STUDY OF 2D CSR EFFECTS IN A COMPRESSION CHICANE

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Abstract

The study of coherent synchrotron radiation (CSR) has been an area of great interest because of its negative impact on FEL performance. The modeling of CSR is frequently performed using a 1D approximation, as 2D and 3D models can become extremely computational intensive. While experimental evidence is lacking in this area most studies show reasonable agreement between 1D and 2D CSR models for beam parameters in existing accelerators. In this work we focus on 2D modeling of CSR in a four-dipole chicane lattice based on the Jefferson Lab FEL. Comparison is shown between several models and measurement for energy loss due to CSR in the chicane. While good agreement is generally observed we also present investigation of several key differences observed in simulation. In particular, showing how the 1D and 2D CSR models deviate in regards to CSR and beam interaction within the drift spaces of the chicane and the downstream drift at the chicane end.

INTRODUCTION

Particle accelerator based light sources such as free-electron lasers (FELs) have made possible the production of extremely intense, short-wavelength light at UV and x-ray wavelengths. The FEL relies on the collective emission of the electron bunch to produce coherent light to reach very high intensities. However, the electron bunches are also susceptible to undesirable coherent effects during transport, which may lead to a reduction in lasing efficiency during the FEL process. Coherent synchrotron radiation (CSR) is one such collective effect that can cause undesirable rises in emittance and energy spread of the bunch. CSR may also be a concern in the proposed electron-ion collider project [1,2], where it may drive the microbunching instability in the electron beam for the ion cooler section [3].

Modeling of CSR in accelerators is complicated by the fact that it is a collective effect that arises from the interaction of particles in a bunch. A brute force calculation of the Lienard–Wiechert fields governing this interaction is far too slow even when using a modest number, on the order of 1E4, of macroparticles. Because of this it is common to adopt a 1D approximation [4] that assumes the bunch may be modeled as a projection of the density onto a line parallel to its longitudinal propagation. This model simplifies the calculation of the CSR field to a single integral which may be easily computed numerically. Good agreement between simulation utilizing the 1D model and experiment has been shown in a number of experiments [5–7].

However, this 1D model may be prone to overestimating the impact of CSR. By condensing the bunch down to a line charge and removing any transverse extent from the calculation the interaction of electrons may be overestimated. This is particularly of concern since CSR is often being generated in magnetic compression chicanes where dispersion from the dipoles will cause the bunch to be spread out in the bending plane.

In this work we will show results using a 2D CSR simulation in the XZ plane performed with the code CSRtrack. Results with the 2D simulation are compared against previous work studying energy loss through the chicane of the Jefferson Laboratory ERL FEL driver [7]. Overall, good agreement is still observed between 1D and 2D CSR models from CSRtrack and simulations with the particle tracking code ELEGANT. A closer look at how the bunch is losing energy as it passes through the chicane shows several peculiarities which seem to be uniquely 2D effects and are not captured in the 1D CSR simulations.

Table 1: Parameters for the Chicane and Bunch used in Simulation

Parameter	Value
Chicane R_{56}	0.52 m
Bunch energy	135 MeV
Bunch charge	135 pC
Bunch length at max compression	150 fs

DESCRIPTION OF THE SIMULATIONS

For these simulations we use the parameters of the JLab IR FEL optical cavity chicane [8], which are given in Table. 1. Our goal is to look at energy loss of the bunch due to CSR as a function of the level of compression the bunch achieves at the end of the chicane. By varying the chirp on the bunch, defined as

$$h = \frac{1}{E_{avg}} \frac{dE}{dz}, \tag{1}$$

or by varying the linear momentum compaction, R_{56}, the bunch length at the chicane entrance σ_{z0} will be changed by

$$\sigma_{zf} = (1 - hR_{56})\sigma_{z0}. \tag{2}$$

When the quantity $hR_{56} > 1$ the bunch will not achieve full compression at the end of the chicane and the bunch is said to be under-compressed. For values of $hR_{56} < 1$ the bunch passes through full compression before growing longer at the chicane exit and the bunch is said to be over-compressed. Of course, when $hR_{56} = 1$ the bunch will achieve maximum compression at the end of the chicane and we will refer to this as critically compressed.

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Simulations were performed using ELEGANT [9] a particle tracking code which includes 1D CSR model of Saldin et al. [4] which can be included in both dipoles and in drifts. The code CSRtrack [10] includes several models for CSR, with a 1D approach that closely follows that in ELEGANT. For our 2D simulations we use CSRtrack's 2D 'g to p' model that takes a pseudo-Green's function approach to calculating the fields in the XZ plane and makes use of Gaussian sub-bunches to model particles of the electron bunch.

SIMULATION RESULTS

The Derbenev Criterion

An estimate of the validity of the 1D CSR model may be made based upon the bunch length σ_z, width in the bending plane σ_x, and dipole radius R, this is given by

$$\kappa \equiv \sigma_x \left(\frac{1}{R\sigma_z^2}\right)^{\frac{1}{3}}. \tag{3}$$

This condition is sometimes called the Derbenev criterion [11], and we will refer to the quantity κ in Eq. 3 as the Derbenev parameter. For the assumptions of the 1D CSR model to be valid we should have $\kappa \ll 1$. For the optical cavity chicane the Derbenev parameter is plotted along the length of the chicane for several different levels of compression in Fig. 1.

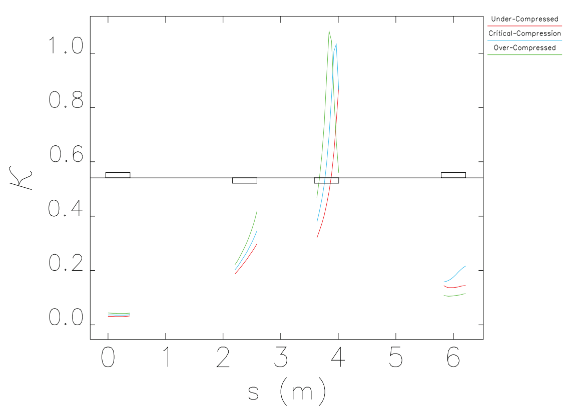

Figure 1: The parameter κ, see Eq. 3 is plotted along the chicane. The dipoles of the chicane are represented as rectangles. Three different cases of compression level are shown.

Especially within the third dipole it is seen that the Derbenev criterion will be badly violated leading to the question of how well predictions of the 1D and 2D models will match. For critical compression and over-compression the bunch will briefly pass through full compression, where it is upright int he longitudinal phase space, in the third chicane. This minimum in σ_z causes the observed rollover in κ and leads to a much larger integrated value of κ than for under-compression.

Energy Loss in the Chicane

The total energy loss, given as the ratio of the final momentum to the initial, through the chicane is plotted in Fig. 2. In general, good agreement is seen between the three different models used, though the 2D CSR simulation does predict greater energy loss than in the 1D, which goes against the general assumption of the behavior for the 2D versus the 1D models.

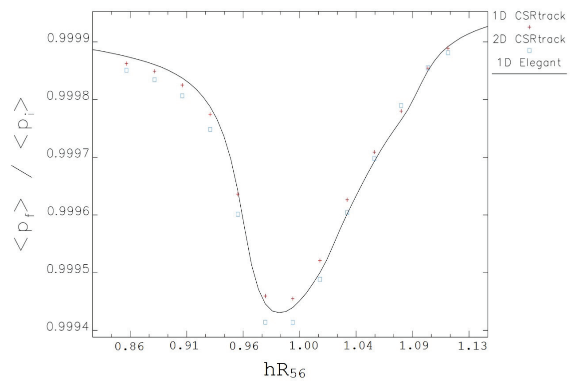

Figure 2: The energy loss due to CSR in the chicane is plotted as a function of the compression measured by hR_{56}. The black line shows the result for ELEGANT, the red and blue symbols show the 1D and 2D results from CSRtrack.

It is interesting then to look at the behavior of the bunch for particular hR_{56} setpoint and observe how the energy changes along the length of the chicane. For the over-compressed case at $hR_{56} = 0.92$ the energy loss along the chicane is shown in Fig. 3. The behavior of the energy loss between the third and fourth dipoles is particularly notable. The 2D CSR results show that the bunch experiences much higher energy loss in this region before regaining some energy at the entrance to the final dipole. Such effects have been seen previously in other CSR simulations [12] and have been attributed to the dipole field inducing a strong transverse velocity component that is antiparallel to the transverse CSR field at the dipole entrance, causing a brief period of energy gain for the bunch.

However, Fig. 3 also shows a much greater energy loss in the drift region between the third and fourth dipole where there is no external field. To understand where this effect might arise from we may look at Fig. 4, a plot of transverse momentum versus longitudinal position for the electron bunch. The particle coloring is based on particle energy change between two successive simulation steps 0.1 m apart with the initial position located 0.25 m from the edge of the fourth dipole. It can be seen that the regions of energy loss and gain are tightly clustered and most of the energy gain and losses occur in a narrow band in longitudinal position that is centered at the head of the bunch where most of the charge is concentrated and CSR fields will be strongest. We can see that the particles that are starting to gain energy are

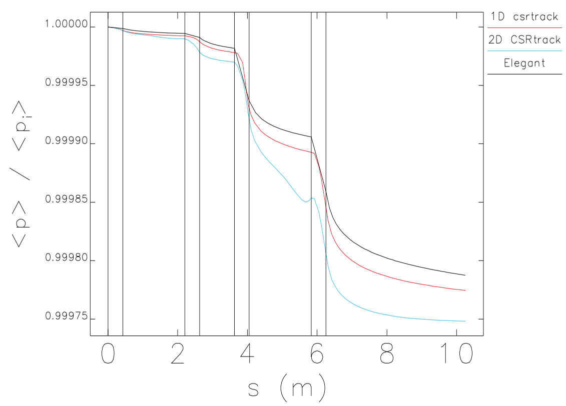

Figure 3: Energy loss as a function of position along the beamline in the chicane. Results are shown for 1D and 2D simulations in CSRtrack and 1D in ELEGANT in red, blue, and black respectively.

at $x' < 0$ suggesting some contribution to the energy change from a horizontal E_x component to the CSR field that is coupling with the transverse motions of the electrons.

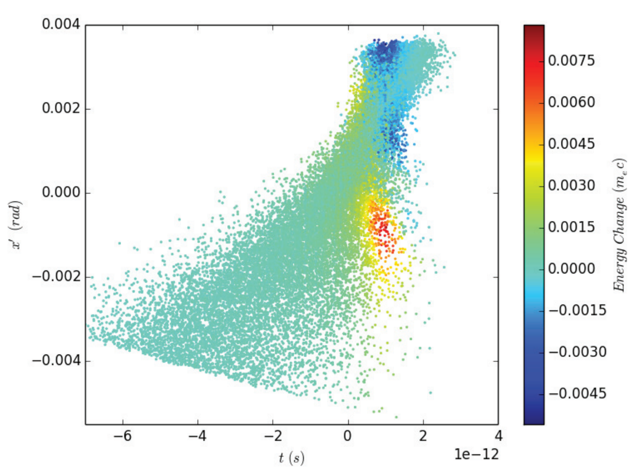

Figure 4: Plot of transverse momentum, x', versus longitudinal position, t, for an over-compressed bunch. The heat map is based upon energy change between two successive steps in the simulation starting 0.25 m from the entrance to the fourth dipole. (Note that in this plot $t > 0$ is the head of the bunch.)

CONCLUSION

Results from 2D CSR simulations of a four dipole magnetic compression chicane with the code CSRtrack show good agreement both with its own 1D model and 1D CSR simulations performed with ELEGANT. The agreement is best when looking at the overall, integrated energy loss through the chicane. However, some interesting phenomena that seem to arise purely from 2D effects and a transverse electric field can be seen upon closer examination of the bunch's energy loss between the third and fourth dipoles of the chicane, in particular.

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