Pis'ma v ZhETF, vol. 105, iss. 9, pp. 531 – 532 © 2017 May 10

# First experimental observation of conical effect in Smith–Purcell radiation

*G. A. Naumenko*[+], *A. P. Potylitsyn*[+], *D. Yu. Sergeeva*[*1)], *A. A. Tishchenko*[*], *M. N. Strikhanov*[*], *V. V. Bleko*[+]

[+] *Tomsk Polytechnic University, 634050 Tomsk, Russia*

[*] *National Research Nuclear University "MEPhI", 115409 Moscow, Russia*

Submitted 19 April 2016
Resubmitted 5 April 2017

DOI: 10.7868/S0370274X17090016

It is well-known that Smith–Purcell radiation from an electron beam moving above a diffraction grating at right angle to grating grooves is concentrated near the plane perpendicular to the grating surface plane. Conical effect in Smith–Purcell radiation consists in the spatial redistribution of the radiation over a conical surface when it is generated by the beam moving at arbitrary angle $\psi$ to the grating grooves. In other words, rotating the grating in its plane one observes the shifts of maxima of radiation both for polar and azimuthal angles.

The Smith–Purcell dispersion relation in this case has the form:

$$\frac{d}{\lambda}\frac{1}{\beta\cos\psi}(1-\mathbf{n}\boldsymbol{\beta}) = m \quad m = 1, 2\ldots, \tag{1}$$

where $d$ is the period of the grating, $\lambda$ is the wavelength of radiation, $\mathbf{n}$ is the unit vector in the direction of observation, $\boldsymbol{\beta} = \mathbf{v}/c$ is the relative speed of the particle, $c$ is the speed of light, $m$ is the diffraction order.

The detailed analytical theory of Smith–Purcell radiation from electrons passing near the grating at $\psi \neq 0$ both for X-ray and optical frequency ranges has been published in [1]. It was shown in [1] that the conical surface has the opening angle $\theta \approx \pi/2 - \psi$ and the positions of Smith–Purcell radiation peaks were defined as

$$\theta_m = \arccos[\beta^{-1} - m\lambda d^{-1}\cos\psi],$$
$$\varphi_m = -\arcsin[m\lambda d^{-1}\sin\psi/\sin\theta_m], \ m = 1, 2\ldots, \tag{2}$$

where $\theta_m$ is the angle between the direction of observation and the grating grooves, $\varphi_m$ is counted out from the perpendicular to the grating surface.

The experiment was performed at the electron beam of the microtron of the Tomsk Polytechnic University with the electron energy 6.1 MeV (Lorentz factor was $\gamma = 12$). The beam represents the train of $N_b$ bunches of the length $\sigma_x \approx 2.3$ mm and the population $N_e/N_b = 6\cdot 10^8$ each. The transversal size of the beam near the target was $\sigma_y = 2.5$ mm. The interval between bunches was 380 ps, and the train duration was $\tau \approx 4\,\mu$s. The aluminium lamellar grating with the period $d = 12$ mm was used as the target, with the grooves width $a = 6$ mm, and the period number $N = 12$.

The expression for the angular distribution of coherent Smith–Purcell radiation is obtained in form:

$$\frac{dW}{d\Omega} = \frac{N_e(N_e-1)}{N_b}\left|\frac{2\pi c}{\lambda_0}\frac{\beta\cos\psi}{1+\tilde{n}_y\beta\sin\psi}\right| \times$$
$$\times \left|\sum_s \frac{d^2W_e}{d\Omega d\omega}\left(\frac{\sin^2(Nd\phi/2)}{\sin^2(d\phi/2)}\times\right.\right.$$
$$\left.\left.\times\frac{\sinh^2(\rho\sigma_z/2)}{(\rho\sigma_z/2)^2}e^{-\frac{\sigma_x^2\xi^2}{2}-\frac{\sigma_y^2k_y^2}{2}}\right)\right|_{\omega=\omega_s}, \tag{3}$$
$$\omega_1 \le \omega_s \le \omega_2,$$

where $N_e$ is the total population of the train of bunches, $\sigma_y$ and $\sigma_z$ are the transversal beam sizes, $\lambda_0$ is the period of bunches, $\tilde{n}_y = -n_x\sin\psi + n_y\cos\psi$, $n_x$ and $n_y$ are the unit wave-vector components in the direction of the grating periodicity and the grating grooves, correspondingly; $d^2W_e/d\Omega d\omega$ is the spectral-angular distribution of radiation from a single electron and a single element of the grating for $\omega = \omega_s$, which can be found in [1] for millimeter wavelengths; $\xi = \frac{\omega}{c}\frac{1+\tilde{n}_y\beta\sin\psi}{\beta\cos\psi}$, $\rho = \sqrt{\xi^2 + (\tilde{n}_y^2-1)\omega^2/c^2}$, $\phi = \omega/c(1-\beta\cos\theta)\beta^{-1}\cos^{-1}\psi$. The values $\omega_s$ are the solution of the equation $\lambda_0\xi = 2\pi s$, $\omega_{1,2}$ are restricted by the experimental parameters and was taken as $\omega_1 = 1.01\cdot 10^{11}\,\mathrm{s}^{-1}$ ($\lambda_1 = 18$ mm) and $\omega_2 = 1.8\cdot 10^{11}\,\mathrm{s}^{-1}$ ($\lambda_2 = 10.1$ mm).

We used a parabolic mirror with the detector placed in its focus in order to avoid the prewave zone effect [2, 3]. The mirror and the detector can be rotated around the grating centre with fixed radius in range $\theta = 80°\div 130°$ and around the electron beam with impact-parameter $h = 15$ mm in order to change the observation azimuthal angle $\varphi$.

---

[1)] e-mail: DYSergeyeva@mephi.ru

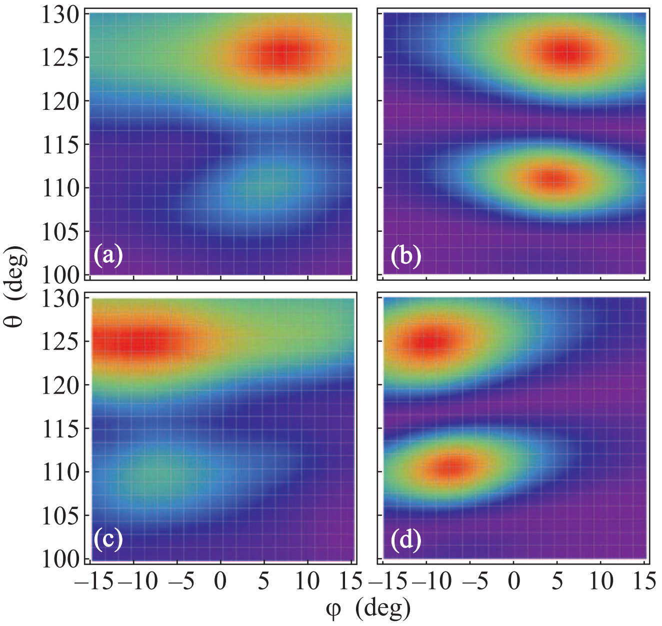

Fig. 1. (Colour online) The angular distribution depending on the polar and azimuthal angles (a) and (b) for $\psi = -3^\circ$, (c) and (d) for $\psi = 5^\circ$, (a) and (c) – experimental data, (b) and (d) – theoretical data. All theoretical curves below are plotted according to Eq. (3) with the given designations

Detector DP20M based on the broadband antenna supplied by a high-frequency diode with parameters described in [4] was used. The detector efficiency in the wavelength region $\lambda = 3 \div 18$ mm is constant with $\pm 15\,\%$ accuracy. The detector sensitivity is 0.3 V/mW. To suppress a long wavelength background from RF system of accelerator the beyond cut-off wave-guide with diameter $d_{wg} = 15$ mm was used which provides cut-off of radiation at $\lambda > 25$ mm.

Experimental dependence of the Smith–Purcell radiation intensity on the polar angle $\theta$ contains maxima around the angles $\theta = 110^\circ, 126^\circ$ which is explained by the high orders multibunched resonances. A macropulse of the microtron consists of $N_b = 10^4$ bunches with the spacing $\lambda_0 = 114$ mm (RF frequency is around 2.7 GHz). Hence, an enhancement of radiation intensity should be observed at the wavelengths $\lambda_s = \lambda_0/s$, $s > 1$ [5]. In our case the maxima observed are caused by resonances with $s = 6, 7$. The same behavior was observed for the first time in the papers [6, 7], authors of which called this effect "frequency-locked Smith–Purcell radiation".

Comparison between the calculated and measured 2D dependences on both the polar $\theta$ and azimuthal angles $\varphi$ in the ranges $\theta = 80^\circ \div 130^\circ$ and $\varphi = -15^\circ \div +15^\circ$ for different values of angle $\psi$ ($\psi = -3^\circ, 5^\circ$) are presented in Fig. 1.

These plots show strong shift of the radiation maximum in azimuthal angle $\varphi$ and weaker shift in polar angle $\theta$. The bigger value of the angle $\psi$ is, the more the radiation maximum shifts in polar angles (conical effect). The azimuthal angle $\varphi$ corresponding to the Smith-Purcell radiation maximal intensity proves to depend linearly on the inclination angle $\psi$.

Thus, in this paper we report on the first observation of the conical effect in Smith–Purcell radiation. The results are in a good agreement with the theory developed in [1]. This effect depends neither on characteristics of the material the grating is made of, nor on the profile of the grating or, say, the effects of interaction between its constituent elements: it is caused only by the orientation of the beam relative to the grating.

The work was supported partly by the Ministry of Science and Education of the Russian Federation, (A.P. – programme "Nauka", D.S. and A.T. – grant # 3.2621.2017/PCh), by the Leverhulme Trust International Network, grant IN-2015-012, and by the Competitiveness Program of National Research Nuclear University "MEPhI".

Full text of the paper is published in JETP Letters journal. DOI: 10.1134/S002136401709003X

---

1. D. Yu. Sergeeva, A. A. Tishchenko, and M. N. Strikhanov, Phys. Rev. ST Accel. Beams **18**, 052801 (2015).
2. D. V. Karlovets and A. P. Potylitsyn, JETP Lett. **84**, 489 (2006).
3. B. N. Kalinin, G. A. Naumenko, A. P. Potylitsyn, G. A. Saruev, L. G. Sukhikh, and V. A. Cha, JETP Lett. **84**, 1103 (2006).
4. A. Aryshev, B. Kalinin, G. Naumenko, A. Potylitsyn, R. Bardai, B. Ishkhanov, and V. Shvedunov, Nucl. Instrum. and Methods B **227**, 175 (2005).
5. D. Yu. Sergeeva, A. P. Potylitsyn, A. A. Tishchenko, and M. N. Strikhanov, Proc. FEL2015, Daejeon, Korea (2015), p. 752.
6. S. E. Korbly, A. S. Kesar, J. R. Sirigiri, and R. J. Temkin, Phys. Rev. Lett. **94**, 054803 (2005).
7. A. S. Kesar, R. A. Marsh, and R. J. Temkin, Phys. Rev. ST Accel. Beams **9**, 022801 (2006).