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## ELECTRON AND ION EMISSION

# A New Class of Portable X-ray Apparatuses Based on Carbon Nanocluster Cathodes

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**Abstract**—Principles of the development of high-power pulsed X-ray sources based on explosive emission from carbon nanoclusters are stated. Designs and main parameters of the developed X-ray tubes ( the electron flow exciting the X-ray radiation is 100–500 A, the voltage is 20–150 kV, the pulse length is 10–20 ns, and the nanosecond pulse repetition rate is $1-10^3$ Hz) are reported.

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## INTRODUCTION

The discovery of explosive electron emission (EEE) has opened fundamentally new possibilities for the design of nanosecond X-ray sources.

It was established that reproducible explosive emission requires special conditions [1, 2]. Understanding of the operating conditions of EEE cathodes made it possible to develop X-ray tubes with long operation life (more than one million switchings). The overwhelming majority of pulsed X-ray tubes use refractory metal cathodes (Mo, W, etc.).

Direct experiments showed [1] that, during EEE, nanometer protrusions and coarse (micron) formations arise on the metal surface. Coarse (micron) protrusions lead to the main erosion of the cathode surface during EEE, transfer of the substance in the cathode–anode spacing, dusting of the anode, and many other harmful phenomena. Recently, it has been demonstrated that carbon is the most promising material for EEE cathodes [1, 3].

In this study, we investigate a new class of X-ray tubes based on different carbon nanoclusters. The X-ray tubes with carbon-based cathodes are characterized by long operation life and significantly wider range of X-ray radiation wavelengths. During operation, the carbon EEE cathodes contaminate the anticathode and other X-ray tube elements to a much lesser extent. During EEE from the carbon materials, substance transfer decreases by more than an order of magnitude. Carbon, being a lighter material with small atomic number, provides much weaker X-ray absorption upon dusting of the output window.

## 1. EXPLOSIVE ELECTRON EMISSION

Explosive electron emission is a special emission process that occurs when nanovolumes of the cathode material explode in a strong electric field under the action of high densities of the field-emission current [1, 2].

This phenomenon was independently discovered by two teams of researchers: G.N. Fursey et al. in studying the ultimate field-emission current densities and the physical mechanism of the vacuum breakdown and the cathode spot of the vacuum arc [4] as well as G.A. Mesyats et al. in the course of observation of the dynamics of development of optical phenomena during the vacuum breakdown with the nanosecond resolution [5].

In [4], based on numerous experiments on explosion of tip field emitters, we proposed a model of initiation of the vacuum breakdown, development of emission processes, and transition to the vacuum arc. In [5], the validity of this model was confirmed for macroscopic electrodes.

The EEE process is quasi-steady-state and is maintained by sequential generation and explosions of new microasperities on the cathode surface.

The important role in maintaining the EEE and ensuring its stationarity is played by the liquid phase. The liquid phase is formed on the cathode surface upon explosion of the substance; these liquid cathode parts interact with the strong electric field and the EEE plasma and form nanometer waves whose ridges work as new centers of the explosive emission [1, 2, 4].

Hardening of these nanoprotrusions leads to formation of microroughnesses, which ensure repeated excitation of the EEE process at further switchings of electric field pulses.

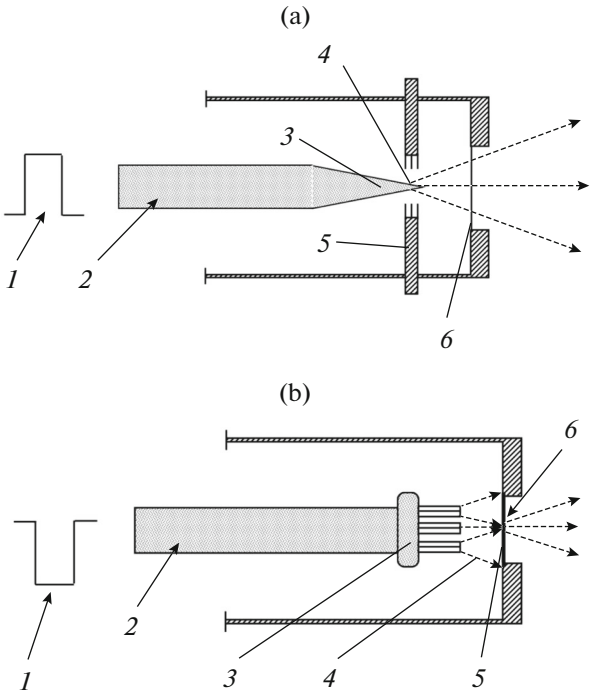



**Fig. 1.** Designs of pulsed X-ray tubes. (a) A pulsed X-ray tube with a pointed anode: (*1*) polarity of the voltage pulse, (*2*) high-voltage input, (*3*) tungsten anode, (*4*) X-ray spot, (*5*) PAN fiber cathode, and (*6*) output window of the beryllium tube. (b) Through-anode pulsed X-ray tube: (*1*) polarity of the voltage pulse, (*2*) high-voltage input, (*3*) multi-point carbon fiber cathode, (*4*) electron beam, (*5*) tube output window (anode), and (*6*) X-ray spot.

Carbon exhibits unique properties as to forming and retaining the nanoprotrusions. It was found that, during the EEE, carbon also passes to the liquid state [1, 2]. This means that the pressure at the explosion epicenter is very high.

An advantage of the carbon material is that nanoprotrusions can be far better kept on its surface. It may be assumed that these nanoprotrusions harden after the EEE process due to decreasing pressure above the formed microrough carbon surface during the plasma spread, rather than as a result of cooling of local cathode areas. Since the pressure drop occurs much faster than cooling, much smaller protrusions can be retained on the surface after switching-off the field as compared to metals. This provides more homogeneous emission and lowers the strength of the electric field required for exciting the EEE.

## 2. LOW-THRESHOLD FIELD EMISSION AND EXPLOSIVE ELECTRON EMISSION

In recent years, a specific property of carbon nanoclusters has been found [6]. It was found that the threshold of excitation of the field emission from these materials is very low. In particular, the fields of the onset of field emission are lower by 2–3 orders of magnitude than in metals and semiconductors.

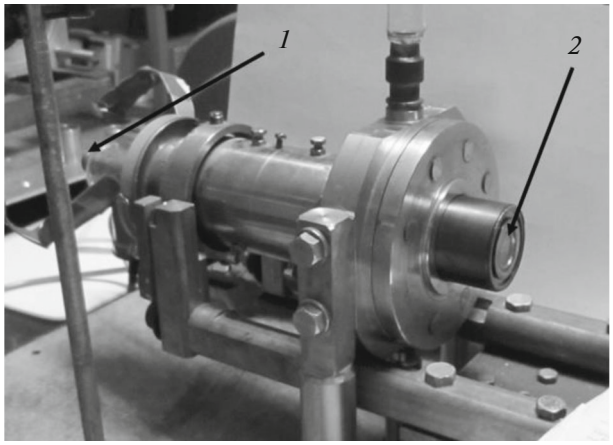



**Fig. 2.** Prototype of the X-ray tube: (*1*) high-voltage input and (*2*) output window.

As was shown above, the main EEE excitation mechanism is the explosive disruption of local cathode areas under the action of the field-emission current with a very high density. Since, in carbon nanoclusters, the excitation threshold of the field emission is much lower, the EEE is excited in lower fields and at lower voltages [6].

## 3. CREATION OF AN X-RAY SOURCE

In this study, we used two variants of the X-ray source: the source with a pointed tungsten anode (Fig. 1a) and the through source with an anode in the form of a tungsten layer deposited onto the output window (Fig. 1b). As the cathode, carbon polyacrylonitrile (PAN) fibers were used.

A prototype of the tube for studying the characteristics of the X-ray source is shown in Fig. 2.

In this prototype, the cathode can be moved relative to the anode using a micrometer screw. The material of the output window is Be. The high-power feeding is provided using special nanosecond generators.

The EEE dynamics was studied with a generator of paired nanosecond pulses and FID Technology generators. The pulse length varied from 10 to 80 ns. The spacing between pulses in the generator of paired pulses could be changed from 2 to 300 ns and the pulse front was 2–3 ns. In the experiments, the pulse amplitude was varied from 15 to 150 kV. The residual pressure in the experimental vacuum chamber was $10^{-8}$–$10^{-9}$ Torr.

The generator of paired pulses allowed determining the minimum relative pulse duration and, correspondingly, the maximum operation frequency of the EEE cathode. The maximum pulse repetition rate for EEE from carbon nanoclusters was 1 kHz.

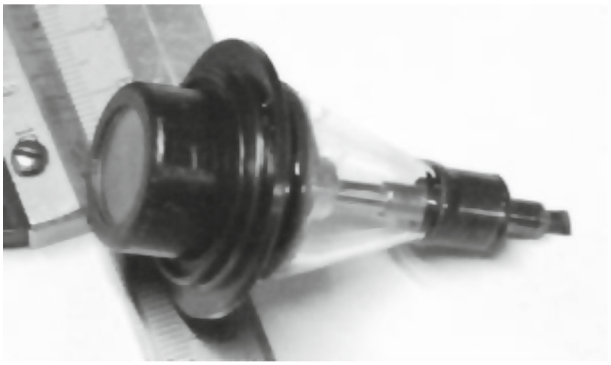


**Fig. 3.** Photograph of the X-ray tube with a glass insulator.

## 4. AUTONOMOUS X-RAY TUBES AND THEIR PARAMETERS

Based on the performed investigations, we designed experimental models of autonomous sealed-off X-ray tubes. One of the samples with a glass insulator is presented in Fig. 3.

The anode is a wedge-shaped tip tungsten rod with a curvature radius of 0.4 mm at the tip. The output window 20 mm in diameter is formed from Be with a thickness of 400–1000 μm. This window leads to insignificant filtration of the low-energy part of the generated radiation.

The residual pressure in the sealed-off tube is about $10^{-7}$–$10^{-8}$ Torr.

The electron current in the tube was determined using a special matched coaxial shunt in the return current circuit and oscillographic measurements. The electron current in the diode is limited by the space charge and is described by the Child–Langmuir law. The current pulse shape in metals is determined by the three-halves power law in a diode with the moving emission boundary [5].

When studying the emission from carbon cathodes, we found out that the motion of the plasma front during the spread almost does not affect the current pulse shape. The current pulse is nearly rectangular. This behavior is caused by the fact that the amount of plasma generated during the EEE from carbon nanoclusters is very small and the plasma spread does not affect the current variation in the vacuum gap between the cathode and the anode.

Depending on the voltage, the maximum currents in the tube were 30 A at $U = 20$ kV and 200 A at $U = 75$ kV.

## 5. DETERMINING THE SIZE OF THE FOCUS SPOT AND THE DIVERGENCE OF THE X-RAY BEAM

The divergence of the X-ray beam depends on the configuration of the EEE cathode and geometries of the cathode-anode space and the X-ray exit part opaque for the X-ray beam. The divergence could also be varied by a special external collimator.

The divergence in the tubes with a pointed anode designed for different applications, including medicine, was about 60°. This fact allowed us to obtain panoramic images with dimensions of 40 × 40 cm at a standard distance of 70 cm.

The size of the X-ray spot was determined using a Loch camera and, in some experiments, a Kumakhov polycapillary column [7].

Optimization of the electrode geometry in tubes with a pointed anode yielded a minimum X-ray spot size of 0.8 mm.

(a)


(b)

(c)

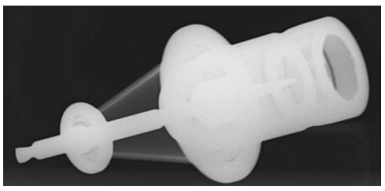
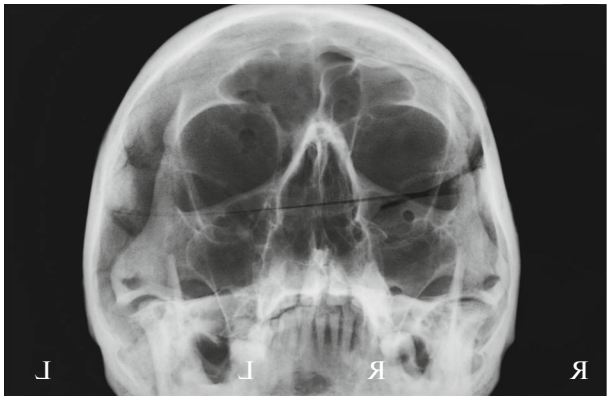


**Fig. 4.** (a, b) Experimental X-ray apparatus (OOO Positivnaya Energiya) and (c) X-ray diffraction pattern of the X-ray tube.

## 6. PORTABLE X-RAY APPARATUSES

Using the developed tube with a PAN-fiber carbon cathode, we fabricated an X-ray apparatus (Fig. 4) with an accelerating voltage of 15–150 kV, a beam current of 50–500 A, a pulse length of 10 ns, a pulse rep-

(a)



(b)

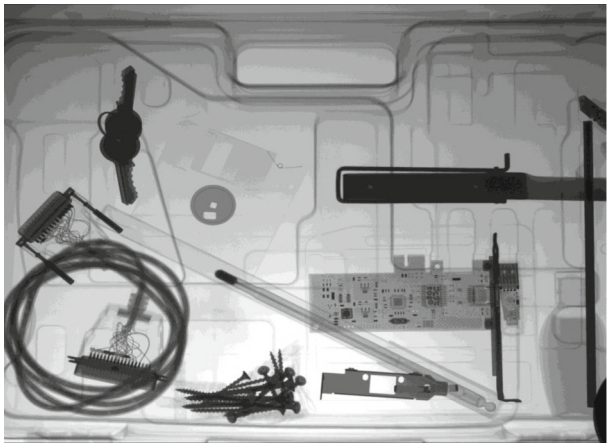


**Fig. 5.** Samples of X-ray diffraction patterns: (a) skull and (b) different elements in a case.

etition rate of 1000 Hz, an X-ray spot size of 0.8 mm, and a mass of 3–6 kg.

The X-ray diffraction patterns obtained using this apparatus are presented in Fig. 5.

## CONCLUSIONS

(1) High efficiency of the EEE cathodes based on carbon nanoclusters has been established. It has been shown that such EEE cathodes can be used in a wide range of operating voltages.

(2) It has been experimentally demonstrated that the EEE cathodes based on different carbon nanoclusters are promising candidates for application in pulsed X-ray tubes. Designs of the pulsed X-ray tubes for portable X-ray apparatus were developed.

(3) It has been shown that this new class of X-ray sources makes it possible to obtain high-power nanosecond X-ray beams in a wide wavelength range.

(4) The possibility of operation of the developed X-ray tubes in a wide range of values of the nanosecond X-ray pulse repetition rate (up to one thousand hertz) was experimentally established.

(5) Designs of X-ray tubes that ensure an X-ray spot size smaller than one millimeter in the output window of the tube were developed.

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