NOVEL APPROACH TO THE ELIMINATION OF BACKGROUND RADIATION IN A SINGLE-SHOT LONGITUDINAL BEAM PROFILE MONITOR

H. Harrison,* G. Doucas, A. J. Lancaster, I. V. Konoplev, H. Zhang,
The John Adams Institute, Department of Physics,
University of Oxford, Oxford OX1 3RH, United Kingdom
A. Aryshev, M. Shevelev, N.Terunuma, J. Urakawa,
KEK: High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Abstract

It is proposed to use the polarization of coherent Smith-Purcell radiation (cSPr) to distinguish between the cSPr signal and background radiation in a single-shot longitudinal bunch profile monitor. A preliminary measurement of the polarization has been carried out using a 1 mm periodic metallic grating installed at the 8 MeV electron accelerator LUCX, KEK (Japan). The measured degree of polarization at $\theta = 90°$ (300 GHz) is 72.6 ± 3.7%. To make a thorough test of the theoretical model, measurements of the degree of polarization must be taken at more emission angles - equivalent to more frequencies.

INTRODUCTION

Developments in particle accelerators place increasing demand on beam diagnostic tools. At facilities operating with sub-ps bunch lengths or experiencing large bunch-to-bunch variation, a non-destructive single-shot longitudinal bunch profile monitor is essential. cSPr has been suggested as a technique for non-destructive longitudinal bunch diagnostics, using spectral analysis of the radiation to determine the bunch profile [1]. This has been successfully demonstrated for a “multi-shot” system [2], now a “single-shot” monitor is being designed. The new monitor will be able to extract all the information needed from each bunch to reconstruct its longitudinal profile. The proof-of-principle “multi-shot” experiments carried out at FACET, SLAC (USA) faced the challenge of extracting the cSPr signal from a high background environment, a problem that needs to be taken into account for any future monitor. It is proposed to use the polarization of cSPr to separate the signal from the background radiation - which is likely to be unpolarized [2] - according to the relation shown in Eq. 1:

$$G_{\parallel} = gG_{\perp} = g\left(\frac{I_{\parallel} - bI_{\perp}}{a - b}\right) \tag{1}$$

where the cSPr signal G_i is expressed in terms of the measured signal I_i and the ratios of the two orientations of radiation $a = \frac{G_{\parallel}}{G_{\perp}}$ and $b = \frac{B_{\parallel}}{B_{\perp}}$.

Previous studies have shown that cSPr is polarized [2–4], however, there has not yet been an extensive study of this property or a conclusive comparison with any theoretical model. Before this idea can be incorporated into the design of the single-shot cSPr monitor it is necessary to perform accurate measurements of the polarization of cSPr and demonstrate that it is possible to predict its degree of polarization via simulation. This paper will demonstrate a good preliminary agreement between the experiment and theory.

THEORY AND SIMULATION

Smith-Purcell radiation is emitted when a charged particle travels above a periodic grating. The particle induces a surface current on the grating surface which emits radiation at the discontinuities of the grating. The radiation is spatially distributed according to the following dispersion relation:

$$\lambda = \frac{l}{n}\left(\frac{1}{\beta} - \cos\theta\right) \tag{2}$$

where λ is the measured wavelength at observation angle θ, $\beta = \frac{v}{c}$ is the normalized electron velocity, l is the grating periodicity and n is the order of emission of radiation.

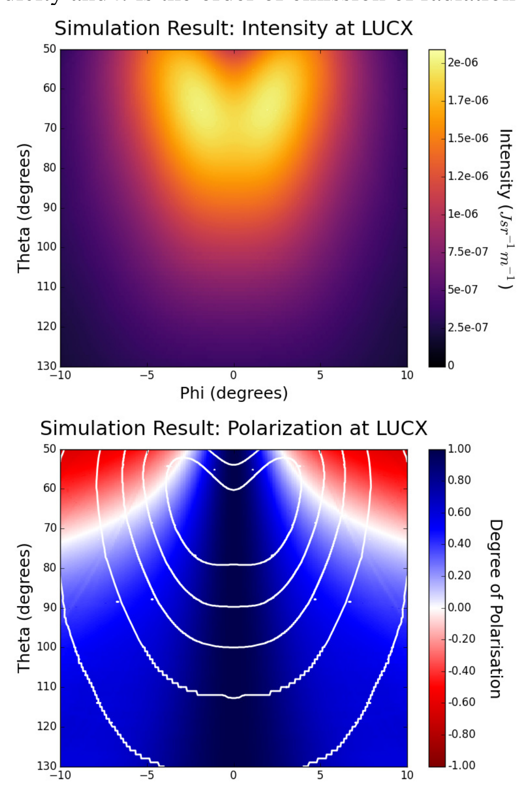

Figure 1: Simulation of intensity (top) and degree of polarization (bottom, contours show intensity), of cSPr generated by the interaction of a 1 mm period grating and an 8 MeV beam. θ and ϕ are the angles along and around the beam.

* hannah.harrison@physics.ox.ac.uk

ISBN 978-3-95450-177-9

The theory of Smith-Purcell radiation has been written about and can be found in a number of papers [5, 6]. The theoretical model used here is the Surface Current Model (SCM), details of which can be found in [7]. SCM combines the effects of the grating geometry and the bunch form. Semi-analytic code developed using SCM predicts the energy emitted at specific positions relative to the grating and the degree of polarization at various observation points.

In Fig. 1 the SCM predicts that cSPr emitted at $\theta = 90°$, $\phi = 0°$ will be 100% polarized with electric field perpendicular to the grating grooves. Any experimental measurement will have to take into account the non-zero acceptance angles $\delta\theta$ and $\delta\phi$ at the detector. For a detector with aperture of 100mm^2 at a distance of 220mm from the grating, the predicted degree of polarization is $\approx 97\%$. These predictions are for a 1 mm period grating using typical beam parameters for the LUCX facility. It is our aim to test this aspect of the theory through comparison with experimental data.

EXPERIMENTAL LAYOUT

The experiment was carried out at LUCX, KEK [8], with the beam parameters shown in Table 1.

Table 1: LUCX, Beam Parameters

Parameter	Expected values
Beam energy, typ	8 MeV
Intensity/bunch, max	50 pC
Bunch length	150 fs to 10 ps
Repetition rate, max	12.5 bunch trains/s
Normalized emittance, $\epsilon_x \times \epsilon_y$	$4.7 \times 6.5\,\pi$mm mrad

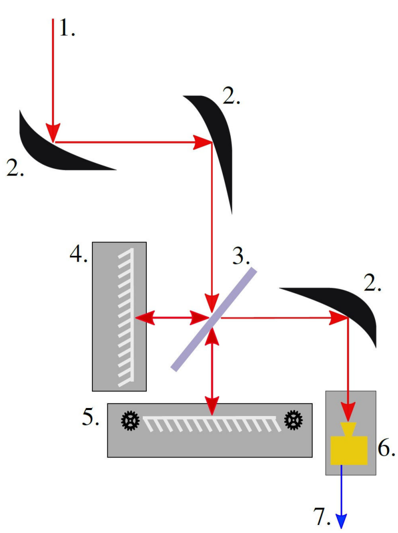

Figure 2: Diagram of Experimental Setup. 1. Radiation from THz Chamber, 2. Parabolic Mirror, 3. Beam Splitter, 4. Plane Mirror, 5. Plane Mirror on Motorised Stand, 6. Detector Mounted on Stand, 7. Signal to ADC or Oscilloscope.

The LUCX facility includes a vacuum chamber for THz radiation studies [9]. A 1 mm periodic sawtooth grating was placed inside this vacuum chamber, with the periodic structure arranged parallel to the beam and the grooves perpendicular to the direction of travel of the beam. According to Eq. 2 the wavelength of first order ($n = 1$) cSPr emitted at 90° from this grating should be 1 mm (300 GHz).

An interferometer was used to measure the frequency spectrum of the cSPr [10]. The layout of the interferometer and optical components interacting with the radiation upon its exit from the chamber are shown in Fig. 2. A Zero Bias Diode with a detection range from 325 GHz to 500 GHz [11] and a cut-off frequency of 268 GHz [12], was used to measure the cSPr emitted. The detector is polarization sensitive, only accepting radiation polarized in one direction. In order to measure the degree of polarization the detector was rotated to different angles, this was achieved by attaching it to a rotating stand. A wire polarizer was also attached to this stand, in front of the detector. By maintaining a constant angle between the polarizer and the detector the polarization dependency of the detector is eliminated from the results, this setup is shown in Fig. 3.

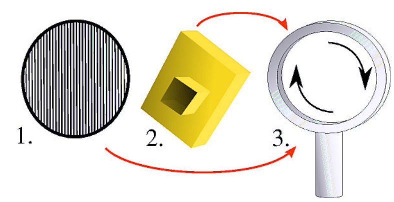

Figure 3: Diagram of Experimental Setup. 1. Wire Polarizer, 2. Detector, 3. Rotating Stand. Red arrows indicate that both the detector and the polarizer are bolted to the rotating stand.

RESULTS

The experimental results are split into two parts. First, determining that cSPr has been generated and is detectable by the system outlined, and second, measuring the degree of polarization. The degree of polarization of cSPr p_g is calculated as shown in Eq. (3) where G_i is the cSPr signal and $\|$ and $\perp$ represent the two possible orientations - parallel to and perpendicular the grating grooves.

$$p_g = \frac{G_{\|} - G_{\perp}}{G_{\|} + G_{\perp}} \tag{3}$$

Detecting cSPr

The grating was positioned close to the electron beam and the interferometer (Fig. 2) was used to generate a frequency spectrum for the radiation emitted at 90° to the grating. This is shown in Fig. 4 and shows a sharp peak around 300 GHz as expected.

This is compared to the frequency spectrum generated by coherent transition radiation (CTR) using the same experimental setup. CTR is broadband and so only limited by the detector response. This is shown in Fig. 4 and demonstrates that the cSPr signal is narrowband and not limited by detector response.

ISBN 978-3-95450-177-9

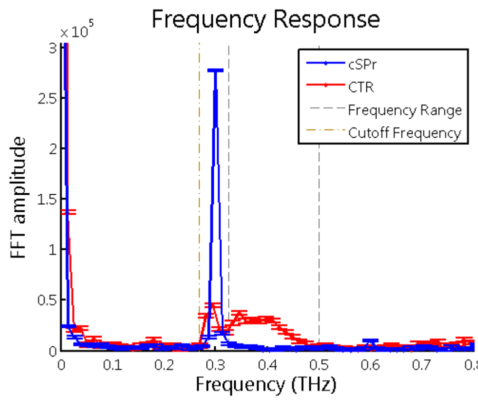

Figure 4: Frequency spectrum of cSPr compared with broadband CTR with the same detector and experimental set-up.

Measuring Degree of Polarisation

In order to calculate the polarization of the cSPr signal the detector and polarizer were attached to a rotating stand as illustrated in Fig. 3, replacing the detector in Fig. 2. The stand was rotated almost 360° and measurements were taken at 2° intervals. When the wire polarizer is parallel and perpendicular to the grating grooves minima and maxima are expected respectively.

According to Malus's Law (Eq. 4) the intensity of polarized radiation is proportional to a squared sinusoid of the rotation angle [13]. The raw data shown in Fig. 5 and has several features of interest which make it inappropriate for fitting with this type of curve. The minima and maxima are not equally spaced (the maxima are found at 80° and 280°) nor are the values of the signal measured at them consistent.

$$I = I_0 \cos\theta^2 \tag{4}$$

It is suspected that the detector was not correctly centered on the rotating stand and moved relative to the focus of the radiation during its rotation. The detector misalignment has been included in the fitting routine for Fig. 5. The model used to create the fit shown in Fig. 5 is given in Eq. 5:

$$y = (a + b\sin(c + d\theta)^2) \times (e + \sin(f + g\theta)^2) \tag{5}$$

where y is the signal, θ is the angle of rotation and a, b, c, d, e, f and g are the coefficients to be estimated. The fit can be split into two parts: the sinusoidal modulation due to the polarization of the incoming radiation Eq. 6 (as described by Malus's law) and the deviation of the detector from the focus of the radiation Eq. 7.

$$y_1 = a + b\sin(c + d\theta)^2 \tag{6}$$

$$y_2 = e + \sin(f + g\theta)^2 \tag{7}$$

The detector misalignment y_2 is plotted in Fig. 6. The raw data is normalized against this to correct for the misalignment of the detector and the rescaled data is fitted with Eq. 6, shown in Fig. 7.

This plot clearly shows two minima and two maxima which are spaced 180° apart respectively and are consistent in value. Substituting the the values of the maxima and minima of this fit into Eq. 3 as $G_{||}$ and $G_{\perp}$ respectively, a value of the degree of polarization at 90° to a 1 mm period grating can be calculated: $72.6 \pm 3.7\%$. This does not consider background radiation (shown previously to be undetectable [4]) so it is likely to be an underestimate of the actual value.

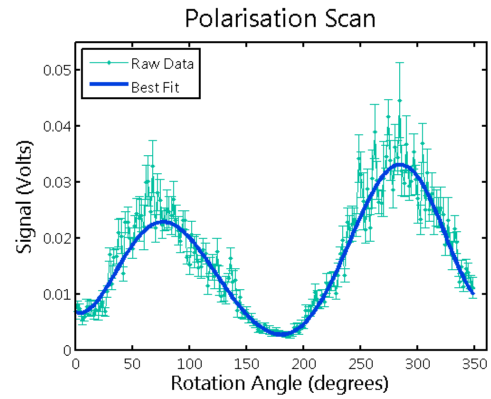

Figure 5: Measured raw data for a 360° rotation of the detector and polarizer (Fig.3). The model used for the fit is Eq. 5 and the goodness of fit parameter is $R^2 = 0.936$.

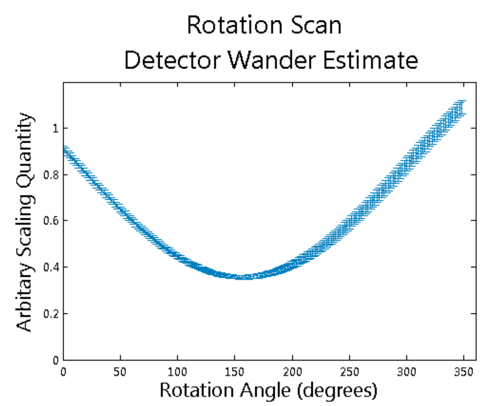

Figure 6: The estimated variation in the signal due to the movement of the detector around the focus of the radiation.

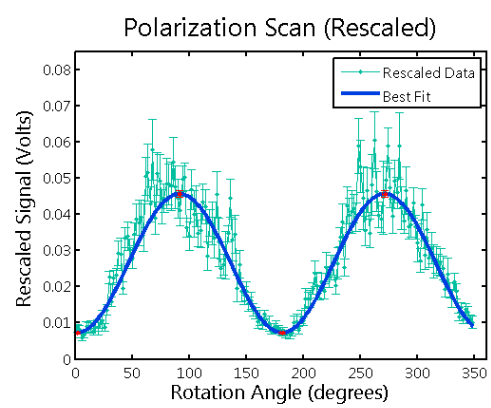

Figure 7: The rescaled data for a 360° rotation of the detector and polarizer (Fig. 3). The mode used for the fit is Eq. 6. The goodness of fit parameter is $R^2 = 0.917$.

ISBN 978-3-95450-177-9

CONCLUSION AND DISCUSSION

The value for the degree of polarization calculated for cSPr at 300 GHz demonstrates that the radiation is polarized with the electric field perpendicular to the grating grooves.Given the unknown noise floor of the data during the experiment, this is likely to be an underestimate of the actual value Fig.1. However, to test the theoretical predictions thoroughly measurements of the degree of polarization at several frequencies (varying θ) and orientations (varying ϕ) will be required. More work is needed to prove that our theoretical model can make accurate predictions about the behavior of the polarization of cSPr, the results so far suggest it would be possible to use the degree of polarization of cSPr to separate it from unpolarized background radiation.

ACKNOWLEDGMENTS

This work was supported by the: UK Science and Technology Facilities Council (STFC UK) through grant ST/M003590/1, the Leverhulme Trust through the International Network Grant (IN–2015–012), the Photon and Quantum Basic Research Coordinated Development Program from the Ministry of Education, Culture, Sports, Science and Technology, Japan and JSPS KAKENHI: 23226020 and 24654076. H. Harrison would like to thank STFC UK (ST/M50371X/1) and John Adams Institute of Accelerator Science (University of Oxford) for supporting their DPhil project. Thanks to Peter Huggard (STFC, RAL) and Byron Alderman (STFC, RAL) for helpful discussion about infra-red detectors. For more information on the design of the longitudinal bunch profile monitor please refer to IBIC MOPG62.

REFERENCES

[1] J. H. Brownell and G. Doucas, “Role of the grating profile in Smith-Purcell radiation at high energies,” *Phys. Rev. ST Accel. Beams*, vol. 8, pp. 1–11, 2005.

[2] H. L. Andrews *et al.*, “Reconstruction of the time profile of 20.35 GeV, subpicosecond long electron bunches by means of coherent Smith-Purcell radiation” *Phys. Rev. ST Accel. Beams*, vol. 17, pp. 1–13, 2014.

[3] Y. Shibata *et al.*, “Coherent Smith-Purcell radiation in the millimeter-wave region,” *Phys. Rev. E*, vol. 57, no. 1, pp. 1061 – 1074, 1998.

[4] H. Harrison *et al.*, “First Steps Towards a Single-Shot Longitudinal Profile Monitor,” *Proc. 7th International Particle Accelerator Conf. (IPAC ’16)*, Busan, Korea, May. 2016, pp. 340– 343.

[5] D. V. Karlovets and a. P. Potylitsyn, “Comparison of Smith-Purcell radiation models and criteria for their verification,” *Phys. Rev. ST Accel. Beams*, vol. 9, pp. 1–12, 2006.

[6] A. S. Kesar, “Smith-Purcell radiation from a charge moving above a grating of finite length and width,” *Phys. Rev. ST Accel. Beams*, vol. 13, pp. 1–8, 2010.

[7] J. Brownell, J. Walsh, and G. Doucas, “Spontaneous Smith-Purcell radiation described through induced surface currents,” *Phys. Rev. E*, vol. 57, no. 1, pp. 1075–1080, 1998.

[8] M. Fukuda *et al.*, “Upgrade of the accelerator for the laser undulator compact X-ray source (LUCX),” *Nucl. Instrum. Meth. Phys. Res. A*, vol. 637, no. 1 (Suppl.), pp. S67–S71, 2011.

[9] A. Aryshev *et al.*, “Development of Advanced THz Generation Schemes at KEK LUCX Facility,” *Proc. 10th Annual Meeting of Particle Accelerator Society of Japan (PASJ’13)*, Nagoya, Japan, Aug. 2013, pp. 873–876.

[10] M. Shevelev *et al.*, “Coherent radiation spectrum measurements at KEK LUCX facility,” *Nucl. Instrum. Meth. Phys. Res. A*, vol. 771, pp. 126–133, 2015.

[11] Virginia Diodes, “Zero Bias Detectors - VDI Model: WR2.2ZBD,” `http://vadiodes.com/index.php/en/products/detectors?id=122/`.

[12] Virginia Diodes, “Virginia Diodes Inc. Waveguide Band Designations,” `http://vadiodes.com/VDI/pdf/waveguidechart200908.pdf`. Last modified 29/06/2010.

[13] H. A. Radi and J. O. Rasmussen, “Interference, Diffraction and Polarization of Light,” in Principles of Physics For Scientists and Engineers, Heidelberg, Germany: Springer-Verlag, 2013, pp. 603–634.

ISBN 978-3-95450-177-9