High-power x-ray tube for micro computed tomography

A A Trubitsyn, E Yu Grachev and E A Kozlov

Ryazan State Radio Engineering University, Department of Industrial Electronics,
Ryazan 390035, Russia

E-mail: assur@bk.ru

Abstract. The present paper has suggested the idea to increase power of the microfocus x-ray tube of the transmission type due to application of the heat pipe as an anode. Ultimate heat power dissipating on such anode under various diameters of the electron beam has been evaluated. Possibility of significant overpowering of the suggested device has been shown in comparison with power of standard ones. Electron-optical scheme of the microfocus tube with electrostatic focusing has been developed.

1. Introduction

The current stage of development of X-ray diagnostics methods can be characterized as a stage of symbiosis of modern X-ray technology and digital information technology. The results of such a symbiosis are most pronounced in microfocus fluoroscopy, where so-called microfocus tubes are used as radiation sources.

In the most positive way, microfocus tubes have proven themselves in X-ray tomography, where the spatial resolution at the level of microns and nanometers is achieved. The corresponding branch of science is called micro computed tomography (μCT) [1]. 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. 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. Main function 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. Material of the target should have a high melting temperature also.

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 5 W on 10 µm diameter of the electron beam cross-sectional area [2]. 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 X-ray shadow images are more qualitative and informative ones. So, main direction of researches aimed at improvement of microfocus x-ray tubes are connected with the increasing of their power.

2. Estimation of the power dissipated by the composite anode

The problem of the composite anode heating by an electron beam with focal spot diameter $2\delta$ has solved in the work [3]. The anode consists of two parts. First part 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). Second part is a layer of refractory metal (for example, W) deposited on the substrate and
having thickness \( h_1 \) and heat conductivity \( k_1 \) and being a target (Figure 1). Main heat exchange with external environment is performed through the anode base being opposed to the target which temperature is considered as equal to \( T_0 \).

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

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

where
\[
L_n = \left( \frac{k_1}{k_2} \right) \frac{\mu_n}{h_2} \left( \frac{\mu_n}{h_1} \right) + \frac{\mu_n}{h_2} \left( \frac{\mu_n}{h_1} \right) + 1
\]

roots of the function \( J_1(x) \) for a first-order Bessel function of the first kind, \( \mu_n \) – roots of the function \( J_1(x) = 0, n = 1, 2, 3 \ldots \) - a serial number of the root, \( P \) – 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 interface of the target and substrate.

Calculations for the composite anode have shown that overheating of the target depends on its thickness. Overheating is considered as exceeding \( T_{\text{max}} \) of the permissible temperature \( T_{\text{adm}} \). So, for tungsten \( T_{\text{adm}} = 1600 \, ^\circ \text{C} \). 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 admissible temperature \( T_{\text{adm}} \) of its heating. For copper \( T_{\text{adm}} = 750 \, ^\circ \text{C} \).

2.1. Estimation of the dissipated power of a composite anode with a super-heat-conducting substrate

One of the main ways to increase the power dissipated at the anode is to improve the thermal conductivity of the substrate. It is logical to formulate and solve the problem of estimating the amount of ultimate power that an anode target can dissipate if the substrate is a superconductor of heat.

Assigning \( k_2 \gg k_1 \) to the above-mentioned facts 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 \( k_2 \):

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

\( P \) – power of the electron beam on the anode surface.
where \( M_n = \text{th} \left( \frac{\mu_n h_1}{R} \right) \).

Let’s mention again that \( T_{\text{max}} \) cannot exceed \( T_{\text{adm}} \) of the target material, i.e. condition \( T_{\text{max}} \leq T_{\text{adm}} \) should be fulfilled. Designating \( \Delta T = T_{\text{adm}} - T_0 \) we obtain a formula for evaluation of the maximally permissible power absorbed by the target of the anode with a super-heat-conducting substrate.

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

(3)

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

The theoretical dependences (3) of the limiting power dissipation \( P_{\text{max}} \) on the thickness \( h_1 \) of the tungsten target of the composite anode with super-heat-conducting substrate at three values of the diameter \( 2\delta \) of the electron beam focal spot are constructed in figure 2. The dependencies are represented by solid lines 1’, 2’ and 3’. Parameters of the target are \( k_1 = 0.98 \text{W/(cm K)}, \Delta T = 1500 \text{ K}, 2R = 0.8 \text{ cm}. \)

![Figure 2](image)

The limiting power dissipated by the W target of the anode with the super-heat-conducting substrate: 1’ - \( 2\delta = 10 \text{ \( \mu \)m}, 2’ - \( 2\delta = 30 \text{ \( \mu \)m}, 3’ - \( 2\delta = 100 \text{ \( \mu \)m}. \)

The limiting power levels dissipated by the standard composite W-Be anode of transmission type: 1 - \( 2\delta = 10 \text{ \( \mu \)m}, 2 - \( 2\delta = 30 \text{ \( \mu \)m}, 3 - \( 2\delta = 100 \text{ \( \mu \)m}. \)

The advantages of microfocus X-ray tubes noted in the article introduction can be maximally realized when using a transmission-type anode, in contrast to reflective-type anodes, by placing the object of investigation at a small distance (a fraction of mm) from the radiating surface of anode.

An alternative calculation model for heating a composite transmission-type anode was constructed in [2], the target thickness of which is negligible. In figure 3, the dashed lines 1, 2 and 3 corresponding to different diameters of the incident electron beam indicate the maximum power levels that the W-Be anode of this type is capable to dissipate. The data are confirmed experimentally.

Let us analyze the data in figure 3 Under great thicknesses (>1 mm) of the anode W target deposited on substrate with an extremely high heat conductivity, a value of the dissipated power is determined by heat resistance of tungsten and so substrate 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 [2]. Tangible benefit in the dissipating power is reached only under very small (<100 \( \mu \)m) thickness of the anode target deposited on a substrate with the high heat conductivity. In this case, the thermal resistance of the target becomes small, and the heat
locally released at the point of electron beam incidence is dissipated actively by the volume of the super-heat-conducting substrate.

Additionally, we note that calculations according to formula (3) have shown a slight growth of $P_{\text{max}}$ under increase of the anode diameter $2R$ up to several centimeters, i.e. the anode diameter is not a critical parameter.

2.2. Technical implementation of the anode with superconducting substrate

The proposed anode 1 of the X-ray source is a heat pipe [4] (in our case the simplest thermosyphon) whose bottom 2 is facing the cathode and is heated by bombardment with accelerated and focused electrons 6 (Figure 3). The heat carrier 8, which is in contact with the target 2, converting to vapor 9, carries energy from the small target heating region 4 and transfers it to another, cooled or forcedly cooled cap 3 of the heat pipe case, and also to the massive body of the anode 11, where the coolant condenses and the liquid phase 10 is returned to the evaporation zone. The cap 3 of the heat pipe case plays an additional role of the window for outputting the X-ray radiation 7 to the outside.

**Figure 3.** The anode unit of the microfocus X-ray tube, made in the form of thermosyphon being the simplest type of heat pipe: 1-heat pipe (anode), 2-bottom of the heat pipe (anode target), 3-cap of the heat pipe (exit window of anode), 4-zone of heat emission (X-ray emission region), 5 - heat sink, 6 - electron flux, 7 - X-ray radiation, 8 - heat carrier, 9 - steam, 10 - condensate, 11 - anode casing.

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. Cap 3 material should have a good heat conductivity for the effective heat sink 5 and low coefficient of the x-rays 7 attenuation for their effective bringing outside. Beryllium is a suitable metal for these purposes.

Corresponding selection of a heat carrier and case material can create heat pipes for operation within the temperature range from 4 to 2300 K. For working in the temperature range, greater than 750 K and comparable with the melting temperatures of structural metals of 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, can provide an effective thermal conductivity of thousands or even tens of thousands of times more than the best conductors of heat - silver and copper [5].

3. Development of the X-ray tube electron-optical scheme

The electron-optical scheme of the tube should ensure the acceleration of the electron beam and its focusing on the surface of the anode. Such schemes are called electronic projectors.

The classical scheme for designing electronic projectors is a sequence of a cathode accelerating lens and several focusing single lenses. In this paper we propose a nonclassical electron-optical
scheme of a microfocus tube (Figure 4), in which, after the initial formation of the electron beam, its focusing begins immediately, i.e. space acceleration and focusing are combined. Moreover, the tube operates in a mode without limiting the cathode emission current.

Figure 4. Results of trajectory analysis of an axially symmetric microfocus tube using CAE FOCUS [6]: 1 - electron beam, 2 - thermionic filament, 3 - anode, 4 - Wehnelt electrode, 5 - focusing electrode, 6 - X-ray radiation.

Figure 5 shows a prototype of the proposed microfocus X-ray tube, developed by the team of authors of this article and manufactured using metal-ceramic technology.

Figure 5. Microfocus X-ray tube manufactured using metal-ceramic technology.

4. Summary
The paper suggests the idea of increasing the power of a microfocus X-ray tube by using a heat pipe as an anode. Estimates of the magnitude of the power dissipated at the anode are determined as a function of the diameter of the focal spot of the electron beam. An electronic-optical scheme of a microfocus tube has been developed.

The research has been carried out at expenses of the Russian Science Foundation grant (project No.18-79-10168).

References
[1] Elliott J C and Dover S D 1982 Journal of Microscopy. 126 211
[2] Podymskiy A A 2016 Power X-ray tubes to X-ray imaging (rus.) PhD Thesis, LETI, S-Petersburg
[3] Haradzha F N 1966 Common X-ray engineering course (rus.) Leningrad, Izdatelstvo “Energiya”
[4] Dun P D and Reay D A 1976 Heat pipes Oxford, Pergamon Press
[5] Ivanovsky M N, Sorokin V P, Yagodkin I V 1978 Physical bases of heat pipes (rus.) Moscow, Atomizdat
[6] Trubitsyn A, Grachev E, Gurov V, Bochkov I, Bochkov V 2017 Proceedings of SPIE 10250 0V-1