FIRST STEPS TOWARDS A SINGLE-SHOT LONGITUDINAL PROFILE MONITOR: STUDY OF THE PROPERTIES OF COHERENT SMITH-PURCELL RADIATION USING THE SURFACE CURRENT MODEL

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Abstract

We propose to use the polarization of coherent Smith-Purcell radiation (cSPr) to separate the signal from background radiation in a single-shot longitudinal bunch profile monitor. We compare simulation and experimental results for the degree of polarization of cSPr generated by a grating with a 1 mm periodic structure at the LUCX facility, KEK (Japan). Both experiment and simulation show that the majority of the cSPr signal is polarized in the direction parallel to the grating grooves. The degree of polarization predicted by simulation is higher than the measured result, therefore further investigation is needed to resolve this discrepancy.

INTRODUCTION

Developments in particle accelerators will place increasing demand on beam diagnostic tools. At facilities with fs bunch lengths or where there is a large amount of bunch-to-bunch variation, a non-destructive single-shot longitudinal bunch profile monitor will be essential. cSPr has been suggested for spectral analysis to allow non-destructive longitudinal bunch diagnostics in particle accelerators [1]. This technique has been demonstrated successfully in a "multi-shot" system [2–4], providing the foundation for the conceptual design of the "single-shot" monitor able to extract all the information needed to reconstruct the bunch profile from a single bunch.

Previous cSPr experiments at FACET, SLAC (USA) needed to extract the cSPr signal in a high background environment [5]. We propose to exploit the highly polarized nature of cSPr (as predicted by theory) to separate the signal from any background radiation (which is expected to be broadly unpolarized [4]).

While experiments have been carried out previously to determine the polarization of cSPr [4,6], there has not been an extensive study. In order to incorporate this feature into the design of the single-shot cSPr bunch profile monitor it is necessary to demonstrate that:

1. cSPr is highly polarized.
2. It is possible to use existing theoretical models to predict the degree of polarization of cSPr

In this paper we present experimental results which demonstrate that cSPr is highly polarized, and that the experimental results are in broad agreement with the Surface Current Model (SCM) predictions.

THEORY AND SIMULATION

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

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

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

Several theories have been proposed to describe Smith-Purcell radiation, a short summary of which can be found in [3,7,8]. The theory used in this paper is the Surface Current Model (SCM), details of which can be found in [9,10]. SCM combines the effects of the grating geometry and the bunch form. Semi-analytic code developed using SCM allows for the prediction of the energy emitted at specific frequencies (or positions). It also makes predictions of the degree of polarization at various observation points, although this aspect of the theory has not been thoroughly tested.

As can be seen from Fig. 1 the SCM predicts that cSPr will be highly polarized with electric field perpendicular to the grating grooves in the region of the highest intensity of radiation. These predictions are made for a 1 mm grating using beam parameters corresponding to those at the LUCX facility. It also predicts some fine structure in the degree of polarization with the most highly polarized radiation being found in the center of the distribution (i.e. at azimuthal angle $\phi \approx 0$).

EXPERIMENTAL SETUP

The experiment was carried out at the LUCX facility at KEK [11] with the beam parameters shown in Table 1.

The LUCX beam line includes a vacuum chamber for THz radiation studies, a full description of which can be found in [12]. A 1 mm periodic grating was placed inside the vacuum chamber, with the periodic structure arranged so that it is parallel to the beam with the grooves aligned

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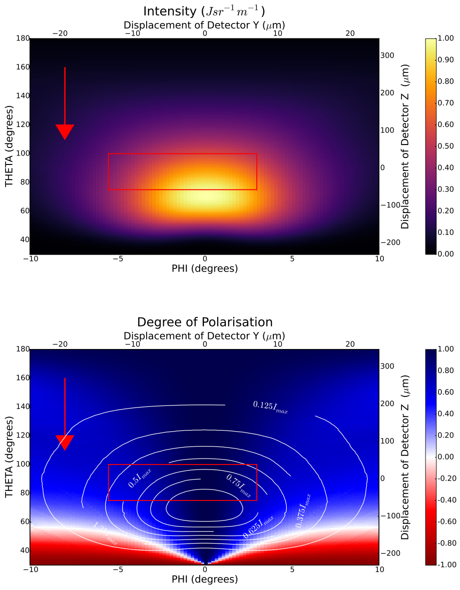

Figure 1: Simulation of intensity (top) and degree of polarization (bottom) with contours showing the intensity distribution for cSPr at the LUCX facility with a 1 mm grating. The arrow shows the direction of motion of the electron beam and the box shows the region in which experimental data was taken.

Table 1: LUCX, RF Gun Section Beam Parameters

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

perpendicular to the direction of travel of the beam. According to the Smith-Purcell dispersion relation (equation 1) the wavelength of first order cSPr emitted at 90° from a grating of this periodicity should be equal to 1 mm (300 GHz). Outside the THz vacuum chamber it is possible to mount detectors on motorized stages which provide two dimensional coverage of the intensity distribution of any radiation exiting the vacuum chamber via the window. An interferometer was used to measure the frequency spectrum of the cSPr, a full description of this set-up can be found in [13]. A Zero Bias Diode with a detection range from 325 GHz to 500 GHz [14], was used to measure the cSPr emitted. In order to calculate the degree of polarization it is necessary to measure the radiation parallel to the direction of the grating grooves and perpendicular to them. The detector is polarization sensitive so the measurements were taken for "horizontal" and "vertical"orientations respectively (the detector was manually rotated by 90°).

RESULTS

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

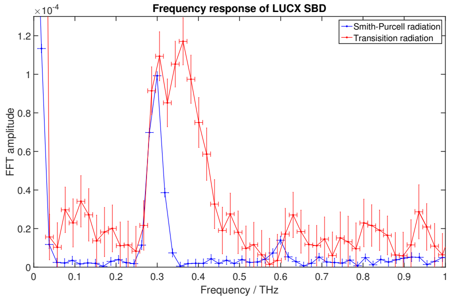

Figure 2: Frequency spectrum of cSPR measured by a detector located at 90° to a 1 mm grating compared with a broadband transition radiation measurement (limited by detector response) with the same detector and interferometer set-up.

To scan the intensity distribution the detector was placed close to the window of the vacuum chamber, 230 mm away from the surface of the grating. Initial measurements were taken with the grating in situ, and with the grating replaced by a planar "blank grating" with the same dimensions as the periodic grating. This allowed for comparison between the intensity of the cSPr signal and the intensity of any background radiation. As can be seen from Fig. 3 the background is low and the signal indistinguishable from measurement when all the THz radiation was blocked.

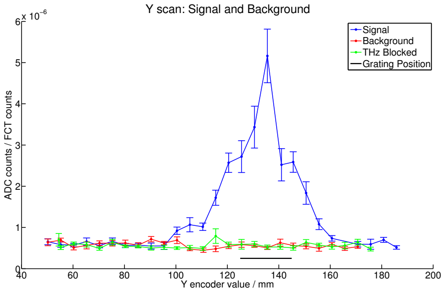

Figure 3: Comparison of cSPr signal and background radiation for a scan measuring the distribution in the ϕ direction.

To calculate the total intensity, the radiation measured in both the horizontal and vertical orientations has to be summed together. The total intensity of radiation and the error on this are shown in Fig. 4. The degree of polarisation of cSPr p_g is calculated as shown in Eq. (2) where G_i is the true cSPr signal, I_i is the measured signal and B_i is the background signal.

$$p_g = \frac{G_H - G_V}{G_H + G_V} = \frac{(I_H - B_H) - (I_V - B_V)}{(I_H - B_H) + (I_V - B_V)} \quad (2)$$

Figure 5 shows the calculated degree of polarization for this experiment for a range of positions across the measured intensity distribution of cSPr, alongside the statistical error. The cSPr measured across this distribution is clearly polarized, corresponding to a larger signal measured for the hori-

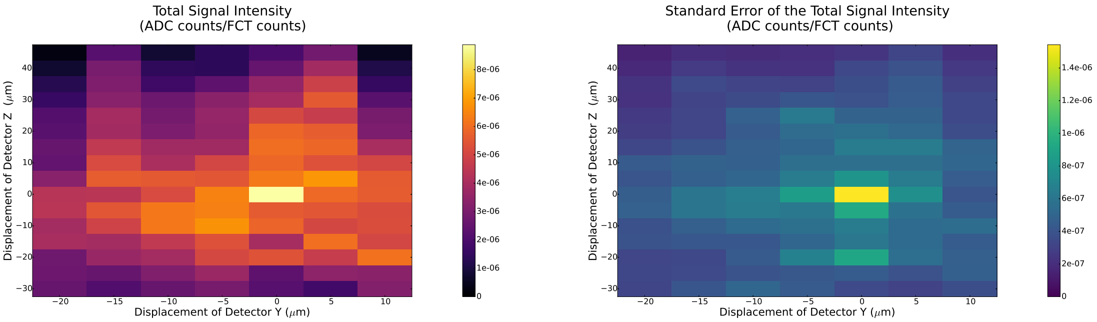

Figure 4: Measured total intensity of cSPR in two dimensions (left) with its associated errors (right). ADC counts are the measured signal at the detector which are normalized by the bunch charge (FCT counts.)

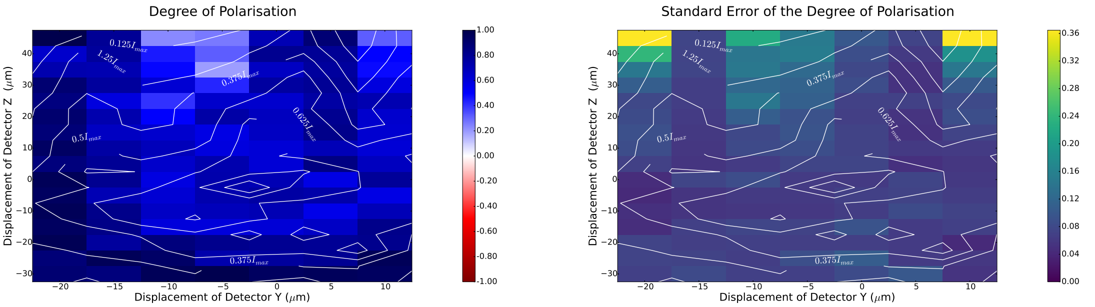

Figure 5: Calculated degree of polarisation of cSPr in two dimensions, with contours for comparison with the intensity distribution (left) and the associated errors (right).

zontal orientation (or radiation polarized parallel to the gratings). This demonstrates that cSPr is partially polarized in the direction parallel to the gratings grooves.

CONCLUSION AND FUTURE PLANS

If we compare the experimental results in Fig. 5 with the SCM based simulation results in Fig. 1 it is clear that the direction of polarization of the radiation matches the numerical model. The measured signal does however have a lower degree of polarization, 0.71±0.04, than was predicted by the SCM, 0.94 (both values taken at the maximum of the intensity distribution). This could be due to a number of issues:

- The simulation was calculated for the far-field, whereas the measurements were taken in the intermediate field.
- When the detector was moved from horizontal to vertical orientation its position could vary. The maxima were used to realign the two sets of measurements, however, this lacks precision.
- It was not possible to measure the frequency for each position where measurements were taken. Therefore, it is not possible to assign accurately angular positions (θ and ϕ) to the Z and Y positions of the detector respectively.
- In the next experiment accuracy of the detector rotation will be improved.

The results given here demonstrate that cSPr is consistently polarized; further measurements to improve resolution, accuracy and to calibrate the intensity measured with the well known cSPr frequency distribution are at the planning stage. Based on the results so far, it should be possible to use the polarization of cSPr to separate the signal from any background radiation in the proposed single-shot longitudinal bunch profile monitor, according to the following relation:

$$G_H = gG_V = g\left(\frac{I_H - bI_V}{a - b}\right) \tag{3}$$

Where the true cSPr signal G_i is expressed only in terms ofthe measured signal I_i and the ratios of the two polarizations of radiation $a = \frac{G_H}{G_V}$ and $b = \frac{B_H}{B_V}$.

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