An X-ray Source for Irradiation of Large-Area Objects

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Abstract – The results of experiments with a three-ring large-area diode performed on an MIG pulse generator are reported. The MIG generator allows electrical pulses up to 2 TW at FWHM 50–60 ns (1.2–1.4 TW and 80–90 ns in our experiments) to be produced at a matched load. In the operating mode of the generator, the current amplitude through the load is up to 2 MA (the current of a relativistic electron beam) at a diode voltage of ~ 500 kV. A large-area vacuum diode with three ring-shaped cathodes is used as a load. When the beam slows down on a condensed foil target, the parameters of the resulting source are the following: the mean energy of X-ray quanta is ~ 70 keV, irradiated area – 500 cm^2, FWHM – 65 ns, and X-ray radiation (10–100 keV) in the flux ~ 50%. It is shown that absorption of radiation by the target is significant at large angles to the diode axis.

1. Introduction

In the mid-1970s, high-voltage pulse generators with a current rise time of about 100 ns and a power of about a terawatt were designed. These devices were applied to studying relativistic electron beams and high-temperature plasma of liners (fast Z-pinches) [1–5]. Today, there are 15 generators whose power is higher than 1 TW and whose current is higher than 1 MA [6], most of them being in the United States and Russia.

One of the directions of research concerned with these generators is generation of relativistic electron beams and development of hard X-ray sources [7–9], in particular, in range 10–100 keV. In the case when the areas to be irradiated are small (5–50 cm^2), use is made of high-current pinched diodes, in other cases, large-area diodes with several cathodes are most suitable. In the latter case, the primary goal is to increase radiation power. This can be achieved only by increasing beam current, since an increase in the diode voltage results in an increase in the fraction of gamma quanta ($h\nu$ > 100 keV) in the spectrum. Therefore, our efforts went into an increase in the vacuum-diode current and into search for an optimal diode construction.

2. Statement of the problem

Vacuum diodes with the mean impedance 0.35–0.50 Ω capable of irradiating large areas (> 100 cm^2) can be built around ring diodes with symmetric current spreading in the inner and outer return conductors [7, 8, 10]. When a one- or multiple-ring electron beam is accelerated in the vacuum diode and stabilized by the self-magnetic fields of currents spreading in inner and outer return conductors interacts with the anode (Ta, 10 to 50 μm thick), the energy of accelerated electrons is converted to X-ray energy. In so doing, a radiation source results, which actually consists of one or several ring-shaped isotropic sources. The mean diameters of the radiation rings are equal to the mean diameters of the ring-shaped cathodes, and the widths of the rings are roughly equal to the width of grooves in the ring-shaped cathodes. The radiation field of isotropic rings is easy calculated by the formulas given in [15]. The number of ring-shaped cathodes in the diode, their diameters, and current distribution in the diode depend on the area to be irradiated and required homogeneity of the radiation field. The larger the number of cathodes in a diode, the higher the field homogeneity. However, the number of ring-shaped cathodes is limited by the necessity to deliver energy through MIVLs. A three-cathode configuration seems to be optimal for a diode irradiating an area of 500 cm^2. The principles of load construction, experimental arrangement, and preliminary experimental results with the three-ring diode are discussed in [12].

Figure 1 shows a load unit with a section of a water transmission line and a three-ring diode around which an X-ray source capable of irradiating an area of 500 cm^2 is designed.

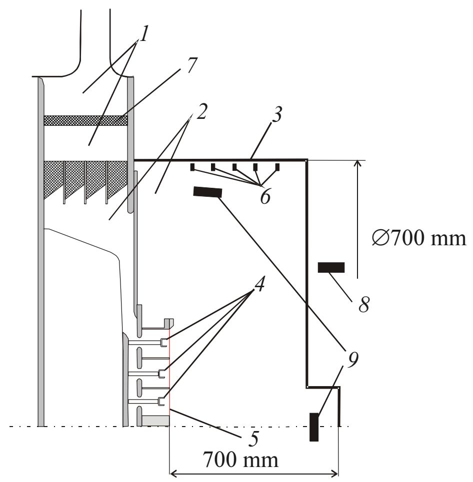

Fig. 1. Load unit: *1* – water; *2* – vacuum; *3* – vacuum chamber case; *4* – cathodes; *5* – foil anode; *6* – LiF detectors; *7* – voltage divider; *8* – SKD1-01 silicon detector; and *9–10* – channel spectrometers

The diode has steel stud-mounted ring-shaped cathodes with 10-, 12-, and 14-mm-wide annular grooves on the inner, middle, and outer cathodes, respectively (to avoid premature short-circuit of the diode by plasma). These are symmetric about the midline of the rings and a foil or a massive anode. For a diode with the total impedance 0.35 Ω, the mean diameters of the cathodes were 56, 142, and 230 mm and the initial sizes of the gaps in the rings were 11.8 (inner diode), 8.7 (middle diode), and 6.7 mm (outer diode).

The accelerating tube was evacuated down to a pressure of $(1–4) \cdot 10^{-4}$ Torr by means of an oil-diffusion pump without freezing. The voltage at the section insulator was measured with a two-stage voltage divider. The current in the circuit was measured using self-integrating Rogowski loops and by integrating signals from B-dot monitors. The derivative of the current was measured with four B-dot monitors arranged symmetrically to form a circle. The signals from each B-dot monitor were added up, and the net signal was recorded. The incident wave voltage, incident wave power, incident wave energy, and diode resistance were calculated from the waveforms of voltage across the divider, current through the load, and time derivative of the current. The radiation doses were measured by LiF dosimeters, X-ray power – by an SKD1-01 silicon detector, radiation spectra were determined with a 10-channel spectrometer with Cu filters. The filter thickness was varied from 0 to 20 mm. An X-ray energy flux was found according to [12] on the basis of X-ray dose and radiation spectrum.

3. Experimental results

The diode voltage, impedance, and current, as well as the X-ray power pulse versus time are plotted in Fig. 2. A radiation output from each ring was determined by LiF collimated detectors. The first detector recorded radiation from inner ring only, the second – from the inner and middle rings, and the third – from the entire target.

The measured ratio of radiation outputs of the rings in our experiments was 1:2.7:5.1 from the inner to outer ring. Such a ratio, in the case of isotropic source, allows us to irradiate an area of 500 cm^2 at the 5 mm distance from the target with homogeneity 1:2. The determined radiation spectra on the diode axis depending on foil-target thickness are shown in Fig. 3.

Some radiation-field parameters depending on the target thickness are shown in the Table.

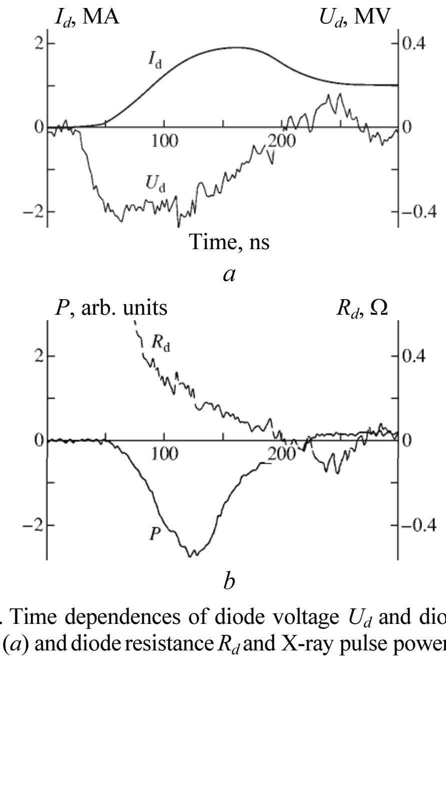

Fig. 2. Time dependences of diode voltage U_d and diode current I_d (*a*) and diode resistance R_d and X-ray pulse power *P* (*b*)

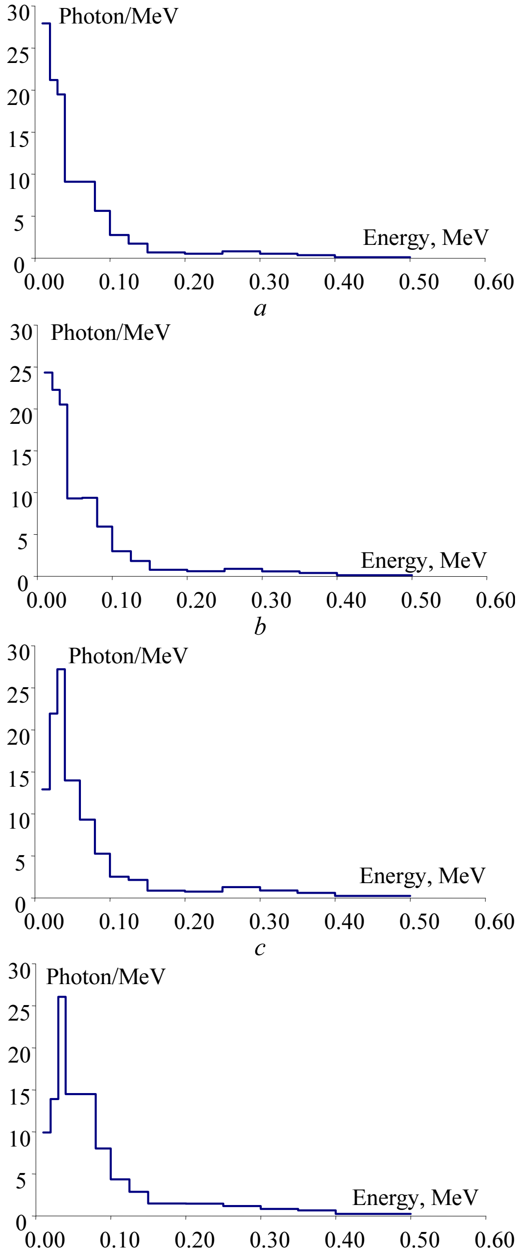

Fig. 3. Radiation spectra along the diode axis at 60 cm from target: *a* – 10 μm Ta target; *b* – 20 μm Ta target; *c* – 30 μm Ta target; and *d* – 40 μm Ta target. (All spectra are normalized to 100 photons)

Table. Radiation-field parameters versus Ta target thickness

Target thickness, µm	Radiation dose at 300 mm from diode axis (R) and 100 mm from target (Z), Roentgen	X-ray energy flux, J/cm^2	X-ray energy flux with $h\nu \le 100$ keV, J/cm^2	The percentage of X-rays with an energy of 10–100 keV in the flux
10	564	0.040	0.017	42
20	632	0.065	0.024	37
30	315	0.055	0.019	35
40	279	0.046	0.014	30

The maximum radiation dose as well as X-ray energy flux and X-ray energy flux with photon energy up to 100 keV were obtained at a 20 µm Ta target.

The experimental doses and those calculated by the formulae [11] for an isotropic source depending on the distance from the target are shown in Fig.4.

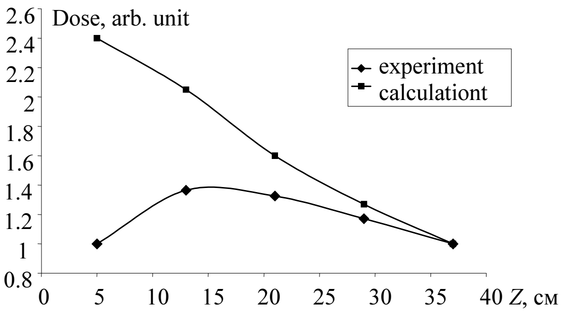

Fig. 4. Experimental and calculated dose distributions for an isotropic source at 325 mm from the diode axis

The radiation spectra from the 20 µm Ta target along the diode axis and at an angle of 70° are shown in Fig. 5. The experiments show that a part of low-energy photons in the spectra is decreasing as the angle between the diode axis and direction of irradiation is increased.

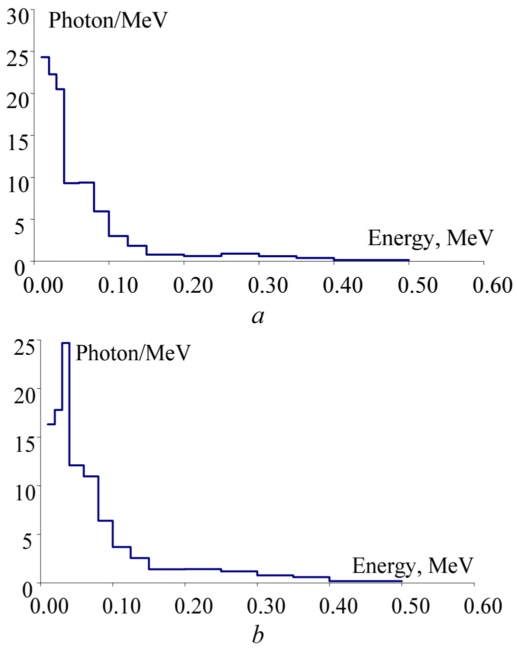

Fig. 5. Radiation spectra from the 20 µm Ta target: *a* – along the diode axis; *b* – at the angle 70°

It was determined that the percentage of X-rays with an energy of 10–100 keV in the energy flux decreased from 44 to 37% when the angle between the diode axis and direction of irradiation increased from 0 to 70°. Figures 4 and 5 show that the radiation source obtained in the experiments had a dose and spectral anisotropy at least at the angles greater than 40° to the diode axis. This should be taken into account in calculation of the radiation-field parameters, especially at small distances from the target.

Steel ring-shaped cathodes with sharp emitting edges and with a flat velvet-covered emitting area were used in the experiments. It was proved that the use of cathodes with flat emitting areas covered with velvet improves current density distribution on the target, which, in turn, improves radiation homogeneity on the irradiated area.

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