NUMERICAL SIMULATION OF PROCESSES IN SUPERCRITICAL ELECTRON BEAM AT THE PRESENCE OF PLASMA

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The first main results of creation of the numerical electromagnetic code "SOM" for research of a virtual cathode at the presence of plasma are presented. The obtained results are the part of the project № 1569 «Development of the collective ion accelerator, based on plasma vircator and periodic magnetic field », performed by agreement with Science and Technology Center of Ukraine. The description of algorithm of a numerical simulation of the virtual cathode in the cylindrical drift chamber is adduced. The implementation of algorithm is carried out by the way of complex of the programs in C++ language. The numerical calculations are made for the upgraded experimental installation "«Agate". It is shown, that at joint injection of a high-current relativistic electron beam ($U_b = 280\,keV$, $I_b = 4{,}6\,kA$) and low-energy, low-current an ion flux in the drift chamber the ion virtual cathode arises, which is pulses periodically. The pulsation frequency makes $300\,MHz$ for hydrogen and $100\,MHz$ for ions of nitrogen. It leads to low frequency time modulation of an output current.

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1. INTRODUCTION

The fundamentals of the ion collective acceleration method are the space charge wave formed by a high-current beam coupling as a result of its space and time modulation. The spatial modulation can be received passing a beam through the corrugated metallic tube [1] or drift chamber with a periodic magnetic field created by a system of aluminum and iron rings [2]. The necessary modulation on time is implemented by slow change of a beam current at the entrance into a system [1, 3, 4].

Necessary for the ion acceleration low frequency modulation can be received by passing a high-current electron beam with a current above space charge limiting current through plasma.

Though in [5] the possible physical mechanism of low frequency modulation also is reviewed, but it's not investigated in detail. It is because that the virtual cathode even in plasma absence is strongly non-linear formation, for the full description which one the numerical methods must be used.

Taking into account of plasma dynamics especially complicates the behavior of a virtual cathode.

In the present report the results of development of a numerical electromagnetic code describing self-consistent dynamics of a virtual cathode in presence of low-energy ions in a cylindrical resonator are presented.

2. THE NUMERICAL ALGORITHM

The algorithm of a numerical modeling is based on particle in cell (PIC) simulation method [5].

The problem formulation is following. Thin annular relativistic electron beam (REB) is injected in the cylindrical drift chamber of radius R and length L through a metal foil. In the drift chamber there is a finite magnetic field enough to magnetize the beam. Beam radius is r_b.

The beam breaks drift space into two areas $I - 0 \le r \le r_b$ and $II - r_b \le r \le R$ (fig. 1). It allows searching for the solutions of Maxwell equations without current sources separately in each of areas, and the connection between them will be set through boundary conditions on the beam surface. As there is only axial coupling of the beam current density, the longitudinal E_z, radial E_r components of an electrical field and azimuthal component of a magnetic field H_φ will be nonzero, which are connected among themselves by set of Maxwell equations:

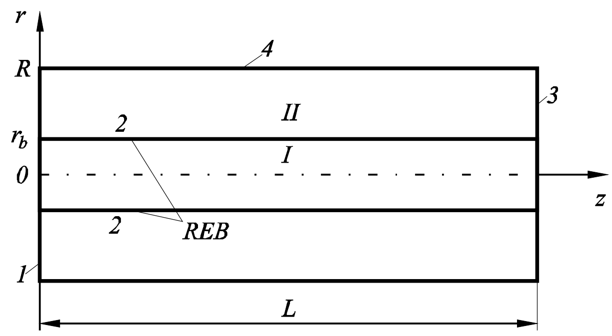

Fig. 1. Tubular REB in the cylindrical resonator

$$\frac{\partial E_r}{\partial t} = -c\frac{\partial H_\vartheta}{\partial z};$$
$$\frac{\partial E_z}{\partial t} = \frac{c}{r}\frac{\partial}{\partial r}\left(rH_\vartheta\right);$$
$$\frac{\partial H_\vartheta}{\partial t} = c\left(\frac{\partial E_z}{\partial r} - \frac{\partial E_r}{\partial z}\right).$$

Boundary conditions consist in condition of vanishing of the tangential component of an electrical field E_z on the metal walls of a resonator, reversal in nil E_r and H_φ at $r = 0$.

On the beam surface the value of E_r, H_φ and $\partial E_z/\partial r$ has a jump determined by the surface density of charge and current:

$$E_r^{II} - E_r^{I} = 4\pi\sigma, \qquad H_\varphi^{II} - H_\varphi^{I} = \frac{4\pi}{c}\bar{j},$$

$$E_z^{II} - E_z^{I} = 0, \qquad \frac{\partial E_z^{II}}{\partial r} - \frac{\partial E_z^{I}}{\partial r} = \frac{4\pi}{c^2}\frac{\partial \bar{j}}{\partial t} + 4\pi\frac{\partial\sigma}{\partial z},$$

where $\sigma(z,t)$ and $\bar{j}(z,t)$ are the surface density of charge and current.

The numerical solution of equations is executed on shifted one to another on space and time grids. The function E_r is determined in time points $t^n = n \cdot \tau$ (τ is time step) in the integer grid nodes on longitudinal and transversal coordinates. The function E_z is determined in the same time points, but in grid nodes shifted on half step on longitudinal and transversal coordinates. Magnetic field H_φ is calculated in half-integer time points in grid nodes shifted concerning a grid E_r on half step on longitudinal coordinate. Radius of an electron beam is supposed to a multiple grid spacing on radius. The value of a field E_z on a beam is calculated through a jump of its derivative and equations, approximating E_z^I and E_z^{II} from internal nodes of computational regions. The same procedure with usage of Maxwell equations allows to receive values $E_r^{I,II}$ and $H_\varphi^{I,II}$ on a beam surface. At the expressions obtained for fields on a beam surface there are surface charge and current densities in grid nodes. The surface charge density is calculates by the mechanism of charge weighting according to a method of macro particles. The size of particles was selected to an equal grid pitch, which corresponds to a "cloud in cell" (CIC) method, therefore weighting of a charge implemented in two nearest grid nodes. The grid current was determined from a continuity equation. The equations of macro particles motion

$$\frac{d}{dt}\left(\frac{mv}{\sqrt{1-v^2/c^2}}\right) = -qE_z(r_b,x,t), \quad \frac{dx}{dt} = v,$$

where $v(t)$ is a z-component of macro particle velocity; $x(t)$ is coordinate, m is rest-mass and q is charge of a macro particle, were calculated under the time-centered "overstep" (or "leap-frog") scheme. Thus the force, which is affects on a macro particle, is calculated by a linear interpolation of an electrical field from two grid nodes, nearest to a particle.

3. TESTING OF THE NUMERICAL CODE

The mentioned above algorithm was realized by the way of complex of the programs in C ++ language. For testing of a numerical code the parameters of the upgraded version of the experimental installation "Agate" were selected: $R = 2{,}5\,cm$, $r_b = 1{,}6\,cm$, input beam current $I_b = 4{,}6\ kA$, energy of beam electrons $U_b = 280\,keV$, $L = 15\,cm$.

For plasma simulation a low-energy ($U_i = 28\,keV$) hydrogen and nitrogen ions were injected into the system. The ion current ($I_i = 92\,A$ for hydrogen and $I_i = 25\,A$ for nitrogen) was adjusted so that in the drift chamber ions compensate an electron space charge. Ion flux and electron beam radiuses were coincident.

Dynamics of process come under the following scheme.

1. For the times of $1\,ns$ order the electronic virtual cathode (VC) within $1.5\,cm$ apart from the left-hand butt end of the drift chamber is forming. The main characteristic feature of this stage is a small amount of ions in the system. Therefore the vircator parameters are practically completely determined by the electrons (fig. 2). Nevertheless ions presence results that the VC position is shifted on $0.7\,cm$ to the right as contrasted to the case, when the ions flow in the drift chamber misses.

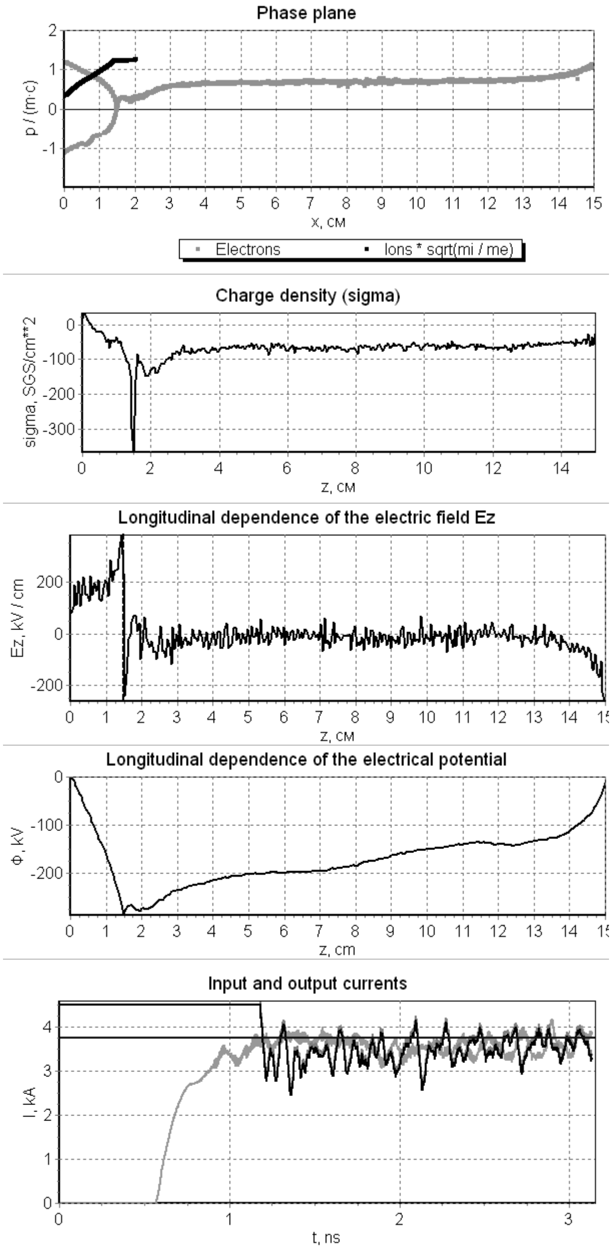

Fig. 2. Parameters of the vircator at the time point $t = 3{,}15\,ns$ from the starting of an injection

2. Later on an ions accumulation in a system results in moving of an electronic VC deep down the drift chamber. The value of an electric field intensity in the VC area drops, that is accompanied by its partial destruction. It results in increasing of an output current. Furthermore at the beginning of the drift chamber the conditions for appearance of an ion VC are formed (fig. 3).

3. Mentioned above factors result that at certain instant ($t = 18\,ns$ for hydrogen and $t = 64\,ns$ for nitrogen) the ion VC will be formed in vircator.

At the same time, the electron VC, practically, completely is destroyed. An

4. ion VC pulses in time, collapsed and restored periodically, that results in appearance of pulses on a curve of an input current, and also to modulation of an output current (fig. 4). The ripple frequency is $300\,MHz$ for hydrogen and $100\,MHz$ for nitrogen ions.

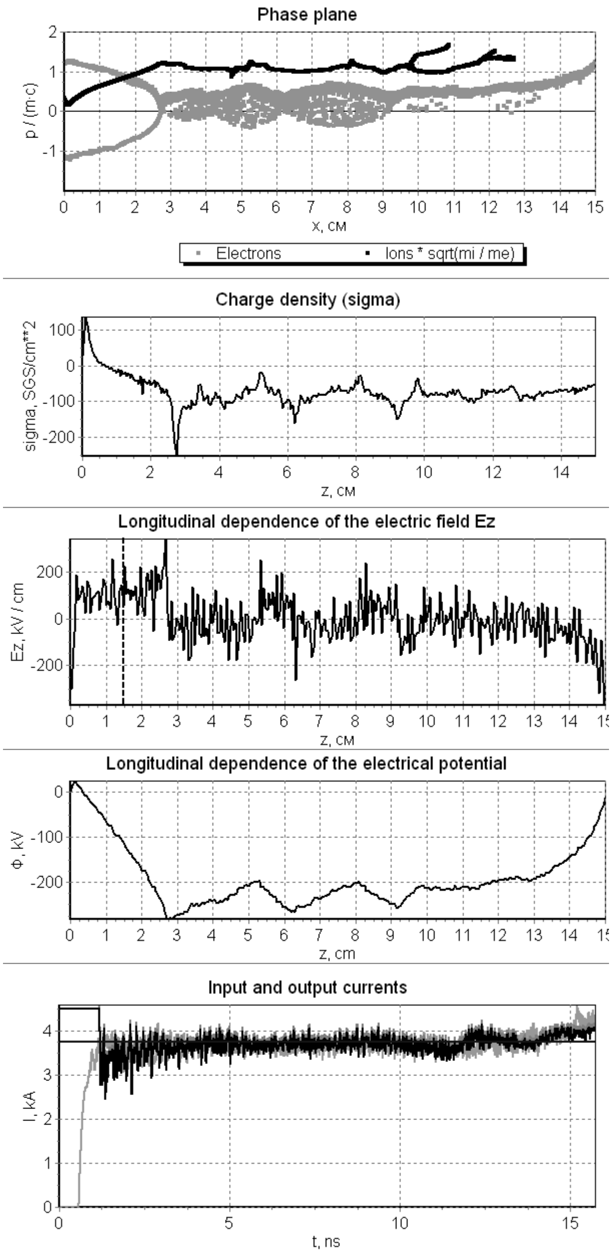

Fig. 3. Parameters of the vircator at the time point
$t = 15{,}75\,ns$ from the starting of an injection

Against a background of ion VC oscillations the regime of periodical appearance of an electronic VC is possible also. This process much more slowly mentioned above, as is a reason of large ion passing time through the drift chamber. The blinking frequency of an electron VC is approximately in 5 times lower than a ripple frequency of an ion VC.

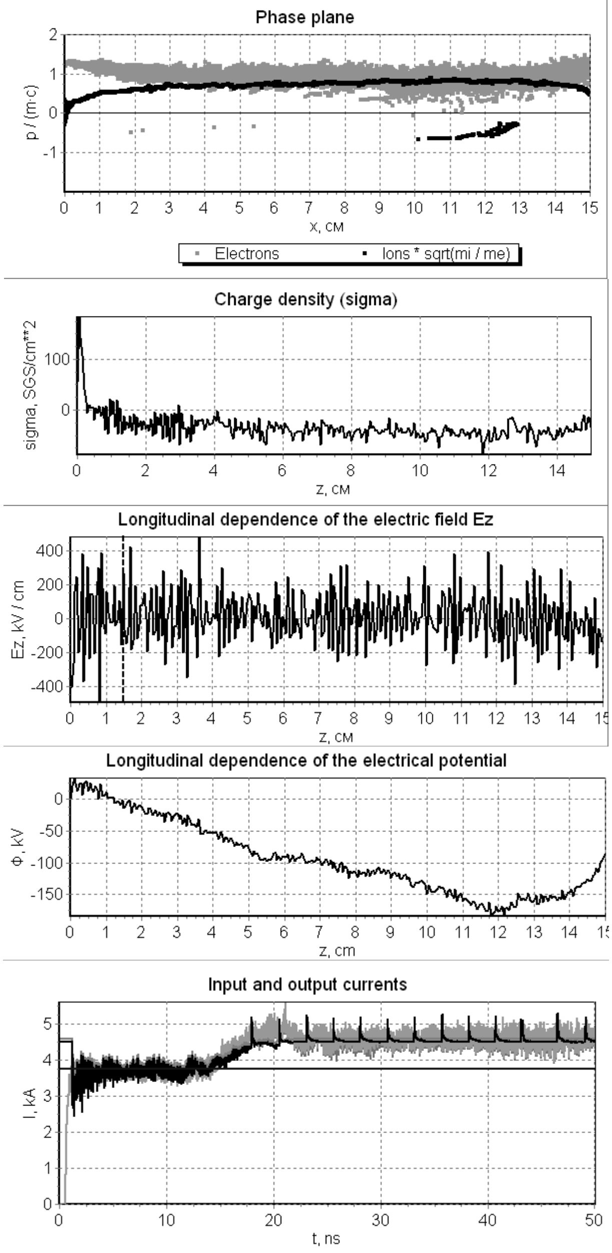

Fig. 4. Parameters of the vircator at the time point
$t = 50{,}05\,ns$ *from the starting of an injection*

4. CONCLUSION

The built numerical code adequately to physical representations describes process of formation of a virtual cathode, its dynamics at transportation of a high-current relativistic beam at the presence of plasma through the cylindrical drift chamber in an approaching of a strong magnetic field. It allows proceeding to creation of similar codes with account of radial motions of charged particles. Such account is especially indispensable at the description of dynamics of ions in a collective ion accelerator.

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ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ПРОЦЕСІВ У НАДКРИТИЧНОМУ ЕЛЕКТРОННОМУ ПУЧЦІ ПРИ ПРИСУТНОСТІ ПЛАЗМИ

П.І. Марков., І.М. Онищенко , Г.В. Сотніков

Представлено перші основні результати створення чисельного електромагнітного коду "COM" для дослідження віртуального катода в присутності плазми. Отримані результати є частиною виконання проекту № 1569 "Розробка колективного прискорювача іонів, заснованого на плазмовому віркаторі і періодичному магнітному полі", виконуваного за договором з Науково-Технологічним Центром України. Приведено опис алгоритму чисельного моделювання віртуального катода в циліндричній камері дрейфу. Реалізація алгоритму виконана за допомогою комплексу програм мовою C++. Чисельні розрахунки зроблені для модернізованої експериментальної установки "Агат". Показано, що при спільній інжекції сильнострумового релятивістського електронного пучка ($U_b = 280\,кеВ$, $I_b = 4{,}6\,кА$)) і низькоенергетичного слабкострумового іонного пучка в камеру дрейфу виникає іонний віртуальний катод, що періодично пульсує. Частота пульсації складає $300\,МГц$ для водню і $100\,МГц$ для іонів азоту. Це приводить до низькочастотної модуляції в часі вихідного струму електронного пучка.

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССОВ В СВЕРХКРИТИЧЕСКОМ ЭЛЕКТРОННОГО ПУЧКЕ В ПРИСУТСТВИЕ ПЛАЗМЫ

П.И. Марков, И.Н. Онищенко , Г.В. Сотников

Представлены первые основные результаты создания численного электромагнитного кода "COM" для исследования виртуального катода в присутствие плазмы. Полученные результаты являются частью выполнения проекта № 1569 "Разработка коллективного ускорителя ионов, основанного на плазменном виркаторе и периодическом магнитном поле", выполняемого по договору с Научно-Технологическим Центром Украины. Приведено описание алгоритма численного моделирования виртуального катода в цилиндрической камере дрейфа. Реализация алгоритма выполнена посредством комплекса программ на языке C++. Численные расчеты сделаны для модернизированной экспериментальной установки "Агат". Показано, что при совместной инжекции сильноточного релятивистского электронного пучка ($U_b = 280\,кэВ$, $I_b = 4{,}6\,кА$) и низкоэнергетического, слаботочного ионного пучка в камеру дрейфа возникает ионный виртуальный катод, который периодически пульсирует. Частота пульсации составляет $300\,МГц$ для водорода и $100\,МГц$ для ионов азота. Это приводит к низкочастотной модуляции во времени выходного тока электронного пучка.