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PLASMA ELECTRONICS

A High-Power Vircator Operating as an X-ray Bremsstrahlung Generator

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Abstract—A vircator capable of generating high-power X-ray pulses due to the multiple transitions of electrons through a thin anode foil transparent to X radiation has been created and put into operation for the first time. The vircator is created on the basis of a direct-action electron accelerator supplied from an inductive energy storage operating with a plasma opening switch. Self-consistent two-dimensional simulations of the electron beam dynamics in the vircator chamber are performed, and the spectra of the generated microwave radiation are determined. Self-consistent one-dimensional simulations of the beam dynamics with allowance for electron scattering in the foil were also carried out, and the X-ray bremsstrahlung spectra were measured. Results are presented from the first experiments on the generation of X-ray bremsstrahlung in vircators with thin (10 μm) and thick (100 μm) tantalum anode foils. For a thin foil, the X-ray (E_γ > 30 keV) dose is eight times as high as that for a thick foil and the average photon energy is 30 keV (against 80 keV for a thick foil). *© 2004 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

In radiation studies, it is sometimes necessary to use intense X-ray pulses with photon energies of E_γ = 20–60 keV. *Z*-pinches, in which the kinetic energy of the imploding plasma is converted into thermal energy, make it possible to produce radiation fluxes with photon energies of E_γ < 5 keV [1]. On the other hand, the use of electron beams with electron energies of E_e = 100–200 keV is limited by the low beam currents and the small cross section for radiative losses. The problem of increasing the intensity of X radiation can be solved only by increasing the accelerating voltage. However, for beams of electrons with energies of E_e = 1–10 MeV, the high efficiency of energy conversion into bremsstrahlung can only be achieved with sufficiently thick targets (0.1–1 mm Ta). Most of the photons from such targets have energies above 200 keV, whereas photons with lower energies are absorbed in the target. One way of increasing the fraction of soft photons is to use schemes with the multiple transitions of electrons through a thin target that is transparent to X radiation (in reflex triodes and vircators, the anode foil can serve as such a target [2]). In this case, the maximum intensity of the generated bremsstrahlung lies in the X-ray range with photon energies lower than those in bremsstrahlung generators with thick targets.

In reflex triodes and vircators, the electron flow oscillates in the potential well formed by the cathode, the anode foil, and the virtual cathode, while X radiation is generated due to the multiple transitions of electrons through a thin (10–30 μm) foil of a high-*Z* material (e.g., Ta). The possibility of generating high-power X-ray pulses with the help of a reflex triode was successfully demonstrated in [3]. The results of calculations of a reflex triode in the YUPITER device with a stored energy of 30 MJ are presented in [4], where it is asserted that this device with an electron beam current of 60 MA and electron energy of 5 MeV is capable of generating radiation pulses with an energy of up to 160 kJ in the photon energy range of 20–60 keV.

Note that, in [3, 4], only reflex triodes were considered, in which the high voltage is known to be applied to the anode foil, whereas the cathode and the reflecting electrode (the collector behind the anode) are grounded. However, the presence of the reflecting electrode can hamper the use of the generated X-ray emission in radiation studies.

In the present paper, a vircator is used for the first time in experiments on X-ray generation. The advantages of vircators over reflex triodes for generating X-ray pulses were pointed in [2, 5]: the vircator design is simpler, the high voltage is applied to the cathode, and the anode foil and collector are grounded. Therefore, in vircators in which the longitudinal magnetic field is uniform near the anode foil and decreases near the collector, there is no problem with utilizing X radiation.

The paper presents the results of one- and two-dimensional self-consistent calculations of the electron beam dynamics in a vircator, as well as the results of the first experiments on studying X-ray bremsstrahlung in vircators with thin and thick anode foils.

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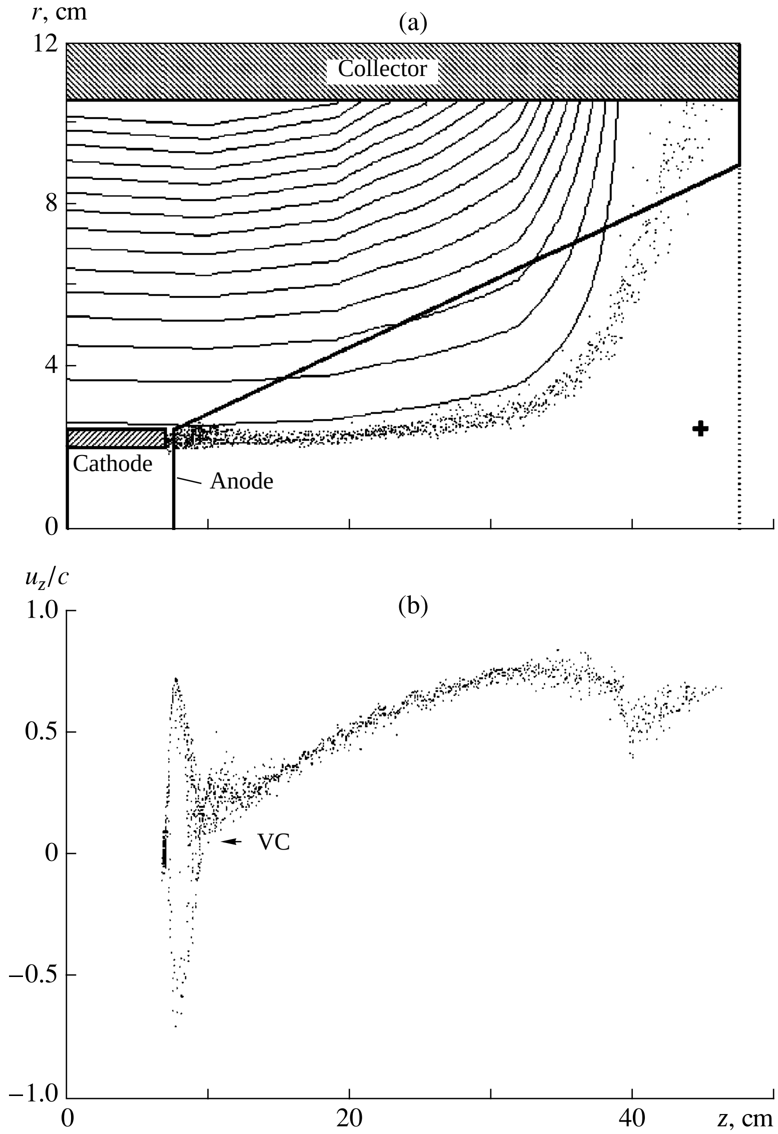

Fig. 1. Results of simulations of the dynamics of an electron beam in a vircator: (a) the instantaneous configuration of the beam (the figure also shows the magnetic field lines; the cross indicates the location of a "detector"—the place where the microwave field was calculated) and (b) the phase portrait of the beam (VC is the virtual cathode).

2. COMPUTER SIMULATIONS OF A VIRCATOR

Before carrying out our experiments, we performed a series of computer simulations:

(i) simulations of the self-consistent two-dimensional dynamics of an electron beam in a nonuniform magnetic field with the aim of determining the region where the electrons reach the collector and searching for the place where X-ray detectors will be best protected from high-energy electrons,

(ii) simulations of the self-consistent two-dimensional dynamics of the formation of a virtual cathode with the aim of calculating the limiting current and the spectrum of the generated microwave radiation (in experiments, the presence of high-power microwaves in the proper spectral range would be indicative of the presence of a virtual cathode in the beam), and

(iii) simulations of the self-consistent one-dimensional dynamics of a beam with a virtual cathode with allowance for electron scattering in the anode foil with the aim of calculating X-ray bremsstrahlung spectra.

All simulations were performed by the particle-in-cell (PIC) method. In the first two cases, we used the well-known KARAT relativistic electromagnetic code [6], while in the third case, we used an original relativistic electrostatic code elaborated by us (see [7]).

First, we present the results of simulations with the KARAT code for an optimized geometry of a vircator and operating conditions used in real experiments.

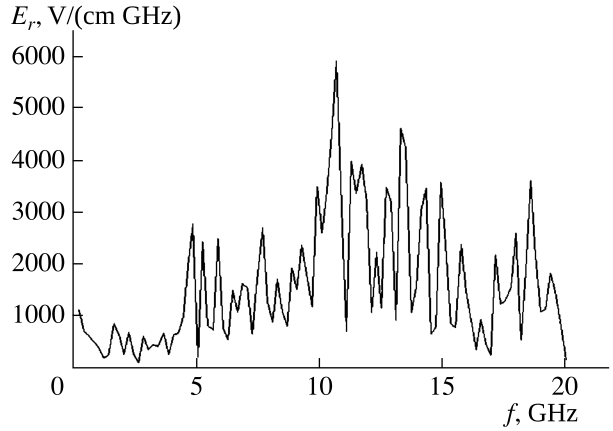

Fig. 2. Calculated spectrum of the radial component of the microwave field at the "detector" location.

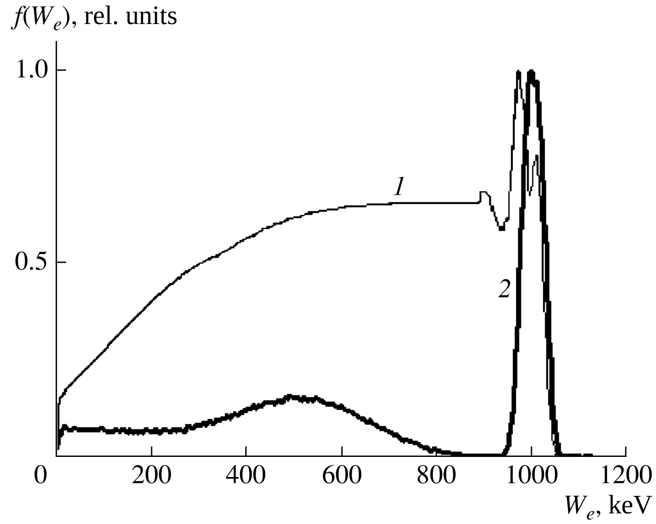

Fig. 3. Normalized spectra of electrons passed through the foil for anode foil thicknesses of (*1*) 10 and (*2*) 100 μm. The spectra are normalized to their peak values.

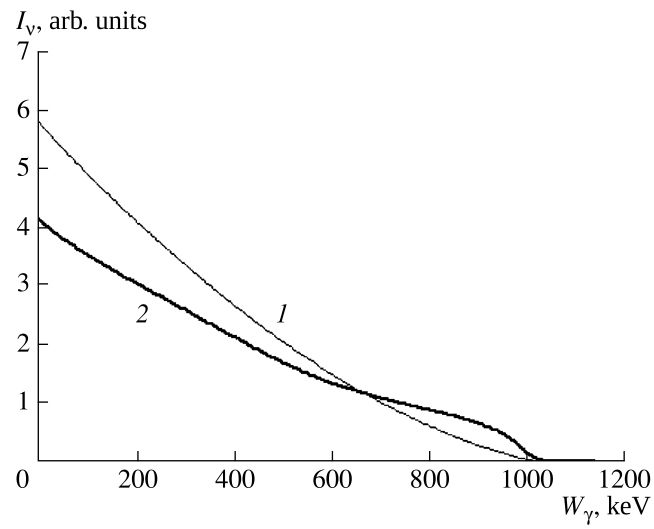

Fig. 4. Normalized X-ray bremsstrahlung spectra for anode foil thicknesses of (*1*) 10 and (*2*) 100 μm. The spectra are normalized to the areas under the curves.

The geometry of the vircator electrode system is shown in Fig. 1a. The electrode system consisted of a hollow cathode, an anode electrode containing a massive collector, a conical holder of the anode (the holder was made of a low-*Z* material transparent for electrons), and a tantalum anode acting as a target. It was assumed that an external magnetic field was applied the vircator, the strength of this field in its uniform part being 4.4 kG. The measured spatial distribution of the magnetic field in the vircator is also shown in Fig. 1a.

The diode voltage was 1 MV, and the beam current was 90 kA. The instantaneous beam configuration is shown in Fig. 1a, from which we determined the region where the electrons reach the collector.

Figure 1b shows an instantaneous phase portrait of the beam. It can be seen from this figure that a virtual cathode is formed in the system; i.e., the beam current exceeds the limiting current.

At the point marked by a cross in Fig. 1a, we calculated the time evolution of the electric field. It was found that intense microwave oscillations were generated at this point in the presence of a virtual cathode. Since the beam electrons near this point move almost along the radius, the oscillations of the radial component of the electric field are most informative. From the Fourier spectrum of the radial electric field shown in Fig. 2, we determined the spectral range of microwave oscillations expected in experiment ($\lambda = 3$ cm).

Let us consider the results of simulations of bremsstrahlung generation with the code elaborated in [7]. In these simulations, the vircator consisted of two cylindrical metal chambers. The first chamber acted as an accelerating diode, while the other acted as a drift space. The diode and drift chambers were separated by a foil. The electron energy loss for ionization in the foil were calculated by the Monte-Carlo method. Hence, we could take into account not only the average energy loss for ionization in the foil, but also fluctuations in this loss. The problem was solved by the PIC method with allowance for relativistic effects. The model particles were identical and shaped as thin washers with given initial inner and outer radii. The simulations were performed for the following vircator parameters: In the diode region, the outer beam diameter was 5 cm, and the beam thickness was 1 cm. The accelerating gap was 0.7 cm long, the drift region of the vircator was 24 cm long, and the outer diameter of the diode and drift chambers was 21 cm. A voltage of 1 MV was applied to the cathode. The injected cathode current was 90 kA. The thickness of the foil anode was 10 μm in the first version and 100 μm in the second version. The anode material was tantalum.

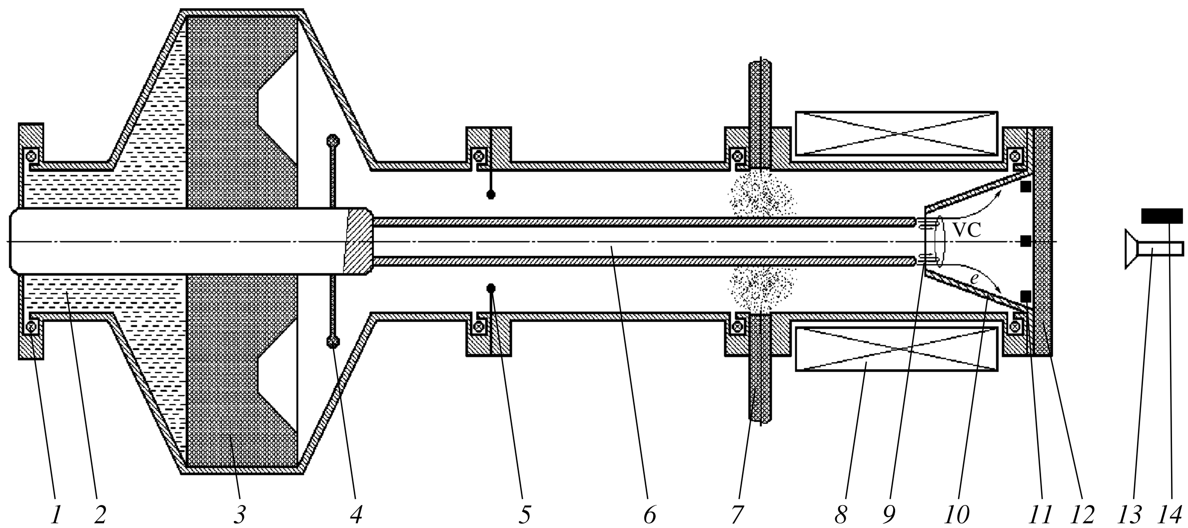

Fig. 5. Schematic of the PIRIT-1 device with a vircator load and the arrangement of the diagnostic equipment: (*1*) Rogowski coil, (*2*) oil-filled section of the inductive storage, (*3*) high-voltage insulator, (*4*) protecting dielectric ring, (*5*) protecting metal ring between the vacuum sections of the inductive storage, (*6*) cathode, (*7*) cable plasma guns of the current opening switch, (*8*) solenoid, (*9*) anode foil, (*10*) conical anode holder, (*11*) thermoluminescent dosimeters, (*12*) microwave output window, (*13*) microwave hot-carrier detector, and (*14*) semiconductor X-ray detectors.

The energy spectra of the particles passing through the anode foil are shown in Fig. 3. It can be seen that, for a 100-μm foil (Fig. 3, curve *2*), the number of low-energy particles is small compared to the case of a 10-μm foil (Fig. 3, curve *1*).

From the data obtained, we calculated X-ray bremsstrahlung spectra by the following formula [8]:

$$I_\nu = k\nu^{2/3}\nu_0^{-2}[(\nu_0 - \nu)^{-1/2} - \nu_0^{-1/2}]^{-2/3}, \qquad (1)$$

where I_ν is the spectral intensity, ν_0 is the frequency corresponding to the short-wavelength boundary of spectrum, ν is the bremsstrahlung frequency, and k is a proportionality factor. The calculated spectra are presented in Fig. 4. It can be seen from these spectra that, in the case of a thin foil, X-ray spectrum is indeed displaced to the soft X-ray region.

3. EXPERIMENTAL STUDIES OF THE VIRCATOR

A vircator for generating X-ray pulses was created on the basis of a direct-action accelerator supplied from an inductive energy storage operating with a plasma opening switch [9]. The maximum current of the inductive storage was 130 kA, and the amplitude of the voltage pulse at the instant at which the storage circuit was open was 1.3 MV.

In the last section of the inductive storage, a load was installed. The load was a vircator vacuum diode containing a 50-mm-diameter thin-walled hollow cathode with a wall thickness of 500 μm. In front of the cathode, a conical thin-walled anode holder with a wall thickness of 500 μm was installed. A 10- or 100-μm tantalum foil was mounted at the end of the anode holder. The length of the interelectrode gap in the diode was 9 mm. The solenoid that was mounted around this

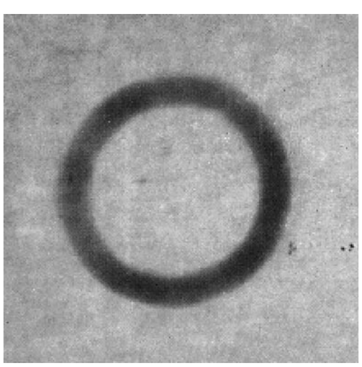

Fig. 6. Pinhole image of the beam.

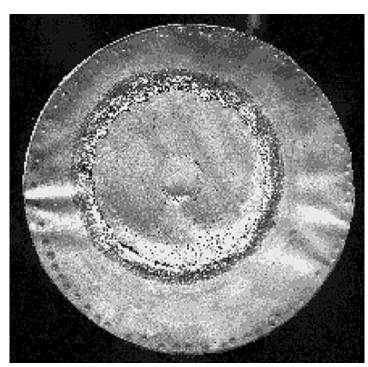

Fig. 7. Beam print on the anode.

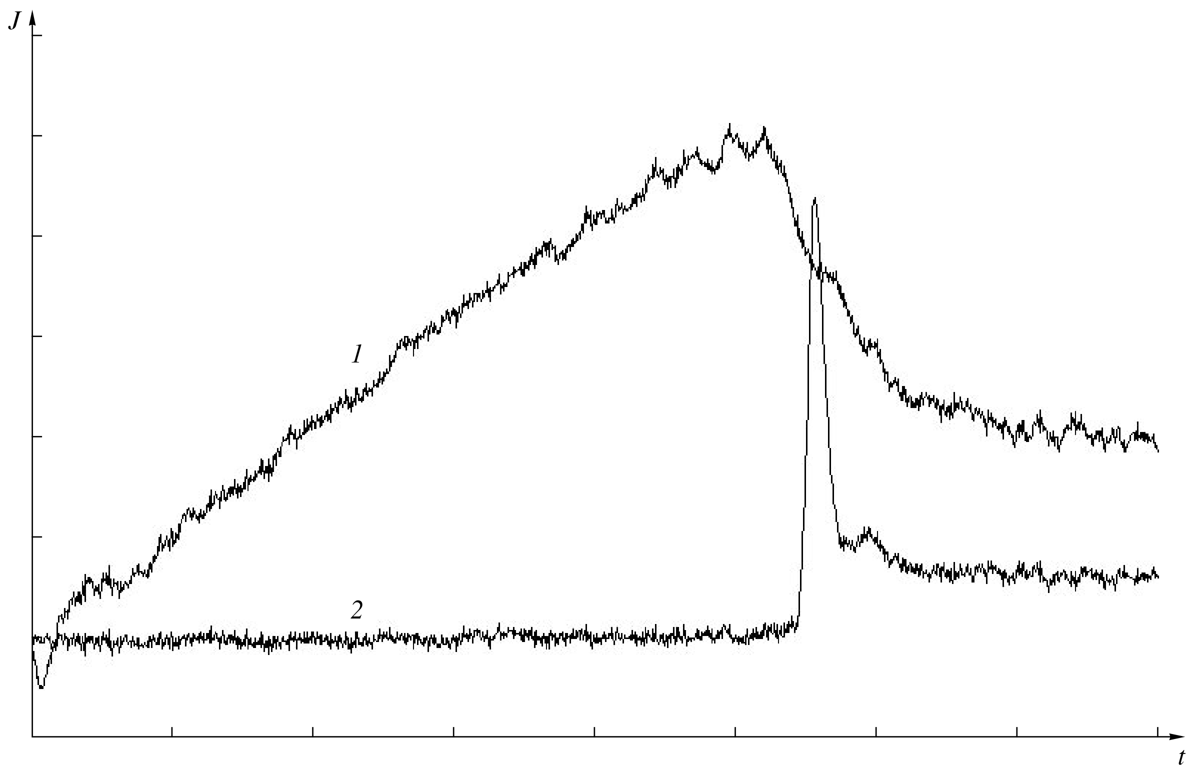

Fig. 8. Waveforms of (*1*) line current and (*2*) load current (20 kA/division) for the case of a 10-μm anode foil. The time scale is 100 ns/division.

section produced an axial magnetic field of 4.4 kG in the diode region.

A schematic of the device with a vircator load is shown in Fig. 5, where the locations of the detectors for measuring various parameters of the system are also indicated.

Currents in different parts of the device were measured with Rogowski coils.

From a pinhole image of the electron beam and its print on the anode foil (see Figs. 6 and 7, respectively), we determined the transverse structure of the beam. The beam cross section was a ring with an outer diameter equal to the cathode diameter. Figures 6 and 7 allow us to determine the shape of the bremsstrahlung source in the anode foil; they also confirm that the results of the above calculations agree well with the experimental results.

The X-ray dose was measured with TLD thermoluminescent dosimeters made of aluminum-phosphate glass containing 87% $MgOP_2O_5$, 13% $Al_2O_{33}P_2O_5$, and 0.1% MnO_2. To measure the duration of X-ray pulses and to estimate their spectrum, we used semiconductor detectors. The detectors were placed at a distance of 700 mm from the anode foil. The emission spectrum was measured by the absorbing foil technique using 2-, 4-, and 7-mm-thick aluminum filters. Microwave pulses were recorded with the help of a hot-carrier microwave detector placed in a 23 × 10-mm waveguide (see [10]). The microwave detector was located 500 mm from the output window.

Microwave radiation was output from the vacuum chamber of the vircator through a 35-mm-thick dielectric window. The thickness of the window was chosen such that it could not be destroyed by the evaporation products of the anode foil. At this thickness, the intensity of X-rays with photon energies of 30 keV (the lower boundary for TLD dosimeters) was attenuated by a factor of 6. For this reason, the TLDs were placed inside the vacuum chamber at a distance of 70 mm from the anode foil, behind a shield protecting them from high-energy electrons.

Figures 8 and 9 show the current waveforms measured in the experiments with a thin anode foil (10 μm Ta). The line-current amplitude is 100 kA, while the load-current amplitude is 90 kA. From the ratio of charges accumulated on the detectors with different filters, we estimated the absorption coefficient and the average photon energy: $\mu \approx 1$ cm^{-1} and $E_\gamma \approx 50$ keV, respectively. The X-ray dose at the TLDs totaled 200 rad.

The experiments with a thick anode foil (100 μm Ta) were performed using the same procedure as in the case of a thin anode (see Fig. 10). A comparison of the waveforms of the X-ray pulses (Figs. 9 and 10) shows that, in the case of a thick foil, the amplitudes of the signals measured behind the filters of different thickness differ

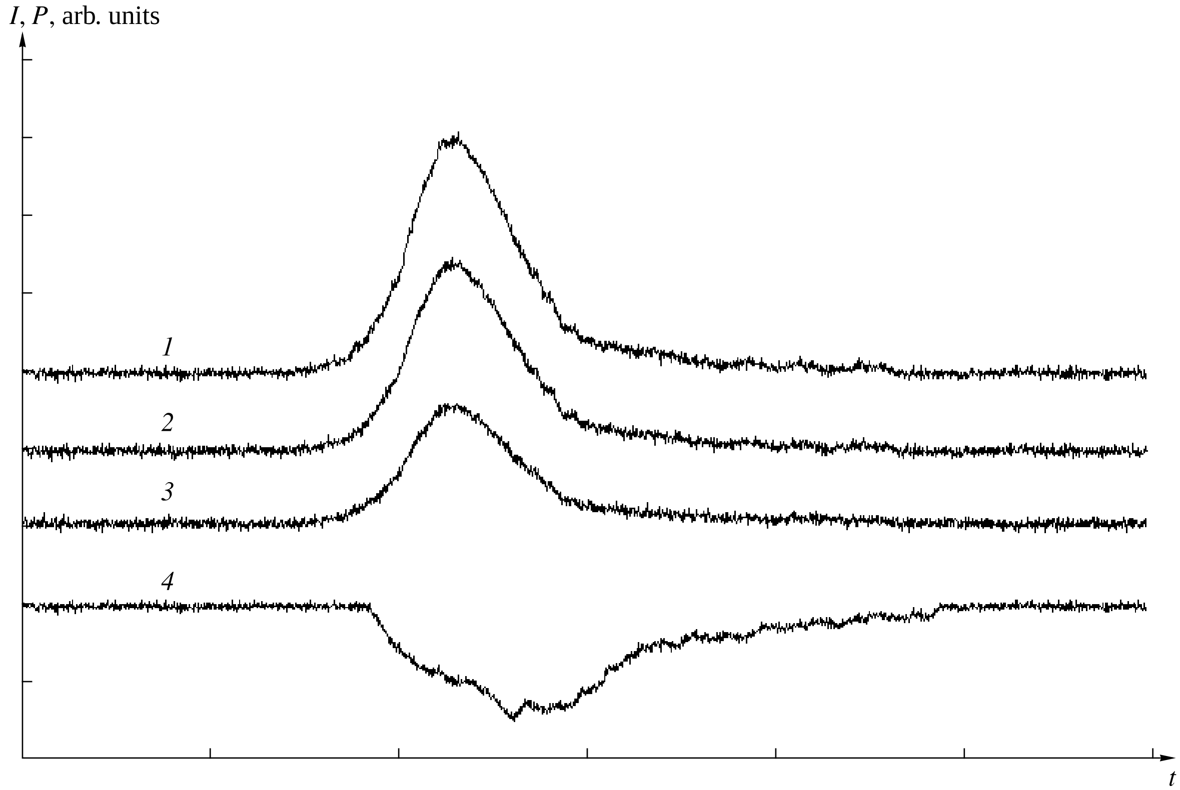

Fig. 9. Waveforms of the X-ray intensity *I* behind Al filters of different thickness: (*1*) 2, (*2*) 4, and (*3*) 7 mm. The anode foil thickness is 10 μm. Curve *4* shows the waveform of the microwave intensity *P* (2 V/division). The time scale is 50 ns/division.

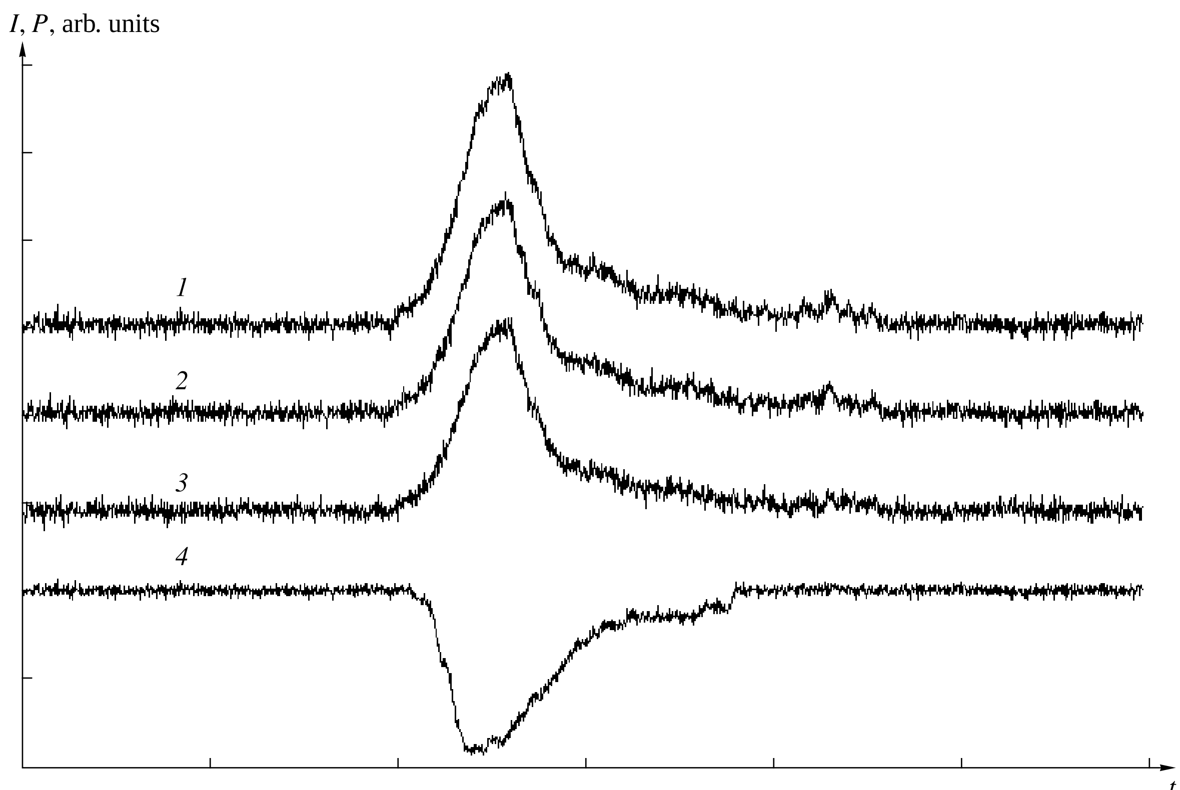

Fig. 10. Waveforms of the X-ray intensity *I* behind Al filters of different thickness: (*1*) 2, (*2*) 4, and (*3*) 7 mm. The anode foil thickness is 100 μm. Curve *4* shows the waveform of the microwave intensity *P* (2 V/division). The time scale is 50 ns/division.

insignificantly. Hence, the emission spectrum contains photons with higher energies as compared to the case of a thin foil. For the thick foil, the absorption coefficient was equal to $\mu \approx 0.54$ cm^{-1} for photon energies of $E_\gamma \approx 80$ keV. The X-ray dose at the TLDs totaled 25 rad.

The signal from the microwave detector confirms the formation of a virtual cathode. The range of 1-MeV electrons in tantalum is ≈ 0.5 mm; hence, a fraction of the beam electrons penetrated into the region behind the anode. However, because of the small number of electron oscillations, the soft X-ray intensity was relatively low. The experiments showed that, for a thin anode, the X-ray dose at energies $E_\gamma > 30$ keV is eight times as high as that for a thick anode.

4. CONCLUSIONS

A vircator capable of generating high-power X-ray pulses due to the multiple transitions of electrons through a thin anode foil has been created and put into operation for the first time. The vircator was created on the basis of a direct-action accelerator supplied from an inductive energy storage operating with a plasma opening switch.

Results have been presented from theoretical and experimental studies on the generation of X-ray bremsstrahlung in vircators with thin (10 μm) and thick (100 μm) tantalum anode foils. For a thin foil, the X-ray dose is found to be eight times as high as that for a thick foil. The spectra of the generated X-ray bremsstrahlung have been measured.

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