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CHERENKOV RADIATION IN PERIODIC WIRE MEDIUM FORMED BY TRANSVERSELY MODULATED ELECTRON BEAMS

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Abstract

We investigate the properties of Cherenkov, quasi-Cherenkov (parametric) and diffraction radiation generated in the periodic conducting wire medium by transversely modulated electron beams. Such beams were recently obtained at Argonne Wakefield Accelerator (AWA) facility using microlens array (MLA) laser shaping technique. We consider in details the case of one dimensional periodic tungsten wire structure and transverse electron beamlets separation of mm scale. We look at possible enhancements of the radiation field due to transverse periodicity of the electron beam.

INTRODUCTION

Interaction of electron beams with periodic conducting structures has been a topic of great interest, as it provides unique capabilities for longitudinal phase-space dechirping, beam density modulation and radiation generation.

Structures consisting of periodical arrays of conducting wires, or "wire medium", have been found to obey the same mathematical formalism as dynamical diffraction theory in crystals [1–3]. Thus, "wire medium" with ultra-relativistic electron beam traversing through may serve as a source of Cherenkov, parametric (quasi-Cherenkov) and diffraction radiation. We also note that alternatively "wire-medium" can be considered in terms of dipole antenna vibrator theory with the similar final expressions for the produced electromagnetic fields [4, 5].

A general requirement for these type of experiments is high beam current with low emittance and energy spread. The necessary beam quality is often challenging to achieve due to space-charge effects, even at modern photocathode-based high-brightness sources. Therefore, the final photon yield is significantly decreased compared to theoretical estimates. One possibility to alleviate this problem is to split the original current into transversely ordered beamlets, lowering the detrimental effects of space-charge per beamlet, while keeping the total longitudinal current. This technique has been extensively studied at the photoinjector of Argonne Wakefield Accelerator (AWA) and used for electron beam magnitezation and photocathode quantum efficiency measurements, and transverse-to-longitudinal emittance exchange (EEX) experiments [6–9]. In this proceeding, we look at the possible effects on the radiation produced by transversely modulated beams in the "wire medium". We consider two choices of electron beam energy - 50 MeV and

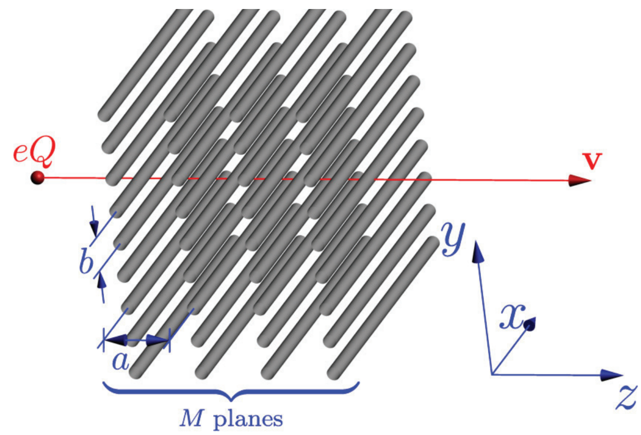

Figure 1: A schematics of periodic conducting wire array with a charge traversing through.

100 MeV, corresponding to the energies at AWA and FAST facilities.

THEORETICAL OVERVIEW

In our previous work we investigated the properties of transition radiation generated in a single perfectly electrically conducting (PEC) plate by an array of beamlets [9]. In this proceeding, we consider a periodic structure consisting of PEC wires instead of single PEC plate (see Fig. 1). Spectral-angular distribution of emitted photons for single electron bunch in this case can be calculated as:

$$\frac{d^2N^s}{d\Omega d\omega} = \frac{e^2Q^2}{\hbar c} \cdot \frac{1}{\omega} \cdot |I^s|^2, \tag{1}$$

where superscript s stands for $(\|, \perp)$ or TM, TE polarizations respectively. Here

$$I^{\|} = \frac{i \sin\theta \cos\varphi}{x_1 x_2} \cdot \frac{\sinh(kbx_1/\beta)}{\cosh(kbx_1/\beta) - \cos(kb\sin\theta\sin\varphi)} \times$$
$$\times \sum_{m=0}^{M-1} e^{ikma/\beta} \left(F_{0m} - F_{1m}\frac{1}{\beta x_2} - iF'_{1m}\frac{x_1}{\beta x_2}\frac{\sin(kb\sin\theta\sin\varphi)}{\sinh(kbx_1/\beta)} \right),$$

$$I^{\perp} = -\frac{1}{x_2} \cdot \frac{\sin(kb\sin\theta\sin\varphi)}{\cosh(kbx_1/\beta) - \cos(kb\sin\theta\sin\varphi)} \times$$
$$\times \sum_{m=0}^{M-1} e^{ikma/\beta} \left(F_{0m} - F_{1m}\frac{1}{\beta x_2} - iF'_{1m}\frac{x_1}{\beta x_2}\frac{\sinh(kbx_1/\beta)}{\sin(kb\sin\theta\sin\varphi)} \right),$$

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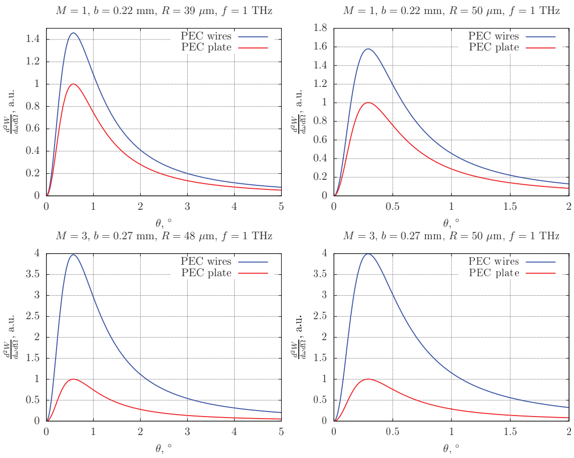

Figure 2: Spectral-angular distributions of radiation from one (top row) and three (bottow row) layers of wires in comparison with transition radiation from PEC plate. Beam energy corresponds to 50 MeV (left column) and 100 MeV (right column).

where $x_1 = \sqrt{\gamma^{-2} + \beta^2 \sin^2\theta \cos^2\varphi}$, $x_2 = \sqrt{1 - \sin^2\theta \cos^2\varphi}$, $\beta = v/c$, $k_z = k\cos\theta$, $k_y = k\sin\theta\sin\varphi$, $k_x = k\sin\theta\cos\varphi$, $k_\rho = \sqrt{k^2 - k_x^2}$, $k = \omega/c$, and θ, φ are polar and azimuthal angles of spherical coordinate system, respectively. Effective amplitudes F_{0m}, F_{1m}, F'_{1m} depend on k, θ, φ and parameters of wire's material (permittivity, conductivity) and can be calculated from Eq. (31) in [10] (when $M = 1$, they are given by Eq. (19)). The total radiation intensity can be found by numerical integration of above expressions with respect to the angular coordinates and frequency. In the case of N beamlets the expressions for I^s should be multiplied by a form-factor f:

$$f = \sum_n e^{-i(k_y y_n + k_x x_n)} e^{i k_y v_y z_n / v_z} e^{-i\omega z_n / v_z}, \qquad (2)$$

where (x_n, y_n, z_n), $n = 1..N$ are coordinates of n-th beamlet at $t = 0$; Q in this case denotes the charge of a single beamlet. In the examples below, the case of tungsten wire array yields very similar results to PEC, therefore the former is further omitted for simplicity.

RESULTS

We first compare the intensity of radiation on axis generated by array of PEC wires of radius R with the intensity of ordinary transition radiation produced by an infinite PEC plate. Figure 2 provides angular distribution of the TM-polarized radiation for 50 MeV and 100 MeV electron beam. We note the enhancement of intensity for three-fold array of PEC wires compared to a single plate. Similarly to the case of transition radiation, the resulting spectrum is broadband, with the peak frequency defined by the bunch length. In order to relief the conditions on electron beam quality, we consider the case of a square array of electron beamlets represented in Fig. 3. Additionally, we further downselect

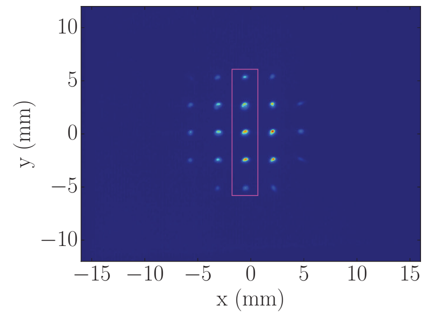

Figure 3: An example of electron beamlets square array produced by MLA shaped laser beam at the photocathode location. The rectangular frame represents selected line of beamlets.

a vertical line of beamlets for simplification. The relative spacing between the beamlets can be controlled via optical imaging at the photocathode or by quadrupole lenses in the electron beamline. The beamlet formation possesses two sets of Twiss parameters, associated with the beam envelope and individual beamlet, offering additional degree of tunability [11, 12].

Figure 4 shows the spectral content of THz diffraction radiation, generated by an ideal thin Gaussian bunch of 1 nC charge and similar spectrum, produced by N ($N = 5, 10, 20$) identical transverse beamlets of the same total charge, spaced vertically (perpendicular to the wires). Here the structure consisting of one layer of wires was considered ($M = 1$), electron velocity v made an angle $\theta_0 = 60°$ with z-axis ($\varphi_0 = 90°$), and radiation peak in diffraction direction was analysed ($\theta \approx 13°$, $\varphi \approx -90°$). It can be seen, that, while at 50 MeV beam energy the resulting intensity is decreased by factor of 2, at 100 MeV it becomes almost identical to the case of a single bunch. We also point out that additional coherence effects, associated with the period of transverse modulation, can be included for the case of electron beam incidence at angle α and very short bunch lengths, similarly to the results obtained in [9].

Recently, longitudinal bunching technique at required frequencies at low charge has been experimentally demonstrated at FAST facility [13]. In combination with MLA spatial laser shaping, it may serve as beam preparation method for the proposed radiation generation scheme.

SUMMARY

We have shown, via analytical and numerical calculations, the transverse periodic modulation of the electron beam preserves peculiar features of radiation spectrum in THz range, while maintaining less stringent parameters on the beam quality. This scheme requires a small addition to the existing photoinjector infrastructure in the form of MLA or any other spatial UV-laser shaper with similar capabilities. The applications of the proposed "wire-medium" radiator can be extended to a temporal beam diagnostics technique or broadband THz source. Finally, periodic PEC (tungsten) wire

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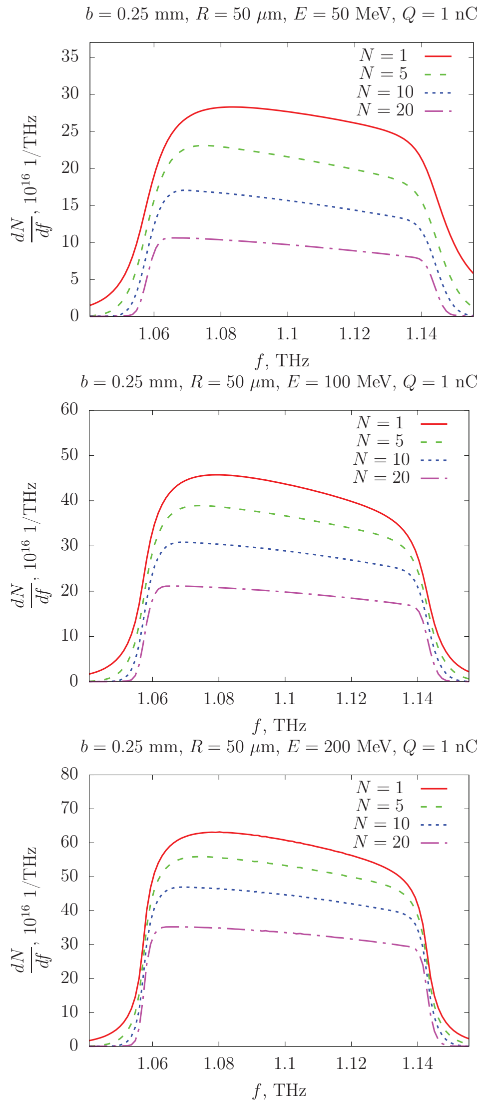

Figure 4: 50 MeV beam (top), 100 MeV beam (middle) and 200 MeV (bottom) comparison of a single 1 nC bunch vs. N beamlets of $1/N$ nC.

array offers higher brightness than a traditional transition radiation obtained with a PEC plate.

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REFERENCES

[1] V.G. Baryshevsky and A.A. Gurinovich. *Nucl. Instr. Meth. B*, 252(1):92–101, (2006).

[2] V.G. Baryshevsky and E.A. Gurnevich. *Journal of Nanophotonics*, 6(1):061713, (2012).

[3] V. G. Baryshevsky and E. A. Gurnevich. *Nucl. Instrum. Meth.*, B402:30–34, (2017).

[4] S. N. Galyamin, V. V. Vorobev, and A. Benediktovitch. *Phys. Rev. Accel. Beams*, 22:043001, (2019).

[5] S. Chuchurka, A. Benediktovitch, S. N. Galyamin, V. V. Vorobev, and A. Halavanau. In *Proc. of IPAC 2018, Vancouver, BC Canada*, page THPAK064, (2018).

[6] A. Halavanau, G. Qiang, G. Ha, E. Wisniewski, P. Piot, J. G. Power, and W. Gai. *Phys. Rev. Accel. Beams*, 20(10):103404, (2017).

[7] Eric E. Wisniewski et al. *Proc. of IPAC 2018, Vancouver, BC Canada*, page TUPMF020, (2018).

[8] A. Halavanau, G. Qiang, G. Ha, E. Wisniewski, P. Piot, J. G. Power, and W. Gai. *Proc. of IPAC 2018, Vancouver, BC Canada*, page THPAK060, (2018).

[9] A. Halavanau, P. Piot, A. V. Tyukhtin, S. N. Galyamin, and A. Benediktovitch. *Proc. of IPAC 2018, Vancouver, BC Canada*, page THPMK023, (2018).

[10] V.G. Baryshevsky and E.A. Gurnevich. *LANL e-print arXiv:1609.05689*, (2016).

[11] R. K. Li, H. To, G. Andonian, J. Feng, A. Polyakov, C. M. Scoby, K. Thompson, W. Wan, H. A. Padmore, and P. Musumeci. *Phys. Rev. Lett.*, 110:074801, (2013).

[12] A. Lueangaramwong, D. Mihalcea, G. Andonian, and P. Piot. *Nucl. Instrum. Meth.*, A865:119 – 124, (2017).

[13] J. Hyun, P. Piot, T. Sen, and J. C. Thangaraj. *Nucl. Instrum. Meth.*, A916:195–203, (2019).