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Application of carbon materials for creation of X-ray sources cathodes

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Abstract

This research is devoted to investigating the properties of X-ray tube models with massive carbon cathode: field emission cathode in DC-mode and pulsed explosive emission cathodes. Construction of device with field emission cathode is described. It is able to operate at non-ultrahigh vacuum conditions. Two types of ring explosive emission cathodes were examined: metal-ceramic with slits (of a comb-shaped kind) and carbon-ceramic. The installation which makes it possible to investigate demountable models of pulsed X-ray tubes was designed. Experiments show better performance of carbon pulse cathode. It generates greater dose rate, possesses shorter current pulse, longer lifetime. Developed devices can be used in medicine, flaw detection, scientific researches and security systems.

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Keywords: X-ray; cathode; carbon material; field electron emission; explosive electron emission; pulse power

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1. Introduction

Carbon materials get wide application range in modern technologies due to its unique properties. The combination of good electrical conductance and high thermal conductivity are essential for electronics. High melting point makes carbon indispensible for metallurgy. Advanced carbon-based materials posses good mechanical properties therefore carbon substitutes metal constructions. Since the end of the 20^{th} century the investigation of carbon-based materials application in vacuum devices has started. The main purpose of such studies is to replace the weakest element of device, filament. Alternative replacement of the hot cathode is a cold, or field emission, one.

Field emission cathodes have a numerous advantages such as reliability, low consumption, small size of the power supply. Carbon nanotubes (CNT) are believed to be the promising carbon-based material for field emission cathode. Due to its geometry features CNT are characterized by a great field enhancement factor. It allows emitter exploitation at low operating voltages. Also carbon materials have a good vacuum properties, high melting point, radiation resistance and low sputtering factor. On the other hand CNT have drawbacks: emission current limitation because of tubes evaporation and destruction under the heating and bombardment by residual gases ions. The last fact results in ultrahigh vacuum (UHV) condition requirement.

Another way to create field emission cathode is using of massive commercial carbon materials. In spite of low field enhancement factor this massive cathode is able to operate at the non-UHV conditions for a long time, emit current of milliampere-order, withstand heating and ion bombardment. Experiments in [1, 2] demonstrate successful application of commercial graphite as field emitter. Cathode reveals good performance at the technical vacuum conditions (10^{-4} – 10^{-2} Pa).

Results of aforementioned studies are used for creating of X-ray tubes with massive carbon cathodes. This article describes both pulsed X-ray tube and one working in DC mode.

2. X-ray tube with the field emission cathode

The next stage after experiments on studying of the carbon-based materials field emission properties is an attempt to create X-ray tube with the new type of cathode. At first, X-ray device working in DC mode is described. Developed vacuum device has axial symmetry and consists of anode, carbon cathode and extractor. The precursor of this construction is the axisymmetric tube with the filament [3]. The sketch of the developed X-ray tube is shown at the figure 1a. Cylindrical anode made of copper (fig. 1b) takes the central place. It's surrounded by the tubular cathode (fig. 1b) with the extractor at the top side (fig. 1c). The last electrode has the form of the ring with slits. Electron emission is obtained from the top side of the cathode under affection of extractor electric field. Beryllium output window in the cap of this devise provides irradiation without significant attenuation. Such geometry is characterized by high efficiency of radiation output because maximum of X-ray yields perpendicular to the window. Also it prevents anode material transport to the cathode surface. Explorations [4] show dependence of field emission cathode efficiency on the emitter shape. The electrostatic shielding of adjacent emitters affects on the cathode properties. The best characteristics are demonstrated by the ring-shaped cathode. Hence chosen electrodes construction is optimal for developed X-ray source and one is expected to be effective. Optimal geometry of electrodes was chosen after computer simulation (fig. 2b). Variation of gaps and dimensions resulted in system with maximal electron current on the anode surface.

Created X-ray tube is studied using experimental unit VUP-4M [5]. Two adjustable power supplies define device operation mode. Integral power source makes possible to change anode voltage in the range 0 – 12 kV. Another one provides alteration of extractor voltage from 0 to 10 kV with current or voltage stabilization. The former determines maximal X-ray photons energy and the latter creates the electric field in order to obtain electron field emission from the cathode surface. Figure 2a shows the circuit diagram of the device.

Experiments with X-ray tube included output radiation spectrum analysis. Obtained images demonstrate typical bremsstrahlung spectra and two characteristic peaks with 8,107 and 8,987 keV energies [6]. These values correspond to copper $K_{\alpha1}$ and $K_{\beta1}$ lines. It proves X-ray photons are formed on the anode surface, device operates properly (according to simulation).

During X-ray tube tests the dose parameters are measured by dosimeter AT-1123. Maximal dose rate 4 mSv/h obtained at 2 mA cathode current, 122 uA anode current and 12 kV anode voltage. Hence the transparency of the extractor is 6%.

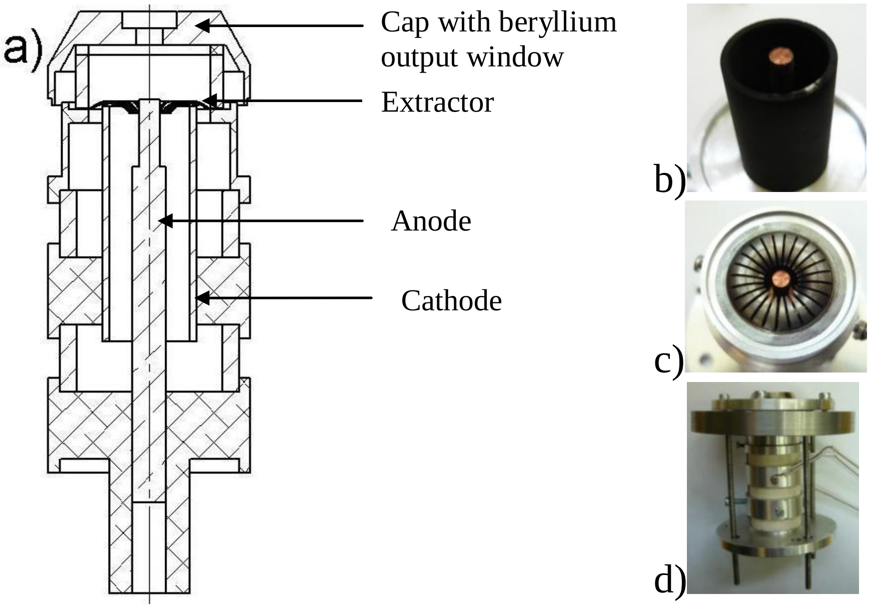

Figure 1. Model of X-ray tube with carbon field emission cathode:
a) sketch; b) anode surrounded by cathode; c) extractor; d) assembled device.

In order to assess the developed device functioning the X-ray images are obtained by means of registration system DRX1 (fig. 3). There is a resistor pin with the diameter of 0,7 mm situated close to the tube output window (8 mm diameter) on the picture. Detector is located right behind the object.

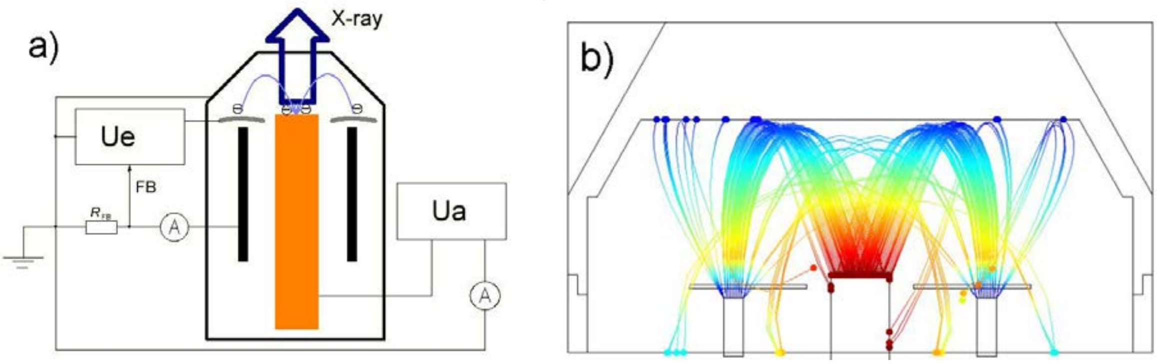

Figure 2. X-ray tube with field emission cathode
a) circuit diagram: Ue – extractor power supply; R_{FB} – feedback circuit for emission current stabilization; Ua - anode power source ;
b) electron trajectories simulation.

Considering previous experiments with carbon field emission cathodes [1, 2], the X-ray tube was tested at the increased pressure conditions. The vacuum level was changing from $3{,}2\cdot10^{-4}$ up to $3\cdot10^{-2}$ Pa by argon bleeding in system. Pressure alteration resulted in anode current and dose rate decreasing. Device demonstrates worse operation parameters at the technical vacuum conditions but it is still able to generate X-ray. The properties of X-ray tube were recovered after pumping and 30 minutes pause.

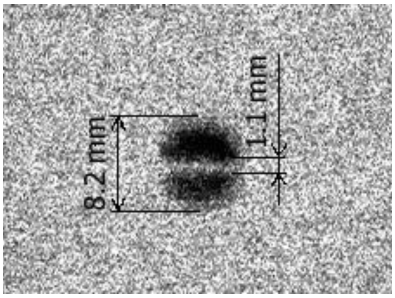

Figure 3. X-ray image of resistor pin with the characteristic dimensions. Overall spot size including penumbra is 8.2 mm.

3. Pulse X-ray tube with the explosive emission cathode

Another developed type of vacuum device with carbon cathode is pulsed X-ray tube. Its functioning is based on the explosive electron emission phenomenon [7]. Under affection of high pulsed voltage with the short pulse rise time the field emission transforms into explosive emission. When the emitter generates strong current and heats up itself thanks to Joule heat the emitting area explodes and plasma with extremely low work function is formed. This process is accompanied by a multiple increase in current, since electron current flows from the formed plasma, rather than from the cathode surface. Instead of several milliamps we obtain current of the hundreds amperes order.

This section presents studying of two types of annular explosive emission cathodes for X-ray radiators: metal-ceramic with slits (of a comb-shaped kind; the metal is tantalum) and carbon-ceramic cathode made of commercial graphite MPG-7 (high-strength and heat-resistant material made of coke-pitch compositions). All cathode systems consist of 2 details: metallic or graphite ring and ceramic disc. The former was set on the last, since such design of a cathode assembly makes it possible to obtain stable emission at multiple pulses. This can be explained by the fact that the breakdown initiation happens at a triple point, the place of metal/graphite-insulator-vacuum contact [8, 9]. As an insulator in X-ray tube models we use the vacuum ceramics VC-94. It's corundum-based material what contains about 94% of α-Al_2O_3. This ceramic material is characterized by good values of electrical resistivity and permittivity: 10^{13} Ohm·cm and 10 respectively. Figure 4 shows the photos of the cathodes under investigation, placed in the X-ray tube.

The operation of this device is provided by high-voltage generator with the voltage magnitude up to 150 kV, pulse duration of nanoseconds order and pulse power up to 10^8 watts [10]. Such generators can be used for gas laser pumping, X-ray radiator power supply and also can have various scientific applications.

The experiments are carried out using specially designed installation. It consists of vacuum system (residual pressure is $2 \cdot 10^{-3}$ Pa), pulse generator and measurement system (dosimeter and oscilloscope). The last section is used for observing parameters and characteristics of pulsed X-ray tubes in order to evaluate the tube lifetime and determine the optimal design for the pulsed X-ray tube. This installation allows investigating different types of tubes as well as the demountable models of pulsed X-ray tubes.

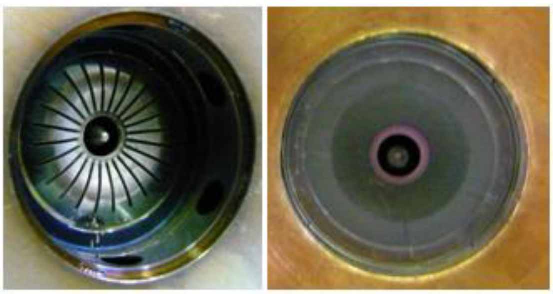

Figure 4. Photographs of X-ray irradiators with different cathodes: left – comb-shaped, right – carbon-ceramic

Experimental data acquisition includes registration of waveforms for tube current and voltage pulses as well as dose rate measurement. This information is obtained for different modes of X-ray tube operation depend on primary supply circuit voltage. This parameter defines the energy of generator pulse.

Figure 5 demonstrates the waveforms of voltage and current pulses for the cathodes under investigation. For each specimen images corresponding to three different voltages determining the charge of the generator first circuit capacitor are presented. The values of these voltages are 175 V, 200 V, 220 V. On the figure one can find averaged plots of the tube current and voltage during the exposure time of 3 seconds and pulse repetition frequency of 200 Hz.

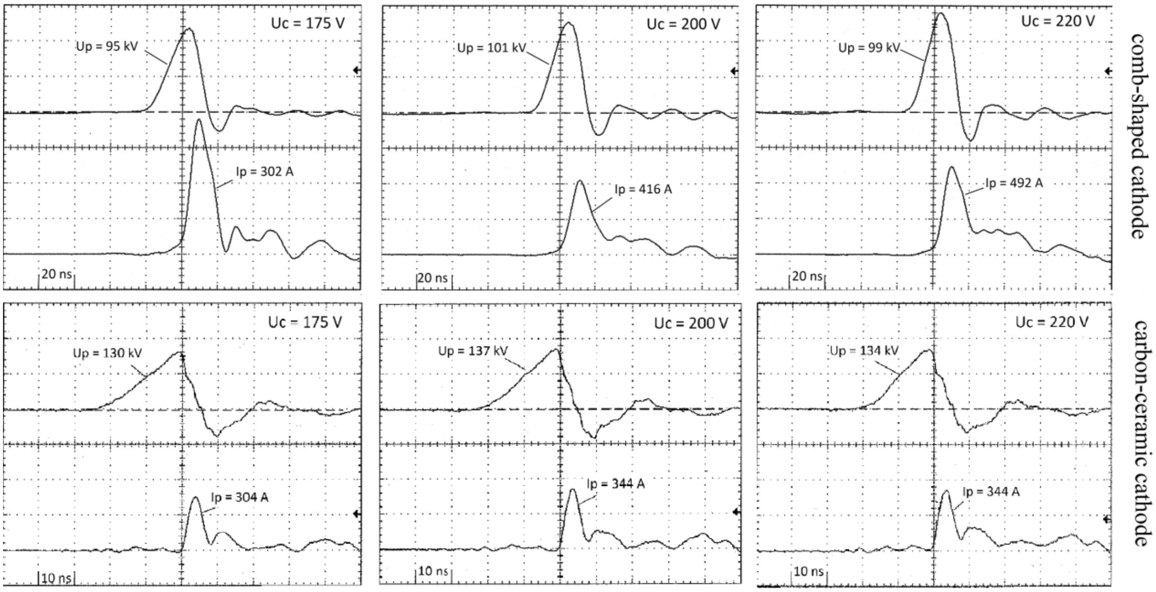

Figure 5. Waveforms of current and voltage pulses

Experimental data processing identified the following features. Electron emission threshold voltage changes at different values of primary voltage. The X-ray tube with a comb-shaped cathode demonstrates lower voltage corresponding to emission initiation (88 kV) compared to another cathode. And it doesn't depend on pulse rise time. The reversed situation can be observed when we deal with the graphite cathode, i.e. the voltage falls from 122 kV to 100 kV while the anode voltage rising increases from 6,2 kV/ns to 8,6 kV/ns.

As concerns dose rates, it was measured at the pulse repetition frequency of 200 Hz and exposure time of 3 s. Distance between irradiator and detector is 40 cm. For the comb-shaped cathode the dose rate was 21 μSv/h and for the graphite-ceramic it was 30 μSv/h. Thus when we use the graphite cathode in the tube we can reduce the generator power in order to get radiation doses respective to the other cathode.

The following interesting result is variation of the X-ray tube current duration at half-maximum. As for the comb-shaped cathode this duration is about 13 ns, while for the graphite cathode it is about 5 ns. When using a carbon-ceramic cathode the current pulse gets compressed in time much more then in case of metal one. Thus operation stability of this cathode should be higher thanks to better duty cycle and decreasing heating.

4. Conclusion

Carried out studies of massive carbon materials emission properties resulted in development of X-ray tubes with field emission and explosive emission cathodes made of commercial graphite. Operating parameters of these devices were investigated. Dose rate of 4 mSv/h was obtained for field emission device in DC -mode. X-ray image of resistor pin was registered with the digital X-ray detector. Also X-ray tube was tested under non-UHV conditions.

Properties of device degraded at increased pressure of residual gases but normal functioning was recovered after pumping and 30 minutes pause. Developed model demonstrates opportunity of massive carbon materials application for creation of vacuum device field emission cathode. Such type of cathode shows reduced vacuum level requirements and can operate at non-UHV.

As to pulse X-ray sources, two types of pulsed explosive emission cathodes for X-ray tube were tested: comb-shaped and carbon-ceramic. All cathodes operate stably. The research demonstrates that using explosive emission cathodes based on carbon materials – carbon-ceramic cathodes – is very promising. It exceeds competitors in a number of parameters. Firstly its radiation dose rate is higher than for other and is 30 μSv/h at the pulse-repetition frequency of 200 Hz and exposure time of 3 s. Secondly it possess higher threshold voltage, subsequently greater radiation energy. Thirdly current pulse is shorter by 2,5-3 times lower, hence electrodes experience less heating and have longer lifetime.

Developed types of X-ray tubes have wide application: medicine, flaw detection, scientific researches and security systems. Pulse cathodes are planning to be used for portable pulsed X-ray apparatuses, which make it possible to reduce radiation doses for patients significantly [11].

Acknowledgements

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