# BEAM DYNAMICS

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# EMERGING TRENDS IN WALL-FREE HALL THRUSTERS DEVELOPMENT

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2D-hybrid model was created for the proposed new type accelerator with a virtual cathode which allows to avoid sputtering of the cathode surface and to preserve the dynamics of accelerated ions. In the framework of the model, it was shown that ions first form a positive space charge in the system center, and eventually, under an action of created own electric field, emerge from both ends of the system.

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## INTRODUCTION

The accelerator with closed electron drift is one of the types of the electric rocket engines and devices for ion-plasma surface treatment of materials, because of they have been intensively developed. The first accelerator of such kind appeared in variants of the accelerator with an anode layer and with a dielectric wall of the acceleration channel [1, 2] Since then the designs have been gradually improved and obtained results have been used in space technology and industry [3]. The creating new resource- and energy-saving economically attractive models of low-thrust engines suitable for spacecraft control has become relevant in the space industry. However, existing models even in modern versions, have certain disadvantages, including significant energy costs, low lifetime of electrodes and transport channel walls where ion flow is formed and accelerated.

One of the most serious problem is the erosion of the accelerator channel wall [4], that has a negative effect on the operation of the accelerator. In order to minimize this effect for accelerator with a long acceleration zone use complex configuration of the magnetic fields and search out operation modes of the accelerator to avoid the contact of plasma ions and electrons and accelerated flow with channel walls. But, given the electron free movement along the magnetic field lines, it is not possible to avoid contact of electrons with the walls. For accelerator with an anode layer trying to resolve this problem by minimizing the channel wall across the magnetic field. But since the wall of the acceleration channel is usually at the same time the pole of the magnetic circuit, it is impossible to avoid contact of the ion flow with the cathode material [5, 6]. So these attempts while are not completed, quite complicated and bring many skepticisms.

One of the promising ways to resolve these problems is the separation of the magnetic and electrical circuits of the accelerator, which is easier to do in the cylindrical geometry to create a converging ion beam. This principle is carried out in the original accelerator with closed electron drift and open walls that was proposed and experimentally studied on a laboratory stand at the Institute of Physics NAS of Ukraine [7 - 9]. The novelty of the proposed method is the use of a virtual cathode parallel to surface of the anode due to the principle of equipotentialization of magnetic field lines which allows to avoid sputtering of the cathode surface and to preserve the dynamics of accelerated ions.

Early a one-dimensional hydrodynamical [7 - 9] and hybrid [10] theoretical models was developed. In the framework of these models, both exact analytical and numerical solutions were obtained. A comparison between the results of both models obtained in model experiments for stationary case testifies to an insignificant influence of the neutral component of a working gas on the formation of the potential drop across the discharge gap for the examined initial conditions. But for correct description (especially high-current mode), it is necessary to model ionization, collisions, and plasma creation, as well as motion of neutrals and formed ions in the whole volume of accelerator, thus need consider two-dimensional hybrid model.

In this paper we discuss the current status and ongoing experimental and theoretical research based on 2D-hybrid model as well as obtained simulation results of the accelerator based on the axially symmetric cylindrical electrostatic plasma lens configuration and the fundamental plasma-optical principles of magnetic electron isolation and equipotentialization of magnetic field lines.

## 1. EXPERIMENTAL RESULTS

### 1.1. EXPERIMENTAL SETUP

Experiments were carried out on a laboratory stand, the schematic diagram of which is shown in Fig. 1 on the left. Vacuum chamber 1 contained a test model of the accelerator with open walls. The accelerator consisted of a magnetic core with permanent magnets 2 and an electrode system with cylindrical anode 3 and cathode 4 formed by a system of pins. The experimental installation allowed a controlled gas input, by using CHA-2 system. The gas pumping was performed with the use of a vacuum unit with an oil-vapor pump. The photo of the accelerator with anode layer and open wall is shown in Fig. 1 on the right. As can be seen from the Fig. 1 on the left, the cathode is composed of two parts that are separated in space. The ends of the cathode pins coincide with the magnetic surfaces that in area between them are parallel to the anode surface. The application of the plasmaoptics principles to the design of a cylindrical accelerator with anode layer and open walls allowed to create an accelerator with virtual cathode that is parallel to the anode surface for its entire width and with cathode that is several centimeters wide. That allows to form a wide flow of accelerated ions to the system axis of symmetry. Due to that each part of the cathode is made in the form of pins, the collecting surface area is significantly reduced, that reduces the contribution of the cathode material in the flow.

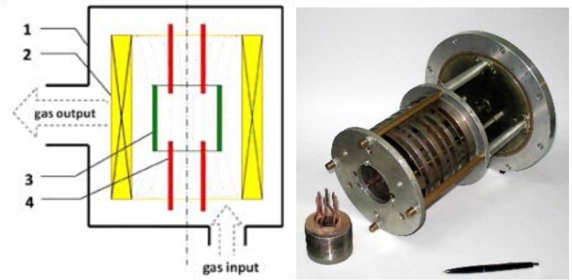



*Fig. 1. Left: Experimental setup; vacuum chamber (1), magnetic system (H = 650…750 Oe) (2), anode (3), cathode (4). Right: Photo of the accelerator with anode layer and open walls*

The discharge in the system glows due to the working gas (argon) ionization by the electrons. Electrons are magnetized and formed stable negative space charge. The created ions are accelerated from the ionization zone towards the cathode.

The formation of the magnetic field is provided by a system of permanent magnets located in the magnetic circuit. By selecting the number and polarity of the magnets in each system layer, it was possible to change the magnetic field geometry in a wide range. In experiment the system of permanent magnets was arranged in such a way that the magnetic field in the gap between the cathode and the anode was parallel to system's axis as much as possible. It was owing to this configuration of the magnetic field that a system with open walls was created.

### 1.2. EXPERIMENTAL RESULTS

As mentioned above, the cathode is composed of two parts separated in space and their edge coincide with magnetic field lines that are parallel to anode surface. The magnitude of the magnetic field is such that Larmor radius of the electron is much smaller than the system radius. Due to this, the principle of the equipotentialization of magnetic field lines with accuracy up to the electron temperature works [11]. Accordingly, a cylindrical virtual surface is formed between these parts, which potential is close to cathode potential. Through the electrons drift in the crossed electric and magnetic field E×H there is a closed Hall current and corresponding space charge, that creates a layer near the anode surface where the main potential drop occurs [12]. With the appearance of the Hall current in the perpendicular direction, the electron current along E becomes small. In turn, the ions are almost unaffected by the magnetic field, because the Larmor radius of the ion is more than characteristic system size [3, 13]. Ions under the electric field influence, moving in the cathode direction, converge to the center and are pushed out of the system along the axis. The electrons exit speed from the system along the axis is quite small and is compensated by the working gas ionization by these electrons. At low pressure, ionization occurs between the anode and virtual cylindrical cathode. With increasing pressure, the anode layer size can reach the radius of the system. The operation modes of the accelerator also change [14].

Note that the operation modes of this kind accelerator are very close to those of the classical accelerator with an anode layer. There are two operation modes of this kind accelerator. The first is low-current, with a clearly visible narrow radiating layer between the anode and cathode, in the range of $10^{-4}$ Torr. The current increases monotonically with increasing applied voltage (Fig. 2). With increasing pressure at a constant applied voltage, this layer gradually occupies the entire volume of the accelerator. During this mode, the ions are mostly formed in a narrow anode layer and move towards the system axis, hardly experiencing the influence of a magnetic field. Accumulating on the system axis, they are pushed out of the volume along it. The study of the distance changing influence between the virtual cathode and anode showed the existence of the optimum. The maximum current on the system axis is fixed at a distance d=10 mm between electrodes, as one can see from Fig. 2.

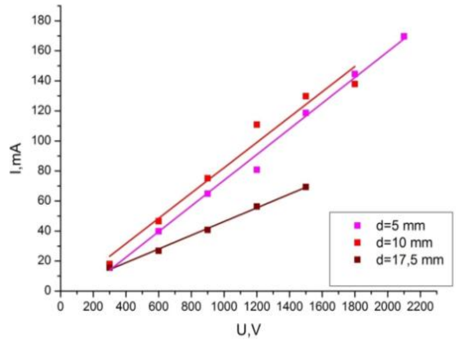



*Fig. 2. Volt-ampere characteristic of the accelerator in low-current mode at a) different distance between the anode and cathode at pressure $10^{-4}$ Torr*

In the second mode – high current, the discharge extends to the entire internal system volume. When the voltage reached a certain value (U > 1.8 kV), the discharge current increased in a jump-like manner (Fig. 3), and the discharge transited into the high-current mode, in which the distinct anode layer was absent. In this mode, a typical discharge current was several orders of magnitude higher (up to 2 A, as can be seen from Fig. 3) than in the low-current mode.

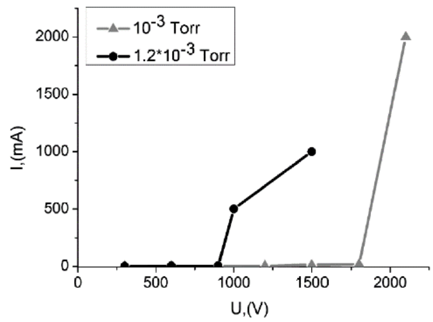


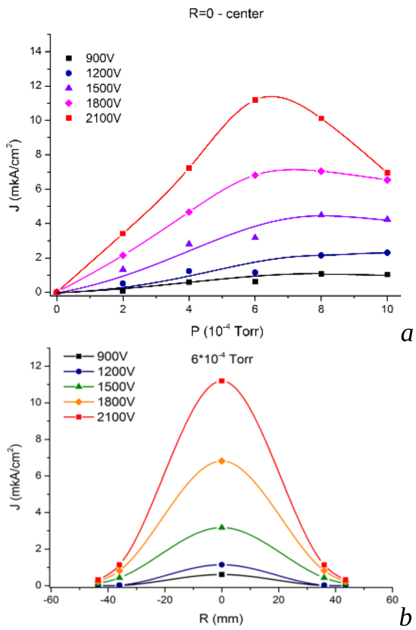

*Fig. 3. Volt-ampere characteristic of the accelerator at different pressure*

Thus, it is evident that the transition into the high-current mode occurs under the influence of two factors: the working gas pressure and the voltage applied across the discharge gap.

Another characteristic feature of the high-current mode is the formation of a plasma torch. At the discharge voltage U > 1.8 kV bright radiation is observed from the system volume from the ends of the cylindrical channel along the rotation symmetry axis. In the discharge concerned, ions are accelerated along system's radius toward system's axis. The torches at the ends, on the contrary, are observed along the axis, perpendicularly to the radius and the direction of initial ion acceleration.

Thus, owing to the discharge geometry, in space limited by electrodes of the accelerator there is an accumulation of ion space charge like a lens with a positive space charge, that was proposed earlier for negatively charged particles beam focusing [15, 16]. The generated ions reach the system axis and accumulate in the region around it. Ions are stored in the cylinder volume until their own space charge creates a critical electric field. This field forces ions to leave the volume. The main part of the generated ions escapes from the system perpendicularly to its radius. Due to this plasma torches are formed at the edges of the device, which are clearly visible in high-current mode. The results of measuring the floating potential along the axis of the system show that under certain conditions along the plasma torch axis there may be a potential drop, which can be used to accelerate the generated ions and form a charged particles beam.

Radial studies of the plasma flow coming out along the system axis in this device at different pressures revealed a significant increase in current density on the axis (Fig. 4). That fact may indicate the plasma acceleration in this direction.



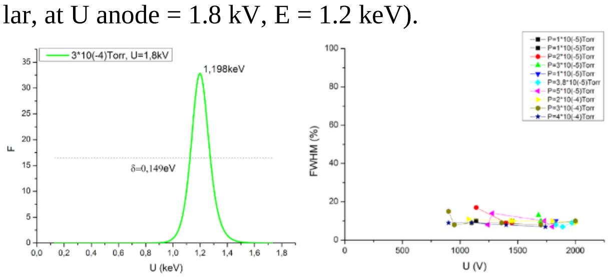

a

b

*Fig. 4. Distribution of the current density along the system radius at the accelerator output (a); The dependence of the current density on the system axis on the pressure in chamber at different values of potential at the anode (b)*

The study of the dependence of the uncompensated current density on the accelerator volume shows the existence of a maximum for a pressure of $6\cdot10^{-4}$ Torr. This operation mode of the accelerator is mostly interesting for use as a prototype of the ion-plasma small rocket engine.

Determination of the ion energy distribution function (see Fig. 5,a) in this accelerator was performed by retarding potential method using a three-grid analyzer (discharge current 1.5…2 A; voltage 1.5…2.1 kV; pressure in the range $10^{-4}$…$10^{-3}$ Torr). The research results showed the formation of a sufficiently monoenergetic beam with of FWHM (as can be seen from Fig. 5,b), at the level of 10% of the average value which reached two thirds of the anode discharge potential (in particular, at U anode = 1.8 kV, E = 1.2 keV).




a b

*Fig. 5. Ion energy distribution function (voltage 1.8 kV; pressure $3{\cdot}10^{-4}$ Torr) (a); The dependence of FWHM (full width at half maximum) on the voltage applied to the anode (b)*

## 2. THEORETICAL MODEL

In the framework of 2D-hybrid model the kinetic description is used in cylindrical geometry for the ionic and neutral components and the hydrodynamic one-dimension on each special layer $z_i<z<z_i+1$ description for the electron ones. Thus, for ions and neutrals description we use Boltzmann kinetic equation:

$$\frac{\partial f_{i,n}}{\partial t}+\vec{v}_{i,n}\frac{\partial f_{i,n}}{\partial \vec{r}}+\frac{e}{M}\left(E+\frac{1}{c}[v\times B]\right)\frac{\partial f_i}{\partial v_i}=St\{f_{i,n}\}. \quad (1)$$

We solved this equation by splitting on the Vlasov equation for finding trajectories of ions and neutrals:

$$\frac{\partial f_{i,n}}{\partial t}+\vec{v}_{i,n}\frac{\partial f_{i,n}}{\partial \vec{r}}+\frac{e}{M}\left(E+\frac{1}{c}[v\times B]\right)\frac{\partial f_i}{\partial v_i}=0, \quad (2)$$

and to correct the found trajectories we considered the collision integral, in which we took into account the processes of ionization and elastic and inelastic collisions:

$$\frac{Df_{i,n}}{Dt}=St\{f_{i,n}\}. \quad (3)$$

The Vlasov equations were solved by the method of characteristics [17]:

$$\frac{d\vec{v}_k}{dt}=\frac{q_k}{M}\left(\vec{E}+\frac{1}{c}[v_k\times B]\right),\quad \frac{d\vec{r}_k}{dt}=\vec{v}_k. \quad (4)$$

To solve these equations the PIC method [18] with Boris scheme [19] was used to avoid singularities at the axis. For initial electric field distribution was taken electric field in the plasma absence: $E(r)=\frac{U_a}{r\ln(r_c/r_a)}$. The Monte-Carlo method was used for modeling of ionization in this field. The probability of a collision of a particle with energy $\varepsilon_j$ during time $\Delta t$ was found from expression [20]:

$$P_j = 1 - \exp\left(-v_j \Delta t \sigma(\varepsilon_j) n_j(\vec{r}_j)\right), \quad (5)$$

here $\sigma(\varepsilon)$ – collision cross-section (elastic, ionization or excitation), $n_j$ – density of similar particles at the point $r_j$. To determine the probability of collision, a random number $s$ is chosen from interval [0,1] with the help of a random number generator. If $s<P_j$, we assume that collision has occurred. It is determined by the ratio of the cross-sections with the random number generator, which collision has occurred – elastic, excitation, or ionization. In dependence of this particle parameters change or new ion add in computational box. The evolution of all particles that are in the modeling region is traced at each time step. For this, motion equations were solved, and new velocities and positions of the particles were found. Particles that move out the modeling box boundaries are excluded from consideration. After quite a long time particle density distribution was found. The ion charge density and current density are calculated from coordinates and velocities particles according to formulas:

$$\rho(r,t) = \frac{1}{V}\sum_j q_j R(\vec{r}, \vec{r}_j(t)),$$

$$j(r,t) = \sum_j q_j v_j(t) R\left(\vec{r}, \vec{r}_j(t)\right), \quad (6)$$

where $R(r,r_j)$ – usual standard PIC – core, that characterizes particle size and shape and charge distribution in it. For a cylindrical coordinate system it has form [21]:

$$R((r_i,z_k),(r_j,z_j)) = \begin{cases} \frac{1}{V_i} * \frac{r_{i+1}^2 - r_j^2}{r_{i+1}^2 - r_i^2} * \frac{h_z - |z_k - z_j|}{h_z}, r_i < r_j < r_{i+1}, |z_k - z_j| < h_z \\ \frac{1}{V_i} * \frac{r_{i-1}^2 - r_j^2}{r_{i-1}^2 - r_i^2} * \frac{h_z - |z_k - z_j|}{h_z}, r_{i-1} < r_i < r_{i+1}, |z_k - z_j| < h_z \\ 0, i \end{cases} \quad (7)$$

here $V_i = 2\pi r_i h_r h_z$ – volume of the cell, $h_r$, $h_z$ – steps in the spatial coordinates.

After that the Poisson equation was solved and new electric field distribution was found. Since electrons are magnetized, we consider their movement in radial plane only, thus can solve for electrons one-dimensional hydrodynamic equations on each layer at z separately. By solving it we find electron density, calculate electric field on each layer and correct particle trajectories. After that the procedure was repeated. Modeling time is large enough for establish of ion multiplication process. The formation of the sufficient quantity of ions is possible due to magnetic field presence, which isolates anode from the cathode. Ions practically don't feel the magnetic field action and move from anode to the axis, where they create a space charge, first in the center of the system. Electrons move along the magnetic field strength line, but due to collisions with neutrals, they start move across the magnetic field. An internal electric field is formed which slows down the ions and pushes out them from the volume along system axis. In Fig. 6 the calculated ion trajectories for different time steps are shown.

One can see that the ions that appear due to ionization move to center of the system. Coinciding on the system axis, they accumulate and create a positive space charge, and then diverge along the axis in both directions under the action of created own electric field. The ion space charge distribution for this case is shown in Fig. 7.

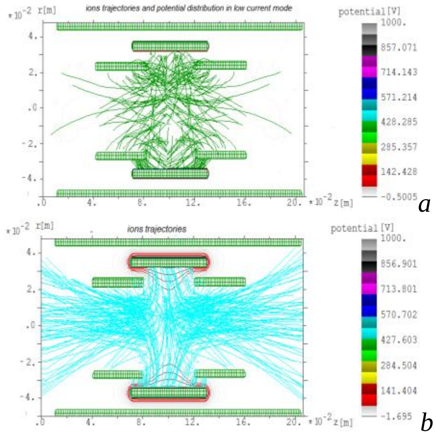



*Fig. 6. Ion's trajectories (calculation for $U_a$=1 kV, H=0.03 T) for different time step $N_t$ =50 (a), $N_t$=200 (b)*

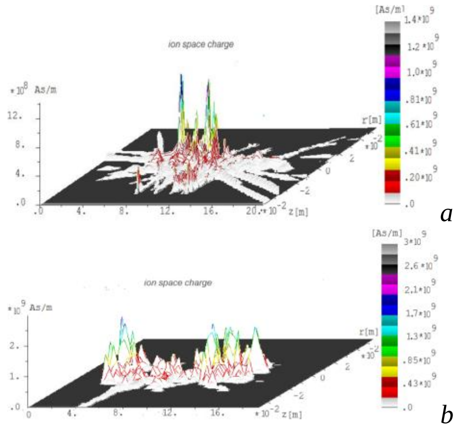



*Fig. 7. Ion space charge for time step 70 (a) and 340 (b)*

The electrons trajectories for this case are shown in Fig. 8,a. One can see that the electrons are magnetized, moving along magnetic strength lines, and their trajectories are almost parallel to the surface of the anode. The ions trajectories are shown in Fig. 8,b.

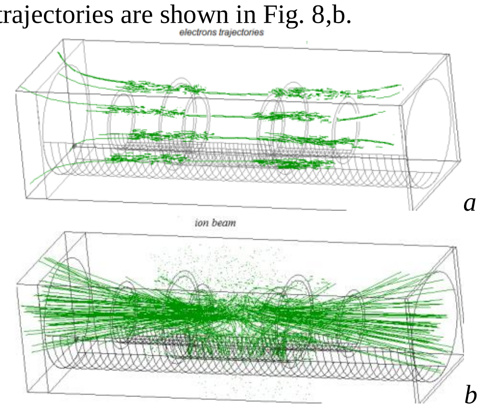



*Fig. 8. Electron (a) and ions (b) trajectories in accelerator for H=0.03 T*

The Fig. 9 shows the potential distribution for different time steps. One can see that at the beginning of ionization, the potential drop is not complete in the gap and even has a negative sign in the center of the system. With ions quantity increasing, they coincide in the center of the system and form a positive space charge cloud, the potential of which even exceeds the applied potential $U_a$.

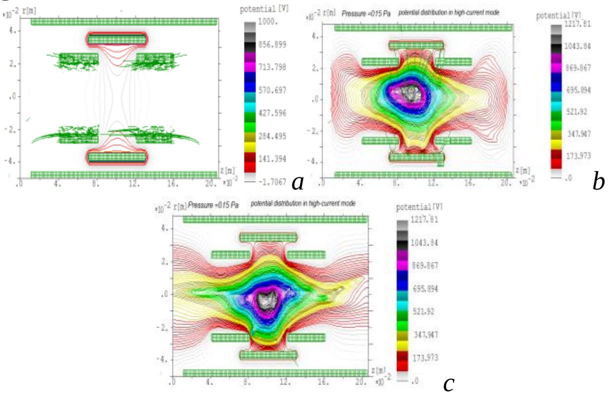


*Fig. 9. Potential distribution for different time step: $N_t$=10 (a); $N_t$=100 (b); $N_t$=300 (c)*

This creates an electric field under which ions begin to move along the axis of symmetry in both directions, from the center to the edges, taking out with them part of space charge, reducing it in the center and creating the space charge bulks at the ends of the system (see Fig. 7).

If we look at the potential distribution along the z-axis, we see that the maximum potential first declines with distance from the center, but then gradually begins to increase (Fig. 10). One can see that at a distance of 0.16 m from system center maximum potential is 222 V (~ 0.22 $U_a$), while at a distance 0.21 m it is already 396 V, which is equal to 0.4 $U_a$, and current density of ion beam reaches 0.7 mA/cm$^2$. Thus, the formed ions, initially accumulated in the center of the system, under action of own created electric field can accelerate and create a powerful ion flux from both ends of the accelerator.

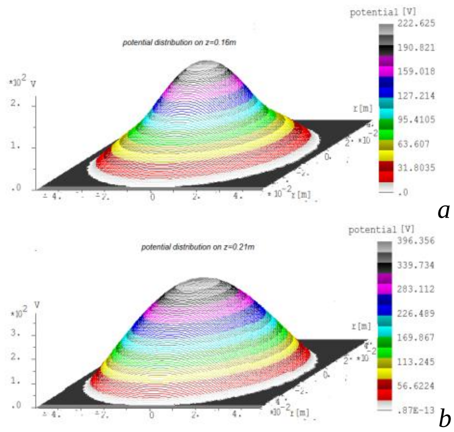


*Fig. 10. Potential distribution on the system axis at different distances from the center of the system: z=0.16 m (a); z=0.22 m (b)*

## CONCLUSIONS

Here we discuss the created 2D-hybrid model and the obtained results showing that the ions first form a space charge in the system center, and eventually, under an action of created own electric field, emerge from both ends of the system. The potential drop formed at the axis can be used for ion beam accelerating.

The formation of the actual traction beam should occur due to the acceleration of ions by the accumulated positive space charge. Thus, such type of accelerator could be of interest for manipulating high-current flow of charged particles as well as it can be attractive for many different high-tech applications for potential devise of low cost and compact thrusters. This may be of particular interest for research in space industry owing to the urgency of the problem of creating new resource- and energy-saving economically attractive models of low-thrust engines suitable for spacecraft control.

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## НОВЫЕ ТЕНДЕНЦИИ В РАЗВИТИИ БЕССТЕНОЧНЫХ ЭЛЕКТОРЕАКТИВНЫХ ДВИГАТЕЛЕЙ ХОЛЛОВСКОГО ТИПА

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Создана 2D-гибридная модель предлагаемого ускорителя нового типа с виртуальным катодом, что позволяет избежать распыления поверхности катода и сохранить динамику ускоренных ионов. В рамках модели было показано, что ионы сначала образуют положительный объемный заряд в центре системы, а затем под действием созданного собственного электрического поля выходят с обоих концов системы.

## НОВІ ТЕНДЕНЦІЇ В РОЗВИТКУ БЕЗСТІННИХ ЕЛЕКТРОРЕАКТИВНИХ ДВИГУНІВ ХОЛІВСЬКОГО ТИПУ

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Створено 2D-гібридну модель пропонованого прискорювача нового типу з віртуальним катодом, що дозволяє уникнути розпилення поверхні катода і зберегти динаміку прискорених іонів. У рамках моделі було показано, що іони спочатку утворюють позитивний об'ємний заряд у центрі системи, а потім під дією власного створеного електричного поля виходять з обох кінців системи.