Numerical Modeling of RF Electron Sources for FEL-Accelerators

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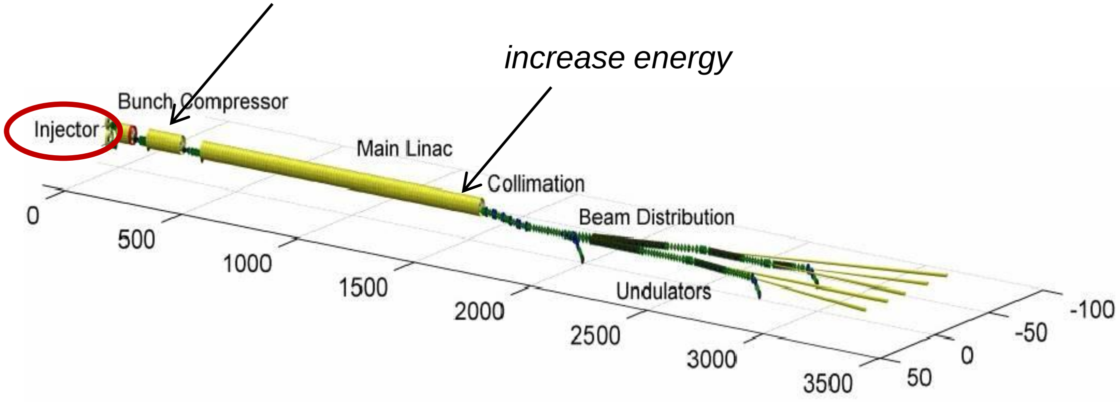
- Low emittance RF electron sources
  - The PITZ photoinjector at DESY
  - Numerical simulations
- Self-consistent simulations with PBCI
  - Beam scraping
  - CDS booster
  - Diagnosis cross
- Summary and conclusions

Low emittance electron sources

The European X-Ray Laser Project (XFEL)

- Electron beam specifications:
  - Peak current (1-10 kA)
  - Emittance (< 1 mm mrad)
  - Energy (10-20 GeV)
  - Energy spread (~0.01 %)
  - Bunch length (10 µm - 1 mm)
  - …



compress,
reduce energy spread (3^{rd} harmonic RF)

increase energy

European XFEL design layout

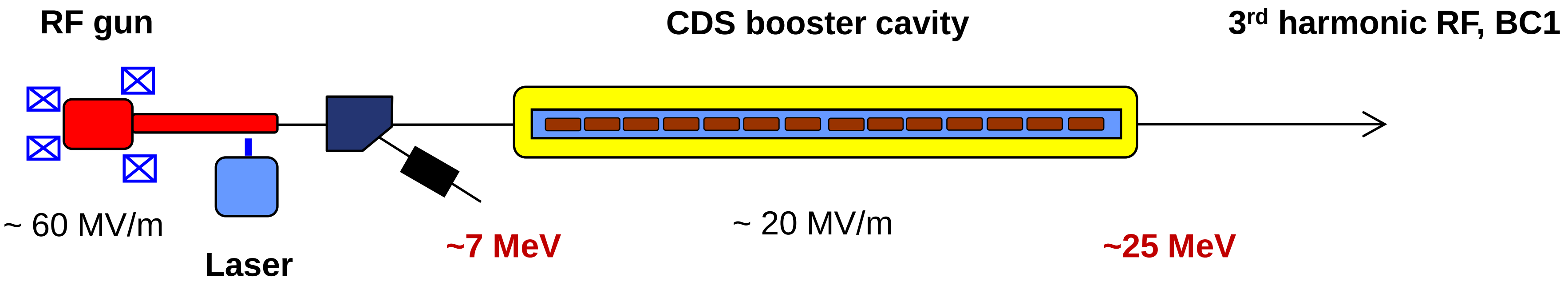
Cannot control transverse beam emittance except for at injection time

⇨ Low emittance source necessary

⇨ **RF photoinjector**

Low emittance electron sources

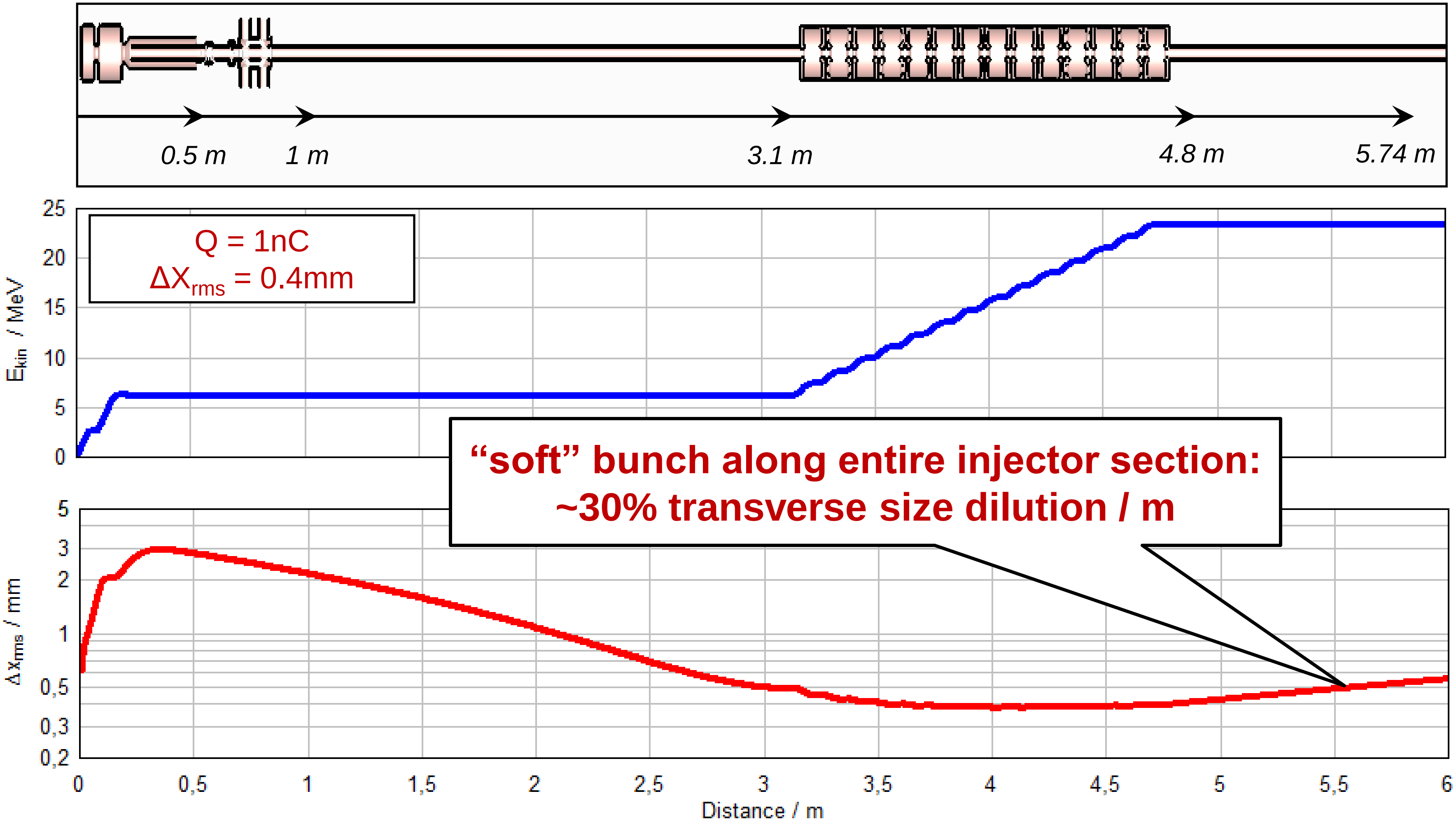
DESY PITZ-1.8 photoinjector setup



RF gun – generate low emittance bunch ⇨ booster – matched acceleration to preserve emittance ⇨ phase space correction compression, acceleration

- 1999: project begin at PITZ facility in Zeuthen, Berlin
- 2003: first operating device – 1.7 mm mrad for 1nC bunch
- 2010: PITZ-1.6 – 1.2 mm mrad
- 2011: PITZ-1.8 meets E-XFEL specification – 0.9 mm mrad

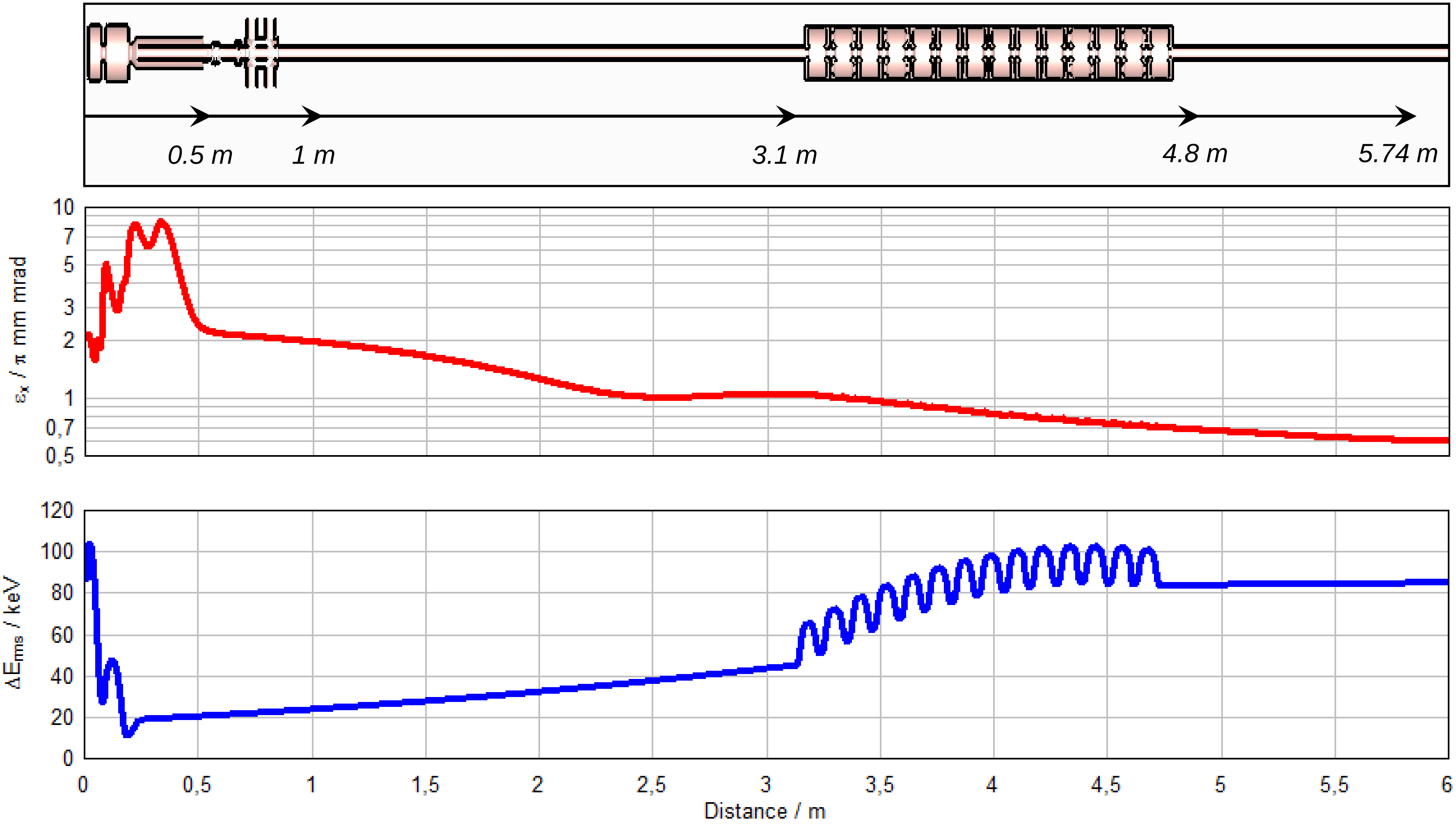
Low emittance electron sources



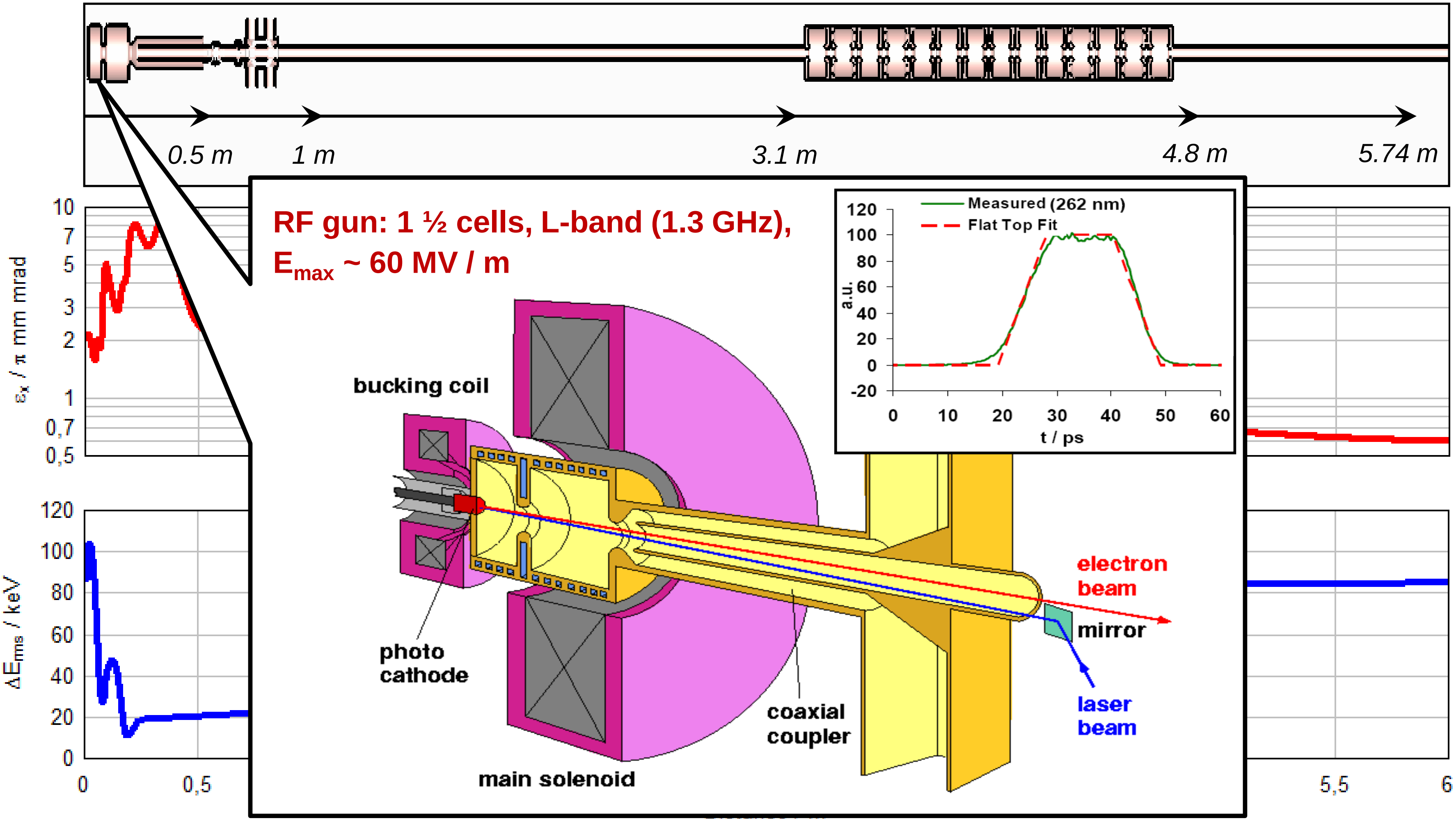
Q = 1nC
ΔX_{rms} = 0.4mm

"soft" bunch along entire injector section:
~30% transverse size dilution / m

Low emittance electron sources

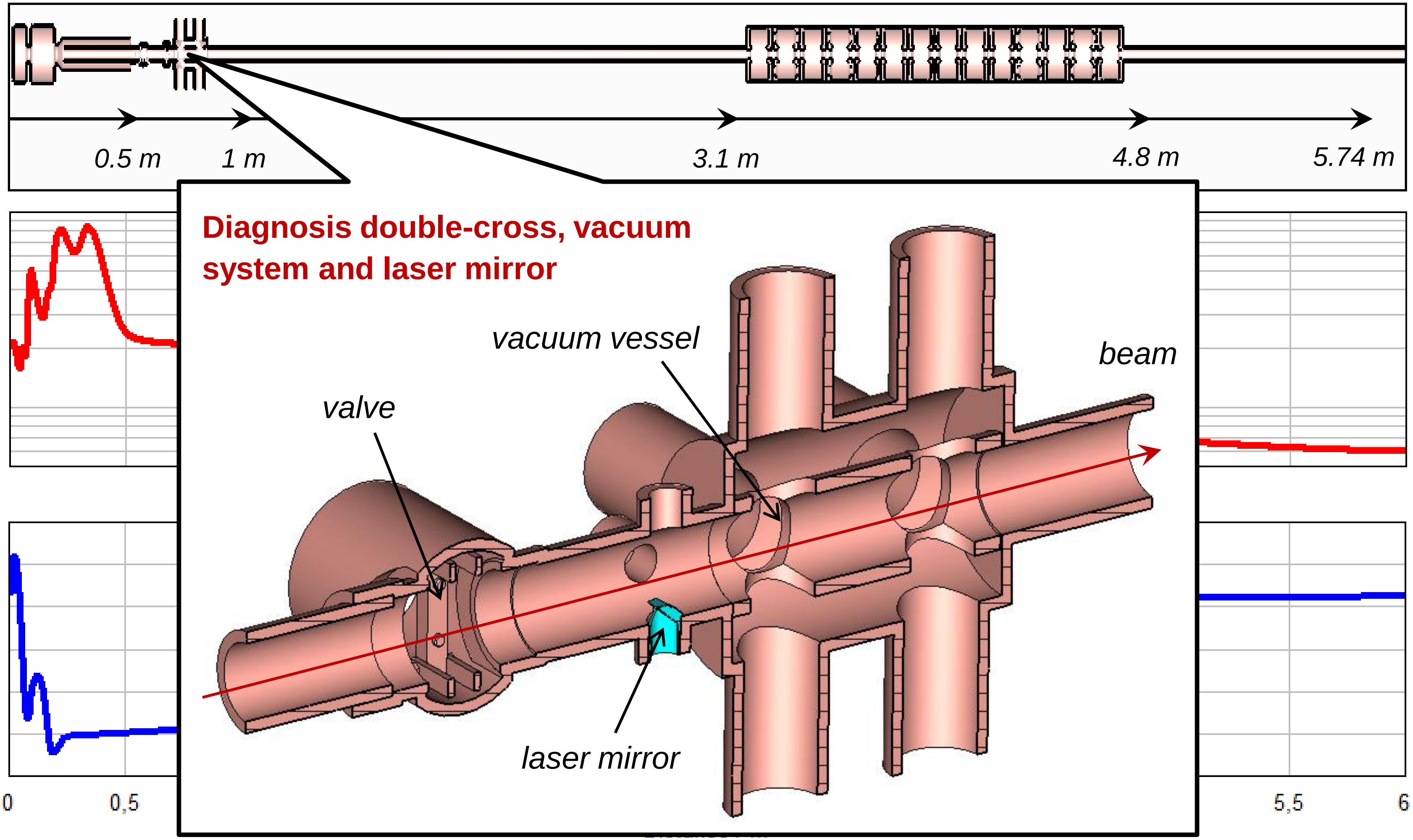


Low emittance electron sources



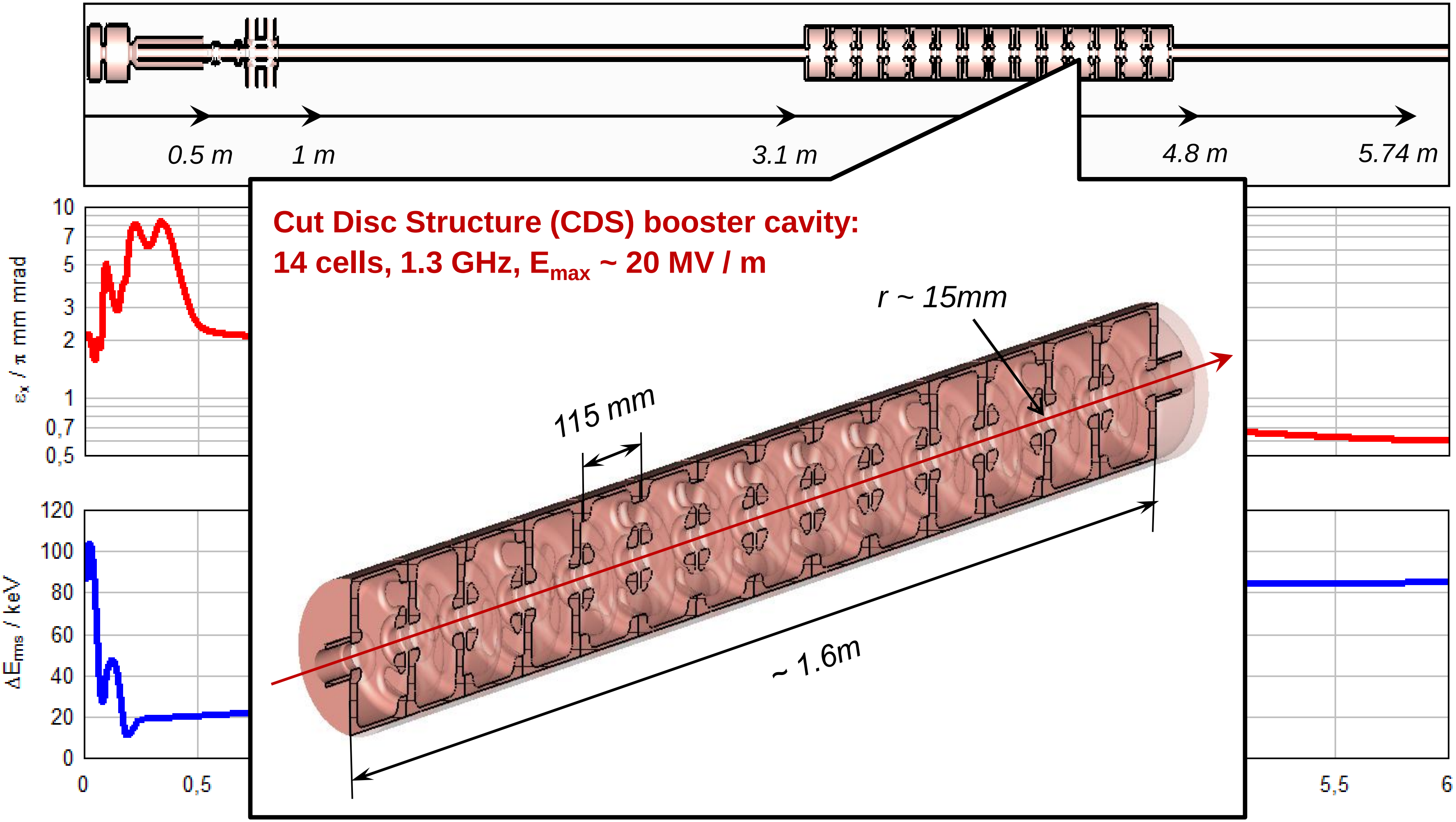
RF gun: 1 ½ cells, L-band (1.3 GHz), E_{max} ~ 60 MV / m

Low emittance electron sources



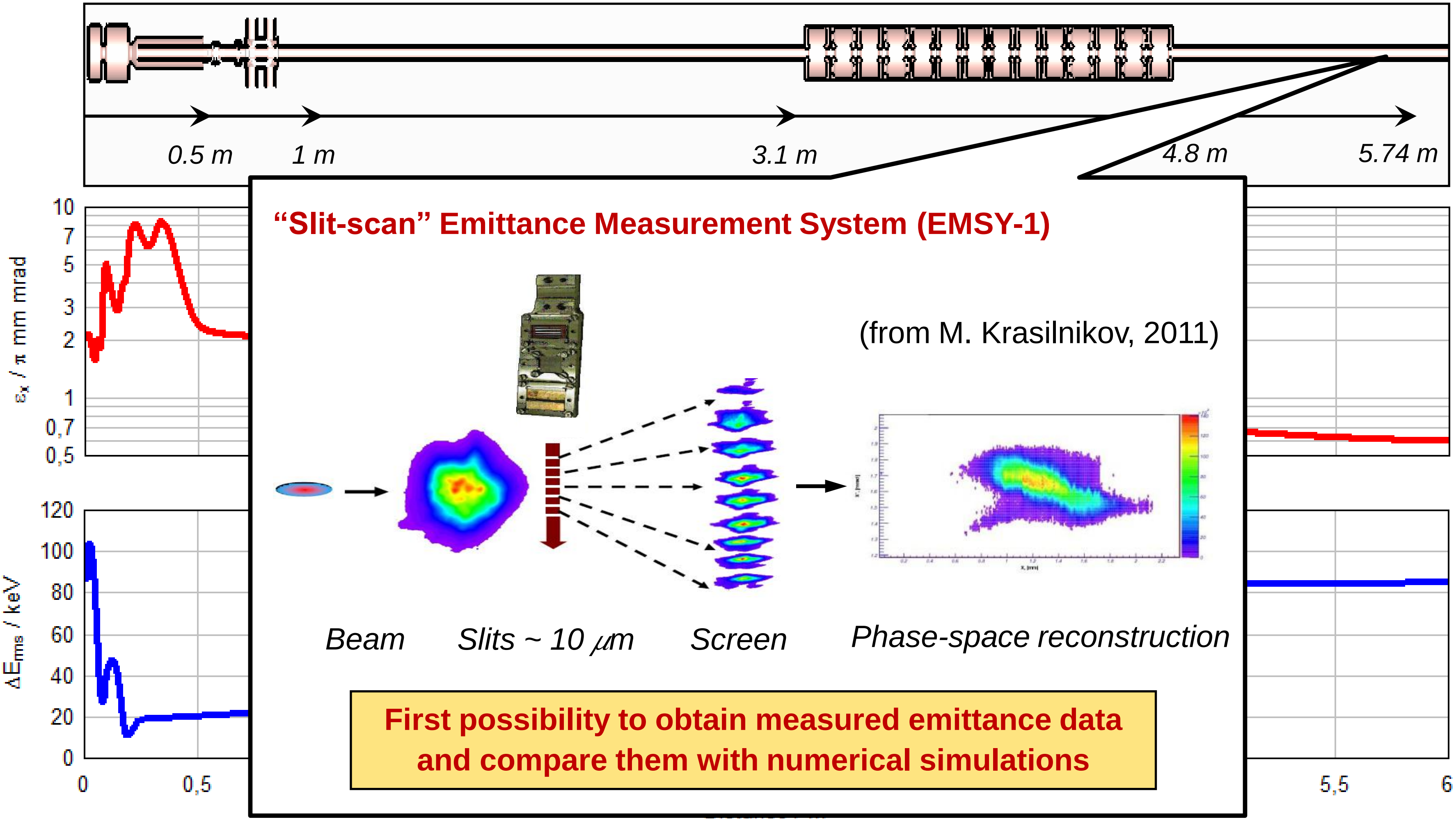
Diagnosis double-cross, vacuum system and laser mirror

Low emittance electron sources



Cut Disc Structure (CDS) booster cavity:
14 cells, 1.3 GHz, E_{max} ~ 20 MV / m

Low emittance electron sources



"Slit-scan" Emittance Measurement System (EMSY-1)

(from M. Krasilnikov, 2011)

First possibility to obtain measured emittance data and compare them with numerical simulations

Low emittance electron sources

(Some) particle tracking codes

- Rest frame space-charge field codes (Parmela, Astra, IMPACT-T, GPT, …)
- Vlasov moment equation solvers (V-code, …)
- Envelope equation solvers (Homdyn, …)
- …

- Use of various physical approximations
- Space-charge fields do not „see“ cavity geometry (except for cathode)
- Wakefields only as fixed external maps or Green functions
- Numerically efficient (mostly axis-symmetric)

Low emittance electron sources

(Some) particle tracking codes

- Rest frame space-charge field codes (Parmela, Astra, IMPACT-T, GPT, …)
- Vlasov moment equation solvers (V-code, …)
- Envelope equation solvers (Homdyn, …)
- …

- Wakefield codes (Echo, Pbci, Gdfidl, CST PS, …)

- Ultra-relativistic beams with fixed beam current only
- No space-charge
- Full-wave in 3D using moving window and dispersion free algorithms

Low emittance electron sources

(Some) particle tracking codes

- Rest frame space-charge field codes (Parmela, Astra, IMPACT-T, GPT, …)
- Vlasov moment equation solvers (V-code, …)

○ First principle

○ No geometry (except for cathode)

○ Computationally extremely inefficient

- Lienard-Wiechert solvers (Tredi, Quindi, …)

Low emittance electron sources

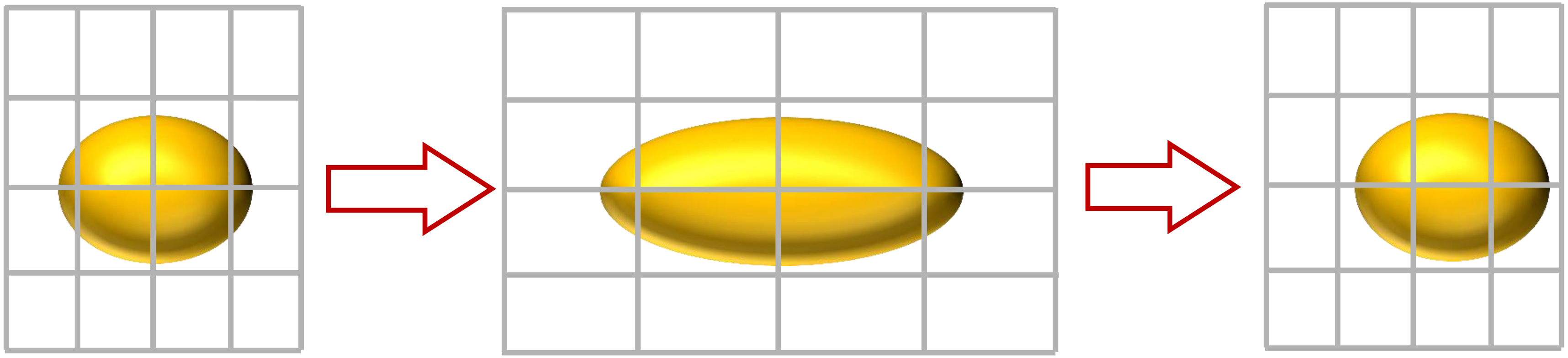
(Some) particle tracking codes

- Rest frame space-charge field codes (Parmela, Astra, IMPACT-T, GPT, …)
- Vlasov moment equation solvers (V-code, …)
- Envelope equation solvers (Homdyn, …)

- First principle
- Full geometry and arbitrary transient beam distributions
- Computationally less efficient in 3D: not applicable for short bunches and long accelerator structures (> 1m)

- Full-wave PIC codes (Mafia, CST PS, Vorpal, …)

Rest frame SC field codes



Bring particles to computational grid

Solve for electrostatic field in the grid

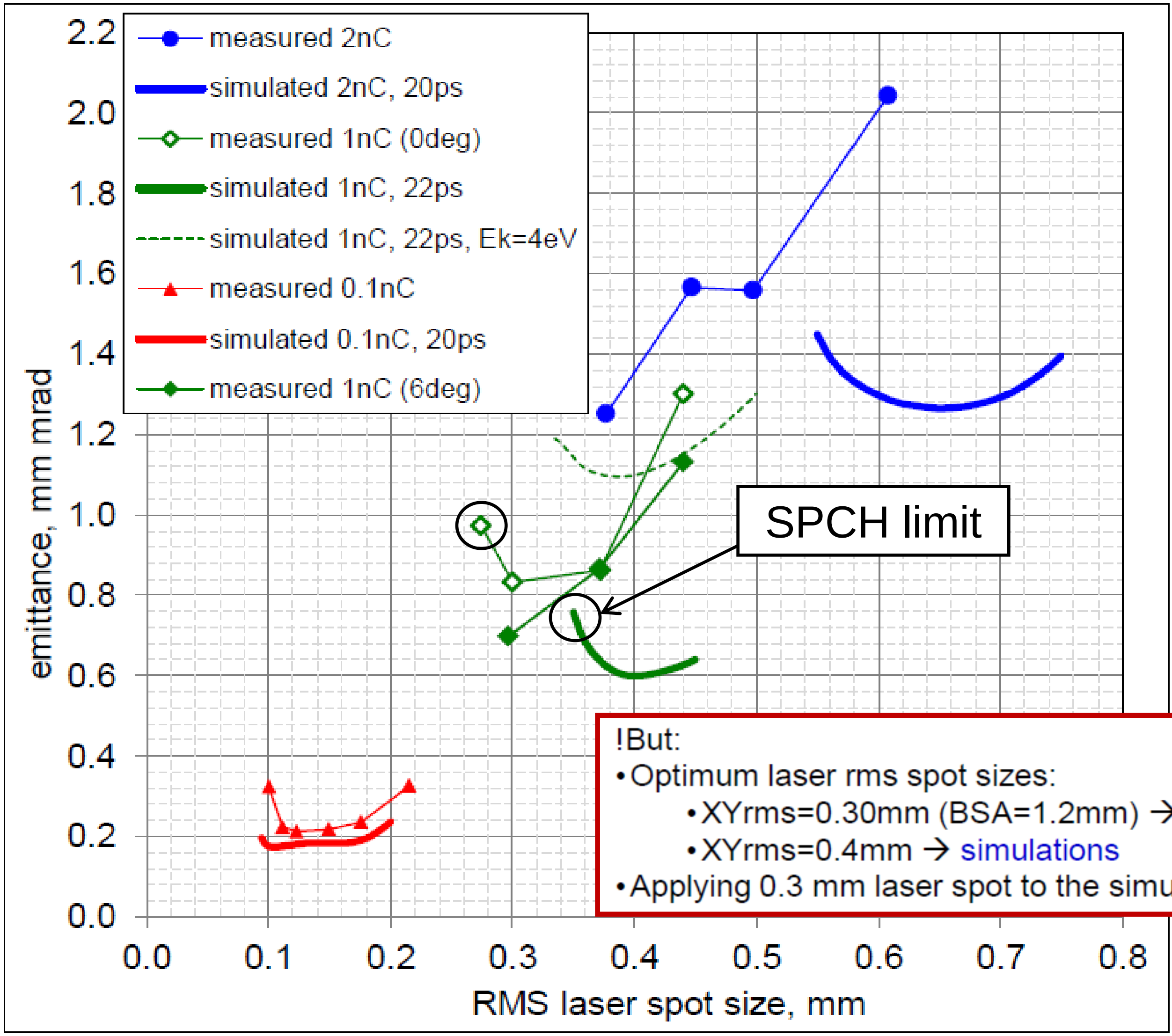
Push particle positions and momenta

Transform (charge) to average rest frame

Transform (fields) back to lab frame

- Influence of rest frame approximation (neglect retardation and acceleration radiation) on simulation accuracy?
- Impact of geometrical wakefields on transverse emittance?

Low emittance electron sources



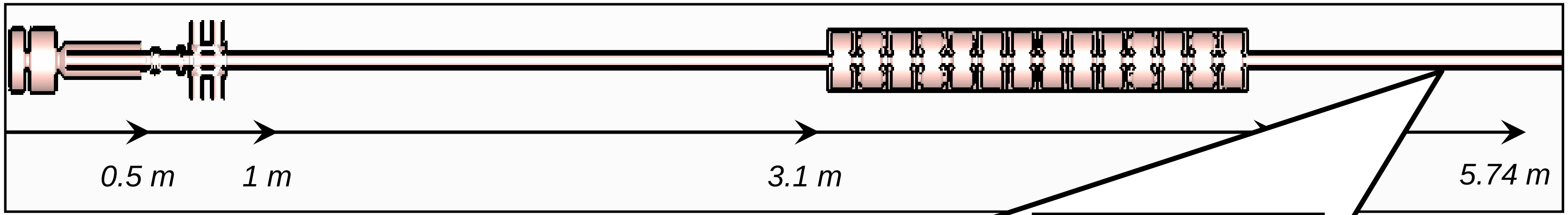
- Optimum machine parameters (laser spot size, gun phase): experiment ≠ simulations
- Difference in the optimum laser spot size is bigger for higher charges (good agreement for 100pC)
- Artificial increase of the thermal kinetic energy at the cathode (from 0.55eV to 4eV) did not improve the situation

(talk from M. Krasilnikov, Zeuthen, 2011)

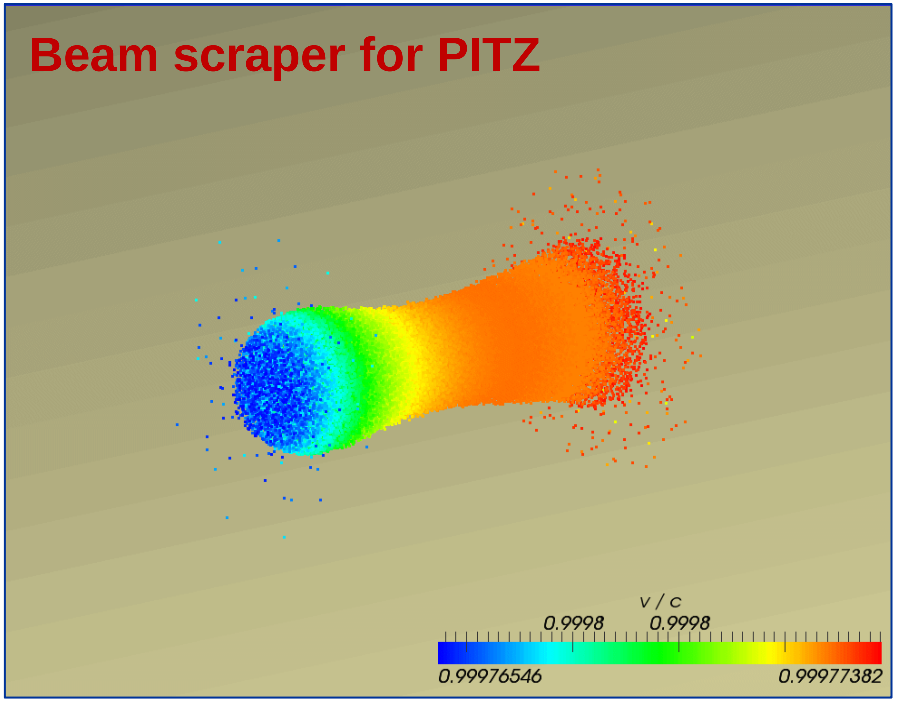
!But:

- Optimum laser rms spot sizes:
  - XYrms=0.30mm (BSA=1.2mm) → experimentally
  - XYrms=0.4mm → simulations
- Applying 0.3 mm laser spot to the simulation – it is impossible to produce 1nC!

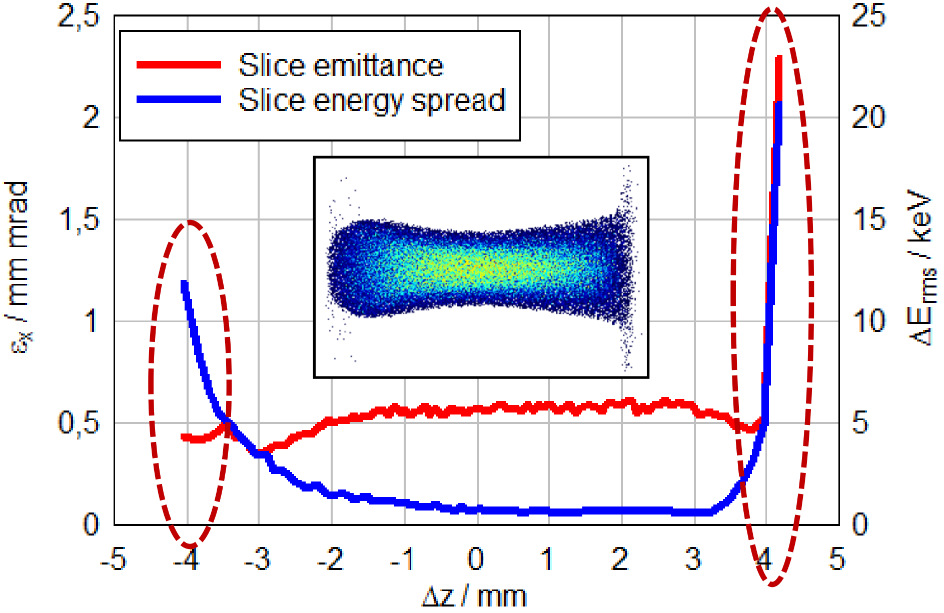
Self-consistent simulations with PBCI



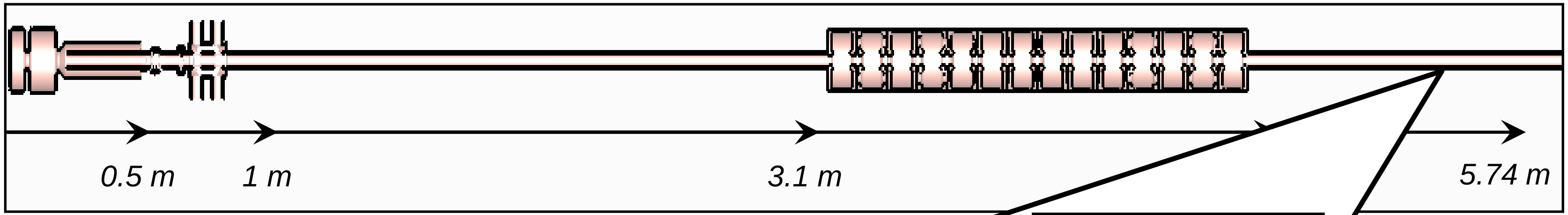
Beam scraper for PITZ



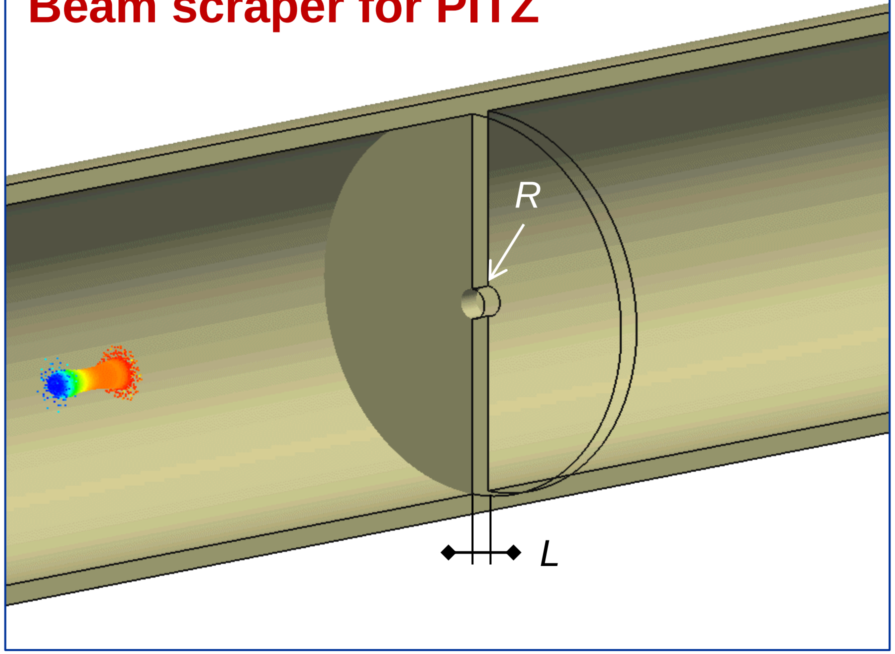
Q = 1nC
ΔX_{rms} = 0.4mm



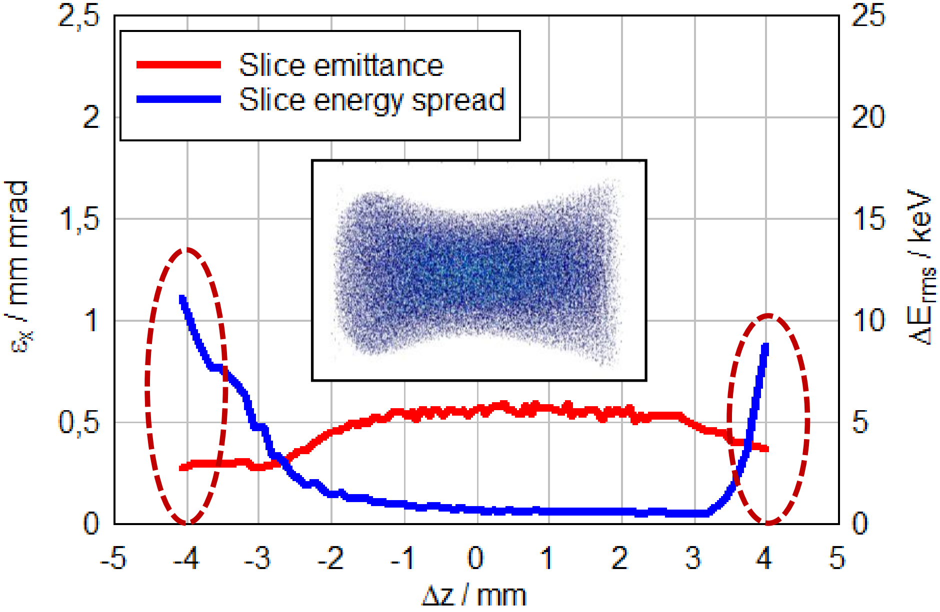
Self-consistent simulations with PBCI



Beam scraper for PITZ

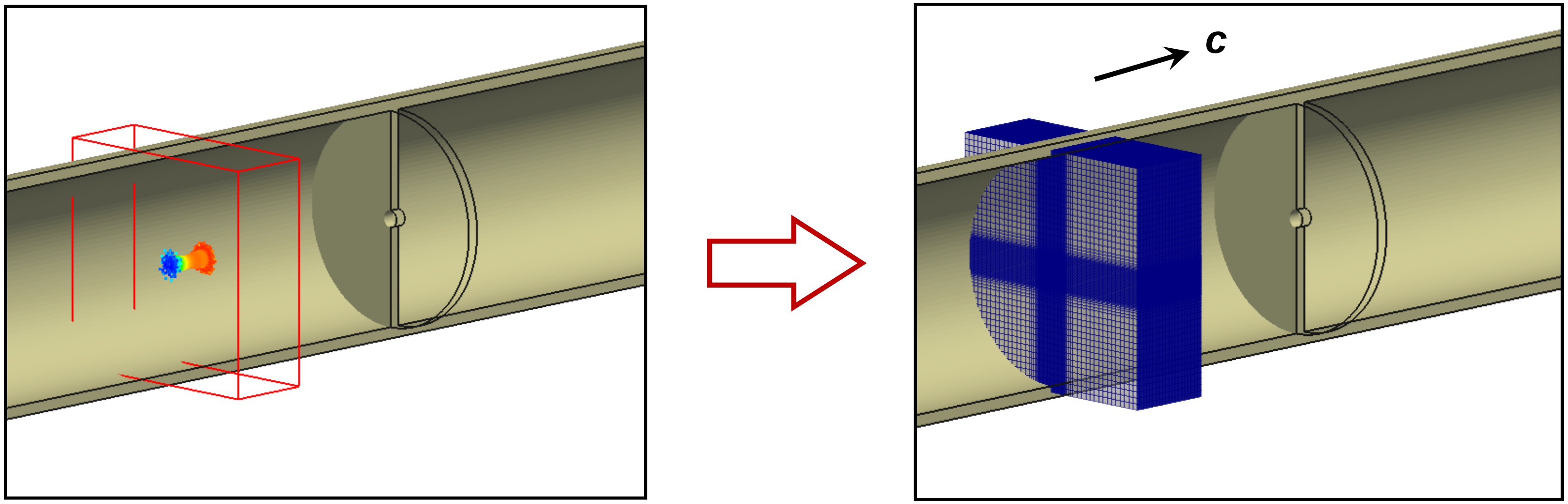


Q = 1nC
ΔX_{rms} = 0.4mm



Self-consistent simulations with PBCI

Particle-In-Cell in the moving window



- Nearly ultra-relativistic but:
  - transverse dynamics over long distances not negligible
  - non-constant current due to scraping

- **Combine moving frame wakefield simulation approach (PBCI) with PIC**

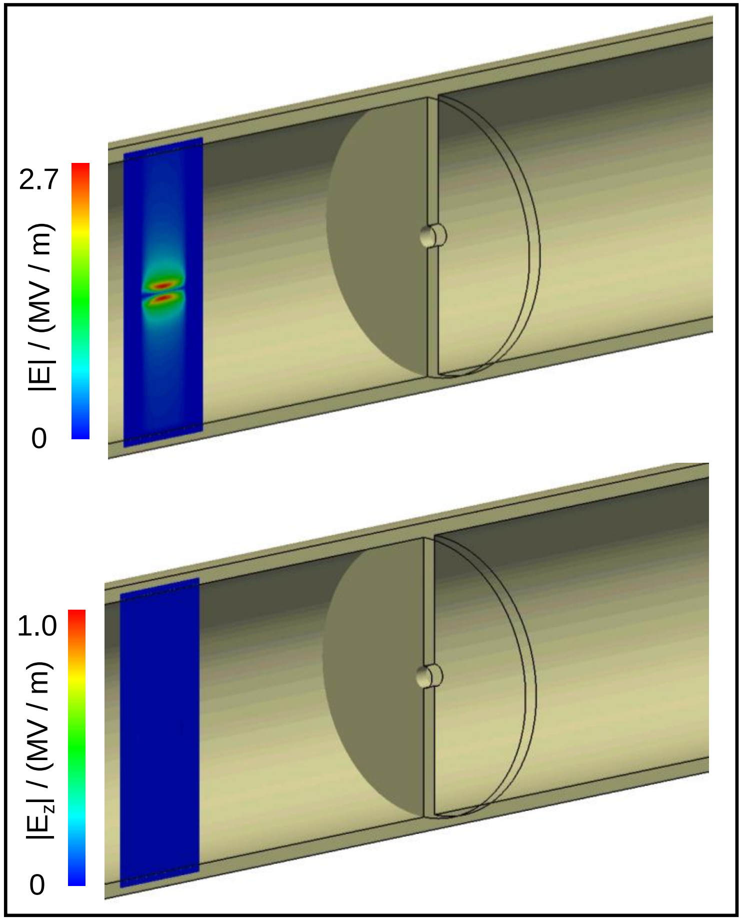
Self-consistent simulations with PBCI

Particle-In-Cell in the moving window

- Dispersion-free EM field solution:
  - Optimum stable time step
  - Computational window moving with c
  - Boundary conditions not needed

- Small discretization domain:
  - **Necessary transverse resolution for bunch and geometry < 50 μm**

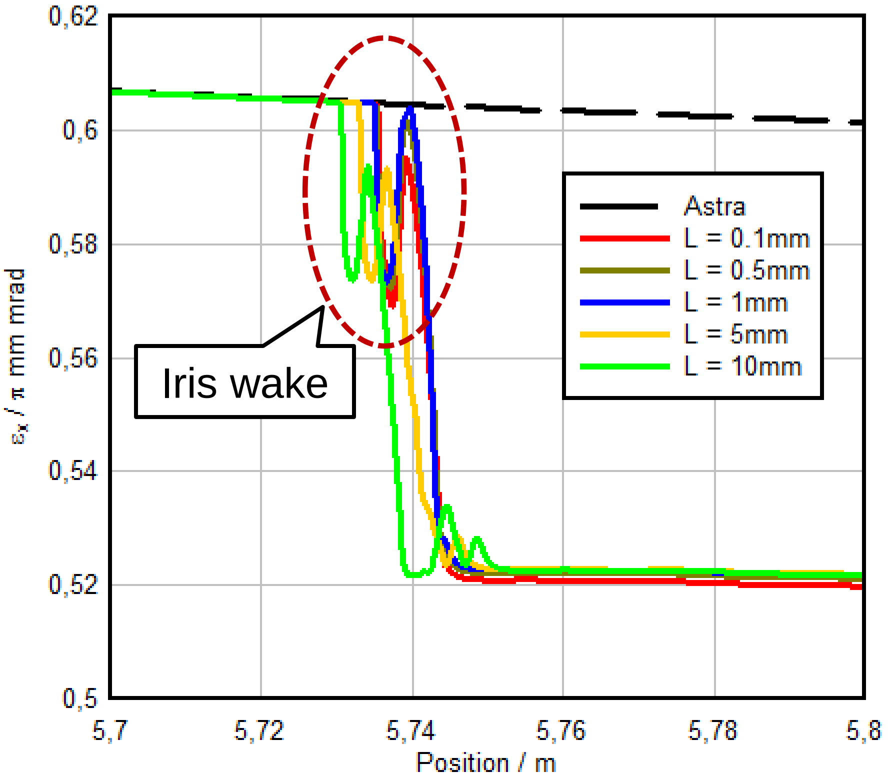
- Simple field initialization:
  - TEM field of ultra-relativistic bunch in pipe of arbitrary cross-section



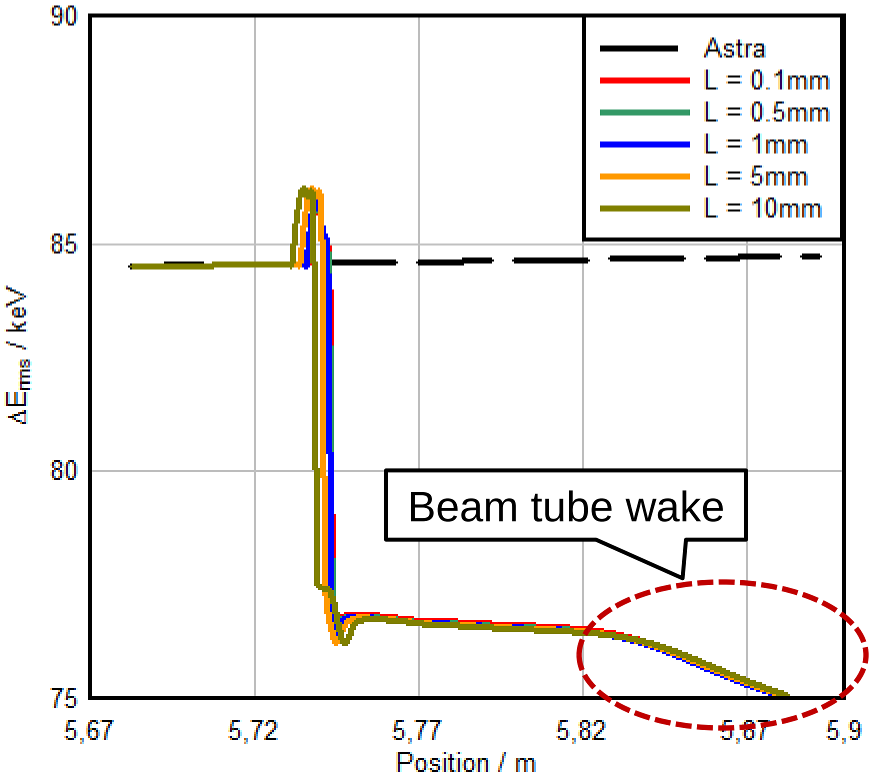
Self-consistent simulations with PBCI

Beam scraper results

Emittance (1nC, 0.4mm, R = 1mm)



Energy spread (1nC, 0.4mm, R = 1mm)

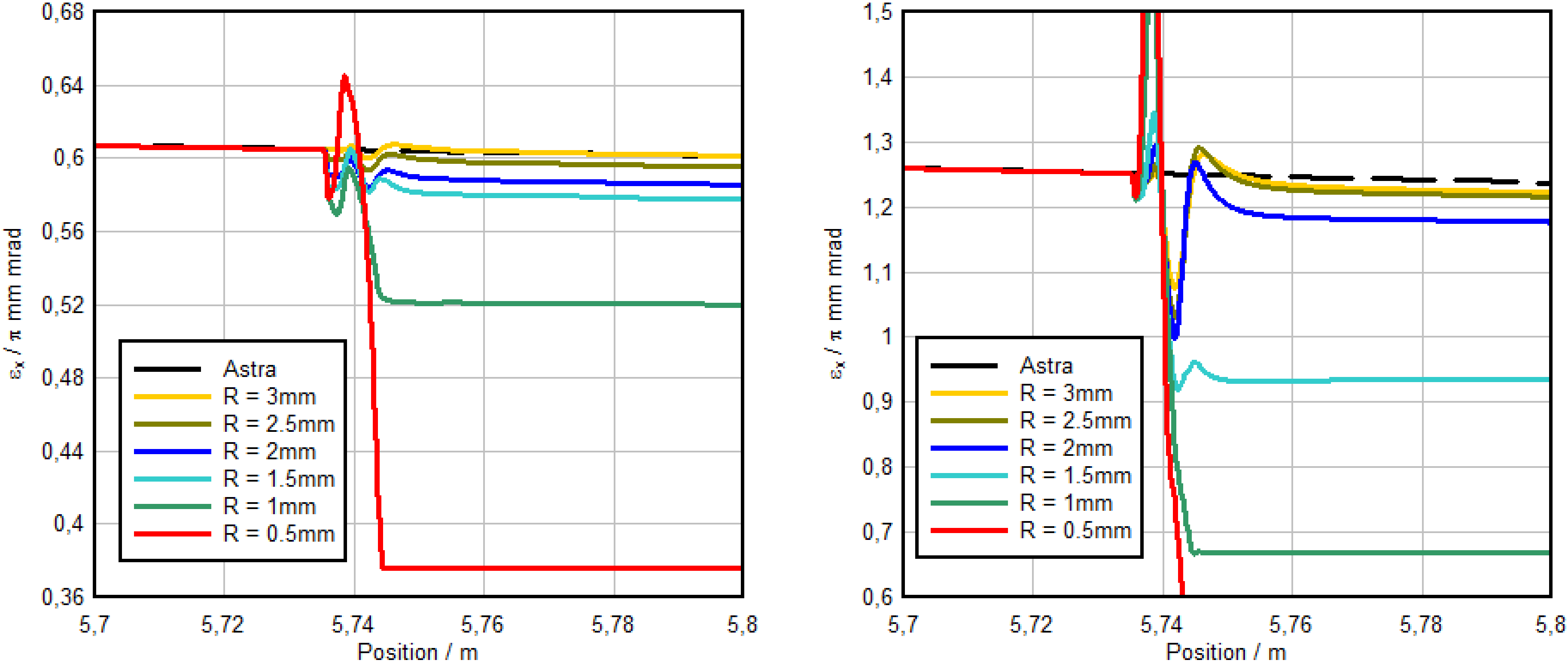


Self-consistent simulations with PBCI

Beam scraper results

Emittance (1nC, 0.4mm, L = 0.1mm)

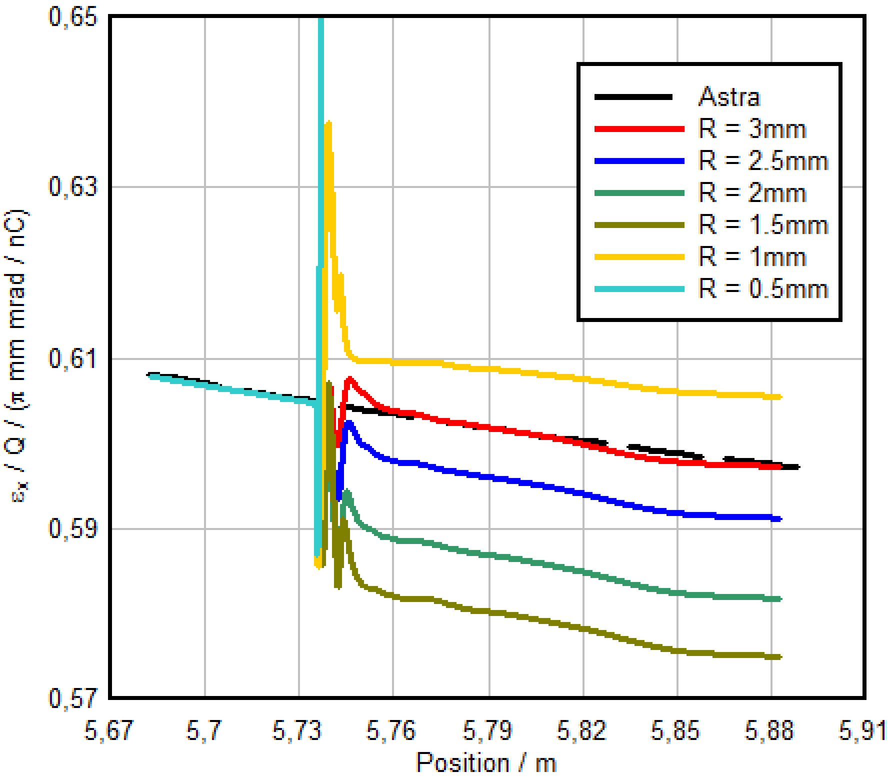
Emittance (2nC, 0.6mm, L = 0.1mm)



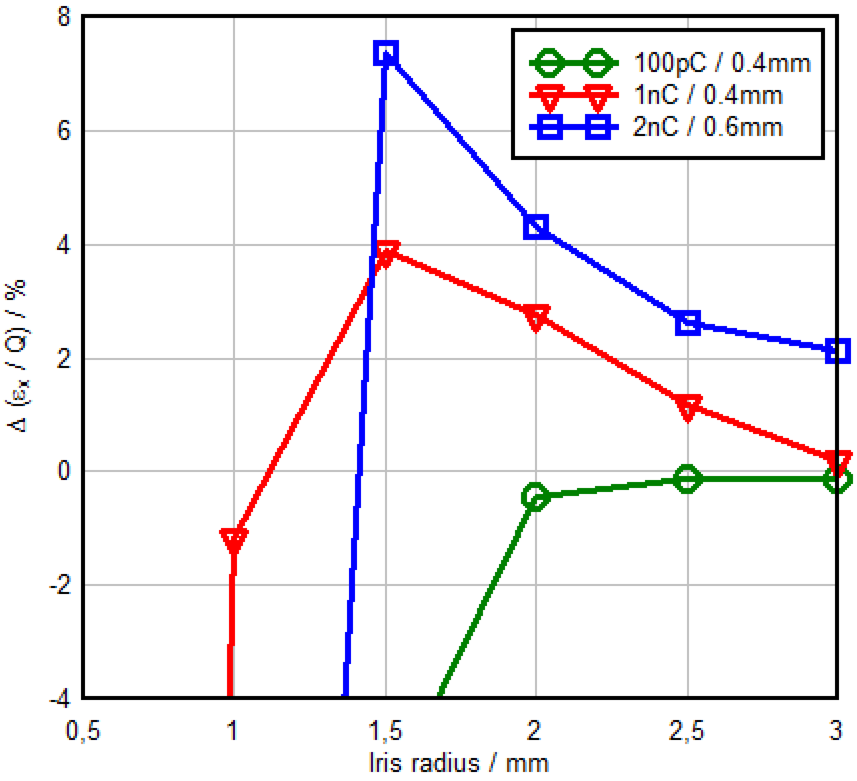
Self-consistent simulations with PBCI

Beam scraper results

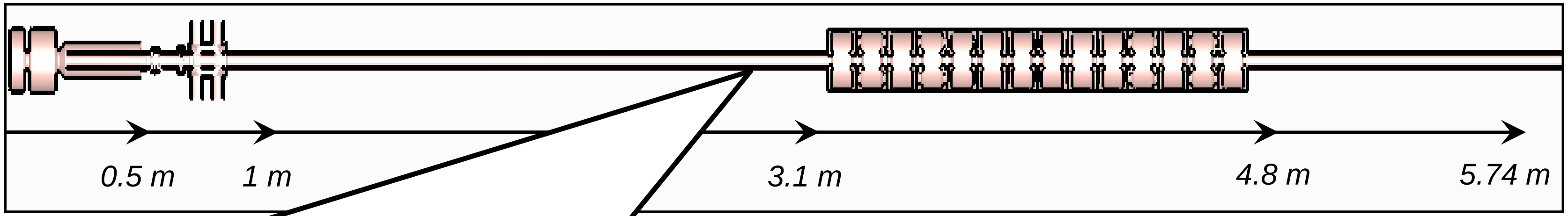
Emittance per Q (1nC, 0.4mm, L = 0.1mm)

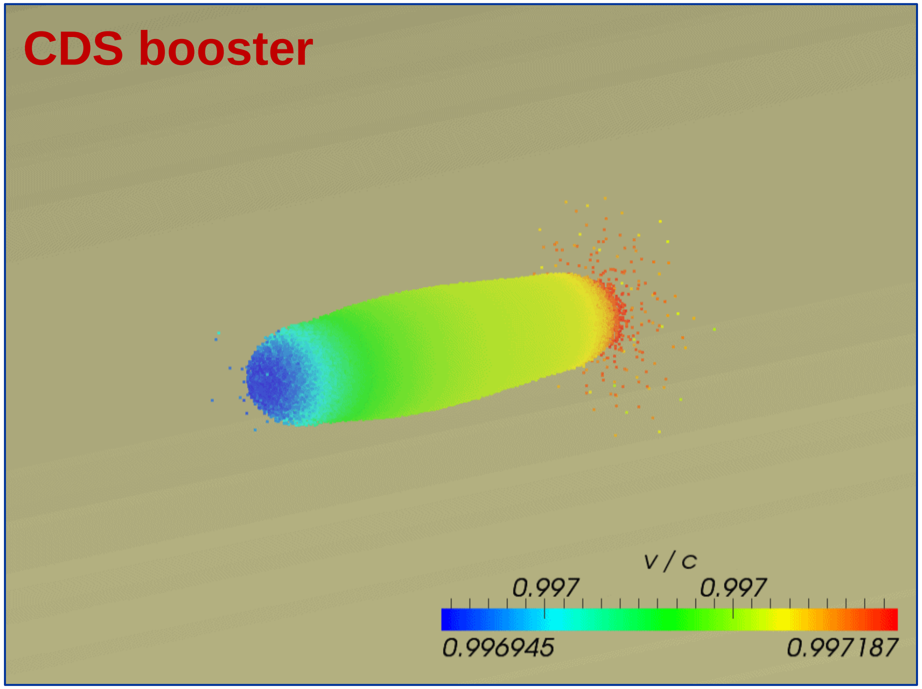


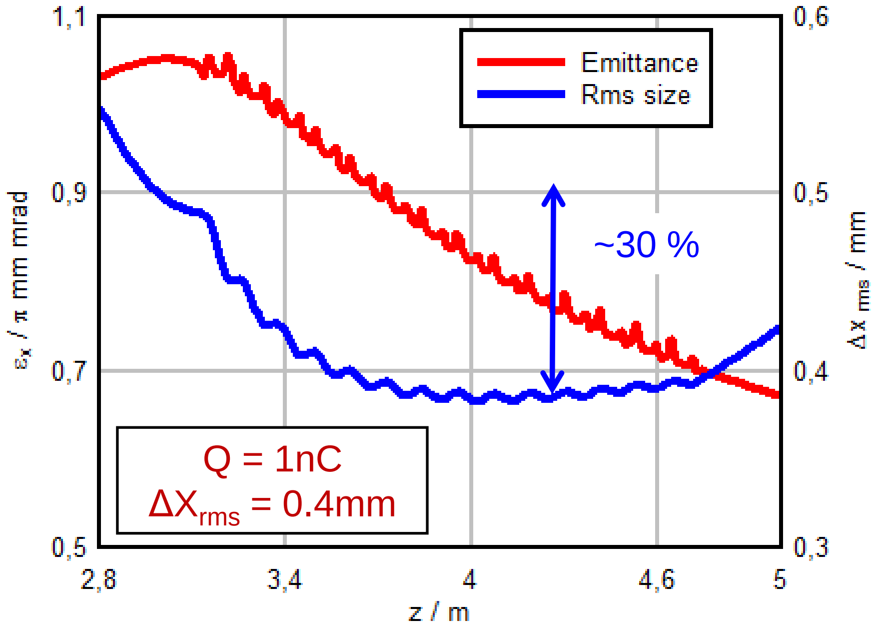
Expected gain in FEL-brilliance



Self-consistent simulations with PBCI

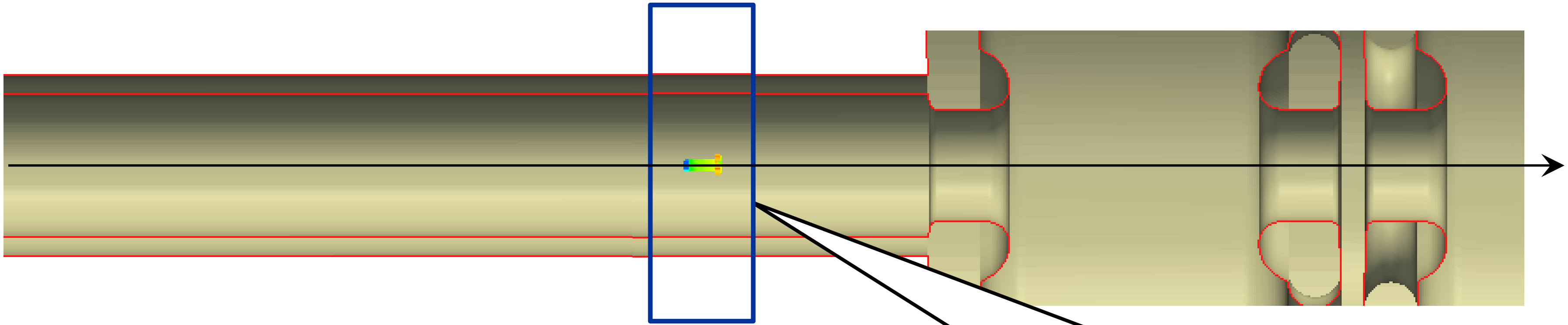






Self-consistent simulations with PBCI

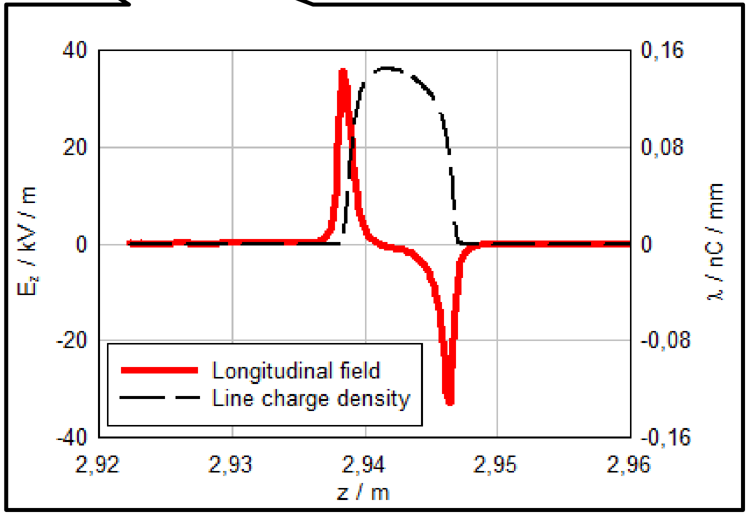
Field initialization procedure



- Transform to (average) rest frame:

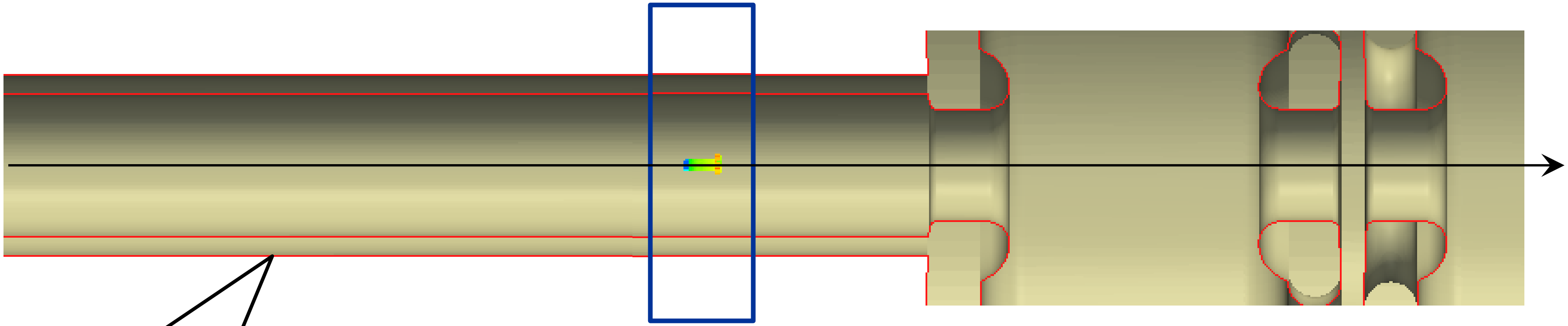
$$\left.\begin{aligned} \rho' &= \gamma\left(\rho - \frac{\beta}{c} j_z\right) := \frac{\rho}{\gamma} \\ j_z' &= \gamma(j_z - v\rho) := 0 \end{aligned}\right\} \Leftrightarrow \boxed{j_z = \rho v}$$

⇨ E-static rest frame solution violates charge conservation in PIC



Self-consistent simulations with PBCI

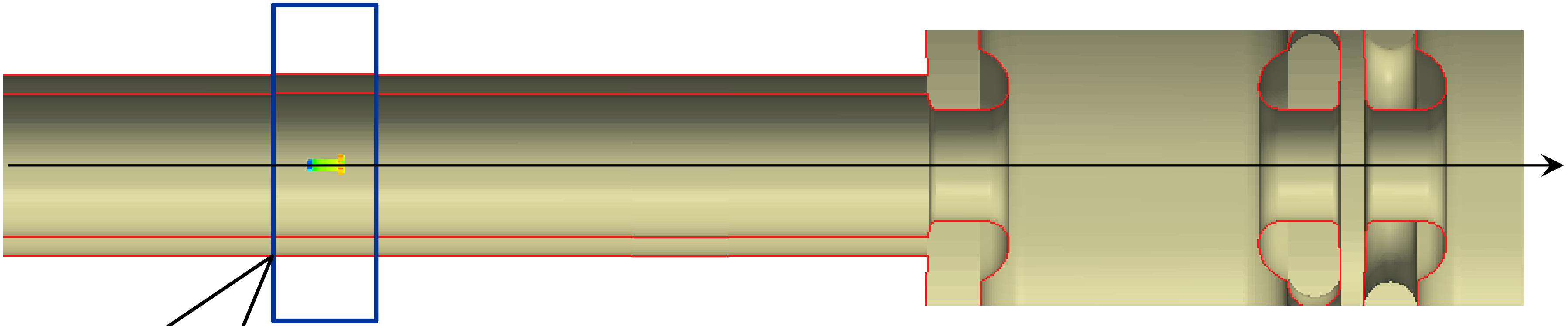
Field initialization procedure



Track backwards with initial velocities

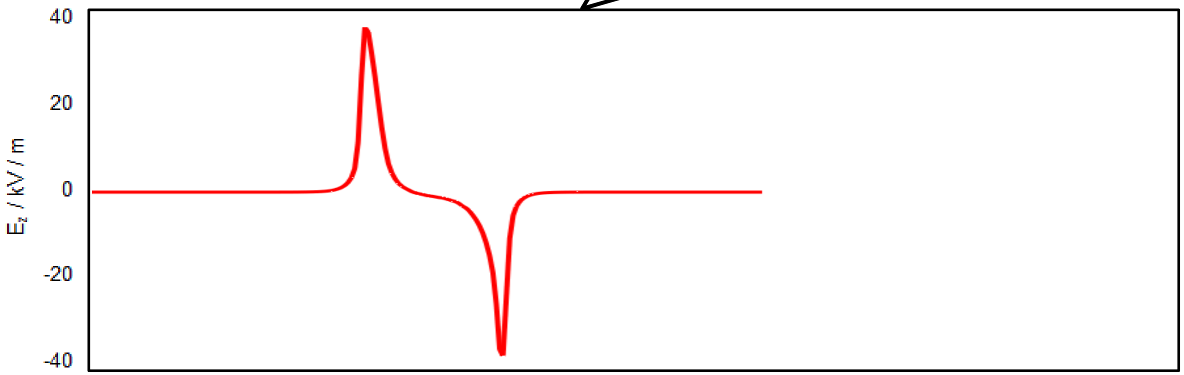
Self-consistent simulations with PBCI

Field initialization procedure



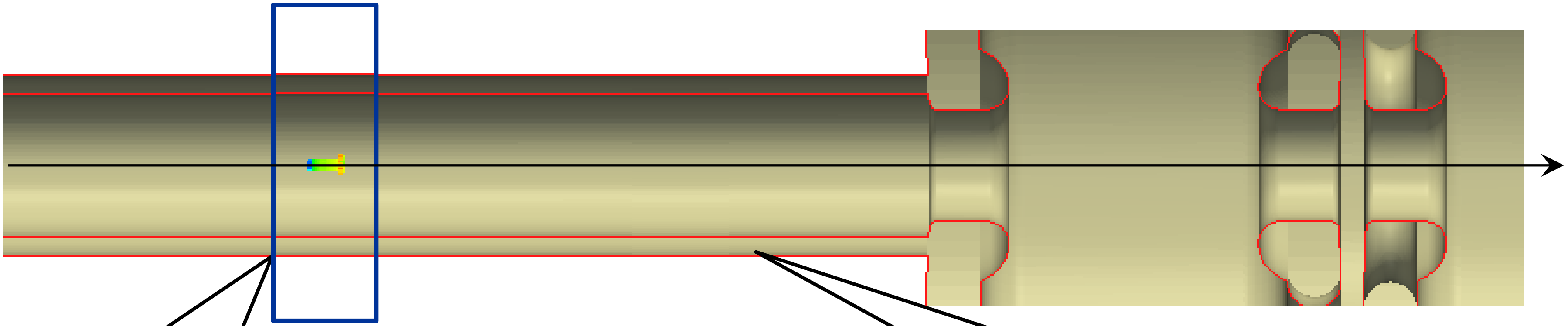
Track backwards with initial velocities

Initialize by rest frame transformation



Self-consistent simulations with PBCI

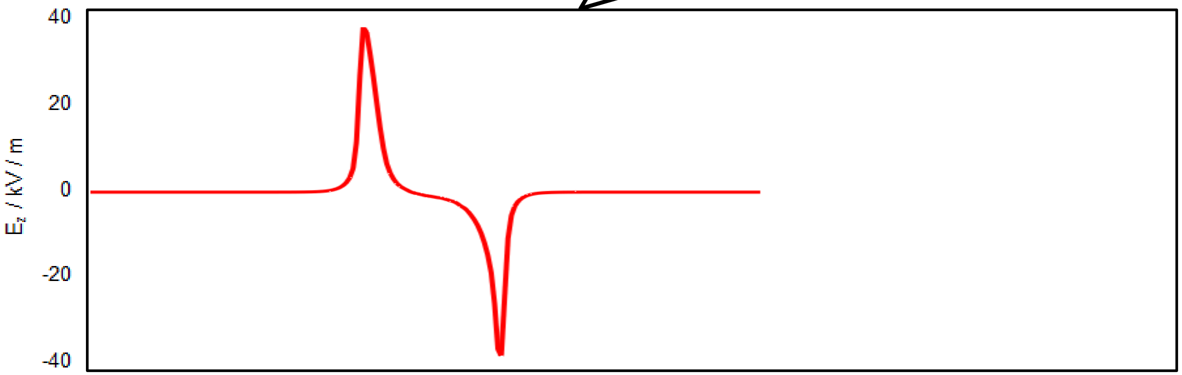
Field initialization procedure



Track backwards with initial velocities

Initialize by rest frame transformation

Track forwards to initial positions / velocities

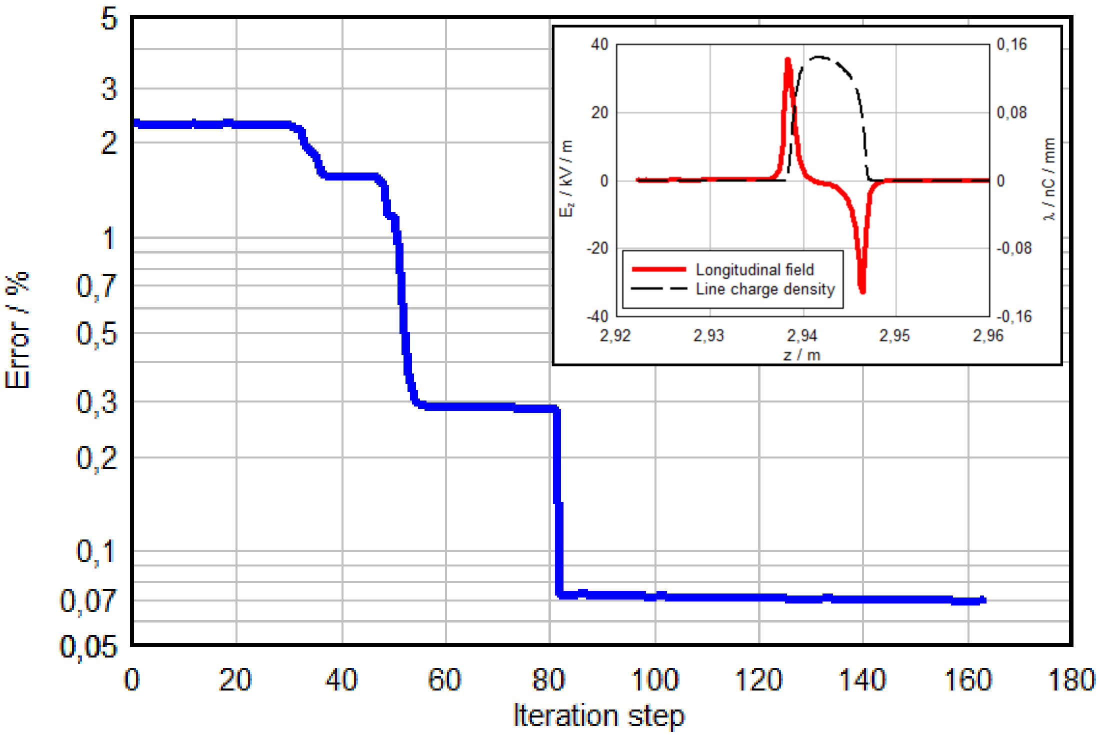


- Build-up consistent initial space-charge fields for PIC
- Include effects of relative motion within bunch

Self-consistent simulations with PBCI

Field initialization procedure

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



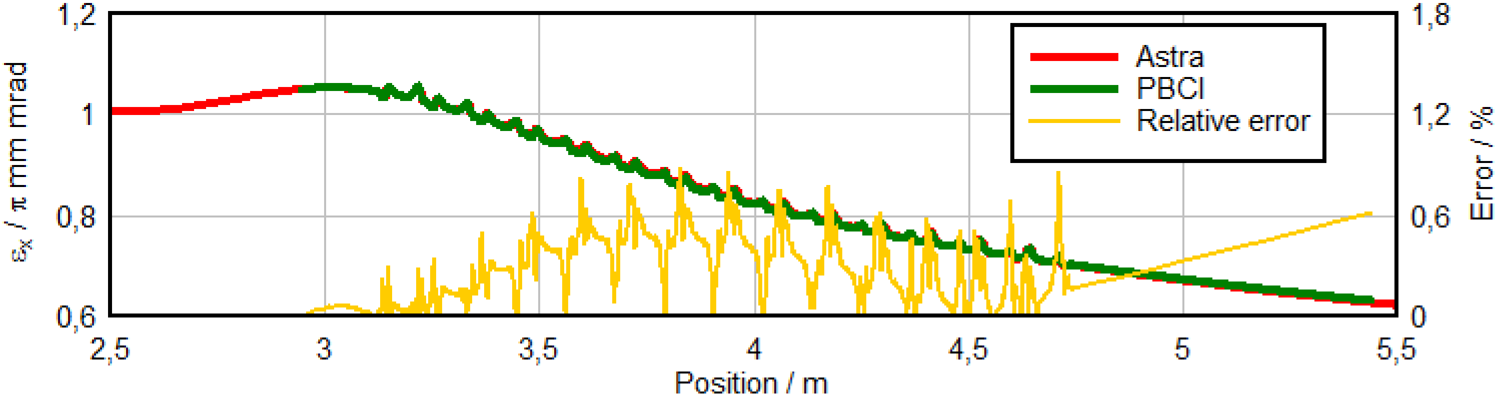
(Typical) data for CDS simulation	
Length	$2.5m$
Grid	$\Delta x = \Delta z = 50\ \mu m$
No. DoFs	300×10^6
No. particles	$0.5 \times 10^5 - 5 \times 10^5$
No. steps	$\sim 100{,}000$
Simulation time	$\sim 12 - 36\ hrs.$

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

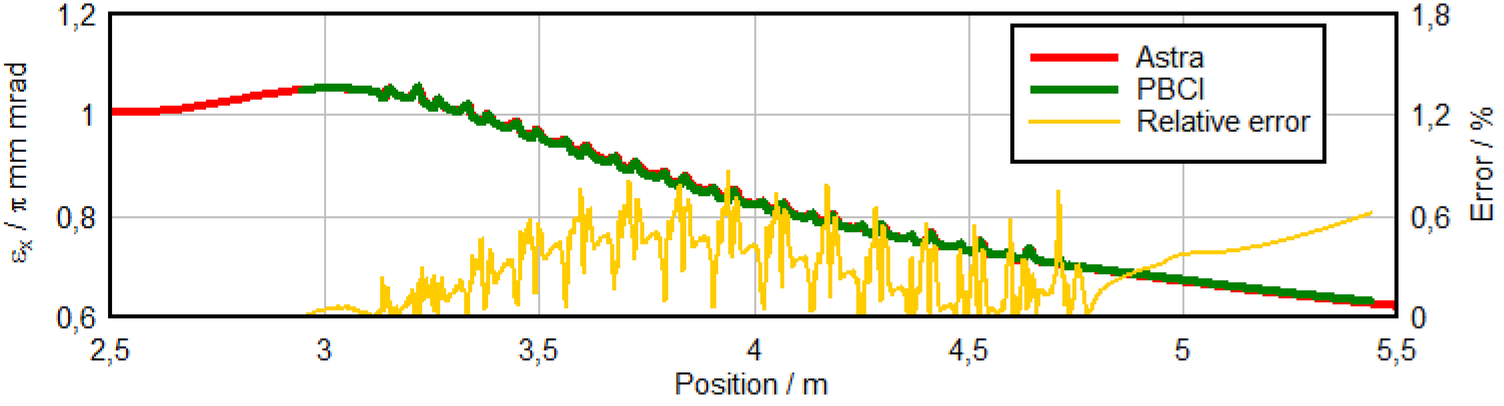
Self-consistent simulations with PBCI

CDS results: emittance

Q = 1nC
ΔX_{rms} = 0.4mm



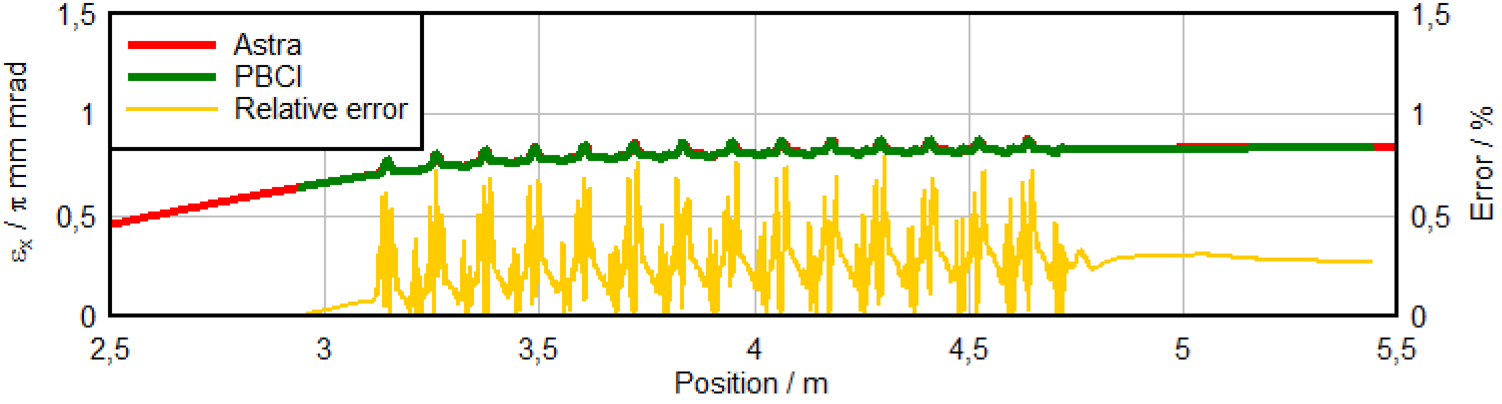
SPCH only



SPCH + Wake

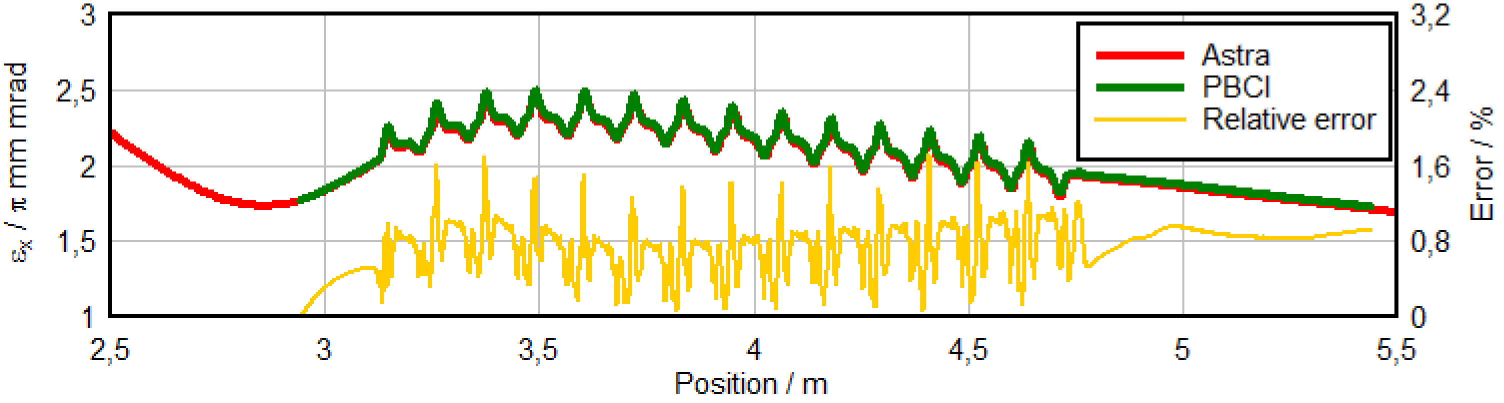
Self-consistent simulations with PBCI

CDS results: emittance



Q = 100pC
ΔX_{rms} = 0.3mm

SPCH + Wake



Q = 2nC
ΔX_{rms} = 0.5mm

SPCH + Wake

Self-consistent simulations with PBCI

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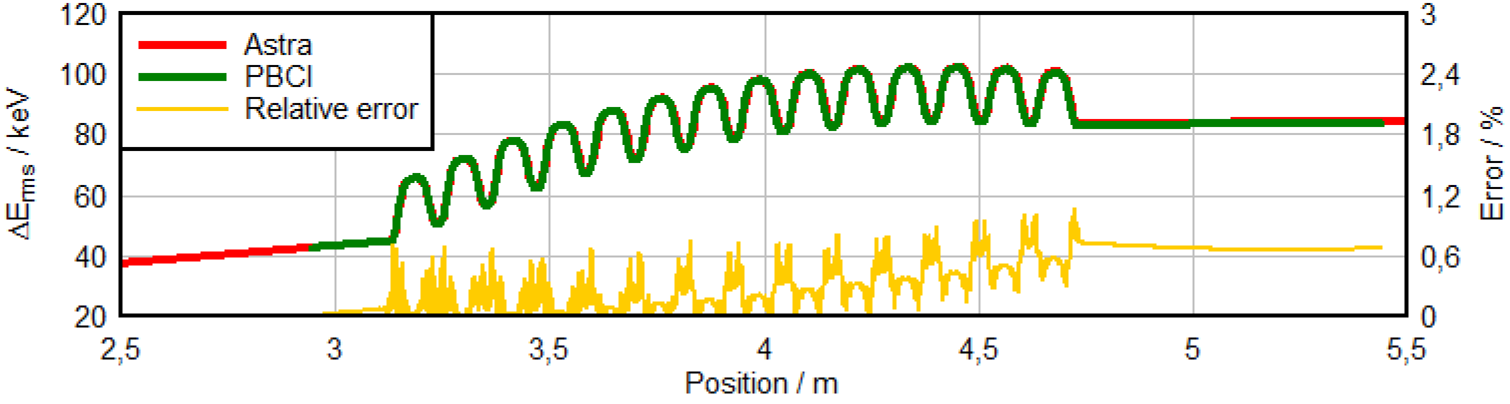
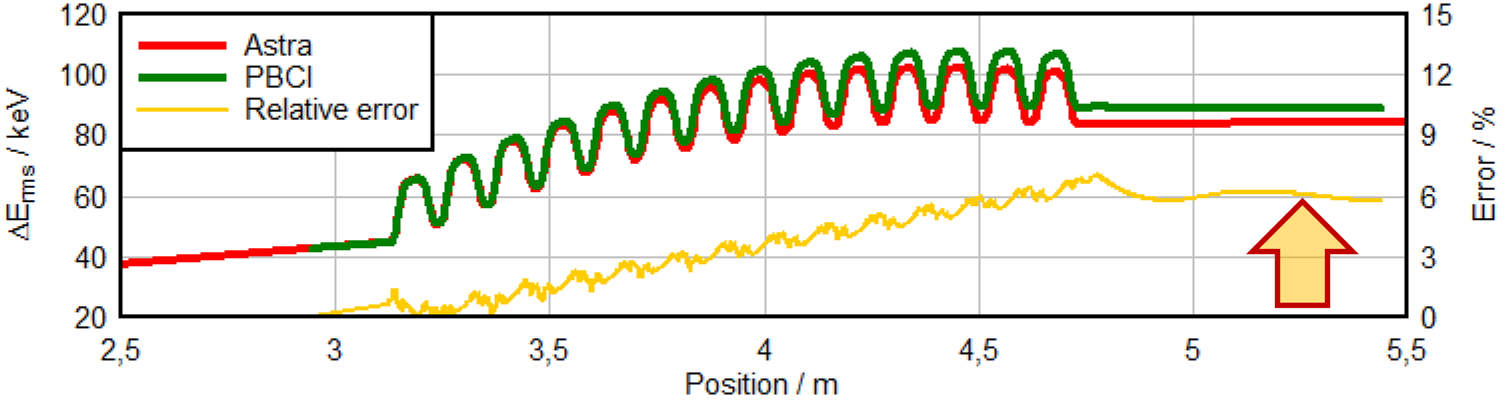
CDS results: energy spread

Q = 1nC
ΔX_{rms} = 0.4mm



SPCH only

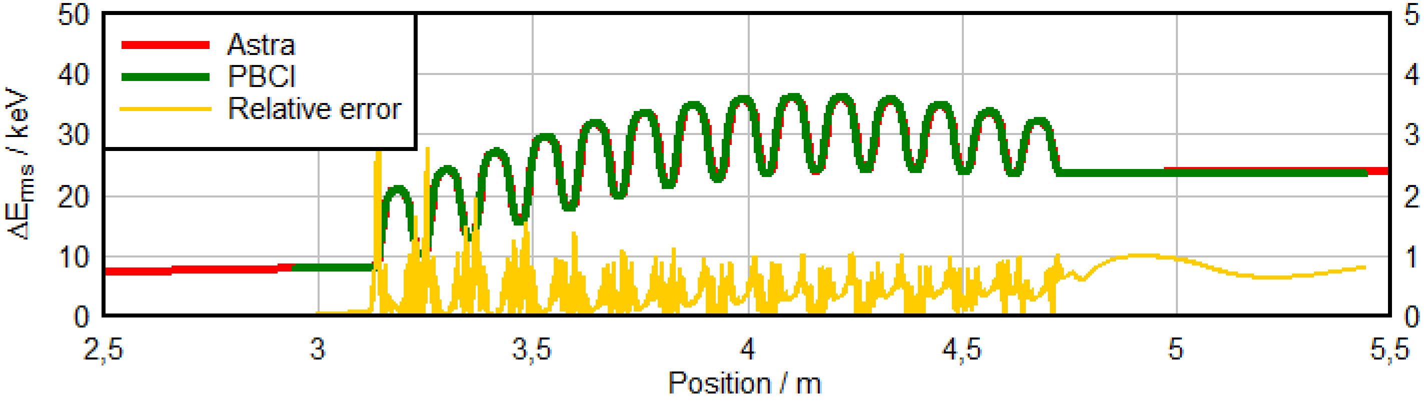


SPCH + Wake

Self-consistent simulations with PBCI

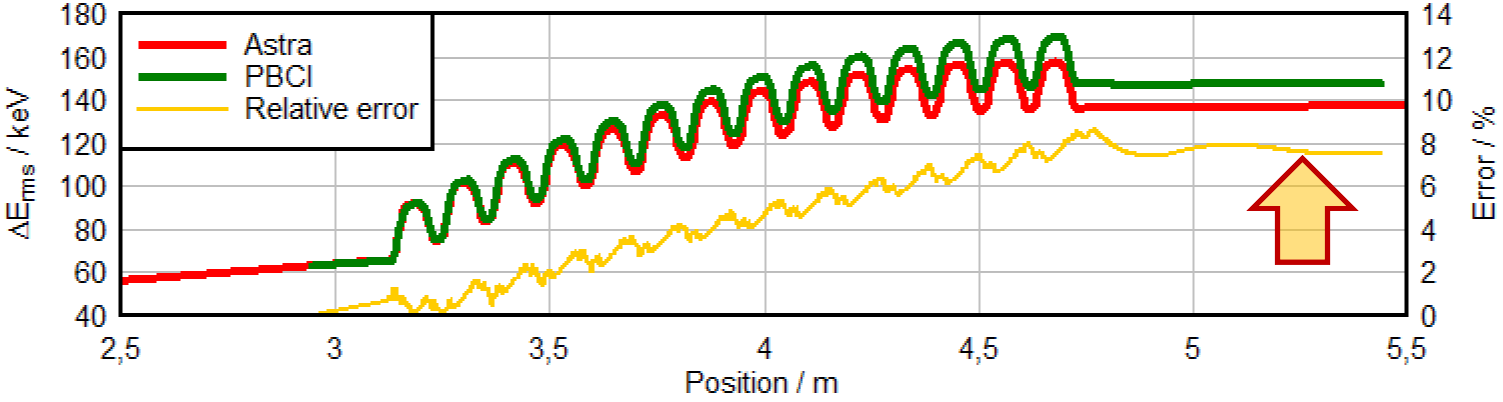
CDS results: energy spread

Q = 100pC
ΔX_{rms} = 0.3mm



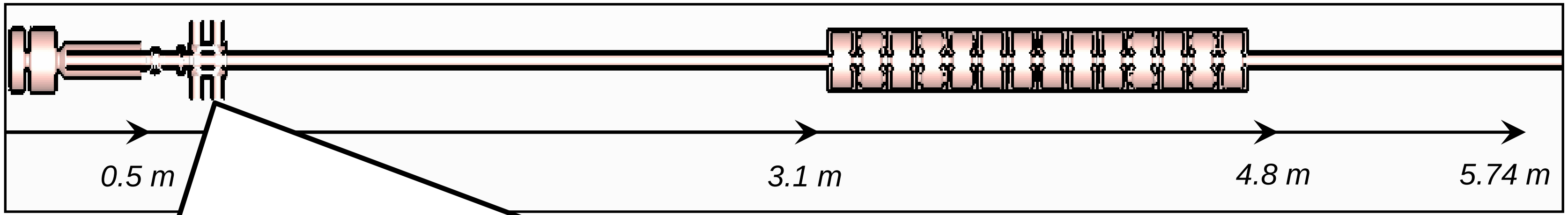
SPCH + Wake

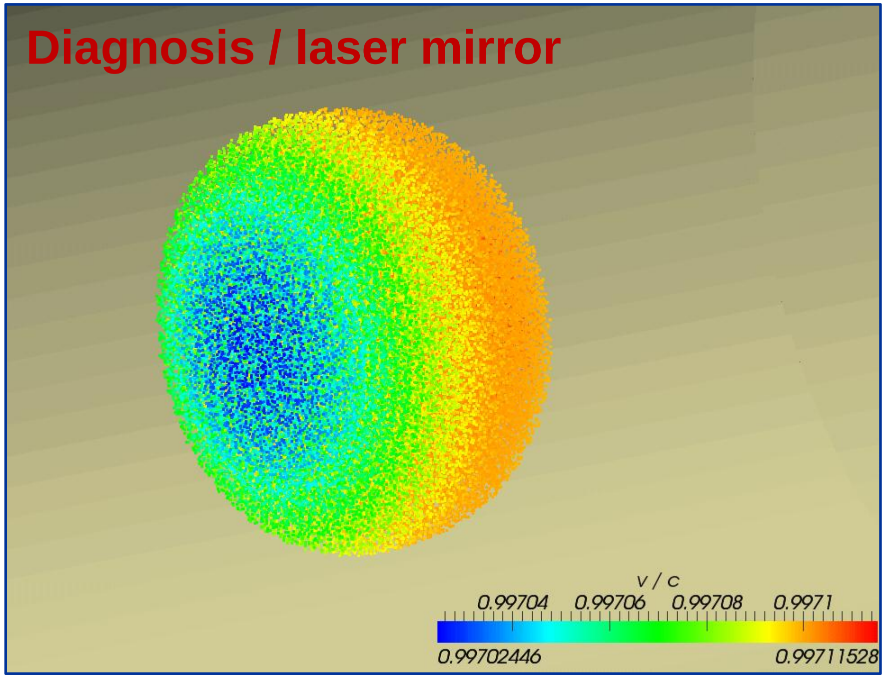
Q = 2nC
ΔX_{rms} = 0.5mm

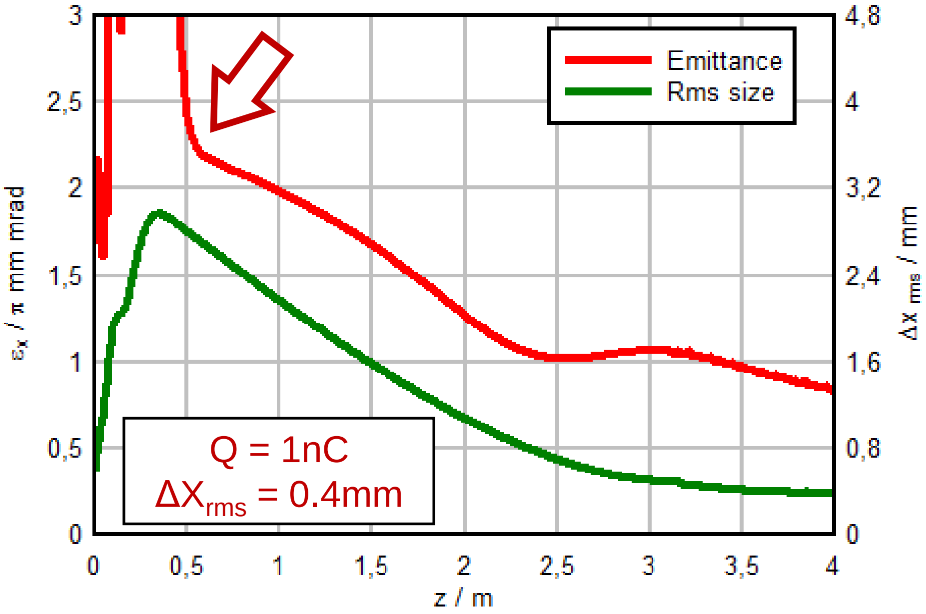


SPCH + Wake

Self-consistent simulations with PBCI



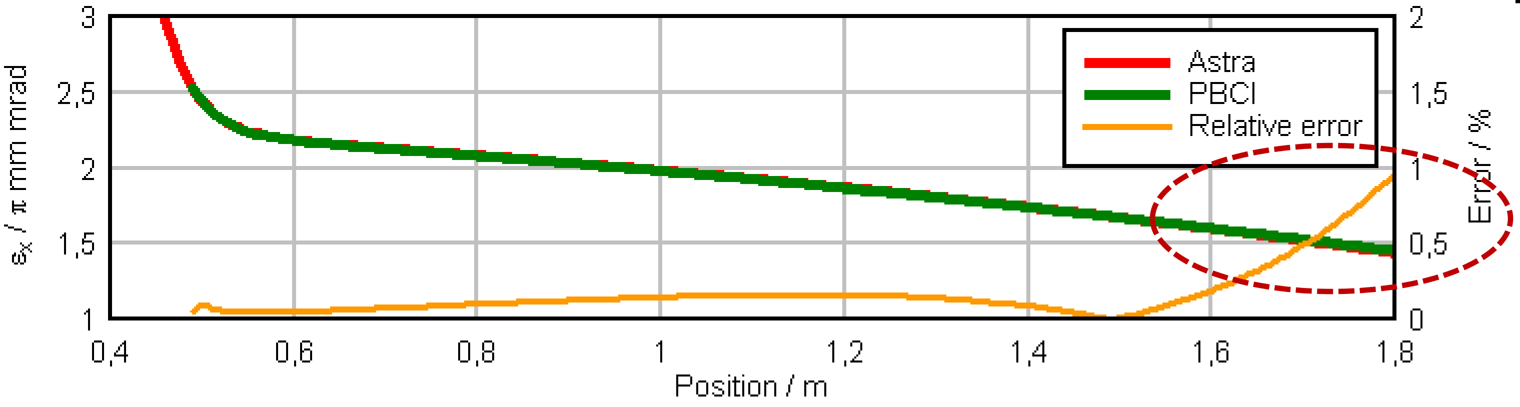




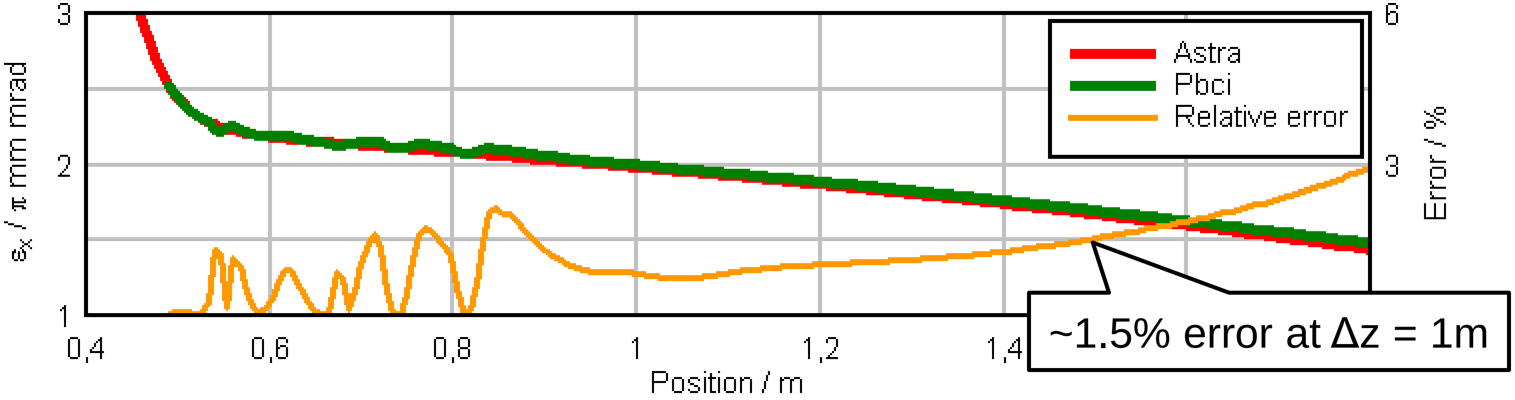
Self-consistent simulations with PBCI

Diagnosis cross results

Q = 1nC
$\Delta X_{rms} = 0.4mm$



SPCH only



~1.5% error at Δz = 1m

SPCH + Wake

Summary and conclusions

Summary

- Beam dynamics simulations for photoinjector including SC and wakefields
  - Impact of geometry on soft beams?
  - Validity of rest frame transformation based computations?
- Introducing SC in PBCI
  - Moving window approach: allows for necessary grid resolution in the simulation of long structures
  - Consistent field initialization at any position within the injector by rest frame transformation + additional iterative procedure

Summary and conclusions

Conclusions

- Long distance self-consistent simulations by combination of moving window / dispersions-free method and PIC
- Beam scraping at injector exit useful for (narrow range of) appropriate parameters
- Retardation field effects not important: gun and cathode region still need to be investigated
- Small impact of geometry on beam emittance: only beams on-axis considered
- Important deviations in energy spread due to wakefields (CDS) observed: should be taken into account by FEL designers
- Differences between measured and simulated emittances at PITZ most probably due to improper emission modeling

Thank You for your attention