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To cite this version:

N. Fuster Martinez, A. Faus-Golfe, J. Resta-Lopez, F. B. Taheri, R. Bartolini, et al.. Feasibility Study of a 2nd Generation Smith-Purcell Radiation Monitor for the ESTB at SLAC. IPAC 13 - The 4th International Particle Accelerator Conference, May 2013, Shanghai, China. Joint Accelerator Conferences Website, pp.634-636, 2013. in2p3-00819835

HAL Id: in2p3-00819835
http://hal.in2p3.fr/in2p3-00819835
Submitted on 29 Jul 2013

FEASIBILITY STUDY OF A 2ND GENERATION SMITH-PURCELL RADIATION MONITOR FOR THE ESTB AT SLAC

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Abstract

The use of a radiative process such as the Coherent Smith-Purcell Radiation (CSPR) is a very promising non-invasive technique for the reconstruction of the time profile of relativistic electron bunches. Currently existing CSPR monitors do not have yet single-shot capability. Here we study the feasibility of using a CSPR based monitor for bunch length measurement at the End Station Test Beam (ESTB) at SLAC. The aim is to design a second-generation device with single-shot capability, and use it as a diagnostic tool at ESTB. Simulations of the spectral CSPR energy distribution and feasibility study have been performed for the optimization of the parameters and design of such a device.

INTRODUCTION

A precise measurement of the bunch length in the fs regime is essential for new light source facilities, X-ray Free Electron Lasers (FELs), Future Linear Colliders (FLC) and new accelerators based on plasma acceleration. A Smith-Purcell Radiation (SPR) monitor based on the measurement of the spectral energy distribution emitted by a grating when a charged particle moves close to it can be used as a diagnostic tool to measure the bunch length in the fs regime. There are two theoretical approaches to explain the SPR phenomenon: one based on the diffraction of the electromagnetic field of charged particles; and the second one based on the acceleration of induced charges on the metallic surface of the grating due to the travelling charged particles. The second approach is adopted on this work. In the far field approximation the grating behaves as a monochromator and the wavelength λ of the radiation emitted is related with the observation angle θ as:

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

where l is the period of the grating, n the order of the radiation and β the velocity of the particles in terms of c.

The coherent spectral distribution of the SPR (achievable when the bunch length is close or smaller that the grating period) is proportional to the time profile of the bunch. Thus, with the measurement of the radiated energy at different angles θ, the bunch shape can be reconstructed. The reconstruction is made by doing an inverse Fourier transform of the spectral energy distribution and using Kramer-Kroening technique to determine the minimal compatible missing phase [1].

A first non single-shot prototype has been installed at the Facility for Advanced Accelerator Experimental Tests (FACET) at SLAC in 2011, where it is currently being tested [2]. Moreover, a simplify prototype has been installed at SOLEIL in 2013 with the aim of better understanding the emitted radiation and improve the detection and amplification system for a possible 2nd generation prototype [3]. Using the information provided by the studies at FACET and SOLEIL we want to go through the design and construction of a new monitor close to a single shot device. In this paper we study the feasibility of using a SPR monitor in the ESTB beamline, where this monitor can be used as diagnostic tool to support ESTB experiments such as single-bunch collimator wakefield tests [4]. By means of simulations we study the level of the SPR signal in the ESTB context and we describe some preliminary experimental studies to investigate ways to amplify such signal.

EXPERIMENTAL APPARATUS

The experimental set up of the first generation SPR monitor is described briefly in this section. The experimental apparatus has a total insertion length in the beam line of about 0.6 m. The monitor consists of a vacuum chamber which contains three gratings plus a blank (smooth piece which allows us to subtract the background to the Smith-Purcell radiation signal) mounted on a carousel and the optical system based on filters, Winston cones and pyroelectric detectors used for the collection and detection of the Far Infrared Radiation (FIR). The optical system components are located outside the chamber. Figure 1 shows a scheme of the current experimental set up installed at FACET [2, 5].

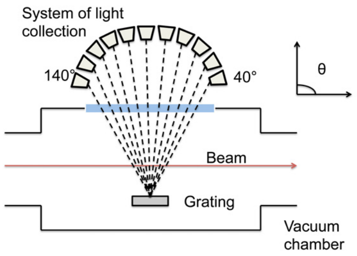

Figure 1: Smith Purcell radiation first generation monitor scheme.

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* Work supported by IDC-20101074 and FPA2010-21456-C02-01

One of the main components of the monitor are the gratings which produce the SPR. Therefore, it is important to make a suitable choice of the grating period configuration looking for an adequate energy spectrum and the achievement of the widest possible wavelength coverage in order to be able to discriminate between different bunch shapes. A scheme of the physical phenomenon is shown in Fig. 2, where the different parameters used for the optimization of the grating design are described:

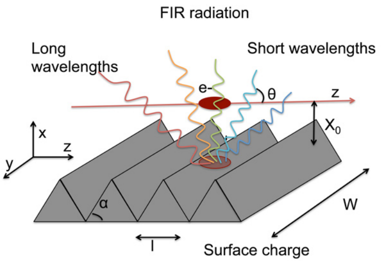

Figure 2: Smith Purcell radiation process.

Here x_0 denotes the distance between the grating and the beam, W the width of the grating, l the period of the grating, α the blaze angle of the grating and θ the observation angle.

So far, the current device needs six data taking runs (for three gratings and three times the blank) and each run integrates over 100 bunches approximately. Going towards a single shot monitor requires to measure the three gratings and the blank at the same time and being able to to detect signal from a single bunch.

SIMULATIONS OF SMITH-PURCELL RADIATION AT ESTB AND SLAC

Preliminary simulations of the Smith-Purcell radiation yield have been performed varying various parameters of the monitor such as the blaze angle of the grating, the grating width, the distance between the beam and the grating and the period of the grating. As an example Fig.3 shows the intensity of the Simth-Purcell radiation for different grating periods at ESTB and FACET using the beam parameters of Table 1, considering a bunch length of 100 μm and the optimal parameters obtained: a blaze angle of 20°; a grating width of 30 mm and a beam-grating separation of 1 mm.

Table 1: ESTB and FACET beam parameters

Beam line	ESTB	FACET
E (GeV)	15	20
f_r (Hz)	1-5	10
N_e(Charges per bunch)	2.1×10^9	1.5-2×10^{10}
$\gamma\epsilon_{x,y}$ (mm-mrad)	4/1	310/13
σ_z (μm)	100-300	20-50

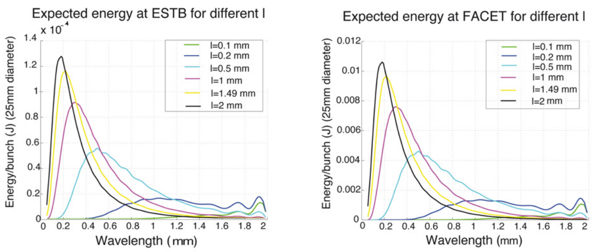

Figure 3: Smith-Purcell radiation signal at ESTB (left) and FACET (right) considering different grating periods.

Figure 3 shows that the same configuration of grating periods, 0.25, 0.5 and 1 mm, can be used for the new prototype because the wavelength covered is the same. These simulations are based on electromagnetic calculations considering the induced charge surface current model [6].

Figure 4 shows the comparison between the signal at ESTB and FACET considering the optimal parameters obtained and mentioned above and a bunch length of 100 μm. One can see a difference of two orders of magnitude between the intensity of the signal at ESTB and FACET. Therefore a study about how to detect and amplify the Smith-Purcell signal is needed in order to achieve enough signal for the bunch profile reconstruction.

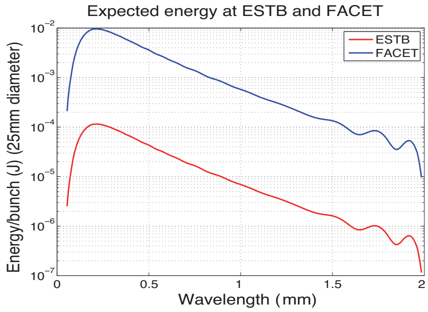

Figure 4: Smith Purcell radiation signal at ESTB and FACET.

Notice that no correction factors have been applied in this study due to transmission losses from the silicon window, the filters, the Winston cones and the efficiency of the mirrors that focus the radiation into the Winston cones. Typically only around a 10% of the radiation produced reaches the detectors. Then it is very important to calibrate and understand the detectors response. Experimental measurements give us that the lowest detectable level of radiation for the current DAQ system is about 10^{-9} J and the highest detectable level is about 10^{-6} J.

Theoretically the SPR is polarized and the degree of polarization can be calculated [7]. The understanding and experimental confirmation of the Smith-Purcell radiation polarization can lead to further improvements on the new SPR prototype. For example, polarizers can be used instead of filters which have to be appropriate for each wavelength and have different transmission patterns, this making more difficult the data analysis. Figure 5 shows a preliminary simulation of the contribution of the two different polarization components using the optimal monitor parameters mentioned above and a grating period of 1.5 mm.

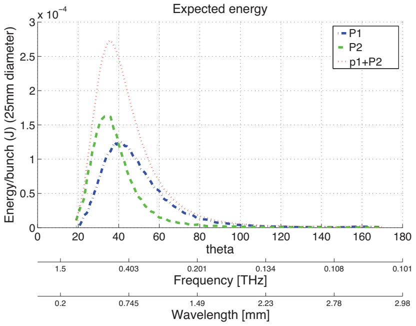

Figure 5: Polarization components of the Smith-Purcell radiation at ESTB for the optimal monitor parameters.

SIGNAL DETECTION AND AMPLIFICATION

Several studies are being carried out to determine how to collect and amplify the Smith-Purcell signal. These studies are based on: a new optical system based on parabolic mirrors; efficiency comparison of different kind of detectors (thermopiles and pyroelectric type detectors) and the use of quartz windows instead of silica windows.

Here we describe briefly preliminary investigations to determine the most convenient detector for the new SPR prototype. An improvement on the understanding of the detectors response and calibration can clearly lead to an improvement on the accuracy of the reconstruction profile. As an example of the preliminary tests made, Figure 6 shows the ratio between the signal from the detectors divided by the signal given as input to the Infrared (IR) source as a function of the source-detector distance for 3 thermopiles (HTS-B31, HMS-J21, TPD-2T-0625) and 1 pyroelectric detector (Eltec-400). The response of these detectors was tested as a function of the distance between an IR source (HSL EMIRS Heimann model) and the detector, the frequency and the amplitude of the signal of the generator connected to the IR source. The output of the detectors was amplified using a large dynamic range amplifier. As can be seen the HTS-B31 thermopile is the most sensitive detector tested. So this study shows the possibility of using a thermopile instead of the Pyro-400 which is the detector used at the current SPR monitor prototype. However more accurate studies will come.

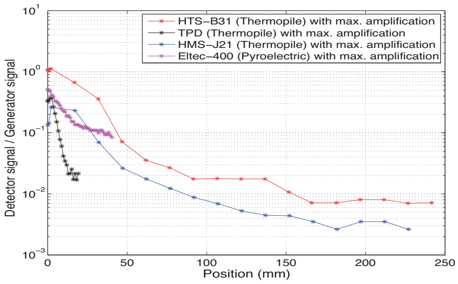

Figure 6: Signal ration for different Pyroelectric and thermopiles detectors from an IR source.

The detection system is very important nevertheless what really matters is the ratio between the Smith-Purcell signal and the background. Most of the background will come from the system that brings the grating close to the beam axis and will be produced by similar phenomenon. At FACET the background level given by experimental measurements is about 10^{-7} J. Ways to increase the ratio signal-background have also to be investigated in order to fulfill the design of a 2nd generation Smith-Purcell monitor. The ratio signal-background can be increased, for example, by: coating parts with an antireflective coating inside of the vacuum chamber and doing a careful design of the geometry of the vacuum chamber.

CONCLUSIONS AND FUTURE WORK

First simulations of the Smith-Purcell radiation yield at ESTB have been performed showing an intensity two orders of magnitude less than the one obtained at FACET. The variation of the parameters of the first generation Smith-Purcell radiation monitor does not provide a considerable increase of the signal, therefore, the output of various detectors is being investigated in order to improve the system to collect and amplify the signal from this radiation. The preliminary study reported on this paper shows the possibility of using thermopile detectors such as the HMS-J21 and HTS-B31 models, instead of a pyroelectric detector. A balance between the cost and response advantages has to be reached. More test will be done at SOLEIL [3]. Further studies and experiments are planned and will provide a better understanding of the Smith-Purcell radiation, enabling an approach to the design and construction of a CSPR based device with single-shot capabilities.

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