THE DESIGN OF A NON-DESTRUCTIVE SINGLE-SHOT LONGITUDINAL BUNCH PROFILE MONITOR USING SMITH-PURCELL RADIATION

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Abstract

The conceptual design for a single-shot longitudinal bunch profile monitor using coherent Smith-Purcell radiation (cSPr) has recently been completed. The exploitation of the directionality and the polarization of cSPr to reduce the length of the monitor and to eliminate background radiation respectively are discussed. The linear polarization of cSPr will be used to separate the signal from background radiation and experiments to test this design will be presented. Alongside the conceptual design an investigation to optimize the number of detection channels needed to produce high quality longitudinal bunch profile reconstructions has been carried out. It has been determined that the number of detection channels can be reduced compared to previous experiments if measurement uncertainty and background radiation are minimized effectively.

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 (E203, FACET, SLAC) [2], now a "single-shot" monitor is being designed. The new monitor will be able to extract all the information needed from a bunch to reconstruct its longitudinal profile.

cSPr is emitted when a charged particle travels above a periodic grating. The particle excites 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:

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

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. A frequency spectrum - used to reconstruct the longitudinal profile - can be built up by placing detectors at different angles with respect to the grating.

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OVERVIEW OF THE CONCEPTUAL DESIGN

A conceptual design for a single-shot, non-destructive longitudinal bunch profile monitor based on cSPr has been developed. It is based on the multi-shot system E203 which was installed at SLAC between 2008 and 2014 [2, 3] with several key changes to make the monitor single-shot. An example of the final design is shown in Fig. 1.

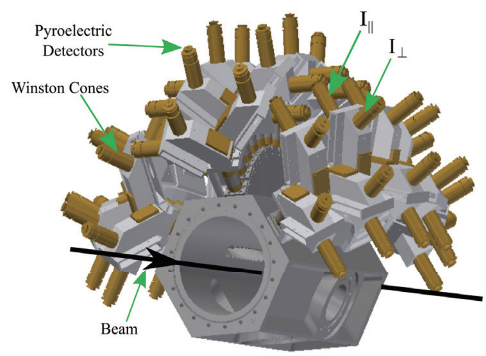

Figure 1: A CAD drawing showing an example of the proposed monitor comprising of 3 gratings, 3 corresponding detector arcs, 33 detection channels and a custom vacuum chamber.

The conceptual design is accelerator independent. However, the parameters of the accelerator in which the monitor is installed will determine many aspects of the final technical design. One example is the type of detector which would be suitable. Ideally pyroelectric detectors would be used as they are cheap and their frequency response is well understood in the range of interest (0.1 -20 THz), however, if the intensity of cSPr is low (in accelerators with low beam energy and charge) it may be necessary to use more sensitive detectors, such as Schottky Barrier diodes [4].

The multi-shot system used 3 gratings (to ensure a large frequency range) placed on a carousel, therefore, measurements using each grating were taken for different bunches. This also required changes to the detector channels (such as changing the filters) for each different grating. The gratings in the new system will be permanently installed, each with a corresponding detector arc of N detection channels (where N is dependent on the technical design, typically N=11). It is important that the monitor is spatially compact to allow for easy installation onto a beamline. 1 grating and detection arc requires approximately 0.4 m of beamline, therefore, 3

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gratings and detections arcs placed sequentially would require more than 1 m of beamline, prohibiting installation in many facilities. It is proposed to locate the gratings at different azimuthal angles around the beam and allowing the detector arcs to overlap longitudinally, this would reduce the beamline required for a 3 grating monitor to approximately 0.7 m. As cSPr has a narrow intensity distribution the radiation emitted from each grating will only interact with its corresponding detector array - located directly opposite to its grating.

BACKGROUND RADIATION ELIMINATION

Previous experiments [2] have show that it can be challenging to extract the cSPr signal in an environment with high levels of background radiation. In order to do this on a shot-by-shot basis it is proposed to use polarizers to separate the signal from the background radiation by implementing the detection channel scheme shown in Fig. 2.

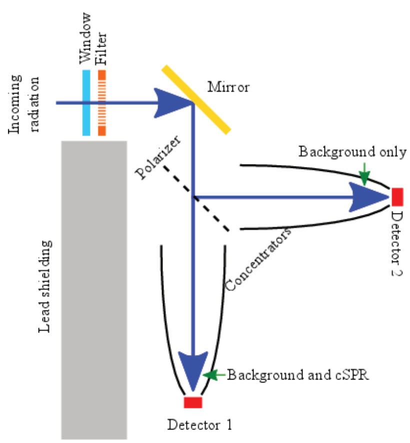

Figure 2: Detection channel schematic with polarizer.

Assuming that the degree of polarization (linear) of the background radiation D_B and of the cSPr signal D_G are known (see Eq. 2),

$$D_B = \frac{B_{\|} - B_{\perp}}{B_{\|} + B_{\perp}}, D_G = \frac{G_{\|} - G_{\perp}}{G_{\|} + G_{\perp}} \qquad (2)$$

the signal measured by the two detectors ($I_{\perp} = B_{\perp} + G_{\perp}$ and $I_{\|} = B_{\|} + G_{\|}$) can be converted to the total cSPr signal ($G_{total} = G_{\perp} + G_{\|}$).

Previous experimental studies [2, 5, 6] have shown that cSPr is linearly polarized, however, there has not yet been an extensive study of this property or a conclusive comparison with any theoretical model.

The degree of polarization of cSPr (D_G) at a range of frequencies with a selection of different gratings will be measured during a planned experimental run at the LUCX facility (KEK, Japan). The LUCX accelerator and its THz radiation chamber have been described previously [7, 8]. A Fabroy-Perot interferometer has been designed for this experiment which can be rotated around the grating to observe different angles (Fig. 3).

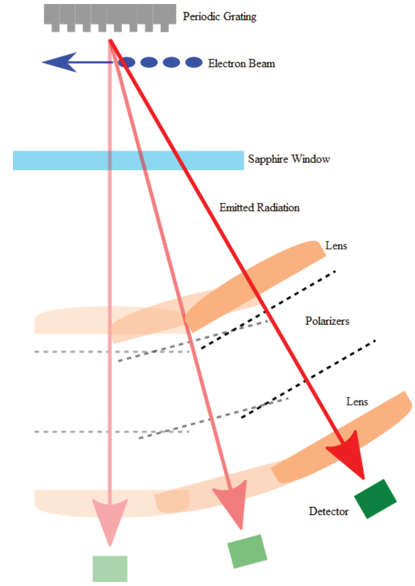

Figure 3: Schematic of Fabroy-Perot interferometer.

The operation of a Fabroy-Perot interferometer is described in [9]. In this system wire grid polarizers will be used as splitters to measure the frequency of the radiation emitted and to measure its degree of polarization. The polarization will be measured by rotating one of the polarizers whilst the other is stationary. This interferometer was recently commissioned at LUCX using silicon wafers as splitters, and had success in measuring a variety of frequencies of cSPr. Figure 4 shows frequencies ranging from 300-500 GHz measured at different observation angles for a 0.7 mm strip grating. A further series of experiments to complete this study are planned in the near future.

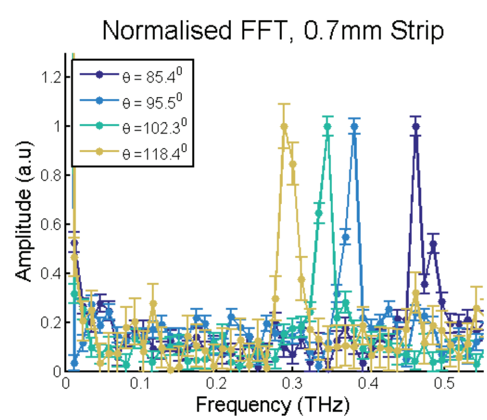

Figure 4: Frequency results using the Fabroy-Perot Interferometer with a 0.7mm strip grating at LUCX.

OPTIMIZING PROFILE RECONSTRUCTION

The conceptual design for the longitudinal bunch profile monitor using cSPr has 3N detection channels (N per grating), and 6N detectors (2 per detection channel). A large number of detection channels produces a well resolved frequency spectrum which improves the quality of the longitudinal profile reconstruction. However, the quality of the reconstruction must be balanced against the cost of the monitor, which has a significant dependence upon the number of detection channels. Therefore an investigation has been carried out to quantify the effect that the number of detection channels has on the quality of the profile reconstruction.

The longitudinal bunch profile is reconstructed from the measurements taken. The frequency spectrum measured is normalized for all other effects to get the amplitude of the Fourier transform of the longitudinal bunch profile, known as ρ. It is then interpolated over the range of frequencies measured and extrapolated to high and low frequencies. Kramers-Kronig relations are used to estimate the associated phase of the ρ profile so that an estimate of the longitudinal bunch profile can be made [10, 11].

Software was developed that generated a ρ associated with synthetic profiles. Each ρ was sampled (one sample per detection channel), interpolated and extrapolated before reconstruction was attempted using Kramers-Kronig. One synthetic profile was used in this investigation - a symmetric Gaussian defined its position μ and width σ. A random component was added to the ρ before sampling in order to simulate the effects of noise (which here refers both measurement uncertainty and background radiation). The results in Figs. 5 and 6 show how well the profile was reconstructed as these two parameters were varied. They show the measured σ of the reconstructed profile is compared to the σ of the original profile and the χ^2 (goodness of fit) comparison between the reconstructed and the original profile respectively. Depending on the requirements of the users at any facility where the monitor is installed it is possible to optimize the number of detectors and their distribution to prioritize either bunch length measurement or profile shape reconstruction.

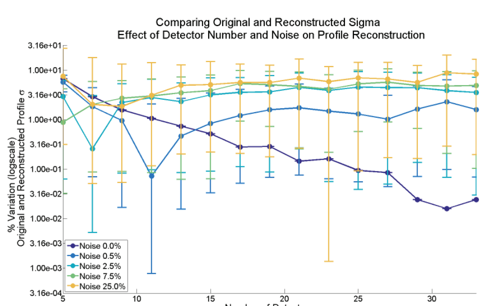

Figure 5: Accuracy of the σ (bunch length) of the reconstructed profile as the noise and number of detection channels are varied.

In Fig. 5 and 6 the case when there is no noise shows a reduction in the reconstruction error when the number of detection channels is increased. However, as the noise increases the number of detectors has less impact on the quality of the reconstruction. Raising the noise level depreciates the quality of the reconstruction, the error for the reconstruction of the profile with 25% noise is an order of magnitude higher than for the reconstruction with no noise. The error in the bunch length measurement increases from 1% to 30% for the same noise variation.

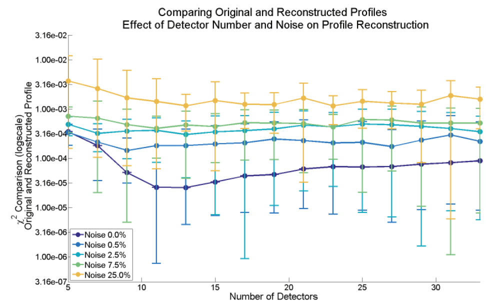

Figure 6: Accuracy of the χ^2 (bunch shape) of the reconstructed profile as the noise and number of detection channels are varied.

These results suggest that a reduction in the number of detection channels would have a minimal effect on the quality of the reconstructions of longitudinal bunch profiles which are Gaussian in shape. It is clear that the most important consideration to achieve high quality reconstruction is the reduction of noise. Implementing a robust background radiation scheme will be essential to the success of the project. Steps must also be taken to reduce any other uncertainty that could arise in the measurements, for example, good calibration of all the detectors used. This study should be expanded to consider other potential factors that could influence the quality of the reconstructions such as variation in the original bunch length or shape.

CONCLUSIONS

The conceptual design of the longitudinal bunch profile monitor using cSPr has been completed. A background radiation elimination scheme using the cSPr polarization has been proposed, and will be tested in upcoming experiments. An investigation into the effect of varying the number of detection channels demonstrates that for simple Gaussian profiles high quality reconstructions are possible with a small number of detection channels. It was demonstrated that the noise levels have a large impact on the quality of the reconstruction and work will be required to address this.

ACKNOWLEDGMENT

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