Superconducting Cavity Imperfection Study for Project X Linac Using ACE3P

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SLAC National Accelerator Laboratory

ComPASS All-Hands Meeting
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Outline

1. Parallel Finite Element EM Code Suite ACE3P

2. Accomplishments for SRF Cavity Study under SciDAC2

3. Project X Linac Study under SciDAC3

4. Project X High Energy 650MHz Cavity Imperfection Study

5. Future Plan

Parallel Finite Element EM Code Suite ACE3P

SLAC has developed a suite of conformal, higher-order, C++/MPI-based parallel finite-element electromagnetic codes for high-fidelity modeling and simulation of large, complex accelerator structures.

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)
- **2012-15 Scientific Discovery through Advanced Computation (SciDAC-3) -** Community Petascale Project for Accelerator Science and Simulation (ComPASS)

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)

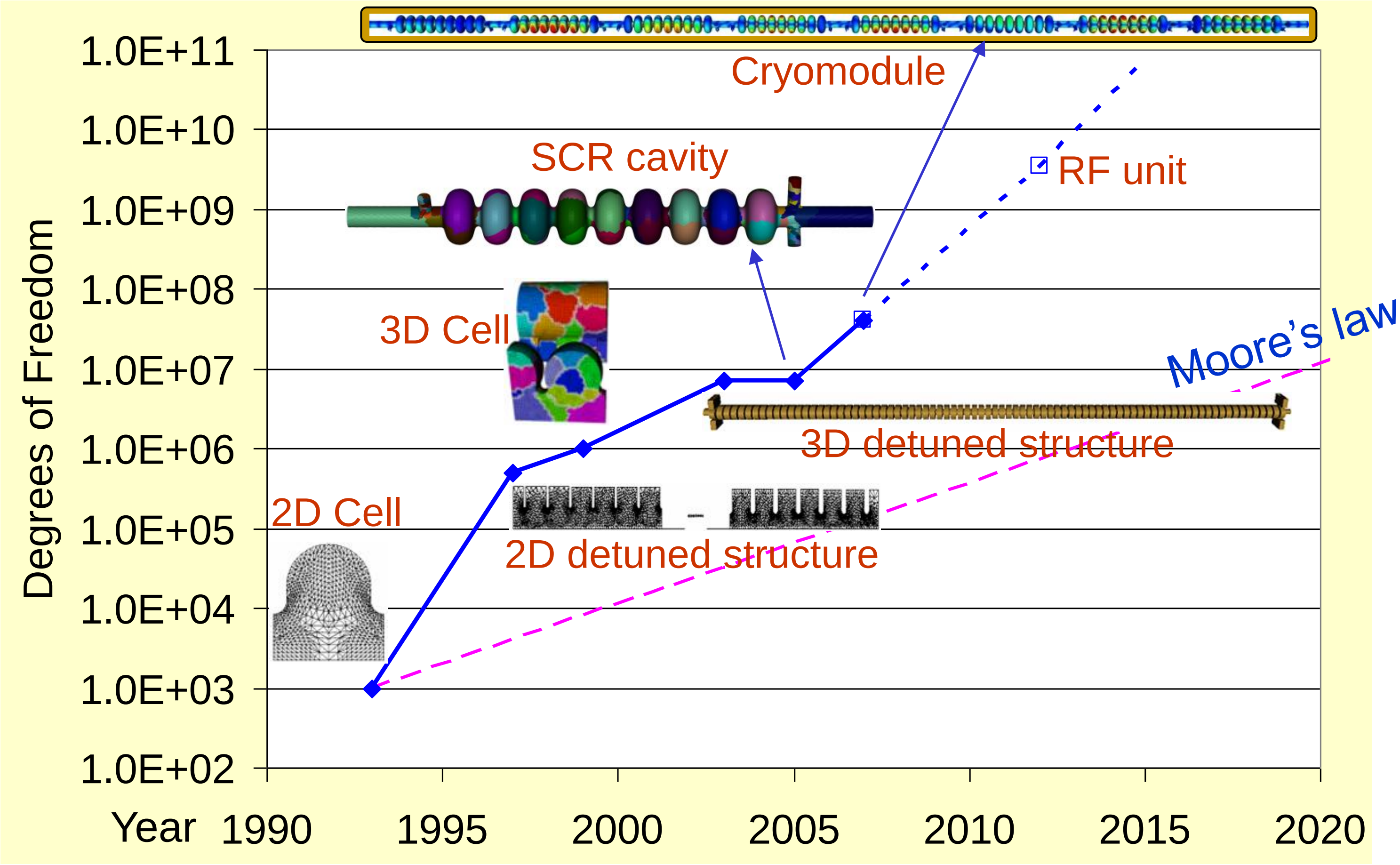
Frequency Domain:	**Omega3P**	**– Eigensolver (damping)**
	S3P	**– S-Parameter**
Time Domain:	**T3P**	**– Wakefields and Transients**
Particle Tracking:	**Track3P**	**– Multipacting and Dark Current**
EM Particle-in-cell:	**Pic3P**	**– RF gun (self-consistent)**
Multi-Physics:	**TEM3P**	**– EM, Thermal & Structural Effects**

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

Goal is the virtual prototyping of accelerator structures.

Omega3P - Towards System Scale Modeling

From single 2D cell to a cryomodule of eight 3D ILC cavities, an **increase of 10^5 in problem size with 10^{-5} accuracy over two decades**



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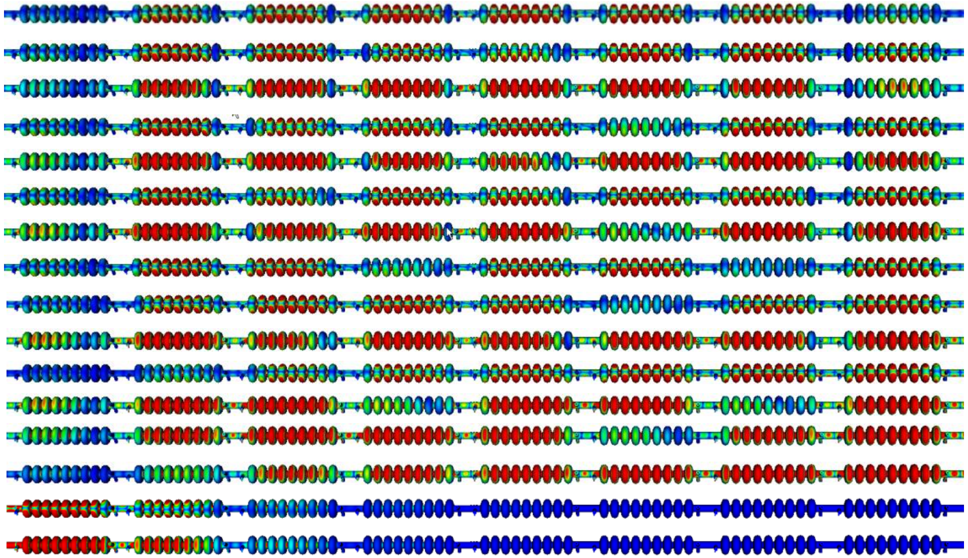
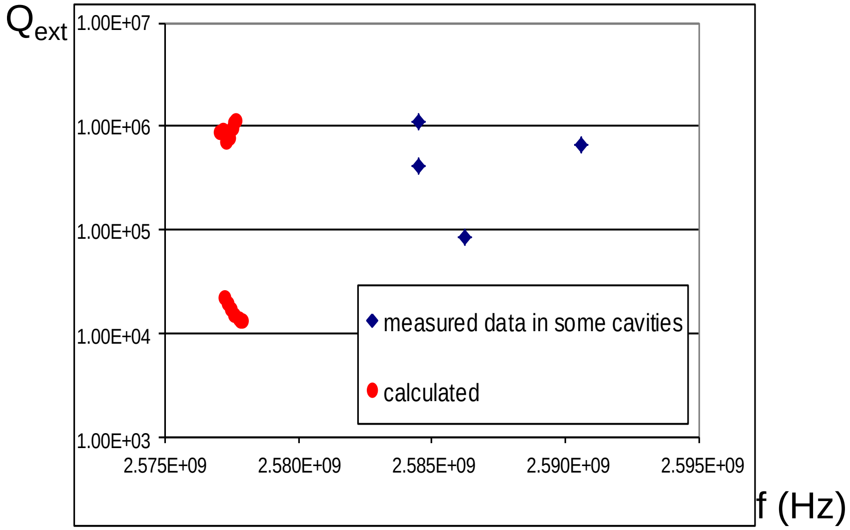
Trapped Modes in ILC Cryomodule – Omega3P



Trapped modes in 3rd dipole band



Comparison with measurements

- Beam induced Higher-order-modes (HOMs) in ILC linac can severely dilute the beam emittance.
- Simulations show that there are trapped modes around 2.6GHz in 3rd dipole band in ILC cryomodule with a high Q (~1.e6).
- Results agree qualitatively with measurements at DESY; discrepancies arise from cavity imperfections.
- Computational requirements: 3M mesh elements, 20M DOFs, 1024 CPUs on seaborg, 300 GB memory, 1 hour per mode

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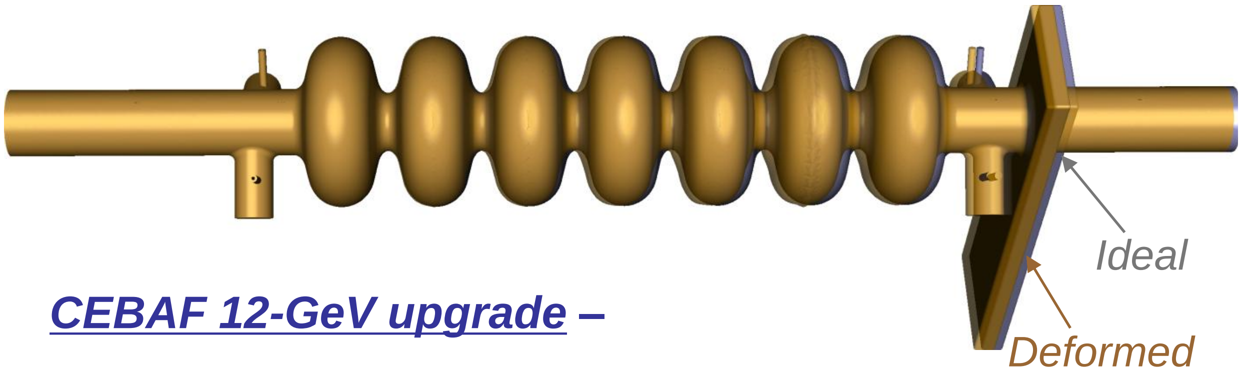
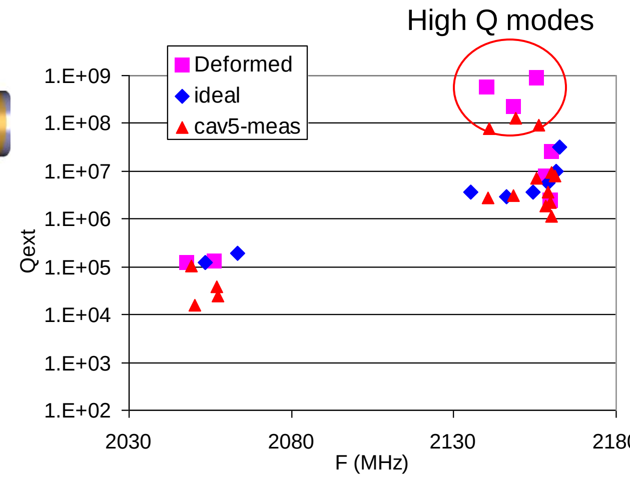
SciDAC Scientific Discovery through Advanced Computing

CEBAF BBU - Solving the Inverse Problem

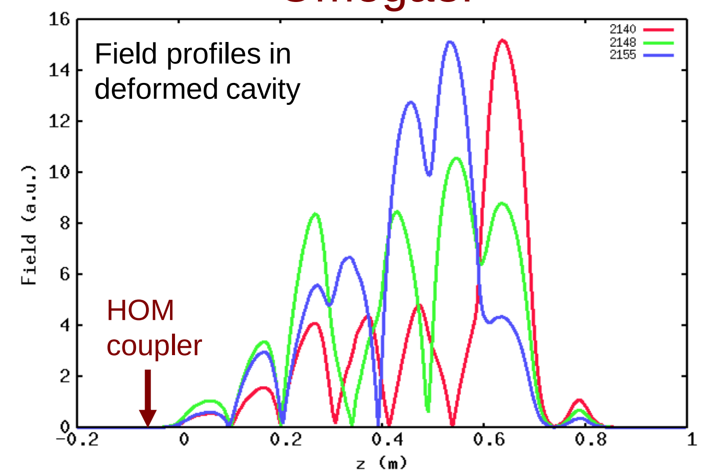




***CEBAF 12-GeV upgrade* –**

- 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

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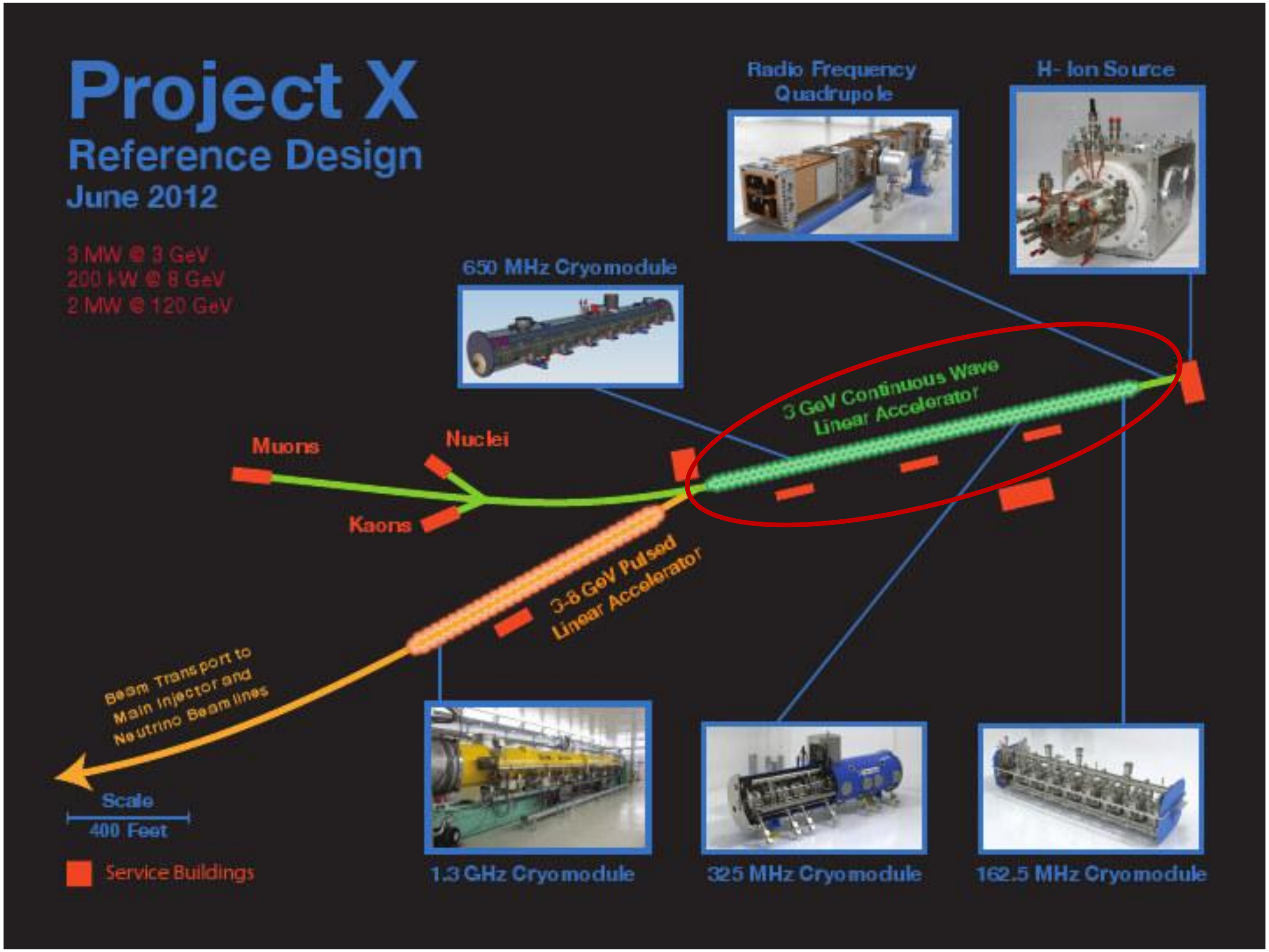
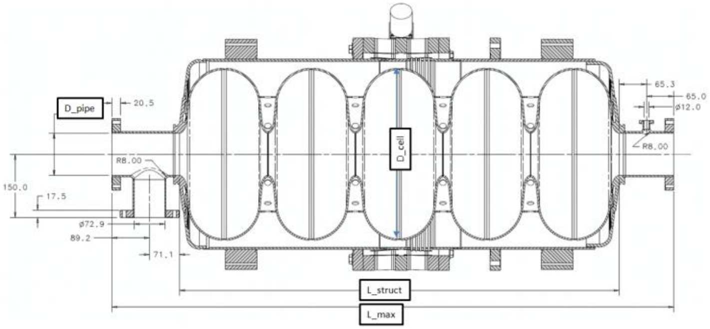
Intensity Frontier Facility - Project X

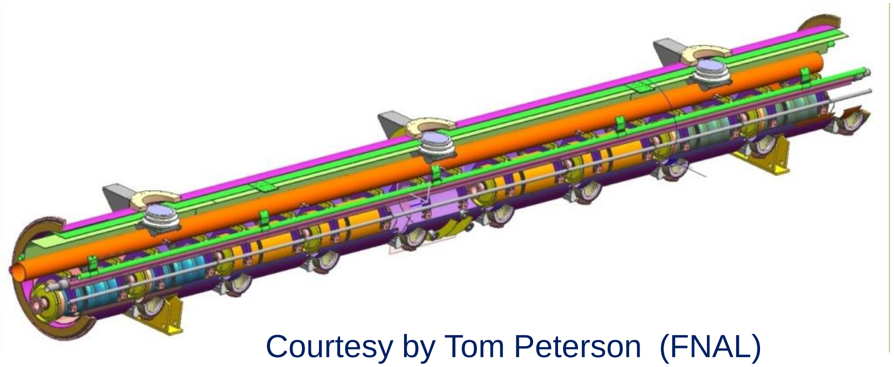


http://projectx.fnal.gov/gallery/reference-design.shtml

High Energy 650MHz Cavity of Project X Linac



Courtesy by A. Lunin **(FNAL)**

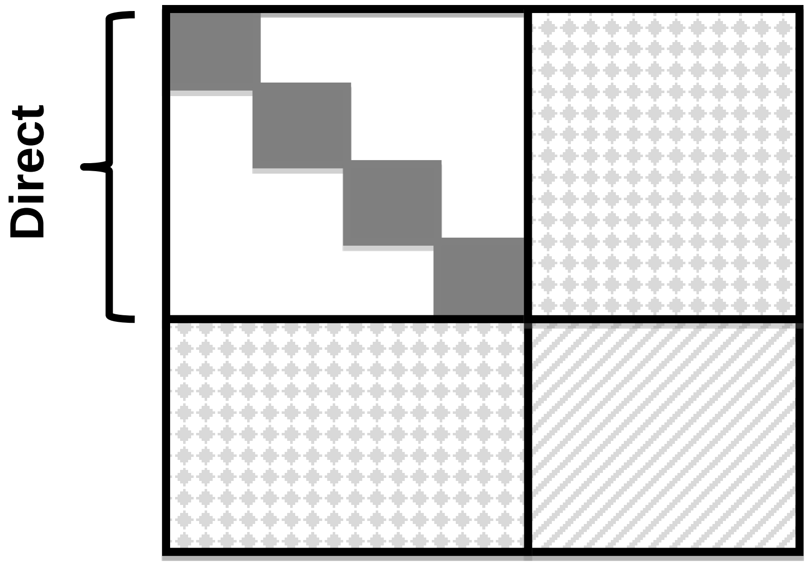


Courtesy by Tom Peterson (FNAL)

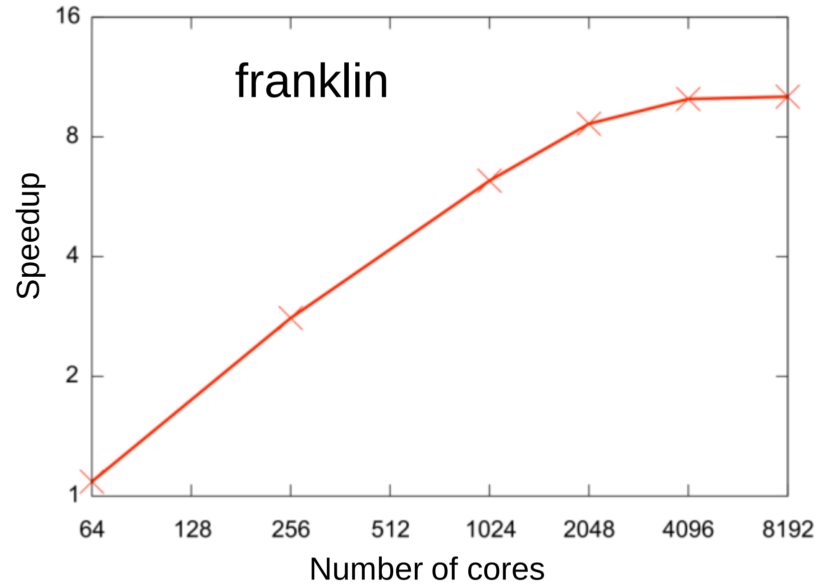
- HOM damper is an expensive and complicated structure. It may limit a cavity performance and reduce operation reliability such as SNS linac;
- SNS linac experience doesn't show necessity of the HOM couplers.
- There is no HOM damper on the Project X 650 MHz cavities under development.
- Fabrication errors and operating mode tuning procedure can cause cavities differ from the ideal one.
- Statistical HOMs properties in presence of cavity imperfections should be investigated to decide whether the HOM dampers are necessary in the high energy part of the Project X linac and in the low energy part as well.

Computation Needs for Project X Linac Study

- **Under SciDAC3 funded by HEP**, through simulation SLAC will assess the beam breakup (BBU) condition and determine if HOM damping is necessary in presence of cavity imperfections in collaboration with FNAL.
- **Under SciDAC3 funded by ASCR**, SLAC will develop and deploy scalable linear solvers on multi/many core architectures on ACE3P eigensolver Omega3P for calculating the eigenmodes in Project X 8-cavity cryomodule in collaboration with LBNL.



Schematic of matrix in hybrid linear solver



Strong scalability

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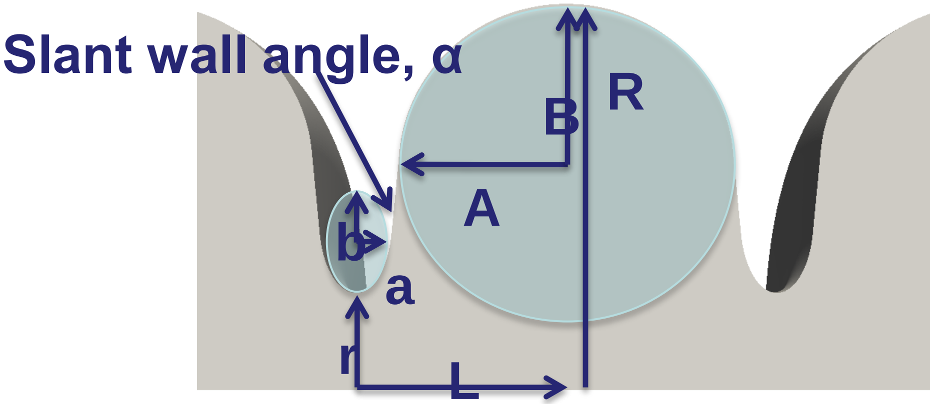
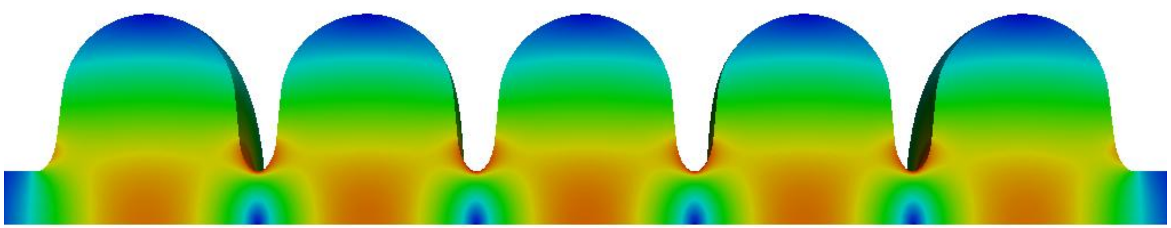
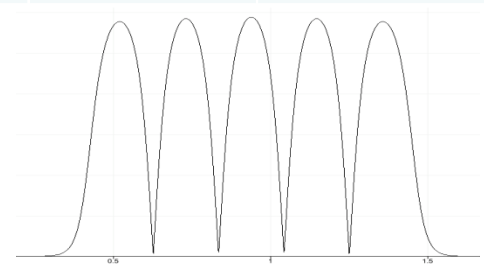
Project X HE 650MHz Cavity



	Mid Cell	End Cell
A (mm)	82.5	82.5
B (mm)	84.0	84.5
a (mm)	18.0	20.0
b (mm)	38.0	39.5
R (mm)	200.3	200.3
r (mm)	50	50
L (mm)	103.8	107.0
α (°)	5.2	7.0

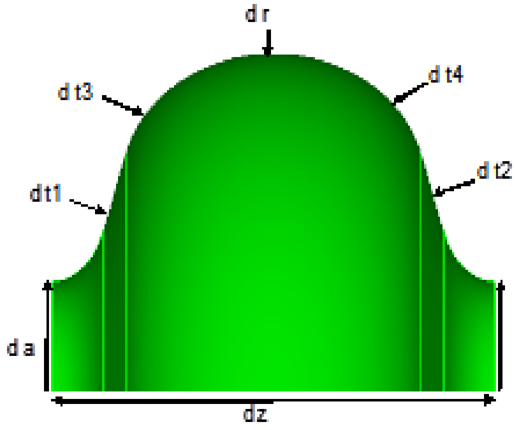
Operating Mode





Electric field distribution and field flatness

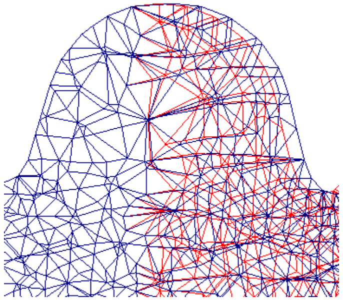
SRF Cavity Imperfection Models



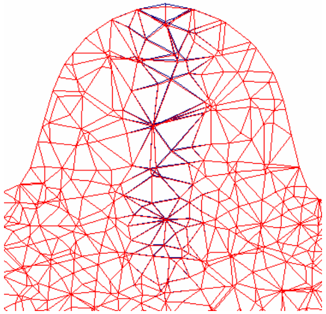
Definitions of shape parameters

Red: ideal cavity,

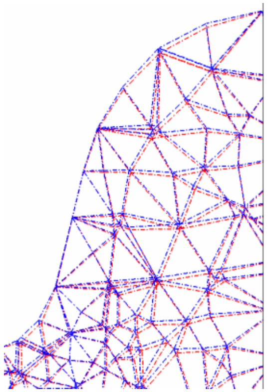
Blue: deformed cavity



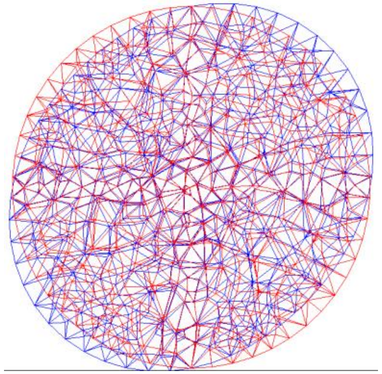
a) Cell length error



b) Cell radius error



c) Cell surface deformed



d) Elliptical cell shape

- *Study the HOM properties in imperfection models and Identify sensitivity of critical dimensions affecting the HOM damping.*

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Project X HE 650MHz Cavity Imperfection Model

Moving mesh for cell 1
dt1 : 0.00478507
dt2 : 0.00271094
dt3 : 0.00271573
dt4 : 0.00324962
dr : -0.00370275

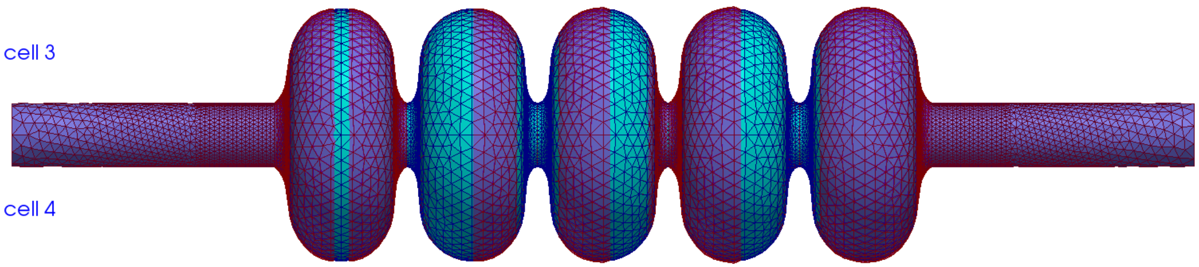
Moving mesh for cell 2
dt1 : -0.00204499
dt2 : -8.19846e-05
dt3 : 0.00208469
dt4 : -0.00256085
dr : -0.000166877

Moving mesh for cell 3
dt1 : -0.00470977
dt2 : 0.00285703
dt3 : -0.00181523
dt4 : 0.00140728
dr : 0.00223501

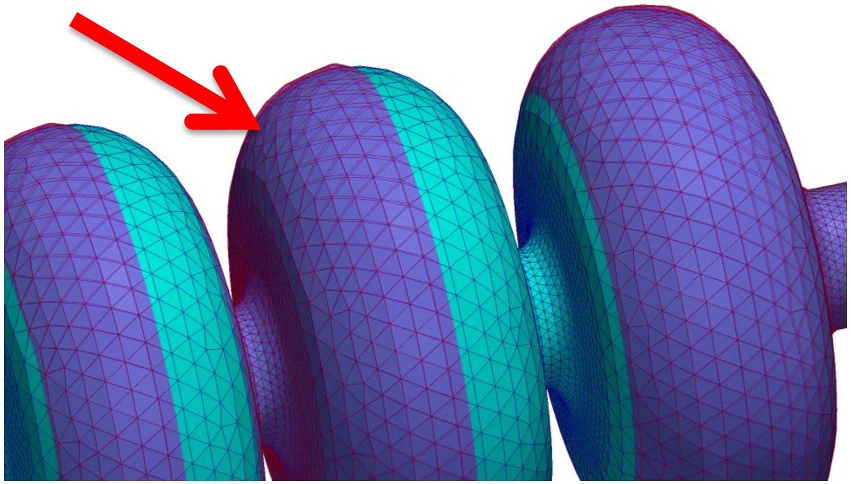
Moving mesh for cell 4
dt1 : 0.00381408
dt2 : 0.00325146
dt3 : -0.00278162
dt4 : -0.000713189
dr : 0.00342942

Moving mesh for cell 5
dt1 : -0.00169559
dt2 : 0.00218977
dt3 : 0.00349279
dt4 : 0.00339398
dr : 0.00267826

- Random deformations applied to all 5 cells.
- Max amplitude: 0.5mm
- 5 random variables x 5 cells = 25 random deformations



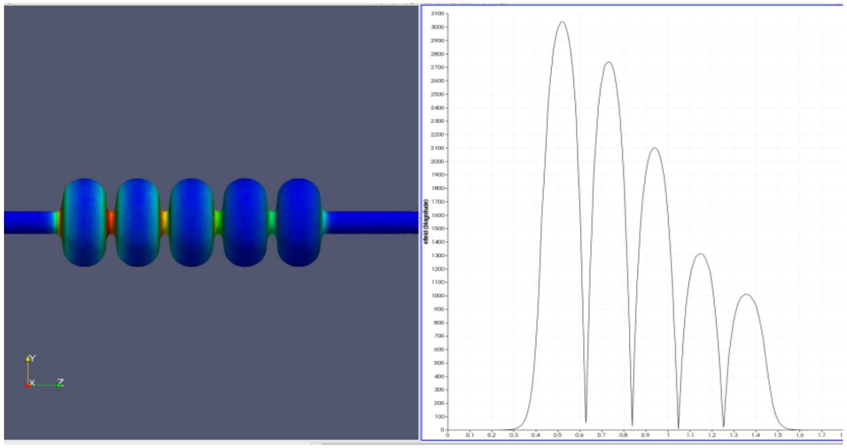
Enlarged for visualization



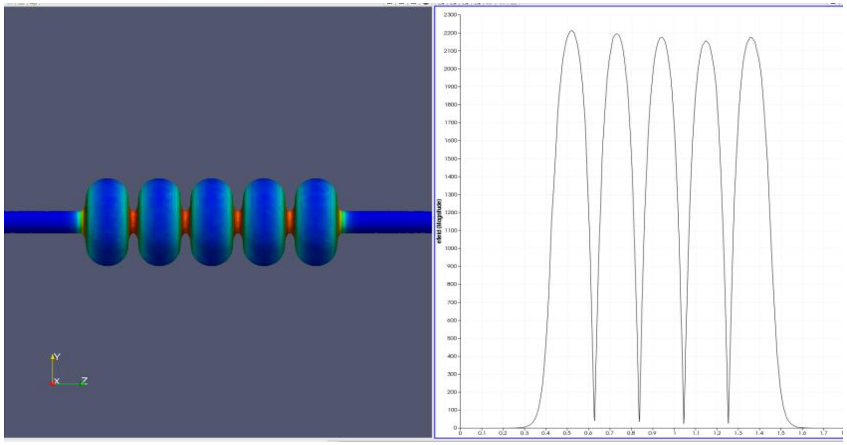
- **Blue : original mesh**
- **Red : deformed mesh**
- Amplitude : 5mm for visualization

Shape Determination for Deformed SRF Cavity

- Cavity imperfection causes the operating mode detuning.
- Each cell length will be adjusted to compensate its cell frequency change.
- Determine the each cell length to make the operating mode field flatness by solving a weighted least square minimization problem.



Cavity Shape Deformed
f = 650.663 MHz, Field unflatness



Cavity Shape Optimized
f = 650.000 MHz, Field Flatness : 97.5 %

	dz1	dz2	dz3	dz4	dz5
mm	0.7009	0.7319	0.6634	0.1476	0.1965

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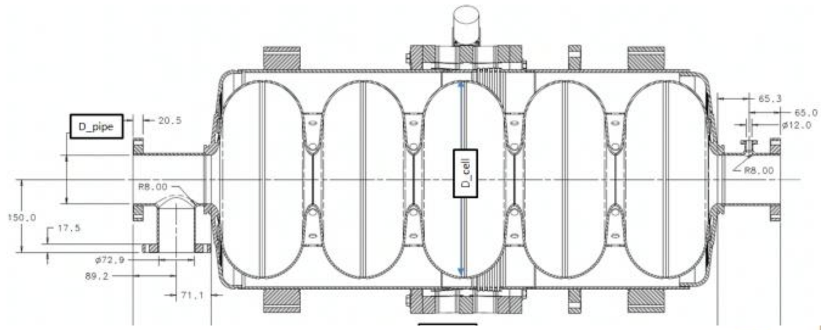
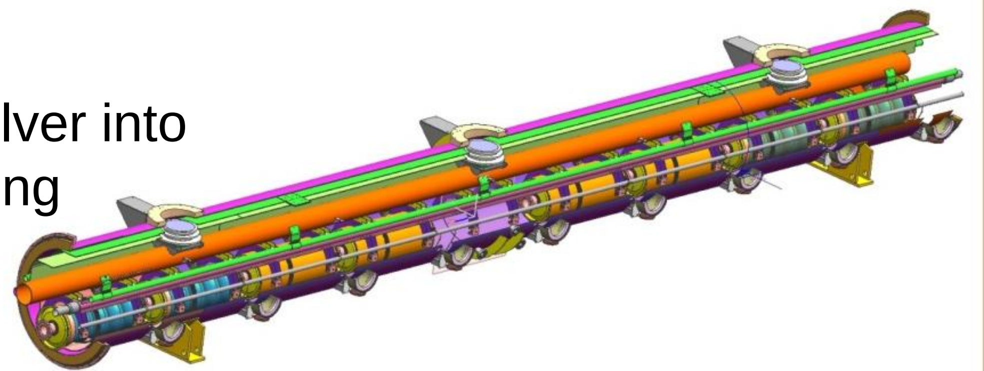
Future Plan

• The mesh distortion method and shape determination tool will be used to investigate the non-propagating HOMs in single Project X 650MHz cavity in presence of cavity imperfections.



• Will implement scalable hybrid solver into Omega3P for solving the propagating HOMs in Project X cryomodule in presence of cavity imperfections.



• The HOMs statistical properties will be analyzed to assess the beam breakup (BBU) condition and determine if HOM damper is necessary in Project X linac.