INVESTIGATION OF UPSTREAM TRANSIENT WAKEFIELDS DUE TO COHERENT SYNCHROTRON RADIATION IN BUNCH COMPRESSION CHICANES

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Abstract

The longitudinal wakefield due to coherent synchrotron radiation (CSR) in the bending magnets of bunch compression chicanes can significantly impact the beam quality in high-brightness FEL light-sources. In addition to single-bend CSR effects, transient radiation that is generated within a bend can follow the electron bunch downstream through one or more lattice elements before interacting with the bunch. An analytical 1-D model is used to estimate the size of these upstream wakefields in the absence of vacuum chamber shielding, and an FFT-based, integrated Green function method for computing these wakefields has been implemented in the code IMPACT to investigate their dynamical effects in the second bunch compressor of a Next Generation Light Source.

INTRODUCTION

The bend-induced collective interaction due to CSR in bunch compression chicanes can pose a significant challenge in the design of FEL light sources, producing transverse emittance growth and increased energy spread in the beam delivery system that can result in decreased quality of the resulting FEL radiation. A variety of 1-D wakefield models of CSR have been developed to study these effects [1]-[3], and the primary difference between these models lies in the approximations made regarding the history of the particles over the transit time of the radiation.

The model described in [2] includes transient radiation due to bend entry and exit by assuming that all particles that lie upstream of the nearest dipole at their retarded times lie within an infinitely long drift space. By contrast, the model described in [3] makes use of more detailed information about the upstream lattice. As a result, it also includes radiation that has been emitted within upstream bending elements. This paper investigates the size of these upstream transient effects for chicanes of practical interest.

ANALYTICAL AND NUMERICAL MODELS

For a bunch with a longitudinal density profile λ, the longitudinal CSR wakefield in units of energy loss per unit length takes the form:

$$W(z,s) = \int_{-\infty}^{z} \lambda(z') K_{CSR}(z+s, z'+s) dz', \quad (1)$$

where K_{CSR} is determined from the Liénard-Wiechert electric field of a point charge and the layout of the lattice [3], z is the longitudinal bunch coordinate, and s is a parameter that specifies the location of the bunch centroid within the lattice. The function K_{CSR} varies on a scale $\sim R/\gamma^3$ that can be many orders of magnitude shorter than the bunch length. One method for evaluating the integral (1) numerically given the density $\lambda(z_j)$ at a collection of longitudinal locations $z_j = z_0 + jh$, $(j = 0, \ldots, n)$ is to represent the density by an interpolating polynomial and to evaluate the integral analytically over each subinterval [4, 5]. For the case of piecewise constant interpolation, the result can be written in the form:

$$W(z_k, s) = \sum_{j=0}^{k} \lambda(z_j) w_{igf}^{k,j}(s), \quad (2)$$

where for terms with $0 < j < k$,

$$w_{igf}^{k,j}(s) = \quad (3)$$
$$I_{CSR}\left(z_k + s, z_j - \frac{h}{2} + s\right) - I_{CSR}\left(z_k, z_j + \frac{h}{2} + s\right),$$

and

$$I_{CSR}(s, s') = -\int_{-\infty}^{s'} K_{CSR}(s, s'') ds''. \quad (4)$$

An explicit expression for I_{CSR} in the case of small bending angles and high energy for an arbitrary lattice consisting of circular arcs (bends) and drifts can be found in [3].

Implementation in IMPACT

The IMPACT code is a parallel particle-in-cell code suite for modeling high intensity, high brightness beams in rf proton linacs, electron linacs and photoinjectors [6]. The model for upstream radiation in equations (2-4) was implemented in IMPACT-Z using an FFT-based, integrated Green function algorithm [4, 5]. This feature provides a fast capability for computing the free-space 1D wakefield due to CSR in an arbitrary lattice consisting of bends and drifts.

To use this feature, an additional input parameter is required for the specification of each dipole and drift element in the IMPACT-Z input file. This parameter specifies the number of upstream elements whose CSR contribution is to be included in the wakefield calculation within that element. In order to provide consistency with the model of [2], it is assumed that the farthest upstream element used in the CSR calculation is an infinitely long drift space.

Upstream Radiation Effects

Consider a 4-bend magnetic chicane whose bends will be denoted as Bend $1, \ldots, 4$, moving downstream from the chicane entry. In this section, we will examine the CSR

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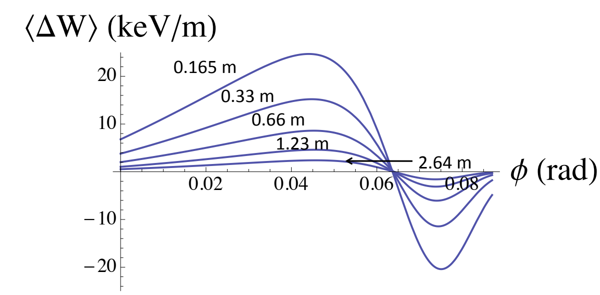

Figure 1: Approximate expression (8) for the difference in mean energy loss with and without the effect of upstream bends for a linearly compressing Gaussian bunch propagating through Bend 3 of the chicane of Table 1. The result is shown for various values of the central drift length.

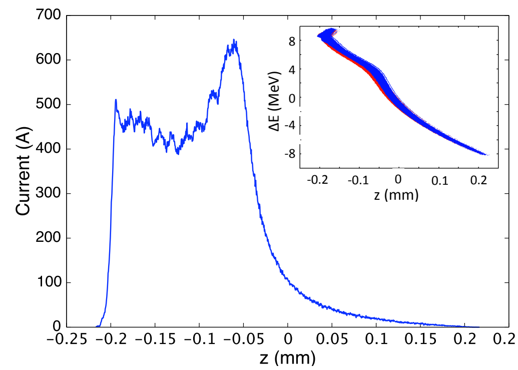

Figure 2: Current profile at the exit of BC2. The head of the bunch appears on the left ($z < 0$). (Inset) Longitudinal phase space at the exit of BC2 with (blue) and without (red) the effects of longitudinal CSR included.

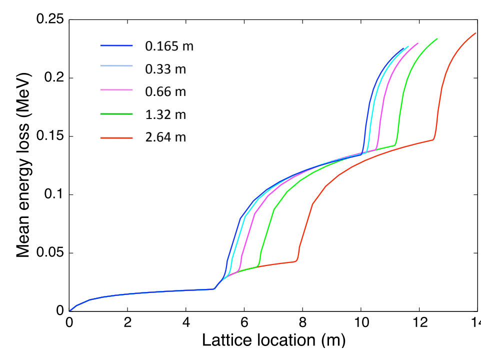

Figure 3: The cumulative loss in the mean energy of the bunch along the length of the chicane is shown for the values $L_c = 2.64$ m, 1.32 m, 0.66 m, 0.33 m, and 0.165 m.

wakefield when the bunch centroid lies within Bend 3. A portion of the particles within the bunch will lie within Bend 2 at their retarded times. Following a procedure similar to [7], one can use the results of [3] to show that in the limit $\gamma \to \infty$, the contribution of these particles to the total wakefield in Bend 3 takes the approximate form:

$$W_L(z, s) = \kappa F_L \lambda(z - \zeta_L), \tag{5}$$

where

$$\kappa = N r_c mc^2/R \tag{6}$$

and

$$F_L = \frac{4\psi(\phi+\psi+2L)}{\phi\{(\phi+\psi)^2 + 2L\psi\}}, \qquad \frac{\zeta_L}{R} = \frac{\phi^3}{24}\frac{\phi+4L}{\phi+L}. \tag{7}$$

Here ψ is the total bending angle of Bend 2, L is the ratio of the central drift length to the bending radius, and ϕ is the angle of the bunch centroid from the entry to Bend 3. By contrast, if we suppose that these particles at their retarded times lie within an infinitely long drift, then we recover Case A of [2]. In the limit $\gamma \to \infty$, it follows that (5) holds with $L \to \infty$ [7].

A convenient measure for the size of the upstream effects is the mean and rms value of the difference ΔW between the wakefields predicted from the two models. Making use of (5) in the case of a Gaussian bunch gives:

$$\langle \Delta W \rangle \approx \frac{\kappa}{\sqrt{4\pi}\sigma}\left[F_L e^{-\zeta_L^2/4\sigma^2} - F_\infty e^{-\zeta_\infty^2/4\sigma^2}\right]. \tag{8}$$

Consider a Gaussian bunch undergoing compression in a chicane described by the parameters of Table 1. Figure 1 shows the quantity (8) as a function of the entry angle ϕ into Bend 3 for various values of the central drift length L_c. In computing these curves, the compression of the bunch is modeled by taking $\sigma_z = \sigma_{z0}/[1 + (C-1)\phi/|\theta|]$ where $|\theta| = 87$ mrad and $C \approx 5$ is the compression factor at the chicane exit.

APPLICATION TO A NEXT GENERATION LIGHT SOURCE

This algorithm was used to investigate CSR-induced dynamical effects in the second bunch compressor of a previously proposed Next Generation Light Source X-ray FEL being studied at Lawrence Berkeley National Laboratory [8]. Basic parameters for the chicane are provided in Table 1. Figure 2 shows the compressed current profile at the exit of BC2, together with the longitudinal phase space at the same location, both with and without the effect of the longitudinal CSR wakefield. The CSR interaction throughout the chicane induces a growth in the rms horizontal emittance of 23% relative to the initial value of 0.65 μm.

We study the effect of varying the length of the central drift L_c, leaving the compression factor of the chicane unaffected while controlling the strength of the upstream wakefield within Bend 3. Figure 3 illustrates the CSR-induced loss in the mean energy of the bunch along the length of the chicane for several values of the central drift length L_c. In order to illustrate the contribution of upstream radiation, Fig. 4 illustrates the difference between

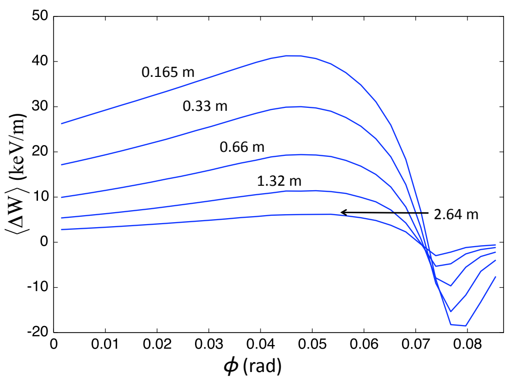

Figure 4: Difference between the longitudinal CSR wakefield in Bend 3 of BC2 as computed using the model of [2] (without upstream transient effects) and [3] (with upstream transient effects) during IMPACT-Z simulation. The average of this quantity over the length of the bunch is shown as a function of bend entry angle. Compare Fig. 1.

the mean CSR-induced energy loss as computed using the two wakefield models [2] and [3] along the length of Bend 3 for the same values of L_c. This difference attains a maximum at 40-50 mrad into the bend and changes sign 10-20 mrad upstream of the bend exit, similar to the curves shown in Fig. 1. The choice of model has a very weak ($\sim 10^{-3}$) relative effect on the final transverse emittance and the second beam moments for all values of L_c considered. The dominant effect of the upstream transient radiation is to introduce a displacement of the bunch centroid in both the horizontal coordinate and momentum, and these quantities are shown in Fig. 5 as a function of the central drift length.

Table 1: Parameters for NGLS BC2 (Factor of 5 Compression). The Initial Beam Distribution is Taken from IMPACT Simulation of the NGLS Design from the Cathode to the Chicane Entrance.

Chicane parameters	**symbol**	**value**
Bend magnet length (projected)	L_B	0.25 m
Drift length (B1→B2, B3→B4)	ΔL	4.5 m
Drift length (B2→B3)	L_c	2.64 m
Bend angle	$\lvert\theta\rvert$	87 mrad
Bend radius	$\lvert R\rvert$	2.88 m
Momentum compaction factor	R_{56}	-70.6 mm
Electron beam parameters	**symbol**	**value**
Nominal energy	E_0	717 MeV
Bunch charge	Q_0	300 pC
Uncorr. initial rms energy spread	$\sigma_{\delta 0}$	4.2×10^{-5}
Linear energy chirp	h	11.4 m^{-1}
Init. rms bunch length	σ_{z0}	373 μm
Init. rms norm. emittance	$\gamma\epsilon_x$	0.65 μm
Init. horizontal size	σ_{x0}	0.22 mm

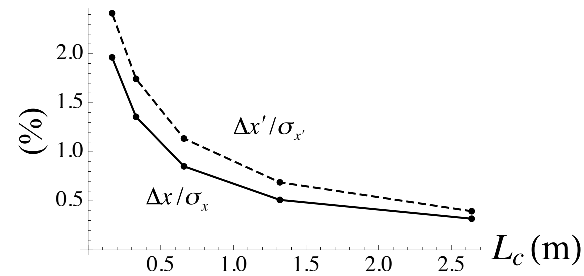

Figure 5: (Solid) Difference between the mean horizontal coordinate as computed using the models of [2] and [3] at the exit of BC2. (Dashed) Difference between the mean horizontal divergence in the two models.

DISCUSSION AND CONCLUSIONS

A one-dimensional free-space wakefield model of CSR including upstream radiation has been implemented in the code IMPACT-Z and used to investigate CSR wakefield effects in the second bunch compressor chicane of a Next Generation Light Source. The difference in mean energy loss due to the coupling with upstream radiation introduces a steering error of 1-3% in the transverse phase plane at the chicane exit. A previous study has investigated upstream radiation effects on the CSR-induced microbunching gain for this system [9], and future work will investigate the effects of vacuum chamber shielding.

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