SPX Cavity Design

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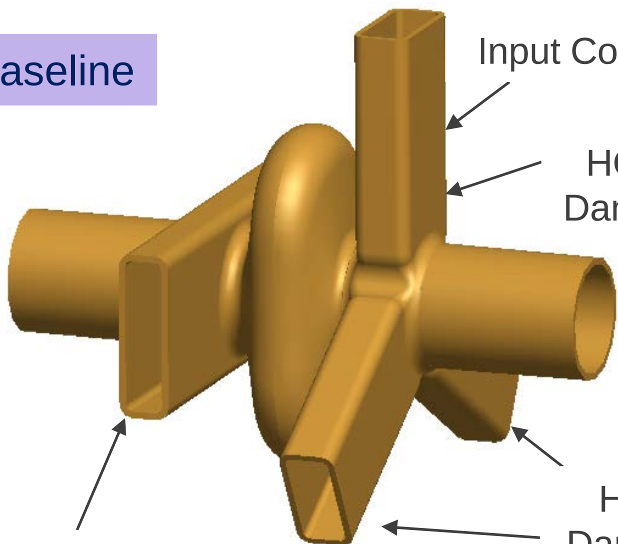
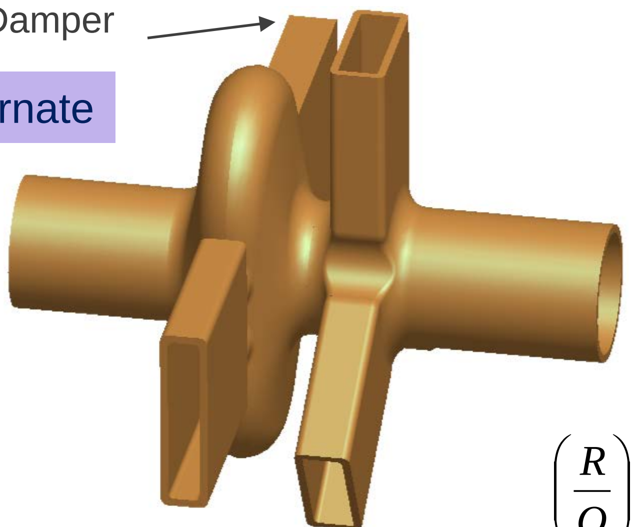
APS / SPX Team
JLAB / SRF Institute
LBNL / Center for Beam Physics

Single-Cell SC Cavity

Baseline



Alternate



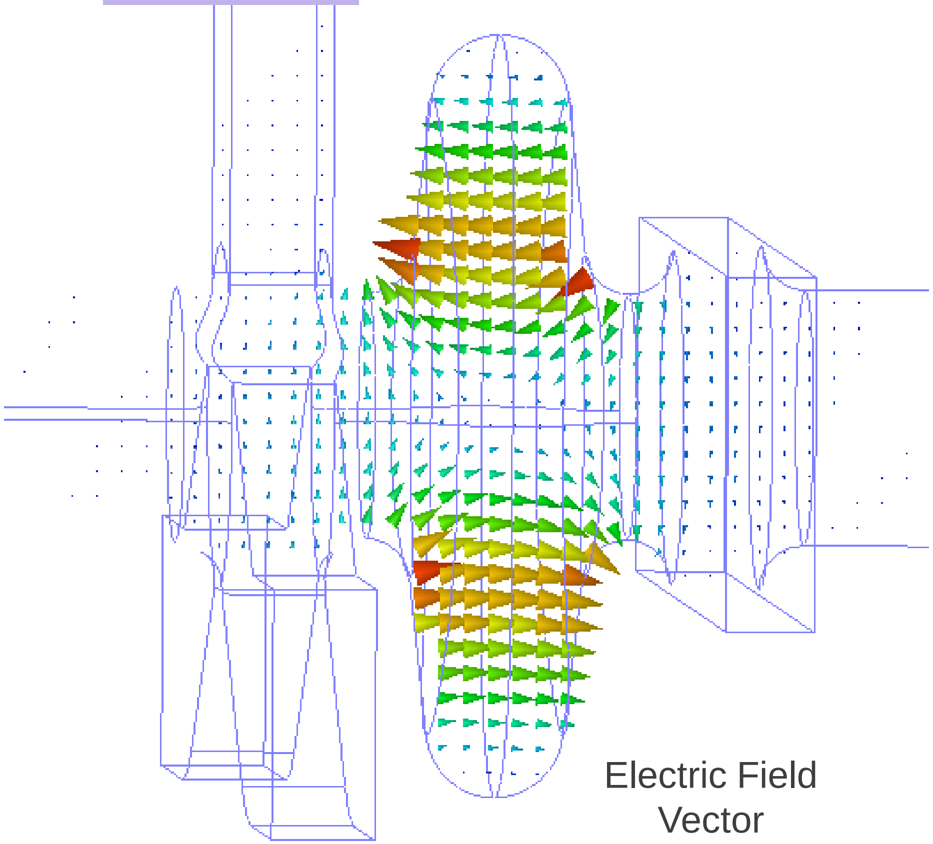
$$\left(\frac{R}{Q}\right)' = \frac{V^2\big|_{r=r_0}}{2\omega U \left(k\, r_0\right)^2}$$

Frequency	2815	MHz
Q_U	~10^9	
V_t	0.5	MV
Energy	0.39	J
$k_{\|\|}$	0.615	V/pC
(R/Q)'	17.8	Ohm
E_{peak} / V_t	83	1/m
B_{peak} / V_t	182	mT / MV
P_{loss}	7	W
I_{beam}	200	mA
Cavity Iris Rad	25	mm
Cavity Beam Pipe Rad	26	mm
Cavity Active Gap	53.24	mm
Q_{ext}	~ 10^6	
Cells / Cavity	1	
No. Cavity	4 * 2	

Parameters for the Baseline Cavity

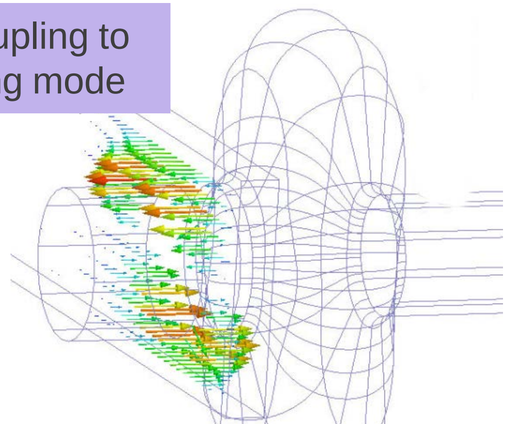
Cavity Deflecting Mode

TM110 dipole mode

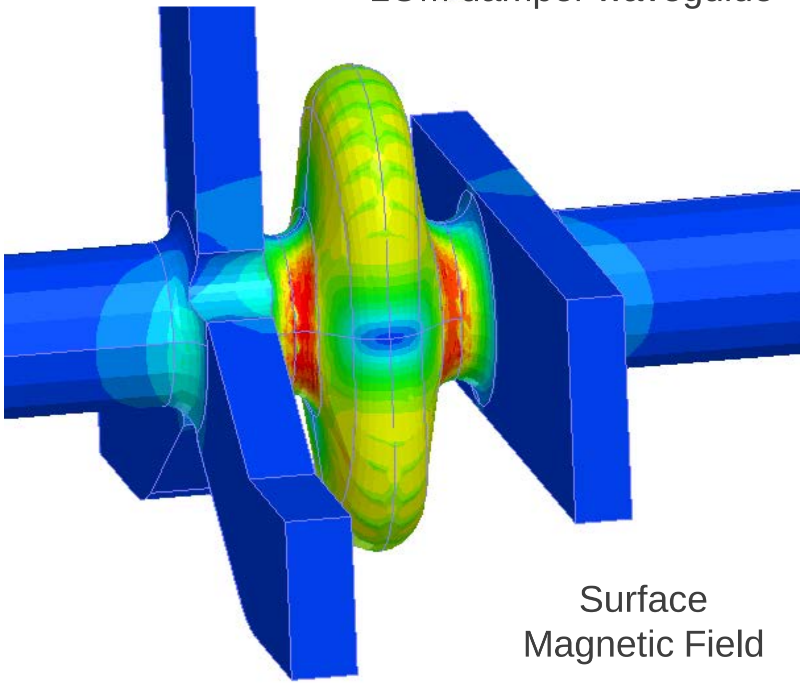


Electric Field Vector

LOM coupling to deflecting mode



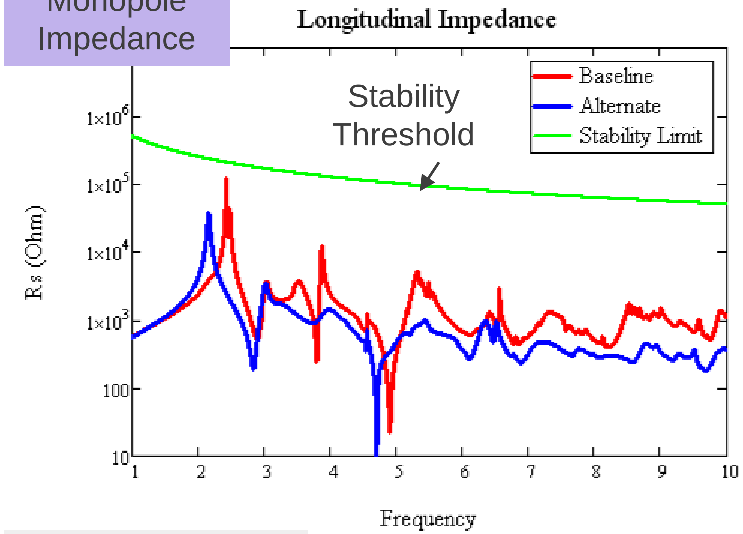
TE_{20} coupling mode to LOM damper waveguide



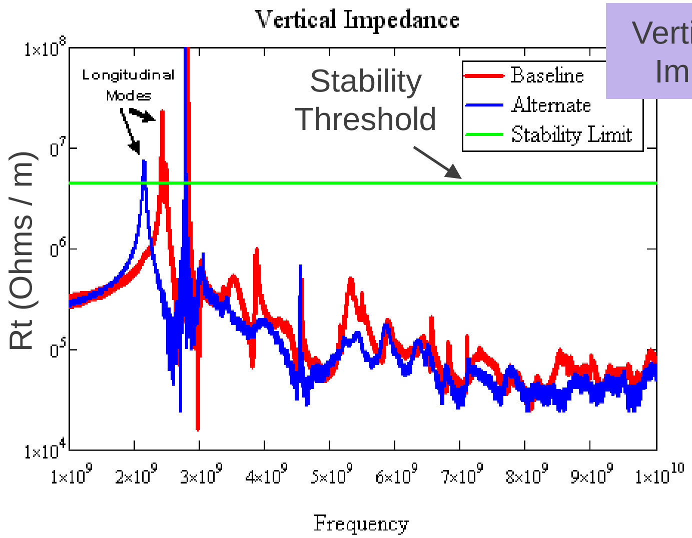
Surface Magnetic Field

Longitudinal and Transverse Impedance

Monopole Impedance



Vertical Dipole Impedance



Monopole Stability Threshold

$$R_s * f_p < 0.5M\Omega - GHz \qquad R_s = \frac{V^2}{2P_l}$$

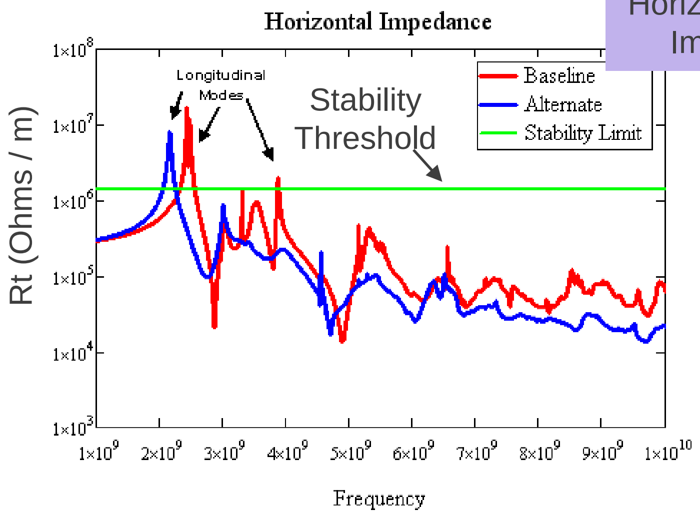
Dipole Stability Threshold

$R_t < 1.5M\Omega / m$ Horizontal dipole

$R_t < 4.5M\Omega / m$ Vertical dipole

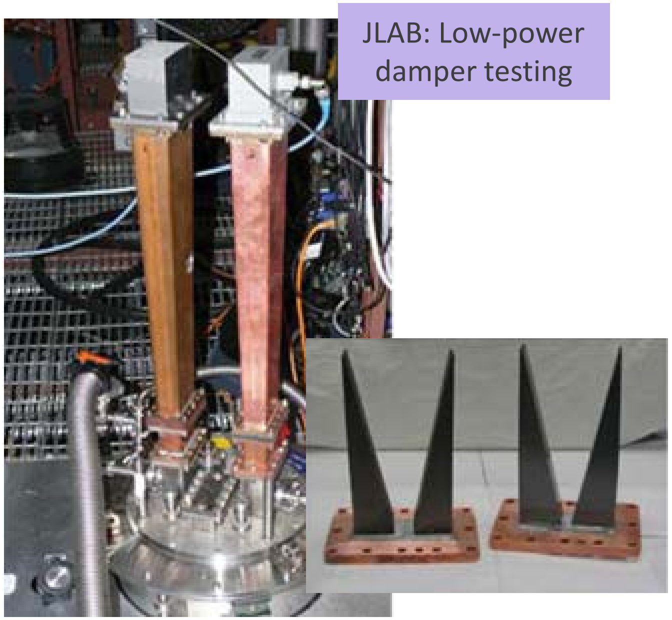
$$R_t = \frac{V^2\big|_{r=r_0}}{2\,P_l\,k\,r_0^2}$$

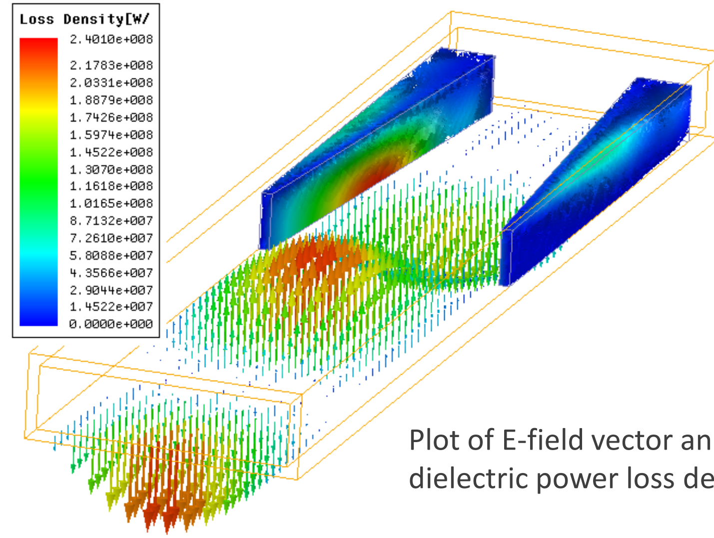
Horizontal Dipole Impedance



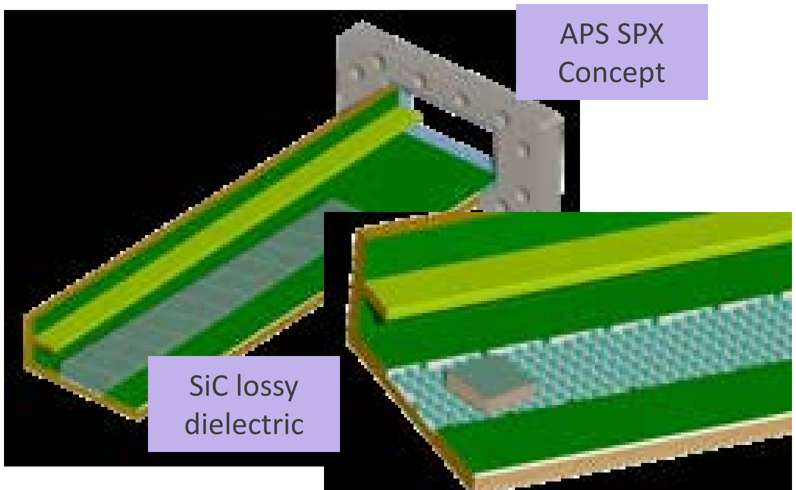
Damper Design Concept

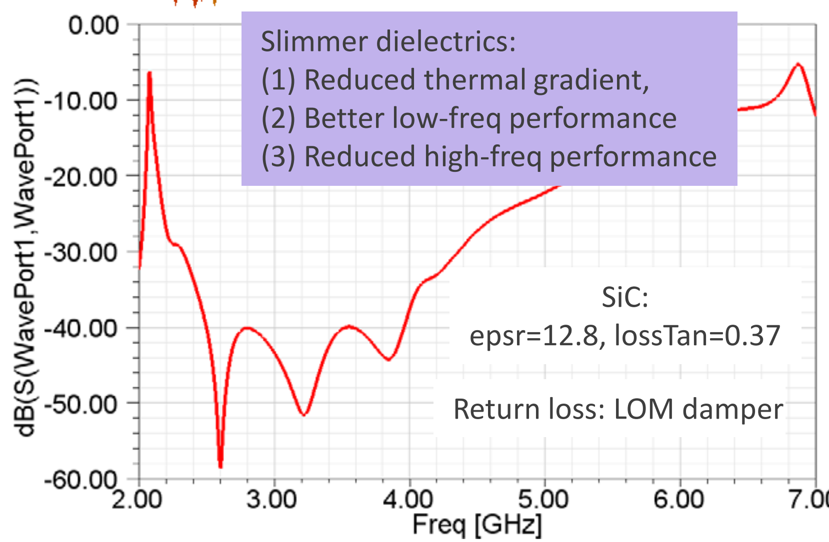
Each SPX cavity must extract kW's of HOM/LOM beam power





Plot of E-field vector and dielectric power loss density

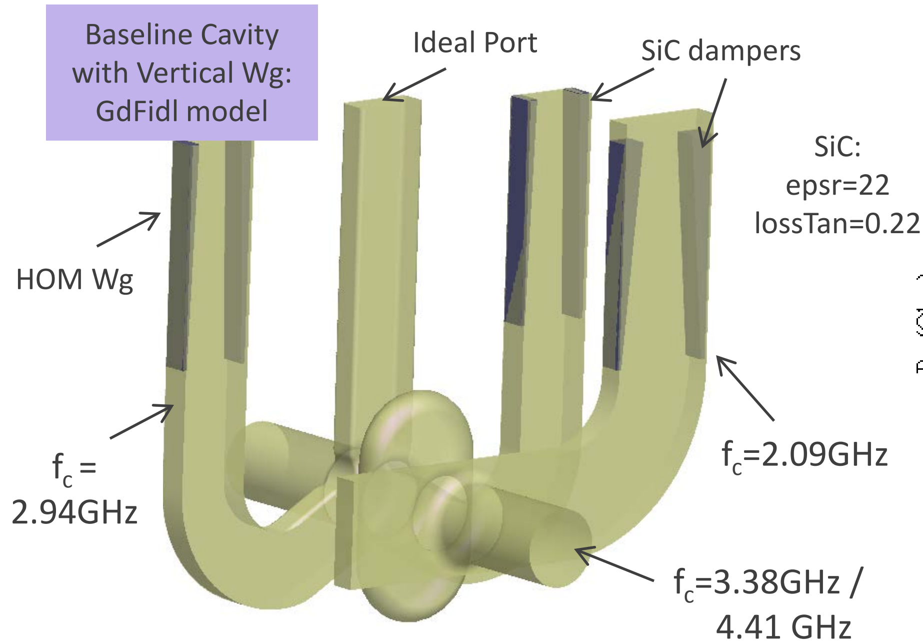


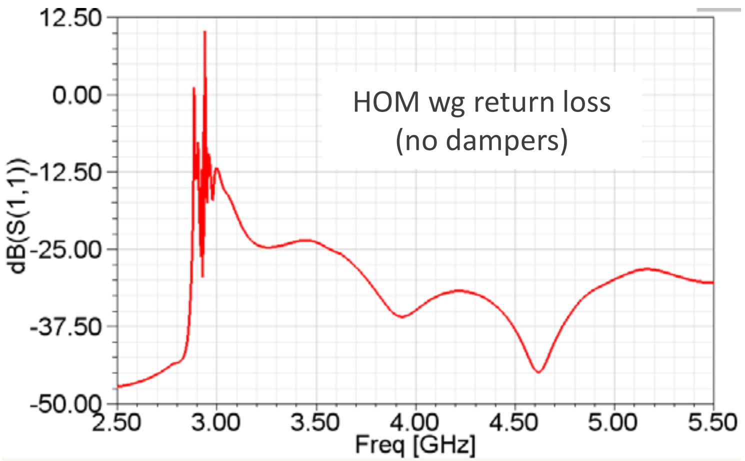


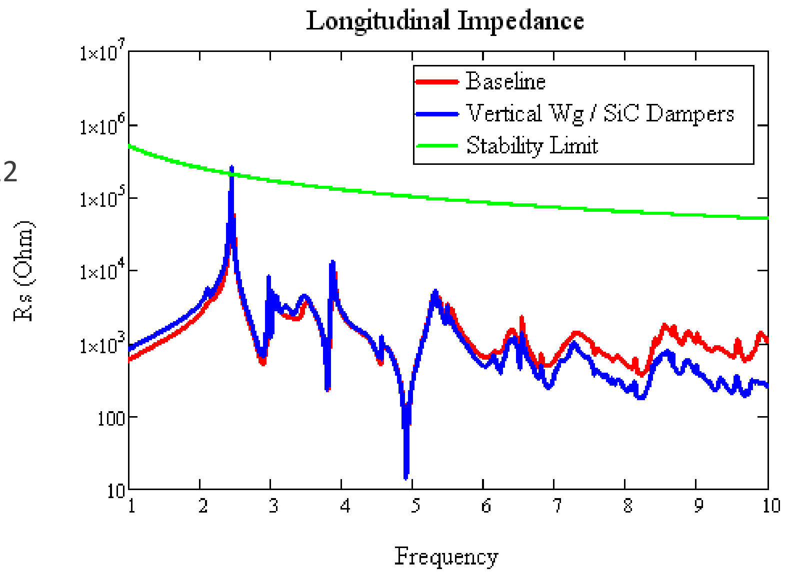
F. Marhauser. "Investigations on Absorber Materials at Cryogenic Temperatures"

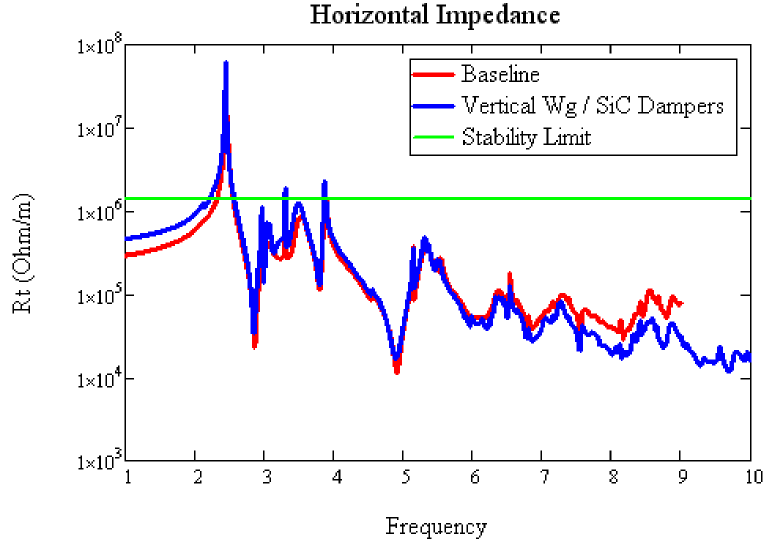
G. Chang: High-Power Damper Concept

Impedance Response with Dampers and Wg Bends







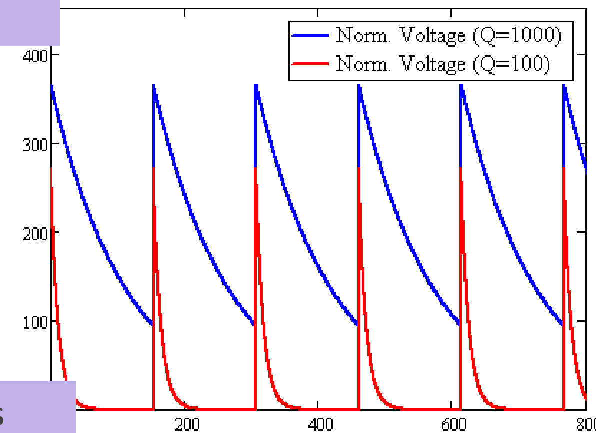


RF Loading of Dampers

- Q_{ext} is typically damped below 1000.
- All ports are assumed to be ideal waveguide ports.
- 24 bunch fill pattern has been assumed
- Non-physical modes due to finite simulation volume have not yet been removed.

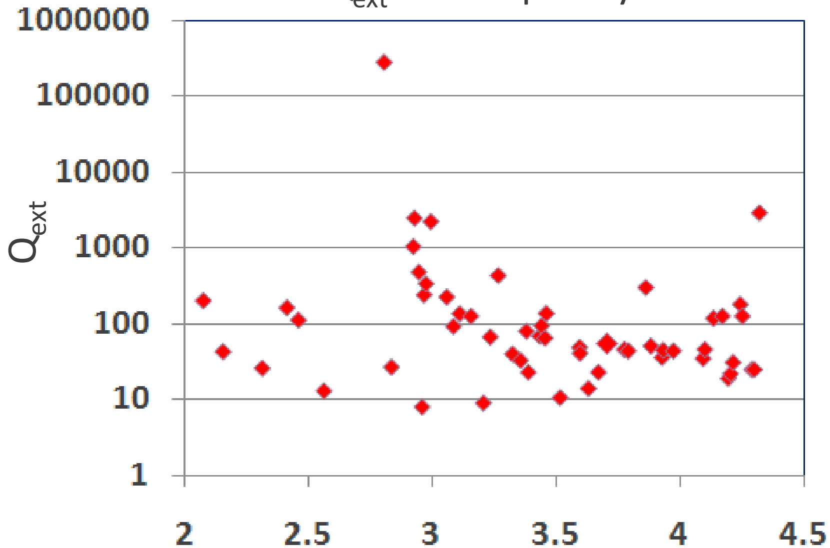
Voltage response in cavity due to beam fill pattern

Normalized Cavity Voltage



Time (ns)

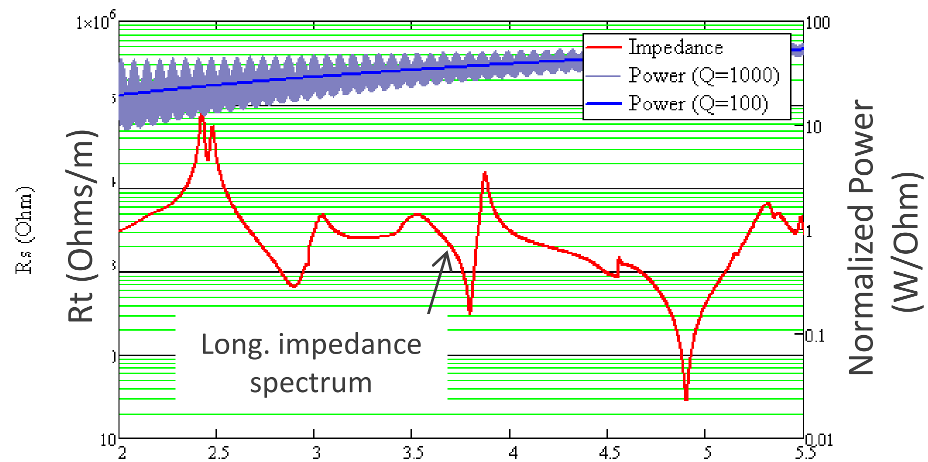
Q_{ext} vs. Frequency



Frequency (GHz)

Power loss spectrum for 24 bunch fill pattern

Normalized Power Loss

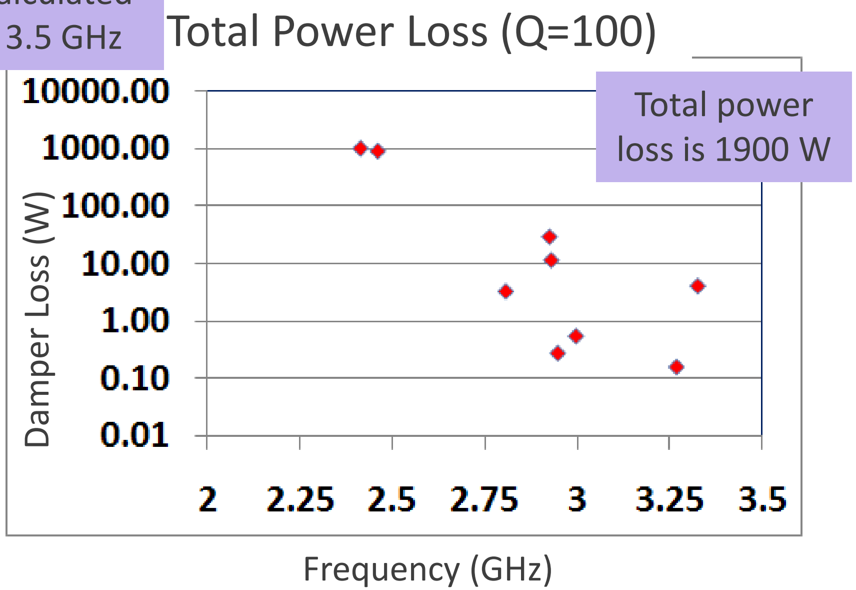


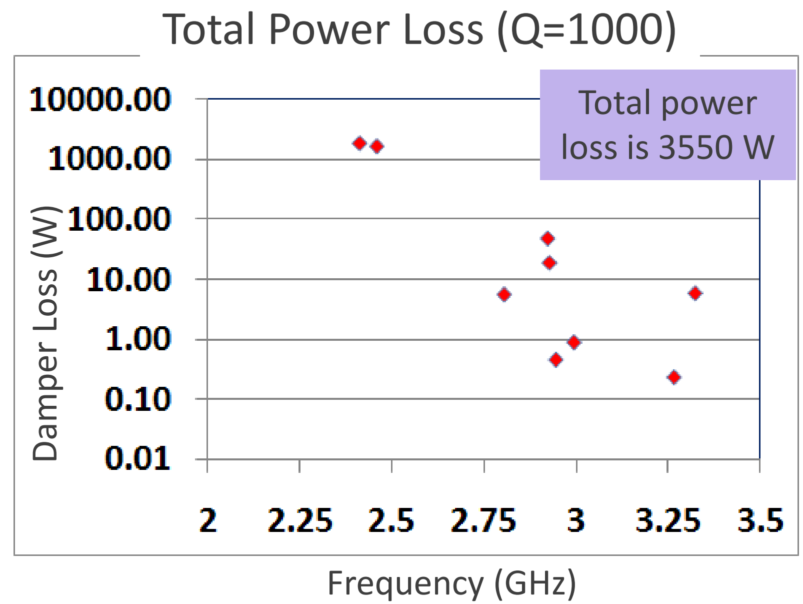
Frequency (GHz)

Sang-Ho Kim, "HOM power in Elliptical SC cavities for Proton Accel," NIM A 2002

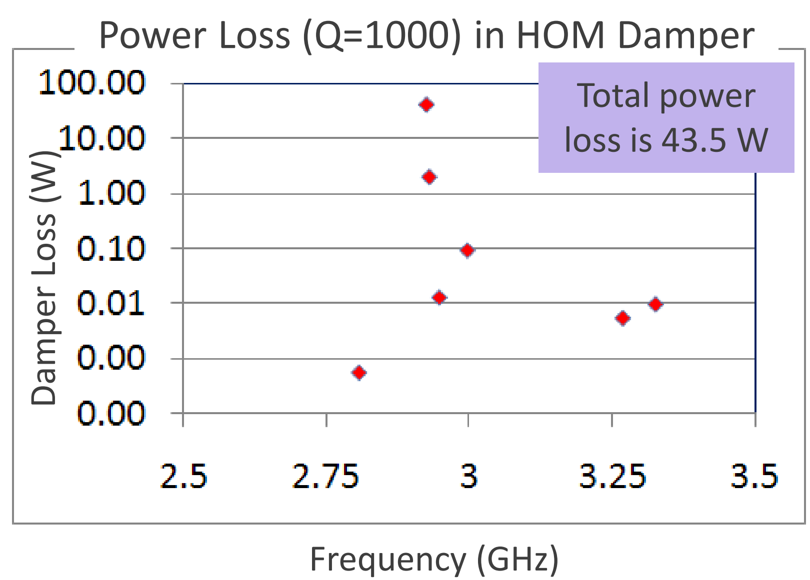
RF Loading of Dampers (II) (Preliminary)

Loss calculated up to 3.5 GHz



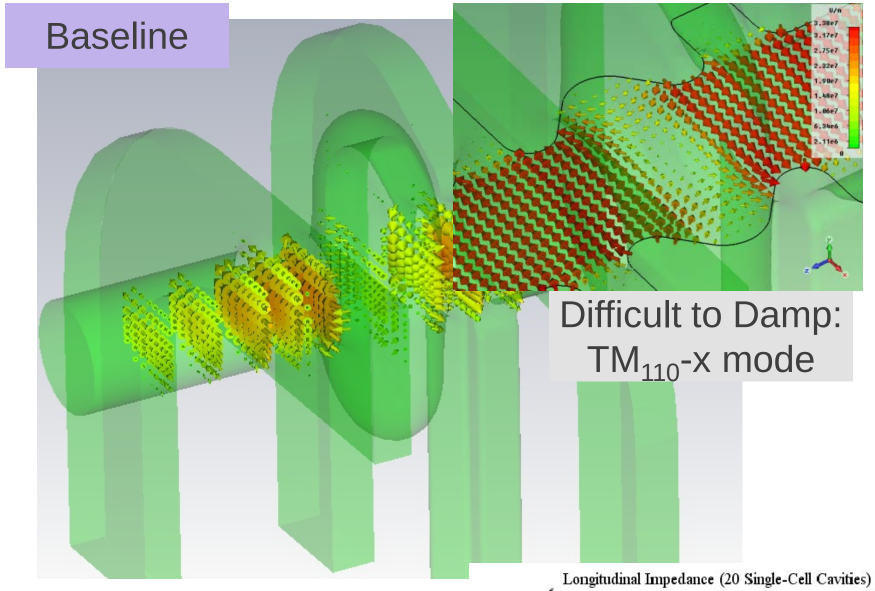


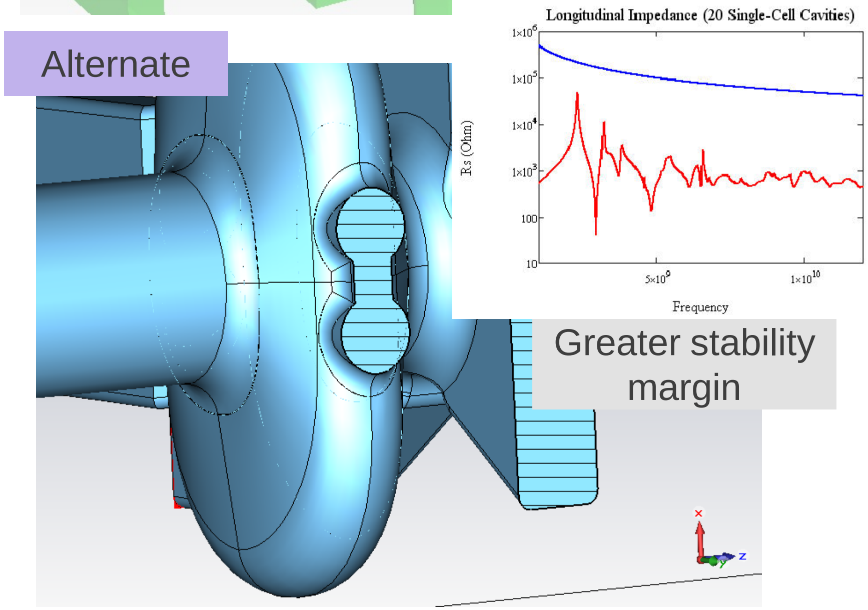
- If losses are sufficiently low in HOM dampers, they may be cooled at 80K.
- Broadband loss calculated with the loss factor is 3.75kW for 24 bunch mode at 200mA.
- Above estimates are too low. Broadband loss should match losses for Q=100 case above.
- Losses in dampers are dependent on which modes in eigenmode simulation are considered to be ‘real’.



Alternate vs. Baseline

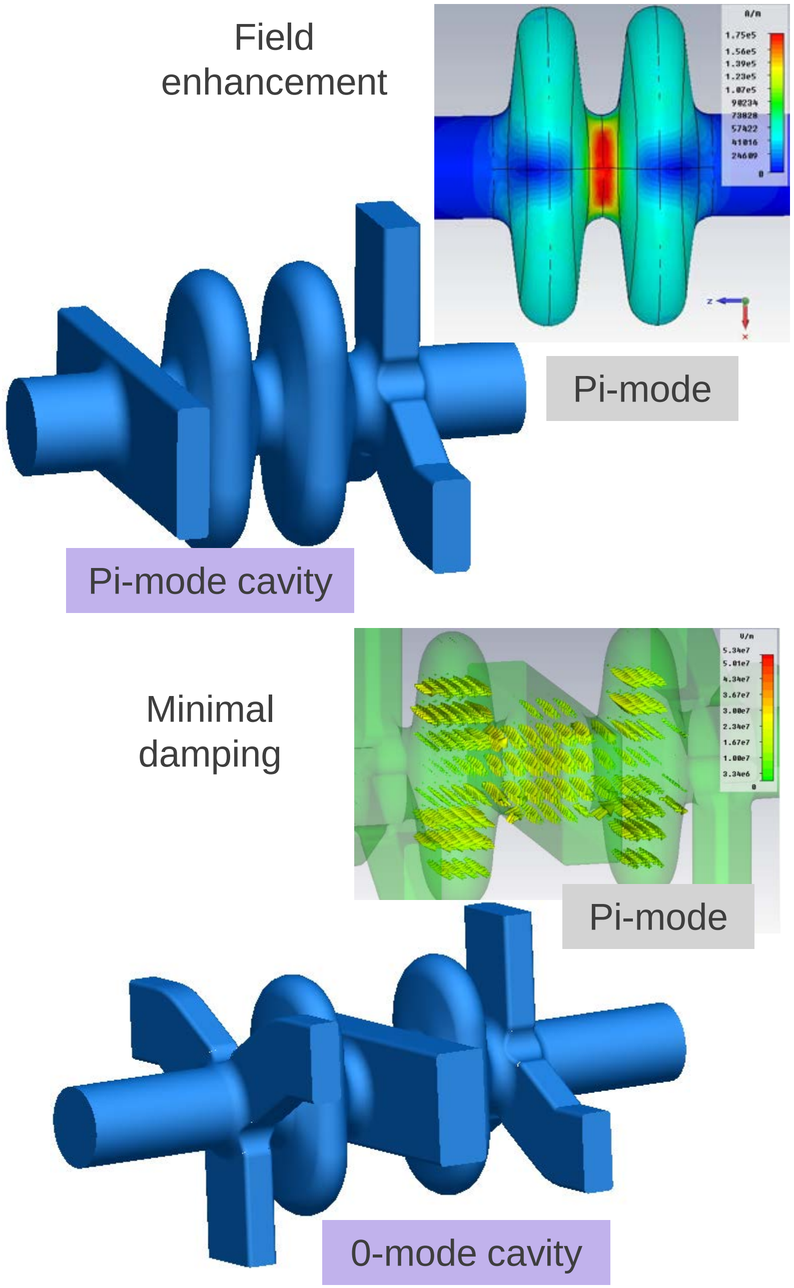
- Alternate Benefits
  - Larger stability margin for 200 mA beam current.
  - Single excited LOM plus two LOM waveguides produce less rf loading of dampers
  - More compact
- Alternate Disadvantages
  - Helium vessel more complicated (discussed later)
  - Additional waveguide penetration for second LOM waveguide
  - Unproven design features
    - Magnetic field enhancement? Numerical results show adequate damping without enhancement
    - Multipacting enhancement? Experimental and numerical results do not show a problem



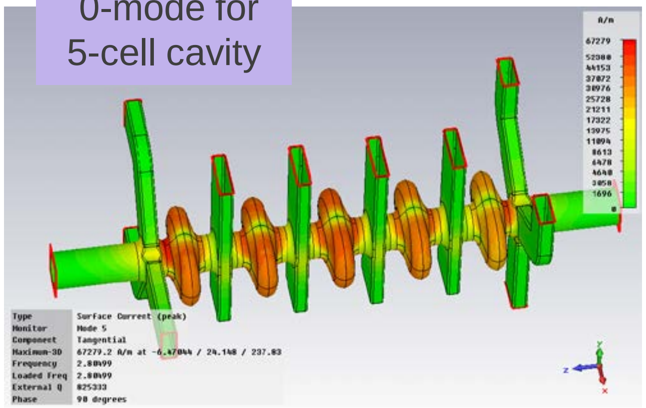


2-cell Cavity Design Concepts

- Multicell cavities have a substantially improved packing factor, as well as reducing the total number of rf systems required.
- Same passband modes are difficult to damp without affecting the operating mode.
- 2-cell TM_{110} cavity operating in the pi-mode suffers from magnetic field enhancement on the iris - little net operating gradient improvement.
- 2-cell TM_{110} cavity operating in the 0-mode requires a ‘drift’ space between cells.
  - Difficult to damp same passband pi-mode due to field configuration in ‘drift’ space and waveguide cutoff frequencies.
  - Impedance of pi-mode must be reduced to below 4.5 MOhm/m. This can only be achieved by reducing the R/Q to a value below 1e-4 (Q_u=~10^9).

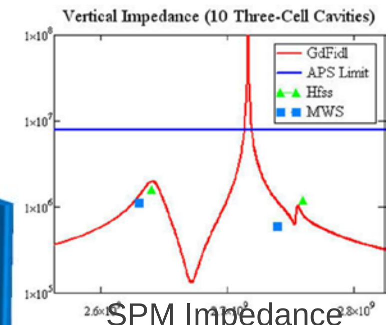


2-1/2 Cell Cavity and Cavity Superstructure Concepts

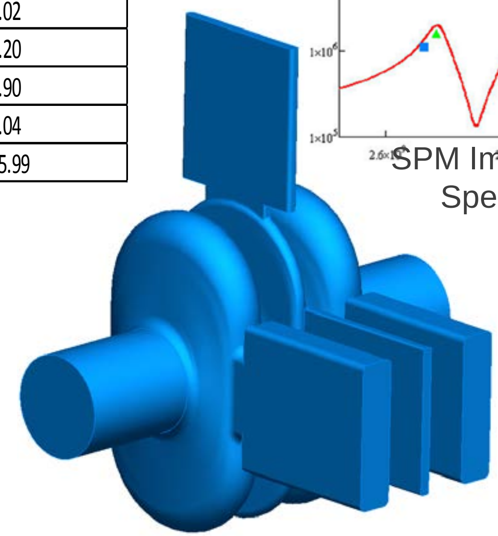


0-mode for 5-cell cavity

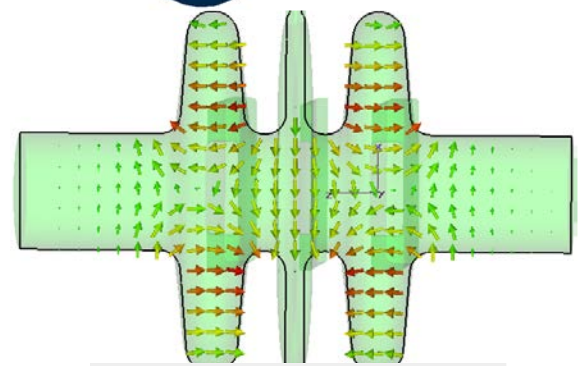
Scaled Frequency	Scaled External Q-factor	Rt/Q
GHz	for a flat 0-mode Hx field	Ohm, at y=1cm offaxis distance
2.794523	1.69E+07	0.02
2.799700	2.96E+06	0.20
2.806271	9.21E+05	0.90
2.811808	5.29E+05	3.04
2.815488	8.07E+05	185.99



SPM Impedance Spectrum



- 2-1/2 cell Cavity
  - Center cell is used to couple the SPM into vertical damping waveguide.
  - 2 pi / 3 mode is not damped in the center cell and is utilized as the operating mode.
  - Difficult to manufacture and process center geometry.
- 5-cell Superstructure
  - Frequencies of the undamped dipole modes must be located in a stable region of APS spectrum, if this is possible.
  - Any number of cavity cells may be utilized in a multi-cell if undamped modes can be properly located.



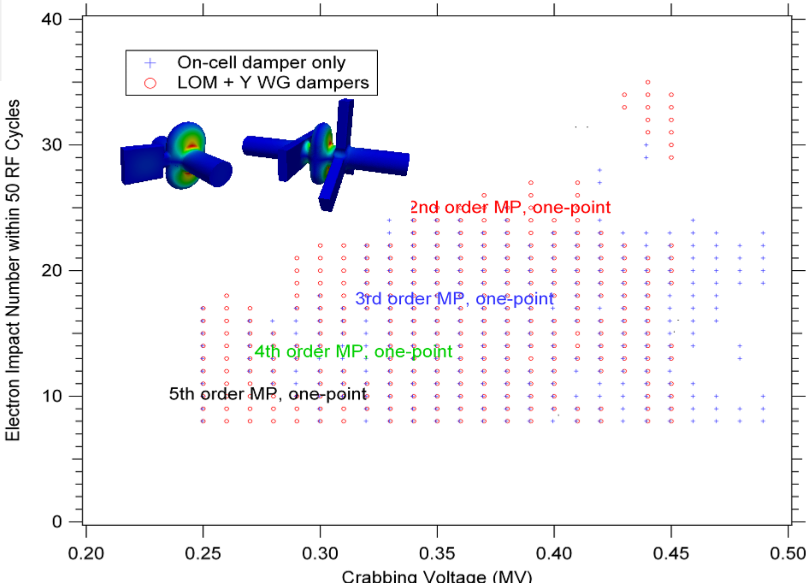
Electric field pattern for the operating mode

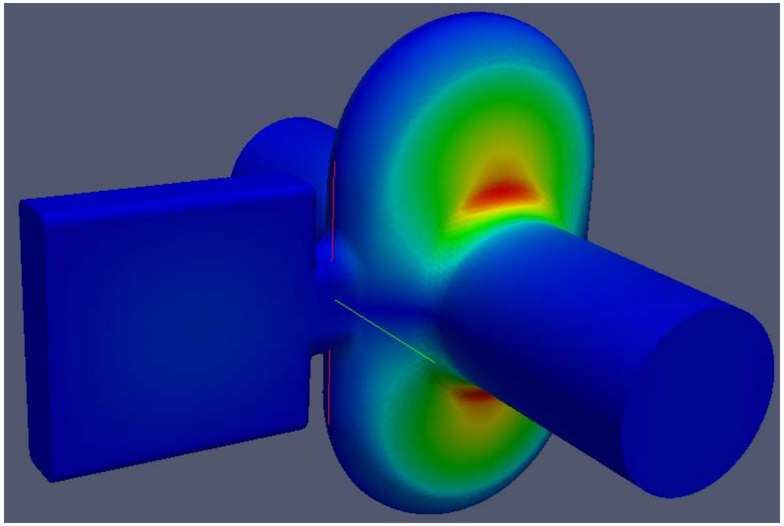
Courtesy: H. Wang, JLAB

Multipacting

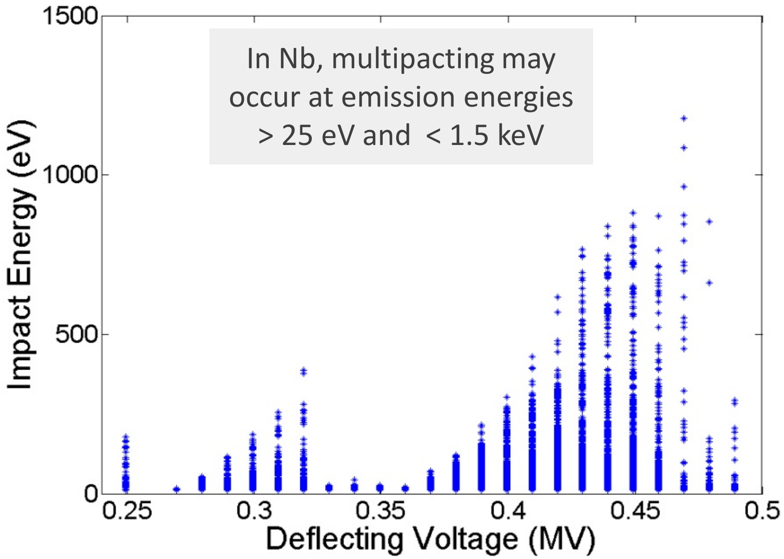
Simulation extended for 50 rf cycles

- 3-D SLAC ACE3P codes were used – already benchmarked extensively against LHC, SNS, and JLAB cavities and couplers.
- For deflecting cavities, multipacting is prevalent in low electric field regions near the beam pipe.
- Proof-of-principle on-cell damper design was evaluated
- Multipacting profile is similar for both baseline and alternate cavity designs





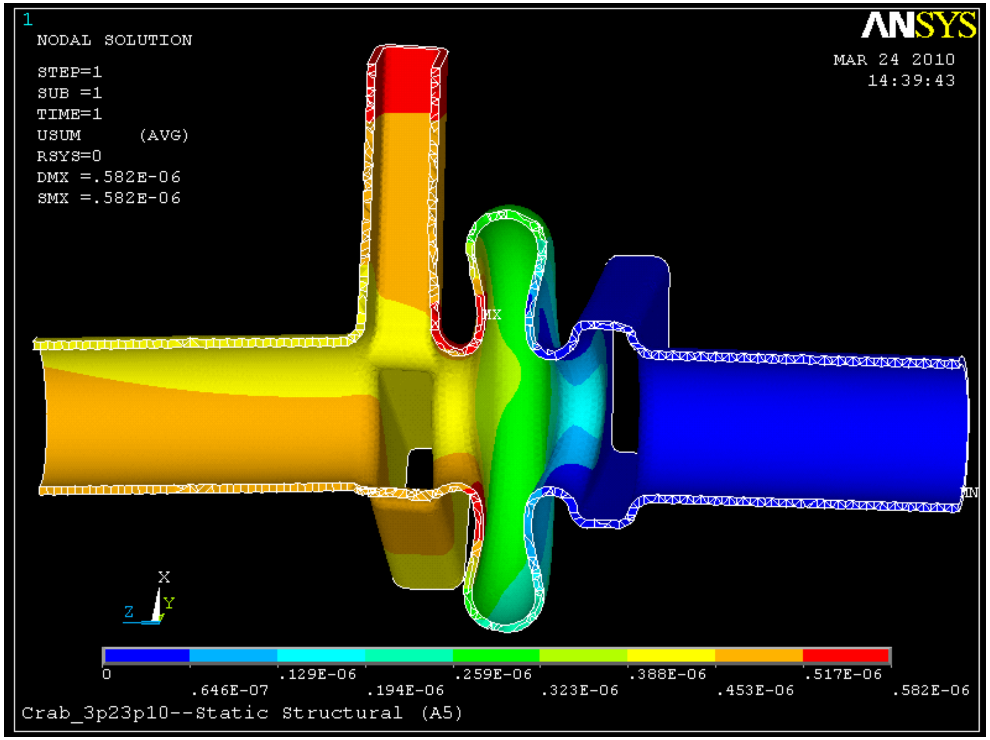
Deflecting mode electric field magnitude in Omega3P

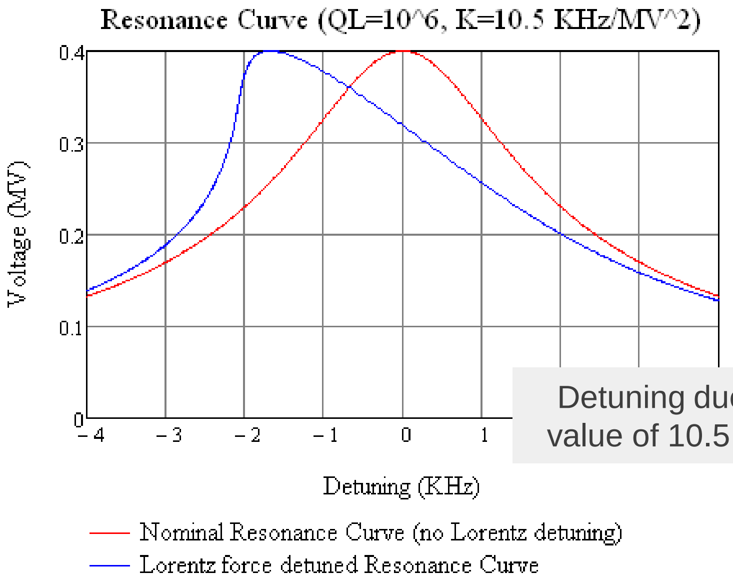


In Nb, multipacting may occur at emission energies > 25 eV and < 1.5 keV

Lorentz Force Detuning

- Detuning was calculated as 10.5 kHz/MV^2.
- LFD always reduces the resonant frequency.
- Structural enhancements may be used to improve response.
- Result will be compared with experimental data once the prototype is completed.





Detuning due to LFD value of 10.5 kHz/MV^2

- LFD of SPX single-cell cavity is 7.9 – 10.5 kHz/MV^2 depending on structural constraints.

$$P_{LFD} = \frac{\mu H^2 - \varepsilon E^2}{4}$$ Radiation pressure

Cryomodule Parameters

Preliminary Estimate of 2K Losses

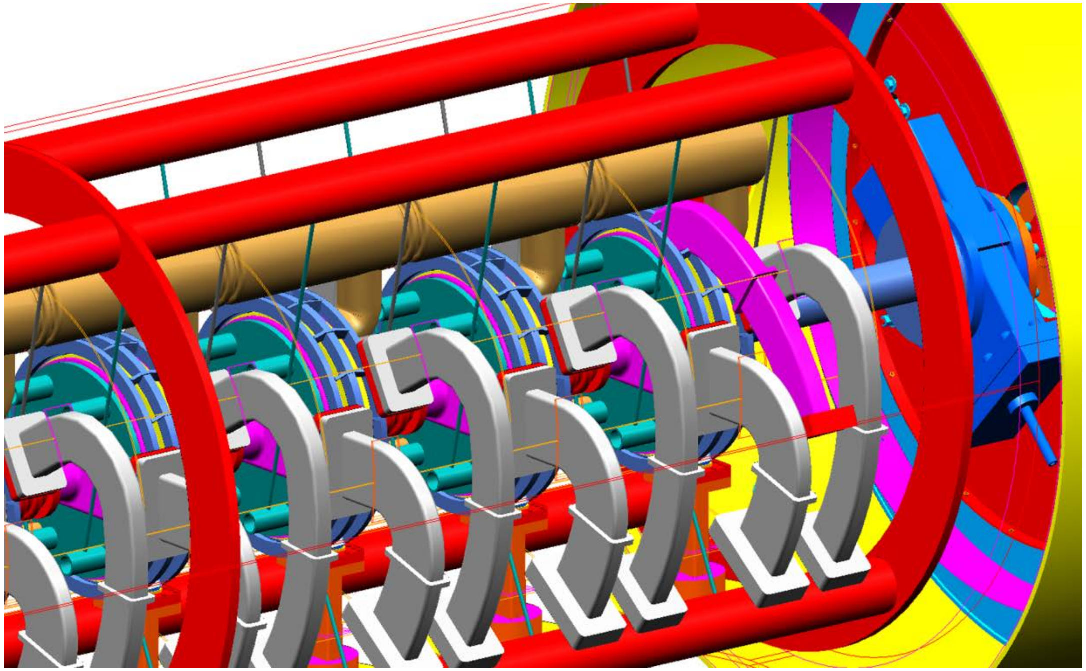
2K Cryogenic Losses	
Static / Dynamic Losses due to Waveguides / Tuners per Cavity	2.4 W
Wall Losses per Cavity @ $Q_u=10^9$	7.0 W
Static Heat Load due to Cryo Losses e.g., Beampipe Transistions / Supports	2.0 W
Total Heat Load (8 cavities) @ $Q_u=10^9$	79 W

Estimated System Parameters

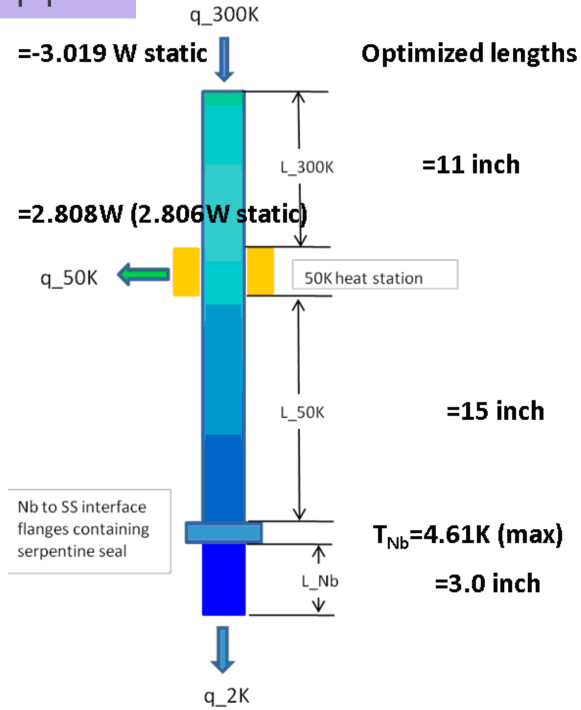
System Parameters	
Slow Tuner Range	+/-200kHz
Number of Cavities per Cryomodule	4 (8)
Total Number of Cryomodules	2
Cavity Offset Alignment Tolerance	0.3 mm
Beam Offset Tolerance	0.05 mm
Klystron Power per Cavity	10 kW

JLAB Cryomodule Concept

- Based on JLAB cylindrical cryomodule design.
- Dampers are located in vacuum shield of cryomodule - similar to JLAB's ampere-class cryomodule concept.
- Blade tuner located around helium vessel chosen for concept



1-D thermal analysis of beam pipe

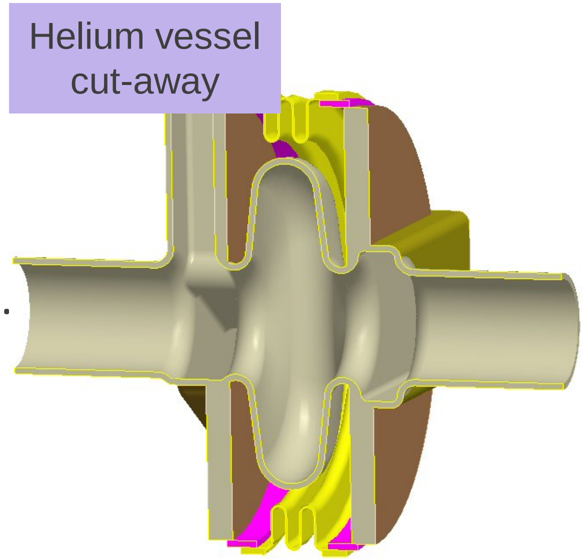


- 1-D analysis of losses along beam pipe from cavity to room temperature estimated 0.26W at 2K with optimized lengths.

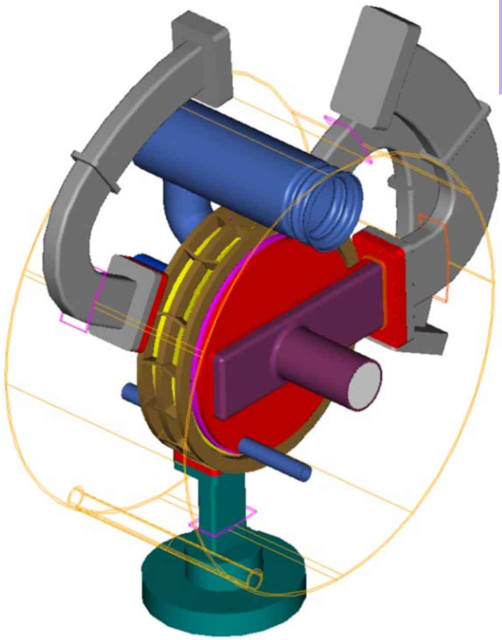
Courtesy: J. Henry, JLAB
G. Cheng, JLAB

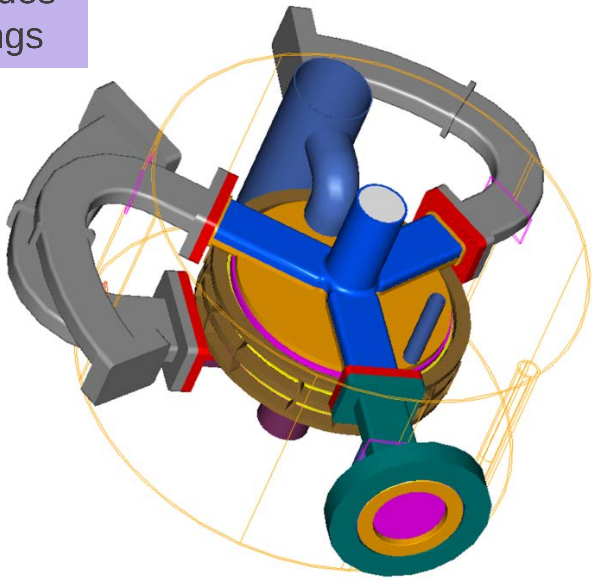
Helium Vessel Concepts

- Helium vessel plates are integral with cavity end groups and utilize existing Nb material during construction.
- Thermal properties of ‘uncooled’ outer portion of end groups must be analyzed.
- Warm ceramic window shown on waveguide input coupler.
- Each helium vessel is fed individually by supply lines and a gas return pipe.



Helium vessel with waveguides and tuner rings

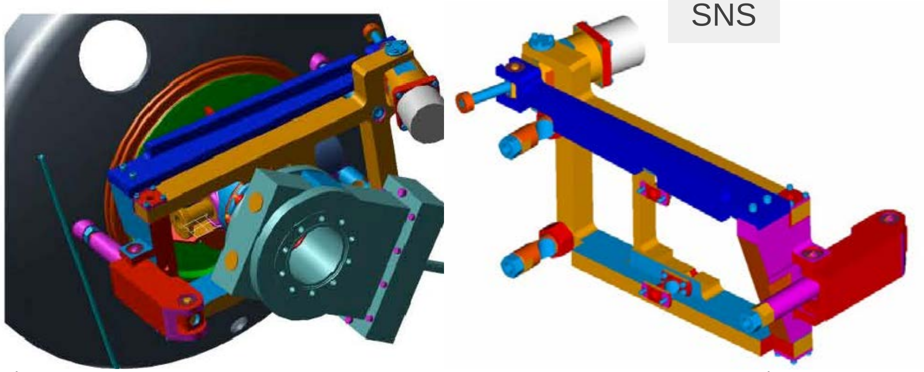




Courtesy: M. Givens, ANL and J. Henry, JLAB

Tuner Options

SNS



	Mechanical	Piezo
Travel (mm)	1.8	10^{-2}
Freq. Range (kHz)	200	2
Freq. Resolution (Hz)	60	NA
Load (N)	8900	15000

Table 1. SNS Tuner Requirements

TESLA

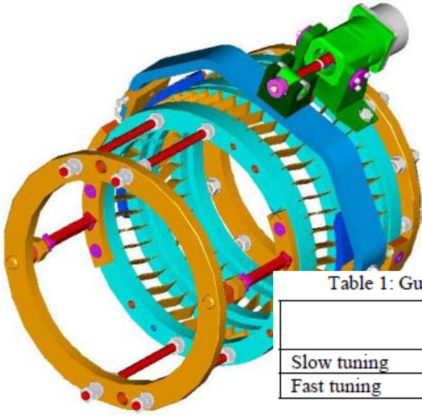
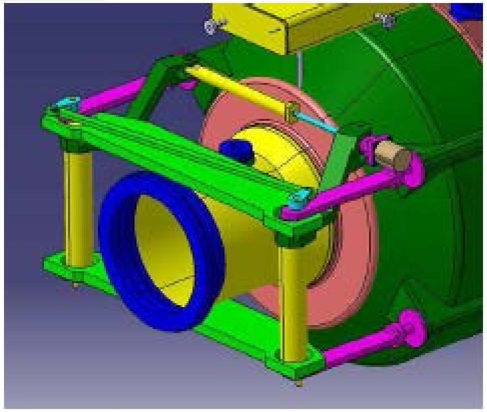


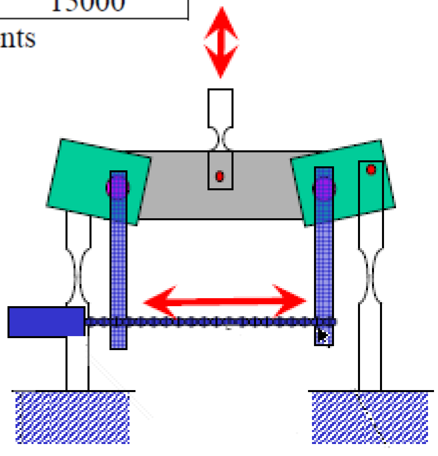
Table 1: Guidelines for a TESLA cavity tuner.

	Frequency range [kHz]	Axial movement [μm]
Slow tuning	~ 500	~ 1500
Fast tuning	~ 1	~ 3

Load case: $\delta_T = 1$ mm (slow tuning)		
Part	Axial force (N)	Axial displ. (mm)
He + disk	-2812.5	-0.110
Tuner	-3037.0	1.000
Cavity	2812.5	0.876
Piezo	-3037.0 / 2	-0.014
He bellow	224.5	0.986

Soleil



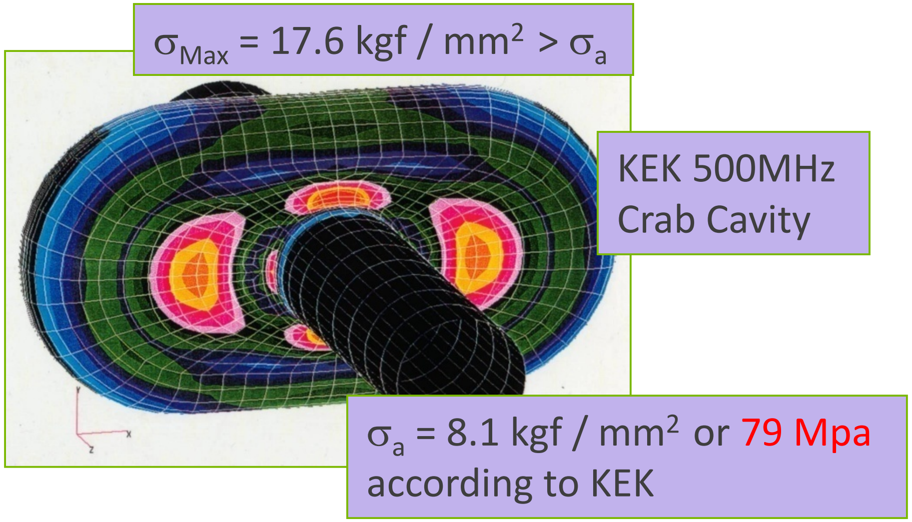


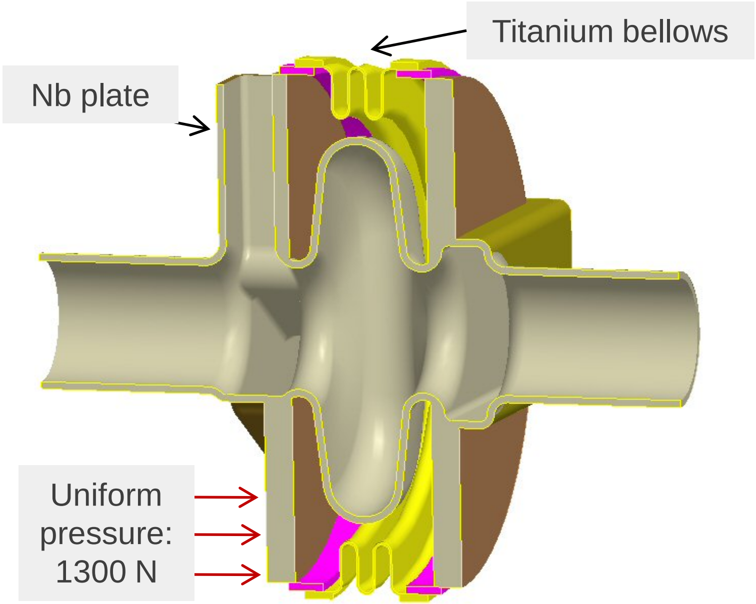
- Maximum strength ~ 30kN
- Nb/Cu cavity
- Helium tank in Stainless Steel

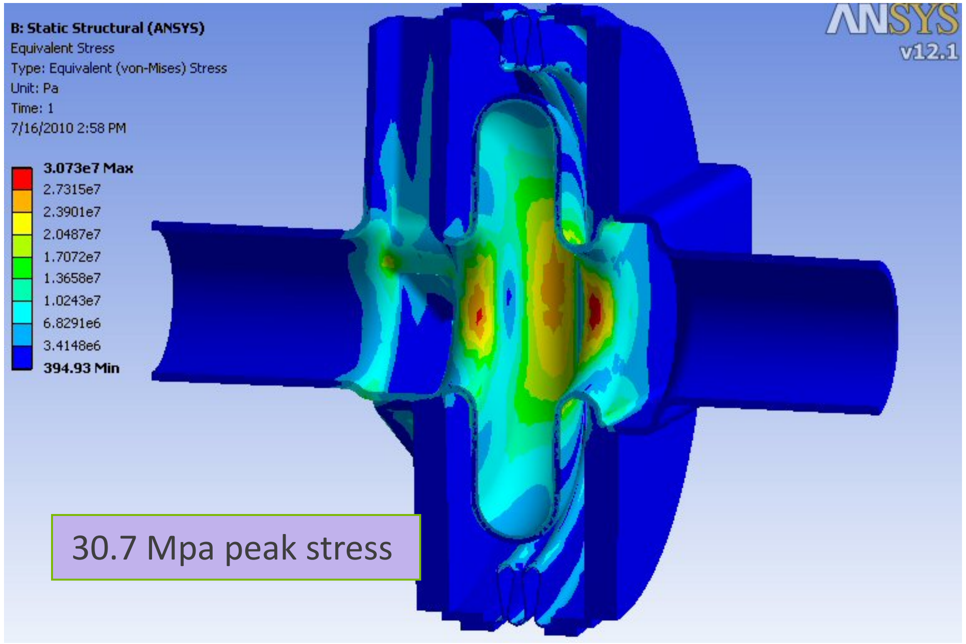
(1) P. Bosland ,"Tunings systems for superconducting cavities at Saclay".
(2) C. Pagani, "Improvement of the Blade Tuner Design for Superconducting RF Cavities".

SPX Tuner Requirements

- Evenly applied axial pressure of ±1300 N along Y-end group plate produces a 500 kHz tuning range.
- Cavity should always be under compression in order to avoid “dead spot” in tuning. A 4000N force creates a 1.5MHz frequency offset.
- Peak stress is located along narrow racetrack dimension => 30 MPa

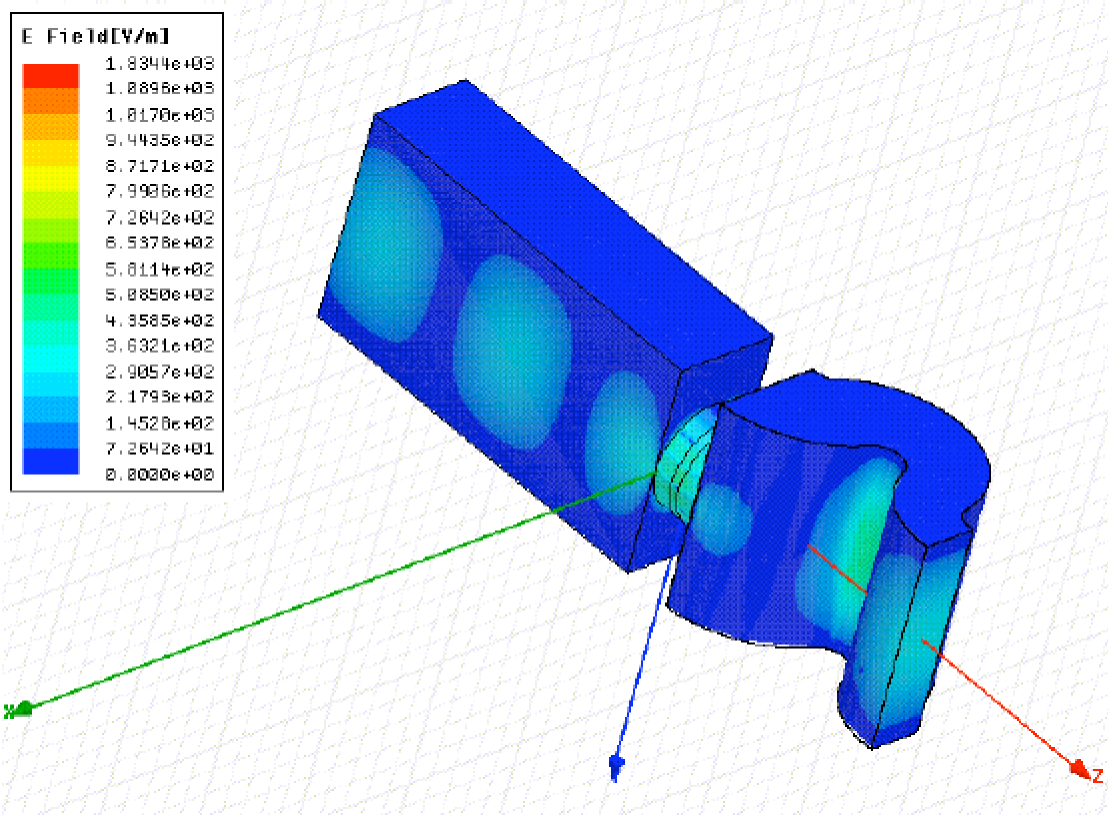


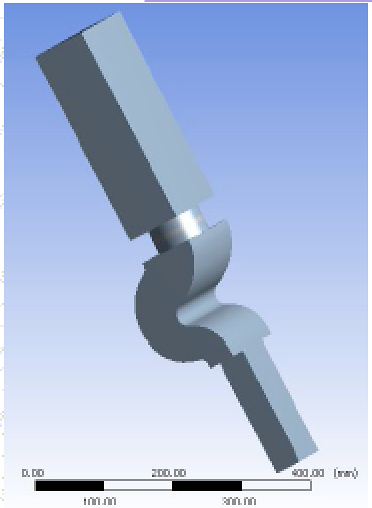




Input Coupler Concept @ 1.5 GHz (JLAB)

Dog-leg bend for radiation protection

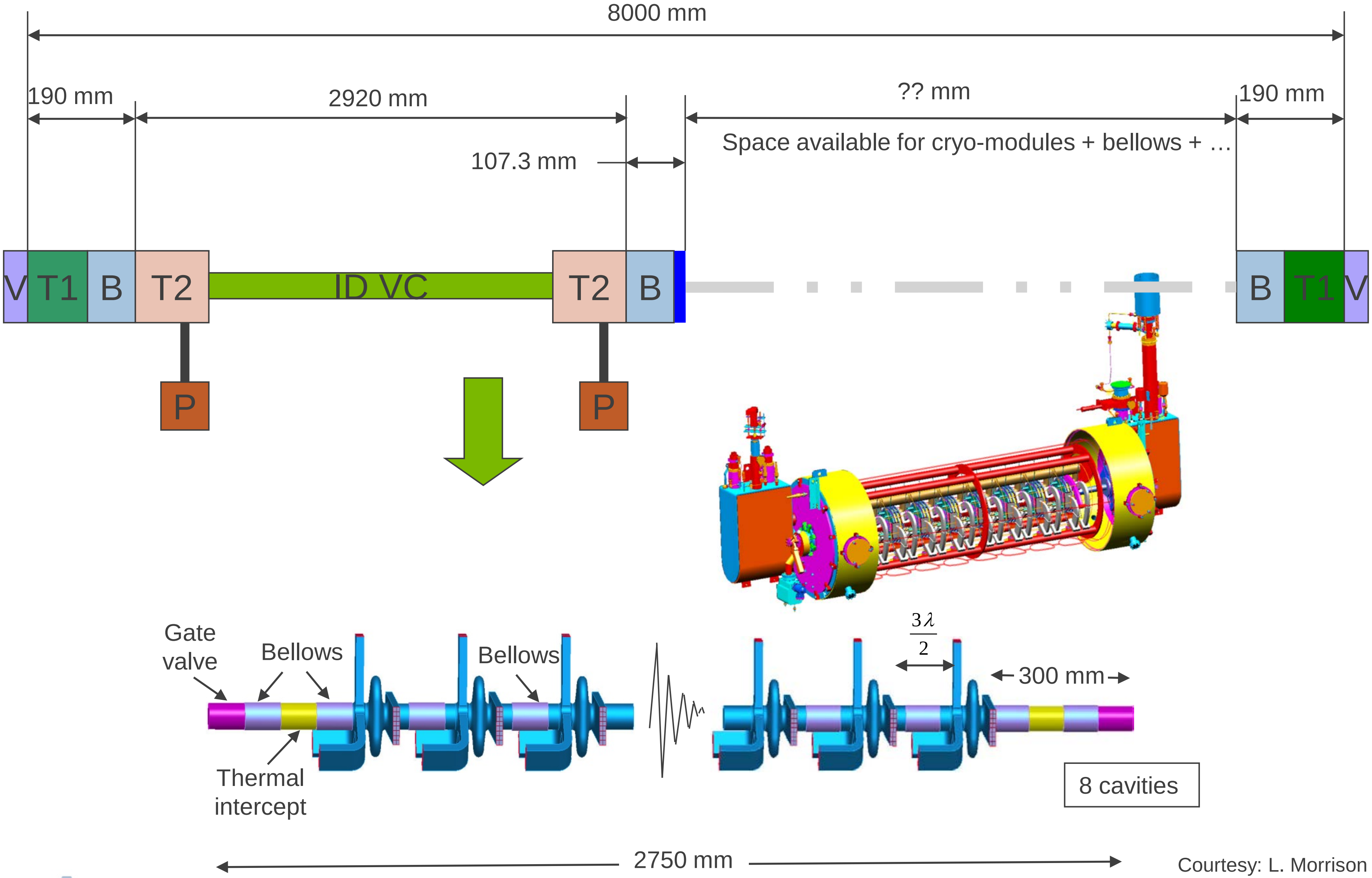




1497 MHz window could be used on a CEBAF style cryomodule

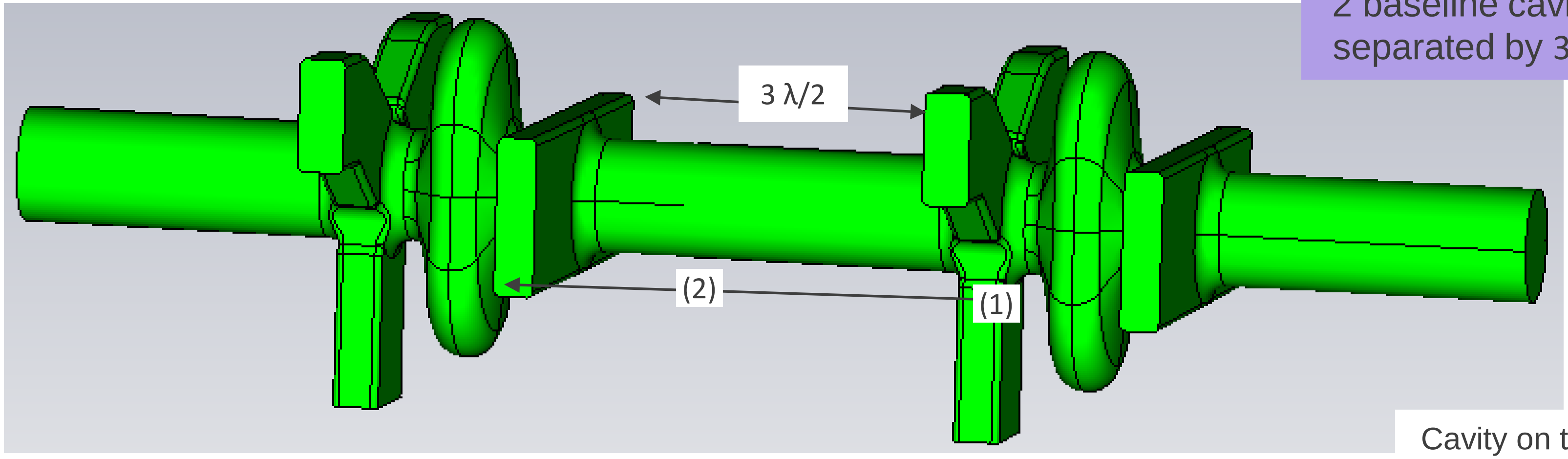
B. Rimmer, “JLAB High-Current Cryomodules,” ERL07

Deflecting Cavity Cromodule Overall Length



Courtesy: L. Morrison

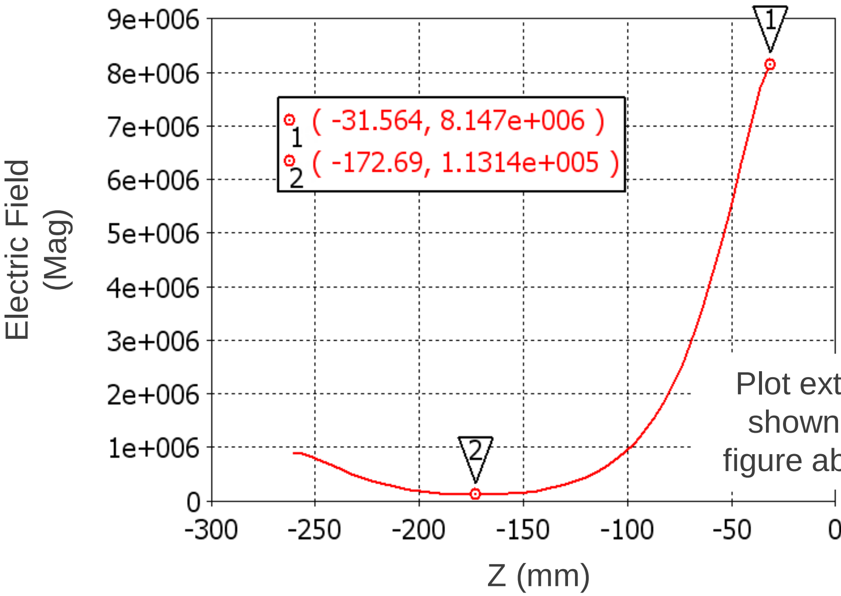
Field Decay Between Cavities



2 baseline cavities separated by 3 λ/2

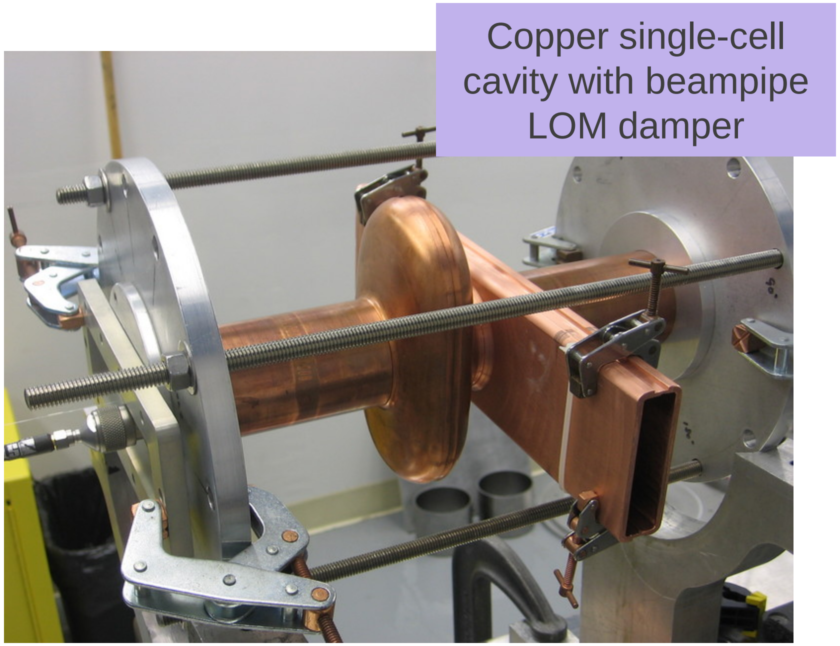
Cavity on the left is OFF

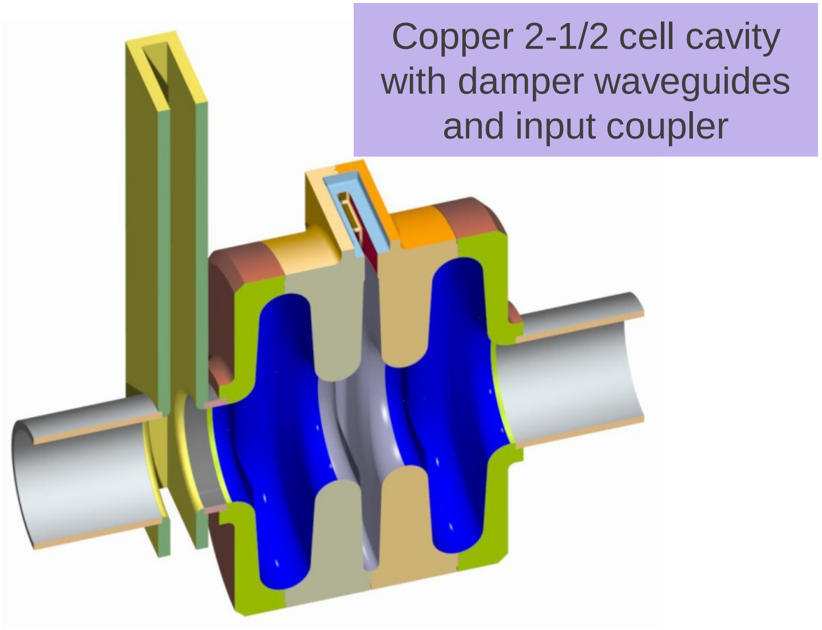
- TM110 cavity fields couple to the low-order TE11 beampipe mode and therefore attenuate more slowly.
- Analytical electric field attenuation between cavity assemblies located 3 λ/2 (160mm) apart is $2*10^{-3}$, or 53 dB.
- Electric field values shown in the line plot show poorer attenuation in addition to coupling to the neighboring cavity.



Plot extent shown in figure above

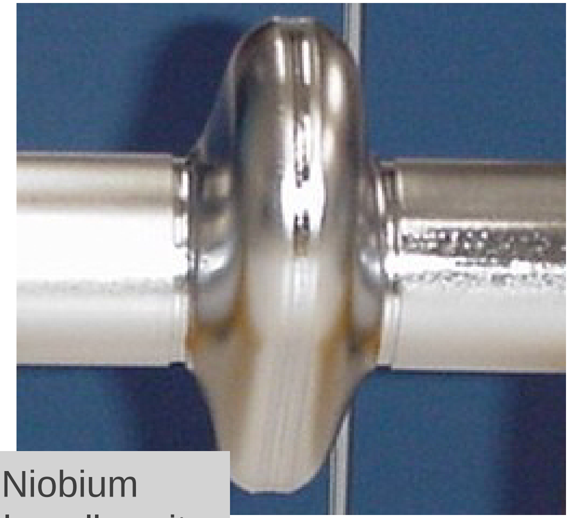
Copper Prototypes at JLAB / ANL





- Analyzed deflecting frequency and quality factor.
- Evaluated LOM / HOM spectrum.
- Validated simulation results.
- Verified LOM damper effectiveness across frequency range below beam cutoff.

Nb Prototypes at JLAB



Niobium single-cell cavity

Niobium 2-cell cavity

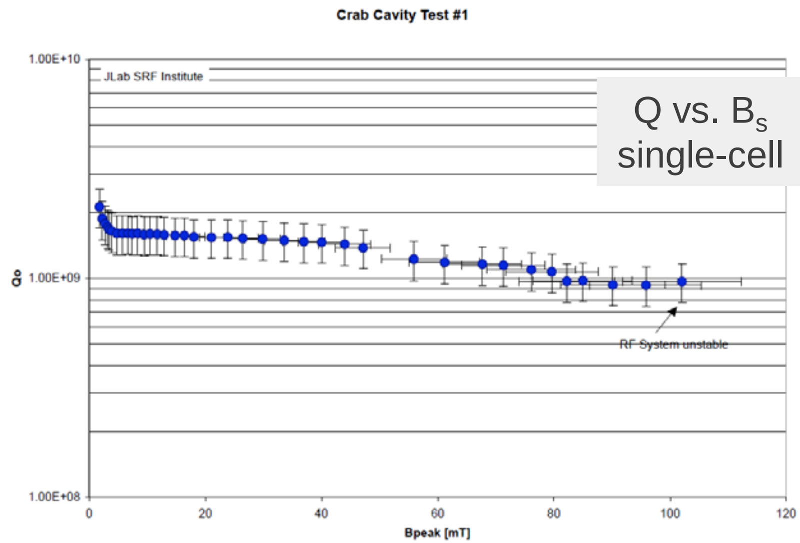
- Prototyped cavities at JLAB
  - Created cavity dies
  - Performed trimming and EB welding.
  - Performed chemistry processing and HPR
- Cavities at 2K for Q, maximum field, and Lorentz force detuning

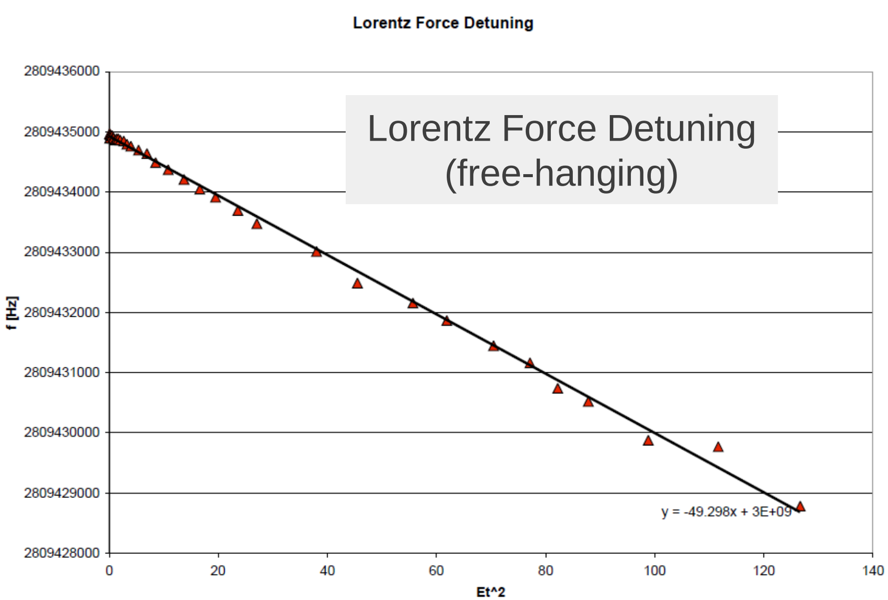
Niobium single-cell cavity with on-cell damper

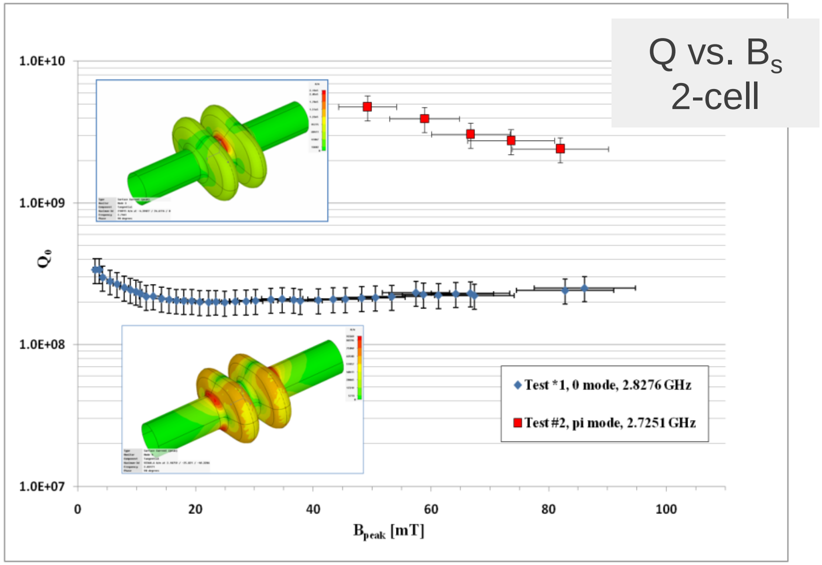
Courtesy H. Wang / R. Rimmer

Experimental Results of Nb cavities at JLAB

- Unloaded Q has been tested for single-cell and 2-cell cavities without damping waveguides at ~10^9.
- LFD for free-hanging case where one beam pipe is constrained ~15kHz / MV^2.
- Baseline single-cell cavity with input coupler and HOM/LOM dampers is preparing to be tested in the vertical test stand.







*Courtesy of H. Wang / R. Rimmer

JLAB Continuing Collaboration

- Design of cylindrical cryomodule will be pursued with Joel and JLAB cryomodule engineers.
  - Vacuum vessel, magnetic / thermal shielding, thermal intercepts, space frame layout.
  - Helium vessel design and layout
  - Cavity and cavity string alignment techniques
  - Helium distribution / end caps
- ANL may acquire an existing JLAB cryomodule for In-Storage Ring test at the APS
- Design of thermal transitions from 2K/80K to room temperature will be pursued between ANL / JLAB mechanical engineers
  - Waveguide input coupler / dampers
  - Beam pipe transition
  - Supports / mounting hardware / tuner
- Thermal simulation of helium vessel concept for validation.

All collaboration efforts are dependent upon the determination of available resources (personnel and hardware)

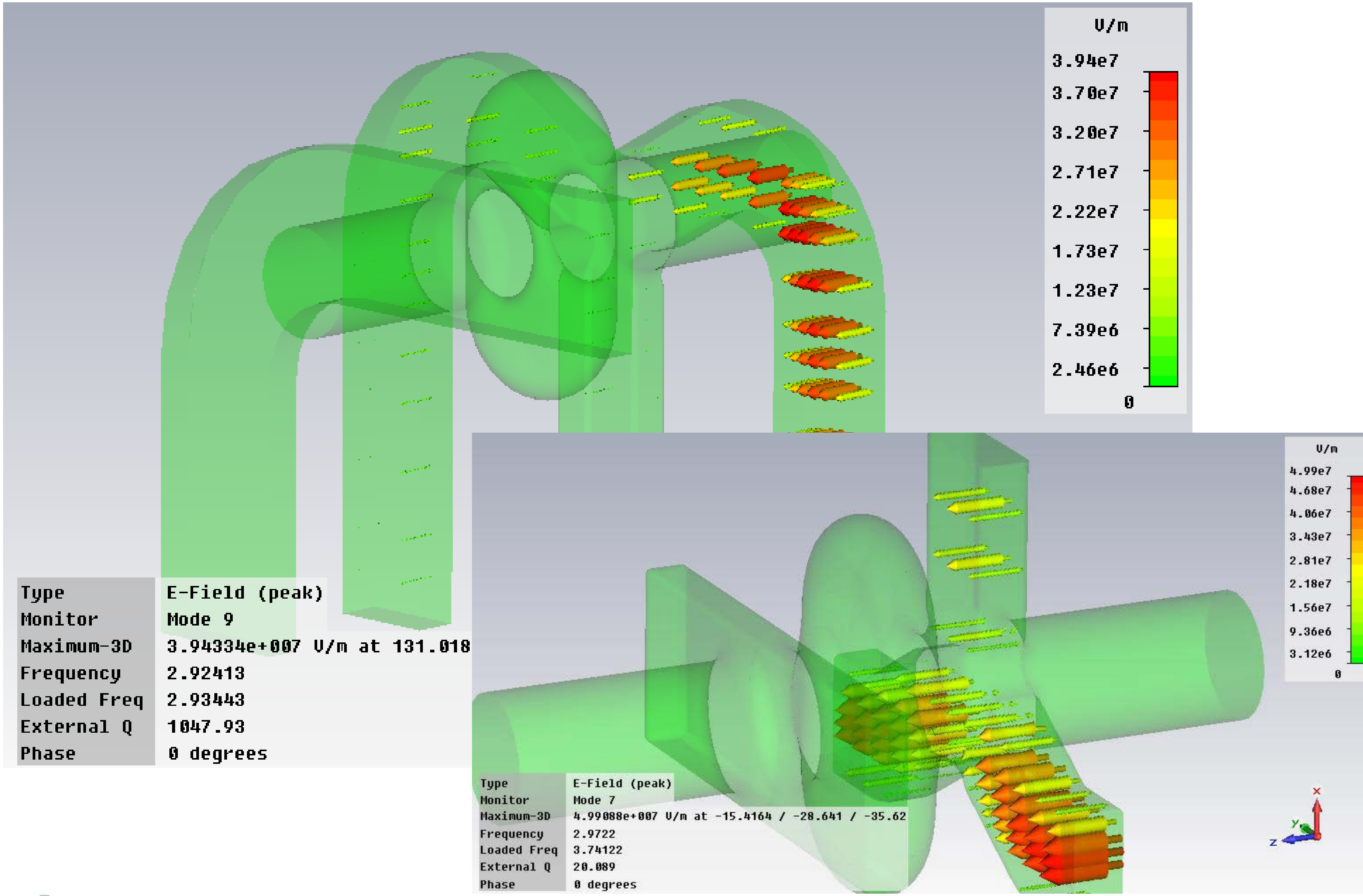
JLAB Continuing Collaboration

- Cavity design improvements, esp. damping and decision of final cavity to be done by Geoff and Haipeng.
- 2K testing in Vertical Test Area (VTA) at JLAB
  - Must share time with existing obligations to ILC, Project X and RIA.
  - Manufacture and testing in the VTA for the SPX baseline and alternate designs are slated for the coming months.
  - Future prototypes and availability must be determined.
- Low-power damper testing of SiC at JLAB. High-power design and testing to be done at ANL.
- Possible ANL redesign of JLAB input coupler window for 2815 MHz.

Workshop Issues

- Cavity
  - Peak field gradient
  - Damping enhancement of LOM and TM110-x for baseline design
  - Baseline and alternate design options (multicell?).
  - Separation distance between cavities
  - Frequency tuning from warm to cold for 2.8154872 GHz.
- Dampers
  - SiC or ferrite material
  - High-frequency damping > 5 GHz important?
  - High-power design possibilities
  - Locate inside cryo vacuum or outside: LOM / HOM dampers
  - Should damper loads with ceramic windows be considered for clean assembly
- Input Coupler
  - Ceramic window design for input coupler
  - Double warm window
  - Locate window after a waveguide bend or jog to protect it from radiation
  - Multipacting analysis
- Tuner
  - End-mount or Blade (SNS / Soleil / Tesla …)
  - +/- 200kHz?
  - Fast tuner necessary?

HOM Damper Loading



HOM Damper Loading