ELECTRON BUNCH SHAPE DETERMINATION BY COHERENT SMITH-PURCELL RADIATION

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Abstract

The angular distribution of coherent Smith-Purcell radiation, produced from the interaction of a 4.75 MeV electron beam with a metallic grating, has been used to infer the longitudinal profile of the electron bunches of the Frascati Microtron. The emitted radiation is in the far infrared and the various wavelengths were collected by varying the angle of observation over the range of 40° to 140°. The radiated power levels were of the order of 100 mW and agree well with the description of the process in terms of surface currents induced on the grating profile. It is concluded that the bunch has an approximately triangular profile, with 80% of the particles contained within 16ps. The technique offers interesting possibilities as a non-intercepting diagnostic tool for the determination of bunch shapes, with minimal disruption to the beam.

1 INTRODUCTION

The next generation of high-energy electron accelerators, Linear Collider and X-ray FEL's, will require beam diagnostic techniques for beam size and pulse shape measurement that are not only sensitive but, also, do not intercept the beam. Radiative processes from the beam itself, such as diffraction radiation (DR) [1-4] or Smith-Purcell radiation (SPR) [5] are likely to play an important role. The latter is the radiation produced from the interaction of the beam particles with a periodic structure, such as a metallic grating. Although the beam itself does not impinge on the grating, the induced surface currents on the periodic structure produce radiation with some interesting and, potentially, useful properties: (a) The emitted intensity is proportional to the number of periods of the grating, hence it is strong compared to, say, diffraction radiation. (b) The wavelength region can be selected through an appropriate choice of grating period (c) The observed wavelength depends on the angle of observation; hence, almost all the emitted wavelengths can be collected by changing this angle. (d) Through a suitable choice of the blaze angle of the grating it is possible to direct the radiation pattern away from the direction of the electron beam, allowing easy observation. Although some of the above features occur in other processes as well, SPR is the only one that combines all of them together.

The basic relationship that connects the angle of observation θ to the emitted wavelength λ and to the period of the grating *l* is:

$$n\lambda = l(1/\beta - \cos\theta)$$

In the above expression, β is the relativistic velocity and *n* is the order of emission. The spontaneous (or incoherent) power is enhanced greatly by coherence effects. These become dominant when the length of the bunch is comparable to the wavelength of the emitted radiation. In this case, the angular distribution of the radiation will become critically dependant on the longitudinal profile of the bunch. The important quantity then is the, so-called, 'coherent integral' S_{coh} defined by:

$$S_{coh} = \left| \frac{1}{\sqrt{2\pi}\sigma_x} \int_0^{\infty} e^{-\frac{x}{\lambda_e}} e^{-\frac{(x-x_0)^2}{2\sigma_x^2}} dx \right|^2 \left| \frac{1}{\sqrt{2\pi}\sigma_y} \int_{-\infty}^{\infty} e^{-ik_y y} e^{-\frac{(y-y_0)^2}{2\sigma_y^2}} dy \right|^2 \left| \int_{-\infty}^{\infty} e^{-i\omega t} f(t) dt \right|^2$$

where *f(t)* in the last integral is the distribution of the particles in the time domain. It is assumed that the profile of the bunch in the other two directions (x and y) is Gaussian. It is possible, therefore, to determine this profile by measuring the angular distribution of the radiation and then comparing it to what is expected theoretically from a number of plausible longitudinal profiles, i.e. functions *f(t)*. Details of the calculation of the induced surface current and the radiated power for the one-electron case are given in [6].

We report on the results of recent 'proof-of-principle' experiments carried out at the ENEA facility at Frascati, Rome that demonstrate the potential of coherent SPR as a non-intercepting diagnostic tool for the determination of the time profile of picosecond electron bunches.

2 EXPERIMENTAL

The experiments were carried out at the ENEA Laboratory, Frascati, using the Microtron accelerator, which is capable of delivering beams at discreet energies between 1.8 and 5 MeV, in steps of 0.8MeV.

2.1 Beam parameters and grating

All the experiments reported here were carried out at 4.75 MeV (γ=10.29). The pulse structure of the accelerator consists of approximately 15ps long bunches, spaced 333ps apart. The pulse train duration is 5µs and the average current in the pulse train was, typically, 100mA; hence, each bunch contains about 2.1x10^8 electrons. The normalized emittance of the beam is approximately 50πmm.mrad and the repetition rate about 1Hz. The size of the beam waist at the centre of the grating was about 1mmx2mm. Its position above the grating surface varied between 1 and 2mm. The grating had a profile consisting of two facets, one at a blaze angle of 14^o relative to the beam direction and the other vertical to the first. Its period was 2.5mm, its overall length 100mm and its width 20mm. It was mounted on an insulated support so that any current intercepted could be measured.

2.2 The optical system

The optical system collects the emitted radiation and transports it to the detector. It has been designed for easy variation of the angle of observation (i.e. wavelength) and for efficient collection of light over a wide range of emission angles. It is shown in schematic form in fig. 1.

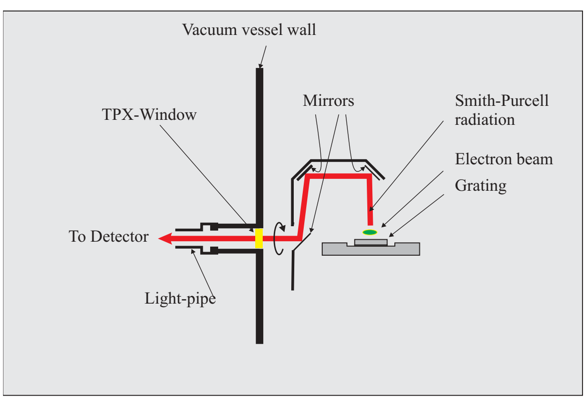

Figure1: Schematic of light-collection system

It consists of three gold-plated copper mirrors, held together in a rigid frame and rotating as a unit around a *y*-axis, through the centre of the grating. The range of angles accessible by the unit lies between 30^o and 170^o. The system is also capable of collecting light at azimuthal angles ϕ up to 30^o, but all the measurements reported here were carried out at ϕ=0^o, with respect to the normal to the grating surface. The maximum solid angle of the system is limited by the last mirror and is equal to 0.05sr. At a given position of the 3-mirror frame, there is a range of emission angles θ that can be collected by the mirrors and transmitted, typically about ±14^o. As the 3-mirror assembly rotates, the effective length of the grating and the range of emission angles accepted by the system, change. For example, when the frame is positioned at 90^o, values of θ between 76^o and 104^o are accepted and the effective grating length is 40mm; this rises to about 70mm at 40^o. Radiation is extracted from the side of the vacuum chamber and, by means of a copper light pipe, is taken to the detector. The light pipe is separated from the vacuum chamber and from the outside world by TPX windows and can be evacuated in order to reduce absorption by the atmosphere; this has not been necessary for the wavelengths reported here. The transmission efficiency of the optical system was determined to be 0.65±10%

2.3 The detector

An InSb electron bolometer, cooled to liquid helium temperature, was used to detect the radiation emerging from the window at the end of the light pipe. The detector was placed behind a screen of lead blocks, in order to reduce the bremsstrahlung background, and was calibrated using an optically pumped far-infrared laser and millimetre wave sources of known power. Its responsivity is 1500V/W at λ=0.6mm, rising to 2250V/W at about λ=2mm and is approximately flat thereafter. Its response time is less than 0.5µs. To avoid saturation of the detector, calibrated mesh filters were employed to attenuate the signal. These had the further property of strongly attenuating unwanted longer wavelength radiation, which was also transmitted by the light pipe and detected by the bolometer. A Fabry-Perot interferometer, using wire mesh mirrors, was occasionally placed between the exit of the light pipe and the detector, in order to check the wavelength of the radiation. However, all the measurements reported here were taken without the use of the Fabry-Perot, by simply rotating the 3-mirror assembly to scan the emitted wavelengths and using a 400 lines/inch mesh filter in front of the detector to reduce the background radiation.

3 RESULTS AND DISCUSSION

The signal from the detector was corrected for the known transmission efficiency of the 400 mesh filter at that particular wavelength and, also, for the transmission efficiency of the optical system. All measurements were normalized to a beam current of 120mA. An independent measurement of the power arriving at the detector was obtained by replacing the InSb bolometer with a pyroelectric detector of known responsivity, with the mirror assembly positioned at 100^o. A figure of 109mW was obtained. The measurements at all other angles were normalized to this value. The experimental points are plotted in figure 2. Also plotted on the same figure are a number of theoretically expected angular distributions of radiated power, derived on the assumption of a particular shape *f(t)* for the longitudinal profile of the bunch. We have considered Gaussian, exponential, triangular, parabolic and cosine-like profiles, although not all of the above are plotted in the figure. The derivation of these curves is based on the treatment of SP radiation in terms of induced surface currents on the periodic structure [6] and begins with an estimate of the specific power output

(W/sr/cm), including the pulse-dependent coherence effects. The geometric properties of the light collecting system, such as solid angle and effective grating length, are then taken into account. These are calculated, multiplied by the specific power and added together for each wavelength that can be collected by the rotating mirror assembly, in order to give the total power, in W, entering the light pipe at that particular position of the mirror assembly. This can then be compared directly to the measured values. In order to deal with pulse shapes that may not be symmetric with respect to the peak particle in the bunch, we have introduced an 'asymmetry factor' ε, which is defined as the factor by which the length of the pulse for t<0 differs from that for t>0 (ε=1 defines a symmetric pulse).

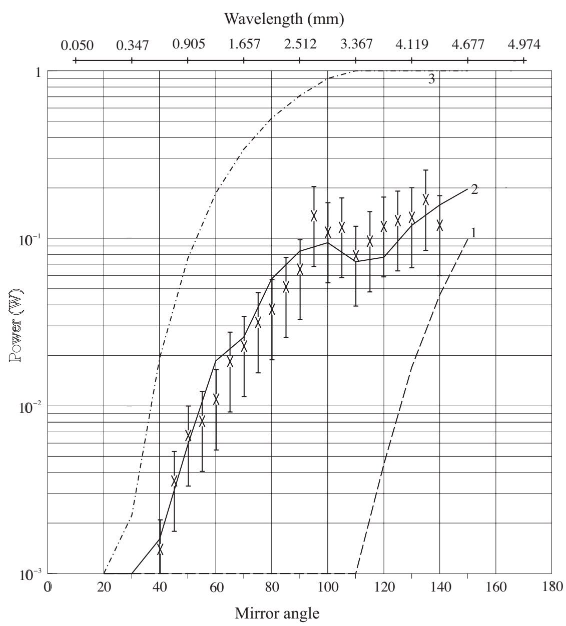

Figure 2. Experimental data fitted with various longitudinal profiles. 1: Gaussian, 2: triangular and 3: exponential (see text for details).

Plausible values for the asymmetry factor ε have been explored. All three curves of fig.2 contain about 80% of the bunch particles within 16ps and have been calculated on the assumption that the centroid of the beam is 2mm above the grating surface. The experimental points are well below the predictions of an exponential shape and above those of a Gaussian. On the other hand, a triangular profile with an asymmetry factor ε=1.4, seems to be in reasonable agreement with the experiment. An interesting feature of this profile, and indeed of all profiles with sharp 'kinks', is the appearance of interference minima, in this case at about 110°. These can be understood, in qualitative terms, as arising from the interference of some of the many harmonics that are bound to exist in the Fourier spectrum of a shape that contains 'kinks'. The degree of asymmetry ε primarily governs the depth of the interference minima. The total error in the power measurements, systematic and statistical, is estimated at about 50%. The appropriate error bars have been placed on the data points. The error in the measurement of the angle is estimated at ±2°.

4 SUMMARY AND CONCLUSIONS

Coherent Smith-Purcell radiation has been used to determine the longitudinal profile of the 4.75 MeV electron bunches of the Frascati Microtron accelerator. The radiated power level peaked at about 100mW, for an observation angle of 100°**,** corresponding to a wavelength of about 2.9mm. The scanned wavelength region extended from about 0.6 to 4.4mm. Comparison of the angular distribution to theoretical predictions, based on a number of plausible profiles, indicates that the bunch profile has an approximately triangular shape, with 80% of the particles contained within 16ps. These results are slightly different to those obtained at lower energy (1.8MeV), when the shape was found to be triangular, but with 85% of the particles inside 14ps. This small discrepancy is probably due to the different operating conditions of the accelerator during the two experiments. We conclude that coherent SP radiation offers an easy and non-intercepting method for the determination of the bunch shape of picosecond and sub-picosecond bunches of relativistic electrons.

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