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Experimental test of the shadowing effect in Smith-Purcell radiation

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Summary. — The observation of a shadowing effect of a relativistic electron Coulomb field for the Smith-Purcell radiation generation is presented in this paper. For this purpose the surface current from the closest surface of grating element to the electron beam was measured for a downstream one shadowed by upstream element. The experimental results showed that shadowing effect for Smith-Purcell radiation depends on grating geometry.

PACS `41.60.-m` – Radiation by moving charges.
PACS `41.90.+e` – Other topics in electromagnetism; electron and ion optics.

1. – Introduction

The shadowing of an electron electromagnetic field in case of diffraction and transition radiation was considered theoretically and experimentally in a number of papers [1-5]. In the pseudo-photon approach for ultra-relativistic electron the properties of electron fields are very close to the properties of real photons. Namely, the field may be considered as a transversal one. There is a region downstream to the conductive or absorbing screen where the Coulomb field is partly missing. In terms of paper [2] this effect is named "shadow effect", and the term "semi-bare electron" has been introduced in [6, 7] to describe a similar effect in the framework of quantum electrodynamics for an electron scattered at a large angle.

For a transversal component of the electromagnetic field of a relativistic electron this effect may be simple explained in the frame of pseudo-photon approach [3]. In [4] the shadowing effect for a Smith-Purcell radiation (SPR) was predicted by Prof. X. Artru (see fig. 1), where the author had noted that the mere addition of the diffraction radiation amplitudes from the different strips neglects the shadow effect, and therefore overestimate the SP intensity.

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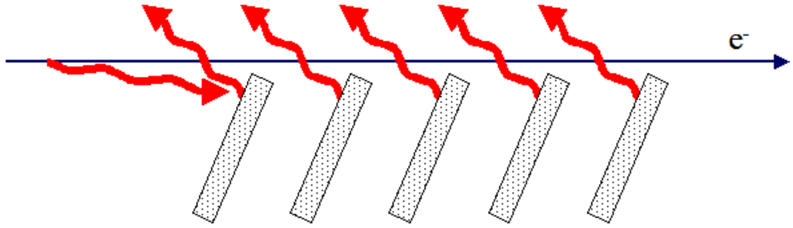

Fig. 1. – (Figure 6 from [4].) Shadowing in a periodical target.

For the experimental test of this effect we may adopt the following method. As shown in [8] the Smith-Purcell radiation may be considered as a resonant backward diffraction radiation. According to [9, 10] in this geometry the surface current viewpoint may be applicable. Radiation from each grating element is defined by the surface current on the surface of the element and the total radiation in the far-field zone results by interference of radiation from all elements of grating. Therefore the problem may be resolved by measurement and comparing of the surface current, induced by an electron beam on the not shadowed and shadowed strip.

For the simplest grating consisting of a set of conducting strips separated by vacuum gaps and locating in a plane the surface current J_s induced by a charge q moving parallel to the grating may be calculated using the approach developed in the paper [11]. Generally speaking the surface current is proportional to the transversal component of the charge electric field:

$$J_s(\omega) \sim E_\perp^0 \sim q \cdot \exp\left[-\frac{h\omega}{c\gamma}\right], \tag{1}$$

where the last multiplier describes the decay of Fourier component of a field with frequency ω, h is the impact-factor (the shortest distance between charge and grating), γ is Lorentz factor.

The shadowing effect in these terms may be introduced as the suppression of a field $E_\perp$ at distance $l \ll \gamma^2 \frac{2\pi c}{\omega} = \gamma^2 \lambda$ from the upstream strip along particle trajectory. It means the surface current induced on a strip surface will decrease beginning from the first one.

2. – Experiment

The experiment was performed on the extracted electron beam of microtron of Tomsk Nuclear Physics Institute with parameters shown in table I. The electron beam is extracted from the vacuum chamber through the beryllium foil with a thickness of 40 μm.

TABLE I. – *Electron beam parameters.*

Electron energy	6.1 MeV ($\gamma = 12$)	Bunch period	380 ps
Train duration	$\tau \approx 4\,\mu$s	Train repetition	6 Hz
Bunches in a train	$n_b \approx 1.6 \cdot 10^4$	Bunch length	$\sigma \approx 2$ mm
Beam size	$\sigma_B \approx 2$ mm	Bunch population	$N_e = 6 \cdot 10^8$

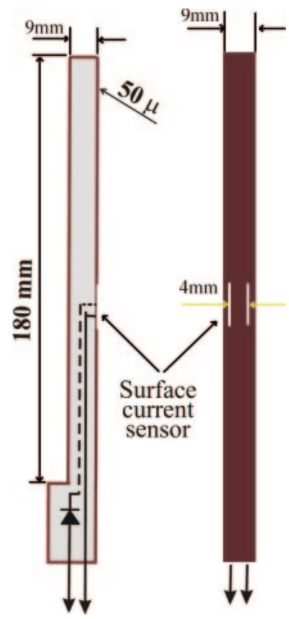

Fig. 2. – Active element of SPR target.

We apply the well-known technique, which is used in strip-line beam position monitors [12]. This sensor registered a surface current component perpendicular to the slits (see fig. 2). The signal from the sensor is rectified by a high-frequency diode for rectification of the signal with frequency up to 100 GHz. The rectified signal was directly measured using a charge-digital converter without amplifier.

The distance L between the slits was chosen to be 4 mm (the quarter of the average wavelength of a registered SPR). According to [12] the strip-line pickup usually operate in a spectral interval between the 3 dB points of the first lobe $\frac{c}{8L} < f < \frac{3c}{4L}$ (here $f = \frac{\omega}{2\pi}$) with maximum of the sensitivity in the point $f_{\max} = \frac{c}{4L}$, *i.e.* for our sensor $10\,\mathrm{GHz} < f < 60\,\mathrm{GHz}$ with maximum in the point $f_{\max} = 20\,\mathrm{GHz}$. The slit width was 0.4 mm. The described sensor was inserted in the element typical for a SPR target element (active element). To be sure that we measure the concerned amount, we had measured the dependence of the surface current on the impact parameter (dots in fig. 4) for single grating element in the geometry shown in fig. 3.

The solid line in fig. 4 is the fit of function (1) to the experimental data. The fit is shown for $\gamma = 12$ and $\omega = 1.02 \cdot 10^{11}$ (*i.e.* $f = 16.2\,\mathrm{GHz}$). Here f is to be assumed as an average value in the investigated spectral region. This value is in good agreement with experimental conditions. The value of J for $h = 5\,\mathrm{mm}$ is 90 ± 10 channels CDC.

For measuring the shadowing effect we had inserted three grating elements of the same geometry but without a sensor (passive elements) upstream to the active element (see fig. 5). In this geometry the active grating element corresponds to the fourth element in SPR target with element width 9 mm and period 18 mm.

The surface current measured using this target for $h = 5\,\mathrm{mm}$ amounted to 32 ± 5 channels of CDC. So the registered shadowing effect is 64%. This effect is of considerable importance to be taken into account in the calculation of SPR.

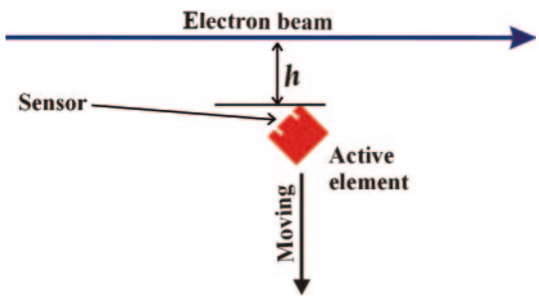

Fig. 3. – Scheme for measurement of the dependence on the impact parameter.

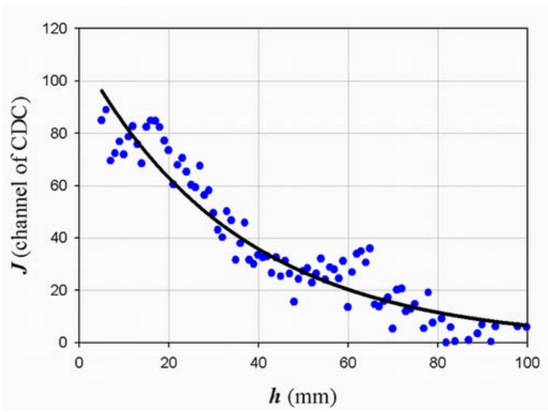

Fig. 4. – Dependence on the impact parameter. Dots are the experimental points. Solid line is the fit using (1).

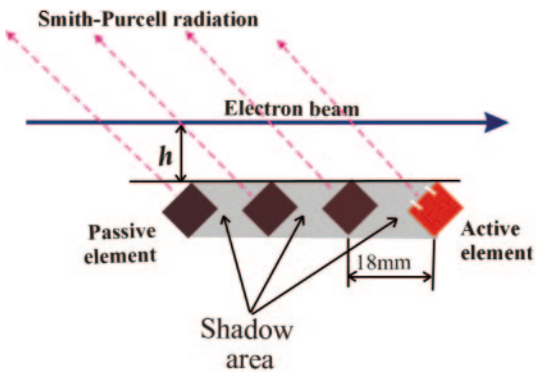

Fig. 5. – Scheme of shadowing measurement for the inclined grating element.

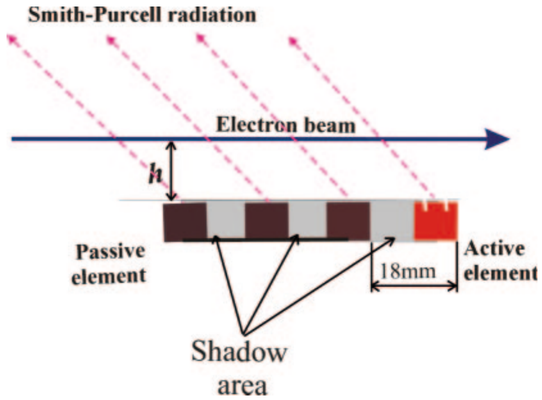

Fig. 6. – Scheme of shadowing measurement for the grating element parallel to the electron beam.

For another geometry shown in fig. 6, where the active surface is parallel to the electron beam, the measured shadowing effect was inside of the experimental error (±7%). We may assert that no significant shadowing effect for this geometry is present.

Finally we may conclude that the shadowing effect in SPR must be taken into account in theoretical calculations depending on target geometry. Probably this is why a large discrepancy between experimental results of SPR intensity and theoretical estimations was observed in many works.

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