OBSERVATIONS OF THE LONGITUDINAL ELECTRON BUNCH PROFILE AT 45MeV USING COHERENT SMITH-PURCELL RADIATION

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Abstract

Coherent Smith-Purcell (SP) radiation has been used to determine the longitudinal profile of the electron bunch at the FELIX facility, FOM Institute. Far-infrared radiation was detected using a simple, compact arrangement of 11 pyroelectric detectors. Background radiation was suppressed through the use of high quality optical filters, and an efficient light collection system. The measured bunch profile was most closely in agreement with 90% of the particles contained within 5.5ps, with an approximately triangular temporal profile.

INTRODUCTION

The time profile of the bunch is of particular importance with regards to the International Linear Collider (ILC) due to 'beam-beam' effects (see [1], [2]). Colliding bunches of electrons/positrons experience strong electromagnetic fields from the opposing bunch, leading to deflection, beamstrahlung, and emittance growth. A 'pinch effect' can also occur at the interaction point of the accelerator, causing either a reduction or expansion of the beam size.

Beam diagnostic devices are therefore of significant importance for the ILC and X-ray Free Electron Laser's (FEL's), to determine beam size and pulse shape. Invasive methods are no longer sufficient since they cause disruption to the beam, which is undesirable. Thus, new *non-invasive* techniques must be developed. One method of measuring the longitudinal bunch profile in a non-invasive way is by using *coherent Smith-Purcell radiation*.

Smith-Purcell radiation is produced through the interaction of a (relativistic) beam of charged particles with a nearby periodic metallic structure (e.g. a grating) [3] [4]. It belongs to a much wider group of radiative processes (transition, diffraction, etc). As the beam passes close to the grating, it induces surface currents on the face of the grating. This produces radiation with properties of particular promise to this field of beam diagnostics:

1. The emitted intensity is proportional to the number of periods on the grating.
2. The period of the grating can be matched to the expected bunch length in order to exploit *coherence effects*.
3. The wavelength of the emitted radiation is angularly distributed — i.e. all wavelengths can be collected by changing the angle of observation.

For an observer at infinity, in the plane that is perpendicular to the grating and contains the beam direction, the relationship between emitted wavelength (λ) and observation angle (θ) is given by the Smith-Purcell equation:

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

where l is the period of the grating, n is the order of emitted radiation, $\beta = \frac{v}{c}$, and v is the velocity of the particle. The wavelengths emitted depend on the periodicity of the grating and in most cases, the radiation is in the far-infrared part of the spectrum.

Coherence effects become dominant when the bunch length is shorter than, or comparable to, the wavelength of emitted radiation. In the coherent regime, the emitted power is enhanced by a factor of N_e, where N_e is the number of electrons in the bunch.

The experiment reported here was carried out at the FELIX facility, FOM Institute, Holland, with the following beam parameters:

- Bunch spacing: 1ns,
- Electrons/bunch: 10^9
- Beam energy: 45MeV,
- Bunch train duration: 5μs.

RECONSTRUCTION OF THE BUNCH SHAPE

Reconstruction of the bunch shape requires the determination of the radiated power over as wide a wavelength range as possible. The experimental arrangement can be seen in figure 1, and further information on the equipment used can be found in [6].

The radiated energy per solid angle is proportional to the square of the magnitude of the Fourier transform of the time profile, $T(t)$ of the bunch:

$$\frac{dI}{d\Omega} \sim \left|\int_{-\infty}^{+\infty} T(t)e^{-\imath\omega t}dt\right|^2 \tag{2}$$

Thus, measuring the radiated energy allows reconstruction of the bunch shape.

Extracting the Smith-Purcell Signal

Precautions were needed to effectively separate Smith-Purcell from 'background' radiation, where 'background'

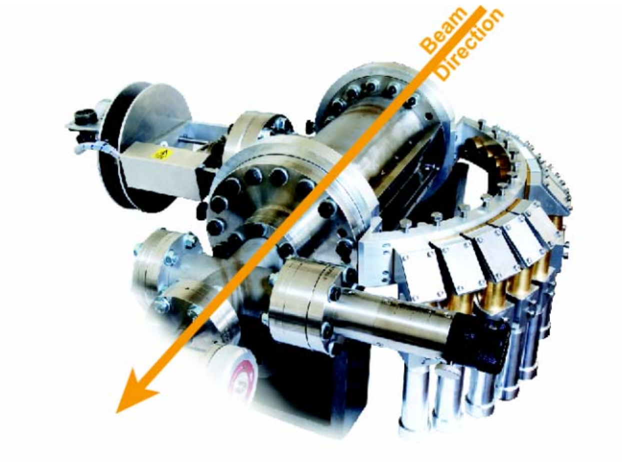

Figure 1: The equipment used in this experiment, including the vacuum chamber (which contains the metallic gratings), crystalline quartz window, and optical system with detectors.

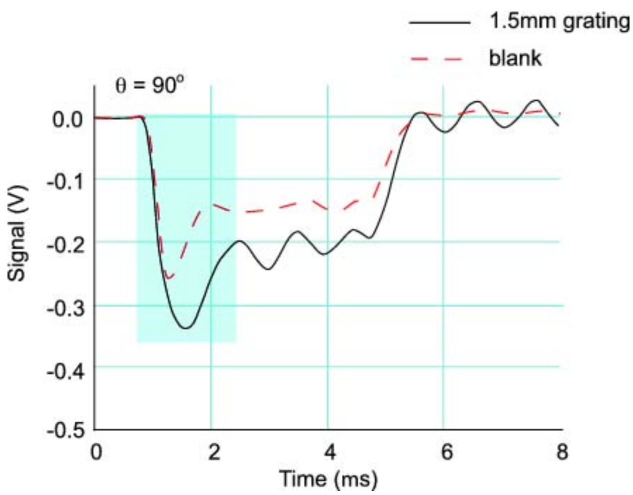

Figure 2: (a) A typical detector output (shaded area is due to X-ray interactions), (b) an unfiltered, filtered, and transmission-corrected filtered signal.

refers to all radiation that does not originate from the periodic structure itself. The first line of defence in discriminating against background radiation was the use of a *'carousel'* of three different period aluminium gratings and one blank (with the same physical dimensions). This could then be rotated by 90° during the experiment, with signals measured with both a grating and the blank. Combined with the optical system it was possible to remove background radiation and arrive at the true SP signal by simple subtraction of the blank signal from the grating signal.

Figure 2 shows a typical detector output, with the shaded area almost entirely due to X-ray interactions with the detector electronics. To minimise their influence, the signal was taken to be the average value between 3 and 4μs.

A variation in detector output of ± 5mV was measured under nominally identical conditions. Therefore, signal levels below 5mV were discarded as unreliable.

Correction Factors

It has already been mentioned that, in order to extract the true Smith-Purcell signal, it is necessary to take into account the power transmission characteristics of the filters. However, there are other loss mechanisms that must be taken into account:

- Losses in the optical system;
  - Incurred through the 0.5mm separation of the light concentrator and the detector,
  - Due to reflection from the surfaces of the crystalline quartz window and its high refractive index ($n = 2.1$),
  - The effective length of grating seen at each observation angle,
- Inaccuracies in grating position,
- The relative efficiencies of the detectors.

'Template' Distributions

The *expected* power-wavelength distribution of SP radiation for different bunch profiles, can be predicted through a number of theoretical models. Figure 3 shows the distributions as predicted by the *surface current model* [5]. Throughout this paper, *'bunch length'* is defined as *containing* 90*% of the particles*.

The power-wavelength distribution, as predicted by the surface current model for a number of simple profiles, therefore acts as a *'template' distribution*, which can be compared to the real data. Through this, it is possible to identify the closest match. However, it is important to note that this method does *not* give a *unique* determination of the longitudinal profile. Alternative methods of extracting the bunch profile are currently being considered.

The Measured Longitudinal Profile

Figure 4 shows the combined data points from the three gratings, plotted against wavelength, for order $n = 1$. Data points falling in the shaded area correspond to detector outputs of < 5mV, and are excluded both from this plot and from the analysis. First the data is fitted with a Gaussian bunch profile with a bunch length of 5.5ps, and second with a triangular profile, which is slightly asymmetric with respect to the reference particle. A bunch length of 5.5ps corresponds to a standard deviation of 1.6ps for a Gaussian distribution. However, it can clearly be seen that the bunch shape is *not* Gaussian, but most closely approximates the triangular profile. Thus, the longitudinal profile measured at the FELIX facility, FOM Institute, most closely matches an asymmetric triangular bunch profile, with 90% of the particles within 5.5ps.

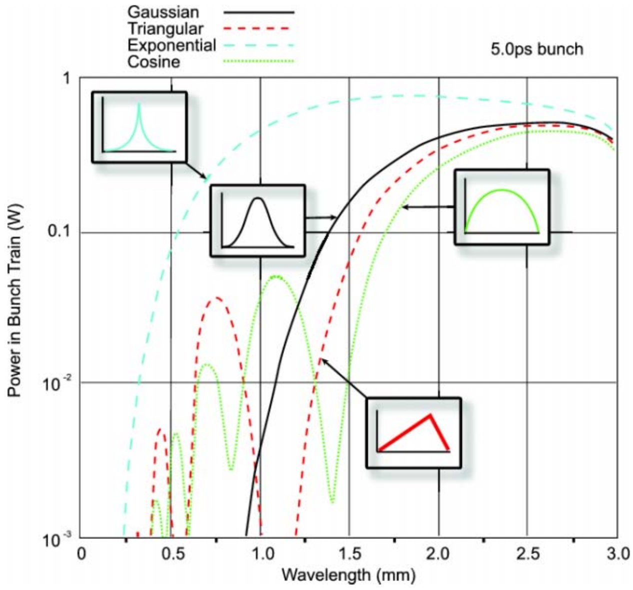

Figure 3: Template distributions for different bunch shapes based on a bunch length of 5ps, calculated using the surface current model.

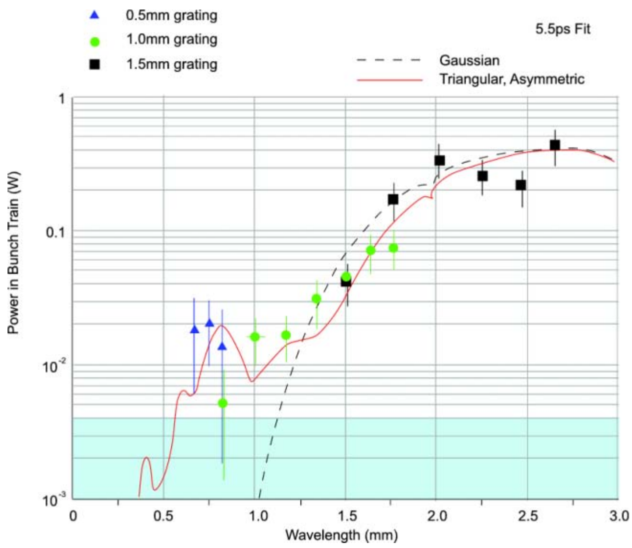

Figure 4: The power-wavelength distribution of Smith-Purcell radiation compared to a Gaussian and triangular longitudinal profile with a bunch length of 5.5ps.

SUMMARY

Coherent Smith-Purcell radiation has been used to determine the longitudinal profile of a 45MeV electron beam at the FELIX facility, FOM Institute. This experiment extended previous work on coherent Smith-Purcell radiation by a factor of 10 in energy, and a corresponding factor of 3—5 towards shorted bunch lengths. It successfully demonstrated that pyroelectric detectors are an effective low-cost, room temperature alternative to cryogenic detectors. The use of pyroelectric detectors also made possible the simple, robust experimental arrangement that was used. Background radiation was successfully suppressed by means of a carefully designed optical system (as detailed in [6]). Additionally, the measured power levels were entirely in line with the predictions of the surface current model.

The bunch profile was determined by applying various 'template' distributions to the measured data, and finding the closest match. It is concluded that the profile could be an (asymmetric) triangular profile, with 90% of the particles within 5.5ps.

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