Coherent radiation of relativistic electrons in wire metamaterial

V Soboleva, G Naumenko, V Bleko

Tomsk Polytechnic University, Lenina str. 2, Tomsk, 634050, Russia

E-mail: sobolevaveronica@mail.ru

Abstract. We present in this work the experimental investigation of the interaction of relativistic electron field with wire metamaterial. The measurements of the spectral-angular characteristics of coherent radiation were done in millimeter wavelength region in far-field zone at the relativistic electron beam with energy of 6 MeV. Used target represent the right triangular prism that consist of periodic placed copper wires. We showed that bunched electron beam passing near wire metamaterial prism generates coherent Cherenkov radiation. Spectral-angular characteristics of radiation from the wire target were compared with the characteristics of Cherenkov radiation generated in similar experimental conditions in a dielectric target (Teflon prism) that has the same form and sizes.

1. Introduction

The different types of metamaterials have been intensively studied in recent years [1–4]. Metamaterials represent composite periodic structures that consist of scattering elements whose dimensions are much smaller than wavelength of the electromagnetic field. The examples of such media can be left-handed materials (LHM), wire metamaterials and other various artificial structures whose electromagnetic properties are not observed in natural materials.

The processes of radiation generation in metamaterials are of large interest to researchers because the radiation generated in such media has very unusual properties. For example, Cherenkov radiation that is generated in the result of interaction of a relativistic charged particle with LHM is propagated in backward semi-sphere. It is so-called backward Cherenkov radiation [5–8]. In the case when a charged particle interacts with a wire medium, radiation is also generated. The properties of radiation generated in wire metamaterials were theoretical studied in paper [9–11]. One of the motivations for this study is that in work [11] have been shown the possibility to boost the Cherenkov emission by several orders of magnitude in such composite structures in comparison to natural media.

In this paper, we present the results of experimental investigation of relativistic electron field with wire metamaterial and dielectric target in similar experimental conditions.

2. Experimental setup and technique

The experiments were carried out at the extracted electron beam of microtron of Tomsk Polytechnic University, with the following beam parameters: electron energy was 6 MeV ($\gamma = 12$), bunch period – 380 ps, macropulse duration varied from 3 to 5 μs, bunch population $N_e = 6 \cdot 10^8$, bunch length $\sigma_b \approx 1.9 \div 2.4$ mm, dimensions of the extracted electron beam 4×2 mm^2, angular divergence of the extracted beam $\sigma = 0.08$ rad. For such bunch length and bunch population the radiation with wavelength $\lambda > 8$ mm is coherent and radiation intensity increases by 8 orders. This fact allows using a room-temperature detector. Used for the measurements detector was produced at Tomsk Scientific Research Institute of Semiconductor Devices on the basis of broadband antenna with high frequency diode built into the center of antenna. This detector makes it possible to register electromagnetic radiation in the wavelength range from 3 to 30 mm.

The design of the studied targets is presented in figure 1. Both of them represent the right triangular prisms that have the same form. Wire target consist of 4 layers placed at the distance 10 mm. The diameter of copper wire is 0.5 mm, the wire period is 1 mm. The length of the both cathetuses is 170 mm. Material of the second target is a Teflon with refraction index $n = 1.41$. The height of Teflon prism is 74 mm. The length of cathetuses is 175 mm.

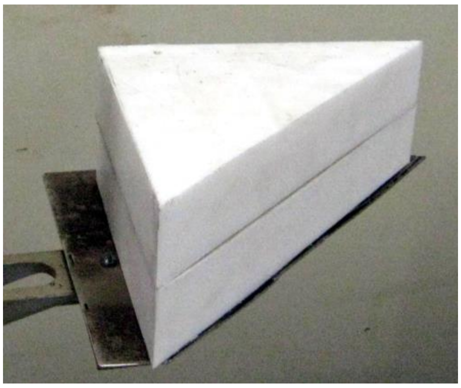
a)  b) 

Figure 1. Design of the targets: a) Wire target; b) Teflon target.

The scheme of the measurements is shown in figure 2. The studied targets were placed close to the electron beam trajectory at the distance 10 mm (impact parameter *h*). The distance from the target to the extraction window was 300 mm. To exclude the effect of pre-wave zone [12] we used the detector located in focus of the parabolic mirror. Both of them are placed on the rod that rotates around the axis, which passes through the center of the emitting surface. In this case, the measured angular characteristics of radiation coincide with the characteristics measured in far-field zone [13].

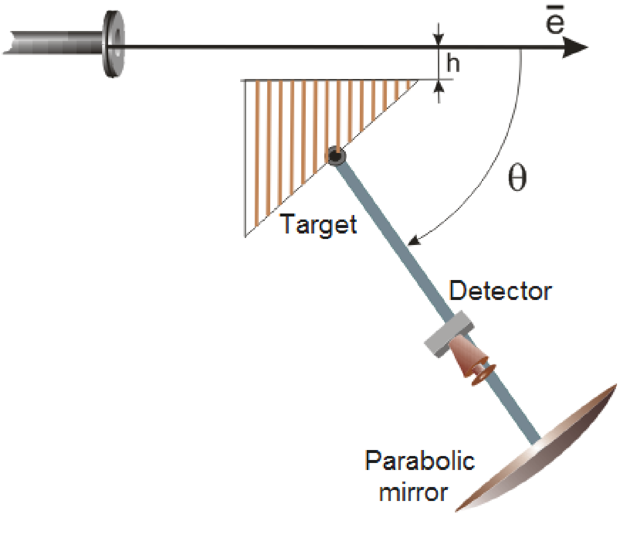


Figure 2. Scheme for the measuring of angular characteristics of radiation.

To show that the observed effect is caused by availability of periodic wire structure (but not target frame) was made a target that represents just a frame of wire target (see figure 3). The measurement of angular distribution of radiation from this target was carried out in the same geometry of experiment (see figure 2).

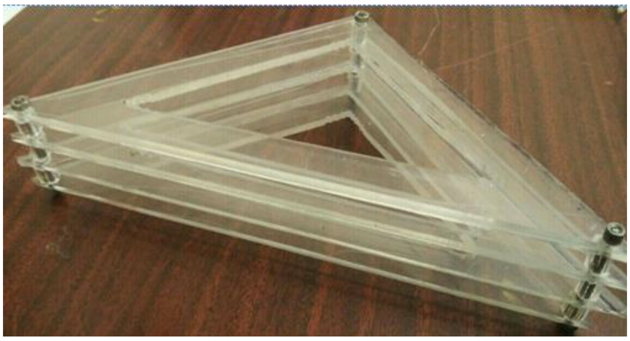
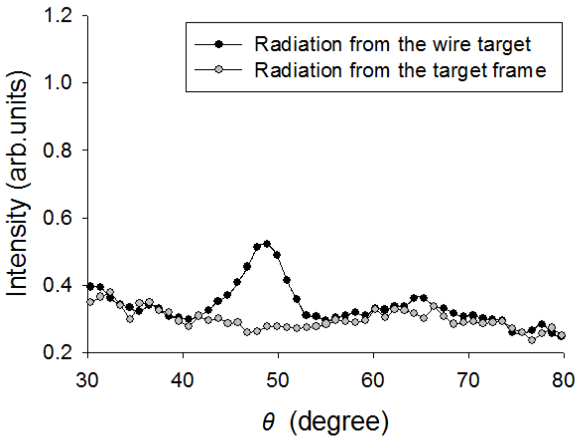


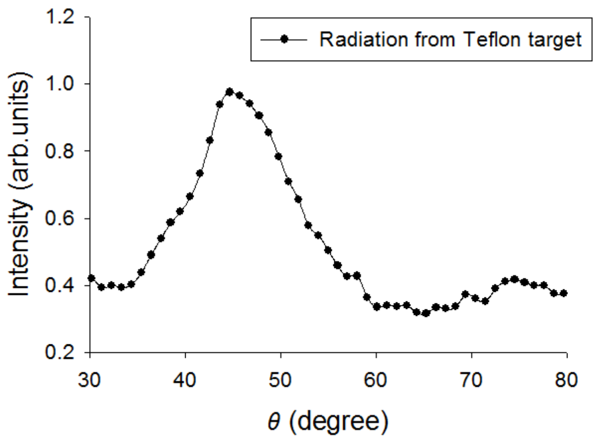
Figure 3. Design of the wire target frame.

3. Measurements

In experiment was measured the horizontal polarization of radiation. Measured angular distributions of radiation from studied targets are given in figure 4.



a)



b)

Figure 4. Angular distribution of coherent radiation from: a) Wire target (black points) and target frame (open circles); b) Teflon prism.

As can be seen from obtained dependences (see figure 4(a)) radiation from the wire target is observed at the angle $\theta = 48^\circ$. This radiation is the result of interaction of relativistic electron field with wire structure of the target. The frame of wire target does not contribute to observed effect in the considered angle range. Radiation from Teflon prism is observed at the angle $\theta = 45^\circ$ (see figure 4(b)). Observation angle of radiation corresponds to the condition for Cherenkov radiation: $\cos\theta = \frac{1}{n \cdot \beta}$ (where β is a velocity of charge in terms of the light velocity, n is a refraction index). As one can see the intensity of Cherenkov radiation from the Teflon prism is more by three times than radiation intensity from wire target. It is caused by that the studied wire target consists of only four layers. However, the increasing of the layers number by an order or more can provide the radiation intensity much more than intensity of radiation from Teflon target of the same dimensions.

In figure 5 are shown the spectra of radiation measured using interferometer with wave front division on the basis of two mirrors, one of which is movable [14].

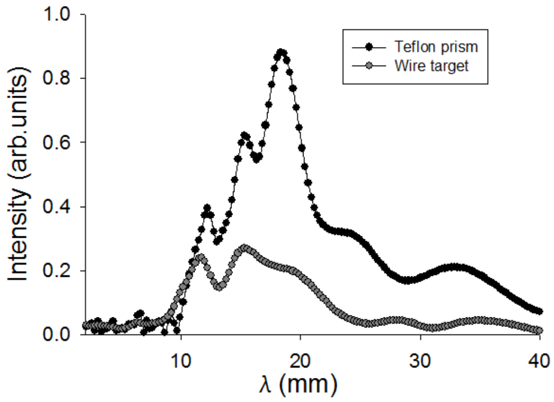


Figure 5. The spectra of radiation from the wire target (gray curve) and Teflon prism (dark curve).

As can be seen from the obtained dependences, the spectra of radiation from wire and Teflon targets have the similar spectral distributions. The radiation intensity from the wire target is smaller than intensity from the Teflon target because we used only four layers of wires.

4. Conclusion

We have shown that bunched electron beam passing near a wire metamaterial prism generates the coherent radiation. Spectral-angular characteristics of radiation from the wire prism were compared with the characteristics of Cherenkov radiation generated in the same experimental conditions in Teflon target that has the same form and similar dimensions. For the future we plan the experimental investigation of the spectral-angular characteristics of radiation in wire metamaterial that has the same period of the wire in the horizontal and vertical planes.

Acknowledgment

This work was supported by grant of Ministry of Education and Science of Russian Federation № 3761.

References

[1] Grbic A, Eleftheriades G V 2004 *Phys. Rev. Lett.* **92** 117403
[2] Lee H, Xiong Y, Fang N 2005 *New Journal of Physics* **7** 255
[3] Pendry J B, Schurig D, Smith D R 2006 *Science* **312** 1780
[4] Kildishev A V, Shalaev V M 2011 *Phys. Usp*. **54** 53
[5] Galyamin S, Tyukhtin A 2010 *Phys. Rev. B* **81** 235134
[6] Tyukhtin A V, Galyamin S N, Belonogaya E S 2010 *Proceedings of IPAC10* **3** 1068
[7] Sheng Xi, Chen H, Tao Jiang 2009 *Phys. Rev. Lett.* **103** 190801
[8] Duan Z Y, Wu B I, Xi S *et al* 2009 *Prog. Electromagn. Res.* **90** 75
[9] Tyukhtin A V, Vorobev V V 2014 *Phys. Rev. E* **89** (1) 013202
[10] Vorobev V V, Tyukhtin A V 2012 *Phys. Rev. Lett.* **108** 184801
[11] Fernandes D E, Maslovski S I, Silverina M G 2012 *Phys. Rev. B* **85** 155107
[12] Verzilov V A 2000 *Phys. Lett. A* **273** 135
[13] Kalinin B N, Naumenko G A, Potylitsyn A P *et al* 2006 *JETP Letters* **84** (3) 110
[14] Naumenko G A, Potylitsyn A P, Shevelev M V *et al* 2009 *Russian Physics Journal* **11** (2) 254