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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 dose rate up to 1.0 Gy/s have been registered in experiments with high-current Glow Discharge. The emissions energy and intensity depend on the cathode material; the kind of plasma-forming gas; and the discharge parameters. The experiments were carried out on the high-current glow discharge device using D_2, H_2, 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 5×10^5 bursts a second and up to 10^6 X-ray quanta in a burst); 2. X-rays in the form of laser microbeams (up to 10^4 beams a second and up to 10^{10} X-ray of quanta in a beam, angular divergence was up to 10^{-4}, the duration of the separate laser beams must be $\tau = 3\cdot10^{-13}$ - $3\cdot10^{-14}$ s, the separate beam power must be $10^7 – 10^8$ W). The emission of the X-ray laser beams occurred when the discharge occurred and within 100 ms after turning off the current. The results of experimental research into the 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. 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 10^6 fast electrons a burst. 2. The emission with a discrete temporal spectrum and emission rate up to 10^{10} 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

Experiments were carried out previously to define a possible mechanism of high energy phenomena in the solid-state cathode medium during high-current glow-discharge. The experimental results showed that the character of the detected X-ray radiation essentially differed from the known X-ray emission types. It indicated the importance of research 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.

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

2. EXPERIMENT METHOD AND RESULTS

The experiments were carried out with the device that produces 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 15µm Be foil for protecting the detectors against visual and ultraviolet radiation (Fig. 1). A periodic-pulse power supply was used for the glow discharge, with a rectangular current pulse. The duration of the discharge current pulses were 0.27 - 10.0ms, period between impulses was 1.0 - 100ms. The discharge was carried out in D_2, 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, and scintillation detectors supplied with photomultipliers [1].

Thermoluminescence detectors are not sensitive to electrical noise and allow registering the absorbed radiation dose quantitatively in absolute units of dose measurement. Thermoluminescence detectors (TLD) based on Al_2O_3 crystal register penetrating radiation beginning from the background values of radioactive radiation of the environment. These were to measure energy intensity and to evaluate the average energy of a soft X-ray emission in the discharge. To determine the average energy a special cassette (seven-channel spectrometer) was used. Seven channels (holes) with a diameter of 5mm each 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 holes. A set of the beryllium foils having thickness 15µm, 30µm, 60µm, 105µm, 165µm, 225µm, 225µm, 300µm (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.

A 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 the scintillation detectors supplied with the photomultipliers (PM). The signal from the 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 - 5ns were used. The time resolution of the entire path from the PM up to an oscillograph (experimentally) was 70 - 80ns. 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 (Fig. 1a) PM-scintillator was placed 21cm from the cathode surface. The channel diameter for extracting the radiation was equal 1.7cm. In the second variant the PM-scintillator was placed 70cm from the cathode, and the diameter of the channel for extracting the radiation was 3.2cm (Fig. 1b). To define the type of penetrating radiation, 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 35cm from the cathode perpendicular 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 when it was in the mode of generating X-ray laser beams was approximately 1000 times as much as the intensity 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 by changing the amplification constant of the oscillograph. Under some experiments the luminous-absorbing filter attenuating the luminous flux coming to the PM was installed between the scintillator and PM. Two types of the filters were used, that attenuated the luminous flux by 50 times and by 2500 times respectively.

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 2p solid angle.

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

The experiments using the PM-scintillator and shields made of the beryllium foil with thickness of 15 μm and 30 μm gave the assessment of the X-rays energy value of $E_{X\text{-}ray} \approx 1.0 – 2.5$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 PM-scintillator detector and the cathode from 21cm up to 70cm resulted in reducing the radiation intensity more, than under the law 1/r2 (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. 6.).

The X-ray laser beam generation occurred under precisely fixed parameters and conditions of glow discharge.

1. The generation occurred only when periodic-pulse current was supplied. It did not occur with direct current, although X-rays as bursts of diffusion radiation did occur with 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 U_{GD}. The generation occurred at $P_{GD}<P_{GDcrit}$, $U_{GD}> U_{GDcrit}$. A small change in the discharge pressure or voltage led to the occurrence of generation (the change in pressure was ΔP_{GD} = 0.2 - 03Torr, and in voltage ΔU_{GD} = 30 - 50V).
3. These parameters were different for various cathode materials (Fig. 5). 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 (Fig. 4.).
5. When operating, the generation intensity gradually decreased (obviously because of degradation of the cathode surface) and stopped in the course of time. This phenomenon was especially clear for cathode materials with a large coefficient of a material sputtered 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 passing the discharge current, $E_{X\text{-}ray}$, keV	1.54	1.26	1.45	1.91	1.48	1.98	1.62	1.36	1.47	1.36
X-ray energy **without** current, $E_{X\text{-}ray}$, 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, φ, $\times 10^{-4}$ W/cm2	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, $\times 10^5$ 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}, $\times 10^{-10}$ 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, $\times 10^5$	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 106 – 1010 photons in a beam). These magnitudes were obtained in assumption that the system of the PM-scintillator 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 100ms 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 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 and Fig. 1b. The magnification of the distance from the cathode up to the system of the PM-scintillator from 21cm up to 70cm resulted in inappreciable reducing the signal (Fig. 7.). These results proved to be true when using 50-multiple optical filters (Fig. 7.).

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 PM-scintillator. 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 £ 0.5MeV. 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 real form of the radiation pulses was observed using the luminous-absorbing filter (Fig. 9.) reducing the luminous flux from the scintillator to the photomultiplier by 2500 times.

The track 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 beam tracks was 6 - 10 μm at a distance 100mm from the cathode and up to 20 – 30μm at 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} (based on the results of measuring the track diameters at various distances from the cathode).

3. SECONDARY PENETRATING RADIATION

The experiments were carried out with the device of the high-current glow discharge [1] with use of H2, 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 - 1.0ms and period of T = 1.0 - 100ms was used. The targets as the shields made of various materials foil (Al, Ti, Ni, Zr, Yb, Ta, W) with thickness of 10 - 30mm and of 1.0 - 3.0mm were arranged at a distance of 21 and 70cm from the cathode (Fig. 10a.), (Fig. 10b). 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. 10b, Fig. 10c.).

When free of the magnetic field, significant attenuation of the PM-scintillator signal was not observed when increasing the distance from the cathode to the detector from 21cm to 70cm (Fig. 11a). Superimposition of the magnetic field with an induction of 0.2T led to complete disappearing of the signal in the PM-scintillator (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 21cm to 70cm, the primary X-ray laser beams kept an ability to generate the secondary radiation when interacting with the targets made of various materials (Fig. 12). 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. The secondary X-ray radiation of two types was observed. 1) - radiation with a continuous time spectrum as separate bursts with intensity up to 106 photons per a burst. This emission began 0.5 - 1.0ms 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. The generation of the secondary penetration radiation is supposed to occur from solid medium of the lead shield.

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 time spectrum of the primary X-ray was a function of the cathode material. Separate bursts were recorded within 85ms after turning off the current. The time spectrum of the secondary radiation also had a discrete character, but the type of this spectrum was a function of the target material. Also this secondary radiation is registered using the X-ray film arranged behind the lead shield (Fig. 13).

A third type of the penetrating radiation was observed as well. This was radiation recorded directly by the photomultiplier placed behind of the target without the scintillator (Fig. 14). In this scheme the target was arranged between the shield with the thickness of 3 mm made of plastic and the PM detector. The type of the secondary radiation was defined by the detector material. This emission began 20 minutes 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 research.

4. DISCUSSION

The features of the X-rays recorded in these experiments are as follows:

- The X-rays leaves the solid-state medium of the cathode material.
- The intensity of the X-rays increases 5 – 6 times when increasing the discharge voltage by 1.3 – 1.4 times.
- The quantity of the X-rays energy is essentially not changed in this case.
- The X-rays emission occurs within 100ms 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 $\Delta\tau_{mst}$ (up to 100ms 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 luminance. In this case the duration of the beams should be of 10^{-11} - 10^{-13}s.

Understanding the mechanism of these level of formation will require additional research. The existence of one of the two physical phenomena can be assumed:

1. Excitation of the interior L, M electronic shells without ionization of the outer electrons.
2. 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.

5. CONCLUSION

Experimental research into this fundamental phenomenon has allowed us to create what is essentially a new type of device: the X-ray solid-state laser with a wave length 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 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 state.

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