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EFFECT OF CSR SHIELDING IN THE COMPACT LINEAR COLLIDER

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Abstract

The Drive Beam complex of the Compact Linear Collider must use short bunches with a large charge making beam transport susceptible to unwanted effects of Coherent Synchrotron Radiation emitted in the dipole magnets. We present the effects of transporting the beam within a limited aperture which decreases the magnitude of the CSR wake. The effect, known as CSR shielding, eases the design of key components of the facility.

INTRODUCTION

The design of the Compact Linear Collider (CLIC) relies on the two-beam acceleration scheme principle of imposing the power of a high charge beam with low energy (Drive Beam, DB). The fundamental requirement that the DB must be of high bunch charge makes beam transport susceptible to collective effects. One such effect is Coherent Synchrotron Radiation (CSR) which is the enhancement of radiation due to the interaction of the bunch with the emitted electromagnetic field. The enhancement factor with respect to incoherent synchrotron radiation from N particles is $1 + f(\omega)[N-1]$ where $f(\omega)$ is the photon frequency-dependent longitudinal form factor of the electron bunch. This means CSR introduces an energy loss that depends quadratically on the bunch charge. The form factor creates a cut off at photon wave lengths that are larger than the bunch length, l_b. CSR shielding can be viewed upon as the added interaction of the beam pipe image charges with the bunch whereby they decrease the power emitted due to CSR. This power scales as [1]

$$P \approx \frac{3^{2/3} N^2 e^2 c \kappa^{2/3}}{l_b^{4/3}}, \qquad (1)$$

where κ is the inverse bending radius. Thus, long bunches are needed to minimize CSR energy loss.

For optimum power extraction from the DB, the bunch length must be kept small although the beam transport in the power extraction region requires a finite bunch length to obtain transverse wake decoherence. This means that simulating CSR is crucial in the CLIC DB. The introduction of shielding in simulations will provide more realistic evaluations of the drive beam performance.

The physics of CSR is in many ways similar to the process of coherent photon emission in a free electron laser. CSR has been observed experimentally in the CLIC test facility (CTF3), where indications of the effect of shielding were also observed [2, 3]. The detailed shape of the CSR wake has not yet been verified experimentally.

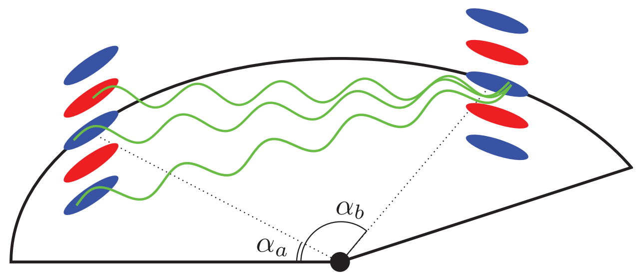

Figure 1: Schematic representation of CSR shielding.

IMPLEMENTATION OF SHIELDING IN PLACET

The beam line tracking code PLACET [4] is well suited for simulation of large portions of the DB complex since much of its functionality has been designed particularly in a CLIC framework. Thus, implementation of CSR shielding is a natural extension of its current CSR functionality. The approach is to calculate a longitudinal wake that modifies the energy of the individual particles in the beam. A schematic representation of CSR shielding is shown in Fig 1. Here is seen a bunch that travels between infinite parallel plates that are parallel to the plane of motion. Image charges on the plates, as well as the bunch itself can interact electromagnetically with the bunch at a later time. If the longitudinal bunch deformation is neglected, the wake on which the bunch travels reaches steady state if the magnet is $L_{mag} \gg \sqrt[3]{24 l_b/\kappa^2}$ if the bunch is traveling in free space. Here, L_{mag} is the magnet length. In contrast, the shielding contribution constantly changes the shape of the wake, adding to the complexity of the physical process.

The implementation relies on [5] to calculate the modification of the wake due to shielding. An assumption of this model is that the bunch is a one dimensional rod of charge. This is valid if $\sigma_x \ll \sqrt[3]{l_b^2/\kappa}$. Furthermore, shielding is modeled by perfectly conducting parallel plates separated by a distance H between which the beam travels in a circular path on a plane parallel to the plates. PLACET uses an ultra-relativistic approximation throughout, which means that the wake is simplified to

$$\begin{aligned}\frac{dE_{shield}}{ds}(s) =& 2Nr_c mc^2 \sum_{n=1}^{Q} (-1)^n \left[\left. \frac{-\kappa\lambda(s_{\alpha,n})}{r_{\alpha,n}} \right|_{\alpha_a}^{\alpha_b} \right. \\ &+ \left. \int_{\alpha_a}^{\alpha_b} \frac{\cos(\alpha)-1}{r_{\alpha,n}} \frac{d\lambda}{ds}(s_{\alpha,n}) d\alpha \right], \qquad (2)\end{aligned}$$

where $\frac{dE_{shield}}{ds}(s)$ is the energy loss per unit length, r_c and mc^2 are the classical electron radius, and rest energy, respectively. $\lambda(s)$ is the longitudinal density of electrons normalized to 1. $r_{\alpha,n} = \sqrt{2 - 2\cos\alpha + (n\kappa H)^2}$, $\alpha_a =$

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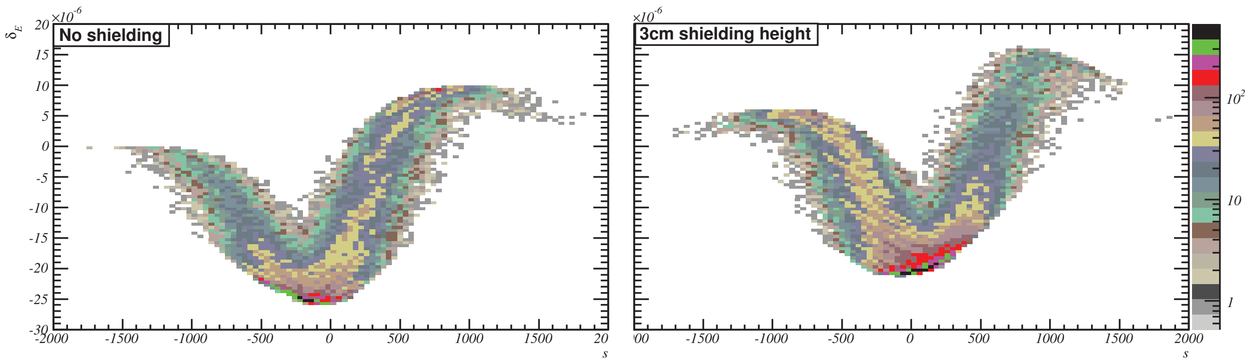

Figure 2: Particle distributions simulated with PLACET including CSR after passing a single magnet. Colour: Number of macroparticles [a.u.]. Left: No shielding. Right: Shielding enabled with the parallel plates separated by 3cm. Parameters: $L_{mag} = 3m$, $\kappa = 1/10$m, Gaussian bunch length 0.3mm, 1nC bunch charge, 800 CSR bins, 0.1m step length.

$\kappa(s - L_{mag})$ and $\alpha_b = s$, $s_{\alpha,n} = s - (\alpha - r_{\alpha,n})/\kappa$. The interpretation of the sum over n is that the physics can be described by a number of image charges with alternating charge sign. Each charge is separated by a distance H from the next one, perpendicular to the plane of motion of the electron bunch. Although this is an infinite summation, only a finite number of image charges can interact with the beam before the end of the magnet. The minimum number of image charges is set so $Q > \frac{R}{H}\sqrt{(\theta + l_b)^2 - 4\sin^2(\theta/2)}$. Apart from the first factor 2 in (2), it should be noted that the contribution from the shielding reduces to the one from regular CSR when the parallel plates are not separated at all and $Q = 1$. In the small angle approximation, this case reduces to the same physics currently implemented in PLACET [4].

The longitudinal density must be evaluated numerically at all points on the s-axis which opens up several options. In practice this is achieved by binning the particles longitudinally. The distribution is then smoothed using Savitzky-Golay filtering which means fitting a polynomial to each point on the longitudinal axis and an even number of it surrounding points. Since the longitudinal density must be evaluated between bins in order to calculate the integral in Eq. (2), these fitted polynomials are used for interpolation at non-integer bin positions.

BENCHMARKING

A number of other codes model the impact on the beam due to CSR. Examples of such codes are are ELEGANT [6], CSRtrack [7] and Bmad [8]. Of these, only CSRtrack and Bmad can model shielding. Bmad uses the 1d model and parallel plates, like PLACET, while CSRtrack implements both the 1d model with parallel plates and more sophisticated 3d models.

PLACET has previously shown very good agreement with ELEGANT in the un-shielded CSR case. The effect of shielding on the longitudinal phase space in simulation is seen in Fig. 2. Here, the bulk of the particles lose less energy than in the un-shielded case, which reduces the total energy loss, but one also sees that the shielding does not smooth the distribution out. However, it is clear that shielding improves the overall transportability of the bunch due to the smaller final energy spread.

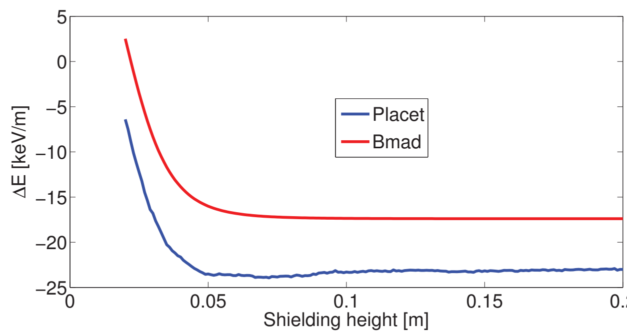

Figure 3: Energy loss in a single magnet as function of the parallel plate distance. Parameters: $L_{mag} = 3m$, $\rho = 1/10$m, Gaussian bunch length 0.3mm, 1nC bunch charge, $4{\cdot}10^5$ macro particles, 800 CSR bins, 0.1m step length, 64 image charges.

In Fig. 3, it can be seen that PLACET, as well as Bmad are self consistent, as they converge to their individual unshielded value when the plates are far apart. At smaller plate separations where shielding is of importance, one sees that the change in energy spread is qualitatively similar between the two codes.

REQUIREMENTS OF THE CLIC DRIVE BEAM

The DB bunches carry a charge of 8.4nC in a millimeter-scale bunch length which makes CSR an important process. To avoid emittance degradation, the bunches must be long when traversing large numbers of bending magnets. The bunches must be 1mm long at the entrance of the decelerators (see Fig. 4) which are the final components of the DB complex, and the phase jitter at this point must be smaller

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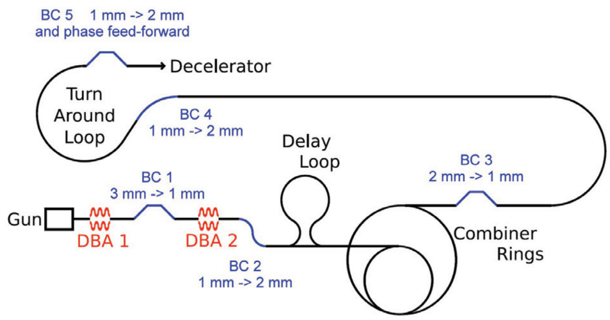

Figure 4: Schematic of the drive beam complex.

than 0.2° at 12GHz bunch frequency [9]. The strict phase stability is necessary to avoid luminosity loss of the CLIC collider itself. To obtain such a small jitter, the phase is corrected just upstream of the decelerators. The correction relies on a phase measurement just upstream of the final turnaround loop belonging to each individual decelerator section. In order for this phase measurement to have a direct physical meaning, the R_{56} between the measurement and the correction must be zero, and the longitudinal bunch distortion must be minimal between these points. This scheme means that the bunch length before entering the phase measurement must be 1mm, but this is too short to traverse the preceding delay loop and combiner rings (Fig. 4) without severe beam deterioration due to CSR. This means that the bunches must be compressed after passage through the recombination complex while they must also be decompressed prior to entering this complex. The maximum energy deviation of the beam must be kept below ± 1% of the nominal energy to be within the energy acceptance of the DB lattices [9]. The RMS energy will thus be a great deal smaller depending on the actual distribution. One can not induce additional energy spread with cavities since the additional energy jitter could result in a phase jitter larger than the tolerance. This means that the bunch compressors and decompressors need meter-scale R_{56} to decompress enough to mitigate the CSR effect, but the bunch decompressors and compressors themselves are susceptible to CSR. Thus, the solutions are to either increase the energy acceptance of the curved lattices or to shield off CSR with the beam pipe aperture. Although this has not been studied in detail, resistive wall impedance will mean that there is a lower limit for this aperture size.

APPLICATIONS OF CSR SHIELDING IN THE CLIC DRIVE BEAM

Since the parameter space is limited, there is no straightforward way to avoid CSR in the recombination complex. Hence we propose to include the effect of CSR shielding in less pessimistic simulations of e.g. emittance growths. The inclusion of CSR shielding does not however mean that bunch de-/recompression is unnecessary. The meter-scale R_{56} is at present still needed in some chicanes, but CSR shielding facilitates better decompression as seen in Table 1, where a bunch compressor with R_{56} = 1.2m is used. The initial emittance is 50μm. Results using Gaussian input beams as well as a more realistic beam from the DB linac are shown here. The more realistic and complex longitudinal profile results in local spikes in the CSR intensity. These spikes occur as a result of the derivative of the longitudinal density becoming large during the course of the decompression.

Table 1: A Bunch Decompressor

Emittance growths [μm]	Gaussian (σ_s=1 mm)	Realistic (σ_s=1 mm)
No CSR	0.0	0.0
+CSR	0.25	9.36
+CSR+shielding	0.08	4.36

CONCLUSION

The effects of CSR shielding have been implemented in PLACET and the results presented. This is important to fully understand the sources of emittance growth and instability through the CLIC DB. The PLACET implementation has been benchmarked against BMAD. Further studies are required to investigate limitations of the PLACET 1d approxation compared to the 3d capabilities of CSRtrack. A version of PLACET including CSR shielding will be available from version 0.99.08 when this benchmarking gives positive results.

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