Accelerating Cavity Design for the International Linear Collider

A. Kabel

A. Candel, Z. Li, C. Ng, L. Xiao, K. Ko
V. Akcelik, S. Chen, L. Ge, L. Lee, E. Prudencio, G. Schussman, R. Uplenchwar

Stanford Linear Accelerator Center

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Outline

- ***SciDAC Parallel Finite Element Codes***
- *ILC Accelerating Cavity Design Issues*
- *Baseline TDR Design*
- *High Gradient Designs – Low-loss, ICHIRO*
- *Crab Cavity Design*
- *Towards Simulating a Cryomodule*

DOE SciDAC's Accelerator Project

Goal – *To develop next generation simulation tools to improve the performance of present accelerators and optimize the design of future machines using flagship supercomputers at NERSC (LBNL) and NLCF (ORNL)*

NERSC	NLCF
Seaborg IBM SP3	Phoenix Cray X1E
9 TfFLOPS, 6 TB+	18 TFLOPS, 2 TB

SLAC Parallel Finite Element Codes

Maxwell's Equations in the Frequency Domain:

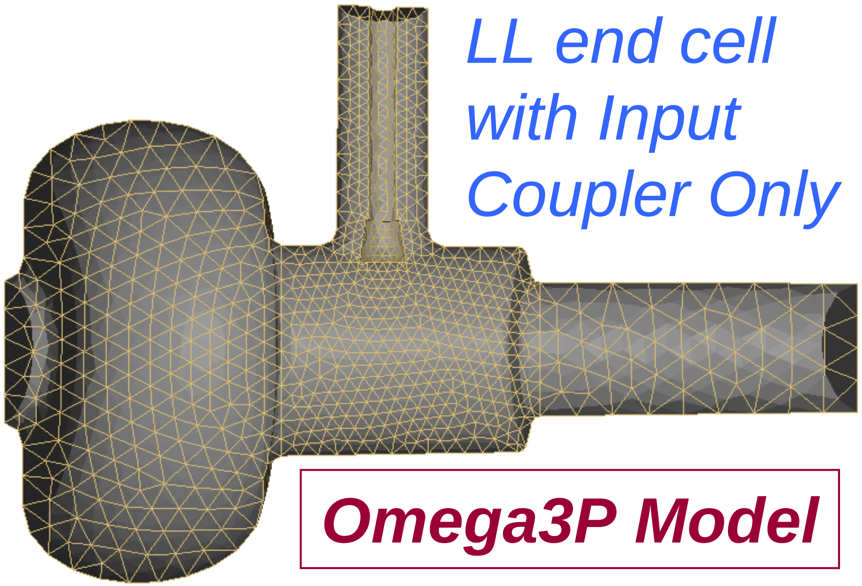
- ***Omega3P*** – *Nonlinear eigensolver to find normal modes in damped RF cavities*

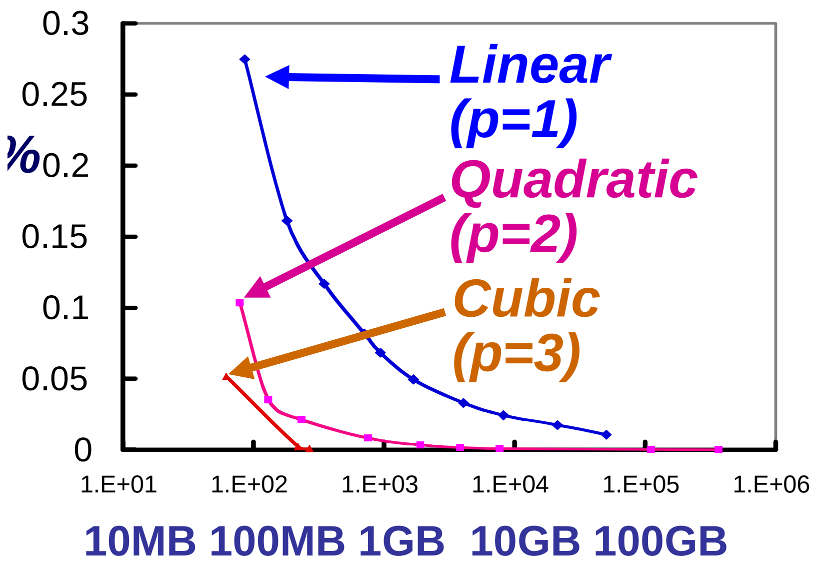
$$\mathbf{K}x + i\sum_j \sqrt{k^2 - k_{c_j}^2}\,\mathbf{W}_j x = k^2 \mathbf{M}x$$

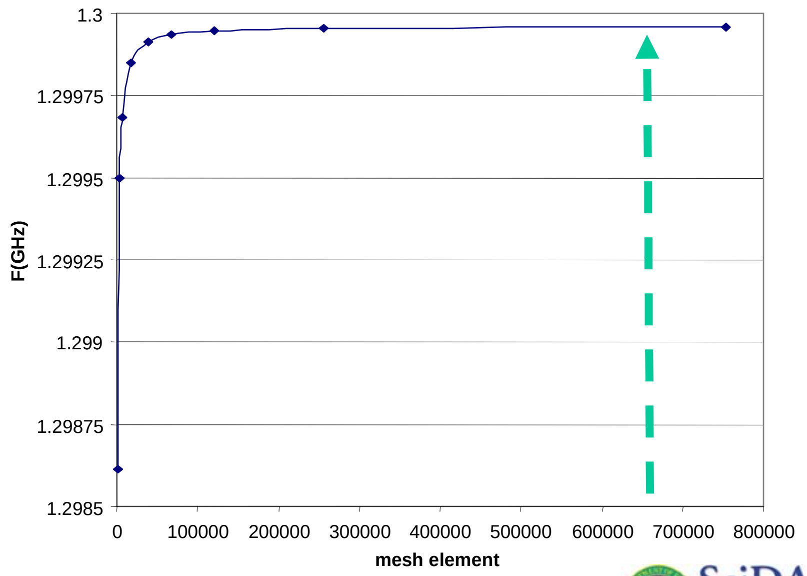
- ***S3P*** – *Scattering matrix solver for RF components*
- ***Track3P*** – *Particle tracking module to calculate dark current and multipacting*

> - Discretization with high-order (p=1…6) tetrahedral finite elements on conformal, quadratic surfaces
> - Parallelization to gain in complexity, accuracy, problem size, and speed (1/N)

Higher-order FEM + Parallel Processing







- *Error ~20kHz out of 1.3GHz or approx 0.0015% using 67000 quadratic elements*
- *Runtime < 1 minute on 16 CPUs using 6 GB memory*

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ILC Accelerating Cavity Design

- ***Accelerating Mode:*** *Frequency 1.3 GHz*
  Field flatness
  High gradient
  Multipacting

- ***Input Coupler:*** *Long processing time, Multipacting*

- ***Higher-order Modes (HOMs):*** Q_{ext} *< # required by beam stability criteria*

- ***HOM Couplers:*** *Notch gap tuning – field emission & antenna pickup heating*

- ***Cavity Deformations:*** *Increase* Q_{ext}

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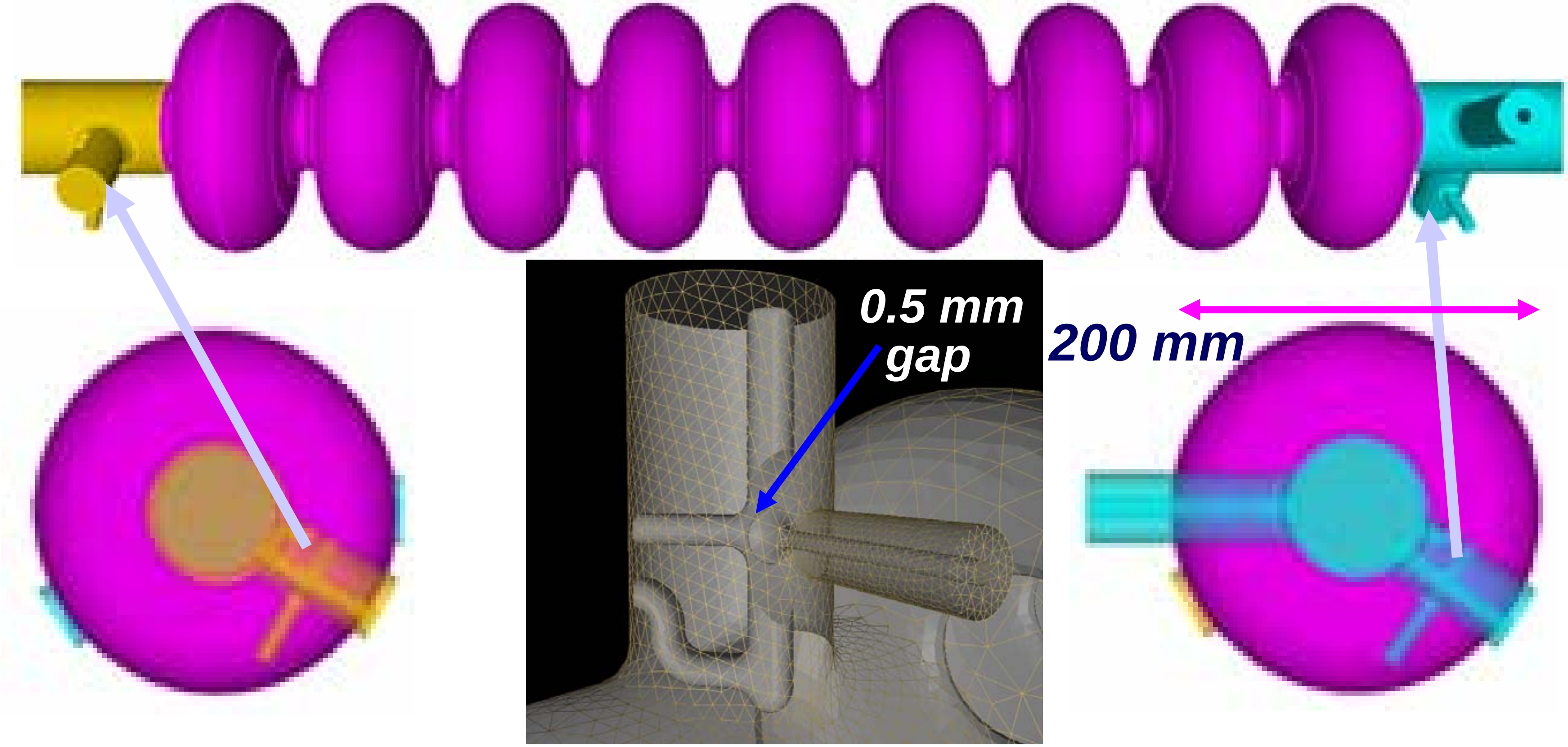
High Fidelity Modeling of TDR Cavity



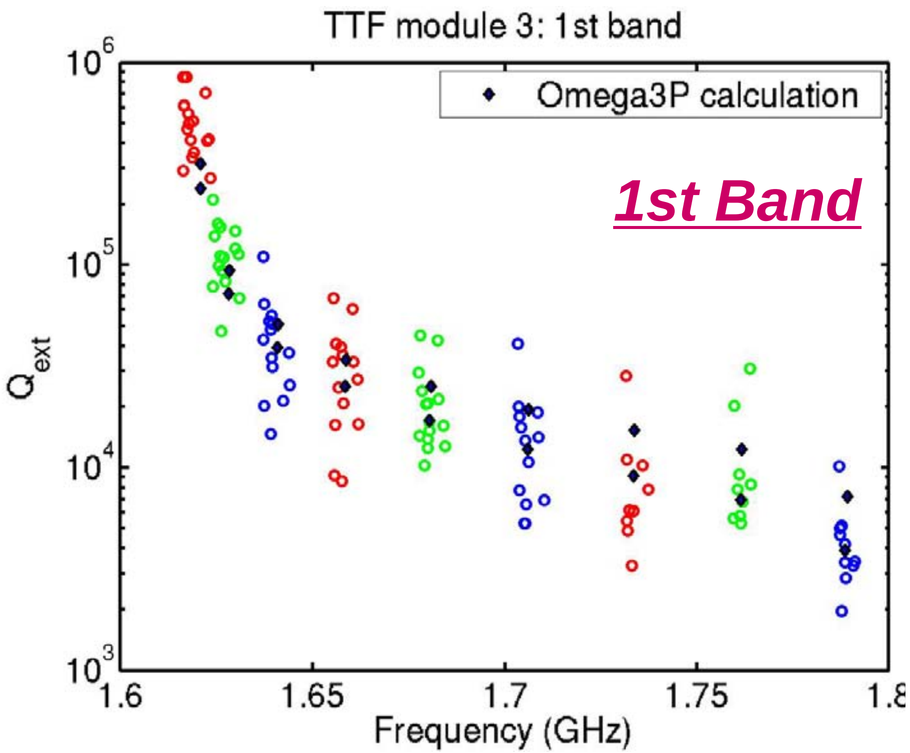
- ***Multi-scale*** *– <u>**HOM coupler**</u> (fine features) versus cell*
- ***Problem size*** *– multi-cavity structure, e.g. cryomodule*
- ***Accuracy*** *– 10s kHz mode separation out of GHz*
- ***Speed*** *– Short turn-around time to impact R&D*

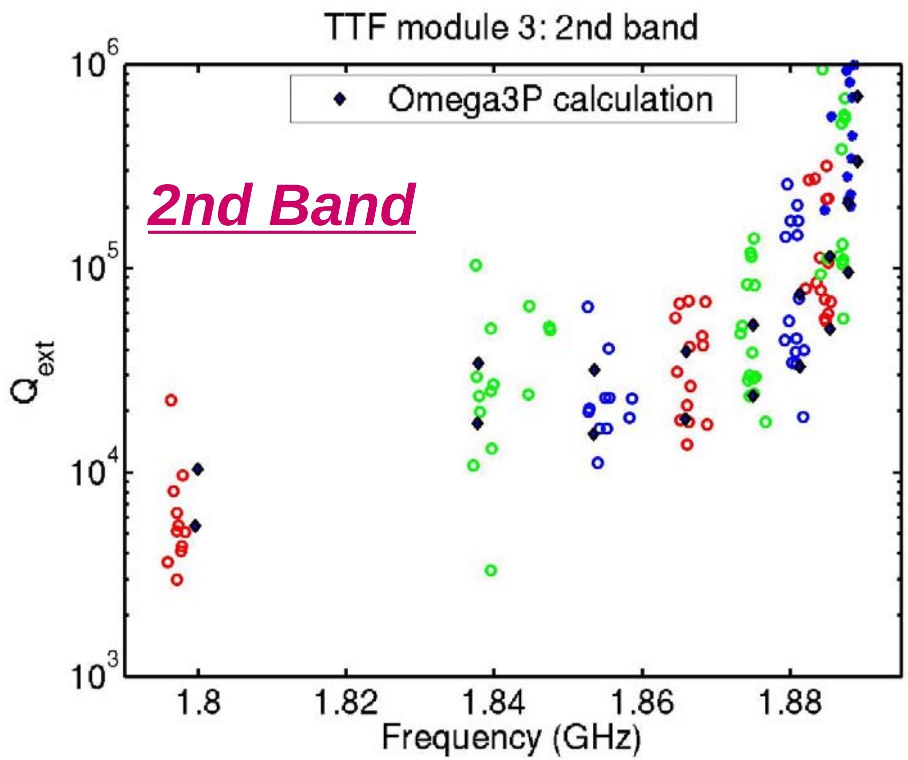
SLAC

SciDAC Scientific Discovery through Advanced Computing

TDR Cavity – HOM Damping (Omega3P)

*Comparing measurements (color) with **Omega3P** (black) complex eigenmode solutions ($Q_{ext}=f_{real}/2f_{imag}$) shows data scatter around ideal cavity results due to shape deformations*



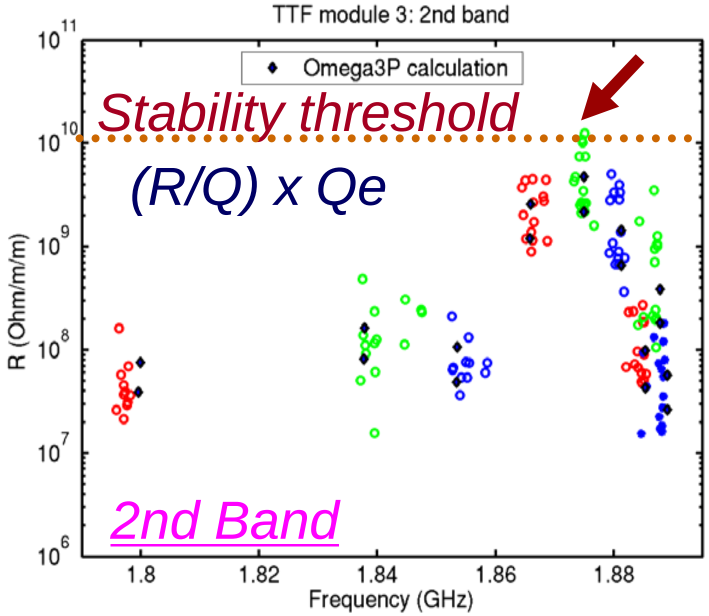


0.53 M quadratic elements, 3.5 M DOFs, 512 CPU with 300 GB on Seaborg, Second Arnoldi with MUMPs, 1 hour per dipole band

Shape Determination from DESY Data

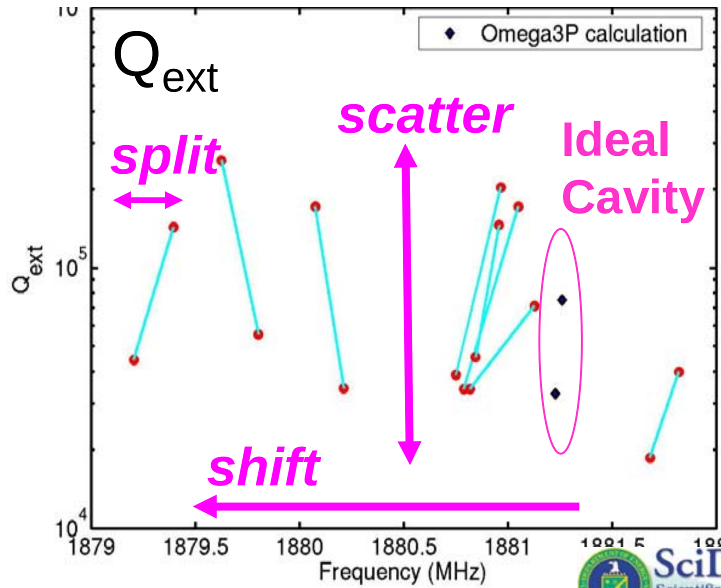
Effects of cavity deformations:

- *Mode splitting is 100s of kHz (10s of kHz in ideal cavity),*
- *Mode frequency is shifted by as much as few MHz,*
- *Q_{ext} scatter towards high side - may lead to dangerous modes.*



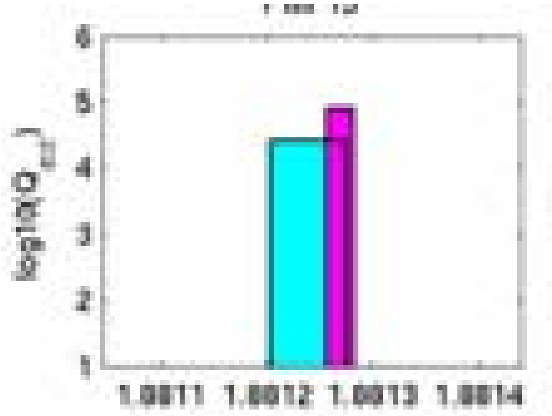
Shape determination:

- *Solve an inverse problem to find cavities' **true** shape*
- *Use measurements from TESLA cavity data bank as input*
- *Goal to identify sensitivity of critical dimensions affecting Q_{ext}*



Mode Rotation in Overlapping HOM pairs

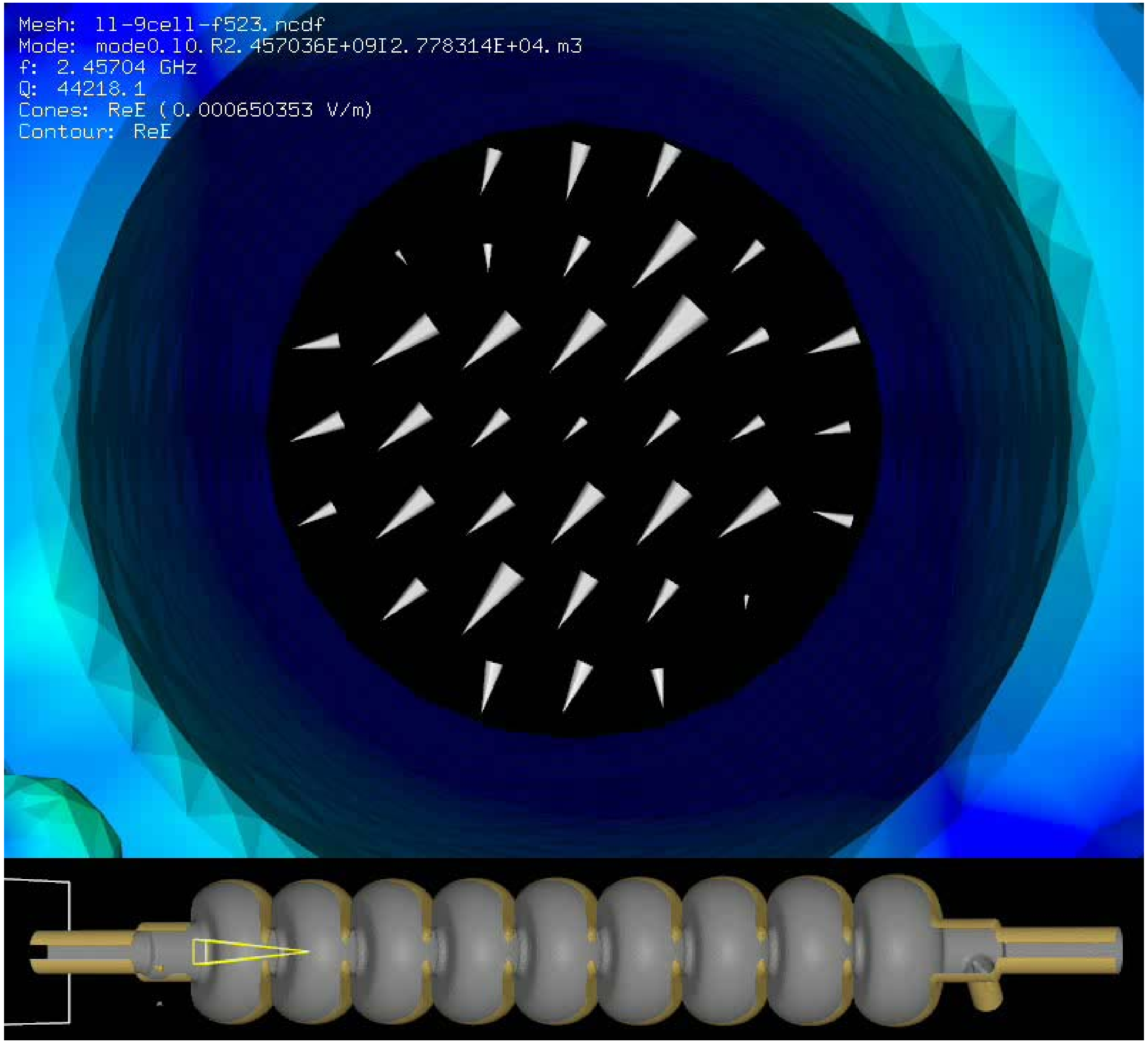
The couplers split the dipole mode degeneracy in the ILC cavity. When the line widths of the mode pair overlaps due to damping, the modes become elliptically polarized and rotate in time.



6th dipole mode pair in 2nd band

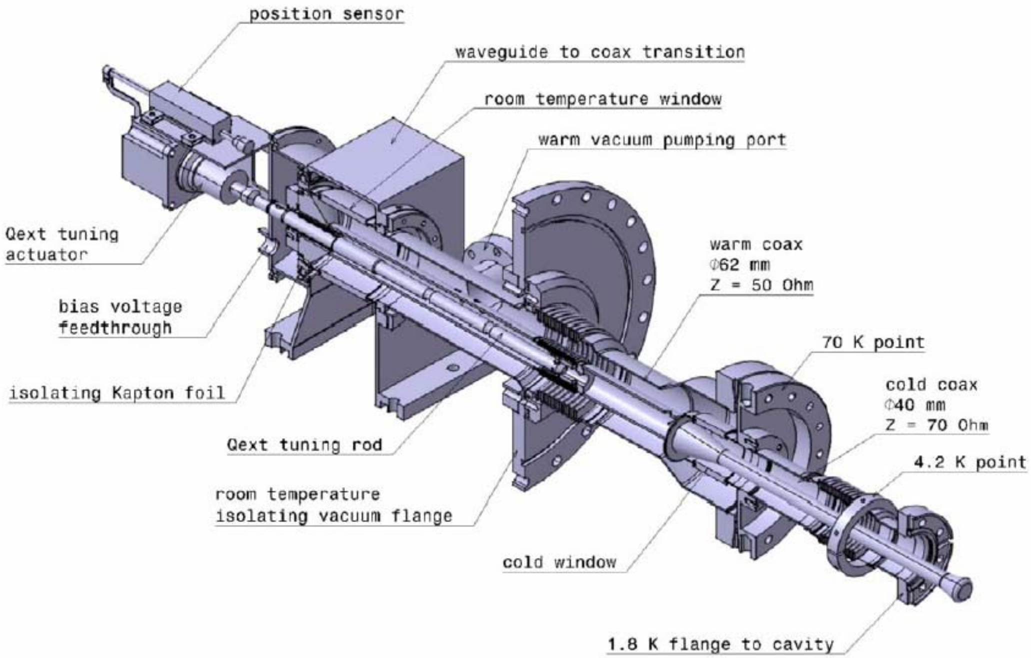
E field of rotating modes

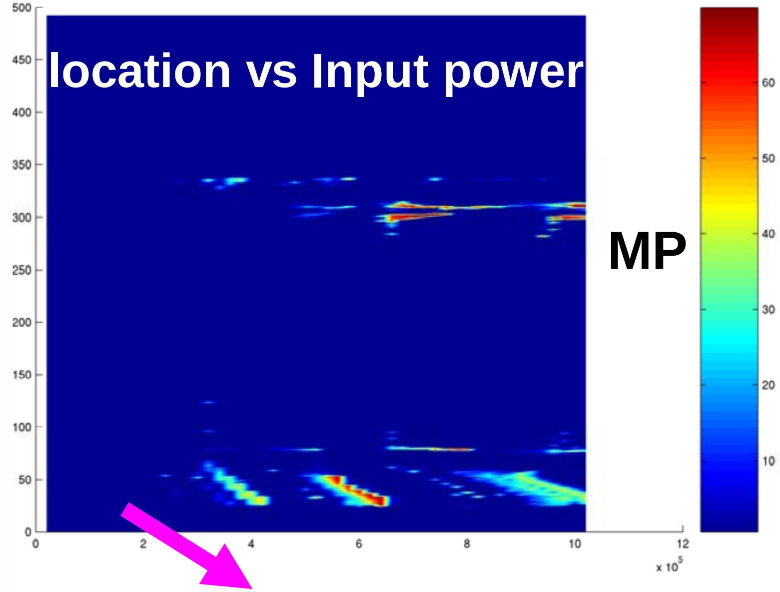
Mode Rotation in Overlapping HOM pairs



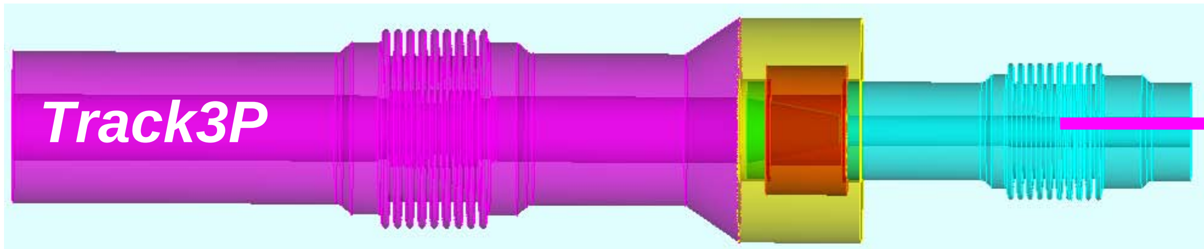
TTFIII Input Coupler - Multipacting

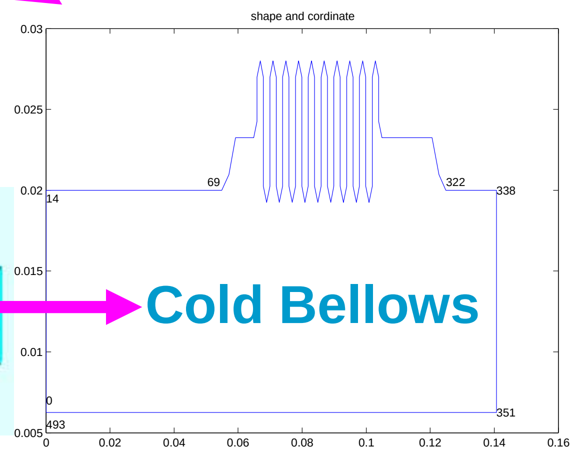
Simulation studies to understand long processing time





500 kW max input power





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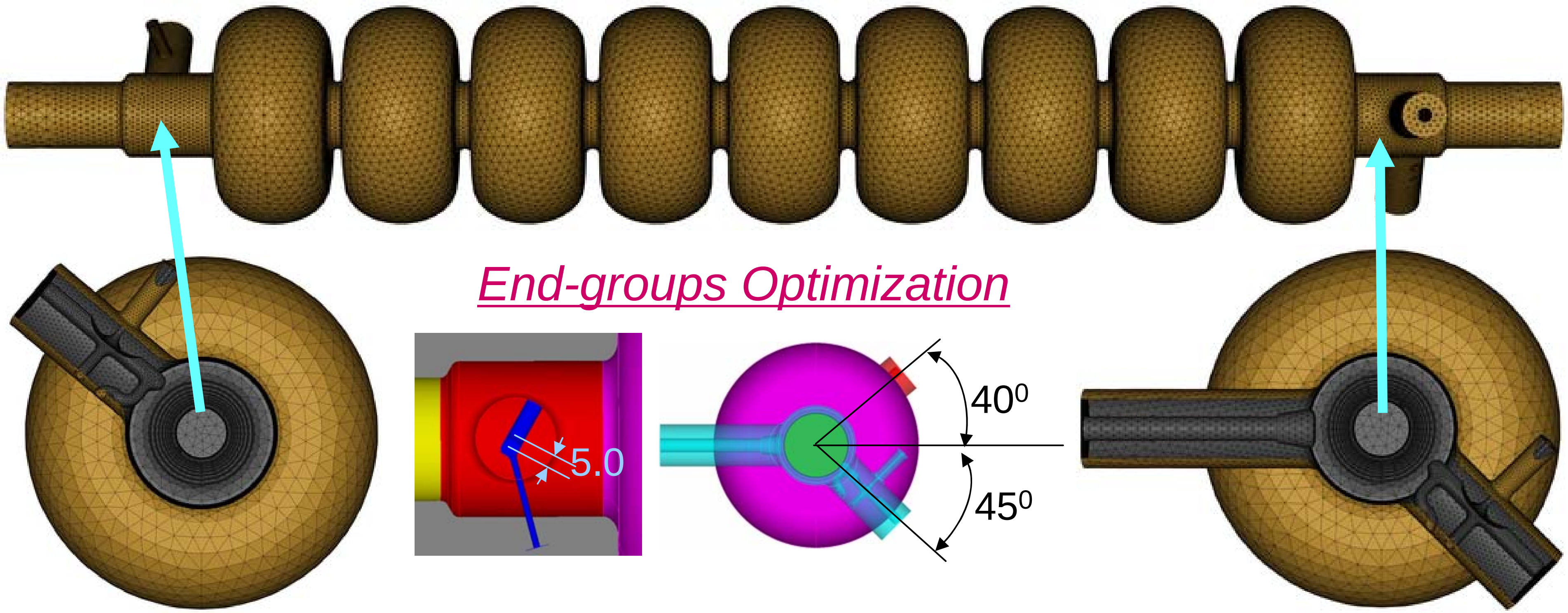
Low-Loss Cavity - HOM Damping

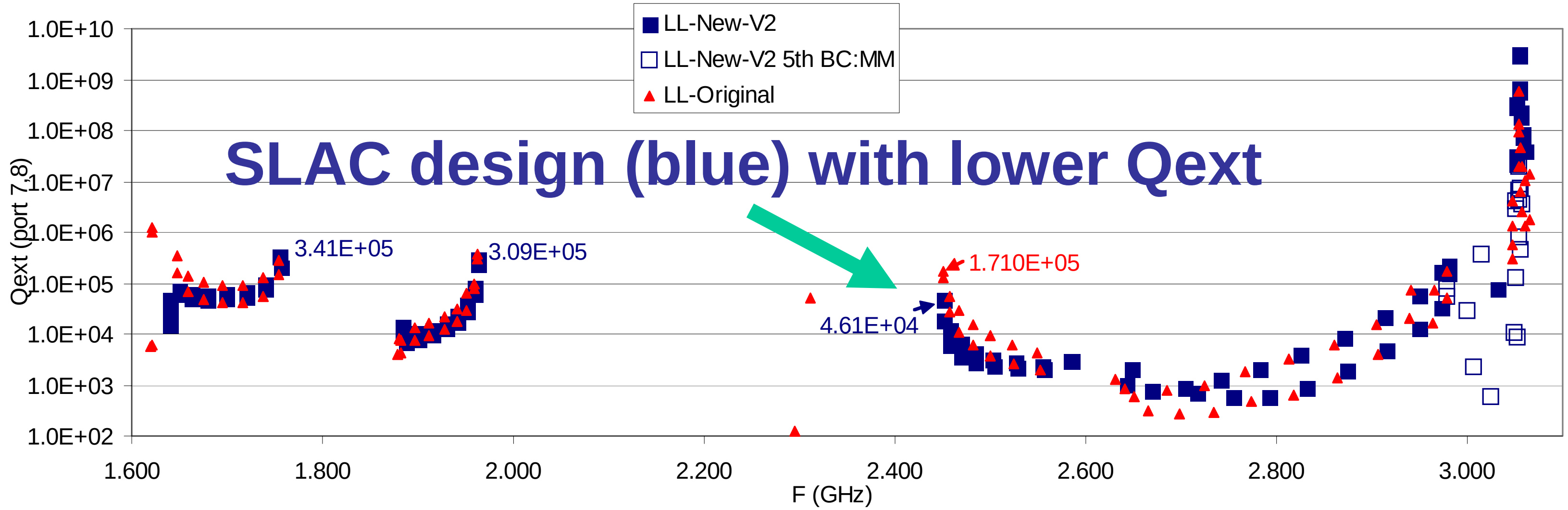
- *Low-Loss (LL) design has 20% cryogenic loss and higher shunt impedance than TDR cavity,*
- *Direct use of TDR HOM coupler provides inadequate HOM damping – dangerous mode in 3rd dipole band,*
- *Optimization of end-groups performed to improve design.*



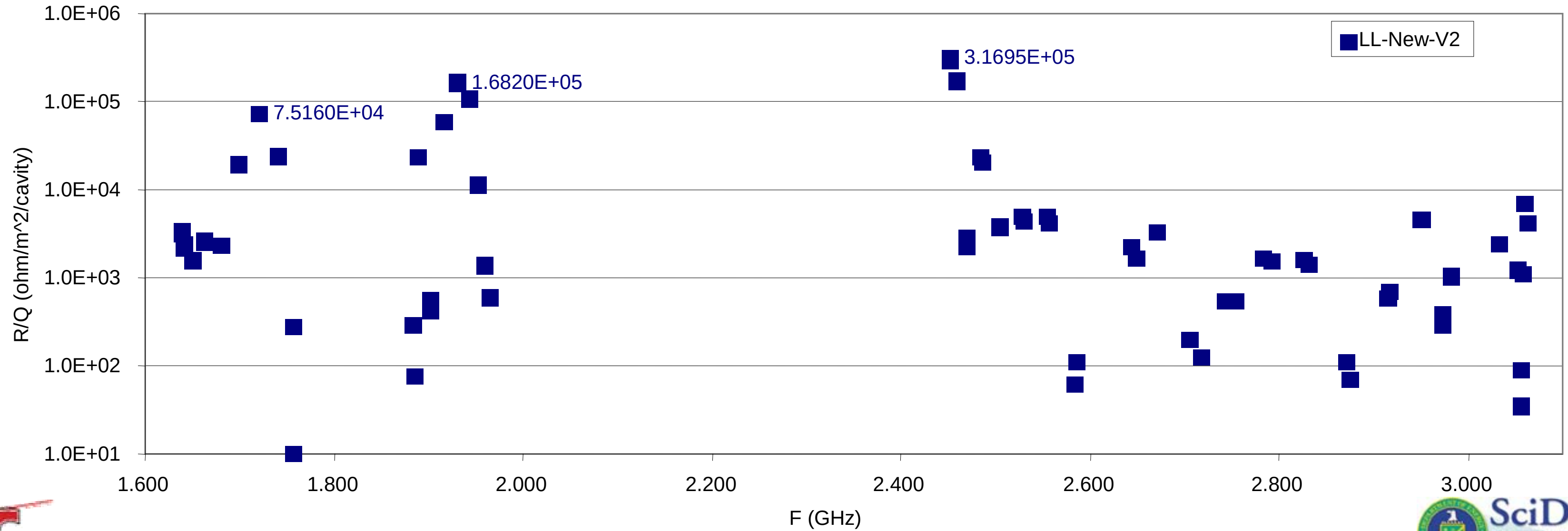
LL Cavity – End Groups Optimization

Similar Improvements carried out for the ICHIRO cavity

Qe



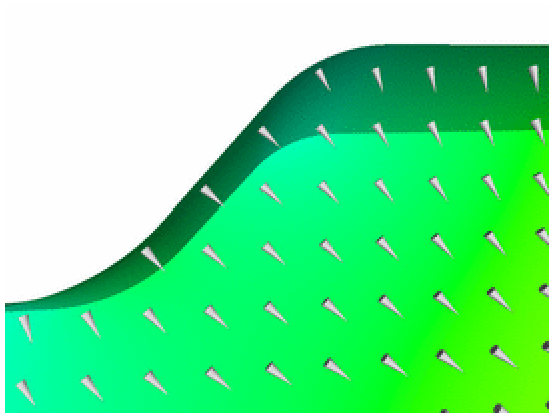
R/Q



ICHIRO Cavity – Multipacting Barriers

- ***ICHIRO** single cell reached ~ 50 MV/m @ KEK*
- *9-cell cavities can't process above 30 MV/m*

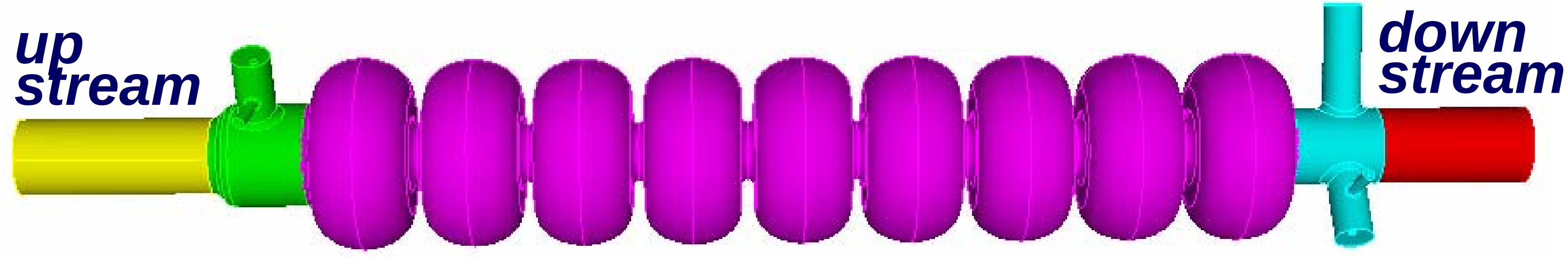
Enlarged Beam Pipe

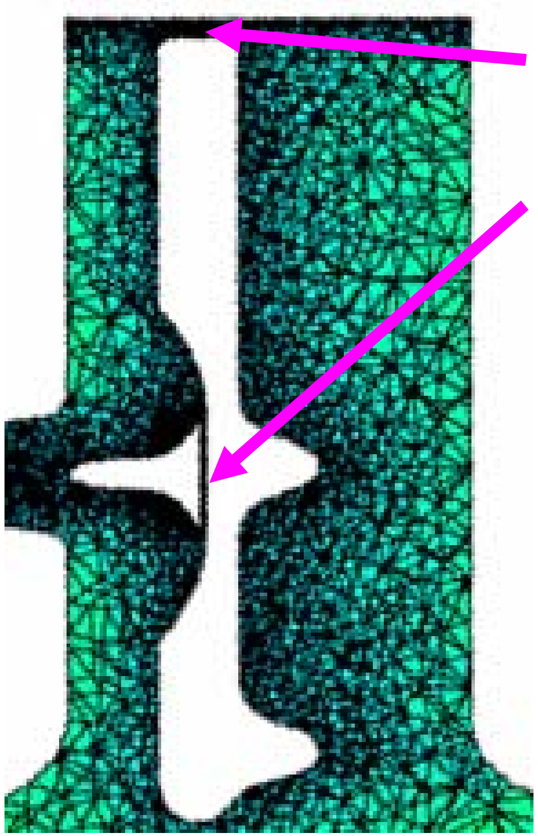


SLAC simulated MP levels [MV/m]	ICHIRO#0 X-ray barrier [MV/m]
	7.4, 9.0, 7-17
12.0	11-29.3, 12-18
13.9	13, 14, 14-18, 13-27, 13-27
16.8	(17, 18)
21.2	20.8
29.4	28.7, 29.0, 29.3, 29.4

K. Saito (KEK)

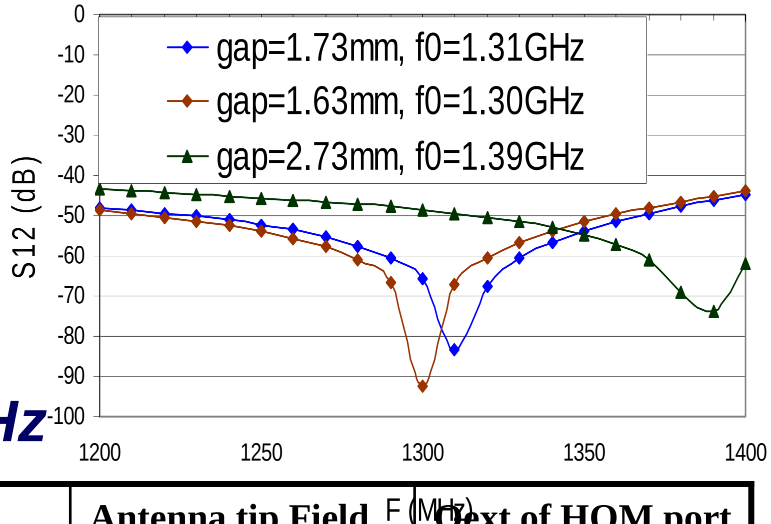
ICHIRO HOM Coupler – Notch Filter





Notch Gap

Antenna Tip



Fields @ 1.3 GHz

Notch gap (mm)	Notch gap field (MV/m)		Antenna tip Field (MV/m)		Qext of HOM port @1.3GHz	
	Up-stream	Down-stream	Up-stream	Down-stream	Up-stream	Down-stream
1.63	16.9	5.0	0.8	0.2	6.1e+9	1e+12
1.73	16.5	4.9	1.4	0.4	5.2e+8	9.e+9
2.73	13.3	3.9	6.1	3.0	1.4e+7	1.7e+8

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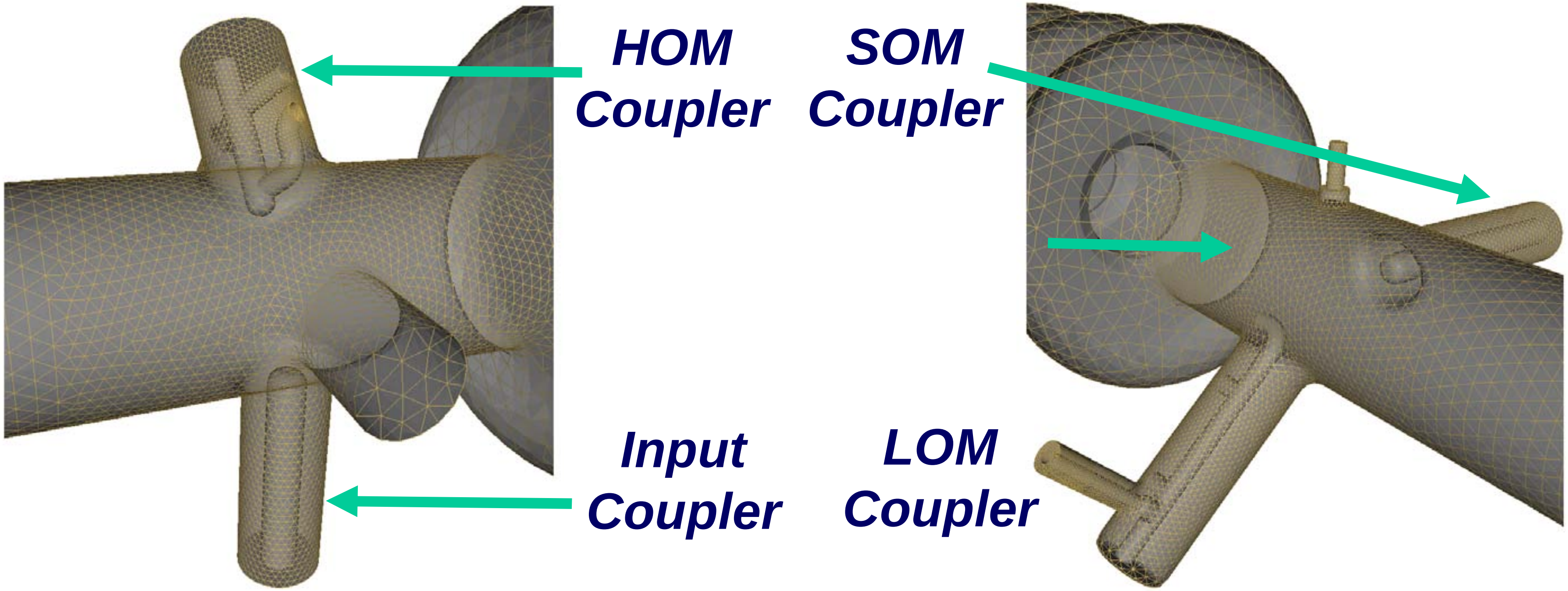
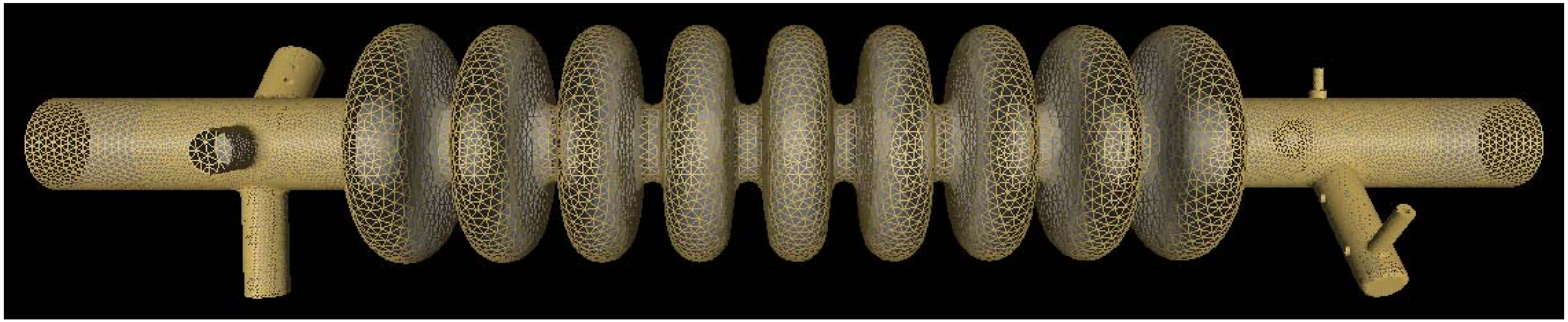
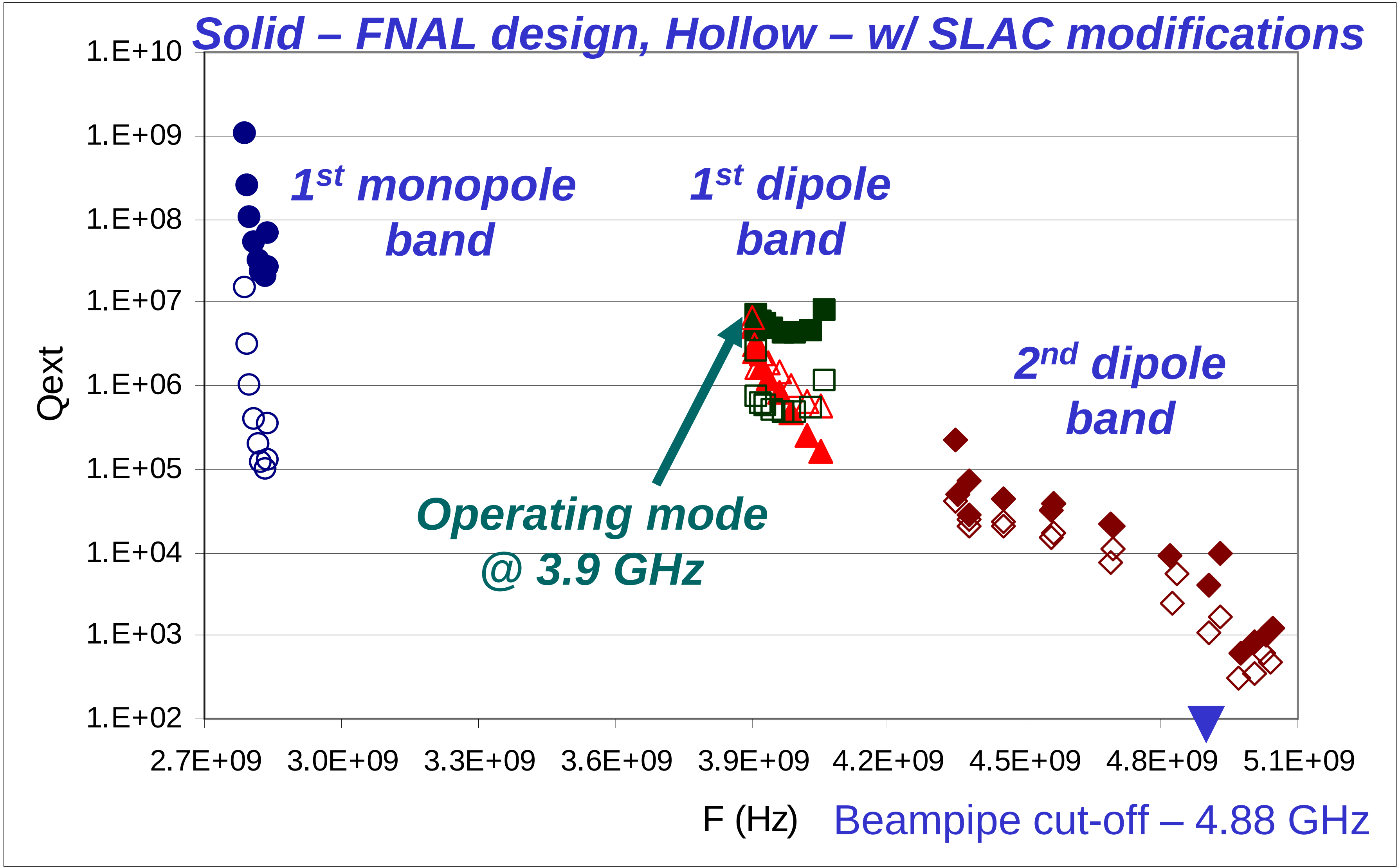
FNAL 3.9 GHz Crab Cavity Design

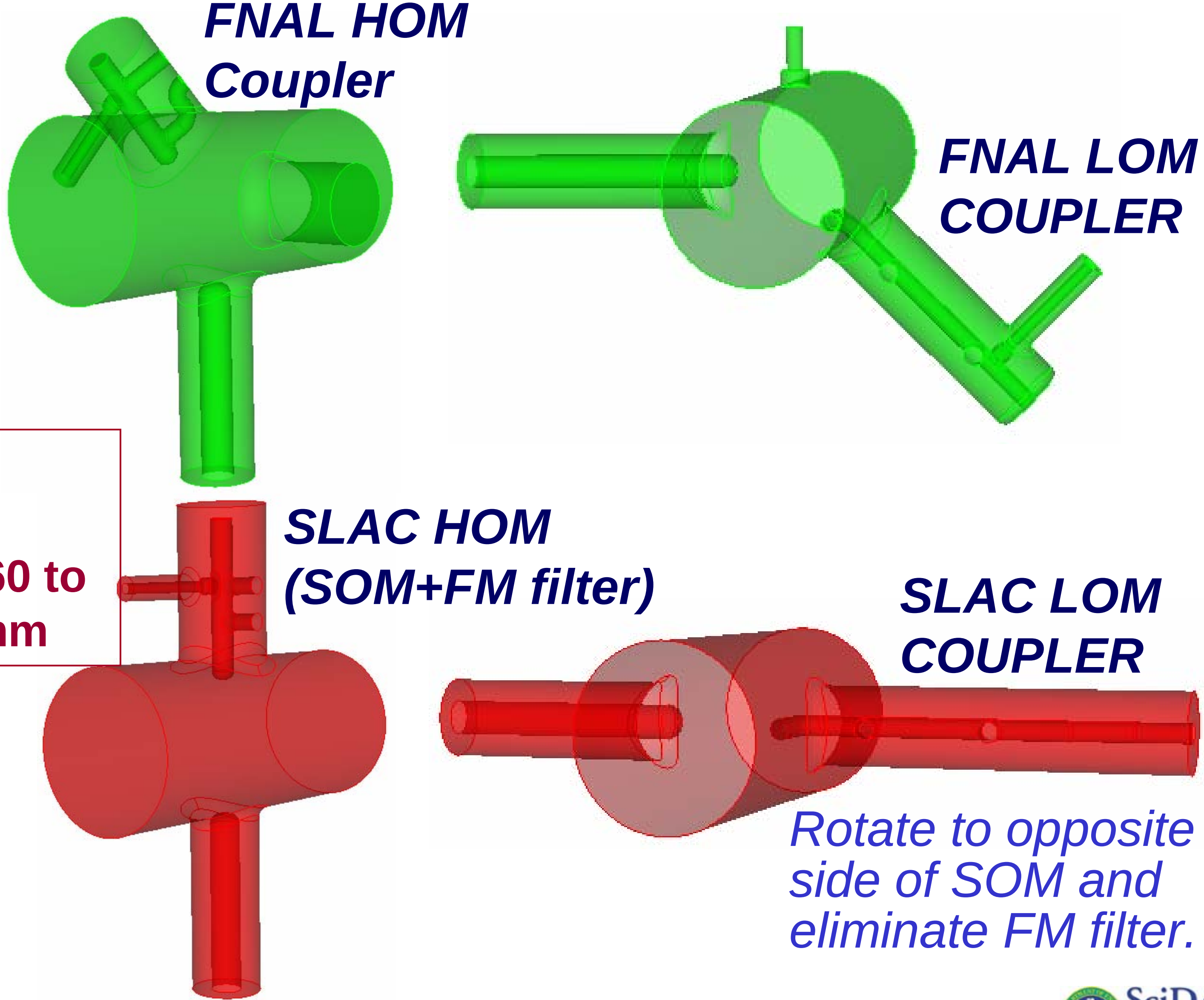




SLAC 1st Improvements

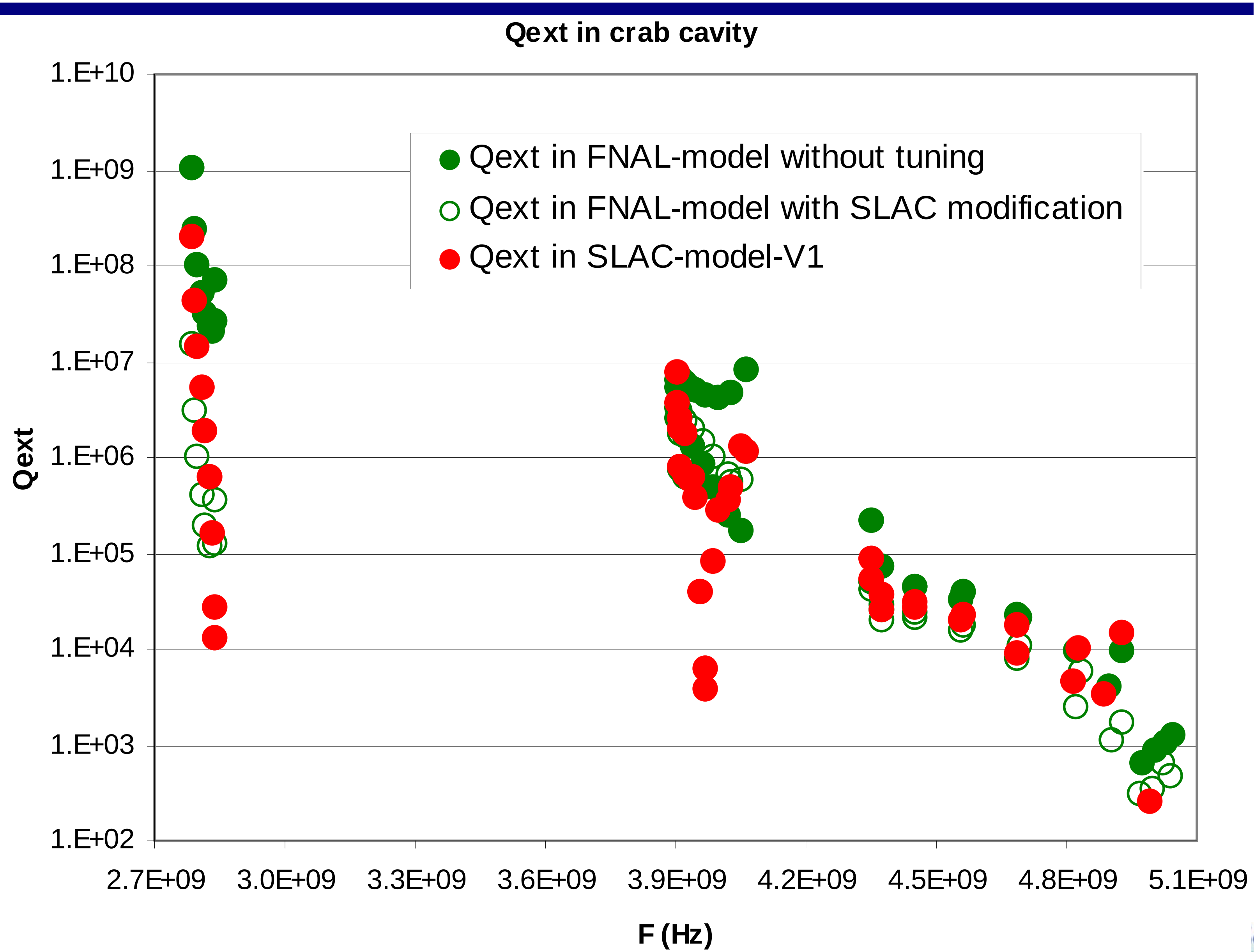


HOM & LOM Coupler Redesign



Notch Gap Sensitivity Reduced -160 to 13 MHz/0.1mm

SLAC's Simplified, Improved Design



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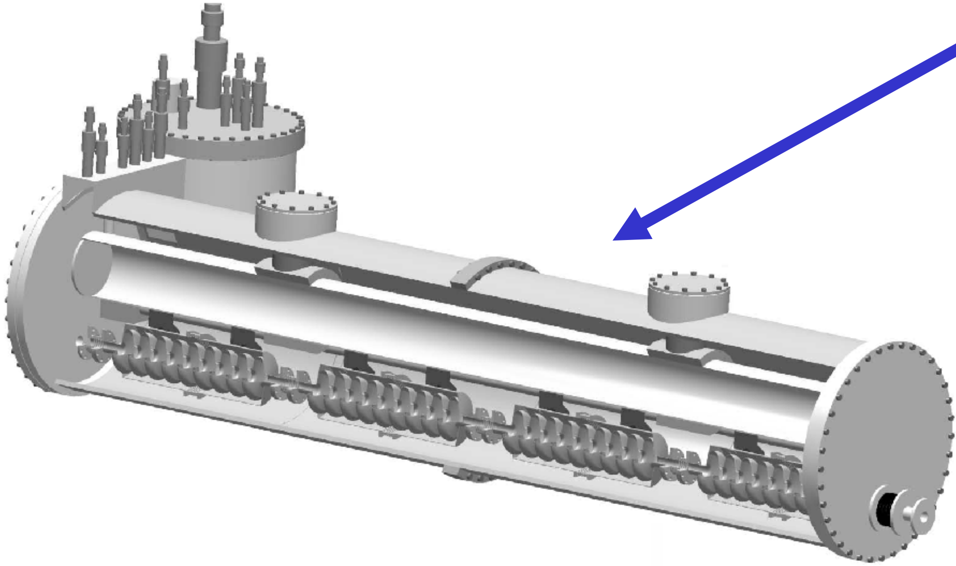
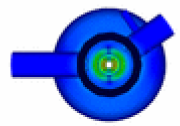
ILC Superconducting Test Facility @ KEK

Trapped Modes in KEK's STF 4-cavity cryomodule
(potential problems with beam stability and local heating)





beam

Trapped Mode seen from the beam frame

Omega3P solved complex eigensystem comprising 2.52 million quadratic tetrahedral elements (over 15.2 million DOFs) on 1000 processors of Phoenix@NCCS

SciDAC
Scientific Discovery through Advanced Computing

Summary & Outlook

- ***SLAC/ACD has developed a set of mature, design-class FEM tools***
- ***We are able to contribute to and impact ILC design***
- ***We are working towards the ILC/SCIDAC grand challenge: entire Cryomodule***