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Correction thruster development based on high-current surface discharge in vacuum

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ABSTRACT

This paper describes the effects of "runaway" electrons and the formation of an electron beam in a nanosecond surface discharge plasma at a pressure of $P \leq 10^{-2}$ mm mercury column. The application of those effects enables the production of a positively charged plasma with a concentration of $n \geq 10^{14}$ cm^{-3} in the discharge chamber volume. Such positively charged plasma can be used in various systems of electric propulsion thrusters. An example of electrostatic *EPT* implementation that produces up-to-date specific characteristics was considered.

1. Introduction

Development of electric propulsion thrusters (*EPT*) for spacecraft orbit correction and interplanetary spacecraft acceleration has recently become an important issue. The main known types of *EPT* are described in detail in the literature [1,2]. Another important application of plasma accelerators is material testing on resistance to space debris environment [3,4]. Because a working body of any *EPT* type is a current conducting medium including plasma, one of the most important problems of increasing the *EPT* performance capabilities is the development of charged plasma sources.

2. Prototype development and testing

Various electrophysical approaches of working body ionization (electron impact, thermal-electric ionization, and strong electromagnetic field ionization–laser radiation) are used for plasma generation with a charged particle concentration of $n > 10^{11}$ cm^{-3}. For impulse *EPT*, a gas-discharge plasma is often used [5].

The present paper considers the possibilities of generating an impulse *EPT* via electrostatic acceleration of its working body using the characteristics of plasma formation by nanosecond surface-discharge.

A surface discharge (*SD*) is a specific type of the electric discharge generated in a sharply heterogeneous electric field along a gaseous-solid dielectric interface; one side of such a solid dielectric is coated with current-conducting layer. The characteristic of *SD* is its ability to grow for long distances (l=5–100 cm) at low discharge voltage values. Numerical calculations and analytical evaluations [6] have revealed that, within the *SD* geometry, in the discharge gap at the high-voltage electrode, the electric field intensity tangential component value (E_τ) exceeds the normal component value (E_n): E_τ=(1–3) E_n (see. Fig. 1). Investigations of *SD* generation in vacuum [7] at pressures of P=(10^{-4} – 10^{-6}) mm mercury column have shown that lines of the dielectric material supplying gas for *SD* formation are the first things appeared in the charge glow spectrum.

Experimental investigations of a nanosecond surface-discharge (*NSD*), i.e., *SD* formed by high-voltage impulses of nanosecond duration [8,9,11,12], indicated that under

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certain conditions, a *NSD* plasma is an intensive source of soft *X-rays* via generation of "runaway" electrons. The "runaway" effect occurs if the tangential component of the electric field intensity in a growing *NSD* plasma exceeds the critical value (E_{cr}, see Table 1), which can be found from the energy balance of an electron moving in the electric field [10].

The conditions required for "runaway" electrons in a *NSD* plasma can be obtained as follows. The Debye radius (R_D), equal to $R_D=\Delta U/E_{cr}$, where ΔU is the potential necessary for achieving E_{cr}, is the spatial scale of charge separation in the plasma. The value $\Delta T_D=R_D/V_T$, where V_T is the thermal velocity of electrons in a plasma corresponding to the plasma frequency, is the time scale of charge separation. Consideration of those two scales gives the expression

$$\frac{\Delta U}{\Delta T}=\frac{dU}{dt}=V_T E_{кр}, \tag{1}$$

where $\frac{dU}{dt}$ is the rate of the electric voltage growth provided by a high-voltage generator forming the *NSD* that results in the "runaway" electrons effect.

Experiments of *NSD* generation in a cylindrical discharge chamber were performed to explore the possibilities of applying the obtained *NSD* results in *EPT* systems (see Fig. 2).

Characteristic oscillograms of the discharge current (I), voltage (U), "runaway" electron current (I_b) measured using the Faraday cylinder, and X-rays recorded in the cathode (I_C) and anode (I_A) windows are presented in Fig. 3. The time of discharge plasma formation near the cathode (C) and anode (A) are indicated by the arrows and measured via the signals from capacitive transducers located near the cathode (C) and the anode (A).

In addition to the investigation of the aforementioned parameters, the runaway electron current signatures behind the metal mesh have been studied (see Fig. 2).

Analysis of the results obtained leads to the following conclusions.

1. The "runaway" electron current is recorded when the discharge plasma reaches anode. As this current occurs, *X-rays* from the anode window is recorded in (1–1.5) 10^{-9} s after the discharge initiation, which is evidence of the generation of electrons reaching the anode, with characteristic energies of W_e~(20–30) keV by the cathode plasma.
2. Signatures of a runaway electron current revealed that the "runaway" electron flow is in the form of an electron beam of 1–1.5 mm diameter in the center of the discharge chamber. The electrons radial movement

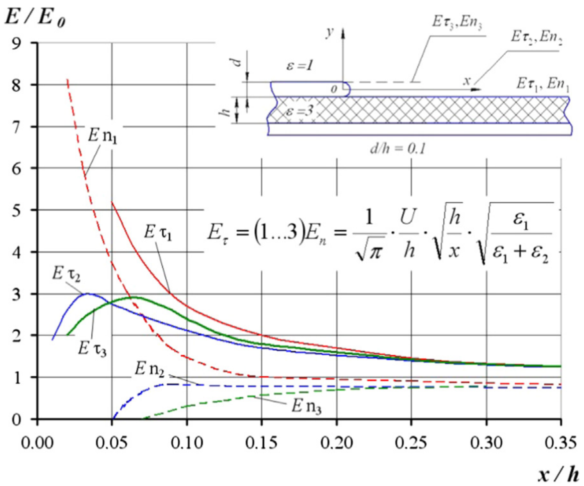

Fig. 1. Electric field intensity distribution in the surface charge geometry. E_n and E_τ – normal and tangential components of electric field intensity, respectively; h – dielectric thickness; d – electrode thickness; $U/h=E_0$ heterogeneous electric field intensity value; and ε – gas and dielectric permittivity.

Table 1

Gas	*He*	N_2	O_2	*Xe*
E_{cr} (kV/cm atm)	17	90	90	140

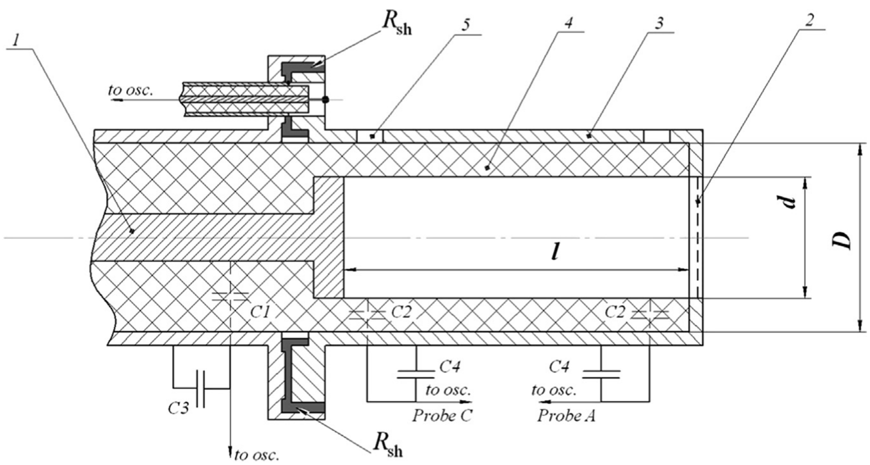

Fig. 2. Schematic of the discharge chamber. 1 – high-voltage electrode (cathode); 2 –grounded electrode-mesh; 3 –grounded metal electrode; 4 – dielectric; 5 – window for *X-rays* recording. *C* and *A* – cathode and anode capacitor probes, respectively; R_{sh} – volume resistance of the discharge current instrument shunt (I); C_1 and C_3 – high-voltage divider circuits for determining (U).