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PIC Simulation for the Electron Source of PITZ

Ye Chen, Erion Gjonaj, Wolfgang Müller, Thomas Weiland

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

- Motivation for this study
- Main procedures in CST
- Grid resolution demands

■ 3D CST Simulation
  ▪ Field Simulation
    - Gun-Cavity simulation
    - Solenoids simulation
  ▪ PIC Simulation
    - Setup
    - Astra particle import
    - Preliminary results

■ Discussions
  - Interpolation in PEC

■ Summary & Further Steps
Motivation & Introduction

- 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
Motivation & Introduction

- Main procedures in CST
  
  - Simulations for gun-cavity & solenoids (CST-MWS & EMS)
  - Tune & Calibrate external fields referring to ASTRA import data
  - PIC simulations at a short distance of (60~130) mm (CST-PS)
  - Beam qualities comparison between PIC simulations and ASTRA
  
  - Continue PIC simulations with finer grid resolutions ($\Delta x, \Delta y, \Delta z \ll 0.05\text{mm}$)
  
  - Broaden the calculation domain as far as possible
  
  - Check the results using different particle distributions
    
  - Investigations with inhomogeneous particle distributions
  
  - Investigate the influence of cathode (material, impurities …)
  
  - Optimizations & Repeat simulations with refined parameters
Motivation & Introduction

- Grid resolution demands for PIC simulations

\[ \Delta x_2, \Delta y_2 \]

\[ \text{Bunch Region} \quad (\Delta x_1, \Delta y_1, \Delta z) \]

\[ \Delta x_2, \Delta y_2 \]

Part of the calculation domain

- \( \Delta x_1 \& \Delta y_1 \& \Delta z \ll 0.05 \text{ mm} \)
- \( d = 2X_{\text{rms}} \)
- \( \Delta x_2 \& \Delta y_2 \approx (2\sim3) \times 0.05 \text{ mm} \)

- By properly choosing \( \Delta x_2 \& \Delta y_2 \) outside the bunch region, there will be mesh-saving solutions to broaden the calculation domain in PIC simulations as far as possible.
**3D CST Simulation-Field Simulation**

- **Setup 1 for Gun-Cavity Simulation (CST-MWS)**

**Local mesh properties**

- A cylinder, not included in the simulation, only for mesh refinement at the cathode.
- $L_z = \Delta z$ (mesh resolution in $z$, 0.01mm-0.05mm).
- $\Delta x$ & $\Delta y$ should be comparable with $\Delta z$ (0.01mm-0.05mm).

To obtain the field ratio we need, the radius of half cell was tuned by $\sim 70\mu m$. 
# Field Simulation

## Gun-Cavity Simulation Results

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>1e-6</td>
</tr>
<tr>
<td>Lines/wavelength</td>
<td>120</td>
</tr>
<tr>
<td>Mesh resolution</td>
<td>0.125mm</td>
</tr>
<tr>
<td>Duration</td>
<td>60h</td>
</tr>
<tr>
<td>Frequency</td>
<td>~1.301GHz</td>
</tr>
</tbody>
</table>

### Field Simulation Parameters

- **Algorithm**: JDM
- **Accuracy**: $1e^{-6}$
- **Sym. planes used**: zoy & xoz

### Field Simulation Results

#### E-field

- **Type**: E-Field
- **Cutplane normal**: 1, 0, 0
- **Cutplane position**: 0
- **2D Maximum**: $2.048e+07$
- **Frequency**: 1.302
- **Phase**: 0

#### H-field

- **Type**: H-Field
- **Cutplane normal**: 0, -0.62223, 0.9990
- **Cutplane position**: 91.11
- **2D Maximum**: $2.243e+04$
- **Frequency**: 1.302
- **Phase**: 0

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17 December 2012 | TU Darmstadt | Fachbereich 18 | Institut Theorie Elektromagnetischer Felder | Dr. Ye Chen | 7
Relative Error \% = \frac{\text{Abs}[ A_{\text{CST}} - A_{\text{Astra}} ]}{A_{\text{Astra}}} \times 100\%

A: Amplitude of \( E_z \)

- (0-55) mm, \( RE \leq 1\% 
- (55-75) mm, A approaches to 0
- (75-105) mm, \( RE \leq 2\% 
- (105-185) mm, \( RE \leq 0.6\% 

Accelerating \( E_z \) in CST & ASTRA

Discrepancies of \( E_z \) in CST & ASTRA
Field Simulation

- Setup 2 for Solenoids Simulation (CST-EMS)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pos. of Main</td>
<td>276 mm</td>
</tr>
<tr>
<td>Cur. of Buck</td>
<td>~31 A</td>
</tr>
</tbody>
</table>

Geometrical Parameters in cm

- cathode position
- main
- bucking

- r=24.50
- r=21.50
- r=17.30
- r=13.00
- r=8.50
- r=6.50
- r=10.00
- r=7.70
- r=7.00
- r=3.00
- r=28.85
- r=25.55
- r=14.00
- z=-20.85
- z=31.05
- z=34.35
- z=-17.15
- z=-15.15
- z=-12.65
- z=-7.35
- z=7.35
- z=12.65
- z=20.85
- z=24.15
- z=34.35
- z=40.00
- z=50.00
Field Simulation

$B_z$ of Solenoids in CST & ASTRA

$B_{z\text{max}} = 0.2279 T$
$B_{z0} \sim 10^{-7} T$

Differences of $B_z$ in CST & ASTRA

$RE \leq 1\%$
PIC Simulation

- Setup 3 for PIC Simulation (CST-PS)

Bunch parameters & External fields data

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ASTRA</th>
<th>CST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch radius</td>
<td>0.4mm</td>
<td>0.4mm</td>
</tr>
<tr>
<td>Bunch length</td>
<td>21.5ps</td>
<td>21.5ps</td>
</tr>
<tr>
<td>Macro Nos.</td>
<td>500k</td>
<td>500k</td>
</tr>
<tr>
<td>$E_z$ at cathode</td>
<td>60.58MV/m</td>
<td>60.58MV/m</td>
</tr>
<tr>
<td>$B_{z_{max}}$</td>
<td>0.2279T</td>
<td>0.2279T</td>
</tr>
<tr>
<td>$E_z$ profile</td>
<td>$\Delta=1%\sim2%$</td>
<td>$\Delta=1%\sim2%$</td>
</tr>
</tbody>
</table>

- Simulation time: $\leq700$ps so far
- Mini. mesh step=$(0.12\sim0.07)$ mm so far
- Lines/$\lambda=100\sim120$, meshcells$\geq115$Million
- 1-PIC Position Monitor
- 18-2D Particle Monitors along the beam line from 6mm to 132mm so far
PIC Simulation

- ASTRA Particle Import

Input Data for ASTRA:

- Lt=21.5E-3
- rt=2E-3
- LE=0.00055
- sig_x=sig_y=0.4
- Q =1
- lpart=500,000
- Species=‘electrons’
- Dist_z=‘p’
- Dist_pz=‘i’
- Dist_y=Dist_x=‘r’
- Dist_px=Dist_py=‘r’
- Ref_zpos=0.0
PIC Simulation

- Preliminary results

Animation of the charged particle beam in the longitudinal direction

\[ z = 132\text{mm} \]

Mesh resolution \( \Delta z = 0.12\text{mm} \)
PIC Simulation

Animation of the transverse particle distributions

<table>
<thead>
<tr>
<th>Monitor</th>
<th>Plot type</th>
<th>Total charge</th>
<th>Particles</th>
<th>Frame</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>pic 2d monitor 1</td>
<td>Gamma</td>
<td>0 C</td>
<td>0</td>
<td>25 / 350</td>
<td>40.2343 ps</td>
</tr>
<tr>
<td>z = 6.3247mm</td>
<td></td>
<td></td>
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<td></td>
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<th>Particles</th>
<th>Frame</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>pic 2d monitor 3</td>
<td>Gamma</td>
<td>0 C</td>
<td>0</td>
<td>51 / 350</td>
<td>100.023 ps</td>
</tr>
<tr>
<td>z = 20.362mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Monitor</th>
<th>Plot type</th>
<th>Total charge</th>
<th>Particles</th>
<th>Frame</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>pic 2d monitor 5</td>
<td>Gamma</td>
<td>0 C</td>
<td>0</td>
<td>88 / 350</td>
<td>174.151 ps</td>
</tr>
<tr>
<td>z = 41.449mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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<tr>
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<th>Plot type</th>
<th>Total charge</th>
<th>Particles</th>
<th>Frame</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>pic 2d monitor 7</td>
<td>Gamma</td>
<td>0 C</td>
<td>0</td>
<td>123 / 350</td>
<td>244.218 ps</td>
</tr>
<tr>
<td>z = 62.429mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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<tr>
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<th>Plot type</th>
<th>Total charge</th>
<th>Particles</th>
<th>Frame</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>pic 2d monitor 9</td>
<td>Gamma</td>
<td>0 C</td>
<td>0</td>
<td>147 / 350</td>
<td>292.198 ps</td>
</tr>
<tr>
<td>z = 76.514mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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<th>Plot type</th>
<th>Total charge</th>
<th>Particles</th>
<th>Frame</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>pic 2d monitor 11</td>
<td>Gamma</td>
<td>0 C</td>
<td>0</td>
<td>159 / 350</td>
<td>316.062 ps</td>
</tr>
<tr>
<td>z = 83.498mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
PIC Simulation

Beam size along the beam line

Astra Simulation
CST-PIC Simulation-1, \( \Delta z = 0.08 \text{mm} \)
CST-PIC Simulation-2, \( \Delta z = 0.07 \text{mm} \)
CST-PIC Simulation-0, \( \Delta z = 0.12 \text{mm} \)
Emittance along the beam line

- ASTRA
- CST PIC-2, $\Delta z=0.07\text{mm}$
- CST PIC-1, $\Delta z=0.08\text{mm}$
Beam energy along the beam line

- Beam Energy from ASTRA
- CST-PIC-1, $\Delta z = 0.07 \text{mm}$
- CST-PIC-2, $\Delta z = 0.12 \text{mm}$
Discussions

- Interpolation in PEC

• Cause
  Difference of the grid resolution around the cathode between field simulation & PIC simulation.

• Outcome
  $E_z$ at the cathode was changed by automatic interpolation.

• Solutions
  - Keep the grid settings exactly the same around the cathode. But the field simulations turn to be much slower because of the very small grid.
  - Make the interpolation take place inside the cathode by shifting the back plane. But it will somehow change the eigenmode a little bit.
Summary & Further Steps

- **Summary**
  - PIC Simulation results at a short distance of 60mm downstream from the cathode showed possibilities of convergence to ASTRA simulation in terms of the beam radius by use of a finer mesh resolution (\(Q=1\)nC, grid resolution \(\Delta z\approx 0.07\)mm so far). But the current resolution is still not enough.
  - Still no good agreement with ASTRA on the beam emittance at a short distance of 60mm by improving the grid resolution.
  - Eigenmode convergence when setting local resolution as \((\Delta x, \Delta y, \Delta z) < 0.05\)mm is relatively very slow.

- **Steps in the near future**
  - Continue PIC simulations by enhancing the grid resolutions.
  - Broaden the calculation domain as far as possible (60mm~200mm, \(\Delta x, \Delta y, \Delta z \ll 0.05\)mm).
  - Check the simulations with different particle distributions\((r=0.3\)mm\).
  - Investigate the cases with inhomogeneous particle distributions at the cathode.
Thank you for your attention!