Investigation of the surface current excitation by a relativistic electron electromagnetic field

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Abstract. Surface current method and pseudo-photon ones are widely used in the problems of diffraction and transition radiation of relativistic electron in conductive targets. The simple analysis disclosed the contradiction between these methods in respect to the surface current excitation on target surfaces. This contradiction was resolved experimentally by the measurement of a surface current on the upstream and downstream target surfaces in diffraction radiation geometry. The experimental test showed, that no surface current is induced on the target downstream surface under the influence of a relativistic electron electromagnetic field in contrast to the upstream surface. This is important for the understanding of a forward transition and diffraction radiation nature and electromagnetic field evolution in interaction processes.

1. About problem
In principle the radiation emitted by relativistic electrons passing through or near material targets can be calculated using the macroscopic Maxwell equations. However so far such calculations for thick conductive targets, when the thickness is much larger than a skin-layer, are absent. Therefore phenomenological concepts, like “surface current viewpoint” and “pseudo-photons”, are widely used for calculation of transition radiation (TR) and diffraction radiation (DR) from conductive targets. Furthermore these concepts are useful for the intuitive understanding of the main features of these phenomena. Let us consider in more details both these concepts in respect to the transition and diffraction radiation of relativistic electrons passing through or near conductive targets.

1.1. Surface current viewpoint
In this approach TR and DR are considered as a radiation of a current, induced on a conductive target surface by the relativistic particle electromagnetic field. This technique for DR from inclined conducting strip is described in [9]. In [8] the similar approach was used both for backward and forward TR and is irrespectively to the thickness of the target surface.
For diffraction radiation this viewpoint was more pronounced in the article of B.M. Bolotovskiy [2], where he places primary emphasis upon the radiation formation length effect, when a charged particle moves over the conductive screen in parallel to the axis z with a velocity v (figure 1). It seems the
formation length notion was introduced by M. Ter-Mik aelian in [1] as a result of interference between a charged particle electromagnetic field and a radiation field emitted by this particle.

According to [2] The ellipse 1 represents the field of the particle. It hits the half-plane screen and induces current in screen, which in turn emit Diffraction Radiation. "It results the peculiar features of the radiation field. The radiation field is such that close to the screen it kills part of the particle field". At positions 3, 4, 5 we see the separation of the radiation field and the Coulomb field at the distance \( \sim \gamma^2 \lambda \), due to their different velocities. It is important, that this point of view assumes the obligatory surface electric current on the target downstream surface irrespectively to the thickness of the conductive target. The association between forward diffraction radiation (FDR) and surface current is evident from the exact solution of Maxwell equations for diffraction radiation field from ideally conductive infinite thin semi-surface in [3], where the diffraction radiation field is expressed directly as a function of surface current:

\[
A(R) = \frac{2\pi e^{i\omega R}}{R} J(k_0, q_0),
\]

(1)

where \( k_0 = -\omega \cdot \sin \psi \cdot \cos \varphi \), \( q_0 = -\omega \cdot \cos \psi \), \( \varphi \) and \( \psi \) are the angles of observation direction in spherical system and \( J \) is the surface electric current density. However, this is not obvious for a thick target, if the target thickness is much larger than a skin-layer.

1.2. Pseudo-photon method

On the other hand, the pseudo-photon method suggested by Fermi [4] and extended by Williams [5] is of considerable current use as the approach for electromagnetic processes theoretical investigations (see for instance [1] and [10]). According to this approach the charged particle field may be replaced by the field of photons, which in this case are named pseudo-photons (In [10] is used the term “virtual quanta”. One should distinguish this term from ones in quantum theory.). This approach provides a good accuracy for ultra-relativistic particles when the particle velocity becomes close to the light velocity \((v \rightarrow c)\) (see [1]). In this case the longitudinal component of the particle electric field is negligible and the particle electromagnetic field being a transversal ones has the same properties as a real photon field.

Let us remind you the properties an interaction of real photons with a thick conductive mirror of a high reflectivity in geometry, shown in figure 1. It is clear that the real photons are reflected almost fully, they don't penetrate through the target and they don't induce a surface current on the target downstream surface. If the particle electromagnetic field and the real photons have the same properties, we may expect the same character of interactions of the particle electromagnetic field with a thick conductive mirror, namely, we may expect, in contrast to the surface current viewpoint, the absence of a surface current on the target downstream surface.
1.3. Deduction
Both these concepts are in principal contradiction in respect to the surface current induction. The resolution of this contradiction may clarify the understanding of the nature of the forward transition radiation (FTR), FDR and other important phenomena. One of the ways of this problem resolution is an experimental test of the surface current on the downstream target surface.

It is not necessary to make an absolute surface current measurement, because we are sure, that backward transition and backward diffraction radiation (BDR) is emitted by the surface electric current on the upstream target surface. We may make the relative measurements and compare a surface current on the both surfaces.

To exclude problems, which may be brought up due to the direct contact of relativistic electrons with a target material, the experiment in DR geometry is more preferable.

2. Experiment

2.1. Experimental setup
The experiment was carried out on the extracted electron beam of Tomsk Nuclear Physics Institute microtron with parameters presented in Table 1.

| Parameter                      | Value                      |
|--------------------------------|----------------------------|
| Electron energy                | 6.1 MeV (γ = 12)           |
| Train duration                 | τ ≈ 4 μsec                 |
| Bunches in a train             | n_b ≈ 1.6 ⨉ 10^4           |
| Bunch period                   | 380 psec                   |
| Bunch population               | N_b ≈ 6 ⨉ 10^8             |
| Bunch length                   | σ ≈ 1.3~1.6 mm             |

Beam parameters of microtron allow using coherent properties of a radiation to investigate DR characteristics and surface current induction in millimeter wavelength region. This possibility increases the surface electric current and diffraction radiation intensity by the 8 orders (proportional to the bunch population) and makes these values achievable for measurement using existing sensors.

For the surface electric current measurement we use the well-known technique, which is applied for the surface current measurement in strip-line beam position monitors [6]. Figure 2 shows the scheme and photography of the surface current sensor being built-in in diffraction radiation target.

![Figure 2. Surface electric current sensor built-in in diffraction radiation target (scheme and photography).](image)

This sensor registered a surface current component perpendicular to the slits.
To have a similarity of BDR and surface current dependence on impact-parameter the sensor strip length L was chosen 3 mm (the quarter of the average wavelength of a registered BDR). The slit width
was 0.4 mm. According to [6] the strip-line pickup usually operate in spectral interval between the 3 dB points of the first lobe \(4/3 \cdot L < \lambda < 8L\) with maximum of the sensitivity in the point \(\lambda = 4L\), i.e. for our sensor \(4\text{m}m < \lambda < 24\text{m}m\) with maximum in the point \(\lambda = 12L\). The DR target with built-in surface current sensor was tested on the real photon beam from the pulse emitter of 6.7 mm wavelength radiation. The test shows that in case of real photons a surface current on the downstream target surface is absent within the experimental error (≈3% of the pulse amplitude from sensor with upstream surface sensor position). The sensitivity of sensor on wavelength 6.7 mm was ≈50 mV/(mA/cm) (experimentally estimated lower limit).

Since BDR is generated by the electric current on the upstream target surface, we may check the correlation between the surface current and BDR intensity by simultaneous measurement of the surface current and BDR. Therefore the scheme of experiment (figure 3) provides the measurement of BDR and surface current simultaneously.

![Figure 3. Scheme of experiment for study of the surface current induction under the influence of a relativistic electron electromagnetic field.](image)

For measurement of BDR angular distribution (see figure 4) we had used the parabolic telescope described in [7], which provides the measurement a BDR in far field zone mode.

![Figure 4. Angular distribution of BDR.](image)
The parabolic telescope and the target with the built-in surface electric current sensor may be moved in horizontal plane to change the impact-parameter $h$. Dependences of BDR intensity on impact-parameter were measured in the maximum of BDR angular distribution. The background from surface current sensor was measured with a strip of sensor stopped up by a conductive foil using conductive glue. The Faraday cup signal allows measuring a zero point of impact parameter using the electron beam intensity suppression when electrons cross the target.

2.2. Results

The measurements were done for upstream and downstream orientations of surface current sensor attended by comparison of results for both cases in the same units. The measured simultaneously a surface current and BDR intensity as a function of impact-parameter for both orientations of sensor (upstream and downstream) after background subtraction are presented in figures 5 and 6. The solid line in figure 5 is the fit by equation for DR intensity $W = A \cdot \exp(-4 \pi h / \gamma \lambda)$ with $A=0.58$, $\gamma=12$ and $\lambda=15.3$ mm. Maximal surface electric current density was 0.15 mA/cm (estimated lower limit).

![Figure 5. Measured dependences of BDR on impact-parameter. Solid line is the fit $W = A \cdot \exp(-4 \pi h / \gamma \lambda)$ with $A=0.58$, $\gamma=12$ and $\lambda=15.3$ mm.](image)

The results presented in figures 5 and 6 show a good correlation between surface current on the upstream surface and BDR in dependence on impact-parameter. Within the experimental error the surface current on the downstream surface is absent.

One may argue that in used geometry of experiment the upstream and downstream surfaces are in asymmetrical conditions in respect to the surface current induction due to the inclination of the target. In our opinion it is not matter, but for a confirmation of this contention we had measured the similar dependence for the symmetrical geometry, when the target is perpendicular to the electron beam direction. In this case we cannot measure BDR, because BDR cone coincides with electron beam. Only surface current on upstream and downstream surfaces was measured. Results of this measurement shown in figure 7 confirm a contention that no surface current on the downstream surface is induced.

![Figure 5. Measured dependences on impact-parameter of the current for upstream and downstream orientation of the current sensor.](image)
Figure 7. Measured dependences on impact-parameter of the surface current for upstream and downstream orientation of the current sensor for target perpendicular to the electron beam. The solid lines is the calculated dependence using [3] for $\gamma=12$ and $\lambda=16.5$ mm.

Fortunately this geometry is convenient for calculation of the measured dependence using the expression for a surface current from [3]. We are interested by the $x$-component (in notation of figure 3) of a surface current when a target is perpendicular to the electron beam in DR geometry. In this case the expression for the $x$-component of a surface current from [3] may be simplified to the formula (1).

$$J_{kq,x} = \frac{\sqrt{\lambda} \left( i\xi + \gamma' \sqrt{4\pi^2 - \lambda^2 q^2} \right)}{\sqrt{4\pi^2 - \lambda^2 q^2 - k\lambda \cdot (i\xi + k\gamma' \lambda)}} \cdot bq\lambda,$$

(1)

where $bq\lambda = -i \frac{e^{\sqrt{\gamma' \lambda}/\gamma}}{8\pi^3 \gamma} \left( \gamma' \sqrt{4\pi^2 - \lambda^2 q^2} - i\xi \right) \exp \left( -\frac{a}{\gamma' \lambda} \xi \right)$,

$$\xi = \sqrt{\lambda^2 q^2 (\gamma^2 - 1) + 4\pi^2}, \quad \gamma' = \sqrt{\gamma^2 - 1}, \quad k \text{ and } q \text{ are the Fourier variables corresponding to a spatial variables } x \text{ and } y, \quad e \text{ is the electron charge, } a \text{ is an impact-parameter. Here the light velocity equal to 1 is assumed.}

To turn to the spatial presentation we may make the backward Fourier transformation:

$$J_x(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{1}{(2\pi)^2} e^{-i(q'y+k'x)} J_{kq,x} dq dk$$

(2)

The final calculation of expression (2) can be performed numerically.
In figure 8 is shown the spatial distribution of the $x$-component surface current density $J_x(x,y)$ calculated using (2) for the experimental conditions: $\gamma=12$, $\lambda=16$ mm and impact-parameter $a=0.2 \gamma \lambda$.

![Figure 8. Calculated spatial distribution of the $x$-component surface current density for $\gamma=12$, $\lambda=16$ mm and $a=0.2 \gamma \lambda$.](image)

It is seen from the figure 8 that a target polarization stretches to the dimensions comparable with $\gamma \lambda$. Using the equation (2) we had calculated the dependence of the surface current density on the impact-parameter with $\gamma=12$ and $\lambda=16.5$ mm in the point which corresponds to the sensor position on the target (the solid line in figure 7). Calculated values were normalized by the experimental data in centre of dependence. The chosen wavelength provides the minimal discrepancy between the calculated and experimental data. Let's notice, that this wavelength is within the interval of the sensor sensitivity.

3. Discussion

In traditional interpretation a forward transition and diffraction radiation from perfectly conducting targets are considered as radiation emitted by surface currents (for instance in [3]). These surface currents are induced by the electromagnetic field of the relativistic electron. However, as it is mentioned above, for $\gamma >> 1$ the electron field properties become close to those of an electromagnetic field in free space, and pseudo-photons are reflected by the mirror almost like real photons and no surface current is induced on a forward surface of a target.

The present experiment has confirmed the second viewpoint based on pseudo-photon method. In this case we need to find another nature of forward transition and diffraction radiation. One may attribute forward transition radiation (FTR) to the current of the travelling electron after traversal of the screen. Indeed this radiation is practically the same as that of a suddenly accelerated electron (see for instance [11]). At the same time this current re-creates the Coulomb field. We can then say that FTR is generated during the transit of electron from the unstable “naked” state to the stable “dressed” state (here the term “transition radiation” seems particularly appropriate). We can find a similar interpretation of this phenomenon in [1]. As for forward DR, it can be viewed as a consequence of the transit from a “half-naked” state to the “dressed” state.

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References

[1] Ter-Mikaelian N L 1972 High-Energy Electromagnetic Processes in Condensed Media (Wiley, New York)
[2] Bolotovskii B N 1982 Preprints of Lebedev Institute of Physics, Russian Academy of Sciences 140 95
[3] Kazantsev A P and Surdutovich G I 1963 Dokl. Akad. Nauk, USSR 147 74
[4] Fermi E 1924 Zh. Phyz 29 315
[5] Wiliams E and Danske K 1935 Vidensk. Selsk. 13 4
[6] Sargsyan V 2004 Comparison of Stripline and Cavity Beam Position Monitors, TESLA Report 03
[7] Kalinin B N, Naumenko G A, Potylitsyn A P et al 2006 JETP Letters 84 3 110
[8] Reiche S and J. B. Rosenzweig J B 2001 Transition Radiation for Uneven, Limited Surfaces. (Particle Accelerator Conference, Chicago)
[9] Brownell J H and Walsh J 1998 Phys. Rev. E 57 1 1075
[10] Jackson J D Classical Electrodynamics, 3rd ed. (J. Willey&Sons, New-York, 1998)
[11] Shul’ga N F and Syshchenko V V 2000 Journal Physics of Atomic Nuclei 63 11 2018