PIC SIMULATION OF LOW-FREQUENCY MODULATION OF SUPER-CRITICAL ELECTRON BEAM AT PLASMA ASSISTANCE

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The results of simulations of virtual cathode dynamics at the presence of plasma are presented. The theoretical analysis of dynamics of the electron-ion formation is based on particle-in-cell method (PIC). Numerical calculations are carried out for the modernized experimental installation "Agate" with intense relativistic electron beam. It is shown that an output electron beam current has a strong temporal modulation. The modulating frequency at injection of hydrogen ions is about 300 MHz.

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1. INTRODUCTION

Basis of a method of collective acceleration of ions is the slow wave of a spatial charge formed by high-current electron beam as a result of its spatial and time modulation. Methods of spatial [1, 2] and time [1, 3] modulations are well-known. At use of beams with current higher than limiting vacuum one the opportunity of time modulation by the virtual cathode field at plasma presence opens [4].

The virtual cathode behavior at the presence of plasma in the strong magnetic field approximation (one-dimensional model) in the cylindrical resonator has been investigate by us earlier [5]. The numerical calculations which have been carried out for ions of hydrogen and nitrogen, have shown, that an electron beam current an output of the resonator is modulated with low frequency. At injection of hydrogen ions this frequency is 300~MHz and at injection of ions of nitrogen it is 100~MHz. The reason of modulation is the formation of a virtual anode on an input of the resonator. Pulsations of a virtual anode result in modulation of input and output electron beam currents.

Serious assumption at this simulation was the guess of the one-dimensional electrons and ions motion. Though at the presence of an electron beam effect of an ion stream space charge on its transversal dynamics is strongly attenuated, the account non-one-dimensionality motions of electrons and ions can qualitatively and quantitatively change the physical processes happening in a virtual cathode at low-energy ions presence.

With the purpose of more precise description and interpretation of results of experimental researches we designed a 2.5-dimensional electromagnetic code. Results of the numerical calculations which have been carried out with the help of a 2.5-dimensional electromagnetic code, virtual cathode featuring self-consistent dynamics in plasma in the cylindrical drift chamber are given below.

2. A STATEMENT OF PROBLEM

The algorithm of numerical model is based on a PIC method [7]. The geometry of calculated system is depicted on Fig. 1. A statement of problem is following.

The relativistic electronic beam having ring cross-section, is injected through the left end (*1*) of drift chamber (*2*). The right end (*3*) of drift chamber can be both opened (emitter), and closed (resonator). The beam width is $\Delta = r_2 - r_1$, where r_1 and r_2 are interior and exterior radiuses of the beam. The beam current is I_b. At the input end of the drift chamber (at $z = 0$) the beam is monoenergetic, transversal components of electron velocities are equal to zero. In the drift space there is an exterior magnetic field with a finite value H_0 of its intensity, directed along the longitudinal z axis of the drift chamber.

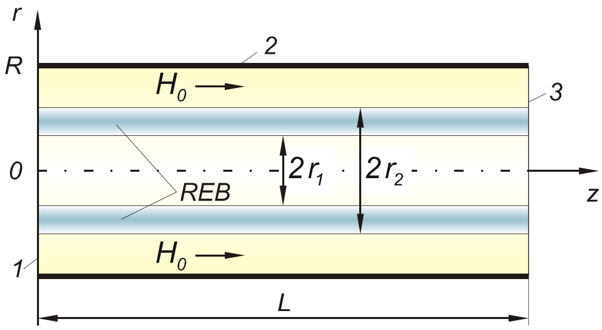

Fig. 1. Geometry of calculated system

3. RESULTS OF NUMERICAL SIMULATION

The algorithm described above has been implemented as a complex of C ++ programs. For numerical calculations we take the parameters of experimental installation "Agat" [4, 5]: radius of the drift chamber is $R = 2.5\,\text{cm}$, inner and outer beam radiuses are $r_1 = 1.5\,\text{cm}$ and $r_2 = 1.7\,\text{cm}$, respectively, electron beam energy is $eU_b = 280\,\text{keV}$, intensity of an external magnetic field is $H_0 = 8\,\text{kOe}$. For simulation we choose a drift chamber length $L = 7.5\,\text{cm}$. The left-hand (input) end of the drift chamber is closed by a metal (conductive) grid, transparent for particles. The right end is opened in a free space. For the specified transverse sizes of the drift chamber and an electron beam energy the limiting vacuum current [6] is 3.76 kA.

For plasma simulating a low-energy hydrogen ions $\left(eU_b = 28\,\text{keV}\right)$ were injected in a system. The ion current $\left(I_i = 92\,\text{A}\right)$ has been taken from a reason that the unperturbed electron and ion densities were approximately equal. The initial cross sizes of an ion stream and electron beam has been chosen equal.

At injection of the ion stream in a vacuum cylindrical waveguide its transported current as well as an electron beam one, is limited by value [8]:

$$I_{ci} = \frac{Mc^2}{e} \frac{\left(\gamma_i^{2/3} - 1\right)^{3/2}}{1 + 2\ln\frac{R}{r_2} + 2\frac{r_1^2}{r_2^2 - r_1^2}\ln\frac{r_1}{r_2}},$$

where $\gamma_i = 1 + eU_i / \left(Mc^2\right)$ and M is an ion mass.

For hydrogen ions flow the space charge limiting current is $I_{ci} = 3.12\,\text{A}$.

Dynamics of processes at joint injection of an electron beam and a hydrogen ion stream occurs under the following plan. For times about 1.67 ns on a distance of around 1.4ч1.6 cm from the left-hand end of the drift chamber the VC is forming. In spite of the fact that the number of ions in system at this time point is small and vircator parameters are practically completely determined by electrons, VC position is shifted deeper into the drift chamber in comparison with a case when the ion stream in the drift chamber is absent.

Hydrogen ions are accelerated in longitudinal electric field of VC and, having arriving at VC, take essential effect on its dynamics. At this time the ions number in the region from an input in the drift chamber up to the VC is already enough great also they are partly compensate an electrons space charge. As a result the VC position starts to move deep into the drift chamber, and the input electron beam current grows.

Such coordinated motion of ion stream forward front and VC position is prolonged down to VC arriving at output end of the drift chamber. At VC motion at some time moments reflected electrons are completely disappear. At these instants an output electron current is equal to an injected current. However, the bunch of electrons, having small longitudinal velocity, does not destroy completely.

VC motion leads to prolonging of hydrogen ions energy increasing. The highest possible hydrogen ions energy observed in numerical experiment at output end of the drift chamber approximately in 2.5 times exceed initial electrons energy.

When VC reaches the right end of the drift chamber an output electron beam current sharply increases.

Simultaneously with the process of VC motion deep into drift chamber and ions acceleration on its front there is also a process of electromagnetic wave excitation by high-current REB described above at the analysis of VC dynamics at ions absence. An excited wave modulates an electron beam and destroys its laminar flow.

On Fig. 2 plots of currents of electron and ion beams currents are given. Minimums on curves of input and output electron currents correspond to complete destruction of the laminar electron beam propagation. At this instant there is enough considerable current on a wall of the drift chamber (a curve 3). As against to only electronic system, at an ion stream presence, the modulation of an output current becomes much deeper. It is concerned with deeper modulation of an input current owing to ions presence. At the time moments, relevant to a laminar flow, the maximum transferred current is higher, and at the time points of complete destruction of a laminar flow the minimum transferred current is lower, since reflected back electrons are broken much more weaker and the reverse electron

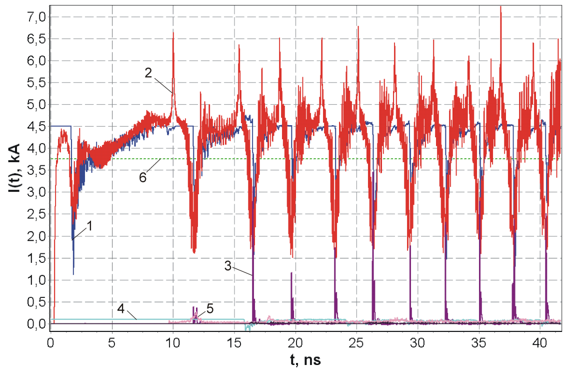

Fig. 2. Plots of electron and ion beams currents of in a time dependence: 1) — an input current; 2) — an output current; 3) — a current on a drift chamber wall; 4) — an input ion current; 5) — an output ion current; 6) — the limiting vacuum electron current

current is higher.

It is necessary to note, that the mechanism of low-frequency modulation described in [5], connected with virtual anode oscillations is also present at given numerical simulation. But, firstly, it has not time to affect at the carried out estimated times and, secondly, the depth of modulation caused by virtual anode oscillations is much lower, than the modulation of an electron current caused by transverse electron beam motion.

4. CONCLUSION

Additional injection of hydrogen ions into the waveguide where for an electron beam the condition of supercriticality is holding, leads to gradual shift of a virtual cathode position deep into drift chamber. This process is continues until the virtual cathode is expels out from the simulated system. During all this time hydrogen ions are accelerated at the virtual cathode front and their peak energy exceeds initial energy of an electron beam approximately in 2,5 times. Further the virtual cathode moving deep into of the drift chamber is recommenced in the system. Thus, process of a virtual cathode origination and its motion along the drift chamber is periodically iterated. At the same time with this process there is the periodic modulation of an electron beam by excited electromagnetic wave. Both specified mechanisms leads to strong time modulation of an output electron beam current. The modulating frequency at injection of hydrogen ions is about 300 MHz.

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МОДЕЛИРОВАНИЕ МЕТОДОМ КРУПНЫХ ЧАСТИЦ НИЗКОЧАСТОТНОЙ МОДУЛЯЦИИ СВЕХКРИТИЧЕСКОГО ЭЛЕКТРОННОГО ПУЧКА В ПРИСУТСТВИИ ПЛАЗМЫ

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Представлены результаты разработки численного 2,5-мерного электромагнитного кода для моделирования динамики виртуального катода в присутствии плазмы. Численный код основан на методе крупных частиц. Выполнено тестирование численного кода на задаче распространения сверхкритического электронного пучка в конечном магнитном поле для параметров экспериментальной установки Агат [4, 5]. Показано, что выходной ток электронного пучка сильно промодулирован во времени. Частота модуляции при инжекции ионов водорода составляет примерно 300 МГц.

МОДЕЛЮВАННЯ ЗА ДОПОМОГОЮ МЕТОДУ ВЕЛИКИХ ЧАСТОК НИЗЬКОЧАСТОТНОЇ МОДУЛЯЦІЇ СИЛЬНОСТРУМОВОГО РЕЛЯТИВІСТСЬКОГО ЕЛЕКТРОННОГО ПУЧКА В ПРИСУТНОСТІ ПЛАЗМИ

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

Представлено результати розробки чисельного 2,5-мірного електромагнітного коду для моделювання динаміки віртуального катода в присутності плазми. Чисельний код заснований на методі великих часток. Виконано тестування чисельного коду на задачі поширювання надкритичного електронного пучка в кінцевому магнітному полі для параметрів експериментальної установки Агат [4, 5]. Показано, що вихідний струм електронного пучка сильно промодульовано у часі. Частота модуляції при інжекції іонів водню складає приблизно 300 Мгц.