Large Scale Finite-Element Electromagnetic Simulations for Projects across DOE Accelerator Complex

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SLAC National Accelerator Laboratory

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SLAC
NATIONAL ACCELERATOR LABORATORY

SciDAC
Scientific Discovery through Advanced Computing

Advanced Computations Department (ACD)

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Massively Parallel Computing in Electromagnetics

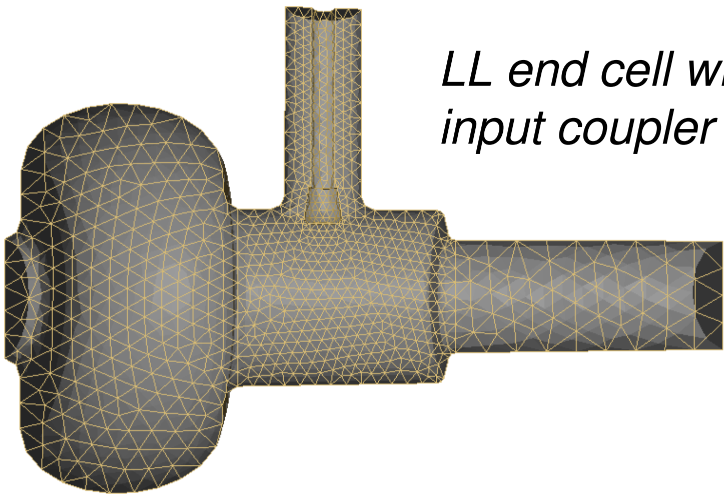
- Develop **Parallel** codes in ***Electromagnetics***
- Perform research in ***Computational Science*** by collaborating with **SciDAC** Centers for Enabling Technologies & Institutes
- Focus on ***Large-scale simulations*** using computers at **NERSC** and **NCCS** (with 1 INCITE and 3 allocation awards)

➢ *solve the most challenging problems in accelerator design, optimization and analysis via High Performance Computing for the DOE-SC complex working on*

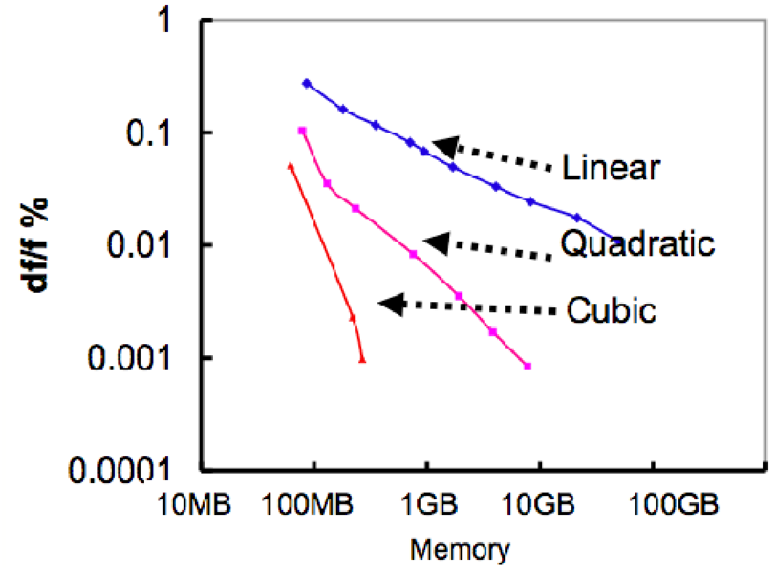
HEP - High Gradient, Laser Acceleration, Muon Collider, ILC, Project X, LARP

NP - CEBAF12 GeV Upgrade   BES – LCLS

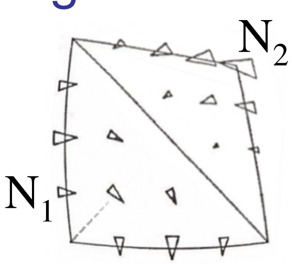
Higher-order Finite-Element Method



LL end cell with input coupler only



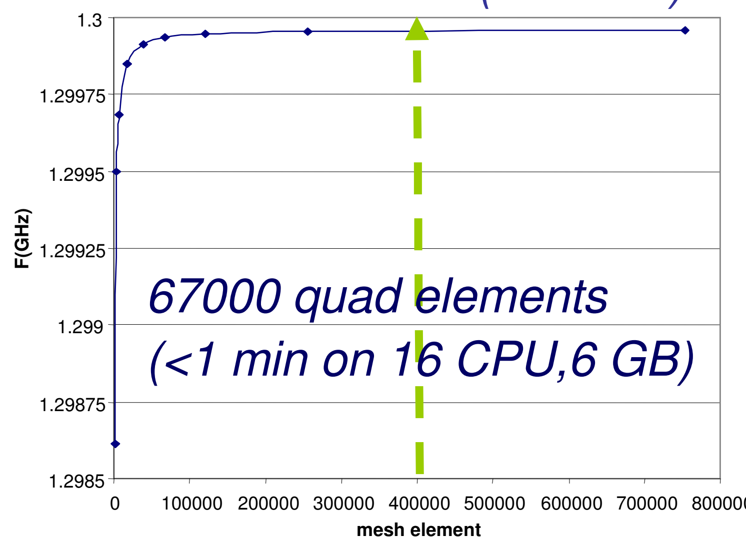
- Tetrahedral conformal mesh with quadratic surface
- Higher-order Finite Elements (p = 1-6)



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

- Parallel processing (large memory & speedup)

Error ~ 20 kHz (1.3 GHz)



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Parallel Electromagnetics Codes

Suite of scalable Finite-Element Electromagnetics codes to model Large, Complex structures with high accuracy:

Frequency Domain:	**Omega3P**	– eigensolver (mode damping, non-linear)
	S3P	– S-parameter
Time Domain:	**T3P**	– transients & wakefields
	Pic3P	– self-consistent particle-in-cell (PIC)
Particle Tracking:	**Track3P**	– dark current and multipacting
	Gun3P	– space-charge beam optics
Multi-Physics:	**TEM3P**	– EM-thermal-mechanical
Visualization:	**V3D**	– meshes, fields and particles

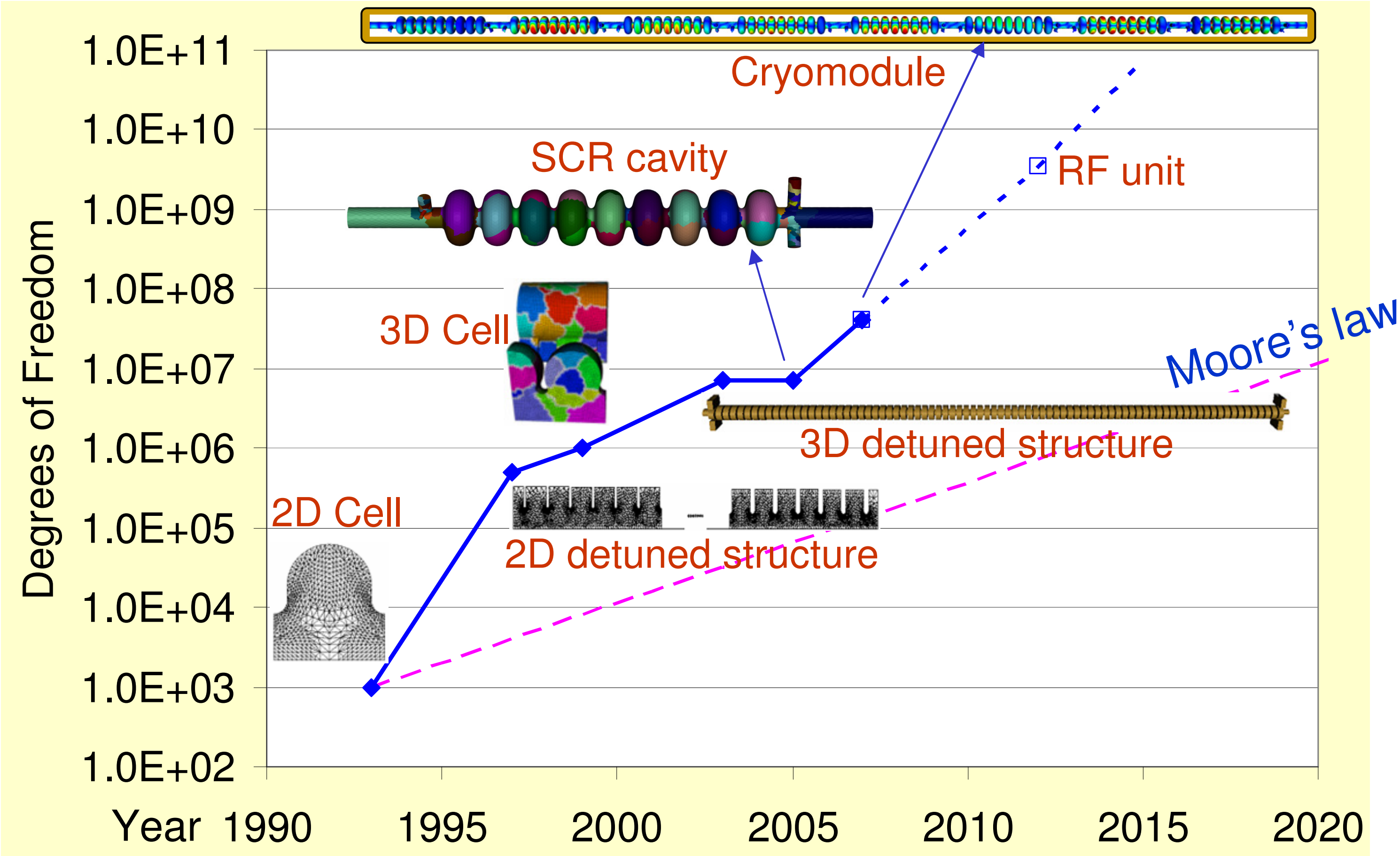
Developed under Grand Challenge and SciDAC1 (2001-2006) in black;
Under development for ComPASS (2007-2011) in red

Development of *Omega3P*

Goal: High Fidelity simulation -> CAD drawing -> hardware fabrication

- from single 2D cavity to a cryomodule of eight 3D ILC cavities

An increase of 10^5 in problem size with 10^{-5} accuracy over a decade



SciDAC Scientific Discovery through Advanced Computing

Activities for Code Development

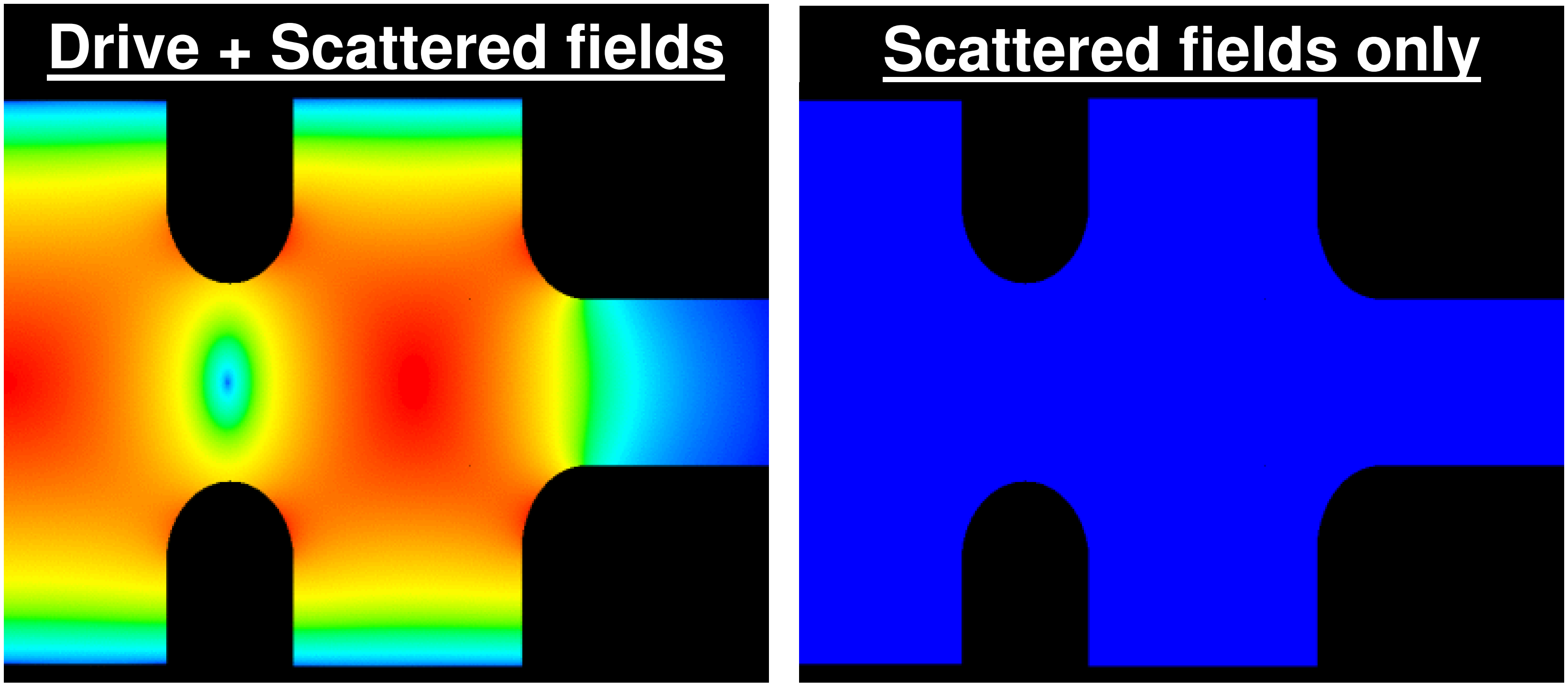
- ***Omega3P***
  - Implement domain specific scalable solvers
  - Develop shape optimization algorithms
- ***T3P***
  - Implement Napoly wakefield integration method
  - Improve moving h/p adaptive refined moving window for beam excitation
- ***Track3P***
  - Develop surface physics models and parallel particle tracking algorithms for dark current simulation
- ***TEM3P***
  - Develop new capabilities for thermal and mechanical solvers for realistic design and analysis of accelerator cavities
- ***Pic3P***
  - Implement realistic 3D emission models and moving window for rf gun simulation

Pic2P - Finite Element 2D EM PIC Code

LCLS RF Gun has been designed to be cylindrically symmetric in beam region

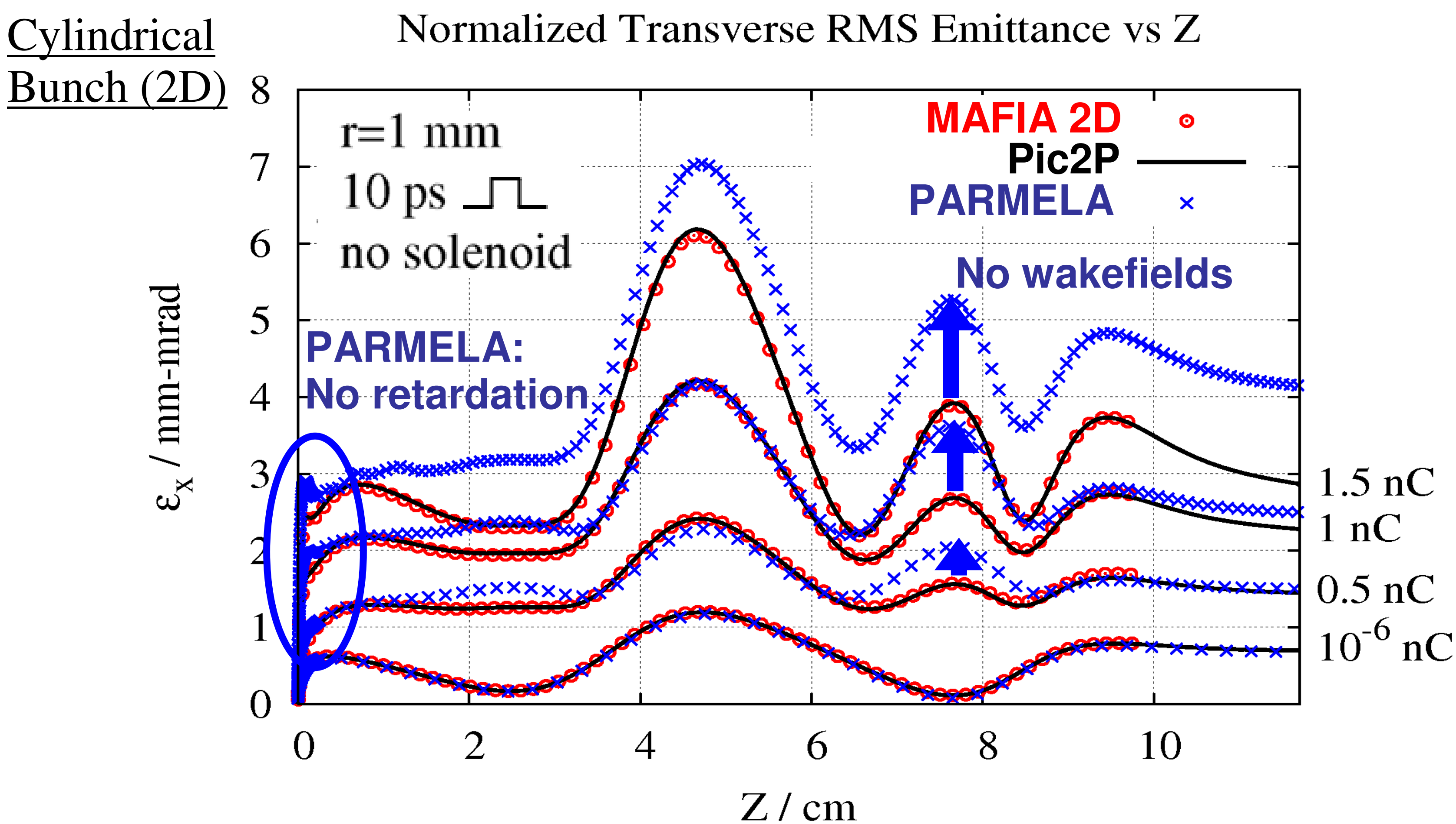
2.856 GHz, 120 MV/m, π-mode

Cylindrical	r=1 mm
Bunch (2D)	10 ps
Q=1nC	no solenoid



Pic2P – Parallel Finite Element 2D EM PIC Code
from 1st principles, accurately includes effects of
space charge, retardation, and wakefields

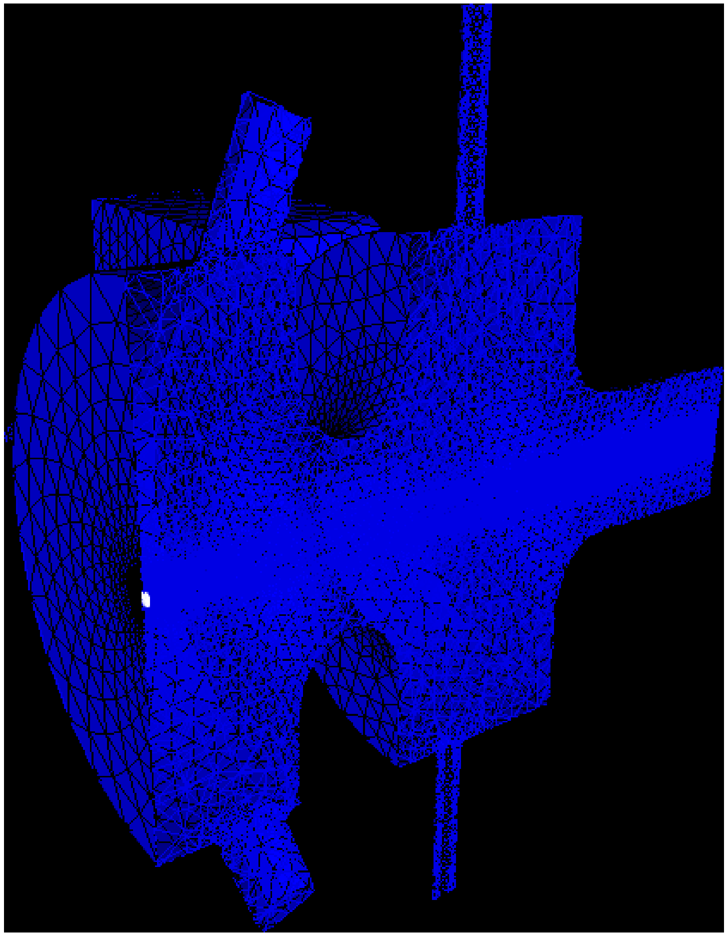
PIC Codes at Space Charge Limit



- **MAFIA and Pic2P results agree**
- **PARMELA results* differ at higher space-charge regime**

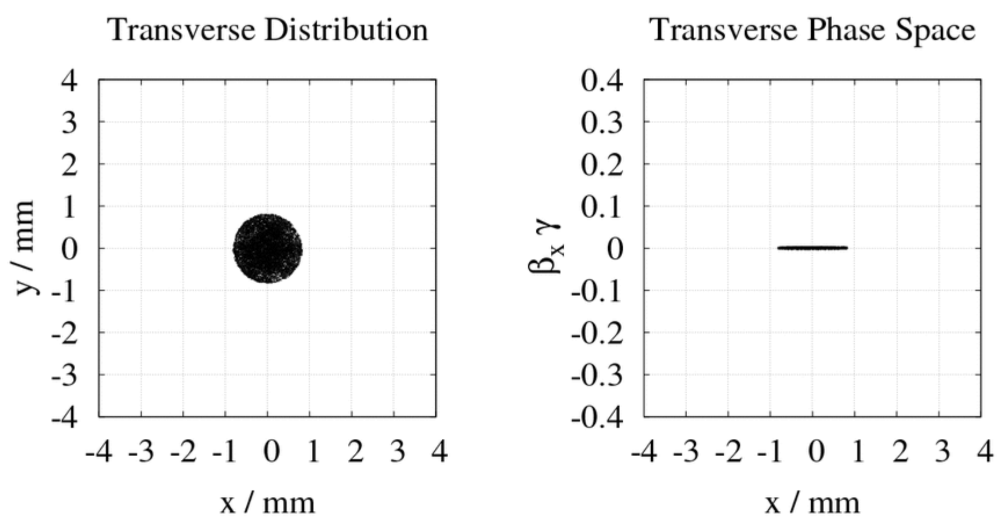
* courtesy Cecile Limborg

Pic3P - LCLS RF Gun Emittance



Evolution of electron bunch and scattered self-fields

*3D emittance calculations with **Pic3P** include space-charge, wakefields and retardation effects from first principles. Parallel processing and conformal higher-order finite elements allow unprecedented modeling accuracy.*



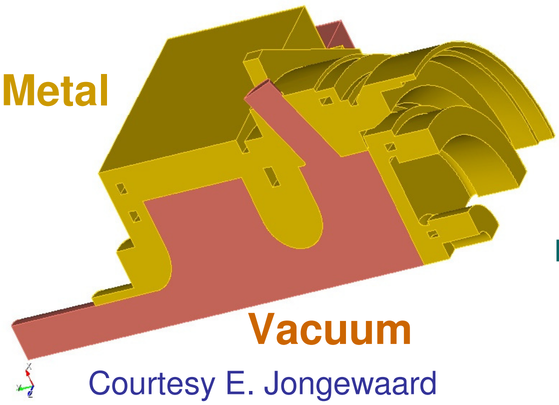
Evolution of transverse phase space, starting from SLAC measured data

In collaboration with LCLS

SciDAC Scientific Discovery through Advanced Computing

Advancing Multi-physics Simulation Tool

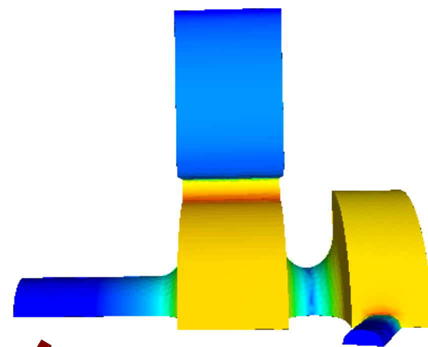
CAD model



Courtesy E. Jongewaard

TEM3P for design and optimization

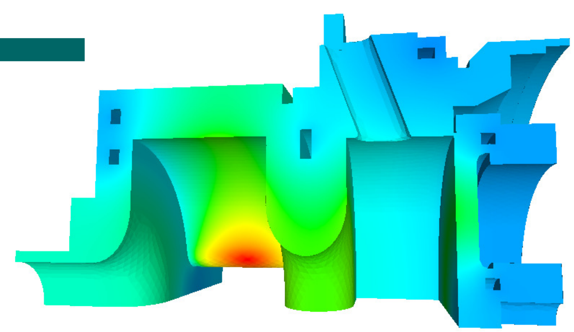
Electromagnetics



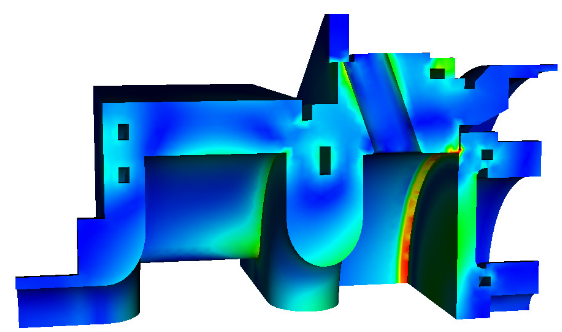
LCLS

***RF* Gun**

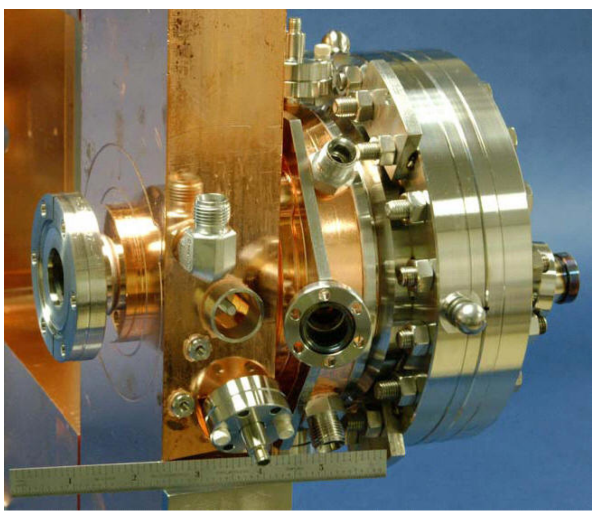
Thermal



Mechanical



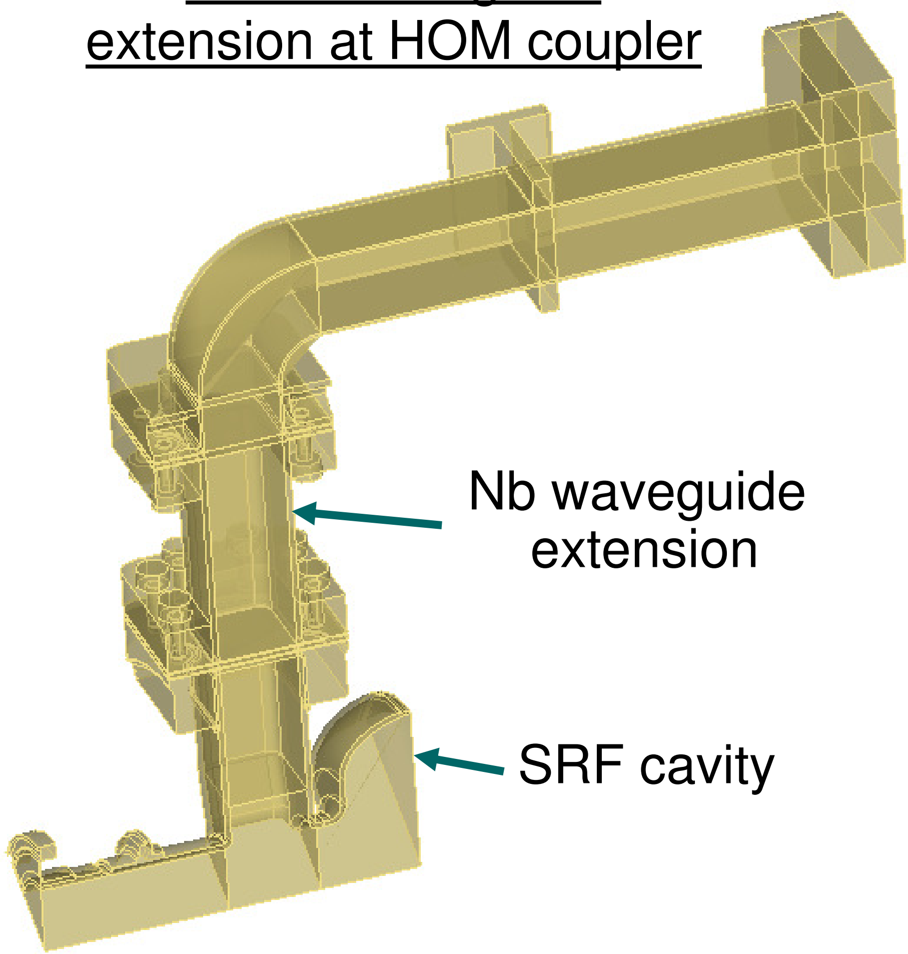
Engineering prototype



Courtesy D. Dowell

In collaboration with LCLS

Tem3P – Cooling of CEBAF HOM waveguide



- ***Simulation goal***
  - Determine design to satisfy cooling requirements including RF and thermal effects
- ***Tem3P code development***
  - Implement thermal shell elements for thin layers
  - Develop nonlinear solver for temperature-dependent material properties
  - Implement boundary condition for He convection cooling

In collaboration with TJNAF

Activities for Accelerator Simulation

High Energy Physics

- ***ILC/Project X*** – Wakefield and HOM effects in cryomodule with cavity imperfection; low-emittance rf gun
- ***LHC/LARP*** – Design and optimization of crab cavity; Wakefield effects in collimator
- ***High-Gradient R&D*** – Optimization of choke cavities for HOM damping; CLIC PETS and HDX accelerator structure
- ***Muon Collider*** – Multipacting & dark current studies for muon cooling cavity
- ***Laser Acceleration*** – Coupler design for optical fiber

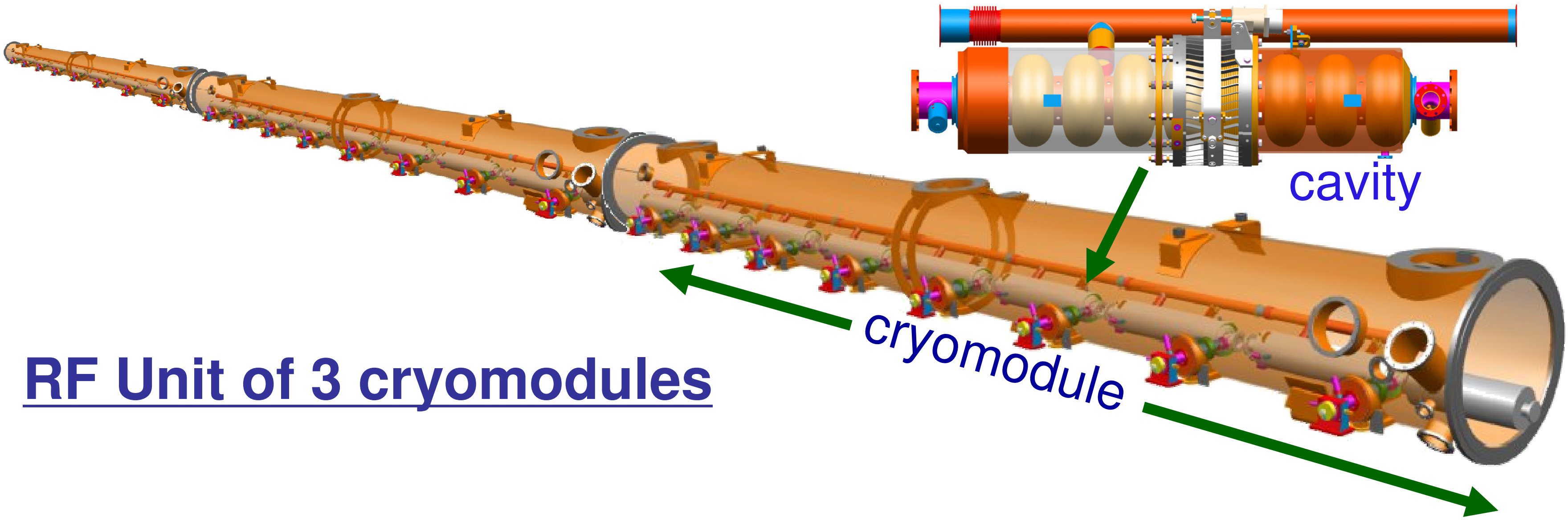
Nuclear Physics

- ***CEBAF 12-GeV Upgrade*** – EM, thermal and mechanical analysis of SRF cavity coupler

Basic Energy Sciences

- ***LCLS RF Gun*** – 3D self-consistent PIC simulation

Modeling an Entire RF Unit of ILC Linac



RF Unit of 3 cryomodules

Physics Goal: Calculate wakefield effects in the 3-cryomodule RF unit (**26** cavities) with realistic 3D dimensions and misalignments

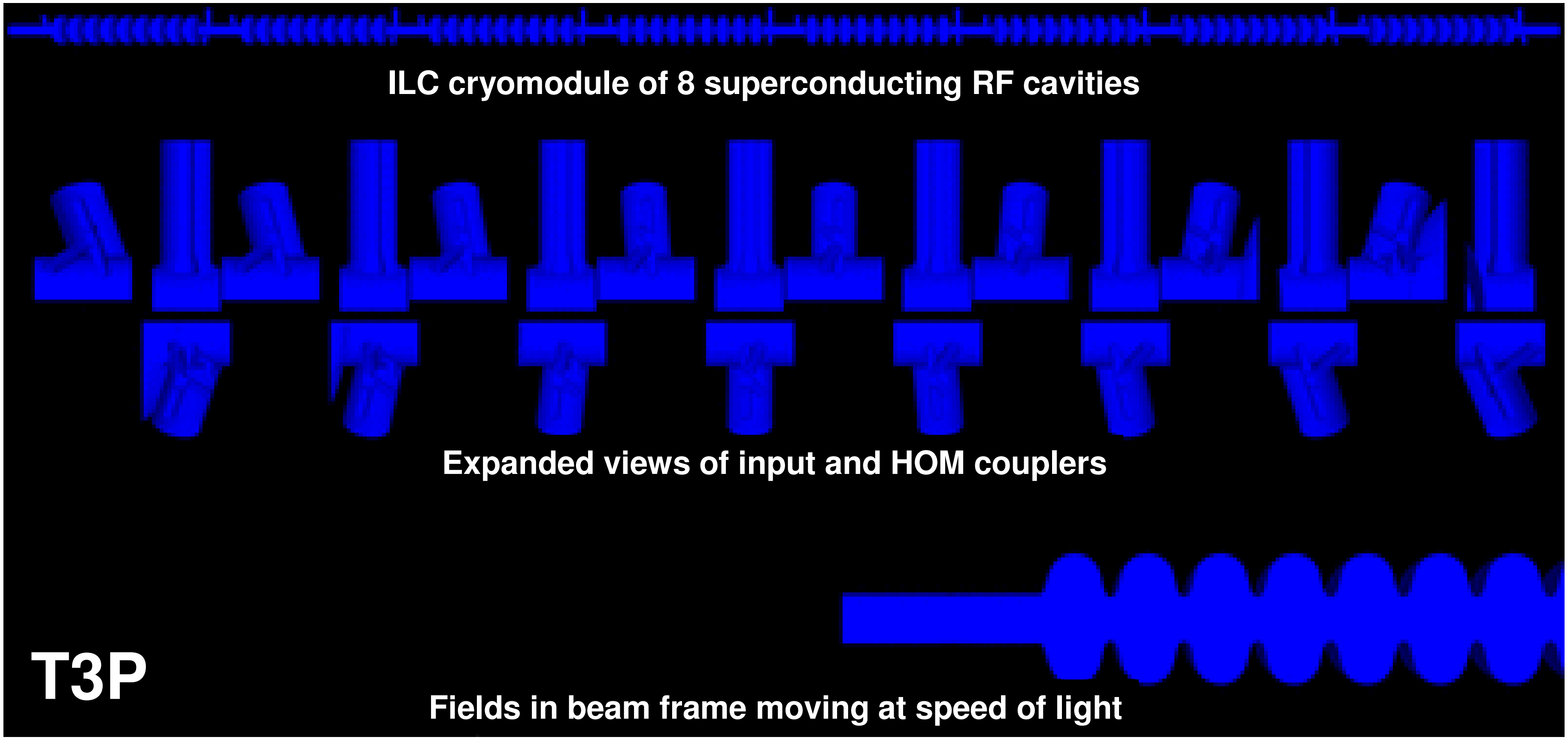
The LARGEST problem for time-domain analysis

- *80 million-element mesh, ~500 million DOFs, 4096 CPUs (Jaguar), 4 seconds per time-step.*

For frequency domain

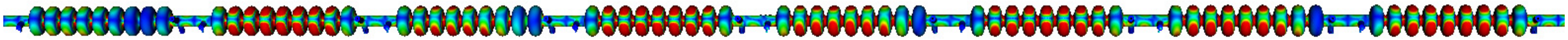
- *3 million-element mesh, ~20 million DOFs, 1024 CPUs (Seaborg), 300 GB memory, 1 hour per mode.*

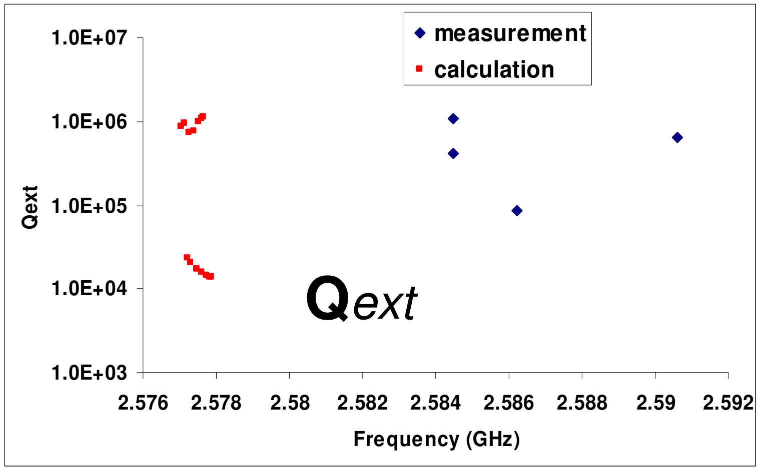
T3P - 1st ever Beam Transit in Cryomodule



Trapped Modes in ILC Cryomodule

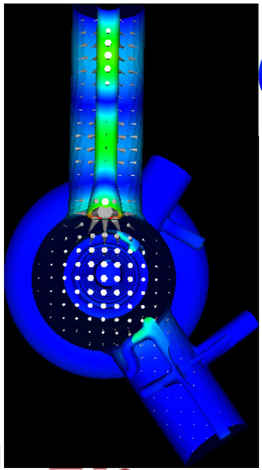
▪ *Trapped modes in 3rd dipole band*

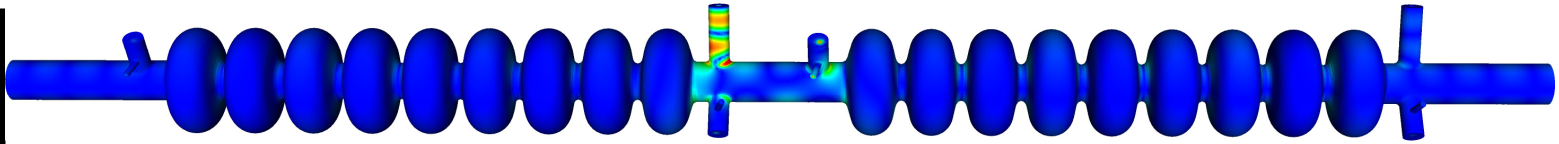




- Modes above cutoff frequency are coupled throughout 8 cavities
- Modes are generally x/y-tilted & twisted due to 3D end-group geometry
- Both tilted and twisted modes cause ***x-y coupling in the beam***

▪ *Trapped mode in beampipe between 2 cavities*

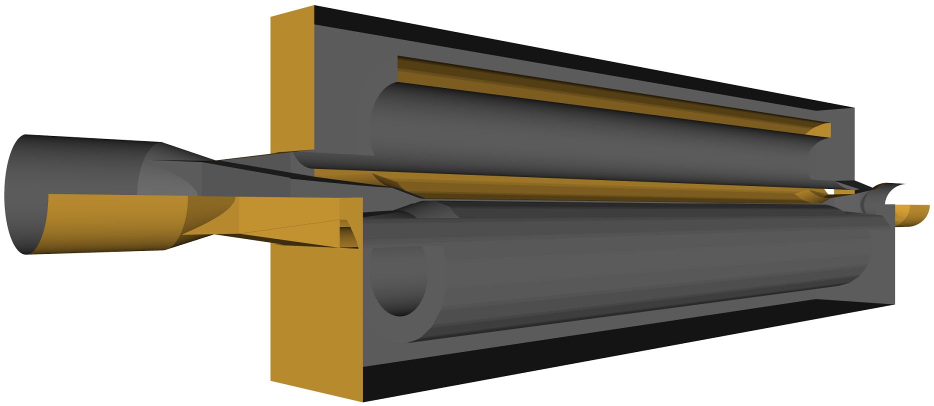




- TM-like mode at 2.948 GHz, higher than 2.943 GHz TM cutoff
- R/Q = 0.392 Ω, Q = 6320
- Mode power = 0.5 mW (averaged)

  (not a concern for heating in this case)

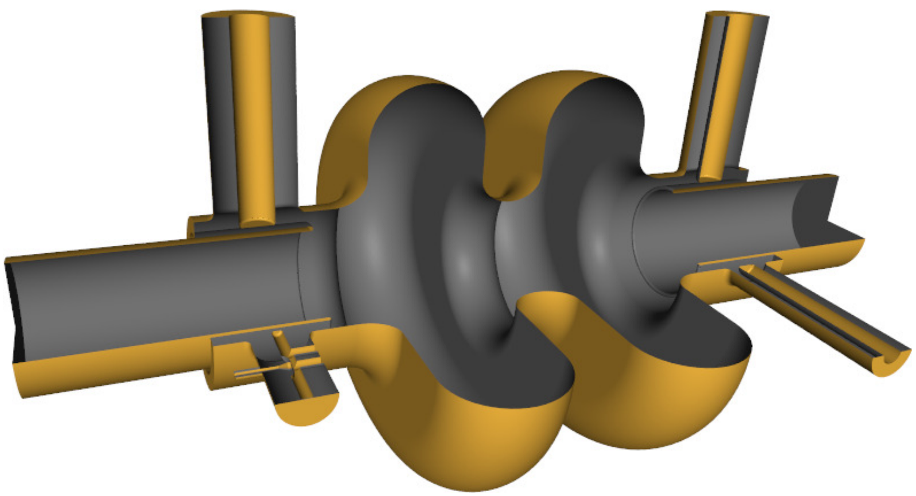
Supporting the LHC



***LHC Collimator* (Upgrade)**

Impedance and beam heating effects are important for the design.

(*Omega3P and T3P*)



***LHC Crab Cavity* (Upgrade)**

The crab cavities rotate the beams at the IP to produce head-on collisions, improving luminosity. Design for strong damping of SOM/LOM/HOM is needed.

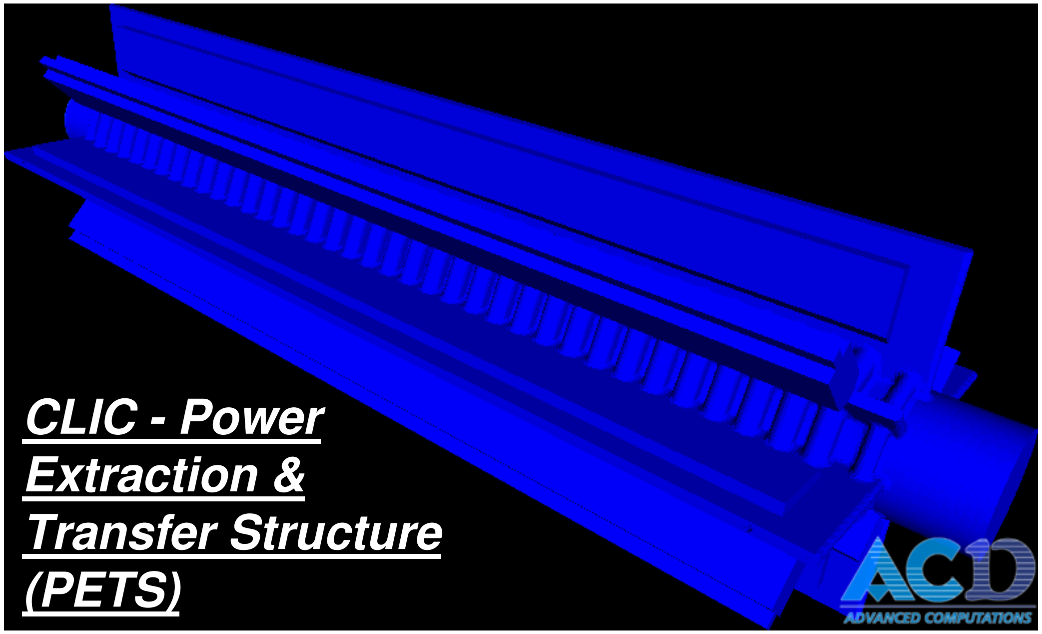
(*Omega3P*)

Baseline Design of crab cavity for LHC upgrade

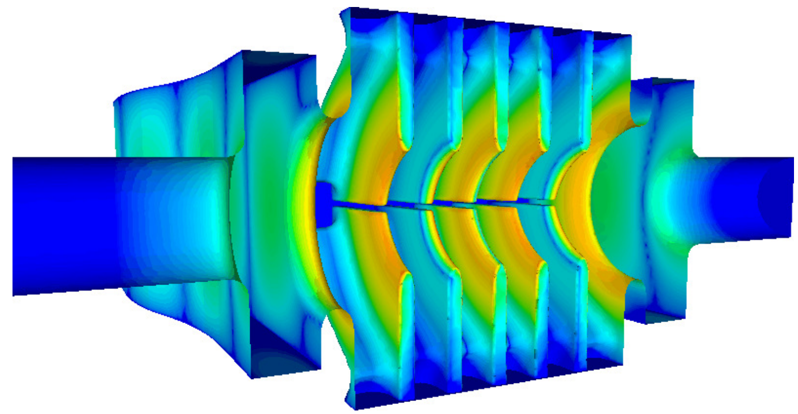
Advancing High Gradient R&D

HOM damping & Multipacting studies are needed for High Gradient Structures

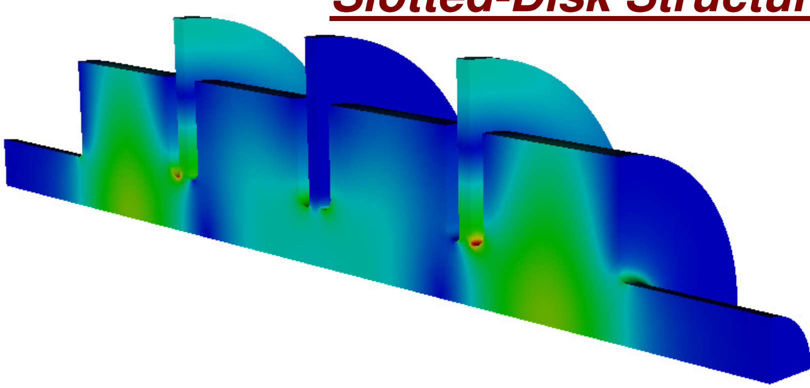
CLIC - Power Extraction & Transfer Structure (PETS)



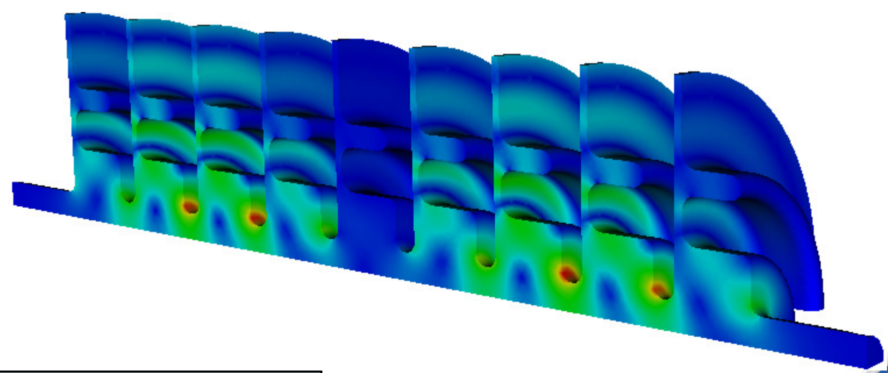
CLIC – Hybrid Damped Structure (HDX)



Slotted-Disk Structure



Choke-Mode Structure



In collaboration with CERN

Track3P - Multipacting in SRF Cavities

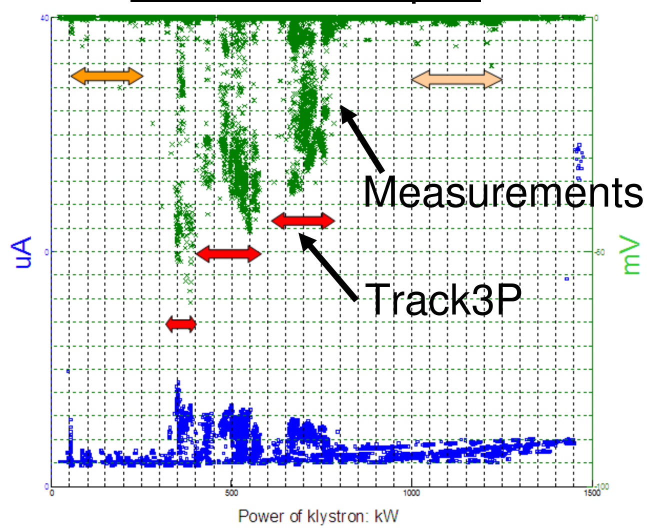
ILC Linac TTF-III cavity coupler

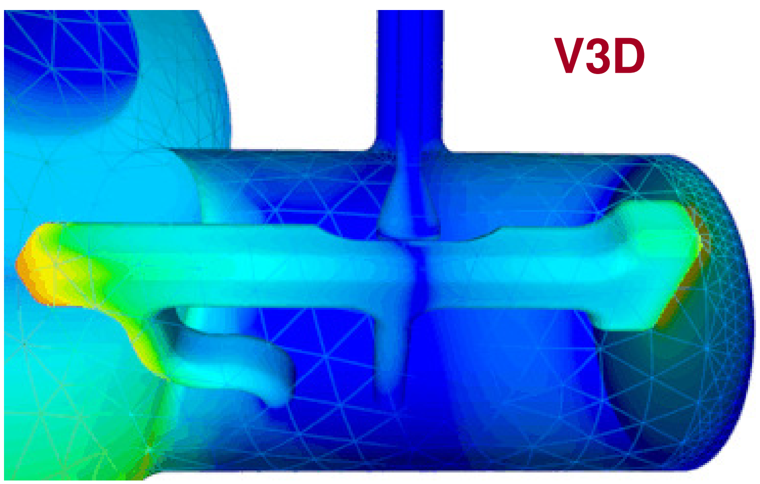
- Simulated MP bands in coaxial waveguide agreed with measurements

SNS SRF cavity HOM coupler

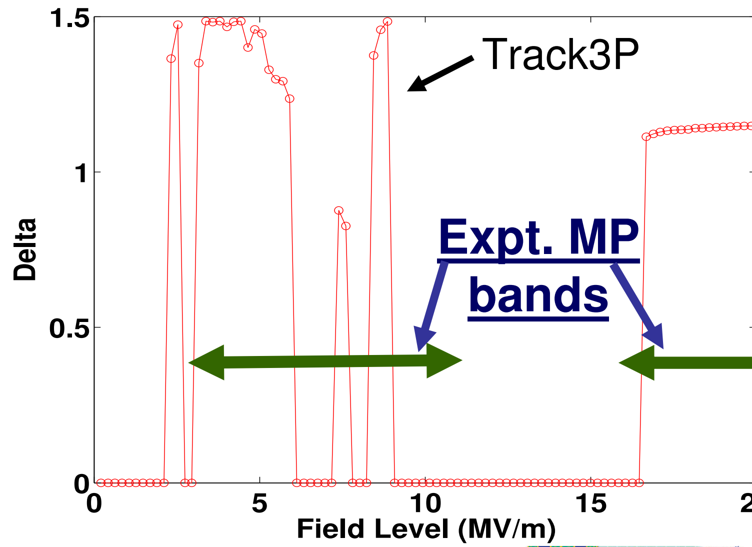
- RF heating observed at HOM coupler
- 3D simulations showed MP barriers close to measurements

MP in TTF coupler



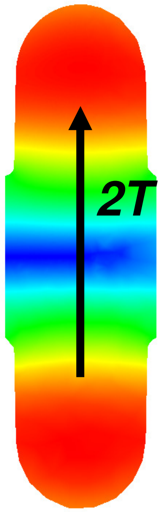


MP in SNS HOM coupler



Advancing Muon Cooling Cavity Design

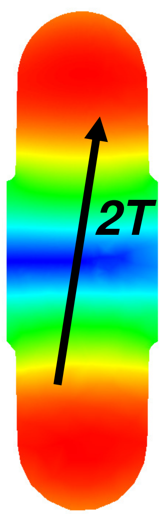
Particle tracking to study multipacting or dark current damage



2 types of resonant trajectories:

- Between upper and lower irises
- Between upper and lower cavity walls

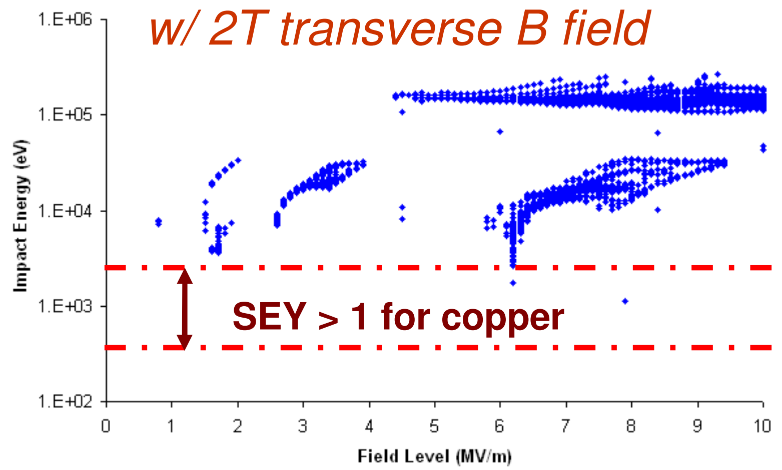
Slight MP activities observed above 6 MV/m

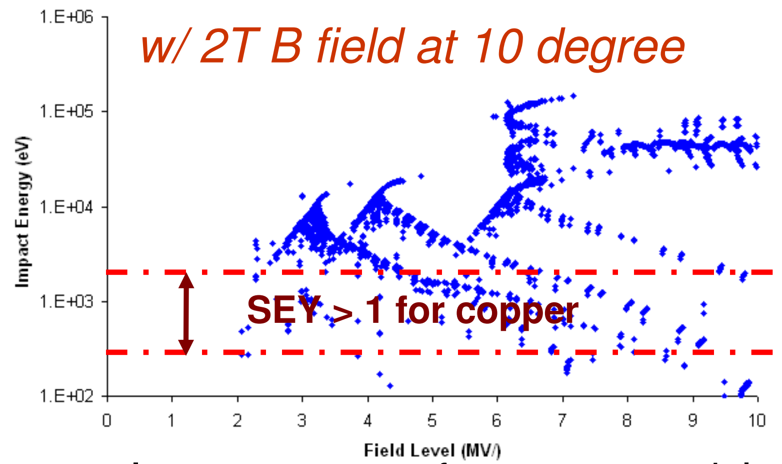


2 types of resonant trajectories:

- One-point impacts at upper wall
- Two-point impacts at beampipe

MP activities observed above 1.6 MV/m





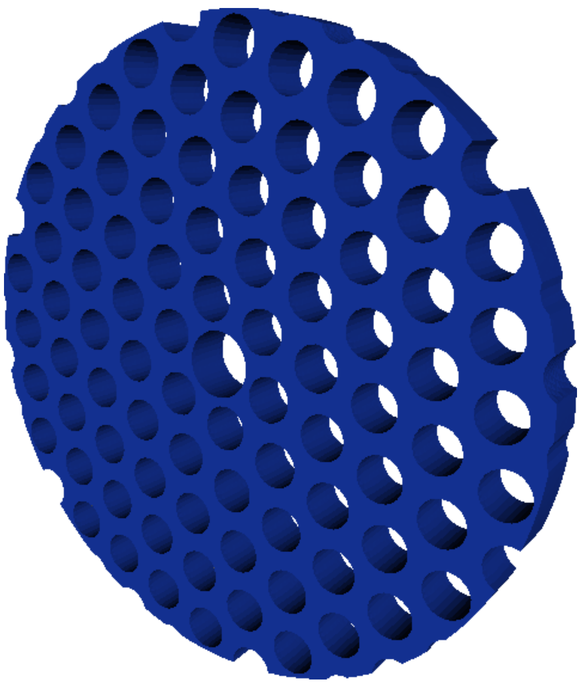
Impact energy of resonant particles vs. field level

In collaboration with BNL and LBNL

Advancing Laser Acceleration

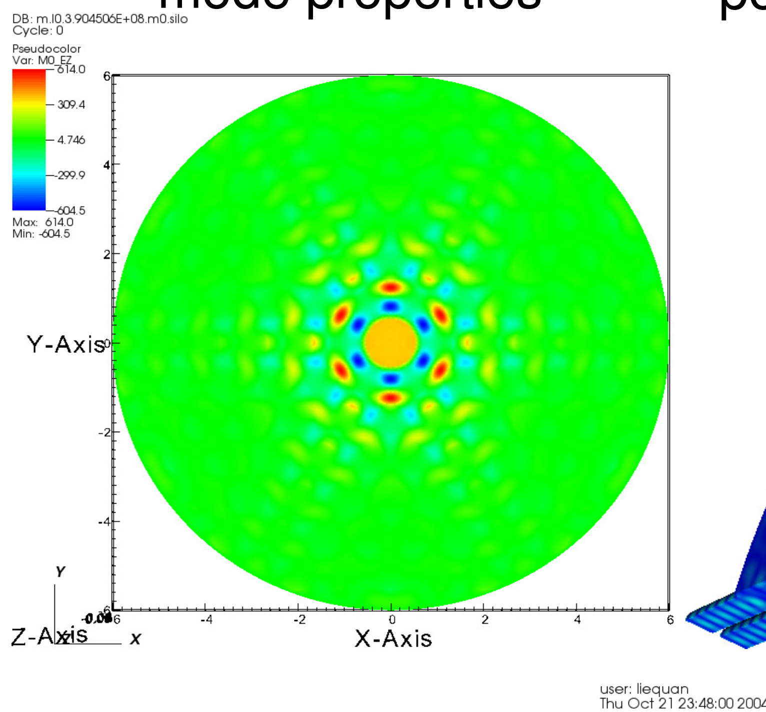
Develop a conceptual design for power coupling into optical fiber

Model of a fiber slab



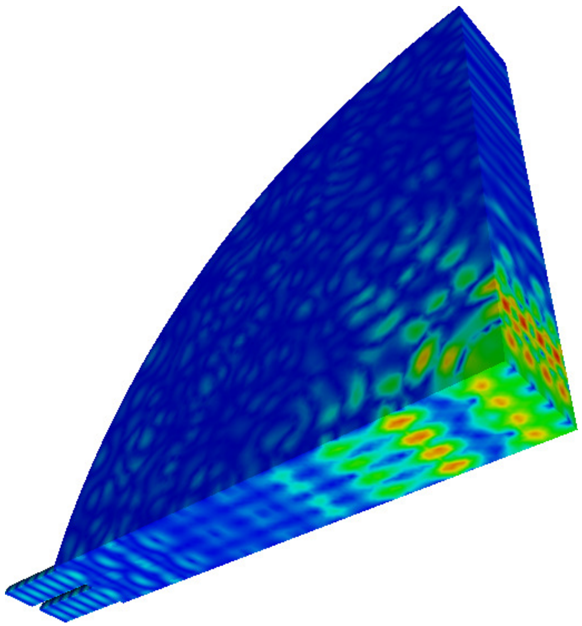
Defect Mode

Omega3P used to determine defect mode properties

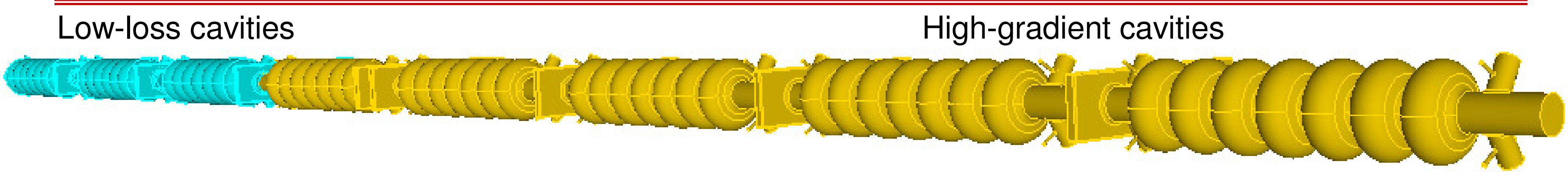


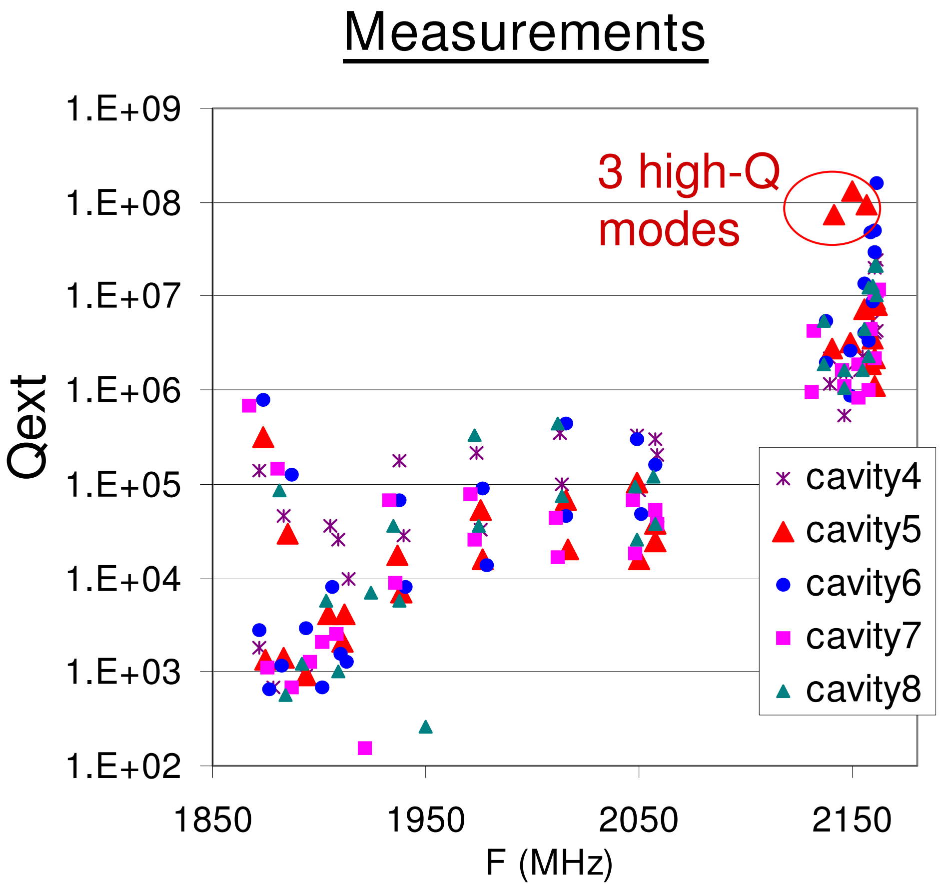
Coupler

S3P used to determine coupling of power to defect mode



BBU in CEBAF 12 GeV Upgrade Cryomodule

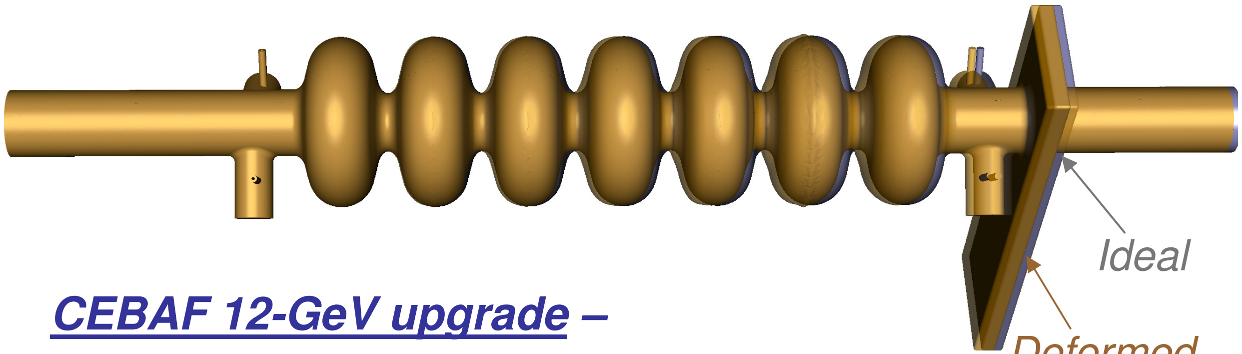


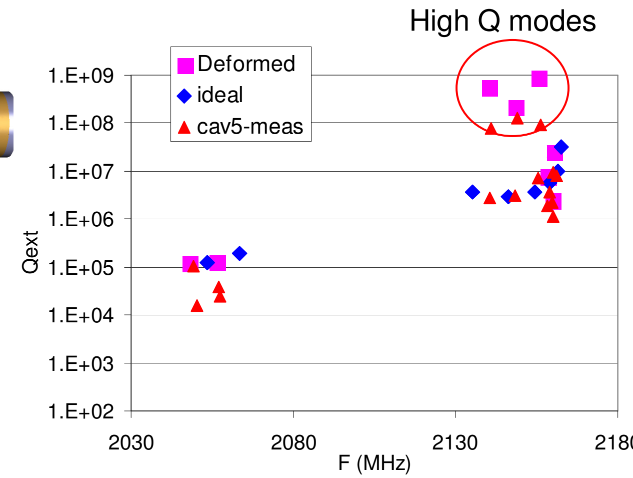


- Tests show 3 abnormally high Q modes in # 5 of the high-gradient cavities
- Beam-breakup (BBU) threshold current is significantly below design value
- Issues could not be resolved experimentally
- SLAC scientists have made great progress in finding a solution by treating it as **an inverse problem**

Courtesy: H. Wang, F. Marhauser, J. Sekutowicz, C. Reece, R. Rimmer (TJNAF)

CEBAF BBU - Solving the Inverse Problem

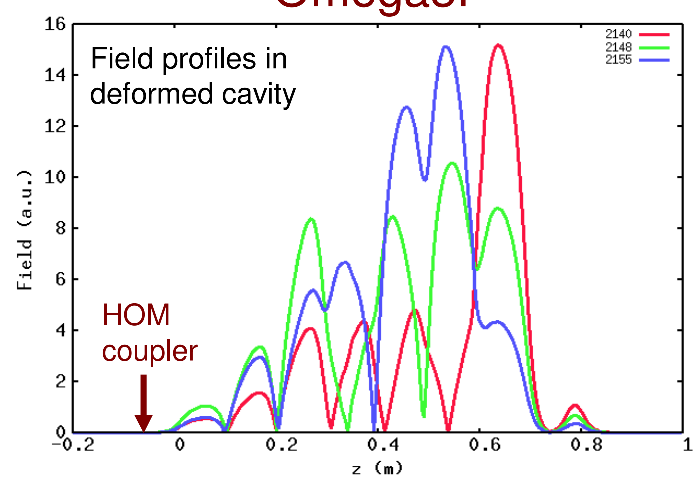




CEBAF 12-GeV upgrade –

- 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

Summary

- *SLAC FEM EM simulation tools have had significant impacts on a broad range of DOE accelerator projects in HEP, NP and BES*
- *Parallel EM codes have been tackling the most computationally challenging problems in accelerator design, optimization and analysis*
- *R&D in computational science via SciDAC (and the coming Exascale) is vital to the success of accelerators*
- *Large payback from collaboration of accelerator modeling and computational science such as JLab BBU analysis*

See following talk on AM/CS efforts on supporting FEM EM