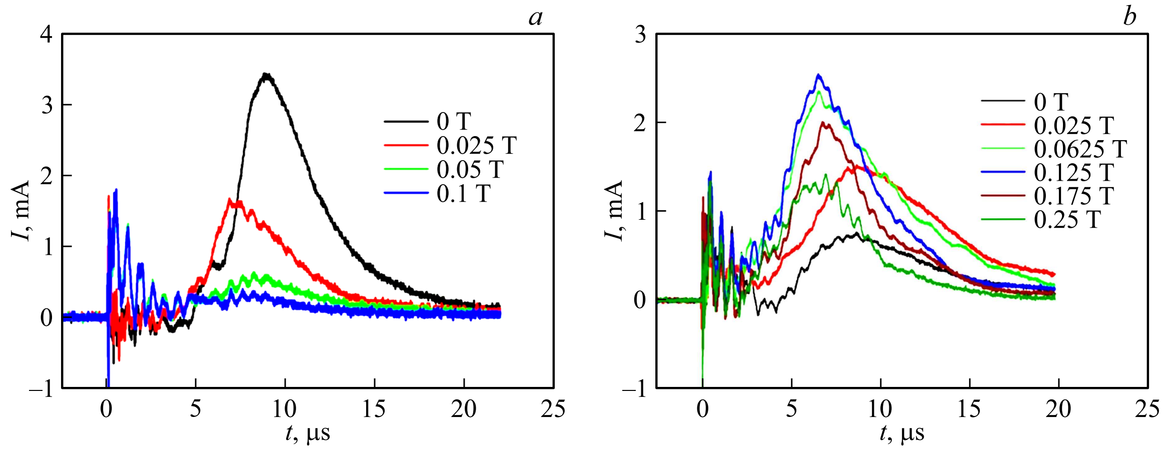

Figure 4. Oscillograms of ion current. Flashover on sulfur surface. Signal from central sensor (*a*) and sensor located on Larmor radius 0.7 m (*b*).

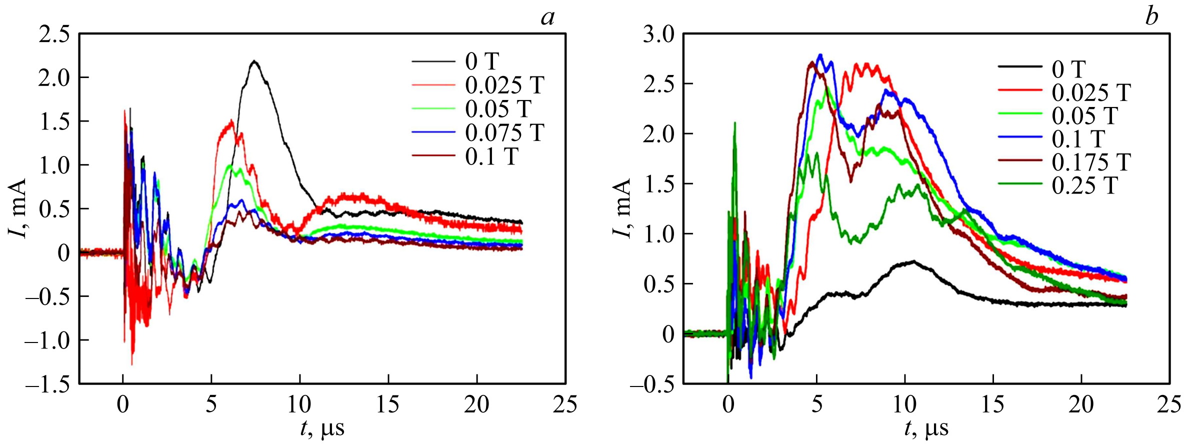

Figure 5. Oscillograms of ion current. Flashover on KCl surface. Signal from central sensor (*a*) and sensor located on Larmor radius 0.7 m (*b*).

all ions are deflected from this receiver. In oscillograms Fig. 4, *b* (sensor at $L = 0.7$ m) the ion current maximum is observed at the magnetic field 0.037 T. The inaccuracy of position determination of all peak maxima observed in oscillograms is at least 10–15%, this is associated with both scattering of signal amplitudes, and with procedure of averaging over several dischsrgess. As a result the inaccuracy of obtained values of mass numbers considering inaccuracy s of measurement of the magnetic field and particle velocities is at least 15–20%. Calculation of m/q for the moment of arrival of most intensive beam fraction with velocity $V = 67$ km/s assuming a single ionic charge gives $M = 36$ a.m.u., within inaccuracy limits corresponding to ion S^+. In field 0.075 T a faint maximum corresponding to molecule S_2^+ is observed. The third maximum is observed at 0.13 T resulting in $M = 140$ a.m.u., this corresponds to S_4^+.

2.2. Single-crystal KCl

When studying the physical mechanisms of development of high-voltage pulse surface dischsrges of the dielectric materials the single-crystals of alkali-haloid compounds, in particular KCl, are widely used as reference material, as they have a lattice with clearly observed directions of the discharge channel, large set of well known thermodynamic parameters. This ensures use of the obtained results to model the plasma generation processes and to evaluate the generated plasma beam parameters.

Fig. 5 shows oscillograms of ion current of beam generated by discharge channel on sample of this single-crystal. Sensor positioned in direction of undeflected beam registers the current signal (Fig. 5, *a*), created by ions arrived in 3–20 μs after dischsrges. The current maximum is at 6 μs, which along the known path to the receiver $s = 0.54$ m gives the velocity of these ions 90 km/s, and the entire group has velocity in range 30–150 km/s. With the magnetic field increasing this signal shape varies, and amplitude decreases. This confirms that part of ionized particles of the beam after passage of the magnetic field region is deflected under the Lorentz force and leaves the trap moving to the neighbouring traps located at angles 15 and 25°.

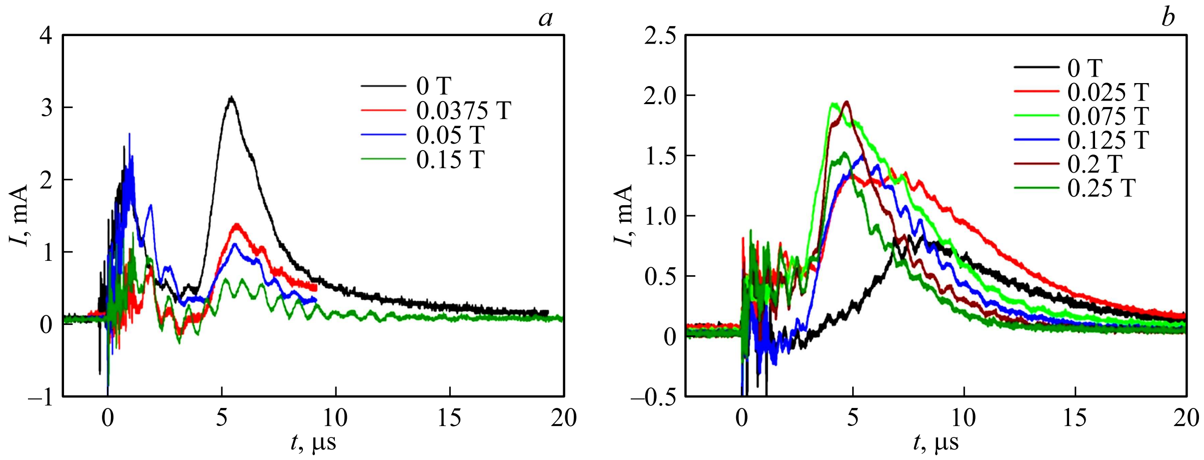

Figure 6. Flashover on polyethylene surface. Signal from central sensor (*a*) and sensor located on Larmor radius 0.7 m (*b*).

Oscillograms from the sensor positioned in the trajectory with Larmor radius 0.7 m (Fig. 5, *b*) have maximum at $B = 0.10$ T for group of ions with velocities close to $V = 87$ km/s. Calculation for this group gives the ion mass $M = 76$ a.m.u. Considering that the experiment inaccuracy is evaluated as about 15–20% when determining the mass numbers, it was specified previously (Section 2.1) for measurements of sulfur, we can conclude that the main most intensive fraction of the charged particles of the plasma beam is in the range of mass of KCl^+, i.e. it represent single ionized molecules of potassium chloride. The second peak of the ion current observed for the fraction with velocities close to 87 km/s at 0.15 T corresponds to particles with $M = 113$ a.m.u., which be in close agreement with mass of K_2Cl^+. The third maximum of the maximum ion current is observed in field 0.2 T. Ion mass $M = 140$ a.m.u. corresponds to it, this is singly charged ion comprising two molecules. As for the presence of single ionized atoms of potassium or chlorine, then, according to intensity distribution of these peaks in the oscillograms, their supply is by about order less than for the main fractions. Further, as far as the major portion of the ionized particles in the beam is composed by sample surface escaping KCl single and double molecules which are ionized in the current discharge channel, then we can suppose that the main fraction of neutral particles has the same composition.

2.3. Polyethylene

Polyethylene was selected for studies as the type sample of polymer carbon-containing material. The ion current oscillograms in two detectors (for initial beam and on Larmor radius $L = 0.7$ m) in magnetic fields below 0.25 T are shown in Fig. 6.

Despite of large noise presence, the oscillograms clearly show the current amplitude dependence on field. Fig. 7 shows dependence of ion current amplitude on Larmor orbit with $L = 0.7$ m on magnetic induction for ions group with arrival time about 5 μs. If magnetic field increases three current maxima are observed: at magnetic field 0.10 and 0.20 T (corresponding velocities are 95 km/s) and low peak at 0.05 T for ions with velocity 104 km/s. Supposing single charged ions the calculation of these peaks gives the mass numbers 30, 60 and 120 a.m.u, respectively. Considering the previous evaluation of experiment inaccuracy (at least 15%) this gives the mass numbers for these peaks in range (30 ± 4),(60 ± 8), (120 ± 20). These values rather close correlate to masses of single ionized complexes of several (one to four) monomers $(C_2H_4)^+$, which ensure prevailing contribution to the plasma beam.

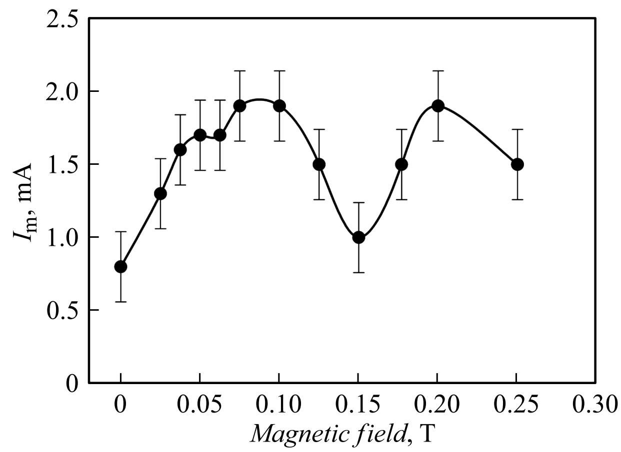

Figure 7. Ion current amplitude of sensor positioned on Larmor radius 0.7 m, vs. magnetic field for component with velocity 90 km/s. Flashover on polyethylene surface.

3. Discussion

Qualitative observations are known from papers [11,12], where plasma of the surface flashover comprises high density of particles in molecular state. Herein obtained experimental data on the fraction composition of the plasma beams of pulse high-voltage discharge of samples of dielectric materials of several various chemical classes at power density of the input energy to discharge of about 10^8 W/cm^2 state that prevailing contribution to them is made by singly charged molecular ions which comprise depending on the substance 1 to 4 and more molecules, and the ionized atoms cover in total maximum 10% of the charged components.

Previously qualitatively similar pattern of mass spectra was obtained also in plasma generation processes under action o long wavelength laser radiation on graphite samples, in particular, in paper of S.A. Kondrashev [13], where at input energy density of CO_2-laser radiation $(10^7 - 10^8)$ W/cm^2 on surface of the graphite target an ion beam is generated comprising singly charged clusters with distribution maximum corresponding to singly charged clusters composed of three carbon atoms, which in the electric field of diode at voltage below 40 kV additionally acquire energy $5 - 40$ keV.

The maximum of ion current [2] at distance from sample 0.6 m previously obtained in similar conditions for polyethylene in measurements with Faraday cylinder of large area $(100\,\mathrm{cm}^2)$ is 1.2 A. During the ion current integration over time and within full solid angle of directional pattern the charge $58\,\mu$C was obtained, which in terms of number of singly charged ions of monomers $C_2H_4^+$ gives $3.6 \cdot 10^{14}$ molecules. Their total mass not considering presence of the ionized molecules comprising two-four monomers is $17 \cdot 10^{-9}$ g or $017\,\mu$g, this is about 6.5% of measured full consumption of sample material $0.27\,\mu$g/dischsrges. This percentage composition is equal to value of usually calculated calculated degree of ionization in the plasma beam. Results of this study indicate the need to consider the significant contribution into mass of the ionized portion of beam of singly charged complexes $[C_2H_4]^{+1}_{1-4}$, which significantly increases its calculated value. Its can be evaluated by the obtained ratio of concentrations of single-, double- and tetramonomer macroions. The done calculation gives the mass of positively charged particles in the beam $0.045\,\mu$g, which is over 16% of total mass of particles in this plasma beam. So, consideration of their contribution for the polyethylene measurements [2] gives much larger mass of charged beam component, which is in agreement with noticeably more efficient acceleration of the plasma beam during dischsrges.

We can also evaluate using the thrust pulse measurement results [2] the value of average velocity of neutral component, if we subtract from the total measured recoil pulse $1.8\,\mu$N·s/discharge the calculated pulse created by the charged fraction $0.9\,\mu$N·s (considering the solid angle of thrust meter), obtained by multiplying mass of multimonomeric components by their velocities. The calculation gives the average expansion velocity of neutral mass fraction about 8 km/s.

So, at surface power density of input energy about 10^8 W/cm^2 the ionized beam fraction, covering about 16% of its mass, has velocity distribution in range $30-200$ km/s. The average velocity of the neutral component, constituting more than 80% of the beam mass, calculated from recoil pulse measurements is $6 - 8$ km/s.

Conclusion

Using the pulse magnetic mass-analyzer we obtained velocity distribution and molecular composition of main, most intensive fractions of the plasma beams of vacuum surface flashover of sulfur, potassium chloride and polyethylene at flashover voltage of 60 kV. It is also shown that in range of discharge current $3 - 6$ kA with thew current density across the discharge channel is up to $6 \cdot 10^5$ A/cm^2 and with duration of about $0.1\,\mu$s the maximum proportion of the integral ion charge of the plasma beam is carried over by single ionized molecules (S_2, KCl and complexes of $2 - 4$ singly charged monomers in polyethylene). At that the integral over carried-over charge portion of single ionized atoms does not exceed 10% of ionized fraction supply. So, proportion of the material carried over by the plasma beam in form of ions is rather higher then during general calculated degree of ionization based on the total number of individual molecules of this substance. In our case for the polyethylene this differs by more than two times. The developed procedure is intended to determine molecular masses and ratio of concentrations of ionized fractions of plasma beams generated on surface of dielectrics during vacuum surface dischsrges of dielectrics, which can be also useful when discussing the mechanisms of substance ionization during this process.

Conflict of interest

The authors declare that they have no conflict of interest.

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