Advances in Electromagnetic Modeling through High Performance Computing

Kwok Ko
Stanford Linear Accelerator Center

SRF 2005, Cornell University

* Work supported by U.S. DOE ASCR & HEP Divisions under contract DE-AC02-76SF00515
What is SciDAC?

- **Scientific Discovery through Advanced Computing**
- **DOE Office of Science (SC) Simulation Initiative**
- **Phase I 5-yr program ending FY06, Phase II follow-on**
- **Orchestrated by ASCR to promote HPC across SC**
- **Supports AM and CS to work with the applications**
- **Total about 20 plus SciDAC projects**
- **HEP Accelerator Simulation Project has 3 components:**
  - **Electromagnetics** (SLAC), **Beam Dynamics** (LBL), **Advanced Accelerators** (UCLA)
DOE/SciDAC Accelerator Simulation Project

SLAC leads the **Electromagnetic Modeling** component

<table>
<thead>
<tr>
<th>High Performance Computing (NERSC IBM SP, ORNL Cray X1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation and Modeling</td>
</tr>
<tr>
<td>Parallel Code Development</td>
</tr>
<tr>
<td>Computational Science</td>
</tr>
</tbody>
</table>

**Accelerators**
- SLAC
- DESY
- KEK
- FNAL
- Jlab
- ANL
- MIT
- PSI

**SLAC**
- Accelerator Modeling
  - SciDAC
    - Computational Mathematics
    - Computing Technologies

**ISICs/SAPP**
- LBNL
- LLNL
- SNL
- Stanford, UCD
- RPI, CMU
- Columbia
- UWisconsin

“DOE Grand Challenge prior to SciDAC”
Parallel EM Code Development

Solve Maxwell’s equations (with particles) in time & frequency domains using unstructured grid and parallel processing to target High Resolution Modeling and End-to-end Simulation.

- Generalized Yee Grid
  - Tau3P/T3P
  - Time Domain Simulation With Excitations
- Finite-Element (up to 6th order basis)
  - Omega3P
  - Frequency Domain Mode Calculation
  - S3P
  - Scattering Matrix Evaluation
- Track3P – Particle Tracking with Surface Physics
- V3D – Visualization of Meshes, Particles & Fields

C++/MPI
Finite Element + Parallel Processing

**Combined features for Accuracy, Speed and Memory**

- **Dense** – 67000 (<1 min on 16 cpu, 6 GB)
- **Coarse** – 2100

Approximations:

- ~1 MHz
- ~20 kHz

**Moore’s Law**
1 CPU ~10’s GB

**Linear Speedup = 1/N**
6080 CPU ~1-4 GB each > TB total

**Conformal Mesh**

- **Quadratic (p = 2)**
- **FE basis**

**SEABORG**
Parallel Electromagnetic Modeling

SciDAC supports collaborations in applied mathematics and computer science (computational science) to enable new advances in electromagnetic modeling through HPC.
To model a chain of cavities within a cryomodule a parallel meshing capability has been developed to overcome the single CPU memory limitation of standard meshing software.
Advances in Parallel Eigensolvers

(SLAC - LBL, Stanford, UC Davis)

Modeling cavities with coupling to external waveguides requires solutions to a nonlinear eigenvalue problem as the boundary conditions now also depend on the eigenvalue as matched waveguide terminations.
Advances in Adaptive Mesh Refinement

( SLAC – RPI)

**Adaptive Mesh Refinement** improves the accuracy in frequency and wall loss calculations at a fraction of resources by speeding up convergence.

For RIA’s RFQ cavity, more accurate frequency and Qo predictions (factor of 10 and 2) reduce the number of tuners and ease tuning procedures, and improve cooling design (P, Ostroumov)
A parallel shape optimization capability is under development for Omega3P to replace existing manual iterative process. Primitive prototype being applied to the ILC cavity. (J. Sekutowicz)
Advances in Visualization

(Rendering **LARGE, 3D multi-stream, unstructured data** is essential for analysis, such as studying mode rotation in the ILC cavity (Visualization Server).)

(Rendering **LARGE, 3D multi-stream, unstructured data** is essential for analysis, such as studying mode rotation in the ILC cavity (Visualization Server).)
**Omega3P** provided the dimensions for 206 NLC Damped Detuned Structure cells. Microwave QC of cells verified frequency accuracy of 1 part in 10,000 as targeted.

Potential $100 million+ savings in NLC machine cost (DDS14% higher shunt impedance than standard design)

**Omega3P** - New core accelerator design capability

“High Resolution Modeling”
**Omega3P/Tau3P** computed the long-range transverse wakefields in an actual 55-cell DDS prototype which was the baseline design for the NLC.

**NLC 55-cell DDS**

**Omega3P**: Sum over eigenmodes

**Tau3P**: Direct beam excitation

"End-to-end Simulation"
NLC Dark Current Pulse

Dark current pulse simulated for the 1st time in an entire structure with Track3P and compared with data, showing agreement in dark current increase during pulse risetime.

Track3P: Dark current simulation

Red – Primary particles, Green – Secondary particles

Dark current @ 3 pulse risetimes

-- 10 nsec
-- 15 nsec
-- 20 nsec

Fig. 7. Pulse shapes of section input, output and dark current for three different rise times of the RF pulse for 30-cavity TW section tests.
**Omega3P** was used to evaluate the damping of localized modes by mounting ceramic tiles on the bellows convolution. Bellows modes were found to be damped to very low Qs.

**Bellows mode** _Ceramic tile absorber_ _Dielectric loss_
**Omega3P/S3P** provided the dimensions for the LCLS RF Gun cavity that meet two important requirements:

- minimized dipole and quadrupole fields via a racetrack dual-feed coupler design,
- reduced pulse heating by rounding of the z coupling iris.

A new parallel Particle-In-Cell (PIC) capability is being developed in **T3P** for self-consistent modeling of RF guns needed for the LCLS upgrade, future light sources and FELs.
JLab 7-cell SRF Cavity (Rimmer, Wang)

2.103654 GHz
high Q mode
causes Y-kick

2.103666 GHz
Low Q mode
causes X-kick

“Cavity for 12 GeV upgrade is in progress”
ILC Low-Loss Cavity Design

An international collaboration comprising DESY, KEK, SLAC, JLab and FNAL is working on a Low-loss (LL) design for the ILC accelerating cavity. The LL cavity shape has 23% less cryogenic loss.

SLAC’s ACD is calculating the HOM damping and optimizing the HOM couplers for the DESY LL cavity (J. Sekutowicz) and the KEK ICHIRO cavity (K. Saito)
ILC Cavity HOM Damping

**Omega3P** computes the complex frequency or $Q_e = \frac{\omega_R}{2\omega_i}$ of HOMs due to damping by the HOM couplers.

Partitioned Mesh of LL Cavity

DESY LL

KEK ICHIRO

18 modes/hour
768 cpu, 300 GB
Work in Progress

- **ILC Cavity modeling** – Optimize HOM damping
  - Effect of Imperfections
  - Multi-cavity interconnections

- **Beam Dynamics** – Wakefields effects (mode rotation)

- **Multipacting** –

- **Code release** – Single CPU version within a year (?)
  
  kwok@slac.stanford.edu