1D CSR with shielding in the PLACET code.

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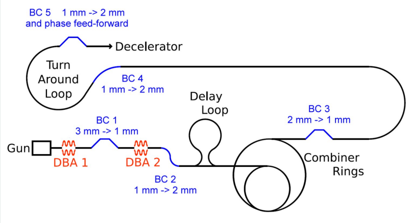
Content

The tracking code PLACET.

- Originally written by Daniel Schulte to simulate the beam delivery systems of future linear colliders. PLACET: Program for Linear Accelerator Correction and Efficiency Tests.
- Has since been expanded significantly with numerous contributors to simulate a multitude of new functionalities.
- E.g. 4 and 6-dim tracking, dynamic misalignments, advanced steering algorithms, fringe fields, long and short range wake fields, extension for halo generation, residual gas scattering, isr in all magnetic elements etc..
- User can set up entire beam lines with common beam line elements and track particles, extract optics functions etc.
- Interfaces Tcl, Octave and Python.
- The code uses the ultrarelativistic approximation.
- One such addition has been CSR in bending magnets (E. Adli). The implementation was in perfect agreement with Elegant.

Motivation

- Emitted csr power $P \approx \frac{3^{2/3} N^2 e^2 c \kappa^{2/3}}{l_b^{4/3}}$.
- The CLIC drive beam needs a complex system of bunch compression/de-compression to mitigate the effects of CSR.
- The phase stability of the CLIC drive beam is a critical parameter.
- Limited energy spread $\rightarrow$ Difficult compression/de-compression.
- Shielding could loosen the requirement for compression - accurate simulation is critically needed.
- LHeC has got interest in plate separations small compared to the bunch length.



Schematic representation of the CLIC drive beam complex.

- The implementation of regular CSR in PLACET is based on Saldin et al NIM A 398 (1997) 392.
- Choose an approach based on image charges to match the existing CSR implementation.

Content

1. Introduction
2. Underlying physics
3. The used model
4. Implementing the process
5. Details of the interface
6. Examples and Benchmarking

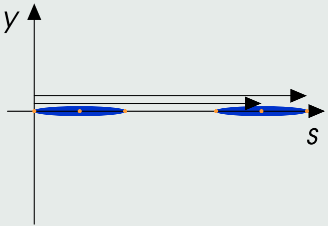
Geometry

Normal CSR

- The beam interacts with itself through an electromagnetic field
- Very low energy photons *sim* the minumim wavelength is approximetely the bunch length.
- The wake propagates ahead of the emitting particle.
- The beam is assumed to have no transverse extent (1 dimension).
- One dimensional model.

CSR shielding

- The beam travels between parallel plates separated by a distance *H*.
- Like being between two perfectly reflecting mirrors.
- The propagating photons must travel longer to interact.
- → The photons can interact with particles in the back of the bunch.
- 1 dimensional model.
- One dimensional condition: $\sigma_x \ll \rho^{1/3}\sigma_z^{2/3}$ must be fulfilled for accurate results.



NOTE Different conventions of the orientation of the *s*-axis. Internally, both normal CSR and the implementation of shielding use

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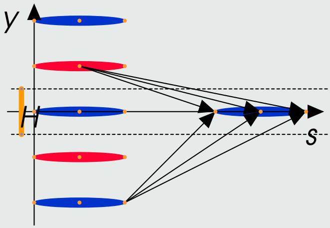

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CSR model

$$\frac{d\mathcal{E}_{\mathrm{CSR}}}{ds}(s)\bigg|_{B_1} = Nr_c mc^2\bigg\{\int_{\alpha_a}^{\alpha_b} d\alpha\bigg(\frac{\beta^2\cos(\alpha)-1}{2|\sin(\alpha/2)|}+\frac{1}{\gamma^2}\frac{\mathrm{sgn}(\alpha)-\beta\cos(\alpha/2)}{\alpha-2\beta|\sin(\alpha/2)|}\bigg)\lambda'(s_\alpha)-\frac{\kappa_1\lambda(s_\alpha)}{2|\sin(\alpha/2)|}\bigg|_{\alpha_a}^{\alpha_b}$$
$$+\int_{\Delta_a}^{\infty} d\Delta\frac{1}{\gamma^2}\frac{\lambda'(z-\Delta)}{\Delta}+\int_{\Delta_b}^{\infty} d\Delta\frac{1}{\gamma^2}\frac{\lambda'(z+\Delta)}{\Delta}$$
$$+\sum_{n=1}^{\infty}2(-1)^n\bigg[\frac{-\kappa_1\lambda(s_{\alpha,n})}{r_{\alpha,n}}\bigg|_{\alpha_a}^{\alpha_b}+\int_{\alpha_a}^{\alpha_b} d\alpha\frac{\beta^2\cos(\alpha)-1}{r_{\alpha,n}}\lambda'(s_{\alpha,n})\bigg]\bigg\} \quad \text{(A1)}$$

with the definitions

$$\alpha_a \equiv \kappa_1(s-B_1),\qquad \alpha_b\equiv\kappa_1 s,\qquad \Delta_a \equiv s-2\beta\frac{1}{\kappa_1}\sin\bigg(\frac{\kappa_1 s}{2}\bigg),\qquad \Delta_b\equiv B_1-s+2\beta\frac{1}{\kappa_1}\sin\bigg(\frac{\kappa_1(B_1-s)}{2}\bigg),$$
$$r_{\alpha,n}\equiv\sqrt{2-2\cos\alpha+(n\kappa_1 H)^2},\qquad s_\alpha\equiv s-s_0-\frac{1}{\kappa_1}(\alpha-\beta\sqrt{2-2\cos\alpha}),\qquad s_{\alpha,n}\equiv s-s_0-\frac{1}{\kappa_1}(\alpha-\beta r_{\alpha,n}). \quad \text{(A2)}$$

NOT included:

- Transverse effects.
- Reflection of photons on beampipe.
- 3D extent of bunches.

- C. Mayes and G. Hoffstaetter, Exact 1D model for coherent synchrotron radiation with shielding and bunch compression, PRST-AB **12**, 024401 (2009)
- Beginning principle is Jefimenko form of Maxwells equation (the usual approach is Lienard-Wiechert fields of relativistic charges)

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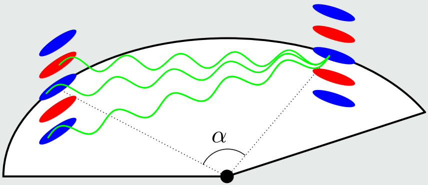
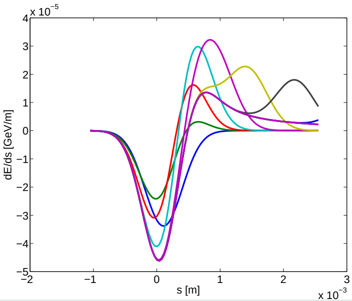
$$r_{\alpha,n} \equiv \sqrt{2-2\cos\alpha+(n\kappa_1 H)^2}, \quad s_\alpha \equiv s-s_0-\frac{1}{\kappa_1}(\alpha-\beta\sqrt{2-2\cos\alpha}), \quad s_{\alpha,n} \equiv s-s_0-\frac{1}{\kappa_1}(\alpha-\beta r_{\alpha,n}). \tag{A2}$$

- Terms 1 and 3 reduce to the CSR already implemented in PLACET when α is small.
- Terms 2,4 and 5 neglected due to $1/\gamma^2$ scaling.
- The (sum of) terms 6 and 7 are CSR shielding. These terms are newly implemented.
- Ultrarelativistic: $\beta = 1$ used.
- Notice the similarity between CSR and CSR shielding.
- Magnitude of wake is energy independant when ultrarelativistic.
- Note that when $H < l_b$, the transient term at α_a is inside the particle distribution.
- Energy conservation is not manifest.

- Choose to perform the integration using the trapezoidal rule.
- Integration is over the retarded angle $\alpha \rightarrow$ allows for accurate inclusion of bunch compression when the bunch distribution is evaluated at the correct *alpha*.
- Inclusion of bunch shape memory (bunch compression) leads to possible decreased numerical stability.
- Numerical stability was re-gained by binning particles differently longitudinally ($\pm$ 3 sigma from mean value).
- Numerical instabilities are particularly prominant at small plate separations.



Phenomenology of wake.



CSR

- The wake varies along the length of the bunch.
- The wake builds up as the magnet is traversed.
- As expected the wake propagates forward and reaches steady state.

CSR shielding

- When image charges are introduced, the wake becomes much more complex.
- As expected the effect vanishes for large plate separations.
- With zero plate distance and 1 image charge, 2 times the normal CSR wake with opposite sign.
- The wake will not reach steady state. New image charges (further away) will alway be able to interact (less strongly).

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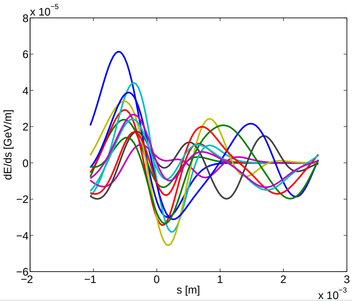

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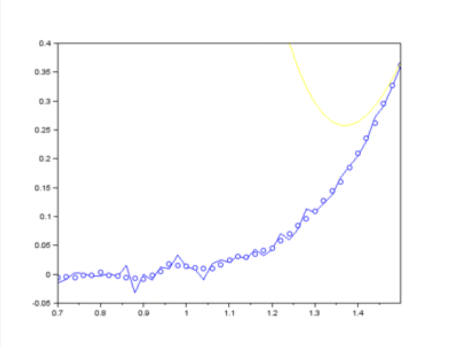
Savitzky-Golay filtering

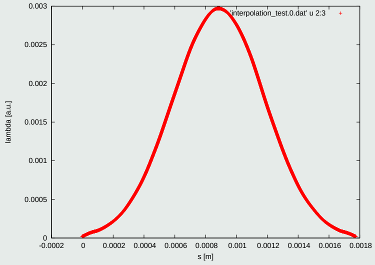


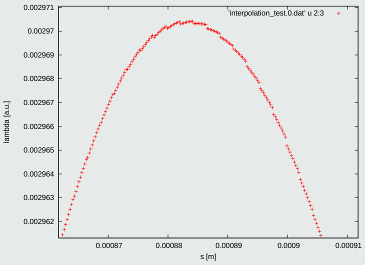
Source: Wikipedia

- Placet already uses Savitzky-Golay filtering to evaluate the charge distribution and its derivative.
- The method does polynomial least-squares fits to a point and a few of its surrounding points - And evaluates the polynomial in the point of interest.
- Normal CSR only needs to evaulate the distrubution at bin centers - we would like to evaulate it anywhere.
- Method allows the evaluation of bunch density and its derivative in positions between bins.

Savitzky-Golay interpolation

- Since an n'th order polynomial is available at each point, one can do interpolation to this order.
- Small residual numerical noise from the interpolation.





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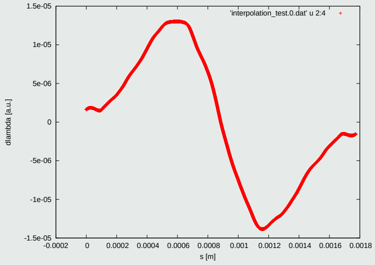
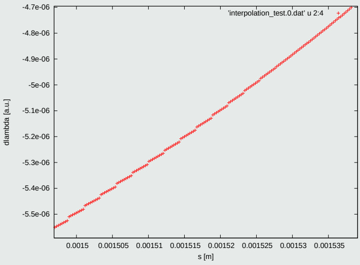




Content

New parameters of SBends in PLACET

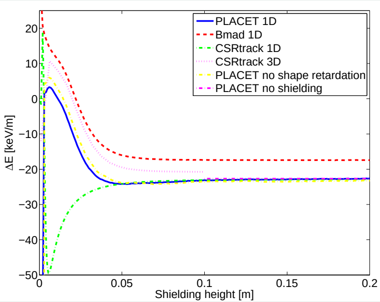
- A new set of parameters are needed to simulate shielding.
- Some parameters are re-used, but take on an additional role in the shieldig case.
- PLACET input files are scripts written in Tcl, but names of the variables are available in e.g. the Octave interface as well.

- Used only by csr shielding.
  - `csr_shielding`: Switch on csr shielding.
  - `csr_shielding_n_images`: Minimum number of images charges (on one side of the plates) used by shielding. This is at the magnet entrance modified at the entrance to the magnet to
    `csr_shielding_n_images`$> \frac{R}{H}\sqrt{(\theta + l_b)^2 - 4\sin^2(\theta/2)}$ with a warning.
  - `csr_shielding_height` Shielding height (m)
- Used by both csr without and with shielding.
  - `csr` Switch on csr.
  - `csr_charge` Total bunch charge.
  - `csr_nbins` Number of bins used to evaluate longitudinal distribution and is derivative
  - `csr_filterorder` Order of polynomial used for Savitzky-Golay filtering.
  - `csr_nhalffilter` Number of bins used on either side of a bin for Savitzky-Golay filtering.
  - `csr_nsectors` Number of sectors the magnet is split into ($\propto 1/\Delta s$)

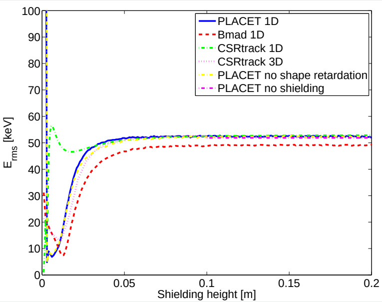
Content

Comparison with other codes

Final mean energy



Final RMS energy



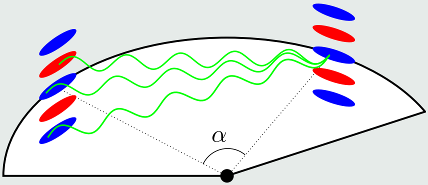
Benchmarking case

- E_0=5GeV.
- $L_{mag} = 3m$
- $\rho = 10m$
- Bunch length 0.3mm
- 1nC bunch charge
- $4{\cdot}10^5$ macro particles
- 800 CSR bins
- 0.1m step length
- >64 image charges.

Parameter set chosen to match that of Phys. Rev. ST Accel. Beams 12, 040703 (2009)

Discussion of code benchmarking.

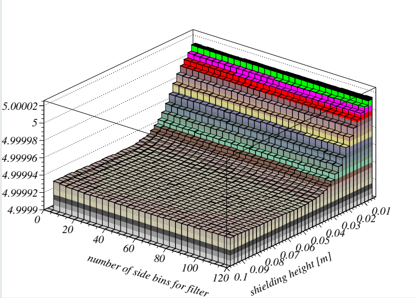
- None of the codes obey energy conservation at small plate separations.
- Even so, there is a similar change in mean+RMS energies when varying the plate distance.
- Not a full input parameter space optimization has been done for other codes than PLACET. There could poteintially be regions of input parameter space where other codes behave differently.



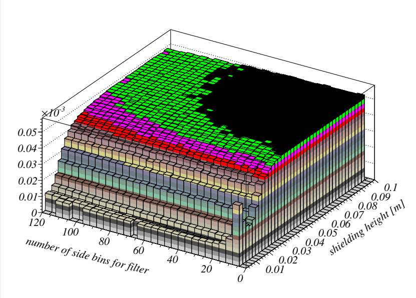
Examples and benchmarking

- Select a point where shielding is very strong: H=6mm.
- Choose a set of parameters that seems reasonnable: `csr_nbins`=1000, `csr_nsectors`=100, `csr_filterorder`=3, `csr_nhalffilter`=30.
- Vary parameters around this parameter set.
- Simulations are stable around this point.

Mean energy



RMS energy



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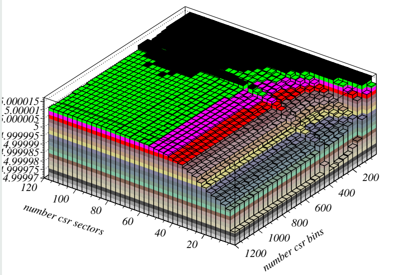

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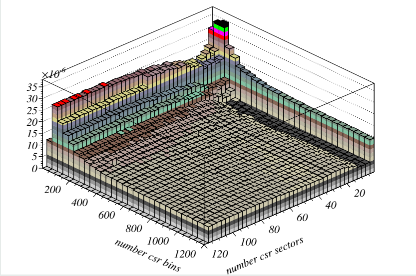

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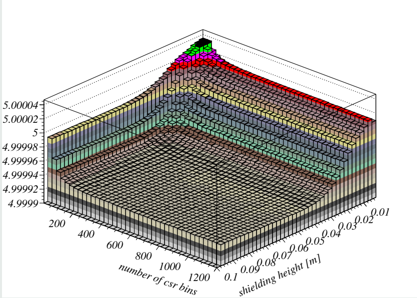

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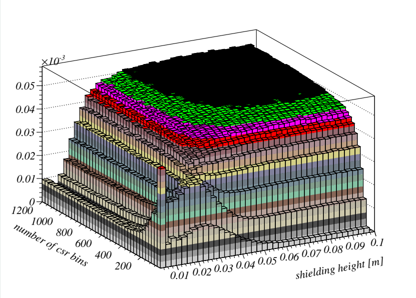

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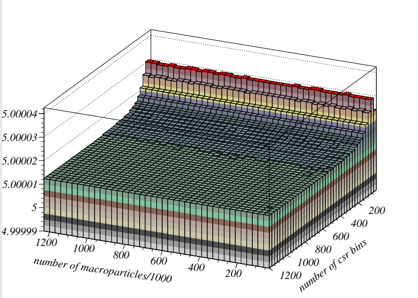

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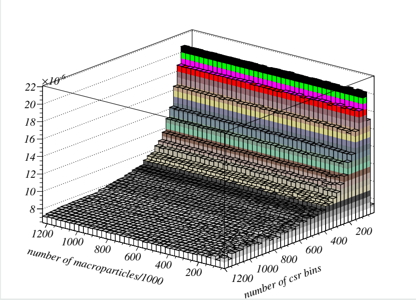
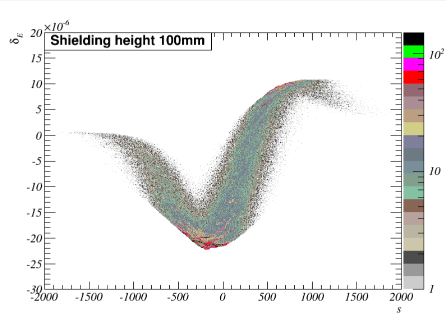
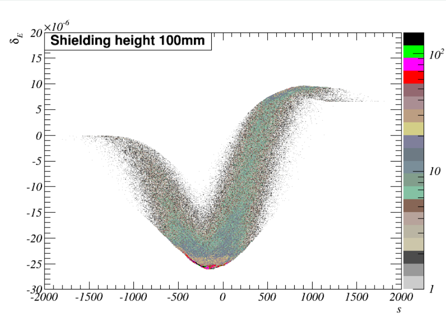


Phase space of final beam.

Bmad



PLACET



- Without shielding, there is some discrepancy between Bmad and PLACET.
- PLACET with no shielding shows perfect agreement with ELEGANT (E. Adli).
- When decreasing the parallel plate distance, the shielding wake can start to interact with the tail of the bunch.
- Large difference between Bmad and new PLACET implementation for small plate separations.

Conclusions and outlook

- CSR shielding is inherently difficult to simulate accurately. Particularly for small parallel plate separations.
- An 1D simulation of CSR shielding with bunch compression has been implemented in PLACET.
- User can input virtually any bunch distribution.
- There are differences between results obtained with different codes.
- Experimental input from e.g. V.Yakimenko et. *al* Proceedings of 2011 PAC, WEP107, might prove helpful.
- In-house experiments at CTF3 H. H. Braun et. *al* SLAC-PUB-9353 do not show detailed results on the energy distribution.
- Micro-bunching effects could in principle be simulated, but this needs testing.
- `http://savannah.cern.ch/projects/placet`