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Conceptual Design of Non-Destructive, Time Profile Monitor for Femtosecond-long Electron Bunches

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Abstract. The main objective of the project is to build a high resolution time-profile monitor for femtosecond electron beams, based on the spectral analysis of coherent Smith-Purcell radiation (cSPr). The monitor will be capable of determining the electron bunch time profile non-destructively and on a shot-by-shot basis. The results of recent experimental and theoretical studies are presented, and the conceptual design of the monitor is discussed.

INTRODUCTION: COHERENT RADIATION SPECTROSCOPY FOR BEAM PROFILE MEASUREMENTS

Accurate knowledge of the longitudinal (time) profile of an electron bunch is important in the context of linear colliders, wake-field accelerators and the next generation of light sources including X-ray Free Electron Lasers (FELs). It is a property that becomes progressively more difficult to determine for femtosecond (fs) long bunches or for trains of micro-bunches [1–7]. These types of short bunches are expected from the next generation of high-gradient particle accelerators (e.g. laser or beam-driven wake-field accelerators) and will be required for the next generation of FELs. Apart from the desirability of determining the profile in a non-destructive manner, it is equally attractive to be able to achieve this in a single shot, i.e., bunch-to-bunch manner. At present, there is no technique that is capable of meeting these requirements. The availability of such a monitor will aid the understanding of the roles of the various parameters (e.g. plasma density and composition, driver pulse duration and geometry of the accelerating region) affecting the electron bunch formation and acceleration, as well as the role of the bunch profile on the light generation from FELs.

There are a number of mechanisms that can be used to generate coherent radiation, including coherent synchrotron radiation, undulator radiation, transition radiation, diffraction radiation and Smith-Purcell radiation. All these mechanisms of radiation generation are used at different facilities [2–8] for bunch diagnostics. Indeed, if the bunch length or its features are shorter than the observed radiation wavelength, the radiation is coherent and its intensity is proportional to N^2 (where N is the number of the electrons in the bunch). The temporal/longitudinal profile of an electron bunch is ‘encoded’ within the continuous spectral distribution of coherent radiation it generates. For fs-long electron bunches, the spectral distribution is typically measured over the GHz to THz region of the spectrum at discrete spectral points. In order to determine accurately the time profile, it is essential to measure the spectrum over the widest possible frequency range and to subtract the background radiation, which is present in a particle accelerator. The reconstruction of the time profile is based on accurate knowledge of the spectrum, and measuring as many frequency points as possible minimizes the uncertainty due to interpolations and extrapolations of the experimental data while recovering a continuous spectrum for instance to evaluate the minimal phase. Once the frequency spectrum has been measured, the temporal profile can be reconstructed using techniques such as the Kramers–Kronig (KK) method.

The ultimate objective of this work is the development of a non-destructive diagnostic device capable of determining confidently the time profile in a single-shot, i.e., one bunch – one profile. In this paper we present the conceptual design of such a device based on cSPr. The road map of such a design development, starting with the discussion of previous studies by the E203 collaboration, and the novel phase reconstruction algorithm development are presented. That research was used as the baseline for this design, and is essential for understanding of the novel conceptual design presented at the end of the paper.

RESULTS OF SMITH PURCELL RADIATION STUDIES AT FACET, SLAC PREVIOUSLY ACHIEVED BY E203 COLLABORATION [6]

The theory of Smith-Purcell radiation has been described in a number of papers (see [5, 6] and references therein). The Smith-Purcell radiation can be observed when an electron bunch travels with velocity βc above the surface of a grating (metallic surface structure) of period l . The charged particles are coupled via the electric field with the surface electrons on the grating, and induce a surface current that propagates along the grating and scatters on the grating's discontinuities, thus generating Smith-Purcell (SP) radiation. Due to periodicity of the grating it disperses the radiation emitted as defined by expression (1), where the emitted wavelength λ , is measured at observation angle θ in the far field zone and n is the order of the emission i.e. $n=1, 2, 3 \dots$

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

The intensity of Smith-Purcell radiation observed from an electron bunch (consisting of N_e electrons) inside a solid angle Ω is:

$$(dI/d\Omega)_{N_e} = (dI/d\Omega)_1 (N_e S_{inc} + N_e^2 S_{coh}), \quad (2)$$

where S_{coh} and S_{inc} are the amplitudes of the coherent and incoherent components respectively.

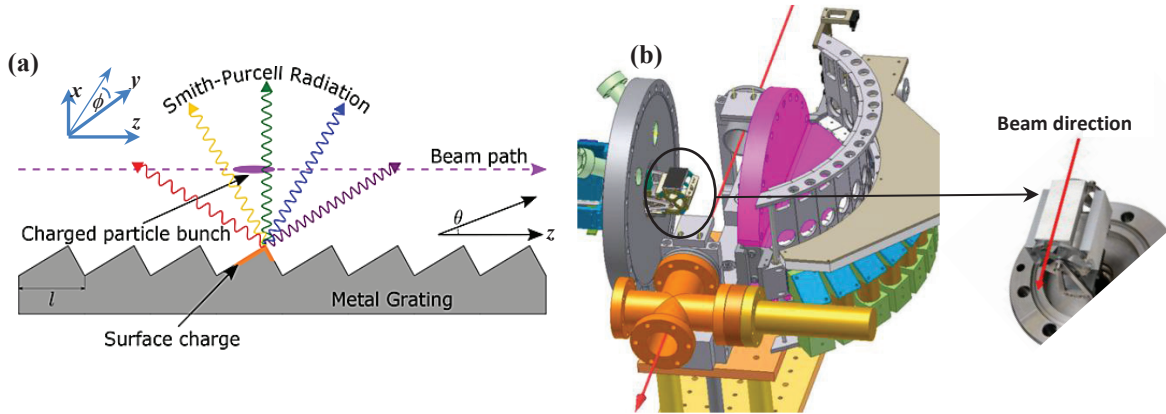


FIGURE 1. (a) Schematic illustrating the SP radiation generation and dispersion by an electron bunch and (b) technical drawing of the E203 experimental chamber with the insertion of a photograph showing a zoom in of carousel with the gratings.

In Fig. 1(a), a schematic of SP radiation generation is shown. The electron is travelling in the z direction, the x axis is the normal to the grating surface and the grooves of the grating are oriented in the y direction. The observation angle θ is the angle between the emitted radiation of a specific frequency and the direction of the electron bunch in the x - z plane, while the azimuthal angle (ϕ) is defined to be zero when the observer is in the x - z plane and ϕ is measured along x - y plane; the origin of the coordinate system is assumed to be at the centre of the grating (Eq. (1) is valid for observation in the x - z plane ($\phi=0$)) and the observer is at 'infinity.' In this case the radiation measured at a specific angle is essentially monochromatic at a given observation point, with a natural line width $1/(nN)$ determined by the number (N) of grating periods.

Study of coherent Smith-Purcell radiation (cSPr), with the aim to explore the possibility of designing a single shot bunch profile monitor was conducted at FACET SLAC [5,6]. The research at FACET was also driven by the goal to develop a reliable technique to determine the missing phase of the signal and retrieve the temporal profile of

the electron bunches using coherent SP radiation. The technical drawing of the set-up is shown in Fig. 1(b). The length of the monitor along the beam line was around 50 cm, and it consisted of a vacuum chamber, a carousel with 3 gratings and a blank, and a system of output optics including the array of the detectors. The gratings and blank were interchanged sequentially, and the measurement of radiation spectrum was averaged over approximately 100 bunches in order to determine an “average” bunch profile [6]. The carousel (insert to Fig. 1(b)) allowed a simple change of the gratings without interrupting the accelerator operation. Each grating covered a specific frequency band, with wavelengths ranging from 1.5 mm to 20 μm (Fig. 2(a)). The gratings and a blank were made from the same material and had identical dimensions (40 mm \times 20 mm \times 5 mm). The blank was used to measure background radiation, which was caused by coherent diffraction/transmission radiation generated upstream of the chamber and due to finite dimensions of the gratings.

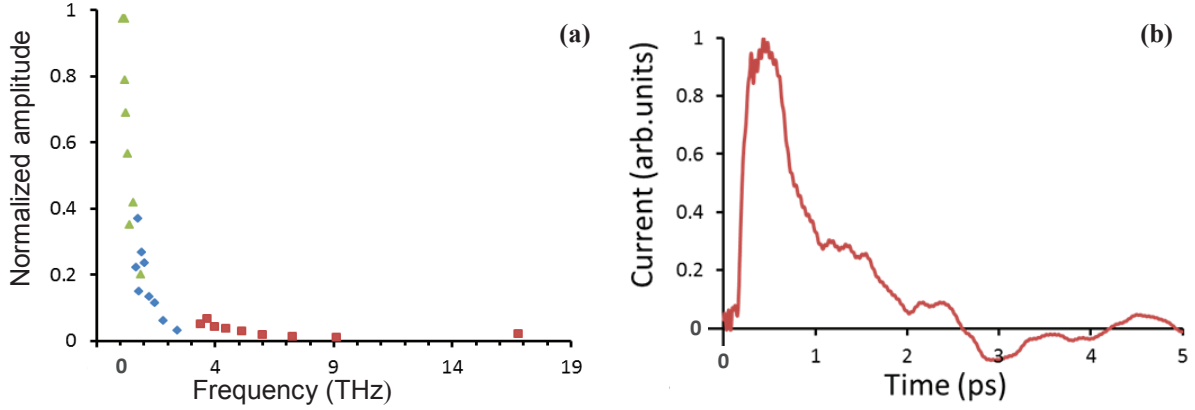


FIGURE 2. (a) The spectrum of cSPr measured from 3 gratings with different periodicity: 1.5 mm (green triangles); 0.5 mm (blue diamonds) and 0.05 mm (red squares). (b) Result of profile reconstruction using the Kramers–Kronig (KK) relation and spectral data shown in Fig. 2(a). (see [5,6] for details)

To measure the spectrum of cSPr, the background signal measured when using the blank should be subtracted from the signal measured when using the grating. In Fig. 2(a), a spectrum measured during the studies of cSPr at FACET, SLAC is shown. It was measured using 3 gratings with different periodicities: 1.5 mm, 0.5 mm and 0.05 mm, and subtracting background signals measured from the blank in corresponding frequency ranges. Using spectral data and applying the Kramers–Kronig (KK) relation [5,6], the phase was recovered and the bunch profile was reconstructed (Fig. 2(b)). Typical features of the profile reconstruction using the KK relation are shown in Fig. 2(b): the presence of unphysical oscillations in the pulse tail, and a sharp rise of the pulse front. Indeed, the problem of retrieving the phase of a signal from a measurement of its power spectrum alone is well known, and has been under investigation for a few decades. It is known that some information about the missing phase can be retrieved from the so-called ‘minimal’ phase ($\theta_m(\omega)$) using the KK method:

$$\theta_m(\omega) = \frac{2\omega}{\pi} \int_0^\infty \frac{\ln(\frac{\rho(\omega')}{\rho(\omega)})}{\omega'^2 - \omega^2} d\omega', \quad (3)$$

where $\rho(\omega)$ is the magnitude of the Fourier transform of the measured signal. Although there are conditions where the minimal phase is adequate, this is not always the case because of the existence of additional contributions, known as the Blaschke phase [11, 12]. Iterative methods [7, 13–15] were designed to resolve this issue, and can give stable and unique solutions for 2D and 3D cases. It is known, however, that the problem is still unresolved in 1D case, such as the determination of the time profile of ultra-short bunches of charged particles.

To improve the bunch profile reconstruction technique, a new algorithm (PCI) was developed. The new algorithm [15] generates the most probable solution, with iterations always converging to a single solution. It is based on a combination of the minimal phase θ_m and an iterative procedure (with repeated iterations between the frequency and time domains), giving the name to the new algorithm a *phase-constrained iterative* (PCI) algorithm. In addition to the minimal phase, it is assumed that the power spectrum is known on the whole frequency domain, initially from measurement, and then from interpolation and extrapolation. The Blaschke phase contribution (if it exists) is a monotonically increasing function of frequency, and thus θ_m provides a *lower limit* for the estimate of the phase, and the integral value F of the function (could be considered as a total charge of the bunch) is also used as

an iteration stopping condition monitoring the convergence to the solution. At each iterative step, the convergence of the solution is monitored using two inequalities, representing the relative and absolute integral errors respectively:

$$\frac{1}{F} \left(\int_0^T |f_{n+1}(t) - f_n(t)| dt \right) \leq \varepsilon_1 \quad (4)$$

$$\frac{1}{F} \left(\int_0^T f_{n+1}(t) dt - F \right) = \delta_{n+1} \leq \varepsilon_2 \quad (5)$$

Here, F is the independently known value of the integral of the target function $f(t)$, ($F=1$ for a charge-normalised distribution), $\varepsilon_{1,2}$ are the predefined acceptable errors appropriate for a specific experiment, and $\varepsilon_{1,2} \ll 1$. The Eq. (4) is an indication that the algorithm is converging to a solution, and (5) gives an indication of the likelihood that the solution is correct. We note, however, that displacements along the time axis, mirror imaging of the temporal profile or equivalently the sign of the spectral phase cannot be determined unambiguously. Figure 3(a) shows the reconstruction of an experimental bunch profile from its frequency spectrum measured at FACET SLAC and shown in Fig. 2(a). Comparing Fig. 3(a) (dashed-dotted line) and Fig. 2(b), one notes that there is no erroneous oscillations observed previously in the pulse tail and also the pulse rise is more smooth. It is clear that the conventional iterative algorithm failed to reconstruct the pulse. Figure 3(b) shows another example of PCI being used to reconstruct a complex synthetic function consisting of the superposition of two Gaussians. The new algorithm performs better compared to the conventional phase recovery techniques in terms of execution time and robustness.

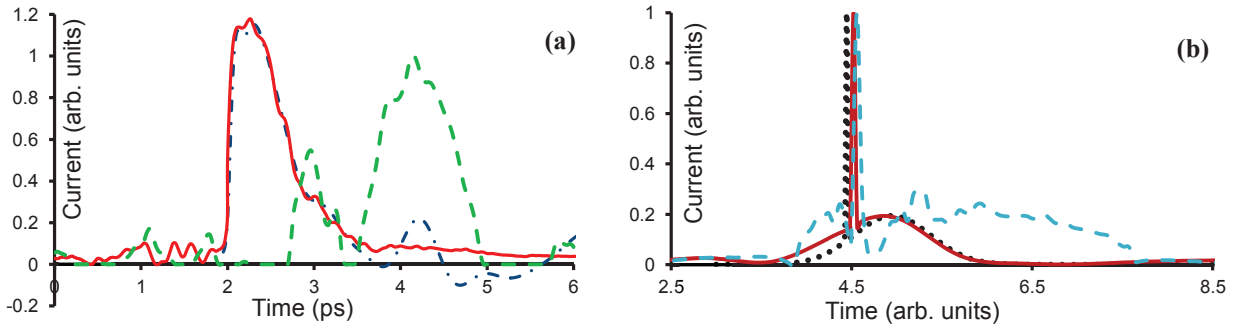


FIGURE 3. (a) The result of profile reconstruction using spectral data measured (Fig.2(a)) and applying: phase constrained (solid line), KK (dash-dotted line) and conventional (dashed line) iterative algorithms. (b) Reconstruction of synthetic function (dotted line) using phase constrained (solid line) and conventional (dashed line) iterative algorithms (see [15] for details).

PRELIMINARY STUDIES AT LUCX KEK AND CONCEPTUAL DESIGN OF SINGLE SHOT BEAM PROFILE MONITOR.

As continuation of the development of the single shot monitor design based cSPr, it was necessary to investigate properties of cSPr that had not been studied or the studies were not completed at FACET by the E203 experiment especially into polarization and directionality. From 2016 experimental work has been carried out at LUCX KEK, Japan using 8 MeV, low charge (50 pC) electron beam [16, 17]. The results demonstrated the possibility of using Schottky-diode THz and sub-THz detectors available on the market to measure cSPr from such low charge and energy beams. The studies have also confirmed and demonstrated that cSPr has a high degree of polarization (in good agreement with theoretical predictions), which can be used to differentiate it from background radiation, which has previously been shown to have a negligible degree of polarization [6, 16]. It was also clear from the experiments that cSPr is directional along the azimuthal coordinate i.e. in plane perpendicular to beam propagation. Using these features of Smith-Purcell radiation (i.e. polarization and directionality), the conceptual design of the monitor presented in Figs. 4(a) and 4(b) was developed. In Fig. 4(a), a 3D drawing that shows the position of the gratings with respect to the beam and output signal ports is shown. The gratings (3 shown in the figure) are positioned sequentially along a cylindrical surface with the electron beam line as an axis of the cylinder, i.e., the gratings are displaced longitudinally and azimuthally along the beam line. The gratings are located at different angles to each other to ensure that the signal from each grating only reaches its corresponding set of detector ports. Each grating will have a dedicated set of filters, splitters and polarizers, as shown in Fig. 4(b). This will allow for the specific design and tuning of all components for the given frequency range which should improve the overall performance of the monitor compared with the E203 setup. Displacing the gratings azimuthally, while keeping them along the beam

path, maintains the compactness of the monitor and, for the setup, shown its footprint should be around 10-20 cm longer as compared with the original E203 design.

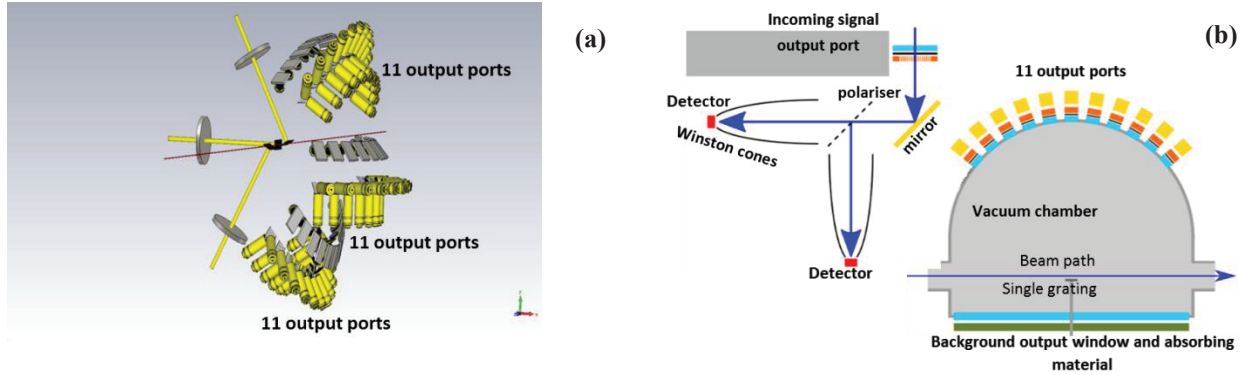


FIGURE 4. (a) The drawing of the conceptual design of the single short SP monitor gratings located around the beam line (dark red line) and 33 ports with two detectors per port to enable the measurements of degree of polarization of the received signal. (b) Schematic diagram of a single grating and its corresponding detection ports, showing the electron beam trajectory and the EM radiation's path to the detectors.

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