# Full EM Particle-in-Cell Simulation of an Electron Gun

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# Task

- **Solve Maxwell's eqs. + Eq. of Motion:**
  - Geometry, # Particles, multi-scale → ~~Full EM-Particle in cell~~

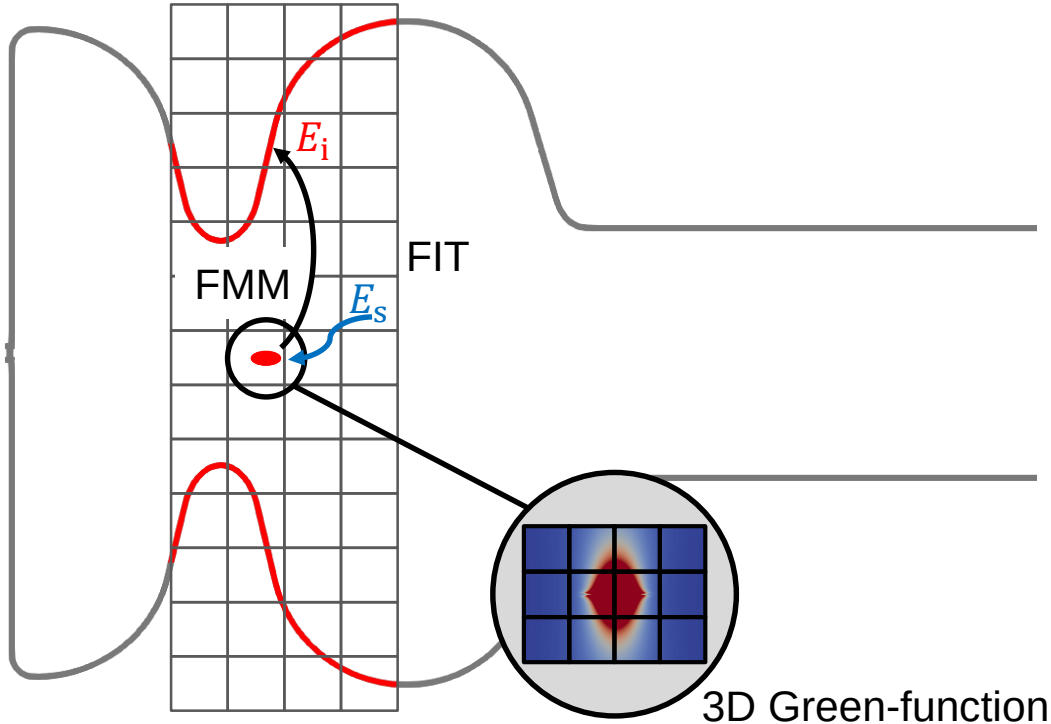
| wake field solver | space charge / particle tracker |
| --- | --- |
| • EM wave eq.<br>• Particles => current<br>− No intermediate feedback | • Poisson eq. in Lorentz frame<br>• Free-space assumption<br>− No transient fields |

Take the best from both?

# Outline

- Scattered Field Formulation vs. Electromagnetic Particle-in-Cell
- Device: Quasi-Traveling Wave Gun
  - (Single) Particle Tracking
  - + Space Charge
  - + Transient (Wake) Fields

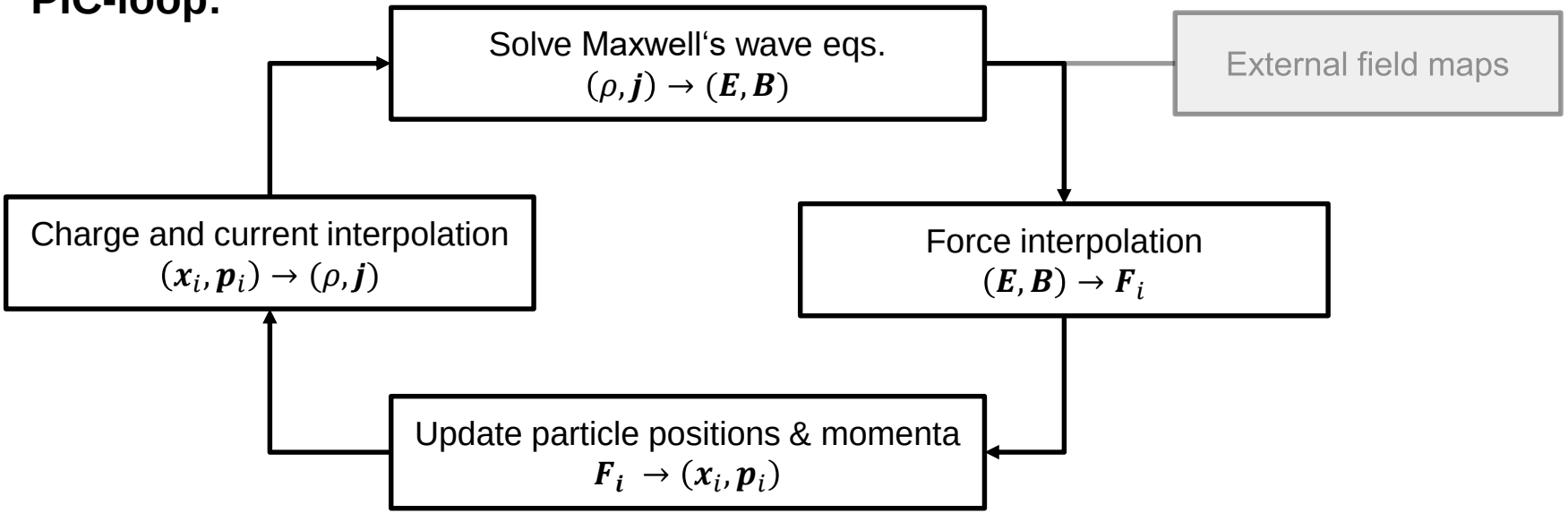
# Coupling: PBCI + REPTIL




- Idea: couple space charge solver (REPTIL) with wake field solver (PBCI) via scattered field formulation
- Mesh-free, fast evaluation of space-charge field on boundary: FMM
- Solvers independent (grid, time step, optimization, …)

# Electromagnetic Particle-in-Cell

- **PIC-loop:**




- Fully self-consistent, “brute-force”

# Coupled Sim. vs EM-PIC

- **Space charge (REPTIL):**
  - Lorentz-frame
  - Local mesh in bunch
- **Coupling (FMM):**
  - Lorentz-frame
- **Wake fields (PBCI):**
  - Global (moving) mesh

→ Validity of modelling choices?

- **EM-PIC:**
  - Single mesh for waves and inter-particle fields
  - Particle current interpolation

→ Computational limits? (here: CST)

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- Scattered Field Formulation vs. Electromagnetic Particle-in-Cell
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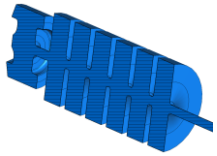
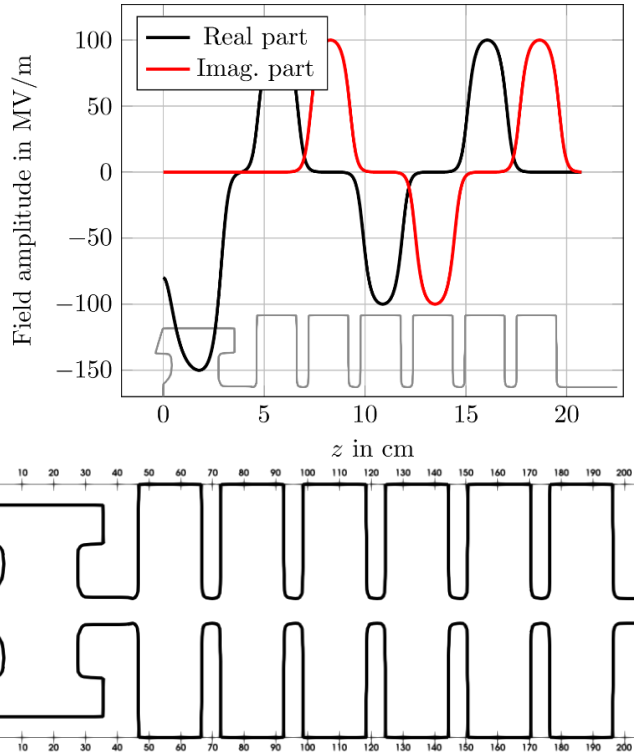
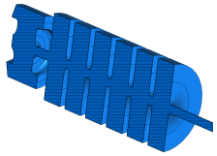
# Quasi-Traveling Wave Gun Model



- Motivation: Natsui, Yoshida (IPAC'14)
- 7 Side-Coupled standing wave cavities (alternating field phase)
- Bending of acc. Field → RF-focusing, no solenoid required
- High bunch charge: 5nC
- Narrow, long geometry: 4mm iris radius, ~20cm acceleration path length

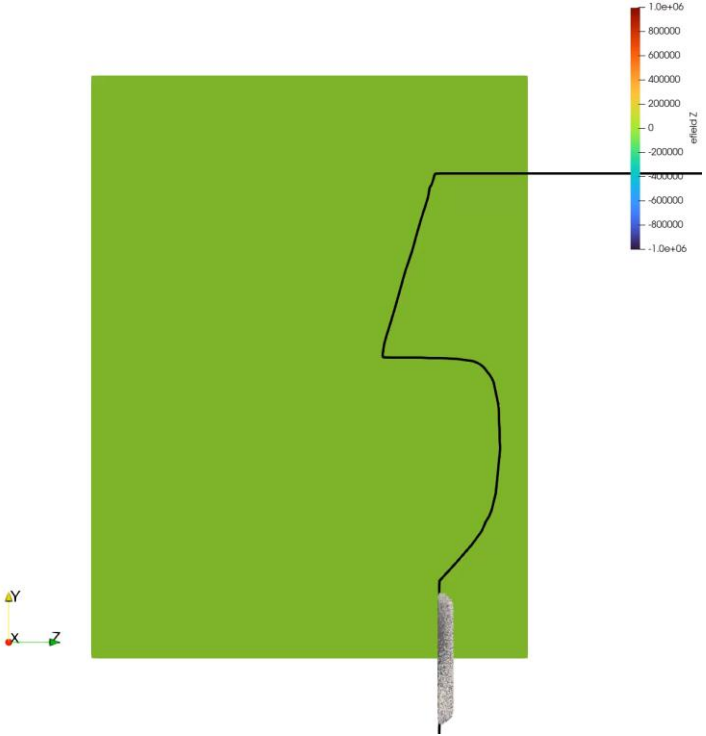


# Quasi-Traveling Wave Gun Model



- Narrow, long geometry: 4mm iris radius, ~20cm acceleration path length
- Video: fields build up over time

| Bunch: | |
|---|---|
| Charge | 5nC |
| Length | ~1.5mm |
| Size | <0.5mm |
| Energy | 14.2MeV at gun exit |

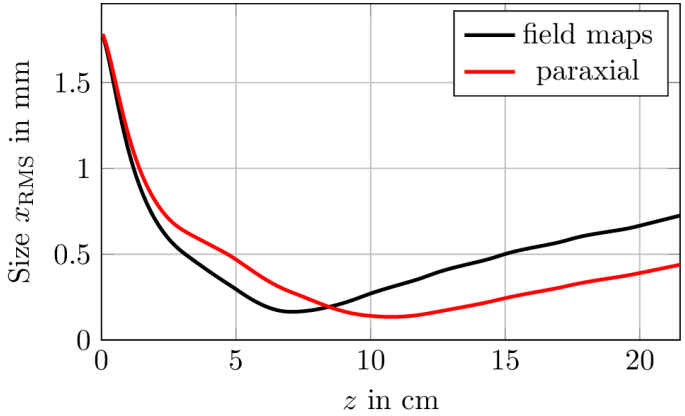


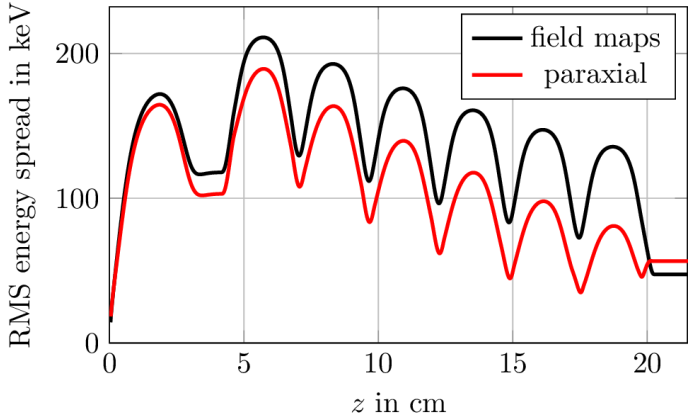
# Paraxial vs. Field Maps: Particle Tracking

- Particle tracking often uses paraxial approximation

$$\partial_z E_{\mathrm{RF}} \gg \partial_\perp E_{\mathrm{RF}}$$

- Here: strong RF field bending requires 3D field maps

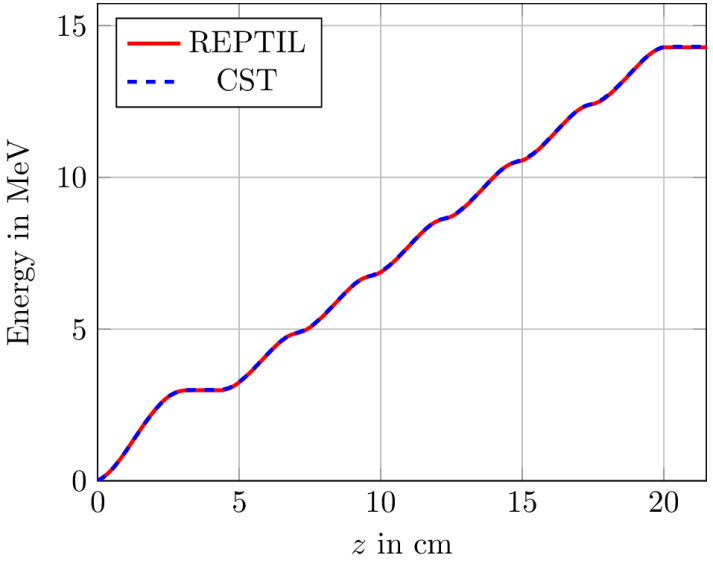


# Single Particle Tracking - REPTIL vs. CST

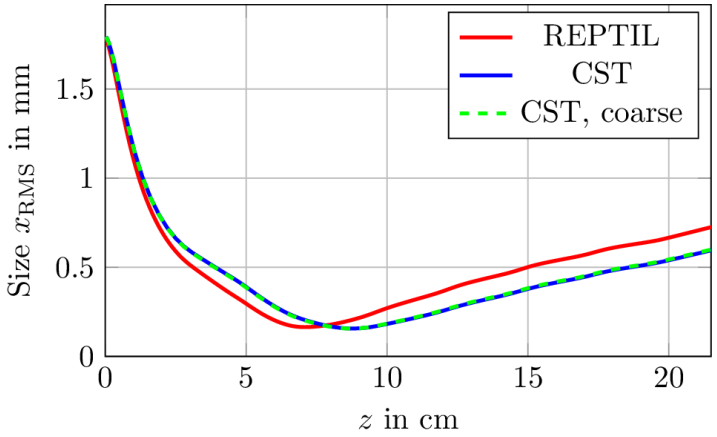
- Tracking: only external fields
- CST: vacuum cylinder

- Relative deviation ~1e-4 – 1e-6
- Crucial for PIC: Field resolution at cathode

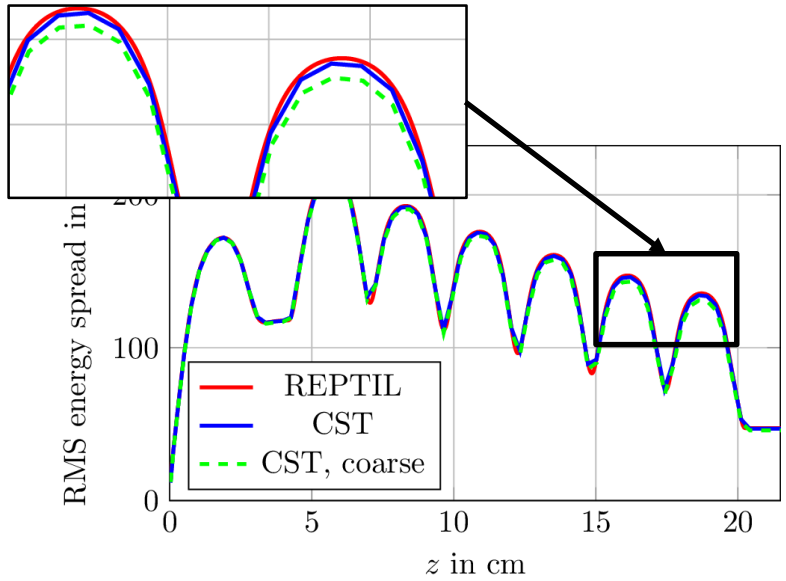


# Particle Tracking - REPTIL vs. CST

- Tracking: only external fields, 1M particles
- CST: particles in vacuum cylinder

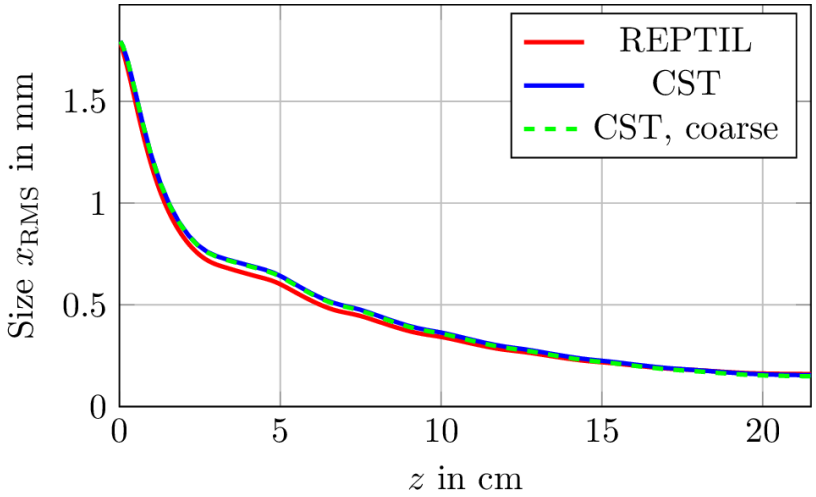


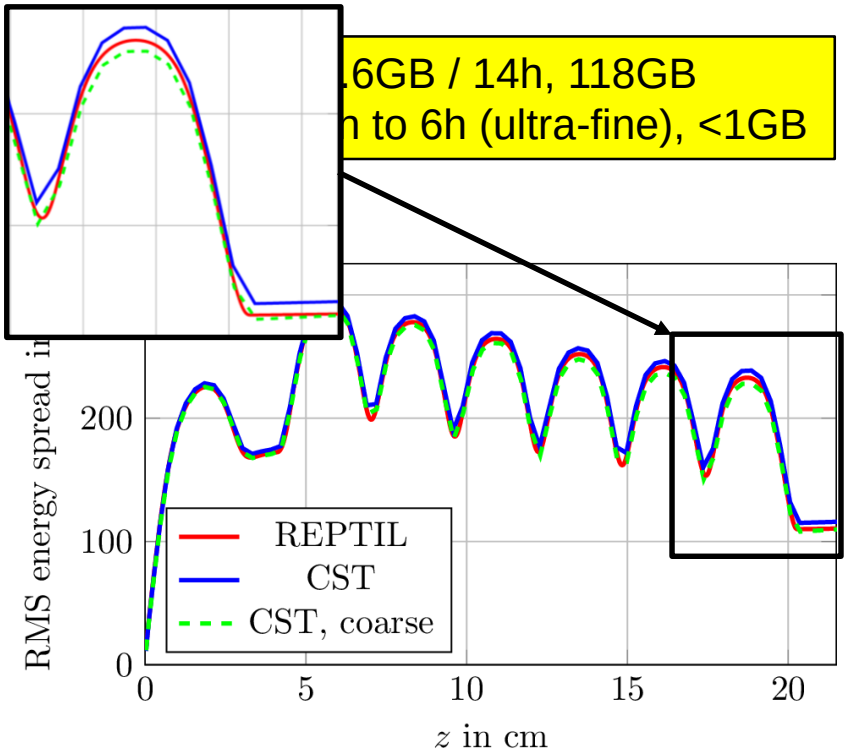

- Energy spread: PIC approaches REPTIL (3% / 1%)



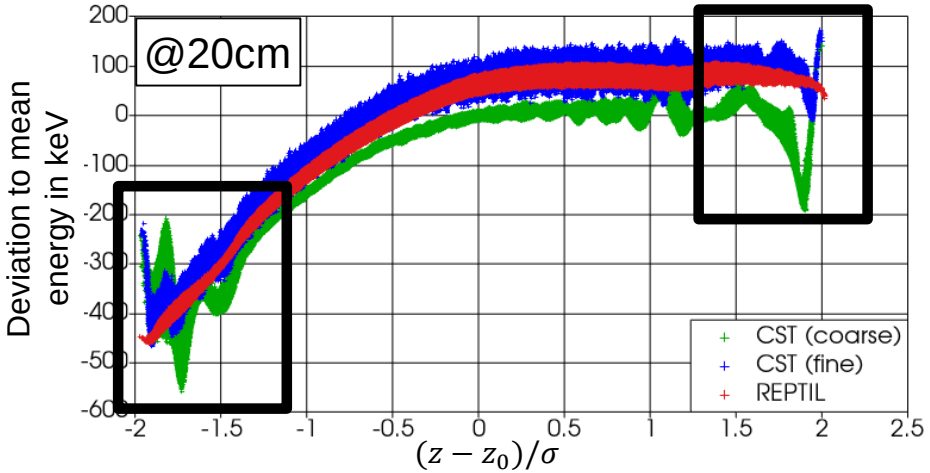
# Tracking + Space Charge – REPTIL vs. CST I

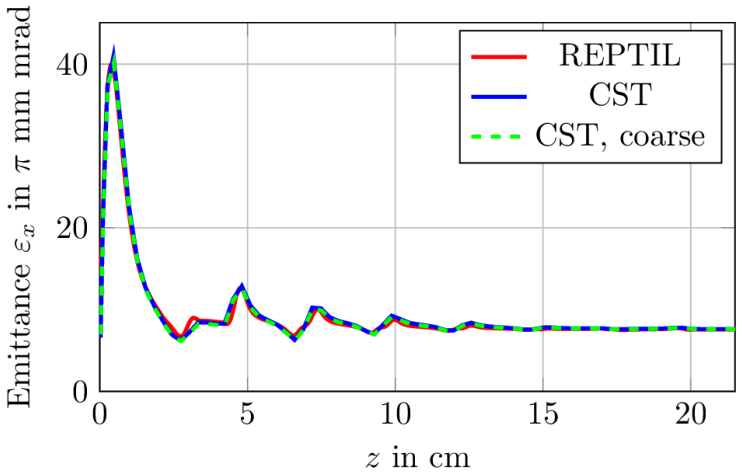
- Add inter-particle fields
- Difficult to provide sufficient resolution over whole gun



# Tracking + Space Charge – REPTIL vs. CST II




- PIC: particle noise

Good agreement between space charge solver and PIC
(also e.g. Setzer 2002)

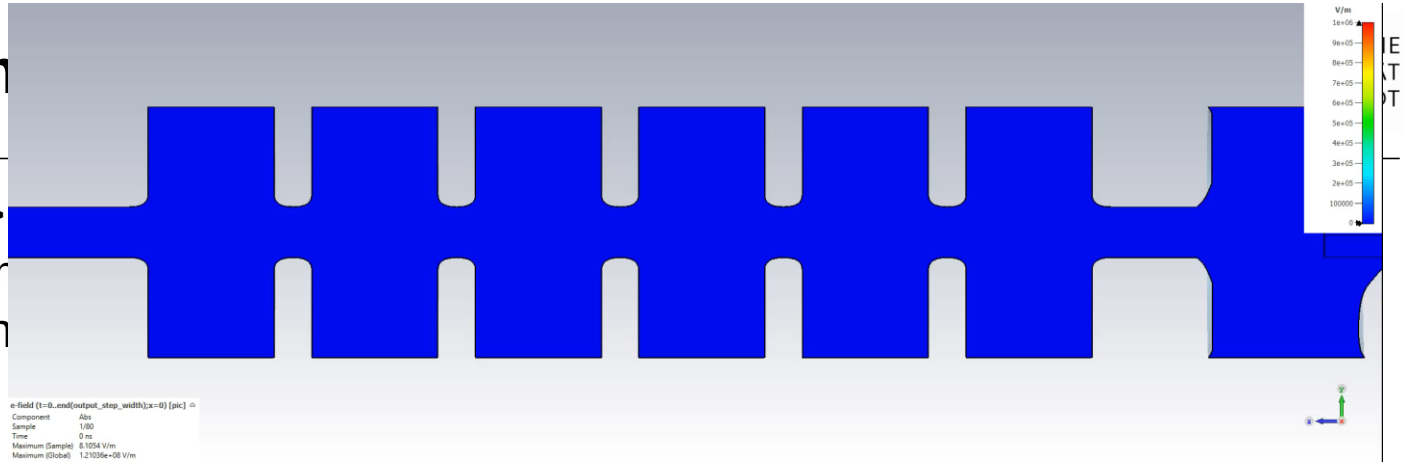
# Including Geometry: CST vs. Coupled Simulation

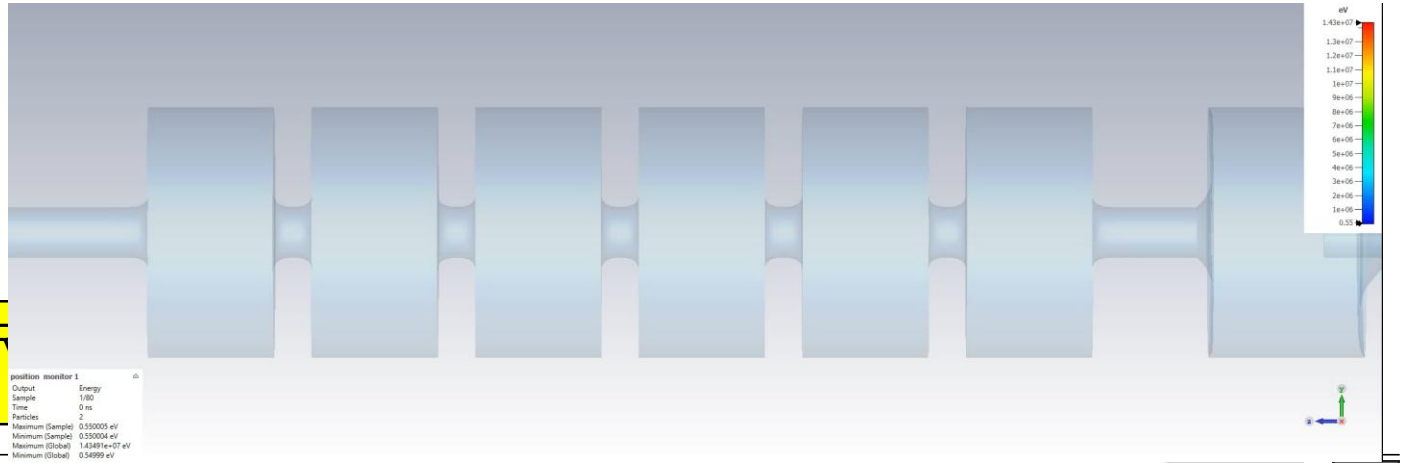
- Full geometry >>1000 Mio. mesh cells
  → Restrict CST model in radial direction and reduce resolution


*CST: 9:40h, 166GB RAM (2/3r) / 23h, 168GB (1/2r)*
Coupled: 6h, 50GB

# Including Geom

- Full geometry >>
  → Restrict CST r
  reduce resolution

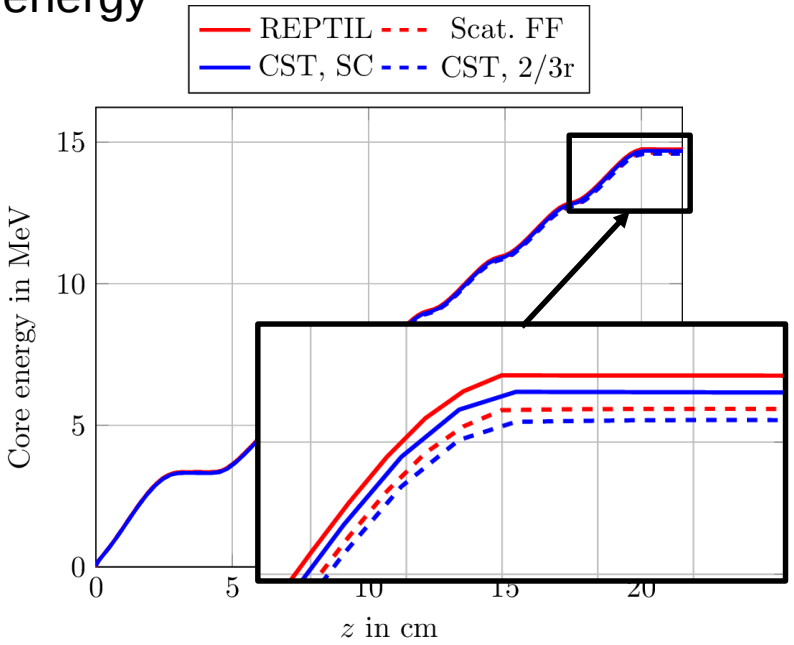


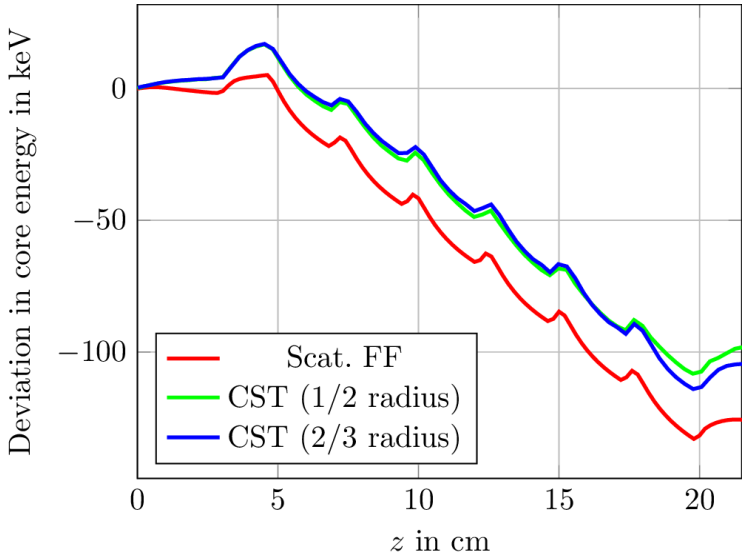




*CST: 9:40h, 166GB R*
Coupled: 6h, 50GB

# Including Geometry: CST vs. Coupled Simulation

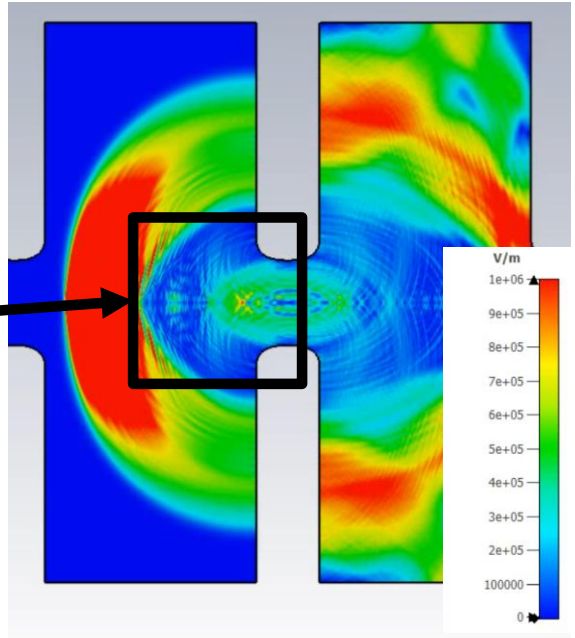
- Quantify effect of wakes: Change in core energy



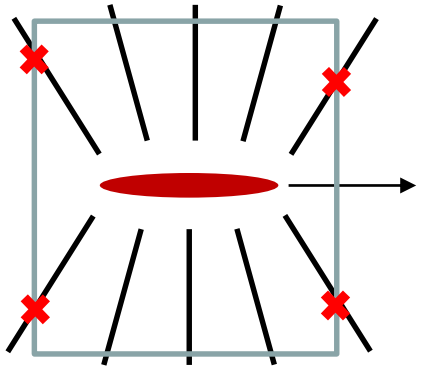
# Summary: EM-PIC Limitations

- **Full EM-PIC in principle possible for (small) gun – BUT:**
- High spatial and temporal resolution of emission
- Parasitic reflections at mesh inhomogeneities
- Transverse resolution of bunch?
- Curse of dimensionality



# Summary: Scattered Field Formulation

- “Just another validation of space charge solvers”
- Validation of coupled space charge and wake field approach for gun simulations



- Outlook:
  - Wakes in dogleg or bunch compressor