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THE PHYSICO-TOPOLOGICAL SIMULATION OF A TRANSMISSION X-RAY TUBE WITH INDUCTION HEATING OF THE CATHODE

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Physico-topological simulation of a transmission X-ray tube (TRT) with inductionally heated thermionic cathode is presented, taking into account physical properties of functional elements and their design. Modeling is based on physical fundamentals for vacuum electronics and electrodynamics using ComSol. The distributions of electromagnetic fields, currents, temperature, and trajectories of thermoelectrons were calculated. The analysis of electron trajectories made it possible to optimize TRT topology and design.

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INTRODUCTION

X-ray apparatus are widely used: in medicine; when analyzing the structure of crystals, meta- and nanomaterials; for non-destructive control of industrial products; to ensure security, etc. The key device of such apparatus is a X-ray tube (RT), most often with radiation through a target, that is, a transmission X-ray tube (TRT), in which the energy of the flow of accelerated electrons is converted into X-ray radiation [1]. When developing new RT to solve new practical problems, it is expedient to use effective methods of physical and topological modeling, which is a key stage of the automated design of electronic devices with parameter calculation and design optimization [2]. Modern computer simulation technologies make it possible to optimize the design of an electronic device of any complexity with a detailed hierarchical analysis of physical processes in the device and the surrounding environment.

A detailed analysis of the accompanying physical processes in the device, taking into account the influence of design parameters on them, can be performed using physico-topological models (PTM), which are structured physico-mathematical models. The purpose of the article is to study such model for TRT of an improved design, namely, with induction non-contact power supply of the heater of the thermionic cathode source of free electrons.

1. PROBLEM OF NON-CONTACT HEATING OF THERMIONIC CATHODE AND ITS SOLUTIONS

In the case of using RT with a thermionic cathode in an apparatus with a grounded anode, it is necessary to use a cathode heating system with high-voltage isolation of the heater outputs and the windings of the incandescent transformer, which complicates the construction of the X-ray apparatus. The use of induction non-contact heating of the thermionic cathode simplifies the high-voltage part of the equipment. In the TRT described in [3], to solve this problem, the thermionic cathode is performed as part of the secondary winding of the incandescent transformer, while the secondary winding in the form of several turns of wire is placed inside the TRT, and the primary winding is outside the TRT. The disadvantage of such a design is its complexity, low mechanical stability of the cathode unit and reduced service life of the wire thermionic cathode.

This paper presents a TRT model, in which a relatively simple in design, stable on shape and reliable cathode heater is used in the form of a rod element that receives energy from an external inductor, and a toroidal magnetic field concentrator is introduced inside the tube to optimize the transfer of power from the inductor to the heater. The concentrator is simultaneously used to focus the flow of thermoelectrons flying to the anode.

2. CONSTRUCTION OF THE SIMULATED TRT WITH INDUCTIONALLY HEATED THERMIONIC CATHODE

The investigated TRT [4] contains envelope 1 made of ceramics (Al_2O_3), copper anode 2 and cathode 3 contacts, dish-shaped thermionic cathode 4, copper anode 5 with target 6 and output window 7, copper toroidal magnetic field concentrator 9, which all are located coaxially (Fig. 1). Thermionic cathode 4 is coated with an electron emission coating (in the model, the operating temperature of the thermal emitter is 500°C). Target 6 is attached from the inside to the exit window 7. X-ray radiation, coming out through it, is generated when the target is bombarded with thermoelectrons from the cathode, which are accelerated by the anode voltage.

Around the concentrator of the magnetic field 9, but outside the envelop 1, there is a copper inductor 8, which is powered by an AC or RF generator. The concentrator 9 is made in the form of a hollow toroid with radial section 11. A molybdenum rod heater 10 is placed inside the concentrator, on the end of which the dish-shaped thermionic cathode 4 is fixed. The side surface of the heater 10 is equipped with thermal insulation in the form of a ceramic tube (Al_2O_3).

Inductor 8 and concentrator 9 work as a coreless AC/RF transformer with two internal secondary single-turn windings: the first single-turn winding is the outer surface 13, and the second single-turn winding is the inner surface 14 of the concentrator 9. The surface of the radial section 11 of the concentrator 9 electrically connects its outer surface 13 with the inner surface 14 to close the current induced by the inductor on the outer surface. The operating frequency of the generator, powering the inductor, is selected in the range of 22...880 kHz.

The cathode contact 3 is electrically connected to the concentrator 9 and the rod heater 10. For mechanical fixing of the concentrator 9 on the cathode contact 3 and cooling, a dielectric spacer 12 made of heat-conducting BeO ceramics is used. To capture secondary electrons from the anode, it is supplemented with a tubular element 15, the open part of which faces the thermionic cathode 4. TRT is a vacuum device, hence it has a shtengel 16 for pumping out.

Focusing of the flow of thermoelectrons to direct most of them to the target is carried out by the side protrusions on the dish-shaped thermionic cathode and the inner surface of the concentrator 9, which is located above the level of the thermionic cathode. The effect of thermoelectron focusing is investigated in the work (see section 4).

3. PHYSICO-TOPOLOGICAL MODEL OF TRT

The structure of the general FTM of the transmission TRT is shown in Fig. 2 [5]. The FTM consists of several partial FTM and takes into account the hierarchy of partial processes in the TRT, as well as the influence of the parameters of the TRT elements on these processes. The initial conditions of each partial physico-mathematical model, which describes a partial process, depend on the result of the calculation of the characteristics of the previous partial physico-mathematical model. And the result of the final process in the hierarchy is used to find out the vector of changes in the initial conditions of the initial process, if the result does not satisfy the given. FTM takes into account [6]:

– TRT parameters: geometric dimensions and physical properties of elements;

– sequence of calculation of partial physico-mathematical models;

– transferring the calculation result of the previous process to the initial conditions of the next process;

– criteria for evaluating the result of calculations.

Table 1

Some boundary and initial conditions

Physico-mathematical model	Initial conditions	Boundary conditions
Electromagnetics	Potentials on the surface, currents through them	Potentials at the frontier of research
Thermal conductivity	Distribution of current sources, properties of materials	Temperature of surfaces, heat flows through surfaces
Emission	Emissive properties of materials, temperature distribution	The task is not limited by borders
Trajectories of electrons	Distribution of the magnetic and electric fields	Electron absorption and reflection at the anode

With regard to processes in TRT, this is electromagnetic induction in the elements and electric currents that heat them. The temperature of the cathode, the thermal emission current, the energy of electrons on the anode and the intensity of the X-ray beam are determined. Physical processes, boundary and initial conditions for them for TRT are given in Table 1.

The boundary determines the area of field research or the surface of device element. All three well-known types of boundary conditions are used when investigating processes in devices with induction by magnetic field of the inductor [7].

3.1. SIMULATION OF ELECTROMAGNETIC FIELDS AND INDUCED CURRENTS

According to the general FTM, the first partial model is a combined model of the electromagnetic field and currents: the alternating current of the inductor generates a surrounding alternating magnetic field; the largest eddy current is induced in the ring concentrator, eddy currents induced in this ring element create their own magnetic field, which is opposite to the direction of the magnetic field of the inductor [8]. The common magnetic field is their superposition. The induction of the magnetic field depends on the inductor current, the geometry of the inductor and the distance from the inductor to the current-carrying elements. The purpose of the study is to determine the distribution of currents in the ring concentrator and the rod heater, which create heat sources according to the Joule-Lenz law.

Maxwell's equations are used to calculate variable electromagnetic fields [9]:

$$\nabla\times\vec{\mathbf{H}}=\vec{\mathbf{J}}+\frac{\partial\vec{\mathbf{D}}}{\partial \mathrm{t}}\,; \qquad (1)$$

$$\nabla\times\vec{\mathbf{E}}=-\frac{\partial\vec{\mathbf{B}}}{\partial \mathrm{t}}\,; \qquad (2)$$

$$\nabla\times\vec{\mathbf{B}}=0\,; \qquad (3)$$

$$\nabla\cdot\mathbf{D}=\rho\,, \qquad (4)$$

where $\vec{\mathbf{E}}$ is the electric field strength, $\vec{\mathbf{D}}$ is the electric flux density, $\vec{\mathbf{H}}$ is the magnetic field strength, $\vec{\mathbf{B}}$ is the magnetic field induction, $\vec{\mathbf{J}}$ is the conduction current density, and ρ is the electric charge density.

Considering the relationship between the magnitudes of the fields [10], equation (1) can be written using conventional notation as

$$\nabla\times\mathbf{H}=\sigma\mathbf{E}+\frac{\partial(\varepsilon\varepsilon_0\mathbf{E})}{\partial \mathrm{t}}\,. \qquad (5)$$

The density of the induced conduction current $\vec{\mathbf{J}}$ at `frequencies below 10 MHz is much greater than the displacement current, so the last term on the right-hand side of equation (5) can be neglected:

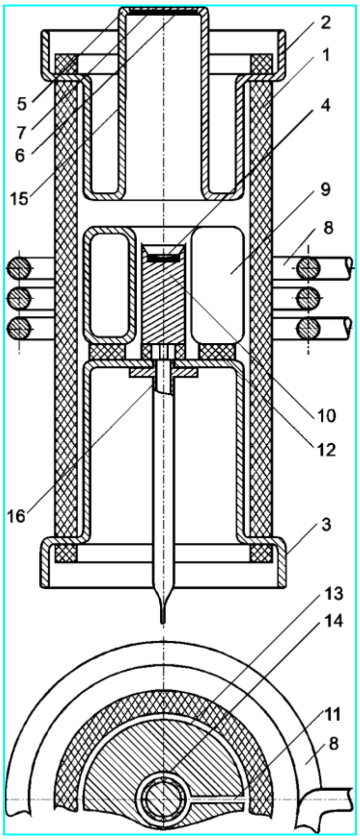
$$\nabla\times\mathbf{H}=\sigma\mathbf{E}\,. \qquad (6)$$

Using vector algebra in equations (1), (2), and (6), it can be shown (again using conventional notation) that:

$$\nabla\times\left(\frac{1}{\sigma}\nabla\times\mathbf{H}\right)=-\mu_{\mathrm{r}}\mu_0\frac{\partial\mathbf{H}}{\partial \mathrm{t}}\,. \qquad (7)$$

Since the induction of the magnetic field B satisfies the condition of zero divergence according to equation (3), it can be expressed in terms of the vector magnetic potential A as:

$$\mathbf{B}=\nabla\times\mathbf{A}\,. \qquad (8)$$



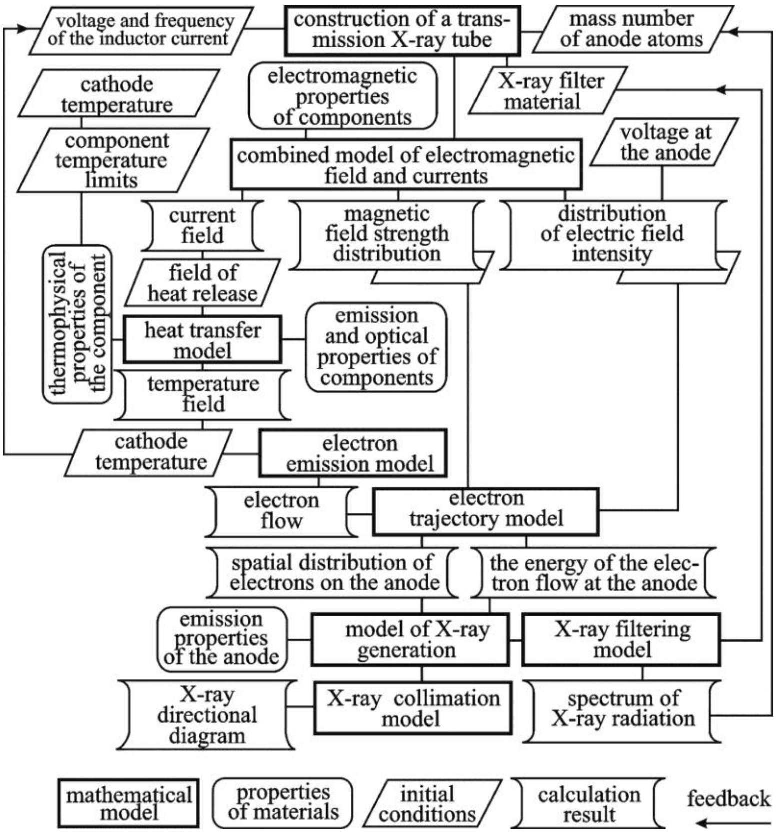


Fig. 1. Construction of TRT and its cross-section (left)
Fig. 2. Physico-topological model of X-ray tube (right)

And then it follows from equations (2) and (8) that:

$$\nabla \times \mathbf{E} = -\nabla \times \frac{\partial \mathbf{A}}{\partial t}. \tag{9}$$

After integration, we get:

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla \phi, \tag{10}$$

where φ is the electric scalar potential and equation (7) is written as:

$$\mathbf{J} = -\sigma \frac{\partial \mathbf{A}}{\partial t} + \mathbf{J}_s, \tag{11}$$

where $\mathbf{J}_s$ is the source current density in the inductor.

Considering the properties of the material as piecewise continuous, neglecting hysteresis and magnetic saturation (vacuum), we obtain equations for calculations [11]:

$$\frac{1}{\mu_r \mu_0}(\nabla \times \nabla \times \mathbf{A}) = \mathbf{J}_s - \sigma \frac{\partial \mathbf{A}}{\partial t}. \tag{12}$$

The condition of non-discontinuity of the normal component of the electric field intensity at the boundary of the media was used as the limiting condition

$$\mathbf{n}_2 \times (\mathbf{E}_1 - \mathbf{E}_2) = \mathbf{0},$$

and the balance of the normal component of the magnetic field strength

$$\mathbf{n}_2 \times (\mathbf{H}_1 - \mathbf{H}_2) = \mathbf{J}_s,$$

where $\mathbf{n}_2$ is the normal to the surface from the side of the vacuum, $\mathbf{E}_1$, $\mathbf{E}_2$, and $\mathbf{H}_1$, $\mathbf{H}_2$ are the intensities of the electric and magnetic fields in the element of the ring element and in the vacuum at their boundary, respectively.

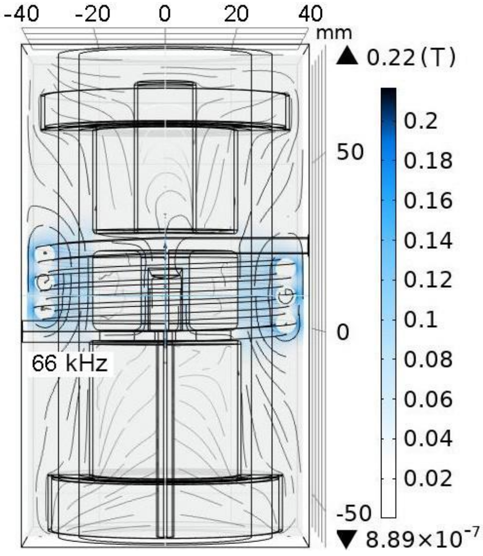


Fig. 3. Induction of the magnetic field in the TRT space

The skin effect was taken into account in the calculations.

Figs. 3 and 4 show examples of calculating the magnetic induction in the space of the TRT and the currents in its elements at the frequency of 66 kHz.

Hereinafter, the calculations in this work were carried out using the COMSOL.

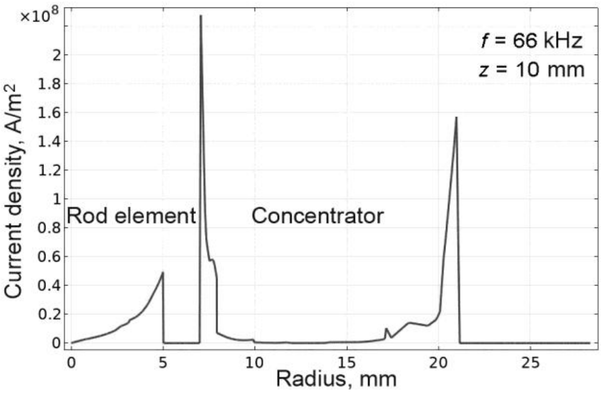


Fig. 4. The currents in the TRT elements are shown below the cathode surface at z = 10 mm

3.2. HEAT MODEL OF TRT

The goal of the simulation was to find the input current of the inductor at the given frequency, which would ensure a temperature of 773 K in the middle of the thermionic cathode surface.

To determine the temperature of the cathode, it is necessary to determine the temperature field in the rod heater and the thermal regime at the boundaries. The problem is to solve the heat conduction equation in an isotropic body that satisfies the initial condition (13) and the boundary condition (14) or (15) [12].

The initial conditions determine the distribution of heat sources:

$$Q\,|_{t=0} = \varphi\,(x, y, z). \tag{13}$$

Boundary conditions:

1. The temperature is given at each point of the surface M(x, y, z, t) ∈ S:

$$u|_S = \mu_1\,(M, t). \tag{14}$$

2. On the surface of the body, the heat flow is set $q = -k\dfrac{\partial u}{\partial \vec{n}}$, then the boundary conditions of the type:

$$\left.\frac{\partial u}{\partial \vec{n}}\right|_S = \mu_2(M,t)\,. \tag{15}$$

The equation is used to find the temperature field:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla \cdot k \nabla T = Q(t)\,, \tag{16}$$

where ρ is the energy density, C_p is the heat capacity, k is the thermal conductivity, and Q is the Joule-Lenz heat. The calculations take into account the change in electrical conductivity of metals as the temperature increases. The electrical conductivity of copper σ was determined as:

$$\sigma = \frac{1}{\left[\rho_0(1+\alpha(T-T_0))\right]}\,,$$

where ρ_0 is the resistance at temperature $T_0 = 293\,\mathrm{K}$, α is the temperature coefficient of resistance, and T is the ambient temperature.

The distribution of heat sources (Joule-Lenz heat) was determined taking into account the skin effect to the currents in the TRT elements.

The second place of heat release is the anode due to heat radiation from the cathode and electron bombardment.

Heat transfer through the contact points between the elements was taken into account.

Heat losses were determined by radiation losses according to the Stefan-Boltzmann law on all elements of the TRT and by convection on the outer sides of the cathode and anode contacts, as well as of the ceramic envelope [13-16].

Materials, from which the elements in the TRT may be made, were taken into account in the TRT model:

– rod heater of the cathode – molybdenum (Mo);

– other metal elements – copper (Cu);

– spacer under the magnetic field concentrator – beryllium oxide (BeO);

– shell around the heater – aluminum oxide (Al2O3).

Table 2 shows the parameters of these materials [17].

Table 2

Parameters of TRT elements materials

Materials	Electrical conductivity, S/m	Thermal conductivity, W/(m·K)	Heat capacity, J/(kg·K)	The density, kg/m^3
Cu	$58.1 \cdot 10^6$	401	384	8960
Mo	$2.5 \cdot 10^6$	138	250	10200
Air	0	0.07…0.08	1100…1200	1.29
Al_2O_3	0	0.0018	60	3600
BeO	0	30…50	1500…1700	2700

Fig. 5 shows an example of calculating the temperature field in the axial section of TRT.

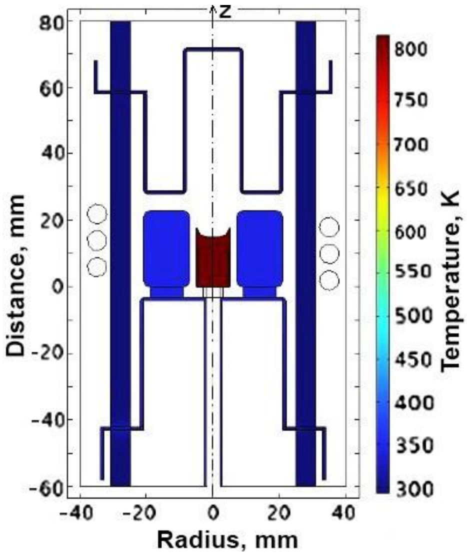


Fig. 5. The temperature field in the axial section of the TRT at zero anode voltage

3.3. SIMULATION OF ELECTRON TRAJECTORIES

This model calculates the shape of an electron beam propagating through the vacuum. To construct the trajectories of electrons from the cathode, the electric potential distribution was previously calculated. An example of such a calculation is shown in Fig. 6.

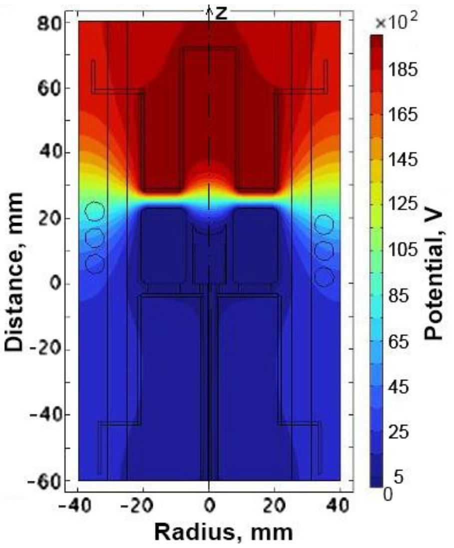


Fig. 6. Distribution of electric potential in TRT at anode voltage of 20 kV

When the electron beam current is large enough for Coulomb interactions to be significant, the beam shape is determined by solving equations for field and electron trajectories [18]:

$$\nabla\cdot\varepsilon_0\nabla V(\mathbf{r})=\sum_{i=1}^{N}e\delta(\mathbf{r}-\mathbf{q}_i)\,; \tag{17}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(m_e\frac{\mathrm{d}\mathbf{q}_i}{\mathrm{d}t}\right)=e\nabla V\,, \tag{18}$$

where m_e is the mass of electrons, e is the elementary charge, ε_0 is the vacuum permeability, V is the electric potential, N is the number of particles, $\mathbf{r}$ is the coordinate vector, $\mathbf{q}_i$ is the coordinate of the i-th particle, δ is the Dirac delta function.

Electrons at the operating voltage of the TRT are non-relativistic. Modeling electron trajectories and the resulting time-dependent electric potential distribution requires a large number of model particles. This model calculates the shape of the electron beam, connecting the time-dependent analysis of particle trajectories with the stationary analysis of the electric potential. The algorithm for modeling beam in the tube operating in a stationary mode consists of the following stages:

1. Calculation of the trajectory of particles, ignoring Coulomb forces.
2. Calculation of the stationary electric field due to the space charge density of the beam.
3. Using the electric potential calculated in step 2 to calculate the particle trajectory. Recalculation of space charge density using new trajectories.
4. Repeat steps 2 and 3 until the electrons reach the surface of the anode.

The initial position of electrons on the surface of the cathode was determined by a uniform distribution. The number of particles is determined by the researcher based on the capabilities of the calculation tools. An example of calculating electron trajectories is shown in Fig. 7. In this test, 500 electrons with zero initial energy were used.

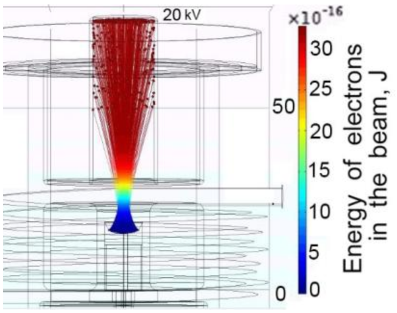


Fig. 7. Trajectories of electrons from the cathode to the TRT target at 20 kV

4. INFLUENCE OF ANODE GEOMETRY ON ELECTRON DISTRIBUTION ON THE TARGET

The X-ray radiation pattern of TRT is determined by the anode design and the radiation area, which is determined by the area of electron bombardment of the anode target.

Fig. 8 shows an example of calculating the trajectory of electrons with a current of 10 A at different distances from the cathode to the target and two values of anode voltage. The shape of the anode spot is affected by the distance and voltage between the anode and the cathode. The calculations for the presented FTM completely reproduced the theoretical data.

Calculations showed that for anode currents up to 10 A, the effect of space electron charge is not significant and does not affect the design and operational parameters of the TRT.

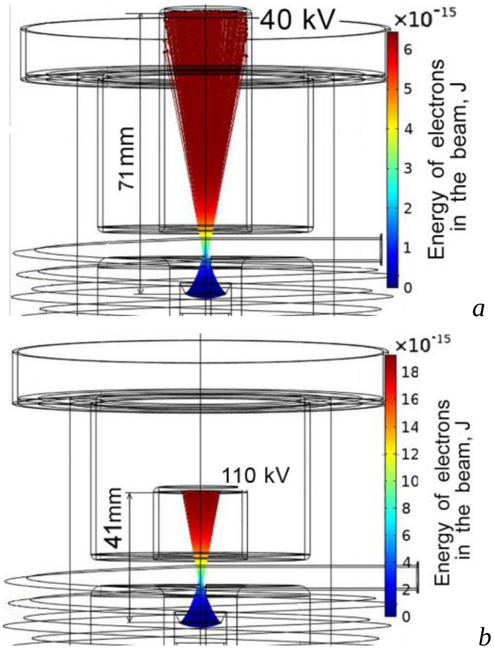


Fig. 8. Trajectories of electrons at different distances from the cathode to the target

CONCLUSIONS

1. The design of TRT with inductive heating of the thermionic cathode by an external inductor is presented. Induction heating allows the cathode heating power source to be isolated from the high voltage TRT electrode system.

2. The physico-topological model (FTM) of the TRT is presented with a hierarchy of related partial models for individual physical processes that ensure the functioning of TRT and make up the general model. That is, the formation of FTM requires the decomposition of the mechanism of action of X-ray tube into separate interconnected physical processes. A similar decomposition was performed to the TRT with an inductor for heating the thermionic cathode with an alternating magnetic field using a magnetic field concentrator as a step-down AC/RF transformer. According to the model, the operation of such TRT was simulated, and the parameters and characteristics of the TRT were calculated.

3. Analysis of the results of calculations of the distribution of electromagnetic fields and current, heat transfer and electron trajectories, taking into account the physical properties of functional elements, allows optimizing the topology and design of the TRT.

4. The consistency of the obtained simulation results and their correspondence to the known practical data from the field of vacuum electronics, X-ray engineering, and induction heating technique [1, 18, 19] allows us to recommend this design of a transmission X-ray tube with an induction-heated thermionic cathode for practical approbation.

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ФІЗИКО-ТОПОЛОГІЧНЕ МОДЕЛЮВАННЯ ТРАНСМІСІЙНОЇ РЕНТГЕНІВСЬКОЇ ТРУБКИ З ІНДУКЦІЙНИМ НАГРІВОМ КАТОДА

С.О. Майкут, А.І. Кузьмичєв, Л.Ю. Цибульський, Н.В. Шинкаренко

Проведено фізико-топологічне моделювання трансмісійної рентгенівської трубки (ТРТ) з індукційним нагріванням катода з урахуванням фізичних властивостей функціональних елементів та їх конструкції і топології. Моделювання базується на фундаментальних рівняннях для вакуумної електроніки і електродинаміки з використанням ComSol. Розраховано розподіли електромагнітного поля, струмів і теплових полів, а також траєкторії електронів, випущених термокатодом. Аналіз траєкторій електронів дозволив оптимізувати топологію та конструкцію ТРТ.