PACS 42.55.-f

Tsudik A.V., Glushkov A.V.

Odessa State Environmental University, L'vovskaya str.15, Odessa
E-mail: tsudikav@gmail.com

SPECTROSCOPY AND DYNAMICS OF NONLINEAR PROCESSES IN RELATIVISTIC BACKWARD-WAVE TUBE WITH ACCOUNTING FOR EFFECTS OF SPACE CHARGE, DISSIPATION AND WAVE REFLECTIONS

An effective universal, approach to solving the problems of quantitative modelling and analysis of the fundamental characteristics of spectroscopy and dynamics of the nonlinear processes in relativistic microwave electronics devices, in particular, a relativistic backward wave tube (RBWT) has been developed and implemented. It has been performed modelling, analysis, and prediction of chaotic dynamics of RBWT with simultaneous consideration of not only relativistic effects, but also the effects of dissipation, presence of space charge, wave reflections at the ends of the decelerating system, etc in a wide range of changes at different values of control parameters, which are characteristic for the distributed relativistic electron-wave self-oscillating systems. From physical viewpoint the transition to chaos in the dynamics of the studied RBWT occurs according to the scenario everywhere in the sequence of period-doubling bifurcations, but with the growth of relativism, the dynamics become fundamentally complicated with the alternation of quasi-harmonic and chaotic regimes (including the appearance of the "beak" effect on the bifurcation diagram) and the transition everywhere intermittency to the high-D attractor.

1. Introduction

At the present time, the study of regular and chaotic dynamics of nonlinear processes in various classes of devices of the so-called relativistic ultra-high-frequency electronics definitely belongs to the number of extremely relevant and extremely complex directions in the physics of elements, systems and devices of electronics. It is well known that the development of relativistic microwave electronics and an increase in the pulse power of microwave radiation by several orders of magnitude was immediately caused by the appearance of high-current electronic accelerators [1-20]. The use of intense relativistic electron beams for the generation of microwave radiation already in the first experiments conducted led to the achievement of record levels of the output power of microwave generators [1-10]. At the moment, with the help of relativistic sources, practically the entire microwave range has been mastered, and for centimetre waves the level of pulse power is over 10^{10} W, for millimetre waves - 10^9 W. The main tasks of relativistic microwave electronics naturally include, first of all, the quantitative study of energy conversion mechanisms of high-intensity electron flows accelerated to relativistic velocities into powerful coherent electromagnetic radiation and, of course, their use in various devices for further application in various fields of science and technology, including, for the purposes of nano-sec location, special radio-technical applications, accelerators with an ultra-fast rate of particle energy collection. Powerful generators of chaotic oscillations of the microwave range are also of great applied interest in the tasks of plasma heating in controlled thermonuclear fusion installations, the construction of modern information transmission systems with such new possibilities as the use of dynamic chaos and other applications [1-6]. However, their application in practice faces a number of problems, in particular, it is about the need to increase the stability and efficiency of generation, increase the energy in the microwave pulse, maintain high coherence of radiation for high values of the generation power, the possibilities of wide adjustment of the generation frequency and so on.

The need to generate electromagnetic radiation of greater power contributed to the study of relativistic RBWT, which are actually the first devices implemented in a one-time mode based on a strong current electron accelerator. The peculiarity of RBWT is that the interaction of the microwave field with the electron beam is carried out through the synchronous harmonic of the wave, which propagates towards the electron flow. In contrast to non-relativistic BWT, the study of nonlinear dynamics of complex processes, different modes of functioning in RBWT is characterized by a significantly lower level of understanding. The inconsistency between the calculated and experimental values of the RBWT parameters is caused, in particular, by the use of simplified numerical models that do not adequately describe its relativistic dynamics, by an insufficiently correct approximation of accounting for only the 1st harmonic of the space charge, and by the observed decrease in the efficiency of the generator at an increase in the current of the high-current beam caused by the increase in the forces of the volume charge, etc.

Here we present a further development of an effective approach to solving the problems of quantitative modeling, analysis and forecasting of the characteristics of spectroscopy and the dynamics of nonlinear processes in relativistic microwave electronics devices, in particular, a relativistic backward wave tube (RBWT) [18-20]. There are presented the results of modelling, analysis, of the RBWT chaotic dynamics with simultaneous consideration of as relativistic effects, as also of the effects of dissipation, presence of space charge, wave reflections at the ends of the decelerating system, etc in a wide range of control parameters, which are characteristic for the distributed relativistic electron-wave self-oscillating systems.

2. Spectroscopy and dynamics of relativistic backward wave tube: Advanced model

Let us consider the system of equations of the dynamics of RWBT, which takes into account the influence of the space charge. It should be noted right away that when deriving the master equations of non-stationary nonlinear theory, in fact within the limits of the method of slowly changing amplitudes, the assumption is usually used that with the appropriate choice of independent variables $\left(\tau \propto t - x/\upsilon_0, \zeta \propto x\right)$. The equations of motion of electrons are written in the same form as in the stationary theory of RBWT [1-4,8-12,18-20]. The same is true when taking into account the influence of the space charge field [8,11,20]. Next, using the traditional notation of the space charge parameter introduced by Peirce, namely:

$$4QC = \left(\omega_p / \left(\omega_0 C\right)\right)^2, \qquad (1)$$

(where ω_p is a plasmas frequency, ω_0 – synchronization frequency, and C is the Peirce interaction parameter), it is possible to write down the system of equations of the dynamics of RBWT taking into account the influence of the space charge, leaving the excitation equation and boundary conditions unchanged. As a result, under the assumption of a wide beam, taking into account the movement of the influence of the space charge, we have the equation of dynamics:

$$\partial^2\theta/\partial\zeta^2 = -L^2\gamma_0^3[(1+\frac{1}{2\pi N}\partial\theta/\partial\zeta)^2 - \beta_0^2]^{\frac{3}{2}} Re[F\,exp(i\theta) + \frac{4QC}{ik}\sum_{k=1}^{M} I_k\,exp(ik\theta)] \qquad (2a)$$

$$\partial F/\partial\tau - \partial F/\partial\zeta + \mathrm{dF} = -L\tilde{I}, \qquad (2б)$$

$$I_k = -\frac{1}{\pi}\int_0^{2\pi} e^{-ik\theta}d\theta_0 \qquad (2c)$$

Note that in (2) the space charge field is represented by a Fourier series in terms of the variable θ, which characterizes the electron phase relative to the high-frequency filling of the wave field, and the finite number of members of the series M is taken into account.

in a number of works (see, e.g., [18-12,18-20]. According to this analysis, the physics of the effect is as follows: while the operating current of the BWT is relatively small, the space charge field does not play a significant role. But when the current increases, due to the occurrence of regrouping in the beam and due to feedback mechanism, from a certain point in time a new automodulation mode may appear in the system. Further, with the increase of the current due to the increase of the space charge, from a physical point of view, the existing Coulomb repulsion prevents the convergence of electrons and their mutual overtaking and, accordingly, the occurrence of rearrangement, which qualitatively should lead to the suppression of automodulation in the system. That is, the influence of the desired effect can be considered as a rather interesting means of qualitatively changing the intensity of one or another mode, in particular, automodulation or even the dynamic chaos mode. At the same time, it should be remembered that only in specific numerical or experimental studies of a certain BWT, an accurate quantitative picture of the impact of the effect can be established. It should be noted that there are currently no qualitative and quantitative data on the indicated effect for RBWT. Another significant factor that can affect the dynamics of real BWT is the effect of the presence of wave reflections at the ends of the decelerating system The qualitative physics of the effect is quite obvious (see, e.g., [1-4,9-12,20]). In fact, it is well known that at the end of the system, where the energy radiated by the beam arrives, only a certain part of it is transmitted to the output path, and the other part is transformed into reflected waves that transfer energy in the opposite direction (in the direction of electron motion). Since such waves are not synchronous with the beam in terms of their phase velocity, they should probably be expected to propagate without significant interaction with the electron beam. At the same time, having reached the opposite end of the system, the sought waves will be partially absorbed, partially reflected, and part of the energy will be transformed back into a working wave, that is, an additional feedback mechanism may take place. Further, if the working and reflected waves are marked with "+" and "-" signs, i.e.:

$$E_+ = \mathrm{Re}\left[\tilde{E}_+(x,t)e^{i\omega_0 t - i\beta_0 x}\right],$$

$$E_- = \mathrm{Re}\left[\tilde{E}_-(x,t)e^{i\omega_0 t + i\beta_0 x}\right]. \tag{3}$$

then for the corresponding complex amplitudes the equations are true [14]:

$$\upsilon_{\text{гр}}^{-1}\frac{\partial \tilde{E}_+}{\partial t} - \frac{\partial \tilde{E}_+}{\partial x} = -\frac{1}{2}\beta_0^2 K_0 \tilde{I}_1 \tag{4a}$$

$$\upsilon_{\text{гр}}^{-1}\frac{\partial \tilde{E}_-}{\partial t} + \frac{\partial \tilde{E}_-}{\partial x} = 0 \tag{4b}$$

with boundary conditions at the ends of the retarding system

$$\tilde{E}_-(0,t) = R_0\tilde{E}_+(0,t),$$

$$\tilde{E}_+(l,t) = R_l\tilde{E}_-(l,t) \tag{5}$$

where R_0 and R_l – complex reflection coefficients at the left and right ends of the deceleration system.

Since, the general solution for the amplitude of the reflected wave can be written as

$$\tilde{E}_-(x,t) = f\left(x - \upsilon_{\text{гр}} t\right),$$

where f – arbitrary function, this variable can be excluded from consideration, leaving only the equations for the operating wave and the boundary condition with a delay:

$$\upsilon_{\text{гр}}^{-1}\frac{\partial \tilde{E}_+}{\partial t} - \frac{\partial \tilde{E}_+}{\partial x} = -\frac{1}{2}\beta_0^2 K_0 \tilde{I}_1,$$

$$\tilde{E}_+(l,t) = \rho e^{i\varphi}\tilde{E}_+\left(0, t - l/\upsilon_{\text{гр}}\right). \tag{6}$$

Here ρ and φ are a modulus and a phase of the product of complex reflection coefficients $R_0 R_l = \rho e^{i\varphi}$.

The master system of equations for RBWT with taking into account wave reflections at the ends of the decelerating system, can be written in the following form:

$$\frac{\partial^2 \theta}{\partial \zeta^2} = -\mathrm{Re}\left[\mathrm{F}\exp(i\theta)\right],$$

$$\partial F/\partial\tau - \partial F/\partial\zeta + \mathrm{dF} = \frac{-L}{\pi}\int_0^{2\pi} e^{-\mathrm{ik}\theta}\, d\theta_0 \quad (7a)$$

$$\theta|_{\zeta=0} = \theta_0, \quad \frac{\partial\theta}{\partial\zeta}|_{\zeta=0} = 0, \quad (7b)$$

$$F(L,t) = \rho e^{i\varphi} F(0, \tau - sL), \quad (7c)$$

where $s = (1-u)/(1+u)$ – parameter of group desynchronization, $u = v_0 / v_{\text{гр}}$ – dimensionless group velocity.

From a physical point of view, the parameter s (or u) is responsible for the frequency distance between adjacent modes that form an equidistant spectrum. It is obvious that the frequencies at which the amplitude of stimulated oscillations is maximal are the natural frequencies of the corresponding resonator. Given this condition, the equidistant spectrum will be:

$$\varphi_n = (2\pi n + \phi)/(1+s), \quad (8)$$

accordingly, the mode distribution is determined by the value $2\pi/(1+s)$.

Obviously, from the point of view of the influence on the dynamics of processes in the RBWT, it is worth expecting a quantitative influence of the presence of wave reflections at the ends of the retarding system of the BWT. But, one could guess that only in specific numerical or experimental studies of a certain RBWT there can be established a precise quantitative picture of the influence of this effect. To carry out numerical calculations with the aim of solving systems of differential equations of the type (2) and others, and further numerical modeling of the dynamics of nonlinear processes in RBWT, a set of programs is applied, which is based on the use of finite-difference schemes of the "predictor-corrector" type and the Thomson sweep method for solving the corresponding system of linear algebraic equations (e.g.[21-26]).

3. New physical results and conclusions

In this subsection, for the first time in the physics of RBWT, we will present the results of a full numerical simulation taking into account all above listed effects. As a master system, a system of differential equations with corresponding boundary conditions is taken: (2)–(7). It should be noted that in such a setting the problem turns out to be very difficult even from a numerical point of view, so below we specify all the input parameters, based, first, on the correspondence to the parameters of real devices (see [1-4,8-12]), secondly, fixing some parameters from the very beginning, keeping in mind the main goal - to investigate the nonlinear dynamics of a specific RBWT, taking into account most of the key physical effects in the chaotic regime, with the clarification and construction of the corresponding bifurcation diagrams in the "relativistic factor - bifurcation parameter" plane, proportional to the electron beam current $L = 2\pi \mathrm{CN}/\gamma_0$.

The following initial values were taken as input parameters: relativistic factor γ_0==1.5 (further on, we will increase γ_0 by 2 and 4 times), electric length of the interaction space $N = k_0 l/(2\pi)$=10, electron speed v_0=0.75s, $v_{\text{гр}}$=0.25s, dissipation parameter D=5dB, starting parameters of reflection: s=0.5, ρ=0.7, $0<\varphi<2\pi$. The choice of φ is due to the fact that the dependence on it is periodic. The influence of reflections leads to the fact that the bifurcation parameter L begins to depend on the phase φ of the reflection parameter. The obvious optimal values of the parameter (formula 8) are those for which φ_0 is close to the resonance frequencies, e.g., $\varphi_{0\sim}$-π. It is obvious that self-excitation of the system will be difficult if φ_0 is located in the center of the interval between two natural frequencies. It is not difficult to estimate the most optimal and suboptimal phase values for self-excitation, respectively, $\varphi \sim 0.48\pi$ and $\varphi \sim 1.48\pi$. In the case of sufficiently large values of the parameter ρ (namely, this case should be considered the most interesting and complex, since for weak reflections the dynamics are similar to those discussed above, and the automodulation mechanism is related to the amplitude nonlinearity of the distributed system), the corresponding automodulation limit will obviously have a complex shape.

In the region $0<\varphi<\pi$ modes with indices n= -1,-2,-3 will be excited. As a result of the strong interaction, the second mode is suppressed, which leads to a two-frequency generation in the stationary mode. In the region $\pi<\varphi<2\pi$ self-modulation occurs for L values smaller than in the previous case. At the same time, the presence of dissipation will increase the corresponding L values.

Fig.1 shows the numerical data for the normalized field amplitude

$$F(\zeta,\tau) = \tilde{E} / \left(2\beta_0 U C^2\right)$$

with the input parameters specified above. The corresponding theoretical results of test modeling of non-stationary processes in RBWT at the values of the bifurcation parameter L: (a) – 2.7, (b) – 3.5, (c) – 4.0.

It should be noted that, in contrast to the dynamics of RBWT, considered in the previous subsection, in the implemented model, all the considered effects have a significant impact. First, taking into account the effect of space charge leads to a certain suppression of automodulation, taking into account dissipation leads to an increase in the bifurcation parameter L, at which automodulation is realized.

The effect of strong reflection leads to a complex picture in the output spectrum of the system. From the beginning, there is a single-frequency generation corresponding to the first mode, but as L increases, this mode is suppressed by the second mode (n=-2).

At L=2.7 (see Fig. 1a), modes with n=-2, -4 have the largest amplitudes. With further growth of the bifurcation parameter L above 3, both even and odd modes are excited (n=0, -1, -2, -3, -4); in fact, the automodulation mode is implemented, while two maxima of the field amplitude, spreading from the collector end to the gun end, are formed periodically along the length of the system, which is the reason for the doubling of the automodulation period.

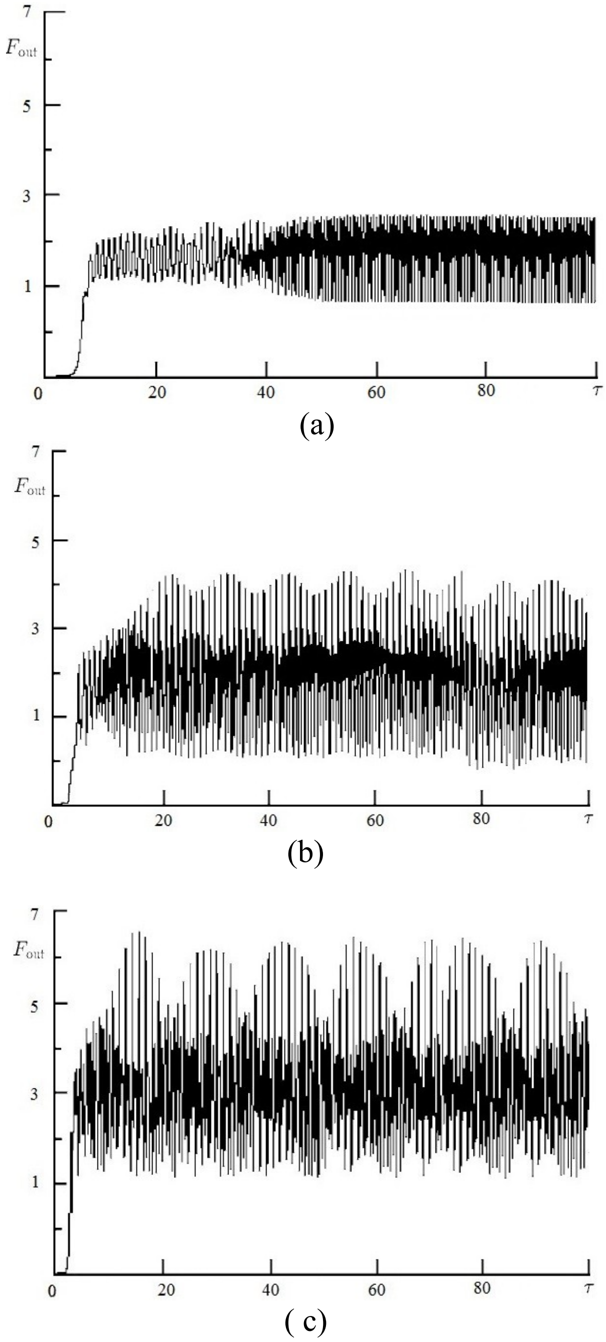

Figure 1. - Numerical data on the time dependence of normalized field amplitude $F(\zeta,\tau) = \tilde{E} / \left(2\beta_0 U C^2\right)$ (our data with accounting for dissipation, a space charge, wave reflections) for bifurcation parameter (a) 2.7; (b)3.5; (c)4.0; (other parameters: γ_0=1.5, $N=$¿10, s=0.5, ρ=0.7, φ=1.3π).

In fig. 2 shows the calculated spectrum of the output signal for the value of the parameter L=3.9-4 (other parameters of the system are as follows: γ_0=1.5, $N=$¿10, s=0.5, ρ=0.7, φ =1.3π).

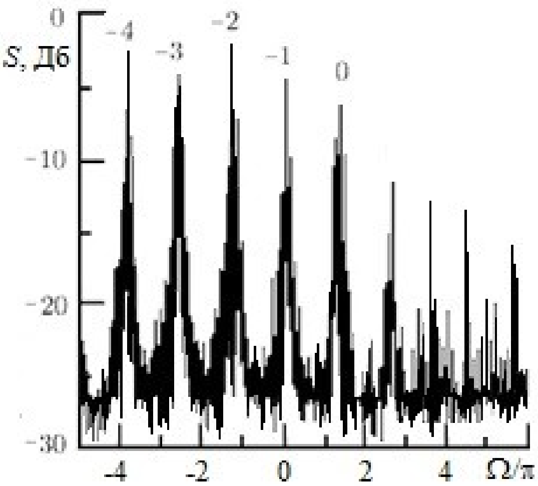

Figure 2 – Theoretical spectrum of the output signal for the value of the parameter L=3.9-4 (other parameters of the system are as follows: γ_0=1.5, $N=$¿10, s=0.5, ρ=0.7, φ=1.3π).

With a further increase in L, the quasi-periodic self-modulation mode is established again (Fig. 1b; period 13.8 ns) and, finally, a significantly chaotic mode appears (Fig. 1c). It is important that the results obtained by us are very well correlated with the results of [8,11], where the dynamics of the BWT is studied with taking into account the effect of reflections, but without taking into account the effect of dissipation and the influence of the space charge field, etc. It is of a great importance to underline that from physical viewpoint the transition to chaos in the dynamics of the studied RBWT occurs according to the scenario everywhere in the sequence of period-doubling bifurcations, but with the growth of relativism, the dynamics become fundamentally complicated with the alternation of quasi-harmonic and chaotic regimes (including the appearance of the "beak" effect on the bifurcation diagram) and the transition everywhere intermittency to the high-D attractor [15,16,18].

References

1. Ginzburg, N.S.; Zaitsev, N.A.; Ilyakov, E.; Kulagin, V.I.; Novozhilov, Yu. Rosenthal P., Sergeev V., Chaotic generation in backward wave tube of the megawatt power level. *Journ. of Techn.Phys*. **2001,** *71,* 73-80.
2. Ginsburg, H. S.; Kuznetsov, S.P.; Fedoseyev, T.N. Theory of transients in relativistic BWO. *Izv. Vuzov. Ser. Radiophys*. **1978,** *21,* 1037-1052.
3. Glushkov, A.V. *Atom in an electromagnetic field*. KNT: Kiev, **2005**.
4. Levush B., Antonsen T.,Bromborsky A., Lou W., Relativistic backward wave oscillator: theory and experiment/ *Phys.Fluid*. **1992**, B4(7), 2293-2299.
5. Levush B., Antonsen T.M., Bromborsky A., Lou W.R., Carmel Y., Theory of relativistic backward wave oscillator with end reflections. *IEEE Transactions on Plasma Sci.* **1992**, 20(3), 263-280.
6. Glushkov, A.V. *Relativistic Quantum theory. Quantum mechanics of atomic systems*. Astroprint: Odessa, **2008**.
7. Glushkov A., Prepelitsa G., Svinarenko A., Zaichko P., Studying interaction dynamics of the non-linear vibrational systems within non-linear prediction method (application to quantum autogenerators) *In: Dynamical Systems Theory;* Awrejcewicz J. et al; Łódz, **2013**; Vol T1, pp 467-477.
8. Ryskin N.M., Titov V.N., Self-modulation and chaotic regimes of generation in a relativistic backward-wave oscillator with end reflections. *Radiophysics and Quantum Electronics.* **2001**, 44, 793-806.
9. Ryskin N.M., Titov V.N., The transition to the development of chaos in a chain of two unidirectionally-coupled backward-wave tubes. *Journ.Techn.Phys*. **2003**. 73, 90-94.
10. Kuznetsov A.P., Kuznetsov S.P., Ryskin N.M., Isaeva O.B., *Non-linearity: From oscillations to chaos*.-Moscow: NIS RHD.-2006.
11. Kuznetsov A.P., Shirokov A.P., Discretre model of relativistic backward-wave tube. *Russian J.of Phys. Ser.PND*. **1997**. 5, 76-83.

12. Kuznetsov S.P., Trubetskov D.I., Chaos and hyperchaos in backward-wave tube. *Russian Journ.of Phys. Ser.Radiophys*.- **2004**, XLVII(5), 1-8
13. Chernyakova, Y.G., Ignatenko A.V., Vitavetskaya L.A. Sensing the tokamak plasma parameters by means high resolution x-ray theoretical spectroscopy method: new scheme. *Sensor Electr. and Microsyst. Techn*. **2004**, *1*, 20-24
14. Ignatenko A., Svinarenko A., Prepelitsa G., Perelygina T., Optical bi-stability effect for multi-photon absorption in atomic ensembles in a strong laser field. *Photoelectronics*. **2009**, *18*, 103-105.
15. Grassberger, P. ; Procaccia, I. Measuring the strangeness of strange attractors. *Physica D*. **1983**, *9*, 189-208.
16. Khetselius, O., Forecasting evolutionary dynamics of chaotic systems using advanced non-linear prediction method *In Dynamical Systems Applications;* Awrejcewicz, J., Kazmierczak M., Olejnik, P., Mrozowski, J., Eds.; Łódz, **2013**; Vol T2, pp 145-152.
17. Khetselius, O.Yu. *Quantum structure of electroweak interaction in heavy finite Fermi-systems.* Astroprint: Odessa, **2011**.
18. Glushkov, A.V. Tsudik, D.A. Novak, O.B. Dubrovsky, Chaotic dynamics of relativistic backward-wave tube with accounting for space charge field and dissipation effects: New effects. *Photoelectronics.* **2018.** 27, 44-51.
19. Tsudik A.V., Glushkov A.V., Ternovsky V., Zaichko P., Advanced computing topological and dynamical invariants of relativistic backward-wave tube time series in chaotic and hyperchaotic regimes *Photoelectronics.* **2020.** Vol.29. P.110-117.
20. Glushkov A.V., Tsudik A.V., Ternovsky V.B., etal, Deterministic Chaos, Bifurcations and Strange Attractors in Nonlinear Dynamics of Relativistic Backward-Wave Tube. *Springer Proc. in Mathematics & Statistics*. **2021**, 363, 125-135.
21. Ivanova, E.P., Ivanov, L.N., Glushkov, A., Kramida, A. High order corrections in the relativistic perturbation theory with the model zeroth approximation, Mg-Like and Ne-Like Ions. *Phys. Scripta* **1985**, *32,* 513-522.
22. Khetselius, O.Yu. *Hyperfine structure of atomic spectra*. Astroprint: Odessa, **2008**
23. Glushkov, A.V., Ivanov, L.N. Radiation decay of atomic states: atomic residue polarization and gauge noninvariant contributions. *Phys. Lett. A* **1992,** *170,* 33-36.
24. Ivanova, E., Glushkov, A. Theoretical investigation of spectra of multicharged ions of F-like and Ne-like isoelectronic sequences. J. Quant. Spectr. and Rad. Tr. **1986**, *36*(2), 127-145.
25. Khetselius, O. Relativistic perturbation theory calculation of the hyperfine structure parameters for some heavy-element isotopes. *Int. J. Quant.Chem.* **2009,** *109,* 3330-3335.
26. Svinarenko, A.A., Mischenko, E.V., Loboda A.V., Dubrovskaya Yu.V., Quantum measure of frequency and sensing the collisional shift of the ytterbium hyperfine lines in medium of helium gas. *Sensor Electr. and Microsyst. Techn*. **2009**, N1, 25-29.

PACS 42.55.-f

Tsudik A.V., Glushkov A.V.

SPECTROSCOPY AND DYNAMICS OF NONLINEAR PROCESSES IN RELATIVISTIC BACKWARD-WAVE TUBE WITH ACCOUNTING FOR EFFECTS OF SPACE CHARGE, DISSIPATION AND WAVE REFLECTIONS

Summary. An effective universal, approach to solving the problems of quantitative modeling, analysis and forecasting of the characteristics of spectroscopy and the dynamics of nonlinear processes in relativistic microwave electronics devices, in particular, a relativistic backward wave tube (RBWT) has been developed and implemented. It has been performed modelling, analysis, and prediction of chaotic dynamics of RBWT with simultaneous consideration of not only relativistic effects, but also the effects of dissipation, presence of space charge, wave reflections at the ends of the decelerating system, etc in a wide range of changes at different values of control parameters, which are characteristic for the distributed relativistic electron-wave self-oscillating systems. From physical viewpoint the transition to chaos in the dynamics of the studied RBWT occurs according to the scenario everywhere in the sequence of period-doubling bifurcations, but with the growth of relativism, the dynamics become fundamentally complicated with the alternation of quasi-harmonic and chaotic regimes (including the appearance of the "beak" effect on the bifurcation diagram) and the transition everywhere intermittency to the high-D attractor.

Key words: relativistic theory, backward-wave tube, spectroscopy, chaotic dynamics

PACS 42.55.-f

Цудік А.В., Глушков О.В.

СПЕКТРОСКОПІЯ ТА ДИНАМІКА НЕЛІНІЙНИХ ПРОЦЕСІВ В РЕЛЯТИВІСТСЬКІЙ ЛАМПІ ЗВОРОТНОЇ ХВИЛІ З УРАХУВАННЯМ ЕФЕКТІВ ПРОСТОРОВОГО ЗАРЯДУ, ДИСИПАЦІЇ ТА ВІДБИТТЯ ХВИЛІ

Резюме. Розроблено новий ефективний універсальний підхід до вирішення задач кількісного моделювання, аналізу та прогнозування характеристик спектроскопії та динаміки нелінійних процесів у пристроях релятивістської мікрохвильової електроніки, зокрема? релятивістської лампи зворотного хвилі (РЛЗХ). Виконано моделювання та фізичний аналіз хаотичної динаміки РЛЗХ з одночасним врахуванням як релятивістських ефектів, так й ефектів дисипації, наявності просторового заряду, відбиття хвиль на кінцях системи, що сповільнюється, тощо, в при різних значеннях керуючих параметрів, характерних для розподілених релятивістських електронно-хвильових автоколивальних систем. З фізичної точки зору перехід до хаосу у динаміці досліджуваної РЛЗХ відбувається за сценарієм через послідовність біфуркацій подвоєння періоду, але з ростом релятивізму динаміка принципово ускладнюється і зводиться до чередування квазігармонійних та хаотичних режимів (включаючи появу нового феноменального ефекту «дзьоба» на відповідній біфуркаційній діаграмі) і в кінцевому результаті переходу через переривчастість до високорозмірного атрактору.

Ключові слова: релятивістська теорія, лампа зворотної хвилі, спектроскопія, хаотична динаміка

This article has been received in October 26, 2021