COHERENT SYNCHROTRON RADIATION INDUCED EMITTANCE GROWTH IN A CHICANE BUNCHER *

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Abstract
Short high-current microbunches are of considerable importance for future linear colliders and electron beam sources of coherent radiation such as x-ray free-electron lasers. There is recent interest in beam degradation associated with the transport of short high-current electron beams in magnetic bends and bunchers. We compare the observed emittance growth in an existing magnetic buncher system at Boeing with that calculated when coherent synchrotron radiation (CSR) effects are included, and conclude that the CSR effects are significant.

1 INTRODUCTION

Though long anticipated [1], CSR from short electron bunches was not observed until 1989 [2]. Recently, there has been concern that CSR might contribute to significant emittance growth of high brightness beams in bends and magnetic bunch compressors. [3]

The emittance growth in a bend of angle α, of a beam with rms radius $\langle x \rangle$, with induced energy spread $\Delta E/E$ is given approximately by $\Delta\varepsilon \approx \langle x \rangle \alpha \Delta E/E$. Energy spread can be induced by conventional and non-inertial space charge forces [4], wakefields and CSR. A discussion of the space-charge induced emittance growth is beyond the scope of this paper. In this paper we evaluate the CSR induced emittance growth a three-dipole chicane buncher used at the Boeing Free Electron Laser Laboratory

It is useful to compare conventional wakefields and CSR. Wakefields, generated by the interaction of the fields of the bunch with the boundary conditions, trail behind the bunch and can cause the disruption of the tail of the bunch. CSR fields are generated in bends, and can propagate toward the head of the bunch by traveling along a chord, resulting in a disruption of the head of the bunch. In a qualitative sense the wake potential and the CSR potential functions look similar, except that the wake potential has its peak toward the tail and the CSR potential toward the head of the bunch. Both effects can also result in bunch lengthening. In practice, the two effects may combine so as to be indistinguishable by time integrated diagnostics. It should be possible, however, to distinguish between the wakefield and CSR effects by using time-resolved emittance measuring techniques.

2 SUMMARY OF CSR PHENOMENA

It is well known that a bunch of length σ_z will radiate coherently at wavelengths $\lambda \geq 2\pi\sigma_z$. We estimate the distance required for the CSR from the tail of the bunch to catch up with the front of the bunch and reach a steady state to be $L_o \approx 5(\rho^2\sigma_z)^{1/3}$ [somewhat greater than found in ref. 5]. Boundary conditions imposed by the vacuum chamber result in three modes of CSR propagation: Free space, diffraction limited propagation for a >> λ; guided wave propagation where $\lambda \leq 2a\sqrt{\frac{a}{\rho}}$ [6]; and waveguide cut off for $\lambda > 2a\sqrt{\frac{a}{\rho}}$. (a = vacuum chamber height, ρ = bend radius)

For the free-space propagation case, we consider CSR in the long-wavelength limit of $\omega \ll \omega_c$, where $\omega_c = \frac{3\gamma^3 c}{2\rho}$. The characteristic angle of emission of the CSR $\theta = \frac{1}{\gamma}\left(\frac{\omega_c}{\omega}\right)^{\frac{1}{3}}$ is > $1/\gamma$. The effective source length (L_s), or formation length, is the distance the electrons must travel in the bend so as to produce a coherent free-space wavefront, $L_s \approx \rho\theta$. The diffraction-limited effective source transverse rms size is $\sigma_s = (\sigma_x^2 + \sigma_r^2)^{0.5}$ where σ_x is the rms electron beam radius and $\sigma_r = \sqrt{\frac{\lambda L_s}{\pi}} = \sqrt{\frac{\lambda\rho}{\pi}\left(\frac{3\lambda}{4\pi\rho}\right)^{\frac{1}{3}}}$. The characteristic distance for propagation is the Rayleigh range $Z_R = 4\pi\sigma_s^2/\lambda$.

The worst possible CSR case, i.e. where guided propagation is optimized, occurs when over the approximate range $\lambda_{max}/20 < \sigma_z < \lambda_{max}/6$. For longer bunch lengths the CSR is cut off by the vacuum chamber, and for shorter the CSR spreads because of diffraction.

Consider the case of the Boeing three-dipole chicane with ρ = 0.6 m; a $\approx$ 7 cm; γ = 35, and bunch compression from σ_z = 7 mm to 1.1 mm [7]. The cut-off wavelength λ_{max} = 48 mm. Therefore the CSR propagation begins as a guided wave and transitions to a quasi-free-space mode as the bunching progresses. The catch-up length L_o goes from 71 cm in the guided mode to 38 cm at the end of the buncher. At the end of the bunching process Z_R = 33 cm.

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3 COHERENT SYNCHROTRON RADIATION INDUCED EMITTANCE GROWTH

The microbunch loses energy due to CSR in two ways: as an average energy loss of all the electrons, and as a differential or gradient energy loss along the length of the microbunch. The average energy loss results in a change in the average bend angle, and results in little emittance growth for a properly designed bend. However, an energy loss gradient can significantly increase both the transverse and longitudinal emittances. In particular, an energy gradient increases the beam divergence, which in its early stages is correlated with position along the microbunch.

In this work we modify the coherent synchrotron radiation overtake potential function given by Derbenev et al. [5] and describe how it is applied to calculate the emittance growth for specific bend designs. The overtake potential function for the linear charge distribution, $\lambda(s)$, is,

$$F_0(x) = \int_{-\infty}^{x} \frac{dx'}{(x-x')^{1/3}} \frac{\partial \lambda(x')}{\partial x'} \qquad [1]$$

resulting in

$$\frac{dE}{cdt} = -\frac{2Ne^2}{\sqrt{2\pi}\, 3^{1/3} \rho^{2/3} \sigma_z^{4/3}} F_0(s/\sigma_z) \qquad [2]$$

for the energy loss gradient along the microbunch per unit distance traveled in the bend. ρ is the bend radius of curvature, σ_z is the rms microbunch length and N is the number of electrons in the microbunch.

The overtake potential function given in Equation [1] applies to the equilibrium situation where the tail radiation has overtaken the head, and radiation emitted by the electrons continually washes over those ahead of them in the microbunch. This radiation field moves energy from the rear to the front of the microbunch at the rate given in Equation [2]. However, at the beginning of the curved trajectory, the tail radiation has not yet caught up with the head electrons, and the overtake potential function is in transition from zero to its equilibrium form while traveling the catchup length, L_0 from the start of the bend.

We account for this startup of CSR at the beginning of the bend by modifying the above definition of the overtake potential function,

$$F_1(sb, x) = \int_{x-sb}^{x} \frac{dx'}{(x-x')^{1/3}} \frac{\partial \lambda(x')}{\partial x'} \qquad [3]$$

Changing the lower integration limit allows only the radiation a distance sb behind electrons at position x to reach them.

The energy loss gradient is shown in Figure 1 for the gaussian linear charge distribution,

$$\lambda(s) = \frac{1}{\sqrt{2\pi}\, \sigma_z} e^{-s^2/2\sigma_z^2} . \qquad [4]$$

The energy loss gradient is given in keV/meter for a 1 nC microbunch in a bend with a 1 meter radius, and is plotted for sb/σ_z from 0.25 to 15.

Figure 1 indicates that the Equation [3] startup prescription reaches the equilibrium form for $sb/\sigma_z > 6$. Therefore our transport calculations use Equation [3] and linearly increases sb/σ_z from zero to 6 to compute the overtake potential function while the microbunch travels its first characteristic overtake length in the bend.

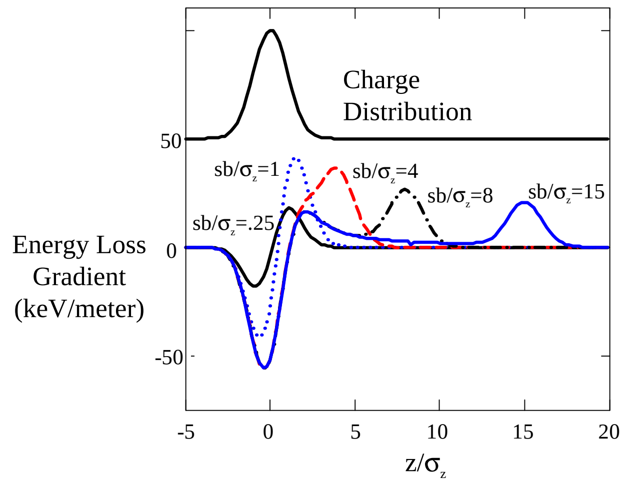

Figure 1. Evolution of the energy loss gradient along the microbunch for 1 nC and a bend radius of one meter. The CSR-induced gradient reaches equilibrium for $sb/\sigma_z > 6$. The transient radiation produced when the bunch enters the bend is seen propagating to the right for $sb/\sigma_z > 4$.

The transport of the microbunch through a multi-magnet bending system is computed using the first order matrix formalism of TRANSPORT [8] along with basic ray tracing to account for any non-linear CSR effects. In our procedure we define an initial four dimensional phase space distribution consisting of the bend plane transverse coordinates x and θ, and the longitudinal coordinates z and $\Delta E/E$. The non-bend plane degrees of freedom are ignored. Each macroparticle is stepped through the bending system with each step consisting of first the matrix transformation followed by a change in energy as given by Equation [2].

4. THE BOEING THREE-DIPOLE CHICANE.

Our example for computing CSR-induced emittance growth in a system of magnets is the Boeing three-dipole chicane. This magnet system is shown in Figure 2 and consists of three n=1/2 dipoles: the outer two being sector magnets, i.e. no pole face rotations, while the center dipole has -19.5 degree rotations on both the entrance and exit pole faces. These rotations on the center dipole make the chicane doubly achromatic. The chicane is non-isochronous with R_{56} = 3 mm/%.

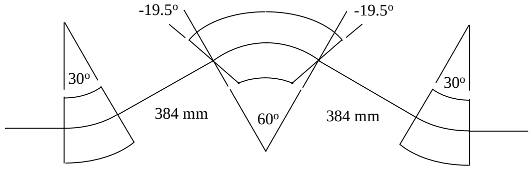

Figure 2. Boeing chicane composed of three n=1/2 dipoles.

For comparison with experiment, we compute the microbunch phase space distributions in the absence of CSR and correlate the z-ΔE/E distribution to compress a 2.7 nC microbunch from 7.0 mm to 1.0 mm (rms). The initial normalized transverse rms emittance is 8.8 π mm-mrad. These are the measured data from a bunch compression experiment recently performed with this chicane [9]. In this matrix model, the beam emittance is unchanged in the absence of CSR when the microbunch is transported around the bend. When CSR is included, the transverse phase space distribution increases in divergence as expected. In this case, the rms emittance increases 11 π mm-mrad due to CSR. The initial and final phase space distributions are shown in Figure 3.

The correlation of the macroparticles with their longitudinal position on the microbunch is shown in Figure 4. There is a clustering of the electrons toward the tail and the spread in divergence is considerably larger than in the front half of the microbunch. Some of the CSR induced emittance growth is correlated, therefore it could be removed using additional beam transport. [10].

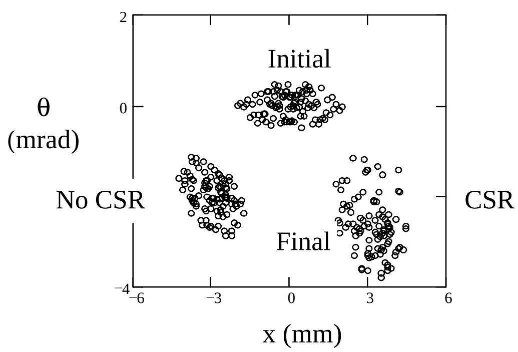

Figure 3. The initial and final transverse phase space distributions, with and without CSR, when the microbunch is compressed. The distributions are offset for display only.

A comparison of these emittance calculations with experimental data [9] is shown in Figure 5. The effect of space charge emittance growth is obtained using PARMELA with its starting emittance normalized to the uncompressed peak current of 50 amperes. The PARMELA calculation of the emittance growth during compression falls short of the compressed data point. However, adding the computed CSR emittance growth in quadrature with the PARMELA calculation results in good agreement with the data.

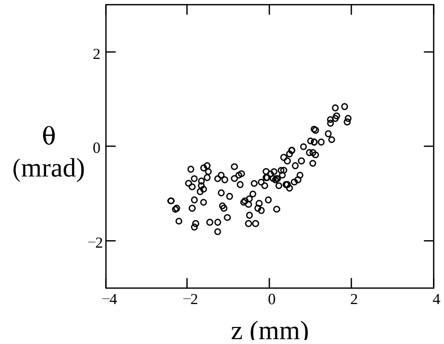

Figure 4. The correlation of divergence with longitudinal position at the exit of the chicane due to CSR.

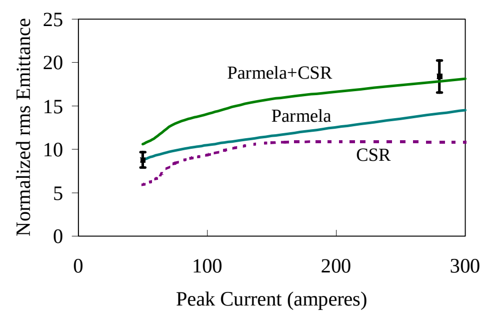

Figure 5. Comparison of experiment with PARMELA and CSR emittance growth calculations.

5 ACKNOWLEDGEMENTS

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