ELECTRON BUNCH LENGTH DIAGNOSTIC WITH COHERENT SMITH-PURCELL RADIATION

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Abstract

We have designed a new technique for measuring subpicosecond electron bunch lengths using coherent Smith-Purcell radiation. This new diagnostic technique involves passing the electron beam in close proximity of a grating with period comparable to the electron bunch length. The emitted Smith-Purcell radiation will have a coherent component whose angular position and distribution are directly related to the electron bunch length and longitudinal profile, respectively. This new diagnostic technique is inherently simple, inexpensive and non-intercepting. We show that the new technique is also scaleable to femtosecond regime.

1 INTRODUCTION

Many advanced concepts such as the fourth generation light sources and plasma wakefield accelerators depend on the ability to generate a high-brightness electron beam with high peak current. The latter has been obtained via bunch compression in a magnetic chicane.[1] Equally important is the ability to characterize the longitudinal profile of the subpicosecond electron bunches. Streak cameras with sub-picosecond resolution are not only expensive and difficult to operate, they are not scaleable to the femtosecond regime. Alternative methods involve generating coherent transition radiation, coherent undulator radiation or coherent synchrotron radiation.[2] From the measured spectra or autocorrelation curves, information about the electron longitudinal profiles is deduced. In this paper, we discuss the use of coherent Smith-Purcell radiation as a technique for diagnosing electron bunch longitudinal profiles.

Smith-Purcell radiation (SPR) has been studied extensively in the past three decades, mainly as a means of generating short-wavelength radiation from low-energy electron beams.[3] Recently, Ishi et al. reported the first observation of coherent SPR from 50 picosecond electron bunches.[4] Independently, Lampel and Nguyen[5] came up with the idea of using coherent SPR as a diagnostic technique for subpicosecond electron bunches. They predicted the coherent SPR would appear at large angles with respect to the beam propagation, and its intensity would be much higher than the incoherent SPR. This paper explores the capabilities of coherent SPR in measuring femtosecond electron bunches and in detecting microscopic longitudinal density fluctuations.

The schematic of the beam diagnostic module for coherent SPR bunch length measurement is shown in Figure 1. The electron beam coming in from the left is focused to a ribbon beam with a vertical waist at the grating. A collimator is used to confine the beam to a well-defined height above the grating. Two mirrors, one cylindrical and one spherical, act like a 90° paraboloid and focus the coherent SPR to a spot at the detector located outside the diagnostic module. The coherent SPR signals at different angles, provided they are within the acceptance angle of the two curved mirrors, are focused to different positions at the focal plane. A detector array located at the focal plane of the curved mirrors is used to cover a range of observation angles at any given time. Alternatively, the two curved mirrors can be rotated together with the pivot at the grating to cover a larger range of angles.

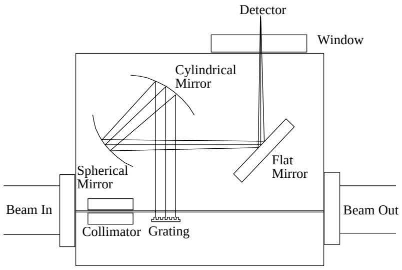

Figure 1. Schematic of the coherent Smith-Purcell radiation bunch length diagnostic module. The detector is at the focal plane of the two curved mirrors.

2 THEORY

When an electron beam passes close to the surface of a metallic diffraction grating, it emits Smith-Purcell radiation (SPR). The SPR wavelength depends on the angle of observation, as given by the well-known dispersion relation,

$$\lambda = \frac{d}{n\beta}(1-\beta\cos\theta)$$

where d is the grating period, n is the diffraction order (in this paper, we will use n=1 order as the higher orders only shift the short-wavelength incoherent SPR to larger angles), β is the usual beam velocity normalized to the speed of light, and θ is the angle of the emitted SPR with respect to the beam propagation direction. When the electron bunch length is less than the SPR wavelength, the radiation emitted by different parts of the bunch add, and the resulting SPR becomes coherent, i.e. its power scales with N^2. Since long wavelengths occur at large angles, the degree of coherent enhancement increases with the angle of observation. The plot of SPR power versus angle thus exhibits high-intensity peaks at large angles. If the electron profile has density modulations at high frequencies, we expect additional coherent SPR peaks to appear at smaller angles but at much higher intensity than the incoherent SPR.

The SPR angular distribution is given by

$$\frac{dP}{d\Omega} = KN\left(1 + f(k)N\right)\frac{\sin^2\theta}{\left(1-\beta\cos\theta\right)^3}e^{-\frac{2\pi h}{\gamma\lambda}}$$

where K is a proportionality constant that includes the electron charge, grating period, order, reflectivity, etc., N is the number of electrons in the bunch, θ is the azimuthal angle of observation, h is the height of the electron beam above the grating, and *f(k)* is the form factor defined by the square of the Fourier transform of the longitudinal density function, $S(z)$

$$f(k) = \left|\int S(z)e^{-ikz\cos\theta}dz\right|^2$$

where $k = 2\pi/\lambda$.

Typical $S(z)$ functions like the gaussian and square distributions have been studied [5]. The corresponding form factors are gaussian and sinc square functions, respectively. Another longitudinal distribution of interest is that of electron beams exiting a wiggler in a free-electron laser (FEL). This distribution is expected to have modulations at the fundamental and odd harmonics of the FEL frequencies.

$$S(z) = \frac{e^{-z^2/2\sigma^2}}{\sigma\sqrt{2\pi}}\left(1 + \sum_{n=1}^{\infty} b_n e^{ink_0\sigma}\right)$$

where σ is the longitudinal rms bunch length. The corresponding form factor is obtained via Fourier transform of the above equation,

$$f(k) \approx e^{-k^2\sigma^2\cos^2\theta} + \sum_{n=1}^{\infty} b_n^2 e^{-(k-nk_0)^2\sigma^2}$$

where b_n is the bunching factor of the n$^{\text{th}}$ harmonic and k_0 is the modulation wavenumber. This expression suggests that with sufficient bunching, e.g. b_n approaching 1, there should be strong coherent SPR signals at the fundamental and odd harmonics of the modulation frequency.

3 CALCULATIONS

To evaluate the temporal resolution of the coherent SPR technique, we performed calculations for a 20-MeV electron beam with 3 different rms bunch lengths, e.g. 40, 60 and 80 microns, corresponding to approximately 120, 180 and 240 femtoseconds. The grating period is 0.8 mm and the beam is a one-dimensional line passing over the grating at a fixed height of 0.1 mm. The number of particles in a bunch is 10^8 (charge ~ 16 pC). The calculated SPR power versus angle is plotted in Fig. 2. As evidenced by these plots, the 60-fs change in the electron bunch length translates into an easily measurable 5° change in the peak location. The calculated coherent SPR angular distributions are, to a good approximation, independent of the electron beam height above the grating.

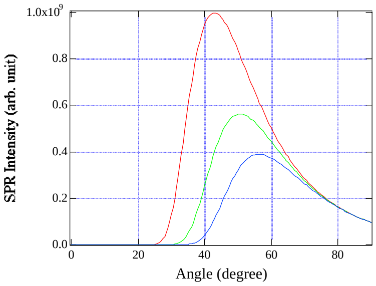

Figure 2. Plot of SPR power versus angle for different bunch lengths. The bunch lengths are 40, 60 and 80 microns from left to right.

Another feature of the coherent Smith-Purcell radiation is its ability to enhance the harmonics. The form factor of a square pulse is the square of a sinc function which contains many harmonics. As the radiation pattern shifts toward smaller angles at higher beam energy, the harmonics, occurring at small angles, are strongly enhanced in intensity. Consequently, the coherent SPR distribution of a square bunch changes drastically as the beam energy increases (Fig. 3).

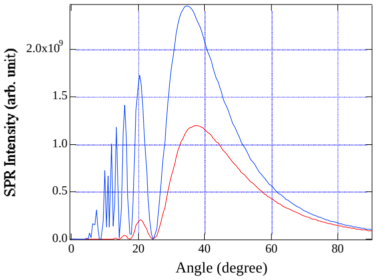

Figure 3. Dependence of coherent SPR pattern of a square pulse on beam energy. The top curve is for 100 MeV beam, the bottom 10 MeV.

Our last calculation involves a gaussian electron bunch with microscopic density modulations, such as those exiting an FEL. For this case, we use a 100-µm rms bunch length and a 30-µm modulation period. The bunching factor for the fundamental is 0.32 and the third harmonic is 0.1. The calculated SPR distribution exhibits, in addition to the coherent SPR of the bunch envelope, two narrow peaks at small angles corresponding to the fundamental and third harmonic, on top of the incoherent SPR background (Fig. 4).

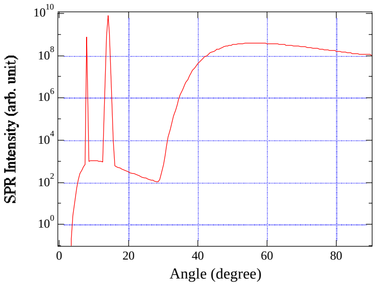

Figure 4. Semi-log plot of SPR power versus angle for an electron bunch with a 100-µm rms bunch length and 30-µm density modulations.

4 CONCLUSIONS

We have shown that coherent Smith-Purcell radiation is potentially a sensitive diagnostic technique for measuring sub-picosecond electron bunches. This new method is also capable of detecting microbunch structures, on the scale of microns (femtoseconds). The new diagnostic technique is simple to implement, does not require any spectrometer or interferometer, and can potentially be used as a non-intercepting, single bunch measurement.

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