# CSR model in GPT


Bas van der Geer

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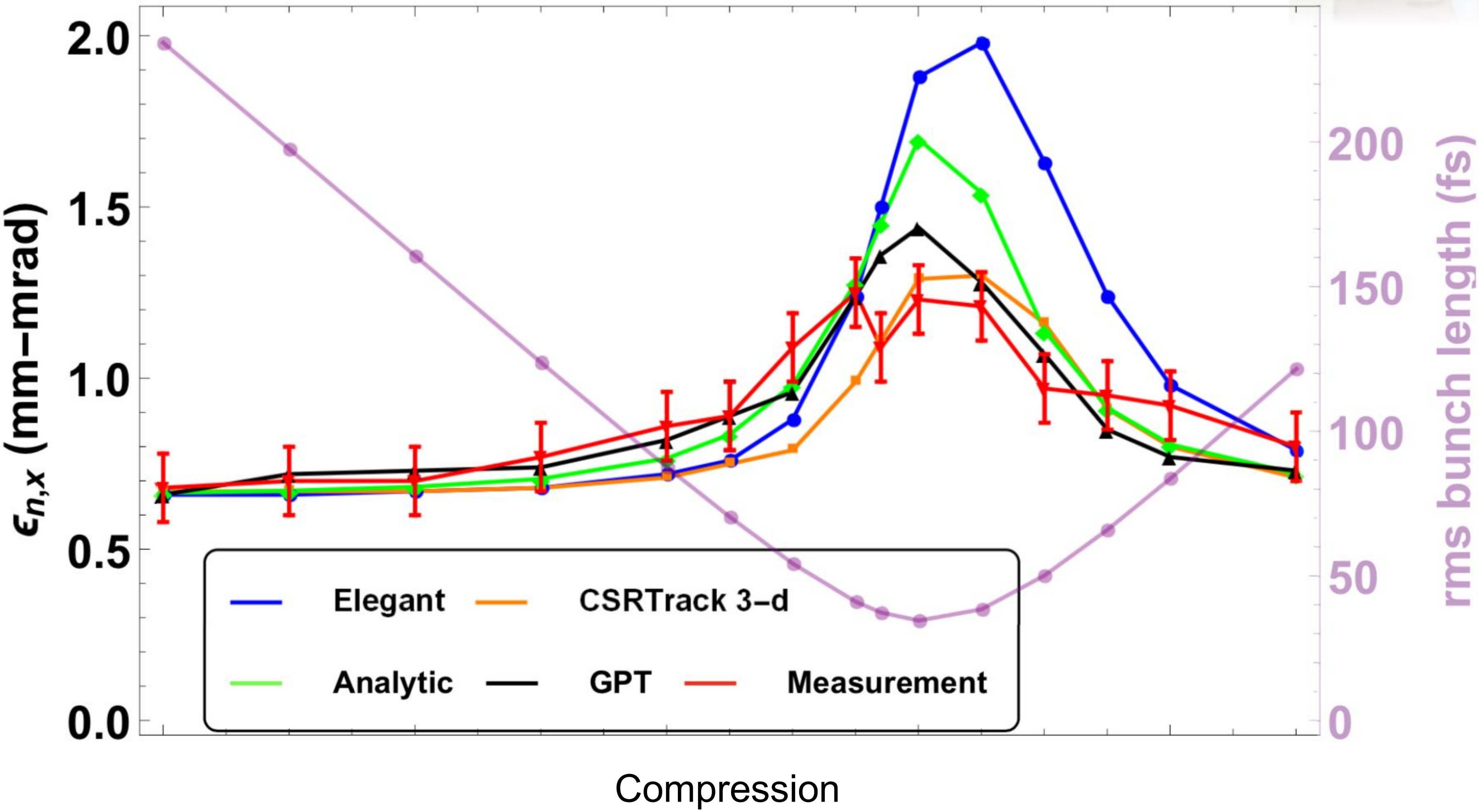
# Top-secret: CSR-measurement vs. simulation codes


Jared Kushner



# CSR model in GPT: Basics

Calculation is based on **Liénard Wiechert fields**

Coulomb term　　　　Radiation term

$$\mathbf{E}(\mathbf{r},t)=\frac{1}{4\pi\varepsilon_0}\left(\frac{q(\mathbf{n}-\boldsymbol{\beta})}{\gamma^2(1-\mathbf{n}\cdot\boldsymbol{\beta})^3|\mathbf{r}-\mathbf{r}_s|^2}+\frac{q\mathbf{n}\times((\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}})}{c(1-\mathbf{n}\cdot\boldsymbol{\beta})^3|\mathbf{r}-\mathbf{r}_s|}\right)_{t_r}$$

$$\mathbf{B}(\mathbf{r},t)=\frac{\mathbf{n}(t_r)}{c}\times\mathbf{E}(\mathbf{r},t)$$

Fields can be summed with

- External beamline components
- Wakefields

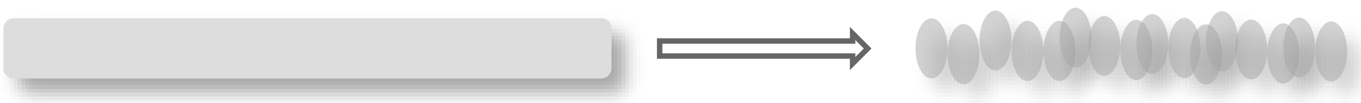
No ultra-relativistic approximations

# CSR model in GPT: Basics

Calculation is based on **stored history**

We use **actual** trajectories because:

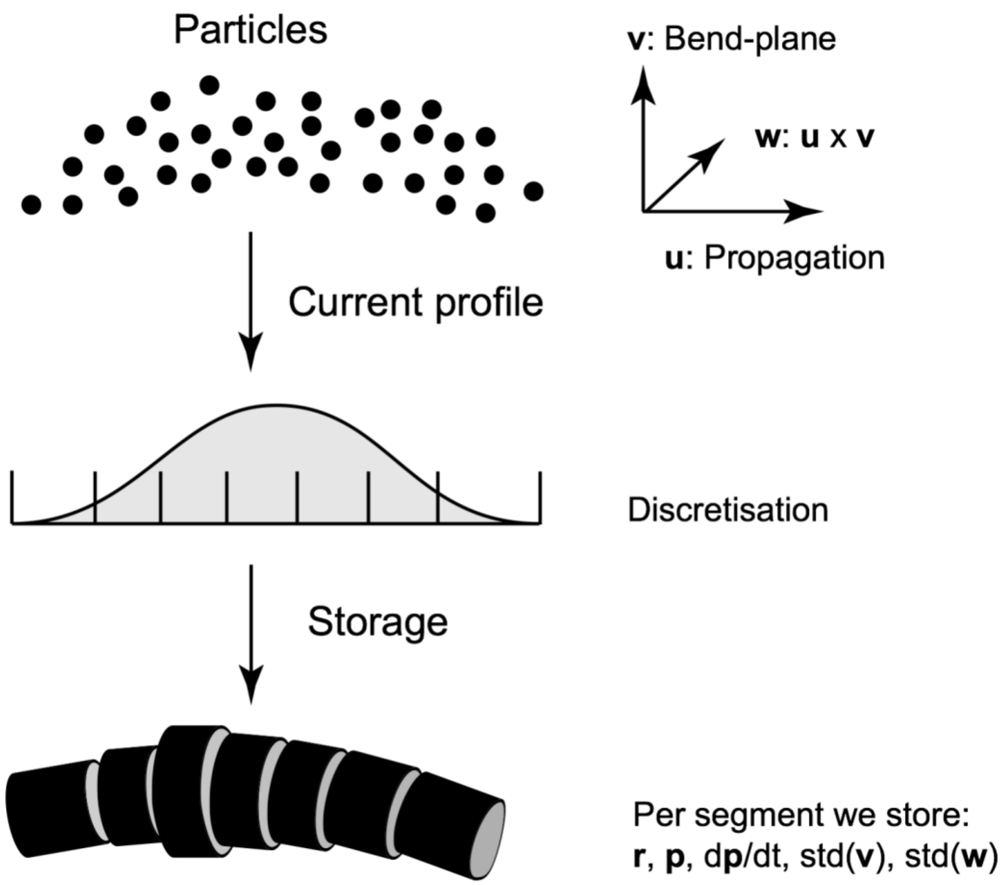
- Aim is to study microbunching where the Longitudinal profile is not constant at all



- The head and tail of the bunch can travel **different paths in dipoles** There is no such thing as a 'reference' trajectory or 'reference' particle

- A misaligned quadrupole can act as a dipole. We want a generic CSR model that 'just works'

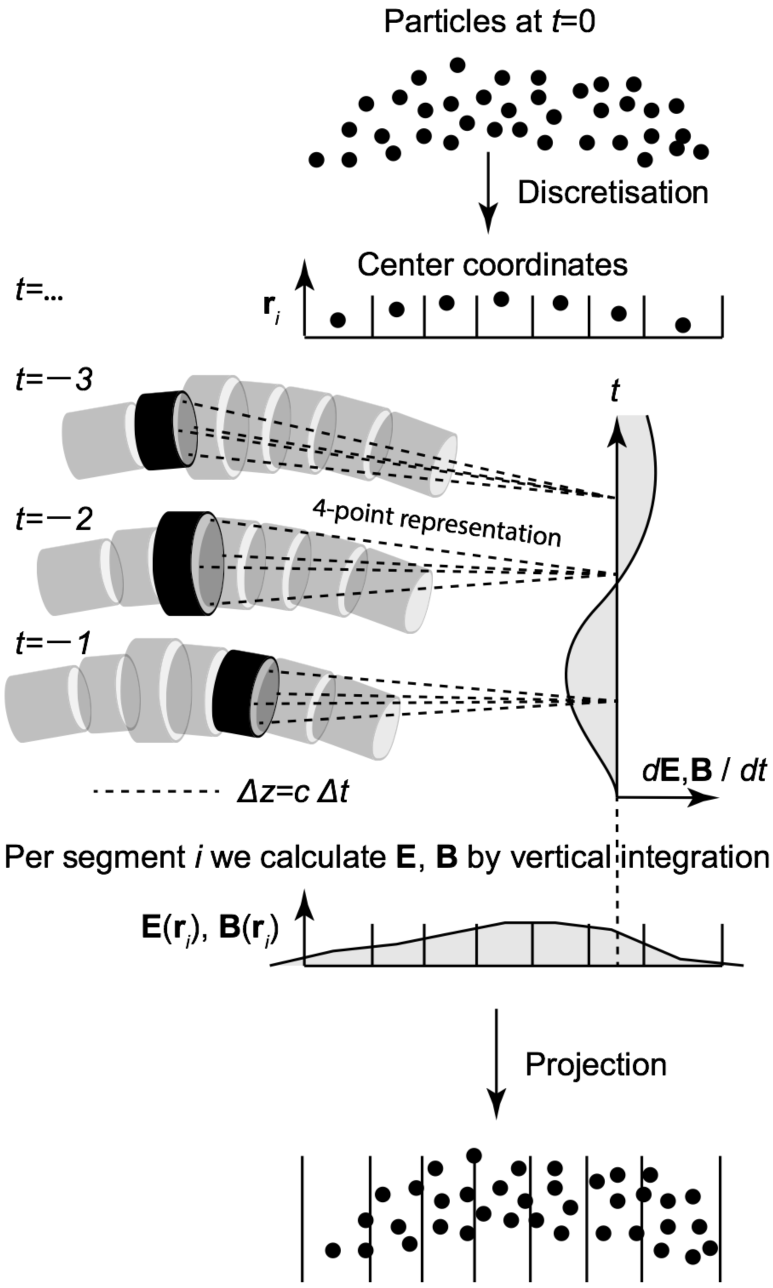
# Storage of bunch slices that radiate




Philosophy:

- Store all *information* that is needed to evaluate the CSR fields anywhere at any later point in time.
- No field-propagation
- No µm-sized meshing over $m^3$
- No shielding
- Non-equidistant discretisation follows charge quantiles to allow higher spacial-resolution at beam-core.

# Field evaluation




Philosophy:

- Apply LW-potentials to stored information, taking into account *actual* retardation conditions.
- We use 4 (or 16) off-axis emission points to model transverse effects.
- We only observe the field at segment-centers, i.e. there is no transverse dependence on fields.

# CSR model in GPT: Integration

The CSR model in GPT is *by design* not aware of the source of transverse acceleration

- No cross-talk in code, more options, fewer bugs

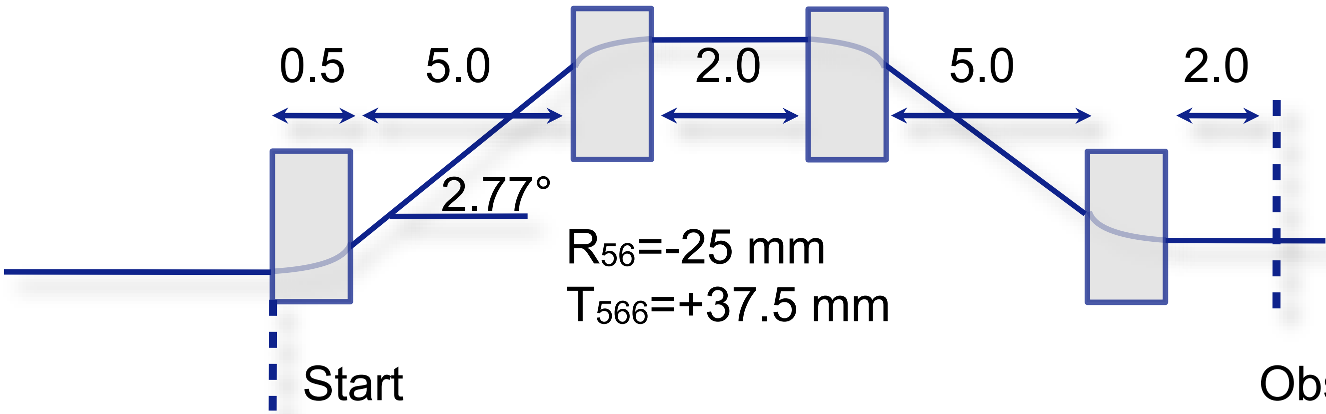
Can be combined with anything:

- field-maps
- fringe-fields
- rf-deflection cavities
- misaligned quadrupoles
- several dipoles/quadrupoles closely packed together
- …

CSR correctly passes through downstream elements

CSR falls off via Liénard Wiechert, not via user-defined knobs

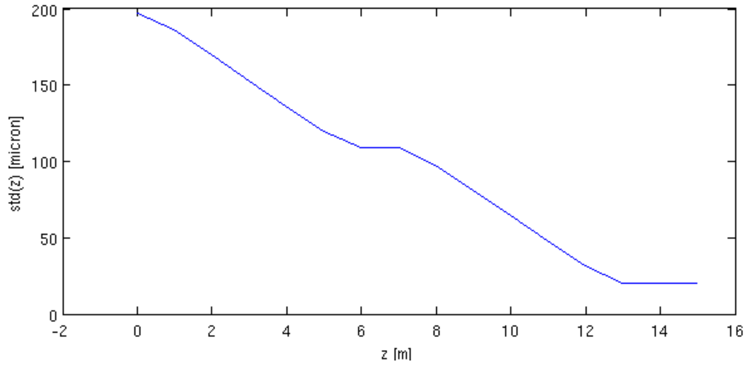
# DESY 2002 workshop: 1 nC, 500 MeV, 200 to 20 µm



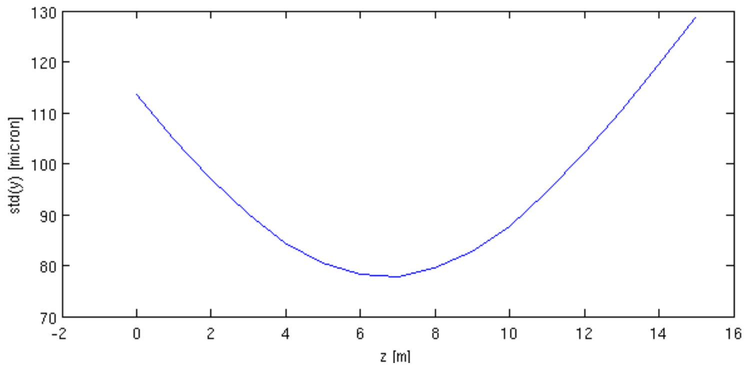

| *Parameter* | *Symbol* | *Value* | *Unit* |
|---|---|---|---|
| Nominal energy | $E_0$ | 0.5 | GeV |
| bunch charge | $Q$ | 1.0 | nC |
| incoherent rms energy spread | $(\Delta E)_{u\text{-}rms}$ | 10 | keV |
| linear energy-z correlation | $a$ | +36.0 | $m^{-1}$ |
| total initial rms relative energy spread | $(\Delta E/E_0)_{rms}$ | 0.720 | % |
| initial rms bunch length | $\sigma_i$ | 200 | µm |
| final rms bunch length | $\sigma_f$ | 20 | µm |
| initial normalized rms emittance | $\varepsilon_{n,x}$ / $\varepsilon_{n,y}$ | 1.0 | mm-mrad |
| initial betatron functions at 1st bend entrance | $\beta_x$ / $\beta_y$ | 40 | m |
| initial alpha-function at 1st bend entrance | $\alpha_x$ / $\alpha_y$ | +2.6 | |

# DESY 2002 workshop: Envelopes

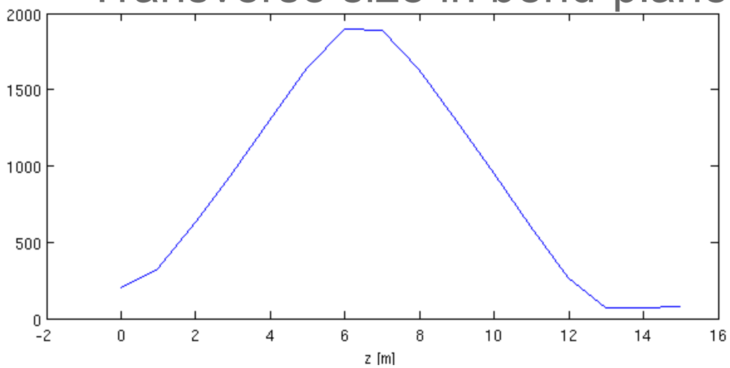
Longitudinal size




Transverse size

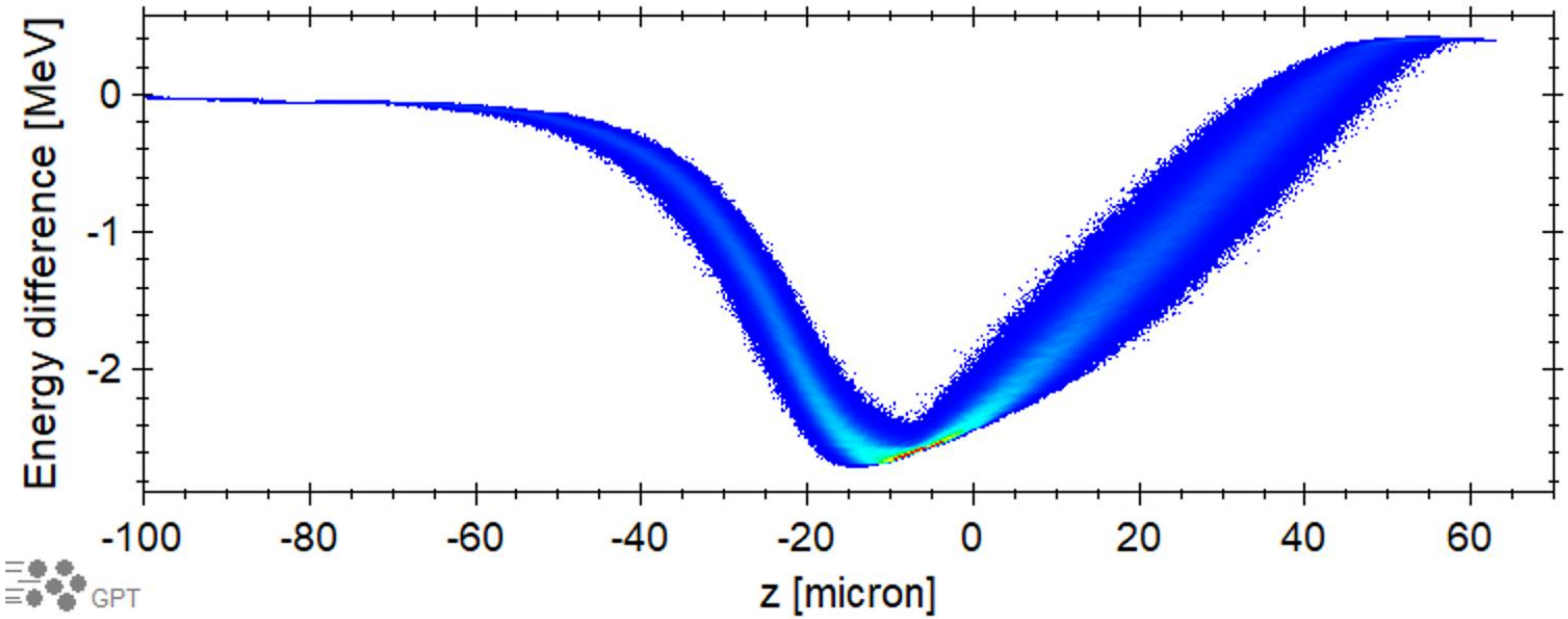



Transverse size in bend-plane



# DESY 2002 workshop: GPT result (2018)

8M particles, 64 cores, 3.5 hours wall-clock time



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# TREDI: fully 3D beam dynamics simulation of RF guns, bendings and FELs

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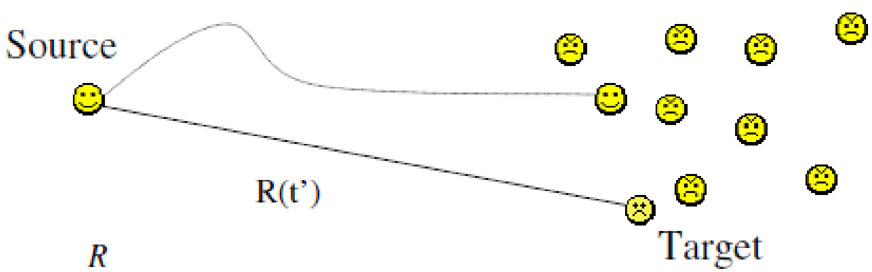
Received 6 April 1999; accepted 30 April 1999

**Abstract**

We describe a three-dimensional code modelling the propagation of charged beams in accelerator devices. The inclusion of space charge fields is taken into account by means of the Lienard–Wiechert retarded potentials. As an illustration of the capabilities of the program, the results of a simulation are given that, describe the beam dynamics from

## SELF FIELDS




$$n = \frac{R}{|R|}$$

Retarded time $t' = t - \frac{R(t')}{c}$

$$E = \frac{n \times \left[(n-\beta) \times \dot{\beta}\right]}{(1-\beta \cdot n)^3 |R|} + \frac{(n-\beta)\left[1-|\beta|^2\right]}{(1-\beta \cdot n)^3 |R|^2}$$

$$B = n \times E$$

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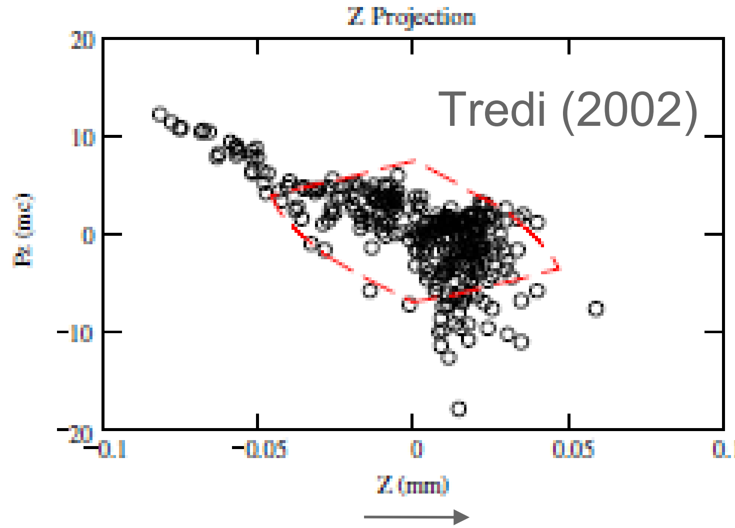


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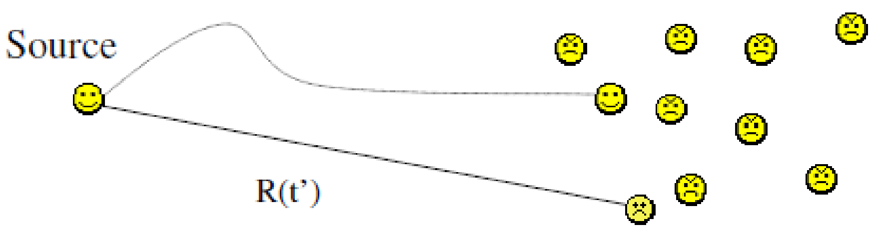


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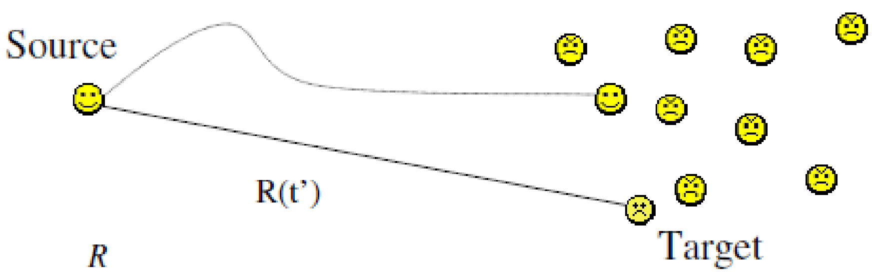


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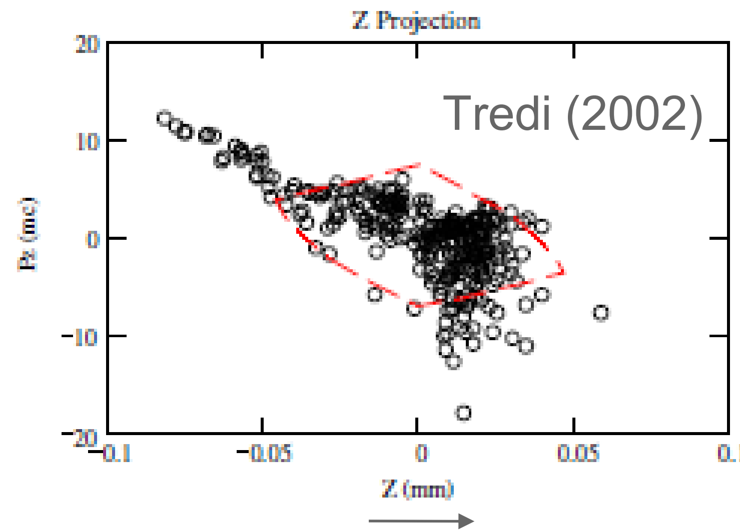
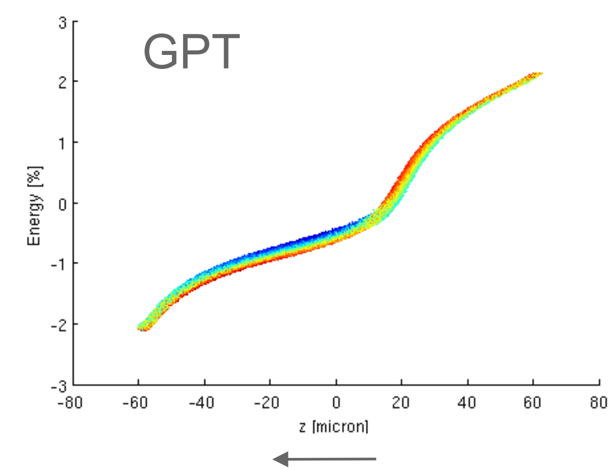
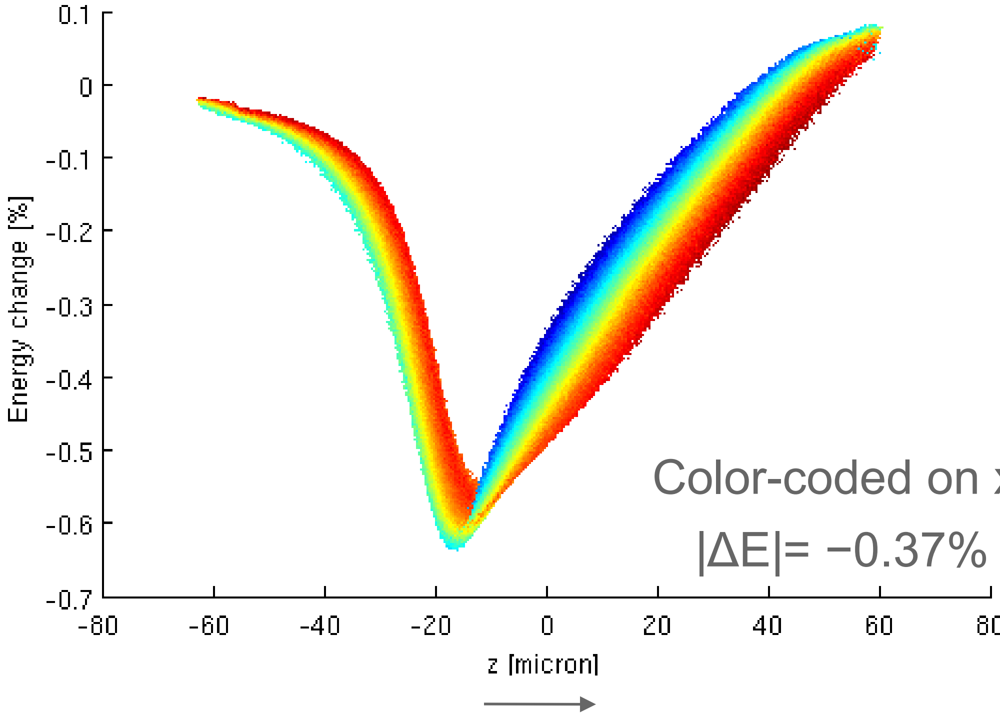


# GPT: CSR results

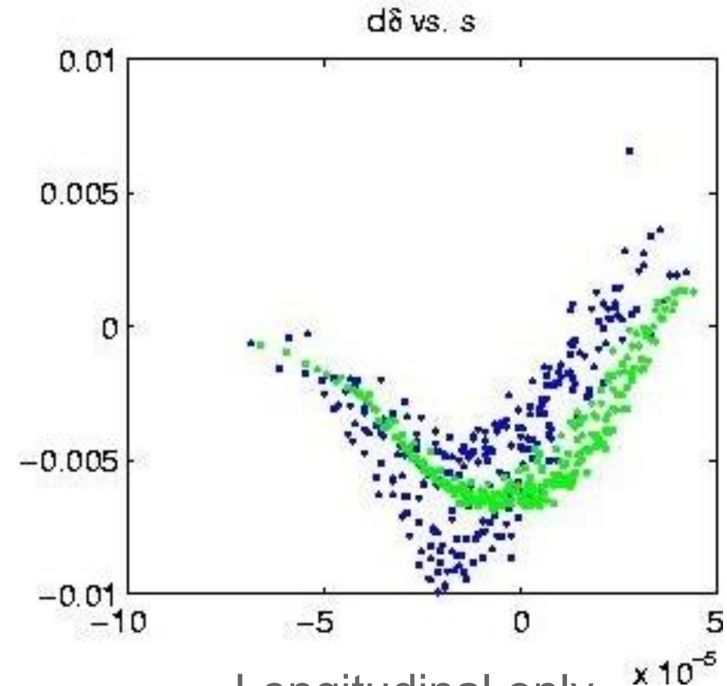
GPT: 8M particles
64 cores: 3.5 hours




Color-coded on x

$|\Delta E| = -0.37\%$

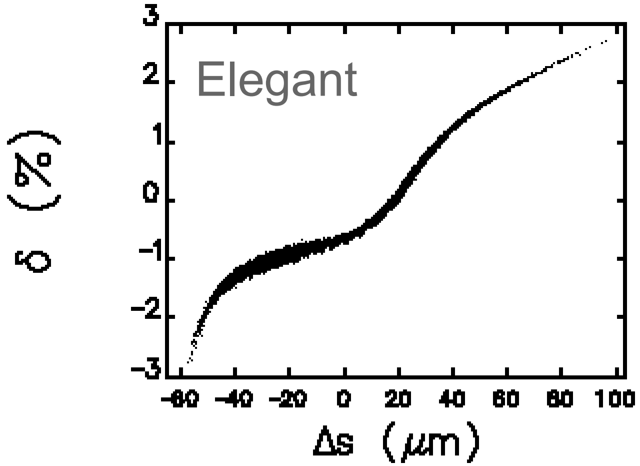
R. Li (2002)

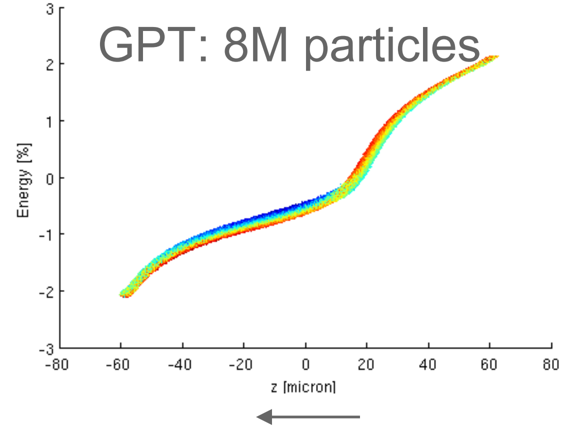


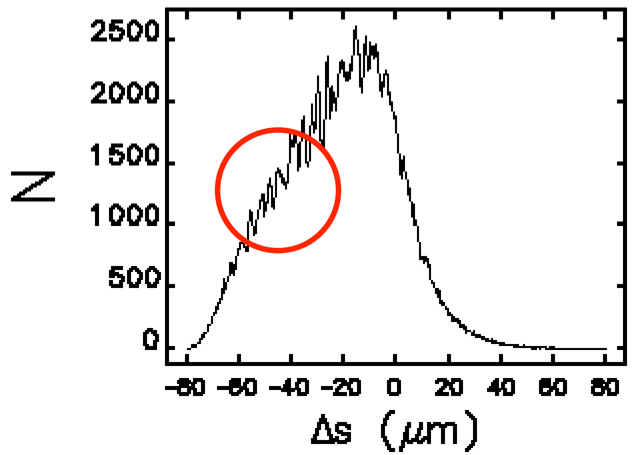

Longitudinal only

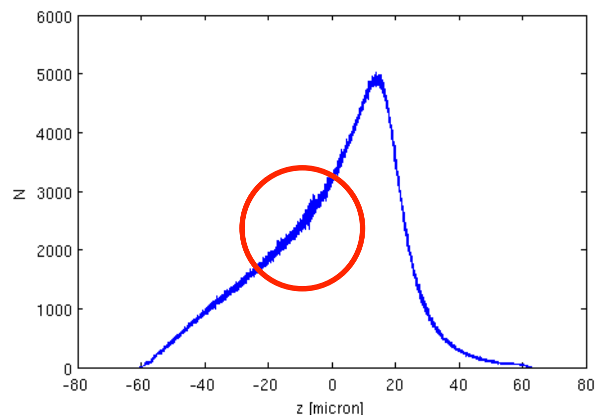
With transverse effects

# CSR results

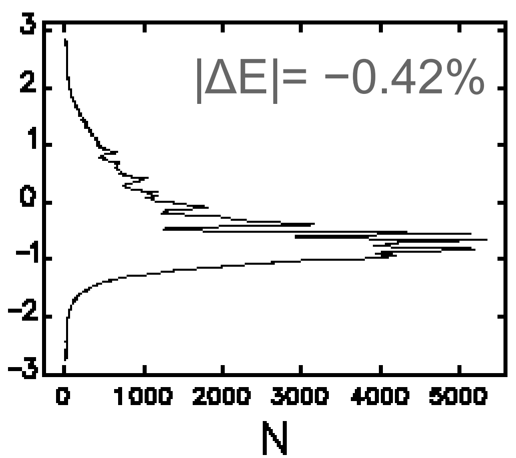


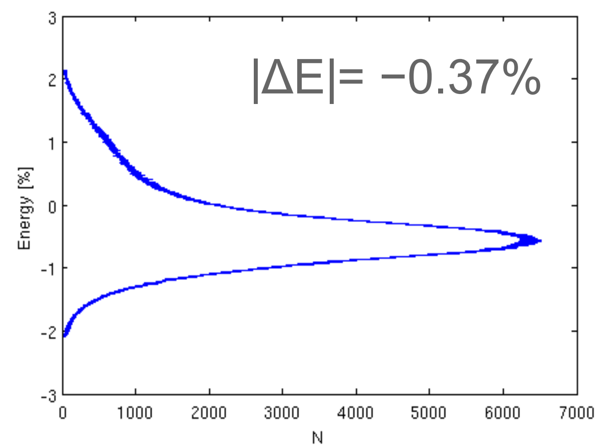




Shape is different



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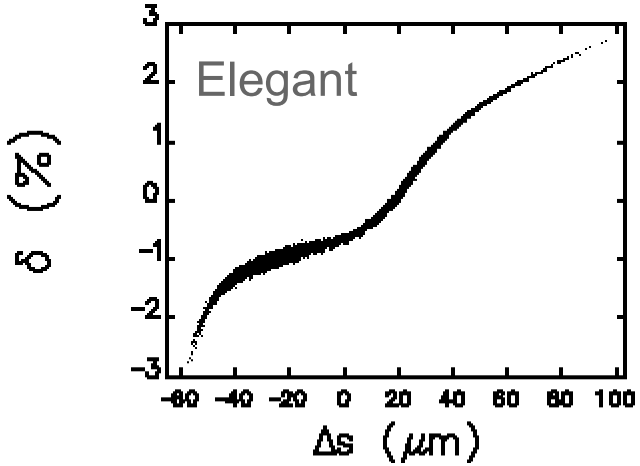
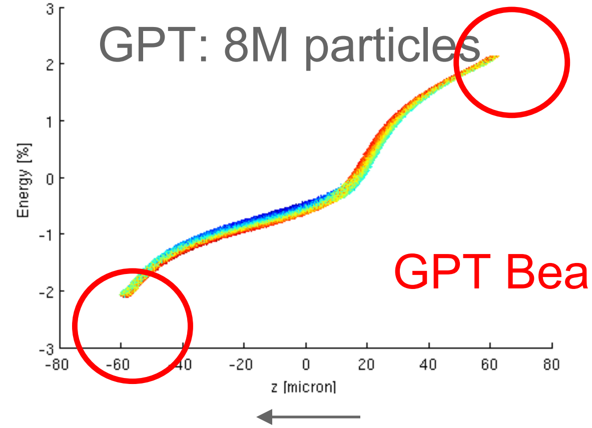
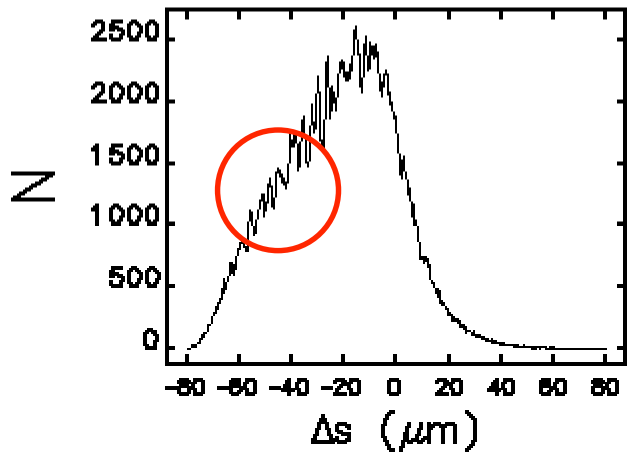
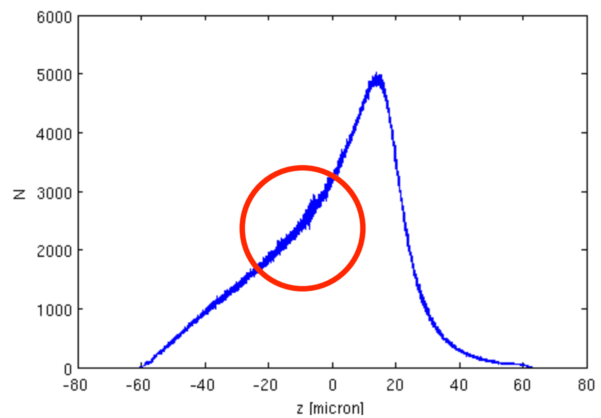



GPT Beam: truncated at 3σ

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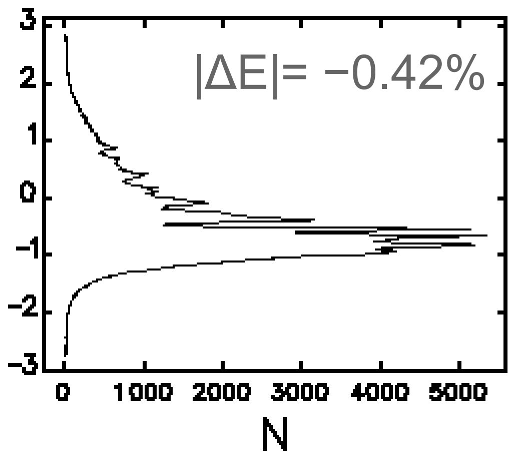
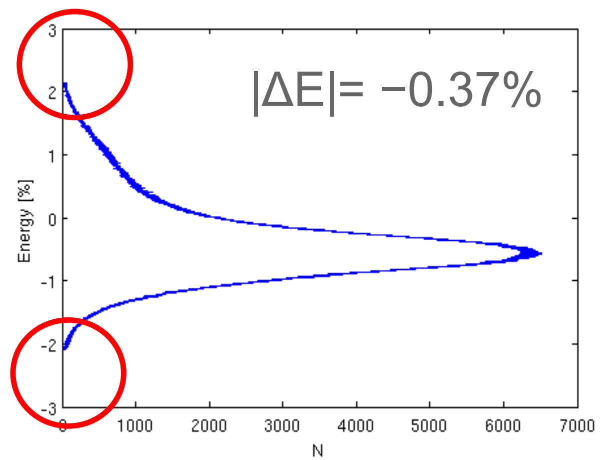
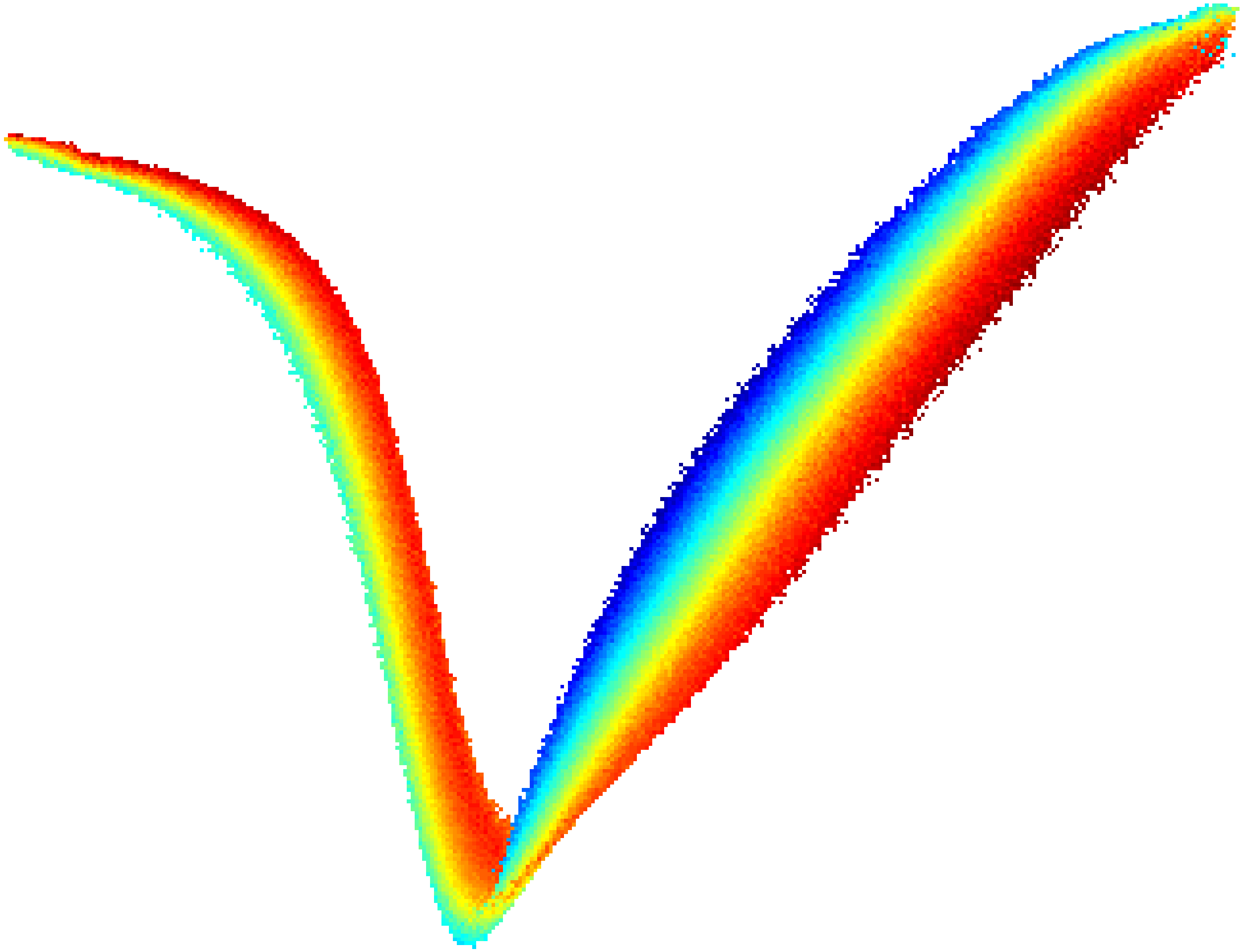


# CSR in GPT: It works!



# CSR model in GPT: Limitations

1D model:

- Fields are assumed to not be a function of the transverse coordinate
- Although transverse size is accounted for

Bunch is assumed to be ‘sliceable’ in the direction of propagation

- The underlying assumption is that all particles in the slice emit the same radiation pattern
- This is not necessarily the case for rollover compression

Free space model

- No shielding effects included

# CSR model in GPT: Performance

## Automatic cleanup

- Segments are removed when light emitted has overtaken the front of the bunch

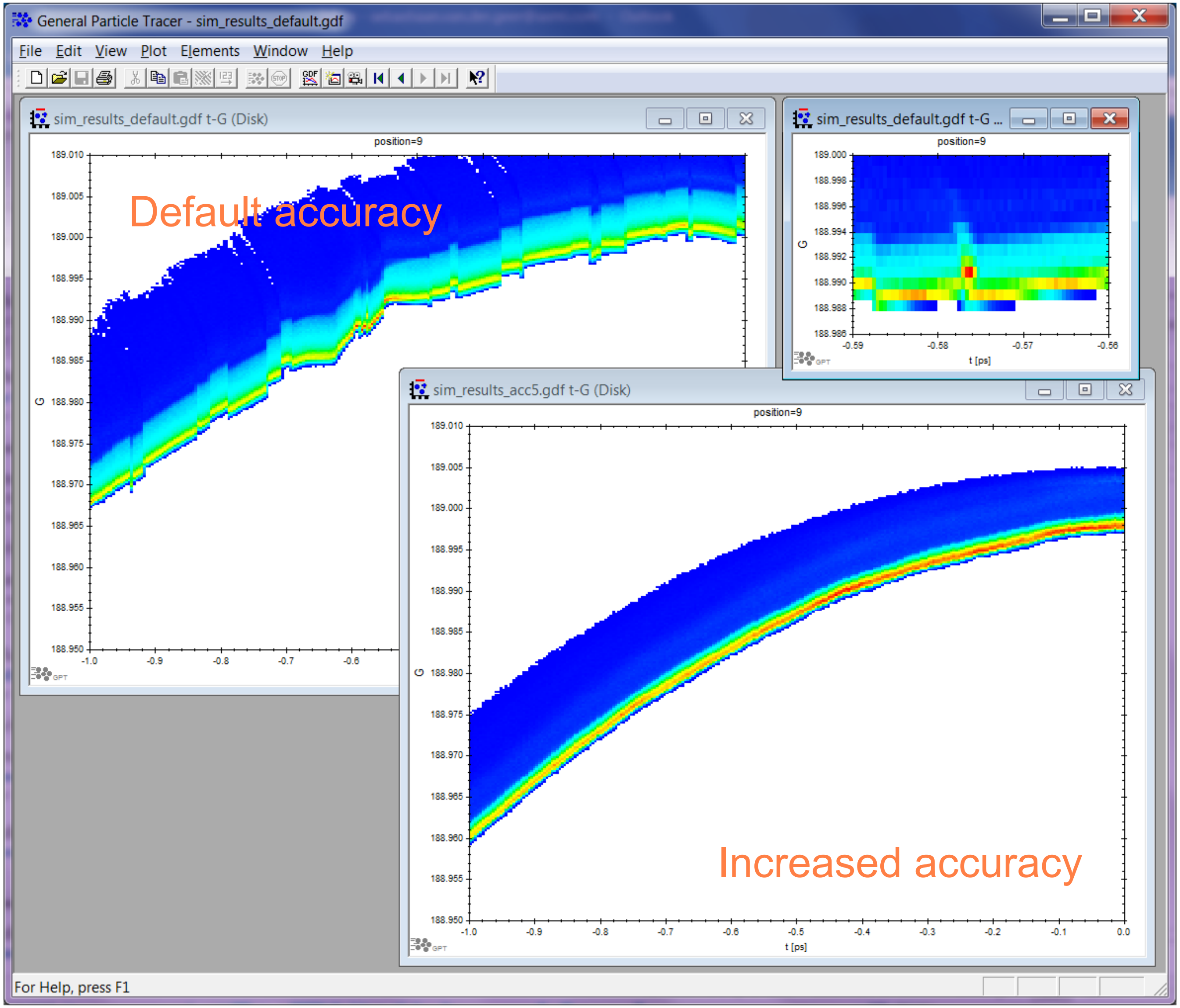
## Hybrid openMP/MPI implementation

- Particles are distributed over MPI nodes.
- Each node maintains only part of the history
  All nodes combined contain all history information
- We prefer cores (openMP) over nodes (MPI) whenever possible to reduce communication overhead
- C++ templates, += operator overloading and custom MPI reduction operators are used to prevent code duplication between openMP and MPI parts of the code

## Typical performance:

- Hours of wall-clock time tracking 8M particles on 64 cores through a chicane.

# Microbunching: Start from cathode, track more particles, 3D spacecharge, run GPT, and fail



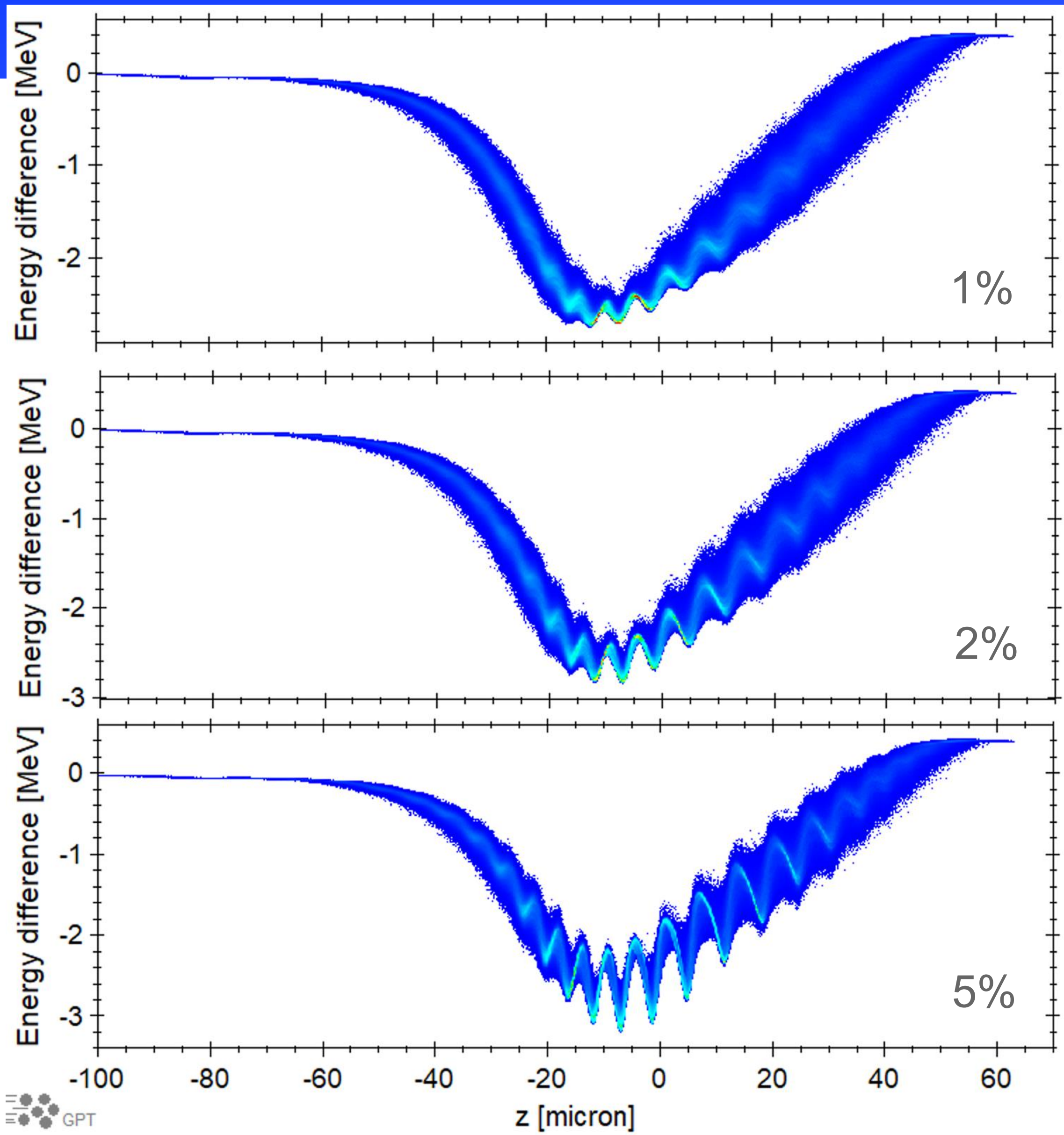

The point is:

- Microbunching simulations need more particles

*and*

- Higher tracking accuracy per particle!

# Towards micro bunching simulations



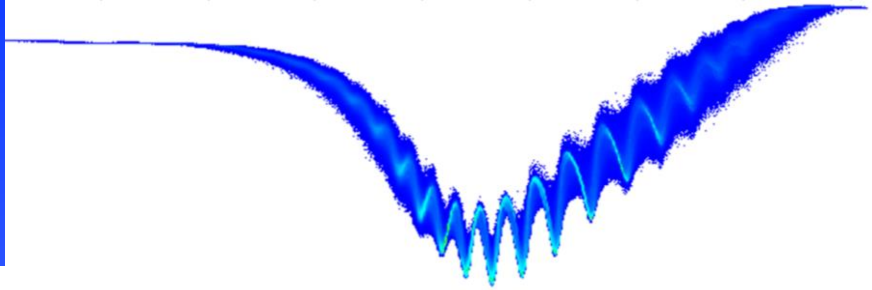

Test-case:

- Same settings: DESY 2002
- Small initial density fluctuation at fixed wavelength

Result:

- Density ➛ energy fluctuation
- Wavelength chirp due to transport

# CSR in GPT: Summary

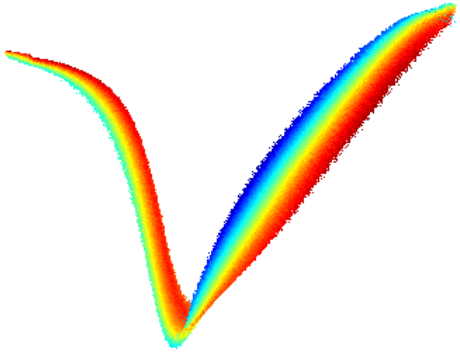


It runs

- Survives all sanity checks so far

Code can handle

- Any beamline geometry: chicanes, arcs, …
- Cases where rigid bunch approximation is not valid
- Relatively large transverse beam sizes
- CSR passing through other components
- Low energy (tested down to 5 MeV)



With more particles it also covers:

- Small transverse sizes (few ten micron)
- High energy (tested up to 500 MeV)
- Micro bunching


GPT CSR
Bas van der Geer
The end

# Questions to the audience:

Is this CSR model useful for FEL simulations?

What is more important?

- Shielding
- Off-axis dependence of fields
- Performance

How many (density) oscillations per pulse need to be studied?

- Is there a maximum