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COHERENT SYNCHROTRON RADIATION SIMULATION FOR CBETA

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Abstract

CBETA, the Cornell BNL Energy-Recovery-Linac (ERL) Test Accelerator [1], will be the first multi-turn Energy Recovery Linac (ERL) with SRF accelerating cavities and Fixed Field Alternating gradient (FFA) beamline. While CBETA gives promise to deliver unprecedentedly high beam current with simultaneously small emittance, Coherent Synchrotron Radiation (CSR) can pose detrimental effect on the beam at high bunch charges and short bunch lengths. To investigate the CSR effects on CBETA, we used the established simulation code Bmad 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 effect involving vacuum chamber shielding and increasing bunch length are being investigated.

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 component 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 increase in energy spread, energy loss, and potential micro-bunching instability. Therefore it is important to simulate the effect of CSR on CBETA, and investigate potential ways for mitigation if necessary. Figure 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 Figure 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

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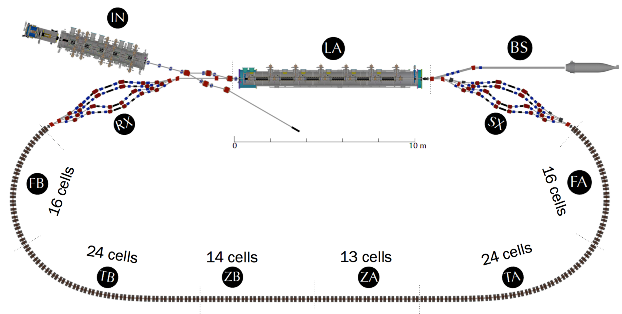

Figure 1: Layout of the CBETA accelerator. The section labeled (LA) is the accelerating LINAC. The sections labelled (SX) and (RX) are the splitters which control the beam optics and time of flights of each recirculation pass. The sections labeled (FA), (TA), (ZA), (ZB), (TB), and (FB) form the FFA beamline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

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.

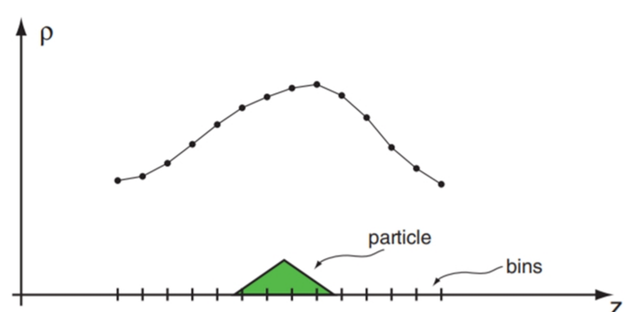

Figure 2: Bmad implementation of CSR. The bunch is divided into a number of bins to allow numerical calculation of the CSR kick.

In theory the energy variation due to the longitudinal CSR kick can be written as [3]:

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

in which $\lambda(s)$ is the 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

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for a distance ds, is then [3]:

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

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

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 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 and has a range of energy acceptance.

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, and CSR simulations usually require N_p ≥100k. Choosing N_b, however, can be complicated. If N_b is too small, the calculation of CSR kicks can be inaccurate due to low 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, the initial bunch distribution, and the lattice itself.

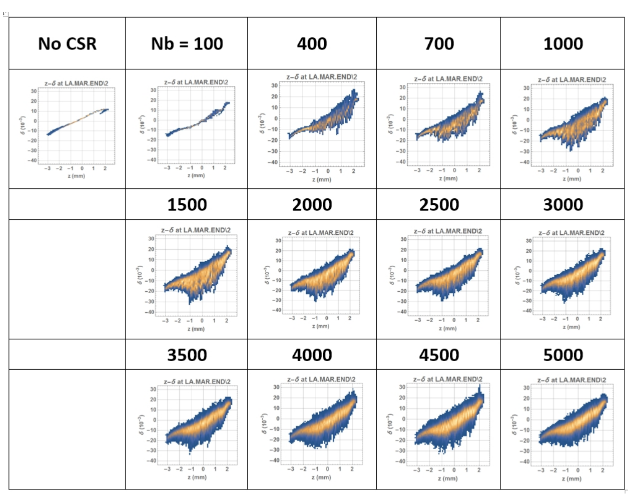

Figure 3: Fig. 1: The results of CSR tracking of a Q = 25 pC bunch with the CBETA 1-pass lattice and varying N_b.

Fig. 3 shows the potential effect of varying N_b on the resultant beam bunch. A pre-simulated GPT bunch with Q = 25 pC and N_p = 600k is tracked though the CBETA 1-pass lattice, and the longitudinal distribution is recorded right after the LINAC pass 2. Clearly CSR increases the energy spread of the beam, but the amount of increase depends heavily on N_b. For $N_b > 2500$ the distribution seems to converge. To keep N_p/N_b not too small, we choose N_b = 3000 for the rest of CBETA simulations in this paper.

Bmad SIMULATION RESULT

As described, CBETA can operate in either the 1-pass or 4-pass mode. 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 and four times for deceleration. The two subsections show the CSR results with the CBETA 1-pass and 4-pass mode for various bunch charges. The initial bunch distribution has been pre-simulated using GPT tracking up to the end of the LINAC pass 1 (42 MeV) to include the space charge effect at low energy [1].

Case 1) CBETA 1-Pass with N_p = 600 k

Figure 4 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 is more severe, causing the increase in energy spread and, via lattice dispersion, the increase in horizontal beam emittance. At Q = 50 pC the final energy spread reaches ±5%. The ideal energy acceptance of the CBETA beam stop is, assuming no halo and other undesired effects, ±7%. So the result indicates that CBETA 1-pass lattice can operate with a 50 pC bunch without particle loss due to CSR. With the maximum repetition rate of 1.3 GHz, this corresponds to a beam current of 65 mA, well exceeding the high design current of 40 mA.

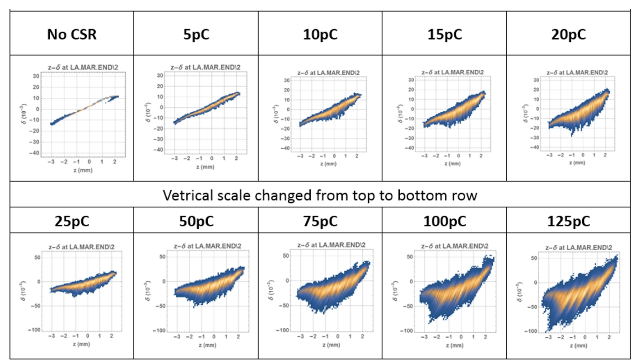

Figure 4: The $z - \delta$ distribution after each of the 8 LINAC passes for CBETA 1-pass with various Q.

Case 2) CBETA 4-Pass with N_p = 100 k

Figure 5 to Figure 7 show the longitudinal and horizontal phase space distributions of the tracked bunch at the end of each LINAC pass 2 with different Q. As observed in the 1-pass results, both the energy spread and beam emittance increase as Q increases. Moreover, as the recirculation pass increases, the energy spread also build up. Note that both x' and δ are 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. 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. For Q = 1 pC the final energy spread reaches ±2%, which falls within the ±7% of the beam stop acceptance. However, 9 out of 100k

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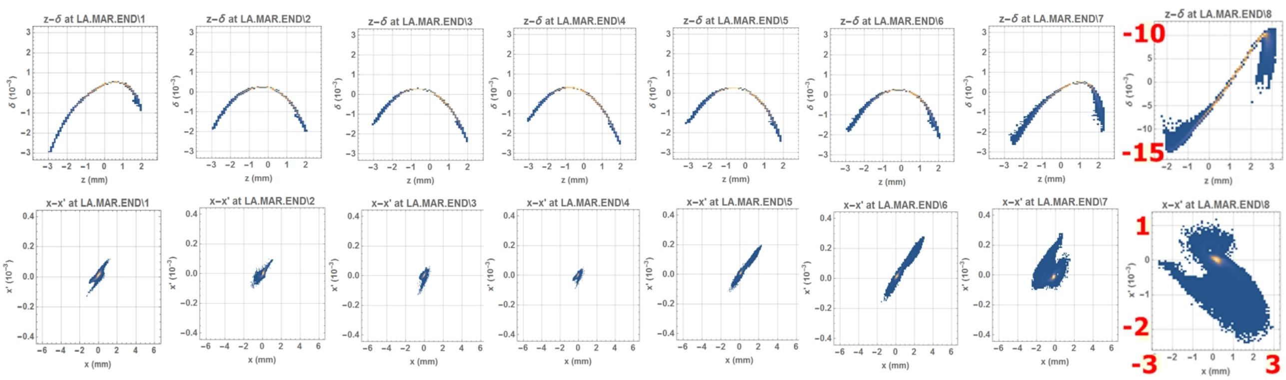

Figure 5: The $x - x'$ and $z - \delta$ distributions after each of the 8 LINAC passes for CBETA 4-pass with no CSR.

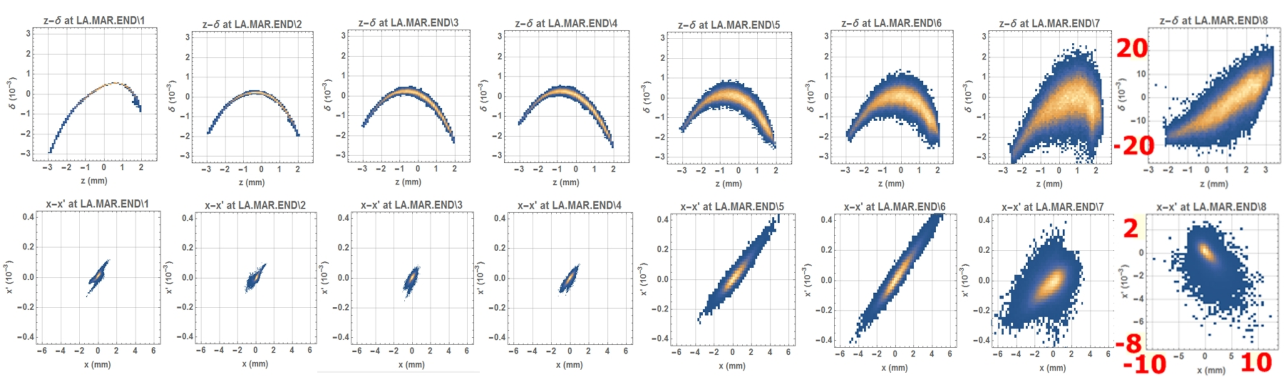

Figure 6: The $x - x'$ and $z - \delta$ distributions after each of the 8 LINAC passes for CBETA 4-pass with $Q = 1$ pC.

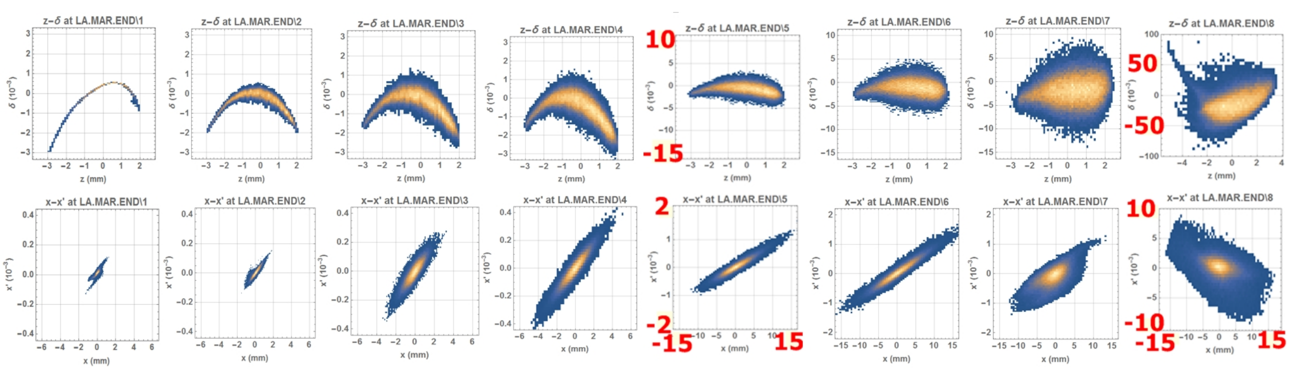

Figure 7: The $x - x'$ and $z - \delta$ distributions after each of the 8 LINAC passes for CBETA 4-pass with $Q = 5$ pC.

particles have been lost during the decelerating passes. For $Q = 5$ pC, 23k out of 100k particles have been lost, which is not acceptable for ERL operation. For the 4-pass mode to reach the design current of 1 mA, a bunch with $Q \geq 3$ pC needs to survive the tracking with no loss.

MITIGATION AND FUTURE PLAN

More simulations are necessary to investigate whether the particle loss was due to improper choice of CSR parameters or the limit of design lattice. On the other hand, two methods to mitigate the CSR effect have been proposed. The first method is to include metal shielding which changes the CSR wakefields. Metal shielding chambers behave like a waveguide which prevents the propagation of CSR fields below the cutoff frequency. Theory and existing experimental data have shown that metal shielding can potential suppress the energy loss and energy spread of the bunch [5] [6]. While all the simulation results in this paper have assumed CSR in free space, Bmad already has the shielding effect implemented via the method of image charges. The challenge of this method will be intensive computation time and more parameter choices. The second method is to increase the bunch length, which directly suppresses CSR interaction by theory prediction. However a longer bunch length affects accelerating phase at the LINAC and can result in undesired ERL operation. Further simulation and optimization will be required.

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