PLASMA ACCELERATOR WITH CLOSED ELECTRON DRIFT AND OPEN WALLS

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We present the original approach to use plasma accelerators with closed electron drift and open walls for creating effective lens with positive space charge. In paper describes one-dimensional model and simplest analytical solutions following from it. The results of the numerical calculation and some experimental investigations data are presented also.

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INTRODUCTION

Plasma accelerators with anode layer are well known and widely used devices. The theory of the physical processes in such kind accelerators with metal walls is well developed due to long time history of their investigations. The same could be related to accelerators with closed electron drift and dielectric walls. However accelerators with closed electron drift and open (gas) walls were not research till now. This type accelerator could be interested for manipulating high-current flow of charge particle. For example, it could be used for elaboration of the low-cost, effective and low maintenance plasma lens with positive space charge cloud. As was shown in our preliminary works [2 - 5] the dynamical positive space charge plasma lens with magnetic electron insulation and non-magnetized ions is effectively focusing and manipulating by high-current beams of negatively charged particles (electrons and negative ions). Another attractive and perspective way using such kind accelerators is the creation of cost-effective, small rocket engines and enhancment ion-plasma technology also that open up novel attractive possibility for effective high-tech practical applications.

In this paper we firstly present and describe model of accelerator with closed electron drift and open (gas) walls. Based on the idea of continuity of total current transferring in the system obtained exact analytical solutions describining potential distribution in acceleration gap. The solution was got for the case of zero electron temperature, as well as in case finite electron temperature, which magnetized electrons acquire in a cross-heating electron field. It is shown that in case when all electrons originated from the gap only by impact ionization, and then go out at the anode due to classical transverse mobility the condition complete potential drop in the gap correspond to equality of the gap length to the anode layer thickness in boundary mode.

1. THEORETICAL MODEL AND SOME SOLUTIONS

For creation an effective lens of positive space charge could be used plasma accelerators with closed electron drift and open walls. The simplified scheme of device is shown in Fig. 1. To analyze the properties of such kind an accelerator we use a one-dimensional hydrodynamic model.

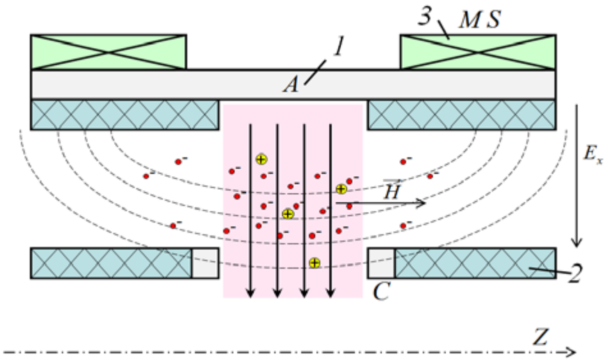

Fig. 1. The simplified scheme of device: 1 – anode; 2 – cathode; 3 – magnetic system

The base equations describe kind system includes Poisson equation:

$$n_e - n_i = \frac{1}{4\pi e}\varphi'' , \qquad (1)$$

here for ion density we could write:

$$n_i(x) = \sqrt{\frac{M}{2e}}\int_0^x \frac{n_e(s)\nu_i ds}{\sqrt{\varphi(x)-\varphi(s)}} . \qquad (2)$$

Will assume that the current density in gap volume is the sum of the ion and electron components:

$$j_e + j_i = j_d , \qquad (3)$$

where j_i, j_e – are ion and electron current density consequently:

$$j_i(x) = e\nu_i \int_0^x n_e(x)dx , \qquad (4)$$

$$j_e(x) = e\mu_\perp\left(n_e E(x) - \frac{d}{dx}(n_e T_e)\right), \qquad (5)$$

ν_i – is the ionization frequency; $\mu_\perp = \frac{e\nu_e}{m\omega_{eH}^2}$ – electron transverse mobility; $E(x) = -\frac{d\varphi}{dx}$ – electric field; φ – potential; ν_e is the frequency of elastic collisions with neutrals and ions and ω_{eH} is the electron cyclotron frequency; T_e – electron temperature that could write in form:

$$T_e(x) = \frac{\beta}{j_e(x)}\int_0^x j_e \frac{d\varphi}{ds} ds . \qquad (6)$$

Thus, taking into account the said above, from (3) we obtain expression:

$$e\nu_i\int_0^x n_e(x)dx - e\mu_\perp\left(n_e\frac{\partial\varphi}{\partial x}+\frac{\partial}{\partial x}(n_eT_e)\right)=j_d\,. \qquad (7)$$

For simplicity in first approximation neglect the diffusion and could consider that $\boldsymbol{n_e}$ is constant along gap, with given the fact that ion current is equals j_d on the cathode from (7) we get:

$$en_e\nu_i(x-1)-\frac{e\nu_e}{m\omega_{eH}^2}en_e\frac{\partial\varphi}{\partial x}=0\,. \qquad (8)$$

Substitute n_e, using the Poisson equation (1) where $n_e >> n_{i.}$, we can obtain from (8) the differential equation of second order and representing this equation in dimensionless form we have:

$$\varphi''\big((x-1)-\alpha\varphi'\big)=0\,, \qquad (9)$$

Here we have introduced the notation $\alpha=\dfrac{\mu_\perp\varphi_a}{\nu_i d^2}$, where φ_a – anode potential, d – gap length. Omitted trivial solution $\varphi''=0$ and taking into account boundary condition $\varphi\big|_{x=0}=1$ we obtain potential distribution within gap in form:

$$\varphi=a\big((x-1)^2-1\big)+1\,, \qquad (10)$$

here $a=1/2\alpha$.

Potential distribution (10) for different values of parameter a is shown in Fig. 2. One can see that under $a=1$ the total applied potential falling down inside of the accelerating gap. In this optimal case

$$d=\sqrt{\frac{2\mu_\perp\varphi_A}{\nu_i}}\,. \qquad (11)$$

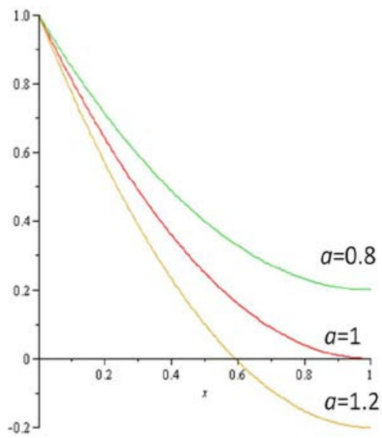

Fig. 2. Potential distribution for different parameters a

Suggested that all electrons originated from the gap only by impact ionization, and then go out at the anode due to classical transverse mobility this expression can represent in form:

$$\delta=\rho_e(\varphi_A)\sqrt{\frac{2\nu_e}{\nu_i}}\,. \qquad (12)$$

This expression coincides with one for classical anode layer (see [6]) accurate within $\sqrt{2}$.

Note, in case when parameter $a < 1$ (the gap length less than δ) potential drop is not completed. For case $a > 1$, when the gap length $d > \delta$ potential drop exceed applied potential. This can be due to electron space charge dominated at the accelerator exit.

Extend our description and take into consideration that n_e changes along gap. As before will study case $T_e = 0$, than for dimensionless equations (7) is true:

$$c\int_0^x n_e(s)ds-bn_e(x)\frac{\partial\varphi}{\partial x}=1\,, \qquad (13)$$

where we introduce notices:

$$b=\frac{\mu_\perp\varphi_a en_0}{j_d d}\,,\; c=\frac{\nu_i den_0}{j_d}\,. \qquad (14)$$

Will consider quasi-neutral plasma $n_e \approx n_i$ for simplicity, so substitute dimensionless equality (2) in (13) get:

$$c\int_0^x n_e(s)ds-b\cdot f\cdot\frac{\partial\varphi}{\partial x}\cdot\int_0^x\frac{n_e(s)ds}{\sqrt{\varphi(x)-\varphi(s)}}=1\,, \qquad (15)$$

here $f=\nu_i d\sqrt{\dfrac{M}{2e\varphi_a}}$.

After some transformations and subject to the fact that ion current is (first term in left part (13)) equals j_d on the cathode, equality (15) could rewrite in form:

$$\int_x^1 ds\,n_e(s)\frac{\partial}{\partial x}\Big(2bf\sqrt{\varphi(x)-\varphi(s)}\Big)=\int_x^1 ds\,n_e(s)\cdot c\,. \qquad (16)$$

Equality integrand gives:

$$\frac{\partial}{\partial x}\Big(2bf\sqrt{\varphi(x)-\varphi(s)}\Big)=c\,,$$

or for potential distribution taking into account boundary condition we have :

$$\varphi(x)=1-\frac{a^2}{4f^2}+\frac{a^2}{4f^2}(x-1)^2\,, \qquad (17)$$

where $a=c/b$, note it is corresponding to parameter $1/\alpha$ introduced above. From (17) could note the behavior of potential distribution depends on ratio $p=\dfrac{a^2}{4f^2}$.

Here parameter f describes impact of ion density. Potential distribution for this case is shown in Figs. 3 and 4.

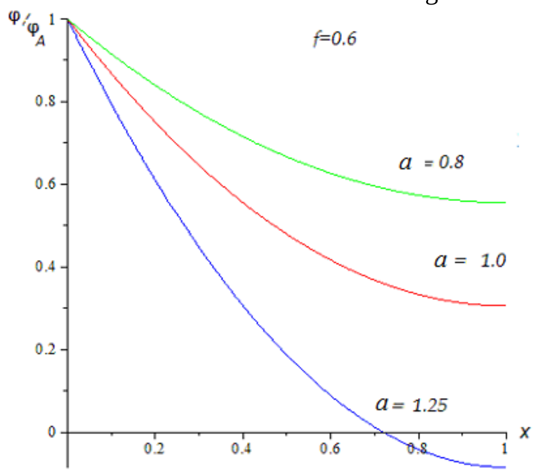

Fig. 3. Potential distribution for quasi-neutral plasma for different parameter α

If we now derived (13) we could obtain equation for electron density:

$$\frac{1}{n_e}\frac{\partial n_e}{\partial x}=\frac{a-\varphi''}{\varphi'}\,. \qquad (18)$$

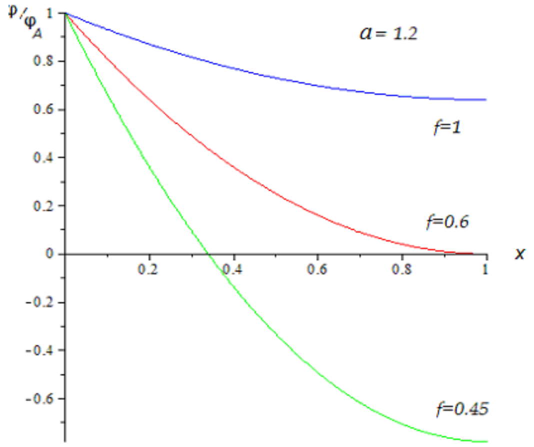

Fig. 4. Potential distribution in gap for quasi-neutral plasma for different values of parameter f

Solution (18) with given (17) has form:

$$n_e(x) = C \cdot (x-1)^{\frac{2f^2}{a}-1}, \quad (19)$$

where C – some constant. Note that if $a = 2f^2$ the electron density doesn't change along the gap and solution (17) is reduced to (10) and $C = j_d / e\nu_i d$. The condition above could rewrites in form:

$$\frac{\tau_{ed}}{\tau_{id}^2} = 2\nu_i \quad \text{or} \quad \tau_{ed}\nu_i = 2\tau_{id}^2\nu_i^2 = 1, \quad (20)$$

where $\tau_{ed} = \frac{d}{\mu_\perp E}$ – electron lifetime, $\tau_{id} = d/v_{id}$ – ion living time. Indeed (20) is some generalization condition of self-sustained discharge in crossed EH fields taking into consideration both electron and ion dynamic peculiarity.

All these solutions were got under condition $T_e = 0$. For clarification temperature effect on the acceleration layer characteristics assume that electrons get energy from electric field E, then (6) could be presented as:

$$T_e = \beta \cdot \varphi, \quad (21)$$

where $0 < \beta \le 1$. In this case from (7) instead of (8) we have:

$$\varphi''\big((x-1) - \alpha(1+\beta)\varphi'\big) = 0 \quad (22)$$

and get solution in form:

$$\varphi = \frac{a}{(1+\beta)} x(x-2) + 1. \quad (23)$$

Similarly to the above for gap length receive:

$$d = \sqrt{\frac{2\mu_\perp \varphi_A (1+\beta)}{\nu_i}}. \quad (24)$$

Note, that it differs from the previous one (11) by factor $\sqrt{1+\beta}$ only, that describes temperature effect. Potential distribution for different value parameters *a* and β is shown in Fig. 5. One can see that with increasing temperature the gap length where potential drop is completed is grows.

Now consider more general model description, assuming that heating losing occurs mostly by different kind of collisions. Introducing characteristic time of temperature loss by collision – τ_0 could write for temperature definition:

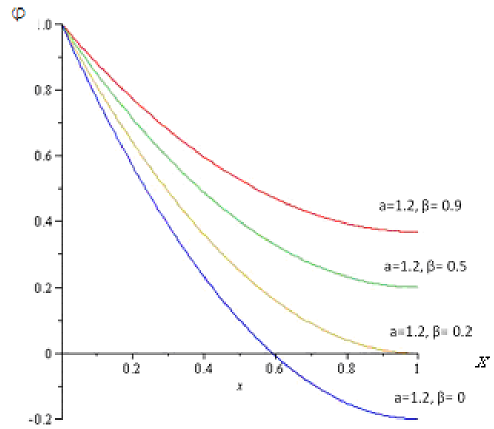

Fig. 5. Potential distribution for different parameters a and β

$$T_e = \frac{j_d E \tau_0}{e n_e}. \quad (25)$$

Thus equation (7) rewritten in form:

$$\mu_\perp \tau_0 \frac{d^2\varphi}{dx^2} - \frac{e\mu_\perp}{j_d} n_e \frac{d\varphi}{dx} + \frac{e\nu_i d}{j_d} \int n_e dx = 1. \quad (26)$$

Dimensionless this equation and Poisson's equation and introducing dimensionless parameters, obtain system:

$$a\varphi'' - bn(x)\varphi' + c\int_0^x n(s)ds = 1,$$

$$n(x) - f\int_0^x \frac{n(s)ds}{\sqrt{\varphi(x) - \varphi(s)}} = g\varphi'', \quad (27)$$

where introduced dimensionless parameters

$$a = \frac{\mu_\perp \tau_0 \varphi_a}{d^2}, \quad g = \frac{\varphi_a}{4\pi d^2 e n_0}, \quad (28)$$

parameters *b*, *c*, *f* – are corresponds to entered above.

In general case this system hasn't analytical solutions and requires numerical calculations. At firstly consider solution under next boundary conditions:

$$\varphi\big|_{x=0} = 1, \qquad \varphi\big|_{x=1} = 0. \quad (29)$$

The results computer simulations are shown in Fig. 6. One can see that for α<0.5 possible potential drop below zero, that could correspond accumulating electron density.

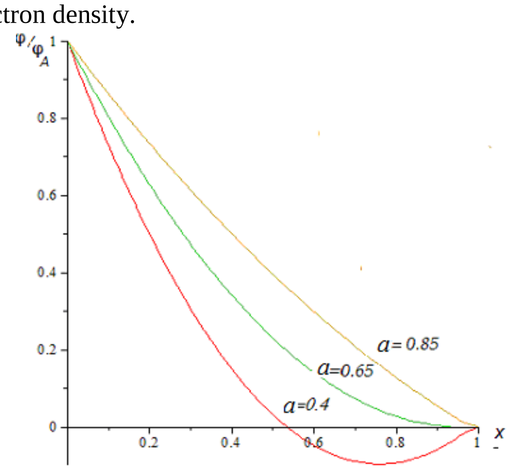

Fig. 6. Potential distribution (numerical simulations) under boundary condition (29)

If we will suggest zero electric field on the cathode layer and change boundary condition (29) on next:

$$\varphi\big|_{x=0} = 1, \qquad E\big|_{x=1} = 0 \qquad (30)$$

got solutions similar to those obtained above (Fig. 7).

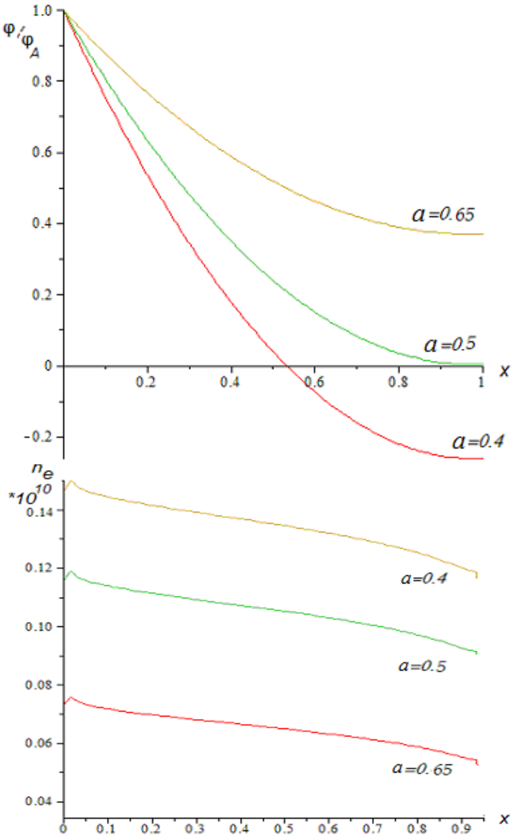

Fig. 7. Potential (up) and electron density (down) distribution (numerical simulations) under boundary condition (30)

As ones can see from Fig. 7 electron density is a little change along the gap. Note, also if we assume that $\tau_0 = \tau_{ed}$ then (25) will be reduced to form: $T_e = \dfrac{j_d d}{\mu_\perp e n_e}$, consequently in (5) the temperature term escapes. Therefore we come back to case (8) and potential distribution (10).

2. EXPERIMENTAL SETUP AND RESULTS

The experimental setup of plasma accelerator, forming ion flow converging towards the axis system had been made for theory testing purpose. It is shown in the Fig. 8.

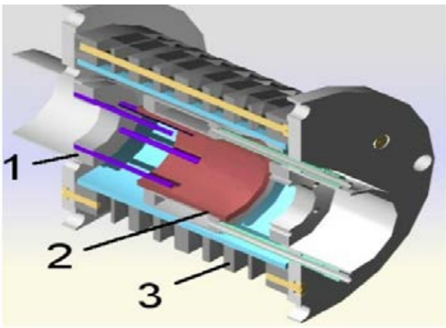

Fig. 8. Experimental setup: 1 – cathode; 2 – anode; 3 – permanent magnets system

Anode diameter is 6.7 cm, cathode is 3.2 cm, distance between anode and cathode is 1.75 cm. Magnetic field H=650…750 Oe, voltage less 2 kV. The working gas is argon. The current-voltage characteristics were obtained in a low-current and high-voltage discharge condition (current about 100 mA, voltage discharge of a few kV). Under such condition experimental current-voltage characteristics must be linear that ones can see in Fig. 9.

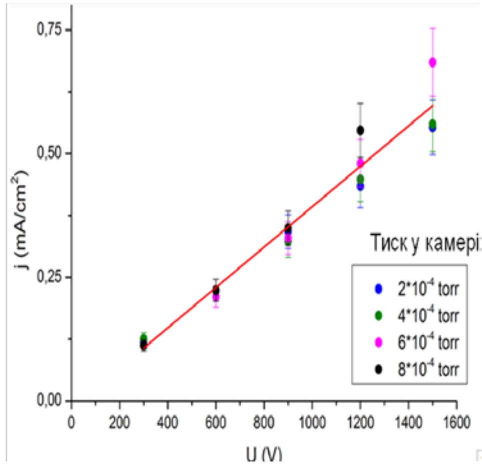

Fig. 9. The current-voltage characteristic

From experimental data can be found electron density, which in our case is equal to $5{\cdot}10^{10}$ cm^{-3}, that is typical for related system. The current is a little depends on gas pressure in the system since anode layer is independent from neutrals concentration (Fig. 10).

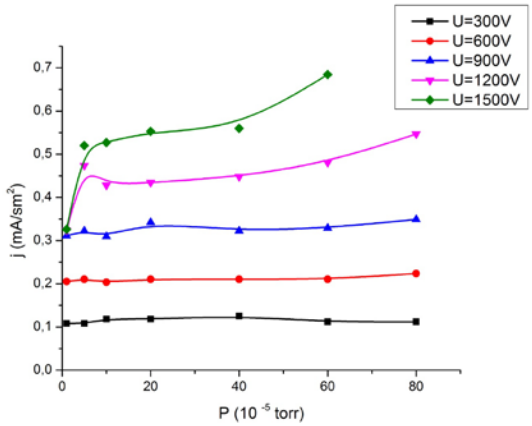

Fig. 10. Current dependence vs gas pressure

Fig. 11 is shown the photo of plasma jet that is observed in high-current mode of accelerator operation.

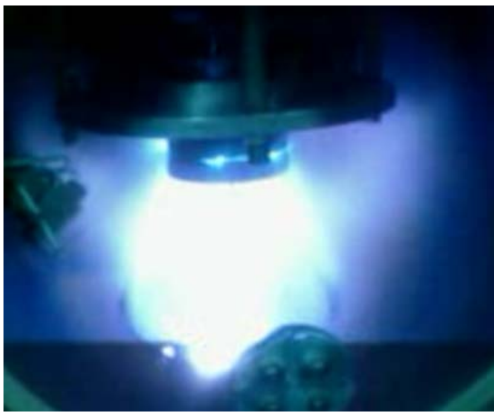

Fig. 11. Plasma jet in high-current mode

It was measured the floating potential and ion current downstream 6 cm from plasma device.

In Fig. 12 is shown dependence floating potential on the system axis vs pressure of working gas in chamber. Anode potential is 1.5 kV.

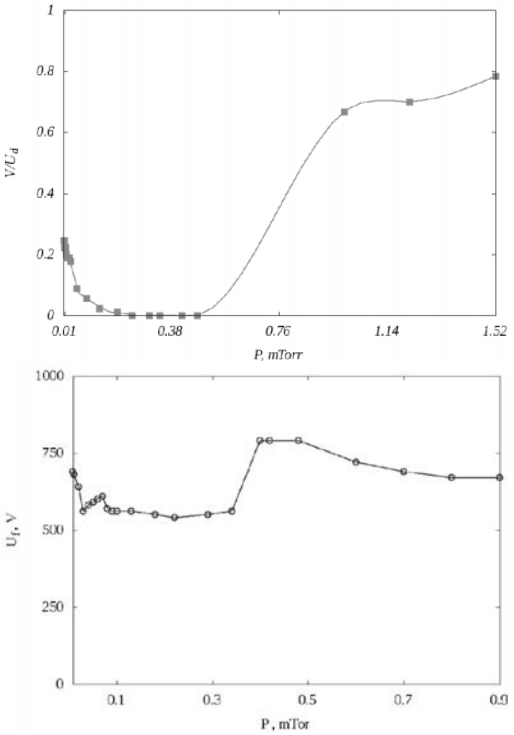

Fig. 12. Floating potential dependence vs working gas pressure (up – at the system exit, down – at the axes)

Ones can (see Fig. 12) the formed potential drop that could be used for ion beam accelerating. In the Fig. 13 is shown ion beam current density dependence on current discharge on the jet axes. The power flow increase with current grows. Note also, the ion current density at torch axes can consist up to 2…3% total discharge current. That opens up too novel attractive possibility for using this kind devices as rocket engines.

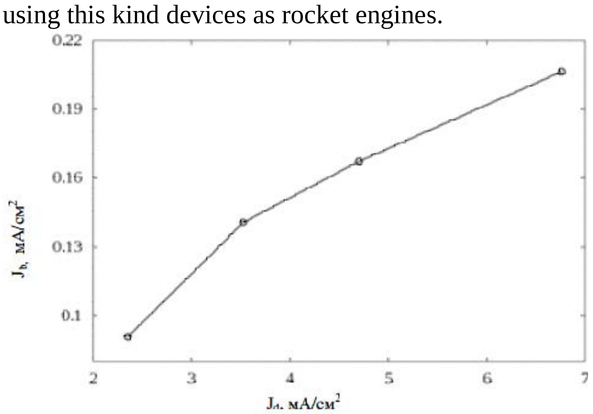

Fig. 13. Dependence current density vs discharge current density

CONCLUSIONS

First, the original approach to use plasma accelerators with closed electron drift and open walls for creation cost effective low maintenance plasma device for production converging towards axis accelerating ion beam was described. Based on the idea of continuity of current transferring in the system are found exact analytical solutions describing electric potential distribution along acceleration gap. It was shown that potential distribution is parabolic for different operation modes as in low-current mode well as in high current quasi neutral plasma mode and can't depend on electron temperature. It is found under conditions that everything electrons originated within the gap by impact ionization only, and go out at the anode due to mobility in transverse magnetic field, the condition full potential drop in the accelerating gap corresponds to equality gap length to the anode layer thickness. In case when the gap length less than anode layer thickness potential drop is not completed. For case when the gap length more than anode layer potential drop exceed applied potential.

Experimental model of accelerator that formed ion flow converging towards the axis system was created. The current-voltage characteristic of the accelerator in different operating mode was defined. In high-current mode of accelerator operation is observed plasma jet. It is shown at the jet axis forms potential drop that could be used for ion beam accelerating. The experimental results are in good accordance with theory data.

Note also that the presented plasma device is attractive for many different high-tech practical applications, for example, like plasma lens with positive space cloud for focusing negative intense charge particles beams (electrons and negative ions) and for potential devises small rocket engines.

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ПЛАЗМЕННЫЙ УСКОРИТЕЛЬ С ГАЗОВЫМИ СТЕНКАМИ И ЗАМКНУТЫМ ДРЕЙФОМ ЭЛЕКТРОНОВ

А. Гончаров, А. Добровольский, Л. Найко, И. Найко, И. Литовко

Впервые описана одномерная модель оригинального плазменного ускорителя с открытыми стенками, представляющая плазмооптическое устройство нового поколения, которое может быть использовано для современных технологий, в частности, для создания плазменной линзы с положительным объемным зарядом, а также малогабаритного ракетного движителя. Получены простейшие аналитические решения и представлены результаты численного моделирования, позволяющие с новых позиций рассматривать физику процессов в ускорителях холловского типа. Приведены результаты экспериментальных исследований.

ПЛАЗМОВИЙ ПРИСКОРЮВАЧ З ГАЗОВИМИ СТІНКАМИ ТА ЗАМКНУТИМ ДРЕЙФОМ ЕЛЕКТРОНІВ

О. Гончаров, А. Добровольський, Л. Найко, І. Найко, І. Літовко

Вперше описана одновимірна модель оригінального плазмового прискорювача з відкритими стінками, яка є плазмооптичним пристроєм нового покоління, для ефективного застосування в сучасних технологіях, зокрема, для створення плазмової лінзи з позитивним просторовим зарядом, а також малогабаритного ракетного двигуна. Отримані прості аналітичні розв'язки і представлені результати числового моделювання, які дозволяють з нових позицій розглядати фізику процесів у прискорювачах холлівського типу. Наведено результати експериментальних досліджень.