# CSR implementation in PLACET

current status and outlooks

E. Adli, August 15, 2007

## Summary of work

- 1D model of CSR wake implemented in Sbend element
- based on paper [Saldin et al.] + updates
- works for arbitrary bunch distributions
- includes transient effects
- follows the implementation as done in elegant (proven approach)
- Choice of implementation done after discussions with Frank Stulle
- Remaining: incorporate CSR wake in drift spaces trailing bends

## Some much-cited papers used for the CSR work

- [Murphy et al.]
  - Cons: limited to circular orbit (steady-state only)
  - Pros: includes some shielding effects (parallel plates, Gaussian only?)
- [Saldin et al.]
  - Pros: applies to circle sector (dipole)
  - Cons: free space CSR (no shielding)

Rationale for following [Saldin et al.] / elegant free space implementation:

* PLACET can provide upper limit of CSR effect ( dedicated codes might then be used if CSR wake is seen to have effect)

* easily benchmarking against proven code available

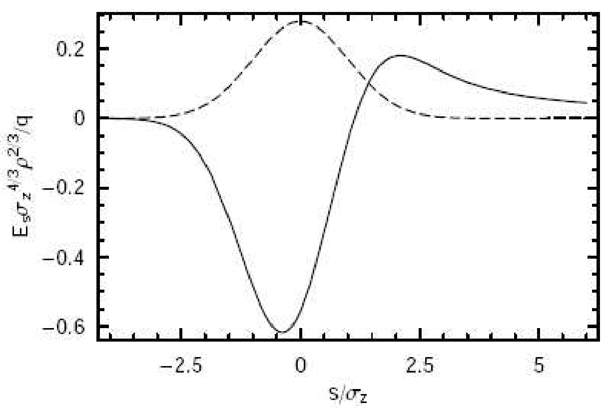
## The famous steady-state CSR wake for Gaussian bunch

Can be calculated as the radiation reaction force, integrated over an arbitrary bunch charge profile, $\lambda(s)$, as [Stupakov]

$$\varepsilon(s) = N \int_{-\infty}^{\infty} E_s(s-z)\lambda(z)dz = K \int_{-infty}^{s} \frac{1}{(s-z)^{1/3}} \frac{d\lambda}{dz} dz$$

where the longitudinal field in a bend is given approximately by:

$$E_s = -\frac{d(\phi - cA_s)}{ds} \propto -\frac{1}{R^{2/3}} \frac{d}{ds} (\frac{1}{s^{1/3}})$$




Steady-state CSR field of a Gaussian bunch [Stupakov]

## Taking into effect transients

Result from [Saldin et al.] (notation from [Borland] ):

$$\frac{dE(s,\phi)}{d(ct)} = T_1(s,R,\phi) + T_2(s,R,\phi)$$

Main component:

$$T_1 = K\int_{s-s_L}^{s} (\frac{1}{s-z})^{1/3}\frac{d\lambda}{dz}dz$$

Transient component:

$$T_2 = K\frac{\lambda(s-s_L)-\lambda(s-4s_L)}{s_L^{1/3}}$$

with $K = -2e^2/(3R^2)^{1/3}$ and $s_L = R\phi^3/24$ (slippage length). Steady state: $s_L \to \infty$ (result above)

$$\frac{dE(s,\phi)}{d(ct)} = K\int_{-\infty}^{s} (\frac{1}{s-z})^{1/3}\frac{d\lambda}{dz}dz$$

## PLACET implementation: outline

- Implemented for PLACET particle beam
- Dipole (Sbend element) divided into $N_1$ sectors
- For each sector: beam is tracked, then CSR wake is calculated and energy change over distribution is applied
- Beam sorted and binned into $N_2$ bins to get longitudinal distribution $\lambda(s)$
- Numerical derivation and integration
- In derivation: filtering over $N_3$ bins for smoothing

## PLACET implementation: user interface

```
Sbend -help ...

-csr [BOOL]  enable Coherent Synchrotron Radiation (CSR)

-csr_nbins [#]   CSR: # of bins ( >= 10 )

-csr_nhalffilter [# of bins]  CSR: Savitzky-Golay filter half-width ( >= 1 )

-csr_nsectors [#]   CSR: # of dipole sectors ( >= 1 )

-csr_savesectors [BOOL]   CSR: save data for each sector
                           [nbin s lambda dlambda dE_ds [GeV/m] ]

-csr_enforce_steady_state [BOOL]   CSR: enforce steady state mode (infinite slip

-csr_charge [C]   CSR: bunch charge    (temporary)
```

Example:

```
Sbend  -length 1.0 -angle [expr 1*0.66667] -e0 $e0 -E1 0.0 -E2 0.0 -six_dim 1
 -csr 1 -csr_nbins 510 -csr_nhalffilter 20 -csr_nsectors 100

-csr_savesectors 1 -csr_charge 1e-9 -csr_force_steady_state 0
```

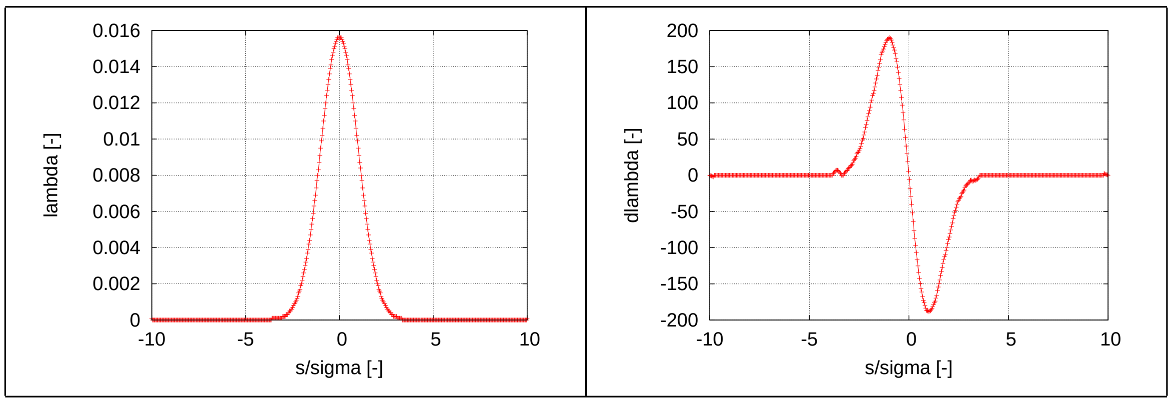
## Test: reproduction of results in [Saldin et al.]

The paper on which the implementation is based contains a test case with a Gaussian bunch with $\sigma_z = 50\mu m$ and a dipole with $R = 1.5m$.

We check the PLACET results with this test-case, which will test both the steady-state and the transient part of the CSR wake.

- PLACET input particle distribution: Gaussian, $N = 10000$, $\sigma_z = 50\mu m$, "cut" at $10\sigma$, $Q = 1nC$

The input distribution was almost ideal Gaussian distribution, binned as follows:




| | |
|---|---|
| $10\sigma,\ \sigma = 50\mu m$ | $10\sigma,\ \sigma = 50\mu m$ |

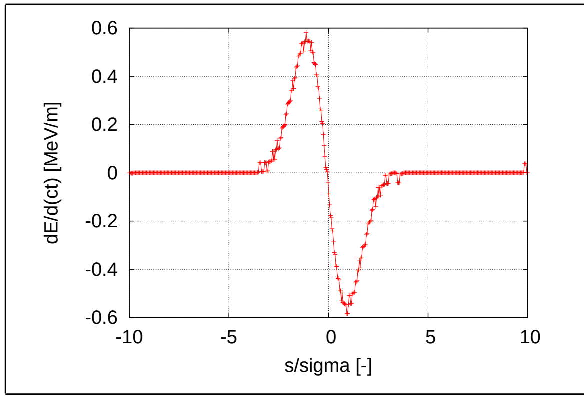
- Other beam parameters: $E_0 = 0.7GeV$

- Dipole parameters: $R = 1.5m$, $l = 1m$

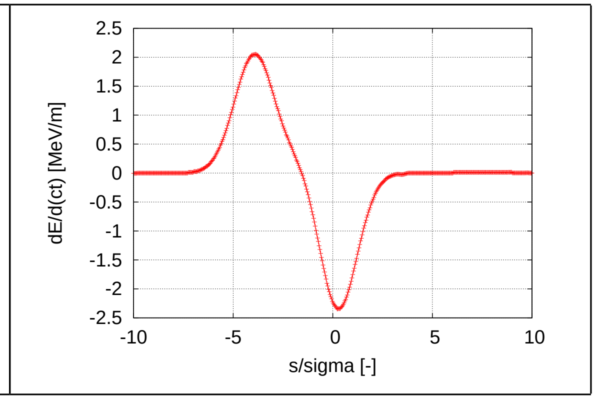
- CSR simulation parameters: csr_nbins=510, csr_nfilter=5, csr_nsectors=100

We track the distribution through the dipole. For this simulation we disable the 6D tracking in order to preserve the distribution at each point. This is done in order to reproduce the results in [Saldin et al.].

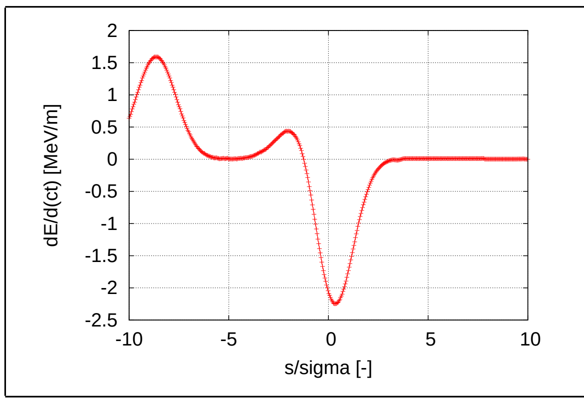
The graphs below shows the CSR wake after {5,14,18,100}cm into the dipole (already after ~35 cm we are in steady-state mode). **We observe that the correspondence with [Saldin et al.] graphs is very good.**



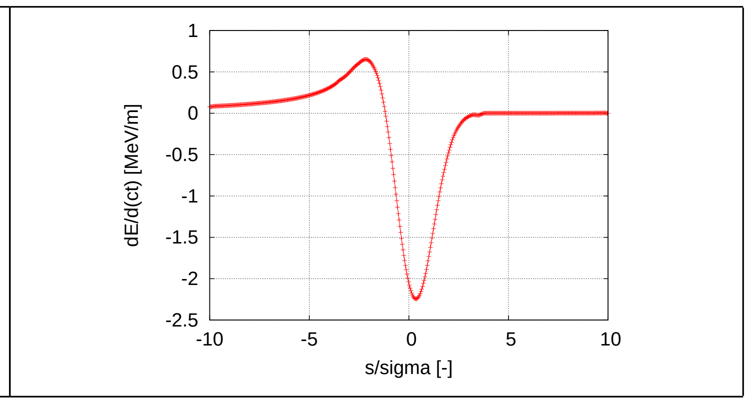

s=5 cm




s=14 cm



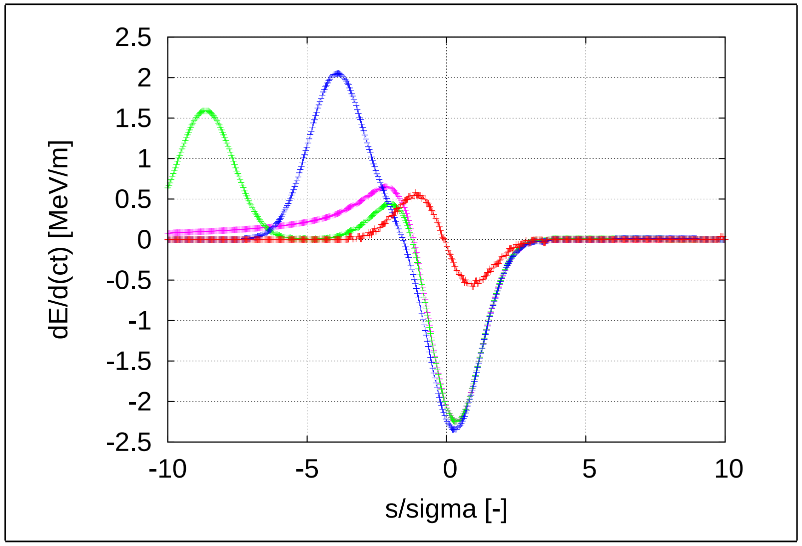

s=18 cm




s=100 cm (steady-state)

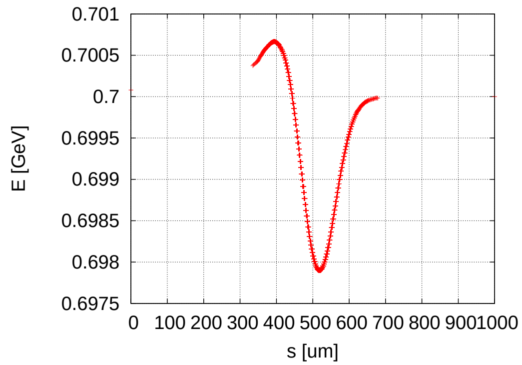
The transient zone length is in the order of the overtaking length:

$$L_0 = (24R^2\sigma_z)^{1/3} = 0.14m$$




s=[0.05,0.14,0.18,1] m

Furthermore, we also plot the final beam energy (again, in the non-realistic case of 4D tracking). We note that the total energy loss for the centered is about ~2 MeV, as it should, while the leading particles have gained some energy.




Total energy loss after dipole (4D)

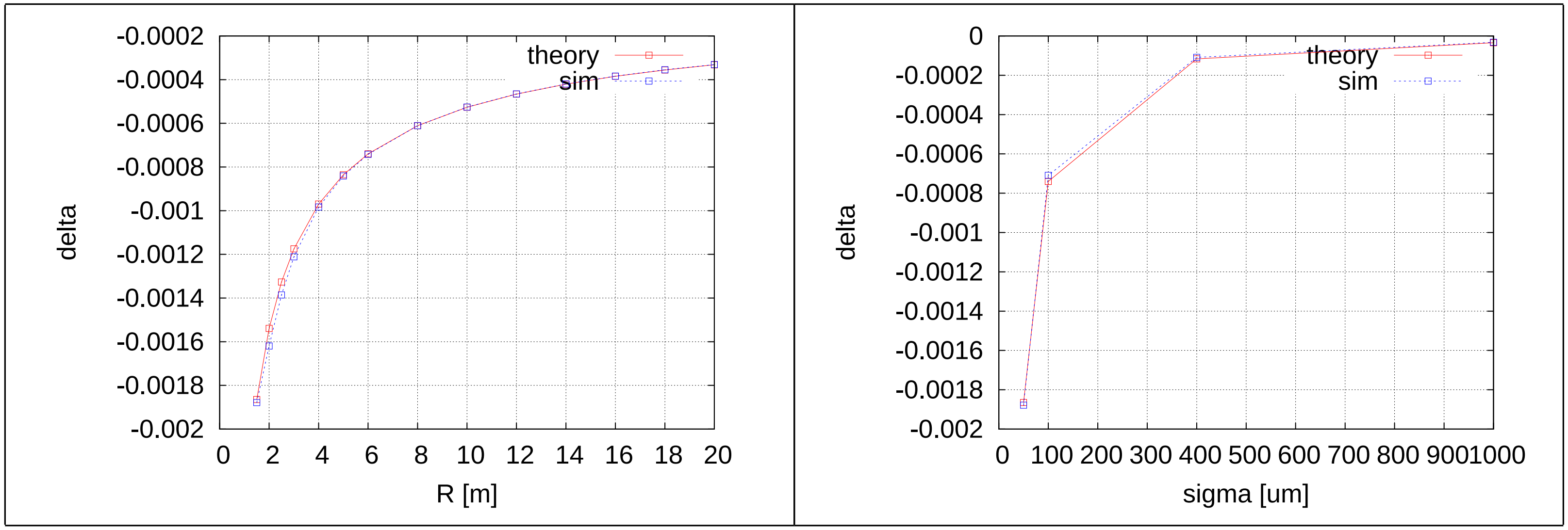
## Test: correct energy loss

Dependence on $R$ and $\sigma_z$

If we assume no transient effect, there exists analytical formulas for the mean energy offset, $<\delta>= (p-p_0)/p_0$ . Scales as $R^{-2/3}$ and $\sigma_z^{-4/3}$ . The exact formulas are found in [Borland].

We check our code against these results (using the -csr_enforce_steady_state switch). We scale with both R and $\sigma_z$.

For $<\delta>$ we get very good correspondence with the theoretical result.




| $< \delta >$ versus R ($\sigma_z = 50\mu m$) | $< \delta >$ versus $\sigma_z$ (R=1.5m) |
|---|---|

## Test: longitudinal dynamics with CSR wake

In order to reproduce [Saldin et al.] we turned off 6D tracking. Now we include the update of the z-variable in our simulations. We can then observe the effect of the CSR wake has on the bunch longitudinal distribution.

We still use the parameters from [Saldin et al.] which in fact is an ultrashort bunch going through a sharp bend.

Leading particles will get an energy increase and longer path length, while the opposite is true for trailing particles. This leads eventually to a bunch compression, as seen from the graphs showing the charge distribution and the CSR wake at various places of a 1 meter long R=1.5 m dipole.

NB: the parameters used here, $E_0 = 0.7GeV$, $\sigma_z = 50\mu m$ and $R = 1.5m$ are quite extreme.

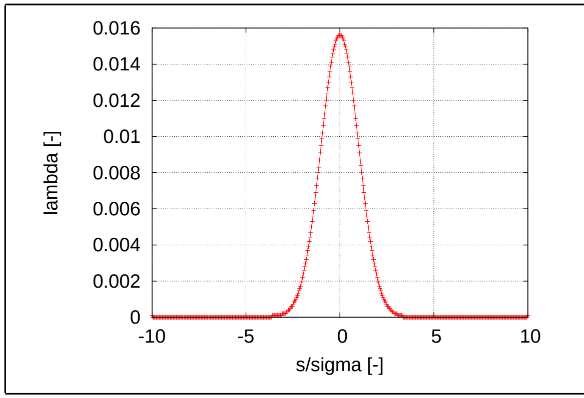
PLACET input particle distribution: Gaussian, $N = 10000$, $\sigma_z = 50\mu m$, “cut” at $10\sigma$, $Q = 1nC$.

Other beam parameters: $E_0 = 0.7GeV$

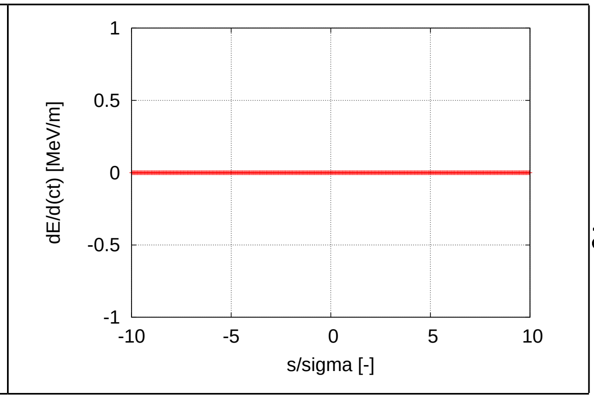
Dipole parameters: $R = 1.5m$, $l = 1m$

CSR simulation parameters: csr_nbins=510, csr_nfilter=20, csr_nsectors=100 (large smoothing)

The graphs below show the bunch longitudinal charge distribution as the dipole is traversed:

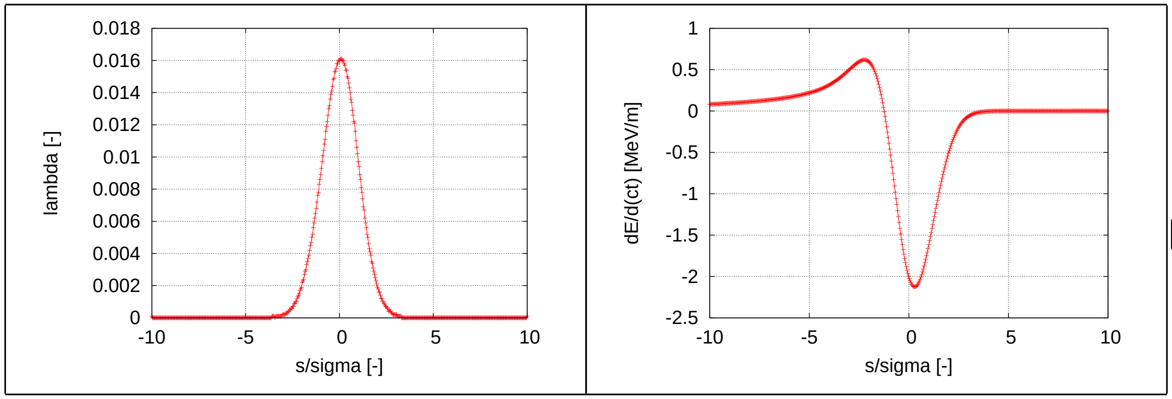



$\lambda,\ s = 0$



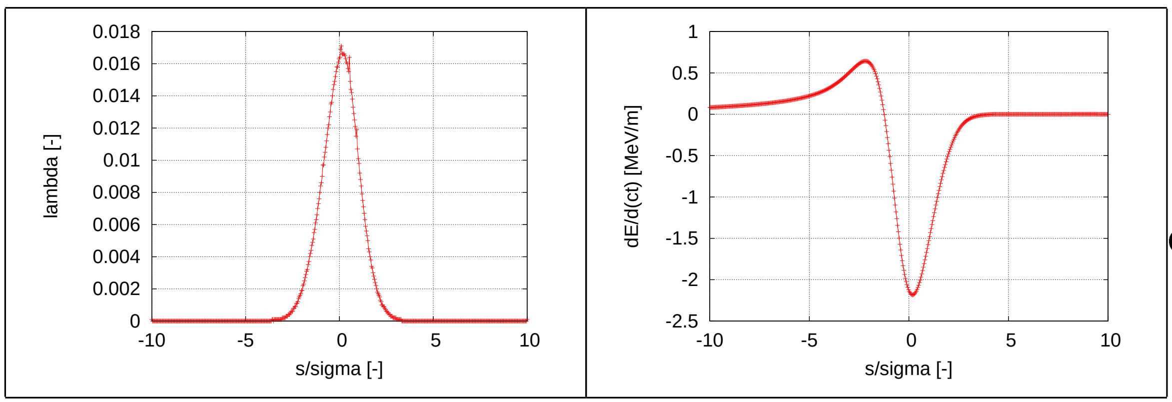

$dE/ds$, s=0

a



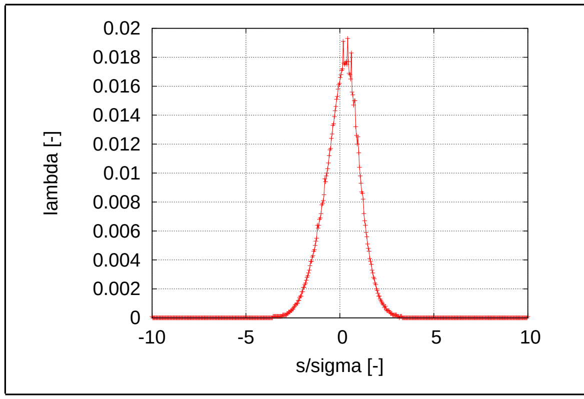

b

| $\lambda,\ s = 0.5m$ | $dE/ds,\ s = 0.5m$ |
|---|---|

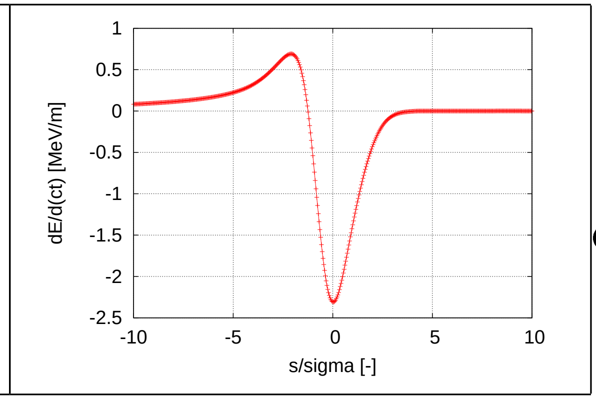



d

| $\lambda,\ s = 0.6m$ | $dE/ds,\ s = 0.6m$ |
|---|---|

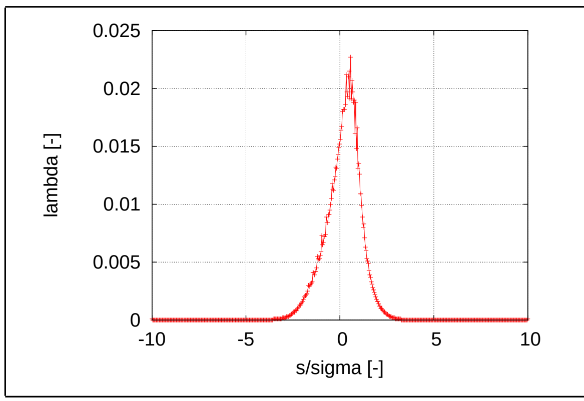



$\lambda,\ s = 0.7m$

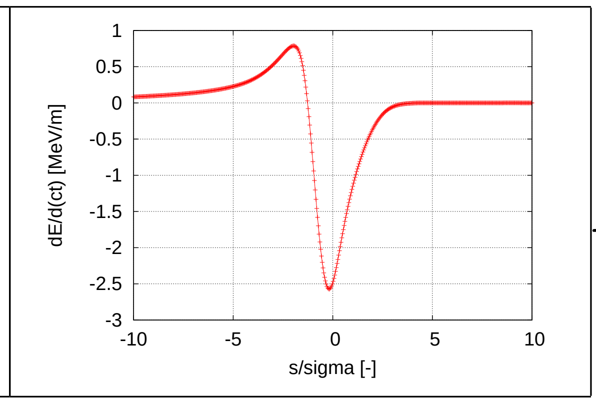



$dE/ds,\ s = 0.7m$

e

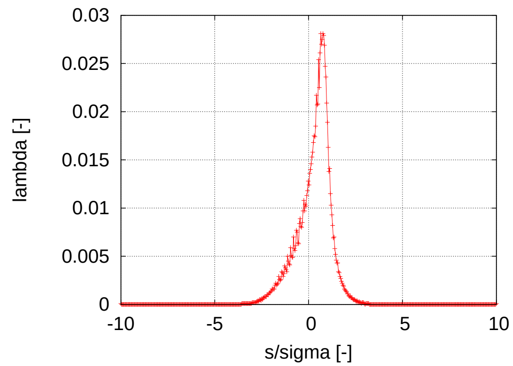


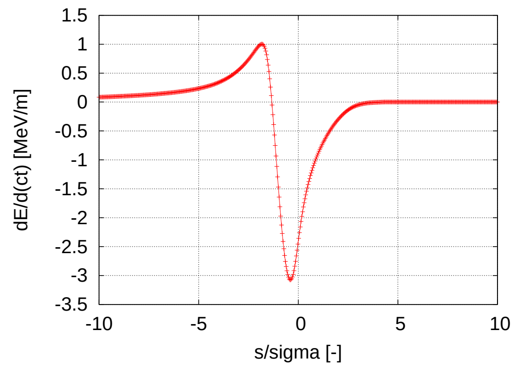

$\lambda,\ s = 0.8m$




$dE/ds,\ s = 0.8m$

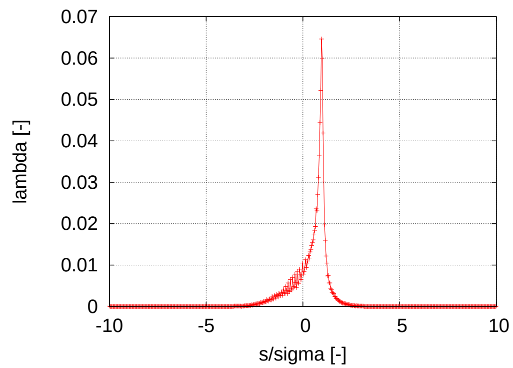
f

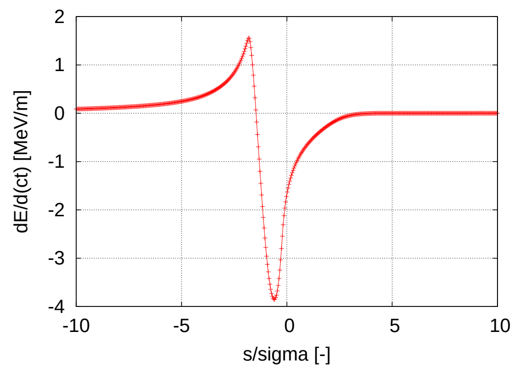



g

| | |
|---|---|
| $\lambda,\ s = 0.9m$ | $dE/ds,\ s = 0.9m$ |

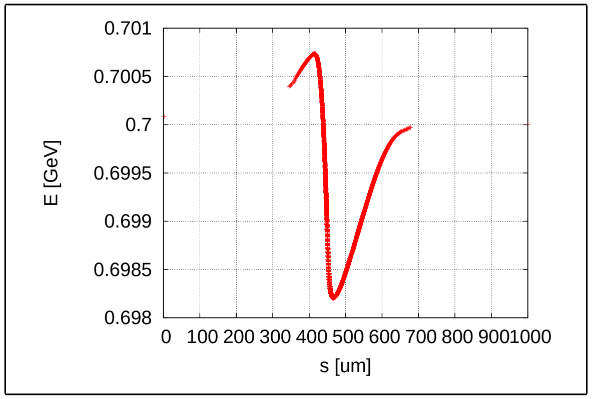



h

| | |
|---|---|
| $\lambda,\ s = 1m$ | $dE/ds,\ s = 1m$ |

The final energy profile of an ultrashort bunch after a sharp bend.



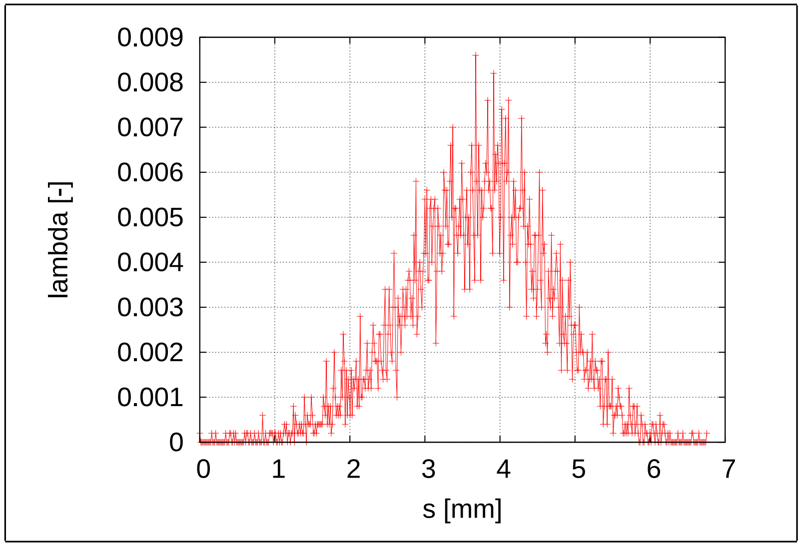
0.701
0.7005
0.7
0.6995
0.699
0.6985
0.698
E [GeV]
0 100 200 300 400 500 600 700 800 9001000
s [um]


$E, \; s = 1m$

## Realistic bunch: sampling / noise effects

The distribution so far was an idealized one. We now go to a more realistic distribution. As example we take a sample drive beam bunch distribution after the 2 BCs as generated by Frank Stulle (NB: not from his latest work).

This distribution has only N=5000, and $Q = 7.8nC$. If we try to bin with 510 bins we see that due to the small numbers of particles per bin we get a very spiky histogram, even a large filter cannot do much good:



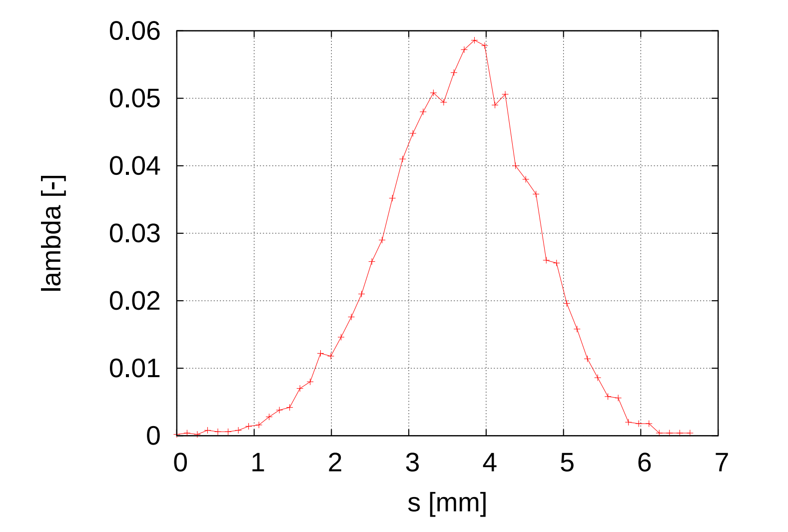

Drive beam distribution

By reducing the number of bins to 100 (and by this reducing accuracy of the wake calculations) we can get more reasonable wakes. For better accuracy we probably need have more particles per bunch.

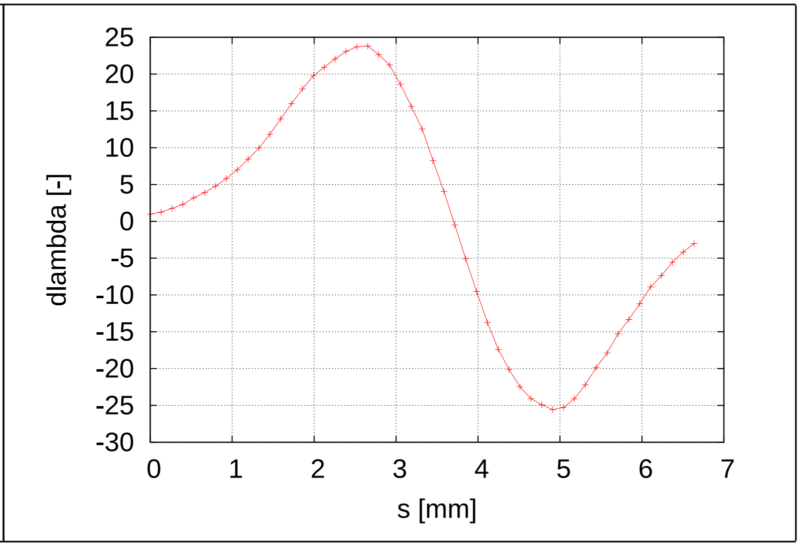
Other beam parameters: $E_0 \sim 2.4 GeV$

Dipole parameters: $R = 1.5m$, $l = 1m$

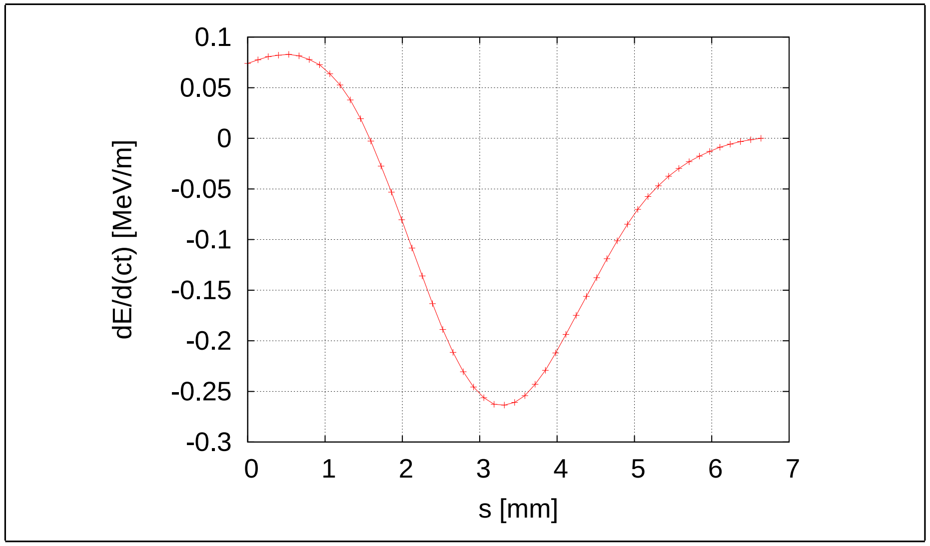
CSR simulation parameters: csr_nbins=51, csr_nfilter=10, csr_nsectors=100




Drive beam distribution




Drive beam distribution




Drive beam wake (steady-state)

## Calculation time considerations

We expect the time consumption to be roughly:

* linear with nsectors

* linear with nbins (binning, integration)

* between nlogn and n^2 with nparticles (quicksort + binning)

However, we don't know how big the absolute terms are, or e.g. whether sorting is quickly a limiting factor (can then think of some tricks).

Some quick tests show:

N=10000, nbins=510, sec=20 -> $T_{sim} \approx 1$s

N=100000, nbins=510,sec=20 -> $T_{sim} \approx 5$s

N=100000, nbins=5100,sec=20 -> $T_{sim} \approx 54$s

—

It seems that the numbers of particles (and thus the sorting term) is not necessarily what drives the running time.

**Still: there is room for optimization of the running time TO BE DONE**

## CSRDrift (to be implemented)

- It is shown e.g. [Stupakov et al.], [Dohlus et al.] that the CSR wake is of significant effect also in the drift space trailing the bend.

- From [Stupakov et al.] :

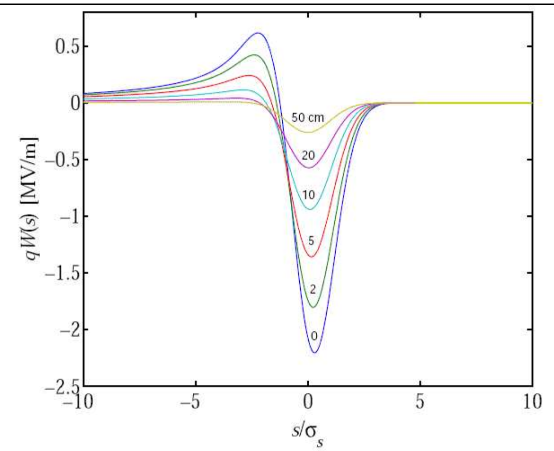



Figure 2: CSR exit wakefield at various distances (in cm) from exit of 50-cm long bend magnet with $R = 1.5$ m, $q = 1$ nC, $\sigma_s = 50$ $\mu$m (compare to Fig. 3 in reference [4]).

CSR drift for wake reached ss

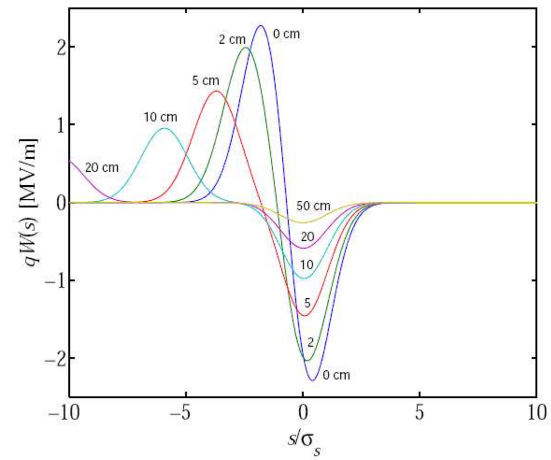



Figure 3: CSR exit wakefield at various distances (in cm) from exit of 10-cm long bend magnet with R = 1.5 m. In this case the bend-exit occurs before steady-state fields have been reached.

CSR drift if wake has not reached ss

- PLACET should also apply this wake.
- Proposed: steady state normally sufficient (left graph)
- CSR drift wake is important for a length of order of the magnet length.

## CSRDrift implementation details

- Proposed: new element CSRDrift (as in elegant). More transparent to user what happens.

- To be discussed: stop CSR drift at first non-CSR drift element sufficient, or more advanced implementation needed (CSR drift wake is important for a length of order of the magnet length)

## Remaining issues and further outstanding work

**Needed before declaring end of this work package:**

* Implementation of CSRDrifts

* Direct comparison with elegant

**Other work :**

* Speed optimizations

* Sliced beams

* More advanced filtering (user options)

  - simple derivation filter might not be enough

  - for sure needed if more details of the CSR effects should be studied (e.g. micro-bunching)

* Shielding effects

## Conclusions

- Free space CSR effect implemented in PLACET Sbend element, for particle beams

- Preliminary testing seems to give good results and correspondence with literature

- CSRDrift needs to be implemented before any real work is performed with PLACET

- Benchmarking directly with elegant code is recommended before declaring implementation as “released”

- A number of issues (better filtering, optimization) can be worked on, if needed

## References

[Saldin et al.]: NIM A 398 (1997) 392

[Murphy et al.]: Part Accel. 57 (1997) 9

[Borland]: Physical Review S.T. - acc. and beams, 4, 070701 (2001)

[Stupakov et al.]: SLAC LCLS-TN-01-12, 2001

[Dohlus et al.]: NIM A 393 (1997) 490

[Stupakov]: USPAS lecture notes, Lansing Michigan, 2007