COMPUTER MODELLING NEW GENERATION PLASMA OPTICAL DEVICES (NEW RESULTS)

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We present new results of computer modeling two new generation plasma optical devices based on the electrostatic plasma lens configuration that open up perspective possibility for high-tech effective applications. There describe development numerical model computer simulation results of a wide-aperture non-relativistic intense electron beam propagating through an axially symmetric plasma optical lens with a non -compensated positive space charge and the results of some theoretical calculations. The described also the original approach to use plasma accelerators with closed electron drift and open walls for generating effective lens with positive space charge.

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INTRODUCTION

The crossed electric and magnetic fields inherent to the cylindrical electrostatic plasma lens (PL) configuration provide the attractive method for establishing a stable plasma discharge at low pressure [1]. One particularly interesting result of this background work was observation of the essential positive potential at the floating substrate. This suggested to us the possibility of an electrostatic PL use for focusing and manipulating high-current beams of negatively charged particles (electrons and negative ions) that based on the use of the dynamical cloud of positive space charge in the conditions of electrons magnetic insulation. An attractive possibilities of perspective application dynamical positive space charged plasma lens with magnetic electron insulation and non-magnetized ions for focusing and manipulating wide-aperture high-current negatively charged particles beams has been shown in preliminary work [2, 3]. The calculated potential distribution in cloud has one-humped form and reached 580 V in maximum and electric field strength was up to 600V/cm that is sufficiently for focusing intensive negative charged particle beams [2].

This paper describes the development numerical model computer simulation results of a wide-aperture non-relativistic electron beam that transported through an axially symmetric device with a positive space charge plasma lens. We describe also the original approach to use plasma accelerators with closed electron drift and open walls for creation cost effective low maintenance plasma lens with positive space charge and possible application for low-cost low energy rocket engine too.

Thus we present here two new generation plasma optical devices that open up novel attractive possibility for effective high-tech practical applications.

1. POSITIVE SPACE CHARGE PLASMA LENS

A new plasma-optical tool for negative charged particle beams focusing and manipulating with a dynamic cloud of non-magnetized free positive ions and magnetically isolated electrons produced by a toroidal plasma source like an anode layer accelerator have been proposed [2]. The computer modelings were performed by means of the PIC-method. Firstly the positive space charge cloud formation was modeling. Under simulations we take into account dynamic of Ar+ ions only, because of magnetic insulation of electrons. Every time interval Δt (~ $4\cdot10^{-8}$ s) N new particles of charge q_i and mass M_i come to the considered volume. The magnitudes of N, Δt, q_i satisfy the relation: $Nq_i/\Delta t=j_iS$. They move from cylinder surface to the system axis with the narrow angular distribution.

Note that the distributions above are inherent to this kind of plasma accelerators with anode layer. The particles move in magnetic field that decreases drastically towards to system axe. At the first step, the motion equation for the particles in space charge fields was solved (time step comprised 10^{-11} s). After the time of Δt, by collecting of all particles with the use the ‘‘cloud in cell’’ method [4] the densities distributions of argon ions were calculated. Electric field was calculated by the distribution of total space charge. After that in corrected electric field the calculation of particles motion were resumed, and introducing the new portion of ions was performed. Equation of motion was solved both for “new” particles and for those that still left in the volume. The calculation continued until reaching a self-consistent solution. The calculation time comprised 10^{-5} s. For that time the stationary state of the lens operation was achieved. This approach was used for dynamic large-area (r=3 cm) electron beam with energy in range (5…20) keV and current from 0.1 to 100 A in positive space charge cloud was examined. For simulation high-current electron beam transport was taking into account the space charge of the particles and the magnetic self-field that may affect on the dynamic beam particles in addition to the external fields. The possibility ionization residual gas by electron beam was taking into account also. Numerical simulations shows clearly that for electron beam current less then 1 A the electrostatic beam focusing occurs. For beam current about of 1 A the potential maximum in the positive space charge region decreases (from 580 to 210 V), it distribution is getting double-humped and electrostatic focusing destroyed (Fig. 1). It is due to that some part of ions comes out from cloud with the propagating electron beam and their number grows with increasing of beam current [3]. Significant part of cloud particles carry out by e-beam along beam line and ions continuing to come in cloud from electrodes couldn't support renewal processes. Thus cloud potential decrease and it distribution changes from one-hump to two-humps. Note that it corresponded to case when beam space charge density a bit exceeds to space charge cloud density. So in this case is possible to improve PL electrostatic focusing property by increasing energy and current density Ar+ ions beam that create positive space charge cloud. In Fig. 2 is shown potential distribution by electron beam propagating for increasing Ar+ ions beam current from 20 till 40 mA. Ones can see potential distribution come back to one-peak form and focusing properties PL was recovered.

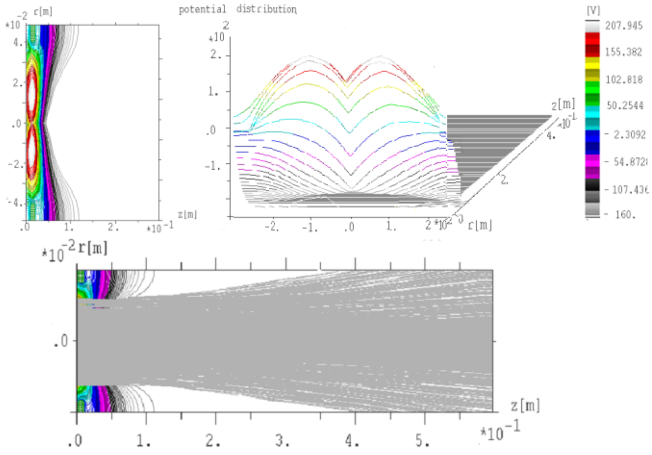

Fig. 1. Potential distribution in PL (top) and electron beam trajectories (down) by e-beam (energy(E_{eb})=10 keV, current(I_{eb})=1 A) passing through PL. Ar+-ions beam energy (E_{ib})=2.4 keV, current (I_{ib})=20 mA, magnetic field (MF) ~50 Oe on the axis

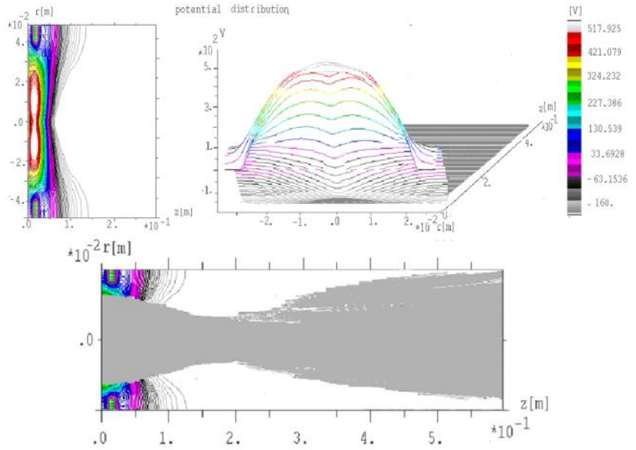

Fig. 2. Potential distribution in PL (top) and electron beam trajectories (down) by e-beam (E_{eb}=10 keV, I_{eb}=1 A) passing through PL. Ion beam(Ar+): E_{ib}=2.4 keV, I_{ib}=40 mA; MF ~50 Oe at the axis

However, the cloud quickly destroys with further electron beam current increasing when beam space charge density significantly exceeds space charge cloud density, (Fig. 3 top) and it is not possible to renew electrostatic focusing properties any way. As can see (see Fig. 3 down) for electron beam with current on the order of tens ampere for which the beam space charge density much more than space charge plasma lens the only the magnetic focusing of the beam provides. Note, that taking into consideration an ionization residual gas by electron beam don't lead to essential changing in simulations of final results.

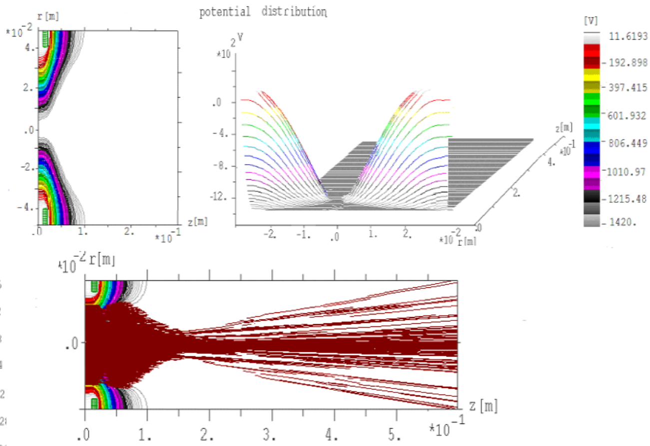

Fig. 3. Potential distribution in PL (top) and e-beam trajectories (down) by e-beam (E_{eb}=10 keV, I_{eb}=10 A) passing through PL. Ar+-ions :E_{ib}=2.4 keV, I_{ib}=100 mA, MF ~100 Oe on the axis

2. PLASMA ACCELERATOR WITH CLOSED ELECTRON DRIFT AND OPEN WALLS

For creating 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. 4 Note, that such kind accelerators are can be attractive for the creation of cost-effective, small rocket engines.

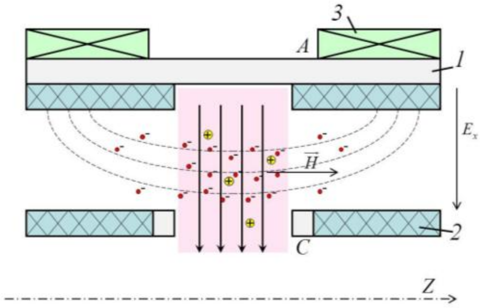

Fig. 4. The simplified scheme of device: 1 – anode, 2 – cathode, 3 – magnetic system

To analyze the properties of such kind an accelerator we use a one-dimensional hydrodynamic model. We assume that the current density is the sum of the ion and electron components:

$$j_p = j_i + j_e. \qquad (1)$$

Taking into account that divergence of ion current is

$$\frac{dj_i}{dx} = en_e\nu_i \qquad (2)$$

with given the fact that it equals j_p on the cathode we get

$$j_i = en_e\nu_i(x-1) + j_p, \tag{3}$$

here ν_i is the ionization frequency. The electron current is

$$j_e = \frac{e\nu_e}{m\omega_e^2}\left[en_eE - \frac{d}{dx}\left(n_eT_e\right)\right]. \tag{4}$$

So, we can get:

$$en_e\nu_i(x-1) + \frac{e\nu_e}{m\omega_e^2}\left[en_eE - \frac{d}{dx}\left(n_eT_e\right)\right] = 0. \tag{5}$$

For simplicity, we neglect the diffusion, then the equation (5) can be rewritten as:

$$en_e\nu_i(x-1) + \frac{e\nu_e}{m\omega_e^2}en_eE = 0. \tag{6}$$

Replacing $E=-\partial\varphi/\partial x$ and using the Poisson equation $\Delta\varphi=4\pi e(n_e - n_i)$, where $n_e >> n_i$. . We can obtain from (6) the differential equation of second order and representing this equation in dimensionless form we get:

$$\varphi''\left((x-1)-a\varphi'\right)=0, \tag{7}$$

where $\alpha = \frac{\mu_\perp\varphi_a}{\nu_i d^2}$.

Here we have introduced the notation: $\mu_\perp = \frac{e\nu_e}{m\omega_e^2}$ – electron transverse mobility, φ_a – anode potential; d – gap length; ν_e is the frequency of elastic collisions with neutrals and ions and ω_e is the electron cyclotron frequency. Omitted trivial solution $\varphi''=0$ and taking into account boundary condition $\varphi|_{x=0}=1$ we obtain potential distribution within gap in form:

$$\varphi = a\left((x-1)^2-1\right)+1, \tag{8}$$

where $a=1/2\alpha$.

Potential distribution (8) for different parameters *a* is shown in Fig. 5. One can see that under *a=1* the total applied potential falling down inside of the accelerating gap. In this optimal case

$$d = \sqrt{\frac{2\mu_\perp\varphi_A}{\nu_i}}. \tag{9}$$

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:

$$\delta = \rho_e\left(\varphi_A\right)\sqrt{\frac{2\nu_e}{\nu_i}}. \tag{10}$$

This expression coincid with one for 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> δ potential drop exceed applied potential. This can be due to electron space charge at the accelerator exit.

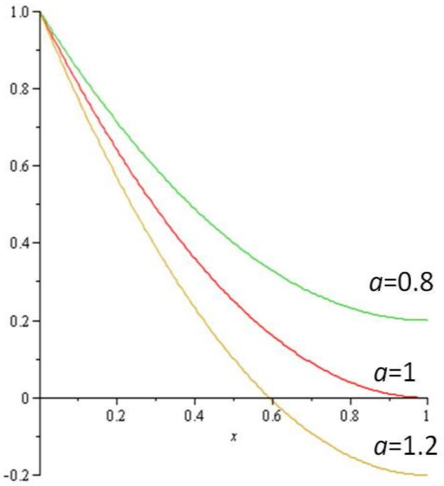

Fig. 5. Potential distribution for different parameters a

CONCLUSIONS

The paper is devoted the description of further development the dynamic a wide-aperture non-relativistic intense electron beam simulation in a cloud of positive space charge plasma lens. It was shown that plasma lens property depends significantly on operating mode and ratio between electron beam and lens current. It is shown the plasma lens significantly improve of electron beam focusing in low-current mode. In case of high-current mode while as electron beam space charge much more than space charge plasma lens the lens operates in plasma mode to create transparent plasma accelerating electrode. The simulation results demonstrate perspective of application positive space charged plasma lens with magnetic electron insulation for focusing and manipulating wide-aperture high-current no relativistic electron beams.

First, the original approach to use plasma accelerators with closed electron drift, equipotentialization magnetic field lines and open walls for creation cost effective low maintenance plasma lens with positive space charge was described too. It is proposed theoretical model self consistent describing the potential distribution in the accelerating gap.

Note that the presented plasma devices are attractive for many different applications in the state-of-the-art vacuum-plasma processing.

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КОМПЬЮТЕРНОЕ МОДЕЛИРОВАНИЕ НОВОГО ПОКОЛЕНИЯ ПЛАЗМООПТИЧЕСКИХ УСТРОЙСТВ

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Представлены результаты численного моделирования двух плазмооптических устройств нового поколения, представляющих интерес для современных технологий. Описаны аксиально-симметрические, цилиндрические, плазмооптические устройства, в физической и конструктивной основе которых лежит электростатическая плазменная линза. Приведены результаты дальнейшего развития численной модели динамики нерелятивистского широкоапертурного интенсивного пучка электронов в облаке положительного пространственного заряда. Впервые описана одномерная модель оригинального плазменного ускорителя с открытыми стенками для использования вкачестве эффективной плазменой линзы спозитивным пространственным зарядом.

КОМПЮТЕРНЕ МОДЕЛЮВАННЯ НОВОГО ПОКОЛІННЯ ПЛАЗМОВООПТИЧНИХ ПРИЛАДІВ

І. Літовко, О. Гончаров, А. Добровольський, Л. Найко, І. Найко, В. Гушенец, Є. Окс

Представлено результати чисельного моделювання двох плазмово-оптичних приладів нового покоління, які представляють інтерес для сучасних технологій. Описано аксіально-симетричні, циліндричні, плазмовооптичні пристрої, в фізичної і конструктивної основі яких лежить електростатична плазмова лінза. Наведено результати подальшого розвитку чисельної моделі динаміки пучка електронів у хмарі позитивного просторового заряду, створеного циліндричним прискорювачем з анодним шаром та магнітною ізоляцією електронів. Вперше описана одновимірна модель оригінального плазмового прискорювача з відкритими стінками для використання в якості ефективної плазмової лінзи з позитивним просторовим зарядом.