

RESEARCH INTO CHARACTERISTICS OF X-RAY EMISSION LASER BEAMS FROM SOLID-STATE CATHODE MEDIUM OF HIGH-CURRENT GLOW DISCHARGE

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ABSTRACT

X-ray emissions ranging 1.2 – 3.0 keV with intensity up to 0.01 J/(s·2 π) have been registered in experiments with high-current Glow Discharge. The emissions energy and intensity dependence of the cathode material used, kind of plasma-forming gas and the discharge parameters has been studied. The experiments were carried out on the high-current glow discharge device using D₂, H₂, Kr and Xe at pressure up to 10 Torr, as well as cathode samples made from Al, Sc, Ti, Ni, Nb, Zr, Mo, Pd, Ta, W, Pt, at current up to 500 mA and discharge voltage of 500-2500 V. Two emission modes were revealed under the experiments: 1 - Diffusion X-rays was observed as separate X-ray bursts (up to 5·10⁵ bursts a second and up to 10⁶ X-ray quanta in a burst); 2 - X-rays in the form of laser microbeams (up to 10⁴ beams a second and up to 10¹⁰ X-ray of quanta in a beam, angular divergence was up to 10⁻⁴, the duration of the separate laser beams must be $\tau = 3 \cdot 10^{-13} - 3 \cdot 10^{-14}$ s, the separate beam power must be 10⁷ – 10⁸ W). The emission of the X-ray laser beams occurred when burning the discharge and within 100ms after turning off the current. The results of experimental research into characteristics of secondary penetrating radiation occurring when interacting primary X-ray beams from a solid-state cathode medium with targets made of various materials are reported. It was shown that the secondary radiation consisted of fast electrons. The secondary radiation of two types was observed. 1- The emission with a continuous temporal spectrum in the form of separate bursts with intensity up to 10⁶ fast electrons a burst. 2- The emission with a discrete temporal spectrum and emission rate up to 10¹⁰ fast electrons a burst. A third type of the penetrating radiation was observed as well. This type was recorded directly by the photomultiplier placed behind of the target without the scintillator. The abnormal high penetrating ability of this radiation type requires additional research to explain. The obtained results show that creating optically active medium with long-living metastable levels with the energy of 1.0-3.0 keV and more is possible in the solid state.

1. INTRODUCTION

The experiments on defining a possible mechanism of high energy phenomena in the solid-state cathode medium of the high-current glow-discharge were carried out before. The experimental results showed that the character of the detected X-ray radiation essentially differed from the known X-ray emission types. It caused importance of the researches into the performances of the detected X-ray radiation from the solid-state medium of the cathode sample material of the high-current glow discharge.

The penetrating radiation passing through the discharge chamber walls made of steel with thickness of 5 mm was recorded under the experiments with the high-current glow discharge. (Fig. 1.) [2]. The experiments showed that it was the secondary radiation occurring when interacting the primary X-ray laser beams from the solid-state cathode medium with the material of the chamber walls and construction elements, lead protective shields [1]. The created 100 % - reproducible technology of generating the X-ray laser beams allowed carrying out the research into the performances of the secondary penetrating radiation.

2. EXPERIMENT METOD AND RESULTS

The experiments were carried out with the device of the high-current glow discharge using deuterium, hydrogen, Kr and Xe. The cathode samples made of Pd and other metals were disposed on the cathode-holder above which a window for output of penetrating radiation was placed. The window was closed by 15 μ m Be foil for protecting the detectors against visual and ultraviolet radiation (Fig.1). The pulse- periodic power supply of the glow discharge with a rectangular shape of a current pulse was used. Duration of the discharge current pulses was 0.27-10.0 ms, the impulses following period was 1.0-100 ms. The discharge was carried out in D₂, Xe, Kr. The X-rays recording was carried out with use of the thermo-luminescent detectors, X-ray films placed above the cathode at various distances, scintillation detectors supplied with photomultipliers [1].

Thermoluminescence detectors are non-sensitive to electrical pickups and allow registering the absorbed radiation dose quantitatively in the absolute units of dose measurement. The thermoluminescence detectors (TLD) by the base of Al₂O₃ crystal, which allow registering values of penetrating radiation beginning from the background values of radioactive radiation of the environment, were used with the purpose of the intensity measurement and evaluation of the average energy of a soft X-ray emission in the discharge. For determination of the average energy the special cassette (seven-channel spectrometer) was used. The seven channels with diameter of 5mm were made in the cylindrical body of the cassette. The detectors in the form of disks with the diameter of 5mm and thickness of 1mm were arranged in the body holes. The set of the beryllium foils having thickness 15 μ m, 30 μ m, 60 μ m, 105 μ m, 165 μ m, 225 μ m, 225 μ m, 300 μ m (in the each hole the foil having the special thickness was arranged) was arranged on the

side of emission input in the body holes. Two TLD detectors were arranged outside the camera for the registration of background value of the emission dose.

The pinhole camera gives a spatial resolution of X-ray emission and an opportunity to determine where the radiation emerges from.

The time characteristics of the penetrating radiation were determined with use of the scintillation detectors supplied with the photomultipliers (PM). The signal from PM was transferred to a fast preamplifier with an amplification constant of $k = 7$ and then to the two-channel computer digital oscillograph with the limit resolution frequency of 50 MHz per a channel. Organic scintillators on the base of polymethylmetacrelate (PMMA) with luminescence time of 3 – 5 ns were used. The time resolution of the entire path from PM up to an oscillograph (experimentally) was 70 – 80 ns. Electrical noise was observed only when passing the front and back fronts of the current impulses feeding the glow discharge.

Three various variants of assembling the discharge chamber with the channel for the radiation extraction was used (Fig.1). In the first variant PM - scintillator detector was placed at a distance of 21cm from the cathode surface (Fig. 1a). The channel diameter for extracting the radiation was equal 1.7 cm. In the second variant PM - scintillator was placed at a distance of 70 cm from the cathode, and the diameter of the channel for extracting the radiation was 3.2cm (Fig. 1b). For defining the penetrating radiation type, the third variant of the experimental assembly included the magnetic system consisting of a constant magnet and an elliptic iron magnetic circuit (Fig. 1c). The axis of the magnetic system poles was at a distance of 35cm from the cathode perpendicularly to the axes of the radiation extraction channel. The magnetic field induction in the gap between poles was 0.2 T.

For the determination of quantitative registration characteristics the thermoluminescence detectors were calibrated in the gamma - emission fields.

The experiments were carried out using the following systems of cathode – plasma-forming gas: Pd – deuterium. The obtained results show that the doses obtained by the corresponding detectors decrease exponentially with increasing the thickness of Be foil.

The main component of the X-ray emission energy is in the range of 1.0-2.5 keV, but there is a component with a higher energy too.

X-ray intensity was registered for the different values of current and voltage.

The procedure of recording and measuring was developed as applied to two modes of the X-ray emission: a mode of the diffusion radiation bursts, generation of X-rays as laser microbeams.

The intensity of the luminous flux from the scintillator in the mode of generating the X-ray laser beams was approximately 1000 times as much as the intensity of the luminous radiation of the scintillator in the mode of the diffusion bursts. In this case the amplification constant of the radiation recording system changed by changing the supply voltage of the photomultiplier and changing the

amplification constant of the oscillograph. Under some experiments the luminous-absorbing filter attenuating the luminous flux coming to PM was installed between the scintillator and PM. Two types of the filters attenuating the luminous flux by 50 times and by 2500 times respectively were used.

The intensity of the X-rays (number of photons a second) coming to the detector was determined by dividing the energy radiation power absorbed by the detector by the energy of an X-ray photon. Further the intensity falling to one detector was given to 2π solid angle.

For the PM scintillator detector the relative intensity of the X-rays was determined as the total of the amplitudes \square_{Ai} of all the X-ray bursts within the time interval of 1 second (Fig.2). Then the relative intensity was given to a physical magnitude by the intensity value measured by the TLD detectors.

The experiments with using the system of the scintillator – PM and shields made of the beryllium foil with thickness of 15 \square m and 30 \square m gave the assessment of the X-rays energy value of $E_{X\text{-ray}} \square 1.0 - 2.5$ keV (for different cathode materials, table 1), that matched to the TLD detectors results well.

The dependence of changing the radiation intensity on the distance was determined using the experimental devices according to the diagrams in Fig.1a and Fig.1b. Magnification of the distance between the scintillator – PM detector and the cathode from 21cm up to 70cm resulted in reducing the radiation intensity more, than under the law $1/r^2$ (Fig.3). Such result could be explained to the fact the radiation indicatrixes of the separate bursts had the elliptic shape with enough narrow angular orientation. The high intensity of X-ray emission allowed obtaining an optical image of the emission area. The pinhole camera with the hole with the diameter of 0.3mm (as an optical lens) was used. The image shows that the cathode area with the diameter of 9mm and especially its central part has the largest luminance (Fig.8).

Generating the X-ray laser beams occurred at the exactly fixed parameters and conditions of the discharge burning.

1-The generation occurred only at supplying by the pulse- periodic current (there is no generation at the direct current, X-ray as the bursts of the diffusion radiation ran also at the direct current).

2- Some critical parameters of occurring the generation by the gas pressure of P_{GD} in the discharge chamber and by the voltage of the discharge burning U_{GD} . The generation occurred at $P_{GD} < P_{GDcrit}$, $U_{GD} > U_{GDcrit}$. Little change of the discharge pressure or voltage led to occurring the generation (by pressure the change was $\square P_{GD} = 0.2-03$ Torr, by voltage $\square U_{GD} = 30-50$ V).

3- These parameters were different for various cathode materials (for example, when using Pd cathode, the X-ray laser generation occurred at pressure being twice as much as when using Ti cathode).

4- The parameters of occurring the X -ray laser generation depended also on the plasma-forming gas.

5- When operating, the generation intensity decreased in due course (obviously because of degradation of the cathode surface) and stopped in the course time. This phenomenon was especially well observed for the cathode materials with a large coefficient of a material spattering in the discharge plasma (for example Al, Pd, Pb).

Table 1.

Material of Cathode	Al	Sc	Ti	Ni	Mo	Pd	Ta	Re	Pt	Pb
Glow discharge voltage, V	1650	1540	1730	1650	1420	1650	1600	1520	1650	1610
Glow discharge current, mA	130	130	170	150	210	138	138	125	138	138
X-ray energy during current, E_{X-ray} , keV	1.54	1.26	1.45	1.91	1.48	1.98	1.62	1.36	1.47	1.36
X-ray energy after current, E_{X-ray} , keV	1.68	1.5	1.46	1.96	1.33	1.71	1.62	1.38	1.75	1.45
X-ray energy flow density, \square , $\square 10^{-4}$ W/cm ²	1.2	1.7	3.18	1.2	1.36	1.4	2.13	0.74	1.9	1.7
Number of X-ray pulses per s, N_p , $\square 10^5$ pulses/s	3.8	3.7	6.0	3.4	2.7	4.0	5.1	2.2	4.4	4.4
Max energy of one X-ray pulse, E_{max} , $\square 10^{-10}$ J	1.2	1.5	1.9	1.5	1.5	1.3	1.4	1.1	1.6	1.3
Number photons in one pulse, n , $\square 10^5$	0.50	0.74	0.83	0.49	0.63	0.41	0.55	0.87	0.68	0.94

The X-rays as laser beams consisted of the separate beams, presumably, having a small diameter (up to $10^6 - 10^{10}$ photons in a beam). These magnitudes were obtained in assumption that the system of the scintillator – PM operated in the linear area, taking into account the magnitude of reducing the amplification constant of the path when recording the X-ray laser radiation. The X-ray laser beams emission occurred during the discharge burning and within up to 100 ms after turning off the current. At the specific parameters of the discharge the generation of the X-ray laser beams was observed only some ms later after turning off the discharge current (up to 20-30 beams after each current pulse). The time oscillograms type of the generated beams depended on the type of the plasma-forming gas (Fig.4) and type of the cathode materials (Fig.5). In this case the amplification constant of the path of recording the radiation was enough large and the upper part of pulses was cut off by the amplifier discriminator. The real form of the radiation pulses was observed using the luminous-absorbing filter reducing the luminous flux from the scintillator to the photomultiplier by 2500 times (Fig.9).

The estimation of the X-ray laser beams divergence was carried out under the experiments with use of the experimental devices according to the diagrams in Fig.1a,b. The magnification of the distance from the cathode up to the system of the scintillator – PM from 21cm up to 70cm resulted in inappreciable reducing the signal (Fig.9b). These results proved to be true when using 50- multiple optical filters (Fig.9c).

The experiments with superimposition of the cross magnetic field showed, that radiation had two components (Fig.7c.) The X-ray laser beams were not diverged in the magnetic field and recorded by the scintillator – PM detector. The other part of the radiation did not hit on the detector. Hypothetically, this part of the radiation was fast electrons with the energy of $\approx 0.5\text{MeV}$. The fast electrons beams can be formed when interacting the primary X-ray laser beams with the walls of the channel for extracting the radiation.

The tracks images of the X-ray laser beams were obtained using the X-ray film placed above the cathode at various distances. The diameter of the laser beams tracks was 6 - 10 μm at a distance of 100mm from the cathode and up to 20 – 30 μm at a distance of 210 mm (Fig.8). High radiation intensity and the process of the photo emulsion solarization gave the positive tracks image. The angular divergence of each beam was estimated up to 10^{-4} (by the results of measuring the tracks diameters at various distances from the cathode).

3. SECODARY PENETRATING RADIATION

The experiments were carried out with the device of the high-current glow discharge [1] with use of H_2 , D_2 , Kr, Xe at pressure up to 10Torr and the cathode samples made of Al, Sc, Ti, Ni, Nb, Zr, Mo, Pd, Ta, W, Pt at current up to 500mA and the discharge voltage of 500-2500V. The pulse-periodic power supply of the glow discharge with the pulses duration of the discharge current of $t = 0.3 - 1.0\text{ms}$ and period of $T = 1.0 - 100\text{ms}$ was used. The targets as the shields made of various materials foil (Al, Ti, Ni, Zr, Yb, Ta, W, Pb) with thickness of 10-30 μm and of 1.0-3.0 mm were arranged at a distance of 21 and 70cm from the cathode (Fig.10a,b). The scintillation detector supplied with the photomultiplier was used for recording the secondary radiation. The device with a channel for extracting the radiation with the length of 70 cm and the magnetic system creating a cross magnetic field relatively to the radiation axis at a distance of 35cm from the cathode was used for defining the type of the secondary radiation (Fig.10c).

The procedure of the secondary penetrating radiation registration and calibration of the detector was similar to the procedure of registration the primary radiation beams [1].

Under the experiments the recording of the time radiation spectrums was carried out within the time between the back and forward fronts of the discharge current (being free of the discharge current).

The radiation type was defined with the device with a channel for extracting the radiation with the length 70cm when being free of the cross magnetic field and the imposed magnetic field was available (Fig. 10c.).

When being free of the magnetic field, considerable attenuation of the scintillator PM detector signal was not observed when increasing the distance from the cathode to the detector from 21 cm to 70 cm (Fig. 11a). Superimposition of the magnetic field with an induction of 0.2T led to complete disappearing of the

signal on the scintillator PM detector (Fig. 11b). Thus, the secondary radiation was the flux of the charged particles (presumably fast electrons) with a small angular divergence.

When increasing the distance from 21 cm to 70 cm, the primary X-ray laser beams kept an ability to generate the secondary radiation when interacting with the targets made of various materials (Fig.12b, 12c.). These results were the additional confirmation of the fact that the X-ray laser beams had a small angular divergence.

The type of the oscillograms of the primary radiation bursts was defined by the cathode material (Fig. 12a). The secondary X-ray radiation of two types was observed. 1) - radiation with a continuous time spectrum as separate bursts with intensity up to 10^6 photons per a burst. This emission began 0.5-1.0 ms later after turning off the discharge current. 2) - radiation with a discrete time spectrum and radiation intensity up to 10^9 photons per a burst. Distribution of the bursts by the time of this radiation was defined by the target material (Fig.12b,c).

The results of recording the radiation bursts were used for the time spectrums construction. The dependence of the radiation bursts amount on the time interval between the back front of the discharge current impulse and forward front of the radiation bursts was under construction. The time spectrum of the primary X-ray laser radiation had a discrete character. The type of the time spectrum of the primary X-ray was defined by the cathode material. Separate bursts were recorded within 85 ms after turning off the current. The time spectrum of the secondary radiation also had a discrete character, but the type of this spectrum was defined by the target material. The generation of the secondary penetration radiation is supposed to occur from solid medium of the lead shield. Also this secondary radiation is registered using the X-ray film arranged behind the lead shield (Fig.13).

The third type of the penetrating radiation was observed as well. This type of the radiation was recorded directly by the photomultiplier placed behind of the target without the scintillator. In this scheme the target was arranged between the shield with the thickness of 3 mm made of plastic and PM detector. The type of the secondary radiation was defined by the detector material. This emission began 20 minutes later after turning on glow discharge current and emitted after turning off the discharge current of 20 minutes and more (Fig.14). An abnormal high penetrating ability of this radiation type requires additional researches.

4. DISCUSSION

The features of the X-rays recorded under these experiments are the following:

- - The X-rays leaves the solid-state medium of the cathode material.
- - The intensity of the X-rays increases by 5 – 6 times when increasing the discharge voltage by 1.3 – 1.4 times.
- - The quantity of the X-rays energy is not changed essentially in this case.

- - The X-rays emission occurs within 100 ms after turning off the discharge current.

The obtained results are the direct experimental proof of existing the excited metastable energy levels with the energy of 1.5 – 2.5 keV in the solid of the cathode sample. Presumably, these excited metastable levels are formed in the volume of separate crystallites. These excited metastable levels exist for the time of τ_{mst} (up to 100 ms and more). Then the relaxation depopulation of these levels takes place, being accompanied with the emission of the X-rays and fast electrons. These beams generation occurs from the solid-state cathode medium presumably for one passing in the mode of super luminescence. In this case the duration of the beams should be of $10^{-11} - 10^{-13}$ s.

Clearing up the concrete physical mechanism of these levels formation requires the additional researches. Existing one of the two possible physical phenomena can be assumed.

- - 1-vibrational deformation of the electron-nuclear system of the solid ions. The core of electronic shells is displaced relative to a nucleus with forming a dipole (an optical polar phonon). The frequency of the formed phonon is much greater than the plasma frequency in a metal.
- - 2-excitation of the interior L, M electronic shells without ionization of the outer electrons.

5. CONCLUSION

The experimental research of this fundamental phenomenon has allowed to create an essentially new type of the device: “The X-ray solid-state laser with a wavelength of the radiation of 0.6 – 0.8nm, duration of separate pulses of 10^{-11} - 10^{-13} s and beam power in pulses up to 10^7 W ”. The obtained results show that creating optically active medium with long-living metastable levels with the energy of 1-3 keV and more is possible in the solid.

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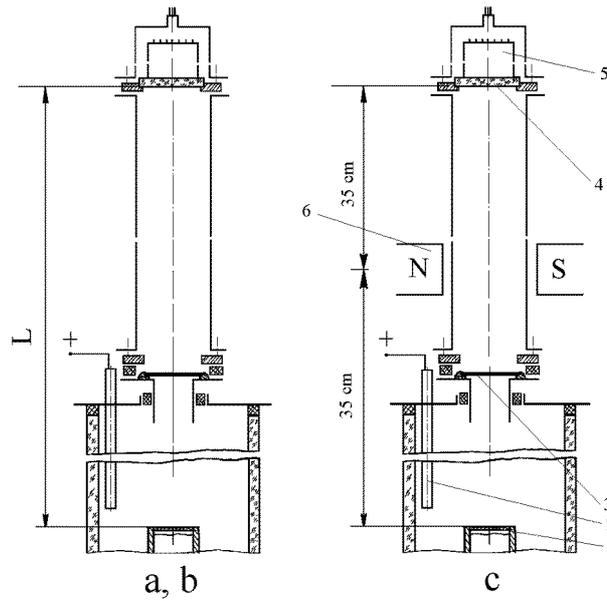


Fig. 1. Various variants of the experimental device: a- system of a scintillator – PM placed at a distance of 21 cm from the cathode, b- system of a scintillator – PM placed at a distance of 70 cm from the cathode, c- system of a scintillator – PM placed at a distance of 70 cm from the cathode with superimposition of the cross magnetic field.

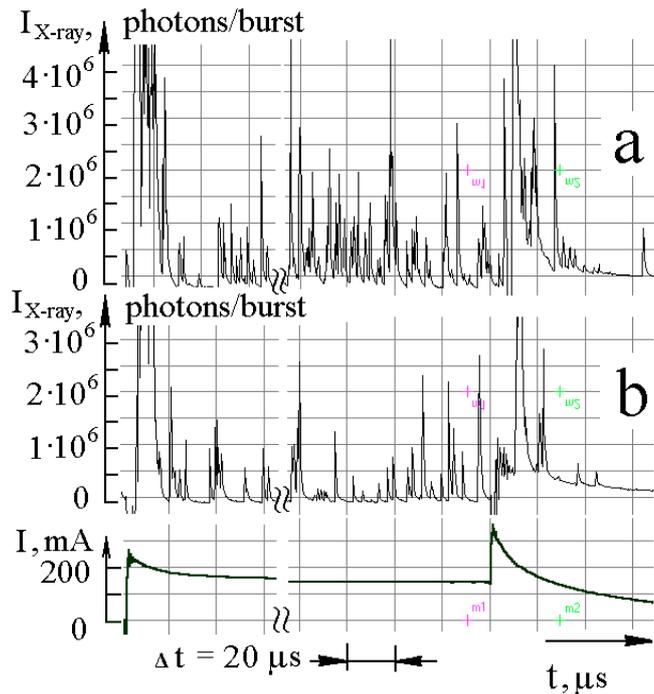


Fig.2. The typical oscillograms of the X-ray emission signal from the system PM –scintillator covered with the Be foil with the different thickness: a – with covered the 15 μm Be shield, b - with covered the 30 μm Be shield.. The system Pd-D2, the discharge current – 150mA.

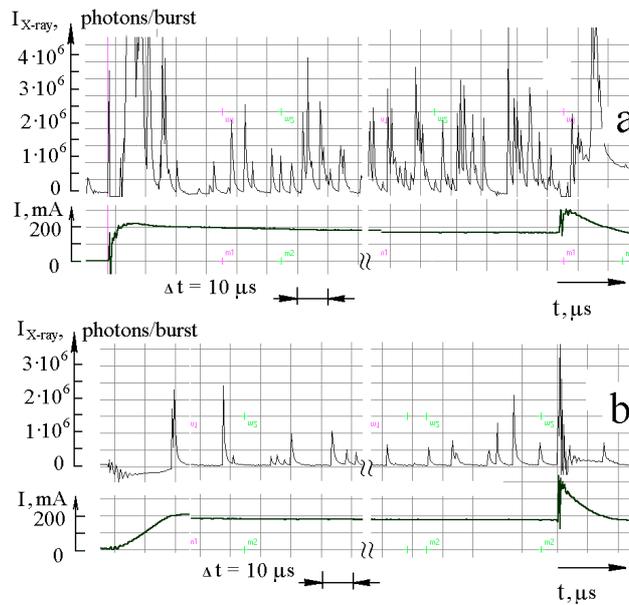


Fig.3. The typical oscillograms of bursts of the diffusive X-ray emission (PM – scintillator) during passing the discharge current. The system Ta – D₂, current is 175 mA. a - PM – scintillator arrange at a distance of 21 cm from cathode (by Fig. 1a); b - PM – scintillator arrange at a distance of 70 cm from cathode (by Fig. 1b).

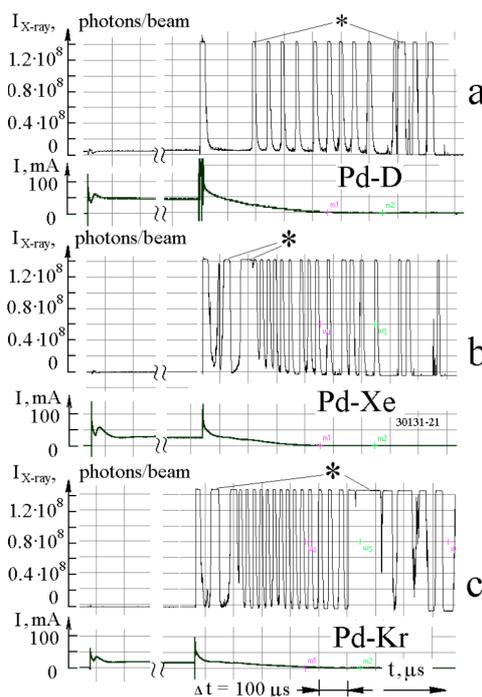


Fig.4. The typical oscillograms of bursts from X-ray laser beams (PM – scintillator) in the discharge for different kind of gases a - D₂, b - Xe, c - Kr. Assembly is by Fig. 1a (the distance from the cathode to the detector is 21 cm). The cathode sample is Pd, current - 50mA. * - the pulse peak was cut a discriminator of amplifier.

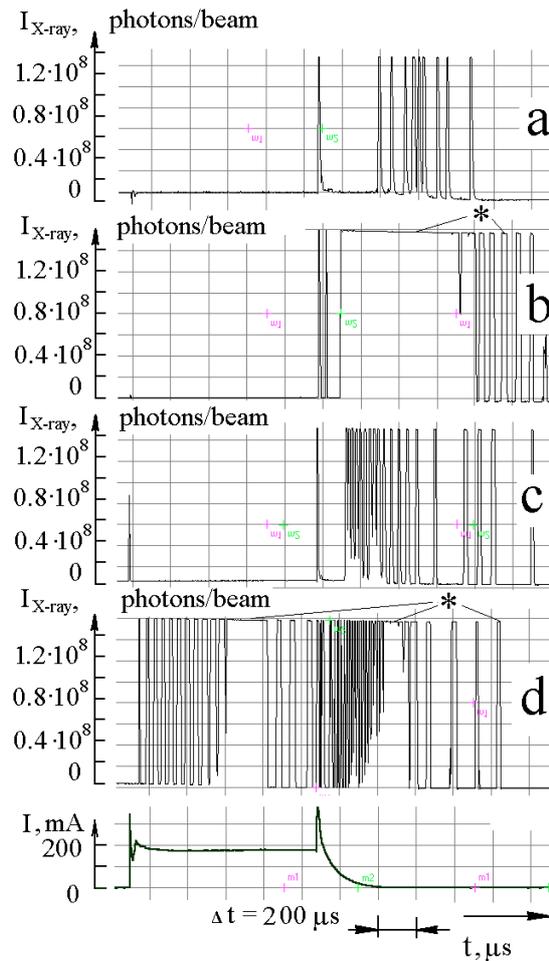


Fig.5. The typical oscillograms of bursts from X-ray laser beams (PM – scintillator) in the D₂ discharge for different kind of cathode samples; a - Al, b - Sc, c - Pb, d - Ta. Assembly is by Fig. 1a (the distance from the cathode to the detector is 21 cm). * - the pulse peak was cut a discriminator of amplifier.

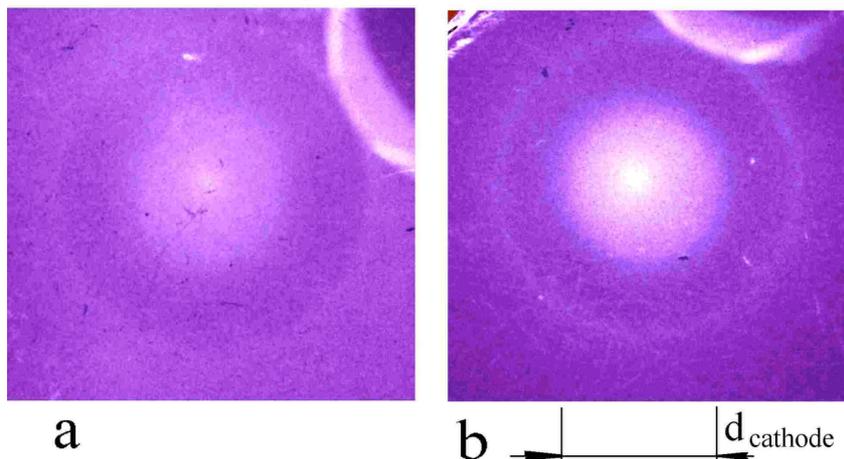


Fig.6. The image of the X-ray cathode obtained using the pinhole. The objective with 0.3 mm diameter closes by the 15 μm Be shield. The system Pd-D₂, the discharge current – 150mA, the exposure time – 1000s, a – voltage is 1350 V, b – voltage is 1850 V. The image is positive.

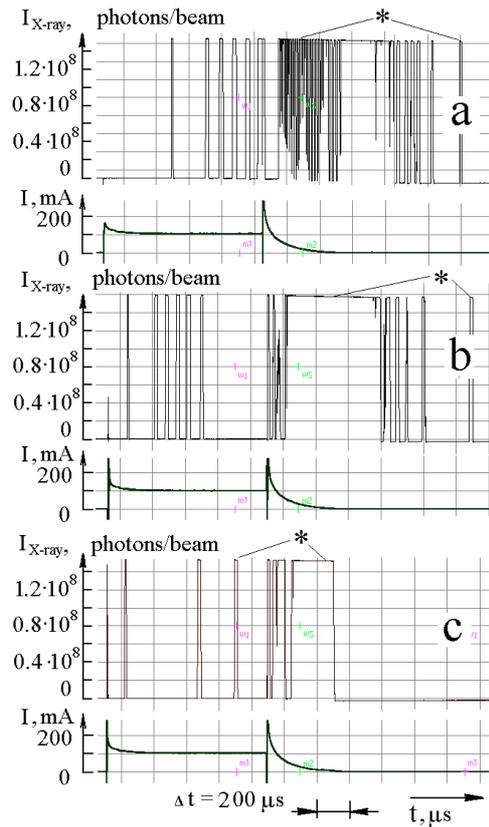


Fig.7. The typical oscillograms of bursts from X-ray laser beams (PM – scintillator) in the discharge for different kind of assemblies. The cathode sample is Ta, D₂, current - 100mA. a - Assembly is by Fig. 1a (the distance from the cathode to the detector is 21 cm without a cross magnetic field). b - Assembly is by Fig. 1b (the distance from the cathode to the detector is 70 cm without a cross magnetic field). c - Assembly is by Fig. 1c (the distance from the cathode to the detector is 70 cm with a cross magnetic field). * - the pulse peak was cut a discriminator of amplifier.

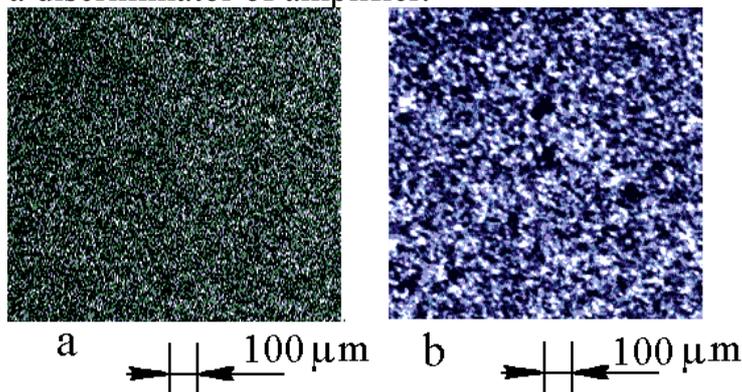


Fig.8. The increased negative image of the flare spots of the roentgen laser beam tracks for the different distances from cathode, the roentgen film “Kodac XBM” covered with the 15 μm Al shield. The system Pd-D₂, the discharge current – 130mA, the exposure time – 1000s, a – for 100 mm from the cathode surface, b - for 210 mm from the cathode surface. The image is negative.

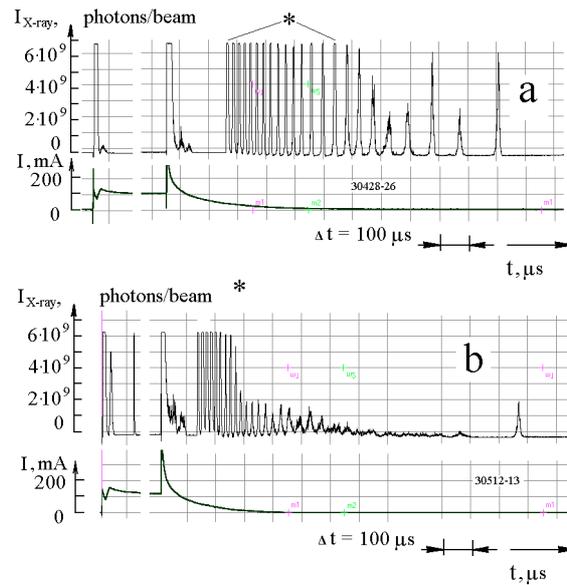


Fig.9. The typical oscillograms of bursts from X-ray laser beams (PM – scintillator with optical filter) in the discharge for different kind of assemblies. a - the cathode sample is Ta; b - the cathode sample is Mo, current - 100mA, D₂. a - Assembly is by Fig. 7a (the distance from the cathode to the detector is 21 cm). b - Assembly is by Fig. 7b (the distance from the cathode to the detector is 70cm). * - the pulse peak was cut a discriminator of amplifier.

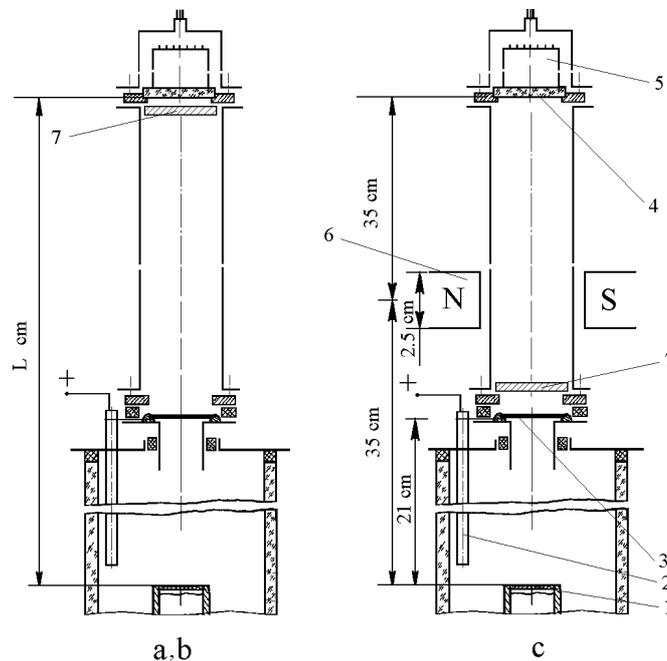


Fig. 10. Schematic representation of an experiment with X-ray targets (secondary penetration radiation research). PM-scintillator system. 1 – cathode sample; 2 – anode; 3 – 15 μ m Be foil screens; 4 – scintillator; 5 – photomultiplier; 6 - magnetic bar (magnetic induction between magnetic poles is about 0.2 T), 7 - X-ray targets made a foil of various materials.

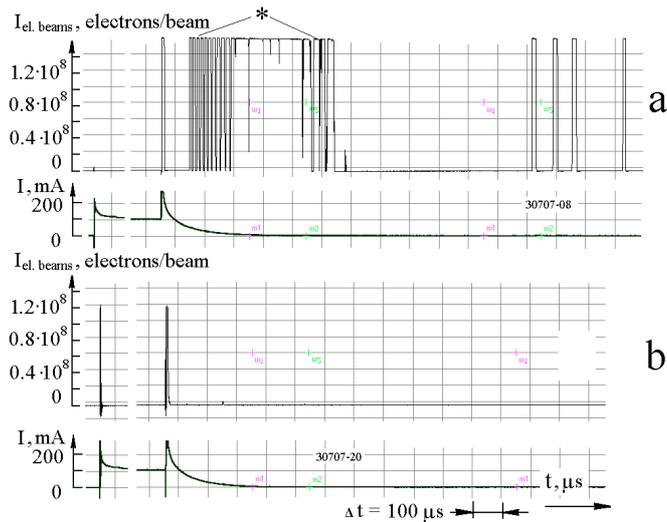


Fig.11. The typical oscillograms of bursts from secondary penetration radiation beams (fast electrons) in the discharge for different kind of assemblies. The cathode sample is Ta; current - 100mA, D₂. a - Assembly is by Fig. 7b (target arrange at a distance of 70 cm from cathode without superimposition of the cross magnetic field). b - Assembly is by Fig. 7c (target arrange at a distance of 70 cm from cathode with superimposition of the cross magnetic field), secondary penetration radiation (fast electrons) don't registered. * - the pulse peak was cut a discriminator of amplifier.

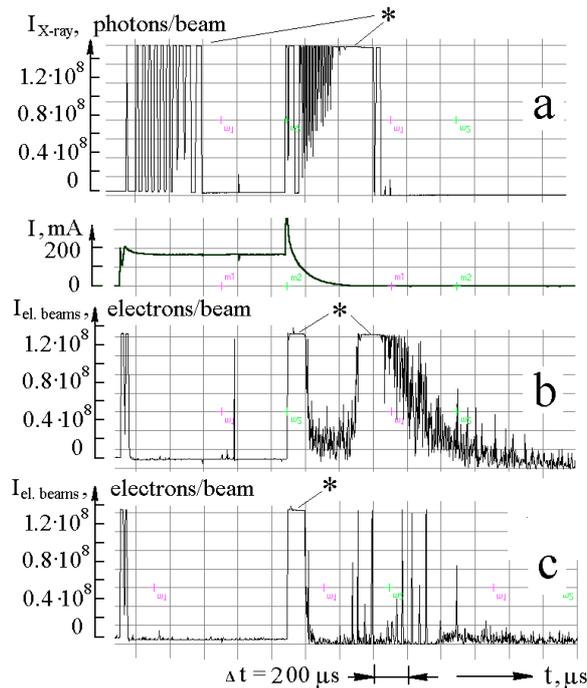


Fig.12. The typical oscillograms of bursts from (a) primary (X-ray laser beams from cathode) and secondary penetration radiation beams (fast electrons) in the discharge for different kind of target materials. The cathode sample is Ta, D₂; current - 180mA. Assembly is by Fig. 2b (target arrange at a distance of 70 cm from cathode). a - primary penetration radiation from cathode; b - Al target of 1.4 mm thickness; c - Yb target of 1.8 mm thickness . * - the pulse peak was cut a discriminator of amplifier.

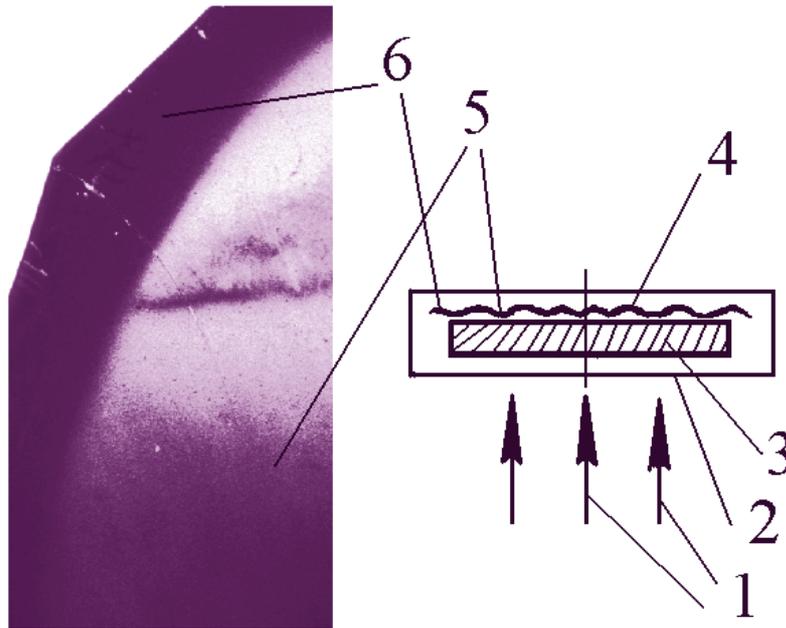


Fig.13. The X-ray film exposed by the secondary penetration radiation from the lead screen with the thickness of 2 mm. The system Mo – D₂, current 220mA, the exposure time – 720s. 1- X -ray from cathode, 2 –15 μm Al shield, 3 – 2 mm lead target, 4 – X-ray film, 5 - area of X-ray film behind lead shield, it is the photoemulsion solarisation presumably, 6 - area of X-ray film behind 15 μm Al shield only. The image is negative.

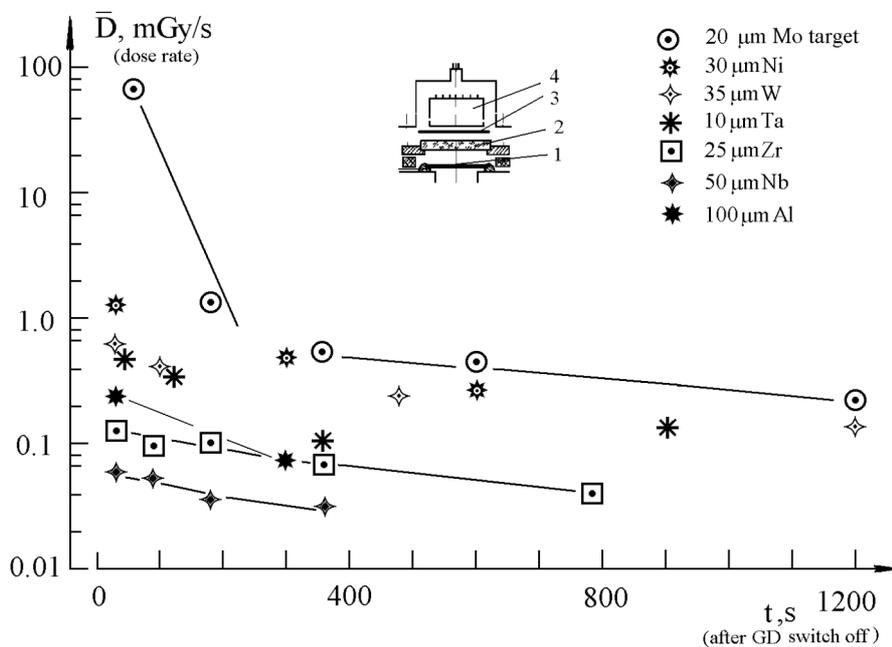


Fig.14. The third type secondary penetration radiation dose rate dependence upon the time after turning off the discharge current. The cathode sample is Ta, D₂; current - 100mA; voltage - 2000 V. 1 –15 μm Be foil shield; 2 –scintillator; 3– X-ray targets made a foil of various materials; 4 – photomultiplier.