Development of a digital software platform for the study of nonlinear dynamics of electronic systems

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***Abstract*— The paper presents the results of applied research on the design and application of an integrated platform for solving applied problems of developing, studying and optimizing high-power electron-plasma devices from the centimeter to THz range based on the results of previous fundamental and exploratory research.**

Keywords— PIC, non-stationary processes of electron-wave interaction; numerical simulation; optimization; digital platform; electron-plasma devices.

I. INTRODUCTION

The development and optimization of efficient high-power generators and amplifiers are one of the most important and rapidly developing areas of modern applied physics. The promise and relevance of advancing microwave devices and devices to a higher frequency region, as well as creating new generators of terahertz (THz) radiation, is due to the fact that currently the THz range (especially the interval 0.2-3 THz) is one of the least mastered in radio physics and electronics [1]. Being outside the modes of operation of traditional microwave (microwave) and optical devices, it belongs to the so-called "technological gap". And although currently there are devices capable of generating terahertz radiation, for example, gyrotrons , free-electron lasers (FEL), quantum-cascade lasers, Gunn diodes, etc. [2-5] due to difficulties in operation, low efficiency and / or lack of reliability, their use is often limited to scientific research, and thus this range is still not readily available for wide use in high-tech industries.

Another important task is the development of power generators and amplifiers of the microwave and sub-THz ranges, without which modern radiophysics, microwave electronics, and plasma physics are inconceivable [6-9]. The need for such devices is due to a number of applied problems and fundamental applications: problems of plasma and solid physics, nanotechnology and spectroscopy, tasks related to information transfer and radiolocation, synthesis of new materials, development of non-destructive testing and security systems, turbulent state of liquids, tasks of biophysics and medicine, etc.

Thus, the obvious need for the development, research, and optimization of powerful devices that can generate and amplify electromagnetic radiation in a wide range.

The solution of the above-described complex scientific and technical problems is almost impossible without the use of modern methods and means of numerical modeling and computational technologies. In particular, this is due to the high cost and high complexity of carrying out field studies and experiments with similar electronics systems, as well as with a low speed of performing such work. This is especially true when new equipment is being optimized or new devices and units are being developed, which is undoubtedly associated with a large volume of measurements when various parameters of such systems are changed. In a full-scale experiment, it is usually not possible to ensure that even the minimum required an array of parameters of the device under investigation is enumerated. Another drawback of experimental studies of electronics systems is often the inability to measure the characteristics of interest due to the limited capabilities of the experimental tools.

An effective method for studying systems of sub-THz and THz electronics, devoid of the above disadvantages, is numerical simulation using modern computing technologies. The most advanced and popular at the moment here are three-dimensional fully electromagnetic codes in which Maxwell's equations are numerically solved to find self-consistent electromagnetic fields in the system, and the large particles method (PIC method) is used to simulate the dynamics of charged particles [10]. This approach well complements and to some extent replaces experimental research, especially during the development stages of prototypes of new devices, as well as the optimization of existing ones [11-17].

Currently, a number of commercial three-dimensional electromagnetic PIC codes are widely known for the numerical study of electronics and radiophysics systems: Magic (USA), CST Particle Studio (Germany / France), VSim (USA), Neptune (USA), WARP (USA), KARAT (Russia) and others. At the same time, all the listed software products have a number of consumer and technical shortcomings, namely: extremely high cost; the difficulty of using most of them; the high degree of universality of these software products and their proximity to the real experiment (especially CST Particle Studio) to the detriment of the possibility of simplifying the models and taking into account the principal features of the sub-THz and THz electronics systems. The latter is most clearly expressed in that, in fact, most commercial codes are a "black box", where it is impossible to disable functions that are not needed at the moment, approximations and modeling capabilities, as well as connect the necessary new ones, remove the required non-standard for this software product characteristics and etc. A critical problem here is also the inability to eliminate, on its own, various numerical nonphysical effects inherent in such PIC codes.

II. RESULTS

In the developed code, the basic mathematical model is the system of equations often used in electronics and plasma physics, consisting of the Vlasov kinetic equation for the electron distribution function and the Maxwell equations for finding self-consistent electromagnetic fields:

$$\frac{\partial f}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{r}} + e\left(\vec{E} + \frac{1}{c}\left[\vec{v}, \vec{H}\right]\right)\frac{\partial f}{\partial \vec{p}} = 0,$$

$$\rho = e\int f\, d\vec{p}, \qquad \vec{j} = e\int f\vec{v}\, d\vec{p},$$

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$$rot\,\vec{E} = -\frac{1}{c}\frac{\partial \vec{H}}{\partial t},$$
$$rot\,\vec{H} = -\frac{1}{c}\frac{\partial \vec{E}}{\partial t} + \frac{4\pi}{c}\vec{j},$$
$$\mathrm{div}\,\vec{E} = 4\pi\rho,$$
$$\mathrm{div}\,\vec{H} = 0$$

here $f = f(\vec{r}, \overrightarrow{p, t})$– is the electron distribution function, ρ and $\vec{j}$ – re the charge and current densities of the electron beam, $\vec{E}$ and $\vec{H}$ – are the electric and magnetic fields, respectively, c – is the speed of light, e – is the electron charge, , $\vec{r}$, $\vec{v}$ and $\vec{p}$ – are the radius-vector, velocity and momentum of electrons, respectively, t – is time.

The Vlasov equation is valid when the condition of the collisionlessness of charged particles is satisfied when the collision integral in the kinetic equation tends to zero. This requirement is fulfilled for the electron flow in the range of spatial and temporal scales of the processes occurring in it that are of interest within the framework of this research. Indeed, the plasma frequency of an intense electron beam, which is the main time scale during the development of various instabilities in it, is significantly greater than the frequency of pair collisions of particles in the beam, and the mean free path of electrons is greater than the characteristic spatial scale of the systems under consideration. with the collective interaction of the electromagnetic field and particles.

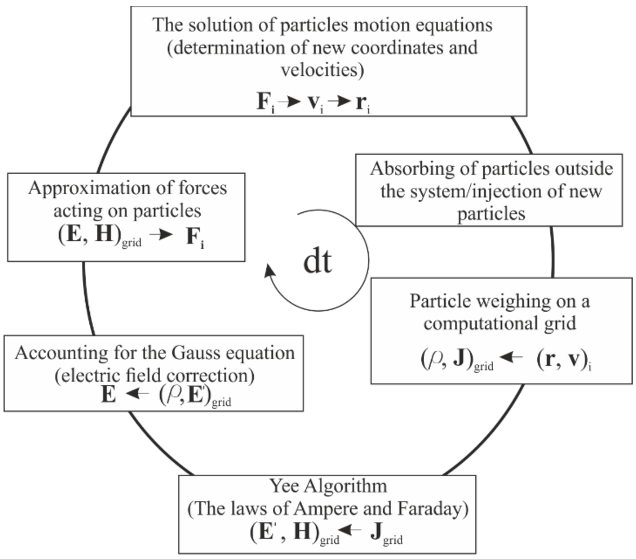

Fig. 1. The algorithm of the method "particle in a cell" at one time step.

To solve this system of equations, the "particle in a cell" method is used. The essence of the method consists of dividing the problem into two parts: the solution of the kinetic equation is modeled using a large number N of “large” particles with the same charge-to-mass ratio; The solution of the field part of the problem is carried out using the Yi algorithm. In this case, the transition to the integral values of the charge density and current from the distribution of particles occurs by weighing the latter on the computational grid. The algorithm for finding the evolution of matched fields at one time step is presented in Figure 1.

Note that when using the concept of “large” particles, such characteristic parameters of the electron flow as the plasma frequency ω_p and the Debye distance λ_d do not change in the model system compared to the real one, which indicates that the proposed mathematical model can correctly reproduce collective phenomena. However, the mean free path and the Debye number (the number of particles in the sphere of the Debye length radius) in the model are reduced, and the frequency of collisions of "large" particles increases in proportion to the weight factor Z, which can distort pair interactions. In order to avoid this, the developed model uses two approaches.

The first is to increase the number of “large” particles so that their number is much larger than the Debye number n_d: $N \gg n_d \gg 1$. The second approach is based on a sharp decrease in the near (pair) interactions of “large” particles due to the transition to particles of finite own volume (finite size) in terms of computational grid. In this case, each particle is a “cloud” of a volume charge with a certain density distribution. With the approach of remote clouds, the interaction force between them first increases, and then, with the beginning of the interpenetration of clouds, weakens. With a full match, the clouds do not interact. This means a decrease in short-range interactions, i.e. collisional effects. The role of the Debye number in this case is played by the number of cloud overlaps $n_m = n_0 d^3_p$, where n_0 is the concentration of “large” particles, dp is the length of “large” particles. Thus, the longer the cloud length d_p, the easier it is to satisfy the condition nm 1 with the same number of particles N.

ACKNOWLEDGMENT

This work has been supported by Russian Foundation for Basic Research (Project 18-32-20135).

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