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STATISTICAL, NONLINEAR, AND SOFT MATTER PHYSICS

FEATURES OF WIRE X-PINCHES OPERATION ON THE COMPACT HIGH-CURRENT GENERATOR KING

 I. N. Tilikin*, T. A. Shelkovenko, A. R. Mingaleev, A. A. Mingaleev, A. E. Ter-Oganesyan, S. A. Pikuz

Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, 119991 Russia

**e-mail: ivan.tilikin@gmail.com*

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Abstract. Experimental studies of 4-wire X-pinches on the upgraded KING generator, consisting of four low-inductance capacitors, with a current maximum of 160–250 kA, current rise time of 150–300 ns at a charging voltage of 45 kV are presented. The possibility of using the generator as a source of soft X-ray radiation using standard X-pinches made of Al, Cu or Mo wires with a diameter of 25 μm is demonstrated. It is shown that the modernization led to an increase in inductance but did not deteriorate the X-pinch parameters. This resulted in the possibility of using this generator to power standard X-pinches and their use as radiation sources for point projection radiography with spatial resolution of about 13-23 μm.

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1. INTRODUCTION

X-pinches of various configurations are excellent sources of both X-ray [1–6] and UV radiation [7, 8]. Such radiation sources are among the most powerful small sources of soft (photon energy less than 5 keV) X-ray radiation with a flux of 10^{15}–10^{16} W/cm^2 [9, 10]. The hot spot formed during the X-pinch explosion has a micron size and picosecond duration [11–13]. Soft X-ray radiation (SXR) from the hot spot allows its use for studying a large number of physical [1, 5, 6, 10] and biologica [5, 14] objects. Additionally, X-pinch can be used as an intense source of hard X-ray radiation [15, 16]. Most of this radiation is generated by accelerated electron beams formed during and immediately after the hot spot explosion, interacting with dense plasma near it. This radiation has energy above 5 keV (often up to many tens of keV) and source size of 40–200 μm. Numerous experiments show that for proper operation of standard X-pinches, it is necessary to provide current of about 50–100 kA and rise time of about 50 ns [17, 18]. At currents above 200 kA, hybrid X-pinches [19] were widely studied, consisting of a short wire (about 2 mm long) placed between refractory conical electrodes made of W with a small Cu admixture. When using such load, hot spot formation is observed [12]. One of the most important factors affecting the hot spot formation process is the current rise rate. As numerous experiments have shown, hot spot formation is only possible if the current rise rate exceeds 1 kA/ns [11]. Recently, small-size current generators built using low-inductance capacitors discharging directly through the load, rather than the traditional Marx scheme using a forming line [12, 20, 21], are gaining popularity. In this scheme, the voltage provided by the generator is much lower compared to the Marx generator, which can not only affect the efficiency of hot spot formation but also limit hard X-ray generation. The generator's low voltage limits the inductance of used X-pinch configurations, which in practice means very close distance between return current paths, reducing access to diagnostics. One of the generators built according to the scheme using capacitor-switch assemblies was the MINI generator, having a maximum current of 250 kA, current rise time not exceeding 220 ns, and output voltage of 40 kV [12]. The generator worked excellently with X-pinches as loads. However, the generator design led to capacitor failure. Similarly, at the Tomsk Institute of High Current Electronics (IHCE SB RAS), the KING generator [22, 23] was developed, having a maximum current of 200 kA and current rise time of about 200 ns at 45 kV voltage. The KING generator was designed to work with

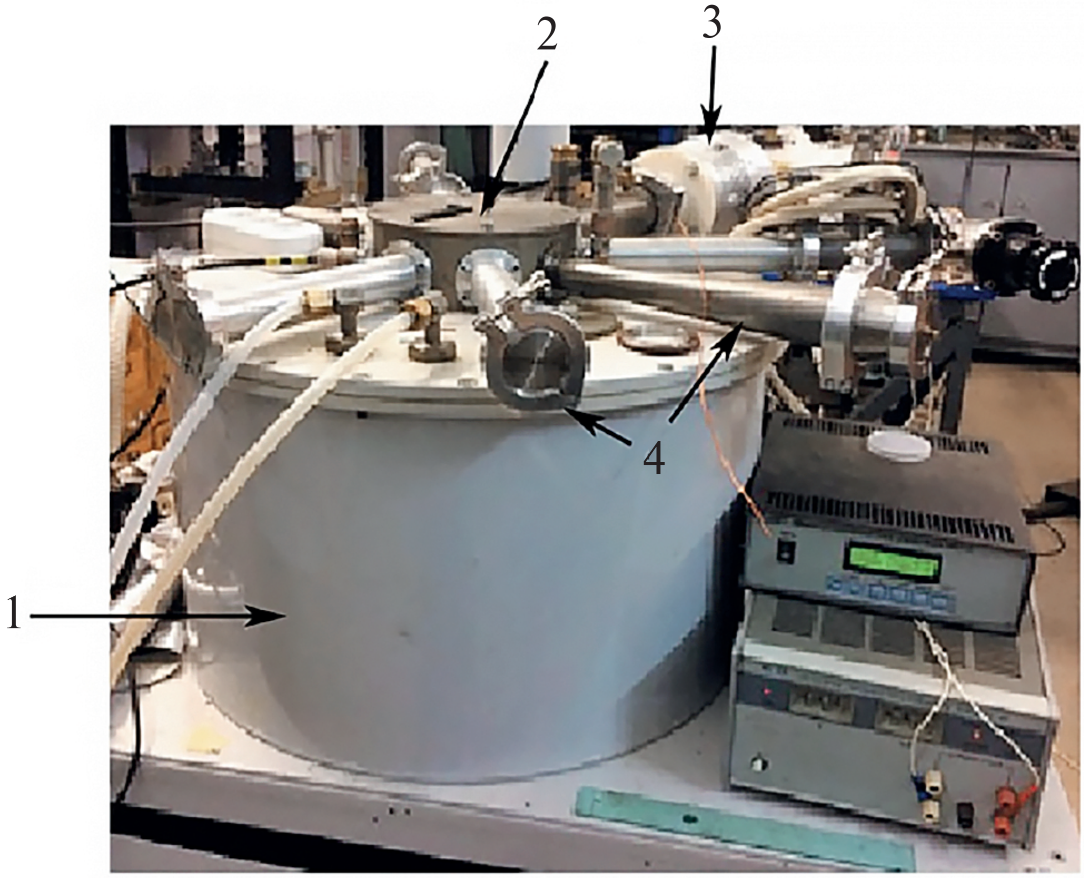

Fig. 1. Photograph of the KING generator exterior: 1 — tank with capacitor-switch assemblies, 2 — vacuum chamber, 3 — vacuum pump, 4 — diagnostic channels

standard X-pinches as a more reliable modification of the MINI generator [12]. Both generators have almost identical design, but the KING generator, while not having such outstanding output parameters and size, is a more reliable and sufficiently compact installation used for research purposes, including work with loads in the form of various X-pinch configurations [24, 25]. The main purpose of these experiments is also to study the possibility of using this low-voltage generator to power standard X-pinches and their use as an SXR source for projection radiography of various objects with high spatial and temporal resolution.

2. EXPERIMENTAL SETUP

The main design feature of the KING generator is the use of HCEIcap capacitors 50–0.25 M, combined with spark gaps connected to the load by a low-inductance feed. The small size of the vacuum chamber allows for rapid evacuation to operating pressures below $5 \cdot 10^{-4}$ Torr. The diameter of the installation itself is only 60 cm. Additionally, the generator needs to be connected to a vacuum system, air pumping system, and power supply unit. The external view of the generator is shown in Fig. 1.

The KING generator was developed to power X-pinches and use them as a source of soft X-ray radiation. The generator has 8 diagnostic channels 4 (Fig. 1). All diagnostic channels are designed to divert radiation from the source for its use. An 8 mm opening is made towards each channel (described below). Such geometry of the output part complicates the diagnostics of the radiation source. Multiple experiments on X-pinch radiation source diagnostics showed that in most shots, a hot spot or several bright spots are formed [12, 13]. The generator was also used for a series of experiments studying UV radiation from the surface of exploding foils [7, 8, 25]. These experiments revealed significant drawbacks in the generator's output part, complicating the study of the plasma object. Therefore, it became necessary to modernize the output part of the KING generator.

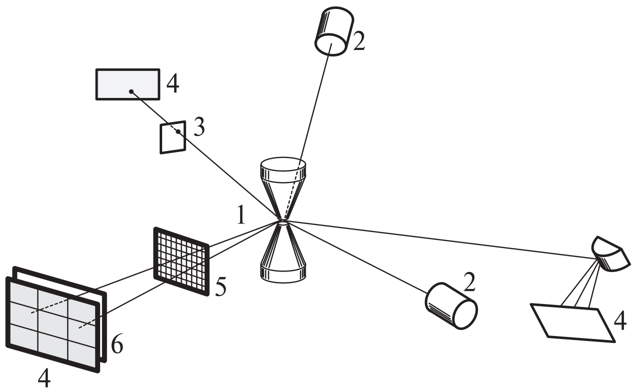

Fig. 2. Diagnostic methods scheme: *1* – generator load, *2* – diamond photodetectors, *3* – camera obscura, *4* – imaging plate or photographic film, *5* – test object, *6* – filters, *7* – CsAP spectrograph crystal

The KING generator is equipped with a wide range of diagnostic devices. The charging voltage is monitored in each shot. The current flowing through the load is monitored using a Rogowski coil. In addition to measuring electrical signals, various methods were used to diagnose radiation source parameters. The layout of diagnostic devices is shown in Fig. 2.

For recording the duration and intensity of X-ray radiation with photon energies from 10 eV to 10 keV, calibrated diamond photodetectors 2 (PCD) [26] were used (Fig. 2). Electrical signals were recorded using Tektronix oscilloscopes with a bandwidth of 1 GHz. The temporal resolution of photodetectors with connecting cables when using these oscilloscopes is about 1 ns. For visualization of radiation sources, a pinhole camera 3 with an aperture from 30 μm to 200 μm was used (Fig. 2). To determine the size of the radiation source, a projection radiography scheme was used to image metal grids as test objects 5 (Fig. 2). Fuji BAS TR imaging plates or Kodak DR-50 X-ray films are used to record X-ray and UV radiation. To record the emitted energy in different spectral ranges, a 7 μm thick Be filter transmitting photons with energies above 700 eV, an 8 μm thick Mylar filter transmitting photons with energies above 1 keV, and a 12.5 μm thick Ti filter transmitting radiation from 2.5 to 5 keV were used, which is the most characteristic spectral region for soft X-ray radiation from the X-pinch hot spot. To determine the plasma parameters of the radiation source, a spectrograph 7 with a convex CsAP crystal (Fig. 2) with a crystal lattice period of 26.6 Å is installed on the KING generator. The crystal radius of curvature is 350 mm. Fig. 3 shows the spectrum acquisition scheme. Imaging plates or X-ray film are used to record

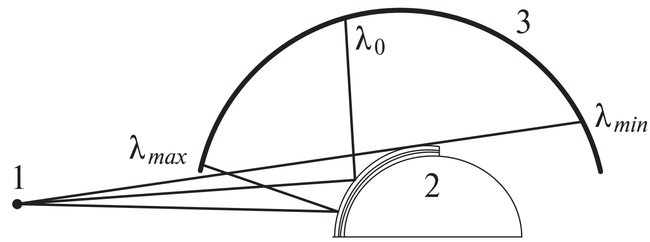

Fig. 3. Diagram of a convex spectrograph installed on the KING generator: *1* – radiation source, *2* – convex CsAP crystal, *3* – imaging plate for spectrum registration

the spectrum. The spectrograph design allows for wide-range adjustment of the radiation incidence angle on the crystal surface, which is selected according to the Bragg-Wolf formula: $2d\sin\theta = m\lambda$, where θ is the reflection angle, d is the crystal interplanar spacing, λ is the radiation wavelength, m is the reflection order. A thin aluminized filter (thickness $\mathrm{Al} < 1$ μm) is installed at the spectrograph input aperture, cutting off background exposure without significantly reducing radiation intensity.

3. EXPERIMENTAL RESULTS

As mentioned earlier, the output section of the KING generator had several radiation output holes with a diameter of 8 mm, and the maximum load length was limited to 8 mm, which did not allow the use of longer loads or the study of larger radiation sources (see Fig. 4 *b*,*d*). In particular, this limited the possibilities for studying foil explosion on such a generator. For greater convenience of using diagnostic devices, the design of the generator output section was modernized. Fig. 4 shows diagrams of the generator output section and photographs of the return current conductor.

In experiments with the new output section, 2 to 4 return current rods were used. The use of such a scheme made it possible to vary the load length over a wide range (up to 20 mm) and study radiation from the surface of large spatial objects [27, 28]. The new design of the generator output section opens up more possibilities for studying X-pinches of various configurations on the KING generator. Series of experiments were conducted with various wires in hybrid and standard 4-wire X-pinch. The table provides summary information about the presence of soft X-ray radiation with quantum energy above 1 keV when using different wires in the load. It can be seen that radiation was recorded in many shots. However, it was noticed that different shots show current of

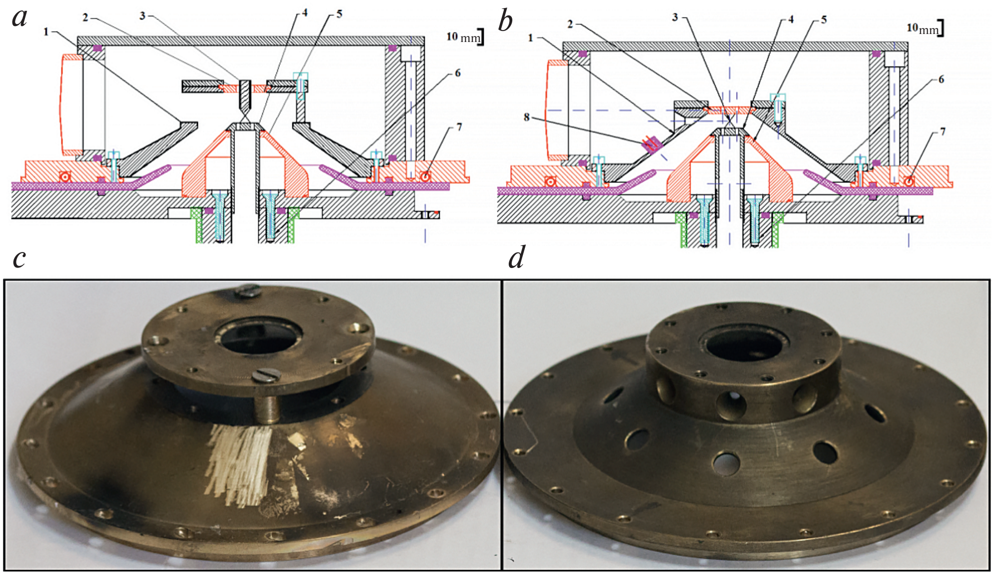

Fig. 4. *a*, *b* – Diagrams of the KING generator output section. *c*, *d* – Photographs of the return current conductor: original (*b, d*) and modernized (*a*, *c*). *1* – return current conductor, *2* – replaceable part of return current conductor, *3* – load, *4* – replaceable part of high-voltage electrode, *5* – high-voltage electrode, *6* – container for collecting weights for standard X-pinch tension, *7* – Rogowski belt, *8* – differential current sensor ("loop")

different shapes, with different current rise rates. As experiments have shown, hybrid X-pinches work much better than standard wire X-pinches across a wide range of current and current rise rate. However, it was previously known that standard X-pinches are more demanding regarding current parameters. The KING generator after modernization allows studying the influence of current parameters on the explosion process of standard X-pinches.

Fig. 5 shows characteristic signal waveforms that were recorded on the KING generator after modernization of the output section during the explosion of standard 4-wire X-pinches with 25 μm thick Cu wires. The results are shown for those shots where soft X-ray radiation was recorded behind a 7 μm thick Be filter ($E\gamma > 700$ eV) and 8 μm thick Mylar ($E\gamma > 1$ keV). It can be seen that the current maximum ranges from 160 to 230 kA. The current rise time to maximum varies from 150 to 300 ns, which corresponds to an average current rise rate to maximum from 0.7 to 1.2 kA/ns. Characteristic features of the current waveform can be noted, which indicate that sometimes capacitors do not operate quite synchronously. Sometimes this leads to an increase in the current maximum (Fig. 5*c*), and sometimes leads to a faster current rise, after which the current remains constant (Figs. 5*b*, *c*). In some shots, a standard sinusoidal-like current waveform is observed, but the current maxima can differ with the same duration (Figs. 5*a*, *c*).

Table. Percentage of shots with soft X-ray radiation with energy above 1 keV during the explosion of hybrid (HXP) and standard 4-wire X-pinches (SXP) on the KING generator

X-pinch	Material	Number of shots	Percentage of shots
SXP	Mo	4	50%
	Al	6	30%
	Cu	8	50%
HXP	Mo	30	90%
	Al	10	100%
	Cu	8	100%

Studies show that if the current rise rate exceeds 1 kA/ns at the moment of plasma compression, bright or hot spots are formed. Separately, experiments investigated the influence of return current rod parameters on the X-pinch explosion process. The number of rods varied from 2 to 4 pieces. The length of the rods varied from 1 to 4 cm. Four shots were performed in each configuration. The parameters of current, voltage, and current rise time remained within standard deviations. SXR generation occurred in approximately 50% cases, as in other experiments

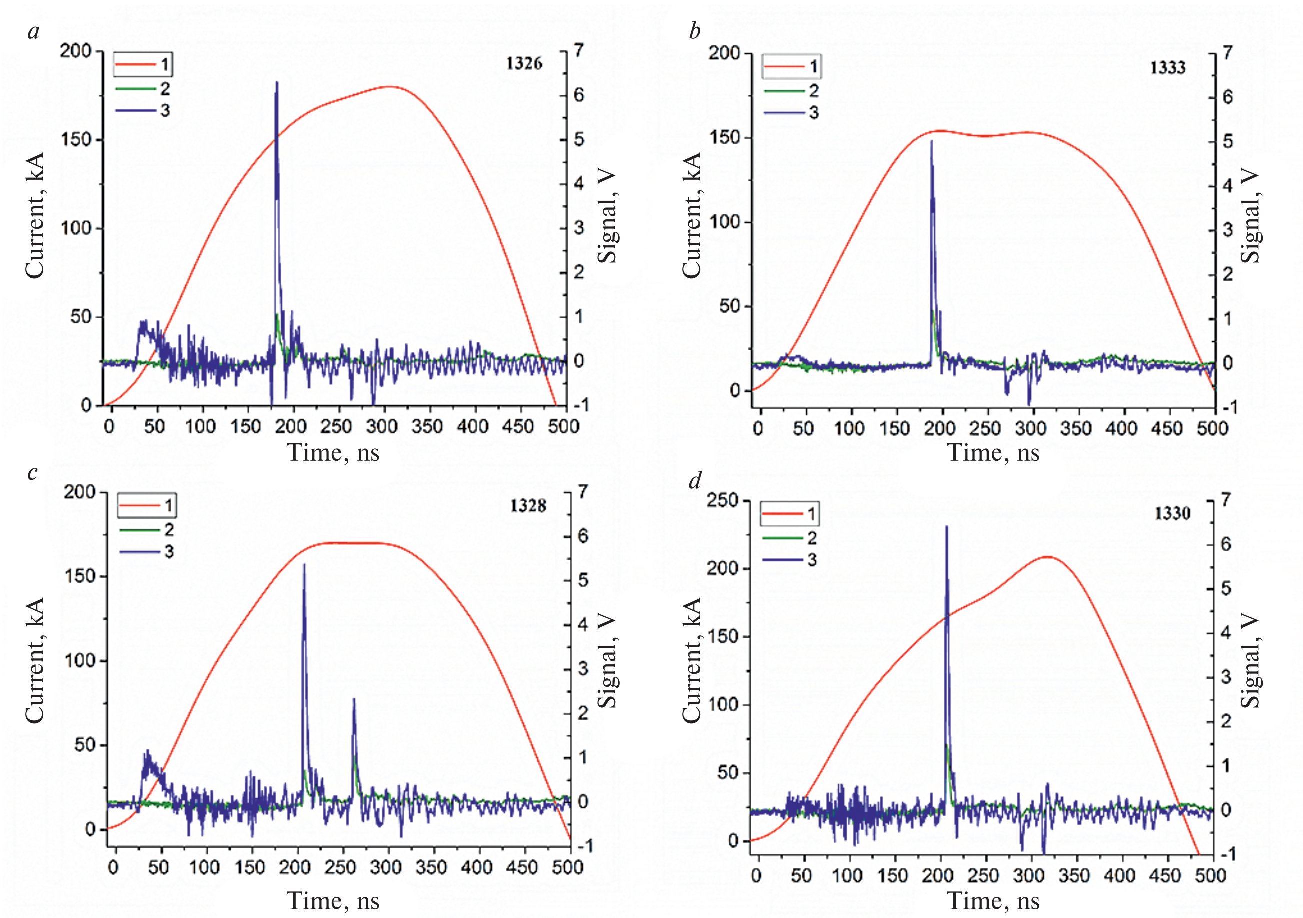

Fig. 5. Oscillograms of current (1) and signals recorded using diamond photodetectors behind an 8 μm thick Mylar filter (2) and 7 μm thick Be filter (3) during the explosion of a 4-wire X-pinch with 25 μm thick Cu wires. Various characteristic signal waveforms are shown (*a*, *b*, *c*, *d*) recorded on the KING generator

(see Table). Thus, it is shown that changing these parameters does not significantly affect the formation of SXR sources during X-pinch explosions. The emerging radiation sources from hot or bright spots were investigated for their potential use. One of the most important parameters is the size of the radiating region. The simplest and most effective method for determining the size of the radiating region in the SXR range is determining the size by image edge blurring in projection radiography scheme. For this, it is necessary to obtain a test object image. Fig. 6 shows an image of a copper mesh with 100 μm pitch, obtained from radiation of a 4-wire X-pinch with Cu wires of 25 μm thickness. The image was obtained behind various filters, which allows assessment of spatial resolution in different spectral ranges.

The density traces of the plates show the dimensions of image edge blurring, which is equivalent to spatial resolution. It can be seen that the resolution ranges from 13 to 23 μm (Fig. 6, 1–3) in various spectral ranges and in different directions: transverse and longitudinal relative to the cathode-anode direction. The smallest size of 12 μm is obtained behind the Ti filter, which corresponds to photon energies from 2.5 to 5 keV, meaning that a hot spot is observed in the experiments. This size is observed in the transverse direction relative to the cathode-anode direction, which is characteristic of X-pinch operation. No significant difference in spatial resolution between transverse and longitudinal directions was recorded, which distinguishes SXP from HXP, where a difference of 2.5–3 times was observed. Fig. 7 shows an enlarged fragment of the oscillogram during the explosion of a 4-wire X-pinch with Cu wires of 25 μm thickness. Fig. 5*b* shows the complete signal from the same shot.

It can be seen that the total radiation duration does not exceed 4 ns, while the structure of this

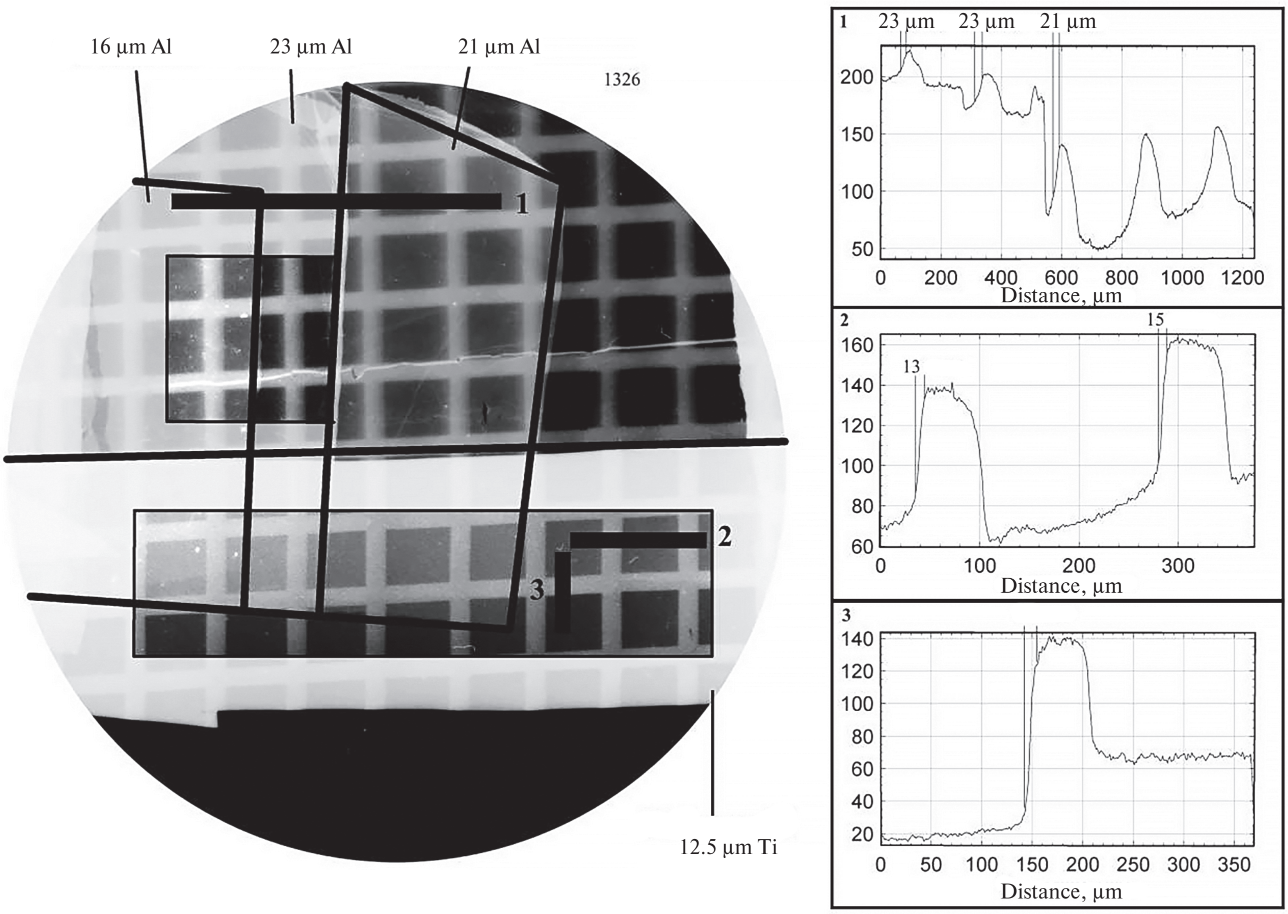

Fig. 6. Image of a copper mesh from radiation of a 4-wire X-pinch with Cu wires of 25 μm thickness, recorded behind various filters, and density traces behind a 12.5 μm Ti filter (1, 2) and behind Al filters of 4, 8, and 16 μm thickness (3). The selected fragments have additionally adjusted contrast for clarity. Magnification 1 : 10

radiation is visible, consisting of several flashes, each no more than 1 ns, which may indicate multiple pinching. The temporal resolution of the recording equipment does not exceed 1 ns, which suggests that in this case, there might be narrower X-ray peaks. On such compact generators, radiation spectra were recorded for the first time, allowing the determination of plasma parameters. Fig. 8*a* shows a characteristic spectrum recorded during the explosion of a 4-wire X-pinch with 25 μm thick Cu wires. The spectrograph angle adjustment allows recording of Ne-like spectrum Cu. On Fig. 8*b* shows a film darkening graph with marked wavelengths. The reconstruction of wavelengths in the spectrum is performed according to the initial calibration, and then precise binding occurs by the most intense lines. In this spectral range, the Cu-plasma emission spectrum can be calculated using the PrismSPECT program [29]. The spectra are calculated for different values of plasma temperature and electron

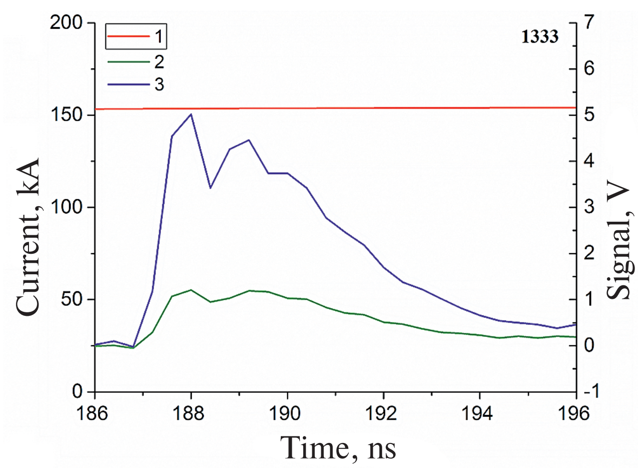

Fig. 7. Enlarged fragment of the oscillogram (full fragment in Fig. 5*b*) of current (1) and signals recorded using diamond photodetectors behind an 8 μm thick Mylar filter (2) and a 7 μm thick Be filter (3) during the explosion of a 4-wire X-pinch with 25 μm thick Cu wire

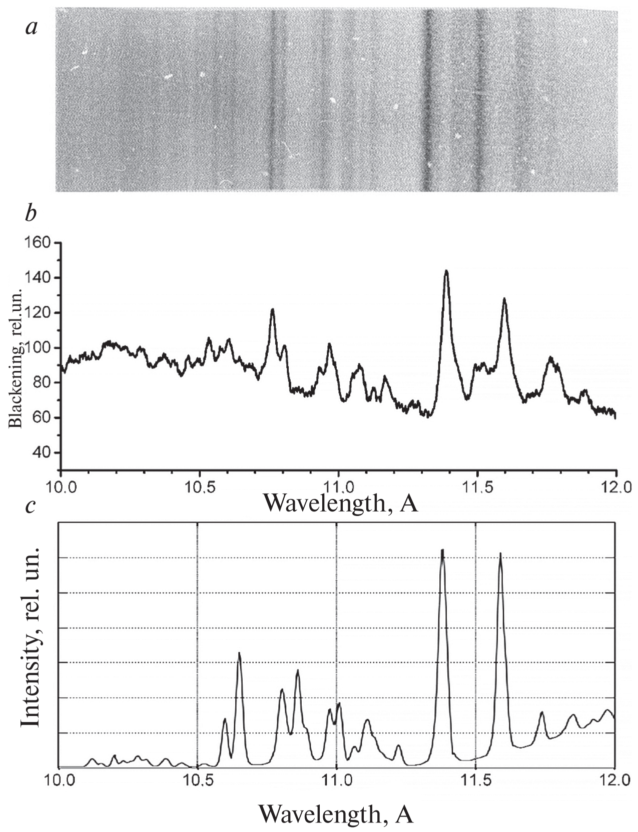

Fig. 8. *a* – Ne-like emission spectrum of Cu, recorded using a convex CsAP crystal during the explosion of a 4-wire X-pinch on the KING generator. *b* – Spectrum trace with restored wavelengths and calculated spectrum of Cu plasma radiation with plasma electron temperature of 150 eV and electron density $5 \cdot 10^{20}$ cm^{-3}

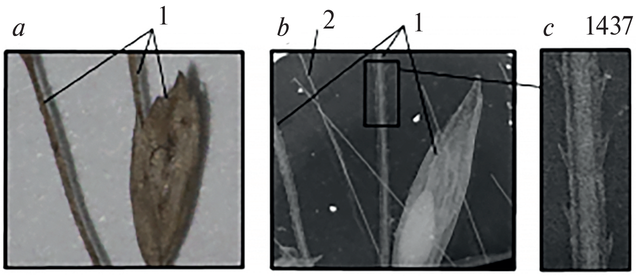

Fig. 9. Photograph (*a*), radiograph (*b*), and enlarged fragment of radiograph (*c*) of biological test objects: *1* – stem and inflorescence, *2* – carbon fiber 10 μm thick. Radiography was obtained behind a 12.5 μm thick Ti filter during the explosion of a 4-wire X-pinch with 25 μm thick Cu wires

density at a given source size, determined from the radiographs of test objects, as shown above. Fig. 8*c* shows the reconstructed spectrum that best matches the experimental one, corresponding to a plasma electron temperature of 150 eV and electron density $5 \cdot 10^{20}\,\text{cm}^{-3}$. Thus, during the explosion of standard X-pinches, thermal radiation from bright plasma points is observed.

Such SXR sources are excellent for obtaining images of various biological and plasma objects with high spatial resolution. The modernized design of the KING generator's output section facilitates the work of radiation output to the studied object. As an example, an image of a biological object was obtained. Fig. 9 shows a photograph (Fig. 9*a*) and radiography (Fig. 9*b*) of an inflorescence and stem. Fig. 9*c* shows an enlarged fragment of the stem, which clearly shows the internal structure and fine details of the biological object, indicating the high quality of the radiation source and the possibility of using such a radiation source for point projection radiography.

4. CONCLUSIONS

Experimental studies of hybrid X-pinches on the modified KING generator showed that changes in the output part of the generator led to an increase in the load inductance, which, in turn, led to an increase in current rise time. However, this had practically no effect on hybrid X-pinches. Standard X-pinches began to work slightly worse, but in most shots, a soft X-ray source is formed. The size of the radiation source is 13–23 μm in the spectral range of 2.5–5 keV. The radiation duration does not exceed 4 ns. It is shown that the most important parameter is the current rise rate until the bright point formation. For the formation of bright points, the current derivative value (dI/dt) above 1 kA/ns is not critical. Bright points in Xpinches were observed at $dI/dt > 0.8$ kA/ns. Spectral studies of plasma parameters were conducted on similar generators. The plasma temperature is 150 eV, while the electron density equals $5 \cdot 10^{20}\,\text{cm}^{-3}$. Thus, the generator can be used both as a source for projection point radiography and for studying various plasma sources. The increased field of view and the ability to study objects up to 4 cm in size open up prospects for studying various plasma objects, such as foils or exploding wires.

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