Advances in Parallel Electromagnetic Codes for Accelerator Science and Development

Kwok Ko

Speaker: Arno Candel

Advanced Computations Group

SLAC

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SLAC NATIONAL ACCELERATOR LABORATORY

SciDAC Scientific Discovery through Advanced Computing

Advanced Computations at SLAC & Collaborations

SLAC Team

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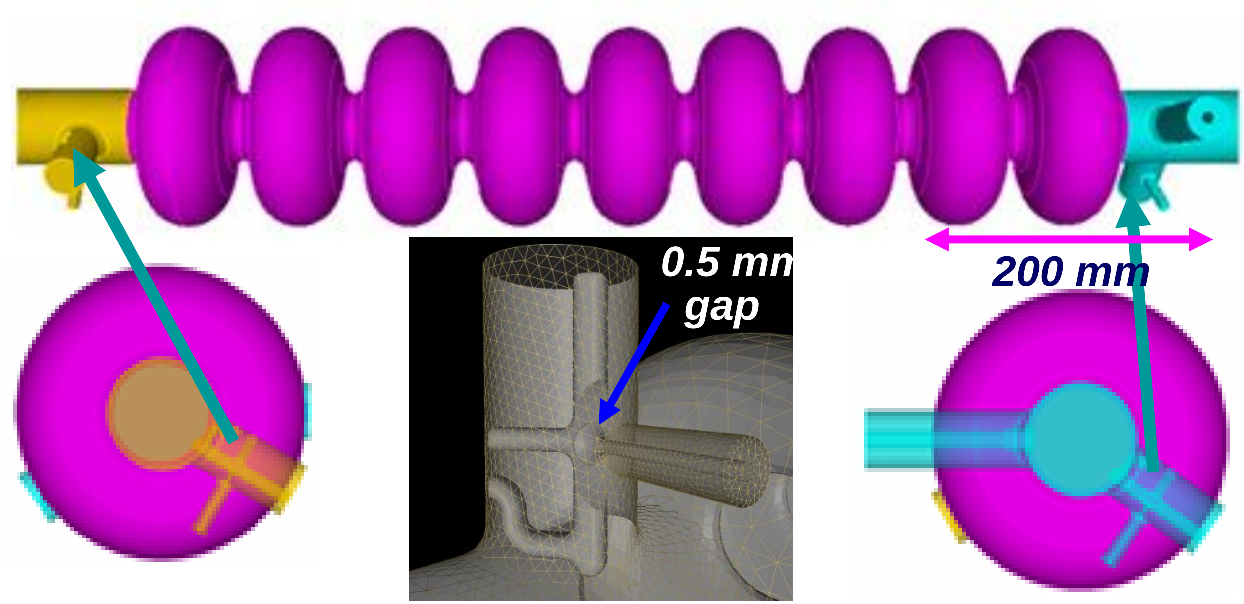
3D Electromagnetic Codes for Accelerators

- MAFIA (CST) – FD, http://www.cst.com
- Microwave studio (CST) – FD, http://www.cst.com
- HFSS (Ansoft) – FEM, http://www.ansoft.com
- ANSYS (Ansys, Inc.) – FEM, http://www.ansys.com
- GdfidL – FDTD, parallel, http://www.gdfidl.de
- **ACE3P (SLAC) - FEM, massively parallel (>10k CPUs)**
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

Parallel EM Code Development at SLAC

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:

1998 *- Xiaowei Zhan, Parallel electromagnetic field solvers using finite element methods with adaptive refinement and their application to wakefield computation of axisymmetric accelerator structure, Stanford University.*

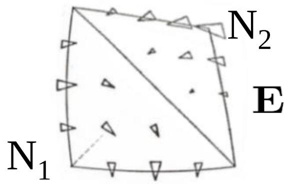
2003 *- Yong Sun, The filter algorithm for solving large-scale eigenproblems from accelerator simulations, Stanford University.*

2009 *- Sheng Chen, Adaptive error estimators for electromagnetic field solvers, Stanford University.*

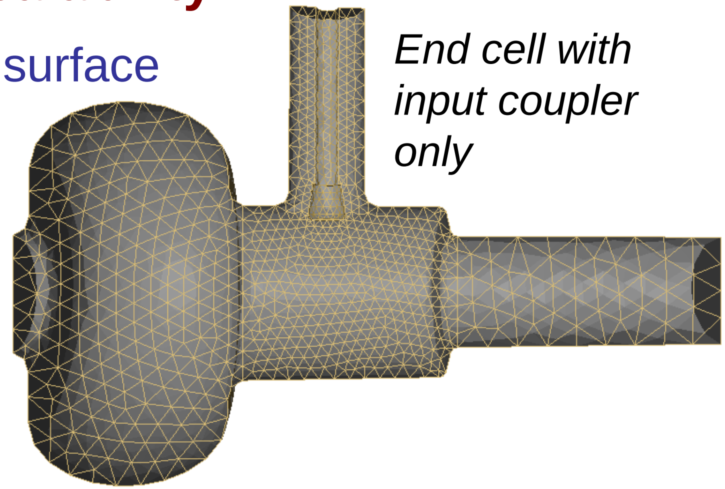
Parallel Higher-order Finite-Element Method

Strength of Approach – Accuracy and Scalability

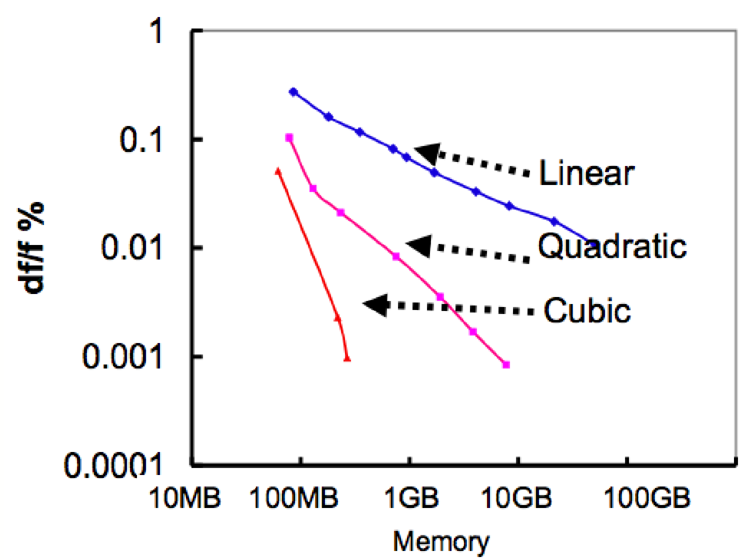
- Conformal (tetrahedral) mesh with quadratic surface
- Higher-order elements (p = 1-6)
- Parallel processing (memory & speedup)



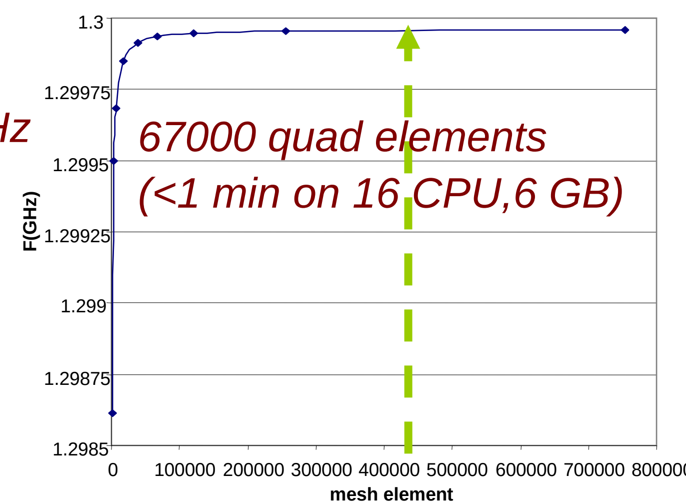
$$\mathbf{E}(\mathbf{x},t) = \sum_i e_i(t) \cdot \mathbf{N_i}(\mathbf{x})$$



End cell with input coupler only



Error ~ 20 kHz (1.3 GHz)



Accelerator Modeling with EM Code Suite ACE3P

Meshing *-* ***CUBIT*** *for building CAD models and generating finite-element meshes.*
http://cubit.sandia.gov.

Modeling and Simulation – **SLAC's suite of conformal, higher-order, C++/MPI based parallel finite-element electromagnetic codes**
https://slacportal.slac.stanford.edu/sites/ard_public/bpd/acd/Pages/Default.aspx

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.

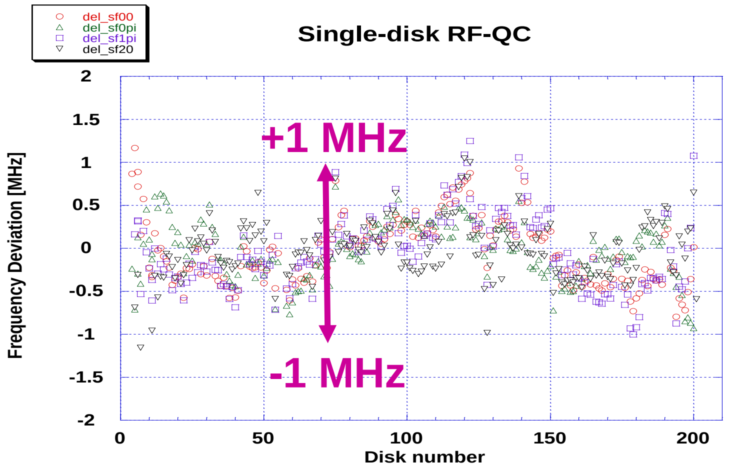
- **Pic3P** calculates the beam emittance in RF gun designs.

Benchmarks of ACE3P with Measurements

Omega3P – NLC Cell Design

<u>*Code validated in 3D NLC Cell design in 2001*</u>

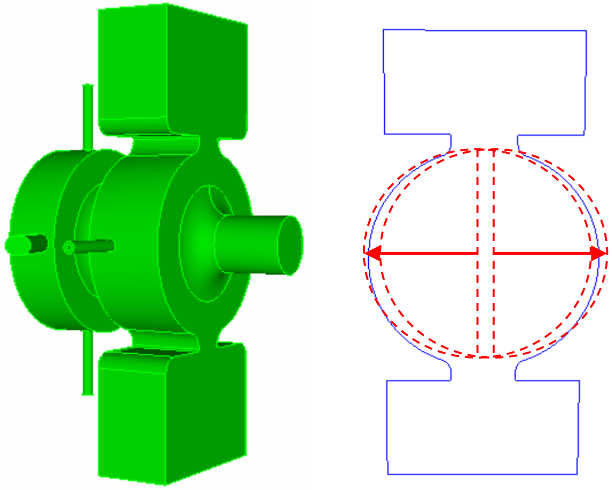
- *Omega3P was used to determine the accelerator dimensions for the JLC/NLC X-Band structures with accuracy orders of magnitude better than machining tolerance,*
- *The structure cells were high precision machined,*
- *Microwave QC verified cavity frequency accuracy to 0.01% relative error (1MHz out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



Omega3P – LCLS RF Gun Cavity

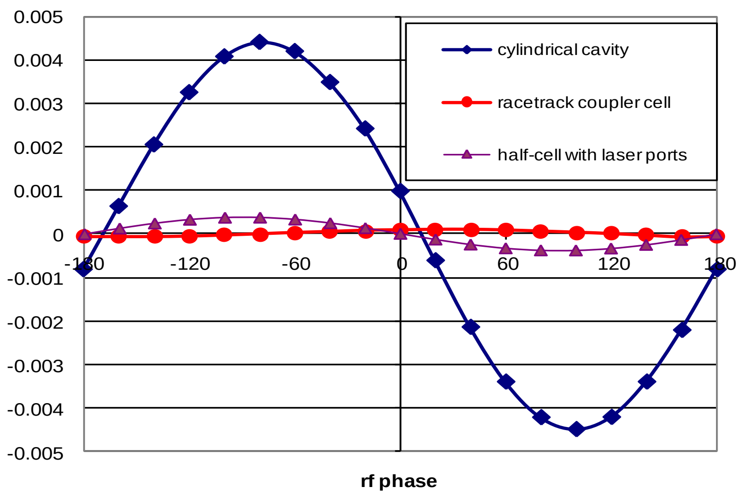
Provided dimensions for LCLS RF gun cavity to meet design requirements:

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



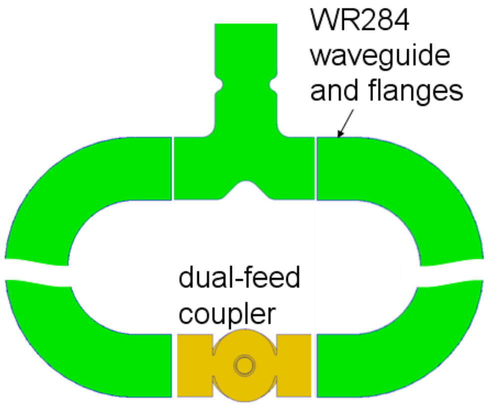
<u>Code validated by Measurement</u>

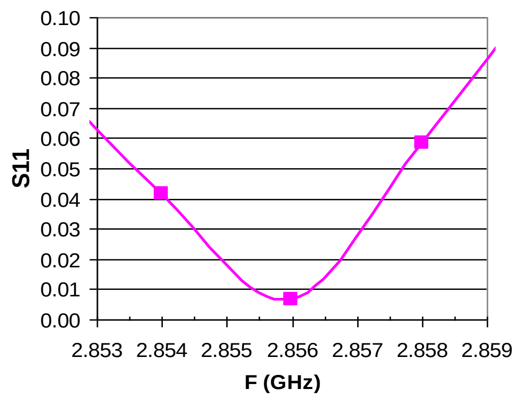
RF parameter	Design	Measured
f_π (GHz)	2.855987	2.855999
Qo	13960	14062
β	2.1	2.03
Mode Sep. Δf (MHz)	15	15.17
Field balance	1	1

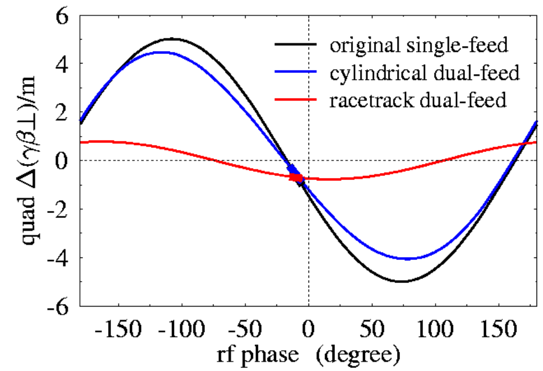


S3P - S-Parameters for LCLS Injector Components

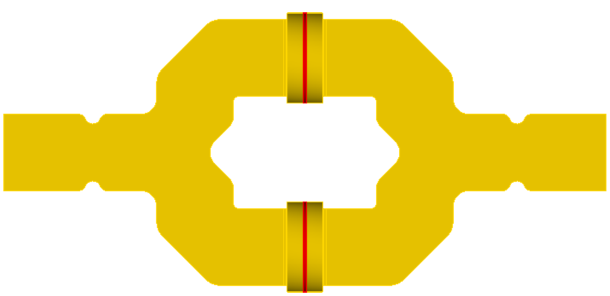
- LCLS injector accelerator structure dual-feed coupler components

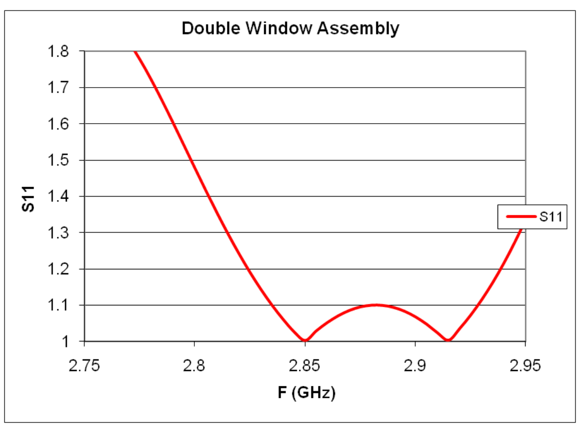






- LCLS RF Gun Dual-window assembly





Track3P – Ichiro Cavity Multipacting

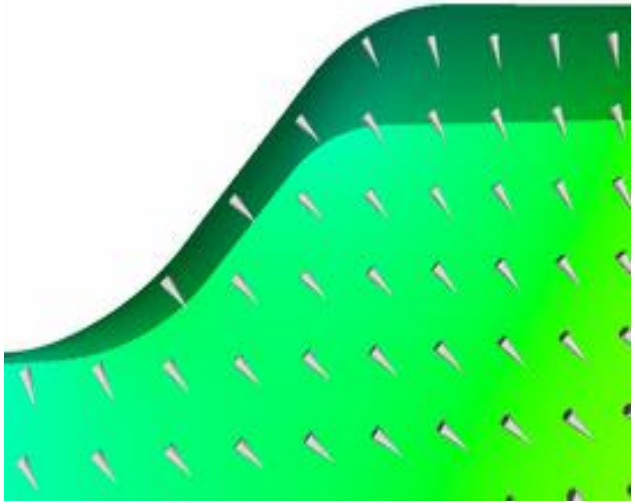
ICHIRIO cavity experienced

- 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**

ICHIRO #0	Track3P MP simulation	
X-ray Barriers (MV/m)	Gradient (MV/m)	Impact Energy (eV)
11-29.3 12-18	12	300-400 (6^{th} order)
13, 14, 14-18, 13-27	14	200-500 (5^{th} order)
(17, 18)	17	300-500 (3^{rd} order)
20.8	21.2	300-900 (3^{rd} order)
28.7, 29.0, 29.3, 29.4	29.4	600-1000 (3^{rd} order)

MP Trajectory @ 29.4 MV/m



K. Satio, KEK

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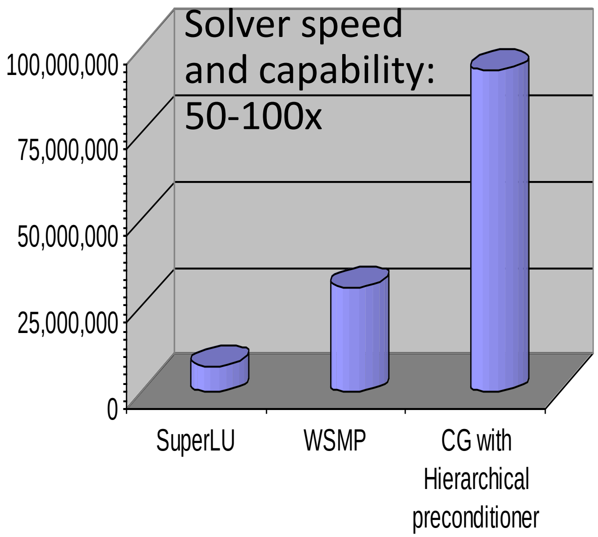
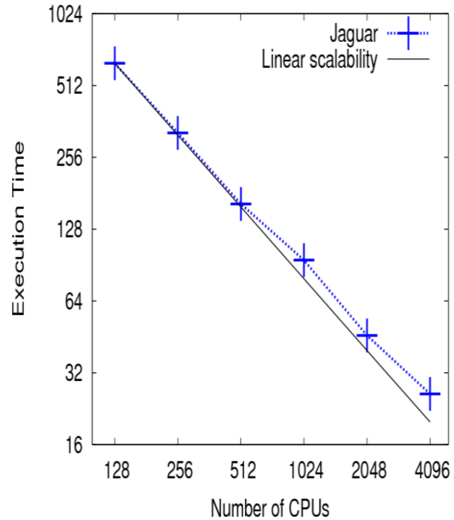
Large-scale Accelerator Simulation requires Computational Science and High Performance Computing

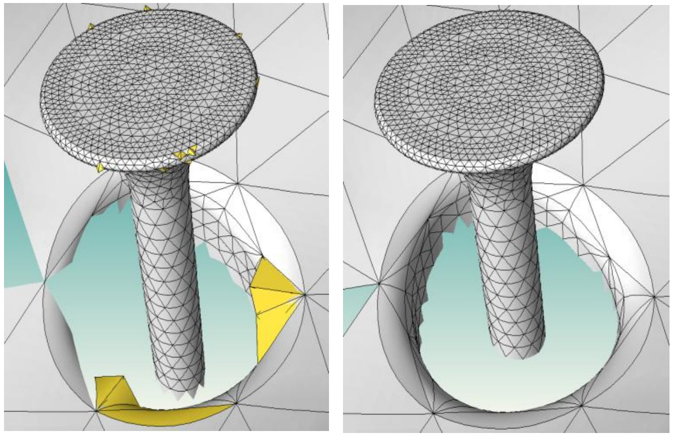
Computational Science R&D under SciDAC

Eigensolver speed and scalability

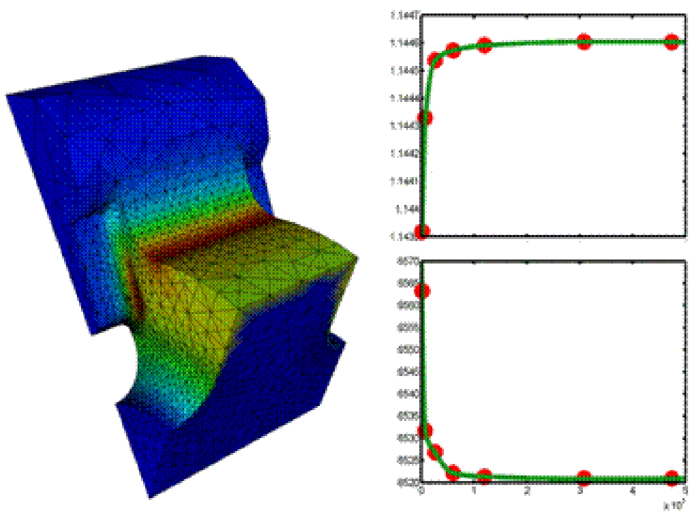




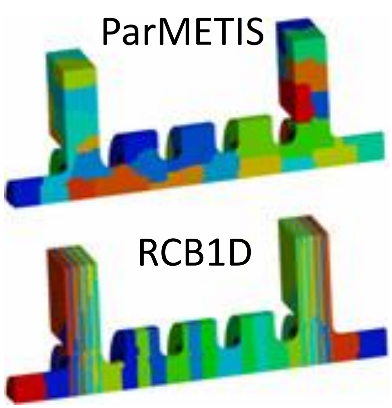
Mesh correction

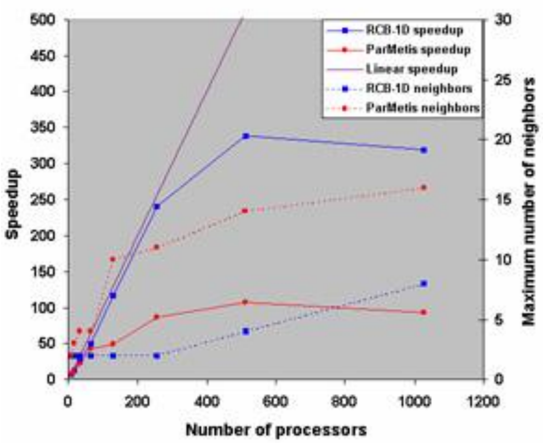


Adaptive mesh refinement



Partitioning scheme for load balancing





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

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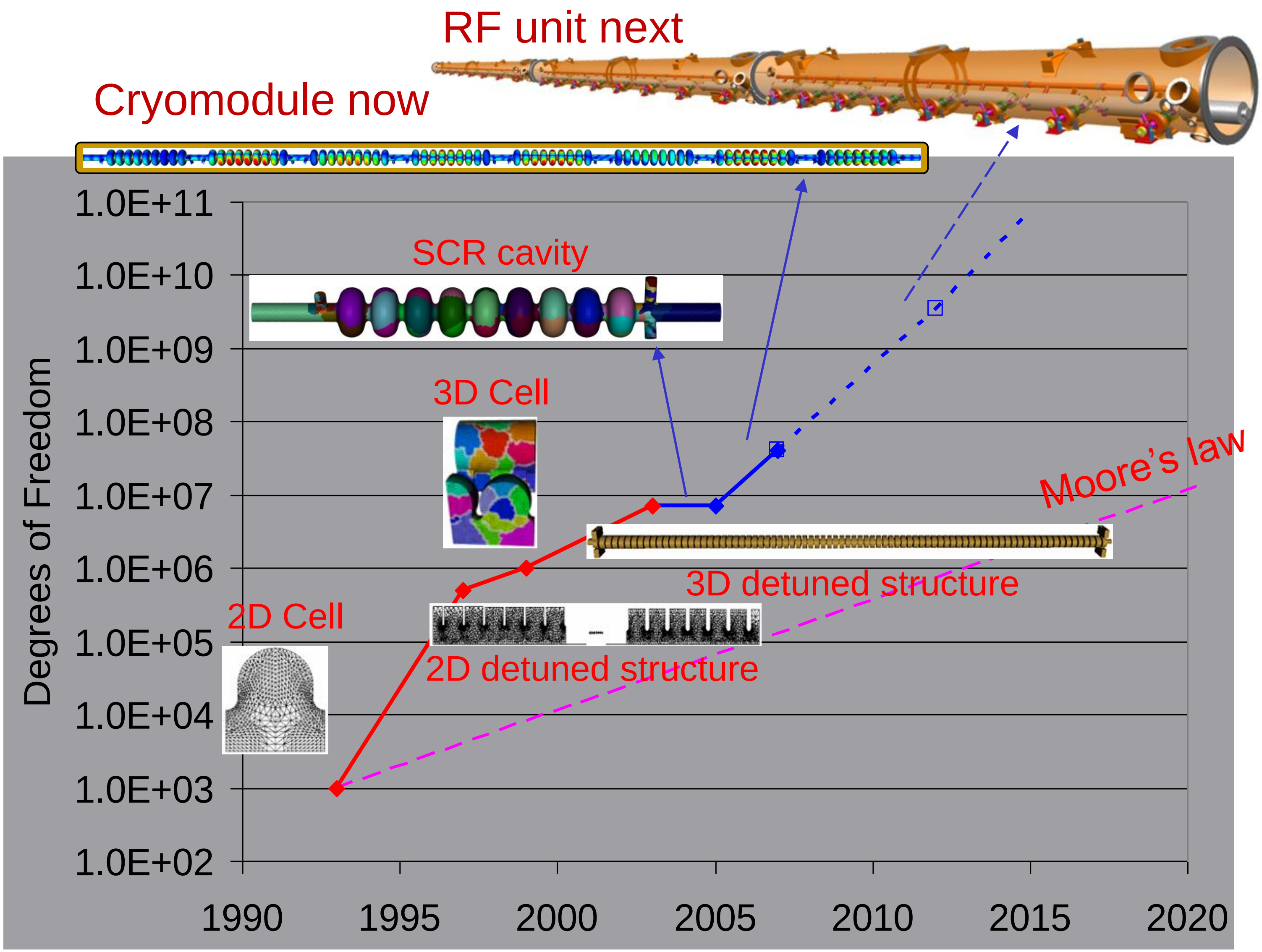
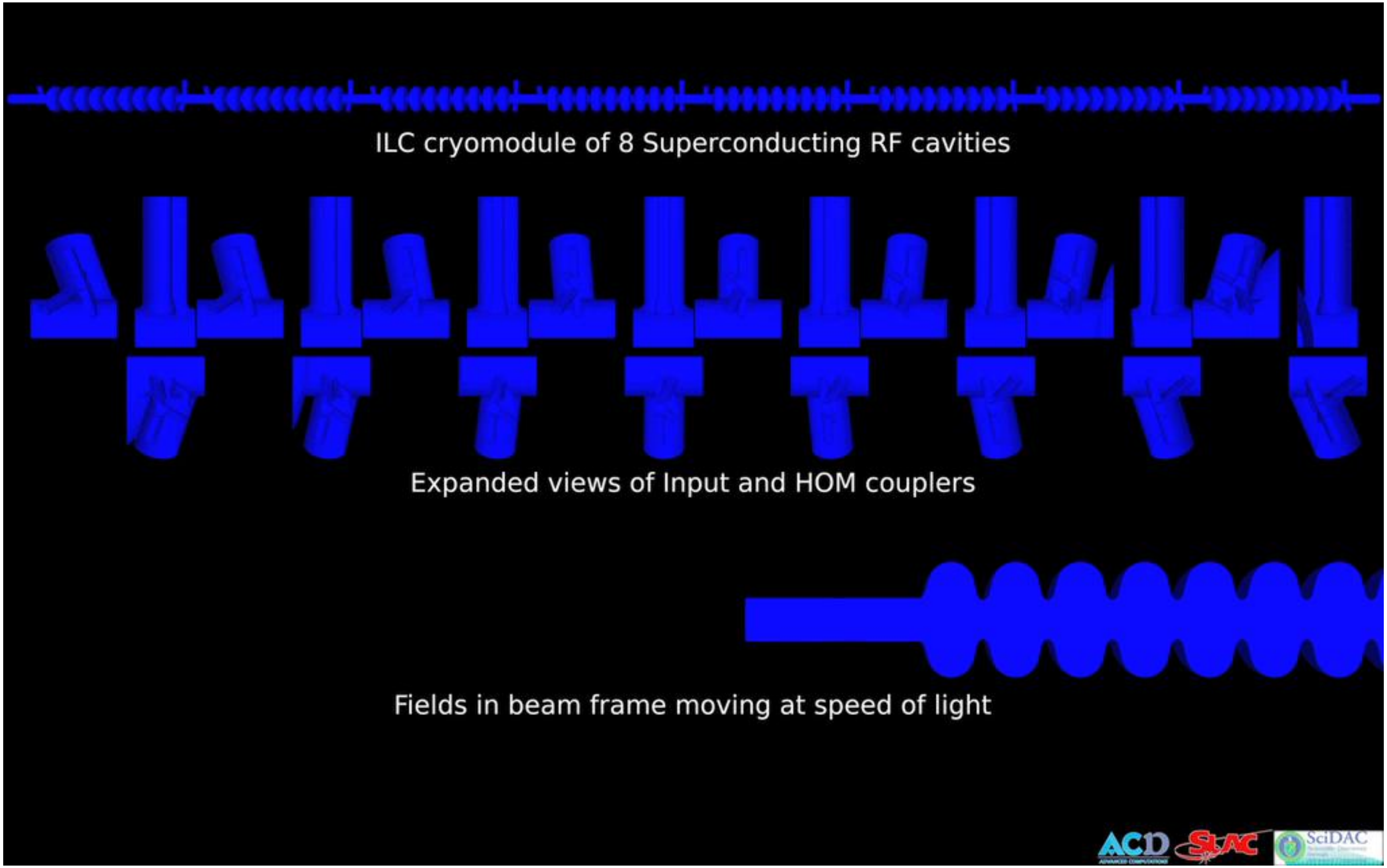
SciDAC Scientific Discovery through Advanced Computing

ACE3P's advances focus on solving challenging problems in Accelerator Science and Development

Omega3P – Towards System Scale Modeling



T3P – Beam Transit in ILC Cryomodule



Visualization by Greg Schussman

T3P – Short Bunch Wakefields in ERL

Energy Recovery Linac

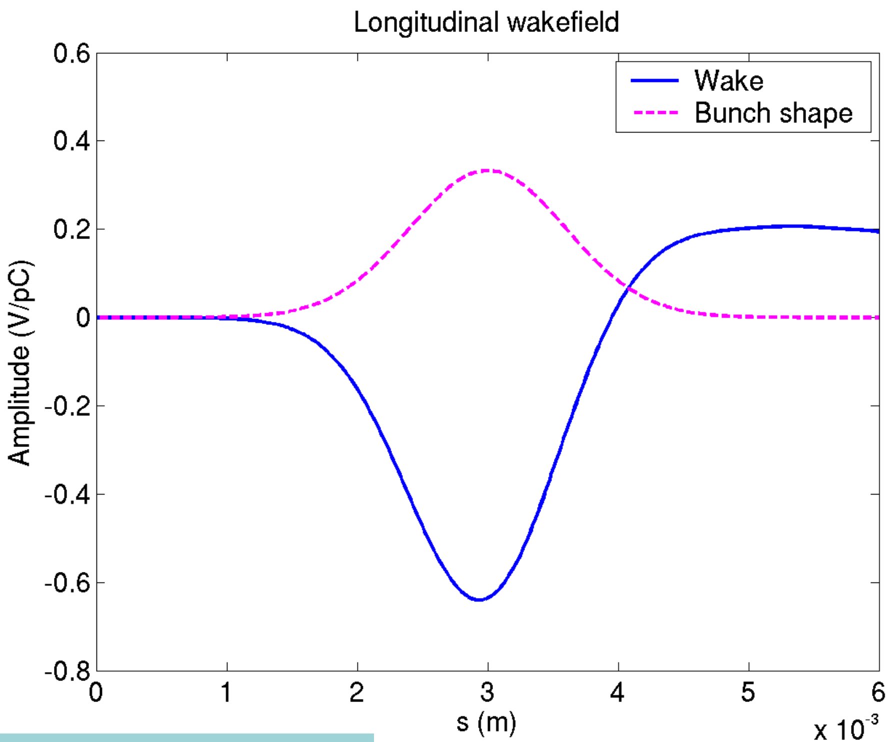
Bunch length = 0.6 mm

Vacuum chamber transition model

Beam direction

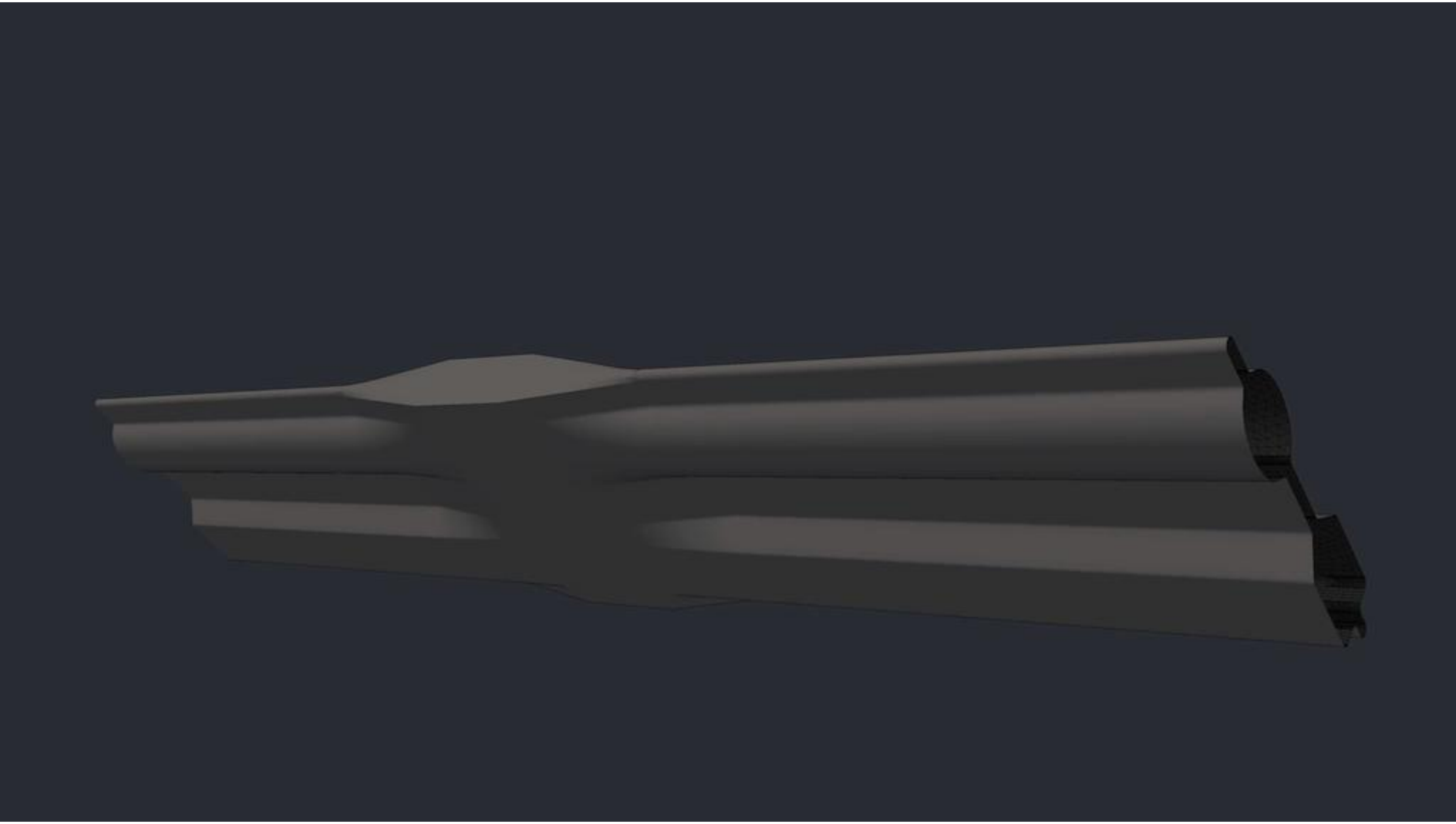
Longitudinal wakefield

Loss factor = 0.413 V/pC



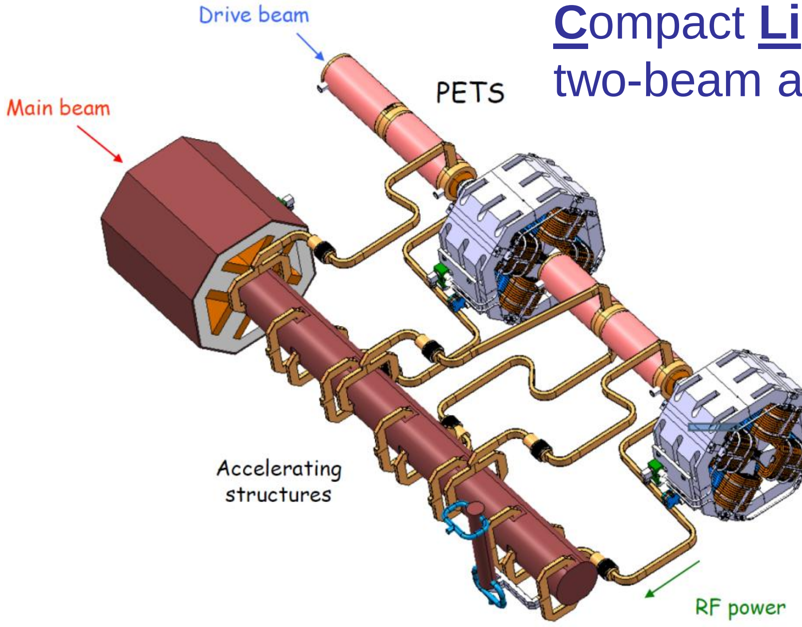
In collaboration with Cornell

T3P – Short Bunch Wakefields in ERL

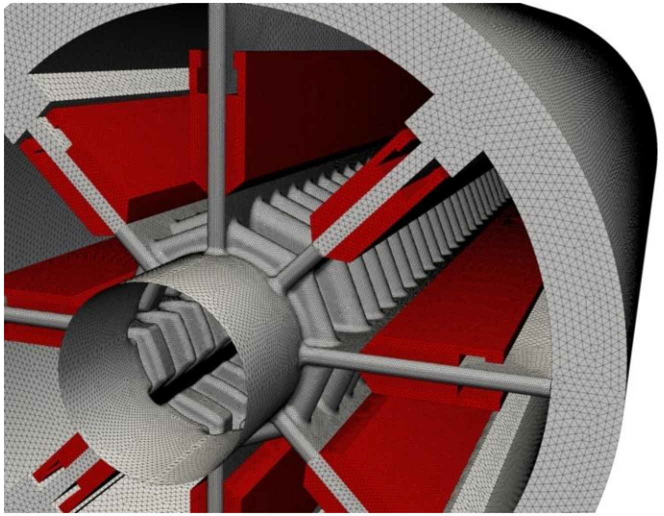


Visualization by Greg Schussman

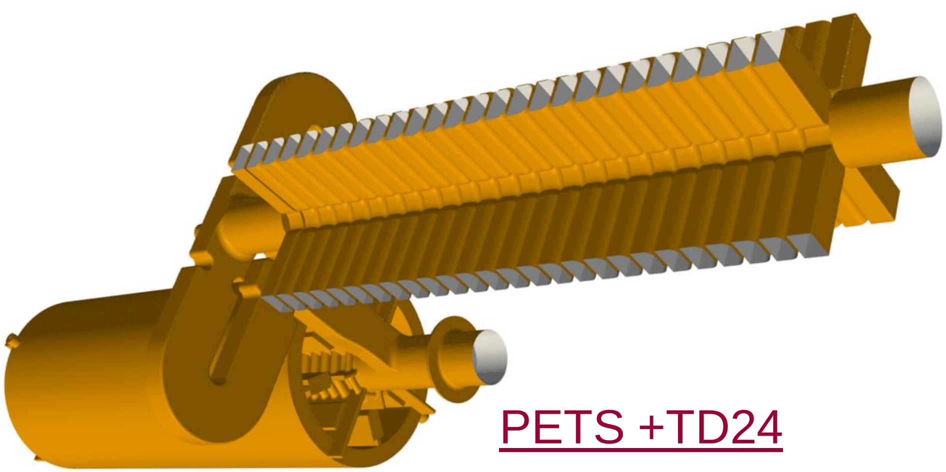
T3P – CLIC Two-Beam Accelerator



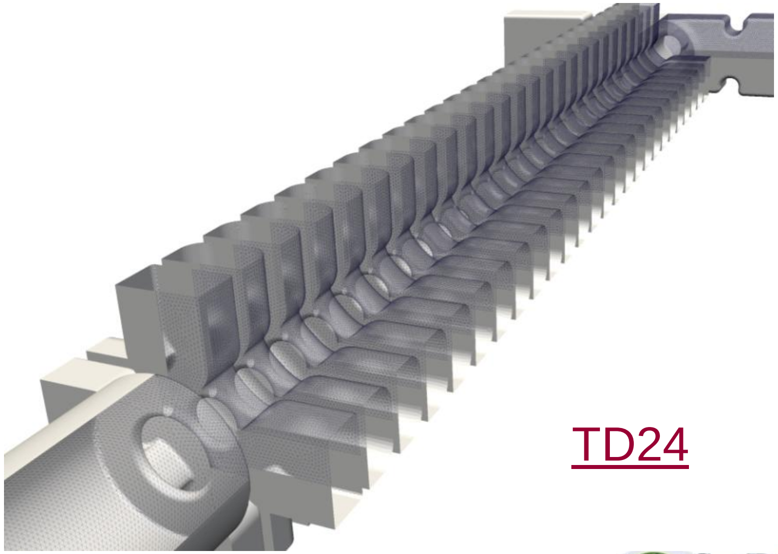
Compact **Li**near **C**ollider two-beam accelerator unit



PETS



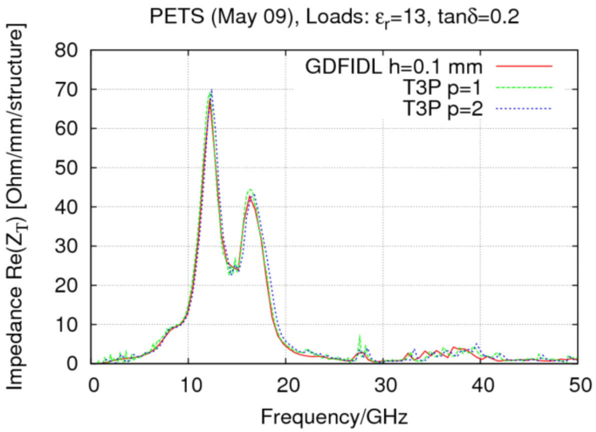
PETS +TD24

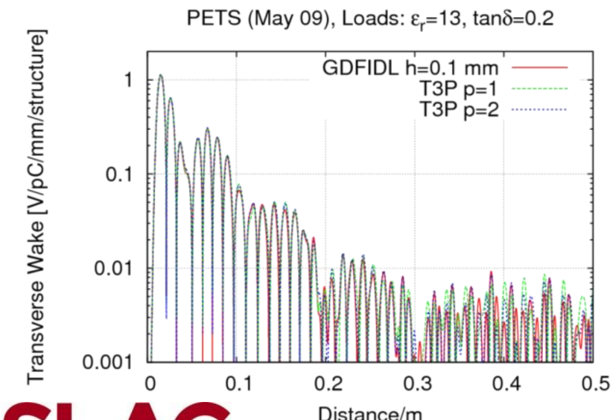


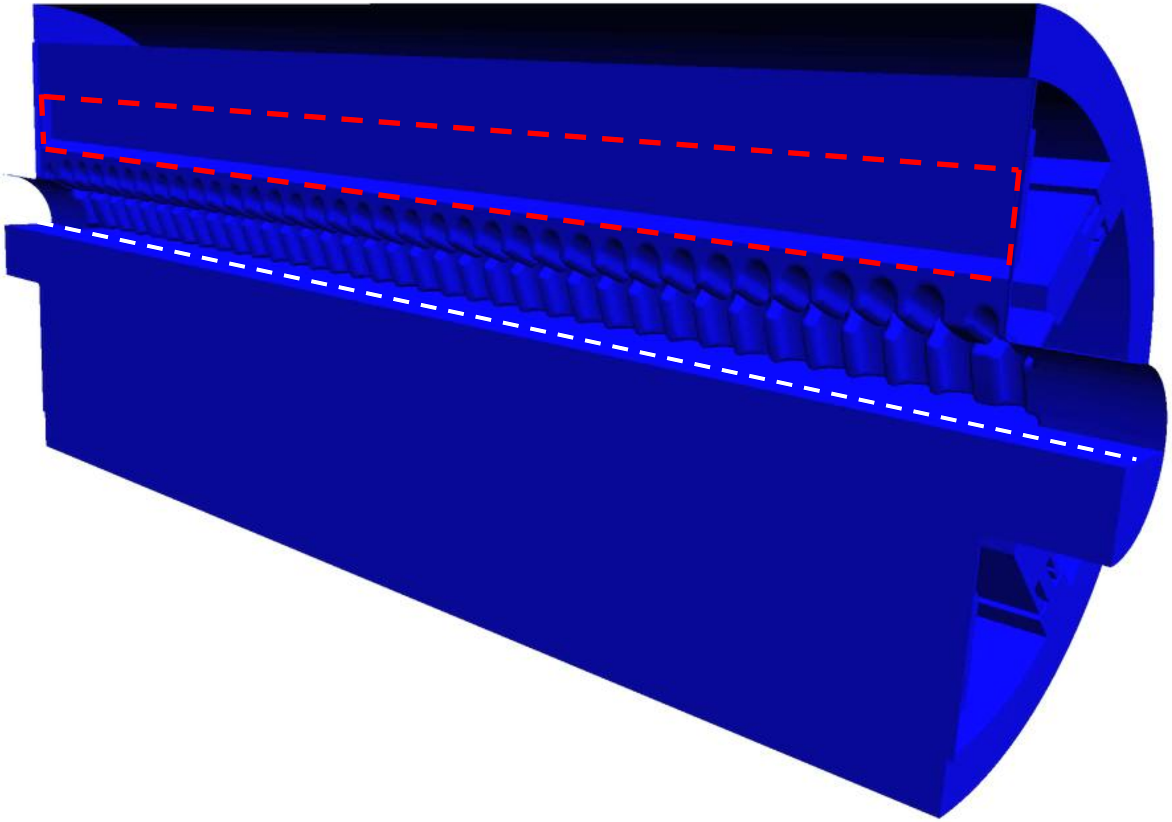
TD24

T3P - CLIC PETS Bunch Transit

Dissipation of transverse wakefields in dielectric loads: eps=13, tan(d)=0.2

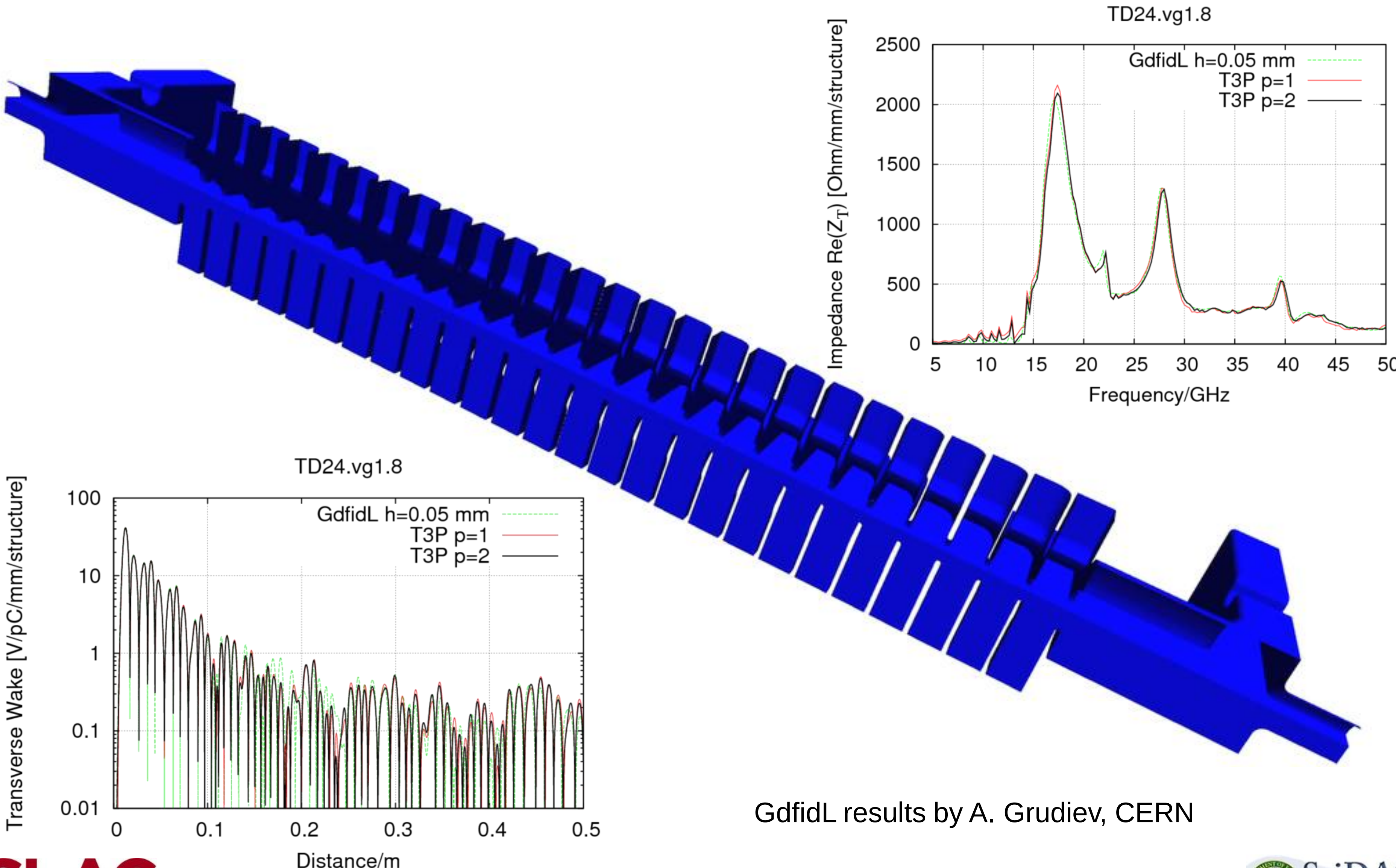






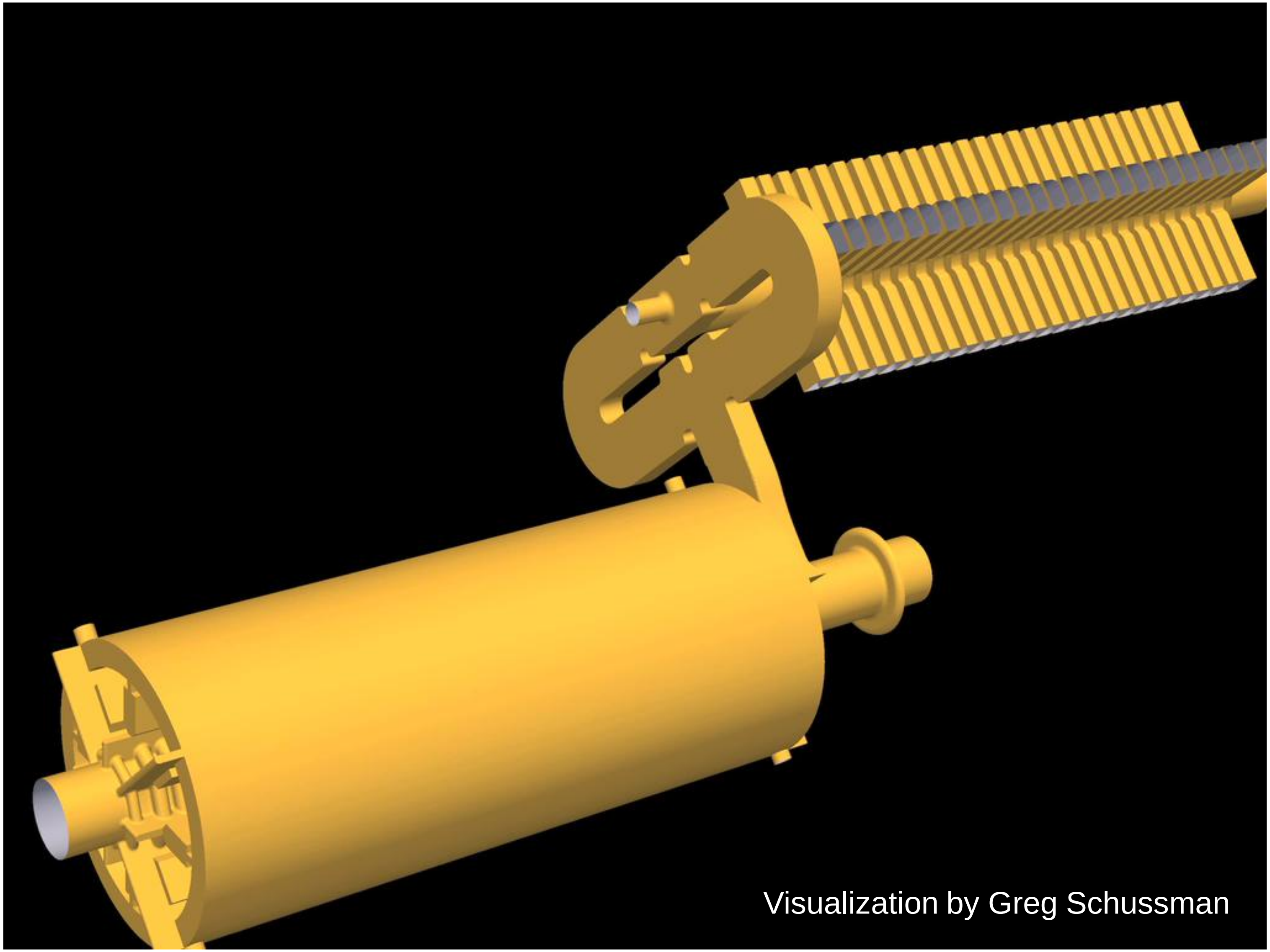
GdfidL results by I. Syratchev, CERN

T3P – CLIC TDA24 Bunch Transit



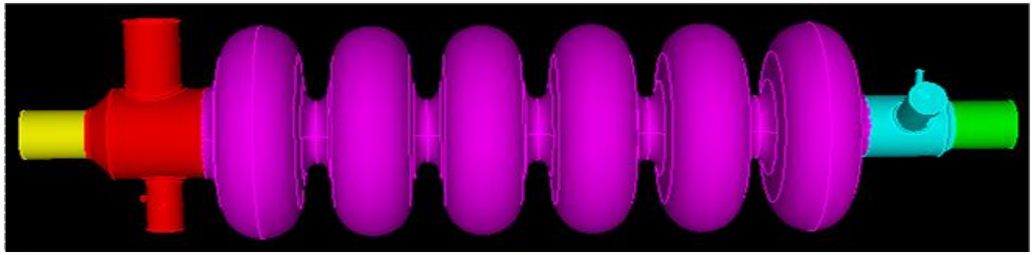
GdfidL results by A. Grudiev, CERN

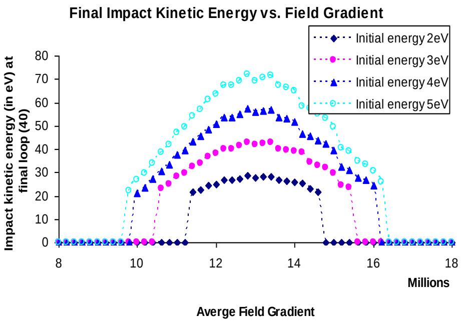
T3P – RF Power Transfer in Coupled Structure



Visualization by Greg Schussman

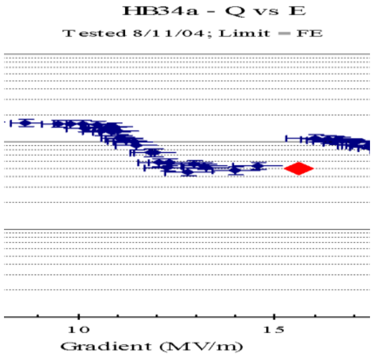
Track3P – Multipacting in SNS Cavity/HOM Coupler





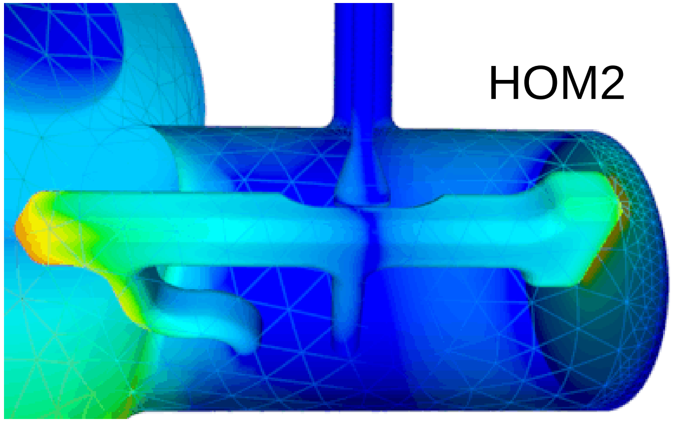
SNS Cavity

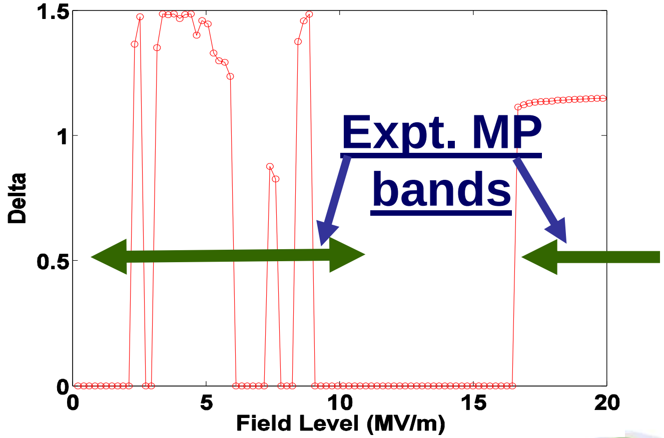
- Both Experiment and Simulation show same MP band: 11 MV/m ~ 15MV/m



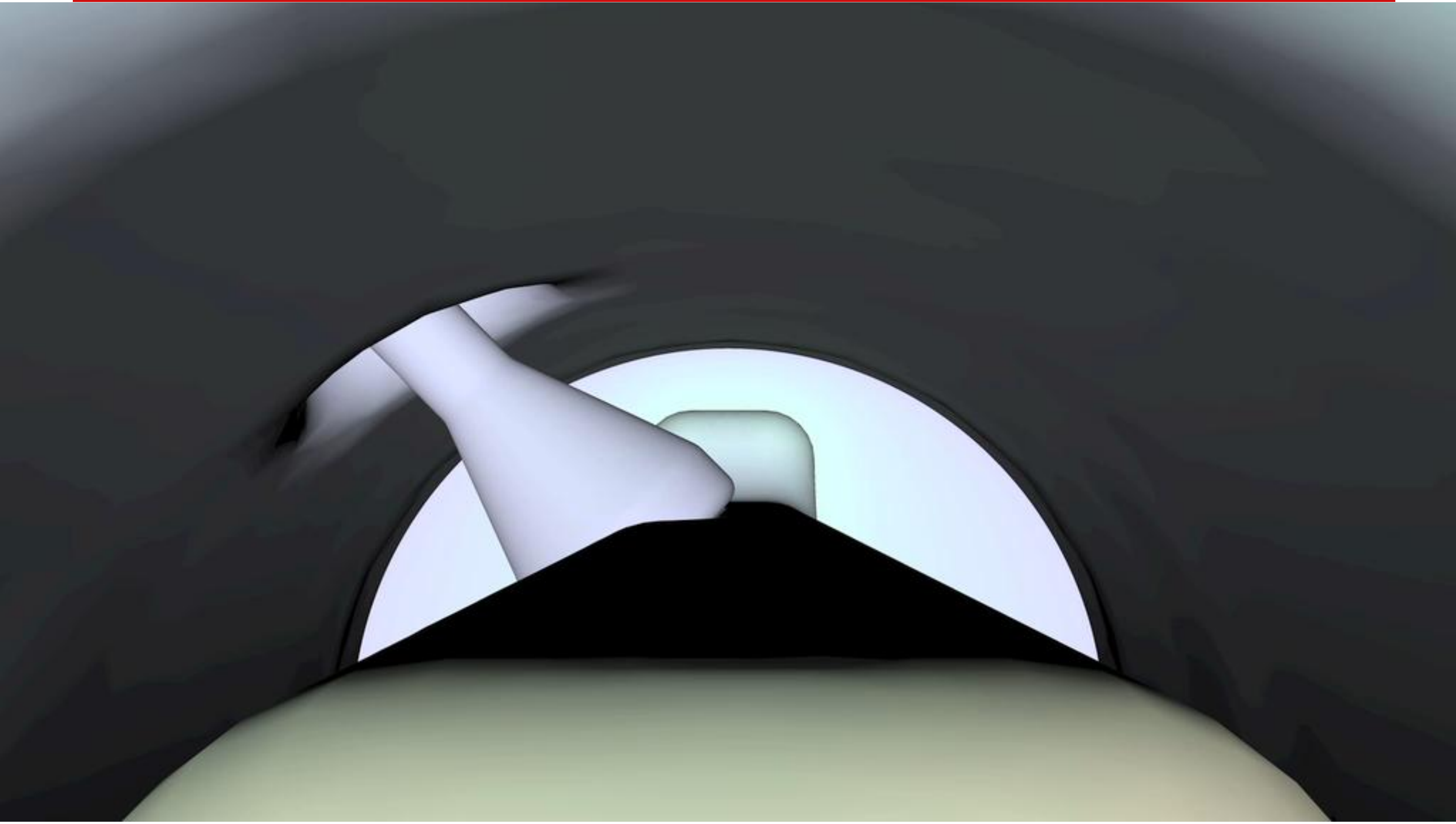
SNS Coupler

- SNS SCRF cavity experienced rf heating at HOM coupler
- 3D simulations showed MP barriers close to measurements



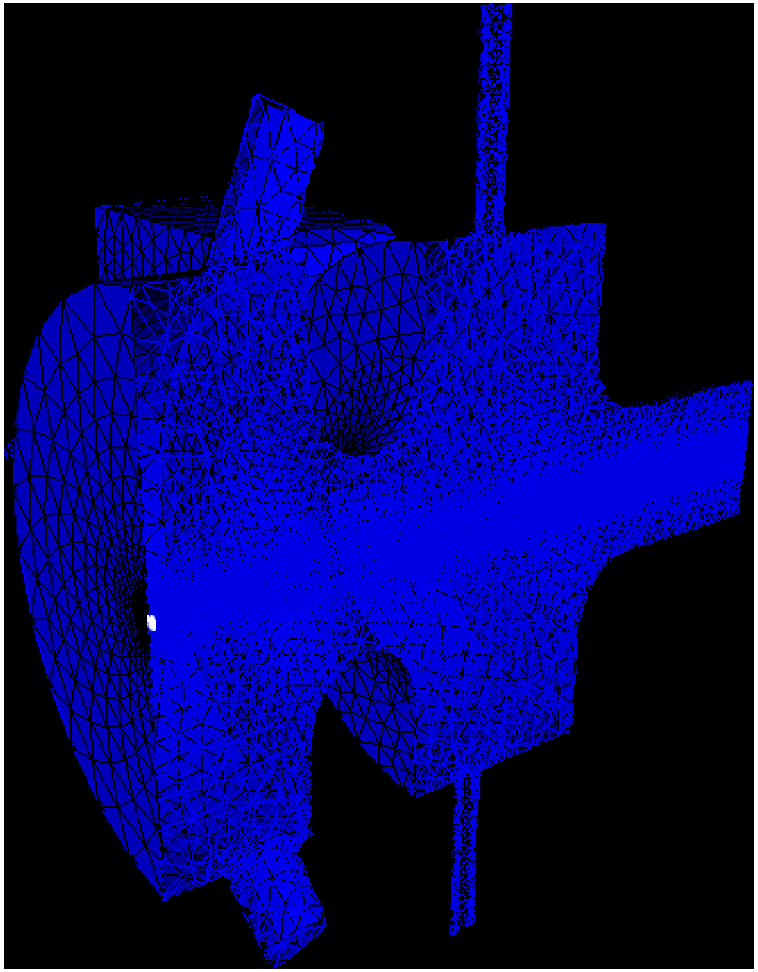


Track3P – Multipacting in SNS Cavity/HOM Coupler



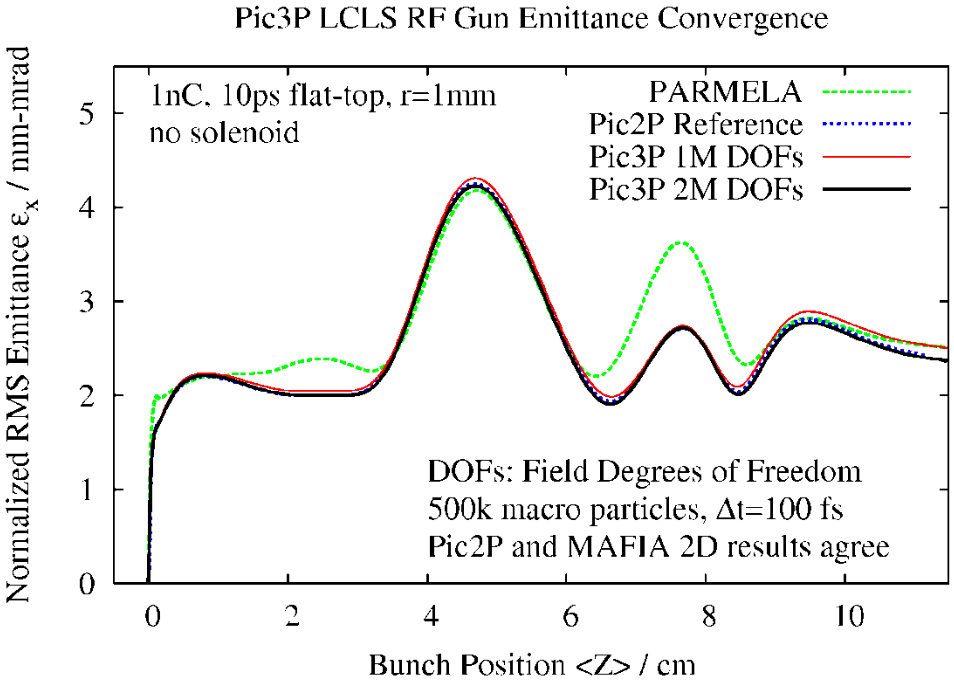
Visualization by Greg Schussman

Pic3P – LCLS RF Gun



Temporal evolution of electron bunch and scattered self-fields

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

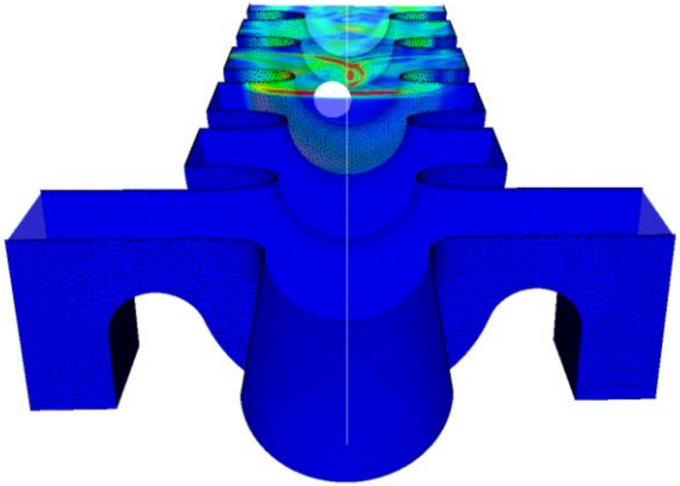


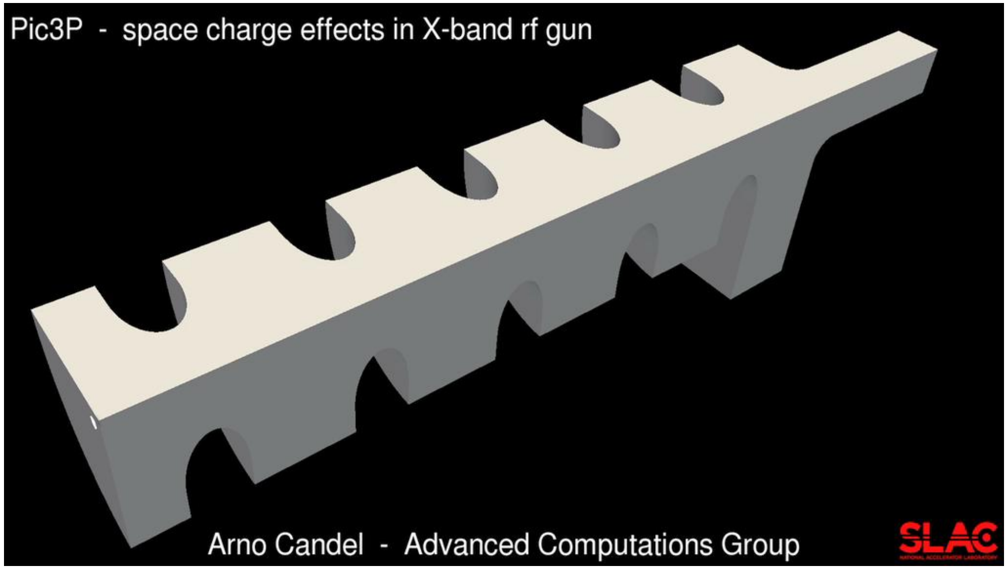
Unprecedented Accuracy due to Higher-Order Particle-Field Coupling and Conformal Boundaries

Pic3P – SLAC/LLNL X-Band Gun

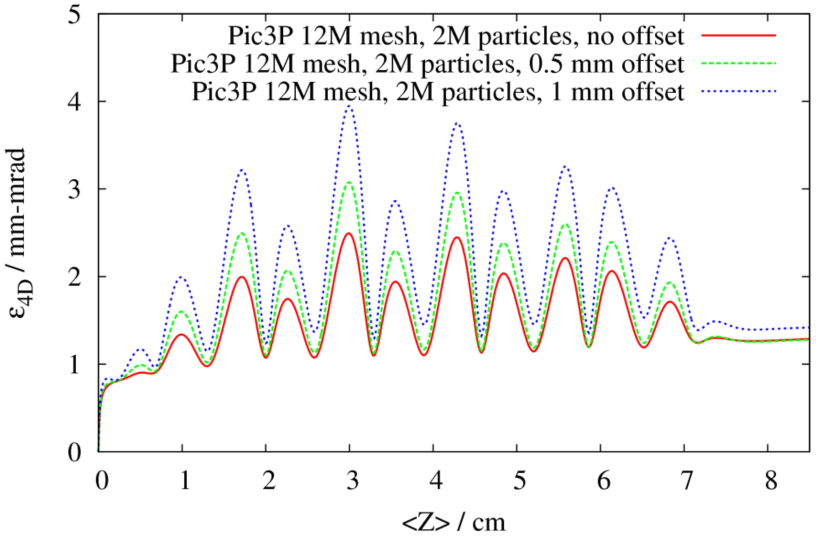
3D Emittance Calculations for Bunch with Offset

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



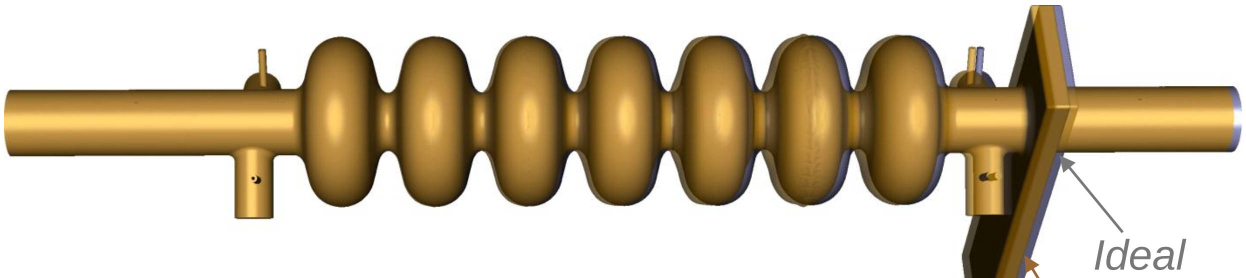


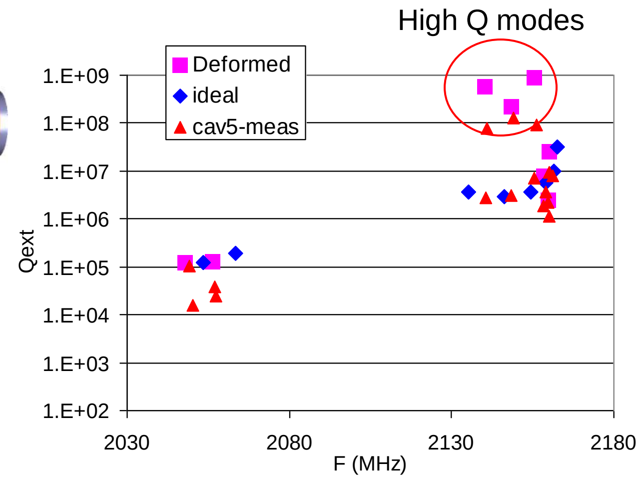
4D Emittance vs <Z>



Solving the CEBAF BBU – Joint Efforts from Accelerator Physics + Experiment + Computational Science + Computing

CEBAF BBU - Solving the Inverse Problem

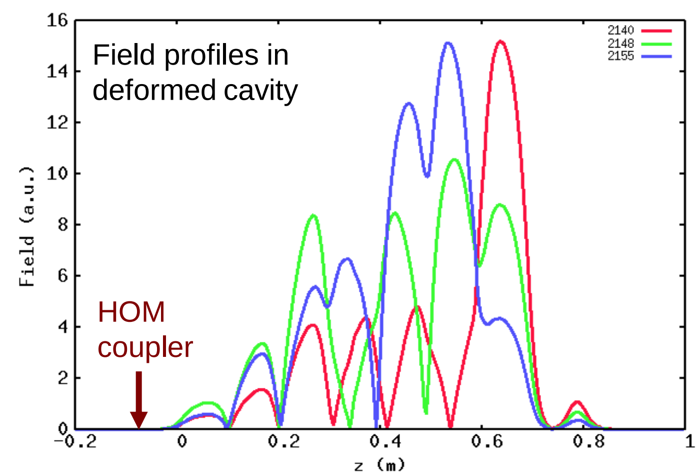




***CEBAF 12-GeV upgrade* –**

- 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

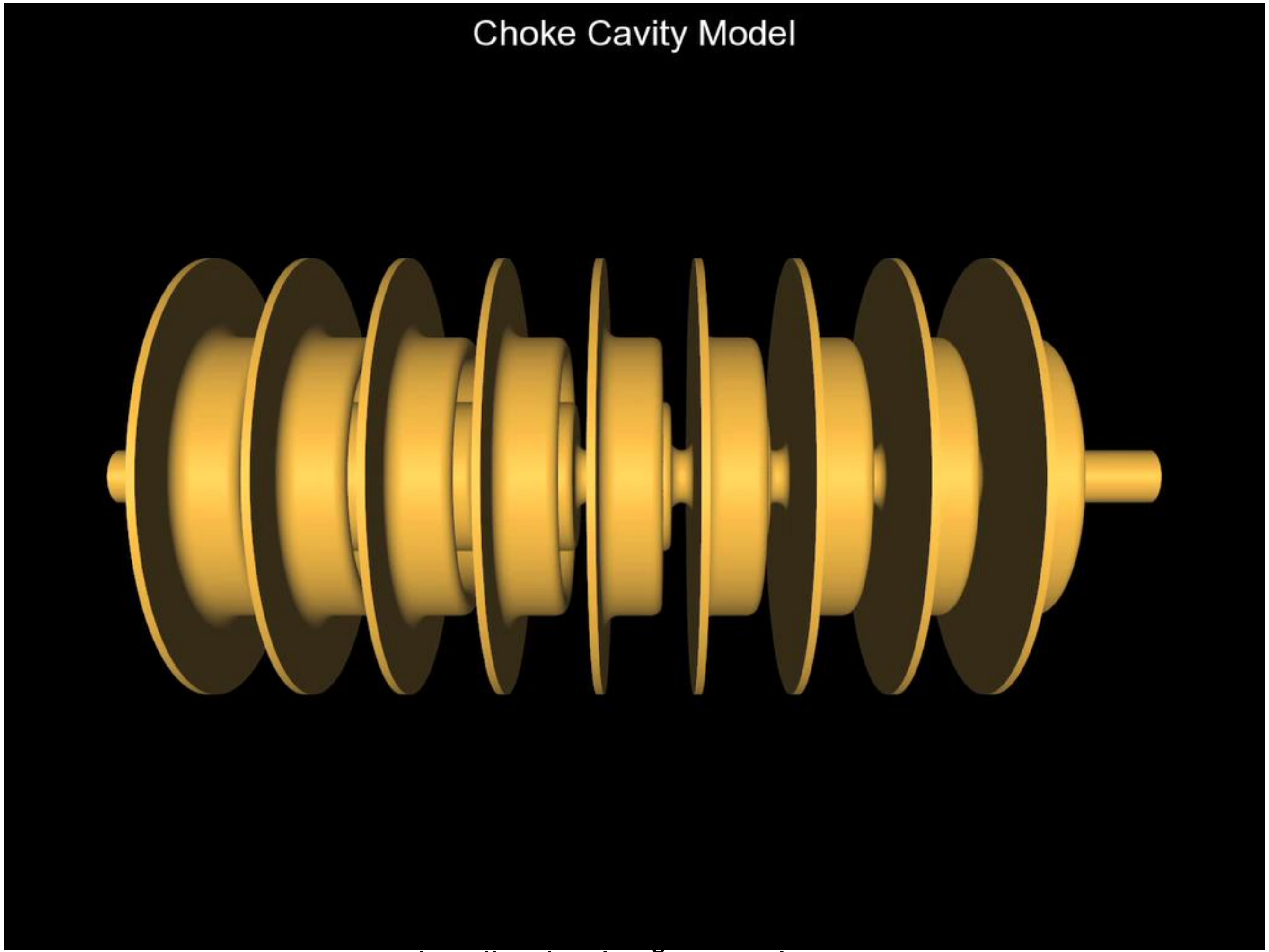
Omega3P



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



Visualization by Greg Schussman

ACE3P User Community – CW10 Code Workshop

CW10 @ SLAC

CW10 ACCELERATOR CODE WORKSHOP — **SLAC NATIONAL ACCELERATOR LABORATORY**

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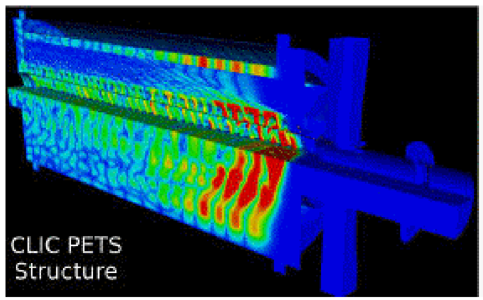

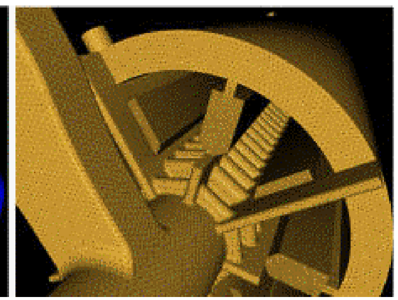

Accelerator Code Workshop (CW10) at SLAC for the ACE3P (Advanced Computational Electromagnetics 3P) Code Suite organized by the Advanced Computations Group (ACG)

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

Contact — ACD-CW10@slac.stanford.edu
650-926-2864
650-926-4603 (FAX)

SLAC ACCESS

All visitors must have a valid photo ID to enter the Laboratory. The SLAC Main Gate is open 24 hours a day, 7 days a week.

MAPS AND DIRECTIONS

» More Information

SLAC GUEST HOUSE

» More Information

SLAC National Accelerator Laboratory, Menlo Park, CA
Operated by Stanford University for the U.S. Dept. of Energy

(http://www-conf.slac.stanford.edu/CW10/default.asp)

CW10 Attendees & Agenda

CW10 @ SLAC

CW10 ACCELERATOR CODE WORKSHOP — SLAC NATIONAL ACCELERATOR LABORATORY

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CW10 @ SLAC

CW10 ACCELERATOR CODE WORKSHOP — SLAC NATIONAL ACCELERATOR LABORATORY

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Agenda

All sessions are 1 hr 45 min

	9/22 Monday	9/23 Tuesday	9/24 Wednesday
			Parallel Sessions
8.30-10.15	**Intro/CUBIT**	**Track3P**	**Pic3P | Applications**
10.15-10.30	*break*	*break*	*break*
10.30-12.15	**ACE3P/ParaView**	**Track3P**	**TEM3P | Applications**
12.15-1.30	*lunch*	*lunch*	*CW10 Ends*
1.30-3.15	**Omega3P/S3P**	**T3P**	
3.15-3.30	*break*	*break*	
3.30-5.15	**Omega3p/S3P**	**T3P**	

SLAC National Accelerator Laboratory, Menlo Park, CA
Operated by Stanford University for the U.S. Dept. of Energy

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.