FIRST MEASUREMENTS OF THE LONGITUDINAL BUNCH PROFILE AT SLAC USING COHERENT SMITH-PURCELL RADIATION AT 28GeV

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Abstract

Coherent Smith-Purcell radiation has been demonstrated as a technique for measuring the longitudinal profile of charged particles bunches in the low to intermediate energy range. However, with the advent of the International Linear Collider, the need has arisen for a non-invasive method of measuring the bunch profile at extremely high energies. Smith-Purcell radiation has been used for the first time in the multi-GeV regime to measure the longitudinal profile of the 28GeV SLAC beam. The experiment has both successfully determined the bunch length, and has also demonstrated its sensitivity to bunch profile changes. The challenges associated with this technique, and its prospects as a diagnostic tool are reported here.

INTRODUCTION

Colliding bunches of charged particles experience strong electromagnetic fields from opposing bunches, which leads to instabilities at the interaction point and a variety of other effects that result in a loss of luminosity [1]. The longitudinal bunch profile plays a significant role in these effects, and is an important parameter to measure in future high energy accelerators such as the International Linear Collider (ILC).

The essential features of a suitable technique are: a) *non-invasiveness*, b) *single shot* capability, *i.e.* requires only one pass of the bunch, c) determination of the bunch length *and profile*.

Smith-Purcell radiation satisfies all the above requirements; in addition it is passive, compact, and inexpensive.

Coherent Smith-Purcell Radiation

Smith-Purcell (SP) radiation belongs to a wider range of radiative processes that includes transition and diffraction radiation. It was discovered in 1953 by Smith and Purcell [2], and has since been proposed as both a possible source of tunable far-infrared radiation, and as a non-invasive technique for measuring the time profile of short, highly relativistic, charged particle bunches.

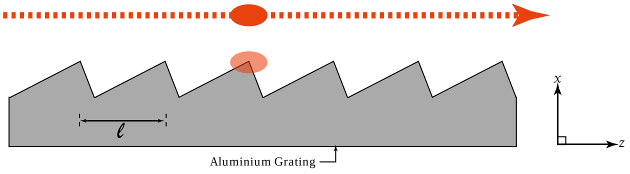

Figure 1: A bunch of charged particles travel above a metallic grating of period l, inducing a surface current which emits SP radiation. The emitted wavelength depends on the angle of observation.

SP radiation is generated when a charged particle travels above a periodic, metallic, structure such as a grating (figure 1). The bunch induces a *surface charge*, which is then accelerated over the grooves of the grating. This accelerated surface charge emits the radiation we know as Smith-Purcell radiation. For an observer at infinity, the wavelength produced is given by,

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

where l is the grating period, n is the order of radiation, θ is the observation angle, β is the relativistic factor $\beta = \frac{v}{c}$, and v is the velocity of the particle.

Coherent SP radiation occurs when the bunch length is *shorter than, or comparable to* the emitted wavelengths. In this situation, the emission due to each particle occurs in phase. In the coherent regime, a bunch of N particles produces radiation whose radiated intensity is $\propto N^2$, and whose spectral distribution depends on the time profile of the bunch. It is thus possible to use coherent SP radiation for longitudinal bunch profile diagnostics.

A clear advantage of Smith-Purcell radiation is that, by a suitable choice of the grating period (eq. 1), the radiation can be shifted into the coherent regime. Also, due to the angular dispersion of wavelengths, a single-shot measurement is possible by detecting at multiple angles simultaneously.

EXPERIMENTAL TECHNIQUE

At SLAC the SP wavelengths produced are in the far-infrared, which itself poses a number of challenges [3]. The equipment used can be seen in figure 2.

Elimination of Background Radiation

Removing background radiation was an essential part of the system. Radiation from an aluminium grating is compared with radiation produced by a 'blank' (non-periodic) piece of aluminium of identical dimensions. The difference between these two measurements will only arise from the periodic structure itself, and thus must be Smith-Purcell radiation. To this end, three gratings of different periodicity (0.5, 1, 1.5mm) are mounted on a carousel-like structure

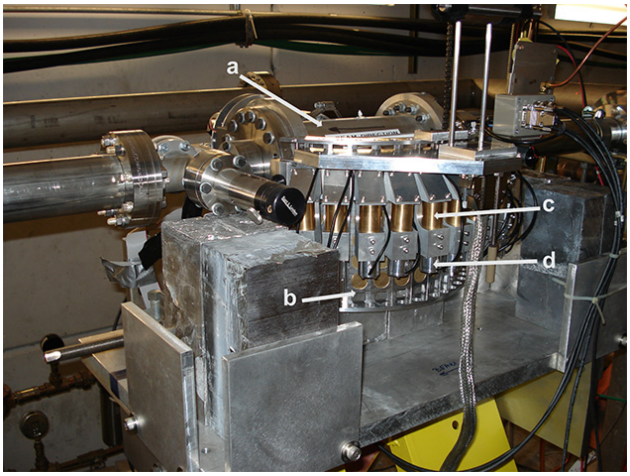

Figure 2: Experimental equipment used at SLAC: (a) vacuum chamber with quartz window, (b) filter changing mechanism, (c) Winston cones, (d) pyroelectric detectors.

along with a 'blank'. This can be rotated remotely during the experiment, so that the comparison between radiation seen from the grating and blank, can be carried out swiftly. The wavelength distribution of the radiated energy was determined from simultaneous measurements from 11 pyroelectric detectors, covering the angular range 40 — 140°. The use of different period gratings expands the range of wavelengths that can be detected, and aids in bunch profile identification.

Optical System

Radiation is collected via a light concentrator (or Winston cone), after passing through a Waveguide Array Plate (WAP) filter associated with the expected SP wavelength. This further discriminates against background radiation.

WAP filters are designed for a specific wavelength, and efficiently remove all other wavelengths outside of a narrow acceptance region. Since different observation angles see different wavelengths (which also depends upon the grating period), many of these filters are required. At SLAC they were mounted upon a special mechanism that inserted the appropriate filter for a given grating and observation port.

RESULTS

The experiment was carried out in End Station A at the Stanford Linear Accelerator Centre (ESA, SLAC) in July 2007. The beam used has the following properties:

- Beam energy = 28GeV.
- Bunch charge = 1×10^{10} — 1.6×10^{10} electrons.
- Single bunch, 10Hz operation.
- Beam position above grating $\sim$ 3mm.

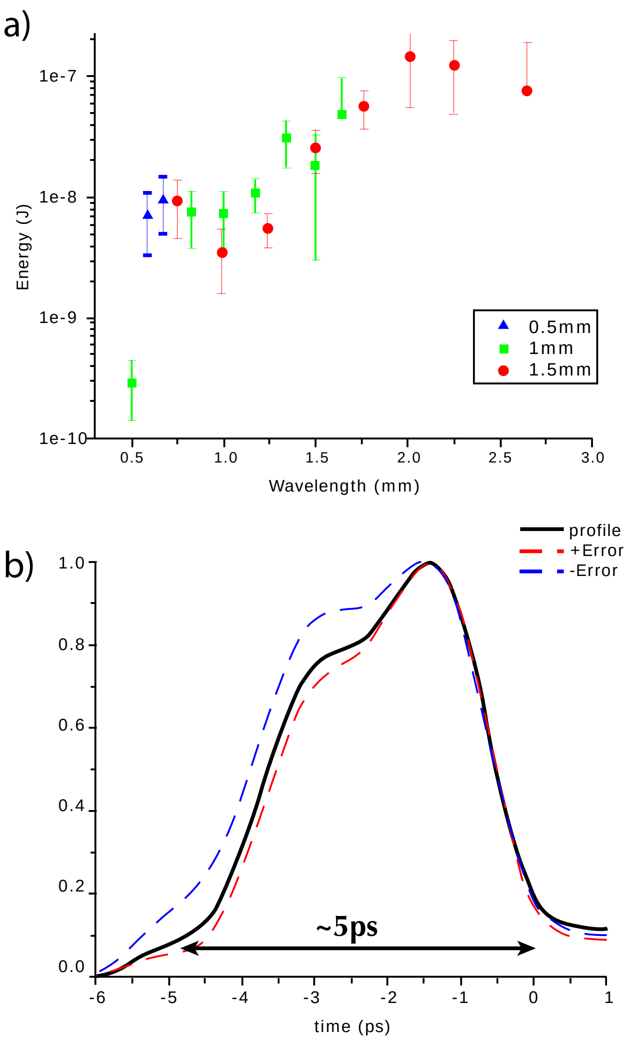

Figure 3: (a) Data from 18/07/07, 2:05 – 2:30am, (b) Kramers-Kronig reconstruction of the bunch profile.

- Beam size above grating: $\sigma_x = 492\mu$m, $\sigma_y = 138\mu$m.

Data was taken over a period of 1 minute ($\sim$600 bunches) for each grating (plus blank). One full cycle of measurements takes typically 30 — 40 minutes, however this could be improved upon.

It should be noted that some processing of the data is required before the bunch profile can be retrieved. For example, various correction factors must be applied so as to account for filter transmission losses, reflection losses, detector calibration and so on. The application of these corrections is outside the scope of this paper.

The bunch profiles shown here were reconstructed by means of the Kramers-Kronig phase retrieval method [4].

The Longitudinal Bunch Profile at SLAC

The longitudinal profile was measured over many hours at SLAC, and has been observed to change with time. Significantly different bunch shapes can be observed that are separated by only a few hours. These changes in the bunch

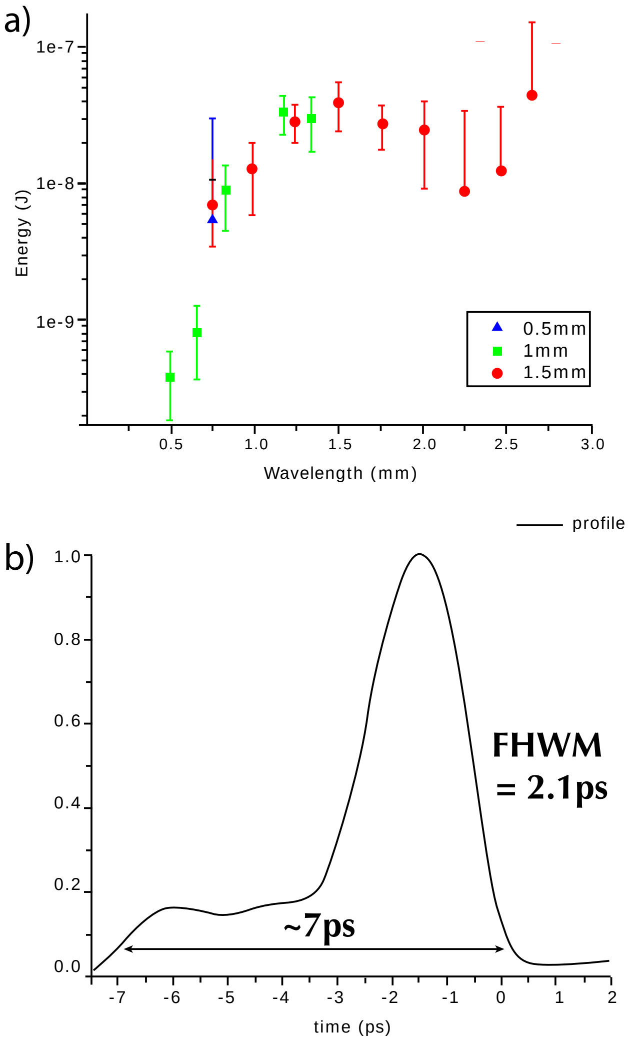

Figure 4: (a) Data from 18/07/07, 6:25 – 6:58am, (b) Kramers-Kronig reconstruction of the bunch profile.

length are consistent with to changes in the bunch length indicator in ESA. Two measurements, taken 4 hours apart from each other, are shown in figures 3 and 4. The dotted lines in figure 3 correspond to the Kramers-Kronig reconstruction of the bunch profile using the maximum and minimum energy as given by the error bars (fig. 3a). A higher energy results in a slightly shorter bunch, and a lower energy results in a slightly longer bunch, as expected.

In addition, short term changes in the bunch profile can be observed in the space of a minute. One of these occasions is shown in figure 5, where changes in the signal measured at 80 — 100° (*i.e.* in the spectral distribution of radiation) are clearly observable. This indicates that SP radiation is highly sensitive to the bunch profile at SLAC.

CONCLUSIONS

Coherent Smith-Purcell radiation has been successfully used to determine the longitudinal bunch profile and length

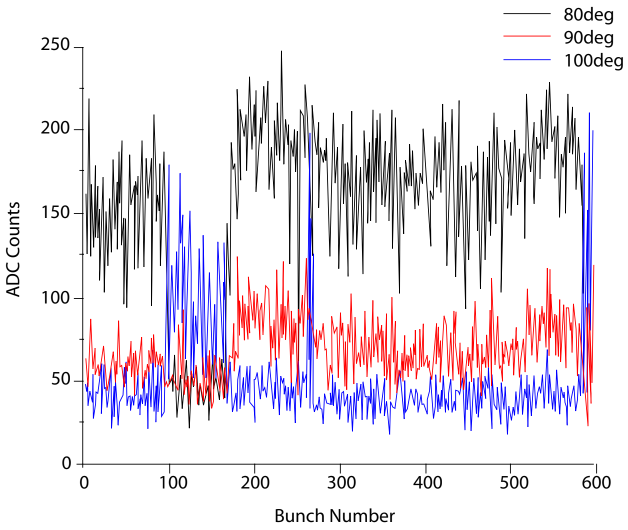

Figure 5: The bunch profile can be seen changing over a one minute period (between bunches 100 – 200). The 80, 90 and 100° angles shown here are most sensitive to bunch profile changes.

of bunches at SLAC, and has shown itself to be a sensitive diagnostic tool.

The bunch profile observed at SLAC is not a straightforward Gaussian profile, but has a more complex structure; it is, therefore, inappropriate to define the bunch length in terms of a single σ value. If we redefine 'bunch length' to be the points at which the profile falls off to 5% of its peak height, then the observed bunch lengths are within the range 4 — 7ps, in line with independent measurements [5]. Note, however, in figure 4, most of the bunch particles are within an approximately Gaussian spike, with FWHM $\simeq$ 2ps.

ACKNOWLEDGMENTS

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