Observation of refraction-contrast effect in images obtained with microfocus bremsstrahlung gamma-rays generated in a narrow internal target of 18 MeV betatron

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Abstract. The first results of experiments demonstrating refraction contrast in magnified (×2.5) images obtained using the Bremsstrahlung gamma radiation of 18 MeV betatron with a narrow tantalum (Ta) target inside are presented. The Ta foil-target with a thickness of 13 µm and a length of 4 mm along the electron beam was mounted in a goniometer inside the chamber of the betatron to guide her along the electron beam. In this case, a linear microfocus source of Bremsstrahlung gamma radiation with vertical and horizontal dimensions of 1.5 and 0.013 mm, respectively, is realized for direct-forward emission of radiation. The obtained magnified images of rectangular steel plates with thicknesses in the region of 15 – 0.3 mm and lead foils with thickness of 25 µm demonstrated a high resolution of their edges due to the refraction contrast effect, which is realized due to the refraction of microfocus gamma radiation on the surfaces of the lateral faces of the samples.

1. Introduction

Currently, the phase contrast method is widely used to obtain enlarged images of micro-objects with enhanced contrast using sources of sharp-focus or parallel beams of monochromatic X-ray radiation and corresponding optics. X-ray sources such as a synchrotron, a X-ray tube and a source of radiation from femtosecond laser plasma are used for research. The first studies with these sources were performed in [1- 4]. But, the effect has not been studied in the more hard (MeV) spectral region.

But, it was shown [5] that enhanced contrast is also formed when microfocus polychromatic radiation is used due to the effect of radiation refraction at the sharp interface between two media with different refractive indices (refraction contrast). In this case, there are a weakening of the intensity of the fraction of radiation passed in the direction of radiation incidence on the interface surface and an increase of the intensity of the radiation in the direction of the refracted beam. In [6], the edge refraction contrast was investigated using polychromatic Bremsstrahlung X-rays generated in the internal microtarget of the compact MIRROCLE synchrotron. The contrasts in the images of a 2 mm thick plastic plate as well as a 1 cm acrylic rod formed by the X-ray part of Bremsstrahlung spectrum were investigated. It has been shown that a pair of bright and dark lines along the boundary between the plastic plate and air in the images is due to the refraction of X-rays.

In [7–9], it was reported about the creation of a source of Bremsstrahlung with a linear microfocus based on a 18 MeV betatron with narrow targets inside the toroidal chamber of the accelerator. Silicon plates with thickness t = 50 and 8 µm and tantalum foil with t = 13 µm and lengths along the electron beam T = 4 mm, which were oriented along the electron beam using an internal goniometer, were used. When dumping accelerated electrons to a narrow target, the radius of the electron beam orbit decreases, and electrons circulate for some time at the radius of target position. In this case, electrons fall on a narrow target with a sufficiently high efficiency due to betatron oscillations of circulating electrons [10]. The horizontal size S_H of the radiation source is equal to the thickness of the target for the direction of emission of radiation along the surface of the target. The vertical size S_V of the linear source is equal to the diameter D_e = 1.5 mm of the electron beam, if the vertical dimension H of the target exceeds the diameter of the electron beam.

Using radiation generated in 50 and 8 μm Si targets [6–8] the magnified (× 3) images of the reference microstructure of the Duplex IQI EN462-5/ASTM E2002–98 device [11] were obtained. The images showed a high resolution of pairs of the thinnest (50 μm) platinum wires of the microstructure of the device, thanks to the microfocus of radiation. In addition, the images showed refraction contrast of the edge of the plastic holder of the microstructure of the device [7, 8].

This paper presents the results of observation of the edge refraction contrast in magnified (× 2.5) images of the edges of several steel plates with thicknesses in the region of 15– 0.3 mm and lead foils 25 μm thick, which were obtained using Bremsstrahlung gamma radiation (energy of photons > 1 MeV, conditionally) generated in an internal 13 μm tantalum target of the 18 MeV betatron with a length of 4 mm along the electron beam. A comparison of obtained results with the picture of the refraction contrast formed by X-rays generated by 18 MeV electrons in the 8 μm silicon target is made.

2. Experimental conditions

Experimental conditions are shown in Figure 1. A tantal target with t = 13 μm, H = 10 mm and T = 4 mm was placed inside the equilibrium orbit of the accelerated electrons, Figure 1a. The goniometer made it possible to orient the target along the direction of the electron beam in order to realize a linear microfocus source of Bremsstrahlung gamma radiation with vertical and horizontal dimensions of S_V = 1.5 and S_H = t = 0.013 mm, respectively, for the "straight-forward" direction of radiation emission. An additional magnetic field generated by the dump coil reduced the orbit radius and the accelerated electrons fell onto the target oriented along the direction of the beam with a frequency of 50 z. The generated radiation escaped through the 50 μm Mylar window of the experimental chamber.

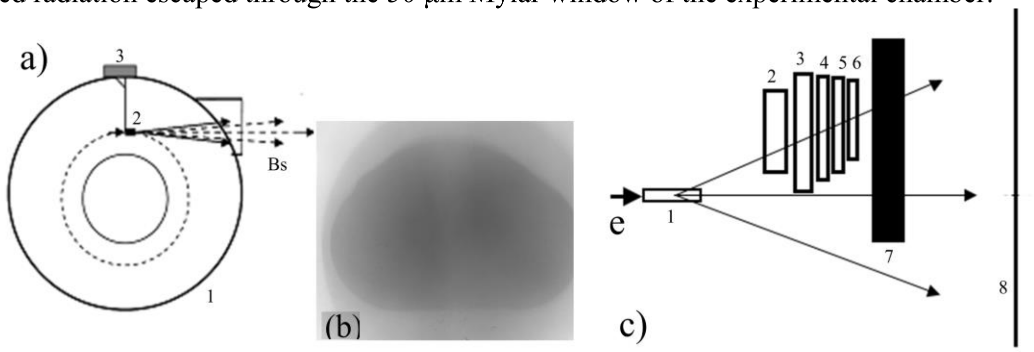

Figure 1. The experimental scheme: a) 1 – betatron chamber (view from above), 2 – thin target, 3 – goniometer, Bs − Bremsstrahlung; b) Photograph of Bs beam ; c) Layout of steel plates in the beam of microfocus Bs gamma-rays of 18 MeV betatron.

Figure 1b shows a photograph of the angular distribution of the radiation generated in the Ta target. The spectrum of Bremsstrahlung of the betatron in our case extends to 18 MeV. In the case of Ta target, the angular distribution differs significantly from the distribution obtained using a Si crystal [7]. A wider angular distribution is observed, which is determined by the stronger scattering of electrons in the heavy material target. The radiation photograph is formed by harder radiation, since the soft part of the generated spectrum is suppressed by strong absorption in the Ta target. This is evidenced by the presence in the photograph (b) the image of the flange of the output window of the betatron chamber, which was not observed in the case of Si target, due to the lower penetration ability of softer photons generated in the Si plate through the thickness of the flange. In the case of a Si target, the image of the angular distribution of radiation is formed mainly by Bremsstrahlung X-rays ($E\gamma$ < 1 MeV, conditionally), since in the case of a fairly easy target, the radiation in this part of the spectrum is large enough, and the X-ray film sensitivity is maximum namely in the X-ray region.

To obtain the magnified (× 2.5) images of the objects under study, they were located in an external goniometer at a distance of 46 cm from the target, and the X-ray film was placed at a distance of 115 cm from the target. The external goniometer made it possible to orient the object of study with respect to the direction of radiation beam emitted from the target, (1) in Figure 1c, and move it inside the radiation cone. The object to be examined is an assembly consisting of a set of steel plates, (2, 3) or (3 - 6) in Figure 1c, with different thicknesses, installed in an external goniometer in a central part of the radiation cone. The edge planes of the plates were oriented along the light strip in the photograph of the angular distribution, Figure 1b, and parallel to the central axis of the radiation cone.

For additional suppression of radiation in the soft part of the spectrum, an additional steel plate (7) 15, 35 or 55 mm thick was used. In addition, this absorber plate modeled the situation when the interfaces between media are in the thick of steel. The radiographic patterns (negative images) of the edges of the steel plates recorded using the X-ray films were processed with the scanner to obtain its positive images and densitograms of these images for subsequent analysis.

3. Experimental results

Figure 2(a) shows the positive image fragment of the Duplex IQI device [11], which was obtained with magnification ×3 using the X-ray radiation generated in the 8-µm-thick Si crystal [9]. The image fragment shows a high contrast image of a pair of 50 µm Pt wires of the device IQI due to the small horizontal size of the radiation source. But, here we pay attention to the formation of contrasts of images of the upper and lateral faces of the angle of the plastic holder 4 mm thick of wire microstructure of the device Duplex IQI. It can be seen that the image of the upper edge of the device, which is perpendicular to the light strip (the direction of the target projection) in the photo of the angular distribution of radiation is blurred because of the large vertical size of the radiation source, which is about 1.5 mm. However, there is a clear contrast in the image of the right edge of the device IQI, which is oriented along the direction of the light strip in the image of the radiation beam. Additionally enlarged image (b) of the edge of the device shows a thin structure consisting of narrow dark and light bands with a distance between them of about 320 µm. This is a typical pattern for refraction contrast at the sharp interface between two media with different dielectric permittivity due to the refractive effect of polychromatic radiation on the interface of the media.

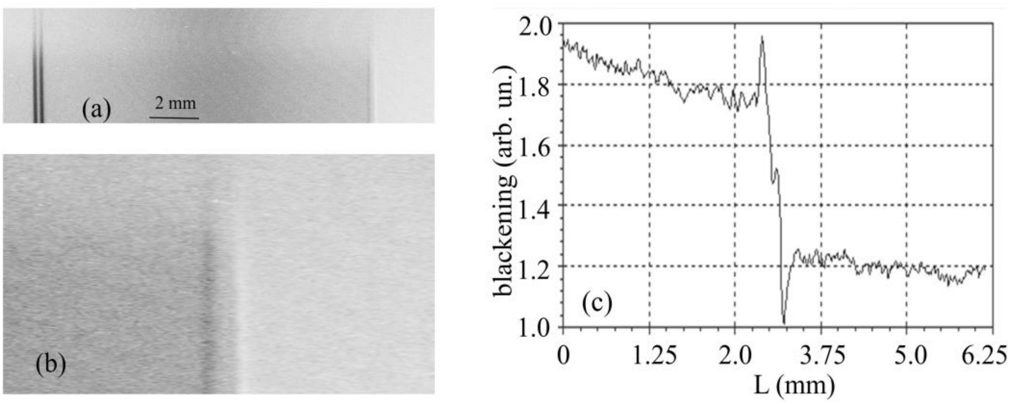

Figure 2. a) - magnified (× 3) image of the 13th pair of Pt wires and the edges of the plastic holder of the IQI device, obtained using radiation from a Si target with a width of 8 µm; (b) - additionally enlarged image of the edge of the holder; d) - densitogram, measured along a line that is perpendicular to the image of the right edge of the device IQI.

Figure 2(d) shows the profile of density of blackening (densitogram) in the image measured along a horizontal line that is perpendicular to the edge image of the plastic holder of the device IQI. The densitogram shows a sharp maximum and minimum of blackening in the photo, which correspond to the dark and light stripes on the image of the edge of the Duplex IQI device.

Figure 3 shows the magnified (× 2.5) image of an assembly of two steel plates (2 and 3 in Figure 1c) 15 and 10 mm thick, respectively, and steel plate-filter (7 in Figure 1c) with a thickness of 30 mm, which was obtained using hard bremsstrahlung generated in 13 μm Ta foil (1 in Figure 1). The rectangular plates were arranged one after another, so that the radiation passed through different thicknesses of steel in different parts of the assembly. The aim of the experiment was to observe the refraction contrast in the images of the edges of the plates with different thicknesses, which are formed by Bremsstrahlung gamma radiation. The plate (7) has served as the absorber of radiation which inhibited the portion of the radiation in the x-ray region of the spectrum. Gamma rays passed through steel plates with a total thickness of 55 and 40 mm in the areas near the markers *1 and *2, respectively. The lateral surface of the right edge of the plate (2) with a thickness of 10 mm was oriented with an accuracy of 0.1° along the direction of the gamma rays that fell on this edge of the plate. The lateral surface of the first plate was parallel to the lateral surface of the second plate.

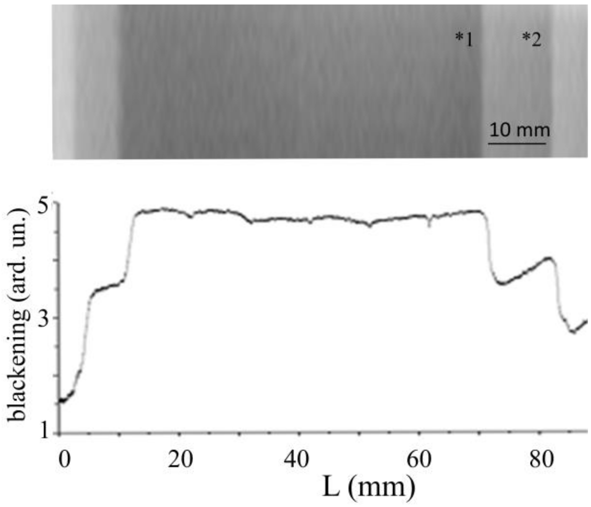

Figure 3. Magnified (× 2.5) image of two steel plates obtained using Bremsstrahlung gamma radiation generated in 13 μm Ta foil by 18 MeV electrons.

Figure 3 shows the enhanced contrast of the images of the right surfaces of the first and second plates. This is determined by the refraction contrast effect. The size of the source in this case is about 13 microns. Images of the left surfaces of the plates are blurred. Images of these faces are formed by part of the radiation emitted by the target at an angle of about 4° relative to the surface of the Ta target. Probably, in this case, the refraction contrast effect is not effective, because of the sufficiently large effective size of the radiation source. The dependence of the effective size of the source extended along the electron beam on the position of the object in the radiation cone was studied in [7]. In our case, the effective horizontal size of the S_H radiation source is $S_H = t + T\cdot|\theta_H| = 280$ μm, since t = 13 μm is the plate thickness, T = 4 mm is the plate length along the electron beam, $\theta_H = 3.83^o$ is the horizontal emission angle from the Ta target in the direction of the left edge of the second plate. In addition, these side faces of the plates are inclined relative to the direction of radiation, which also affects the edge contrast.

Below, Figure 3 shows the densitogram of the image measured along a horizontal line that is perpendicular to the images of the edges of the plates. The densitogram shows sharper blackening changes in the photo, which correspond to the right edges of the plates. The densitogram shows an increase in blackening to the left of the edge of the 10 mm plate and a decrease in blackening to the right of its edge, which is due to the edge refraction contrast. But, the blackening profile here differs sharply from the blackening profile at the edge refraction contrast in the edge image formed by softer radiation generated by 18 MeV electrons in the 8 μm Si plate, Figure 3. There is no bright maximum and minimum, as in the densitogram in Figure 3d.

Figure 4(left) shows the images of an assembly consisting of a steel plate (3) 10 mm thick and three steel plates (4 – 6) (see Figure 1) 5 mm thick each, which are placed behind the steel plate-absorber (7 in Figure 1) thicknesses of 15, 35 or 55 mm. the Images were obtained with magnification of 2.5 using hard Bremsstrahlung radiation generated in 13 μm Ta foil. The rectangular plates were arranged one after another, so that the radiation passed through different thicknesses of steel in different parts of the assembly.

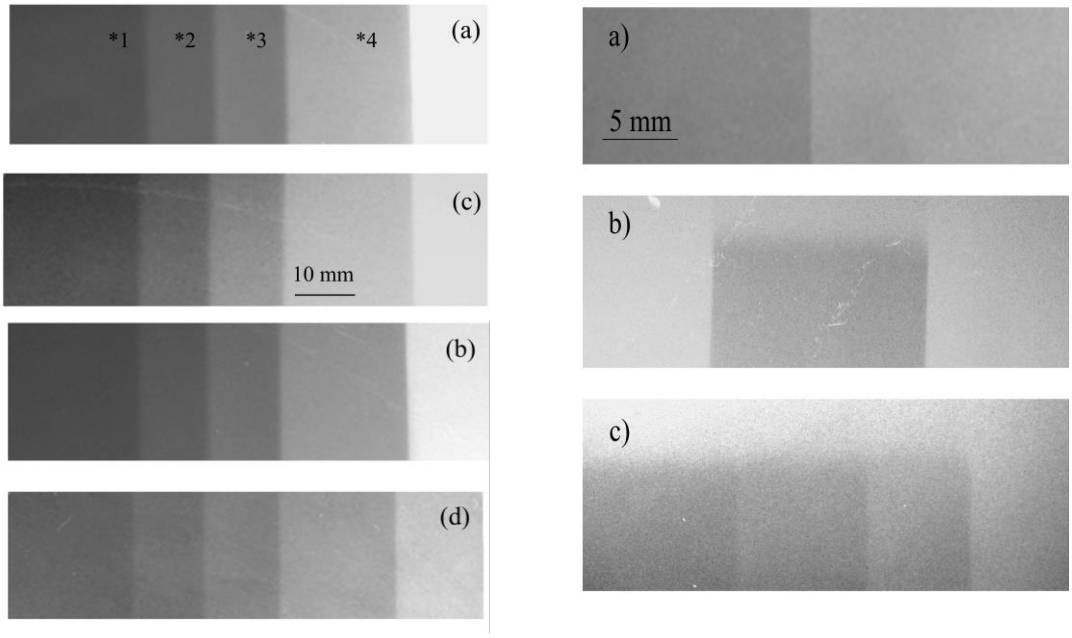

Figure 4. Left: magnified (× 2.5) images of an assembly of four steel plates: a) - without an additional steel absorber plate; c - d) - with additional steel absorber plates 15, 35 and 55 mm thick, respectively; Right: Images of edges of 0.9 and 0.3 mm steel plates, (a) and (b), and assembly of three 25 μm lead foils (c).

The aim of the experiment was to observe the phase contrast in the images of the edges of plates with thicknesses smaller than in the first case, but with plates-absorbers with large thicknesses. As in the first case, the steel plate (7) served as a radiation absorber, which increased the proportion of Bremsstrahlung radiation in the gamma-ray spectrum. The lateral surface of the right edge of the plate (4) was oriented along the direction of Bremsstrahlung gamma rays that hit this edge of the plate. The side surfaces of the plates (5) and (6) were parallel to the side surface of the plate (4). Figure 3 shows the increased contrast of the images of the side surfaces of the plates, due to the refraction contrast effect.

But, the images of the edges of the plates are formed by radiation with different microfocus and different soft part of the spectrum. The effective source size for the plate edges (4 – 6) is about SH = 13, 24 and 35 μm, respectively. Gamma rays passed in the areas near the markers *1-*4 through steel plates with the following common thicknesses: (a) 25, 20, 15 and 10 mm; (b) 40, 35, 30 and 25 mm; (c) 60, 55, 50 and 45 mm; (d) 80, 75, 70 and 65 mm, respectively. By increasing the plate thickness (7), that is at harder radiation spectrum due to the absorption of photons of the soft part of the spectrum, the difference in blackening in different parts of the image is smoothed. However, the phase contrast is still high, which determines the sufficient detectability of the edges of the assembly plates.

The edge refraction contrast was also observed at much smaller plate thicknesses. Figure 6(right) shows the edge image of a steel plate 0.9 mm (a) thick, a steel plate 0.3 mm (b) thick, and the corner of an assembly of three lead foils 25 μm (c) thick, arranged one after the other. As in the case of thicker steel plates, the images in Figure 6(right) demonstrate the refraction contrast of edge images of vertically arranged edges of thinner plates due to the small horizontal size of the radiation source. The upper edges of the 0.3 mm steel plate (b) and 25 μm Pb foils (c) are blurred, since the vertical size of the radiation source is about 1.5 mm.

4. Conclusion

The magnified (× 3) images of the microstructure holder of the Duplex IQI device obtained using Bremsstrahlung X-rays generated in the 8 μm Si target of the 18 MeV betatron demonstrate an enhanced contrast of the holder edge due to the effect of refraction contrast. The results demonstrate the fine structure of refraction contrast in X-ray images due to the source microfocus. The effect of refraction contrast observed for the first time in the gamma-ray region of Bremsstrahlung spectrum in the magnified (×2.5) images of steel plates and Pb foils with thicknesses in a wide range from 15 mm to 25 μm indicates the high quality of the radiation beam emitted by the microfocus source based on the 13 μm Ta target of the 18 MeV betatron. But, at the given geometry of experiment (× 2.5-magnification) the fine structure of refraction contrast was not observed, probably, because of much smaller angle of refraction of much more hard radiation forming the images in this case.

The high quality of the radiation beam generated by a microfocus source based on a compact betatron can provide high-resolution magnified images with the participation of the absorption and refraction contrasts in the formation of images of products made of heavy materials. Such a source can be useful in laboratory physical experiments, for example, in materials science for the study of internal boundaries of media and defects in the composite materials. Betatron generates both microfocus Bremsstrahlung X-ray and gamma radiation with a spectrum up to the electron energy, while the microfocus tubes have reached so far the photon energy of Bremsstrahlung radiation of 750 keV [12]. Therefore, a betatron-based microfocus source can be used to study much thicker samples. In addition, the microfocus Bremsstrahlung gamma radiation of the compact betatron can be also effective for studies of possible wave effects in gamma optics.

Acknowledgments

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