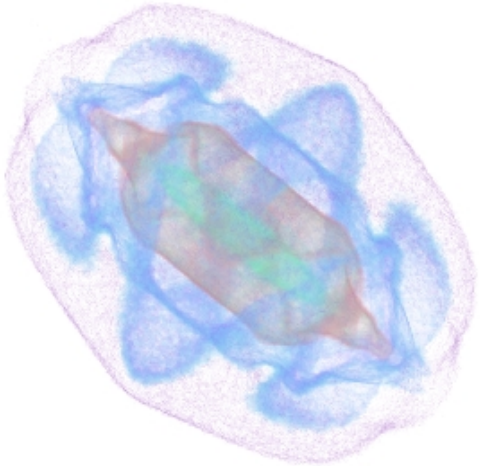
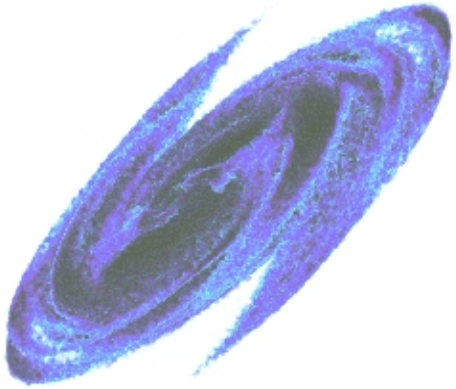
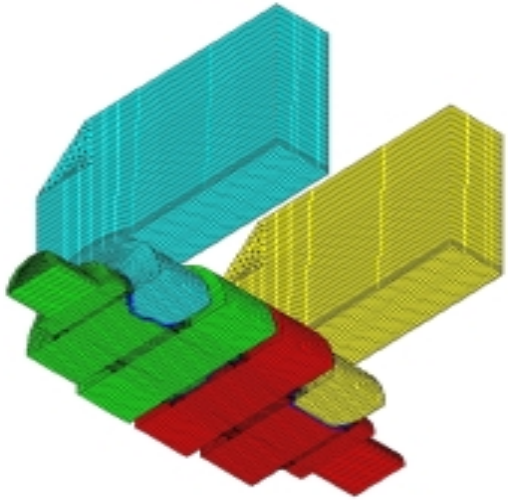
Computational Accelerator Physics Grand Challenge
FY99 Status Report

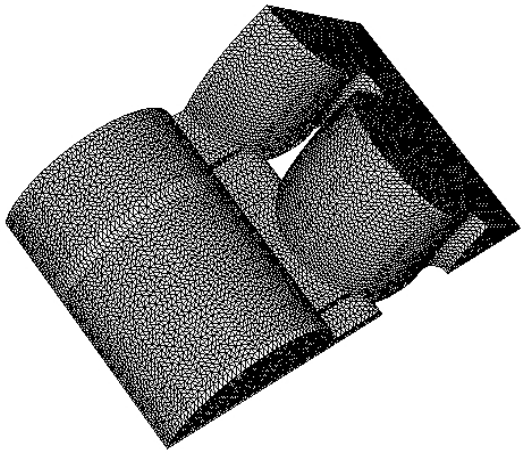


Robert Ryne[1] and Kwok Ko[2]

[1]Los Alamos National Laboratory
[2]Stanford Linear Accelerator Center







Team Members and Collaborators

J. Ahrens[5], T. Cleland[5], J. Cummings[5], V. Decyk[4],
N. Folwell[2], G. Golub[3], S. Habib[1], W. Humphrey[5],
S. Karmesin[5], P. McCormick[5], A. McPherson[5],
J. Painter[5], J. Qiang[1], Z. Li[2], B. McCandless[2],
G. Mark[5], W. Mi[3], C.-K. Ng[2], M. Saparov[3],
W. Saphir[6], Y. Sun[3], M. Wolf[2]

[1]Los Alamos National Laboratory
[2]Stanford Linear Accelerator Center
[3]Stanford University
[4]University of California, Los Angeles
[5]Advanced Computing Laboratory
[6]National Energy Research Scientific Computing Center

Motivation for Grand Challenge in Computational Accelerator Physics

- Future accelerators will push the frontiers of beam intensity, beam energy, and system complexity
  - Examples: SNS, NLC, LHC, APT, ATW, μ-collider, 4th generation light source, rare isotope accelerator
- Modeling on parallel computers is essential for design decisions
  - evaluate/reduce risk
  - reduce cost
  - optimize performance
- Example problems:
  - predicting beam halo in SNS and APT
  - designing ***large*** electromagnetic structures for NLC
  - modeling high power klystrons

Grand Challenge Goals

- Develop a new generation of accelerator modeling tools targeted to high performance computing platforms

- Apply tools to present and future accelerator applications of national importance

- Help ensure success: projects on-schedule, within budget, meeting all performance requirements.

Grand Challenge Benefits for Science and Technology

- Large scale simulations provide a ***tool of discovery*** to explore beams in novel configurations and under extreme conditions
  - plasma accelerators w/ gradients ~ 1-100 GeV/m
  - cooling for muon-based neutrino sources and colliders
  - stripping/separation/reacceleration for production of isotopes

- Large scale simulation, coupled with theory and experiment, will help advance the frontiers of accelerator technology and lead to major discoveries in beam-driven science.

Status: *"Parallel Computing Works"*

Progress in the Grand Challenge has already enabled simulations ***3-4 orders of magnitude*** greater than previously possible

Example: Parallel beam dynamics simulations w/ 500M particles

- Parallel beam dynamics and electromagnetics codes developed under the Grand Challenge have been applied to
  - NLC
  - SNS
  - APT
  - ALS
  - PEP-II
  - W-band structures

Grand Challenge Focus Areas: Beam Dynamics and Electromagnetics

- Beam Dynamics:
  - development of a suite of parallel particle simulation codes to perform high resolution, end-to-end simulations of intense beams propagating through a variety of accelerator systems
- Electromagnetics:
  - development of a suite of parallel field solvers capable of modeling large, complex beamline components and systems using a variety of approaches (eigenmode, time-domain,…)

- A comprehensive set of capabilities to enable an accelerator physicist/engineer to solve a wide range of beam dynamics and electromagnetics problems in accelerator design and analysis
- Problems that can only be solved w/ parallel computing resources

Development of large-scale parallel applications involves the integration of many pieces

Electromagnetics

- Parametric Geometry - CAD models to facilitate optimization
- Mesh Generation - impacts matrix conditioning/time-stepping
- Adaptive Refinement - improve accuracy/optimize resources

Beam Dynamics

- Frameworks - accelerator system geometry, models of beamline elements,...
- Transfer Map Methods -Symplectic maps corresponding to beamline elements
- Particle Managers - to minimize communication in parallel PIC codes

Both

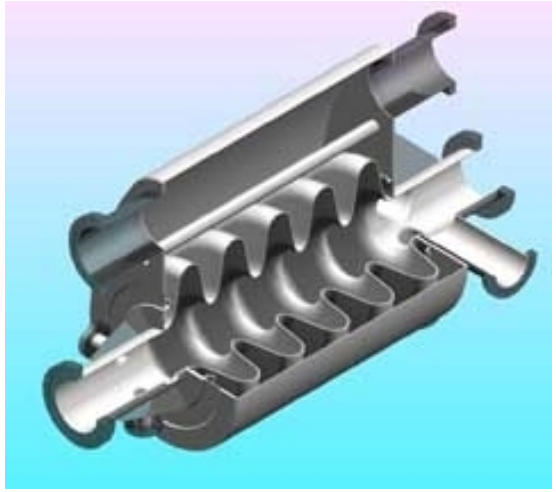
- Parallel Solvers - scalable algorithms with fast convergence
- Domain Decomposition - partitioning tools for load balancing
- Visualization - efficient post-processing of large data sets; feature extraction and scientific discovery in simulation results
- Performance/Error Analysis - computer science/applied math

Success depends on integrating the combined efforts of a multi-disciplinary team including physicists, applied mathematicians, statisticians, computer scientists, software engineers, geometry builders, visualization experts,...

Large Scale Beam Dynamics Simulations are Needed to Accurately Model Beam Halo

- Future high average power accelerators will have to operate with very low losses
- Excess losses
  - cause radioactivity, degrade components
  - hinder/prevent hands on maintenance
  - reduce reliability and availability

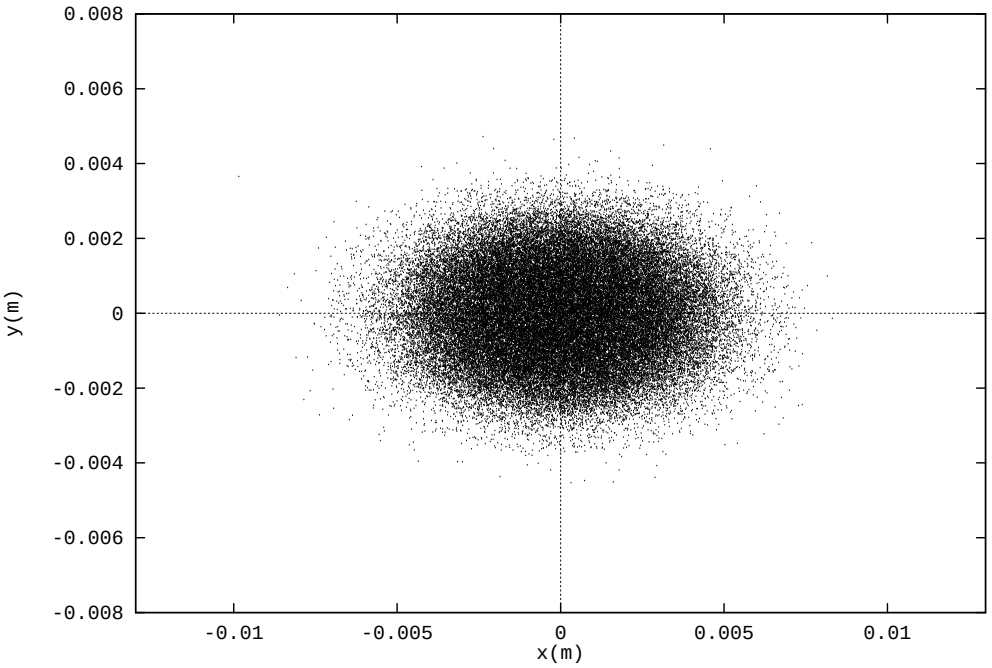
Allowed loss is ~ 0.1-1 nanoampere/meter @ 1GeV



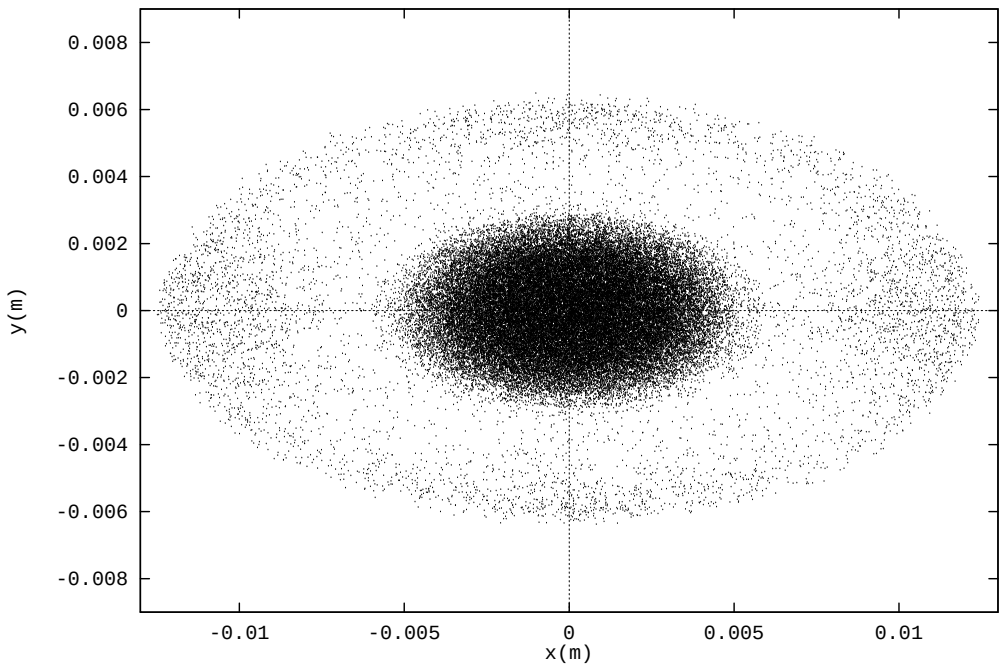
- Major loss mechanism: large amplitude "halo" particles striking the beam pipe

High-Resolution modeling using 0.1-1 billion particles is necessary to make quantitative predictions of beam halo

A major source of halo: *beam mismatch*



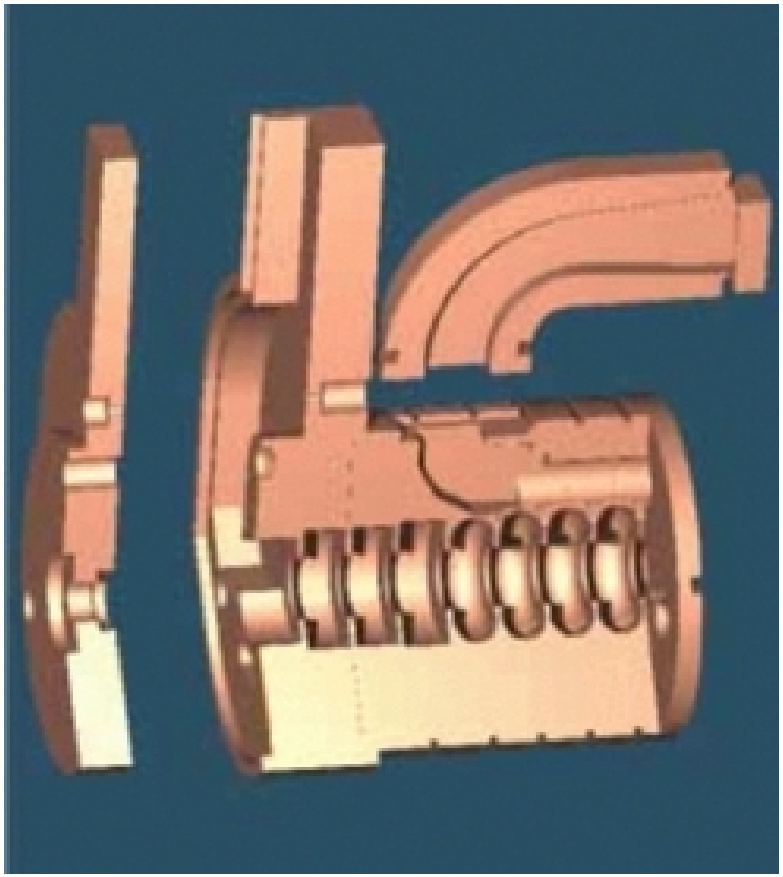
Matched beam



Mismatched beam

Large Scale Electromagnetic Simulations

DDS for the NLC



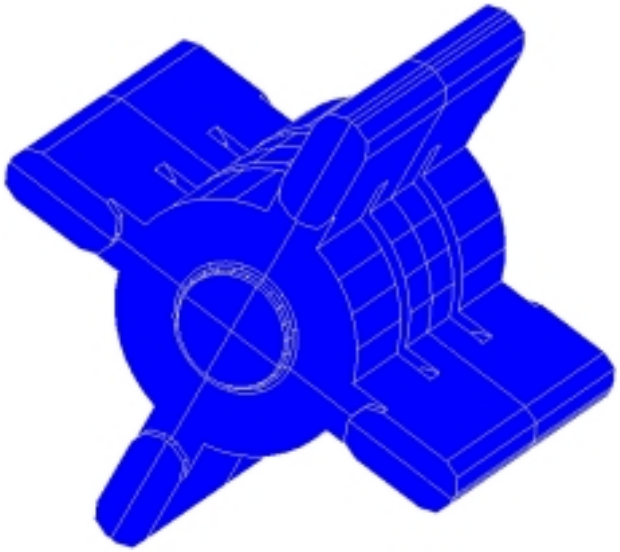
- Cell Design requires frequency error of 1 part in 10,000 with mesh size close to fabrication tolerance (no tuning of cell)
- Wakefield Analysis needs entire section (206 cells) modeling to verify the DDS scheme in suppressing emittance growth

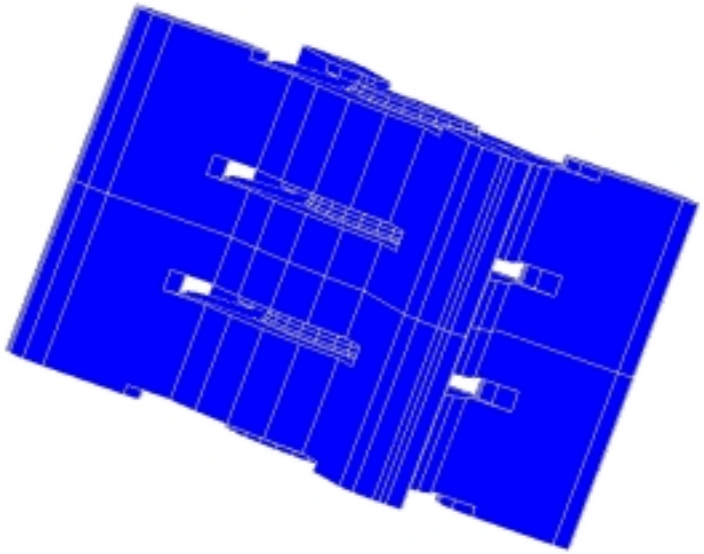
Simulating these problems spans a range from 10^6 to 10^9 degrees of freedom !

"High-Resolution" design and "System-Scale" analysis are only possible on <u>Massively Parallel</u> Computers

DDS Modeling

- Individual Cell Design - requires frequency accuracy to within 0.01 % because cell to cell dimensions vary on the same order.
- Whole Structure Analysis - simulates all 206 cells to obtain a global solution of the fields.





- Both types of modeling are beyond desktop computing resources.
- Modeling tools that utilize multi-processors are being developed under the Grand Challenge.

Parallel Beam Dynamics Solvers

IMPACT - *3D Parallel Beam Dynamics code for modeling intense beams*

- POOMA, F90/MPI, and HPF implementation
- Reuse of existing parallel problem solving environments and libraries (e.g. POOMA, PLIB)
- Parallel Particle-In-Cell (PIC) approach
- *Particle managers* to minimize communication
- Modern approach: split-operator methods, canonical variables, numerically computed maps for realistic beamline elements,...

Work in progress on other parallel beam dynamics codes:

- LANGEVIN3D: parallel Fokker-Planck solver
- Stochastic integrator for systems w/ multiplicative noise
- Hybrid Langevin/DSMC solver
- C++ time-based solver (not z-based)
- Parallel MaryLie w/ space charge

Parallel Electromagnetic Field Solvers

Omega3P - *3D Parallel Eigensolver for calculating resonant modes of cavities*

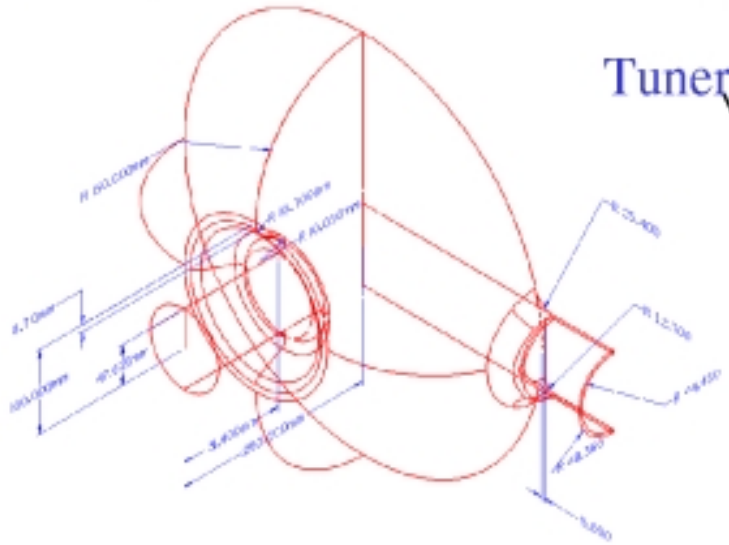
Tau3P - *3D Parallel Time-Domain Solver to simulate transmission structures*

Solver features:

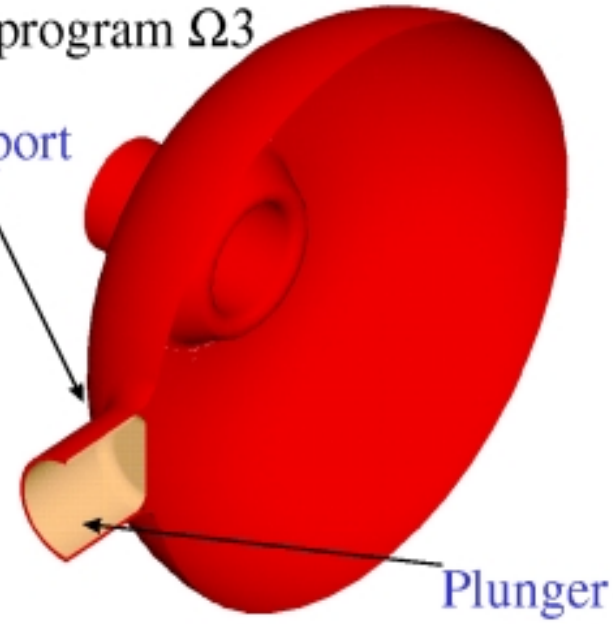
- C++ implementation w/ MPI
- Reuse of existing parallel libraries (e.g. ParMETIS, AZTEC)
- Unstructured grid for conformal meshes (e.g. FE formulation)
- New solver algorithms for fast convergence & scalability
- Adaptive refinement to improve accuracy & performance
- Variety of approaches: 3D Finite Element w/ linear and quadratic basis functions (Omega3P eigensolver); unstructured Yee grid (Tau3P time-domain solver)

Parameterized solid model

– Analyze cavity with tuner using program Ω3



Engineering drawing



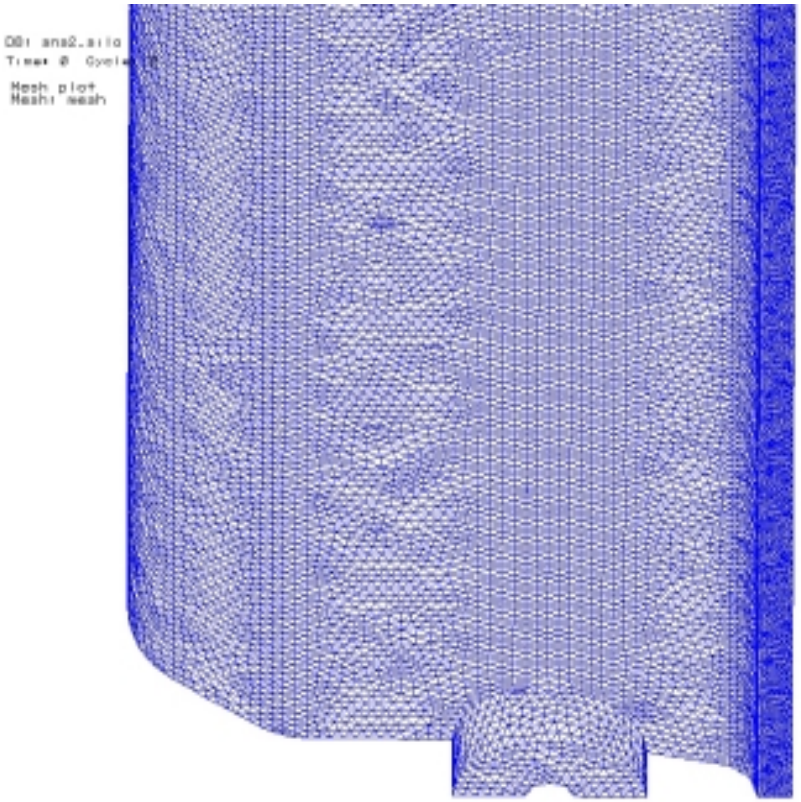
Parametric Solid model

- Interface to a variational solid modeler EMS/Intergraph
- Can resolve necessary features (e.g., small distance between the tuner port and the plunger)
- Easy to change plunger position

Mesh Generation

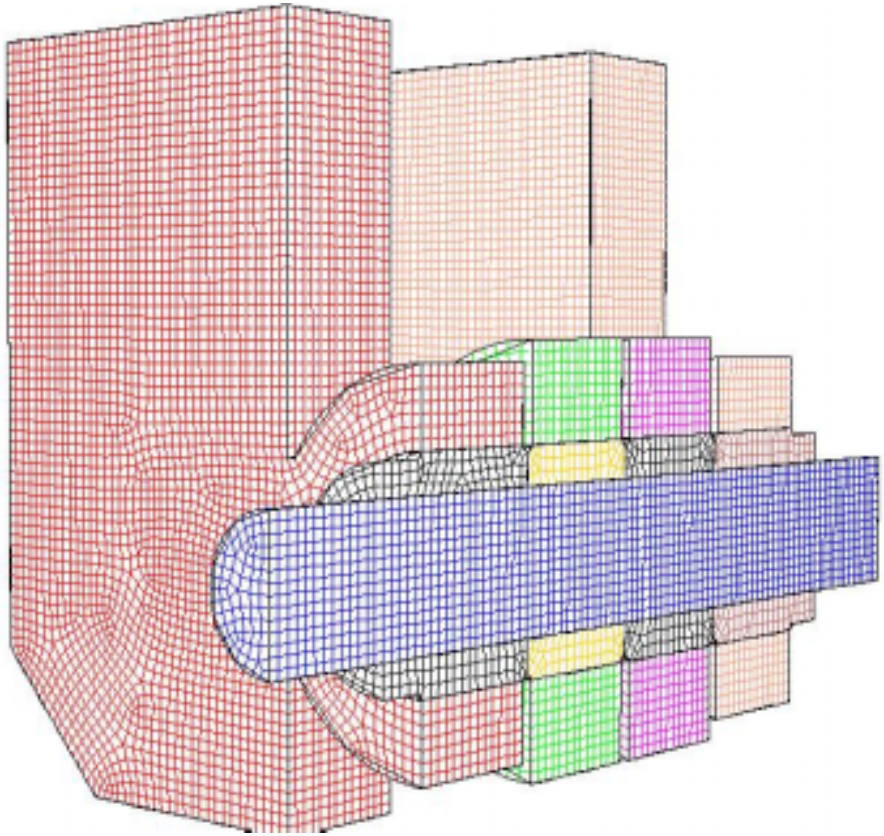
Size of meshes limited by workstation memory - *Parallel Mesh Generation*

Tetrahedral mesh for ***Omega3P*** from ***SIMAIL*** (Simulog)



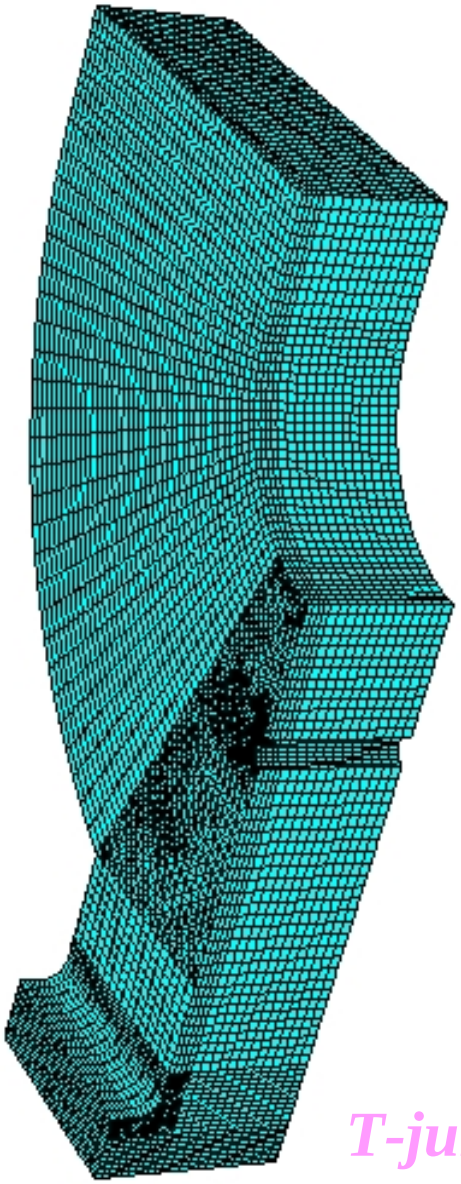
RFQ Cavity for SNS

Hexahedral mesh for ***Tau3P*** from ***CUBIT*** (Sandia)



Input Coupler for NLC

Mesh Generation



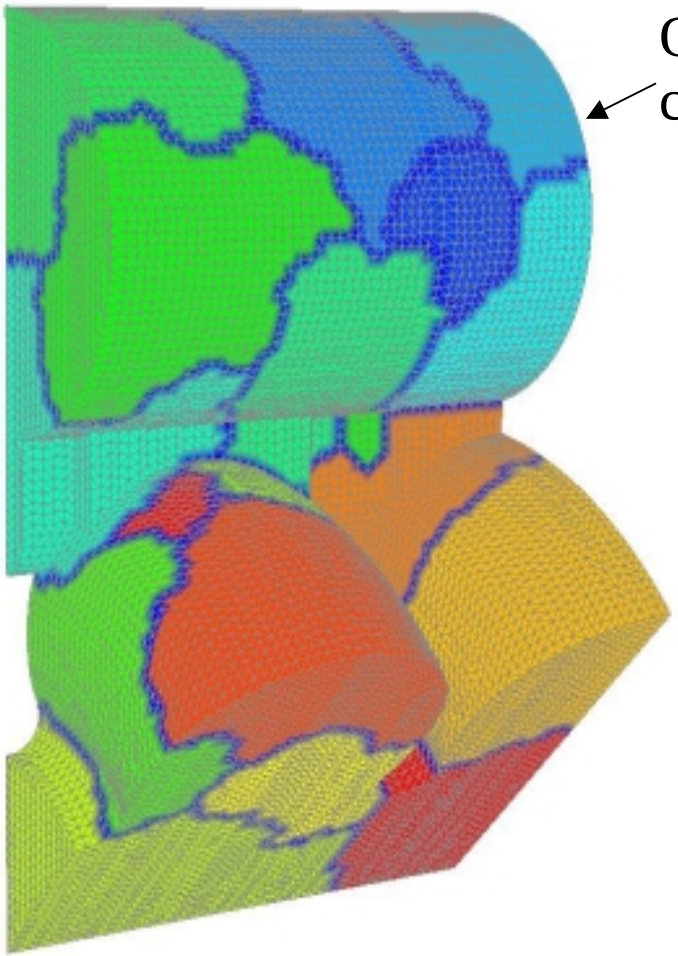
T-junction at X-Band

- ***Tau3P*** interfaces to any mesh generator such as ***SIMAIL*** & ***CUBIT***
- Presently supports hexahedral and pentahedral elements
- Maintaining reasonable element aspect ratio is key to time step and stability issue
- Predominantly uniform elements preferred for parallel efficiency

Domain Decomposition

Partitioning to optimize load balance & minimize communication

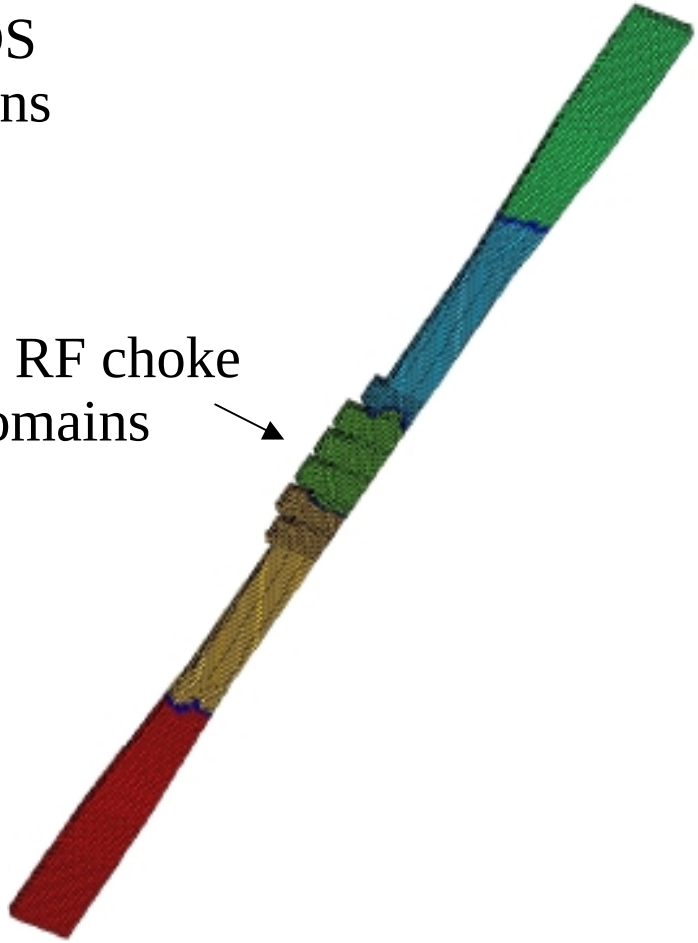
Omega3P



Octant of 1.5 DDS cells in 16 domains

Tau3P

Quarter of RF choke in 4 domains



Simulation Examples

- IMPACT
- Omega3P
- Tau3P

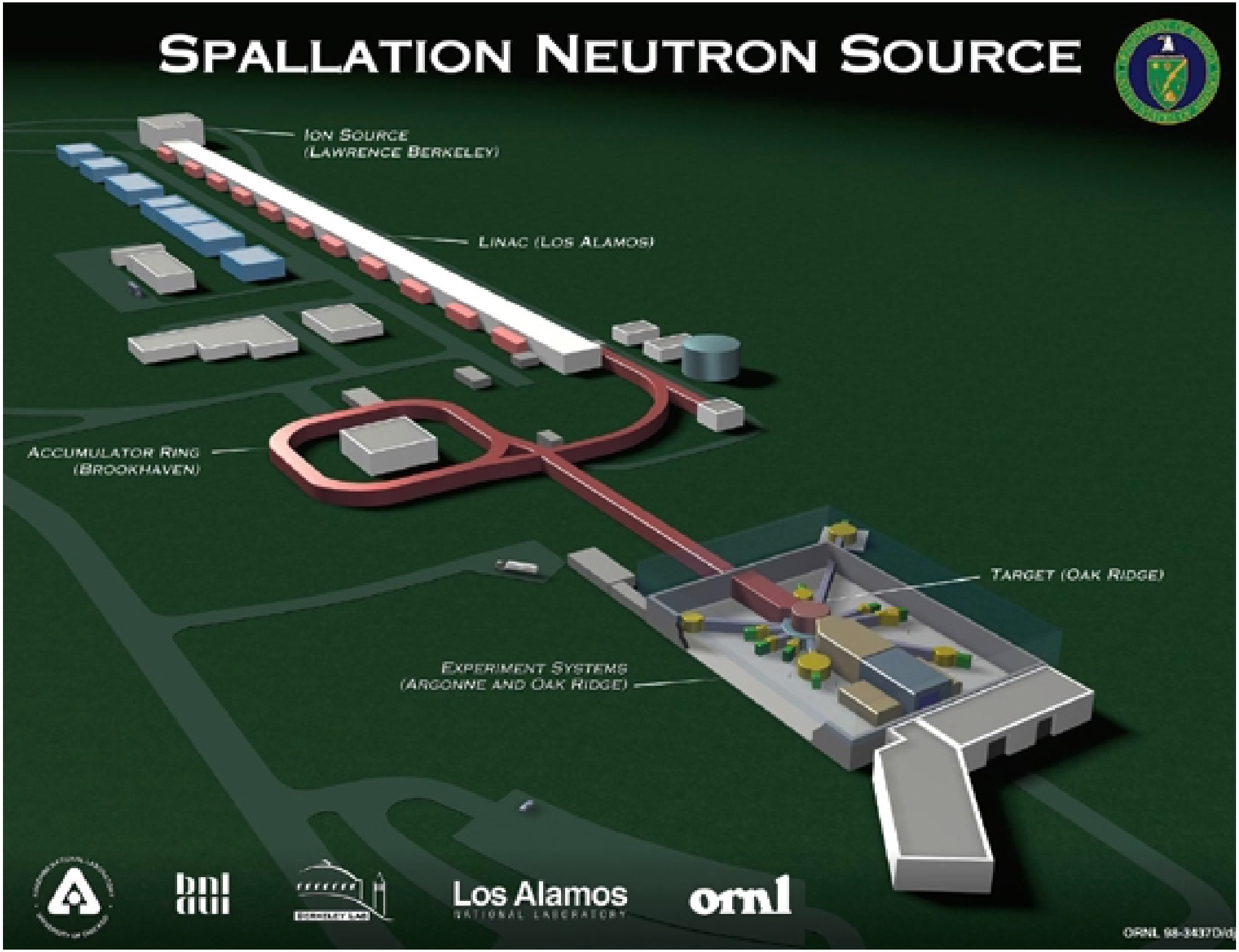
Large-Scale SNS Simulations using IMPACT

- 100M particle simulations require ~5 hours on 256 processors
- Simulations have been performed with > 500M particles
  - Approaching real-world number of particles (900M for SNS)
- Large scale essential for predicting maximum particle amplitude

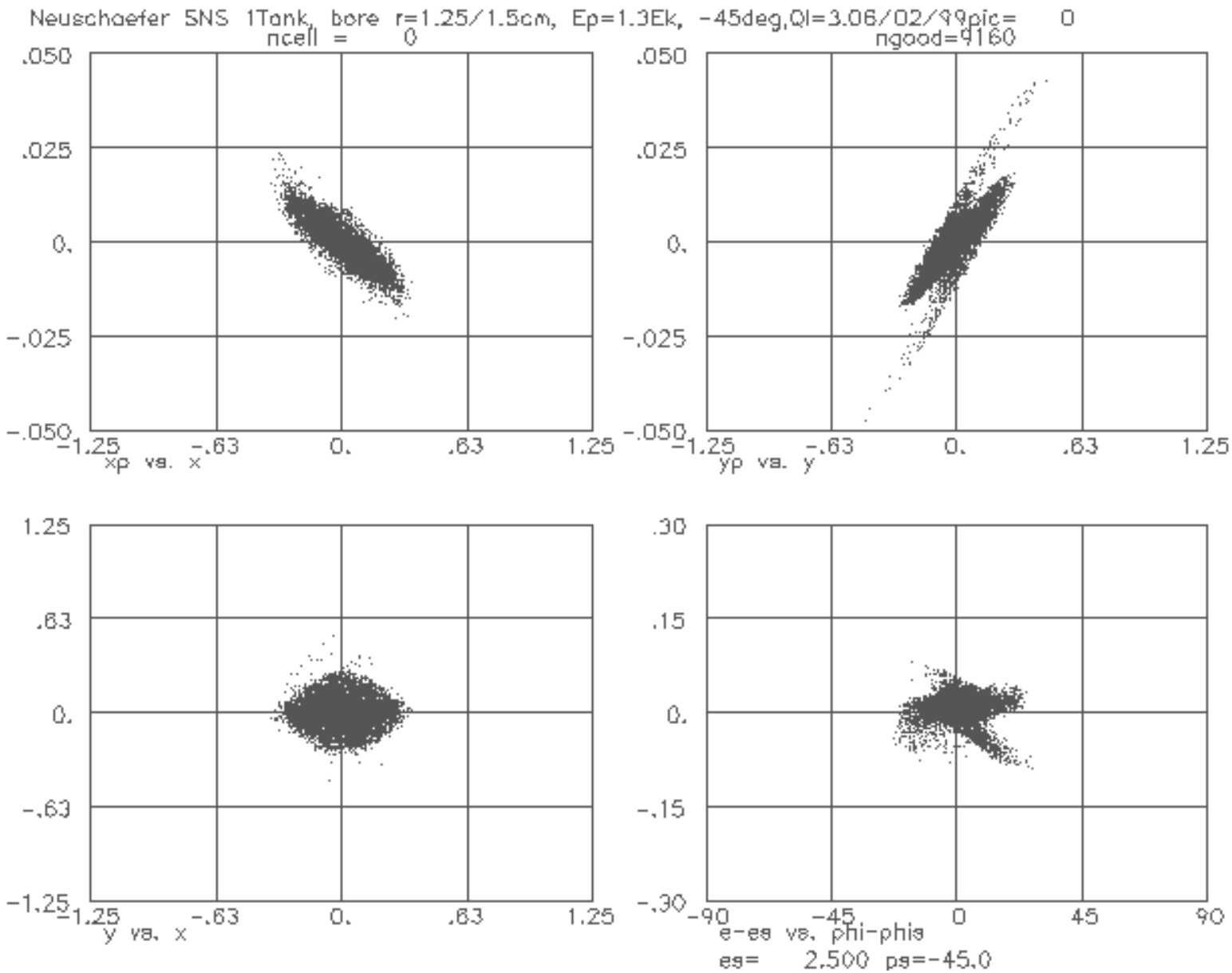
Compared with a 100 million particle, 3D IMPACT simulation on 256 processors, a 1 million particle, 2D simulation using legacy code on a PC is 1/100 the size and require 10x longer (1 weekend) to execute.

Parallel computing results in a ***3 order-of-magnitude*** increase in simulation capability

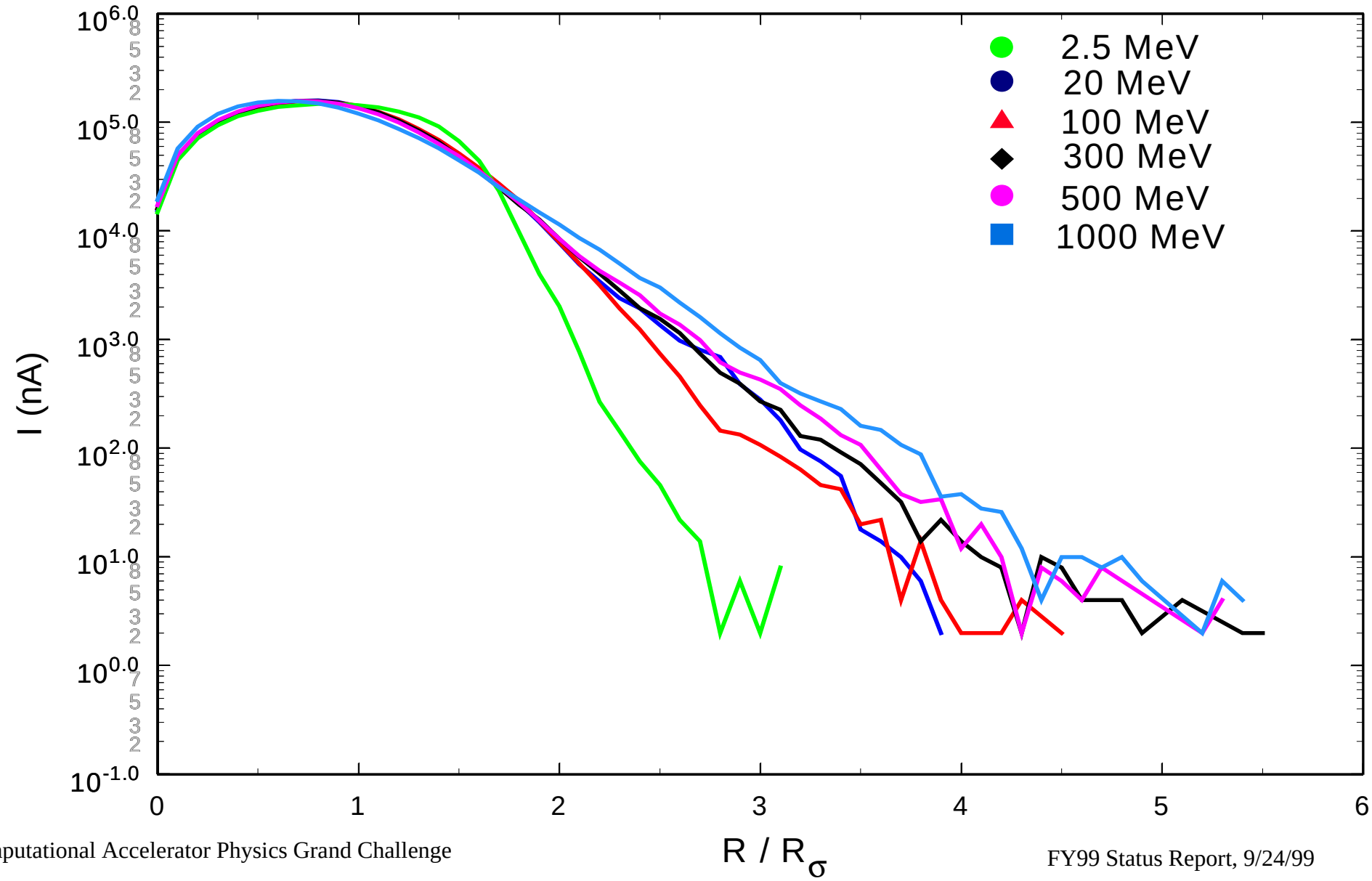
Spallation Neutron Source



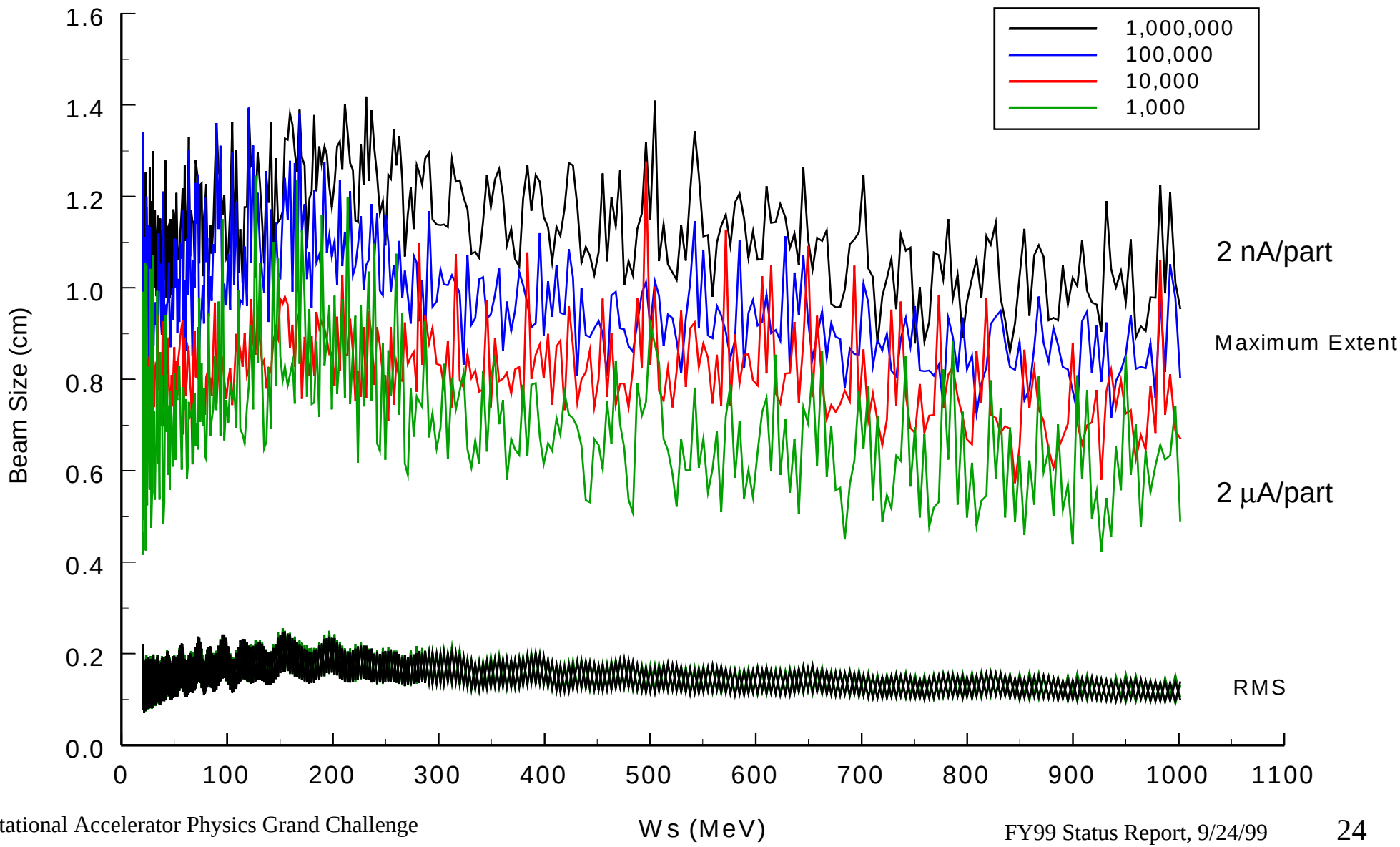
Phase Space Projections of DTL Injected Beam

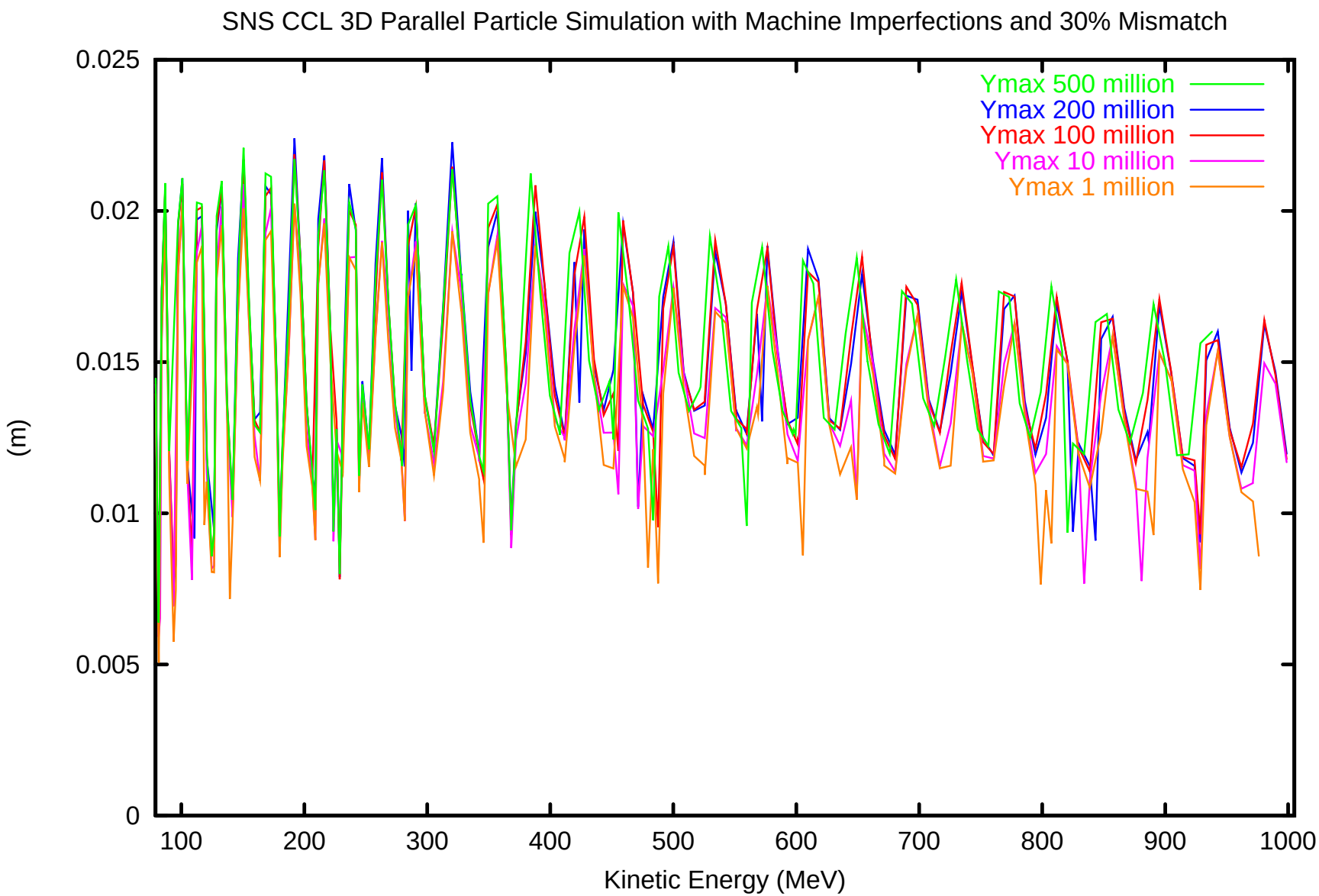


Beam Distribution Evolution: 10,000 particle simulation Including Machine Imperfections, No Mismatch



CCDTL/CCL Beam Profile
With Machine Imperfections, No Mismatch

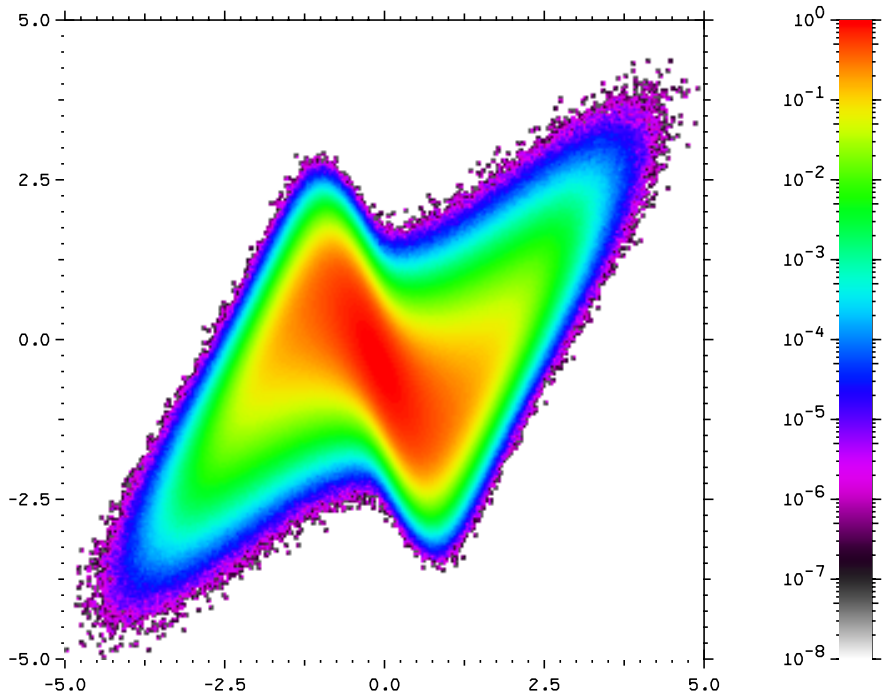




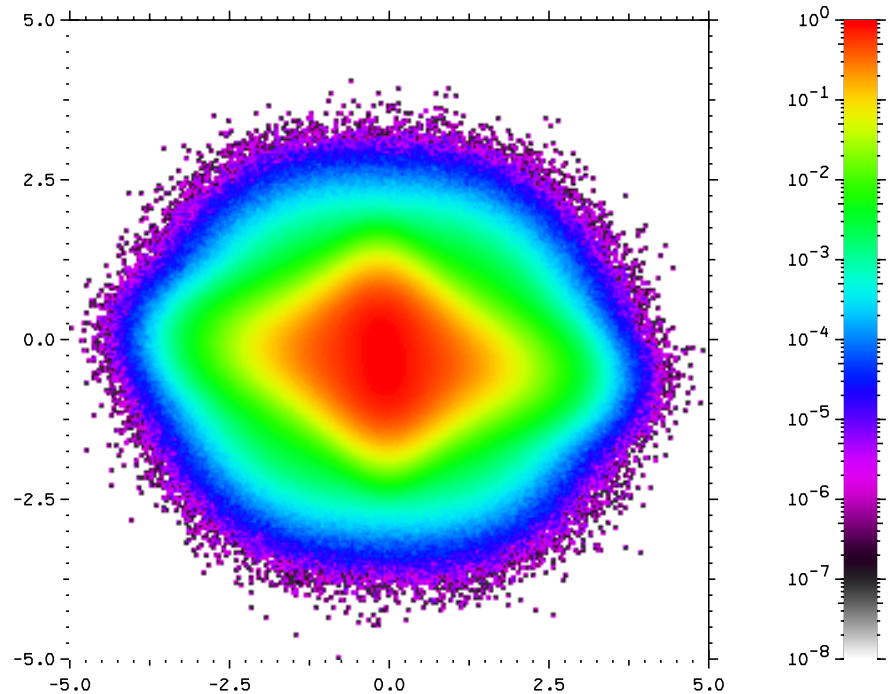
Maximum particle amplitude in the SNS linac with varying # of simulation particles, run on the ACL Nirvana system using 32-1024 processors

Plots of "Integrated Density" from a 500 million particle SNS simulation

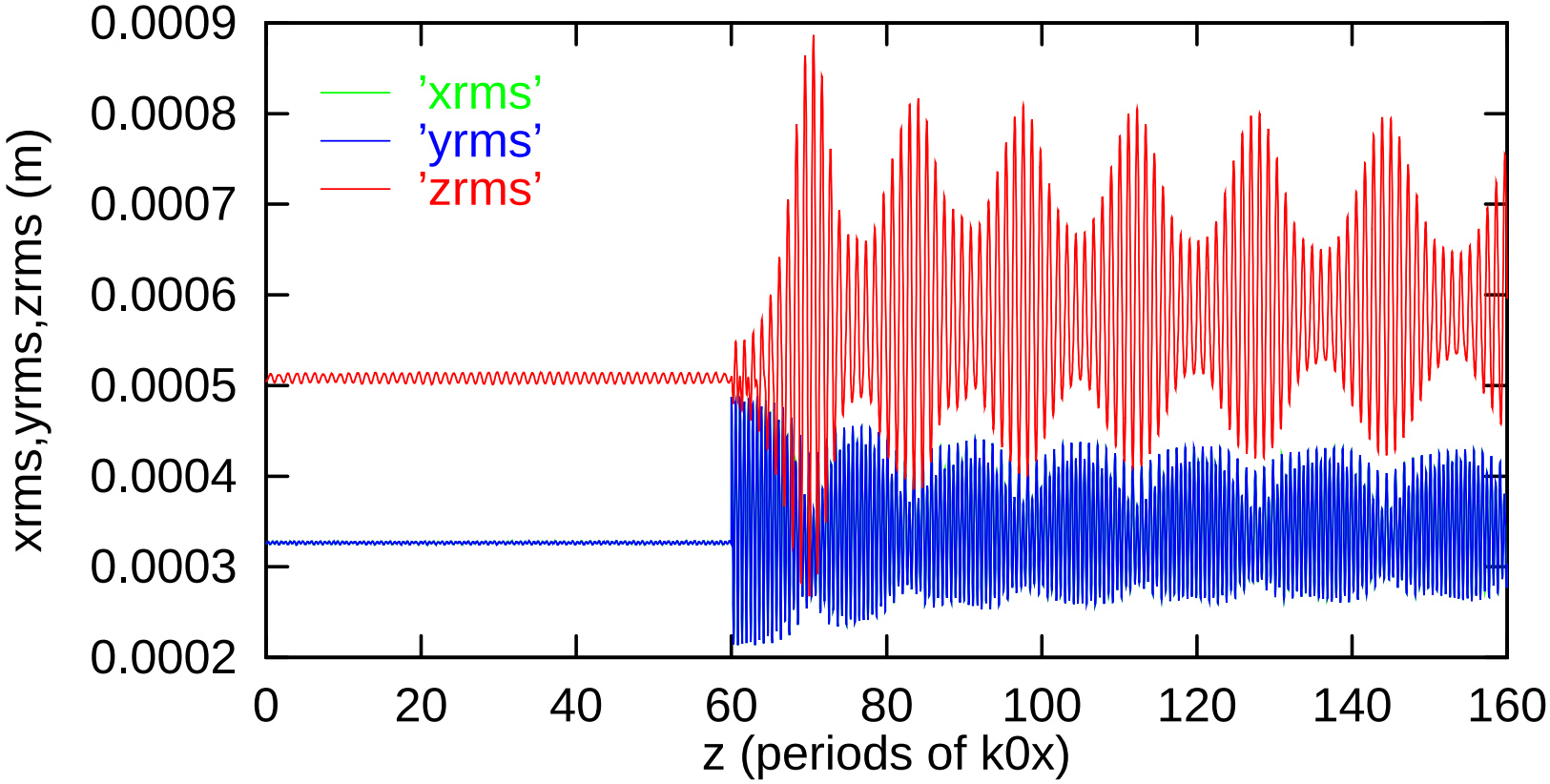
X-P_X Plot



X-Y Plot

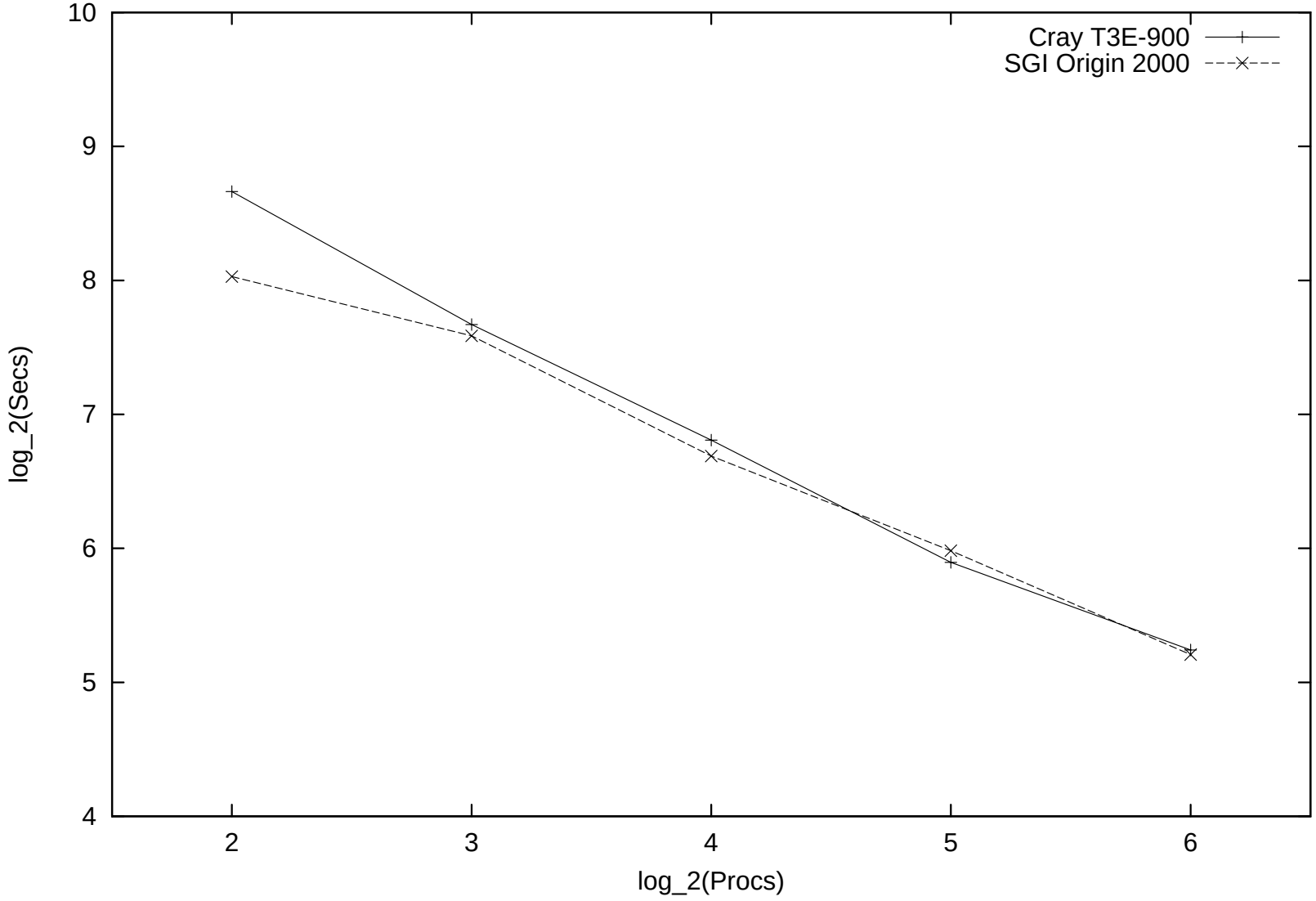


Halo formation due to longitudinal/transverse coupling

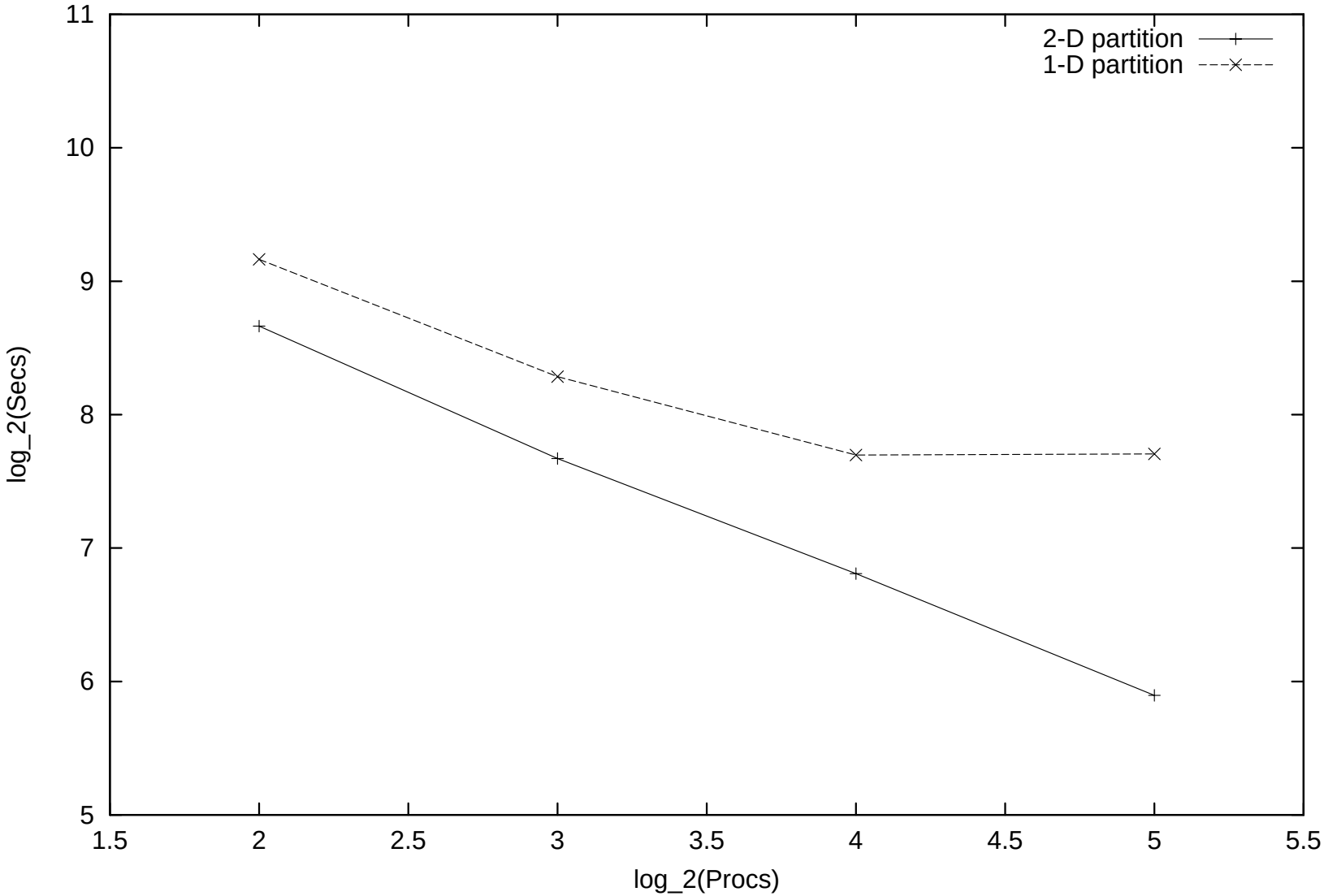


Output from an IMPACT simulation performed on the T3E showing excitation of a longitudinal mode by an initial transverse excitation applied at z=60. The simulation results validate analytic calculations, which predict strong coupling at the parameters chosen, for which the transverse eigenfrequency is 2x the longitudinal eigenfrequency. [From "Coherent Coupling Criterion for Three-Dimensional Halo Formation," I. Hofmann, J. Qiang, and R. Ryne, 1999 Particle Accelerator Conference]

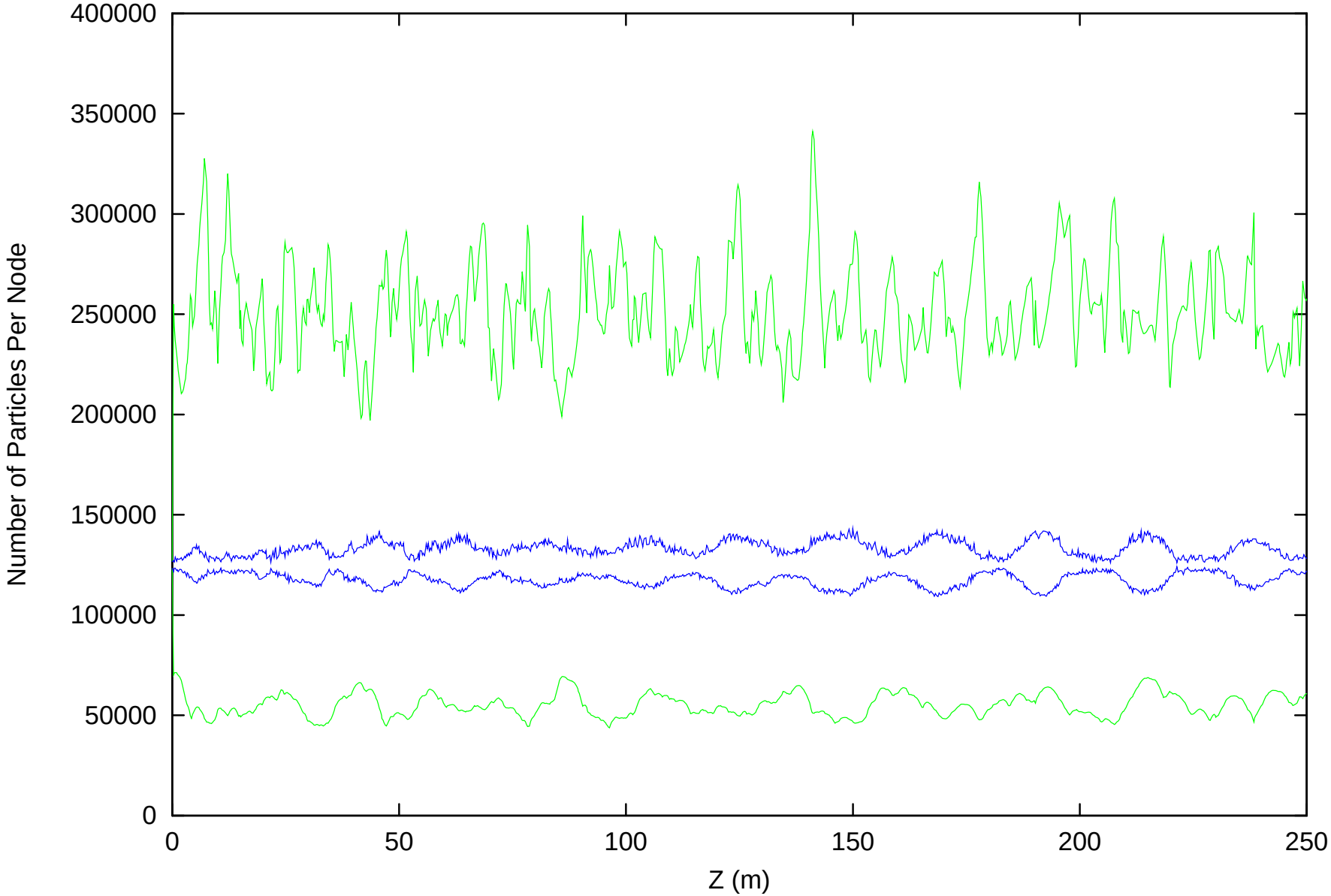
IMPACT scaling with # of Processors



IMPACT Scaling for different domain decomposition



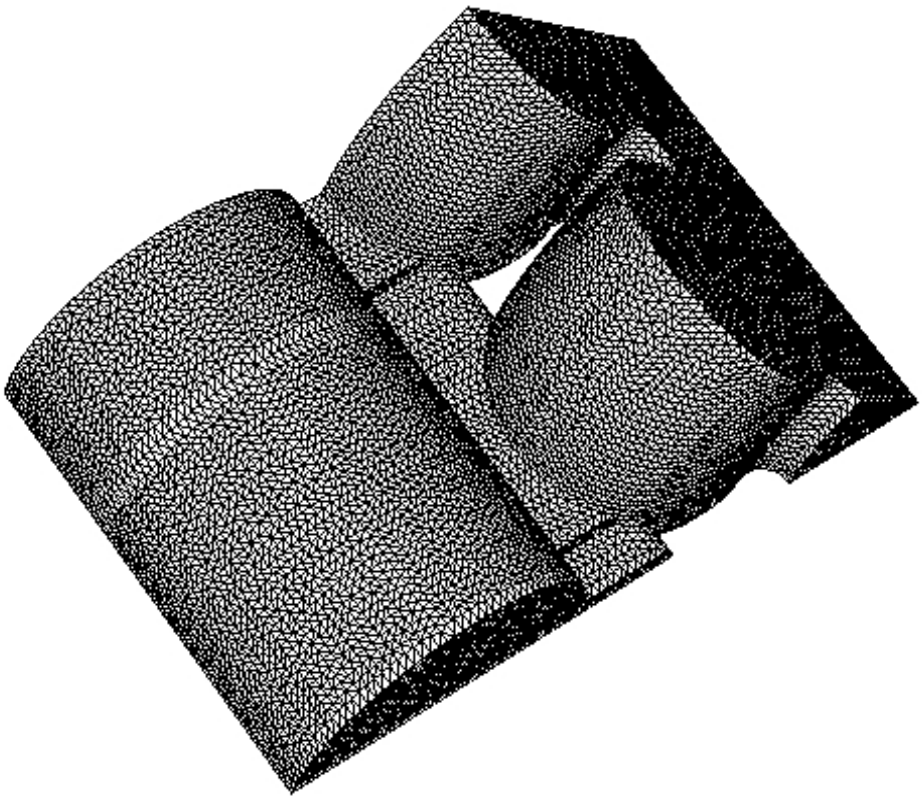
IMPACT: Success of Dynamic Load Balancing



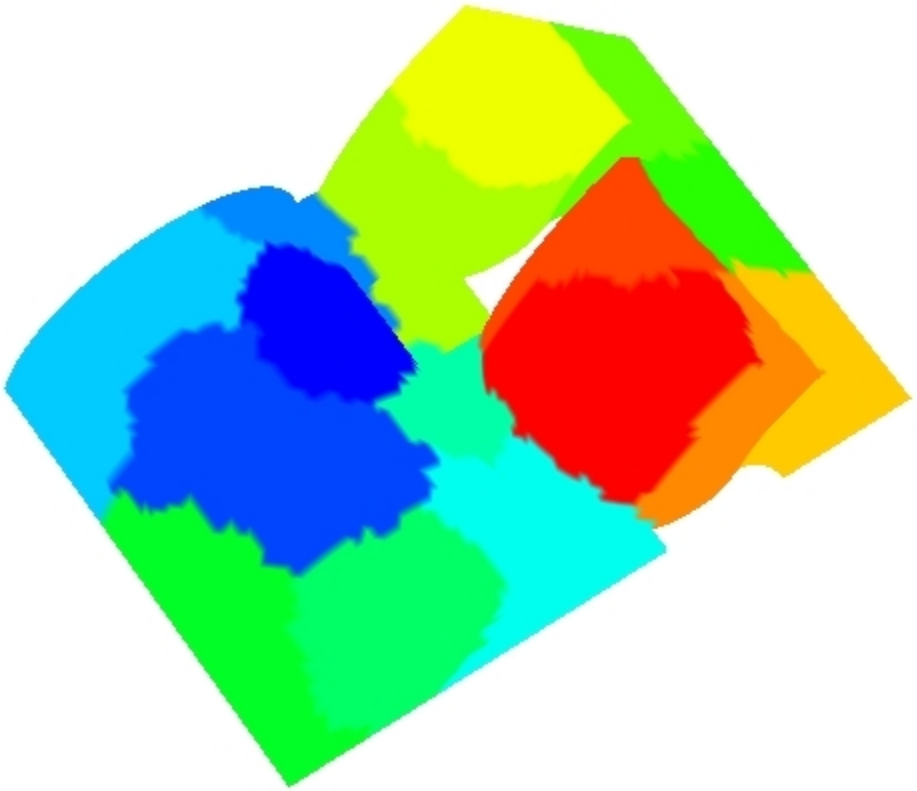
Omega3P Example

- Damped Detuned Structure (DDS) cell design

DDS Cell Domain Decomposition

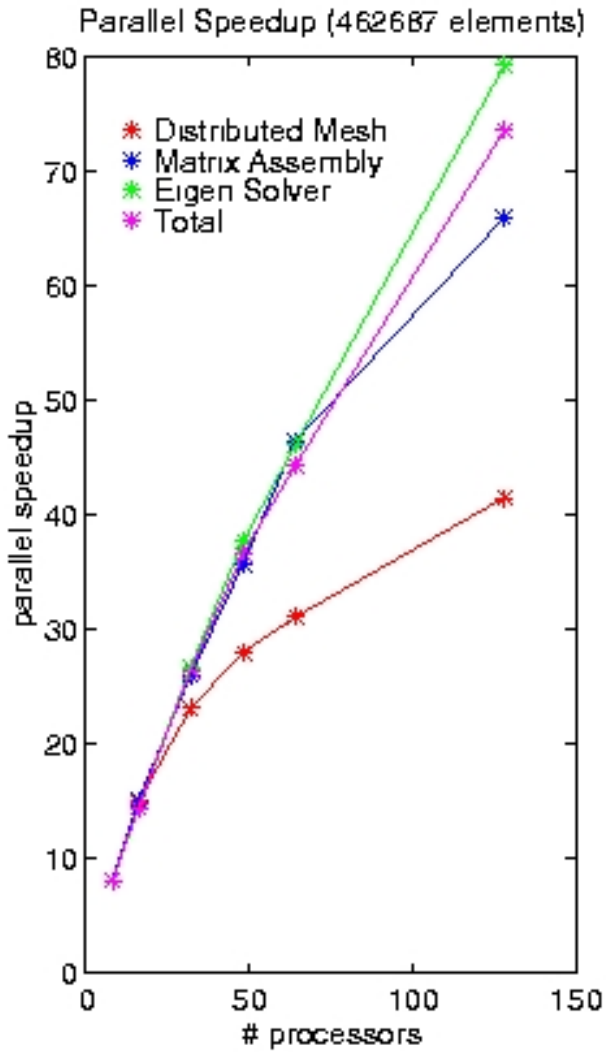


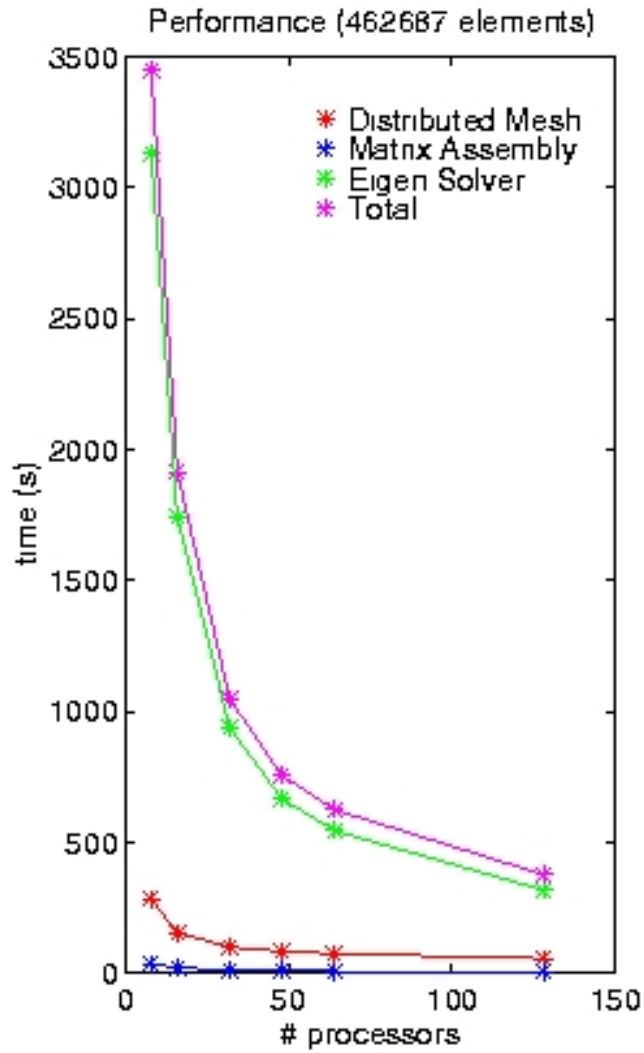
Mesh (with 462687 Elements)
of one octant of 1.5 DDS Cells.



The same mesh partitioned
into 16 (roughly equal) pieces

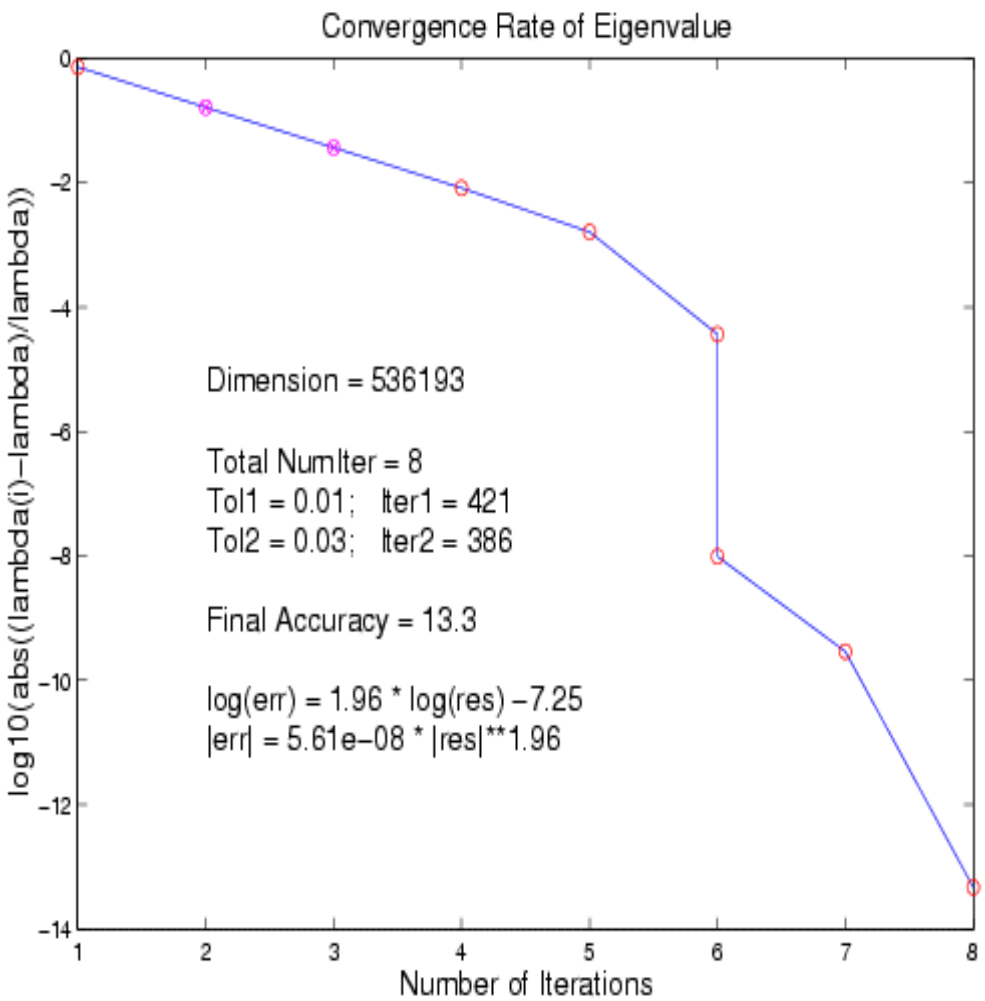
Omega3P Scaling Study

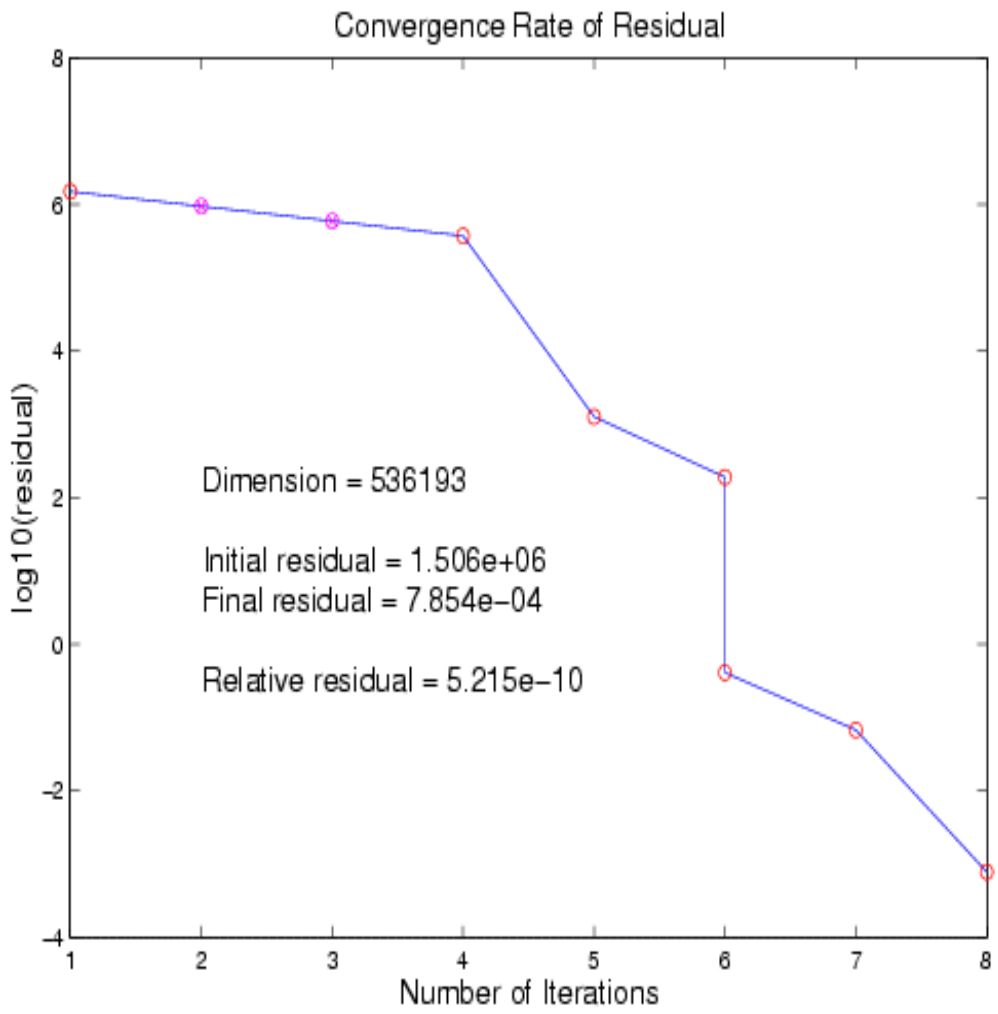




Performance on the NERSC T3E as a function of # of processors

Parallel Eigensolver





Omega3P *convergence on DDS example with 500K DOF's*

Tau3P Examples

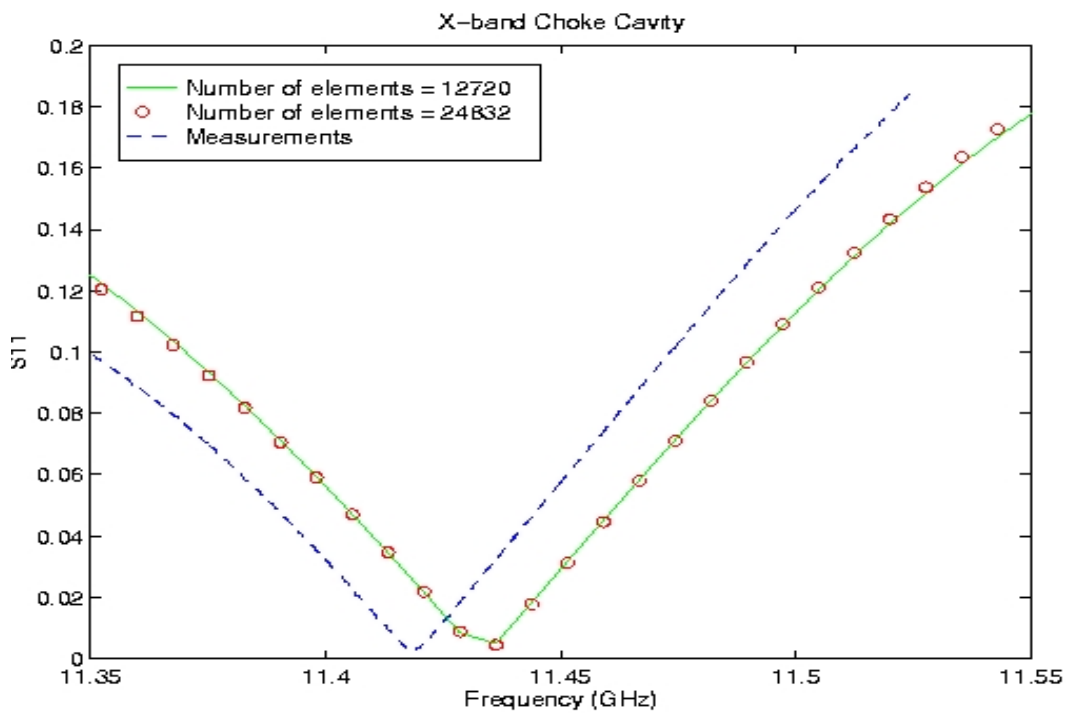
- Rf choke
- X-band NLC input coupler

S-Parameter Broad-Band

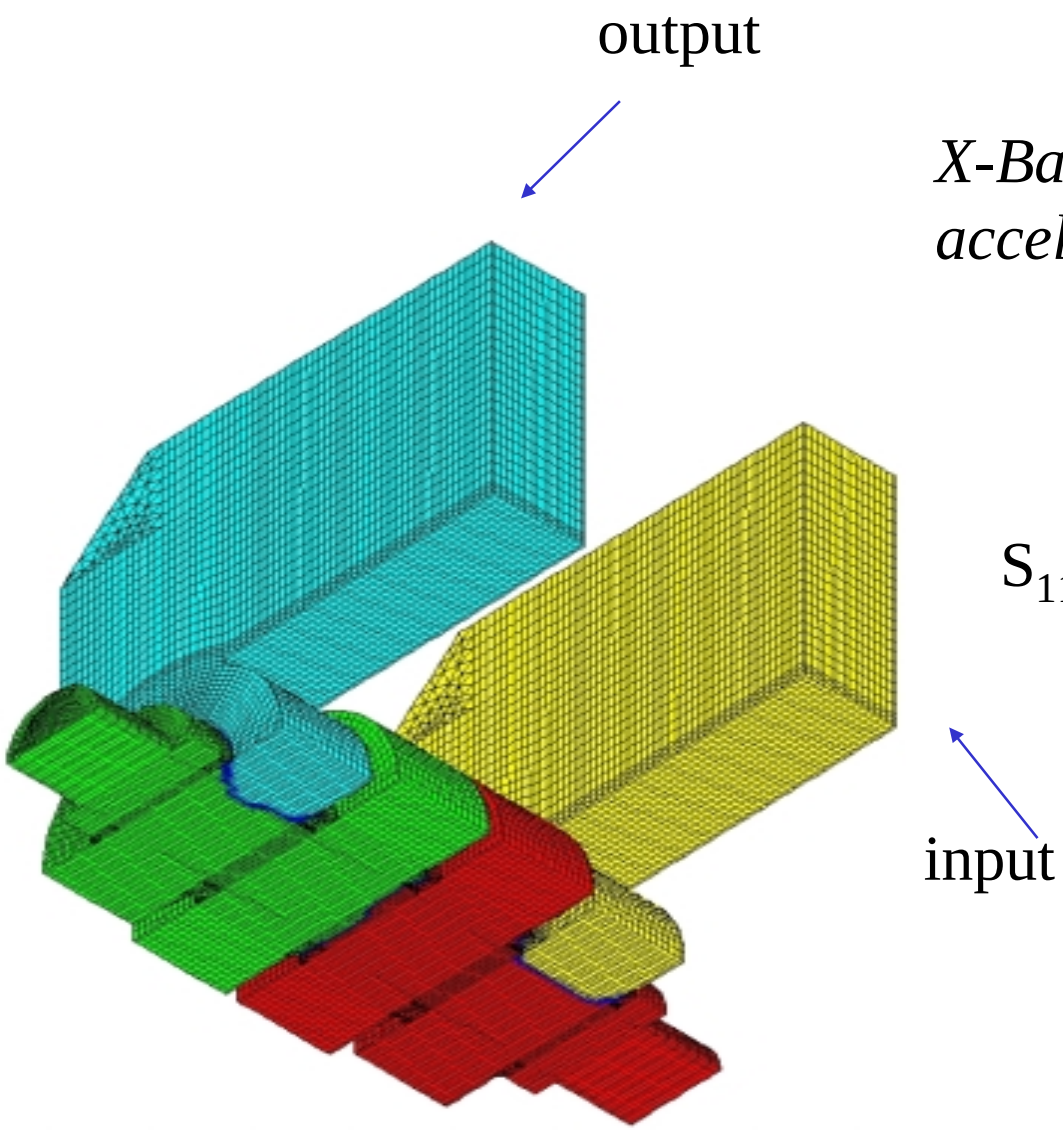
X-Band RF choke-cavity for pulse heating experiments

Long taper not modeled effectively on structured grid

Measured data - D. Pritzkau



S-Parameter Single-Frequency



X-Band Input Coupler for NLC accelerator section

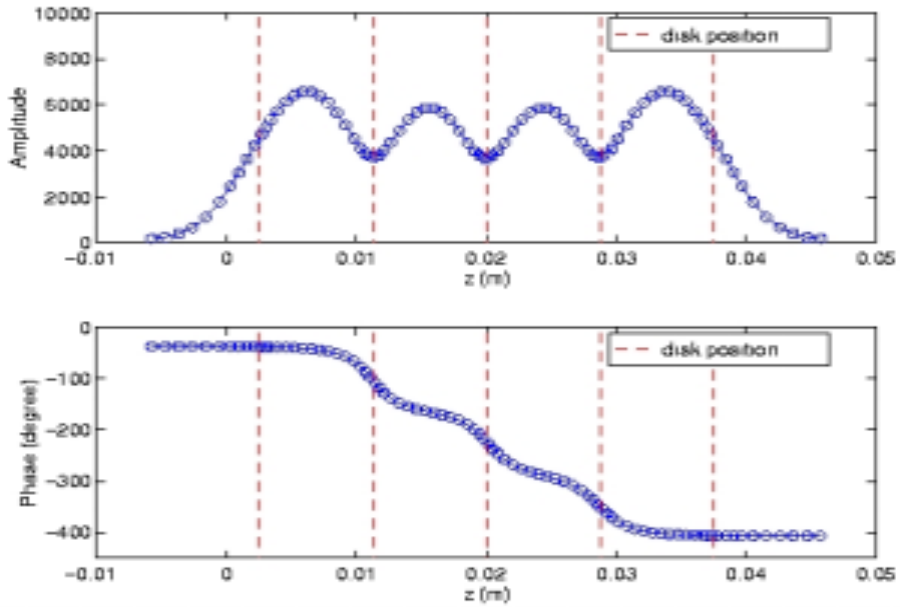
Match:

$S_{11} \sim 0.005$ @ 11.424 GHz

Coupler Fields at Matched Frequency

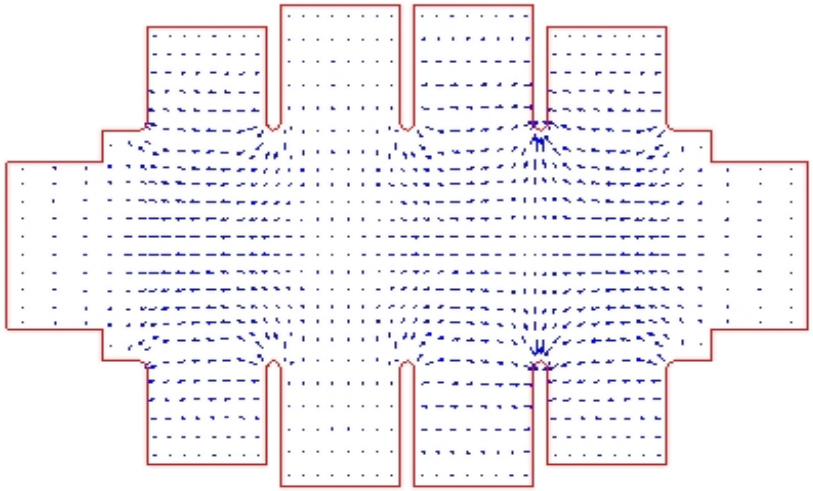
Longitudinal electric field on axis

- *Amplitude: coupler field ~15% higher than structure cell field*
- *Phase: 60° in coupler cell, 120° in structure cell*



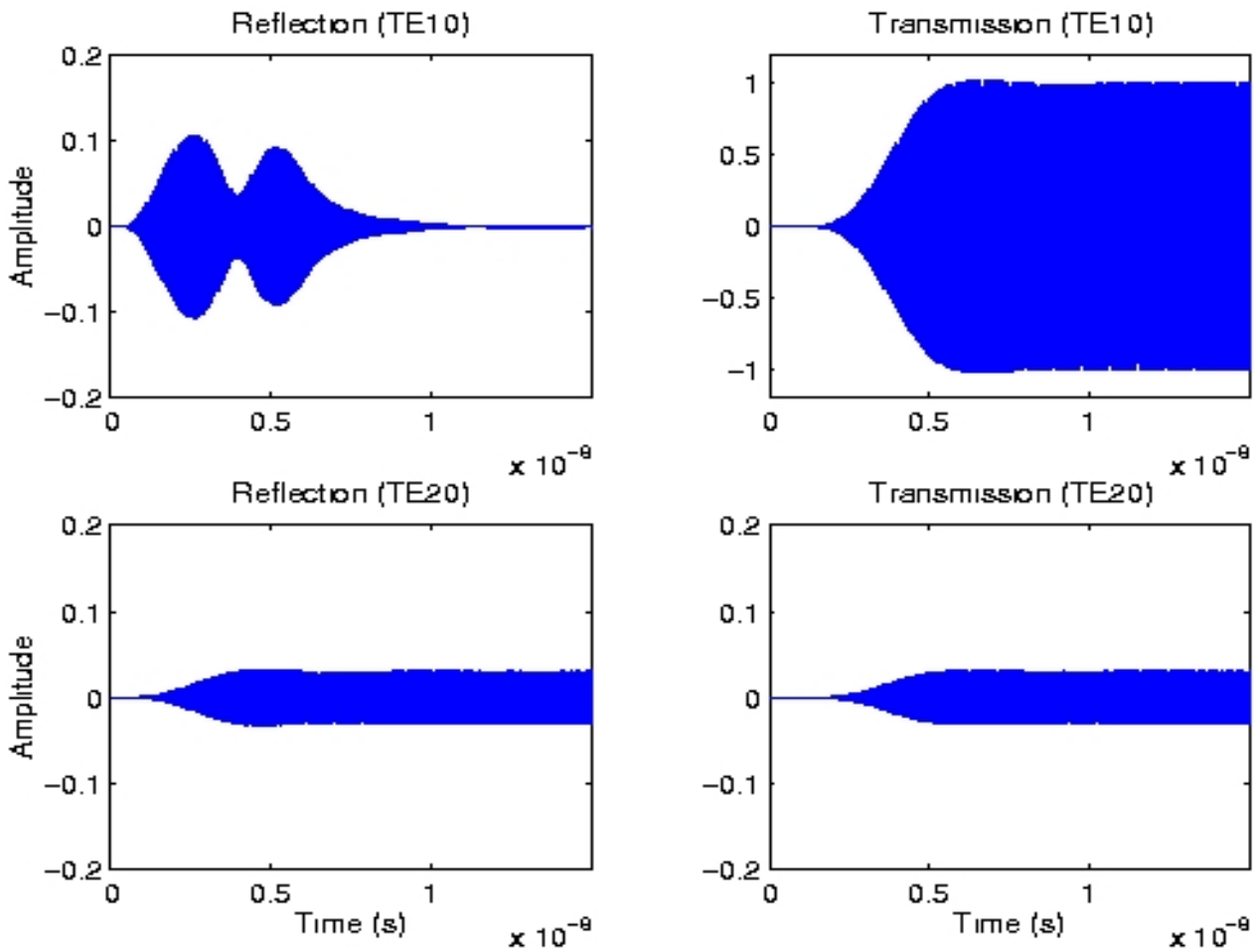
Snapshot of electric field vector at structure x-section

- $2\pi/3$ accelerating mode



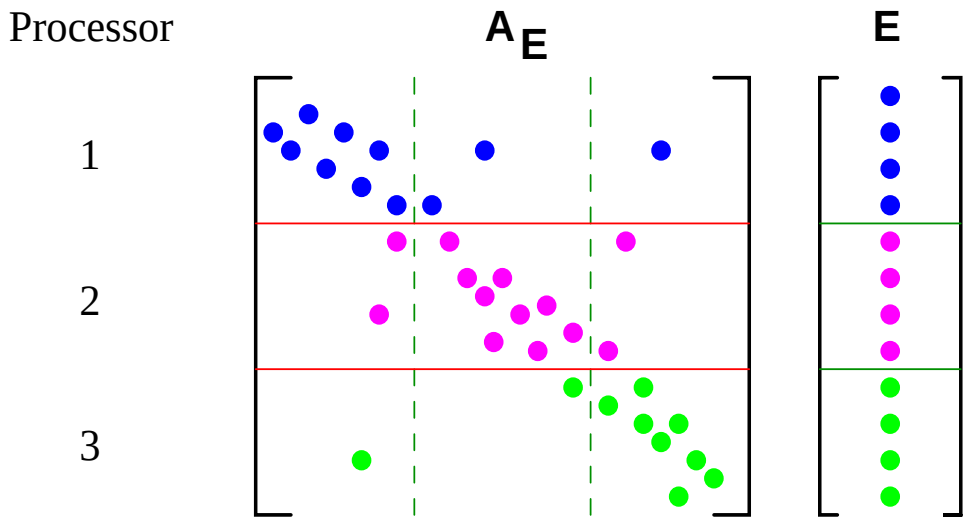
Signals in Input/Output Ports

Input Port Reflections ***Output Port Transmissions***



Parallel Efficiency

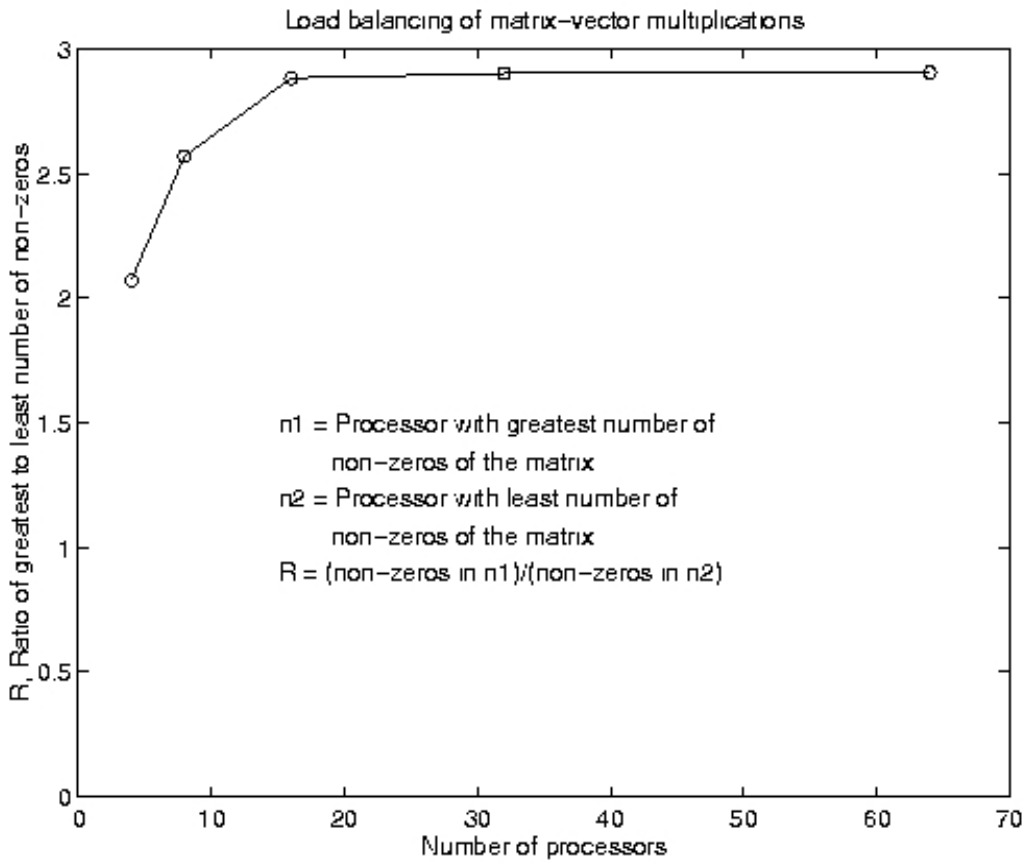
Tau3P parallelization is predominantly on the matrix-vector operations during time advancement. Due to the mixture of orthogonal and non-orthogonal elements on the mesh, the matrix bandwidth (# of non-zeros in a row) varies so that straightforward partitioning on distributed or shared memory machines would result in significant load imbalance.



An improved partitioning scheme is in progress

Load Balancing

RF choke example on SGI/CRAY-T3E at NERSC
- load imbalance for this mesh approaches 3 to 1 as # of processors increases



LARGE SCALE VISUALIZATION

Why do we need large-scale visualization?

- **Huge** data sets
  - e.g. 0.1 - 1 billion particles, 5 - 50 GByte/timestep, TBytes per simulation
- Visualization is needed to ***better understand the physics***
  - provide physical picture of charge distribution
  - show time-evolution of the beam in phase space
  - explore very low density regions (beam halo)

High performance computing and visualization are needed to *reduce, render* & *explore* the data, and *provide guidance* & *validation* in the design process

Successful Approach to Visualizing Beam Dynamics

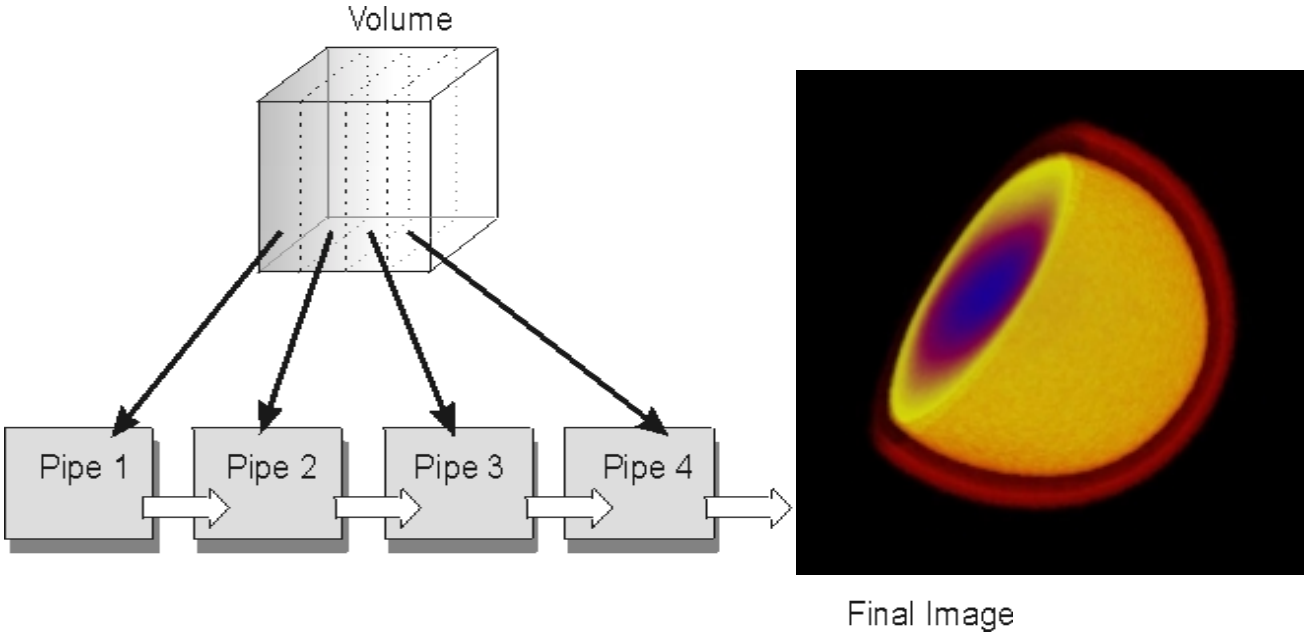
- Relies on volume rendering of density distribution
  - Determine the bounds of the distribution
  - Map particles into voxels of a volume
  - Use hardware-accelerated volume rendering

- Usefulness of this approach:
  - Supports semi-interactive rendering rates (5 frames/sec for 512^3)
  - Provides interactive editing of the transfer function

- Two approaches to supporting larger volumes
  - Make multiple passes, render subsets during each pass
  - Increase available texture memory (multiple IR pipes)

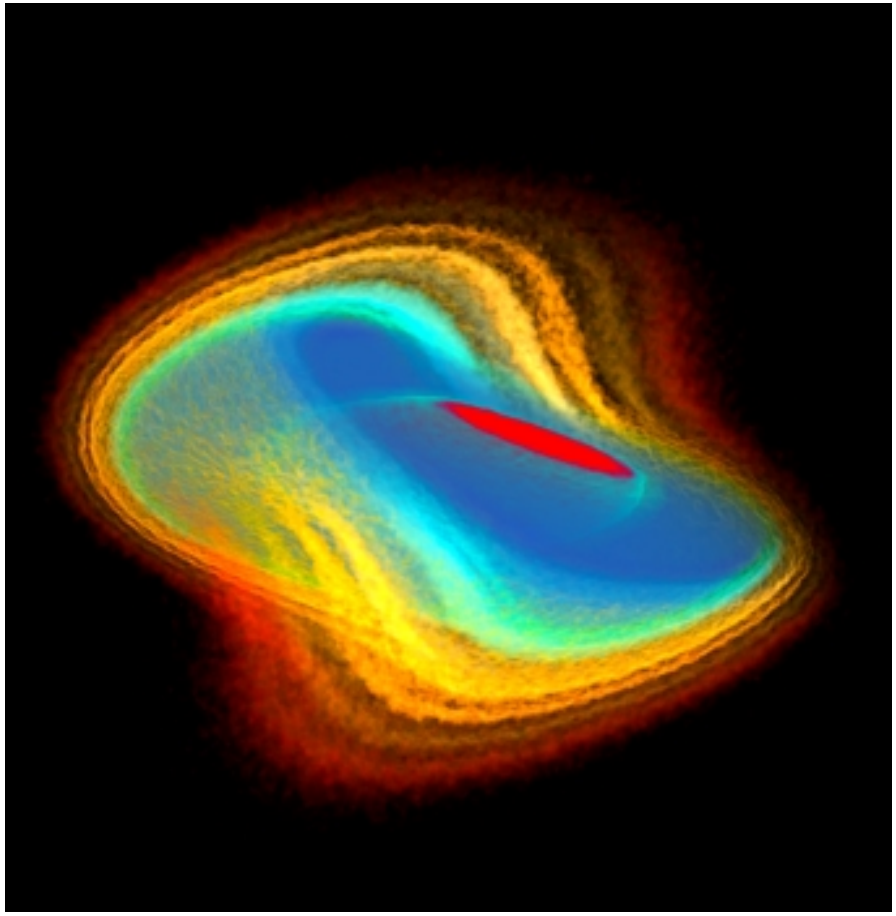
High Performance Volume Rendering

- By equally subdividing a volume and assigning each subset to a pipe we can:
  - Support larger data sets -- texture memory scales with each pipe.
  - Maintain rendering performance -- fill rate scales with each pipe.
  - Disadvantage -- pipeline architecture causes latency to scale with each pipe.

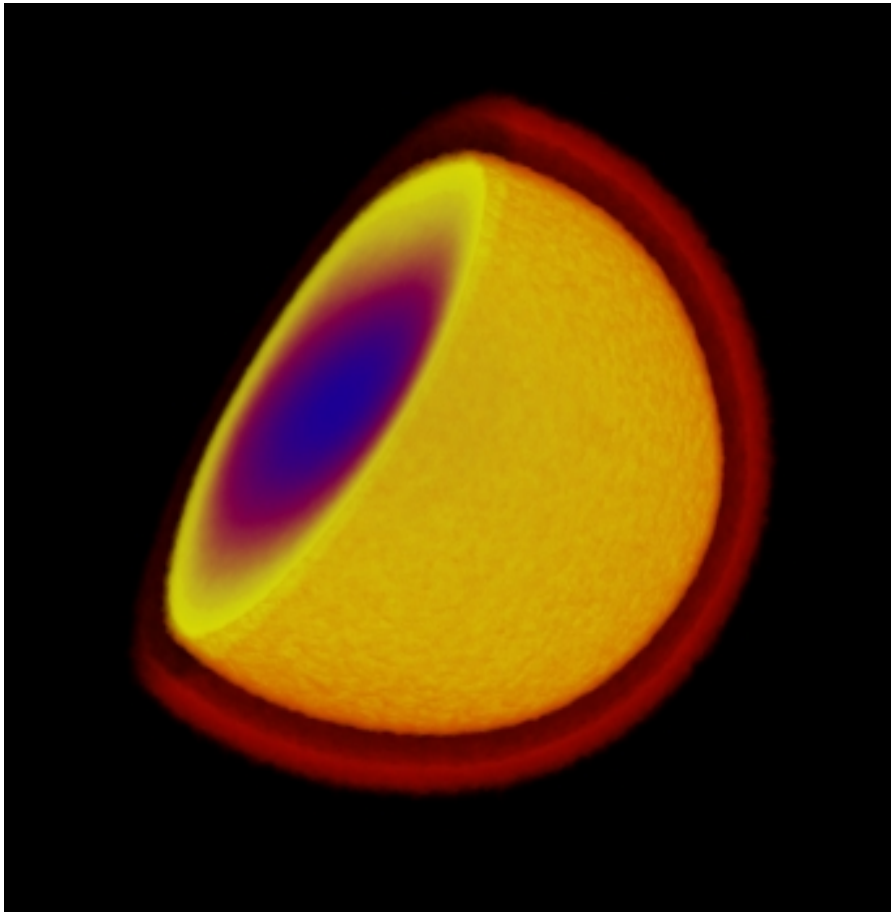


Early work done in collaboration with SGI.

Volume Rendering of APT Simulation Results



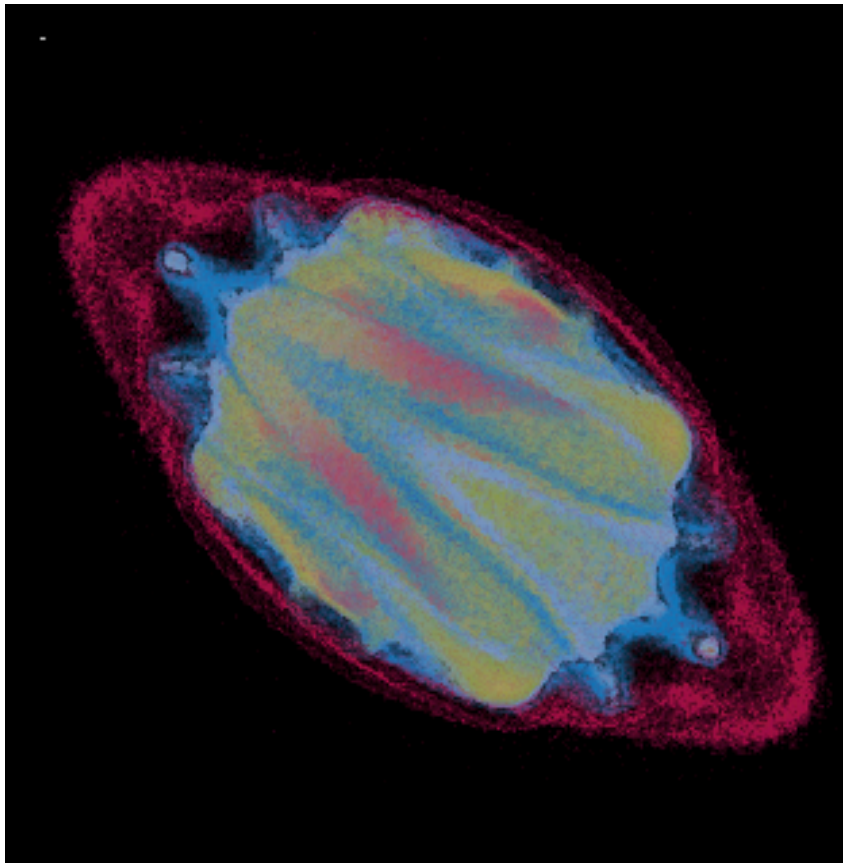
x-p_x-z space



x-y-z space

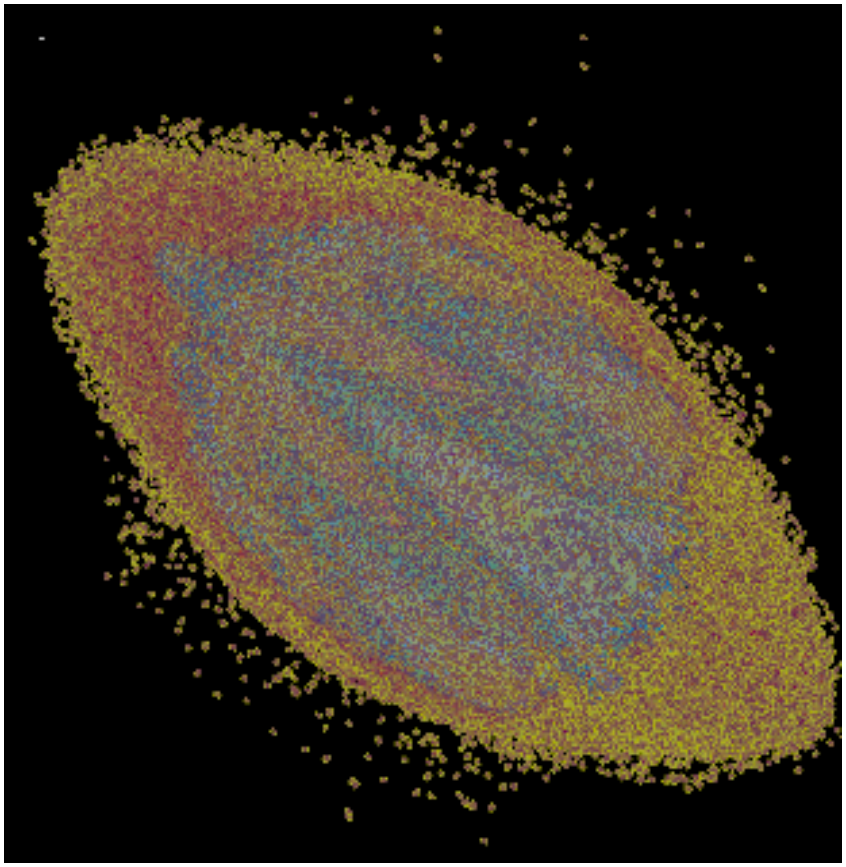
Volume Rendering of SNS Simulation Results

Transparency to see inside volume



x-p_x-z space

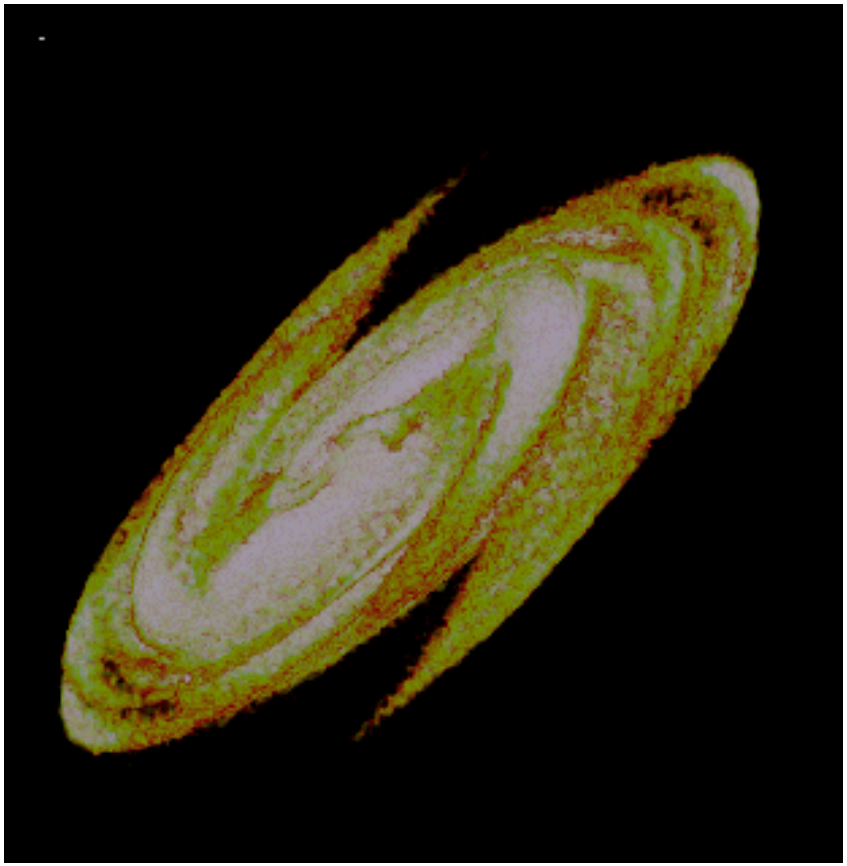
Opacity to accentuate halo



x-p_x-z space

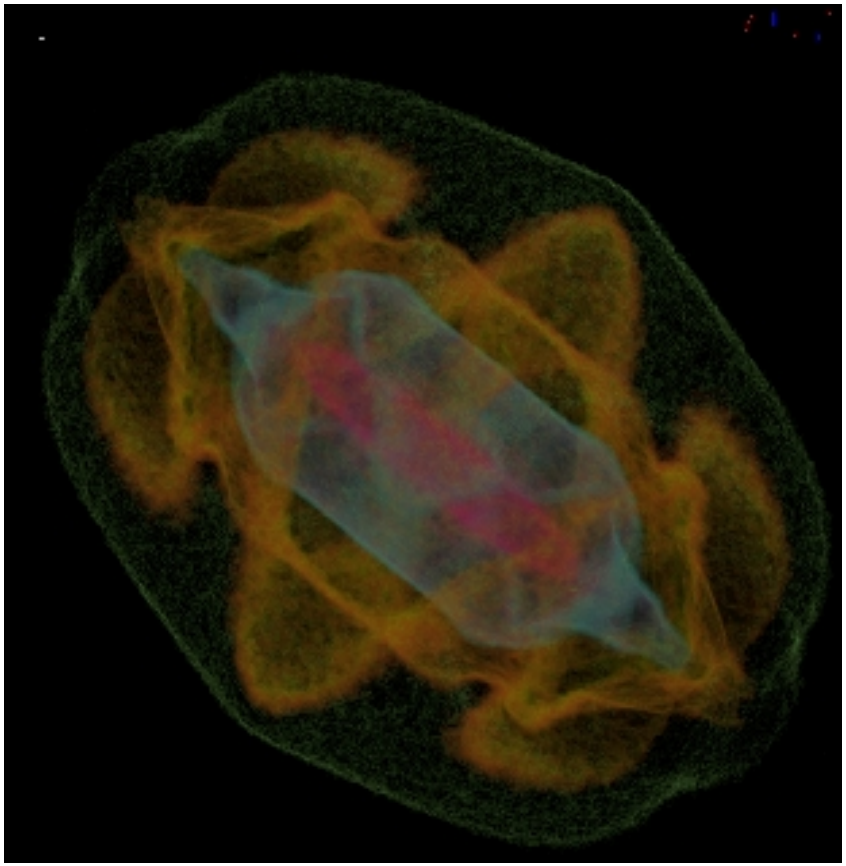
Volume Rendering of SNS Simulation Results

Oriented to exhibit x-p_x space



x-p_x-z space

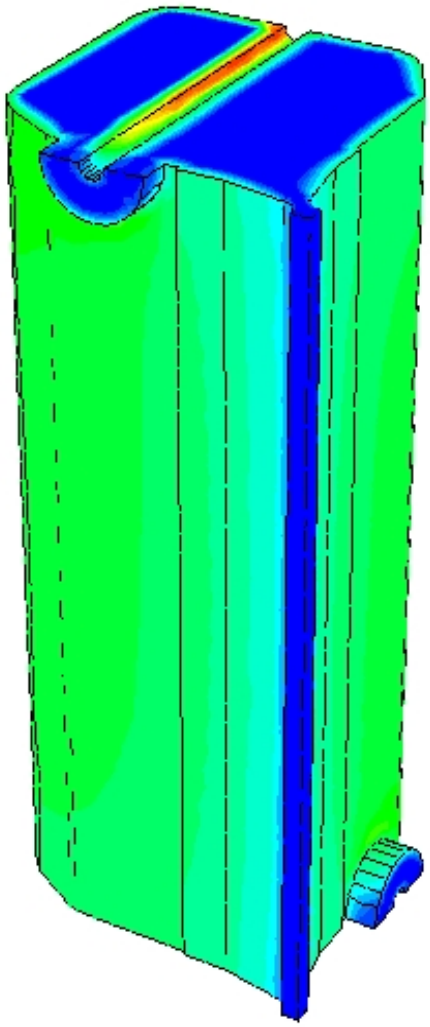
Alpha & color maps set to show 4 isosurfaces



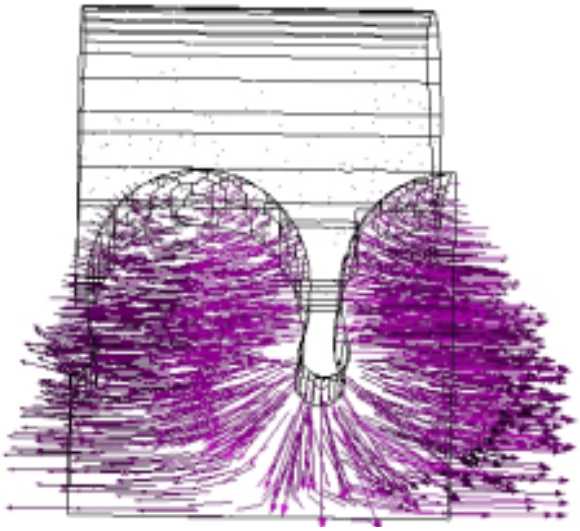
x-p_x-z space

Visualization of Electromagnetics Results

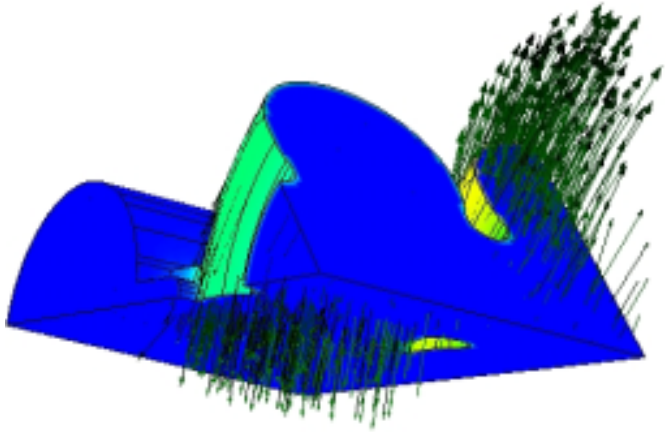
Parallel Rendering will be needed with LARGE data sets



MODULE F
(INRIA)



MESHTV
(LLNL)



Other Visualization Activities

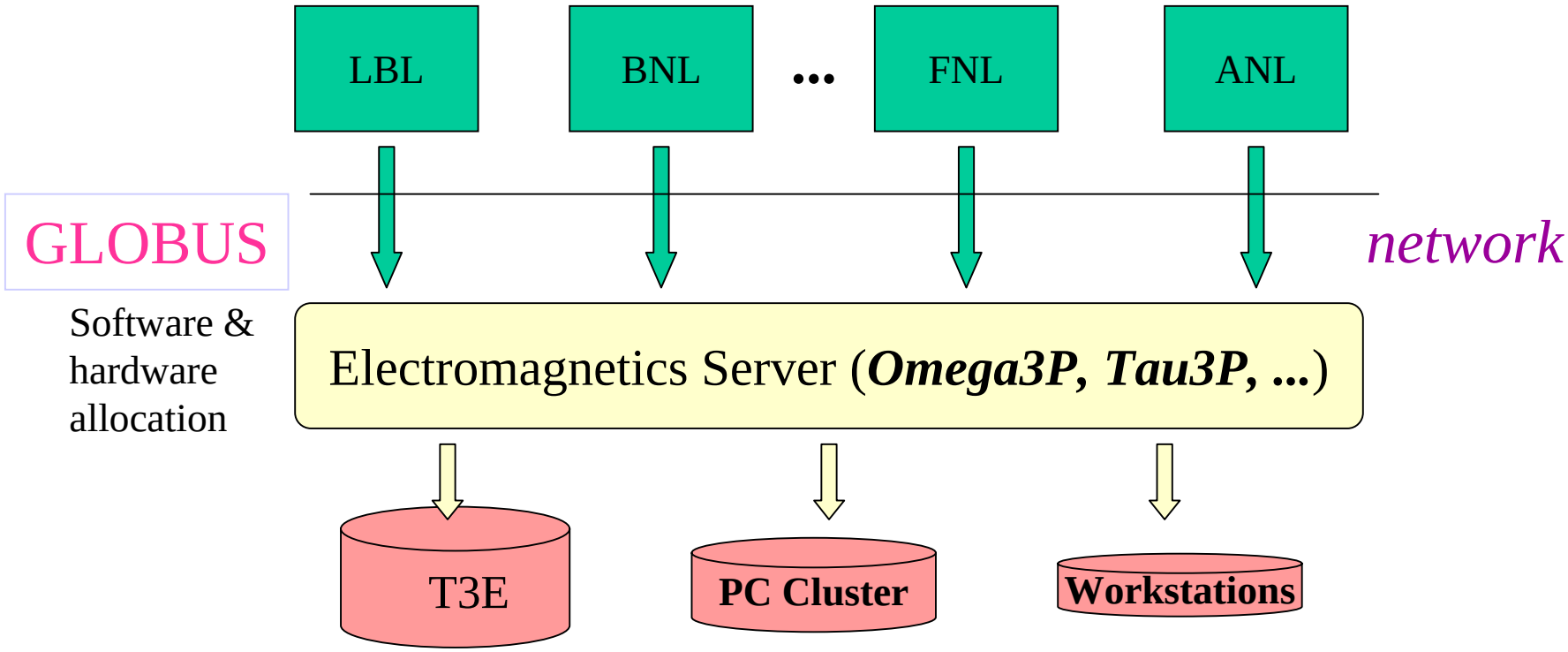
- Visualization Toolkit
  - extending serial implementation to support parallel and distributed visualization computations
    - data, pipeline and task parallelism
    - shared and distributed memory implementation
- Next Generation Internet
  - Corridor One
    - LANL, ANL, LBNL, Illinois, Princeton and Utah
    - Focus: Using NGI technologies to enable scientific visualization and large-scale data understanding at a distance

Accelerator Grand Challenge will be used as an Application Driver

Capability Sharing

Support DOE Labs in designing next-generation accelerators
(NLC, SNS, LCLS, Muon Collider, Light Sources ……)

"Client/Server Model with GUI front end" - NERSC, ANL & STAR Inc.



34-node PC Cluster @ SLAC

Omega3P running on cluster using MPI

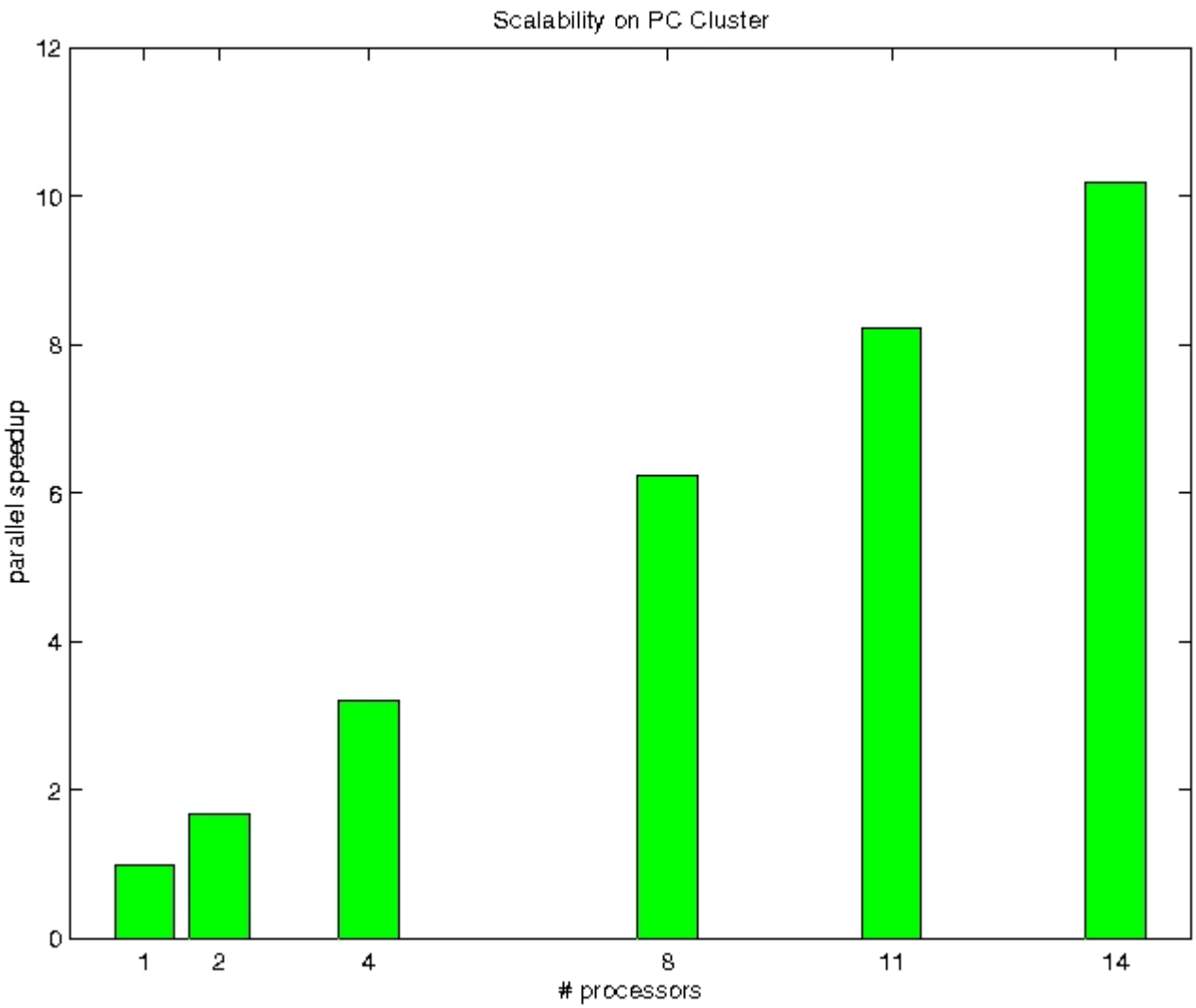
Performance is within 25% of T3E up to 16 processors

Possible low cost, scalable alternative to supercomputers

Effective resource for high resolution component design

- Collaborative effort - SLAC (ARDA, SCS, BaBar) & LBL (NERSC)
- Specs: 17 Dell 410 systems, each with dual 450 MHz Pentium II processors, 256 MB memory, one 9 GB disk connected with a Cisco 5505 Fast Ethernet switch
- Operating system: RedHat Linux version 2.0.36

Scaling of Ion Tracking Code on SLAC PC Cluster



72-node PC Cluster @ LANL

- Specs
  - 400 MHz Pentium II, 24 GByte RAM, 100 BaseT
- Cluster Development Kit (CDK) from Portland Group
  - C, C++, F77, F90, HPF
  - MPI, PVM
  - Profiler
  - Debugger
  - Batch management system
- Operating System: ***Extreme Linux***

Conclusions

Codes developed under the Grand Challenge are having a major impact on the community

- Applied to NLC, SNS, APT, ALS, PEP-II
- 100M particle linac simulations are now ***routine***
  - Approaching real-world charge resolution
- Numerical "cold-tests" of structures is now possible
- Use of parallel codes for NLC/DDS design has resulted in improved designs and *significant* cost savings

Future Plans

Much work remains to be done:

- End-to-end beam dynamics simulation: parallel codes for beam sources, RFQs, linacs, circular machines, beam-beam, cooling,...
  - New features: other boundary conditions, collisions, wakes…
- Complex version of Omega3P - for lossy structures
- Tau3P with rigid beam - for direct calculation of wakefield effects
- Tightly coupled Beam Dynamics & Electromagnetics
  - Hybrid grids (regular & irregular portions)
- Improved algorithms: better performance & scalability
- Software engineering: maintainability, extensibility…
- Model evaluation:
  - Experiments at U.Md, LANL/LEDA, BNL, GSI,…
  - Statistical methods

Presentations at Technical Meetings

1. R. Ryne et al., "Prediction of Beam Halo Using Parallel Supercomputers," presented at the 7th Workshop on High-Intensity High-Brightness Hadron Beams, Lake Como, Wisconsin, September 1999.
2. K. Ko et al., "Large Scale Electromagnetic Modeling of Accelerator Structures and Components using High Performance Computers," Invited talk, 1999 Particle Accelerator Conference, New York, NY, March 1999.
3. R. Ryne et al., "The U.S. DOE Grand Challenge in Computational Accelerator Physics," Invited talk, XIX International Linac Conference, Chicago, IL, August 1998.
4. C.-K. Ng, B. McCandless, Y. Sun, M. Wolf, and K. Ko, "Tau3P: A Parallel Time-Domain Solver for the DOE Grand Challenge," 1999 International Particle Accelerator Conference, New York, NY, March 1999.
5. B. McCandless, Z. Li, Y. Sun, and K. Ko, "Omega3P: Modeling Next-Generation Particle Accelerators," 1999 Particle Accelerator Conference, New York, NY, March 1999.
6. J. DeFord and K. Ko, "3D Optimization Using a Client/Server Software Topology," 1999 Particle Accelerator Conference, New York, NY, March 1999.
7. I. Hofmann, J. Qiang, and R.D. Ryne, "Coherent Coupling Criterion for Three-Dimensional Halo Formation," 1999 Particle Accelerator Conference, New York, NY, March 1999.
8. J. Qiang, R.D. Ryne, and S. Habib, "Parallel Object-Oriented Design in Fortran for Beam Dynamics Simulation," 1999 Particle Accelerator Conference, New York, NY, March 1999.
9. J. Qiang, R.D. Ryne, and S. Habib, "Beam Halo Studies Using a Three-Dimensional Particle-Core Model," 1999 Particle Accelerator Conference, New York, NY, March 1999.
10. R.M. Jones, N.M. Kroll, R.H. Miller, T. Higo, K. Ko, Z. Li, R.D. Ruth, V. Srinivas, and J.W. Wang, "The Dipole Wakefield for a Rounded Damped Detuned Linear Accelerator with Optimized Cell-to-Manifold Coupling," XIX International Linac Conference, Chicago, IL, August 1998.
11. A.V. Fedotov, R.L. Gluckstern, S. Kurennoy, and R.D. Ryne, "Halo Formation in 3D Bunches with Different Phase Space Distributions," XIX International Linac Conference, Chicago, IL, August 1998.
12. J.J. Barnard, S.M. Lund, and R.D. Ryne, "Self-Consistent 3D Simulations of Longitudinal Halo in RF Linacs," XIX International Linac Conference, Chicago, IL, August 1998.
13. B. McCandless et. al, "Omega3P, Modeling the Next Generation of Accelerator Structures," Supercomputing'98, Orlando, Florida, November 7-13, 1998.
14. M. Saparov et. al, "Multithreaded Sparse Matrix Library with Dynamic Load Balancing," Supercomputing'98, Orlando, Florida, November 7-13, 1998.
15. Y. Sun et. al, "A Hybrid Scheme to Improve Jacobi-Davidson Method on Eigenvalue Problems," International Workshop on Accurate Solution of Eigenvalue Problems, Penn State University, University Park, PA, July 20-23, 1998.

Selected Publications

1. J. Qiang, R.D. Ryne, S. Habib, and V. Decyk, "An Object-Oriented Parallel Particle-In-Cell Code for Beam Dynamics Simulation in Linear Accelerators," accepted for publication in the Proceedings of SC'99, Portland, OR, November 1999.
2. P.S. McCormick, J. Qiang, and R.D. Ryne, “Visualizing High-Resolution Accelerator Physics,” IEEE Computer Graphics and Applications, 19(5), pp. 11-13, September 1999.
3. W. Humphrey, R. Ryne, T. Cleland, J. Cummings, S. Habib, G. Mark, and J. Qiang, "Particle Beam Dynamics Simulations Using the POOMA Framework," in Lecture Notes in Computer Science #1505, Springer-Verlag, Dec. 1998.
4. A.V. Fedotov, R.L. Gluckstern, S. Kurennoy, and R. Ryne, "Halo Formation in 3D Bunches with Different Phase Space Distributions," Phys. Rev. ST Accel. Beams 2:014201, 1999.
5. R.L. Gluckstern, A. Fedotov, S. Kurennoy, and R. Ryne, "Halo Formation in Three Dimensional Bunches," Phys. Rev. E 58:04, October 1998.
6. J. Qiang, R.D. Ryne, and S. Habib, “Object-Oriented Parallel Particle-In-Cell Code for Beam Dynamics Simulation in Linear Accelerators,” submitted to J. Comp. Phys.
7. J. Qiang, R.D. Ryne, and S. Habib, “Beam Halo Studies Using a Three-Dimensional Particle-Core Model,” submitted to Phys. Rev. E.
8. C. Adolphsen et al., “Wakefield and Beam Centering Measurements of a Damped and Detuned X-Band Accelerator Structure,” Proceedings of the 1999 Particle Accelerator Conference, New York, NY, March 1999
9. G. Bowden et al., “A Compact RF Power Coupler for the NLC Linac,” Proceedings of the 1999 Particle Accelerator Conference, New York, NY, March 1999
10. I. Hofmann, J. Qiang, and R.D. Ryne, "Coherent Coupling Criterion for Three-Dimensional Halo Formation," Proceedings of the 1999 Particle Accelerator Conference, New York, NY, March 1999
11. Z. Li et al., “RDDS Cell Design and Optimization for the NLC Linac,” Proceedings of the 1999 Particle Accelerator Conference, New York, NY, March 1999
12. R. Ryne et al., "The U.S. DOE Grand Challenge in Computational Accelerator Physics," Proceedings of the XIX International Linac Conference, Chicago, IL, August 1998.
13. J. Qiang and S. Habib, "A Second-Order Stochastic Leap-Frog Algorithm for Multiplicative Noise," (in preparation).

Appendix: Some Code Details

- IMPACT
- Omega3P
- Tau3P

IMPACT: Algorithms and Parallel Implementation

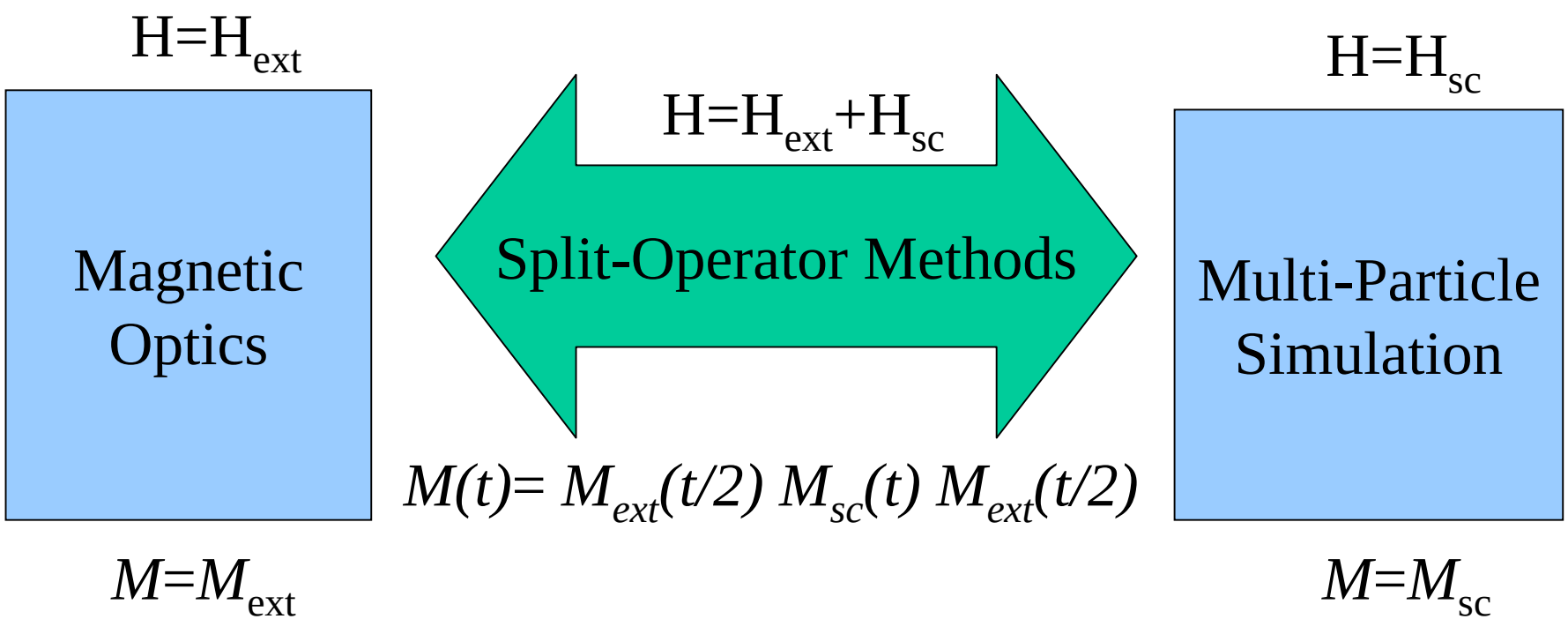
- Split-operator method with $H=H_{external}+H_{space\ charge}$
- Canonical variables (x,p_x,y,p_y,t,p_t)
- Simple quantities computed "on the fly" via num. integration
  - reference trajectory
  - maps for nonidealized beamline elements

Philosophy: Don't take tiny steps to push ~100M particles;
Do take tiny steps to compute maps, then push with maps

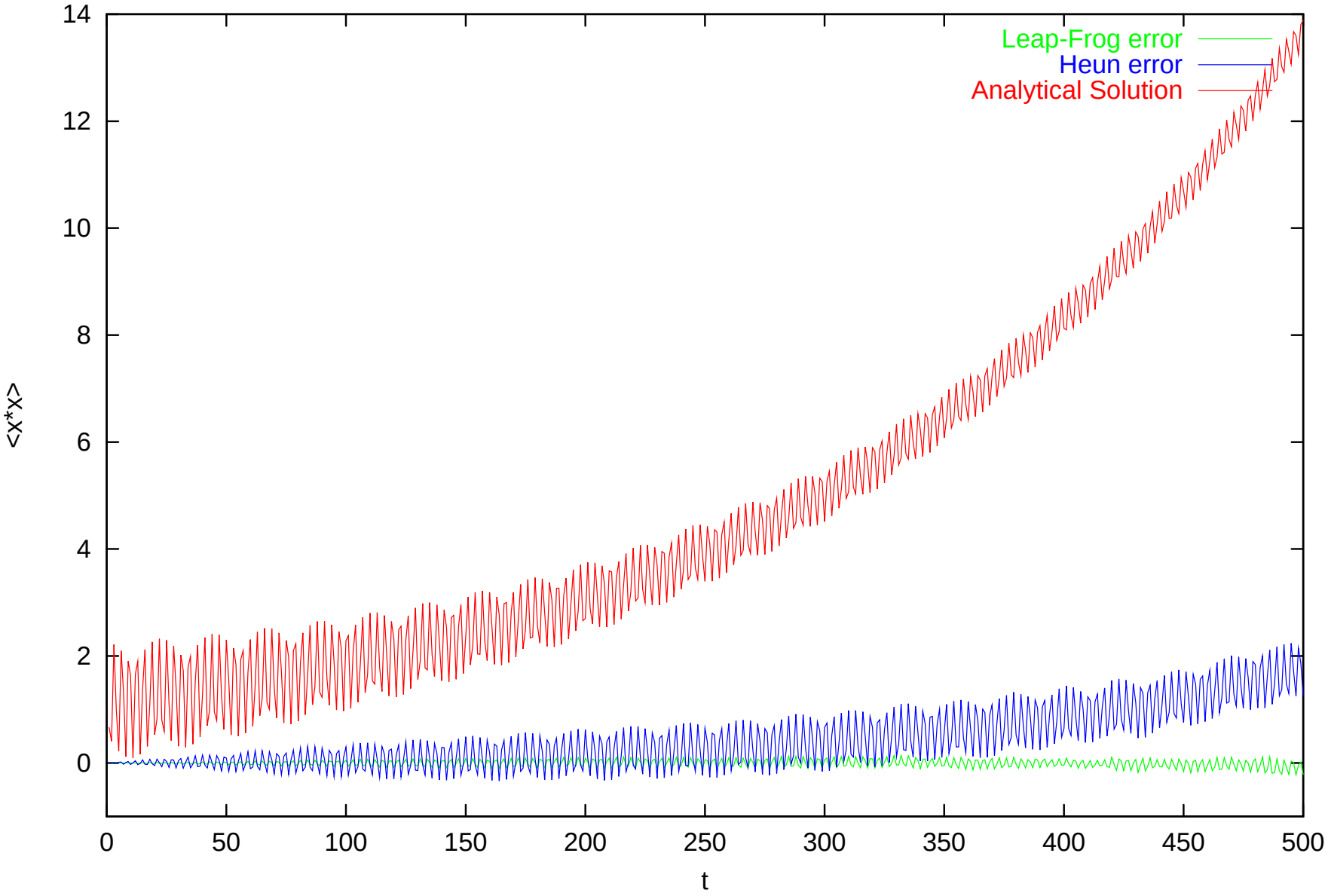
- Particle-In-Cell approach: (1) charge deposition on a grid, (2) field solution, (3) field interpolation from grid to particles
- Field solution via FFT-based convolution (open boundaries)
- Parallel "particle manager," dynamic load balancing

Split-Operator Approach

How to turn ***any*** Magnetic Optics code into a tracking code with space charge



Stochastic Leap-Frog Integration Algorithm for Modeling Systems with Multiplicative Noise



Status of IMPACT

IMPACT (Integrated Map and Particle Accelerator Tracking code)
- *3D parallel beam dynamics code developed "from the ground up"*

- Combines Magnetic Optics with Parallel Particle-In-Cell methods
- Maps for rf structures obtained using on-axis fields from rf cavity codes
- Routinely run with 100M particles (100x the size of problems run using serial codes; parallel runs performed in 1/10 the time)
- Features include dynamic load balancing, optimized cross-box FFT's
- Used in 48-hour, 2048 processor Nirvana acceptance test
- Sent to vendors for 30 T-Op procurement

500 million particle production runs performed on 1024 processors of Nirvana system to model SNS linac

- Test runs performed with 1 billion particles on Blue Mountain

Omega3P - A Parallel Eigensolver

Based on Omega3, a finite element (linear & quadratic elements) eigensolver with mesh refinement capabilities.

Key components for parallelization:

- Mesh Distribution - domain decomposition of the geometry mesh for balanced load on each processor.
- Matrix Assembly - finite element formulation and generation of the Mass and Stiffness for the generalized eigenvalue problem:

$$Kx = \lambda Mx$$

- Eigensolver - linear algebra operations to support the Jacobi-Davidson method.

Omega3P - Software Components

- **Omega3P -** application module layered on DistMesh and EigenSolver and contains the finite element formulation and postprocessing. It uses MeshTV (from LLNL) for visualization.

- **DistMesh -** a library for operating on distributed unstructured meshes. Operations include parallel file I/O, partitioning, distribution, global numbering, and refinement. DistMesh makes use of ParMETIS (from U of Minnesota) for partitioning.

- **EigenSolver -** code for solving the generalized eigenvalue problem using a Hybrid algorithms. It uses Aztec (from Sandia National Lab) for solving sparse linear systems in parallel.

Hybrid Scheme in Eigensolver

An optimized combination of three powerful methods:

- Spectrum transformation and bandpass polynomial filtering,
- Inexact Krylov subspace projection,
- Modified Jacobi-Davidson local refinement

This results in solver accuracy and convergence as well as parallel scalability far superior than other algorithms.

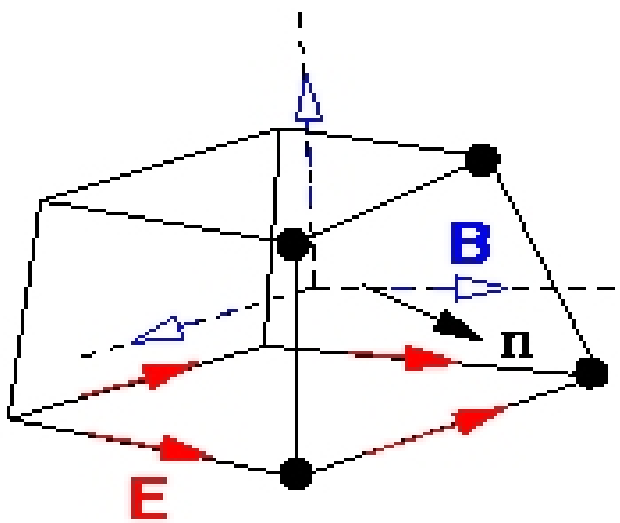
Introduction to Tau3P

Tau3P is developed under the ***DOE Grand Challenge*** as part of a suite of advanced electromagnetic simulators that utilize High Performance Computers to model RF components for next-generation accelerators such as the NLC.

An **essential** feature of the new tool set is the use of **unstructured grids** for conformal meshing:

Tau3P

- Non-orthogonal dual grid
- Electric field on primary grid
- Magnetic field on dual grid



Time-Domain Method on Unstructured Grid

Integral representation of Maxwell equations

$$\circ\, E \bullet ds = -\frac{\partial B}{\partial t} \bullet dA$$

$$\circ\, H \bullet ds^* = \frac{\partial D}{\partial t} \bullet dA^*$$

Discrete Surface Integral Method

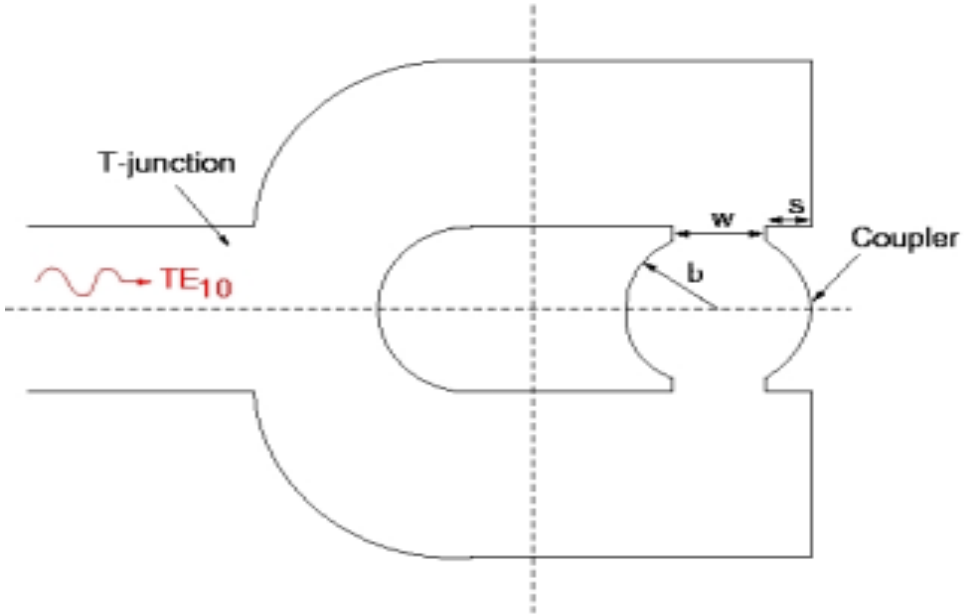
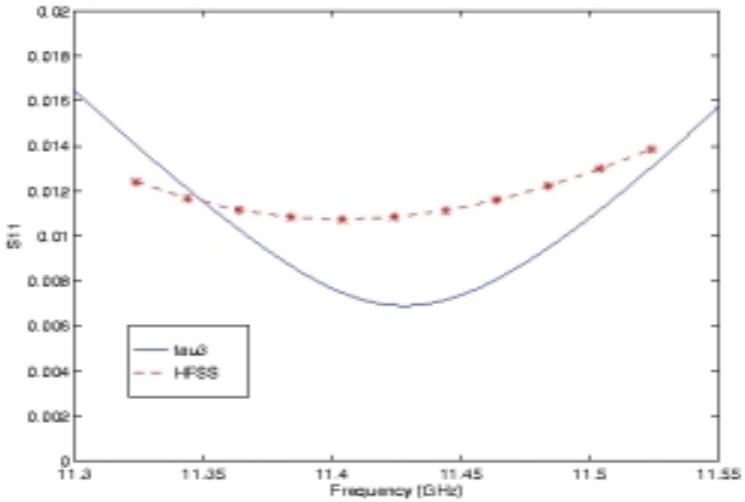
- Leapfrog time advancement scheme with filtering
- Same as FDTD when grids are orthogonal
- Fields on grid averaged over neighboring cells

Ref: N. K. Madsen, J. Comp. Phys., **119**, 34 (1995)

S-Parameter - Broad Band

Tau3P implements the broadband matched-impedance boundary condition at the waveguide ports to allow for pulse transmission so that S-parameter calculation can be determined over a frequency range in a single simulation.

X-Band Input Coupler



T-junction Match over 200 MHz