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MITIGATION OF COHERENT SYNCHROTRON RADIATION BY BUNCH PROFILE OPTIMIZATION AND SHIELDING

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Abstract

The mitigation of the effects of coherent synchrotron radiation (CSR) is a key challenge in generating high brightness beams. Shielding by parallel plates installed in the dipole magnet vacuum chambers shows promise, both in simulation and experiment at small shielding gap separations. In this work, we investigate the combined use of longitudinal profile shaping and shielding to reduce CSR induced emittance growth in a 4 dipole chicane. The CSR wake is calculated using a 3D technique currently in development that represents the particle distribution with smooth 3D shape functions. Our results indicate current profiles that result in smaller emittance growth at separations larger than the scales at which shielding on a Gaussian beam causes effective CSR mitigation.

INTRODUCTION

Collective effects like Coherent Synchrotron Radiation (CSR) within a bunch represent a significant challenge in the generation of high brightness beams. In particular, for short bunches of high intensity propagating through a bend – as is required for X-ray free electron lasers (FELs) – the radiated CSR wake can have serious effects on the beam dynamics, such as the expansion of the transverse phase space [1] and the generation of microbunching instabilities [2]. Several mitigation strategies have been proposed in the literature, ranging from placing parallel plate shielding walls inside the vacuum chamber of the bending magnet [3], tuning of the overall optical lattice [4], and careful shaping of the longitudinal current profile to flatten out the CSR wake [5].

While the shielding effect has been experimentally observed to cancel out the CSR wake, the required length scales for the gap separation varies with the bunch length σ_z as $\sqrt[3]{R\sigma_z^2}$ for Gaussian beams [6], necessitating very small gaps for short bunches. In this work, we extend the method proposed in [5] and investigate the potential use of wall separations larger than the aforementioned length scale in conjunction with shaping of the initial beam profile.

We evaluate the CSR fields through direct integration of Jefimenko's equations with the charge and current distributions represented by smooth shape functions – in particular, we use products of Gaussians in the longitudinal and transverse dimensions whose widths and amplitudes can be tuned depending on the bunch being modeled. This forward evaluation is then used as part of a nonlinear minimization algorithm to obtain optimal initial profiles.

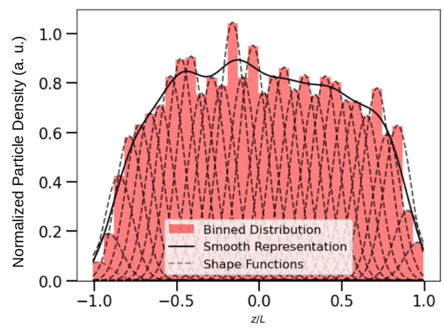

Figure 1: An example of constructing a smooth particle distribution from a binned macroparticle ensemble. z/L is the longitudinal position in relation to the bunch length. The shape functions are depicted before final normalization.

FORMULATION OF THE FORWARD PROBLEM

Our simulation approach computes the radiated electric fields by integrating Jefimenko's equation for a smooth bunch profile in 3D space:

$$\begin{aligned}\mathbf{E}(\mathbf{r},t) =& \frac{1}{4\pi\epsilon_0}\int d\mathbf{r}'\left[\frac{\mathbf{R}}{|\mathbf{R}|^3}\rho(\mathbf{r}',t_r)+\frac{\mathbf{R}}{c|\mathbf{R}|^2}\frac{\partial}{\partial t}\rho(\mathbf{r}',t_r)\right]\\ &-\frac{1}{4\pi\epsilon_0}\int d\mathbf{r}'\frac{1}{c^2|\mathbf{R}|}\frac{\partial}{\partial t}\mathbf{J}(\mathbf{r}',t_r).\end{aligned} \tag{1}$$

Here, $\mathbf{R} = \mathbf{r} - \mathbf{r}'$ and $c(t - t_r) = |\mathbf{R}|$ is the constraint satisfied by the retarded time t_r. The charge and current densities, ρ and $\mathbf{J}$ respectively, can be described using shape functions as follows:

$$\rho(\mathbf{r}',t) = Q_b\sum_i S_i\left(\mathbf{r}'(t)\right) \tag{2}$$

$$\mathbf{J}(\mathbf{r}',t) = Q_b\frac{\partial\mathbf{r}'(t)}{\partial t}\sum_i S_i\left(\mathbf{r}'(t)\right) \tag{3}$$

where, Q_b is the bunch charge and $S_i(\mathbf{r}')$ is a sufficiently smooth shape function in $\mathbb{R}^3$. Existing solution methods

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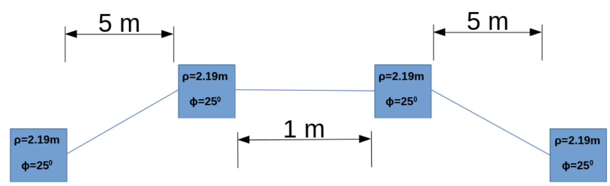

Figure 2: Layout of the magnetic chicane used in the optimization.

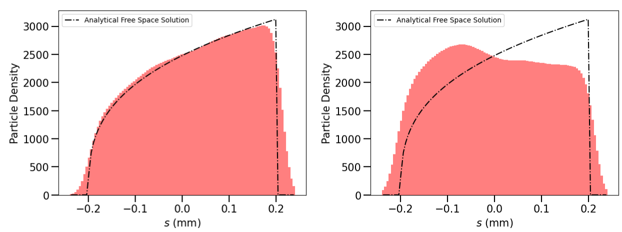

Figure 3: Optimized profile for (Left) an unshielded magnet and (Right) a magnet shielded by parallel plates with a 1 cm gap.

in 2/3D typically proceed by simplifying Eq. (1) into Liénard–Wiechert fields by assuming point particles or obtain a equivalent formulation with different predefined shape functions. In this work, we employ a different approach wherein the macroparticle ensemble is binned as shown in Fig. 1. Gaussian shape functions along each dimension of a specified width are next used to represent each bin, with the amplitudes normalized so that the overall distribution integrates to 1 over the volume of the bunch. The consequences of following this approach are as follows:

1. The bunch profile is differentiable everywhere in space, making $\dot{\rho}$ and $\dot{\mathbf{J}}$ available for integrating Eq. (1).
2. The history of the bunch can be reconstructed by storing the shape function weights rather than the phase space of the individual macroparticles.
3. Since the quadrature points used in integrating Eq. (1) are at fixed points with respect to the axis of the bunch, calculating the retarded time only involves solving a quadratic equation , as opposed to requiring nonlinear inversion for general particle trajectories.

Validation of our approach at the 1D limit has been demonstrated in a prior proceeding article [7]. Validation for 2/3D problems will be expanded on in a future publication.

PROBLEM SETUP

Consider the problem of mitigating CSR induced emittance growth in a magnetic chicane, using 4 dipole bending magnets, each with bending radius $\rho = 3.0$ m and bending angle $\phi = 25^\circ$ as shown in Fig. 2. A 1 nC, 100 MeV bunch with FWHM length of 3 mm and initial Twiss parameters $\alpha = 2.6$ m, $\beta = 40$ m and normalized emittance $\gamma\epsilon = 10^{-2}$ μm is sent into the chicane. These specific parameters ensure that the bunch length at the entry to the last chicane is still larger than the transverse size, thus staying close to a 1D limit for the beam. As described in greater detail in [5], the CSR-induced projected emittance growth through a chicane is primarily due to the longitudinal energy spread experienced by the bunch in each dipole. As the wake strength scales inversely to the bunch length, the last magnet in the sequence induces the largest energy spread.

The bunch profile at the entrance to the last magnet was described using 32 shape functions in the longitudinal dimension. The weights associated with each function was tuned using a direct search ('PatternSearch') algorithm from the PyMoo [8] package such that the longitudinal energy spread was minimized.

VALIDATION WITHOUT SHIELDING

For an ultra-relativistic beam traversing a magnet without shielding, an analytical longitudinal current profile can be derived to minimize longitudinal energy [5]

$$\lambda(s) = \frac{4}{3}\frac{(s-a)^{1/3}}{(b-a)^{4/3}}. \tag{4}$$

Here, λ is the normalized bunch profile, and $b-a$ the length of the bunch. We attempted to reproduce this shape by minimizing our chosen cost function for a 100 MeV bunch with image charges in the magnet turned off. The results of the optimization are shown in Fig. 3 (Left). As is evident, the inverse solution agrees closely to the analytical result, with small deviations near the discontinuity at 0.2 mm due to the bunch having finite energy.

OPTIMAL CURRENT PROFILES WITH SHIELDING

Next, we modified the forward problem so that the bending magnet has parallel shielding walls (described by 16 layers of image charges) 1 cm from the axis of the bunch. The optimal profile for this problem, obtained in the same manner as the no-shielding case, is reported in Fig. 3 (Right). However, with shielding contributions, the inverse solution places a bulk of particles just behind the middle of the bunch. The physical consequences of this change can be explained by the energy change curves reported in Fig. 4. Since the chosen gap size (1 cm) is significantly larger than $\sqrt[3]{R\sigma_z^2}$ (for our parameters this is ~ 1 − 2 mm) , the wakes for a Gaussian profile change very little through the range of gaps analyzed. However, the optimal profile for free space, while having a very flat wake without shielding sees a drop in energy loss near the back of the bunch, causing an increase in energy spread. The optimal shielded profile compensates for this by placing more particles near the back, creating a very flat wake with low energy spread when shielding walls are included.

We then used the optimized current profiles for both the free space case and the 1 cm gap case, together with a Gaussian profile to study energy spread downstream of a dipole

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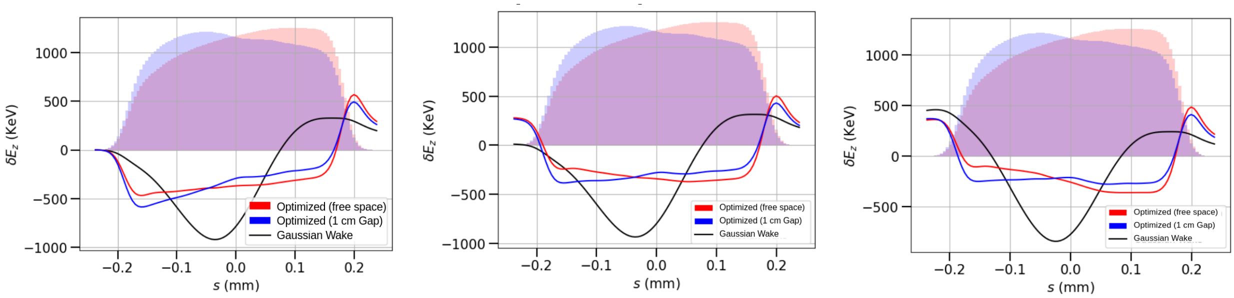

Figure 4: Comparison of the on-axis integrated energy change over the 4th dipole along the bunch for (Left) an optimized profile for an unshielded magnet (Center) a profile optimized for a 1 cm gap separation (Right) a profile optimized for a 0.8 cm gap separation. Note that the shielded profiles produce a flatter wake in the middle of the bunch.

Table 1: Normalized Projected Emittance Downstream of Chicane

Profile	Gaussian (No Shielding)	Gaussian (1 cm)	Optimized (Free Space)	Optimized (1 cm)
Emittance (µm)	5.65	5.50	2.24	1.51

with various gap sizes. As shown in Fig. 5, the solution for 1 cm gap causes slightly worse spreading than the free space solution for large gap sizes, but starts performing ~ 15 – 50% better around the gap size that it was designed for, due to the bunch being constructed specifically to compensate for the image charges. To verify this result, we tracked bunches with each of the profiles discussed so far through the chicane in Fig. 2. The bunch was initialized with a longitudinal chirp of -0.4, which results in a factor of 10 compression by the entrance to the last dipole. In order to simplify the beam transport through the magnet, CSR was turned off in the first three magnets. The $x' - z$ phase space downstream of the last magnet is reported in Fig. 6, and the corresponding projected emittance reported in Table 1. The results indicate that the combined use of shielding and profile optimization produces a meaningful reduction in emittance growth at gap sizes that are larger than the limit required for an unshielded Gaussian bunch. In particular, using a 1 cm gap along with an optimal profile designed for it saw an improvement of about 30% in emittance reduction compared to profile optimization alone.

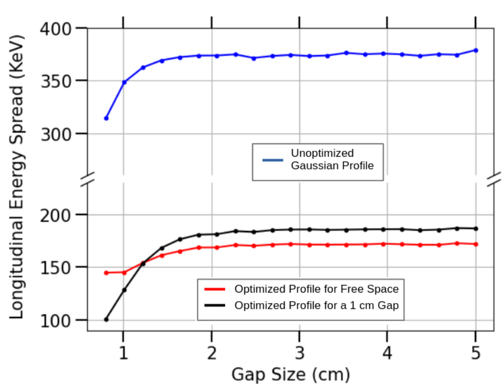

Figure 5: Average longitudinal energy spread downstream of the dipole as a function of gap separation. Each point represents a simulation with 10,000 particles generated using the corresponding profile and gap size tracked through the 4th dipole.

CONCLUSION AND FUTURE PLANS

In this work, we have reported on the current state of development of a new CSR simulation tool that accounts for 3D bunch shapes and shielding. Combining our method with a nonlinear minimizer, we derived an optimum longitudinal profile shape that minimized CSR induced emittance growth through a chicane. Rigorous analysis of optimal profiles at different shielding gaps, compensation for the influence of the first three dipoles, and investigation of the contribution of transverse profile shapes will be pursued.

ACKNOWLEDGEMENTS

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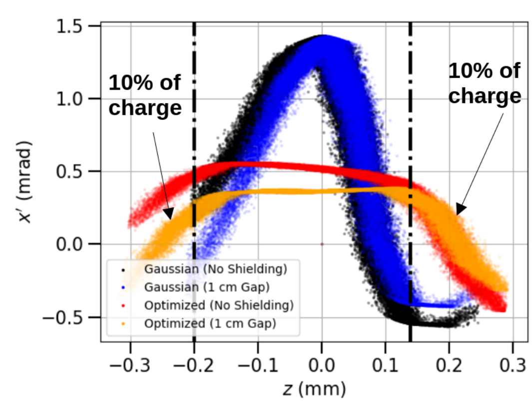

Figure 6: $x' - z$ phase space downstream of the chicane. The "Optimized (1 cm Gap)" distribution within the vertical black lines contains 80% of the charge.

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