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SIMULATION OF HIGH-POWER KLYSTRONS WITH HETEROGENEOUS FOCUSING MAGNETIC FIELD

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Abstract. The work shows a significant effect of the focusing magnetic field on the output characteristics of the klystron. When the calculations are done using nonlinear one-dimensional models, optimization of the parameters makes it possible to obtain versions of devices with the efficiency of 0.8 – 0.9 and higher. However, when testing these options using nonlinear two-dimensional models that take into account the radial motion of electrons, there is a significant discrepancy in the output characteristics obtained from the one-dimensional and two-dimensional models. This is due to the fact that during the motion of the electron beam, the radii of the leading centers of the large particles change the coefficients of interaction of the particle fields with the electromagnetic fields of the resonators change, which leads to a change in the output characteristics of the klystrons: efficiency, output power, and gain. On the other hand, it seemed that setting a large focusing magnetic field to exclude the radial motion of particles could eliminate this drawback, however, another problem arises here - the magnetic system for focusing becomes unacceptably large and it is technically difficult to obtain magnetic induction values of more than 2 T (the weight of the magnetic system can be several hundred kilograms). Therefore, one should choose the magnetic field induction for focusing the electron beam no more than 1T. In this paper, a two-dimensional nonlinear mathematical model (2.5D) is proposed that takes into account the azimuthal component in the equations of motion. In the model, the induction of the focusing magnetic field is set in the form of tables. This makes it possible to set the inhomogeneity of the magnetic field at any place in the interaction space of the klystron. The calculation of a powerful relativistic klystron with an accelerating voltage of 1000 kV and the beam current of 250 A was carried out. The use of an inhomogeneous magnetic field makes it possible to reduce the deposition of electrons in the region of the gaps. Therefore, a decrease in the electron deposition leads to an increase in the durability of klystrons.

Keywords: klystron, relativistic, O-type amplifier, resonator, optimization, magnetic field, focusing, induction, two-dimensional.

Conflict of interests. The authors declare no conflict of interests.

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Introduction

The klystron is the first microwave device that uses the conversion of the velocity modulation of the electron beam into density modulation, followed by the extraction of energy from grouped electron bunches. In the klystron, the following main nodes can be distinguished. The cathode node serves to emit electrons into the interaction space. Under the influence of the accelerating voltage, an electron beam is created on which a longitudinal constant magnetic field is applied, which is necessary for focusing the electron beam. To create a magnetic field, the permanent magnets or solenoids are used.

Next, the electron flow enters the grouper, which consists of one or more resonators. In the grouper, the electron flow, interacting with the fields in the gaps of the resonators, is modulated in terms of velocity and density. The result is – dense bunches of electrons are formed in the electron flow. Next, the electron flow enters the energy selector, which may consist of one or more resonators. In the energy selector, the electron bunches are slowed down and the kinetic energy of the bunches is converted into the energy of the electromagnetic field of the selector resonators and removed from the resonator to be used in various devices. After passing through the selector, not all electrons are slowed down, in other words they gave up their energy, therefore, an integral part of the klystrons is a collector, on which the remaining electrons settle. Their kinetic energy on the collector is dispersed in the form of heat.

Currently, due to the wide use of klystrons in various fields: in radio engineering systems, in power transmission systems using microwave electromagnetic waves, in space communications, radar, radio navigation, it is constantly required to improve such parameters as efficiency, gain, output power, frequency bands, durability of devices, and other parameters. With this in mind, the work on improving the characteristics of klystrons is constant.

In previous works [1], in the two-dimensional model of the klystron, the induction of the focusing magnetic field was set to be the same over the entire region of electron flight. To create a focusing magnetic field, both permanent magnets [3–8] and solenoids [4–8] are used.

When optimizing the parameters in the optimal versions of the devices, significant electron deposition in the region of the exit gaps was often observed. The settling of electrons on the walls of the gaps of the resonators at high powers of the electron beam leads to the scorching of the walls of the gaps and to the failure of the device. This led to the need of developping a program that allows to change the magnetic field in the region of interest in order to reduce electron deposition.

Main Part

The previously developed two-dimensional mathematical model [1] is supplemented by taking into account the azimuthal component in the equations of motion. The azimuthal component is determined using the conservation law for azimuthally symmetric fields (in the adiabatic approximation) [2]: $m_1 r_0^2 \dot{\varphi}_0 - \frac{e r_0^2}{2} B_0(z_0) = m\, r^2 \dot{\varphi} \; - \frac{e r^2}{2} B_0(z\;)$.

Let's rewrite this equation in the following form: $\frac{m_0}{f_0} r_0^2 (\dot{\varphi}_0 - \Omega_0 / 2) = \frac{m_0}{f_1} r^2 (\dot{\varphi} \; - \Omega \; / 2)$.

From this equation we can determine: $\dot{\varphi} = M^0 / r^2 + \Omega / 2$,

where $\Omega_0 = \frac{e}{m} B_0(z_0)$; $\Omega = \frac{e}{m} B_0(z)$; $m = m_0 / f_1$; $f_0 = \sqrt{1 - (\frac{v_0}{c})^2}$; $f_1 = \sqrt{1 - (\frac{v}{c})^2}$; $B_0(z)$ – distribution of the magnetic field on the axis; $M^0 = M \cdot f_1 / f_0$; $M = r_0^2 (\dot{\varphi}_0 - \Omega_0 / 2)$; $r_0, \dot{\varphi}_0, \text{v}_0, \Omega_0$ – values of the corresponding parameters in the input section.

Based on the developed model, a program was compiled and calculations were made for a powerful relativistic ten-resonator klystron with an accelerating voltage of 1000 kV and an electron beam current of 250 A. The number of the electron stream layers is 3, the number of electrons in the layer is 32. The klystron has 7 resonators in the grouper and a distributed selector on 3 autonomous resonators. To speed up calculations in the mathematical model, the grouper is calculated according to the numerical-analytical method described in [1]. By means of this technique, in this version of the klystron, the first six cascades of the buncher were calculated. The remaining cascades of the klystron were calculated using a two-dimensional nonlinear model. The optimization of voltages and phases at the gaps of the resonators to the maximum efficiency was carried out, therefore the calculation was carried out with the matching of the fields in the gaps of the resonators.

First, a variant was calculated for the constant focusing magnetic field with the induction B = 0.5 T along the entire length of the klystron. The number of settled electrons – 4, all electrons are from the first layer. Electron efficiency equals = 0.81, the total efficiency for the resonators is 0.79, the current transmission coefficient is 0.958. the power of the settled electrons is 0.008. Fig. 1 shows graphs of changes in the radial coordinates of particles for three layers. From fig. 1 one can see that most of the electrons settled in the area of the last gap.

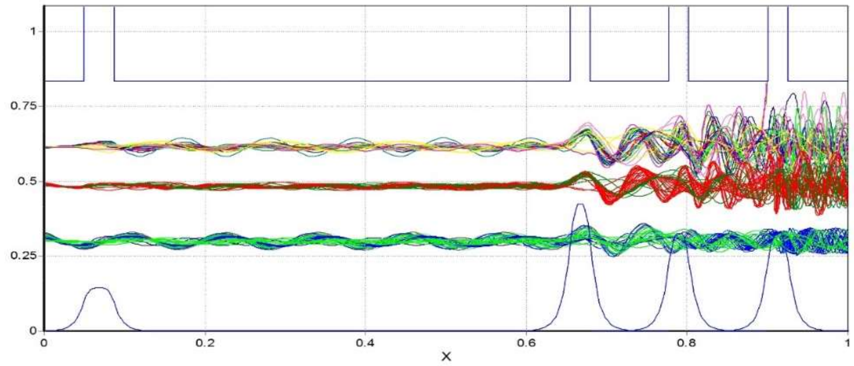

Fig. 1. Graphs of changes in the radial coordinates of particles from the longitudinal coordinate *X* for three layers. Magnetic field induction B = 0.5 T.

At the lower magnetic field B = 0.4 (T) of settled electrons – 8, all electrons from the first layer. Electronic efficiency = 0.783, the total efficiency for the resonators is 0.776, the current transmission coefficient is 0.916. the power of the settled electrons is 0.023. Figure 2 shows the graphs of changes in the radial coordinates of particles for three layers. Fig. 2 shows that most of the electrons settled in the area of the last gap.

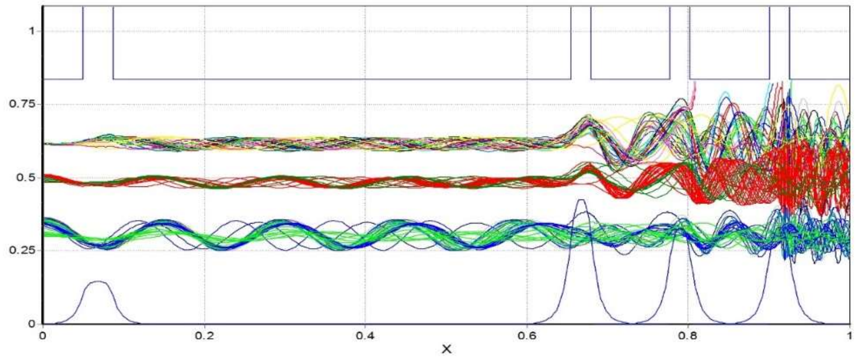

Fig. 2. Graphs of changes in the radial coordinates of particles from the longitudinal coordinate *X* for three layers. Magnetic field induction B = 0.4 T.

At the magnetic field B = 0.2 (T) of settled electrons – 50, that corresponds to the layers: 26, 13, 12. Electronic efficiency = 0.685, the total efficiency for the resonators is 0.698, the current transmission coefficient is 0.479, and the power of the settled electrons is 0.204. Fig. 3 shows the graphs of changes in the radial coordinates of particles for three layers. One can see that most of the electrons settle in the region of the eighth and tenth gaps.

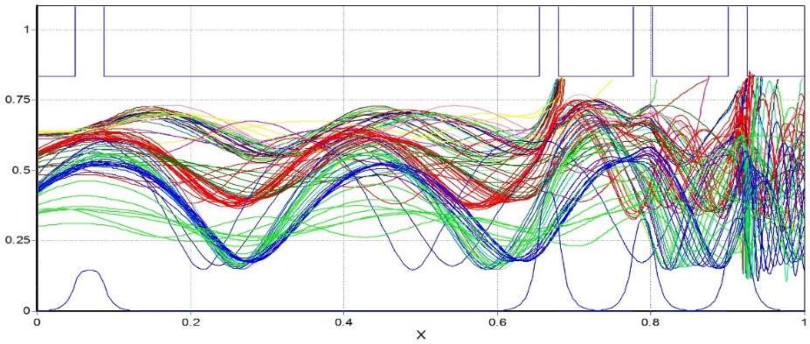

Fig. 3. Graphs of changes in the radial coordinates of particles from the longitudinal coordinate *X* for three layers. Magnetic field induction B = 0.2 T.

For further calculations, the option with the induction of an inhomogeneous focusing magnetic field at the beginning of the interaction region B = 0.5 T was chosen.

The induction of an inhomogeneous focusing magnetic field at the distance (Fig. 4) $X = 0$ (the beginning of the interaction region) to $X = 1$ (the end of the interaction region – the electrons left the last gap) changed linearly from B = 0.5 T to B = 0.8 T.

Fig. 4 shows the dependences of the transverse coordinates *Y* of the centers of motion of large particles on the longitudinal coordinate *X* for three layers for an inhomogeneous magnetic field. There are no settled electrons.

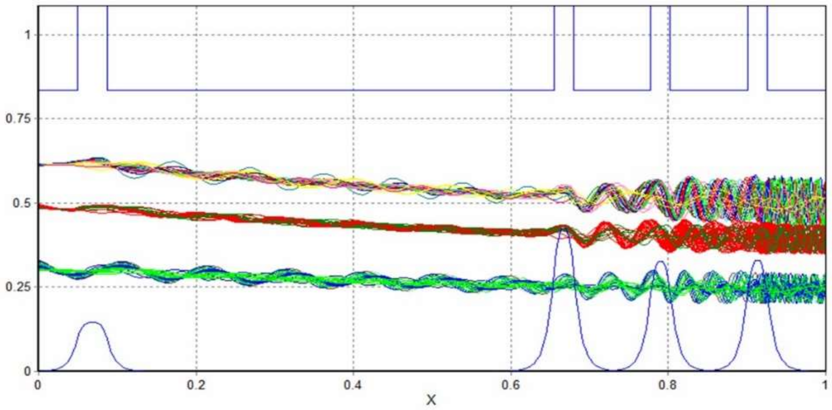

Fig. 4. Dependences of the transverse coordinates *Y* of the centers of motion of large particles on the longitudinal coordinate *X* for three layers for an inhomogeneous magnetic field.

As a result of optimization, the electronic efficiency of 0.797 was obtained, the output power was 196 MW. There are no settled electrons. The total efficiency for the resonators is 0.785, the current transmission coefficient is 1, the power of the settled electrons is 0.

Conclusion

A two-dimensional nonlinear model (2,5D) was proposed in order to calculate the interaction processes in klystrons, taking into account the inhomogeneous focusing magnetic field. It was noted that the electron deposition on the walls of the resonator gaps at high powers of the electron beam leads to the scorching of the walls of the gaps that in turn results in the failure of the device. The usage of the developed model allows to eliminate electron deposition in the output gaps, that leads to an increase in the durability of powerful klystrons.

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Authors' contribution

Aksenchyk A.V. carried out the formulation of the problem for the study, prepared the manuscript of the article.

Kirynovich I.F. зerformed calculations of variants of klystrons for different induction of the focusing magnetic field and plotting.

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