Global optimisation of the longitudinal beam profile in the CLIC drive beam.

With emphasis on post-linac dynamics.

J. Esberg,R. Apsimon, A. Latina, D. Schulte

CERN, Geneva Switzerland.

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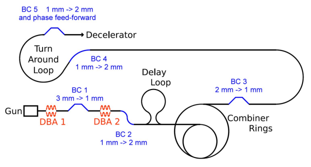
Content

Requirements of the lost-linac longitudinal dynamic

Requirements

- Phase jitter of delivered beam (including phase feed forward) must be small - 0.2° at 12 GHz.
- Bunch charge jitter must be small - $0.75 \cdot 10^{-3}$ - $\rightarrow$ limit on energy collimation.
- Bunch length at decelerators must be 1 mm for optimum form factor.
- Phase correction before decelerator (induces R_{56}).
- Phase measurement at a point where $R_{56}=0$ as measured from the exit of the DBL.
- Global $R_{56}=0$ from end of DBL to decelerator.
- Increased bunch length in the recombination complex due to CSR.
- Common belief that a factor 2 decompression in σ_z is needed.



Scheme for obtaining goal

1. Decompress after DBL to avoid CSR in the recombination complex.
2. Recompress after recombination complex to allow for phase measurement.
3. ~~Decompress to to avoid CSR in the turnarounds.~~ Strong decompression not needed in new turnaround design.
4. ~~Recompress to to get global $R_{56}=0$ and a bunch length of 1mm.~~ Assure isochronisity of turnarounds.

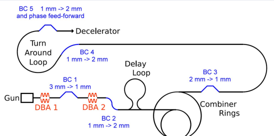
Motivation

- Increasing the energy acceptance of various lattices of the drive beam complex is a nontrivial task.
- It is very hard to get the energy acceptance above $\pm 1\%$ $\rightarrow$ low energy spread.
- The energy loss to coherent synchrotron radiation (CSR) increases with decreasing bunch length $\rightarrow$ long bunches.
- We need long bunches with low energy spread through large parts of the drive beam complex.

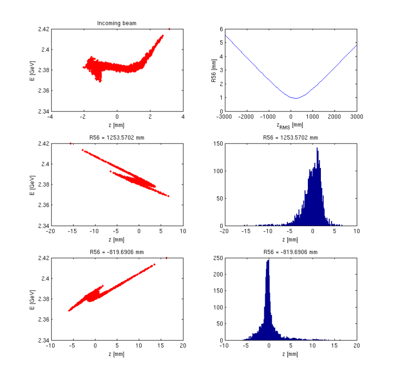
BUT

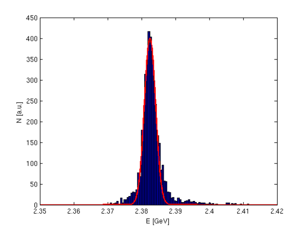
- Bunch compressors/de-compressors need energy spread to work and we need short bunches in decelerators for drive beam efficiency.

- We do not want to induce additional energy spread to aid the bunch compressors.
  - To avoid drive beam phase errors.
  - We would have “remove” the energy spread of the beam again to facititate downstream beam transport.
- The bunch de-compressors themselves suffer under CSR.
- We need to eliminate the need for either long bunches or low energy spread.
- Unlikely that we can increase acceptance of lattices.
- The horizontal emittance budget is nearly completely used by the recombination complex (50% increase in emittance) - without collective effects (CSR, resistive wall ...). Indications that CSR deteriorate the beam significantly.
- $\rightarrow$ look into an effect that decreases the effect of CSR - CSR shielding.



Incoming beam hypothesis





- Beam directly after the DBL. Gaussian distribution at the DBL entrance.
- $\sigma_{z,RMS} = 1mm$
- RMS energy spread: 0.17%
- Top-to-bottom energy spread: 2.15%
- To get a factor 2 decompression in σ_z we need an R_{56} of $\sim$1.25 m
- Top-to bottom energy spread just under the limit of accceptance of recombination complex and turnaround loops (see talk by R. Apsimon, this session).
- Optimum bunch would look more like a truncated Gaussian in energy space with sharp cut-offs.

Content

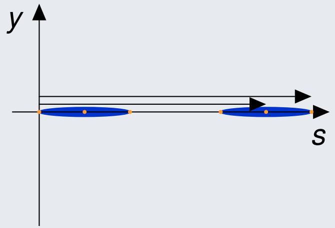
Geometry

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 travel s between parallel plates separated by a distance H.
- Like being between two perfectly reflecting mirrors.
- The propagating photons must travel longer to interact.
- $\rightarrow$ The photons can interact with particles in the back of the bunch.
- 1 dimensional model.
- One dimensional condition: $\sigma_x \ll \rho^{1/3}\sigma_z^{2/3}$ - we are close to the limit.



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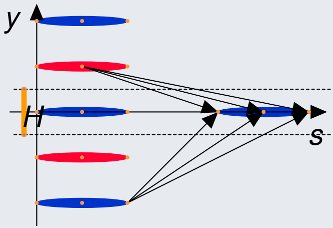


Content

CSR model

$$
\begin{aligned}
\frac{d\mathcal{E}_{\mathrm{CSR}}}{ds}(s)\Big|_{B_1} = N r_c m c^2 \Big\{ & \int_{\alpha_a}^{\alpha_b} d\alpha \Big(\frac{\beta^2 \cos(\alpha) - 1}{2|\sin(\alpha/2)|} + \frac{1}{\gamma^2} \frac{\mathrm{sgn}(\alpha) - \beta\cos(\alpha/2)}{\alpha - 2\beta|\sin(\alpha/2)|} \Big) \lambda'(s_\alpha) - \frac{\kappa_1 \lambda(s_\alpha)}{2|\sin(\alpha/2)|} \Big|_{\alpha_a}^{\alpha_b} \\
& + \int_{\Delta_a}^{\infty} d\Delta \frac{1}{\gamma^2} \frac{\lambda'(z-\Delta)}{\Delta} + \int_{\Delta_b}^{\infty} d\Delta \frac{1}{\gamma^2} \frac{\lambda'(z+\Delta)}{\Delta} \\
& + \sum_{n=1}^{\infty} 2(-1)^n \Big[\frac{-\kappa_1 \lambda(s_{\alpha,n})}{r_{\alpha,n}} \Big|_{\alpha_a}^{\alpha_b} + \int_{\alpha_a}^{\alpha_b} d\alpha \frac{\beta^2\cos(\alpha) - 1}{r_{\alpha,n}} \lambda'(s_{\alpha,n}) \Big] \Big\} \qquad \text{(A1)}
\end{aligned}
$$

with the definitions

$$
\alpha_a \equiv \kappa_1(s - B_1), \quad \alpha_b \equiv \kappa_1 s, \quad \Delta_a \equiv s - 2\beta \frac{1}{\kappa_1} \sin\Big(\frac{\kappa_1 s}{2}\Big), \quad \Delta_b \equiv B_1 - s + 2\beta\frac{1}{\kappa_1}\sin\Big(\frac{\kappa_1(B_1 - s)}{2}\Big),
$$

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

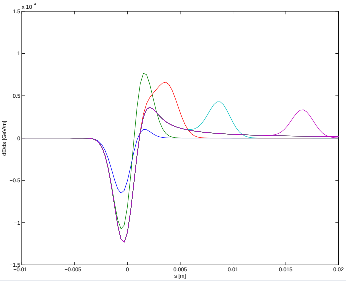
- Terms 1 and 3 reduce to the CSR already implemented in PLACET when α is small.
- Terms 2,4 and 5 neglected due to $1/\gamma^2$ scaling.
- The (sum of) terms 6 and 7 are CSR shielding. These terms are newly implemented.
- Ultrarelativistic: $\beta = 1$ used.
- Notice the similarity between CSR and CSR shielding.
- Magnitude of wake is energy independant when ultrarelativistic.

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)
- Longitudinal space charge is a natural inclusion in the theory.

Phenomenology of wake/ analytical cross check.



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 after a distance $L \gg \sqrt[3]{\frac{24 l_b}{\kappa^2}}$.

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.
- It might be hard go gain a true intuition for the process.
- Shown here: 15 image charges on each side of plates separated by 5 cm.
- Relatively small reduction in the original wake - in some cases even worsens the wake.
- Steady state is not reached.

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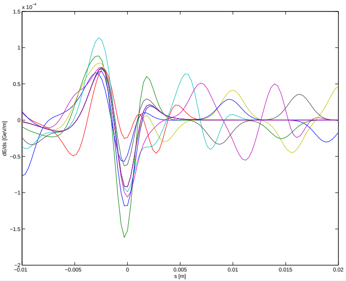

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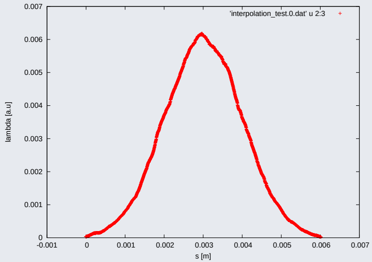
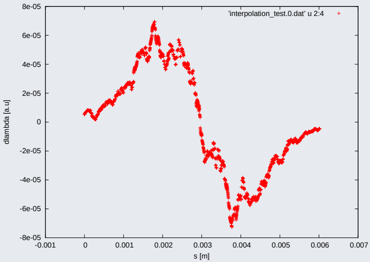
Content

Savitzky-Golay interpolation

- 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.
- Since an *n*'th order polynomial is available at each point, one can do interpolation to this order.
- Some residual numerical noize from the interpolation, but I consider it to be good enough.
- The density remains unaltered in the bin centers.





Content

Examples and benchmarking

- Test implementation of shielding by freezing longitudinal motion.
- Compare to theory - under conditions where steady state is dominant for normal CSR.
- Placet shielding calculation becomes unstable at small plate separations.

Longitudinal phase space

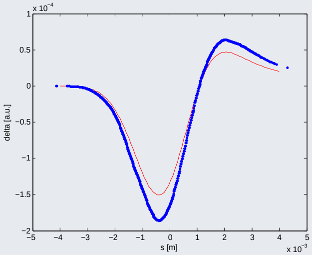
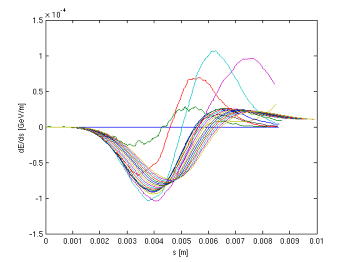


Figure: No shielding

PLACET wakes



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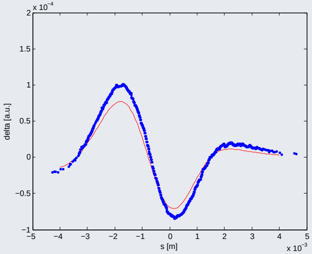
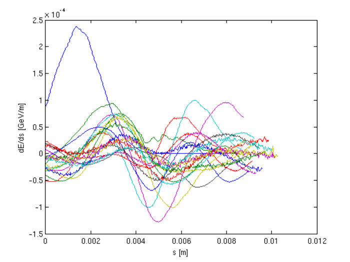


Figure: Plate height 4 cm

PLACET wakes



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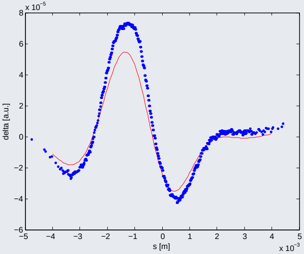

Figure: Plate height 3 cm

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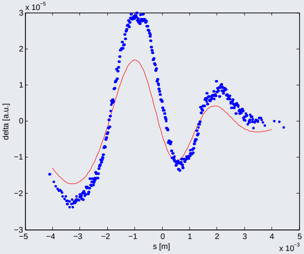

Figure: Plate height 2 cm

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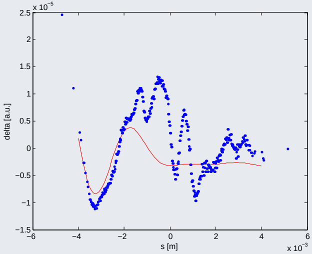
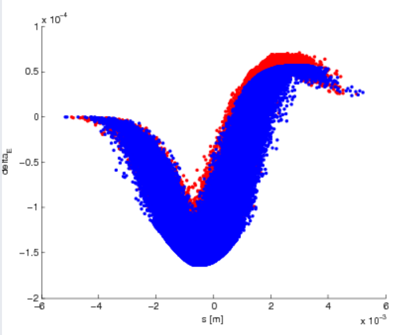


Figure: Plate height 1 cm

Benchmarking PLACET against Bmad

- Chose 15 image charges for all calculations (including analytical one). It means that the results with small plate distances are unphysical, but still comparable to theory.
- Close to unshielded steady state BMAD and PLACET agree for large plate distances.

ρ=10m, L=5m, Bmad in red, PLACET in blue



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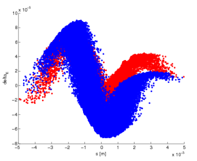

Figure: 4 cm plate distance

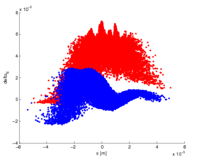

Figure: 2 cm plate distance

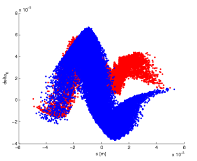

Figure: 3 cm plate distance

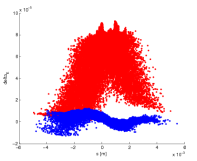

Figure: 1 cm plate distance

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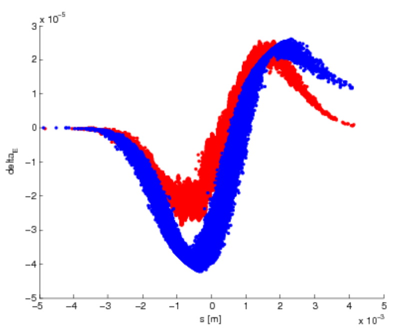

Figure: No shielding

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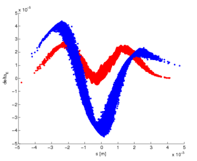

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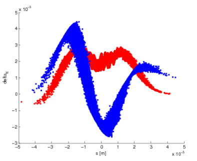

Figure: 3 cm plate distance

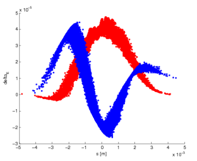

Figure: 2 cm plate distance

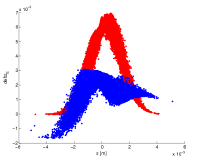

Figure: 1 cm plate distance

Content

CSR shielding in a real system

Preliminary bunch decompressor

- Investigate the effect of shielding on the initial bunch de-compressor.
- Lattice designed for an R_{56} of 1.2 meters to get factor 2 decompression for realistic beam.
- 4 cm plate separation.
- Initial emittance 50μm.
- choose 0.17% energy spread for Gaussian beam to get roughly same decompression
- Emittance growth of real beam is large is due to the high longitudinal density of the beam core.
- With the realistic beam, the emittance growth is more than halved by the shielding.

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

- The large difference between the Gaussian and realistic beam most likely due to the sharp rise/fall in density at the bunch head/tail during decompression. While the tails are folded in, the longitudinal density becomes large locally. To be determined

Choosing dipole parameters in the turnaround lattice

- In order to choose lengths of the drive turnaround magnets a study of the effect of ISR and CSR was done to determine impact on emittance growth.
- Fix the bending angle and vary the Sbend length
- In principle: $\Delta\epsilon = \int \frac{<d\epsilon>}{ds} ds = \int \int \frac{d^2 N}{ds d\delta} \delta^2 \mathcal{H}(s) d\delta ds$
- where $H(s) = \left(\gamma D^2 + 2\alpha D D' + \beta D'^2\right)$
- but spectrum relatively complex (depends on form factor) $\frac{d^2 N_C}{dE_\gamma ds} = (1 + f(E_\gamma)(N-1)) \frac{d^2 N_I}{dE_\gamma ds}$

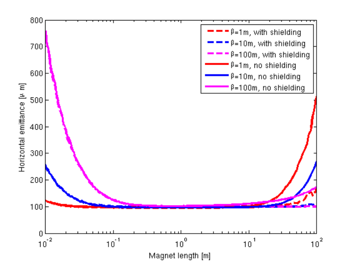

Figure: Horizontal emittance

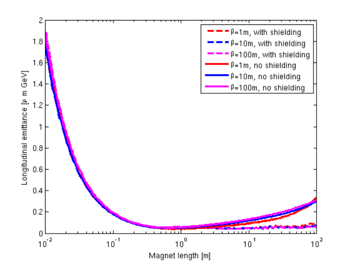

Figure: Longitudinal emittance, zero initial energy spread

Conclusions/wish list

- Preferred bunch profile has got heavy energy tails in energy.
- Bunch profile must have a maximum top-to bottom energy spread of $\sim$2% (sharp energy cutoff) dictated by turnarounds and recombination complex.
- Preferably chirped with lowest energies towards the bunch bunch tail.
- No steep rise in longitudinal density.

- Caution work in progress.
- Are the CSR models and implementations sufficient? (parallel plates, 1D model)
- Reflection from chamber walls could prove an important process as well.
- Still some cross checks of PLACET CSR shielding to do.
- Dialogue with D. Sagan (author of Bmad) to determine regions of validity of codes.
- Need to test with parameters similar to in Phys. Rev. ST Accel. Beams 12, 040703 (2009) to re-create well documented results with Bmad.
- We might choose to include CSR shielding in all calculations $\rightarrow$ In that case, we must trust shielding completely.
- Do we need an experiment to verify CSR models?

Thank you