RF And Wakefield Modeling For the ILC Main Linac

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SLAC Parallel Codes under SciDAC1

- Electromagnetic codes in production mode:

Omega3P – frequency domain eigensolver for mode and damping calculations

S3P – frequency domain S-parameter computations

T3P – time domain solver for transient effects and wakefield computations with beam excitation

Track3P – particle tracking for dark current and multipacting simulations

V3D – visualization of meshes, fields and particles

SLAC Parallel Codes under SciDAC2

Codes under development:

- *Electromagnetics*

  Gun3P – 3D electron trajectory code for beam formation and transport

  Pic3P – self-consistent particle-in-cell code for RF gun and klystron (LSBK) simulations

  TEM3P – integrated EM/thermal/mechanical analysis for cavity design

- *Beam dynamics*

  Nimzovich – particle-in-cell strong-strong beam-beam simulation

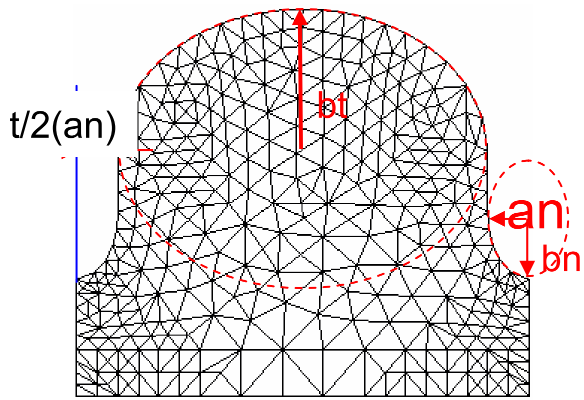
Applications To ILC R&D

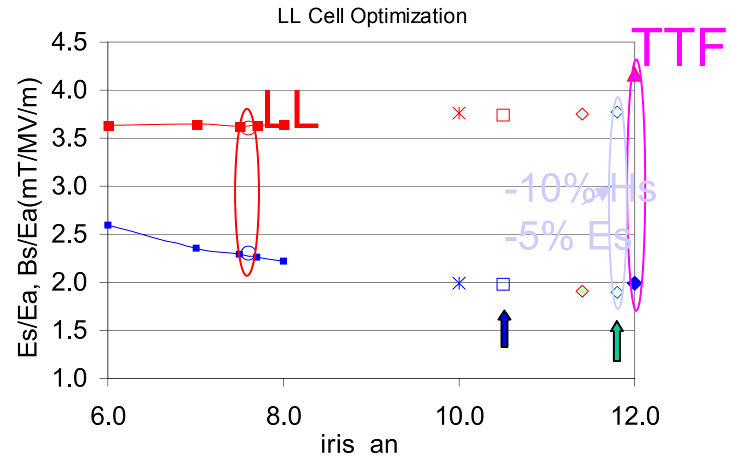
- *Accelerating Cavity (DESY, KEK, JLab)*
  - *Alternative design*
  - *HOM damping*
  - *Coupler asymmetry effects*
- *Cavity imperfection modeling*
  - *Effects On HOM damping*
  - *3D Wakefields and beam dynamics*
- *Cryomodule and RF unit simulation*
  - *Trapped modes*
  - *Wakefidls, x-y coupling effects*
- *Cryomodule HOM heating*
  - *Beamline absorber*
  - *Heat load distribution in low temperature environment*
- *Integrated multi-physics tools for RF/Thermal/Mechanical analysis*
- *Input Coupler study*
- *L-Band Sheet Beam Klystron – Gun and window modeling*
- *BDS Crab Crossing (FNAL/UK) - Deflecting cavity*
- *Damping Ring (LBNL) – Impedance calculations*

Alternative Cavity Design – HOM Damping

A=30mm LL/Re-entrant Cell Comparison

LL

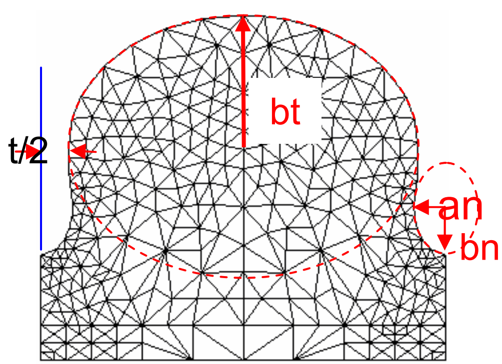


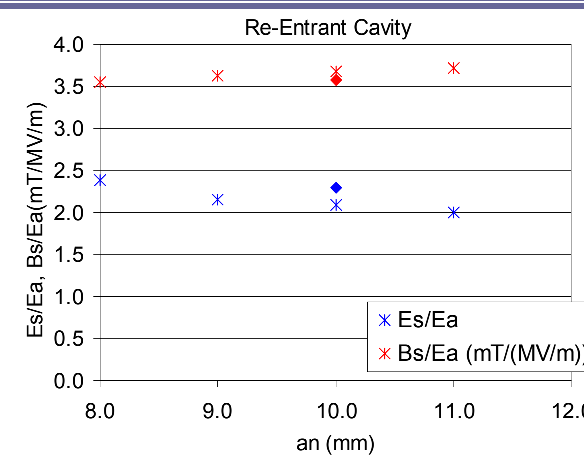


	an	bn	Es/Ea	Hs/Ea	Bs/Ea (mT/(MV/m))	Ea ((MV/m)/180mT)
TTF cell (a=35mm)	12.00	19.00	1.984	0.00332	4.168	43.19
Original LL (a=30mm)	7.60	10.00	2.303	0.00287	3.608	49.88
opt-3 (a=30mm) 0mm slope	10.50	17.10	1.984	0.00295	3.712	48.49
a=30mm 0mm slope	11.80	20.80	1.894	0.00300	3.770	47.75

5% Es reduction
10% Hs reduction

Re-entrant





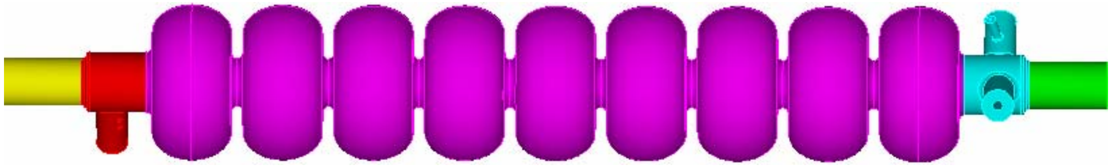
t	an	bn	bt	Es/Ea	Hs/Ea	Bs/Ea (mT/(MV/m))	Ea ((MV/m)/180mT)
12	8	11.0	36.000	2.390	0.002826	3.551	50.69
15	10	11.5	38.000	2.299	0.002850	3.581	50.26
16	9	14.0	36.000	2.153	0.002885	3.625	49.65
16	10	17.0	35.500	2.095	0.002930	3.682	48.89
18	11	17.2	35.000	2.005	0.002960	3.720	48.39

At low Es, re-entrant comparable to LL

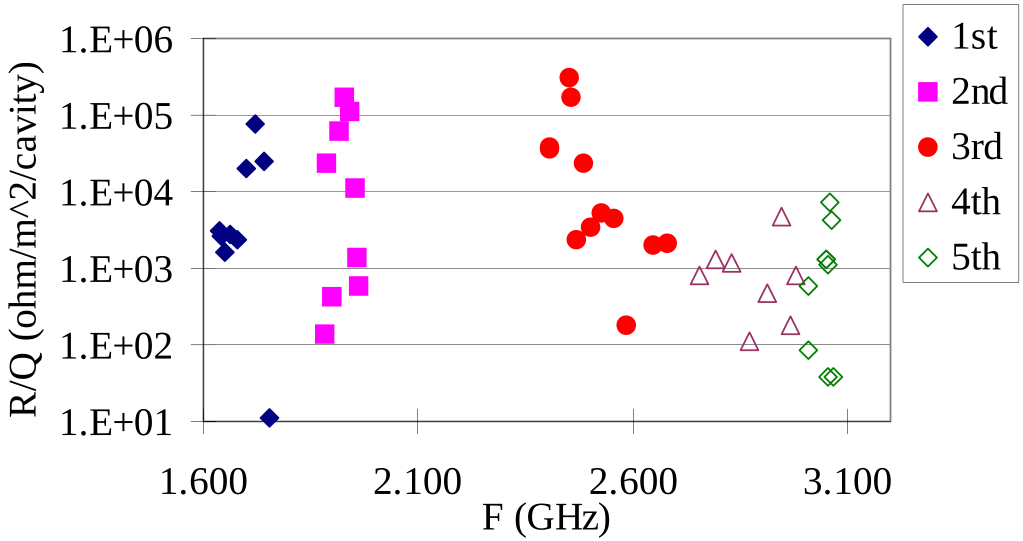
LL Cavity End-group Design

LL Shape

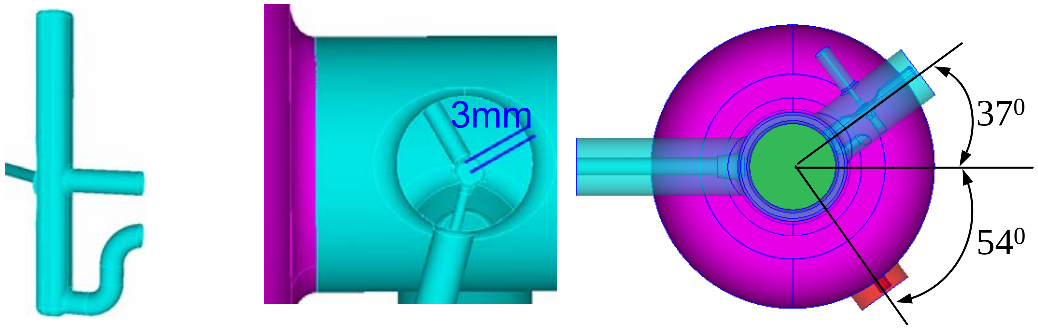
- >15% higher R/Q (1177 ohm/cavity)
- >12% lower Bpeak/Eacc ratio
- 20% lower cryogenic heating

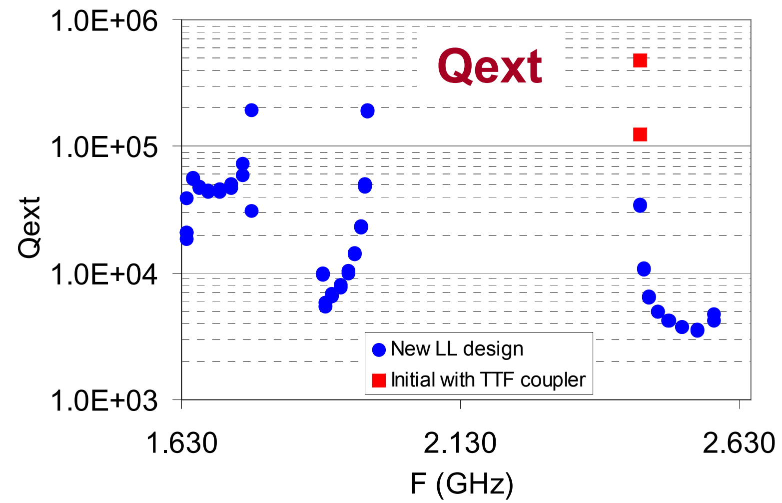


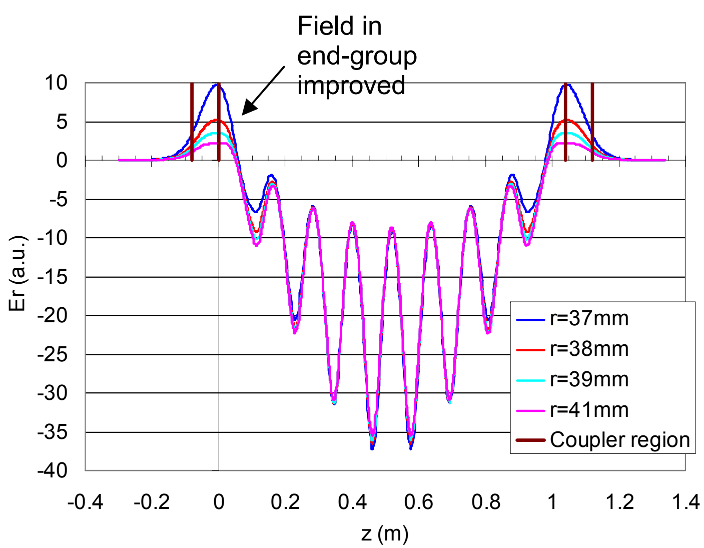
- Most important modes are 0-mode in the 3rd band
- High R/Q in the 1st&2nd bands are up to 1/3 of the 3rd band
- Beam pipe tapers down to 30-mm, 3rd band damped locally by HOM couplers
- Damping criteria: 3rd band mode Qext<10^5 (?)

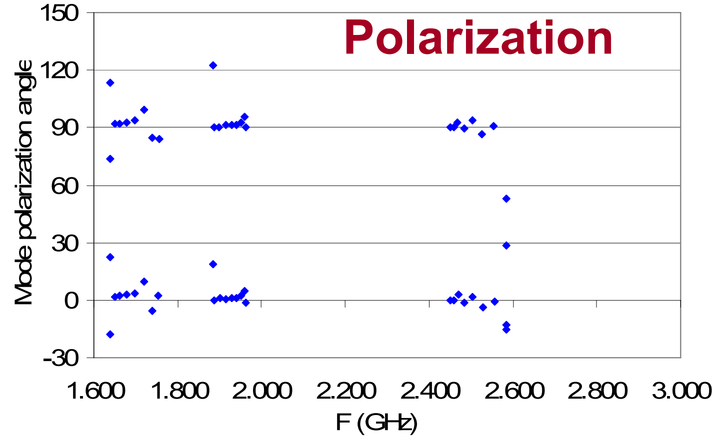


LL Cavity End-group





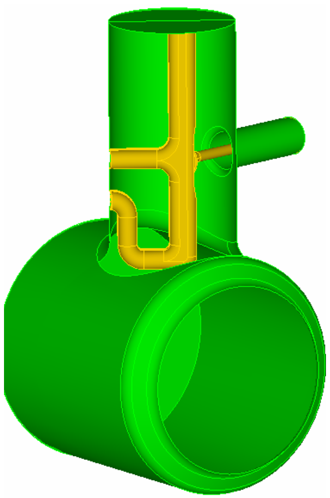


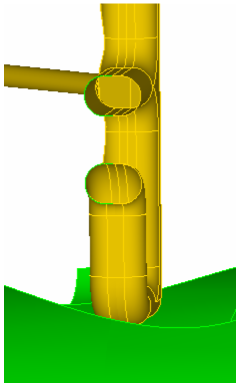


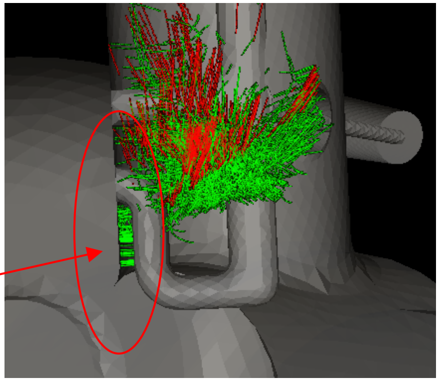
Effective damping achieved by optimizing:

- End-group geometry to increase fields in coupler region
- Loop shape and orientation to enhance coupling
- Optimized azimuthal coupler orientation for x-y mode polarization

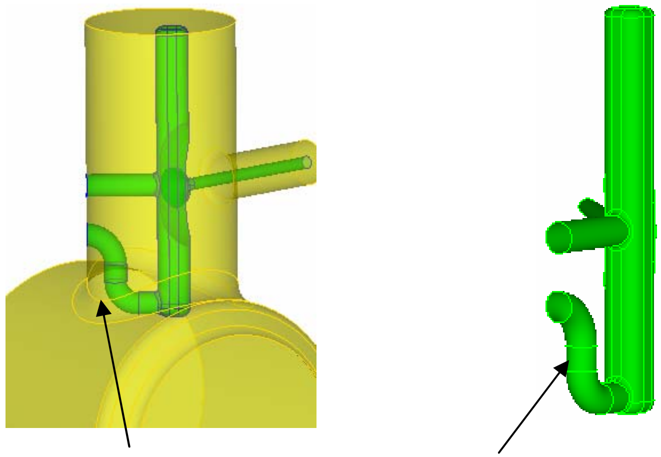
Multipacting in HOM Coupler







Initial optimized design: multipacting in the gap between the flat surface and outer cylinder at field levels starting from 10-MV/m and up.



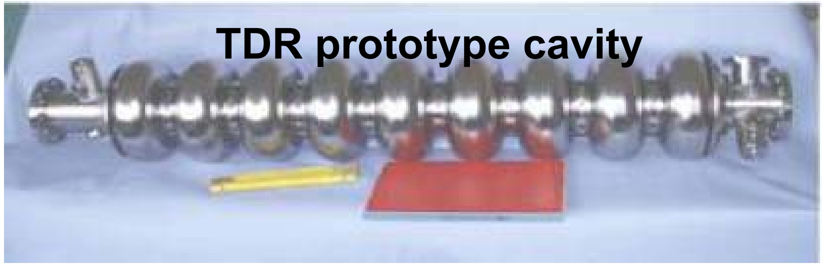
Re-optimized loop: with round surfaces and a larger gap.

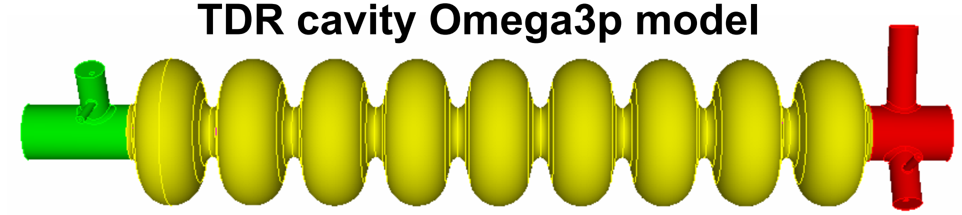
- No multipacting up to 50MV/m.
- Qext for the 3rd band mode is $3.4x10^4$

Cavity Imperfection

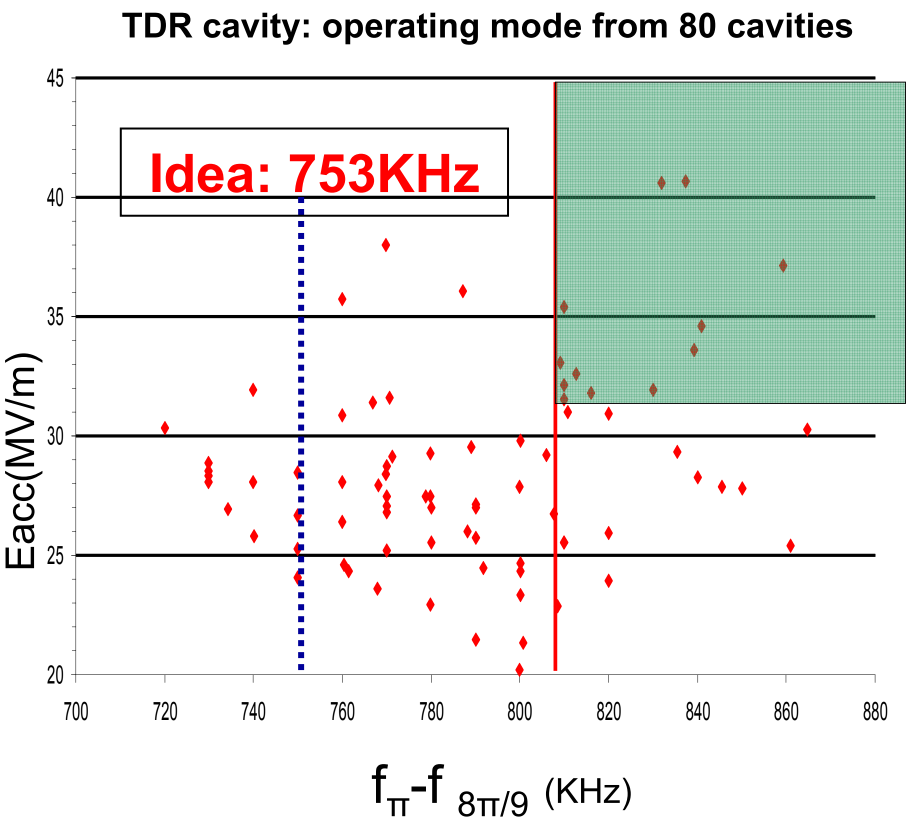
- HOM damping
- X-Y coupling
- Effects on beam emittance

TESLA Cavity Measurement Data

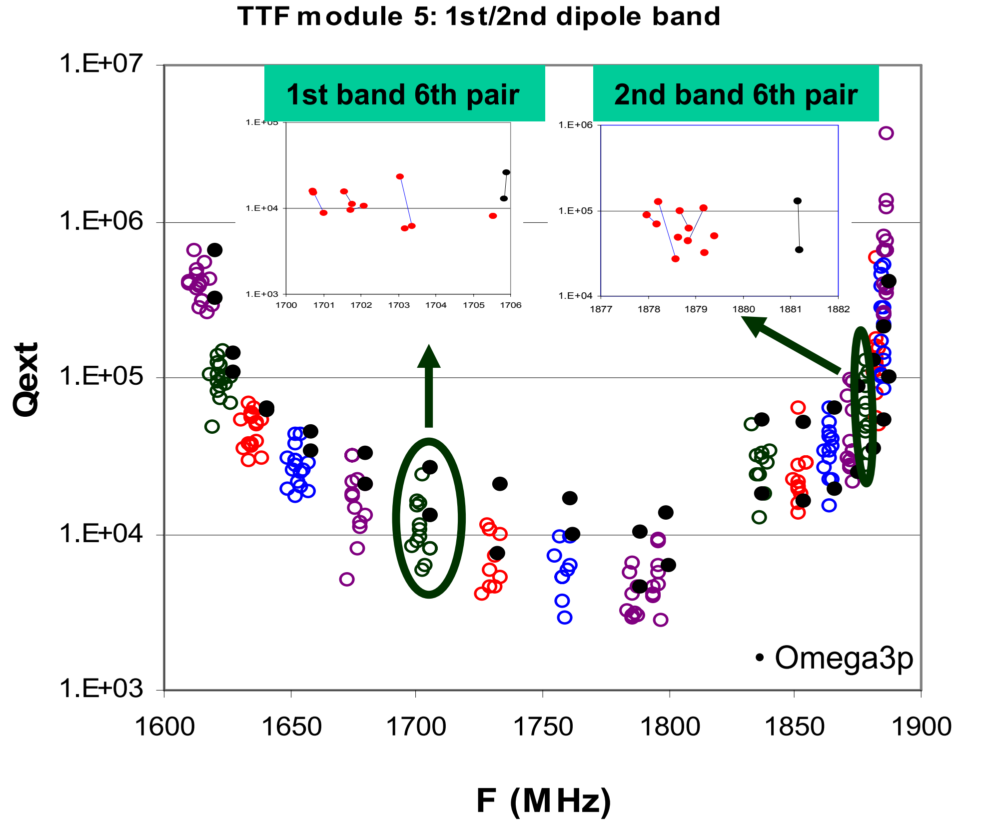




The actual cell shape differ from the ideal design due to *fabrication errors*

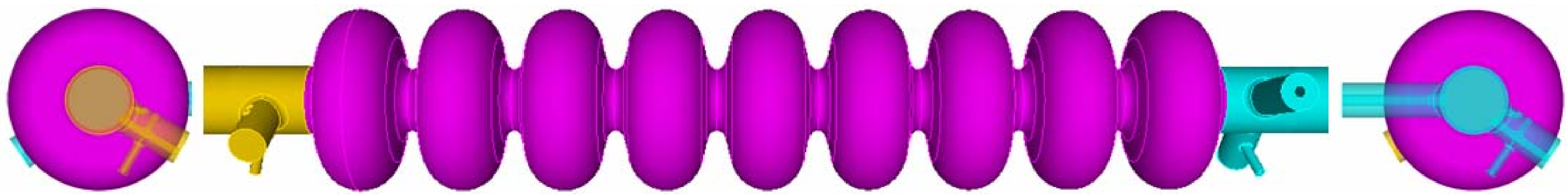


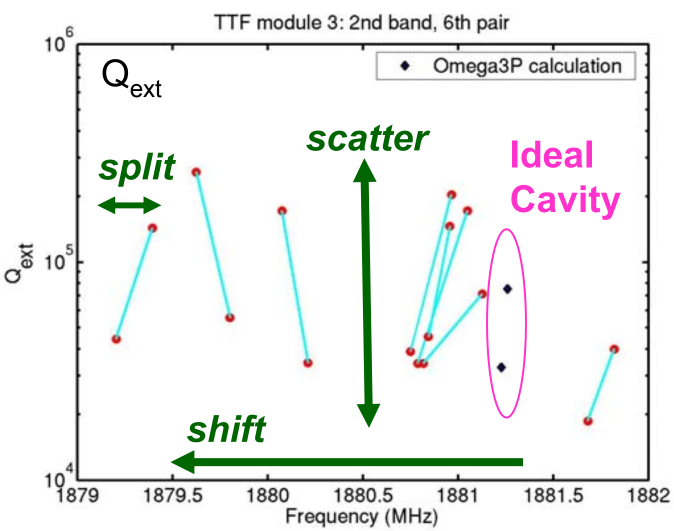
The mode spacing increases.

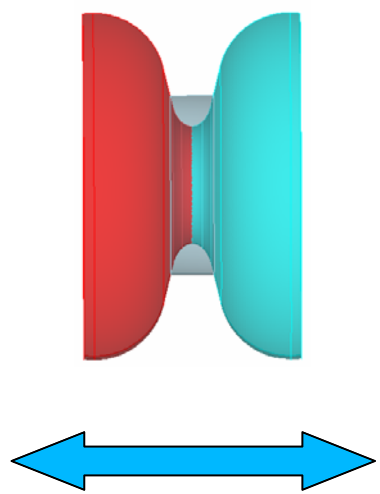


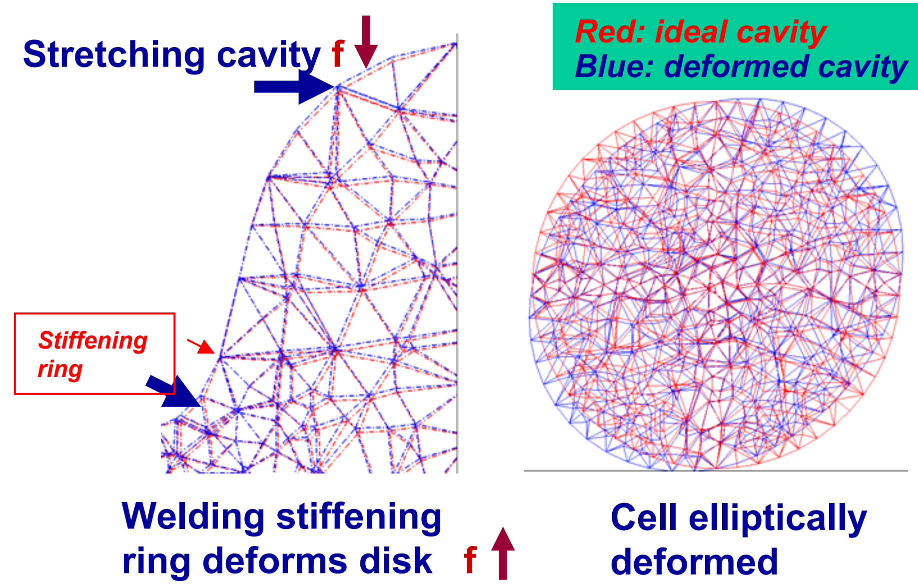
Dipole mode frequencies shift and Qext scatter.

Modeling Imperfection Of ILC TDR Cavity









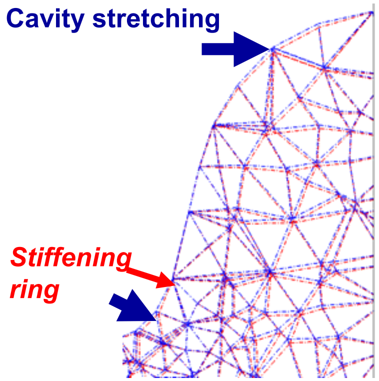
- Determine shape deformation from measured cavity data, inverse and forward methods
- Important to understand effect on Qext and x-y coupling of beam dynamics

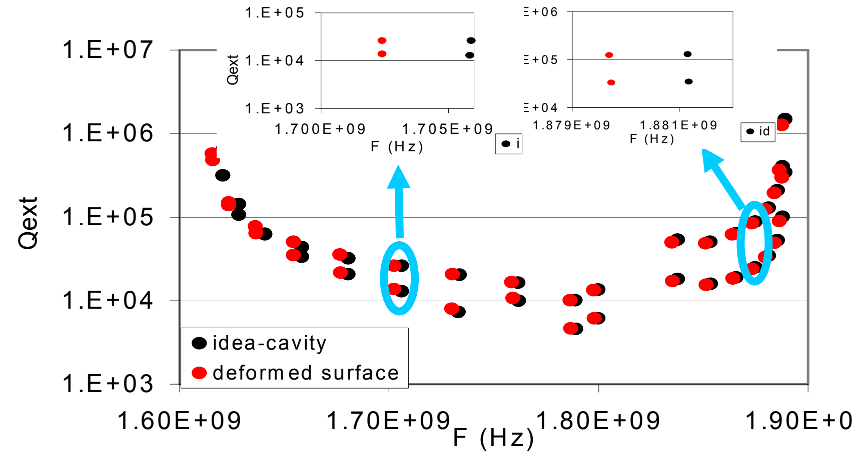
- Actual deformation? – geometry measurement data will be very helpful

Cylindrical Symmetric Deformation (*200micro on top/607micro on disk*)

- cause frequency shift

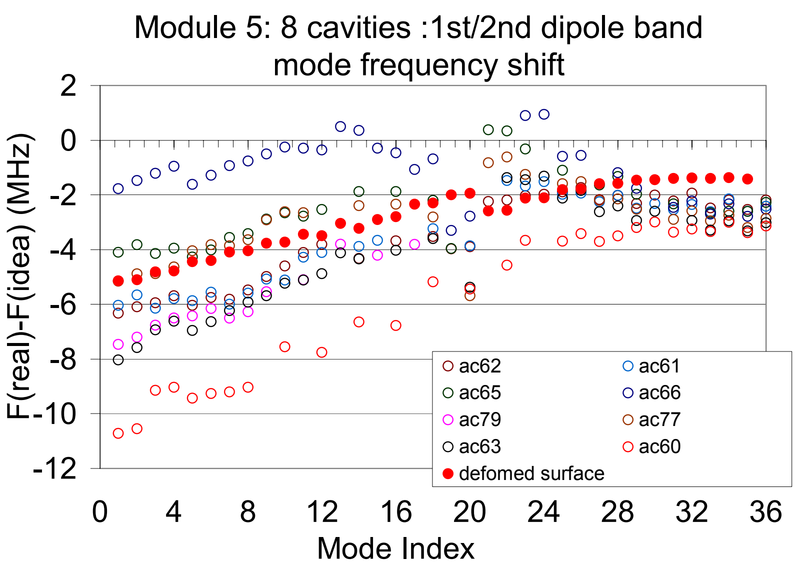
Ideal v.s. deformed

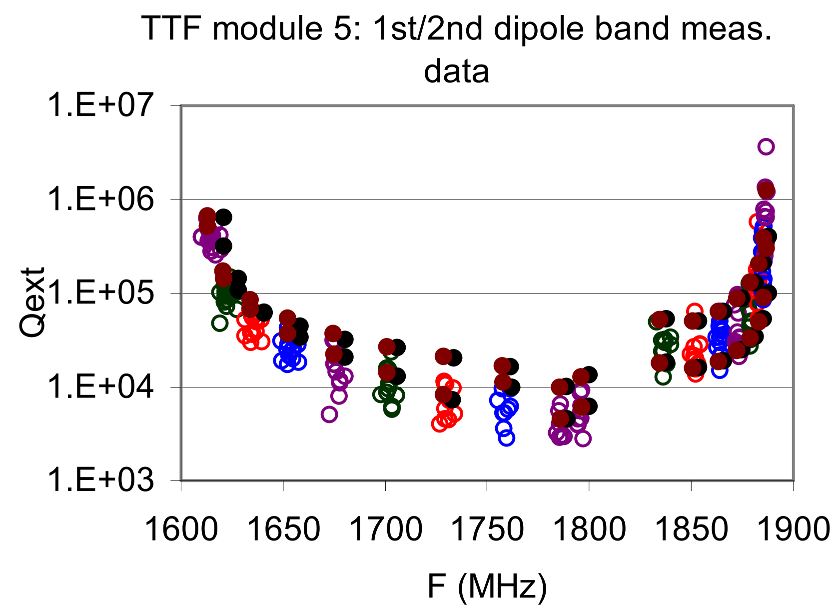




fπ-f8π/9=772KHz within meas. Range. 1st/2nd dipole band mode freq. shift roughly fit measurement data.

8-cavity measurement v.s. simulation/fitting

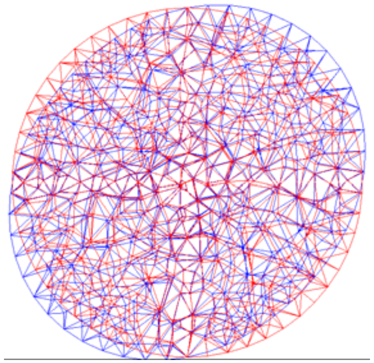




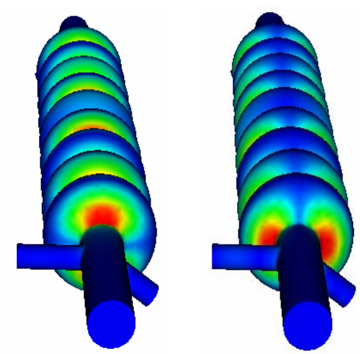
Need add randomness to imperfection parameters to model "realistic cavities"

Cell elliptical deformation (dr=250micro)

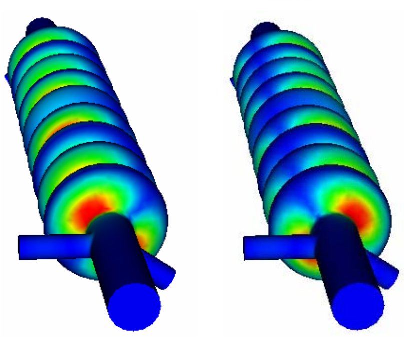
- cause mode Mode x-y coupling& Qext scattering

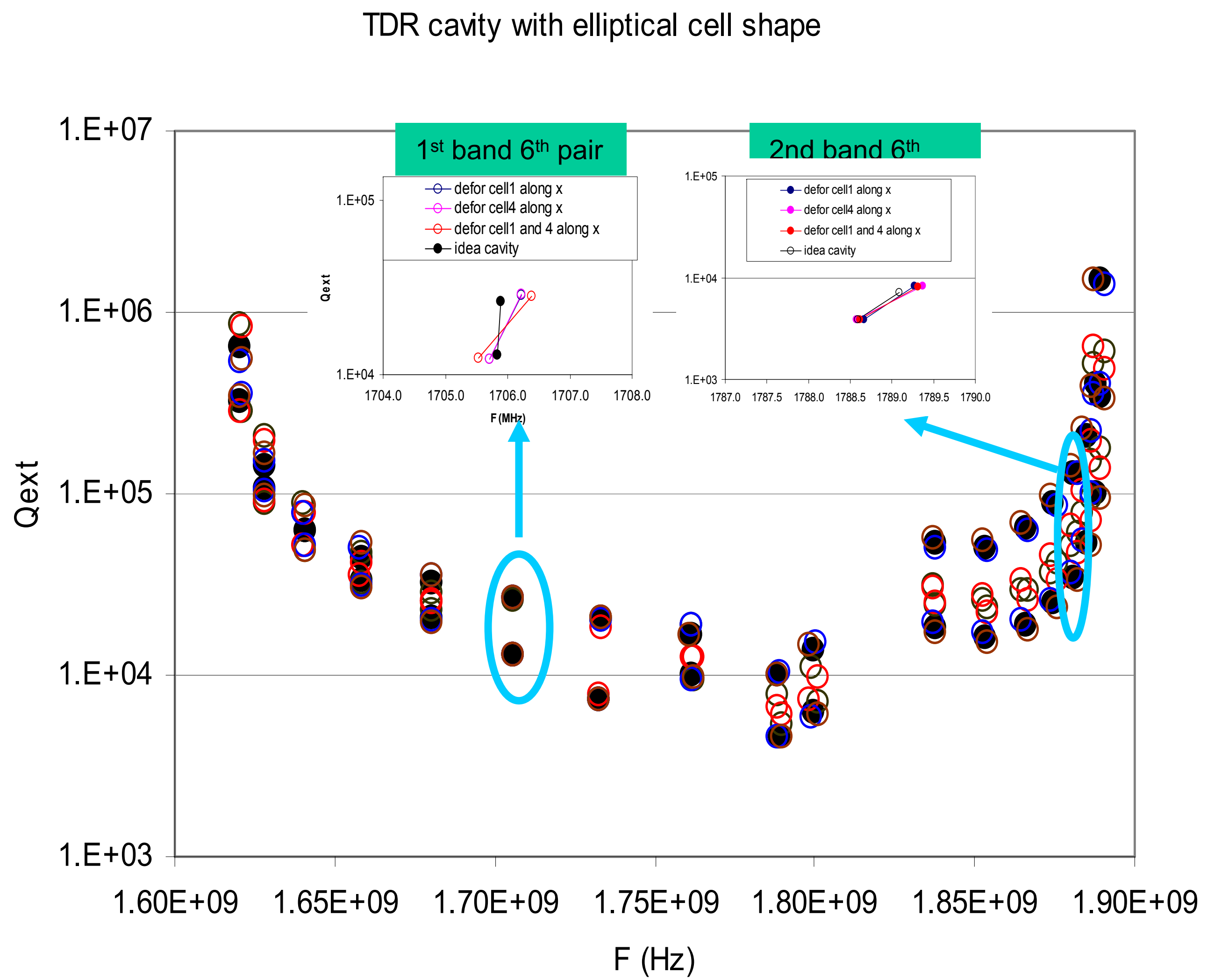


ideal cavity



elliptically deformed cavity





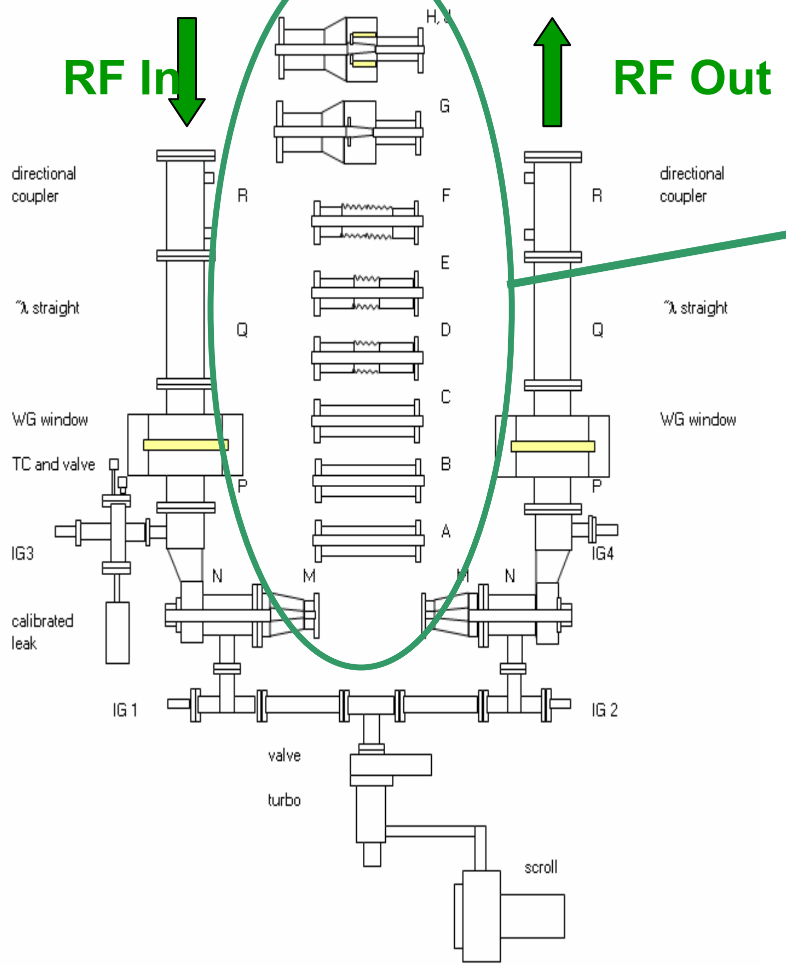
Coupler RF and SW Kicks

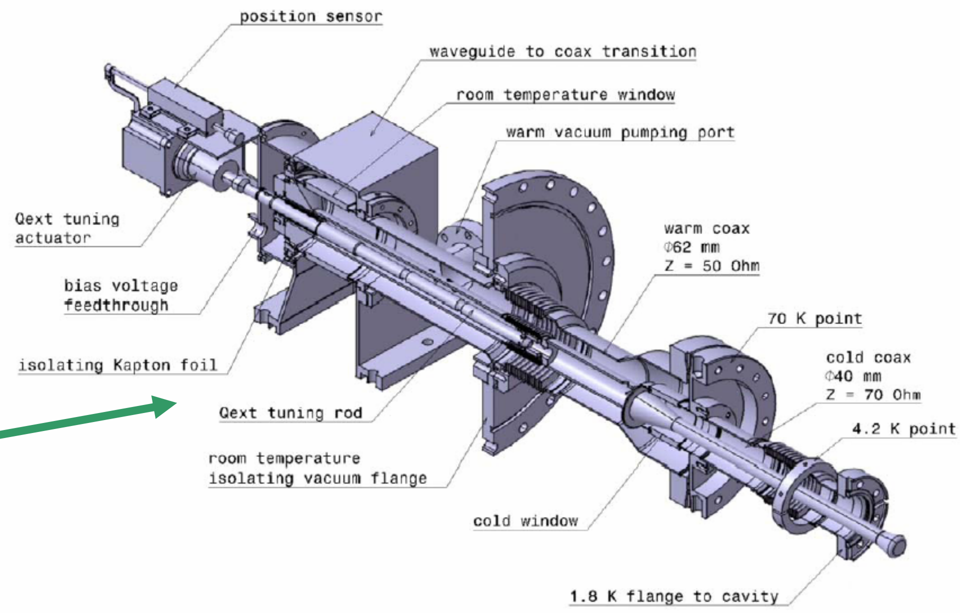
- Found to be important issues
- Studies being carried out

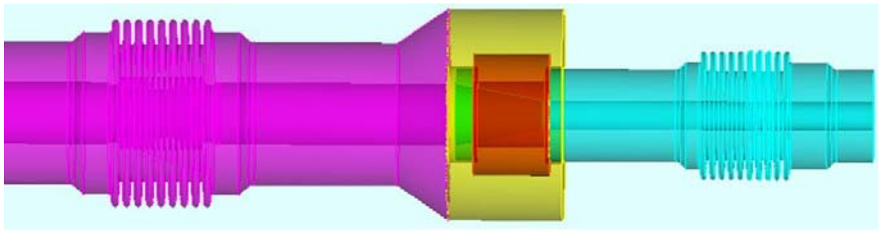
- See for details
  - Igor Zagorodnov and Martin Dohlus talk, ILC Workshop, DESY, 31 May, 2007
  - Z. Li cavity KOM talk, Sept. 20, 2007

TTFIII Coupler – Multipacting Analysis

MP simulations are carried out in support of ILC test stand at SLAC (LLNL) to study the cause of the TTFIII coupler's long processing time







Track3P model

Multipacting Simulation – Track3P

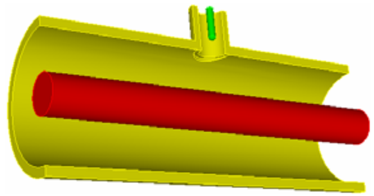
- 3D parallel high-order finite-element particle tracking code for dark current and multipacting simulations (developed under SciDAC)

- Track3P
  - traces particles in resonant modes, steady state or transient fields
  - accommodates several emission models: thermal, field and secondary

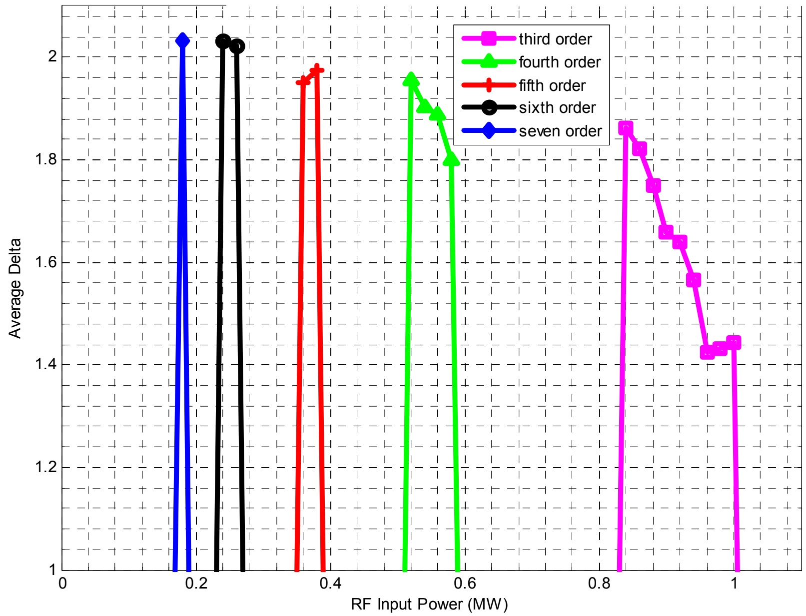
- MP simulation procedure
  - Launch electrons on specified surfaces with different RF phase, energy and emission angle
  - Record impact position, energy and RF phase; generate secondary electrons based on SEY according to impact energy
  - Determine “resonant” trajectories by consecutive impact phase and position
  - Calculate MP order (#RF cycles/impact) and MP type (#impacts /MP cycle)
- Track3P benchmarked extensively
  - Rise time effects on dark current for an X-band 30-cell structure
  - Prediction of MP barriers in the KEK ICHIRO cavity

Mulitpacting in Coax of TTFIII Coupler

Cold coax

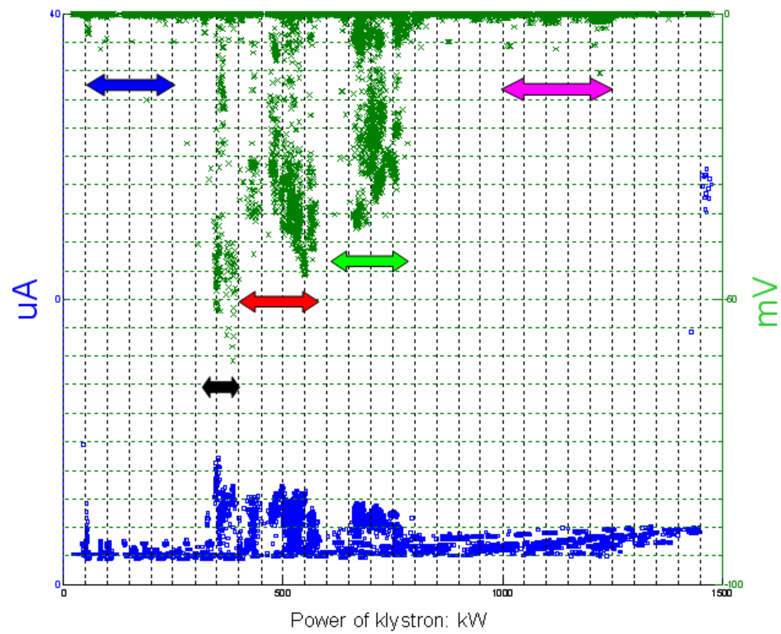


Track3P simulation



(F. Wang, C. Adolphsen, et. al)

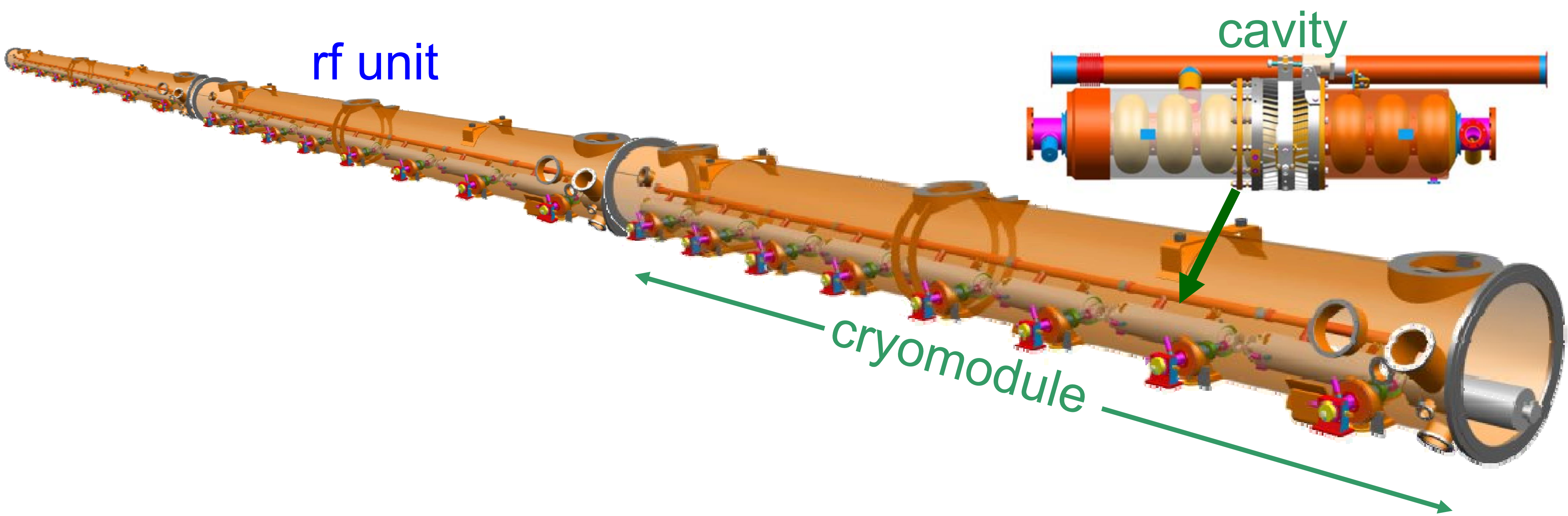
After high power processing



Simulated power (kW)	**170~190**	**230~270**	**350~390**	**510~590**	**830~1000**
Power in Coupler (kW)	**43~170**	**280~340**	**340~490**	**530~660**	**850~1020**
klystron power (kW)	**50~200**	**330~400**	**400~580**	**620~780**	**1000~1200**

More simulations being carried out to understand measurement details.

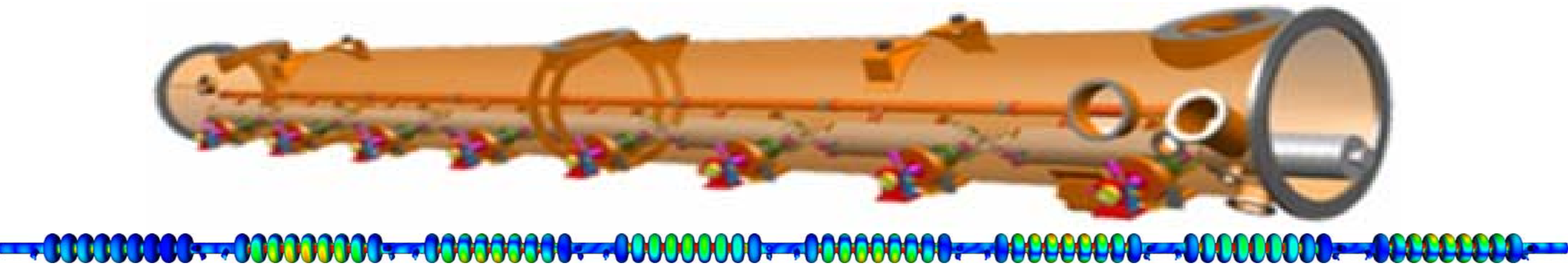
Modeling ILC Cryomodule & RF Unit



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

- *Trapped mode and damping*
- *Cavity imperfection effects on HOM damping*
- *Wakefield effect on beam dynamics*
- *Effectiveness of beam line aborsorber*

ILC 8-Cavity Module



A dipole mode in 8-cavity cryomodule at 3^{rd} band

First ever calculation of a 8 cavity cryomodule

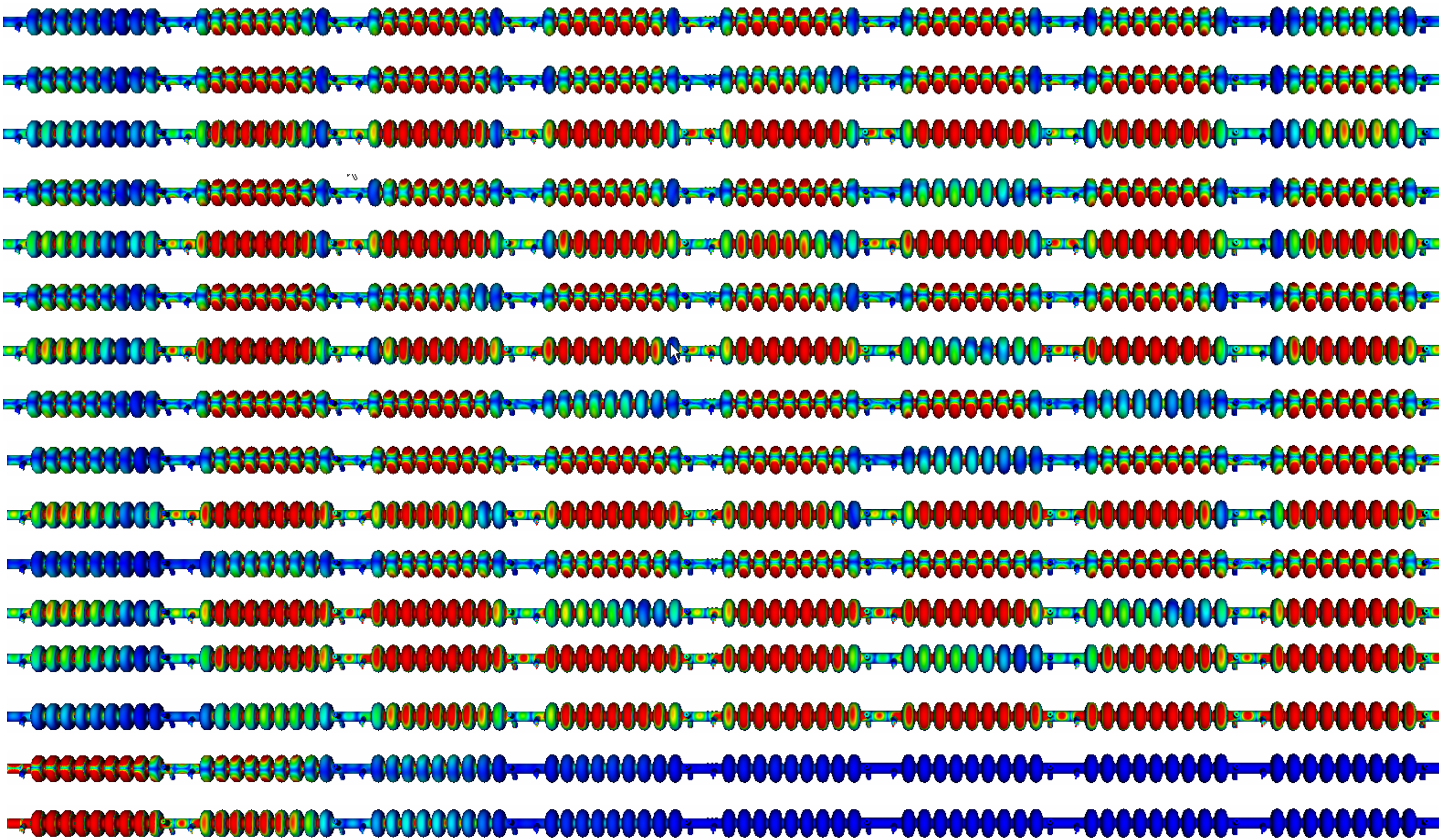
- *~ 20 M DOFs*
- *~ 1 hour per mode on 1024 CPUs for the cryomodule*

To model a 3-module RF unit would require

- *>200 M DOFs*
- *Advances in algorithm and solvers*
- *Petascale computing resources*

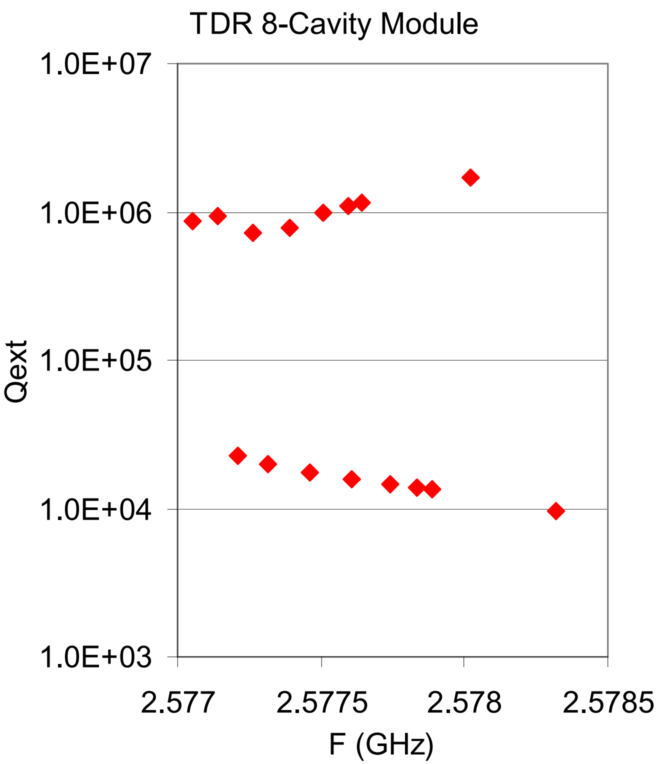
TDR 8-Cavity Module 3rd Band Modes From Omega3P Calculation

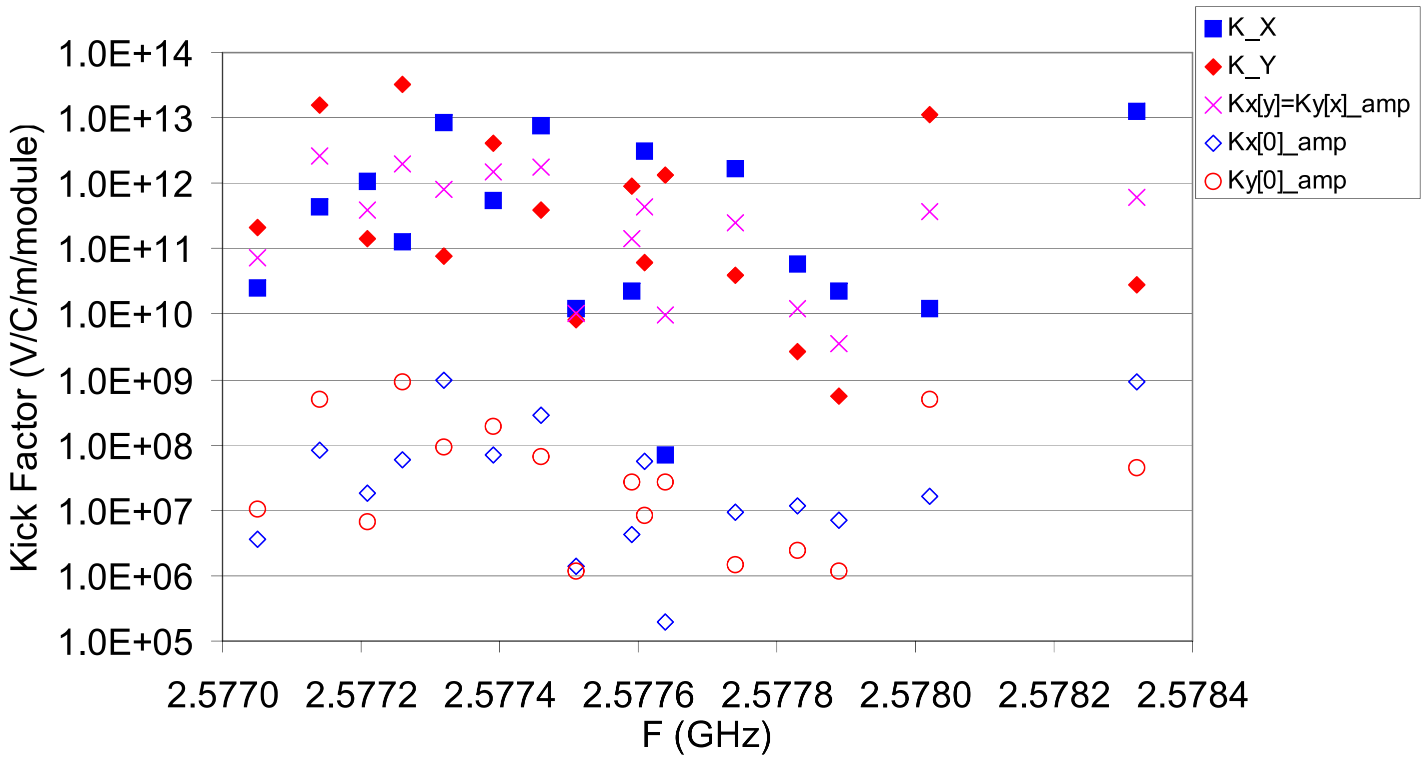
(R. Lee)



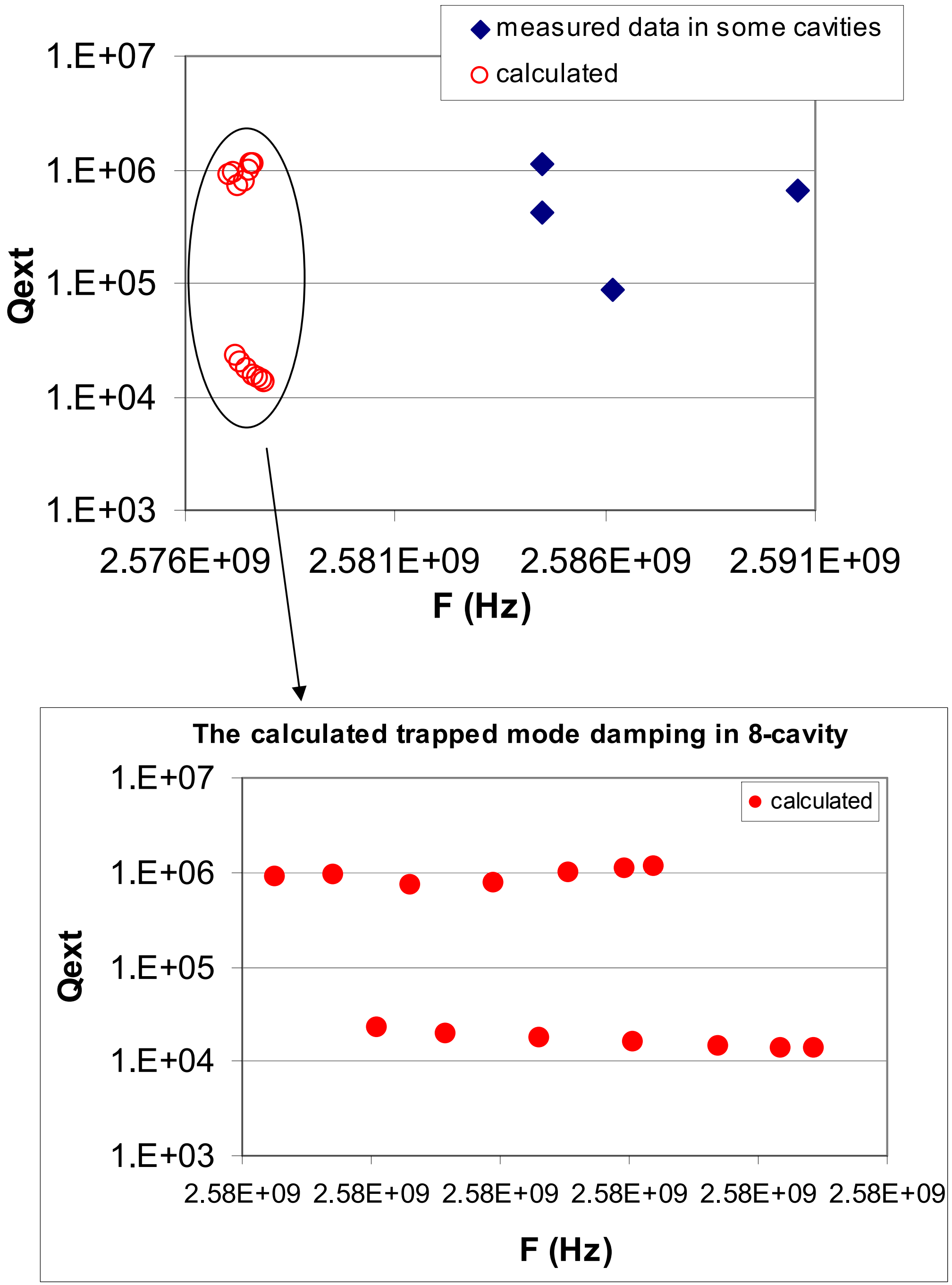
Calculated on NERSC Seaborg: 1500 CPUs, over one hour per mode

Kick Factor Of One Set Of 3rd Band Modes in the 8-Cavity TDR Module





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



One polarization mode is well damped.

INVESTIGATION OF A HIGH-Q DIPOLE MODE AT THE TESLA CAVITIES

N. Baboi*, M. Dohlus, DESY, Hamburg, Germany
C. Magne, A. Mosnier, O. Napoly, CEA, Saclay, France
H.-W. Glock, Uni Rostock, Germany

At TTF several experiments have been made in order to study the HOMs. By modulating the beam current [2], several high impedance modes have been found to have a very high Q [3]. Specially a mode around 2.585 GHz, the last of the 3rd dipole band, having an estimated impedance R/Q = 15 Ω/cm^2, was found to be badly damped in 2 cavities of the first module. Nevertheless, the other polarization of the same mode is better damped. It was found that this mode is badly damped in one of the cavities of the 2nd and 3rd modules as well. The results are summarized in Table. 1.

Table 1. Results of HOM investigations for the last mode of the 3rd dipole passband (R/Q = 15 Ω/cm^2)

Cavity nr./module	Freq. [GHz]	Q
#3 (S10) / 1	2.5845	$1.1 \cdot 10^6$
#6 (S11) / 1	2.5862	$8.6 \cdot 10^4$
#5 (A15) / 2	2.5845	$4.2 \cdot 10^5$
#7 (S28) / 3	2.5906	$6.5 \cdot 10^5$

Recent Advances in Solver and Meshing - Improving Modeling Efficiency

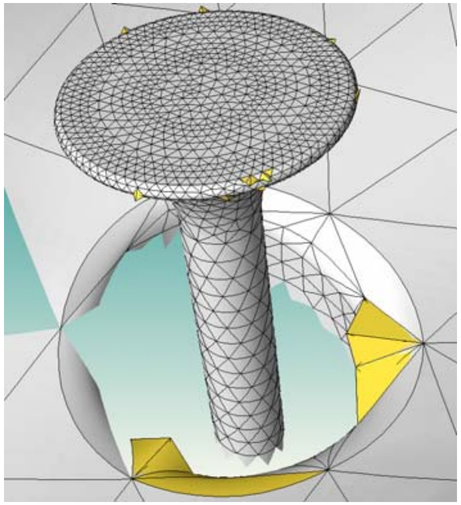
Linear Solver

Simulation capabilities limited by memory available even on DOE flagship supercomputers – develop methods for reducing memory usage

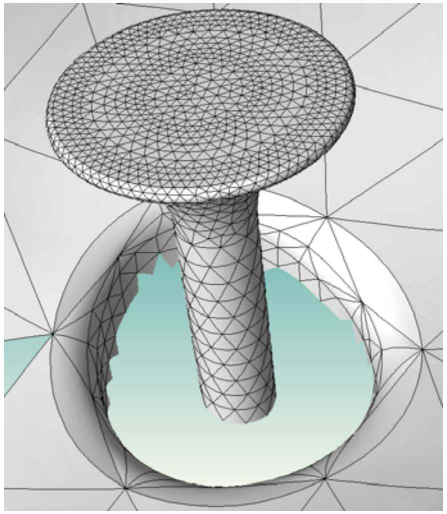
Method	Memory (GB)	Runtime (s)
MUMPS	155.3	293.3
MUMPS + single precision factorization	82.3	450.1

Meshing

- Invalid quadratic tets generated on curved surface
- Collaborated with RPI on a mesh correction tool
- Runtime of corrected model faster by 30% (T3P)

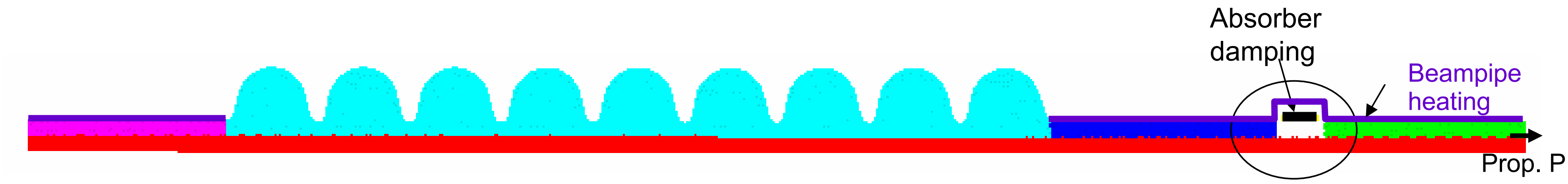


Invalid tets (yellow)



Corrected mesh

Beamline Absorber Study Using T3P



Calculate the total energy generated by the beam

$$Kloss = \frac{1}{Q}\int_0^{+\infty} W_z(s)q(s)ds$$

Lossy dielectric conductivity $\sigma=\omega\varepsilon_i$ $\varepsilon_i=4$

Calculate the total energy stored in the cavity

$$Energy(t) = \int (\frac{1}{2}\varepsilon E(t)^2 + \frac{1}{2}\mu H(t)^2)dv$$

Calculate the energy absorption in the beam line absorber.

$$Energy(t) = \int \int \sigma E^2(t)\,dvdt$$

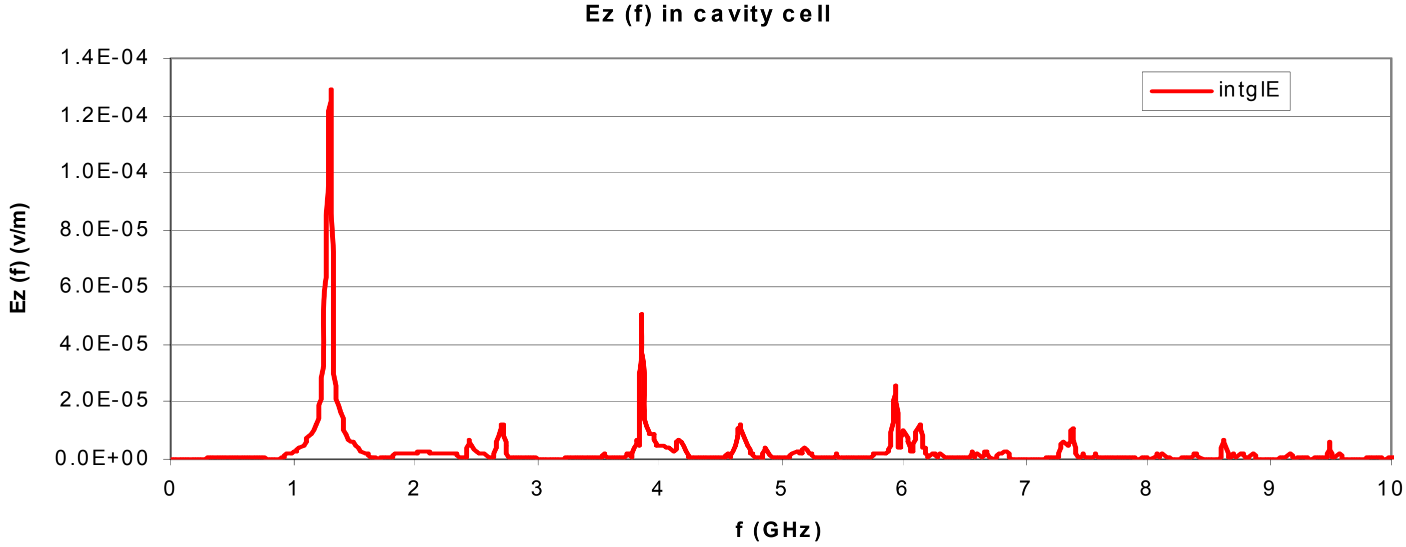
Calculate the power heating on the NC beam pipe

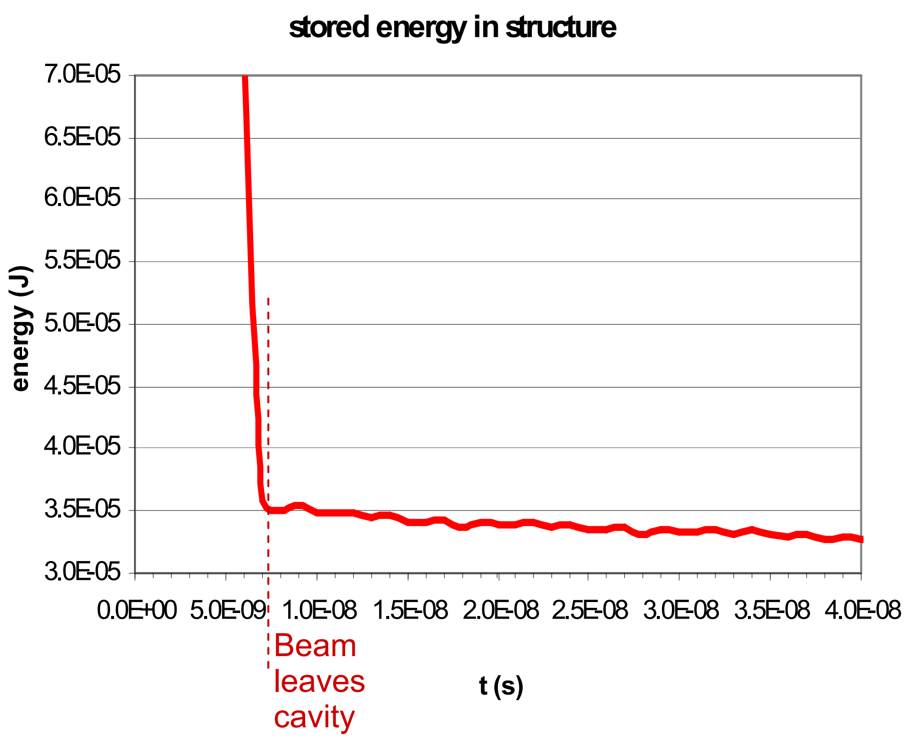
$$Energy = \int \frac{1}{2\pi} Rs(\omega) H_t^2(\omega) d\omega ds$$

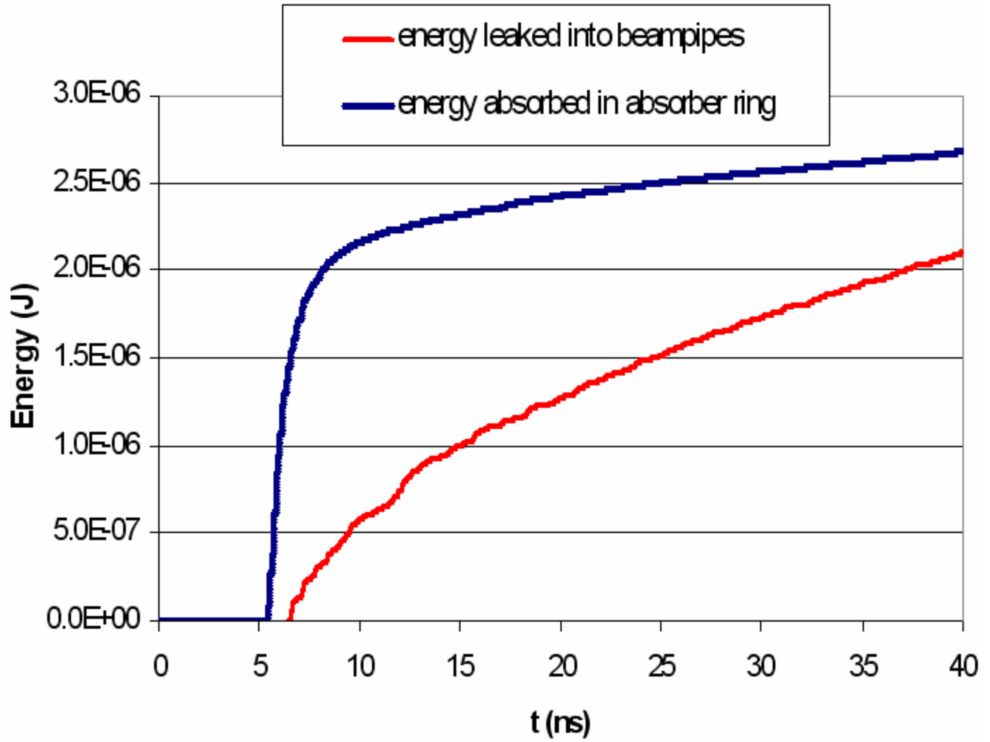
Calculate power propagating in beam pipe

$$Energy\ (t) = \int \int \vec{E}(t) \times \vec{H}(t).\vec{n}\,dsdt$$

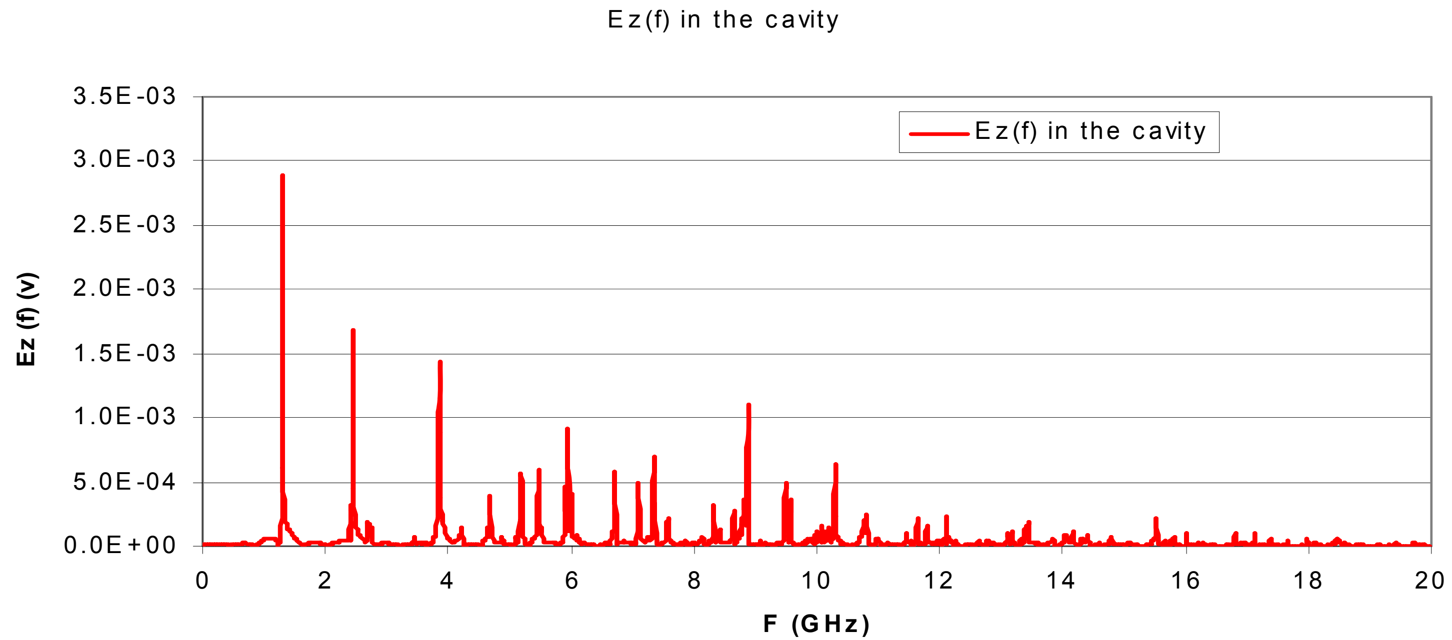
Eg.1: single cavity with beamline absorber **(εr=15, absorber conductivity=0.6)**
bunch: ***σz=10mm Q=3.2nc, beam on axis***

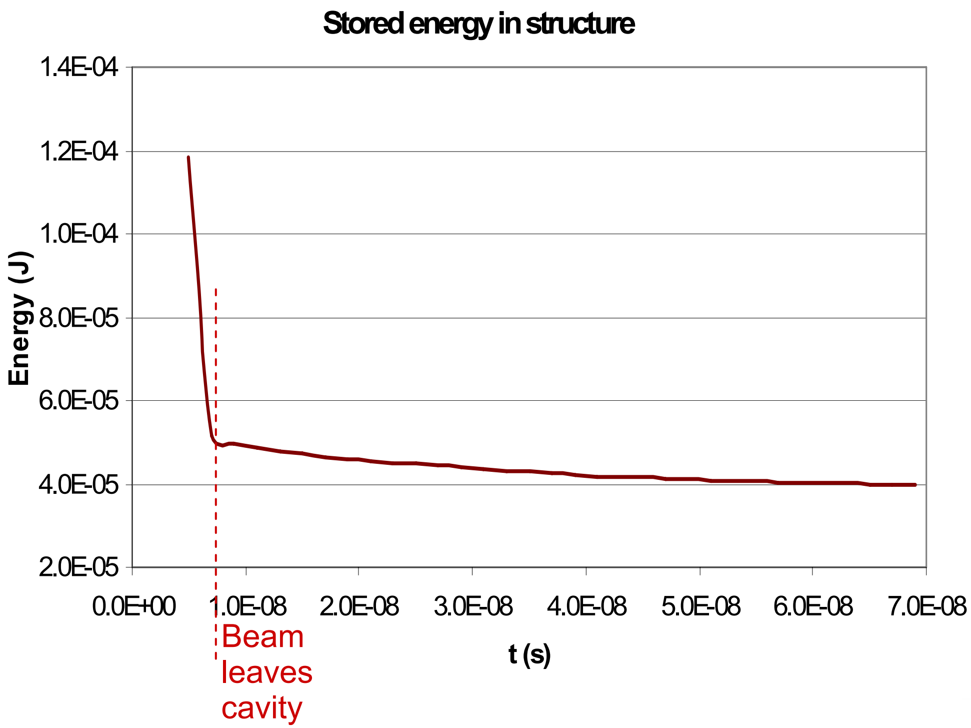


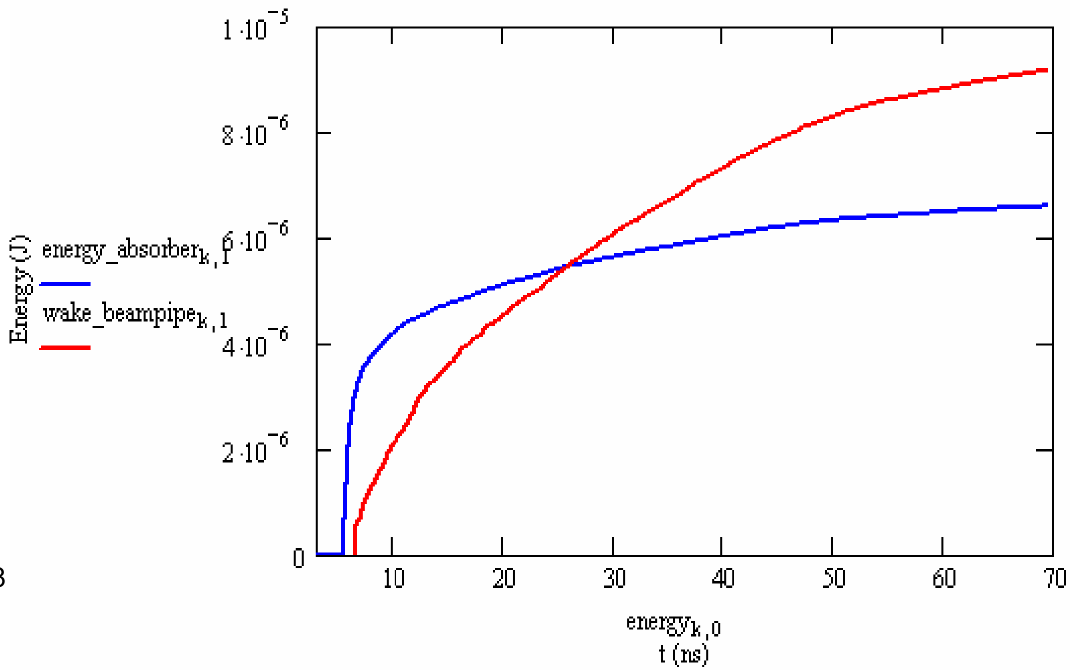




Eg.2: single cavity with beamline absorber ***(εr=15, absorber conductivity=0.6)***
bunch: ***σz=5mm Q=3.2nc, beam on axis***







Results for Single cavity with beamline absorber

One bunch Q=3.2nc, bunch length=0.01m Loss factor (V/pc)=3.566V/pc	**Lossy dielectric conductivity σ=0.6** **Within 40ns**	
Total Energy Generated by Beam (J)	**3.65e-5**	
Total Energy Left in cavity (J)	*3.27e-5*	
(Total Energy due to fundament mode (J))	*(2.06e-5)*	
Total Energy into beam pipe (J)	*2.10e-6*	0.78:1
Total Energy Loss in the absorber (J)	*2.68e-6*	
Total Energy Loss on the NC beampipe wall (J)	1.24e-8	

One bunch Q=3.2nc, bunch length=0.005m Loss factor (V/pc)=5.14V/pc	**Lossy dielectric conductivity σ=0.6** **Within 70ns**	
Total Energy Generated by Beam (J)	**5.26e-5**	
Total Energy Left in cavity (J)	*3.97e-5*	
(Total Energy due to fundament mode (J))	*(2.12e-5)*	
Total Energy into beam pipe (J)	*9.164e-6*	1.4:1
Total Energy Loss in the absorber (J)	*6.586e-6*	
Total Energy Loss on the NC beampipe wall (J)		

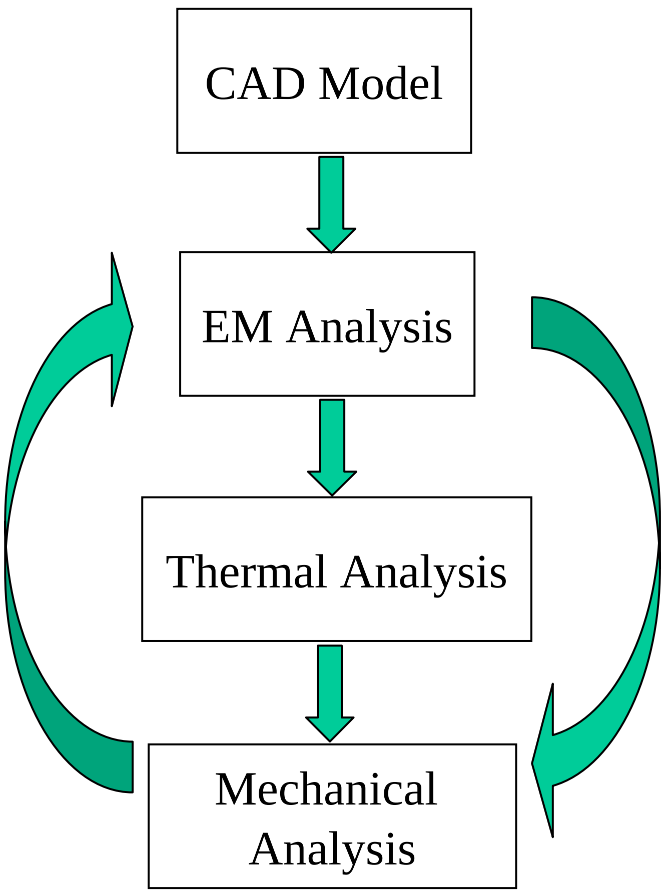
Next steps:

- Short bunches – big challenges in memory and computation time
- Frequency dependent lossy material
- Multi-cavity – cascading effects
- HOM power leakage through HOM couplers – 3D simulation

Multi-physics Analysis for Accelerator Components

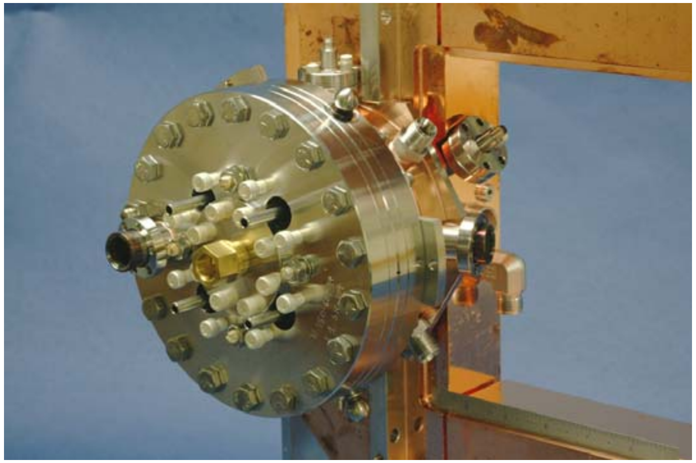
- Virtual prototyping through computing
  - RF design
  - RF heating
  - Thermal radiation
  - Lorentz force detuning
  - Mechanical stress
  - Optimization
- Large-scale parallel computing enables:
  - Large system optimization
  - Accurate and reliable multi-physics analysis
  - Fast turn around time
- TEM3P – integrated parallel multi-physics tools
- -> Analyze RF/Thermal/Mechanical effects in ILC cavity and module

TEM3P: Multi-Physics Analysis

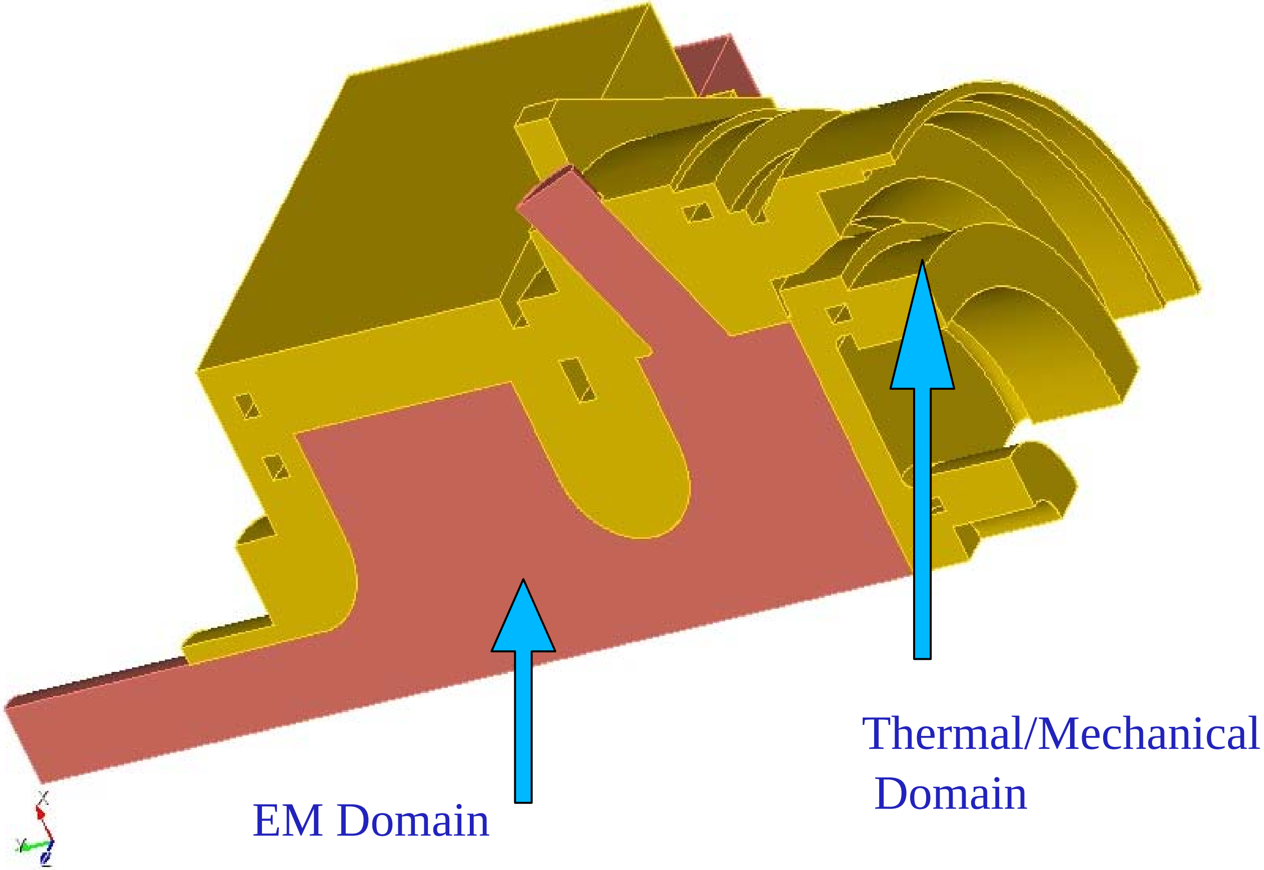


- Finite element based with high-order basis functions
  - Natural choice: FEM originated from structural analysis!
- Use the same software infrastructure as Omega3P
  - Reuse solvers framework
  - Mesh data structures and format
- Parallel

TEM3P for LCLS RF Gun – Benchmark Example

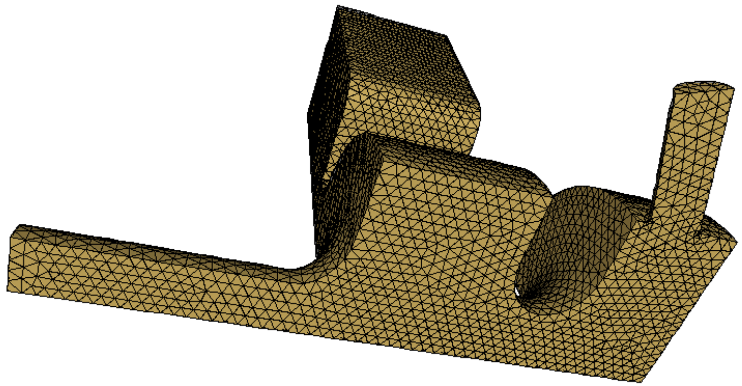


CAD Model (courtesy of Eric Jongewaard)

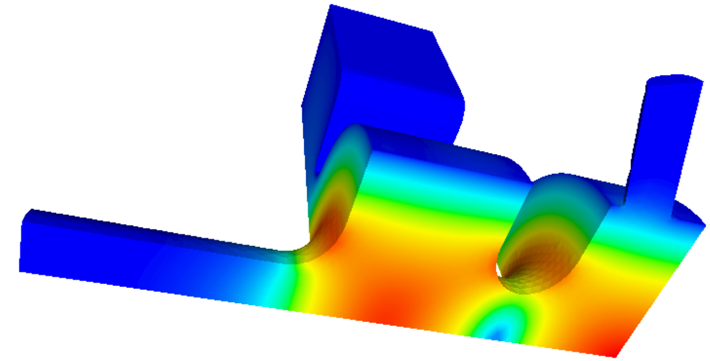


Benchmark TEM3P against ANSYS

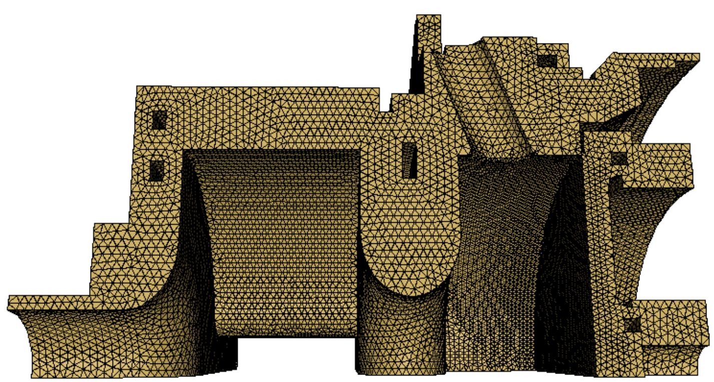
RF Gun EM Thermal/Mechanical Analysis



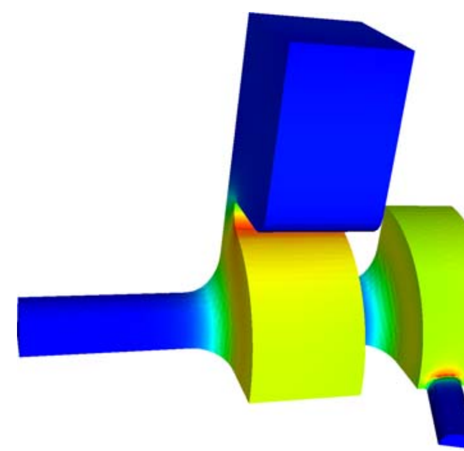
Mesh for RF analysis



Operating mode: 2.856GHz



Mesh for Thermal/Mechanical analysis
Mesh: 0.6 million nodes.
Materials: Copper + Stainless steel
Thermal analysis: 7 cooling channels



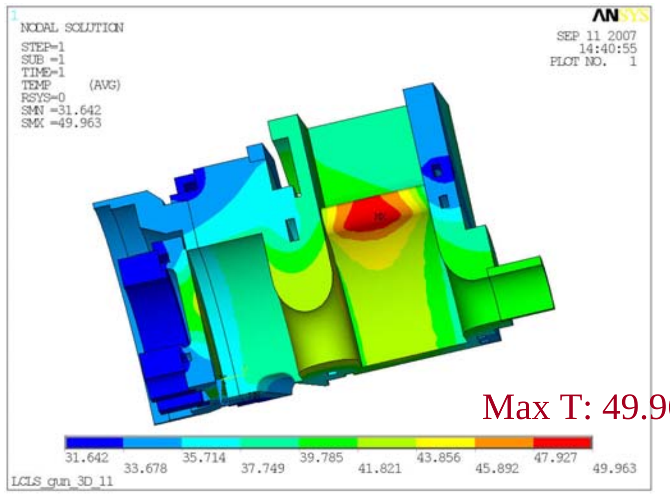
Magnetic field on the cavity inner surface generates RF heat load

Thermal/Mechanical Analysis Benchmarked With ANSYS

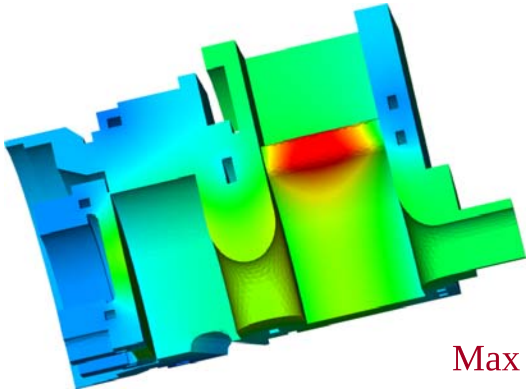
ANSYS

TEM3P

Temperature Distribution →

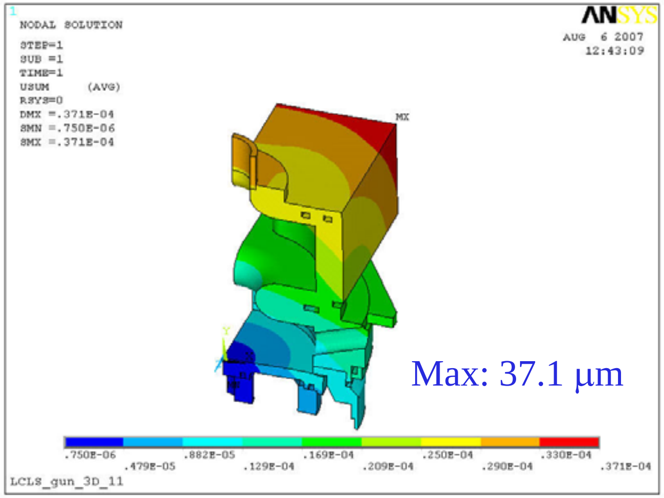


Max T: 49.96 C



Max T: 49.82 C

Displacement →

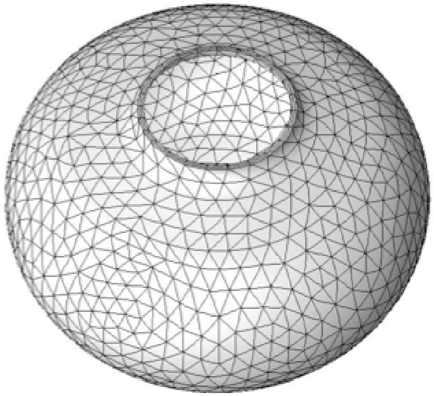


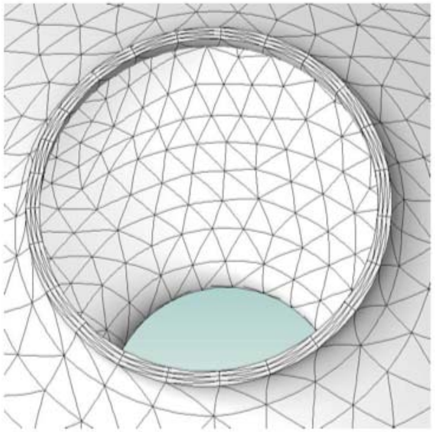
Max: 37.1 μm

Max: 36.99 μm

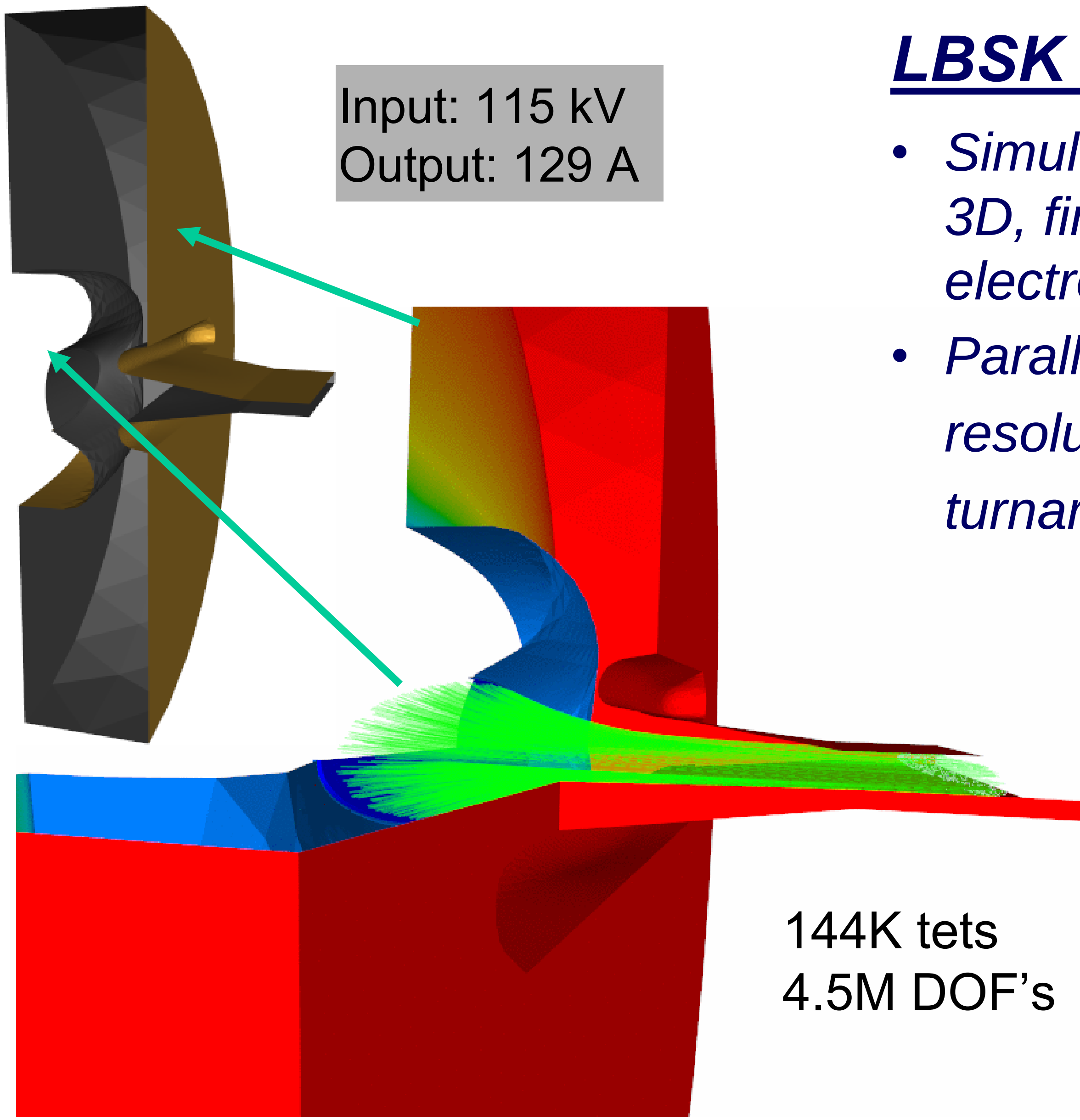
Multi-physics Analysis for SRF Cavities and Cryomodules

- Thermal behaviors are highly nonlinear
  - To implement nonlinear temperature dependent materials
- Meshing thin shell geometry
  - Anisotropic high-order mesh will reduce significant amount of computing
  - Working with RPI/ITAPS





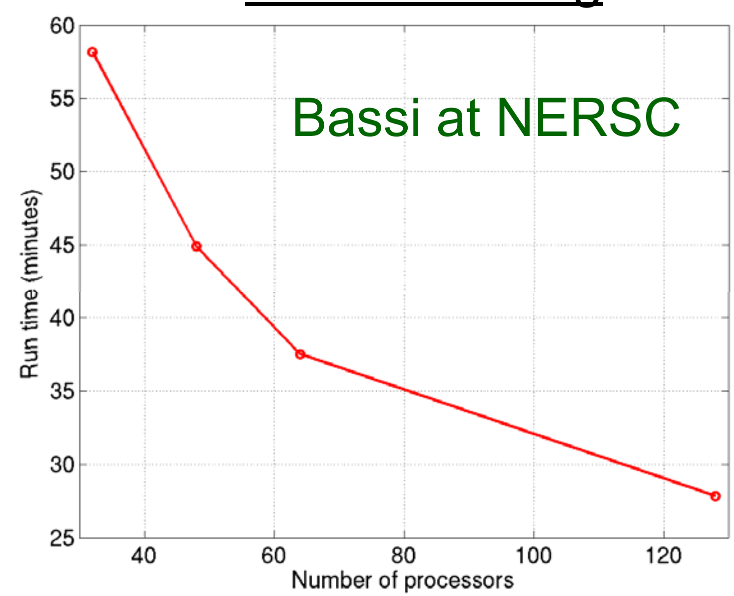
L-Band Sheet Beam Klystron



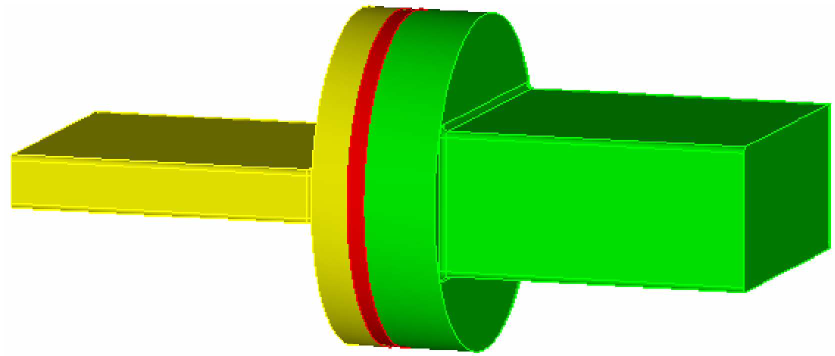
***<u>LBSK gun</u>* –**

- *Simulated using GUN3P, a parallel, 3D, finite-element (up to 4th order) electron trajectory code*
- *Parallel computation allows high resolution simulation with fast turnaround time*

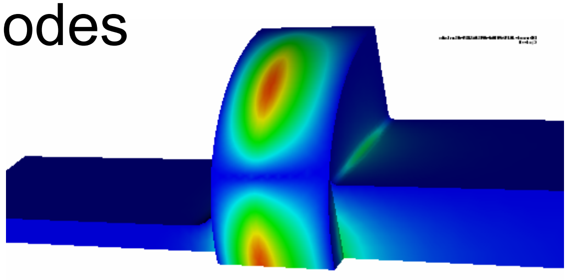
<u>Parallel scaling</u>

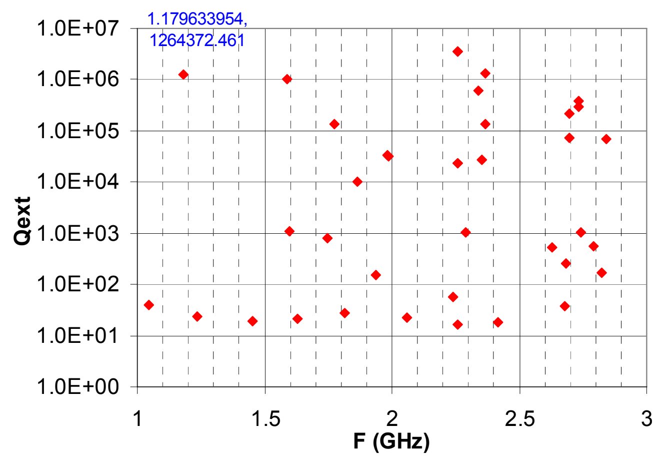


LSBK Window Modeling

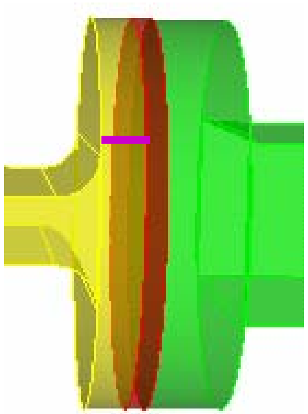


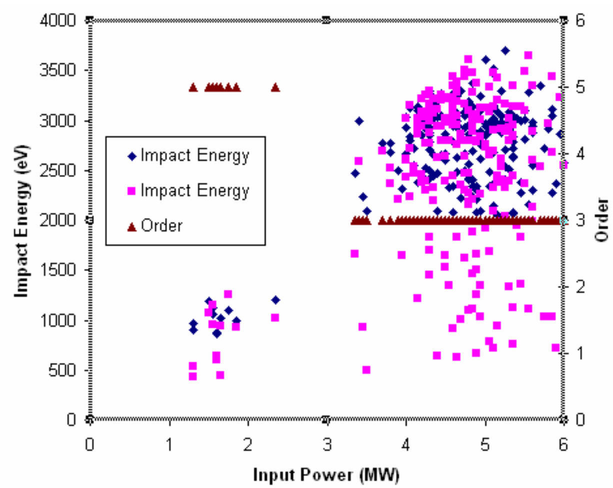
- Trapped modes





- MP analysis





Summary

- A suite of parallel codes in electromagnetics and beam dynamics was developed for accelerator design, optimization and analysis
- Have applied these codes to the ILC cavity design, cavity imperfection analysis, multi-cavity wakefield calculations, RF heating calculation, etc.
- Integrate RF/Thermal/Mechanical capability is being developed for multi-physics analysis.
- Through the SciDAC support and collaborations, advances in applied math and computer science are being made towards Petascale computing of large accelerator systems such as the ILC RF unit, etc