ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEXBA3

CSR PHASE SPACE DILUTION IN CBETA*

W. Lou, G. H. Hoffstaetter, D. Sagan, CLASSE, Ithaca, NY, USA
C. Mayes, SLAC, Menlo Park, CA, USA

Abstract

CBETA, the Cornell BNL Energy-Recovery-Linac (ERL) Test Accelerator [1], will be the first multi-turn ERL with SRF accelerating cavities and Fixed Field Alternating gradient (FFA) lattice with a range of energy acceptance. While CBETA gives promise to deliver very high beam current with simultaneously small emittance, Coherent Synchrotron Radiation (CSR) can cause detrimental effects on the beam bunches at high bunch charges. To investigate the CSR effects on CBETA, the established simulation code Bmad is used to track a bunch with different parameters. We found that CSR causes phase space dilution, and the effect becomes more significant as the bunch charge and recirculation pass increase. Potential ways to mitigate the CSR effects, including adding vacuum chamber shielding and increasing bunch length, are being investigated.

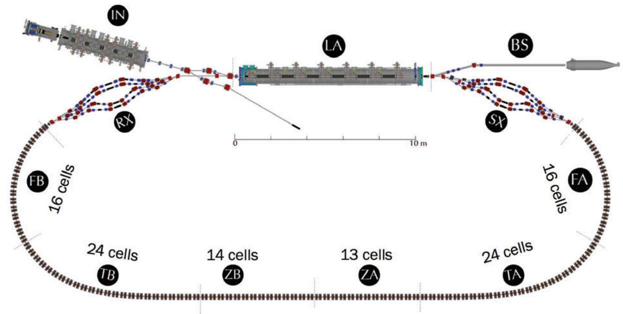

Figure 1: Layout of the CBETA accelerator. The section labeled (LA) is the accelerating LINAC. The sections labelled (SX) and (RX) are the splitters which control the beam optics and time of flights of each recirculation pass. The sections labeled (FA), (TA), (ZA), (ZB), (TB), and (FB) form the FFA beamline which can accommodate four recirculating orbits with an energy range from 42 MeV to 150 MeV.

INTRODUCTION

Synchrotron radiation occurs when an electron traverses a curved trajectory, and the radiation emitted can give energy kicks to the other electrons in the same bunch. While the high frequency components of the radiation spectrum tend to add up incoherently, the low frequency part, with wavelength on the order of the bunch length, can add coherently. These are termed incoherent and coherent synchrotron radiation respectively (ISR and CSR). While the total intensity for ISR scales linearly with the number of charged particles (N_p), it scales as N_p^2 for CSR. For an ERL which aims for high beam quality like CBETA, CSR can pose detrimental effect on the beam, including energy loss, increase in energy spread, and potential micro-bunching instability. Therefore it is important to run CSR simulation for CBETA, and investigate potential ways for mitigation. Fig. 1 shows the design layout of CBETA. Note that with adjustment on the time of flights, CBETA can operate as a 1-pass or 4-pass ERL.

CSR SIMULATION OVERVIEW

Cornell Wilson Laboratory has developed a simulation software called Bmad to model relativistic beam dynamics in customized accelerator lattices [2], and subroutines have been established to include CSR calculation [3]. As Fig. 2 shows, a bunch of particles is divided into a number of bins (N_b) in the longitudinal direction. During beam tracking, N_b is constant, and the bin width is dynamically adjusted at each time step to cover the entire bunch length. The contribution of a particle to a bin's total charge is determined by the overlap of the particle's triangular charge distribution and the bin. With Δz_b denoting the bin width and ρ_i denoting the total charge in the i^{th} bin, the charge density (λ_i) at the bin center is taken to be $\rho_i/\Delta z_b$. In between the bin centers, the charge density is assumed to vary linearly.

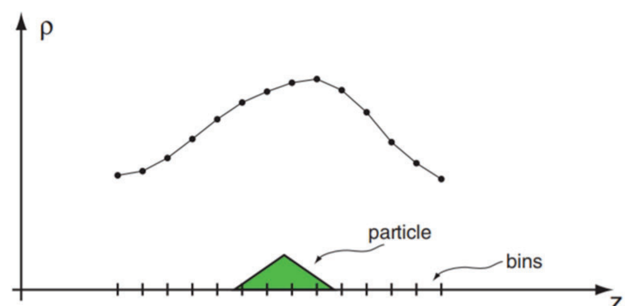

Figure 2: Bmad implementation of CSR. The bunch is divided into N_b bins in the longitudinal direction for calculation of CSR kicks.

In theory the CSR wakefield can be written as [3]:

$$\left(\frac{d\mathcal{E}}{ds}\right) = \int_{-\infty}^{\infty} ds' \frac{d\lambda(s')}{ds'} I_{\text{CSR}}(s - s'), \tag{1}$$

in which $\lambda(s)$ is the longitudinal charge density, and I_{CSR} comes from solving the Liénard-Wiechert retarded field with two charged particles on a curved trajectory. In Bmad the energy kick received by a particle centered at the j^{th} bin, after travelling for a distance ds, is modelled in Bmad as [3]:

$$d\mathcal{E} = ds \sum_{i=1}^{N_b} (\lambda_i - \lambda_{i-1}) \frac{I_{\text{CSR}}(j-i) + I_{\text{CSR}}(j-i+1)}{2}, \tag{2}$$

with $I_{\text{CSR}}(j) \equiv I_{\text{CSR}}(z = j\Delta z_b)$.

* This work was performed with the support of NYSERDA (New York State Energy Research and Development Agency).

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEXBA3

The CSR simulation in Bmad has been benchmarked with CSR theory and other simulation code including A&Y and elegant [3]. CSR in Bmad can also include the space charge calculation and the one dimensional vacuum shielding effect. Moreover, the simulation code can handle the case when the design orbit of the beam does not follow the reference orbit of the lattice [4]. This is exactly the case for the FFA beamline in CBETA which consists of displaced quadrupole magnets.

CSR PARAMETER CHOICE

Given a bunch with fixed charge Q, the two most important parameters in CSR simulations are the total number of particles (N_p) and bins (N_b). A large N_p generally increases the simulation accuracy at the cost of computation time. It is usually recommended to have $Np \geq 100$k, but a beamline with more or longer curved trajectories may require more. Choosing N_b is not as straightforward as N_p. A small N_b can result in inaccurate calculation of CSR kicks due to low longitudinal resolution. However, if N_b is too large, the number of particles per bin can be too small, potentially resulting in numerical noise. A proper choice of N_b therefore depends heavily on N_p and the lattice itself.

Table 1 below summarizes the choice of N_p and N_b in the previous simulations presented in IPAC 2019 [5] and the new choice in this paper. Results from previous simulations seem to have significant numerical noise and micro-bunching effect, potentially due to insufficient amount of particles per bin. We therefore increased both N_p and N_p/N_b in hope to obtain more accurate results. The new results are presented in the next section. To check whether the micro-bunching effect comes from numerical noise, convergence tests for the parameters will be required.

Table 1: CSR parameters used in previous simulations presented in IPAC 2019 and in this paper.

Parameters	1-pass	4-pass
IPAC May 2019	$N_p = 600$k $N_b = 3000$	$N_p = 100$k $N_b = 3000$
NAPAC Sep. 2019	$N_p = 1$M $N_b = 2500$	

Bmad SIMULATION RESULT

The two subsections show the CSR results with the CBETA 1-pass and 4-pass mode for various Q. During each recirculation pass, the primary contribution of CSR comes from the FA and FB sections during which the bunch undergoes the most curved trajectories. In the 1-pass mode the beam traverses the LINAC twice, once for acceleration and once for deceleration. In the 4-pass mode the beam traverses the LINAC for 8 times, four times for acceleration followed by four times for deceleration. The initial bunch distribution has been pre-simulated using GPT tracking up to the end of the LINAC pass 1 (42 MeV) to account for the space charge effect at low energy [1].

Case 1) CBETA 1-Pass with $N_p = 1M, N_b = 2500$

Figure 3 shows the longitudinal phase space distributions of the tracked bunch at the end of LINAC pass 2 with different Q. As Q increases the CSR effect becomes more significant, causing the increase in energy spread and, via lattice dispersion, the increase in horizontal beam emittance. At $Q = 50$ pC, 50 out of 1M particles has relative energy spread exceeding ±5%. The ideal energy acceptance of the CBETA beam stop is, assuming no halo and other undesired effects, ±7%. This limit is exceeded between 75 pC to 100 pC. So the result indicates that CBETA 1-pass lattice can operate with a 75 pC bunch without particle loss due to CSR. With the maximum repetition rate of 1.3 GHz, this corresponds to a beam current of 97.5 mA, well exceeding the high design current of 40 mA. At $Q = 125$ pC, 1.3k out of 1M particles are lost due to excessive energy spread. The overall findings for CBETA 1-pass are similar to the previous result in [5].

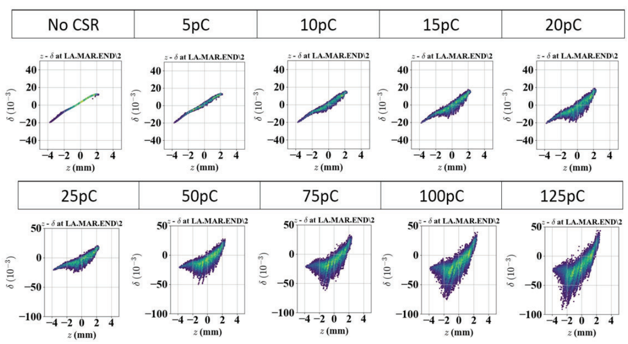

Figure 3: The $z - \delta$ distribution after each of the 8 LINAC passes for CBETA 1-pass with various Q.

Case 2) CBETA 4-Pass with $N_p = 1M, N_b = 2500$

Figures 4-6 show the longitudinal and horizontal phase space distributions of the tracked bunch at the end of each LINAC pass, from 1 to 8, with different Q. As observed in the 1-pass results, both the energy spread and beam emittance increase as Q increases. Moreover, the energy spread also builds up over the recirculation passes. Note that both x' and δ are unitless quantities (scaled by the reference momentum P_0), which explains why the spreads increase more severely during the four decelerating passes than the four accelerating passes.

For $Q = 1$ pC, 215 out of 1M particles have been lost during the final two decelerating passes. However, all the surviving particles have a final energy spread less than ±5%, which is acceptable for the beam stop. In contrast to the previous results in [5], the overall energy spread now becomes much less, especially during the decelerating pass. The improvement becomes more significant at $Q = 5$ pC. While the previous result loses 23k out of 100k particles, only 658 out of 1M are lost with the new parameter choice. This indicates that the old parameter choice has insufficient N_p or N_p/N_b for the 4-pass lattice, and is subject to numerical noise. The new results show more promise for CBETA

North American Particle Acc. Conf. NAPAC2019, Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEXBA3

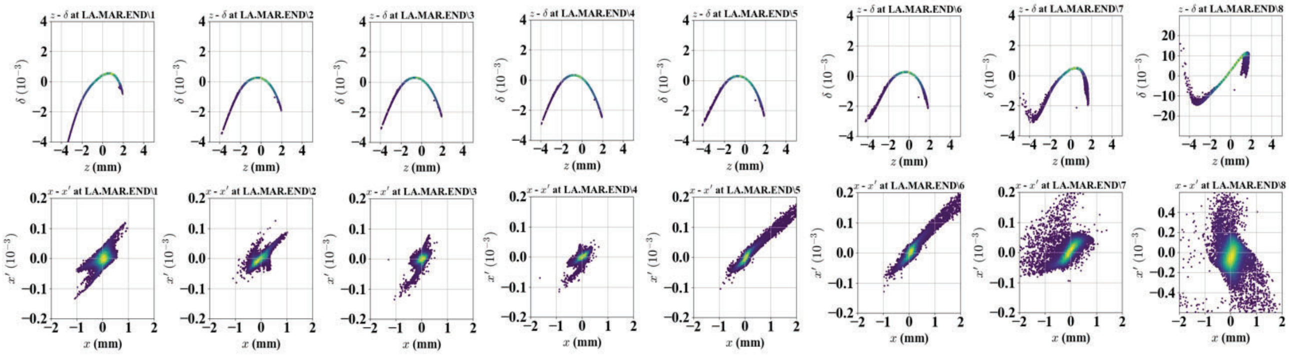

Figure 4: The $x - x'$ and $z - \delta$ distributions after each of the 8 LINAC passes for CBETA 4-pass with no CSR.

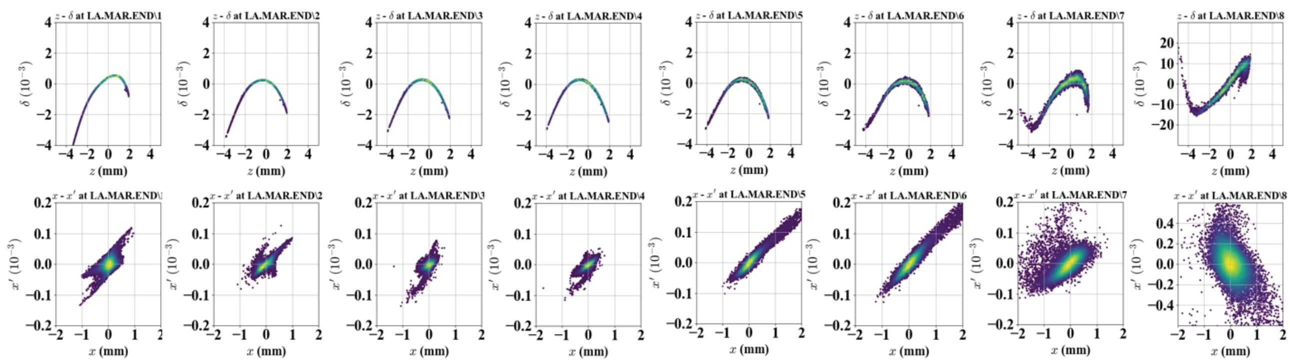

Figure 5: The $x - x'$ and $z - \delta$ distributions after each of the 8 LINAC passes for CBETA 4-pass with $Q = 1$ pC.

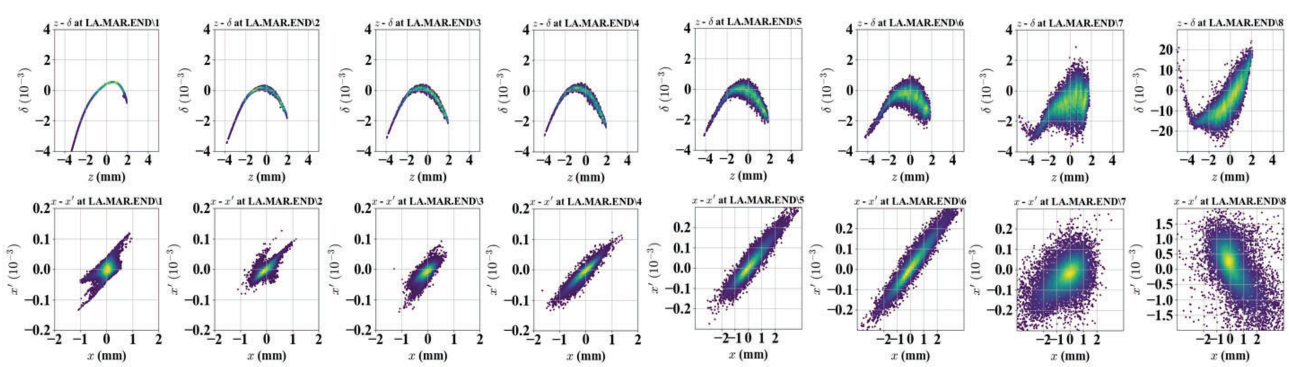

Figure 6: The $x - x'$ and $z - \delta$ distributions after each of the 8 LINAC passes for CBETA 4-pass with $Q = 5$ pC.

to reach its design current of 1 mA, which requires a bunch with $Q \geq 3$ pC to survive the entire lattice.

During the decelerating passes, micro-bunching structures can be seen in the longitudinal phase space. Whether this is a physical or numerical effect, or a combination of both, requires further study. Also, more simulations are required to check if particle loss is due to improper choice of CSR parameters or the limit of design lattice.

MITIGATION AND FUTURE PLAN

Two methods have been proposed to mitigate the CSR effect. The first method is to increase the bunch length, which directly suppresses CSR interaction by theory prediction. Figures 7 and 8 below respectively show the relative energy loss and energy spread due to CSR as a 25 pC Gaussian beam traverses the 16 FA cells along the 42 MeV orbit with various initial bunch lengths σ_z. As σ_z increases, both the energy loss and spread decrease, as expected by theory.

Although increasing σ_z can mitigate CSR effects in the FFA arc, it can introduce greater energy spread at the LINAC and can result in undesired ERL operation. Further studies are required to calculate the optimal σ_z for CBETA.

The second method is to include metal shielding, which behaves like waveguides preventing the propagation of CSR fields below the cutoff frequency. Theory and existing experimental data have shown that shielding can potentially suppress energy loss and energy spread of the bunch [6] [7]. While all the simulation results in this paper have assumed

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEXBA3

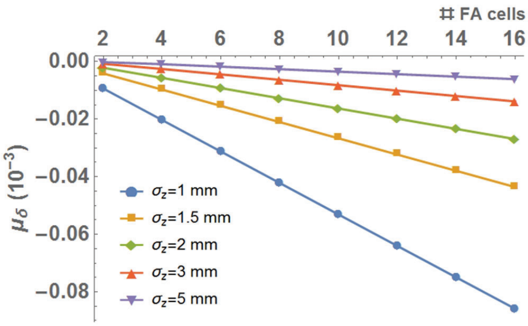

Figure 7: The relative energy loss $< \delta >$ of a Gaussian beam with various initial bunch lengths σ_z.

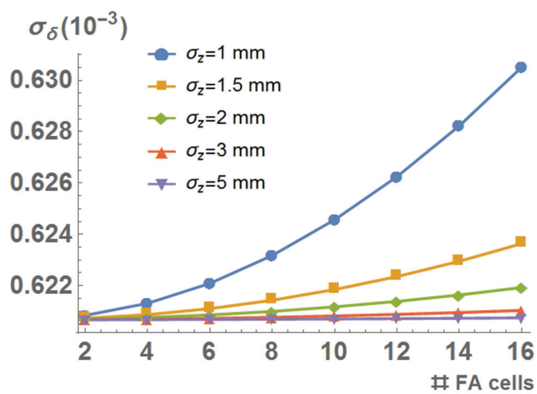

Figure 8: The relative energy spread σ_δ of a Gaussian beam with various initial bunch lengths σ_z.

CSR in free space, Bmad already has the shielding effect implemented with the method of image charges. The challenge of this method is the increased computation time and number of parameter choices. Simulations with shielding for the FA section are currently in progress.

REFERENCES

[1] G.H. Hoffstaetter, D. Trbojevic *et al.*, *CBETA Design Report*, `https://arxiv.org/abs/1706.04245`

[2] D. Sagan, *Bmad Simulation Software*, `https://www.classe.cornell.edu/bmad/`

[3] D. Sagan *et al.*, *Phys. Rev. ST Accel. Beams*, vol. 12, p. 040703, 2009.

[4] D. Sagan and C. E. Mayes, "Coherent Synchrotron Radiation Simulations for Off-Axis Beams Using the Bmad Toolkit", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 3887–3890. doi:10.18429/JACoW-IPAC2017-THPAB076

[5] W. Lou, C. M. Gulliford, G. H. Hoffstaetter, C. E. Mayes, D. Sagan, and N. Tsoupas, *Coherent Synchrotron Radiation Simulation for CBETA* in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 406-409. doi:10.18429/JACoW-IPAC2019-MOPGW124

[6] C. Mayes and G.H. Hoffstaetter, "Exact 1D model for coherent synchrotron radiation with shielding and bunch compression," *Phys. Rev. ST Accel. Beams*, vol. 12, p. 024401, 2009.

[7] V. Yakimenko *et al.*,"Experimental Observation of Suppression of Coherent-Synchrotron-Radiation–Induced Beam-Energy Spread with Shielding Plates," *PRL*, vol. 109, p. 164802, 2012.