

Helicon electron source for operation with aggressive propellant

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The mathematical model of processes in induction high-frequency sources of plasma and electrons is presented in approximation of single-component magnetic hydrodynamics. The preliminary estimations of depths of a magnetic skin layer and current layer are given. The boundary conditions are formulated describing flows of particles, motion and energy on a surface of the device. Test results are shown.

I. Introduction

Electric propulsion thrusters now are widely used for spacecraft orbit correction. As a rule, plasma-ion or Hall thrusters with xenon are used for these purposes. However, the cost of xenon is currently quite high. It is proposed to use the residual atmosphere or interplanetary or near-planet space to reduce the mass and the cost of spacecraft.

Implementation of this scheme requires the development of cathodes, operating on "collected" propellant. According to the diversity of planetary atmospheres structure the development of "omnivorous" cathode is urgent and necessary task for the immediate future.

Widely used scheme of hollow activated cathodes with special substances for reducing of work function at work on the inert gases, may be vulnerable when working in the aggressive environment – the oxygen of Earth's atmosphere, methane and ammonia atmosphere of Venus, etc. The problem is solved when of high-frequency discharge induced by non-stationary magnetic field is used as electron source.

Helicon electron source scheme is represented, including the inductor fed by a sinusoidal voltage, an external coil fed by constant voltage and the discharge circuit, in which a cathode is one of the end surfaces with external location of the anode – a simulator of thruster ion beam.

II. Helicon Electron Source Mathematic Modeling and Testing

Mathematical model of processes inside the hollow

The equations are written down in two-dimensions form with supposition about axial symmetry of a task. The transport of motion is described by the equation of viscosity, where the influences of a magnetic field on dissipative processes in rarefied substance are taken into consideration.

The operation of induction high-frequency sources of the charged particles - electrons, plasma – is based firstly on ionization of gas in the high-frequency discharge. Axially symmetric magnetic field of inductor, created by a source $\sim U_c$ of variable (periodic) in time of voltage, induces in volume the periodic angular electrical field. Under action of last one periodic angular current of electrons arises, which collisions with atoms of gas cause their ionization.

In the circuit submitted on a fig. 1 the device operates as electrons (mainly) source.

Electrons emitted outside achieve the anode directly or through the discharge in the device served by a source. Then through a circuit of a source of a direct discharge voltage U_d they flow to metallic back wall of ionizer and come back into discharge volume inside the electrons shells of atoms formed at a metallic wall as a result of surface recombination of ions born in volume of a source.

Orifice plate here can be as well dielectric as metallic. Presence of an additional voltage source displacing

orifice plate potential according to potential of a metallic wall is possible in the latter case. All surfaces of a source can be dielectric in a mode of plasma generation that automatically provides a total current equal to zero from a source – with currents on source structure elements equal to zero.

Preliminary estimations

The inductor voltage source frequency usual for called devices is $\nu \sim 10$ MHz. The preliminary estimations (with neglect of viscosity in electrons movement) for linear sizes of 1 cm order had shown as follows:

- skin layer depth δ (the depth of magnetic field penetration into plasma) and current layer depth (current attenuation depth) make ~ 1 mm;
- field tension in skin layer $E \sim 10$ V/m;
- electrons cyclotron frequency $\omega_c \sim 10^7$ 1/s;
- electrons cyclotron radius $r_c \sim 0.1$ m;
- electrons angular velocity $V_{e\psi} \sim 10^4$ m/s.

The consideration of electrons motion viscous transition can some increase the skin layer depth and significantly increase the current layer depth. In any case the preliminary estimation show that the screening of inductor field by plasma own magnetic field is significant but not extreme one – the enough precision with finite elements method use is achievable with hollow radial size division in several hundreds elements. The great value of r_c there allows to neglect Hall effect in the transition of particles, motion and energy.

Initial equations set

Let us consider the plasma inside the hollow like three component substance including electrons, single charge positive ions and neutral atoms. Each of components is described by substance, motion and energy equations:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \vec{V}_e) = \frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \vec{V}_i) = -\frac{\partial n_a}{\partial t} - \nabla \cdot (n_a \vec{V}_a) = -n_e n_a v_e \sigma_i = n_e n_a v_e \sigma_i, \quad (1)$$

$$m_e \frac{\partial}{\partial t} (n_e \vec{V}_e) + m_e n_e \vec{V}_e \cdot \nabla \vec{V}_e + m_e \vec{V}_e \nabla \cdot (n_e \vec{V}_e) + \nabla (n_e k T_e) + \nabla \cdot \vec{\pi}_e +$$

$$+ e n_e (\vec{E} + \vec{V}_e \times \vec{B}) = -v_e \left[n_a \left(\sigma_{ea} + \sigma_i \frac{A_i p_e}{m_e V_e} \right) + n_e \sigma_{ei} \right] m_e n_e \vec{V}_e, \quad (2)$$

$$m_i \frac{\partial}{\partial t} (n_e \vec{V}_i) + m_i n_e \vec{V}_i \cdot \nabla \vec{V}_i + m_i \vec{V}_i \nabla \cdot (n_e \vec{V}_i) + \nabla (n_e k T_i) - e n_e \vec{E} = -\frac{m_i}{2} n_e n_a v_{ia} \sigma_{ia} \vec{V}_i + m_e n_e^2 v_e \sigma_{ei} \vec{V}_e, \quad (3)$$

$$m_i \frac{\partial}{\partial t} (n_a \vec{V}_a) + m_i n_a \vec{V}_a \cdot \nabla \vec{V}_a + m_i \vec{V}_a \nabla \cdot (n_a \vec{V}_a) + \nabla (n_a k T_a) =$$

$$= \frac{m_i}{2} n_e n_a v_{ia} \sigma_{ia} \vec{V}_i + m_e n_e n_a v_e \left(\sigma_{ea} + \sigma_i \frac{A_i p_e}{m_e V_e} \right) \vec{V}_e, \quad (4)$$

$$\frac{\partial}{\partial t} \left[n_e \left(\frac{m_e V_e^2}{2} + \frac{3}{2} k T_e \right) \right] + \nabla \cdot \vec{q}_e + e n_e \vec{V}_e \cdot \vec{E} = -n_e n_a v_e \sigma_i e \varphi_i, \quad (5)$$

$$\frac{\partial}{\partial t} \left[n_e \left(\frac{m_i V_i^2}{2} + \frac{3}{2} k T_i \right) \right] + \nabla \cdot \vec{q}_i - e n_e \vec{V}_i \cdot \vec{E} = n_e n_a v_e \sigma_i \frac{3}{2} k T_a - \frac{1}{2} n_e n_a v_{ia} \sigma_{ia} \left[\frac{m_i V_i^2}{2} + \frac{3}{2} k (T_i - T_a) \right], \quad (6)$$

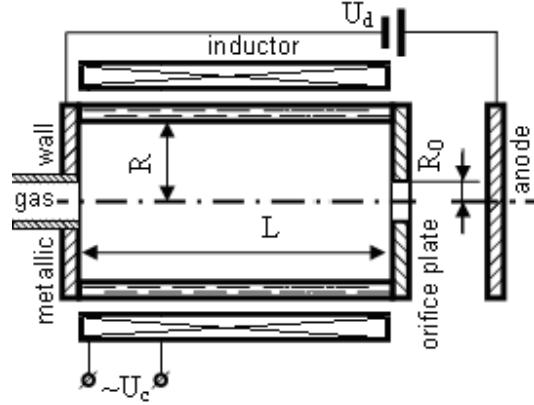


Figure 1. Induction high-frequency electrons source

$$\frac{\partial}{\partial t} \left[n_a \left(\frac{m_i V_a^2}{2} + \frac{3}{2} k T_a \right) \right] + \nabla \cdot \vec{q}_a = \frac{1}{2} n_e n_a v_{ia} \sigma_{ia} \left[\frac{3}{2} k (T_i - T_a) + \frac{m_i (V_i^2 - V_a^2)}{2} \right] - n_e n_a v_e \sigma_i \frac{3}{2} k T_a, \quad (7)$$

where T_e, T_i, T_a – electrons, ions and atoms temperatures;

$\vec{q}_e, \vec{q}_i, \vec{q}_a$ – electrons, ions and atoms energy flow densities;

π_e – electrons viscosity tensor.

Rarify discharge substance requires the use of unwrapped expressions¹:

$$\frac{\partial \pi_e}{\partial t} + \nabla \cdot (\vec{V}_e \pi_e) + \overbrace{n_e k T_e \nabla \vec{V}_e} + \frac{e}{m_e} (\pi_e \times \vec{B} - \vec{B} \times \pi_e) \approx -\frac{3}{2} v_e n_e \sigma_{ee} \pi_e, \quad (8)$$

$$\begin{aligned} \frac{\partial \vec{g}_e}{\partial t} + (\vec{V}_e \cdot \nabla) \vec{g}_e + \frac{7}{5} \vec{g}_e \nabla \cdot \vec{V}_e + \frac{9}{5} (\vec{g}_e \cdot \nabla) \vec{V}_e + \frac{2}{5} \vec{g}_e \times (\nabla \times \vec{V}_e) + \\ + \frac{e}{m_e} \vec{g}_e \times \vec{B} + \frac{5}{2} \frac{n_e k^2 T_e}{m_e} \nabla T_e = -n_e v_e \sigma_{ee} \vec{g}_e \end{aligned} \quad (9)$$

where $\vec{g}_e$ – conductive component of electrons energy flow density (heat conduction).

Tensor $\widehat{\mathbf{D}}$ in (8) relates to initial tensor $\mathbf{D}$ as:

$$\widehat{\mathbf{D}} = \mathbf{D} + \mathbf{D}^* - \frac{2}{3} \delta \text{Tr } \mathbf{D}, \quad (10)$$

where $\mathbf{D}^*$ – then tensor, connected with tensor $\mathbf{D}$;

$\text{Tr } \mathbf{D}$ – tensor $\mathbf{D}$ track;

δ – trivial (unitary) second rank tensor:

For mn element $\widehat{D}^{(mn)}$ of the tensor $\widehat{\mathbf{D}}$ the expression (10) means:

$$\widehat{D}^{(mn)} = D^{(mn)} + D^{(nm)} - \frac{2}{3} \delta_{mn} \sum_k D^{(kk)}, \quad (11)$$

where:

$$\delta_{mn} = \begin{cases} 0, & m \neq n \\ 1, & m = n \end{cases}. \quad (12)$$

Discharge non-stationary mode

Ions flow through Langmuir border near all the surfaces of the hollow is realized with ion-sonic velocity. With ion-sonic velocity value $V_{is} \sim 10^3$ m/s the characteristic time of ions reaction on conditions change thus has the order:

$$t_i \sim \frac{R}{V_{is}}, \frac{L}{V_{is}} \sim 10^{-6} \text{ s}, \quad (13)$$

which is sufficiently higher then temporary scale of external descriptions change $T \sim 10^{-8}$ s.

So the distribution of ions parameters can be considered like stationary one. Thus the electrons movement in axial and radial directions is caused (through self-contained electric field) by ions movement – axial and radial projections of electrons mass flow velocity do not exceed in order the ion-sonic velocity and are sufficiently lower than electrons individual sonic velocity. It means that:

- non-stationary mode of process requires the consideration only in angular projection of equations (2) and (9) as well as in axial-angular and radial-angular components of equation (8);

- only angular projection of electrons mass flow velocity (not limited by self-contained field in closed movement but caused only by inducted angular electric field) as well as in axial-angular components of viscosity tensor are of our interest in electrons motion transition.

Besides this, with consider of $r_c \gg R, L$ it is possible to neglect by composed with magnetic field in equations (8), (9). So the equations (1), (2), (3), (8) и (9) in projection (and components) achieve the forms:

$$\frac{\partial}{\partial x} (n_e V_{ex}) + \frac{1}{r} \frac{\partial}{\partial r} (n_e V_{er} r) = \nu_e^{(i)} n_e, \quad (14)$$

$$k T_e \frac{\partial n_e}{\partial x} + e n_e E_x \approx 0, \quad (16)$$

$$k T_e \frac{\partial n_e}{\partial r} - \frac{m_e n_e V_{e\psi}^2}{r} + e n_e E_r + e n_e V_{e\psi} B \approx 0, \quad (17)$$

$$m_e n_e \frac{\partial V_{e\psi}}{\partial t} + \frac{\partial \pi_e^{(x\psi)}}{\partial x} + \frac{1}{r^2} \frac{\partial}{\partial r} (\pi_e^{(r\psi)} r^2) + e n_e E_\psi \approx -\nu_e^{(p)} m_e n_e V_{e\psi}, \quad (18)$$

$$m_i n_e V_{ix} \frac{\partial V_{ix}}{\partial x} + k T_i \frac{\partial n_e}{\partial x} - e n_e E_x = -\nu_e^{(i)} m_i n_e V_{ix}, \quad (19)$$

$$m_i n_e V_{ir} \frac{\partial V_{ir}}{\partial r} + k T_i \frac{\partial n_e}{\partial r} - e n_e E_r = -\nu_e^{(i)} m_i n_e V_{ir}, \quad (20)$$

$$\frac{\partial \pi_e^{(x\psi)}}{\partial t} + n_e k T_e \frac{\partial V_{e\psi}}{\partial x} + \frac{2}{5} \frac{\partial g_{e\psi}}{\partial x} \approx -\nu_e^{(\pi)} \pi_e^{(x\psi)}, \quad (21)$$

$$\frac{\partial \pi_e^{(r\psi)}}{\partial t} + n_e k T_e r \frac{\partial}{\partial r} \left(\frac{V_{e\psi}}{r} \right) + \frac{2}{5} r \frac{\partial}{\partial r} \left(\frac{g_{e\psi}}{r} \right) \approx -\nu_e^{(\pi)} \pi_e^{(r\psi)}, \quad (22)$$

$$V_{ex} \frac{\partial g_{ex}}{\partial x} + V_{er} \frac{\partial g_{ex}}{\partial r} + \frac{5}{2} \frac{n_e k^2 T_e}{m_e} \frac{\partial T_e}{\partial x} = -\nu_e^{(g)} g_{ex}, \quad (23)$$

$$V_{ex} \frac{\partial g_{er}}{\partial x} + V_{er} \frac{\partial g_{er}}{\partial r} + \frac{5}{2} \frac{n_e k^2 T_e}{m_e} \frac{\partial T_e}{\partial r} = -\nu_e^{(g)} g_{er}, \quad (24)$$

$$\frac{\partial g_{e\psi}}{\partial t} + \left(\frac{3}{5} \frac{V_{e\psi}}{r} - \frac{2}{5} \frac{\partial V_{e\psi}}{\partial r} \right) g_{er} = -\nu_e^{(g)} g_{e\psi}, \quad (25)$$

where:

$$\nu_e^{(i)} = n_a \nu_e \sigma_i, \quad (26)$$

$$\nu_e^{(p)} = \nu_e \left[n_a \left(\sigma_{ea} + \sigma_i \left(1 + \frac{\Delta_i p_e}{m_e V_e} \right) \right) + n_e \sigma_{ei} \right], \quad (27)$$

$$\nu_e^{(\pi)} = 3 \nu_e \left[n_a \left(\sigma_{ea} + \sigma_i \frac{\Delta_i p_e}{m_e V_e} \right) + n_e \left(\sigma_{ei} + \frac{\sigma_{ee}}{2} \right) \right], \quad (28)$$

$$\nu_e^{(g)} = n_e \nu_e \left(\sigma_{ee} + \frac{7}{5} \sigma_i \right) g_{ex}. \quad (29)$$

Boundary conditions for viscosity and heat conduction

Dissipative transition of motion (viscosity) means the motion transition without mass transition and is connected in our conditions with electrons motion loss during the reflection from heterogeneities of potential barrier near dielectric and back metallic borders of hollow.

Dissipative transition of energy (heat conduction) means energy transition without mass transition or with the last one but not in proportion to value $\frac{5}{2} k T_e + \frac{m_e V_e^2}{2}$. The first circumstance is also connected with energy loss during the reflection from heterogeneities of potential barrier near dielectric and back metallic borders of hollow. The second one – with non-equilibrium energy transport by electrons overcoming the barrier:

$$q_{en} = n_e V_{en} \left(e \Delta \varphi + 2 k T_e + \frac{m_e V_e^2}{2} \right), \quad (30)$$

where $\Delta \varphi$ – potential barrier near the surface;

index n means the normal to the surface.

So the boundary conditions for axial-angular and radial-angular components of viscosity can be written as:

$$\begin{aligned} \pi_e^{(x\psi)} \Big|_{x=0} &= -m_e n_e \frac{v_e}{4} V_{e\psi} \eta_e^{(p)}, \\ \pi_e^{(x\psi)} \Big|_{x=L, r>R_0} &= m_e n_e \frac{v_e}{4} V_{e\psi} \eta_e^{(p)}, \\ \pi_e^{(r\psi)} \Big|_{r=R} &= m_e n_e \frac{v_e}{4} V_{e\psi} \eta_e^{(p)}, \end{aligned} \quad (31)$$

where $x=0$ и $x=L$ – axial coordinates of metallic wall and orifice plate;

R_0 – orifice radius;

$\eta_e^{(p)}$ – the share of electrons motion losing in the scattering on the barrier near the surfaces.

Boundary conditions for heat conduction can be written as:

$$g_{ex} \Big|_{x=0} = g_{er} \Big|_{r=R} = -n_e \left[\frac{v_e}{4} \frac{m_e V_{e\psi}^2}{2} \eta_e^{(\varepsilon)} + V_{is} \left(e \Delta \varphi - \frac{1}{2} k T_e \right) \right], \quad (32)$$

where $\eta_e^{(\varepsilon)}$ – the share of electrons energy losing in the scattering on the barrier near the surfaces.

It is possible to show considering equations (23) – (25) and (32):

$$\left| \frac{\partial T_e}{\partial x} \right| \sim \left| \frac{\partial T_e}{\partial r} \right| \sim \frac{2}{5} \frac{m_e}{n_e k^2 T_e} v_e^{(g)} n_e \times \left[\frac{v_e}{4} \frac{m_e V_{e\psi}^2}{2} \eta_e^{(\varepsilon)} + V_{is} \left(e \Delta \varphi - \frac{1}{2} k T_e \right) \right]. \quad (33)$$

The potential barrier in this case is equal near the dielectric surfaces and closed near the metallic one to the flown potential:

$$e \Delta \varphi_f = \frac{1}{2} k T_e \ln \frac{m_i}{2 \pi m_e}. \quad (34)$$

Electron source testing with argon

The circuit of testing with external magnetic field and high frequency antenna and experimental stand are is shown on figs. 2, 3. RF antenna generates the harmonic magnetic field, which in turn induces the electric field accelerating the electrons producing the plasma. The anode is the collector of electrons beam. The optimization here means the finding of operation mode with the highest value of anode current.

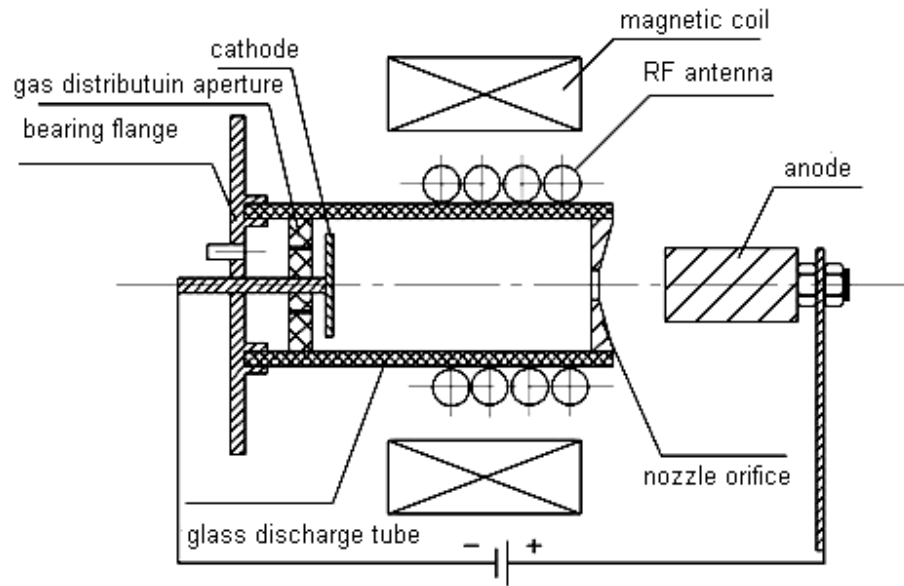


Figure 2. The circuit of testing with external magnetic field and high frequency antenna

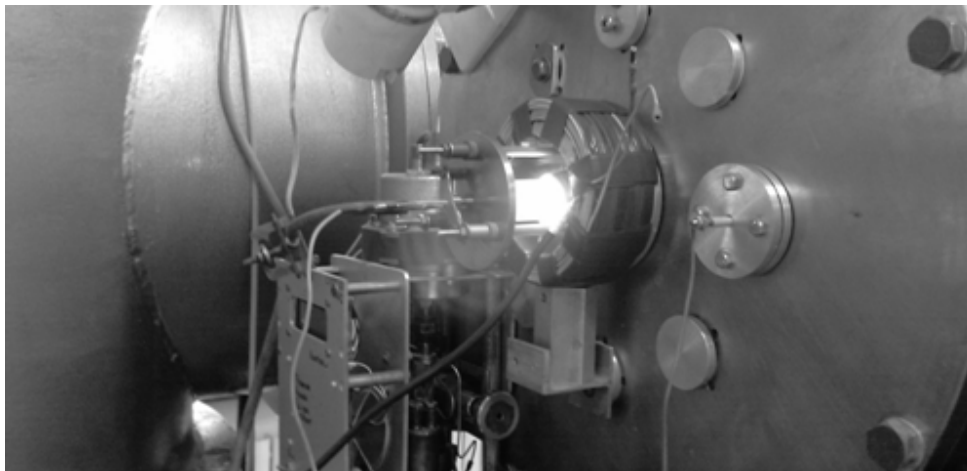
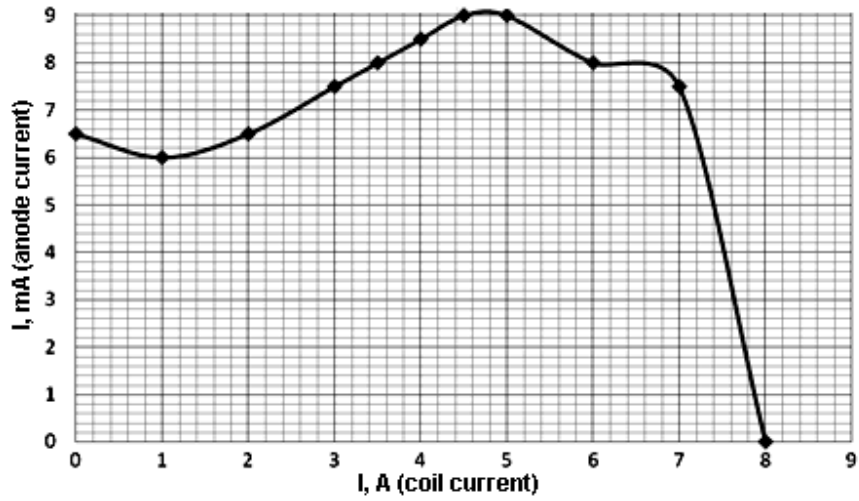


Figure 3. Experimental stand with a helicon electron source (cathode neutralize)

The following typical source operation modes were found during the tests while operation on argon and nitrogen, depending on the mass flow rate and inductor frequency:

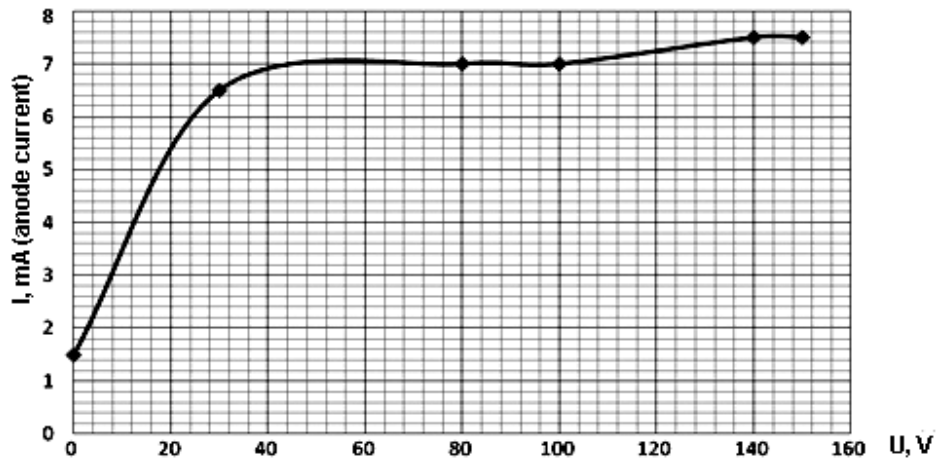
- low-intensity mode with same type of an external magnetic field influence, with increase of which the increase in the intensity of the glow discharge was observed with the appearance of a well seen exhaust beam and electron current value rise;
- "bright" mode (only when operation on argon) with initial increase in emission intensity following by its decrease was observed with the increase of the magnetic field.

Test results are represented lower on figs. 4 – 7.



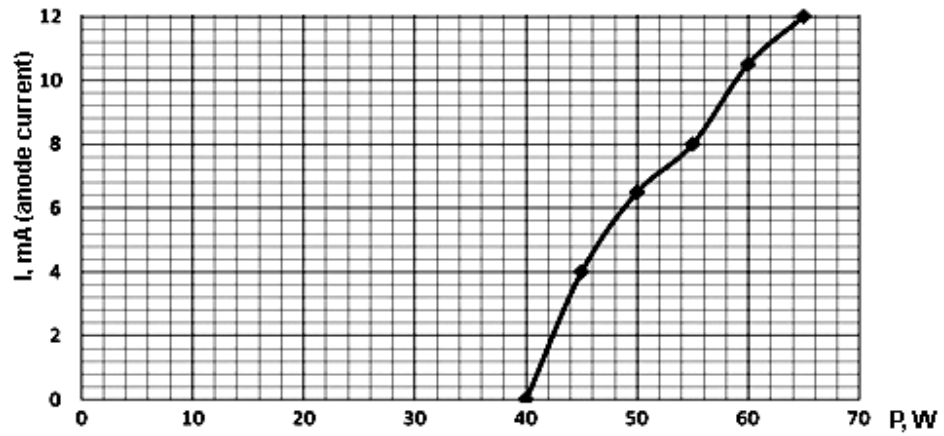
discharge voltage (cathode – anode) = 150 V, antenna voltage=50 V, mass flow rate=0.2 mg/s

Figure 4. The dependence of anode current on coil current



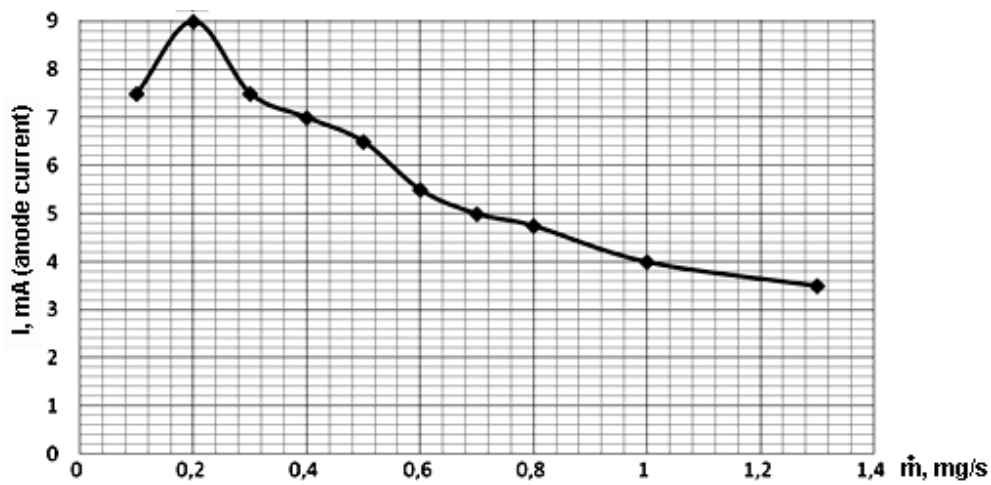
external magnetic coil current=2.2 A, antenna voltage=50 V, mass flow rate=0.2 mg/s

Figure 5. The dependence of anode current on discharge voltage



discharge voltage (cathode – anode) = 150 V, mass flow rate=0.2 mg/s, without external field

Figure 6. The dependence of anode current on RF antenna power supply



discharge voltage (cathode – anode) = 150 V, antenna voltage=50 V, external magnetic coil current=4.5 A

Figure 7. The dependence of anode current on mass flow rate

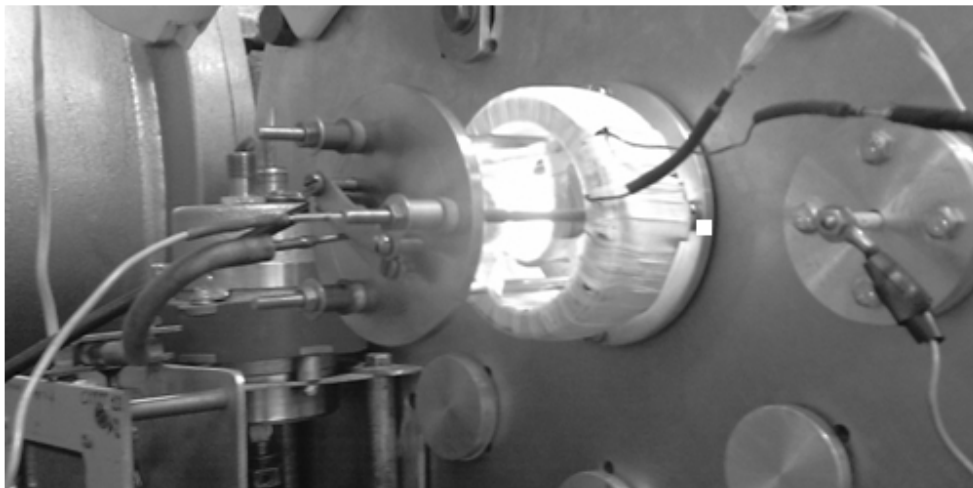
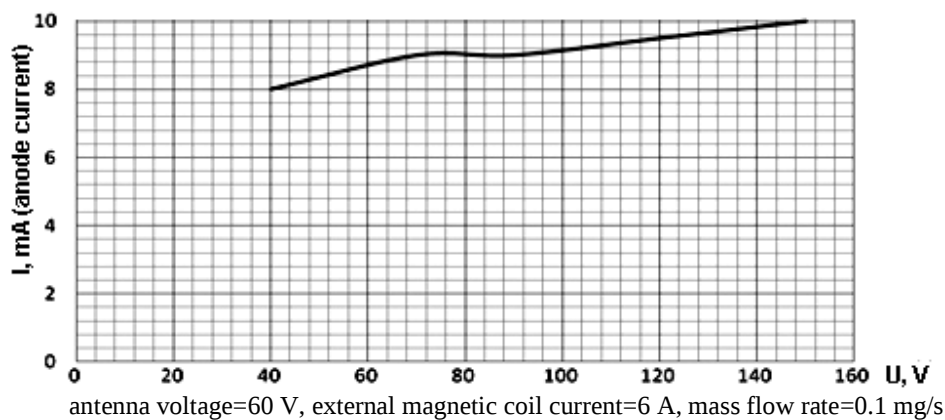


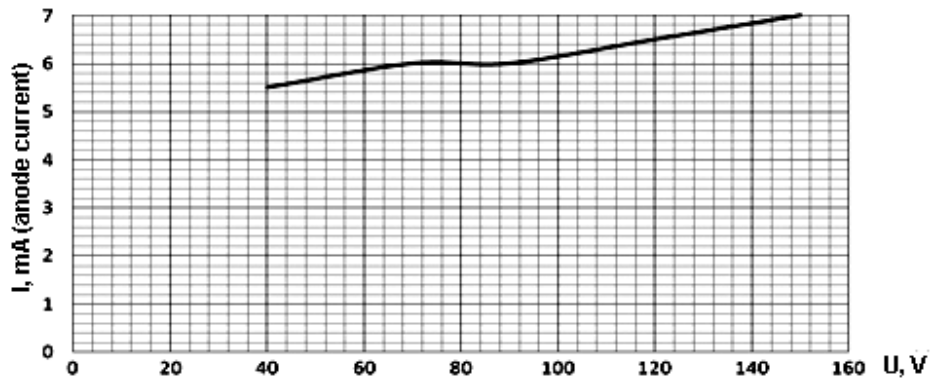
Figure 8. Experiment with a helicon electron source

Other test results are represented lower on figs. 9 – 13.



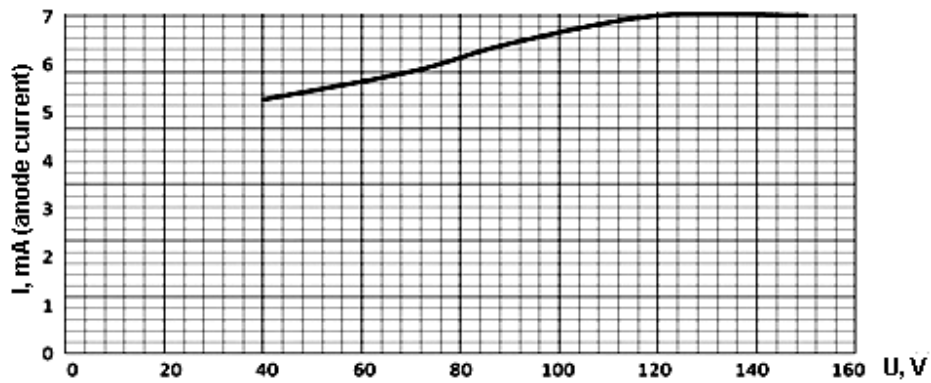
antenna voltage=60 V, external magnetic coil current=6 A, mass flow rate=0.1 mg/s

Figure 9. The dependence of anode current on discharge voltage



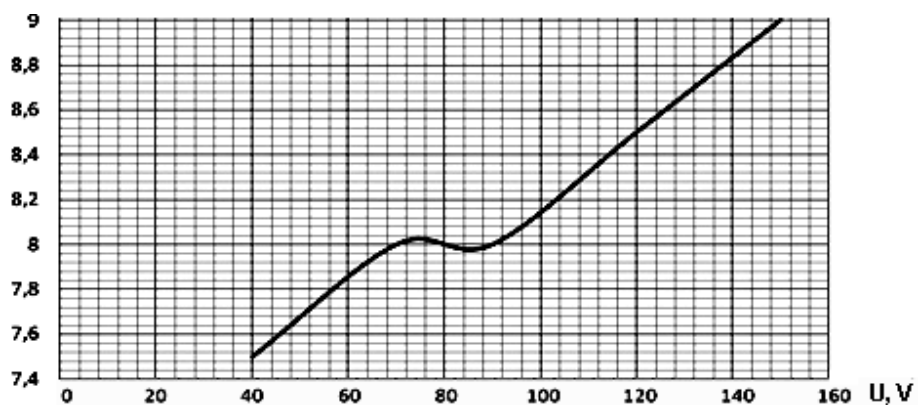
antenna voltage=60 V, external magnetic coil current=6 A, mass flow rate=0.3 mg/s

Figure 10. The dependence of anode current on discharge voltage



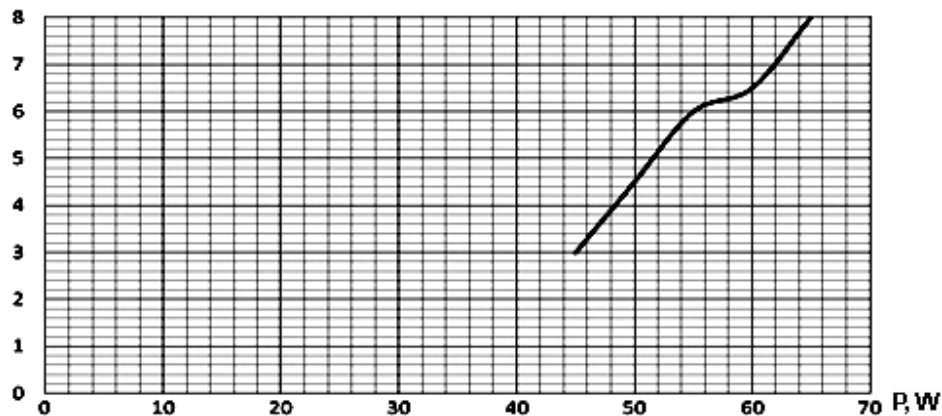
antenna voltage=60 V, external magnetic coil current=6 A, mass flow rate=0.5 mg/s

Figure 11. The dependence of anode current on discharge voltage



antenna voltage=60 V, external magnetic coil current=6 A, mass flow rate=0.7 mg/s

Figure 12. The dependence of anode current on discharge voltage



discharge voltage=100 V, mass flow rate=0.1 mg/s, without external field
Figure 13. The dependence of anode current on antenna power supply

Electron source testing with nitrogen

While testing with nitrogen with discharge voltage 100 V, RF antenna power supply ~80 W and mass flow rate 1.2 mg/s unstable process was observed with red light of plasma luminescence and very low discharge current value ~1 mA.

It can be explained as a result of great resistance of nitrogen plasma because of electrons energy losses on N₂ molecular oscillatory and rotary excited states. The same effects are expected to take place in operation with O₂ (Earth atmosphere), CO₂, H₂SO₄ (Venus), NH₃, CH₄ (Venus, Titan).

"Bright" mode was not observed in tests with nitrogen.

III. Conclusion

Experimental tests with helicon electron source on Ar and N₂ had shown the principle serviceability of device. At the same time the testing on N₂ results can not be considered yet as satisfactory ones because of extreme high power supply and as a consequence – electron energy cost.

It means the necessity of more detailed research of device operation with great scale of all the factors variation (including device configuration) to find the most optimal combination of them with appropriate value of electrons energy and gas cost.

Calculation with use of represented mathematical model would be of great importance here forecasting the device behavior and being able to reduce sufficiently experiments expenses.

References

¹Nesterenko, S.Yu., "Extended system of distribution function moments equations for rarified plasma description", *Proc. Of the International Conf. And School on Plasma Physics and Controlled Fusion. Book of Abstracts.* – Alushta, 2004 – pp.108-110.