NOVEL GRATING DESIGNS FOR A SINGLE-SHOT SMITH-PURCELL BUNCH PROFILE MONITOR

A. J. Lancaster*, G. Doucas, H. Harrison, I. V. Konoplev,
John Adams Institute, Department of Physics, University of Oxford, Oxford, OX1 3RH, UK

Abstract

Smith-Purcell radiation has been successfully used to perform longitudinal profile measurements of electron bunches with sub-ps lengths [1]. These measurements require radiation to be generated from a series of gratings to cover a sufficient frequency range for accurate profile reconstruction. In past systems the gratings were used sequentially and so several bunches were required to generate a single profile, but modern accelerators would benefit from such measurements being performed on a bunch by bunch basis. To do this the radiation from all three gratings would need to be measured simultaneously, increasing the mechanical complexity of the device as each grating would need to be positioned individually and at a different azimuthal angle around the electron beam. Investigations into gratings designed to displace the radiation azimuthally will be presented. Such gratings could provide an alternative to the rotated-grating approach, and would simplify the design of the single-shot monitor by reducing the number of motors required as all of the gratings could be positioned using a single mount.

INTRODUCTION

Modern and future particle accelerators provide challenges for longitudinal beam profile monitors by producing short bunches with highly variable profiles. A successful monitor will have to resolve sub-ps bunches in a non-destructive manner on a single-shot (bunch-by-bunch) basis. Possible techniques which could enable such a monitor include electro-optic measurements [2] and the use of coherent radiation spectroscopy [3] [4]. This paper presents a preliminary conceptual design for a single bunch profile monitor based on coherent Smith-Purcell radiation (cSPR), with an emphasis on changes to the design of the metallic grating used to generate the radiation.

SMITH-PURCELL RADIATION

Smith-Purcell radiation arises when a charged particle bunch travels near to a periodic metallic structure. The electric field of the particles induces a surface charge on the surface of the structure which then follows the particles, giving rise to a surface current. Discontinuities in the structure result in changes to the current and so to the emission of radiation. Each period will emit radiation in the same way, giving rise to a far field dispersion relation which links the wavelength of the radiation to angle of emission.

* andrew.lancaster@physics.ox.ac.uk

To use cSPR as a beam diagnostic it is necessary to predict the intensity of the radiation which will be generated, which requires several functions to be understood. The first step is to calculate the radiation produced by a single particle travelling above a single period of the grating. The effect of the grating periodicity can then be incorporated to give the expected intensity distribution from a single particle travelling above the full Smith-Purcell grating. It is at this stage that the dispersion relation becomes apparent.

The particle bunch must then be modelled. Assuming that the transverse bunch profile remains constant throughout we can describe the charge distribution as $T(x, y)Z(z, t)$, and the intensity of the cSPR is then found to be proportional to the Fourier transform of the longitudinal bunch profile. This means that by measuring the intensity of the cSPR along with other relevant beam parameters it is possible to retrieve the frequency components of the particle bunch and determine the longitudinal profile [5].

Coherent Smith-Purcell radiation has already been used to perform longitudinal bunch profile measurements at FACET, SLAC [1]. The E203 experiment sequentially measured three gratings with different periods, with three additional blank measurements to perform background subtraction. Each grating provided 11 frequency measurements, giving 33 measurement points in total. These measurements had to be taken over an extended period of time as the gratings were mounted on a carousel. As each accelerator will have different measurement requirements 33 frequency measurements has been taken as the target for the design of the single-shot device. The key constraints on the monitor are that background subtraction needs to be performed without the use of blanks and that the device must be compact.

The first constraint can be addressed by taking advantage of the high degree of polarization of Smith-Purcell radiation, which is predicted by theory and has been confirmed experimentally [6]. Previous measurements have shown the background signal to be broadly unpolarized [1]. This means that cSPR will be split asymmetrically by a polarizer but the background radiation will be evenly split. By using a pair of detectors it would therefore be possible to subtract the background radiation from the cSPR signal on a bunch-by-bunch basis. Such a detector layout is shown in Fig. 1.

The second constraint can be met by rotating the three gratings azimuthally around the particle beam. By positioning the three gratings at ϕ=0° and ±60° there is enough space for the three sets of detectors to be positioned in a compact region along the beam pipe. The layout, shown in Fig. 2, is approximately 160 mm longer than the E203

ISBN 978-3-95450-177-9

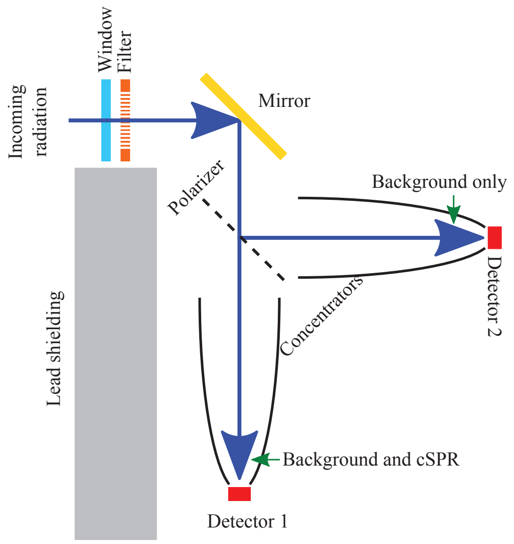

Figure 1: Two detector system to enable background subtraction on a shot-by-shot basis. By subtracting the signal from detector 2 from the signal from detector 1 it is possible to extract the SPR signal without backgrounds (assuming that it is perfectly polarized).

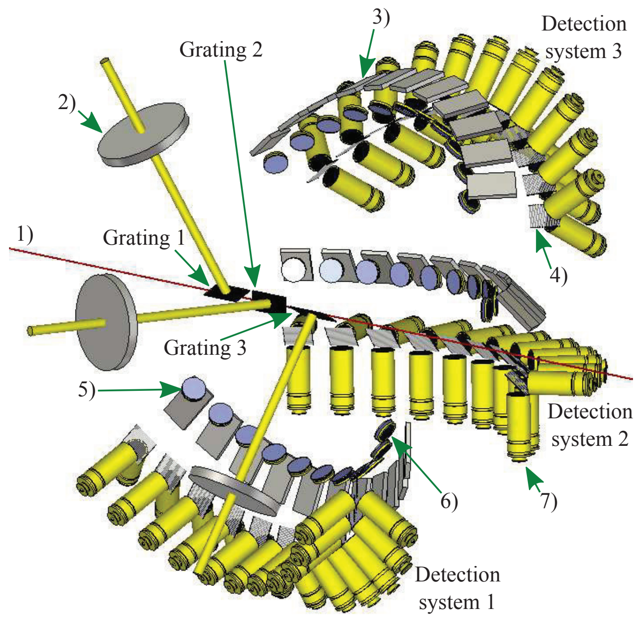

Figure 2: The proposed layout of a single-shot longitudinal profile monitor. The components are: 1) beam path, 2) vacuum feedthroughs, 3) mirrors, 4) polarizers, 5) vacuum windows, 6) filters and 7) concentrators and detectors. Grating 1 illuminates detection system 1. Components are to scale. Schematic drawn using CST Microwave Studio [7].

system which has been deemed to be reasonable until constraints from specific accelerators are determined.

Other components (such as vacuum windows, band-pass filters and mirrors) are expected to be similar to the E203 system, with the notable exception of the detectors. The E203 experiment used pyroelectric detectors because their broad frequency response meant that they could be used with all three gratings, but in a single-shot device this is no longer necessary. This enables more sensitive devices with narrow frequency ranges, such as Schottky barrier diodes, to be used. The specific choice of detector architecture would be linked to the requirements of each application.

MODIFYING THE GRATING DESIGN

A key factor in the performance of a cSPR longitudinal profile monitor is the number of radiation frequencies which can be sampled, although the choice of frequencies is also important. To sample a single frequency requires two detectors in the proposed system, meaning that the cost of detectors will be a major factor in the design of a final device. The cost of the rest of the system should be minimized to either compensate for the cost of the detectors or to enable more to be incorporated into the device.

The obvious approach to simplifying the system would be to reduce the number of motors and vacuum feedthroughs required to position the three gratings. It is not possible to mount three gratings in the orientations shown in Fig. 2 on a single mount without modifying their design, because variations in the beam position would asymmetrically change the beam-grating separation, leaving some gratings with optimal separation and others either too close or too far from the beam.

A possible solution to this problem is to angle the rulings of the gratings with respect to the direction of travel of the beam. This has been studied by Sergeeva et. al. [8] who investigated Smith-Purcell radiation generated by an infinitely wide gratings with the electron beam travelling at non-normal incidence to the facets, which causes the Smith-Purcell radiation to be emitted at non-zero azimuthal angles and so provides a mechanism to distribute the radiation while ensuring the gratings have a consistent beam-grating separation.

To take advantage of this effect it is necessary to make radiation intensity predictions for a grating with a finite width. A program based on the NAG libraries [9] is in development to achieve this using the surface current model. An electron propagates in the $\hat{\mathbf{z}}$ direction at a fixed height above the grating. The grating is modelled as a flat sheet of perfect conductor with gaps consisting of vacuum. The user defines the shape of a single facet and the number of facets which make up the grating. At the current stage we assume that the electron is ultra-relativistic and so the electric field (and so the surface current) is only calculated directly below the electron. This assumption means that the model provides qualitative distributions but does not currently provide quantitative results.

Two example grating facets and their associated intensity distributions (as calculated by the program) are shown in Fig. 3. Grating A is a standard (normal incidence) 0.5 mm

ISBN 978-3-95450-177-9

period grating, and grating B has the same physical period but its rulings are rotated by 30° with respect to the direction of particle propagation, which increases the facet length by a factor of $1/(\cos\delta)$ where δ is the angle of rotation. The gratings have 120 facets, meaning that the plots show the intensity associated with the wavelength given by the Smith-Purcell dispersion relation at each angle.

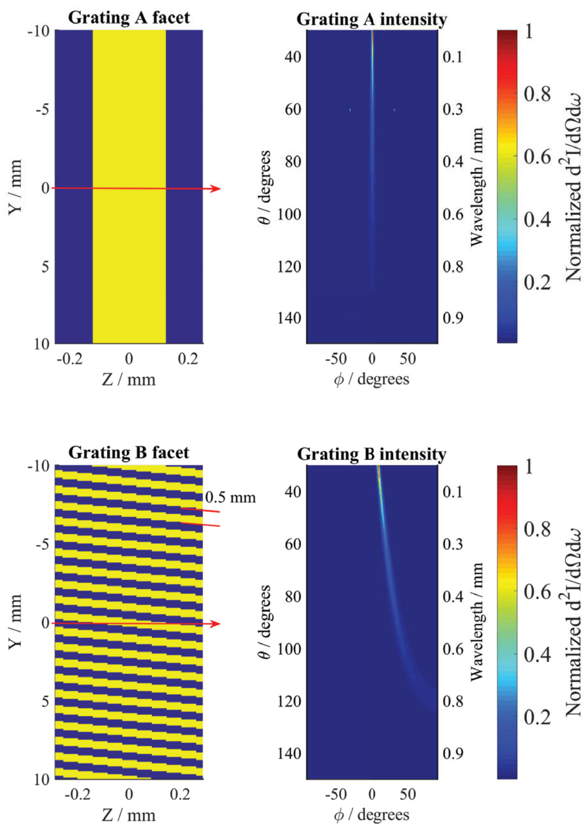

Figure 3: Two example grating facets and their associated intensity distributions. Yellow indicates conductor and blue indicates vacuum. Grating A is a "standard" grating, whereas grating B has been rotated with respect to the direction of beam propagation ($\hat{\mathbf{z}}$), shifting the ϕ position of the peak of the intensity distribution. Note that the Y-axis covers 20 mm but the Z-axis only covers around 0.5 mm which exaggerates the effect of the rotation. The beam propagation direction is shown by the red arrows.

It is clear that the radiation from grating A is emitted along ϕ=0°, whereas the radiation distribution for grating B is displaced from the ϕ axis, with a minimum value of ϕ=9° at θ=30°. The position of the maximum of the intensity distribution can be predicted by considering the system as a pair of coupled diffraction gratings, one in the direction of beam propagation and a second perpendicular to it. The first gives the SPR dispersion relation, where λ is the emitted wavelength, l is the grating period, n is the radiation order, β is the particle speed as a fraction of the speed of light and θ is the emission angle where 0° is the beam direction and 90° is perpendicular to the grating surface, with the addition of the $\cos\delta$ term to model the stretch of the period as the grating is rotated (Eq. 1). The perpendicular periodicity of each facet can be viewed as a standard diffraction grating, meaning that the radiation peak can be predicted using the relation given in Eq. 2 for order m. By equating the wavelengths it is possible to predict the ϕ-position of the peak of the intensity distribution, as given in Eq. 3.

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

$$\lambda = \frac{l}{m\sin\delta}\sin\theta\sin\phi \tag{2}$$

$$\sin\phi = \frac{m\tan\delta}{n\sin\theta}\left(\frac{1}{\beta} - \cos(\theta)\right) \tag{3}$$

The ϕ values predicted by Eq. 3 (see Fig. 4) agree with the results of the calculation program to within the resolution of the simulation. By using three gratings with different values of δ it should be possible to spatially distribute the radiation without needing to change the ϕ positions of the gratings and therefore correct changes in beam-grating separation for all three gratings simultaneously.

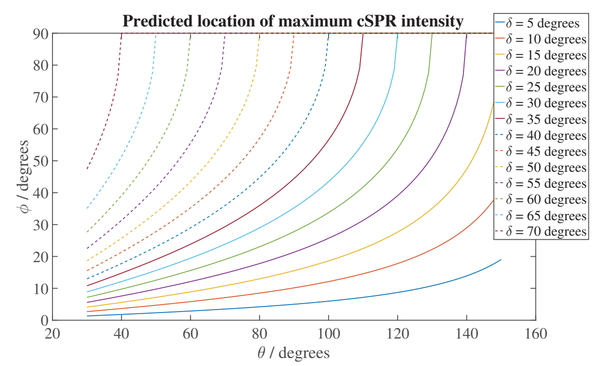

Figure 4: Predicted locations of peak cSPR intensity according to Eq. 3 for a particle beam with γ=39000 and n = m = 1.

A further improvement would be to combine the three gratings into one, as shown in Fig. 5 which combines a grating with a facet length of 1.5 mm and δ = 0° with a grating with a facet length of 0.75 mm and δ=20° and a third grating with 0.5 mm facet length and δ=−20°. The grating was 60 mm long, meaning that there were 40 0° facets, 80 20° facets and 120 −20° facets. The predicted radiation intensity distributions for each facet length in Fig. 5 show that the radiation is either spatially or chromatically separated, with the highest intensities distributed either at ϕ=0° or at +ve or -ve ϕ angles. The spatial distributions may cause difficulties when manufacturing the vacuum chamber because of the variations in ϕ-angle with θ, so designs should be sought which alleviate this problem.

CONCLUSION

A preliminary concept for a single-shot cSPR longitudinal bunch profile monitor has been developed. Novel grat-

ISBN 978-3-95450-177-9

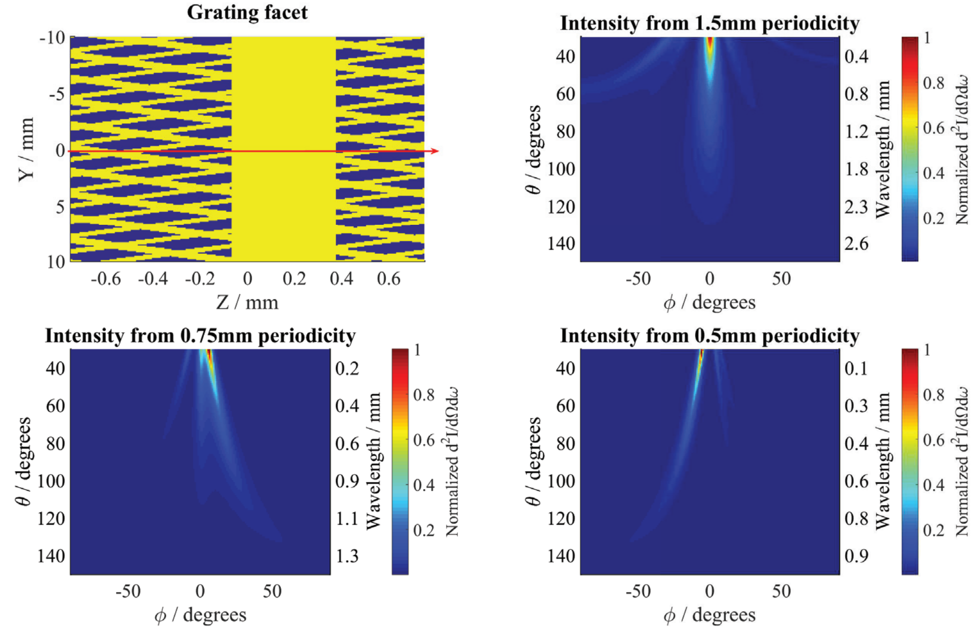

Figure 5: A facet which combines three gratings of different periodicities into a single grating. Yellow indicates conductor, blue indicates vacuum and the beam propagation direction is shown by the red arrow. The calculated intensity distributions associated with each periodicity predict that the radiation should be spatially and spectrally separated.

ings could be selected to spatially disperse the radiation at a reduced cost, enabling higher performance for given financial constraints. Rotated gratings are currently under study, although the intention is to use more complex designs to allow f or easier manufacturing of the vacuum chamber. The grating simulations require further development to move beyond qualitative distributions. The radiation intensity from any novel grating design would require extensive experimental testing before it could be used in a bunch profile monitor.

ACKNOWLEDGEMENTS

This work was supported by the UK Science and Technology Facilities Council (STFC UK) through grant ST/M003590/1 and studentship ST/M50371X/1, the Leverhulme Trust through International Network Grant IN–2015–012 and by the John Adams Institute of Accelerator Science (University of Oxford). We also thank P. Huggard (STFC, RAL) and the RAL Space Millimetre-Wave Technology Group for useful discussions on THz detectors.

REFERENCES

[1] 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, no. 5, p. 052802, May 2014.

[2] G. Berden *et al.*, “Time resolved single-shot measurements of transition radiation at the THz beamline of flash using electro-optic spectral decoding”, in *Proc. EPAC’06*, Edinburgh, Scotland, May 2006, paper TUPCH027, pp. 1058–1060.

[3] S. Wesch *et al.*, “A multi-channel THz and infrared spectrometer for femtosecond electron bunch diagnostics by single-shot spectroscopy of coherent radiation”, *Nucl. Instrum. Meth. Phys. Res. A*, vol. 665, p. 40–47, Feb. 2011.

[4] A. D. Debus *et al.*, “Electron Bunch Length Measurements from Laser-Accelerated Electrons Using Single-Shot THz Time-Domain Interferometry”, *Phy. Rev. Lett.*, vol. 104, no. 8, p. 084802, Feb. 2010.

[5] J. H. Brownell *et al.*, “Spontaneous Smith-Purcell radiation described through induced surface currents”, *Phys. Rev. E*, vol. 57, no. 1, p. 1075–1080, Jan. 1998.

[6] H. Harrison *et al.*, “Novel approach to the elimination of background radiation in a single-shot longitudinal beam profile monitor”, presented at IBIC’16, Barcelona, Spain, Sep. 2016, paper TUPG5, this conference.

[7] *CST Studio Suite 2015*, CST Computer Simulation Technology AG., `www.cst.com`

[8] D. Yu. Sergeeva *et al.*, “Conical diffraction effect in optical and x-ray Smith-Purcell radiation”, *Phys. Rev. ST Accel. Beams*, vol. 18, no. 5, p. 052801, May 2015.

[9] *The NAG Library*, The Numerical Algorithms Group (NAG), Oxford, United Kingdom, `www.nag.com`

ISBN 978-3-95450-177-9