Sparx Note 7
December 2001

Simulation Tools for High Brightness Electron Beam Dynamics in a Linac driven SASE FEL

The Sparx beam dynamics group

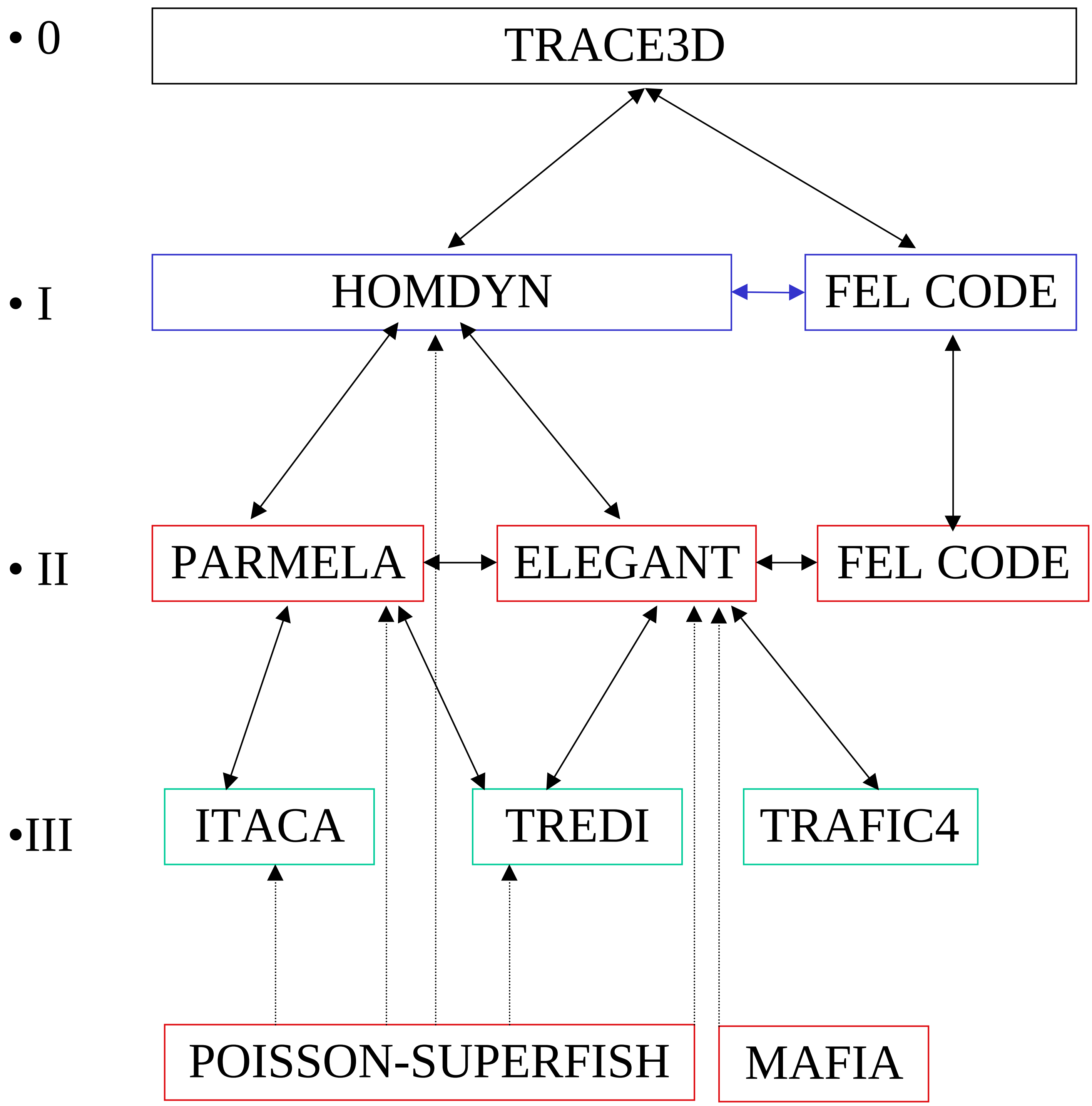
INFN/ENEA

Main issues:

- External Forces (Acceleration and Focusing)
- Collective Self-Fields (Space Charge, CSR)
- Environment (Wake Fields long. & transv.)
- Long Term Effects (Multi-bunches loading)

Start To End Simulation

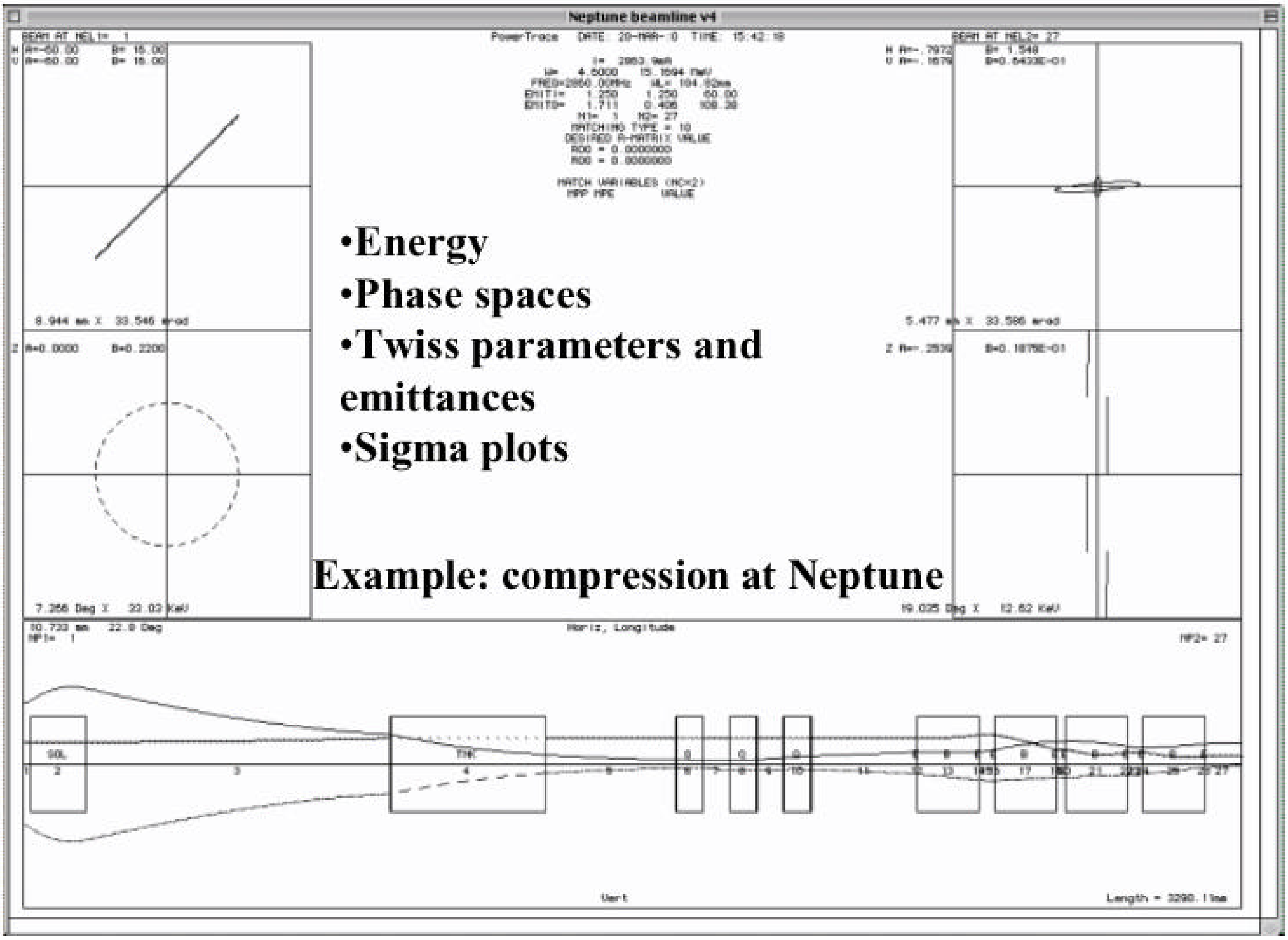
- 0 Matrix Code
- I Semi-Analytical Codes
- II Tracking Codes
- III Self-Consistent Codes



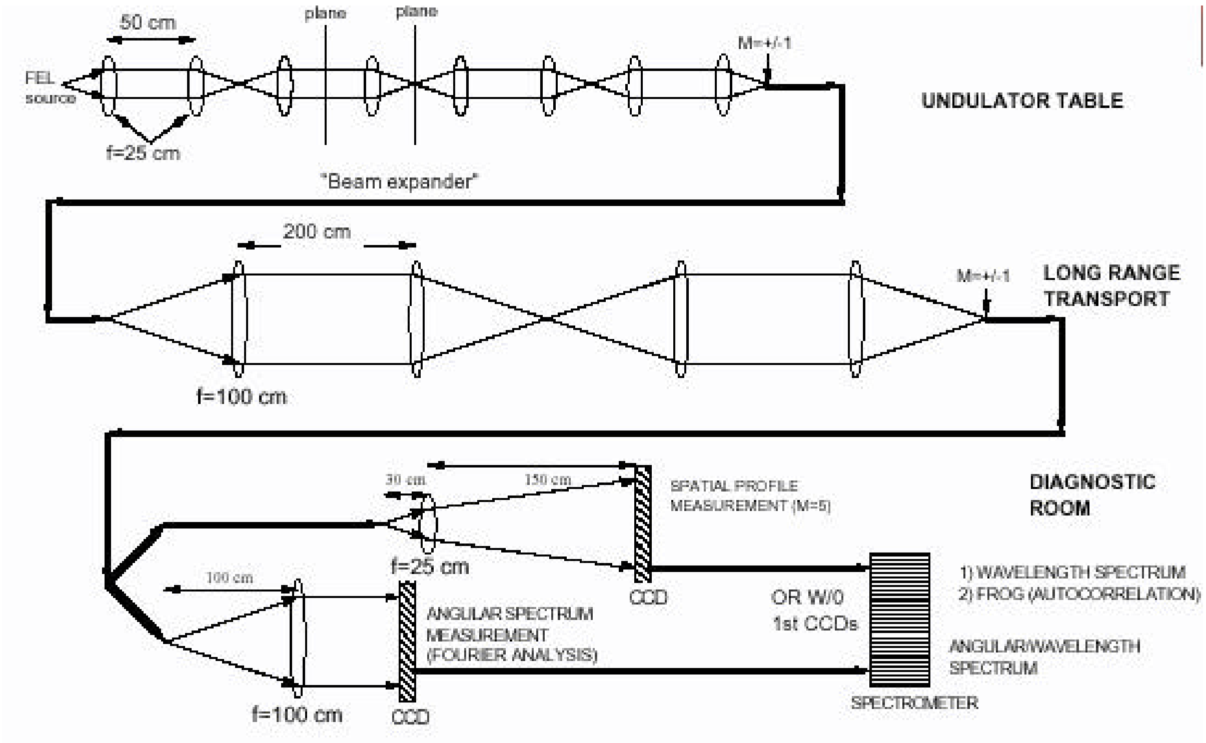
TRACE 3D

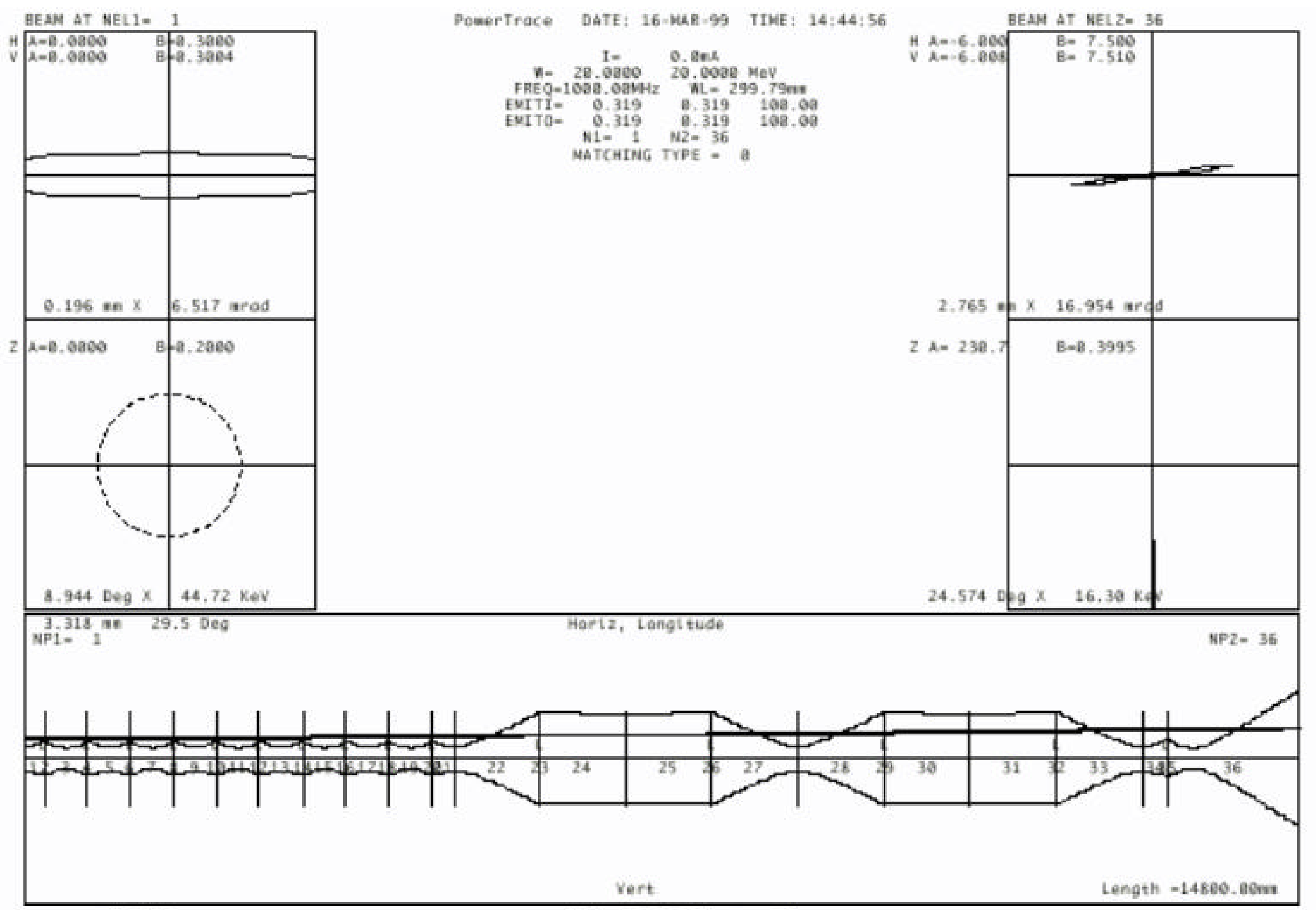
- 3D Linear Optics 6x6 σ-matrix (Transport)
- Acceleration,Focusing,Bending and Wigglers
- Rms envelope description of an equivalent ellipsoidally symmetric uniform beam including Space Charge and Wake Fields effects

- Automatic Matching



• Photon beam transport $\varepsilon \sim \lambda / 4\pi$

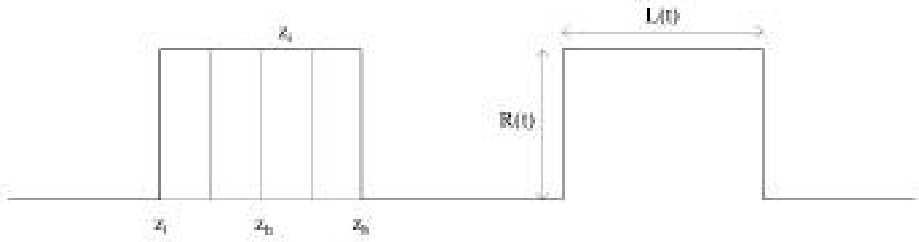




HOMDYN

Long term multi-bunch beam cavity interaction for relativistic and non relativistic beams,

Current density description of bunches by uniform multi-slice cylinder ==> envelope equations



Normal modes expansion of cavity fields

Space Charge

$$^{2}E - \frac{1}{c^{2}}\frac{\partial E}{\partial t} = \mu \frac{\partial J}{\partial t}$$

$$J = f(R, L)$$

$$F_b = q(E + v \times B)$$

$$\dot{p}_b = F_b$$

Main Features

• Accurate description of accelerating structures (SW & TW) and solenoids

• Quads, Wiggler, (Compressor)

• Analytical description of space charge

• Short range longitudinal wake fields

•Multi-bunch longitudinal effects (transient beam loading)

Works in progress:

• CSR effects
• Multi-bunch transverse effects

PARMELA (versione 3.14)

(Lloyd Young, Lanl)

Tiene conto di

- Emittanza termica
- Carica spaziale (2D e 3D)
- Distribuzione dei campi elettrici e magnetici

Non tiene conto di

- ISR e CSR
- Wake fields trasversi
- “Resistite wall” wakefields nei magneti

Include

Effetto dei wake fields sullo spread di energia (tramite formula empirica: fit di dati di TBCI)

SIMULAZIONE START-TO-END CON PARMELA

Iniettore Banda S + Linac Banda S

COMPRESSORE RF + COMPRESSORE MAGNETICO

Condizioni iniziali:
Q=1 nC, Emittanza termica = 0.3π mm mrad, regione del gun: punto di lavoro di LCLS

Il calcolo è stato suddiviso in 11 parti (save/restart)

L'iniettore fino a 150 MeV può essere calcolato con 5000 particelle
Il calcolo completo include il compressore magnetico che richiede il calcolo 3D della carica spaziale e di conseguenza un numero maggiore di particelle (40000).

Tempi di calcolo su PC PENTIUM III 800 MHz:

- Np=5000, fino a 150 MeV = 2 ore
- Np=40000, fino a 2 GeV = 16 ore e 30 minuti

Numerically induced emittance growth in quasi-laminar beams by finite size particles (clouds) interacting with self-fields interpolated on the mesh

- Example: *Axi-symmetric systems*

  Particles are actually *Rician* charge (and current) **density distributions**, whose size is ~ mesh step

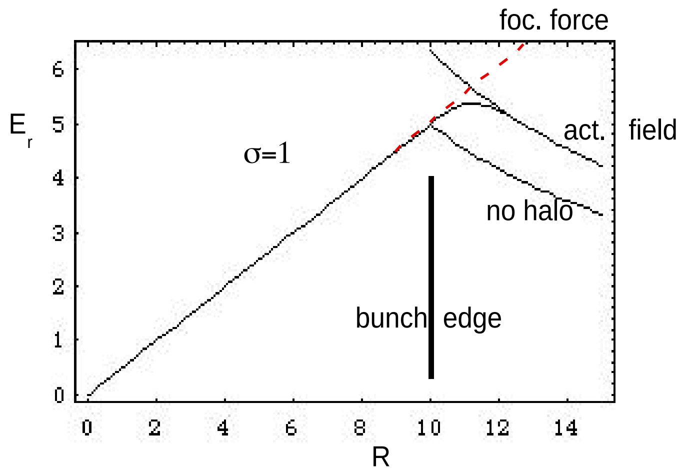
  ⇓

  Cylindrical bunches with uniform charge distribution will be modeled with an *outer gaussian halo* at the edge

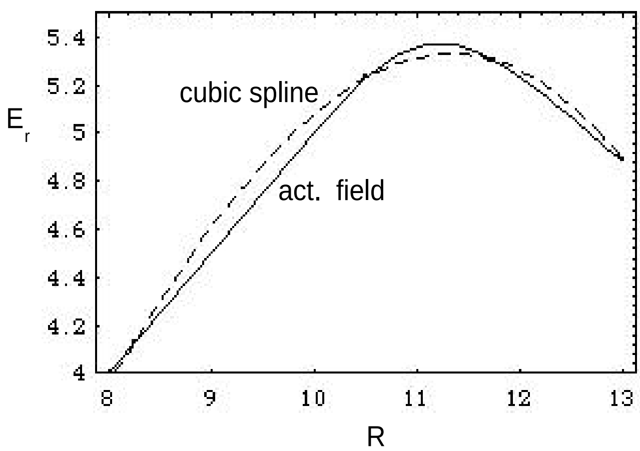
  ⇓

  The *transverse self-field* will have a *non-linear behavior* at the bunch edge

Cont. on emittance growth



Interpolation algorithm introduces *non linear behavior* in the field even at *inner radii* than the gaussian halo

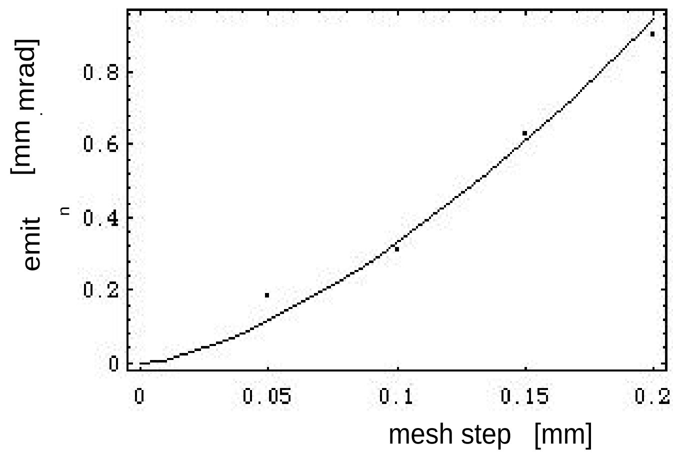


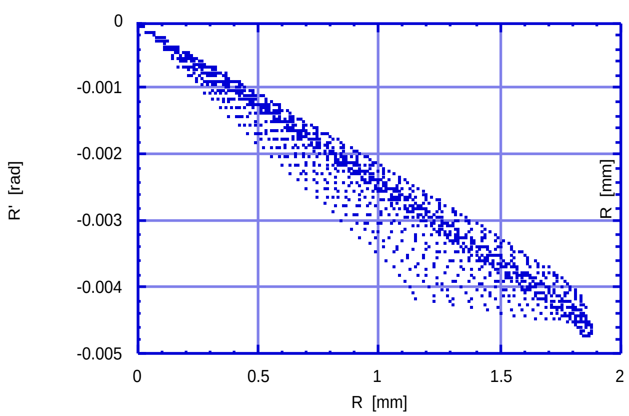
Cont. on emittance growth

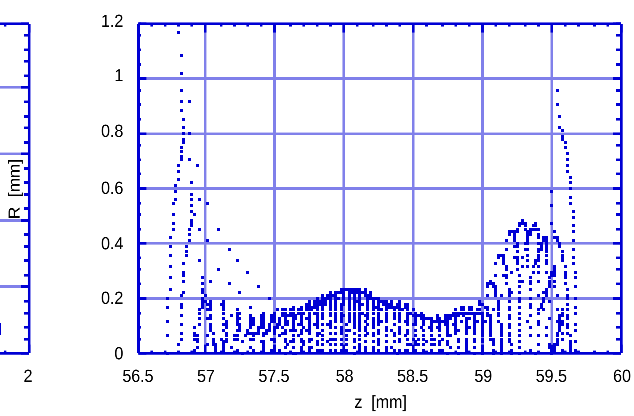
- The resulting *emittance growth* is

(x = Rician particle width / cathode laser spot)

$$\Delta\varepsilon_n \quad \frac{.07\, Q_{bunch}\, x^{3/2}}{\pi\varepsilon_0 E_{cath} L_{bunch}}$$







Operations Analysis Group
Michael Borland borland@aps.anl.gov

General Capabilities of elegant
ELEctron Generation ANd Tracking

- Tracking single and multipass machines.
- Perturbation/variation of accelerator parameters.
- Orbit/trajectory computation and correction.
- Optics calculations and correction.
- Optimization of tracked and computed quantities.
- Dynamic aperture determination.
- Generation of macro-particles with various distributions.
- Macro-particle data to/from SDDS files.
- Copious SDDS output of results.

Operations Analysis Group
Michael Borland borland@aps.anl.gov

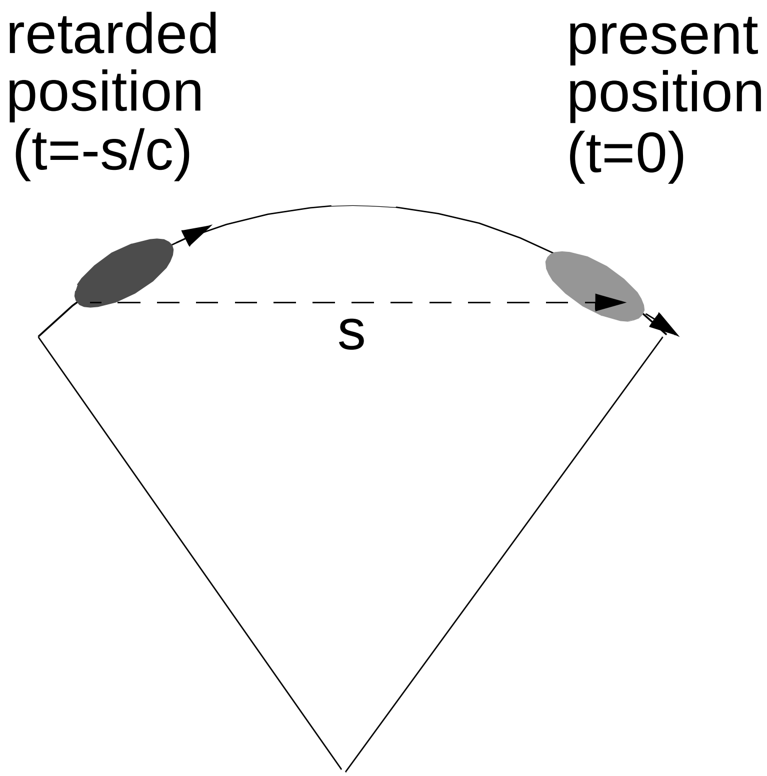
Overview of Physics in elegant

- Track in 6D with matrices, canonical integration, numerical integration, or mixture.
- Time-dependent elements: rf cavity, rf deflector, kicker, traveling wave linac, etc.
- Collective effects: impedances, CSR, IBS*.
- SASE FEL computations.
- Collimators and scrapers.
- Quantum excitation*, radiation damping*, scattering.
- Misalignments.

*rings only.

Operations Analysis Group
Michael Borland borland@aps.anl.gov

Qualitative Explanation of CSR



Curved trajectory allows radiation from tail to catch up with the head.

Particles in bunch radiate coherently at wavelengths much less than the bunch length.

This radiation produces a position-dependent energy modulation along the bunch.

Operations Analysis Group
Michael Borland borland@aps.anl.gov

How CSR Affects the Bunch

- CSR imposes a longitudinal-position-dependent energy modulation on the bunch. This will show up in the *energy spectrum*.
- This modulation is imparted inside a dipole and inside the chicane, producing a modulation of the slopes of particle trajectories.
- This results in a growth of the *projected emittance* in the bending plane.
- CSR also introduces *x-p correlations*. These can be seen on a vertical bend ("Dowell diagnostic") after the chicane.

Operations Analysis Group
Michael Borland borland@aps.anl.gov

Simulation of CSR Effects

- Inside dipoles, use free-space, 1-D formalism of Saldin, *et al.,* in NIM A 398 (1997):

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

where R is the bend radius, ϕ is the angle into the bend, and $s = ct$. The two terms are

$$T_1(s, R, \phi) = K \int_{s-s_l}^{s} \lambda'(z)\left(s-z\right)^{-\frac{1}{3}} dz$$

and

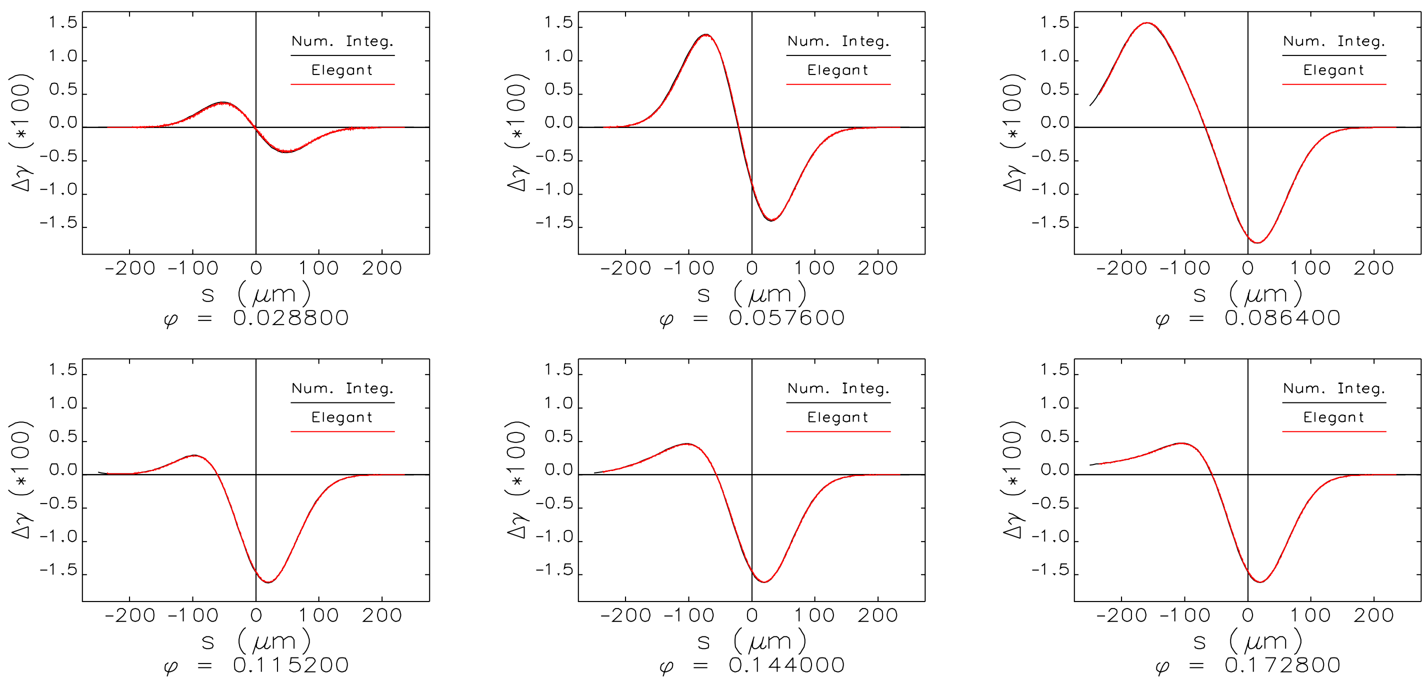
$$T_2(s, R, \phi) = K\frac{\lambda(s-s_l)-\lambda(s-4s_l)}{s_l^{1/3}}$$

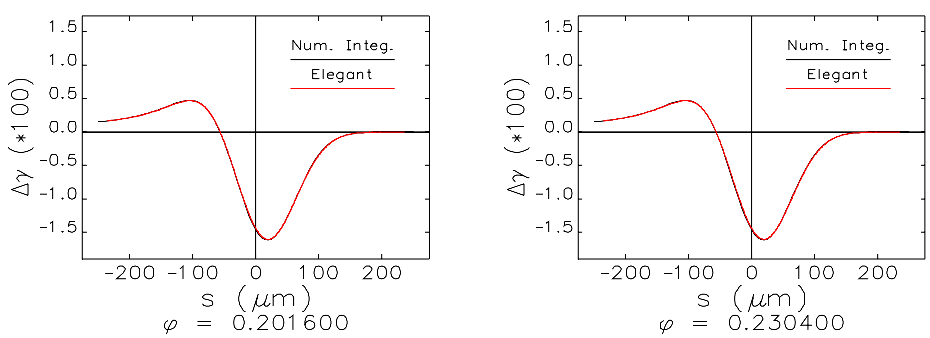
where $K = \frac{-2e^2}{(3R^2)^{1/3}}$, $s_l = \frac{R\phi^3}{24}$ is the slippage length, and $\lambda(s)$ is the longitudinal density of the bunch.

- Dipoles are cut into ~100 slices and the CSR wake is computed from the longitudinal density at the end of each slice. This is used to modify the energy of each simulation particle.

Operations Analysis Group
Michael Borland borland@aps.anl.gov

Examples of CSR Wakes in a Dipole





Gaussian beam

R = 1.5m

$\sigma_z = 50\mu m$

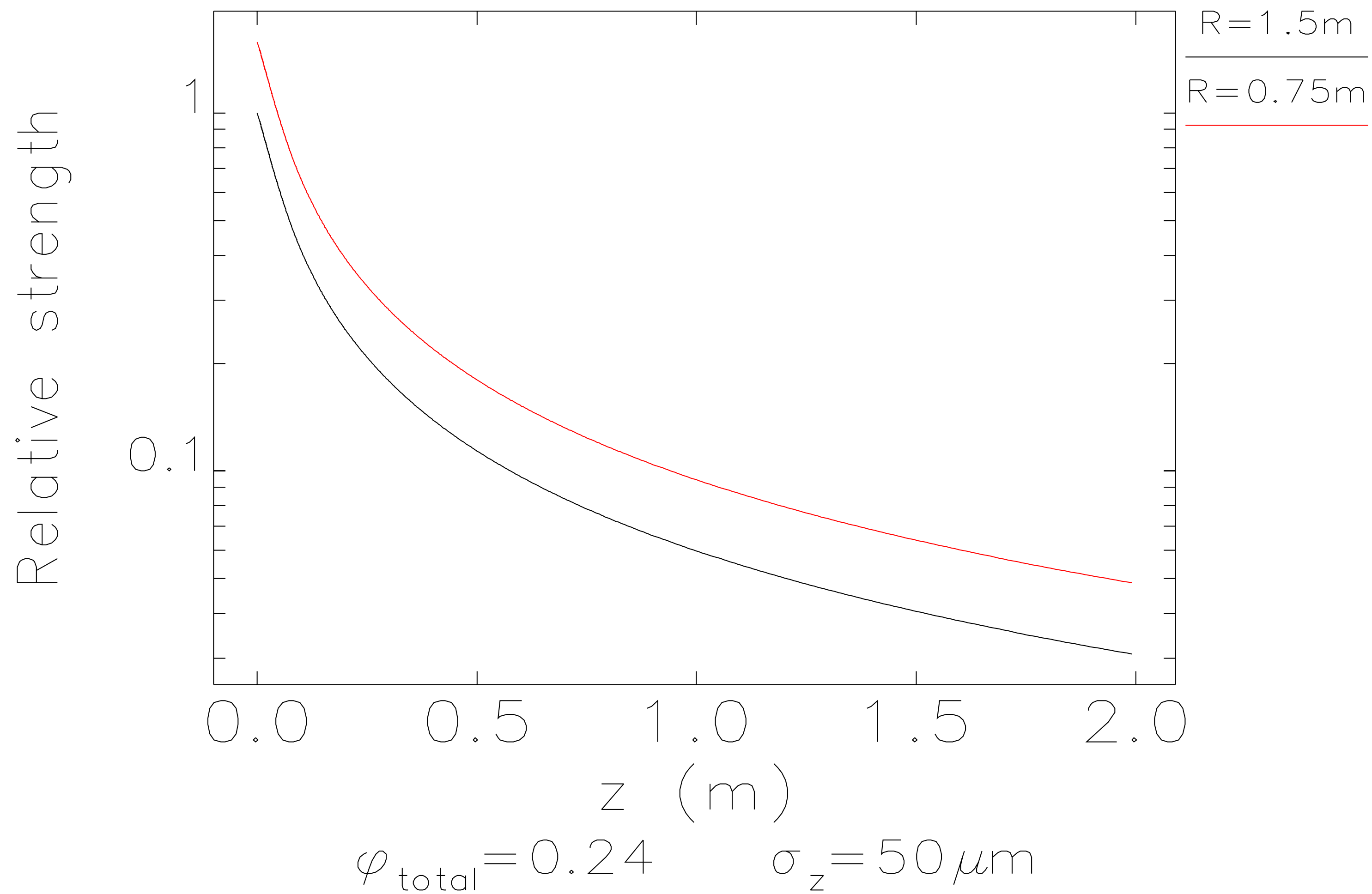
Operations Analysis Group
Michael Borland borland@aps.anl.gov

Simulation of CSR in Drift Spaces

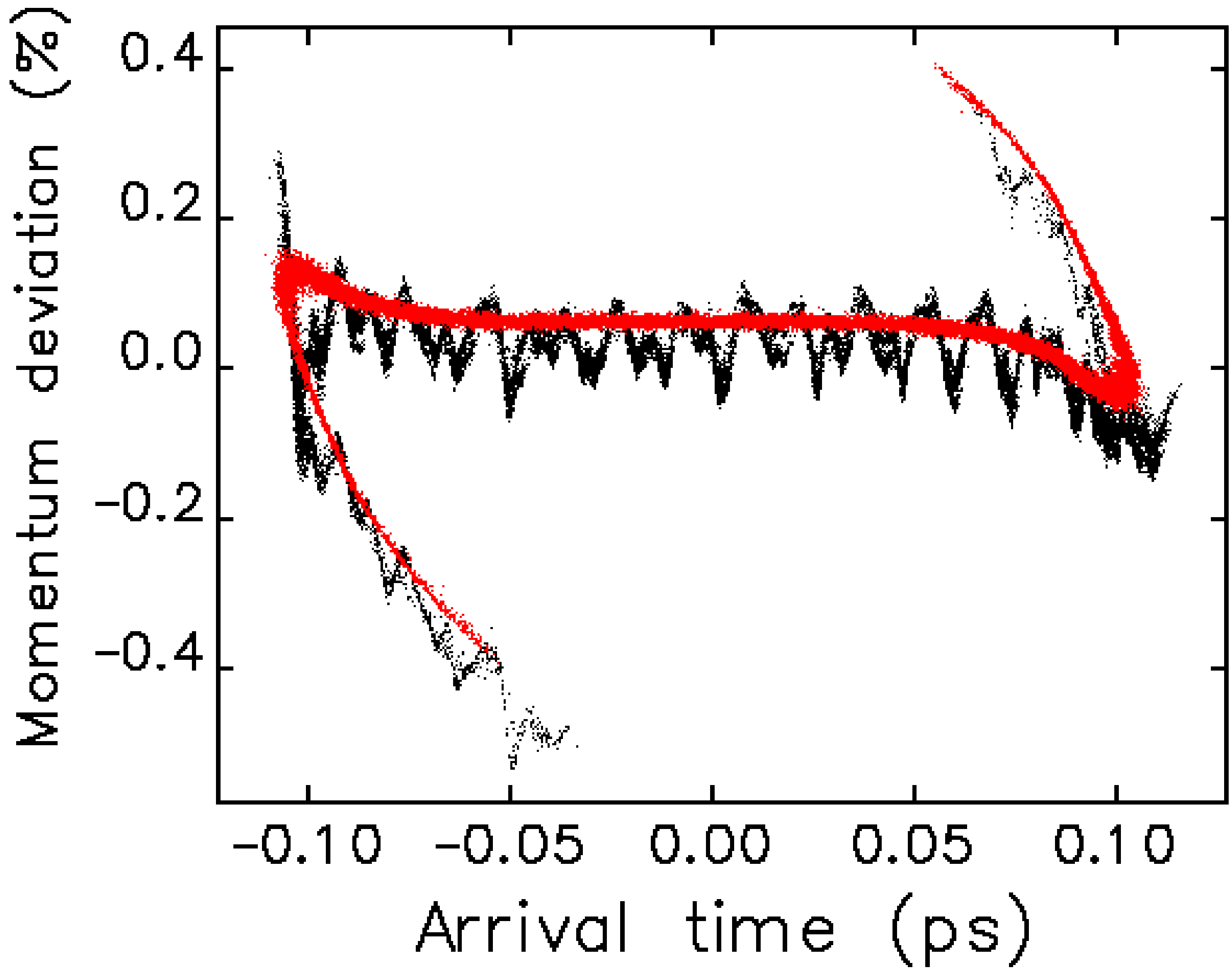
- CSR effects are not confined to dipoles, as the radiation continues to propagate with the beam.
- After dipoles, assume the terminal CSR wake propagates with gradual attenuation but fixed shape. This is confirmed by detailed simulations (Dohlus *et al.*).
- Attenuation length is roughly given by the "overtaking length," $(24\sigma_z R^2)^{1/3}$.
- Saldin *et al.* give equations for this radiation for an idealized rectangular beam distribution. In **elegant**, these are used to determine how quickly the radiation attenuates.

Operations Analysis Group
Michael Borland borland@aps.anl.gov

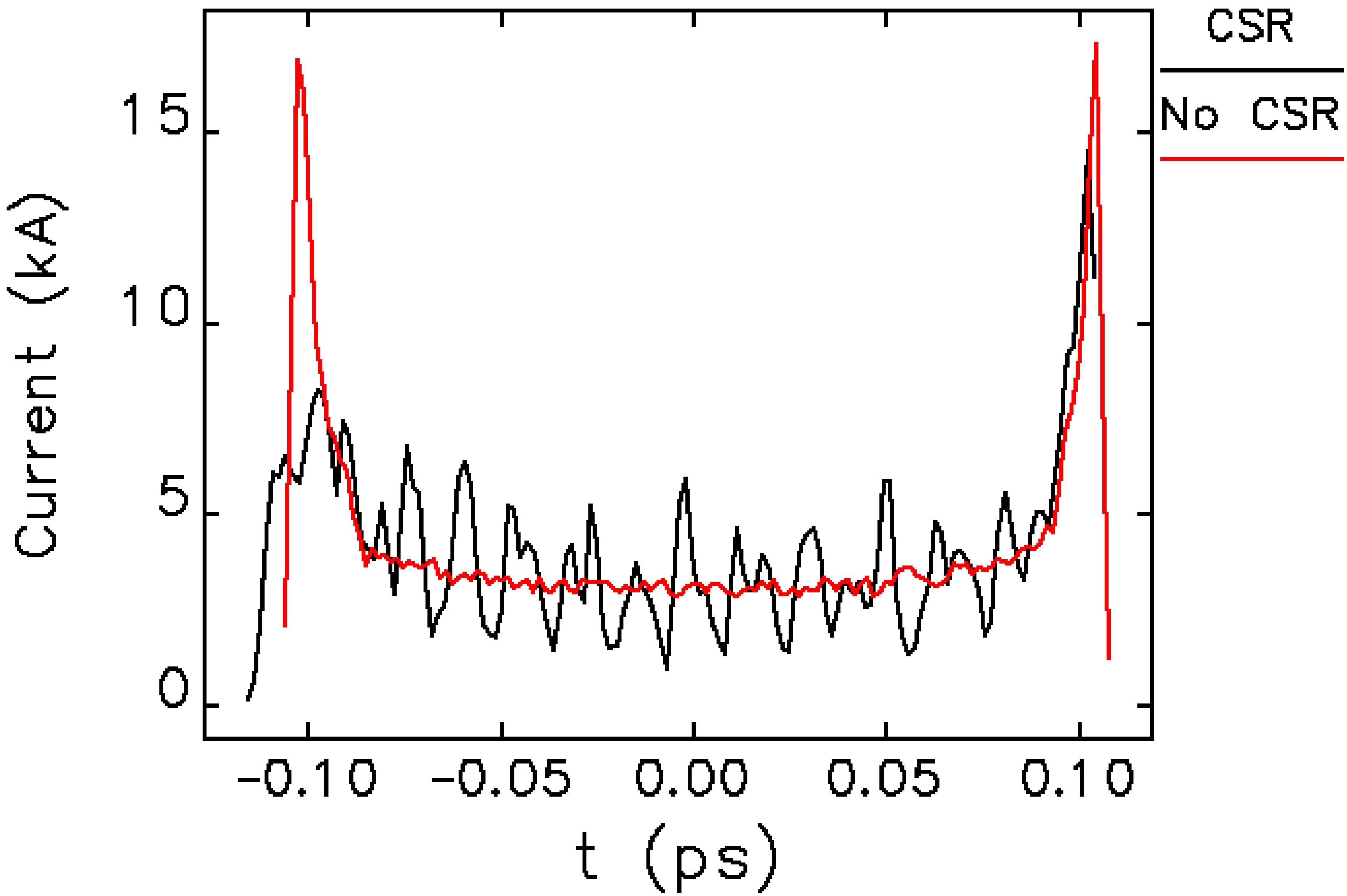
Attenuation of CSR in Drift



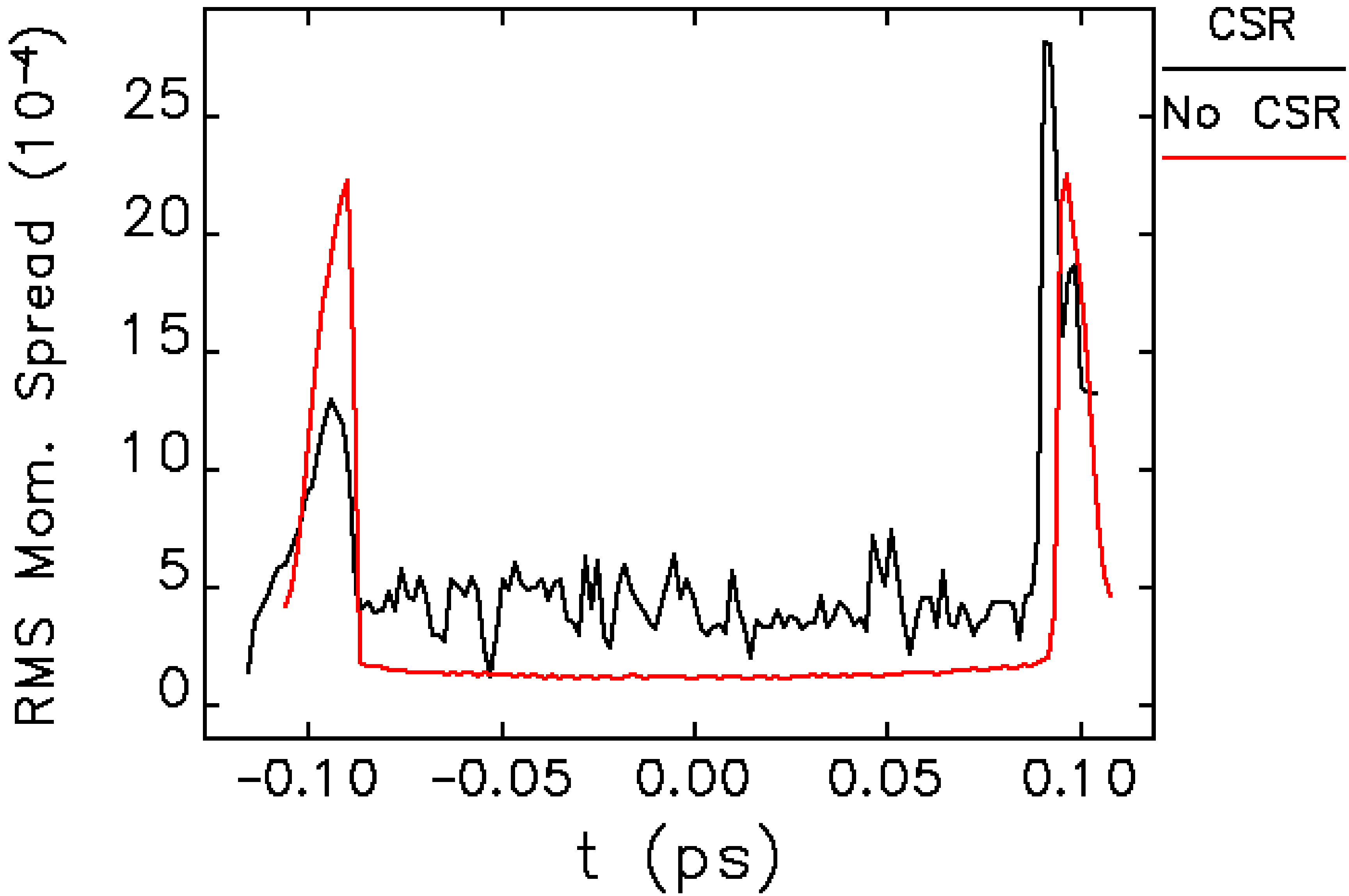
Longitudinal Phase Space at Undulator Entrance



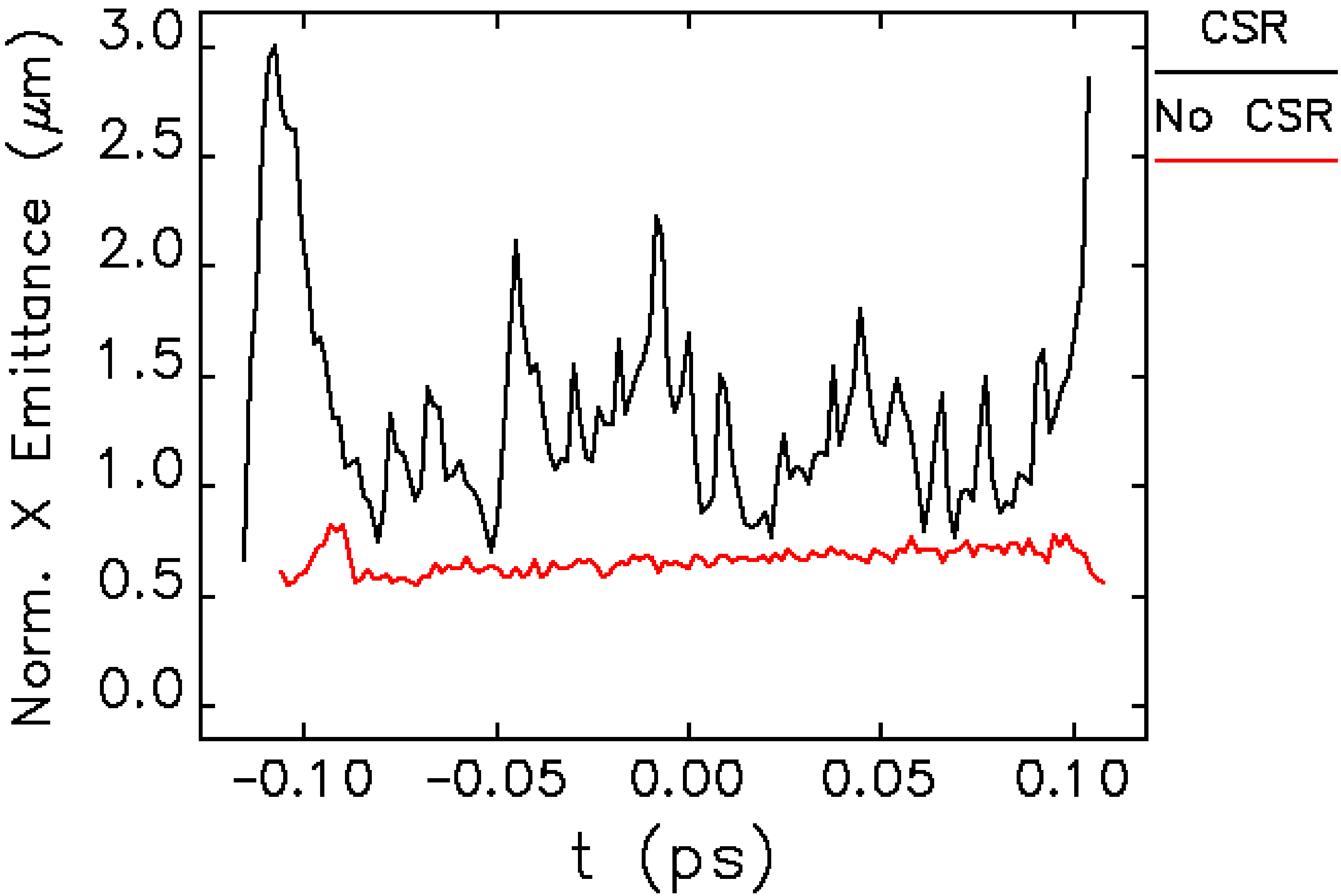
Slice Analysis



Slice Analysis



Slice Analysis



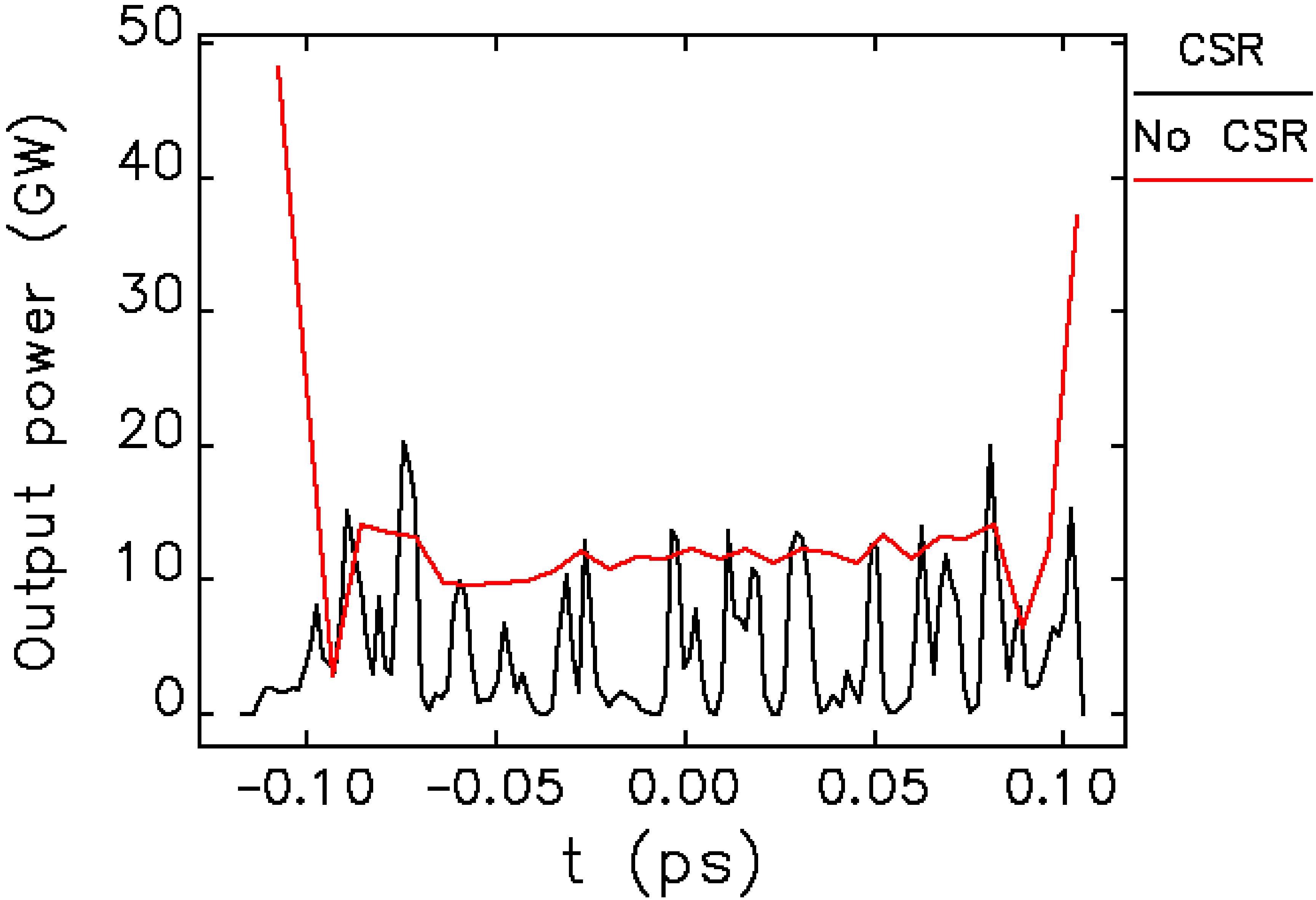
Predicted FEL Performance

- Results are averaged/summed the central 80% "core slices"

CSR ?	***Current (kA)***	***Bunch length (ps)***	***Frac. mom. spread (10^{-4})***	***Norm. x emit. (μm)***	***Gain length (m)***	***Output power (GW)***
no	3.3	0.17	0.49	0.66	3.2	10.7
yes	3.5	0.18	1.6	1.2	5	3.5

- Only a fraction of the slices saturate when CSR is included
- Bunch compressor design being revisited to reduce CSR problems.

Output Power Along the Bunch



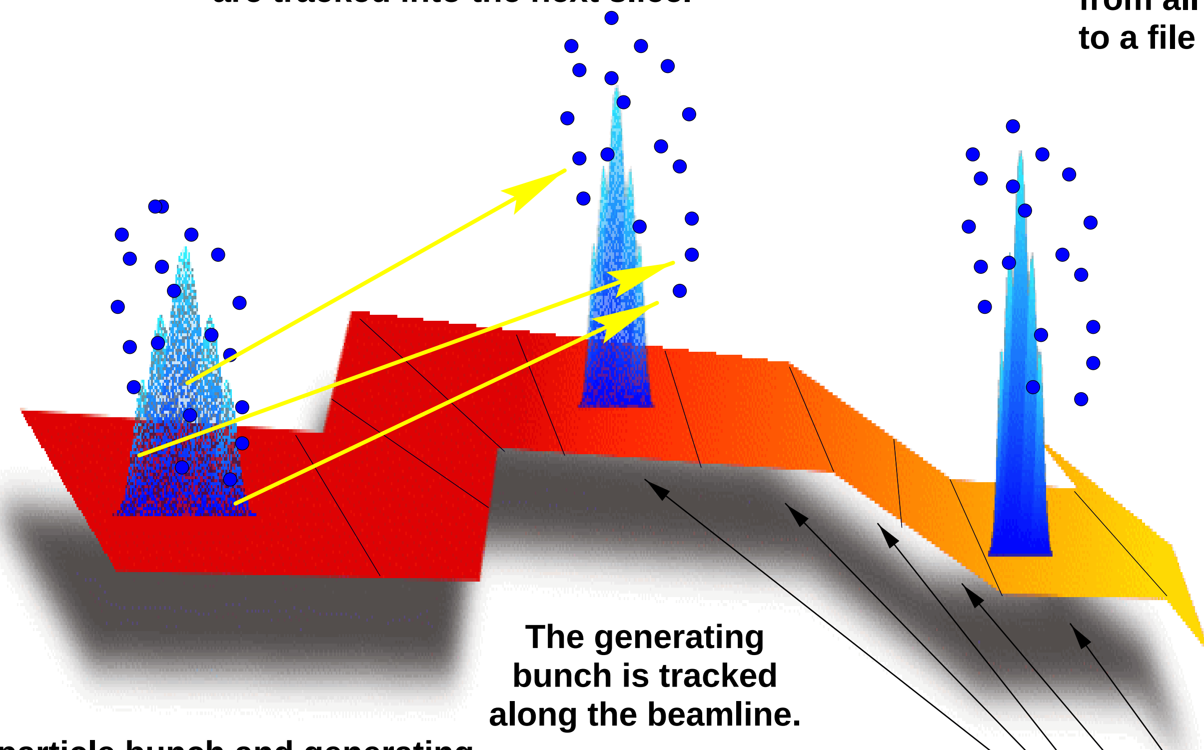
2.2 What TraFiC^4 Does:

- Handle retardation effects correctly $\rightarrow$ use cartesian coordinates
- Calculate all fields from first principles
- Don't use linear approximations
- Consider the full six-dimensional phase space
- Don't use point particles $\rightarrow$ use continuous charge distributions
- Use pointlike probe particles
- Handle shielding

TraFiC^4 = Track particles in the Fields of Continuous Charge distributions in Cartesian Coordinates. (Written by Andreas Kabel, based on the WAKE code by M. Dohlus, A. K., T. Limberg)

In each slice and for each particle, the retarded position of each generating sub-bunch is found. The fields are calculated and are applied to the probe particles. The particles are tracked into the next slice.

The procedure is repeated up to the exit slice. The phase-space distribution from all slices is written to a file and postprocessed.



The generating bunch is tracked along the beamline.

Probe particle bunch and generating bunch are set up according to the optics of the beamline.

The beamline is divided into slices.

Tredi

Authors: *M.Quattromini,L.Giannessi* (***ENEA Frascati***)

Main features

Full 3D Monte Carlo

SC effects →Lienard-Wiechert potentials (velocity & acceleration EM fields);

SC field regularization →effective charge rescaling (fully covariant procedure);

Devices

- Rfguns,Drifts,Magnets,Linacs,Undulators, both analytical & mapped (axis profile);

To be done (soon)→include

- radiation effects (energy loss);
- more devices (4poles, bendings, etc.);
- describe tilted devices;
- capability of loading mapped devices;
- regularize acceleration fields;
- more frontends (MathCad, IDL);
- make multi-platform (Unix,Win etc.);
- parallelization (MPI,SMP);
- include SDDS support (data exchange with other programs, e.g. FEL codes);