

# New microfocus bremsstrahlung source based on betatron B-18 for high-resolution radiography and tomography

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**Abstract.** New microfocus source of hard bremsstrahlung (photon energy  $> 1$  MeV), based on the betatron B-18 with a narrow Ta target inside, for high-resolution radiography and tomography is presented. The first studies of the source demonstrate its possibilities for practical applications to detect the microdefects in products made from heavy materials and to control gaps in joints of parts of composite structures of engineering facilities. The radiography method was used to investigate a compound object consisting of four vertically arranged steel bars between which surfaces were exposed gaps of  $10\ \mu\text{m}$  in width. The radiographic image of the object, obtained with a magnification of 2.4, illustrates the good sensitivity of detecting the gaps between adjacent bars, due to the small width of the linear focus of the bremsstrahlung source.

## 1. Introduction

The production of a microfocus radiation source based on relativistic electron beams is important for high resolution radiography and tomography. Ordinary betatrons generating secondary hard radiation caused by interaction of the internal electron beam with the target (typically a thick target), that is larger in its area than the cross section of the millimeter-size beam, are used for obtaining the images of a number of objects. But, in [1, 2] the idea was proposed to use internal target much smaller than diameter of the electron beam of the cyclic accelerator to reduce the focal spot of the generated Bremsstrahlung. Here, if the beam will circulate for a sufficiently long time on the radius of the micro-target location, then, due to betatron oscillations, electrons will fall on such a target with a sufficiently high efficiency.

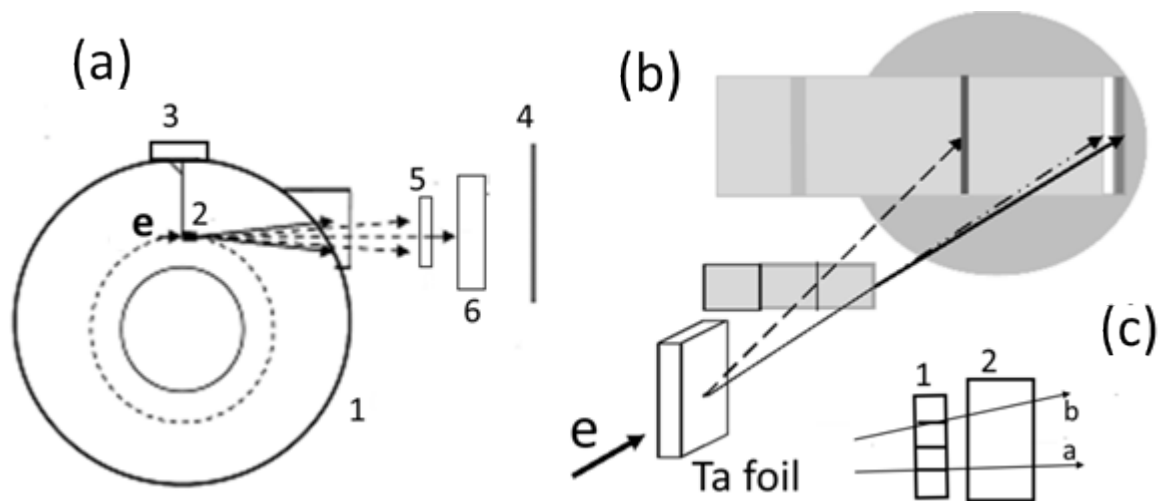
This paper presents the results obtained for generation of linear-microfocus Bremsstrahlung under interaction of 18 MeV electrons with thin target which was oriented along the direction of the internal beam of the B-18 betatron in order that the electrons can interact with the narrow front face of the target. Magnified images of the compound steel object have been obtained using the radiations generated in the narrow internal Ta targets, the width of which is approximately 100 times smaller



than the diameter of the electron beam. The formation of the object structure image with participation of the absorption and phase contrast effects is shown.

## 2. Experimental setup

The experimental setup is shown in Figure 1. A thin Ta target was placed on a thin vertical goniometer holder inside the equilibrium orbit of the accelerated electrons, Figure 1a. Additional magnetic field generated by the dump coil within 30  $\mu$ s reduced the orbit radius and the electrons fell onto the internal target. The generated radiation escaped through the 50  $\mu$ m Mylar window of the experimental chamber, passed through an investigating object and fell on the Agfa D-4 X-ray film placed at a distances of 114 cm from the target, Figure 1b.



**Figure 1.** The experimental scheme: a) 1 – betatron chamber, 2 – narrow target, 3 – internal goniometer, 4 – X-ray film, 5 – object of investigation, 6 – steel-plate X-rays absorber; b) Locations of narrow target on the electron beam and object on radiation beam, and also the scheme of object radiogram; c) 1 – steel object (view from above), 2 – steel-plate X-rays absorber.

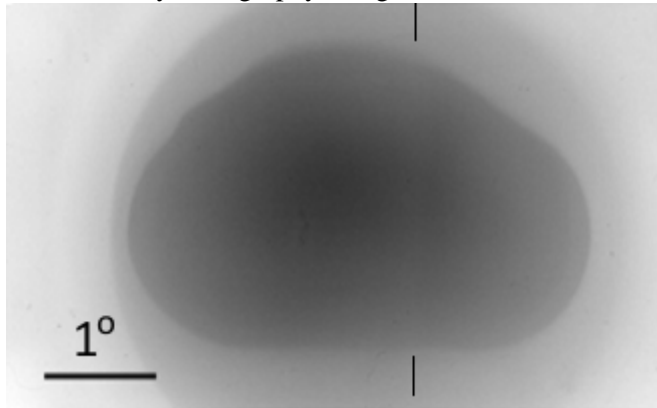
The 13- $\mu$ m-thick Ta target with the vertical  $L = 5$  mm and horizontal  $T = 4$  mm (along the direction of the electron beam) sizes were used in the experiments. The object of investigation was installed on an external goniometer at a distance of 48 cm from the target. The steel plate could be placed at a distance of 24 cm from the object in order to absorb the X-rays (photon energy  $E_\gamma < 1$  MeV). The object photographs obtained using hard bremsstrahlung ( $E_\gamma > 1$  MeV gamma-rays), were processed with the scanner to obtain negative and positive images of the object structure for subsequent analysis.

## 3. Experimental results

Figure 2 shows the photograph of angular distribution of the radiation generated by 18 MeV electrons in the 13  $\mu$ m Ta target oriented at angle  $\theta_o = 0.3^\circ$  with respect to the electron beam. The angular distribution of radiation generated in the Ta target differs significantly from the distribution obtained using the 50  $\mu$ m Si target [3]. In [3] the radiation beam photographs were formed mainly by 5 – 50 keV X-rays. Therefore, in that case, the investigation of absorption contrast and size of the radiation source focus was carried out using the *Duplex IQI* microstructure (thin wires) [4].

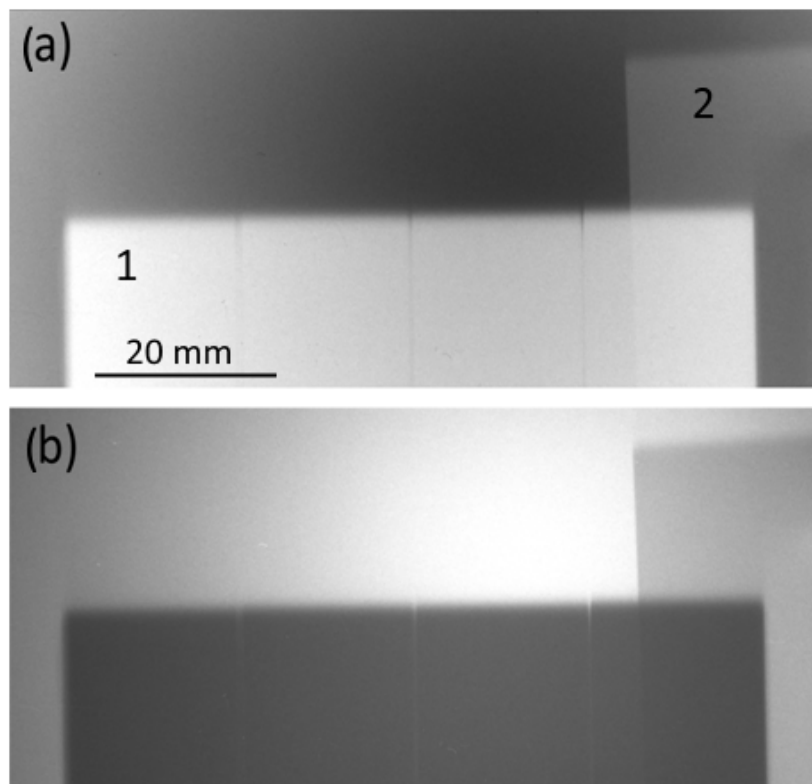
In our case of Ta target, the radiation photograph is formed by hard radiation, since the soft part of the generated spectrum is suppressed by absorption in the heavy target material. This is evidenced by the presence of the image of the flange of the exit window of betatron chamber, which were not detected using the softer photons generated in the Si target, because of their less penetrating power. The *Duplex IQI* can be used effectively with radiation energies up to 400 keV. When using energies in the MeV range the results may not be completely satisfactory. Therefore, in order to investigate the

formation of the image contrast by hard bremsstrahlung we used a compound steel object consisted of four bars, Figure 1c (1), with dimensions of  $9 \times 9 \times 35 \text{ mm}^3$  with the  $10\text{-}\mu\text{m}$ -width gaps between their polished surfaces. The gaps were as a model of inaccuracy of the assembly of the object, which should be detected by radiography using the created source.



**Figure 2.** Photographs of angular distribution of X-rays at  $13 \mu\text{m}$  Ta target orientation  $\theta_0 = 0.3^\circ$  with respect to the direction of electron beam. Vertical marks show the projection of target plane on X-ray film.

The image of the object with three  $10\text{-}\mu\text{m}$  gaps between the bars was obtained with a magnification of 2.4 using hard bremsstrahlung ( $E_\gamma > 1 \text{ MeV}$ ) generated in the Ta target. There exists also the image of the  $0.5 \text{ mm}$  thick steel plate attached to the object. The negative (a) and positive (b) images of the object presented in Figure 3a, b show good enough resolution of the gaps. It can be also seen that the gap image width increases from the right gap to the left one. This increase of the gap image is due to the different orientation of the bar surfaces forming the gaps, relative to the axis of radiation cone.



**Figure 3.** Negative (a) and positive (b) images of the object (1) and thin steel plate (2).

The object was oriented so that the surfaces of the steel bars, which formed the right gap was parallel to the part of gamma-rays that passed along these surfaces, Figure 1c (arrow a). The surfaces of the middle and left gaps have the angles of inclination (for example, arrow b in Figure 1c), relative to the directions of the gamma-rays  $\theta_z = 1^\circ$  and  $2^\circ$ , respectively. Therefore, one obtains the images of the projections of these gaps that formed by gamma rays passing at the angles  $\theta_z$  to their surfaces (for example, arrow b in Figure 1c). This effect is clearly seen in Figure 4 where the gap images additionally increased are shown.



**Figure 4.** The increased images of left (a), middle (b) and right (c) gaps.

The width  $S_z$  of gap image can be estimated as  $S_z = L_2 ((t_z + l \cdot \theta_H) + S_H) / L_1 - S_H$ , where  $t_z$  and  $l$  are the width and length of the gap,  $L_1$  and  $L_2$  are the distances from the target to the sample and up to the X-ray film,  $\theta_H$  is the horizontal angle of emission of radiation from the target in the direction of the gap and  $S_H = (t + T \cdot \theta_H)$  is effective horizontal size of the source;  $t$  and  $T$  – target thickness and length along electron beam. It is seen that  $S_z$  increases with increasing the angle  $\theta_H$  that is equal, in our case, to the value of the angle  $\theta_z$ .

In addition, the images in Figure 3 show an enhanced contrast of the images of the right edge of the object and the left edge of thin steel plate. This is due to the phase contrast effect [5], since the source size in this case is close to  $13 \mu\text{m}$ . The image of the left edge of the object is blurred because the image is formed by radiation emitted from the target at an angle of about  $\theta_H = 3^\circ$  to the surface of the target. Probably, in this case the phase contrast effect is not realized because of the large effective size of the  $S_H$  radiation source, which is defined above and equal, in this case,  $S_H = 222 \mu\text{m}$ . In order to achieve best resolution of the defects or media interfaces in the images formed by an absorption or phase contrast, it is necessary to orient them along the direction of the plane of the internal target. The dependence of effective size  $S_H$  of a source extended along the electron beam on the position of the object in the radiation cone was investigated in [3].

Vertical effective size  $S_v$  of the source is equal to the diameter  $D_e$  of the electron beam because is practically independent on the vertical emission angle  $\theta_v$ , since the angular width of the emission cone is several degrees. In our case,  $D_e = 1.48 \text{ mm}$ , therefore the images of the object and thin steel plate upper edges are blurred due to a large vertical size of the radiation source.

Figure 5 shows the images additionally increased of middle and right gaps without (a) and with the additional steel plate, (2) in Figure 1c, with the thickness of 20 mm (b) or 40 mm (c).



**Figure 5.** Images of middle and right gaps without (a) and with 20 (b) and 40 mm (c) steel plate.

The steel plates were additionally used as X-ray absorbers, which increased the fraction of radiation in the gamma-ray region of the spectrum of bremsstrahlung. This also simulated a situation

where the gaps are in the steel bulk. It is seen that at increasing the thickness of additional steel plate up to 40 mm one can also detect the 10- $\mu$ m-width gaps between the steel bars of the compound object.

#### 4. Conclusion

The study has shown the possibility to successfully generate hard radiation in a narrow target which width is about one hundred times smaller than the diameter of the betatron electron beam, and to use this radiation for obtaining the magnified high resolution images of micro-defects into products made of heavy materials with participation both the absorption and phase contrast effects in formation of the images.

In our case, the radiation spectrum of the betatron generated in narrow internal targets extends from several keV to 18 MeV. For light targets, the images of non-thick objects are formed by a soft part of the radiation spectrum [3]. In our case of heavy target, the radiation spectrum is dominated by hard radiation due to strong absorption of radiation of the soft part of the bremsstrahlung spectrum in the target. The radiation generated in such target is applicable for obtaining images of thick objects made from heavy materials.

The images of a compound object consisted of four steel bars demonstrated the high resolution of a series of 10  $\mu$ m gaps between adjacent bars due to the small horizontal size of the focal spot of the linear microfocus bremsstrahlung source. The results also demonstrate the edge phase contrast due to the high degree of spatial coherence of the radiation.

The obtained results attest to the high quality of the radiation beam generated by new microfocus source based on compact betatron that can also be used in a laboratory physical experiment, for example, in materials science to study internal interfaces of media, microdefects and microinclusions in the heavy composite materials. In our case, the 18-MeV betatron-based linear microfocus source generates bremsstrahlung with a spectrum up to the electron energy, while the microfocus X-ray tubes widely used for various purposes have so far reached the photon energy of 750 keV [6].

#### Acknowledgements

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