Characteristics of radial ion-plasma accelerators

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Abstract. The characteristics of two-stage ion-plasma accelerators are presented. These accelerators are based on a discharge in a transverse highly-inhomogeneous magnetic field and can form radially converging and divergent flows. It is shown that for a radially convergent flow the width of the ion acceleration zone is limited by the condition of a transition through the ion sound point in the vicinity of the plasma ion emitting boundary.

1. Introduction
The use of accelerators that form a radially convergent (IRD) and radially divergent (IRR) quasineutral ion fluxes, is promising in vacuum ion-plasma deposition technologies for the inner and outer surfaces of extended cylindrical parts. Two-stage ion-plasma accelerators (IU) [1] were developed in the All-Russian Electrotechnical Institute on the basis of high-current and high-voltage discharges in a transverse strongly inhomogeneous magnetic field.

Their characteristics have been thoroughly studied in [2]. The parameters of the IU can be regulated over a wide range (ion energy 0.1 to 40 keV and current density up to 100 mA/cm²). This allows to carry out various technological operations: cleaning, etching, coating and implantation in a continuous mode for a single injection of the part into a vacuum chamber on the same accelerator. These IEDs are used to create tribological pairs with a low coefficient of friction and increased wear resistance. The inner surface of the cylinders and the outer edge of the piston rings were irradiated with molybdenum and argon ions at an energy of 30 keV and a current density of 1 mA/cm². High-strength hydrophobic and dusty DLC (diamond like carbon) films are obtained on the surface of high-voltage insulators made of ceramics and silicone rubber.

The properties of the deposited hydrocarbon coatings on the substrates of various materials (Mo, Cu, Al, Si, SiO₂ and silicone rubber) have been determined by X-ray photoelectron spectroscopy (XPS), Reflected Electron Emission (EIS) spectroscopy, Reflected Electron Emission (ESR) spectroscopy and spectroscopy of characteristic Energy losses (SCPE) [3]. Investigations of the elemental composition of the samples were carried out at REC Nanotechnologies of the Moscow Power Engineering Institute. The XPS method made it possible to diagnose a small admixture of oxygen in the surface, in addition to carbon, which is more than 97 %. The exception is rubber, where the oxygen content reaches 29 %. Studies of a series of samples by the SPCE method were carried out at an energy of 3 keV. Spectrometric analysis showed the presence of a characteristic peak.

The loss of energy (4.9 eV) clearly indicates the presence of hydrogen on the surface of the samples under study. This peak is present in the spectra for all 6 samples. This allows us to consider the data of the coating hydrocarbon. The thickness of the DLC film is 5–15 nm.
2. Experimental results and their discussion

The device and principle of operation of radial control devices are described in [1]. Ions are drawn by a radial electric field from the active zone of a high-current discharge in a transverse magnetic field through an annular gap in the cathode electrode. The magnetic field created by permanent ring magnets reaches a maximum in the gap region and amounts to 0.07 T for the IGRD and 0.2 T for the IRIS. The gap has a width of 2 mm, the radius of the cathode for the IRS is 20 mm and for the IRIS 110 mm. These dimensions are set by the possible dimensions of the machined parts. The gas dynamic conditions and the ion current to the collector in these accelerators will be quite different. Plasma-forming gas is fed through a damping gap in the annular anode to the zone of high-current discharge. It maintains a constant pressure, for example for argon 0.3 Pa. Then, through the annular gap in the cathode, the gas enters the accelerating gap, where the pressure is 0.03 Pa and further into the vacuum chamber, which is pumped out by a turbomolecular pump with a capacity of 1000 l/s.

Figures 1 and 2 show the characteristic dependencies of the current on the collector \( I_c \) on the magnitude of the accelerating voltage \( U_a \) for different currents of the high-current discharge of the first stage of the accelerator for the IRIS and the IGDR, respectively. For each of the accelerators for small values of the ion current, there is a region of a floating potential which, as the accelerating voltage increases, becomes a mode of forming a space charge layer that limits the current. On the current-voltage characteristics, the inflection point is observed. Above it, the rate of current increase with increasing voltage decreases. Figure 3 shows a photograph of the plasma stream that flows from the first stage of the accelerator to the chamber under the potential of the cathode. It is seen that the flux is limited in radius. With increasing current, the minimum radius that a plasma stream can reach, decreases, remaining finite.

![Figure 1. Volt-ampere characteristics of the IRIS at different currents of high-current discharge (0.1 Pa, Ar).](image1)

![Figure 2. Volt-ampere characteristics of the ICR for different currents of high-current discharge (0.03 Pa, Ar).](image2)
The equilibrium states of the azimuthally symmetric collisionless ion flux compensated by Boltzmann electrons are described by self-consistent equations of hydrodynamics and Poisson, which can be represented as:

\[
\left( \frac{r_0}{r_1} \right)^2 \frac{d}{d\rho} \left( \rho \frac{dy}{d\rho} \right) = \frac{1}{1 + 2 \left( \frac{c_s^2}{V_0^2} \right) y} - \rho e^{-y} ; \quad V^2 = V_0^2 \left( 1 + 2 \frac{c_s^2}{V_0^2} y \right) ; \quad j = \frac{1}{\rho} j_0 ; \quad j_0 = e n_0 V_0,
\]

boundary conditions: \( y(1) = 0 \), \( y(\rho_1) = \varphi_0 \), \( \rho_1 = r_2/r_1 \),

where \( \rho = r/r_1 \), \( y(\rho) = e(\varphi_0 - \varphi)/T_e \), \( \varphi = \varphi(\rho) \) is the potential distribution in the accelerating gap, \( \varphi_0 = \varphi(1) \), \( r_1 \) is the potential and radius of the flame emitter of ions, \( R_2 \) is the radius of the collector, \( r_D = (e_0 T_e)(e^2 n_0) \) is the Debye radius, \( n_0 \) and \( T_e \) are the plasma concentration and electron temperature at the emitting boundary, \( c_s^2 = T_e/M \) is the ion sound velocity, \( e \) and \( M \) are the charge and mass of the ion, \( E_0 \) is the dielectric constant of the vacuum. The condition \( \rho_1 \geq 1 \) corresponds to the ERI, and \( \rho_1 \leq 1 \) is the IRIS. The ion current density depends on \( \rho \) and for IRIS increases as approaching the axis \( r = 0 \).

From the quasineutrality condition of the plasma near the emitter \( r \approx r_1 \) we obtain

\[
\rho = \frac{e^y}{\sqrt{1 + 2 \left( \frac{c_s^2}{V_0^2} \right) y}}.
\]

It follows that \( \rho \) has a minimum \( \rho_m = \exp(y_0)/(c_s/V_0) \) for \( y_0 = (c_s^2 - V_0^2)/2c_s^2 \) and therefore, if quasineutrality is observed, a radially divergent ion flux can be formed in the supersonic flow \( V_0 \geq c_s \) and radially convergent under the subsonic condition \( V_0 < c_s \). In this case, the quasineutral flow zone is bounded along the radius \( \rho_1 \geq \rho \geq \rho_0 \). Numerical calculations of potential distributions and volt-amperage characteristics for two types of accelerators are in satisfactory agreement with experiment, but require further development, taking into account the non-one-dimensionality of the flow and the presence of a magnetic field in the drift space.

3. Conclusion

It is established that on the basis of a discharge in a highly inhomogeneous magnetic field and a two-step acceleration scheme, it is possible to form both radially divergent and radially converging ion-plasma flows. The parameters of the ion beam can be controlled within a wide range. This opens the possibility to perform several technological operations on one accelerator and to modify the surface of extended cylindrical parts. The theoretical model above is consistent with the experimental results for both the IRIS and the IGRD.

References

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