Erion Gjonaj

Technische Universität Darmstadt,
Computational Electromagetics Laboratory (TEMF)
Schlossgartenstr. 8
64289 Darmstadt, Germany

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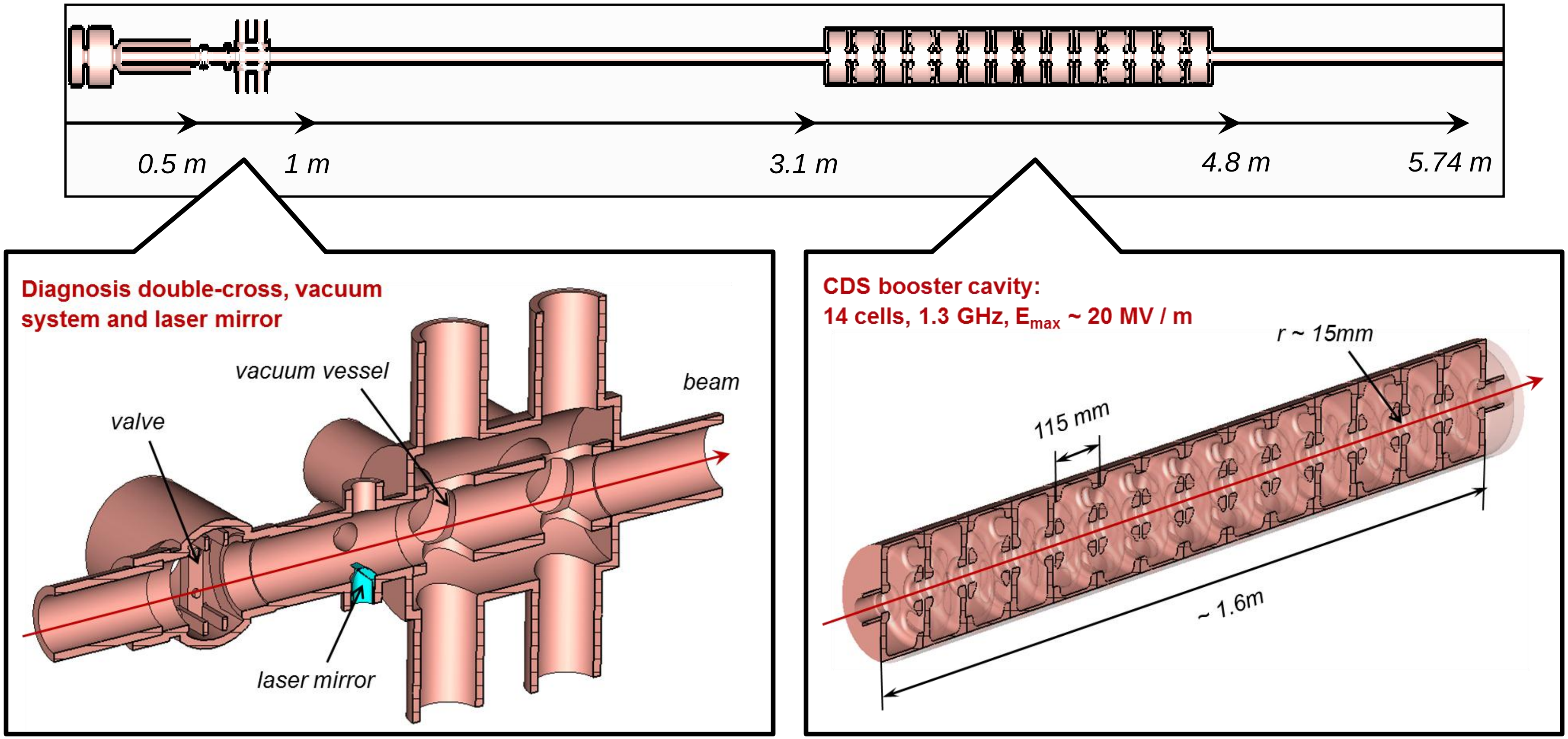
DESY/TEMF Meeting - Status 2012

DESY, Hamburg, 17.12.2012

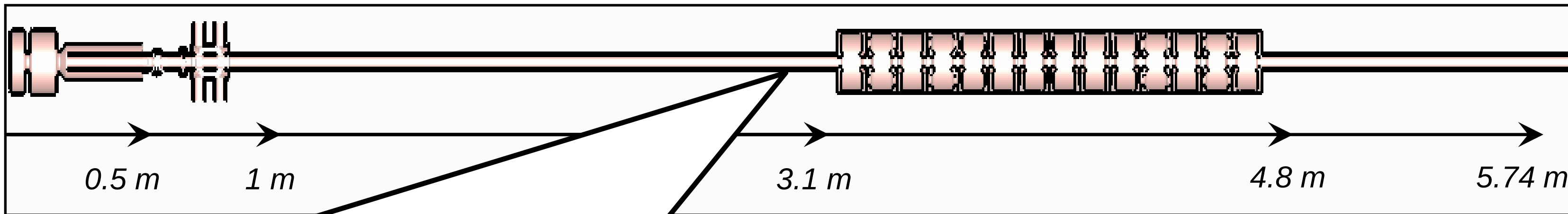
Contents

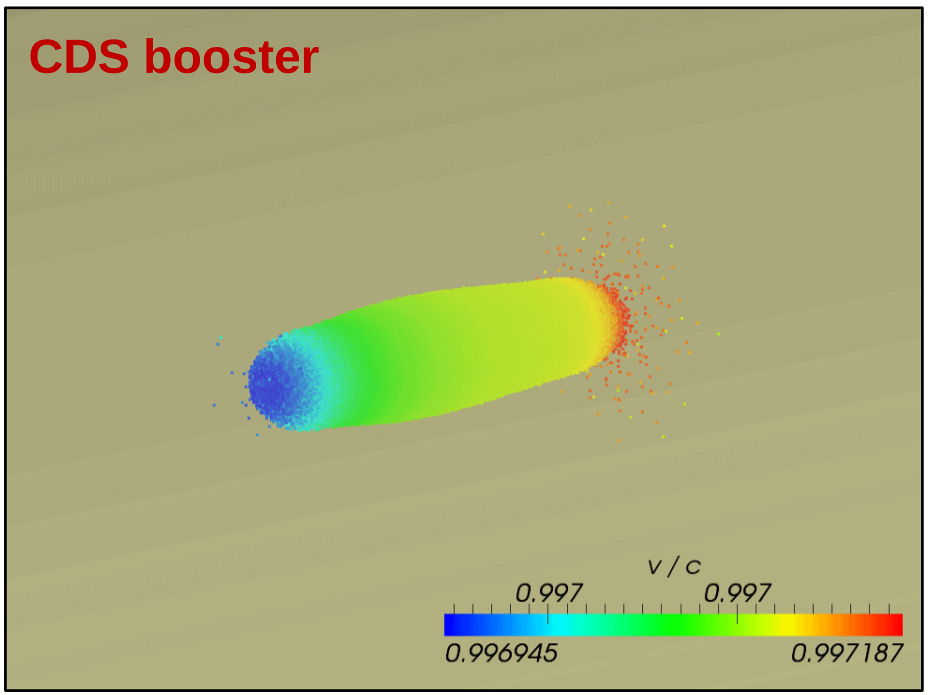
Motivation

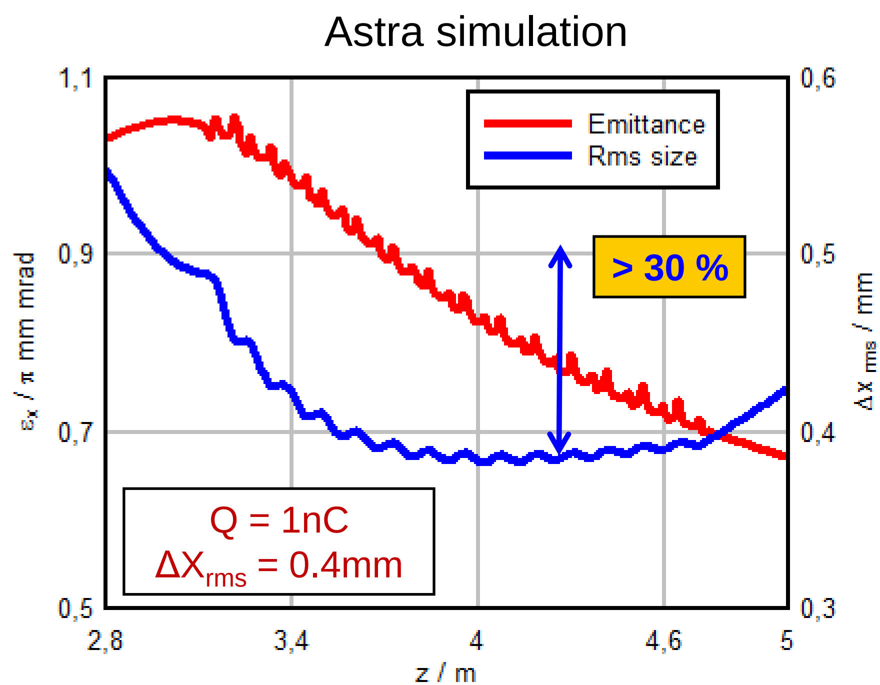


What is the effect of geometry on beam dynamics for PITZ?

Motivation


0.5 m
1 m
3.1 m
4.8 m
5.74 m


CDS booster
v / c
0.997
0.997
0.996945
0.997187


Astra simulation
Emittance
Rms size
> 30 %
Q = 1nC
ΔX_rms = 0.4mm
ε_x / π mm mrad
Δx_rms / mm
z / m
1,1
0,9
0,7
0,5
0,6
0,5
0,4
0,3
2,8
3,4
4
4,6
5

Full wave simulations with PBCI

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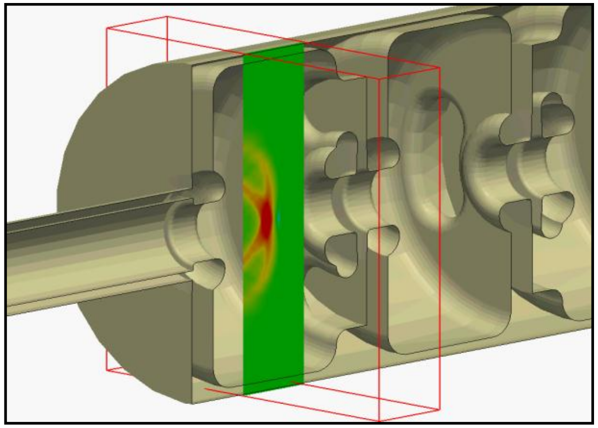
- Self-consistent simulations necessary:
  - Bunch not ultra-relativistic: wakefield codes not applicable
  - Transverse dynamics: wake potential / Green function approach invalid
  - Space charge and wakefield effects not separable
- Standard PIC simulations so far not possible:
  - Long propagation distance: huge mesh
  - High spatial resolution necessary: huge memory / solver times
  - Consistent field initialization not trivial

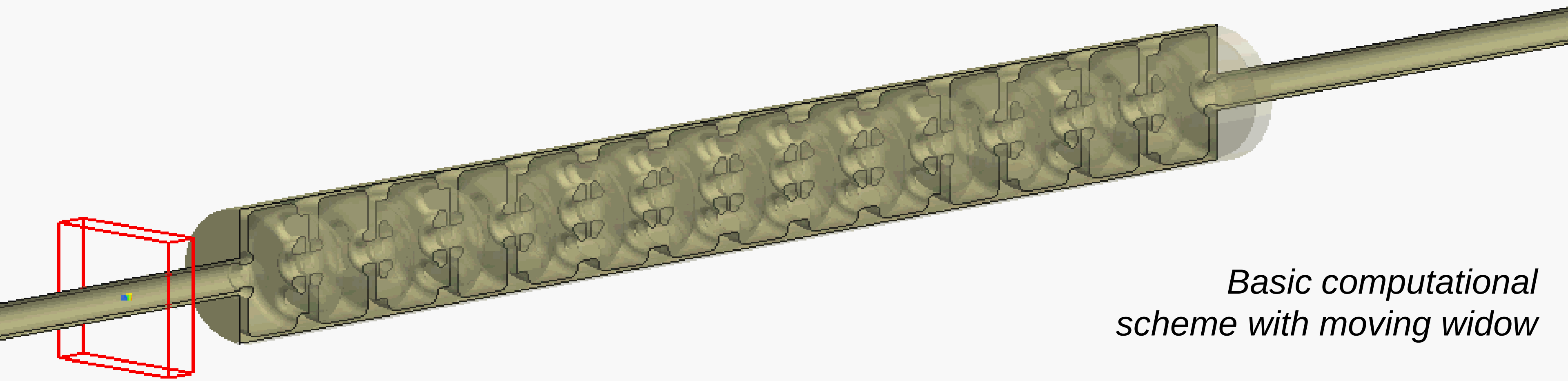
- Idea: combine moving window approach of PBCI with PIC

Full wave simulations with PBCI

Particle-In-Cell in the moving window



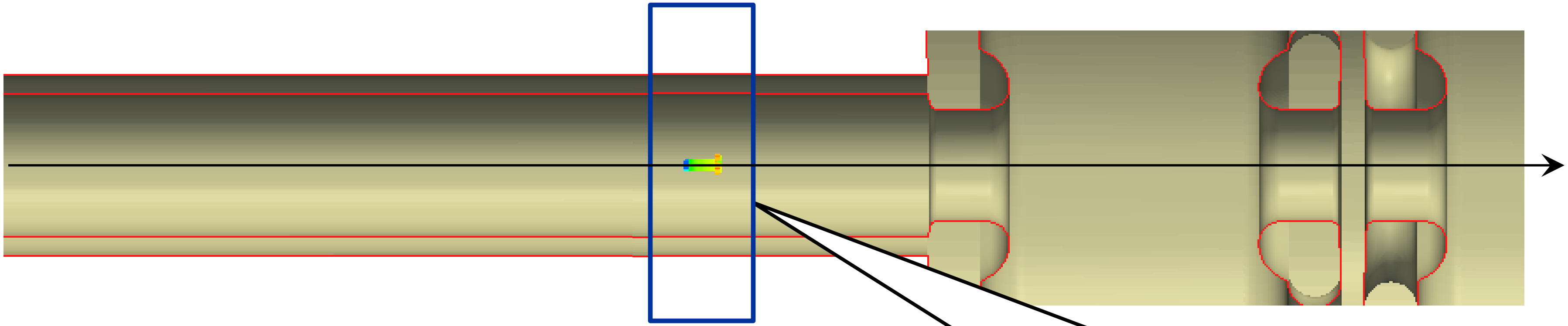
- Dispersion-free method with optimal stability
- “Small” computational window:
  - necessary transverse resolution for bunch ~50 μm
- Initial particle distribution from ASTRA
- **Self-consistent initial fields?**

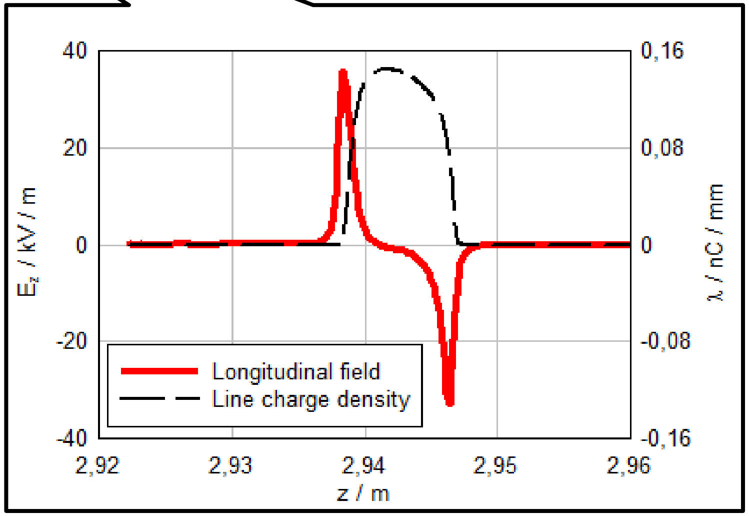


Basic computational scheme with moving widow

Full wave simulations with PBCI

Field initialization procedure





- Exact field initialization not possible
- Best available approximation: solution by rest frame transformation
- Parasitic low frequency fields due to relative motion within bunch: will decay in the beam pipe

Full wave simulations with PBCI

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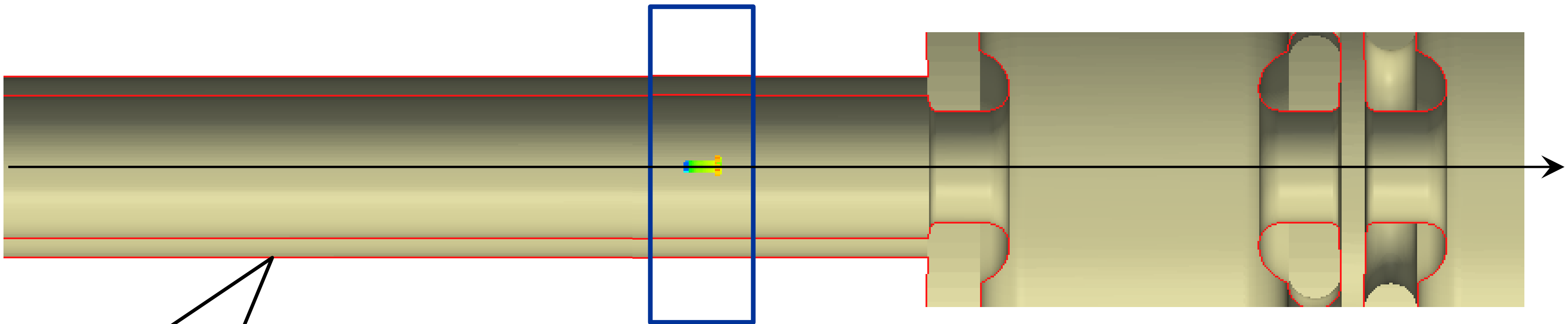
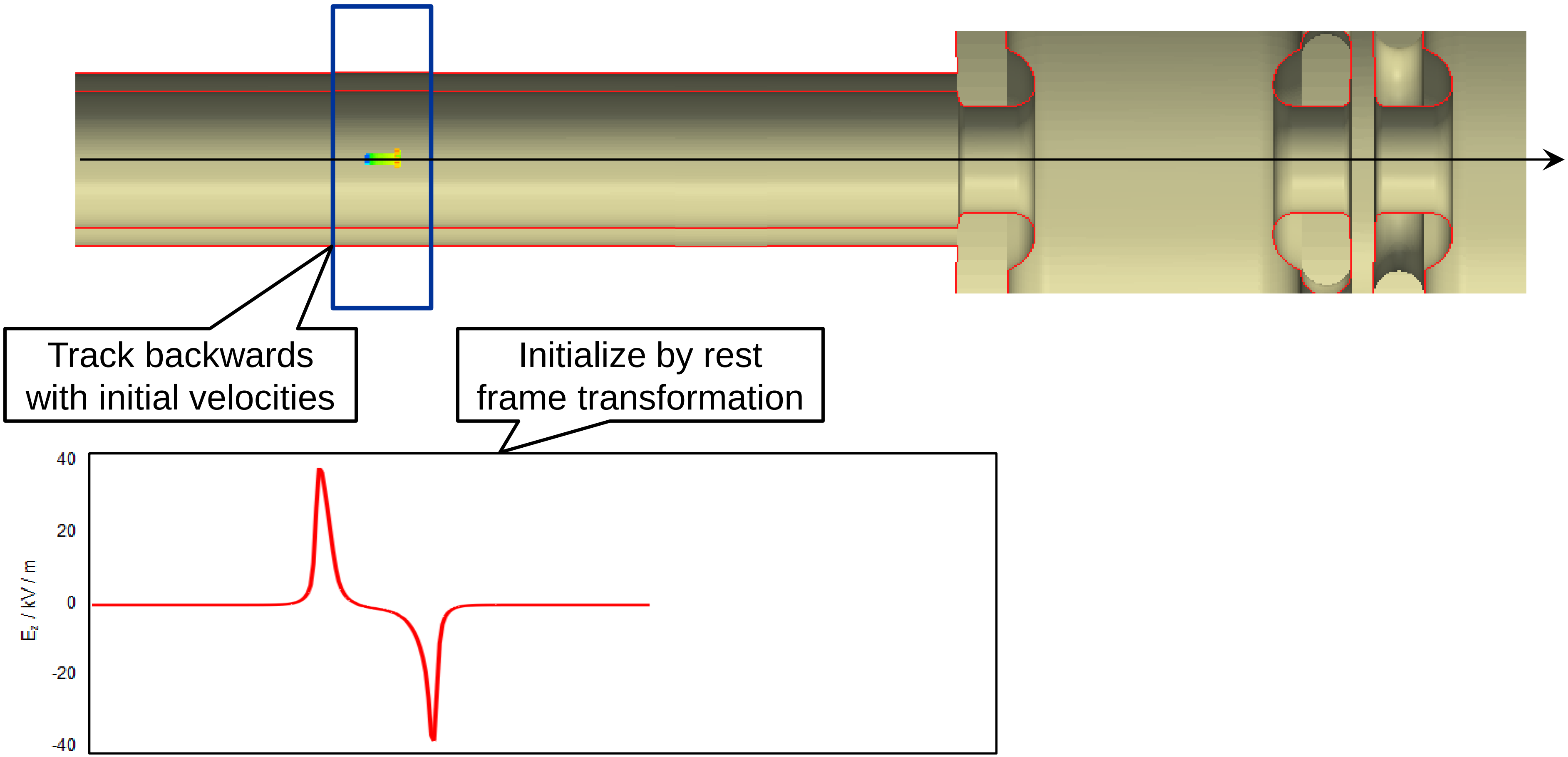
Field initialization procedure



Track backwards
with initial velocities

Full wave simulations with PBCI

Field initialization procedure



Full wave simulations with PBCI

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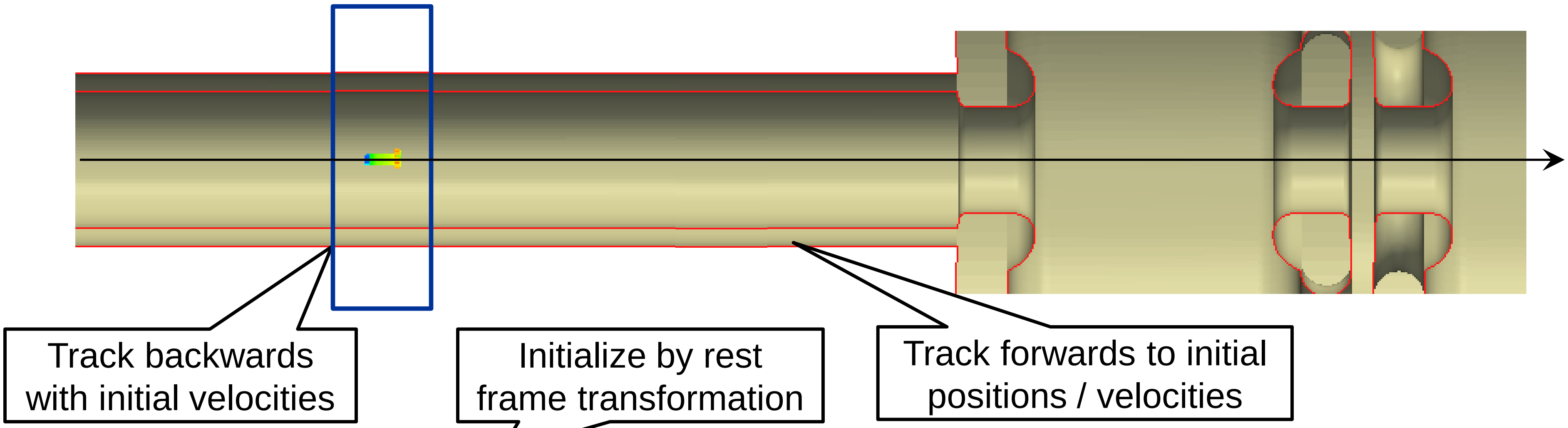
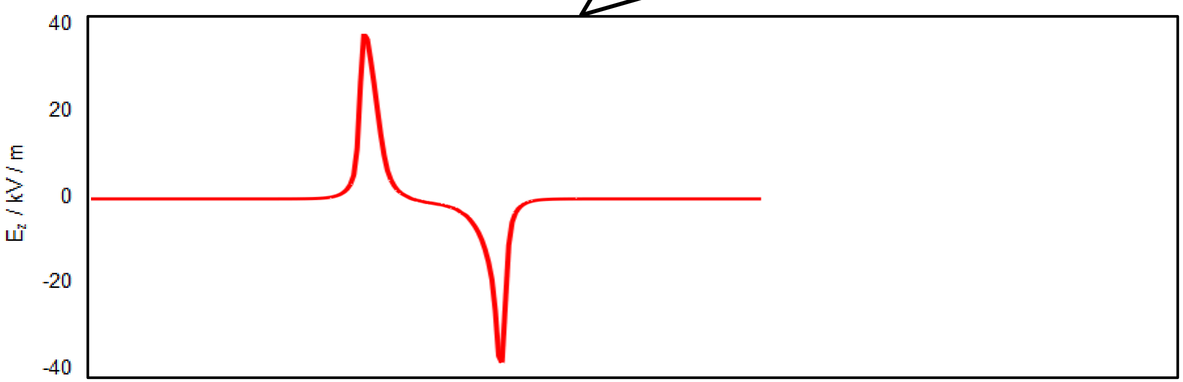
Field initialization procedure



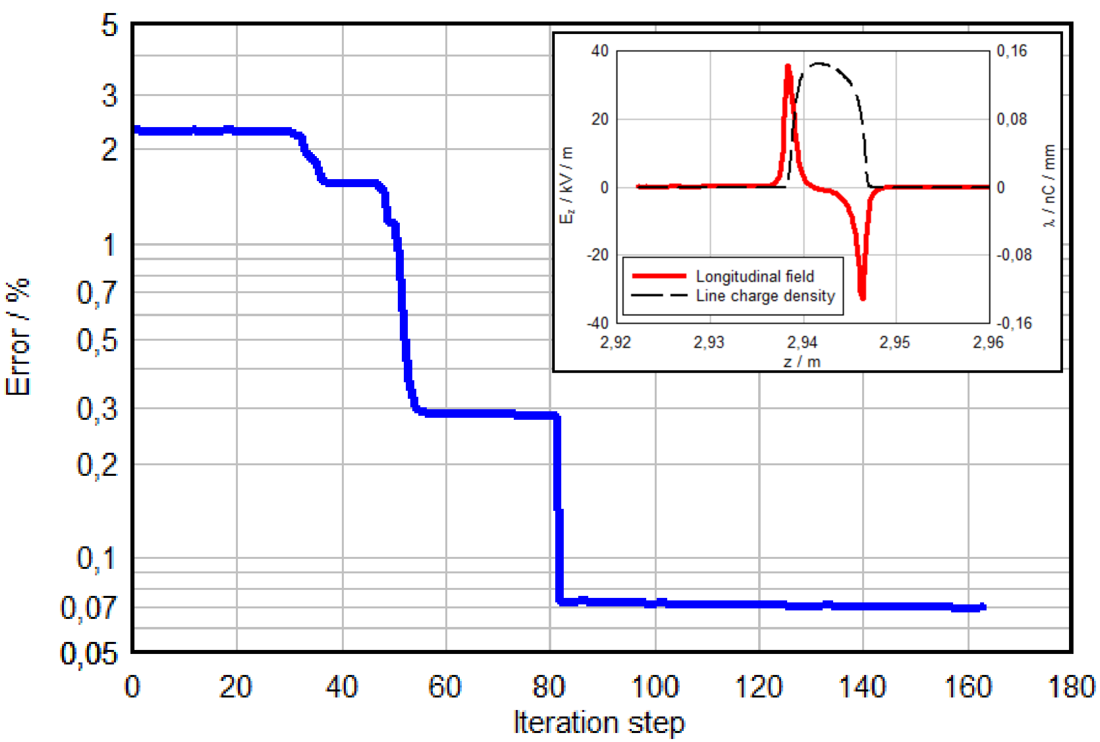


Similar approach for MAFIA-TS3 by Setzer et al., EPAC 2004, WEPLT061 (not using rest frame solution)

Full wave simulations with PBCI

Field initialization procedure

Relative error of $||E_z||$ vs. iteration step



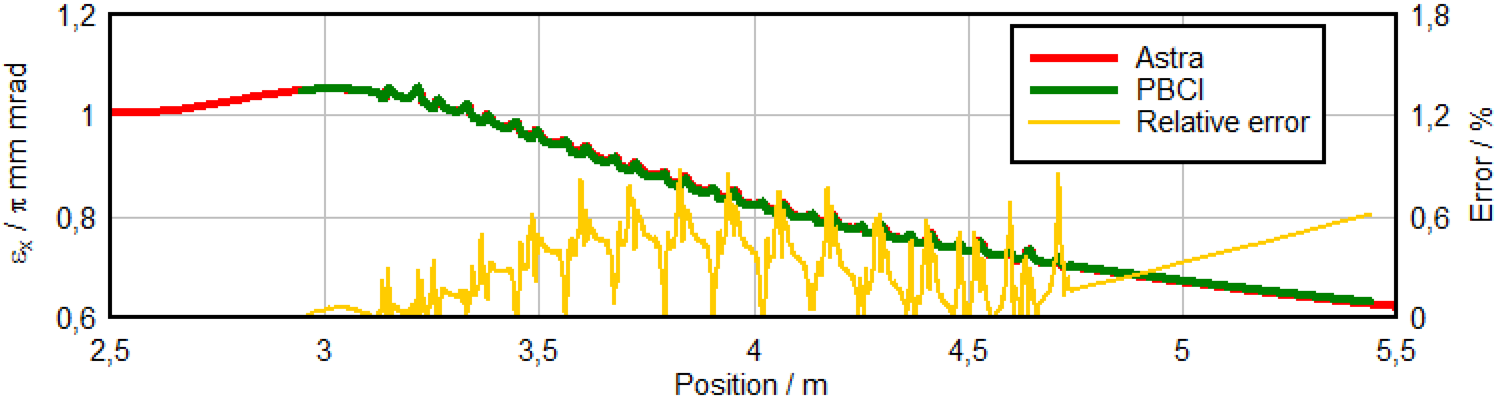
(Typical) data for CDS simulation	
Length	$2.5m$
Grid	$\Delta x = \Delta z = 50\ \mu m$
No. DoFs	300×10^6
No. particles	$0.5 \times 10^5 - 5 \times 10^5$
No. steps	$\sim 100{,}000$
Simulation time	$\sim 24 - 72\ hrs.$

- Fast convergence (1-2 window lengths sufficient)
- Very low cost compared to total simulation time

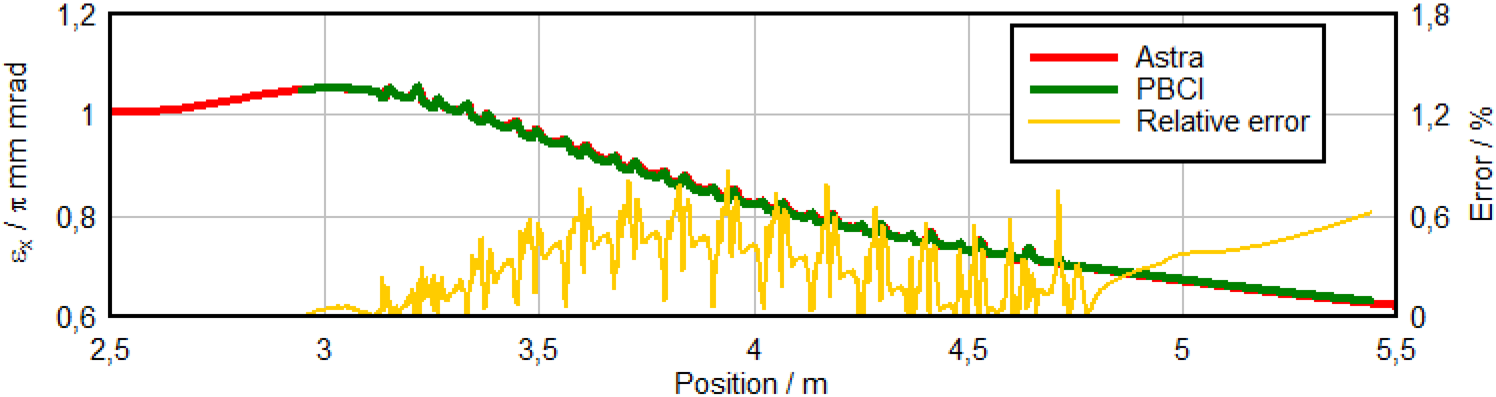
Full wave simulations with PBCI

CDS results: emittance

Q = 1nC
ΔX_{rms} = 0.4mm



SPCH only

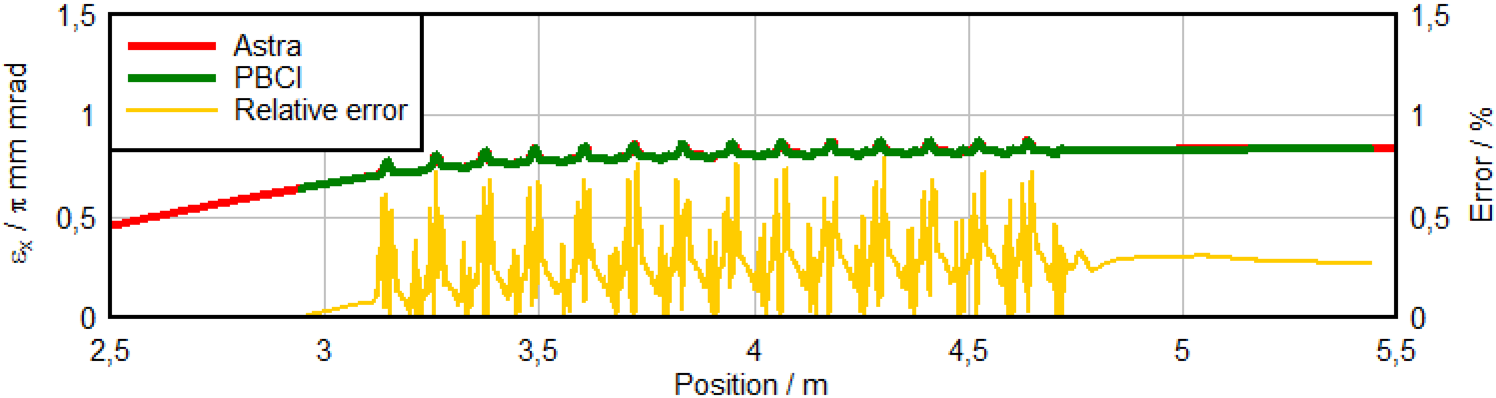


SPCH + Wake

Full wave simulations with PBCI

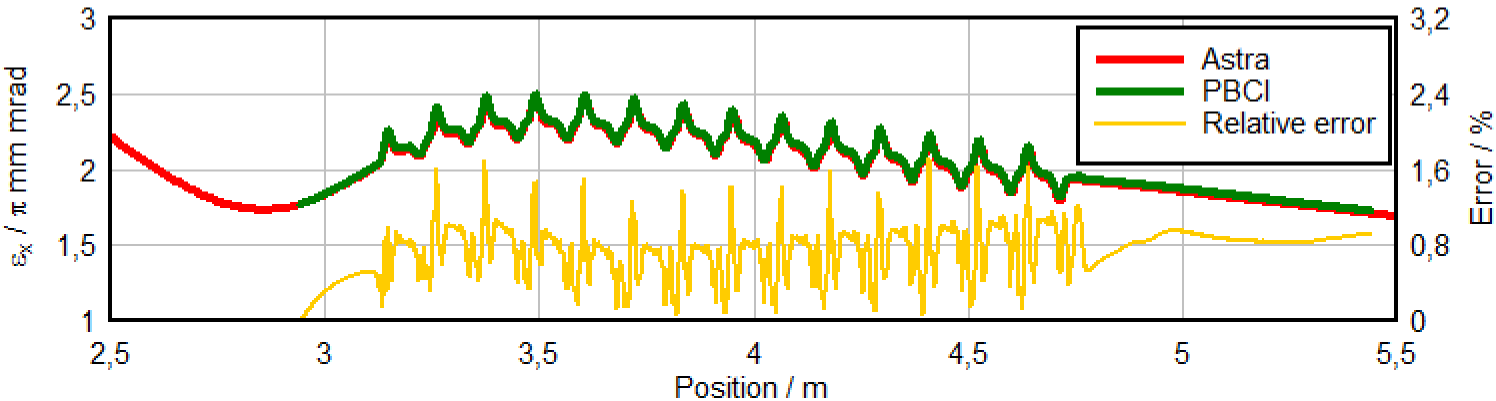
CDS results: emittance

Q = 100pC
ΔX_{rms} = 0.3mm



SPCH + Wake

Q = 2nC
ΔX_{rms} = 0.5mm

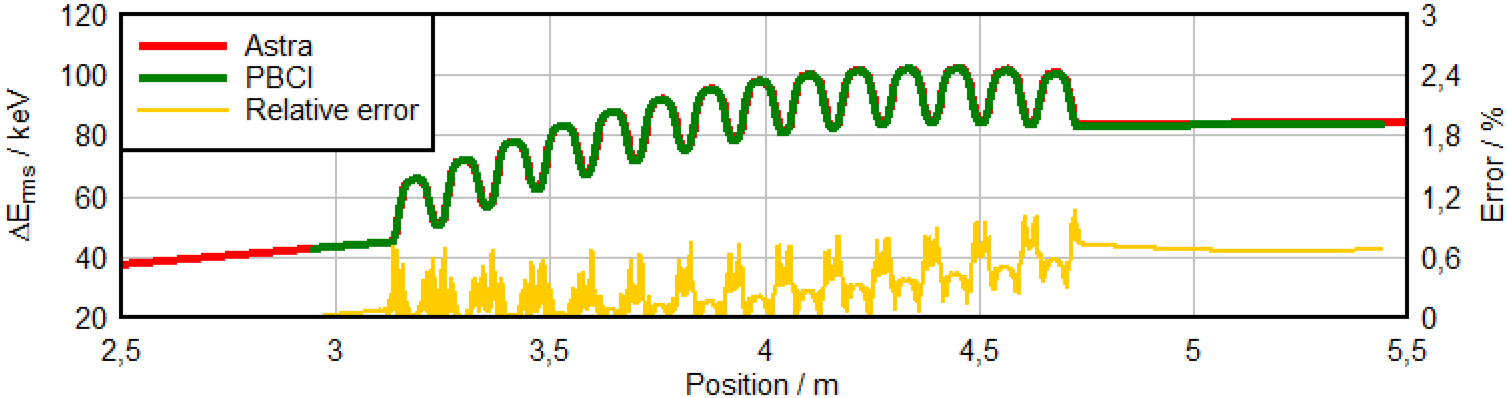


SPCH + Wake

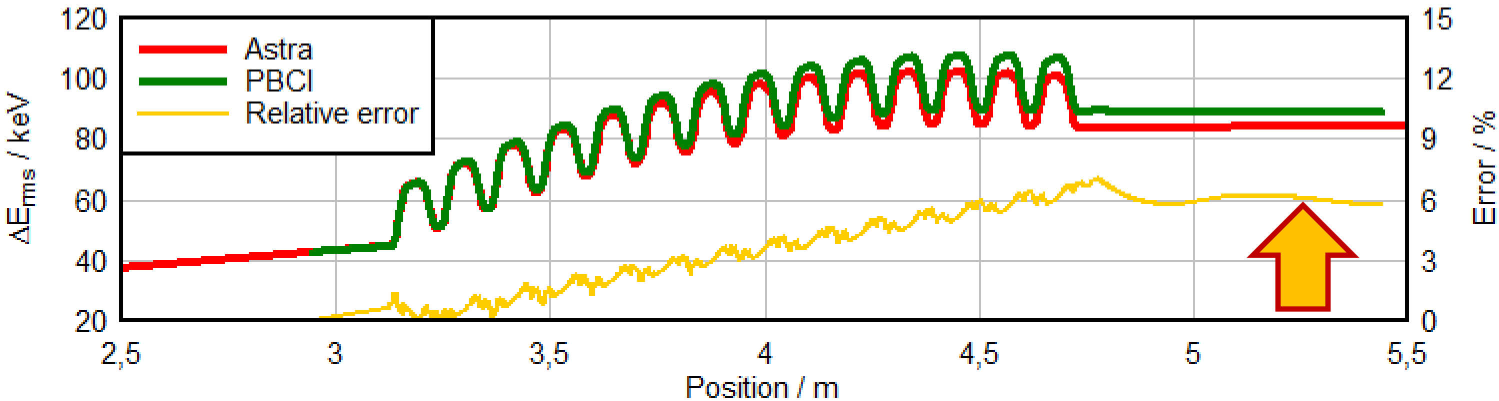
Full wave simulations with PBCI

CDS results: energy spread

Q = 1nC
ΔX_{rms} = 0.4mm



SPCH only

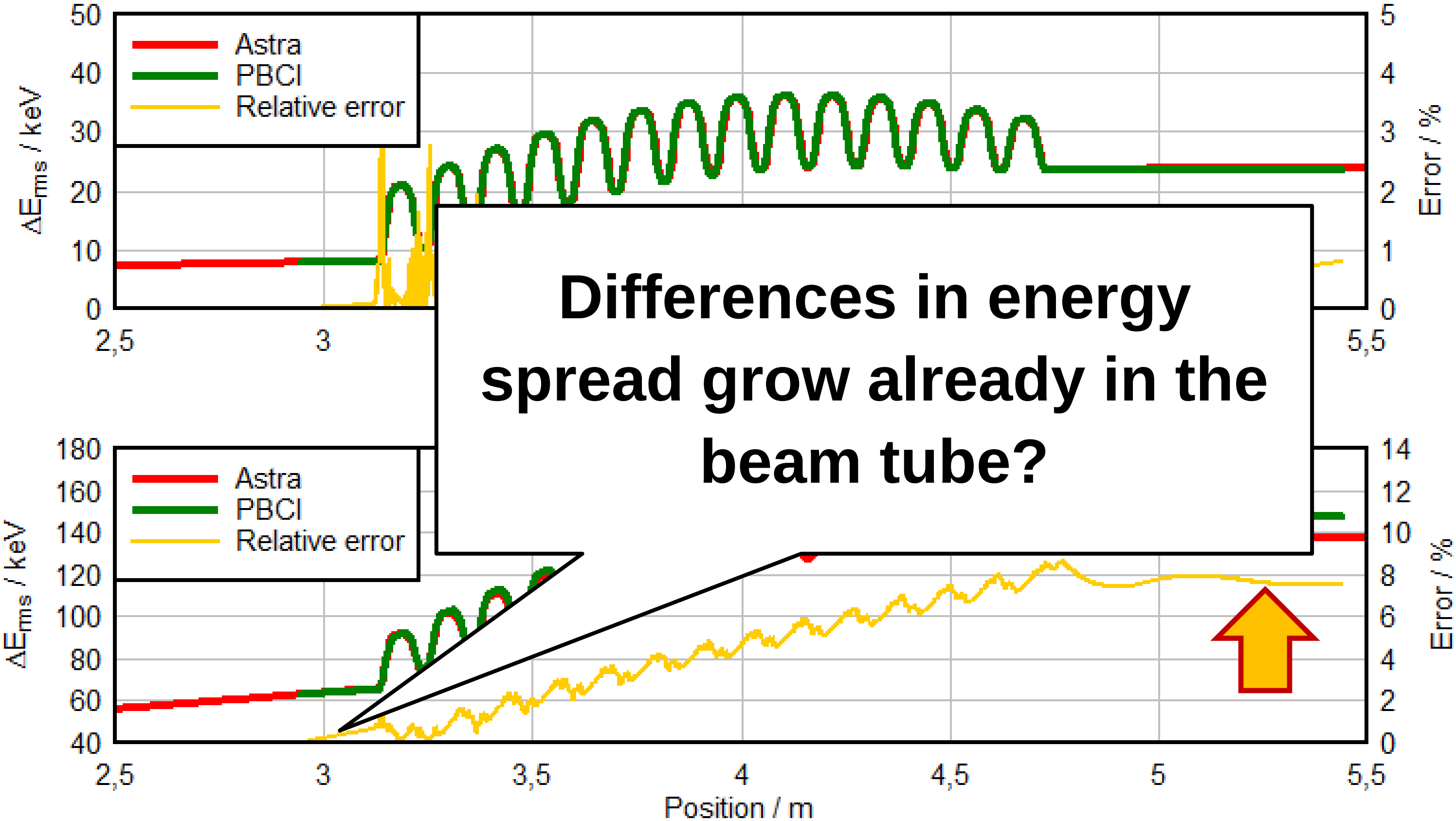


SPCH + Wake

Full wave simulations with PBCI

CDS results: energy spread

Q = 100pC
ΔX_{rms} = 0.3mm



SPCH + Wake

Differences in energy spread grow already in the beam tube?

Q = 2nC
ΔX_{rms} = 0.5mm

SPCH + Wake

Rest frame simulations with PBCI

- Large energy spread deviations between Astra and PBCI:
  - Wakefields?
  - PBCI (dispersion errors, initial fields, charge errors, particle noise)?
  - Astra (physical simplifications)?
- **Rest frame PIC-Poisson solver in PBCI**
  - Particle distribution from Astra
  - Finite differences with PEC / free-space boundary conditions
  - Beam tube of arbitrary cross-section
  - Fast parallel multigrid solver
  - Moving (but non-adaptive) mesh imported from CST Studio™

Rest frame simulations with PBCI

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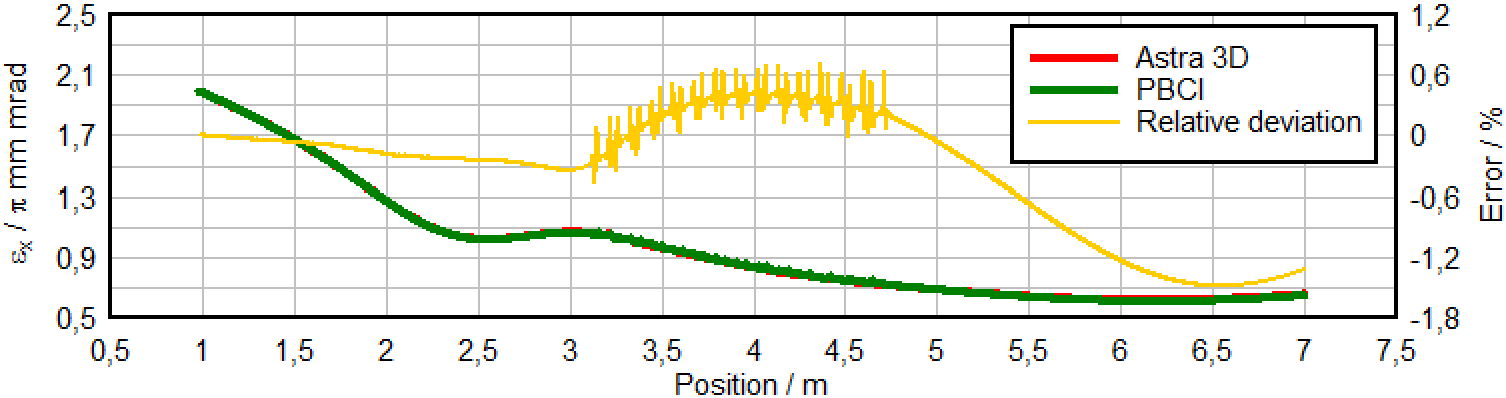
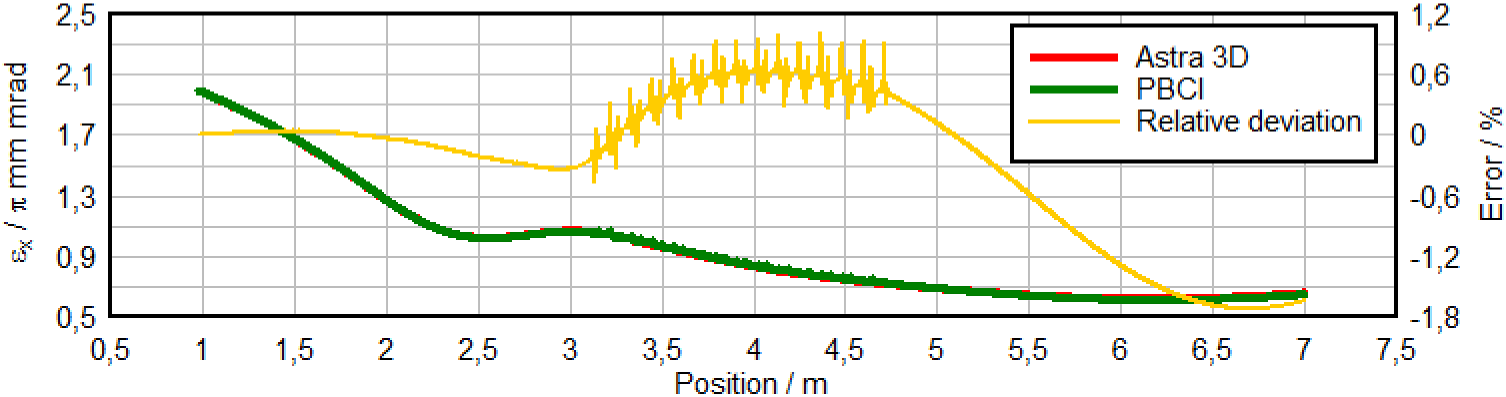
CDS results: emittance

Q = 1nC
ΔX_{rms} = 0.4mm



Free space

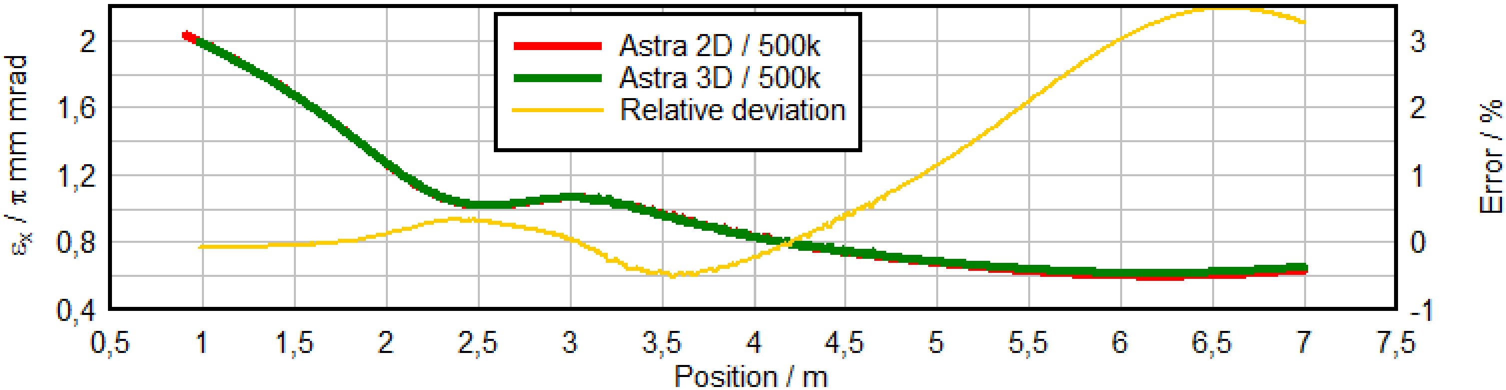


Beam tube

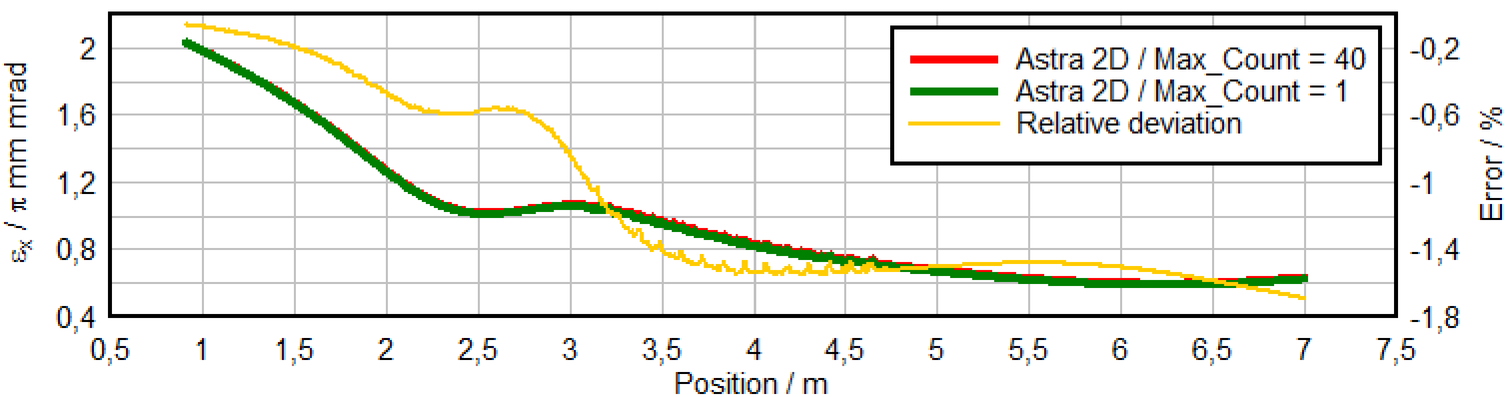
Rest frame simulations with PBCI

CDS results: influence of parameters

Q = 1nC
ΔX_{rms} = 0.4mm



Free space

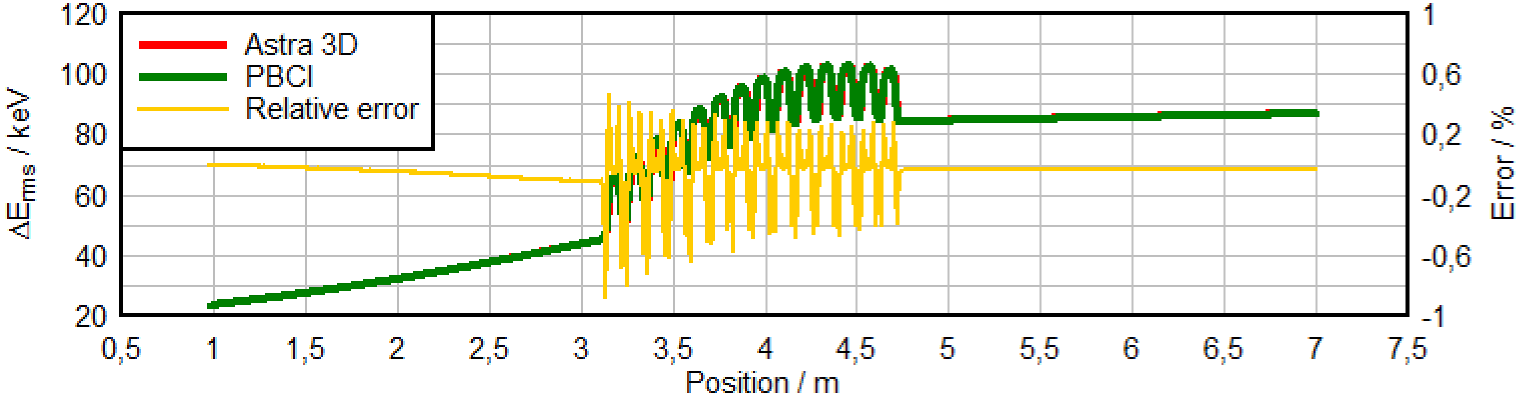


Free space

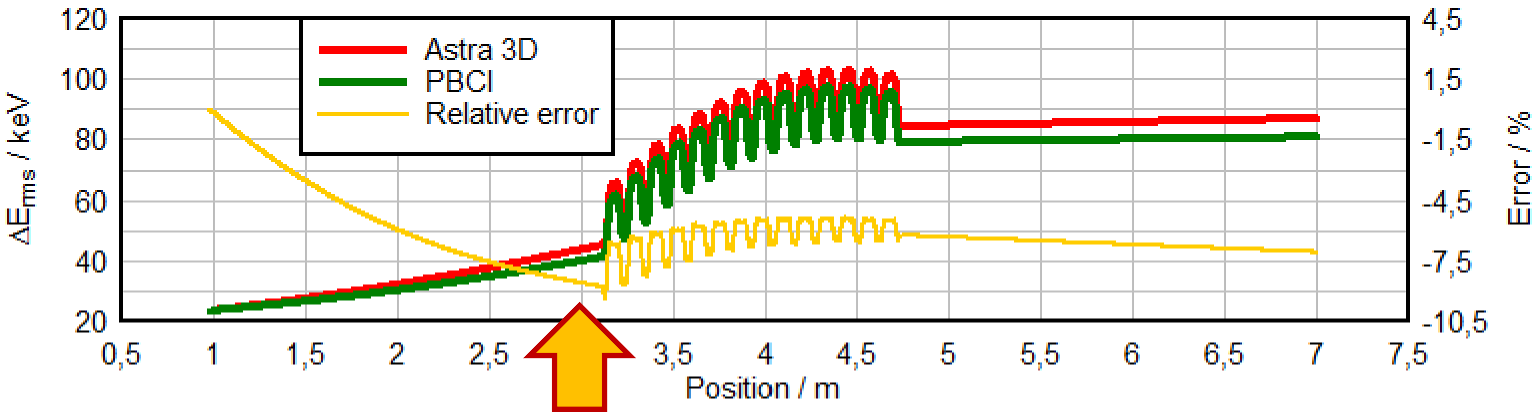
Rest frame simulations with PBCI

CDS results: energy spread

Q = 1nC
ΔX_{rms} = 0.4mm



Free space



Beam tube

Rest frame simulations with PBCI

Energy spread estimation

Longitudinal impedance for transversely uniform beam in perfectly conducting pipe*

$$Z_{\|}(r,\omega) = -\frac{i\,L}{\omega\pi\,a^2\varepsilon_0}\left\{\frac{r^2}{a^2} - \frac{2r}{a} I_1(\sigma r)\left[K_1(\sigma a) + \overbrace{\frac{K_0(\sigma b)}{I_0(\sigma b)} I_1(\sigma a)}\right]\right\}$$

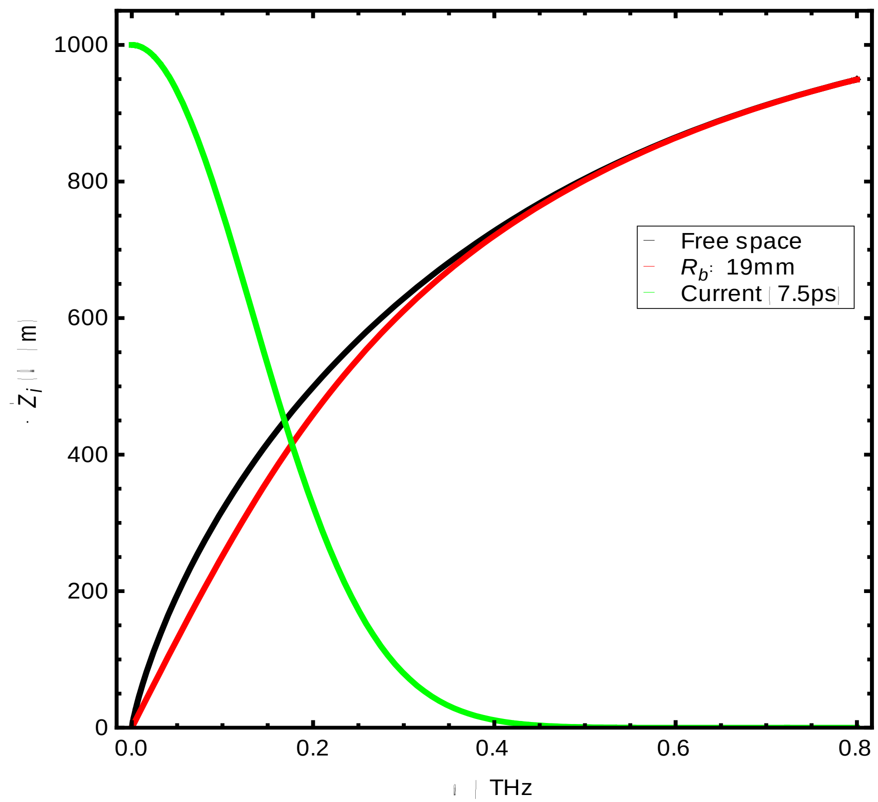
$$\widehat{Z}_{\|}(\omega) = \frac{1}{L}\frac{1}{\pi\,a^2}\int_0^a 2\pi r\, Z_{\|}(r,\omega)dr$$

a, b – beam radius / pipe radius

$\sigma = \omega\ /\ c\beta\gamma$

*Al-khateeb et al, Phys. Rev. E, 63 (2001)

$a = 2mm, \gamma = 10$



Rest frame simulations with PBCI

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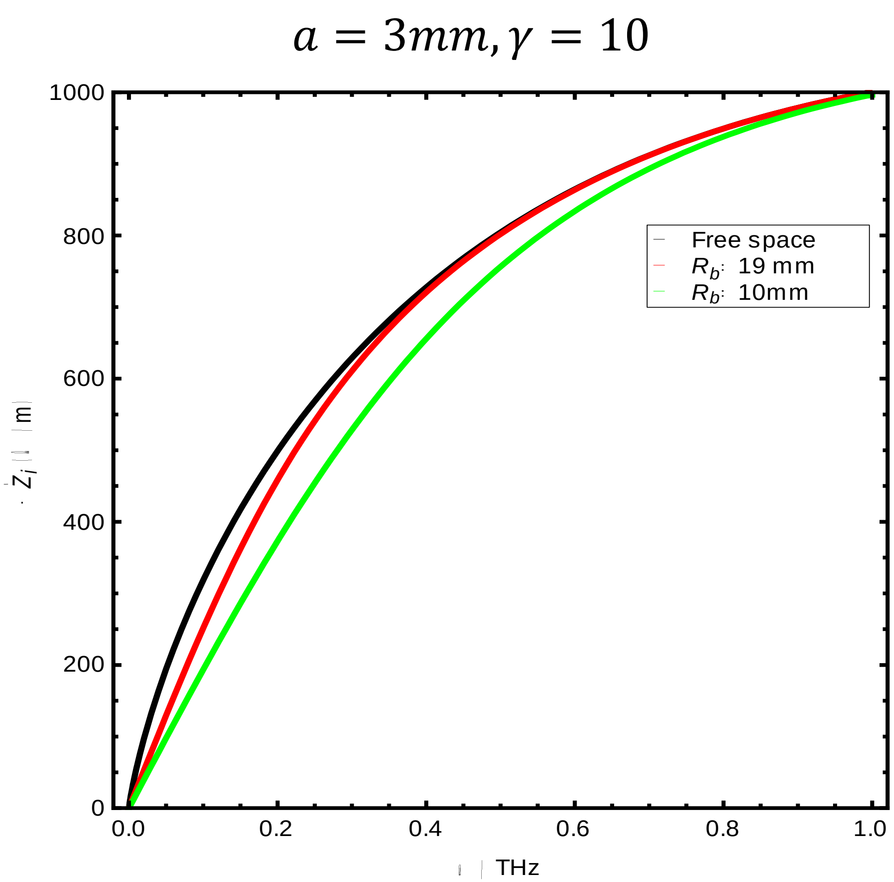
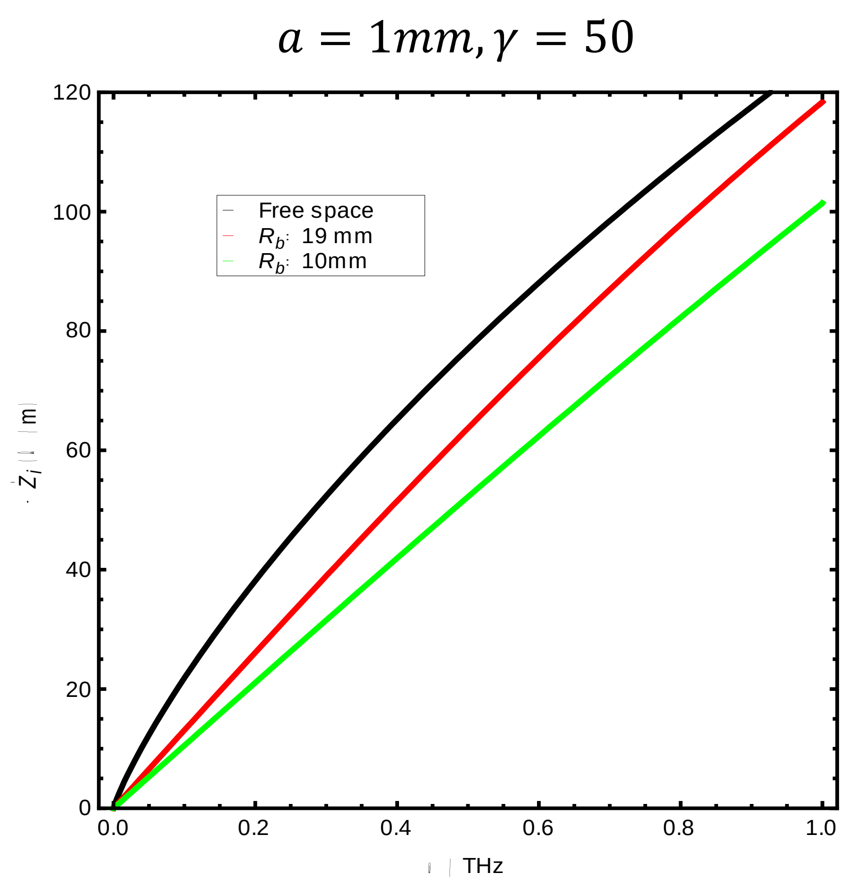
Space charge impedances

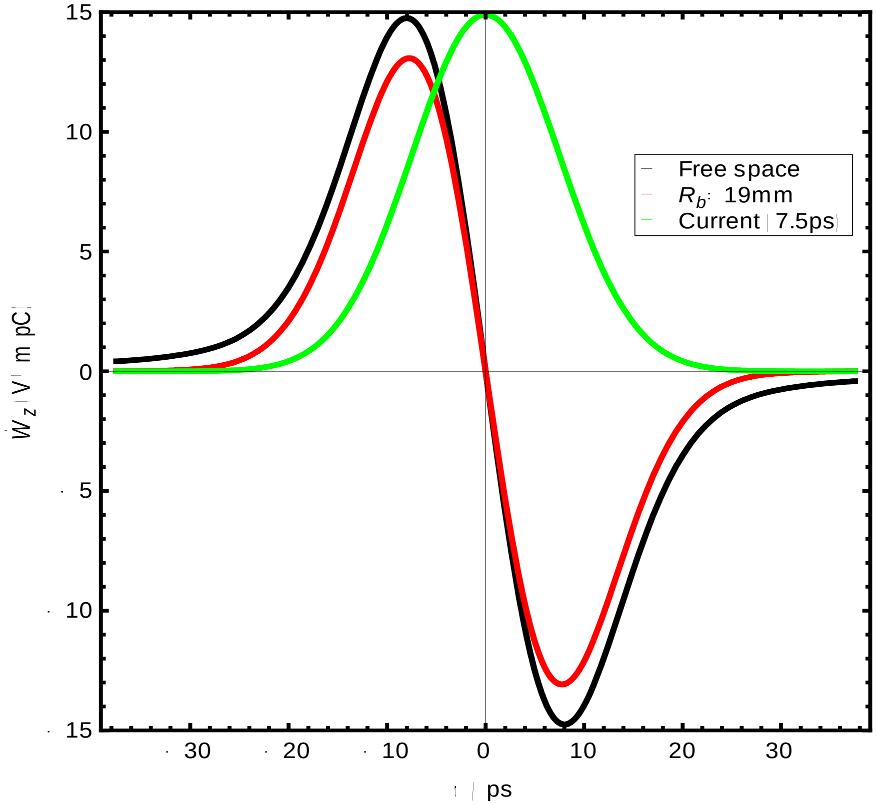




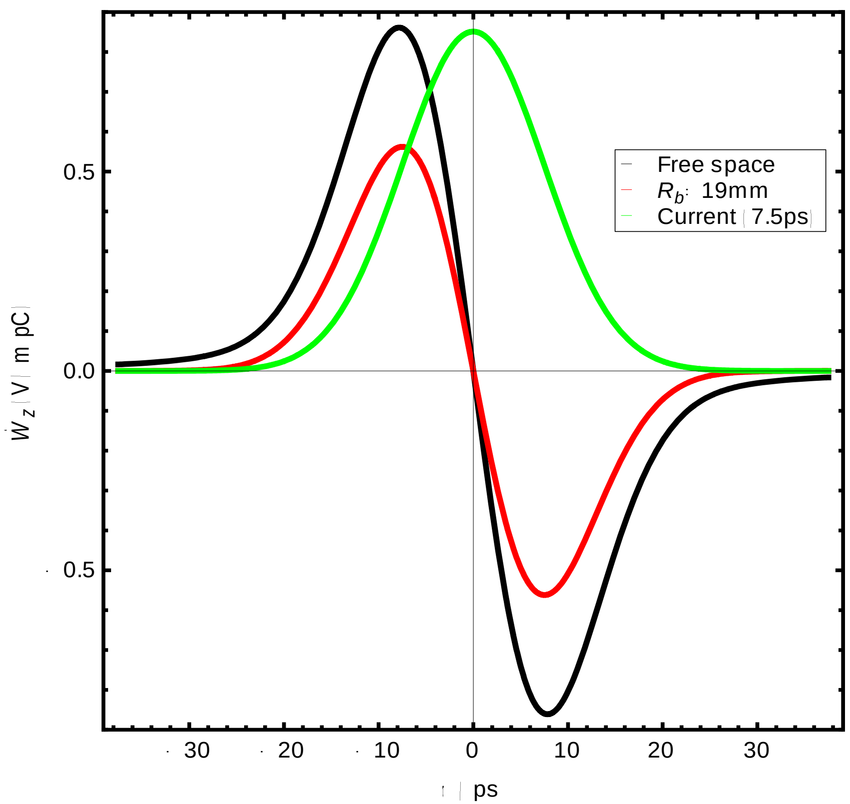
Rest frame simulations with PBCI

Bunch wake functions

$a = 1mm, \gamma = 10$



$a = 1mm, \gamma = 50$



Rest frame simulations with PBCI

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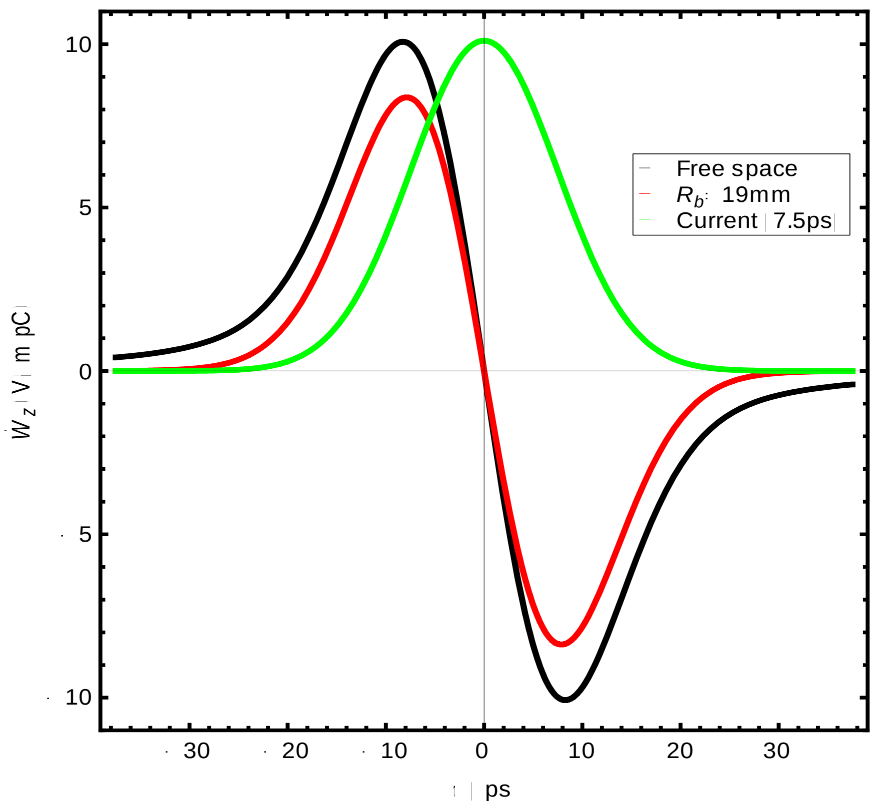
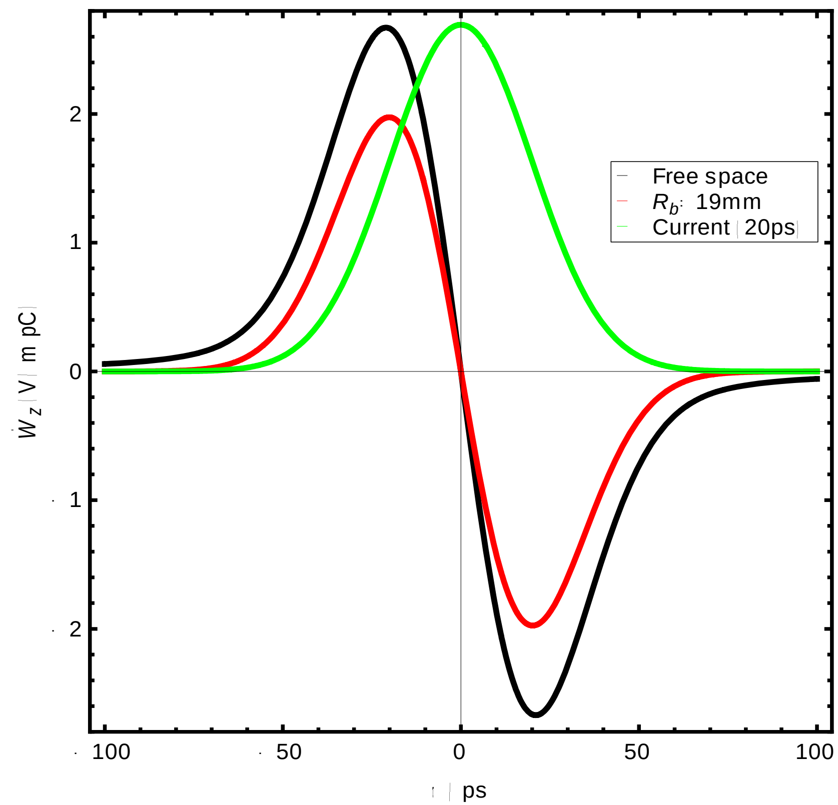
Bunch wake functions

$a = 3mm, \gamma = 10$



$a = 1mm, \gamma = 10$ (long)



Rest frame simulations with PBCI

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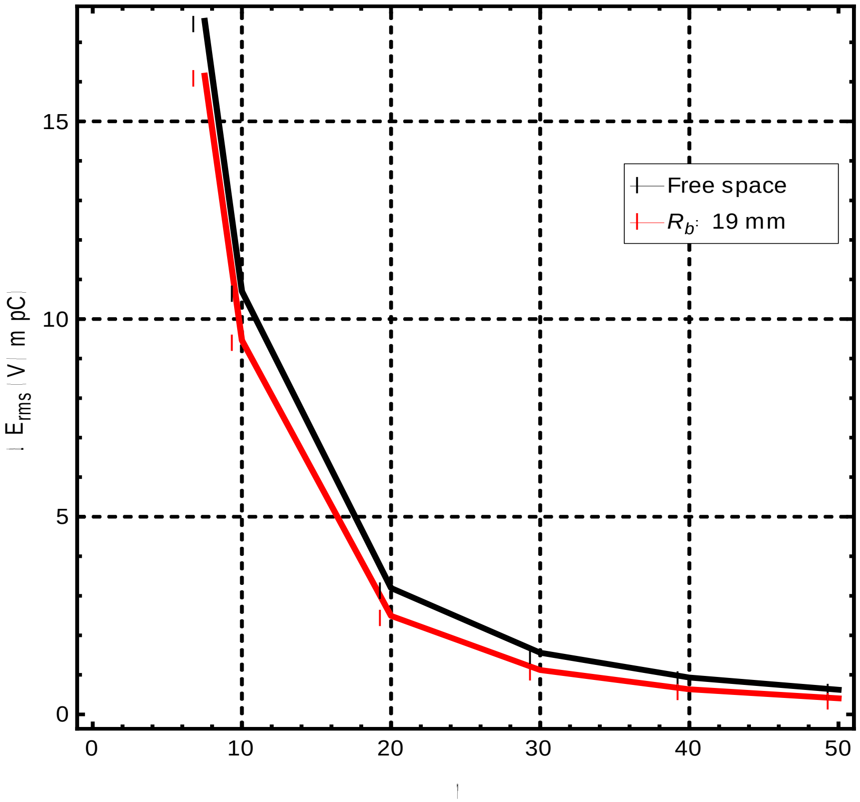
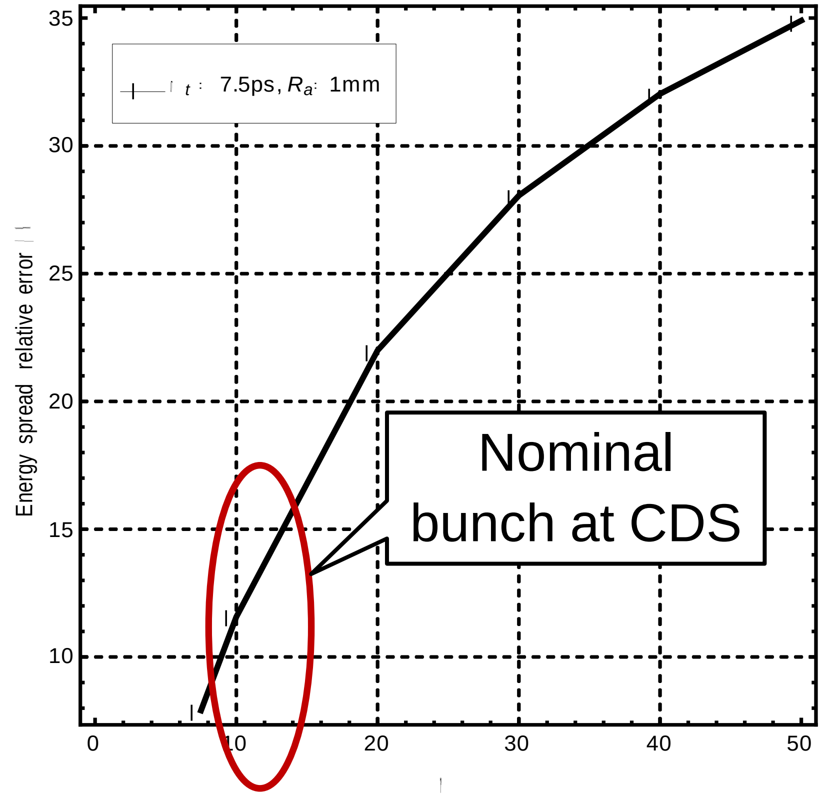
Energy spread vs. γ

$a = 1mm, \sigma_t = 7.5ps$

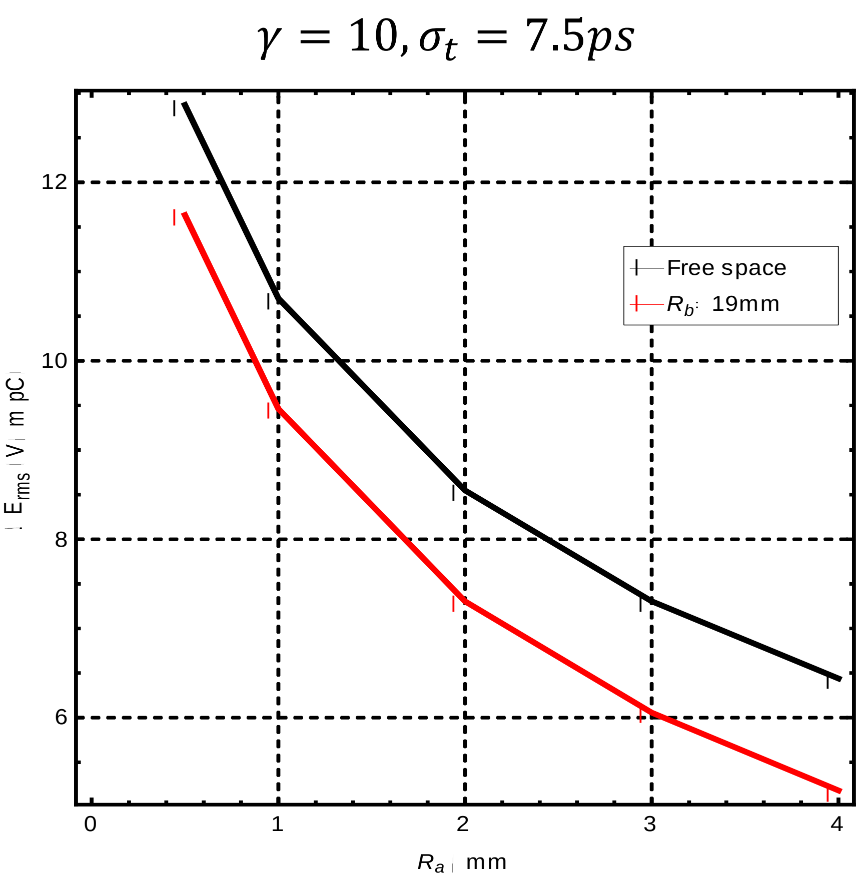


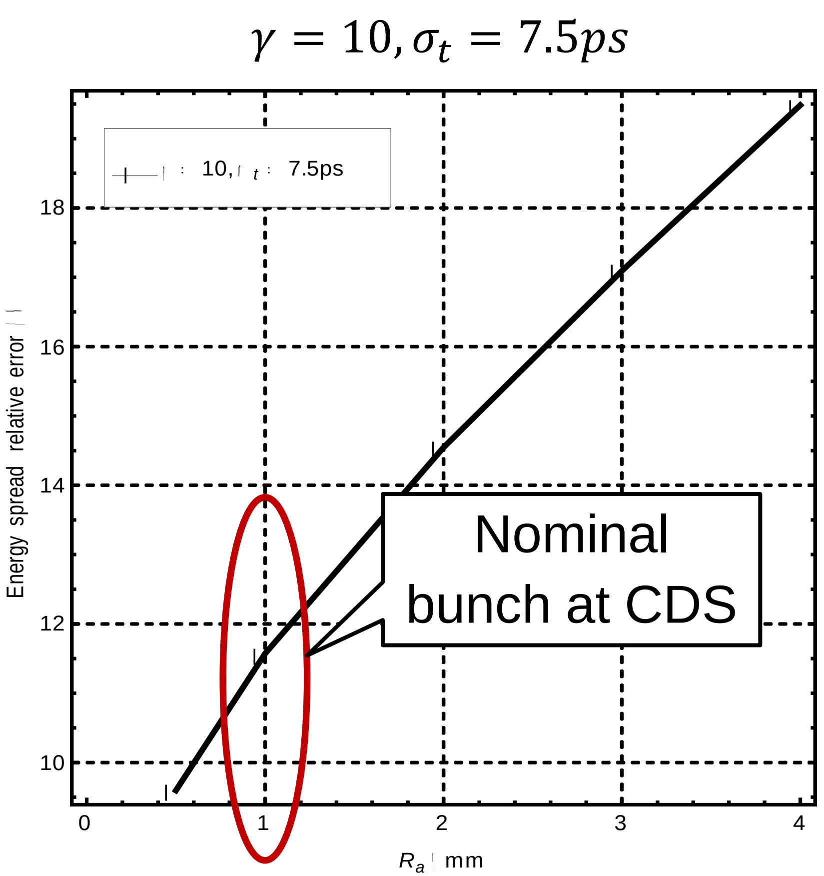
$a = 1mm, \sigma_t = 7.5ps$



Rest frame simulations with PBCI

Energy spread vs. a

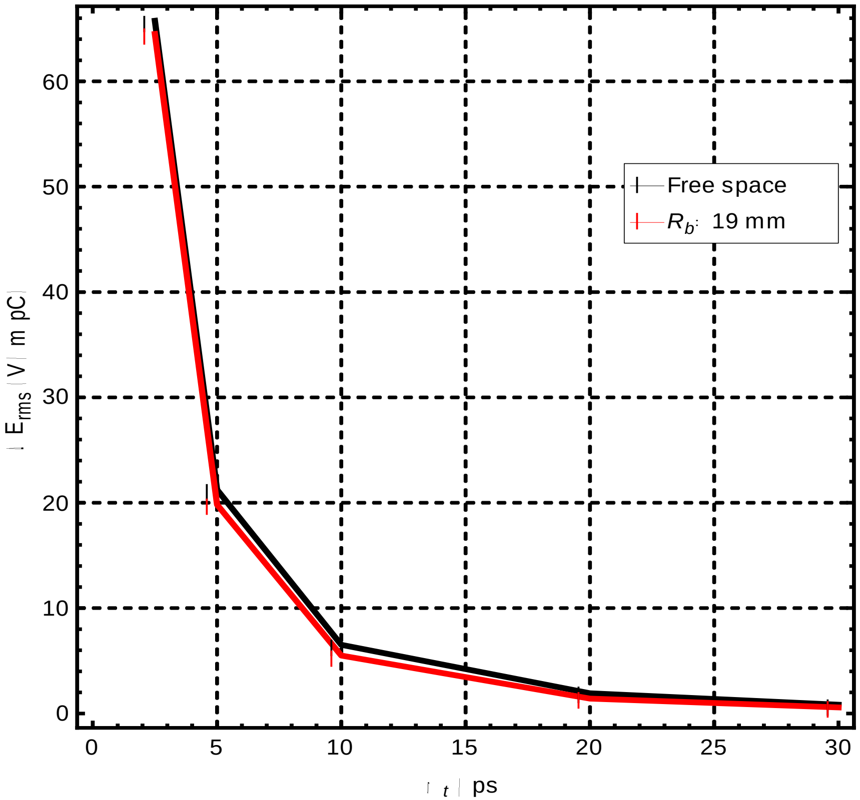




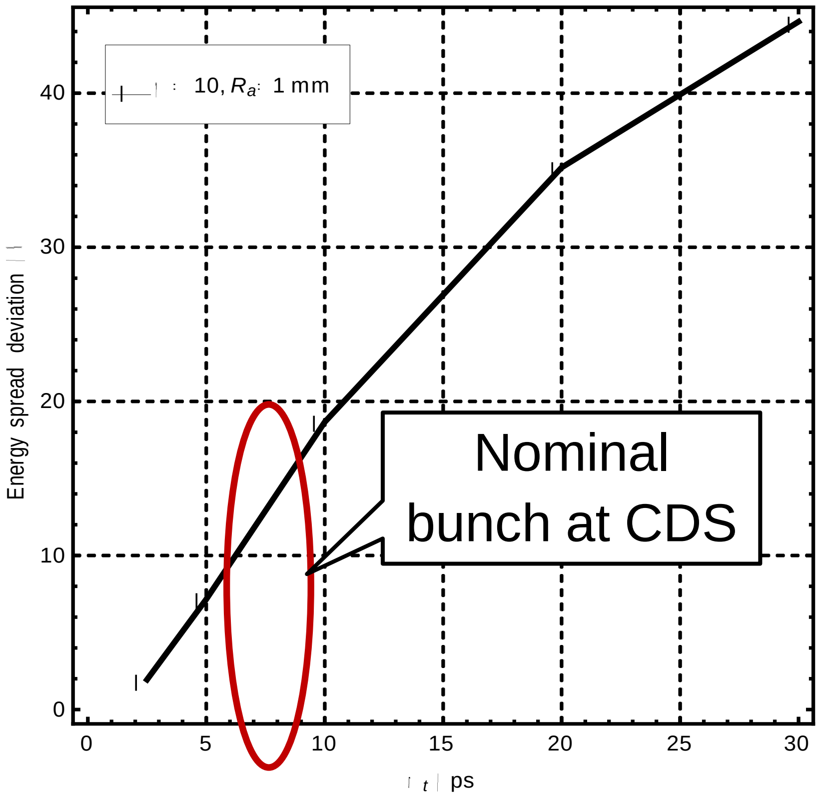
Rest frame simulations with PBCI

Energy spread vs. bunch length

$\gamma = 10, a = 1mm$



$\gamma = 10, a = 1mm$



Summary & Conclusions

- Space charge & wake fields simulations with PBCI
  - For scraper iris and diagnosis cross (see Gjonaj et al, ICAP 2012)
  - CDS booster:
    - No significant emittance growth due to wakefields
    - but large discrepancies (10-20%) in the energy spread compared to Astra
- Rest frame PIC-Poisson solver implemented in PBCI
  - CDS booster:
    - Perfect agreement with Astra for free-space boundary conditions
    - Analytical estimation confirms systematic error in Astra by neglecting longitudinal beam tube impedance
- Ongoing work with PIC-Poisson / EQS solver at the cathode

Thank You for your attention