Advances in Parallel Electromagnetic Codes for Accelerator Science and Development

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Speaker: Arno Candel

Advanced Computations Group
SLAC
Sept. 17, 2010

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Advanced Computations at SLAC & Collaborations

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3D Electromagnetic Codes for Accelerators

- **MAFIA (CST)** – FD, [http://www.cst.com](http://www.cst.com)
- **Microwave studio (CST)** – FD, [http://www.cst.com](http://www.cst.com)
- **HFSS (Ansoft)** – FEM, [http://www.ansoft.com](http://www.ansoft.com)
- **ANSYS (Ansys, Inc.)** – FEM, [http://www.ansys.com](http://www.ansys.com)
- **GdfidL** – FDTD, parallel, [http://www.gdfidl.de](http://www.gdfidl.de)
- **ACE3P (SLAC)** - FEM, massively parallel (>10k CPUs) [https://slacportal.slac.stanford.edu/sites/ard_public/bpd/acd/Pages/Default.aspx](https://slacportal.slac.stanford.edu/sites/ard_public/bpd/acd/Pages/Default.aspx)
Motivation to Design the ILC Cavity

International Linear Collider Cavity

Modeling challenges include:

- **Complexity** – HOM coupler (fine features) versus cavity
- **Problem size** – multi-cavity structure (e.g. cryomodule)
- **Accuracy** – 10s of kHz mode separation out of GHz
- **Speed** – Fast turn around time to impact design
DOE’s High Performance Computing Initiatives and SLAC support

- 1998–2001 HPC Accelerator Grand Challenge
- 2001-07 Scientific Discovery through Advanced Computation (SciDAC-1) - Accelerator Science and Technology (AST)
- 2007-12 Scientific Discovery through Advanced Computation (SciDAC-2) - Community Petascale Project for Accelerator Science and Simulation (ComPASS)

PhD Research:


Parallel Higher-order Finite-Element Method

Strength of Approach – Accuracy and Scalability

- **Conformal** (tetrahedral) mesh with quadratic surface
- **Higher-order** elements ($p = 1-6$)
- **Parallel** processing (memory & speedup)

\[
\mathbf{E}(\mathbf{x}, t) = \sum_i e_i(t) \cdot \mathbf{N}_i(\mathbf{x})
\]

End cell with input coupler only

Error ~ 20 kHz (1.3 GHz)

67000 quad elements (<1 min on 16 CPU, 6 GB)
Accelerator Modeling with EM Code Suite ACE3P

Meshing - CUBIT for building CAD models and generating finite-element meshes. 

Modeling and Simulation – SLAC’s suite of conformal, higher-order, C++/MPI based parallel finite-element electromagnetic codes

ACE3P (Advanced Computational Electromagnetics 3P)

Frequency Domain:  
Omega3P – Eigensolver (damping)  
S3P – S-Parameter

Time Domain:  
T3P – Wakefields and Transients

Particle Tracking:  
Track3P – Multipacting and Dark Current

EM Particle-in-cell:  
Pic3P – RF gun (self-consistent)

Postprocessing - ParaView to visualize unstructured meshes & particle/field data. 
http://www.paraview.org/.

Goal is the Virtual Prototyping of accelerator structures
**ACE3P Capabilities**

- **Omega3P** can be used to
  - optimize RF parameters
  - reduce peak surface fields,
  - calculate HOM damping,
  - find trapped modes & their heating effects,
  - design dielectric & ferrite dampers, and others

- **S3P** calculates the transmission (S parameters) in open structures

- **T3P** uses a driving bunch to
  - evaluate the broadband impedance, trapped modes and signal sensitivity,
  - compute the wakefields of short bunches with a moving window,
  - simulate the beam transit in large 3D complex structures

- **Track3P** studies multipacting in cavities & couplers by identifying MP barriers, MP sites and the type of MP trajectories.

- **Pic3P** calculates the beam emittance in RF gun designs.
Benchmarks of **ACE3P** with Measurements
Code validated in 3D NLC Cell design in 2001

- Omega3P was used to determine the accelerator dimensions for the JLC/NLC X-Band structures with accuracy orders of magnitude better than machining tolerance,
- The structure cells were high precision machined,
- Microwave QC verified cavity frequency accuracy to 0.01% relative error (1MHz out of 11 GHz) as required for beam stability.
Provided dimensions for LCLS RF gun cavity to meet design requirements:

- Reduce pulse heating by rounding of the z-coupling iris
- Minimize dipole and quadrupole fields via a racetrack dual-feed coupler design

**Code validated by Measurement**

<table>
<thead>
<tr>
<th>RF parameter</th>
<th>Design</th>
<th>Measured</th>
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<tbody>
<tr>
<td>( f_\pi ) (GHz)</td>
<td>2.855987</td>
<td>2.855999</td>
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<tr>
<td>( Q_0 )</td>
<td>13960</td>
<td>14062</td>
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<tr>
<td>( \beta )</td>
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<td>2.03</td>
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<tr>
<td>Mode Sep. ( \Delta f ) (MHz)</td>
<td>15</td>
<td>15.17</td>
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<tr>
<td>Field balance</td>
<td>1</td>
<td>1</td>
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</table>
S3P - S-Parameters for LCLS Injector Components

- LCLS injector accelerator structure dual-feed coupler components
  - WR284 waveguide and flanges
  - dual-feed coupler

- LCLS RF Gun Dual-window assembly
ICHIRIO cavity experienced
- Low achievable field gradient
- Long RF processing time

- Hard barrier at 29.4 MV/m field gradient with MP in the beampipe step
- First predicted by Track3P simulation

<table>
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<tr>
<th>ICHIRO #0</th>
<th>Track3P MP simulation</th>
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<tr>
<td>X-ray Barriers (MV/m)</td>
<td>Gradient (MV/m)</td>
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<tr>
<td>11-29.3 12-18</td>
<td>12</td>
</tr>
<tr>
<td>13, 14, 14-18, 13-27</td>
<td>14</td>
</tr>
<tr>
<td>(17, 18)</td>
<td>17</td>
</tr>
<tr>
<td>20.8</td>
<td>21.2</td>
</tr>
<tr>
<td>28.7, 29.0, 29.3, 29.4</td>
<td>29.4</td>
</tr>
</tbody>
</table>
Large-scale Accelerator Simulation requires Computational Science and High Performance Computing
Computational Science R&D under SciDAC

Eigen solver speed and scalability

Solver speed and capability: 50-100x

Mesh correction

Adaptive mesh refinement

Partitioning scheme for load balancing

ParMETIS

RCB1D

Execution Time vs. Number of CPUs

Partitioning scheme for load balancing

ParMETIS

RCB1D
HPC Resources for Accelerator Modeling

DOE Computing Resources @ LBNL and ORNL to meet SciDAC, Accelerator projects as well as the CW10 user community needs:

Computers -

NERSC at LBNL - Franklin Cray XT4, 38642 compute cores, 77 TBytes memory, 355 Tflops

NCCS at ORNL - Jaguar Cray XT5, 224,256 compute cores, 300 TBytes memory, 2331 TFlops 600 TBytes disk space

Allocations –

NERSC - Advanced Modeling for Particle Accelerators - 1M CPU hours, renewable
- SciDAC ComPASS Project – 1.6M CPU hours, renewable (shared)
- Frontiers in Accelerator Design: Advanced Modeling for Next-Generation BES Accelerators - 300K CPU hours, renewable (shared) each year

NCCS - Petascale Computing for Terascale Particle Accelerator: International Linear Collider Design and Modeling - 12M CPU hours in FY10
ACE3P's advances focus on solving challenging problems in Accelerator Science and Development
T3P - Beam Transit in ILC Cryomodule

ILC cryomodule of 8 Superconducting RF cavities

Expanded views of Input and HOM couplers

Fields in beam frame moving at speed of light

Visualization by Greg Schussman
Page 19
T3P - Short Bunch Wakefields in ERL

Energy Recovery Linac

*Bunch length = 0.6 mm*

Beam direction

**Longitudinal wakefield**

Loss factor = 0.413 V/pC

In collaboration with Cornell
T3P - CLIC Two-Beam Accelerator

Compact Linear Collider two-beam accelerator unit
Dissipation of transverse wakefields in dielectric loads: \( \varepsilon = 13, \tan(\delta) = 0.2 \)

GdfidL results by I. Syratchev, CERN
T3P - CLIC TDA24 Bunch Transit

GdfidL results by A. Grudiev, CERN
**Track3P – Multipacting in SNS Cavity/HOM Coupler**

### SNS Cavity
- Both Experiment and Simulation show same MP band: 11 MV/m ~ 15MV/m

### SNS Coupler
- SNS SCRF cavity experienced rf heating at HOM coupler
- 3D simulations showed MP barriers close to measurements
Track3P - Multipacting in SNS Cavity/HOM Coupler

Visualization by Greg Schussman
Racetrack cavity design: Almost 2D drive mode. Cylindrical bunch allows benchmarking of 3D code Pic3P against 2D codes Pic2P and MAFIA.

Temporal evolution of electron bunch and scattered self-fields.

Unprecedented Accuracy due to Higher-Order Particle-Field Coupling and Conformal Boundaries.
3D Emittance Calculations for Bunch with Offset

- $f=11.424 \text{ GHz}$, 200 MV/m peak $E_z$ on cathode
- Solenoid $B_z_{\text{max}} = 0.5658 \text{ T at } Z=6.3 \text{ cm}$
- Beer can ($r=0.5 \text{ mm, } 2 \text{ ps flat top, } 0.4 \text{ ps rise time}$), 250 pC
- Bunch injected 30 degrees after zero-crossing

4D Emittance vs $<Z>$
Solving the CEBAF BBU - Joint Efforts from Accelerator Physics + Experiment + Computational Science + Computing
CEBAF BBU - Solving the Inverse Problem

CEBAF 12-GeV upgrade –

- Beam breakup (BBU) observed at beam currents well below design threshold
- Used measured RF parameters such as $f$, $Q_{ext}$, and field profile as inputs
- Solutions to the inverse problem identified the main cause of the BBU instability: Cavity is 8 mm shorter – predicted and confirmed later from measurements
- The fields of the 3 abnormally high Q modes are shifted away from the coupler
- Showed that experimental diagnosis, advanced computing and applied math worked together to solve a real world problem as intended by SciDAC

In collaboration with TJNAF – R. Rimmer, H. Wang
Optimizing the Choke Mode Cavity Performance

The procedure based on nonlinear iterations with Newton type algorithms that solves the Jlab inverse problem can be used to optimize the performance of the choke mode cavity in reducing the wakefield effects of higher-order dipole modes.
Ace3P User Community - CW10 Code Workshop

CW10 @ SLAC

Accelerator Code Workshop (CW10) at SLAC for the Ace3P (Advanced Computational Electromagnetics 3P) Code Suite organized by the Advanced Computation Group (ACG)

Date — September 20-22, 2010
Time — See agenda
Place — SLAC National Accelerator Laboratory
Menlo Park, California

Contact — ACD-CW10@slac.stanford.edu
650-926-2664
650-926-4603 (FAX)
# CW10 Attendees & Agenda

## Attendees

<table>
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## Agenda

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Session</th>
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<tbody>
<tr>
<td>9/22 Monday</td>
<td>8:30-10.15</td>
<td>Intro/CUBIT, Track3P</td>
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<tr>
<td></td>
<td>10.15-12.15</td>
<td>ACE3P/ParaView, Track3P, TEM3P</td>
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<td></td>
<td>12.15-1.30</td>
<td>lunch</td>
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<tr>
<td>9/23 Tuesday</td>
<td>1.30-3.15</td>
<td>Omega3P, T3P</td>
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<tr>
<td></td>
<td>3.15-5.30</td>
<td>T3P</td>
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<tr>
<td>9/24 Wednesday</td>
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<td>All sessions are 1 hr 45 min</td>
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**Note:** Parallel Sessions, Lunch times are excluded from the session schedule.
Summary

- Parallel finite-element (FE) electromagnetics (EM) method demonstrates its strengths in high-fidelity, high-accuracy modeling for accelerator design, optimization and analysis.

- ACE3P code suite, developed under DOE SciDAC and SLAC support, has been benchmarked and used in a wide range of applications in Accelerator Science and Development.

- Advanced capabilities in ACE3P's modules Omega3P, S3P, T3P, Track3P, and Pic3P have enabled challenging problems to be solved that benefit accelerators worldwide.

- Computational science and high performance computing are essential to tackling real world problems through simulation.

- The ACE3P User Community is formed to share this resource and experience and we welcome the opportunity to collaborate on projects of common interest.