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DEVELOPMENT OF HIGH POWER MICROFOCUS X-RAY TUBE

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In this paper, we propose and study a new method for increasing the power of a microfocus X-ray tube of transmission type. The proposed method is based on the idea of using a heat pipe as a tube anode. A theoretical expression is obtained for the maximum power dissipated at such an anode, depending on the diameter of the electron beam and the thickness of the tungsten target. It is shown that the power of the proposed tube can be many times higher than the power of tubes with standard composite anodes. An electron-optical scheme of a tube with electrostatic focusing is proposed and analyzed.

Keywords: microfocus X-ray tube, composite anode, heat pipe, electron-optical circuit

Introduction

Currently there is a trend that a share of microfocus tubes is increasing in the market of X-ray equipment [1-4]. Microfocus x-ray tubes are tubes having about 10 μm diameter of radiation area. Advantages of microfocus sources of x-ray radiation in comparison with macrofocus ones are the following:

- high locality of the impact onto observable or processed objects;
- decrease of the radiation dose into areas being adjacent with the object;
- better quality of shadow images under the similar radiation dose;
- ability to obtain magnified x-ray images.

There are two known variants to perform anodes of microfocus tubes: reflecting and transmission types which consist of an anode body (substrate) and target, as a rule [5]. The target is most often deposited onto the anode body electrochemically. Material of the anode body (substrate) should have high heat conductivity for effective heat removal from the area of X-ray generation in the target. Besides, in the case of transmission type anodes, a substrate plays an additional role of the output window that is why most often made of metal having a high coefficient of the X-ray transmittance. Main purpose of the target is emission of x-ray quanta, so according to the Moseley law it is made of material with a high atomic number. Natural requirements of high melting temperature and low vapor tension are applied to the target.

Advantages of microfocus x-ray tubes can be maximally realized using anodes of the transmission type as opposed to anode of the reflecting type due to placing of the observable object at a short distance (fractions mm ÷ units mm) from the radiating surface. Main disadvantage of classical sources of the transmission type is that the upper limit of power dissipating on the planar anode is not high and does not exceed 1 W on 1 μm^2 of the electron beam cross-sectional area [1, 5]. Following increase of the power density leads to destruction of the anode material. The higher the power dissipating on the anode as well as x-ray radiation intensity is, the more qualitative and informative shadow images are. So, the researches main direction aimed at improvement of microfocus x-ray tubes of the transmission type are connected with increase of their power. Part of researches is directed at optimization of multilayer solid structures applied as an anode. Main concept of such anodes is a sequential deposition of several pairs of layers “target-substrate” [6]. Experiments have shown a practical reasonability to create multilayer structures of the “sandwich” type for dissipation of high heat powers and increase of effectiveness of the X-ray radiation generation (“fluorescence yield”), for example structures with such sequence as Ta-Cu-Ta-Cu-Ta. Another part of researches is connected with a search of nontraditional or new materials characterized by significant heat conductivity, for example, diamonds [1] used as substrates.

However, such methods cannot provide with qualitative increase of power. At present microfocus tubes with anodes of new type based on “liquid” metals have the greatest luminosity. Liquid metal anode differs because metal has been already melted and there is no reason to worry about its melting. In liquid jet sources having a record intensity of radiation diverging from a small area, a strong local heating of liquid metal is

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prevented by regeneration of the material in the area of radiation due to its replacement by a fresh portion at velocity 100 m/s [7]. Main disadvantage of X-ray sources with liquid metal anodes is their technical complexity and, as a consequence, high cost. The present paper has suggested a method of qualitative increasing microfocus tube power due to usage of the so called "heat pipe" as an anode [8]. Heat pipes (HP) [9] are able to dissipate a record number of heat from small areas of local heating.

1. Development idea

Technical problem solved in the present paper is a creation of a microfocus x-ray tube with antransmission type anode which construction allows dissipating great heat powers released as a result of bombardment of the target surface by focused high-energy electrons. Design of the anode 1 of the suggested x-ray source is represented as a heat pipe which casebottom 2 faced to the cathode is a target and heated due to bombardment by accelerated and focused electrons 6 (Fig. 1).

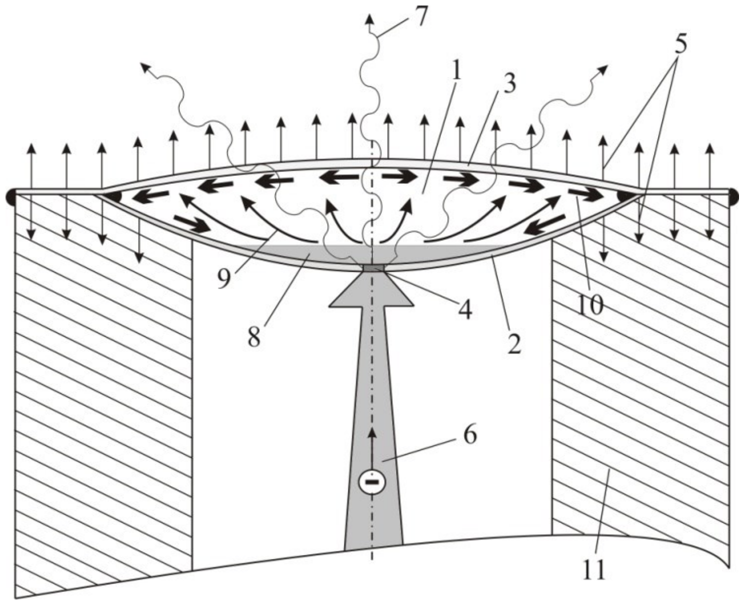

Fig.1. Anode unit of the microfocus x-ray tube executed in the form of a simple type of the HP-thermosyphon: 1 – a heat pipe (anode), 2 – a heat pipe bottom (anode target), 3 – a heat pipe cap (anode output window), 4 – a zone of heat release (area of x-ray emission), 5 – a heat sink, 6 – a electron flow, 7 – X-ray radiation, 8 – a heat carrier, 9 – vapor, 10 – a condensate, 11 – an anode case.

Heat carrier8 contacted with target 2 converting into vapor 9carries energy away from the small area 4 of target heating and transfers it to another cold and forced cooling cap3 of the heat pipe case and also a thick case of the anode 11 where a heat carrier is condensed and in a liquid phase 10 returns to the evaporation zone. Cap3 of the heat pipe case plays an additional role of the window for bringing of x-ray radiation 7 outside. Heat pipe is an effective tool for heat removal since a molecular mechanism for transfer of kinetic and vibrational energy of the chaotic motion of single particles of the evaporator substance operates here instead of rather slow electron mechanism for heat transfer in the continuous metal thermal transmission line. Heat flow evaluated by a lot of kilowatts passes away under velocity of the liquid evaporation about several grams per second. Generated condensate returns to the evaporation zone or under influence of capillary forces provided by placement of the specialized capillary structure inside the heat pipe or, as it is shown in Fig.1, due to gravity action (the last construction is usually called as a thermo-syphon).

Thickness of the target 2 should be enough small for effective transfer of heat to the heat carrier 8 but not less than a length of the electron free path in the metal which it is made of. For effective generation of x-ray quanta, the target 2 is better to be made of metal with a high atomic number, for example tungsten. Cap3material should have a good heat conductivity for the effective heat sink 5 and low coefficient of the x-ray 7 decay for their effective bringing outside. Beryllium is a suitable metal for these purposes.

2. Evaluation of a value of the power dissipated by the anode "heat pipe"

The functional diagram of the heat pipe includes two elements: a target locally heated by an electron beam and a volume adjacent to the target containing a coolant and providing heat removal from it to the surrounding space. As already noted, the same "target / heat-conducting substrate" scheme underlies composite anodes. Paper [10] solved the task of the composite anode heating by an electron beam which focal spot diameter is 2δ. The anode is represented as a thick cylindrical substrate with diameter $2R$ and height $h_2$made of metal with good heat conductivity k_2 (for example, Cu or Be) with a layer of refractory metal (for example, W) deposited on its base and having thickness $h_1$and heat conductivity $k1$, being a target (Fig.2). Main heat exchange with external environment is performed through the anode base being opposed to the target which temperature is considered as equal to T_0.

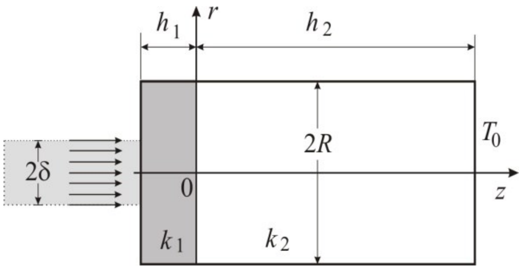

Fig.2. Diagram of the composite anode design.

For the steady-state condition a mathematical formulation of the axially symmetric task includes two steady-state heat conduction equations into cylindrical coordinates$r0z$in relation to the target temperature T_1 and substrate temperature T_2

$$\frac{\partial^2 T_1}{\partial r^2} + \frac{1}{r}\frac{\partial T_1}{\partial r} + \frac{\partial^2 T_1}{\partial z^2} = 0,$$

$$\frac{\partial^2 T_2}{\partial r^2} + \frac{1}{r}\frac{\partial T_2}{\partial r} + \frac{\partial^2 T_2}{\partial z^2} = 0,$$

and boundary conditions

$$\left.\frac{\partial T_1}{\partial r}\right|_{r=R} = \left.\frac{\partial T_2}{\partial r}\right|_{r=R} = 0,$$

$$-k_1 \left.\frac{\partial T_1}{\partial z}\right|_{z=-h_1} = \frac{Q}{\pi\delta^2},$$

$$T_1|_{z=0} = T_2|_{z=0},$$

$$k_1 \left.\frac{\partial T_1}{\partial z}\right|_{z=0} = k_2 \left.\frac{\partial T_2}{\partial z}\right|_{z=0},$$

$$T_2|_{z=h_2} = T_0,$$

$$-k_2 \left.\frac{\partial T_2}{\partial z}\right|_{z=h_2} = \frac{Q}{\pi R^2},$$

where, $\frac{Q}{\pi\delta^2}$ isa density of theheat flow Q in the tube focus in the case of uniform distribution of the electron beam density along the cross-section, $\frac{Q}{\pi R^2}$ is a density of the heat flow dissipating into the external environment from the butt end $z=h_2$.

Solution of the boundary-value problem in a center of the focal spot surface($z=-h_1$, $r=0$) on the target surface where the temperature is maximum, has the form [10]

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$$T_{max} = T_0 + \frac{P}{\pi R^2}\left(\frac{h_1}{k_1} + \frac{h_2}{k_2}\right) + \frac{P}{\delta k_1}\sum_{n=1}^{\infty} L_n \frac{J_1\left(\mu_n \frac{\delta}{R}\right)}{\mu_n}\ , \quad (1)$$

where $L_n = \frac{\frac{k_1}{k_2}\text{th}\left(\mu_n \frac{h_2}{R}\right) + \text{th}\left(\mu_n \frac{h_1}{R}\right)}{\frac{k_1}{k_2}\text{th}\left(\mu_n \frac{h_1}{R}\right)\text{th}\left(\mu_n \frac{h_2}{R}\right) + 1}$, $J_1(x)$ is a first-order Bessel function of the first kind, μ_n are roots of the function $J_1(x)=0$, $n=1, 2, 3$ … is a serial number of the root, P is power of the electron flow on the anode surface.

Formula (not mentioned here) for temperature in the point $z=0$, $r=0$ has the same form at the border of the target and substrate partition. Calculations for the composite anode have shown that overheating of the target depends on its thickness. Overheating is considered as exceeding T_{max} of the permissible temperature T_{adm}. So, for tungsten T_{adm}=1600 °C [10]. Under thick layer of the target its surface can be heated up to the limiting values, while the heat-conducting substrate has a low temperature. Under decreasing of the target thickness, the substrate will be heated more and more and ultimate power of the electron beam will be determined by the permissible temperature T_{adm} of its heating. For copper T_{adm}=750 °C [10]. It is obvious that there is an optimal target thickness when useful peculiarities of the target (high temperature of melting) and substrate (high heat conductivity) will be used. In the present paper evaluation of the power dissipated by the anode performed in the form of a heat pipe is executed in approximation of the equivalent heat conductivity. Concept “equivalent heat conductivity” is often used for determination of heat pipe efficiency [9]. For example, classical cylindrical pipes with water under temperature 150°C as a heat carrier have heat conductivity in hundred times more than copper. Heat pipes can be created for operation in the temperature range from 4 to 2300 K by the appropriate choice of the coolant and the housing material. For operation in the temperature ranges greater than 750 K and comparable to the melting temperatures of structural metals in vacuum electronics devices, high-temperature heat pipes are used. High temperature heat pipes are often called heat superconductors. Indeed, pipes with liquid metal coolants, for example, sodium, are capable of providing effective thermal conductivity thousands and even tens of thousands of times more than the best heat conductors: silver and copper [9].

A metal with a high atomic number, for example, tungsten, can be used as the target material for the heat pipe anode. The thermal conductivity of tungsten is 0.98 W / (cm K).Since the thermal conductivity of the substrate, the role of which in our case is played by the volume of the heat pipe, is tens of thousands of times higher than the thermal conductivity of tungsten, then setting $k_2 \gg k_1$ in formula (1) we obtain the following expression for evaluation of the maximum temperature of the anode consisting of a target with heat conductivity k_1 and substrate having a significant heat conductivity k_2:

$$T_{max} = T_0 + \frac{P}{k_1}\left[\frac{h_1}{\pi R^2} + \frac{1}{\delta}\sum_{n=1}^{\infty} M_n \frac{J_1\left(\mu_n \frac{\delta}{R}\right)}{\mu_n}\right], \quad (2)$$

where $M_n = \text{th}\left(\mu_n \frac{h_1}{R}\right)$.

Correctness of the obtained expression (2) is confirmed by practical coincidence of calculation results(absolute calculation error does not exceed 0.0001 K) performed according to equations (1) and (2), firstly, for thick targets (h_1>1 mm), when the influence of the thermal conductivity of the substrate is insignificant; secondly, for thin targets (1 μm<h_1<1 mm) and substrates of real thickness with a high thermal conductivity k_2> 10000 W / (cm K). All of the above allows us to consider formula (2) as an adequate estimate of the maximum heating temperature of the target of the "heat pipe" anode.

Let’s mention again that T_{max} cannot exceed T_{adm} of the target material. i.e. condition $T_{max} \le T_{adm}$ should be fulfilled. Designating $\Delta T = T_{adm} - T_0$ we obtain a formula for evaluation of the maximally permissible power absorbed by the target of the anode “heat pipe”

$$P_{max} = \frac{k_1 \Delta T}{\frac{h_1}{\pi R^2} + \frac{1}{\delta}\sum_{n=1}^{\infty} M_n \frac{J_1\left(\mu_n \frac{\delta}{R}\right)}{\mu_n}}. \quad (3)$$

Power in formula (3) has a dimension [Watts], and distances and radiuses are measured in [cm].

In table 1 results of calculations of the permissible power dissipating on the tungsten target of the anode “heat pipe” (W-HP) according to expression (3) under various values of thickness $h_1$of the target and diameter 2δ of the focal spot of a beam of electrons are shown in columns 3÷8. Target parameters are k_1=0.98W/cm·K, ΔT=1500 K, 2R=0.8 cm.

Table 1 - Ultimate power dissipating by the W target of the anode “heat pipe”.

2δ	Thin layer W (W-Be)	h_1 (W-HP)					
		3 mm	1 mm	100 μm	10 μm	1 μm	100 nm
1	2	3	4	5	6	7	8
2 μm	0.4 W	0.46 W	0.461 W	0.464 W	0.48 W	0.68 W	4.64 W
10 μm	2.2 W	2.31 W	2.313 W	2.35 W	2.78 W	11.56 W	115.77 W
30 μm	6.7 W	6.94 W	6.97 W	7.31 W	12.51 W	103.9 W	1.04 kW
100 μm	22. 3 W	23.22 W	23.52 W	27.82 W	115.6 W	1. 16 kW	11.6 kW
200 μm	44.6 W	46.69 W	47.91 W	68.12 W	462 W	4.62 kW	46.2 kW

Paper [11] constructed a simulation model for heating of the composite anode of transmission type. The anode is considered as a homogeneous disk made of material of the substrate. It is explained by the fact that thickness of the target is small (several μm), temperature drop is insignificant, so target temperature can be considered as equal to the substrate surface temperature. Column 2 of the table 1 shows results of evaluation of the ultimate power dissipated by such anode (thin W target on thick Be substrate) for comparison. According to results of calculations (see table 1) dependencies of the ultimate dissipating power on thickness of the target of the anode “heat pipe” under two values of the focal spot diameter are shown in Fig.3. To visually assess the advantages of such an anode design the dotted lines (a) and (c) show levels of maximum powers which a standard composite W-Be anode of the transmission type can dissipate according to evaluations [11].

Let’s analyze data from Table 1 and Fig.3. Under great thicknesses (h_1 >1 mm) of the W target of the anode “heat pipe”, a value of the dissipated power is determined by heat resistance of tungsten and heat pipe does not ensure heat removal from the heating zone. So, in this case ultimate heat power only insignificantly exceeds the power dissipated by the standard composite W-Be anode described in [11].Tangible benefit in the dissipating power is reached only under very small (h_1 <100 μm) thickness of the target of the anode “heat pipe”, since in this case the thermal resistance of the target becomes insignificant and the thermal power begins to be actively dissipated by the working volume of the heat pipe.

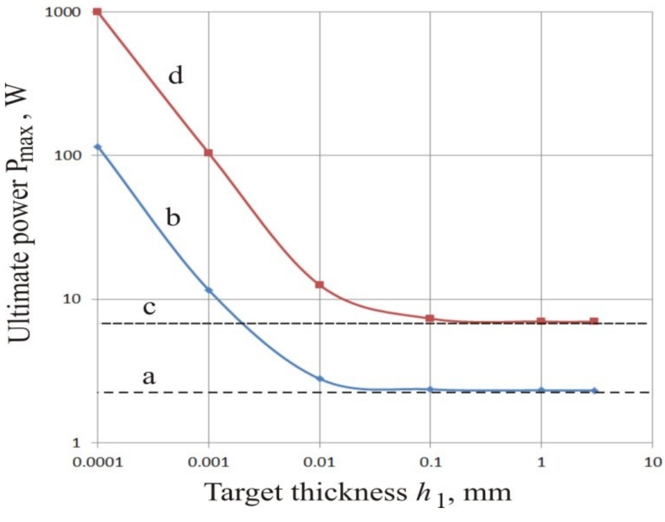

Fig.3. Ultimate power dissipating by the W target of the anode “heat pipe”:b –2δ=10 μm, d - 2δ=30 μm. Levels of the ultimate power [11] dissipated by a standard composite W-Be anode of the transmissiontype: a - 2δ=10 μm, c - 2δ=30 μm.

It is obvious that application of material with such small thickness is technologically complicated, i.e. the scientific problem becomes the technological problem. But it has a solution. In particular, melting of the "thick" layer of tungsten by an electron beam with the specified power under the first switching of a microfocus tube provides a required thickness of the material in the area of focus. Additionally, we note that calculations according to formula (3) have shown a slight growth of P_{max} under increase of the anode diameter $2R$ up to several centimeters, i.e. the anode diameter is not a critical parameter. Thus, in the case of usage of a heat pipe as an anode there is no optimal thickness of the target, the thinner the target is, the greater power can be dissipated from the heating area. It is main advantage of usage of the heat pipe as an anode of the microfocus x-ray tube.

3. Tools for simulation of the electron-optical scheme of the microfocus tube

At the end of the theoretical stage of the development of a high-power microfocus tube its electron optical scheme is simulated. Numerical methods have the most accurate evaluations regarding forecasting parameters of devices of electron optics with the complicated electrode configuration. Numerical simulation of the electron-optical systems (EOS) traditionally includes three independent sections calculation of:

- electrostatic and magnetic fields in operating volume;
- charges particles trajectories in the system electromagnetic field;
- EOS integrated characteristics such as angular focusing of the specified order, dispersion, resolving power, aberration distortions, etc.

For effective solution of problems of numerical simulation of electron-optical systems in the framework of the present paper the home made software CAE «FOCUS» [12 - 14] has been used. It is a combination of several software modules: *Design*, *Field_E*, *Field_M, Path_S, Path_D,* each of which solves an independent task:

- module *Design* is intended for formation and modification of the EOS construction,
- module *Field_E* realized a method of boundary elements for calculation of the EOS potential distribution function,
- module *Field_M* ensures a calculation of the distribution function of the magnetic field induction of a set of solenoids by the method developed by authors and called as the Current Elements Method,
- module *Path_S* is intended for the trajectory express-analysis of static EOS,
- module *Path_D* suggests a more powerful set of user functions and analytical possibilities under execution of the three-dimensional trajectory analysis of systems with variable electric and constant magnetic fields.

4. Development of the x-ray tube electron-optical scheme

Electron-optical scheme of the tube should ensure acceleration of the electron flow and its focusing on the anode surface. Classical scheme of the low-voltage emission system construction used in electron guns of spectrometers, electron microscopes and others is represented as a sequence of the cathode lens and several single lenses, besides the first electrode of each single lens is an inter mediate accelerating anode where a hole diaphragm is performed. This diaphragm ensures an electron transit and decreases an angular spread of the electron beam in order to set a required focus sharpness at the output.

Microfocus tube cannot be constructed according to the classical scheme because of several reasons. Firstly, due to high voltages applied to electrodes of the tube, placement of focusing lenses between the cathode and anode (anti-cathode) taking into consideration requirements for electric strength of the constructions will lead to a sharp increase of its dimensions along the axis z. Secondly, restriction of the angular spread of the already accelerated electron beam by means of intermediate diaphragms will cause a spurious emission of X-rays from walls of these diaphragms. That is why we suggest such electron-optical scheme when after the primary formation of the electron beam, its focusing begins immediately, i.e. space of acceleration and focusing becomes combined. Moreover, the tube operates in the mode without restrictions of the cathode emission current. Besides, effective cathodes with indirect heating, for example impregnated ones, are better to be used as a cathode for provision with high power on the anode. Emitting surface of such cathodes is more often represented as a planar circle with large diameter. CAE "FOCUS" has allowed developing an electron-optical scheme of the x-ray tube under conditions of high reliability of results.

Results of the trajectory analysis of the microfocus tube are shown in Fig.4. Trajectory analysis has been performed not taking into account influence of the space charge, since level of current in the tube does not exceed several mA. The tube operates in the following way. Electrons 1 emitting from the base of the cylindrical thermal emissivity cathode 2 arrive to the accelerating electric field between the cathode 2 with a potential V_c and the anode 3 having a positive potential V_a. Hereinafter, all potentials are considered in relation to the potential of cathode V_c. Electron flow 1 forms an image with diameter 2δ on the anode 3 target. Formation of the image is performed by the electric field created by a small negative potential V_w on the Wehnelt electrode 4 and also positive potential V_f on the focusing electrode 5 and accelerating potential V_a on the anode 3. Area of interaction of accelerated electrons 1 with material of the anode 3 target becomes a source of emission of x-rays 6. Tube electrodes are located in the ceramic case 7.

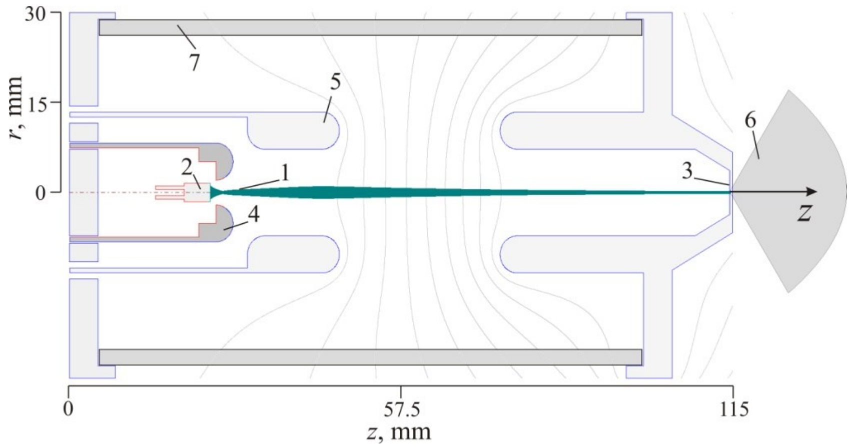

Fig. 4. Electron-optical scheme of the axially symmetrical microfocus tube: results of the trajectory analysis.

Wehnelt electrode serves for the primary formation of the electron flow and adjustment of dimensions of the effective area of electron emission from the cathode due to change of the potential V_w, value because diameter $d_0$of the zero-equipotential close to the cathode surface (Fig. 5) depends on a value of this potential. Zero equipotential divides a cathode area into two sub-areas: I and II. Electrons emitted by the cathode (including its lateral surface) higher than the zero equipotential (sub-area I) return to the cathode; electrons emitted lower than the zero equipotential (sub-area II) become a part of the flow moving to the anode. This effect is a result of action of the electrostatic force F_e which directions are shown in Fig.5 in corresponding sub-areas.

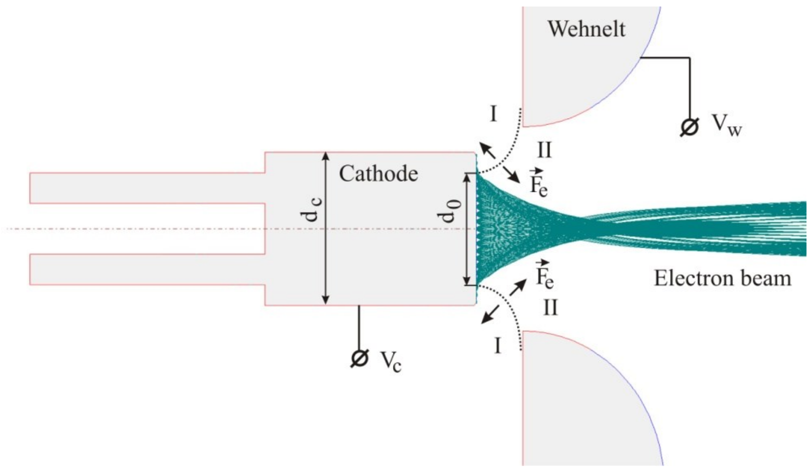

Fig.5. Formation of the electron beam in the cathode area. Pointed line is a zero equipotential.

Fig. 6 shows a dependence in relation to diameter d_0/d_c of the zero equipotential on a value of the potential V_w of the Wehnelt electrode, where d_c is a cathode diameter. Dependence shows a possibility of significant decrease of the emission area diameter by increasing of an absolute value of the negative potential V_w. Let's note that for positioning of the smallest cross-section (focus) of the electron flow on the anode target surface, a corresponding adjustment of the potential V_f of the focusing electrode (fig. 6, curve V_f) is required. Unfortunately, decrease of the emission area does not lead to decrease of the focal spot diameter 2δ (fig. 6, curve 2δ/d_c). It is connected with presence of angular aberrations of the researched EOS. Following stage of current researches suggests a development and optimization of the anode "heat pipe" construction,

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minimization of the electron flow focal spot diameter due to optimization of the electron-optical scheme of the microfocus tube, production of the experimental sample and performance of experimental researches.

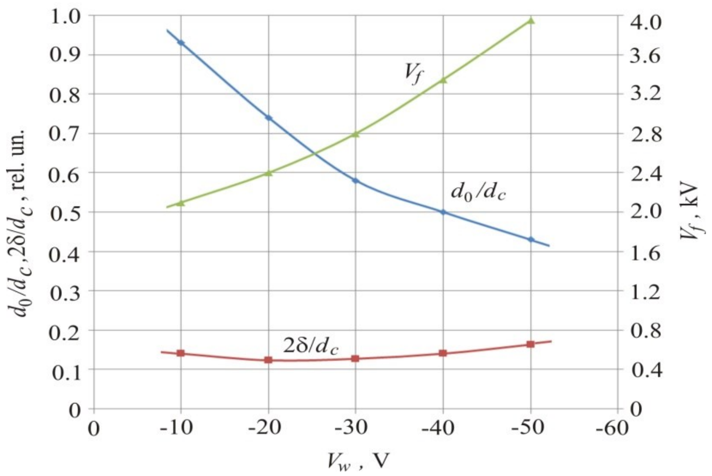

Fig.6. Dependencies of geometrical and electrical parameters of the microfocus tube on the Wehnelt electrode potential. Anode potential is V_a=80 kV.

Conclusion

The present paper has suggested an idea to increase power of the microfocusx-ray tube due to usage of the heat pipe as an anode. Values of the limiting power dissipated on the anode have been evaluated depending on a diameter of the electron flow focal spot. The power of the tube with the anode of the heat pipe can be tens and hundreds of times higher than the power of standard tubes with composite anodes of the transmission type. Electron-optical scheme of the microfocus tube has been developed, which provides acceleration of the electron flow and its transportation from the emission region to the focal point with a 10-fold compression of the section radius.

Acknowledgments

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REFERENCES

1 X-ray W or X Microfocus Tubes. Available at: www.x-ray-worx.com/x-ray-worx/index.php/en/ microfocus-x-ray-tubes-overview (Jan13, 2020).

2 X-ray Hamamatsu Microfocus Tubes. Available at: www.hamamatsu.com/eu/en/community/xndt/x-ray_sources.html (Jan13, 2020).

3 X-ray Comet Microfocus Tubes. Available at:www.globalspec.com/industrial-directory/x-ray_tube_comet (Jan13, 2020).

4 X-ray Oxford-Instruments Microfocus Tubes. Available at: www.oxford-instruments.com/products/ x-ray-tubes-and-integrated-sources/ microfocus-x-ray-systems (Jan13, 2020).

5 Ivanov S.A., Schukin G.A. *X-ray tubes for engineering.* Leningrad, 1989, 200p. [in Russian]

6 Korenev S. *Target from Production of X-rays.* USA Patent: US 6,463,123, 2002.

7 Hemberg O., Otendal M., Hertz H. M. Liquid-metal-jet anode electron-impact x-ray source. *Applied Physics Letters*. 2003, Vol. 83, No. 7, pp. 1483-1485.

8 Trubitsyn A.A. *Microfocus transmission X-ray tube with high level of dissipated power*. Russian Patent No. 2653508, 2018, 9 p.

9 Dunn D., Reay D.A. *Heat pipes*. Oxford, New York: Pergamon Press, 1976, 299 p.

10 Haradzha F. N. *Common X-ray engineering course*. Leningrad, 1966, 568 p. [in Russian]

11 Podymskiy A.A. *Power X-ray tubes to X-ray imaging*. PhD Thesis, S-Petersburg, 2016, 148 p. [in Russian]

12 Gurov V., Saulebekov A., Trubitsyn A. *Analytical, Approximate-Analytical and Numerical Methods in the Design of Energy Analyzers*. In Advances in Imaging and Electron Physics. Hawkes P.W. (Ed.). 2015, London: Academic Press. Vol. 192, 209 p.

13 Trubitsyn A., Grachev E., Gurov V., Bochkov I., Bochkov V. *CAE «FOCUS» for Modelling and Simulating Electron Optics Systems: Development and Application. Proceedings of SPIE*. 2017, Vol. 10250, p.102500V-1.

14 Software CAE FOCUS: Available at: www.focuspro-soft.com.

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