Nonlinear Phenomena in Complex Systems, vol. **25**, no. 2 (2022), pp. 168 - 176

Simulation Techniques for Vacuum Electronic Devices

S. N. Sytova[*]
Institute for Nuclear Problems, Belarusian State University,
11 Bobruiskaya Str, 220006 Minsk, BELARUS

(Received 25 April, 2022)

This article is devoted to overview of principles of simulation the nonlinear processes of radiation emission in different types of vacuum electronic devices. Such devices are travelling wave tubes, backward wave tubes, multiwave Cherenkov generators, free electron lasers and masers, volume free electron lasers (VFEL). In all these devices a charged particle beam moves through a slow wave structure and interacts there with an electromagnetic field. Regarding VFEL simulation, computer code VOLC is considered. It is a tool for VFEL express simulation, being very fast and giving numerical results in reasonable agreement with theoretical and experimental physical results.

PACS numbers: 41.60.Cr; 35Q60, 35F20, 65M06
Keywords: simulation, nonlinear dynamics, vacuum electronic device, volume free electron laser
DOI: https://doi.org/10.33581/1561-4085-2022-25-2-168-176

1. Introduction

Since the 40s of the 20th century, intensive theoretical and experimental research of radiation emission of charged particles during their passage through spatially-periodic structures and interaction there with an electromagnetic field has been carried out for various types of electronic vacuum devices (VED) [1]–[5]. Such devices are the following: travelling wave tubes (TWT) [6]–[8], backward wave tubes and oscillators (BWT and BWO) [9]–[11], multiwave Cherenkov generators (MChG) [12], [13], free electron lasers (FEL) [14]–[16], free electron masers (FEM) [17], [18], and volume free electron lasers (VFEL) [19]–[22]. There are VED amplifiers and generators, operating in a wide spectrum range from Terahertz to X-ray. References above contain both some of the earliest works in the field and some of the recent ones. And it is impossible to list all such references devoted to VED over the past 80 years. Some references on VED physical principles can be found [23].

The VED widespread use in military and commercial applications requires their reliable operation at high power, high efficiency and low cost. Currently, vacuum electronics amplifiers and generators, in addition to being used in satellite communication systems, television and radio broadcasting, various microwave heating devices for industrial and domestic use, are widely used in scientific research in high-energy particle accelerators, plasma heating for controlled thermonuclear fusion, as well as in medical systems as compact accelerators for nuclear magnetic resonance etc. [3].

The performance of considered devices is ensured by the use of so-called slow wave structure (SWS). They can be different types of spatially-periodic one-dimensional (1D), two-dimensional (2D) or three-dimensional (3D) structures (resonators) made from various materials as well as a system of magnets (so-called undulator) in the case of FEL. SWS are constantly developed and optimized to increase efficiency and improve device performance based on new materials and advanced technologies [24]–[27].

Moving through SWS, charged particles are grouping into bunches and interacting there with slow electromagnetic waves. Type of radiation in such an interaction can be different: synchrotron radiation in FEL, Smith-Purcell and Cherenkov

---

[*] E-mail: `sytova@inp.bsu.by`

radiation in TWT, BWT, FEM, MChG, quasi-Cherenkov and parametric radiation in VFEL.

All proposed references demonstrate the variety of VED from the one hand and commonality in the physical principles used from the other hand, as well as the complex nonlinear dynamics of their functioning. Theoretical and experimental studies of each new type of such devices are of great importance for science and practice.

2. Simulation of vacuum electronic devices

Simulation techniques consisting in the use of numerical methods on a computer makes it possible to use complex nonlinear models that cover all the essential features of any process under study for a wide range of physical parameters. In computational experiments it becomes possible to obtain a complete quantitative description of this process [28], [29].

Let us list the main stages of computer simulation of the devices mentioned above.

1. Development of a theoretical (physical and mathematical) model of radiation processes (including equations for electromagnetic waves and particle beam).
2. Study of dispersion equations and the determination of conditions of radiation generation occurring at the linear stage of the process.
3. Generalization of the model, introduction of dimensionless variables, refinement of boundary conditions etc.
4. Development of numerical methods for solving obtained systems of equations, selection of grid patterns etc.
5. Development of a software package for simulation based on points 3 and 4.
6. Investigation numerically of the nonlinear stage of device functioning, including, if necessary, its investigation as a dynamic chaotic object.

Instead of points 4 and 5, one can use ready-made software packages (if available).

To describe electromagnetic fields in the theoretical model of any of the above devices, Maxwell's equations are used. The slowly varying envelope approximation (SVEA) [30], [31] allows to simplify the system of equations.

The dynamics of charged particle beams can be described using the motion equations or the Vlasov equation with various approximations [32], [33]. Also the electron phase averaging method [34] is well known and widely used for TWTs, BWTs, etc.

Discretization of the constructed complex mathematical model plays a decisive role to successful computational experiments. Discretization methods use various difference approximations [35], [36]. In particular, when solving non-stationary electrodynamical problems for electromagnetic fields, including the complete system of Maxwell's equations, the method of finite differences in the time domain is actively used. This is a finite-difference time-domain method (FDTD) or Yee scheme [37], [38].

Particle-In-Cell (PIC) technique [32], [39], [40] is widely used to simulate the dynamics of the interaction of charged particles with a field.

Besides, last thirty years in the process of rapid development of modern computer technology and the explosive increase in the volume of software, an urgent problem has arisen here. There are requirements on validation and verification of such software.

In this regard, a number of leading scientific, technical professional and military institutions, including the Institute of Electrical and Electronics Engineers (IEEE), the US Department of Defense, the American Institute of Aeronautics and Astronautics (IAAA) have formulated approaches and developed guidelines and standards on problems of modeling, verification and validation of systems, software and hardware [41]–[43]. A large number of scientific papers on this topic have also been published [44]–[46], including well-known monographs [32], [39] and others.

The term "verification" refers to the process of determining how a model implementation accurately represents its conceptual description and specifications. Validation refers to the process of determining the degree to which a model is an accurate representation of the real world in terms of the model's intended use.

In other words, during verification, the question is asked: “Are we building the product right?”, “Are we creating the software product correctly?”. That is, does the software comply with its specification. Validation asks the question: “Are we creating the right product?”. That is, whether the software does what the user really needs.

The authors of [32] emphasize that in any case the author of the computer program himself must be confident in it and knows the limits within which it must work. This confidence must be real, and all the components of the program (e.g. the movement of particles, simulation of fields, etc.) must be tested firstly separately and then together to obtain predictable computational results.

Many computer codes have been verified by comparing the results of each other, as well as on the results of experimental studies.

For VED simulation a number of computer programs have been created [47], [48], including KARAT [49], OOPIC (Object Oriented PIC) [50], MAGIC [51], MAGIC2D and MAGIC3D [52], PARMELA [53], GENESIS [54], Puffin [55], GINGER [56], MEDUSA [57], OCELOT [58] and others.

Also at present, due to the exponential increase in the complexity and volume of the calculation, much attention is paid to the problems of parallelization, efficient use of supercomputers and distributed computing on arrays of computers. An example is the computer code MEDUSA/OPC [59] for the complete simulation of the SASE FEL LCLS (self amplified spontaneous emission FEL at Linac Coherent Light Source, Stanford, USA).

In addition to the widely used codes mentioned above, the new ones are constantly developing. For example, reference should be made to a super-fast time-dependent FEL simulation code, named FALCON, and its applications on the Shanghai soft X-ray FEL facility (SXFEL) [60], as well as code MITHRA [61].

Also the powerful CST (Computer Simulation Technology) software package [62] should be mentioned. It allows 3D modeling of the electromagnetic field for the design, analysis, and optimization of various electromagnetic components and systems.

Most of the above software products are very expensive and, due to their complexity, often require considerable effort to obtain simulation results for the specific installations. But such computer codes allows researchers to avoid the formulation of the systems of equations that describe the physical processes of their model. Unfortunately, in this case some nonphysical results can be obtained [63].

Using cited above and other computer codes, the nonlinear dynamics and chaos of FEL [64]–[68], BWO, TWT [70], [71] etc. were simulated. The methods of suppression of pulsed chaotic regimes in VED [72], [73] allows to increase significantly (by an order of magnitude) the radiation power.

3. Theoretical model of VFEL

VFEL is an electronic device operating on the radiation of relativistic electrons moving in two-dimensional (three-dimensional) spatially periodic structure [19]–[22]. Here such structures (SWS) are natural or artificial electromagnetic (photonic) crystals. Electrons are in synchronism with one or more electromagnetic waves in SWS. Such waves are situated at an angle to each other, forming a non-one-dimensional volume distributed feedback (VDFB). For them the conditions of Bragg diffraction are satisfied near the degeneracy point of the roots of the dispersion equation. These VFEL principles are valid for all wavelength range [20], [22]. None of the other above devices uses the geometry of Bragg

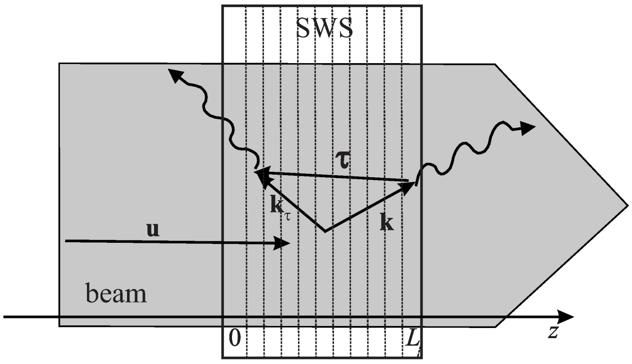

FIG. 1: Two-wave VFEL in Bragg geometry.

diffraction near this point.

In a simple mathematical model of a two-wave VFEL an electron beam with velocity **u** “fall” at some angle onto a semi-infinite spatially-periodic resonator (SWS) of the thickness L. In a case of so-called the Bragg geometry (see Fig. 1) a transmitted electromagnetic wave with a wave vector **k** and a diffracted wave with wave vector $\mathbf{k}_\tau = \mathbf{k} + \tau$ are formed in the system under diffraction conditions. τ is the resonator reciprocal lattice vector. Electrons of the beam in SWS begin to group into the radiating phase and generate quasi-Cherenkov radiation with wave vector **k** if the phase velocity of the electromagnetic wave lags slightly behind the velocity of the electron beam in accordance with the synchronism (Cherenkov) condition:$(\omega - \mathbf{ku})/\omega \sim \delta \ll \mathbf{1}$. δ is the deviation from the exact fulfillment of this condition. ω is a frequency.

In the case of formation in the system two strong waves due to dynamic Bragg diffraction, the solution of the Maxwell’s equations, using SVEA, is presented in the form:

$$\mathbf{E}(\mathbf{r}, t) = \mathbf{e}(E(t, z)e^{i(\mathbf{kr}-\omega t)} + E_\tau(t, z)e^{i(\mathbf{k}_\tau \mathbf{r}-\omega t)}),$$

where **e** is a vector of polarization. E and E_τ are complex-valued amplitudes of two strong electromagnetic waves with wave vectors **k** and $\mathbf{k}_\tau$.

Let us present here only the following system of VFEL equations in the common form. Its coefficients can be found in [74], [75]:

$$\frac{\partial E}{\partial t} + a_1 \frac{\partial E}{\partial z} + b_{11} E + b_{12} E_\tau =$$
$$= \Phi \int_0^{2\pi} (2\pi - p) \left(e^{-i\Theta(t,z,p)} + e^{-i\Theta(t,z,-p)} \right) dp,$$

$$\frac{\partial E_\tau}{\partial t} + a_2 \frac{\partial E_\tau}{\partial z} + b_{21} E + b_{22} E = 0,$$

$$\frac{\partial^2 \Theta(t, z, p)}{\partial z^2} = \Psi \left(k_z - \frac{\partial \Theta(t, z, p)}{\partial z} \right)^3 \cdot$$
$$\cdot \mathrm{Re} \left(E(t - z/u, z) e^{i\Theta(t,z,p)} \right),$$

$$E(t, 0) = 0, E_\tau(t, L) = 0,$$

$$\Theta(t, 0, p) = p, \quad \frac{\partial \Theta(t, 0, p)}{\partial z} = k_z - \omega/u,$$

$t > 0,\ z \in [0, L],\ p \in [-2\pi, 2\pi]$.

The VFEL system of equations in the most general form for n-wave diffraction and m electron beams is given in [76].

In our system the electron beam dynamics is obtained by averaging over the phases of electron entry into the interaction region. But unlike the system for BWTs, TWTs etc. [34], where the electron dynamics is determined only by the time of electron entry into the resonator, we take into account the influence of the spatial transverse point of electron entry on the its dynamics into the interaction region at $z = 0$. So, this gives the possibility to average over two phases, i. e. over the moment of the entry and the transverse coordinate of electron entry. Therefore it gave the possibility to simulate VFEL fine physical effects in the region of degeneracy of the roots of the dispersion equation and in the case of phase-matching of several modes with the beam.

The linear stage of VFEL operation has been studied quite well [20], [22], but it is quickly replaced by a nonlinear stage. It is clear that the nonlinear stage of the VFEL operation, described by proposed system of equations, can be considered only using numerical methods [74]. A similar remark applies to all other vacuum electronic devices [28], [29], [32] etc.

4. Computer code VOLC

To simulate various VFEL schemes, the software package VOLC (“VOLume Code”) was developed in Fortran 90. It allows to simulate two- and three-wave VFEL geometries with one or two electron beams. VOLC is a non-stationary 1D program. It is very fast with respect to large 2D or 3D codes. But as a result of carefully taking into account the VDFB conditions and the phases of electrons in the beam, the 1D VOLC code allows to simulate the complex three-dimensional dynamics of the electron beam and the propagation of electromagnetic waves in the three-dimensional VFEL SWS.

For VOLC testing, numerical results were compared with analytical ones in the case of stationary solution of the standard problem of diffraction in a resonator without and with an electron beam. The first one allows to test and verify the simulation of electromagnetic fields in the system. The second one checks the motion of electrons in the system.

Then it was examined the fulfillment of all basic laws of VFEL functioning in a wide range of parameters as well as the sensitivity of solution to changes in the initial conditions in the system. It is shown that for efficient generation there is an optimal set of VFEL parameters [74]. VOLC allows to quickly pre-calculate the experimental conditions, which can be simulated then with greater accuracy using “heavy” computer codes (discussed above) on supercomputer technology. Thus, the software VOLC is intended for express simulation of the operation of various types of VFEL, including VFEL experimental physical installations at the Institute for Nuclear Problems of Belarusian State University.

It has been shown [75], [76] that VFEL is a chaotic system. Its nonlinear generation dynamics is due to the nonlocal nature of the interaction of an electron beam with an electromagnetic field under diffraction conditions and VDFB. When studying the VFEL chaotic nature, its space-time and phase dynamics were investigated, various dynamic modes of operation with complex transformation were obtained numerically. The study of VFEL as a chaotic dynamical system is important to control chaos and to choose optimal set of VFEL parameters.

In this paper let us give only one result of VFEL simulation by VOLC. This is an establishment of the process of dynamical diffraction during the passing of an electron beam through VFEL resonator. Based on the simulation results, a video was created, eight frames of which are shown in Fig.2 and Fig.3. A point in time is shown below each plot. The abscissa demonstrates SWS of the length $L = 40$ cm. The ordinate axis corresponds to the field amplitude modulus.

Here a scheme of VFEL generator from Fig.1 was considered. The curve 1 in plots corresponds to the amplitude $|E(z,t)|$ of transmitted wave. At $z = 0$ it is equal to zero. The curves 2 depict the diffracted wave $|E_\tau(z,t)|$ that begins to rise from the right SWS border at $z = L$. The curve 3 corresponds to right-hand side of the first equation in the system above. It increases from the left to the right during electron passing through the resonator.

So, it is seen that all the curves grow rapidly and then dynamically “breathe” in space and time, redistributing their amplitudes. The beam curve 3 has large “humps” in the first half of the resonator. This means that the electrons, grouped into bunches, begin to transfer the energy to the electromagnetic field. Closer to the SWS exit, the beam amplitude decreases. That is, electrons radiate less and physical forces act on them, forming well-observed “parasitic” modes. That is, the beam curve, in contrast to the wave amplitude curves, loses its smoothness starting from the middle of the resonator.

However, these “spurious” frequencies due to dynamic diffraction and VDFB are not transmitted to electromagnetic waves. This is the clear example of the implementation of the basic VFEL law of suppression of parasitic modes inside the resonator. Thus not all spurious frequencies that arise in the electron beam are transferred to the transmitted wave, and even more so to the diffracted one.

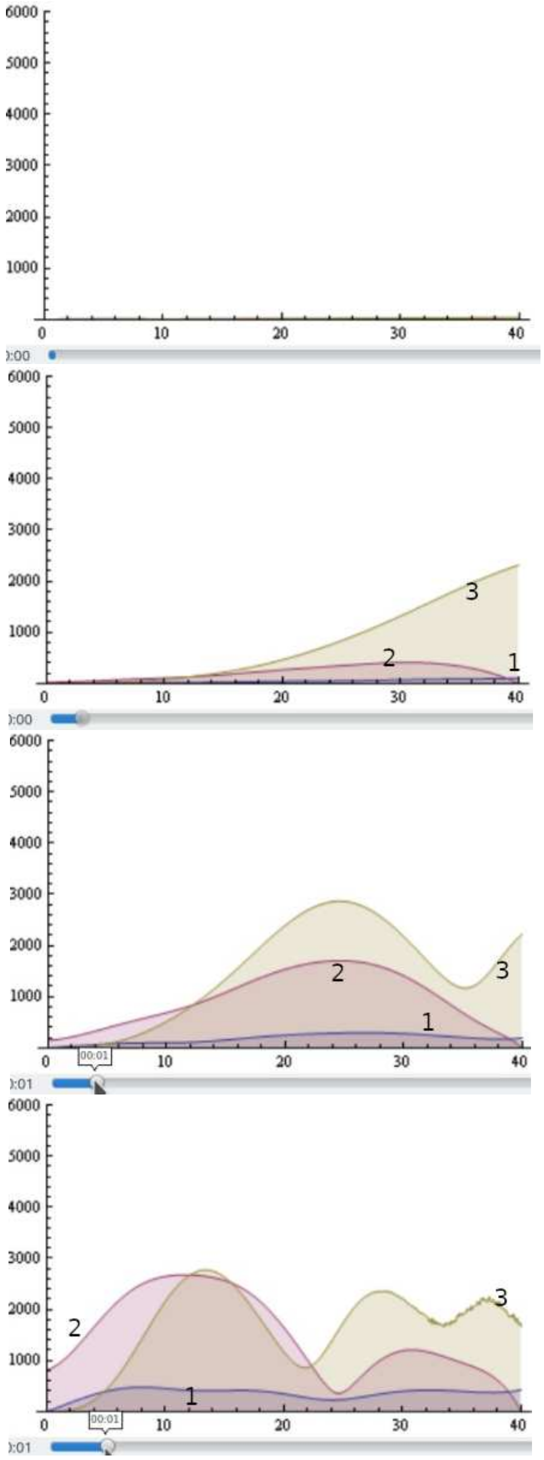

FIG. 2. (color online) Distribution of VFEL wave amplitudes in space and time.

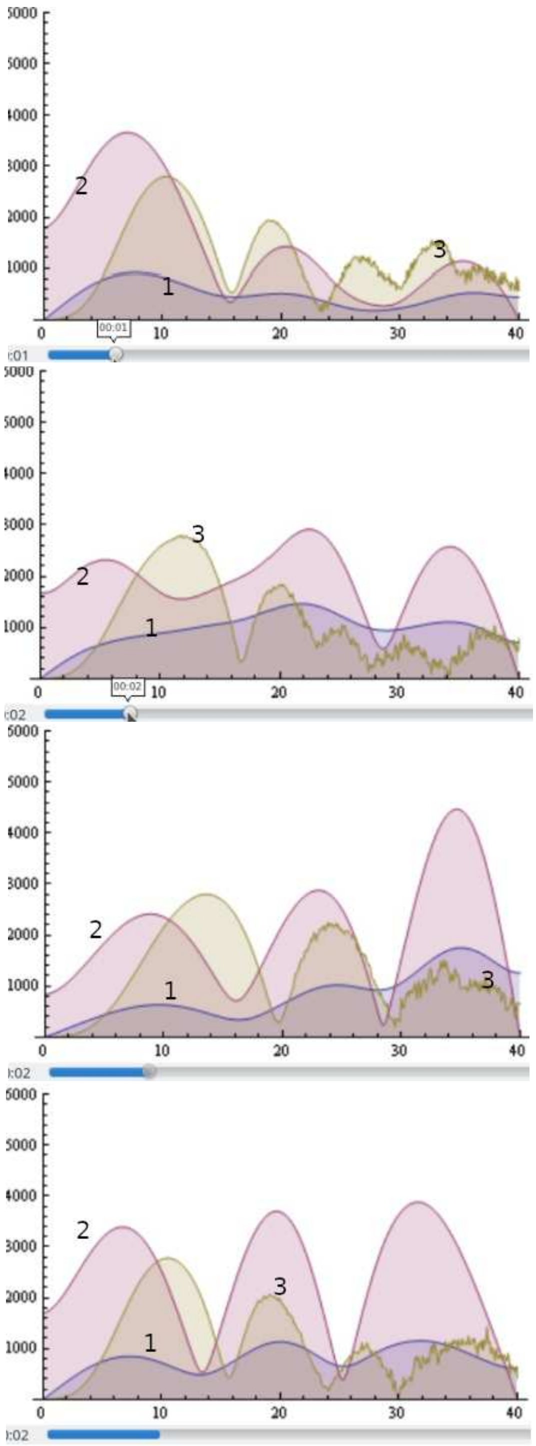

FIG. 3. (color online) Distribution of VFEL wave amplitudes in space and time (continuation).

5. Conclusion

An overview of VED simulation techniques is given including VFEL simulation. The performed computer simulation using code VOLC confirmed the main physical laws and principles of VFEL operation. It makes possible to investigate numerically operation of VFEL experimental installations.

References

[1] J.W. Gewartowski, H.A. Watson. *Principles of electron tubes.* (Van Nostrand, Princeton, NJ, 1965).

[2] T.C. Marshall. *Free Electron Laser.* (McMillan, 1985).

[3] R.J. Barker *et al. Modern Microwave and Millimeter-Wave Power Electronics.* (Wiley-IEEE Press, Singapore, 2005).

[4] S.E. Tsimring. *Electron Beams and Microwave Vacuum Electronics.* (Wiley, Singapore, 2006).

[5] A.S.Jr. Gilmour. *Microwave and Millimeter-Wave Vacuum Electron Devices: Inductive Output Tubes, Klystrons, Traveling-Wave Tubes, Magnetrons, Crossed-Field Amplifiers, and Gyrotrons.* (Artech House, 2020).

[6] R. Kompfner. The traveling-wave tube as amplifier at microwaves. Proc. IRE. **35**(2), 124 (1947).

[7] D. Shiffler, J.A. Nation, G.S. Kerslick. A High-Power, TWT Amplifier. IEEE Trans. Plasma Sci. **18**(3), 546 (1990).

[8] C. Paoloni *et al.* Millimeter wave traveling wave tubes for the 21st Century. J. Electromag. Waves Appl. **35**(5), 567 (2021).

[9] R. Kompfner, N.T. Williams. Backward-Wave Tubes. Proc. IRE. **41**(11), 1602 (1953.)

[10] J.A. Swegle, J.W. Poukey, G.T. Leifeste. Backward wave oscillators with rippled wall resonators: Analytic theory and numerical simulation. Phys. Fluids. **28**(9), 2882 (1985).

[11] S. Li, J. Wang, D. Wang. Relativistic Surface Wave Oscillator in Y-Band with Large Oversized Structures Modulated by Dual Reflectors. Sci. Rep. **10**(1), 336 (2020).

[12] S.P. Bugaev *et al.* Relativistic multiwave Cherenkov generators. IEEE Trans. Plasma Sci. bf 18(3), 525 (1990).

[13] S. Ting, Y. Liu. Particle simulation of a millimeter wave multiwave Cherenkov generator producing GigaWatt power levels. Int. J. Infrared and Millimeter Waves. **19**(3), 385 (1998).

[14] W.B. Colson. Theory of a Free Electron Laser. Phys. Let. **59A**, 187 (1986).

[15] J. Madey, M.O. Scully, P. Sprangle. The free electron laser: conceptual history. Physica Scripta. **91**, 063003 (2016).

[16] G. Geloni, Z. Huang, C. Pellegrini, CHAPTER 1:The Physics and Status of X-ray Free-electron Lasers. In: *X-Ray Free Electron Lasers: Applications in Materials, Chemistry and Biology.* (2017). Pp. 1-44

[17] M. Thumm, Free-electron masers vs. gyrotrons: prospects for high-power sources at millimeter and submillimeter wavelengths. Nucl. Instr. Meth. Phys. Res., **A483**(1-2), 186 (2002).

[18] A.K. Kaminsky *et al.* Experimental demonstration of free electron maser operation in the regime of non-resonant trapping. Appl. Phys. Let. **115**(16), 163501 (2019).

[19] V.G. Baryshevsky, I.D. Feranchuk. Parametric beam instability of relativistic charged particles in a crystal. Phys. Let. **A102**, 141 (1984).

[20] V.G. Baryshevsky, K.G. Batrakov, I. Ya. Dubovskaya. Parametric (quasi-Cerenkov) X-ray free electron lasers. J. Physics D: Appl. Phys. **24**, 1250 (1991).

[21] V.G. Baryshevsky *et al.* First lasing of a volume FEL (VFEL) at a length range $\lambda \sim$4-6 mm. Nucl. Instr. Meth. Phys. Res. **A483**, 21 (2002).

[22] V.G. Baryshevsky, A.A. Gurinovich. Photonic crystal-based compact high-power vacuum electronic devices. Phys. Rev. Acc. Beams. **22**, 044702 (2019).

[23] S.N. Sytova. Nonlinear dynamics of radiation of high-current beams of charged particles in spatially periodic structures. J. of the Belarusian State University. Physics. **1**, 62 (2021).

[24] S.C. Yurt, M.I. Fuks, S. Prasad, E. Schamiloglu. Design of a metamaterial slow wave structure for an O-type high power microwave generator.

Phys. Plasmas. **23**(12), 123115 (2016).

[25] A. Rosa *et al.* Microwave index engineering for slow-wave coplanar waveguides. Sci. Rep. **8**, 5672 (2018)

[26] N. Panahi, S. Saviz, M. Ghorannevis. The new wave-ring helical (WRH) slow-wave structure for traveling wave tube amplifiers. J. Theor. Appl. Phys. **11**, 269 (2017).

[27] Y.G. Goren, T. Chen. Asymmetrical slow wave structures to eliminate backward wave oscillations in wideband traveling wave tubes. US patent US9202660B2 (2013).

[28] T. Tanaka. Numerical methods for free electron laser simulations, J. Electromag. Waves Appl. **32**(3), 371 (2018).

[29] K.-J. Kim, Z. Huang, R. Lindberg. Simulation Methods for FELs. In: *Synchrotron Radiation and Free-Electron Lasers.* (2017). Pp. 246-254.

[30] B. Van der Pol. VII. Forced oscillations in a circuit with non-linear resistance. (Reception with reactive triode). The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science. **3**(13), 65 (1927).

[31] F. Arecchi, R. Bonifacio. Theory of optical maser amplifiers. IEEE J. Quant. Electr. **1**, 169 (1965).

[32] C.K. Birdsall, A. B. Langdon. *Plasma Physics via Computer Simulation*, 1st Edition. (CRC Press, Boca Raton, 1991).

[33] G. Colonna, A.D' Angola. *Plasma Modeling.* (IOP Publishing, IOP Publishing, 2016).

[34] L.A. Vainshtein, V. A. Solntsev. *Lectures on microwave electronics.* (Sov. Radio, Moscow, 1973). (in Russian).

[35] P.D. Lax. Differential equations, difference equations and matrix theory. Comm. Pure Appl. Math. **11**, 175 (1958).

[36] R.J. LeVeque. *Numerical Methods for Conservation Laws.* (Birkhauser Verlag, Birkhauser Verlag, 1992).

[37] K.S. Yee. Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equation in Isotropic Media. IEEE Trans. Antenna Prop. **14**(3), 302 (1966).

[38] A. Taflove, S.C. Hagness. *Computational Electrodynamics: The Finite-Difference Time-Domain Method.* (Artech House, London, 1995).

[39] R.W. Hockney, J.W. Eastwood. *Computer Simulation Using Particles.* (CRC Press, Boca Raton, 1988).

[40] J. Qiang CRC Press An Object-Oriented Parallel Particle-in-Cell Code for Beam Dynamics Simulation in Linear Accelerators. J. Comp. Phys. **163**(2), 434 (2000).

[41] DoD Modeling and Simulation (M&S) Verification, Validation, and Accreditation (VV&A). Instruction number 5000.61 (U. S. Department of Defense, 2003).

[42] Guide for the Verification and Validation of Computational Fluid Dynamics Simulations. AIAA Report G-077-1998. (American Institute of Aeronautics and Astronautics, 1998).

[43] IEEE Standard for System, Software, and Hardware Verification and Validation. IEEE Standard. (2016). Pp. 1012-2016

[44] W.L. Oberkampf, T. G. Trucano. Verification and validation in Computational Fluid Dynamics. Progress in Aerospace Sciences. **38**, 209 (2002).

[45] R.G. Sargent. Verification and validation of simulation models. Proc. WSC, IEEE Computer Society, (2011). Pp. 183-198

[46] D. Pelletier. Verification, validation, and uncertainty in computational fluids dynamics. Candian J. Civ. Engineer. **37**, 1003 (2010).

[47] S. Reiche. FEL Simulations: History, Status and Outlook. Proc. FEL. **2010**, 134 (2010).

[48] B. Garcia et al. Comparing FEL Codes for Advanced Configurations. Proc. FEL. **2017**, 60 (2017).

[49] V.P. Tarakanov. Code KARAT in simulations of power microwave sources including Cherenkov plasma devices, vircators, orotron, E-field sensor, calorimeter etc. EPJ Web of Conferences. **149**, 04024 (2017).

[50] J.P. Verboncoeur, A.B. Langdon, N.T. Gladd. An object-oriented electromagnetic PIC code. Computer Physics Comm. **87**, 199 (1995).

[51] B. Goplen et al. User-configurable MAGIC for electromagnetic PIC calculations. Computer Phys. Comm. **87**(1-2), 54 (1995).

[52] The MAGIC user's manual. MRC/WDC-R-556 (2006).

[53] L. Young, J. Billen. The particle tracking code PARMELA. Proc. PAC. **2003**, 3521-3523 (2003).

[54] S. Reiche. GENESIS 1.3: a fully 3D time-dependent FEL simulation code. Nucl. Instr. Meth. Physics Res. **A429**, 243 (1999.)

[55] L.T. Campbell, B.W. J. McNeil. Puffin: A three dimensional, unaveraged free electron laser simulation code. Phys. Plasmas. **19**, 093119 (2012).

[56] W.M. Fawley. An Enhanced GINGER Simulation code with Harmonic Emission

and HDF5 IO Capabilities. Proc. FEL. **2006**, 218 (2006).

[57] S.G. Biedron, H.P. Freund, S.V. Milton. Development of a 3D FEL code for the simulation of a high-gain - harmonic generation experiment. SPIE, Free-Electron Laser Challenges II, part of SPIE's Phothonics West'99, SPIE paper no. 361417 (1999).

[58] I. Agapov *et al.* FEL Simulations with OCELOT. Proc. IPAC **2015**, 210-212 (2015).

[59] J. Einstein *et al.* FEL Simulations using Distributed Computing. Proc. IPAC **2016**, 483-486 (2016).

[60] L. Zeng *et al.* A Super-Fast Free-Electron Laser Simulation Code for Online Optimization. Photonics. **7**, 117 (2020).

[61] A. Fallahi, A. Yahaghi, F.X. Kartner. MITHRA 1.0: A full-wave simulation tool for free electron lasers. Computer Physics Comm. **228**, 192 (2018).

[62] CST STUDIO SUITE 2017 Offers EM Simulation on Every Scale. Microwave J. February, 2 p. (2017).

[63] S.A. Kurkin *et al.* Simulation of Instabilities in a Relativistic Electron Flow in CST Particle Studio. Math. Modelling. **29**(7), 109 (2017).

[64] P.J.M. van der Slot *et al.* Time-Dependent, Three-Dimensional Simulation of Free-Electron-Laser Oscillators. Phys. Rev. Let. **102**, 244802 (2009).

[65] H.J. Kim *et al.* MAGIC3D Simulation of an Ultra-compact, Highly Efficient, and High-power Reltron Tube. IEEE Trans. Dielectrics and Electrical Insulation. **16**(4), 961 (2009).

[66] M. Billardon Chaotic behavior of the storage-ring free-electron laser. Nucl. Instr. Meth. Phys. Res. **A304**, 713 (1991).

[67] C. Bruni *et al.* Chaos in free electron laser oscillators. Eur. Physics J. **D55**, 669 (2009).

[68] C.-B. Kim, K.-S. Hong. Control of chaos in free-electron laser. Nucl. Instr. Meth. Phys. Res. **A403**, 161 (1998).

[69] N.M. Ryskin, V.N. Titov. Self-modulation oscillatory modes in a relativistic backward-wave oscillator. Radiophys. Quant. Electronics. **42**(6), 500 (1999).

[70] G.S. Nusinovich et al. Wave coupling in sheet- and multiple-beam traveling-wave tubes. Phys. Plasmas. **16**, 063102 (2009).

[71] S. Meyne *et al.* Large-Signal. II. 5-D Steady-State Beam-Wave Interaction Simulation of Folded-Waveguide Traveling-Wave Tubes. IEEE Trans. Electron Devices. **63**(12), 4961 (2016).

[72] S. Bielawski et al. Suppression of the pulsed regimes appearing in free-electron lasers using feedback control of an unstable stationary state. Phys. Rev. E **69**, 045502 (2004).

[73] A.M. Dolov, S.P. Kuznetsov. Chaos-Controlling Technique for Suppressing Self-Modulation in Backward-Wave Tubes. Tech. Phys. **48**(8), 1074 (2003).

[74] K.G. Batrakov, S.N. Sytova. Modelling of Volume Free Electron Lasers. Comp. Math. Math. Physics. **45**, 666 (2005).

[75] S.N. Sytova. Comparison of One-Dimensional and Volume Distributed Feedback in Microwave Vacuum Electronic Devices. Int. J. Nonlin. Phen. Compl. Syst. **15**(4), 378-386 (2012).

[76] S.N. Sytova. Methods of chaos control in radiation of charged particles moving in non-one-dimensional periodical structures. Int. J. Nonlin. Phen. Compl. Syst. **20**(2), 144 (2017).