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Sensitivity of detection of micro-objects in radiography of thick composite steel objects using a new source of microfocus bremsstrahlung based on a betatron

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The possibility is shown and the sensitivity of detecting microobjects in the radiography of thick steel objects using microfocus ($13\,\mu$m) bremsstrahlung of a new source based on a betatron with an electron energy of 18 MeV is evaluated. The image contrast and resolution of a pair of thin ($48\,\mu$m) Duplex IQI wires are demonstrated, which is the basis for determining the sensitivity of microobject detection.

Keywords: betatron, electron beam, bremsstrahlung, radiography.

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Betatrons with a submillimeter focus (e.g., the compact SIB-7 model with electron energy $E_e = 7$ MeV and focus size $\Delta F = 0.3$ mm) are used often for radiography and tomography of large-size steel articles as sources of hard bremsstrahlung produced by accelerated electrons with megaelectronvolt energies in thick and broad internal targets. High-energy X-ray tubes (e.g., the MXR-451HP/11 model [1] with $E_e = 450$ keV and $\Delta F = 0.4$ mm) are also used widely. However, since X-ray tubes with megaelectronvolt electron energies are commercially unavailable, the thickness of articles examined this way is limited.

Sources of hard bremsstrahlung with a microfocus (less than 0.1 mm) spot are needed for high-resolution radiography and tomography of parts of large-size objects. The results of the first experiments with a new microfocus source based on the B-18 ($E_e = 18$ MeV) betatron with narrow silicon (50 and $8\,\mu$m in width) and tantalum ($13\,\mu$m in width) targets inside have been reported in [2,3]. Enlarged images of the wire microstructure of a Duplex IQI instrument [4] and steel plates were obtained with these targets, which are approximately 30, 187 (Si), and 115 (Ta) times narrower than the electron beam diameter (1.4 mm). Therefore, the contrast of images of pairs of thin Duplex IQI wires, which is used to evaluate the image quality and the focus spot size, was high [5]. The significance of phase contrast in imaging of edges of plastic and steel plates with Si targets of the B-18 betatron has also been discussed in [3]. In the case of polychromatic bremsstrahlung, edge contrast may be formed due to refraction of radiation at the edge surface [6]. Note that the concept of application of an internal target with a size smaller than the beam diameter of an orbit accelerator for reducing the focus spot size of bremsstrahlung has been proposed for the first time in [7,8].

The capacity of a microfocus bremsstrahlung source based on the B-18 betatron to reveal planar microgaps and microinclusions in thick steel articles has been demonstrated in [9]. Enlarged images of gaps $10\,\mu$m in width between steel blocks and tantalum foil $13\,\mu$m in thickness, which were positioned behind steel barriers with a thickness of 40 and 55 mm, revealed a high sensitivity of their visualization.

In the present study, enlarged images of Duplex IQI obtained with the use of microfocus hard bremsstrahlung produced by 18 MeV electrons in a Ta ($13\,\mu$m) betatron target are examined. These images were produced in radiography of a different thick composite object, which was the primary test object and consisted of four or five thick steel plates. Pairs of thin wires of a Duplex IQI instrument positioned above the composite object were used as models of microobjects that were not anticipated to be present in the study of a thick composite object. Images of Duplex IQI and the primary test object, which were positioned in front of an additional thick (20 mm) steel plate, provided an opportunity to estimate the sensitivity of visualization of microobjects in such a complicated scenario with the irradiation dose needed to examine the primary thick object being too high for visualization of microobjects. In radiography, the sensitivity of a certain technique is characterized by the ratio of the microobject thickness to the thickness of a barrier behind which this microobject still remains distinguishable in an image. The visibility of a microobject is specified by the contrast and blurriness of its image, which is governed by the size of the radiation source. As the source grows larger, the image contrast decreases, since the image becomes blurrier. This has a negative effect on the sensitivity of the tested technique.

The diagram of the experiment is presented in Fig. 1, *a*. A tantalum target with thickness $t = 13\,\mu$m, height $H = 10$ mm, and length $T = 2.5$ mm along the electron beam was positioned on a goniometer inside the betatron

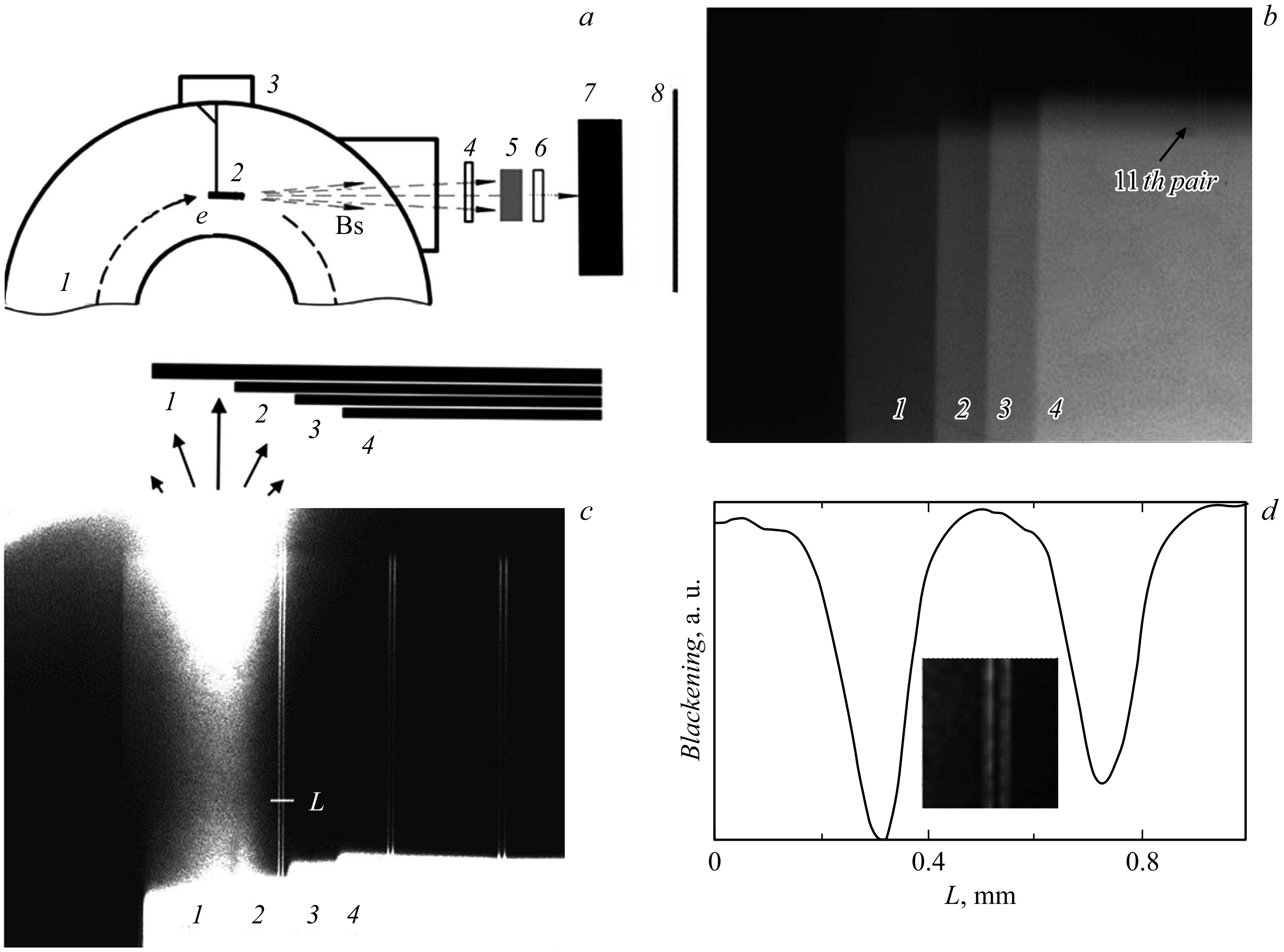

Figure 1. *a* — Diagram of the experiment. *1* — Betatron chamber, *2* — target, *3* — goniometer, *4* — Duplex IQI, *5* — object for radiography, *6* — steel plate 15 mm in thickness, *7* — steel plate 20 mm in thickness, *8* — X-ray film; *b* — fragment of the radiographic image of a composite sample with Duplex IQI placed on top; *c* — another fragment of the image of a composite sample with Duplex IQI enhanced via the „brightness–contrast“ adjustment; *d* — densitogram of the image of the 13th pair of Duplex IQI wires. An enlarged fragment of the image of the 13th wire pair is shown in the inset.

chamber at a radius shorter than the orbit radius of accelerated electrons and was oriented along the electron beam. An additional magnetic field produced by the dump winding at the end of the acceleration cycle reduced the orbit radius of electrons, and they eventually reached the target. Radiation produced in the electron–target interaction left the chamber through a window and interacted with the studied sample positioned on an external goniometer at distance $L_1 = 48$ cm from the target. An X-ray film was mounted at distance $L_2 = 114$ cm from the target. The zoom factor for the object image was $M = L_2/L_1 = 2.37$. A Duplex IQI instrument was positioned at distance $L_1 = 38$ cm $(M = 3)$ above the composite object. Images were scanned for subsequent analysis.

The object for examination of edge images was formed by a 10-mm-thick plate and three steel plates with a thickness of 5 mm with their edges shifted relative to each other (*1–4* in the lower part of Fig. 1, *a*). The Duplex IQI instrument was used to model a microobject (a pair of thin wires) that was not anticipated to be present in radiography of the primary object.

Figure 1, *b* presents a fragment of the enlarged image of the composite object $(M = 2.37)$ and Duplex IQI $(M = 3)$. The Duplex IQI image, which is positioned above the image of the composite object, is almost indistinguishable, since the irradiation dose needed to obtain a quality image of the thick (25 mm) studied object is too high. Figure 1, *c* shows another image fragment enhanced via the „brightness–contrast“ adjustment. Pairs of wires are visible here, but the image of the composite object is too bright, and the edges of plates are indiscernible.

Figure 1, *d* presents the densitogram (measured along line *L* in Fig. 1, *c*) of the image of the 13th pair of Pt wires 48 μm in diameter with a 50 μm gap between them. This densitogram has a high contrast, and the 13th pair of wires is resolved clearly. The minima in the densitogram have almost no overlap.

In the next experiment, a fifth steel plate with a thickness of 15 mm was added to the composite object, which then grew in thickness to 40 mm. An additional 20-mm-thick steel plate was also used. It was positioned behind Duplex IQI and the composite object at a distance of 100 mm and acted as an absorber of two parts of radiation that were transmitted through the composite object only or through Duplex IQI only.

Figure 2, *a* shows the upper and lower parts of the enlarged ($M = 3$) positive image of Duplex IQI with Pt wire pairs 13–8 and the composite object obtained with the use of the steel absorber plate. The exposure time was longer than the one set in the first experiment, since the irradiation dose had to be adjusted for a thicker (40 mm) composite object behind a thick (20 mm) barrier. This dose was too high for Duplex IQI. Therefore, the images of wire pairs 13, 12, and 11 are indistinguishable.

Figure 2, *b* presents the additionally magnified fragment of the positive image from Fig. 2, *a* with visible 13th and 12th Duplex IQI wire pairs. This image was enhanced via the „brightness–contrast" adjustment. Its densitogram is shown in the lower part of Fig. 2, *b*. Wire pairs are seen fairly clearly even when the steel absorber plate is present. However, background radiation scattered in the studied object and the absorber plate produced a significant contribution to the imaging process, thus reducing the quality of the Duplex IQI image. The visibility of the

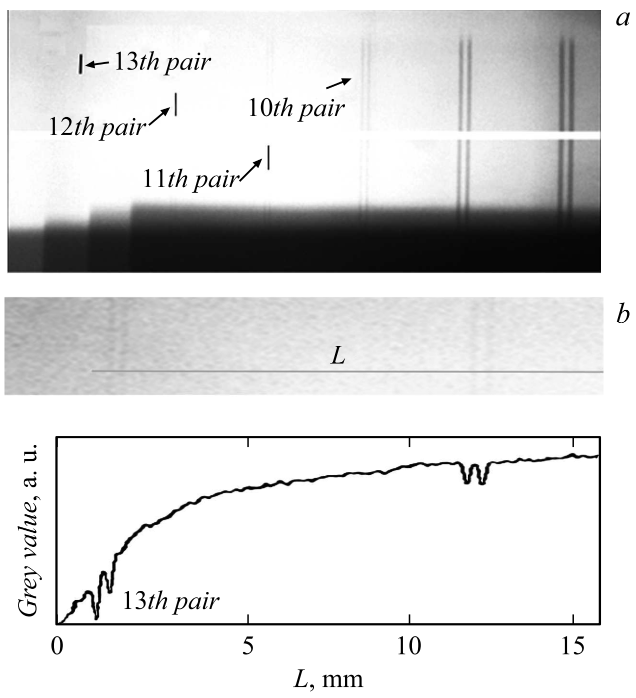

Figure 2. *a* — Upper and lower parts of the enlarged positive image of the composite object and Duplex IQI with Pt wire pairs 13–8, which was obtained with a steel absorber plate 20 mm in thickness; *b* — additionally magnified fragment of the positive image of Duplex IQI with the 13th and 12th pairs of Pt wires and densitogram measured along line *L* in the image.

13th pair in Fig. 2, *b* provides an opportunity to estimate the sensitivity of radiography in this case. For example, at photon energy $E_\gamma = 1$ MeV, a Pt wire 48 μm in diameter is equivalent in absorption to a steel wire 149 μm in diameter. The sensitivity of radiography is characterized by the ratio of the equivalent wire thickness to the absorber plate thickness and is close to 0.75%. However, the image of the 13th pair of Pt wires has a fairly high contrast and sharpness, and the double minimum corresponding to this pair in the densitogram is easy to identify. This implies that the sensitivity of the method is higher than the one established in the experiment.

High-contrast images of the clearly resolved 13th pair of thin (48 μm) wires of the Duplex IQI instrument were obtained in radiography of the thick primary study object, which was constructed from several steel plates, with the irradiation dose being non-optimal for visualization of thin wires. A high sensitivity of detection of such microobjects in radiography of large-size objects (with objects of both types positioned behind a thick (20 mm) steel barrier) with microfocus bremsstrahlung of the betatron was also demonstrated. Note that the examination of Duplex IQI with radiation of a compact SIB-7 betatron (electron energy, 7 MeV; focus size, $\Delta F = 0.3$ mm) and an MXR-451HP/11 X-ray tube (450 keV, $\Delta F = 0.4$ mm) without a composite object and a thick steel barrier produced images with only the 9th pair of Pt wires, which have a diameter of 130 μm and are spaced 260 μm apart, resolved.

The presented results are a significant supplement to the data that have been obtained earlier in our studies into the process of imaging of objects, which were assembled from thin and thick parts, in the presence of absorption and refraction effects.

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Conflict of interest

The authors declare that they have no conflict of interest.

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