SRF Crab Cavity Development at JLab for SPX Project of APS

Haipeng Wang

for the team of

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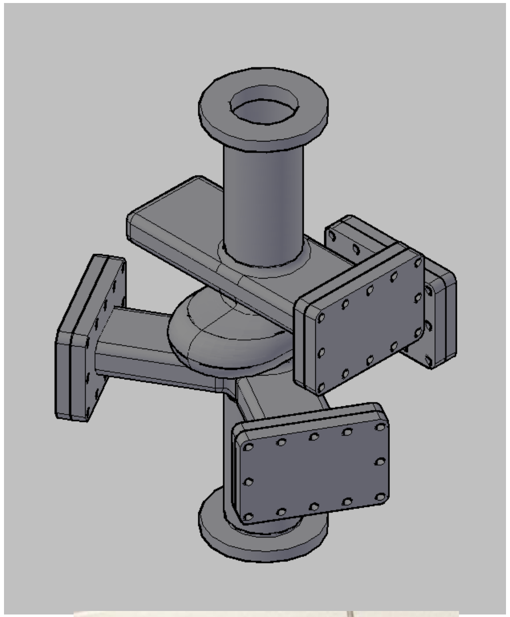
and

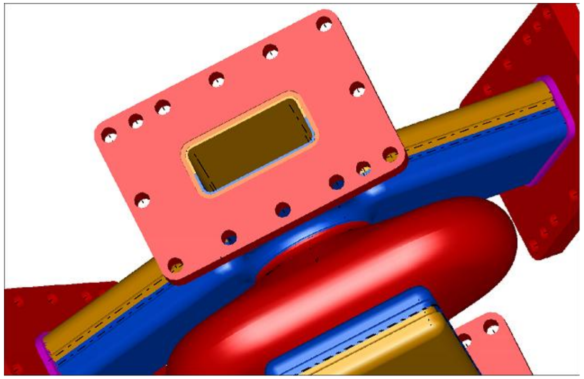
G. Waldschmidt, A. Nassiri, Argonne, IL 60439, USA

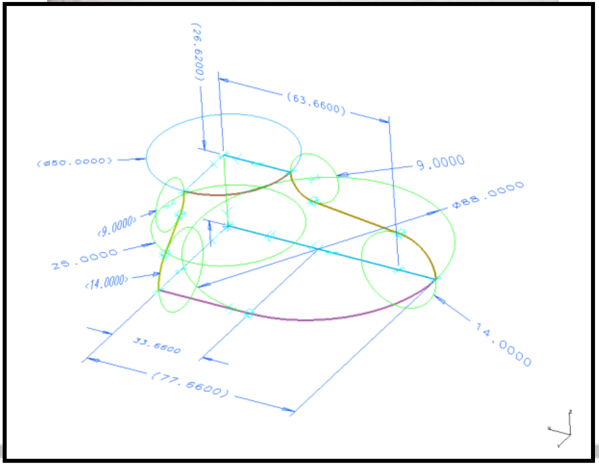
Two recent PAC papers about Baseline cavity design and prototype results

PAC 2009 Paper:
Design, Prototype and measurement of a Single-cell Deflecting Cavity For The Advanced Photon Source

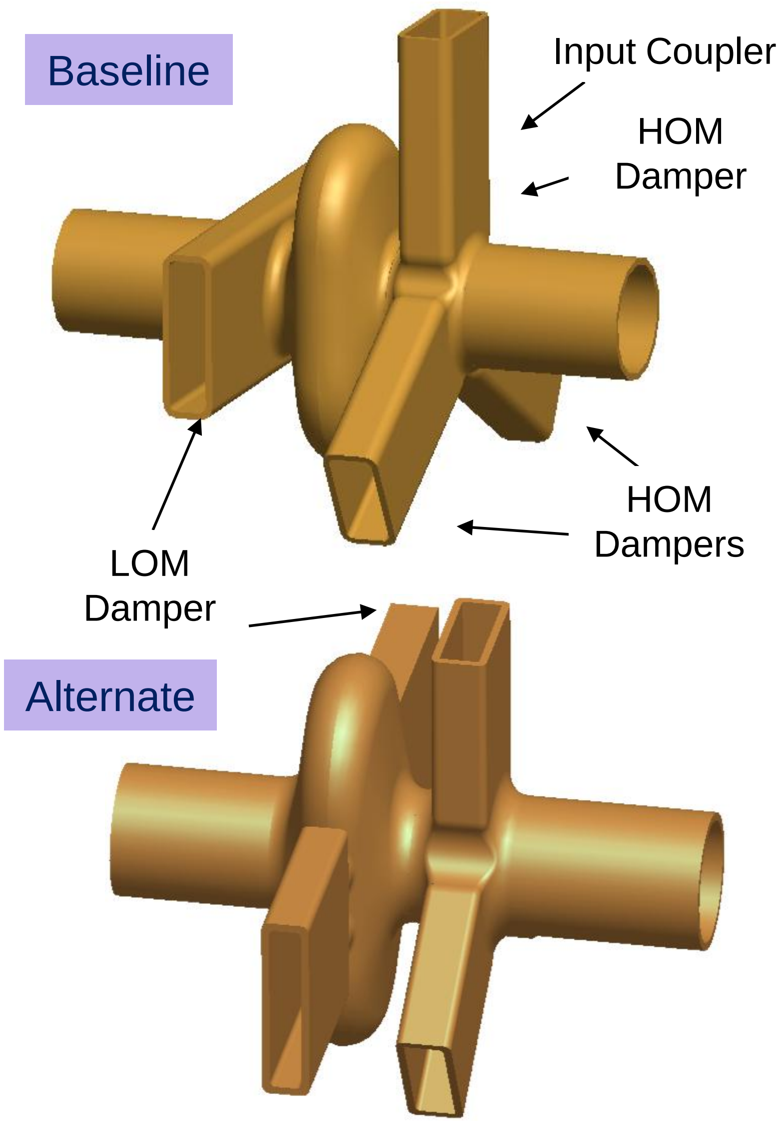
IPAC 2010 Paper:
Design and Prototype toward a Superconducting Crab Cavity Cryomodule for the Advanced Photon Source



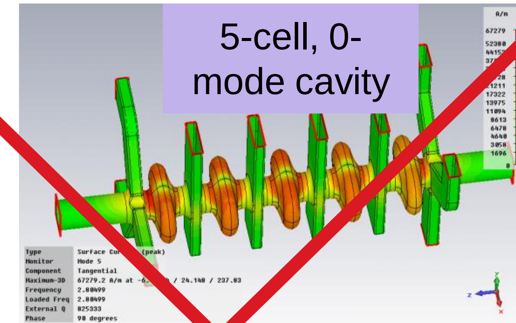




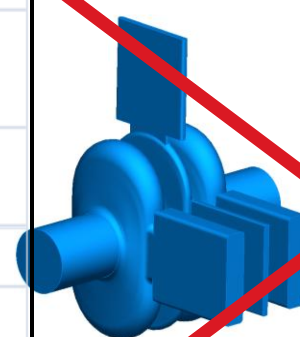
Baseline verses Alternate cavity, single-cell verses multi-cell

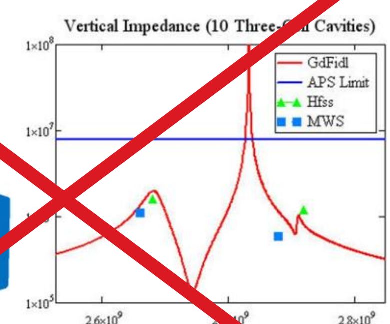


Frequency	2815	MHz
Q_0	1×10^9	
V_t	0.5	MV
Energy	0.39	J
$k_{\parallel}$	0.615	V/pC
(R/Q)	35.6	Ohm
E_{peak} / V_t	83	1/m
B_{peak} / V_t	195.6	mT / MV
P_{loss}	7	W
I_{beam}	200	mA
Cavity Iris Rad	25	mm
Cavity Beam Pipe Rad	26	mm
Cavity Active Gap	53.24	mm
Q_{ext}	2×10^6	
Cells / Cavity	1	
No. Cavity	8 * 2	

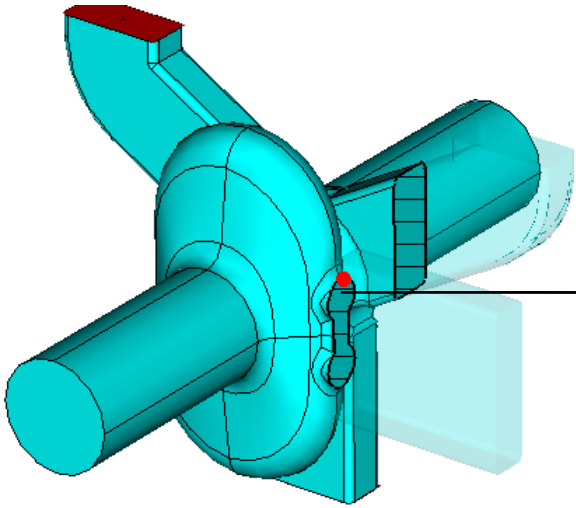


Scaled Frequency	Scale[illegible] External [illegible]-factor	Rt/Q
GHz	f[illegible] a flat 0-mode Hx [illegible]	Ohm, at y=1cm offaxis distance
2.794523	1.69E+07	0.02
2.7997[illegible]	2.96E+06	0.20
2.[illegible]06271	9.21E+05	0.90
2.811808	5.29E+05	3.[illegible]4
2.815488	8.07E+05	185.99

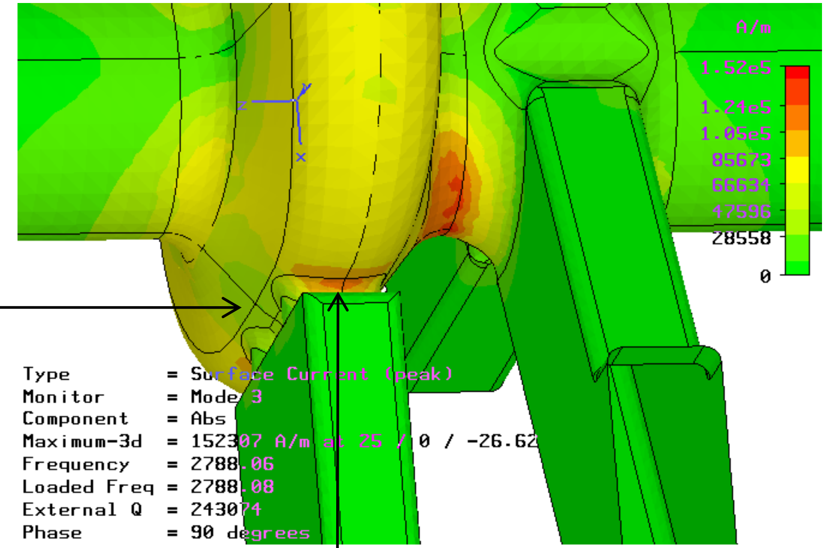




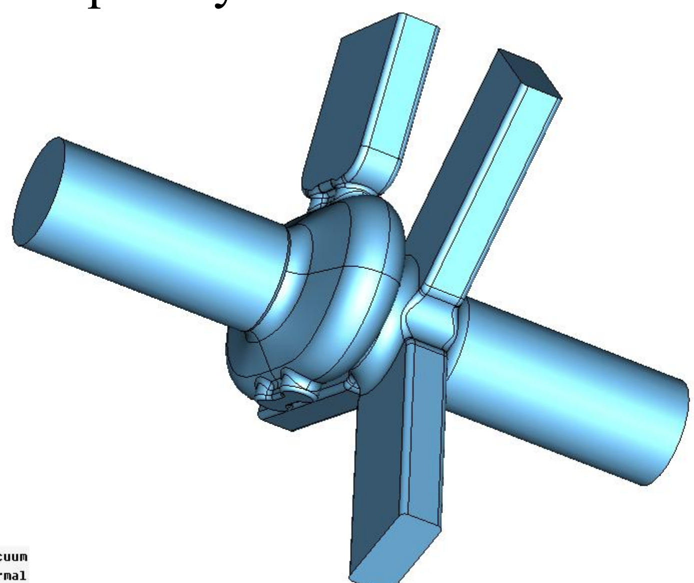
- On-cell LOM/HOM Damping by Dog Bone Wedged Waveguide



First report by Jiaru Shi on EPAC 2008



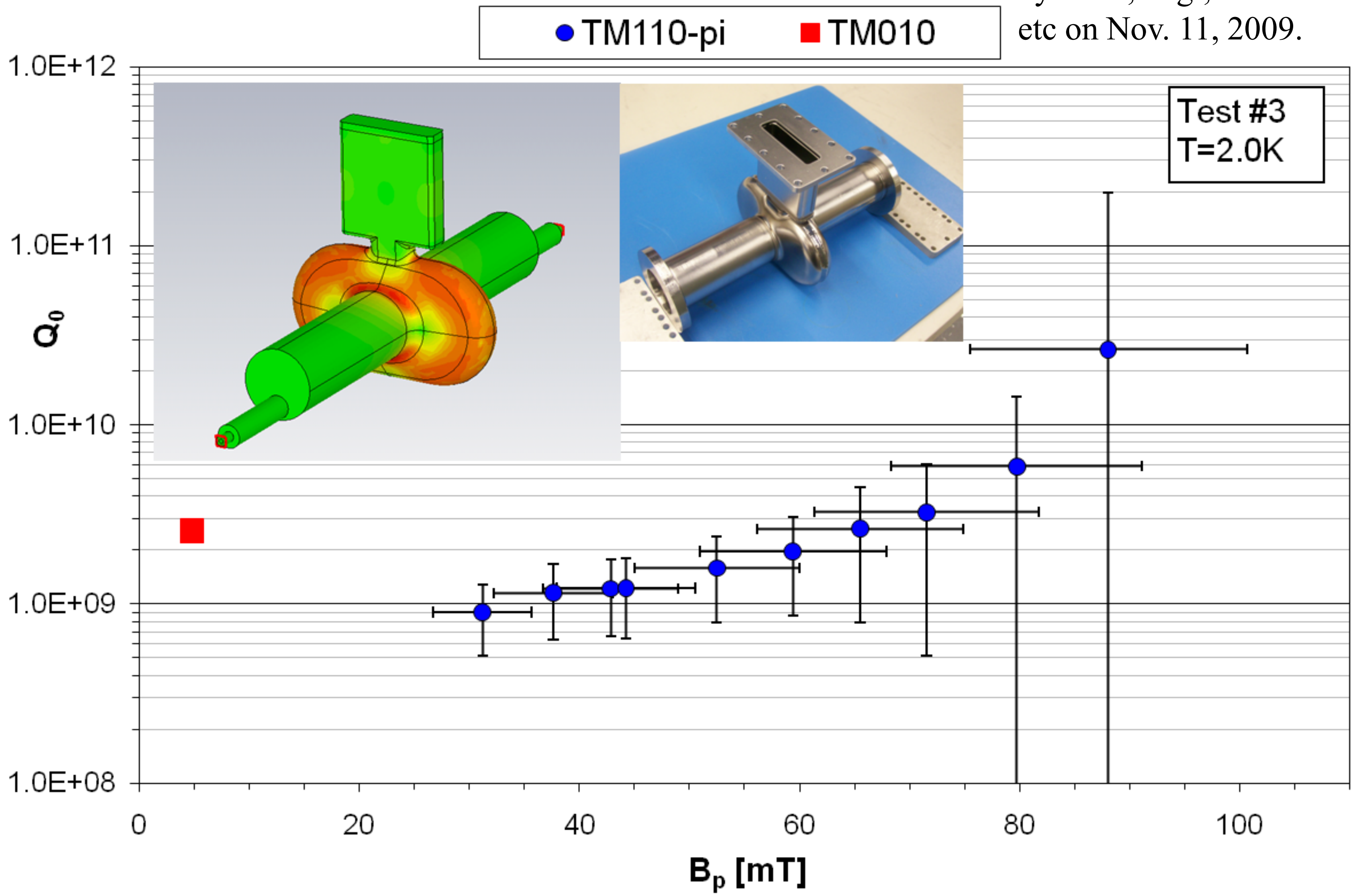
- **B_{neck}/B_{iris}=~0.8**
- **B_{max}/V_{def}=157.7mT/MV (single-cell iris) to 195.6mT/MV (+end WG iris)**



- **dummy "dog bone" stub, one on-cell damper is better than two, more promising.**
- **LOM-WG mode, 2.176GHz, R/Q=22.3Ω Qext=21.1**
- **LOM-cell mode, 2.334GHz, R/Q=49.2Ω Qext=12.2**

Third cold RF test on a single-cell, on-cell damper crab cavity

by Peter, Gigi, Ben and Haipeng etc on Nov. 11, 2009.

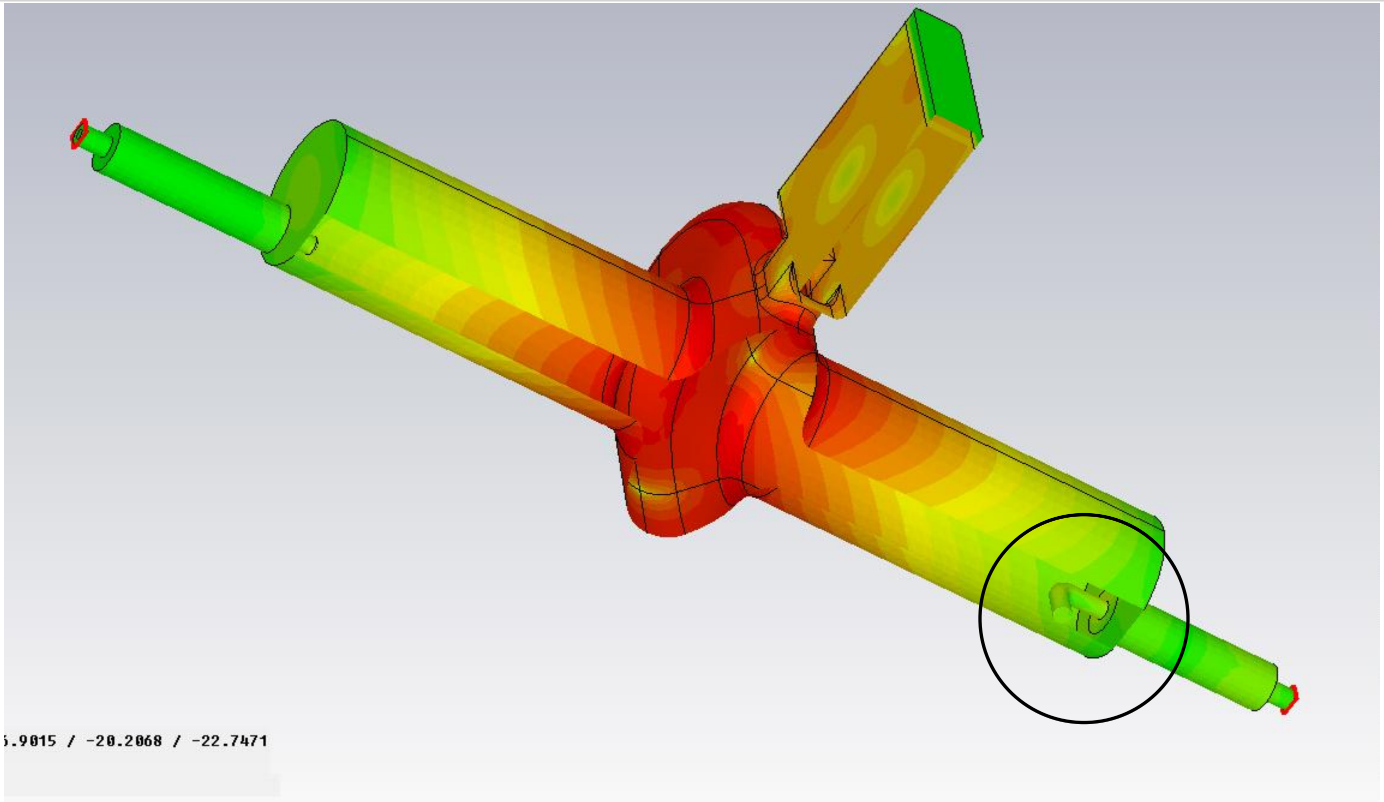


Discussion on the third RF test result

- The treatments of high temperature bake with Ti box for material purification and later a heavy BCP help the material impurity removal and also degas of hydrogen.
- We have reached nearly 90mT (100mT is the design goal) on the surface magnetic field.
- The low power Q0 was good at beginning (also confirmed by the TM010 mode), but un physically increased with higher field.
- This error related to the input coupler was weak under-coupled and too much reflected power to calculate the Q0 accurately.
- The good news is NO multipacting in this test. That confirmed SLAC's Track3P code's prediction (Zenghai). We are still working on the better benchmarks on other examples on both Omega3P/Track3P and VORPAL codes)
- This result need to be confirmed and we are now\prefer the alternate design for the SPX due to a better LOM/HOM damping and a larger impedance safety margin.

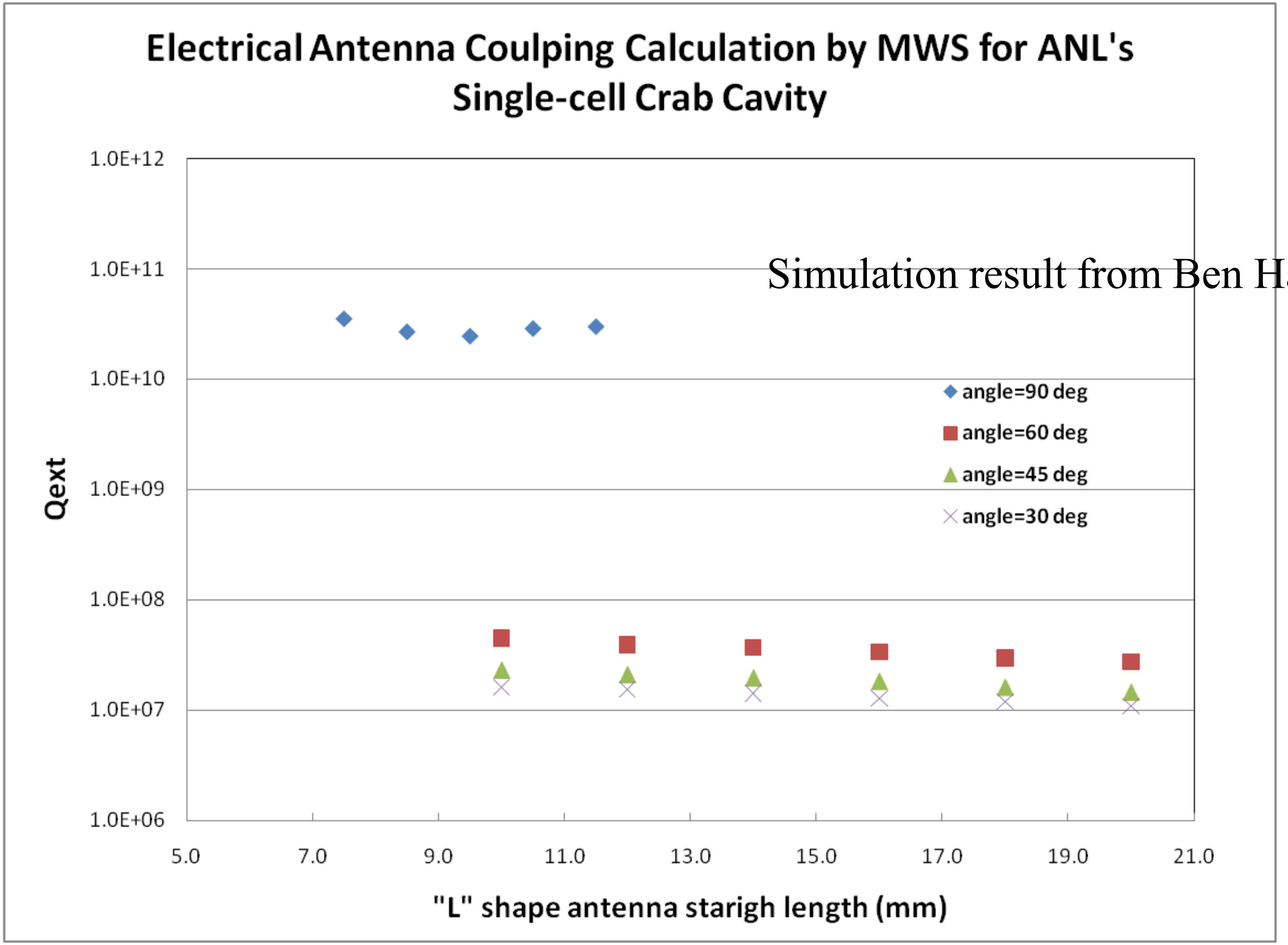
Discussion on the third RF test result, coupling issue (continued)

- Traditional SRF VTA tests normally use E-antenna
- E coupling to crab cavity's TM110 mode is not depending on the antenna straight length but very sensitive to the rod tilt angle



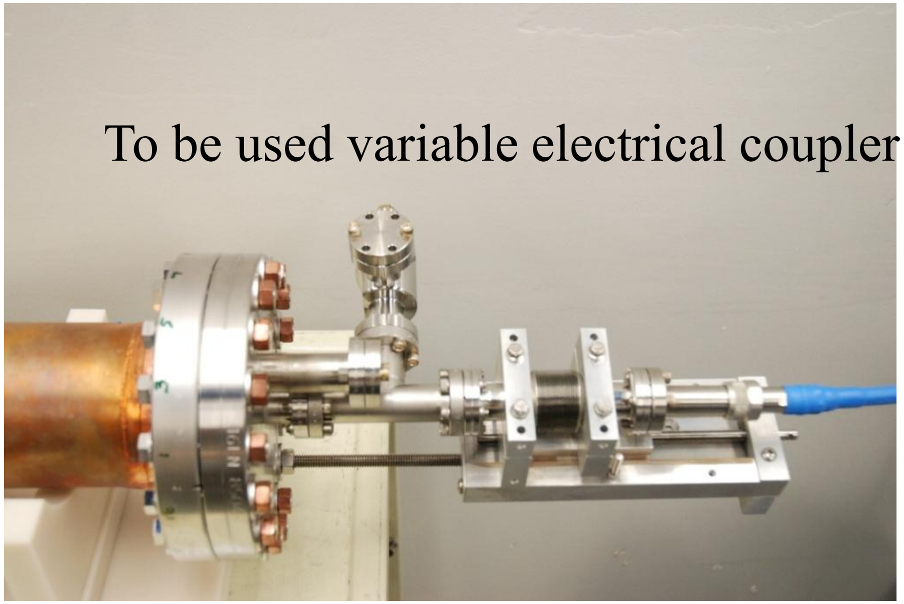
- Using "L" shape E-antenna can reduce the titling angle dependence but the rotating angle becomes critical to high Qext setup
- Using a loop H-antenna and variable coupler is a better solution. Need simulation and experimental studies.

Discussion on the third RF test result, coupling issue (continued)

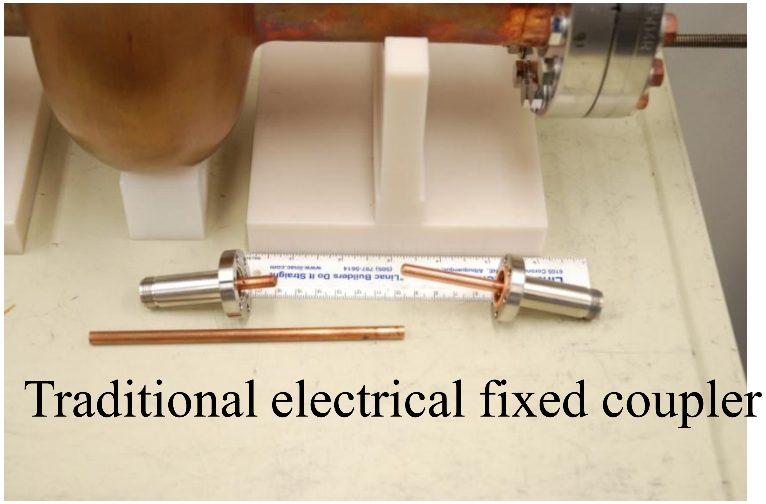


Simulation result from Ben Hall

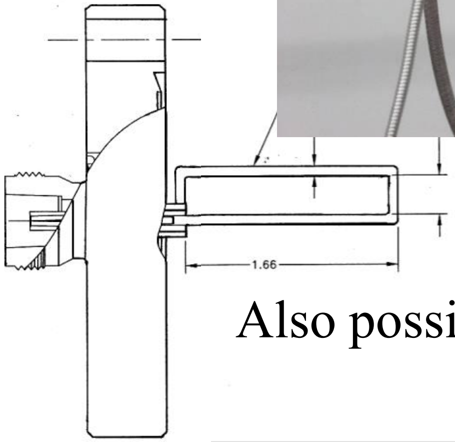
We need a better variable and magnetic coupler for vertical test



To be used variable electrical coupler

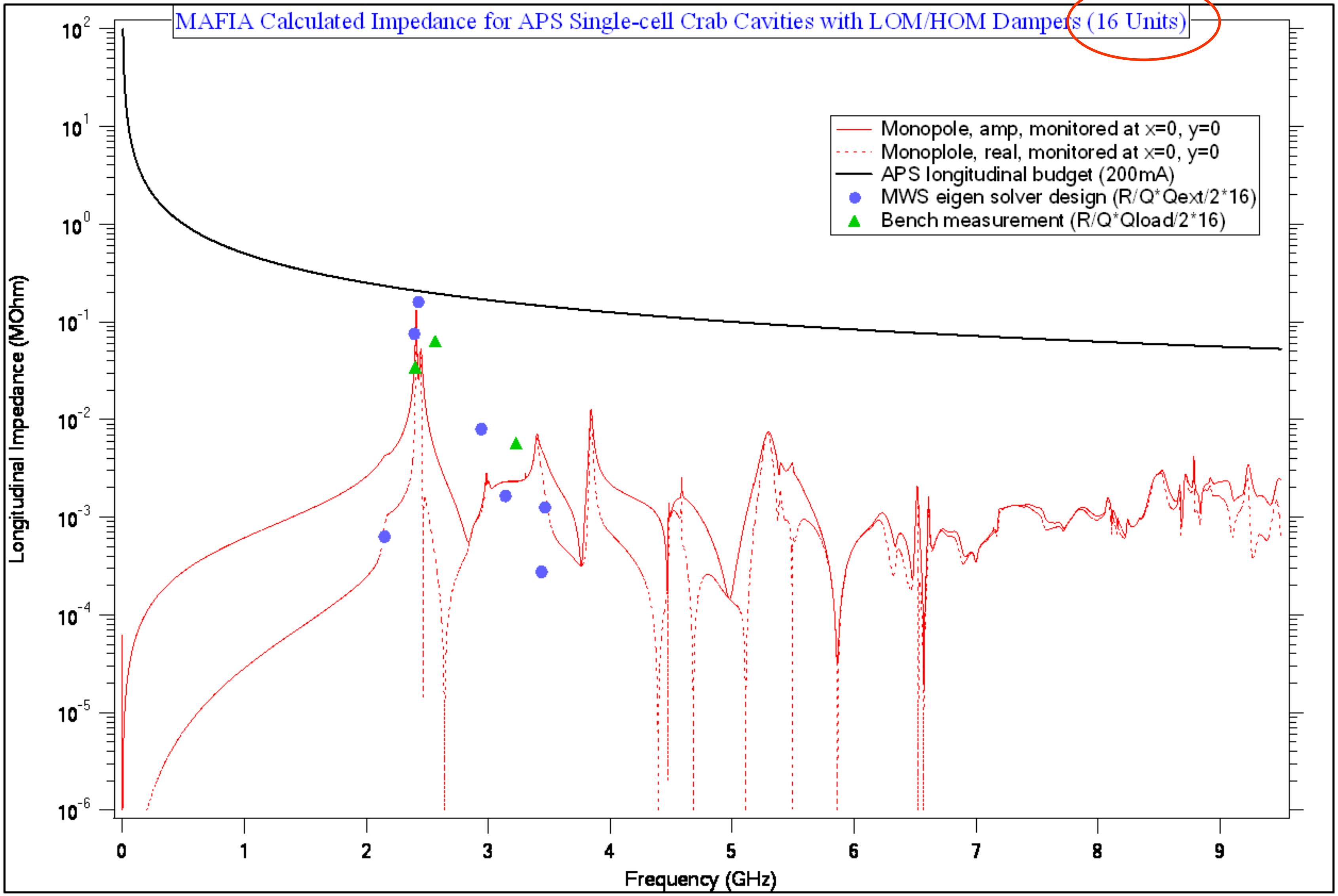


Traditional electrical fixed coupler

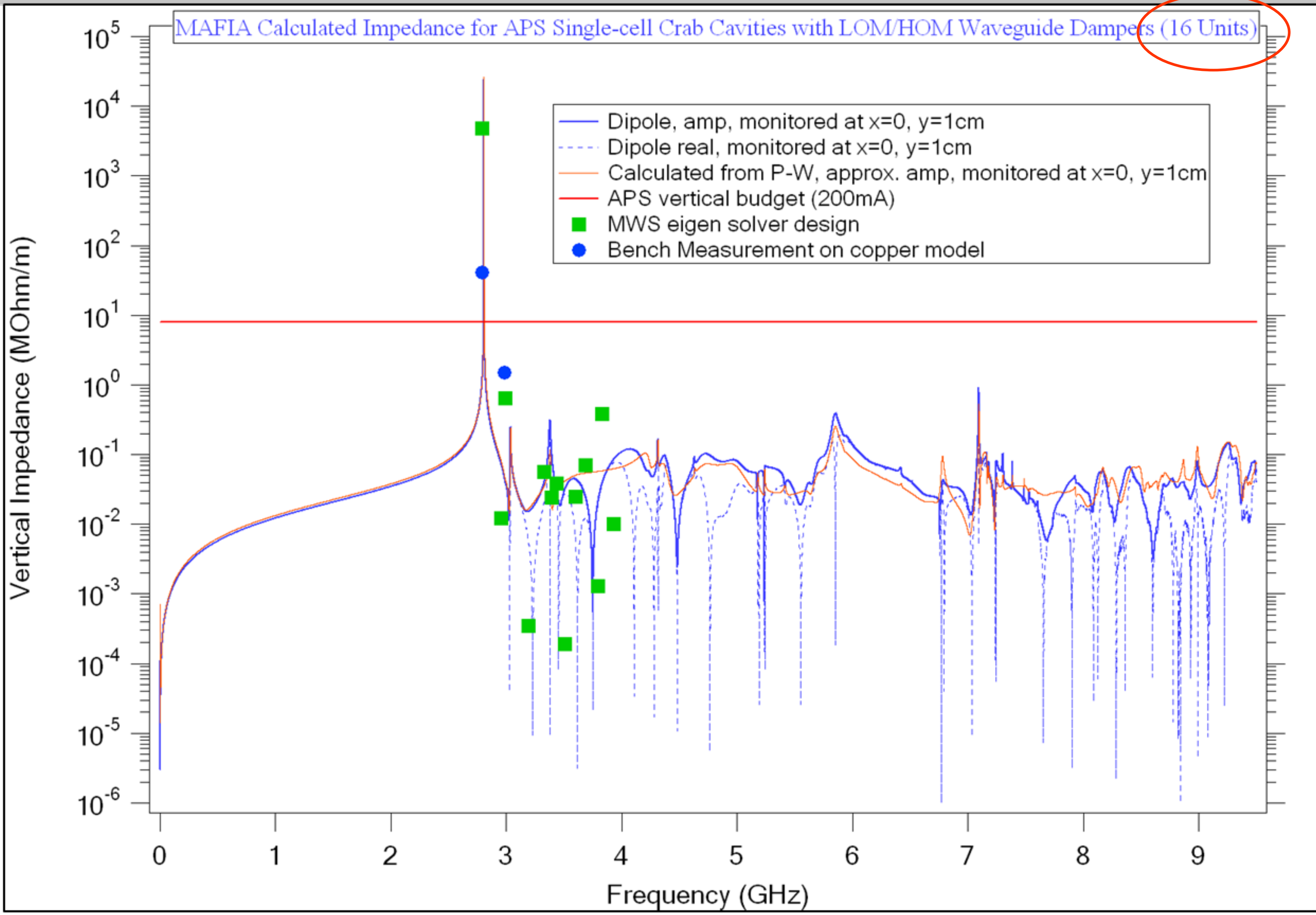


Also possible using a loop coupler

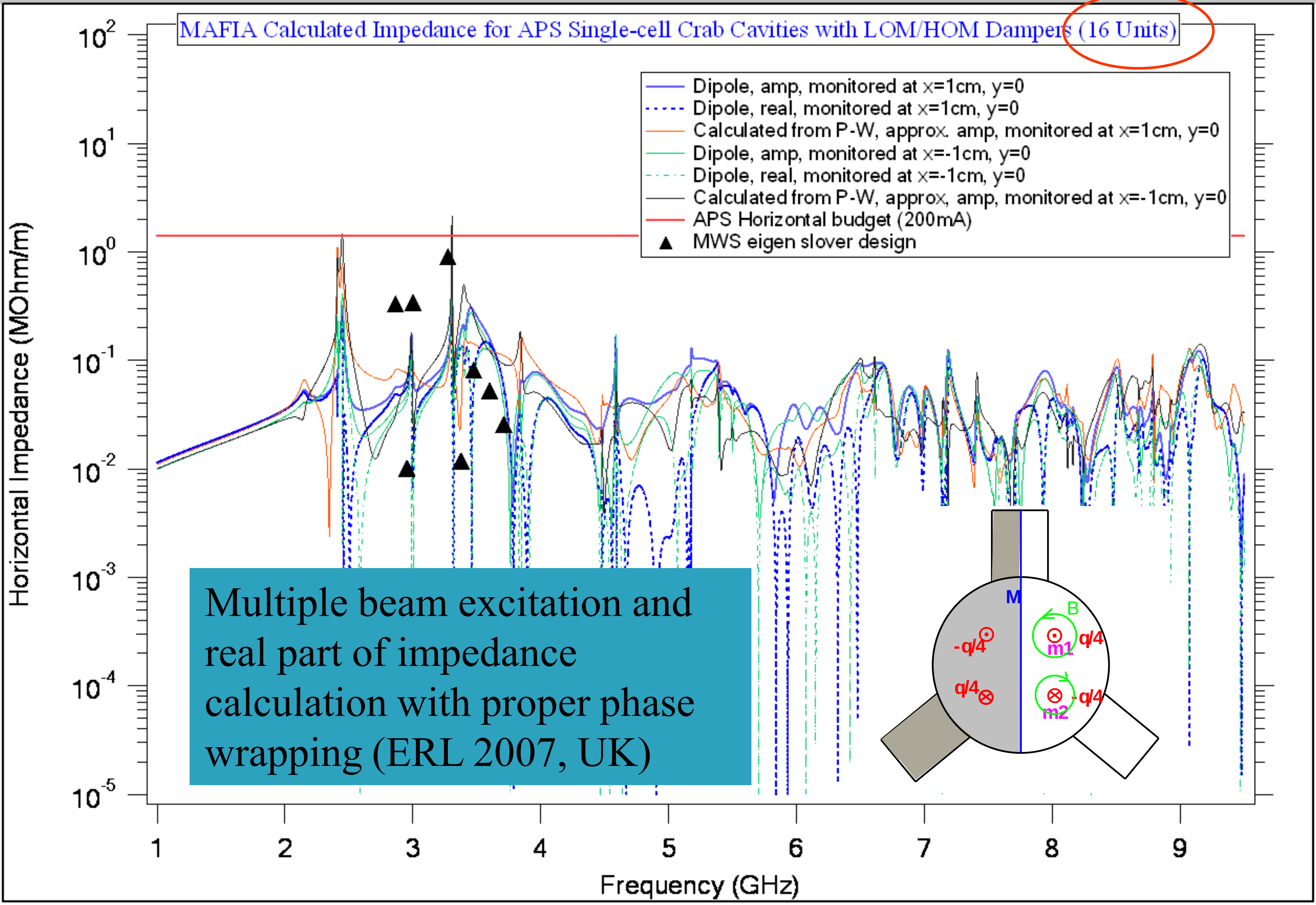
ANL's Baseline Crab Cavity Unit Design with LOM and HOM Waveguide Dampers



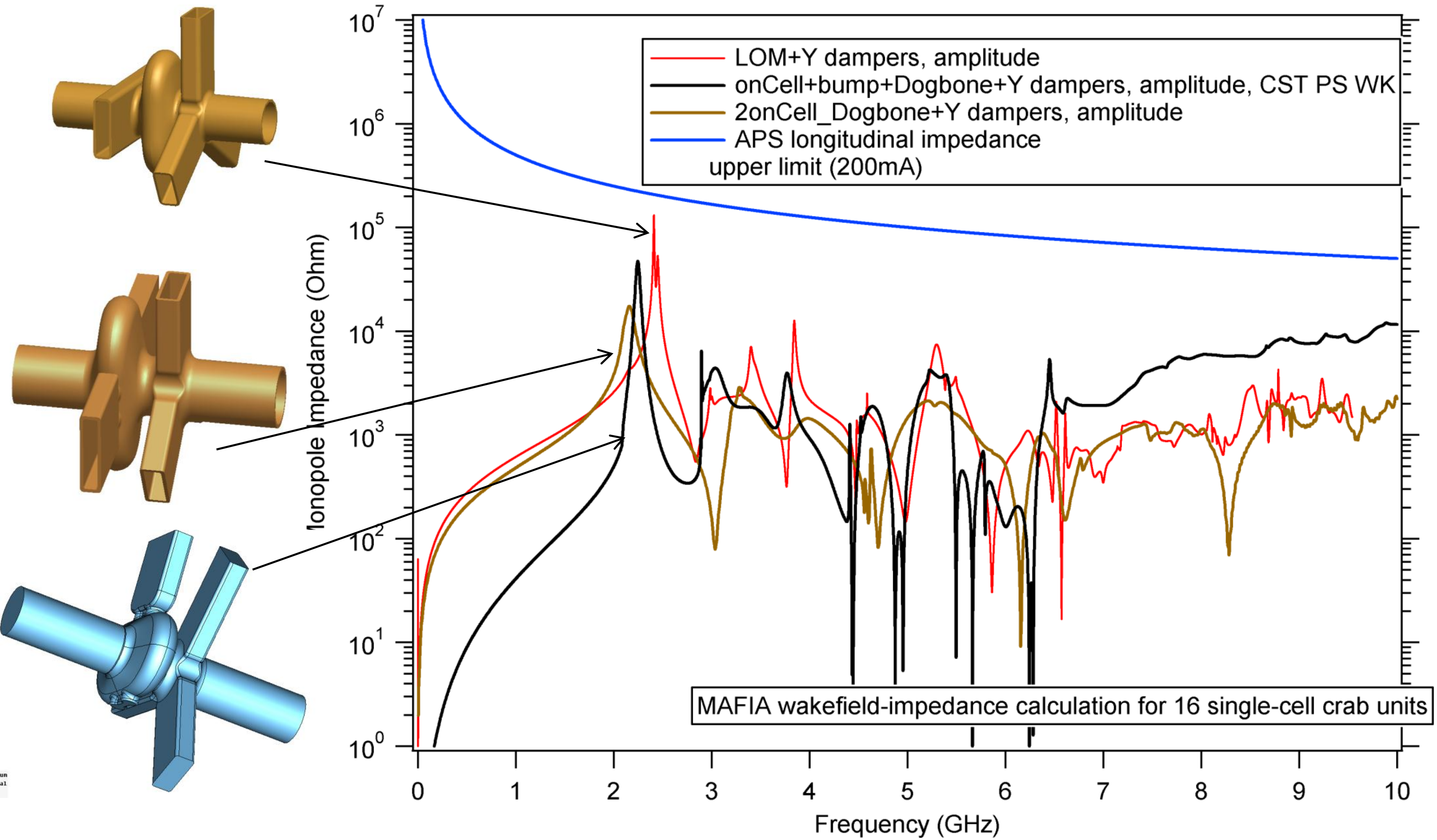
ANL's Baseline Crab Cavity Unit Design with LOM and HOM Waveguide Dampers



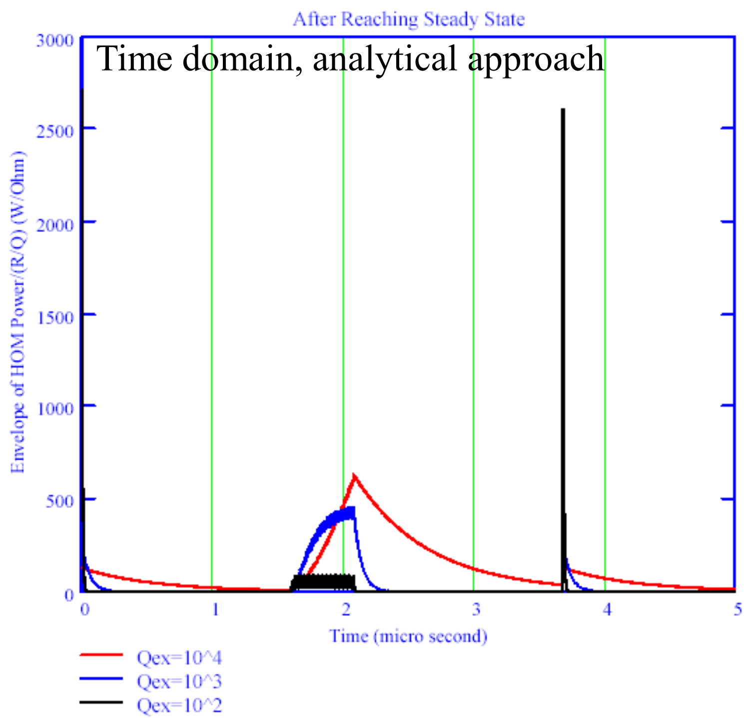
ANL's Baseline Crab Cavity Unit Design with LOM and HOM Waveguide Dampers

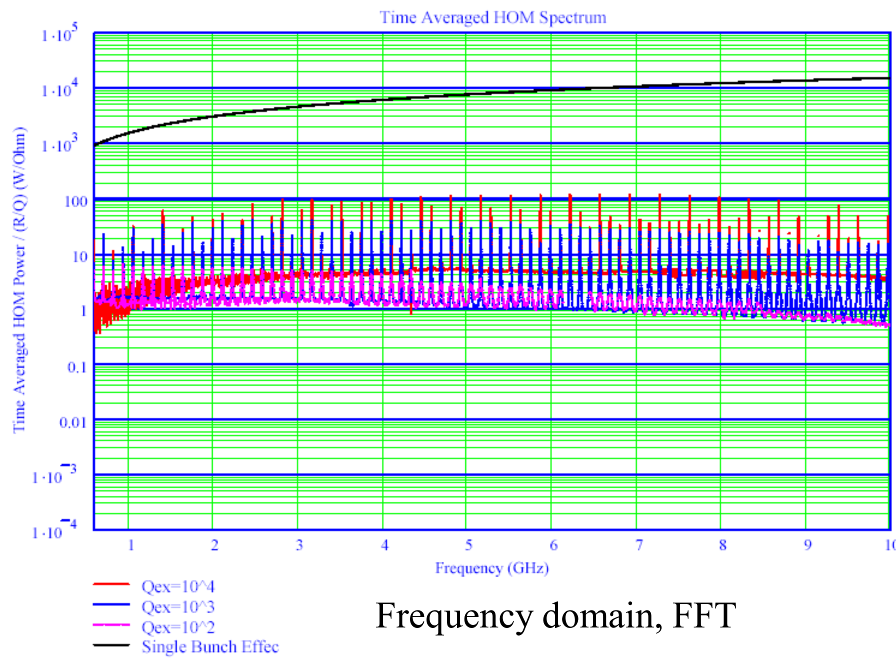


Longitudinal Monopole Impedances between Baseline and Alternate Designs



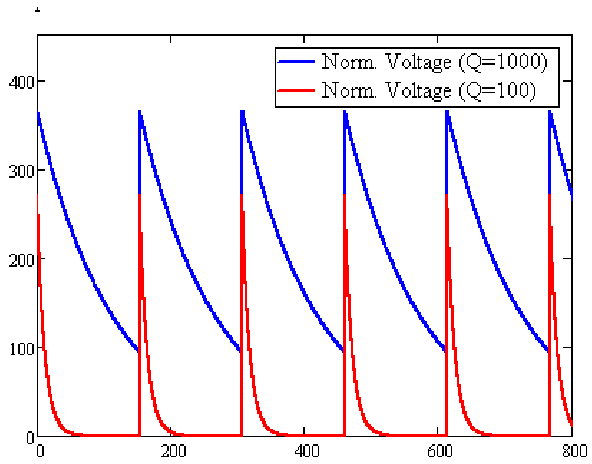
HOM Power Spectrum in APS' Hybrid Beam Bunch Fill Mode



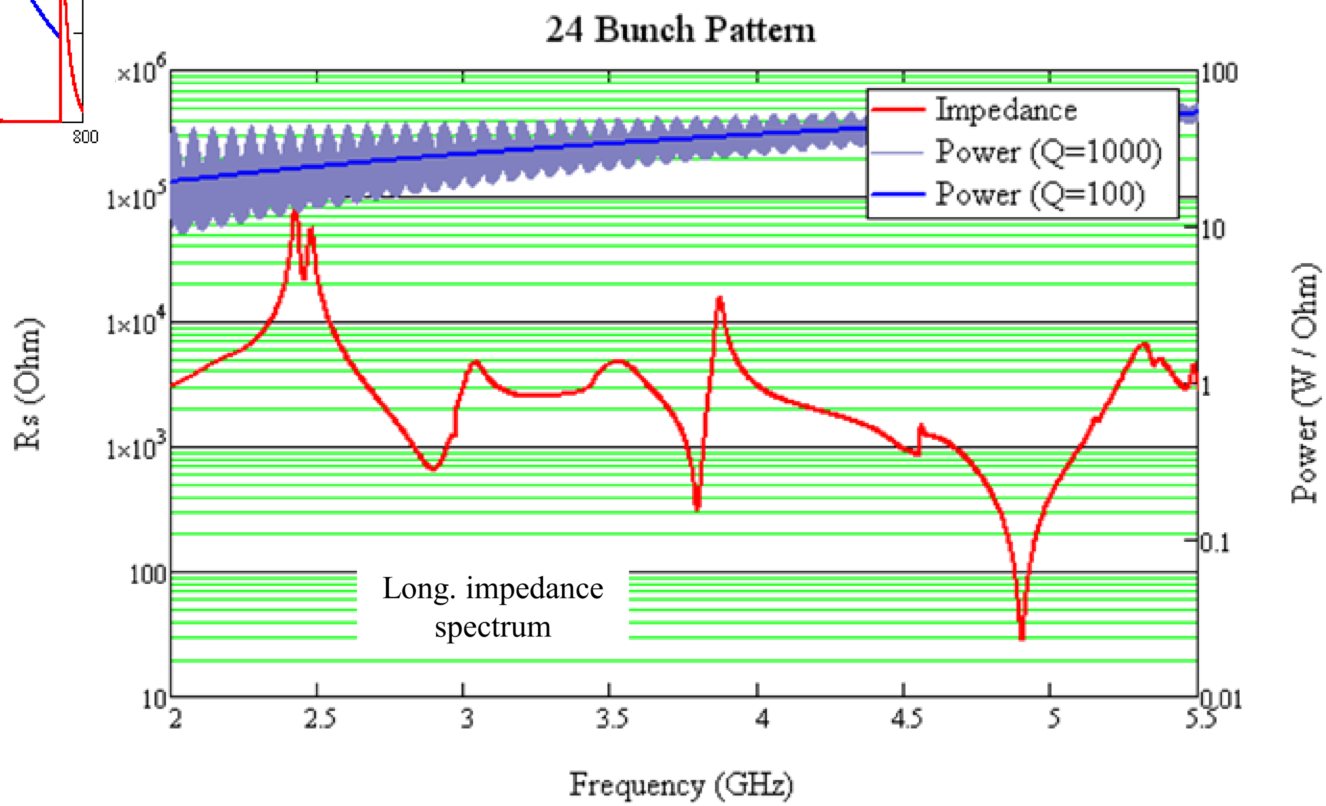


The estimated total beam induced RF power into the cavity from longitudinal modes due to the APS hybrid mode bunch pattern (16mA/86mA) [4] would be 2.45 kW, where 51 W is damped in each waveguide load.

HOM Power Spectrum in APS' 24 Beam Bunch Fill Modes

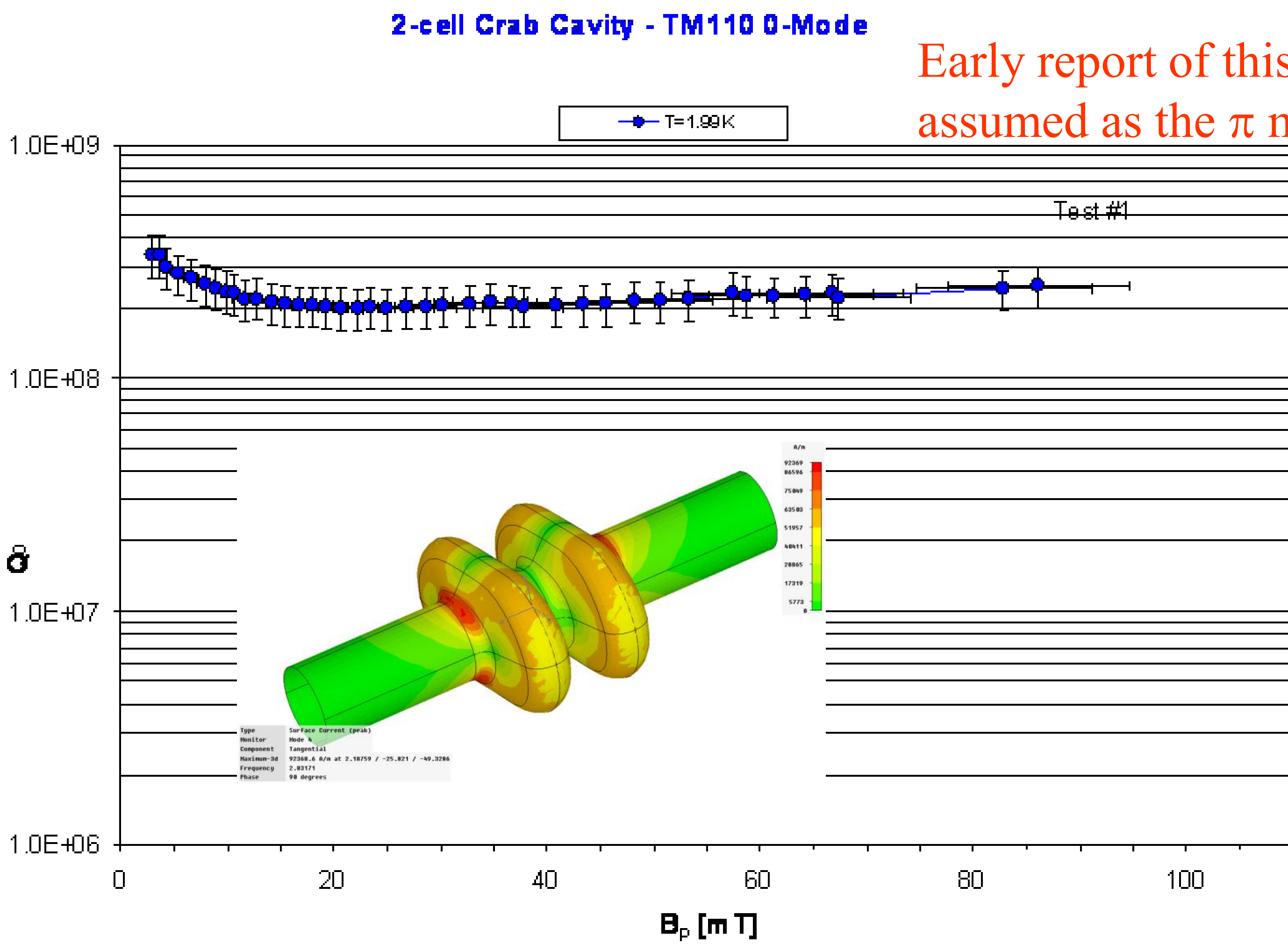


Sang-Ho Kim, "HOM power in Elliptical SC cavities for Proton Accel," NIM A 2002



Cold RF Test on a Two-cell Large Grain Nb Crab Cavity

by Peter and Gigi on July 18, 2008



Early report of this test #1 was assumed as the π mode.

Cold RF Test on a Two-cell Large Grain Nb Crab Cavity

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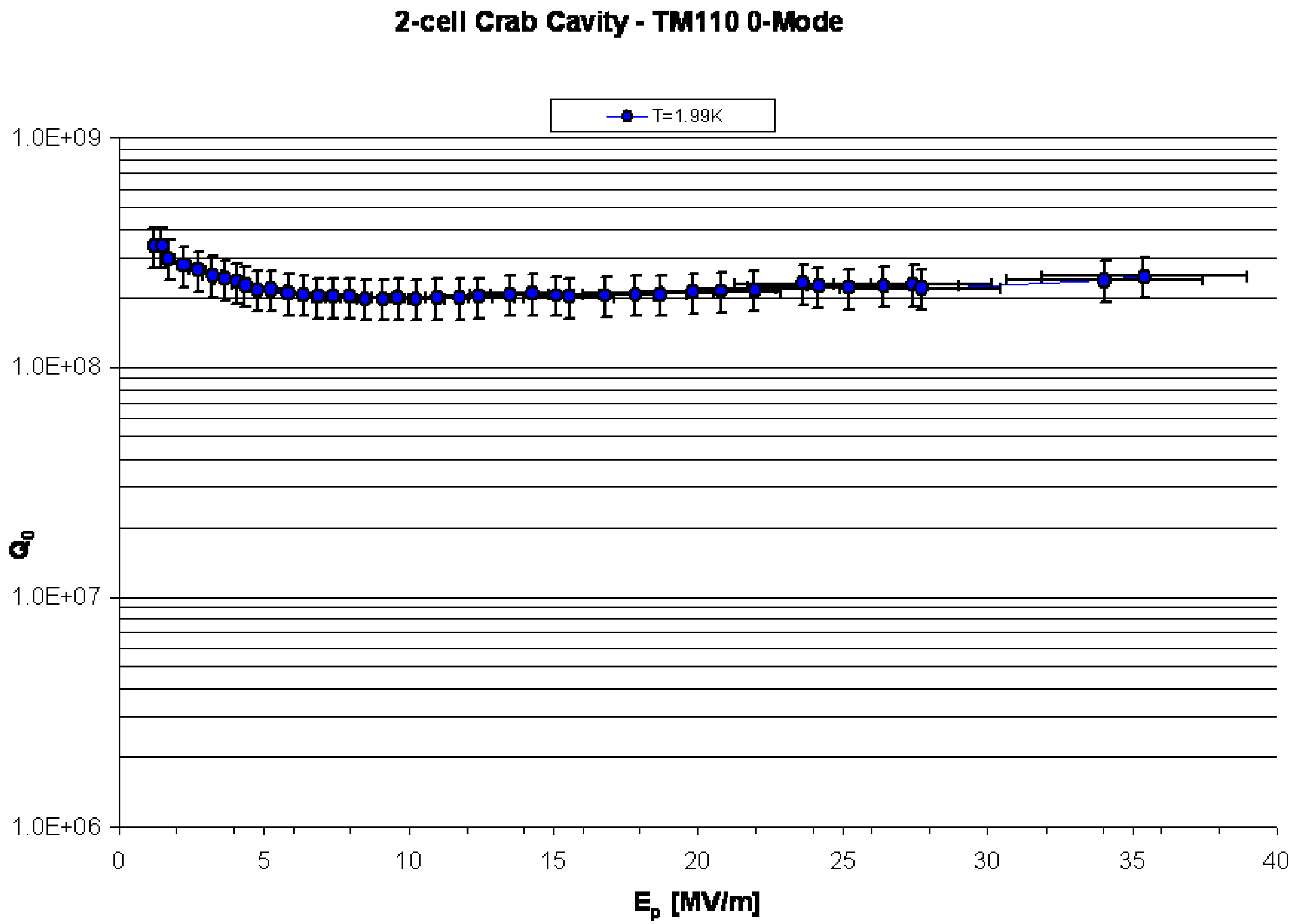

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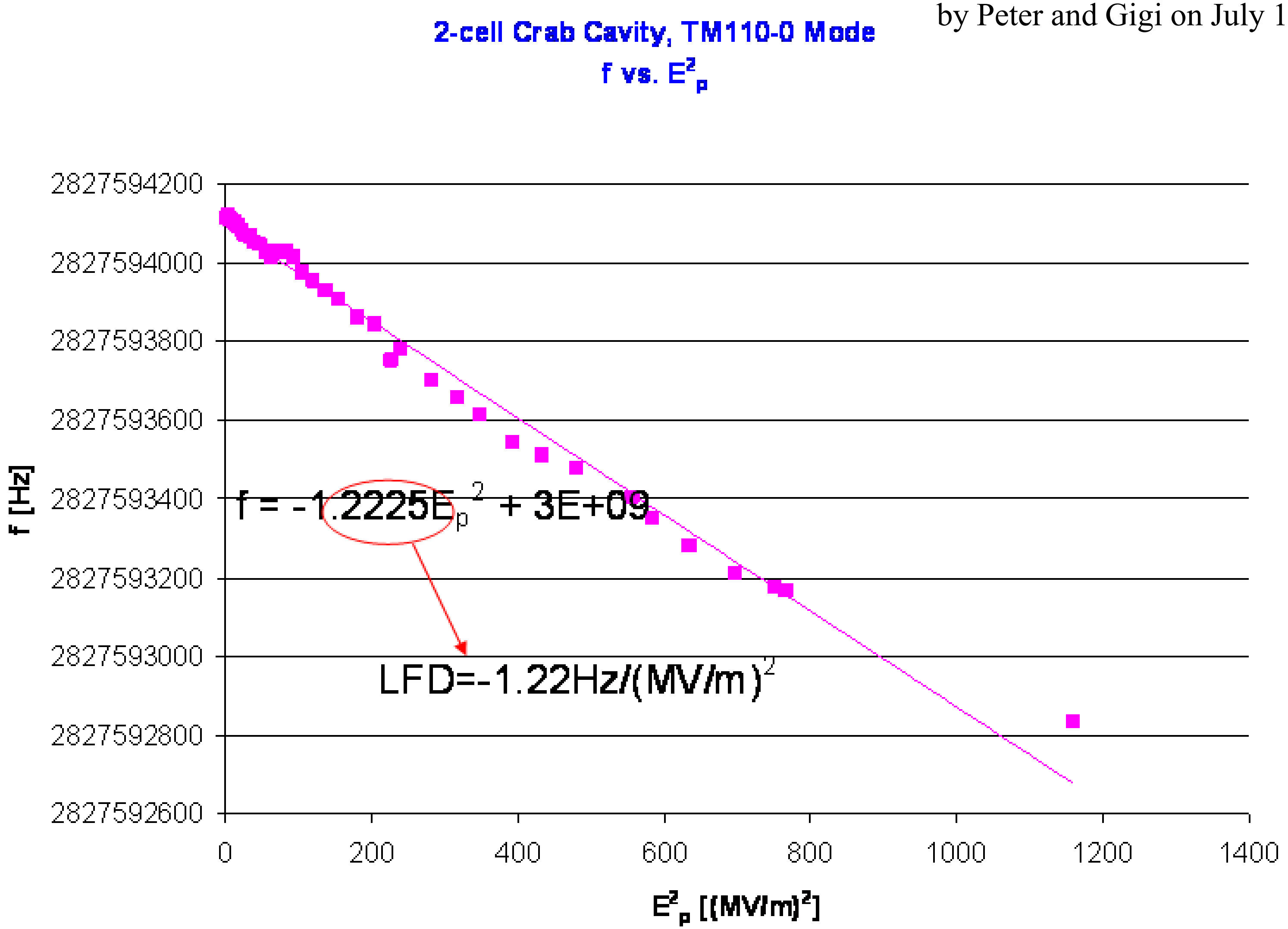
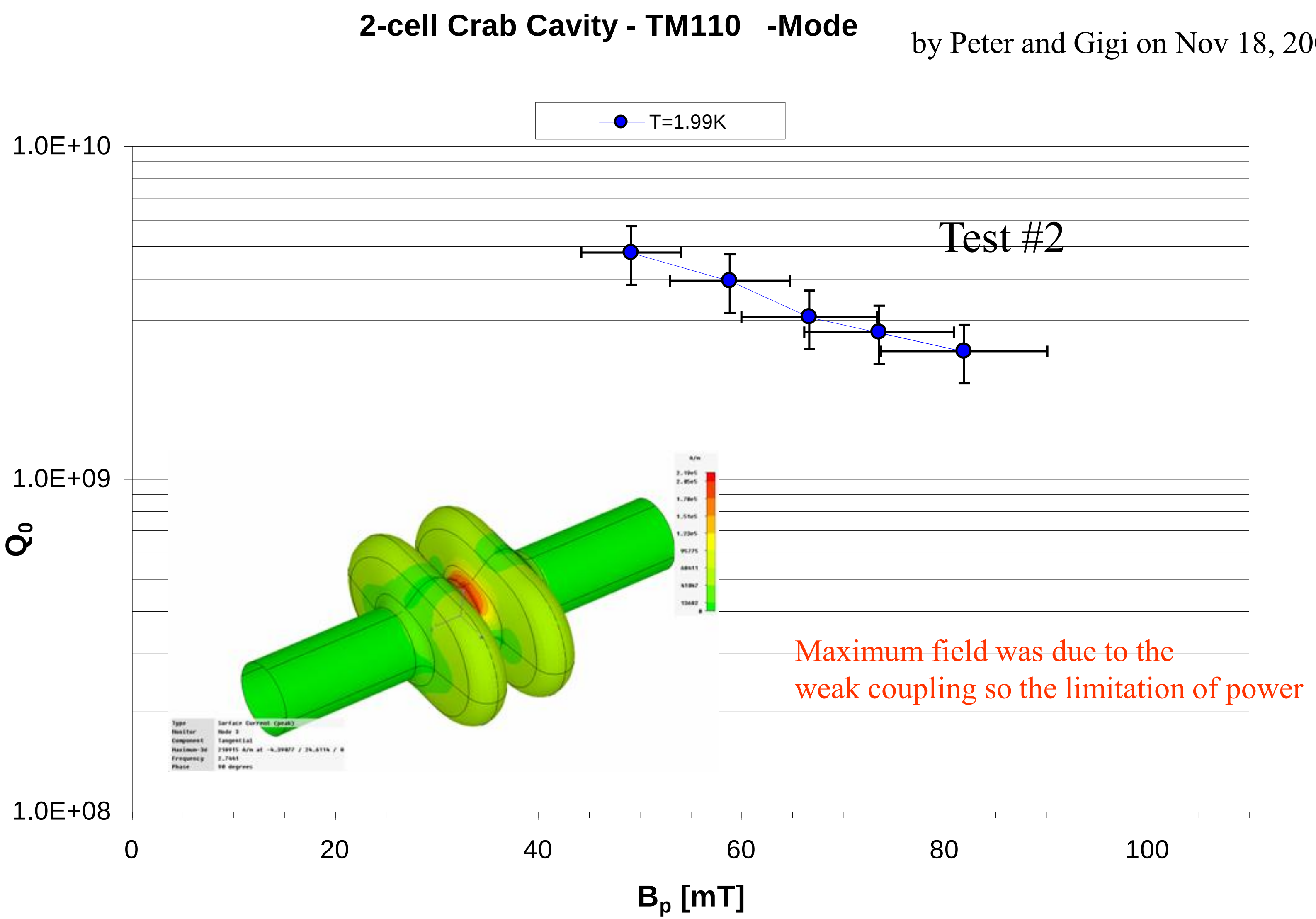


Cold RF Test on a Two-cell Large Grain Nb Crab Cavity

by Peter and Gigi on Nov 18, 2008



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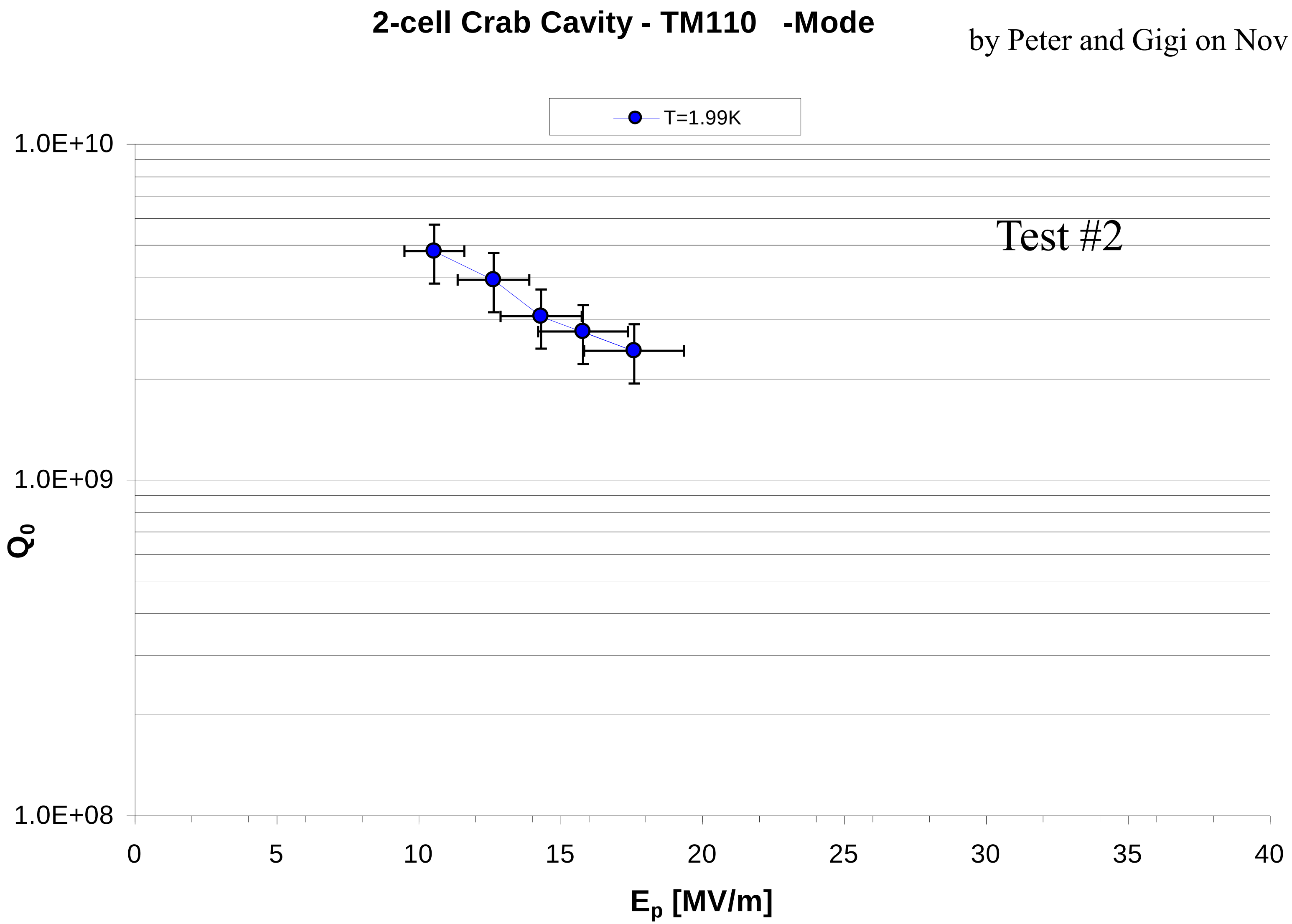
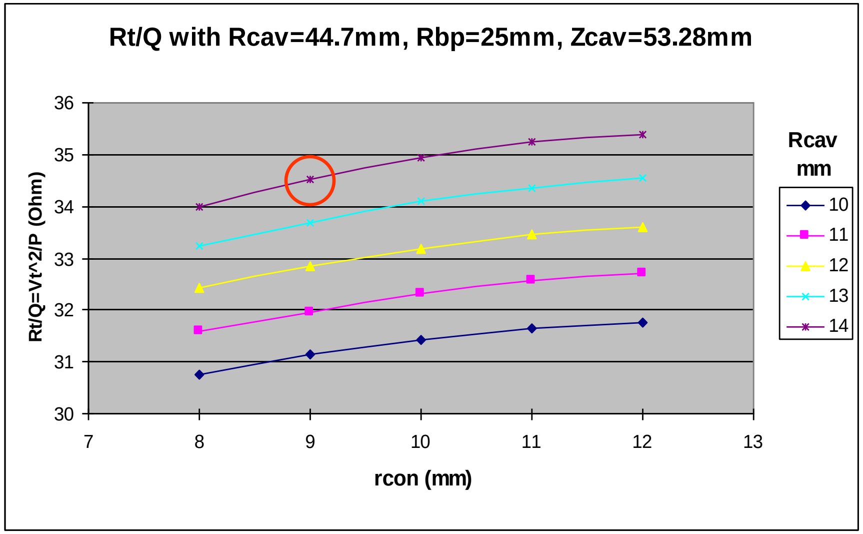
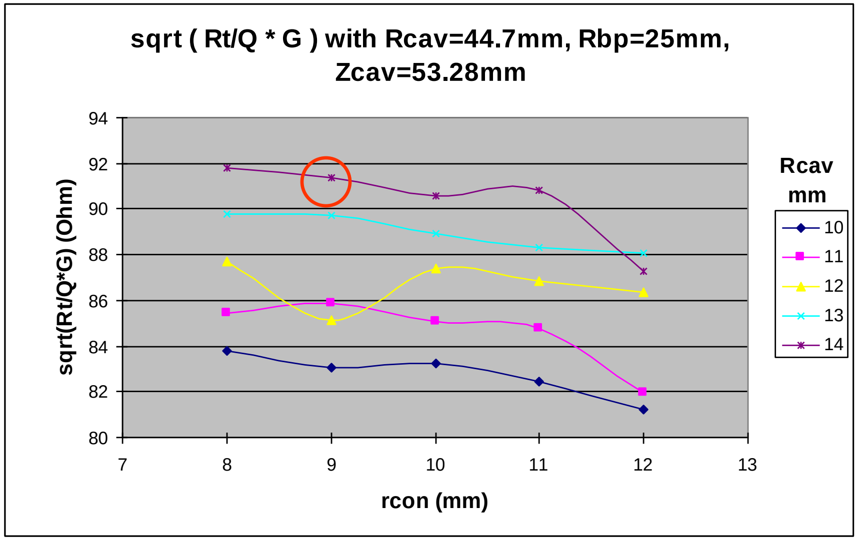
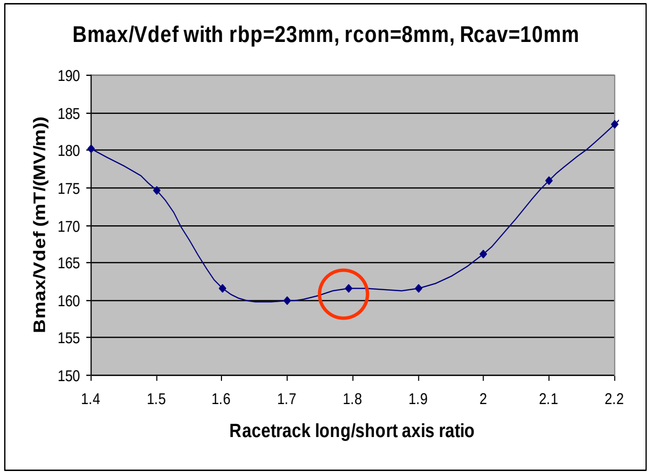


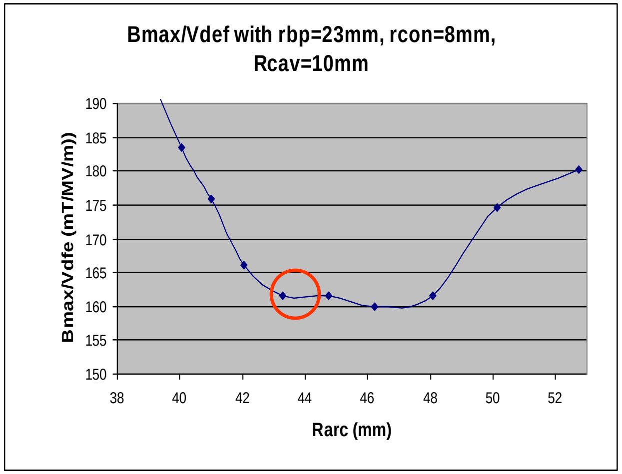
Squashed Elliptical Cavity Shape Optimization, first reported in LHC-CC08 BNL Workshop, Feb, 2008

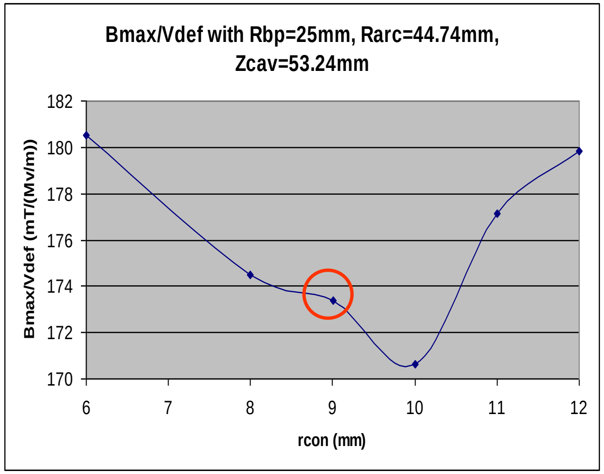




MWS ,ANSYS, HFSS and Gdfidl simulation by Jiaru and Geoff







Squashed Elliptical Cavity Shape Comparison

		optimized squashed dimensions mm	scaled to 800MHz JLab-ANL-LBNL	KEK crab dimensions	scaled to 800MHz KEK
racetrack radius	Rarc	44	154.9	241.5	153.6
beam pipe radius	Rbp	25	88.0	94	59.8
cavity equator radius	rcav	14	49.3	90	57.3
cavity iris radius	rcon	9	31.7	20	12.7
cavity iris-to-iris distance	zcav	53.24	187.4	294.5	187.3
cavity racetrack half straight length	yline	33.66	118.5	191.5	121.8

Scaled KEK and JLab-ANL-LBNL's crab cavity shapes to 800MHz

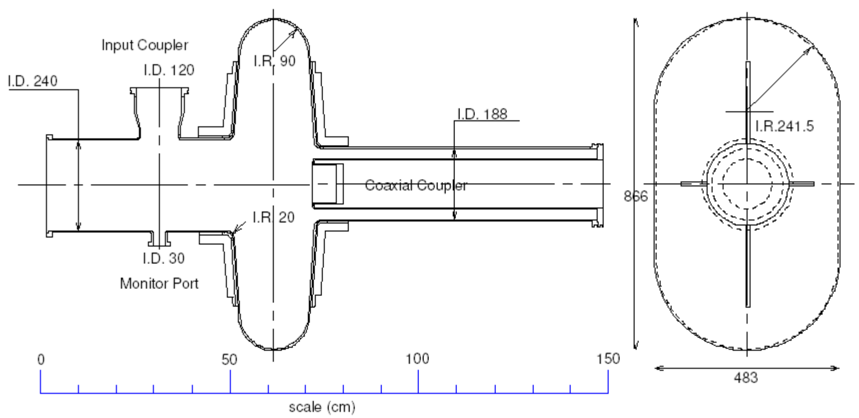
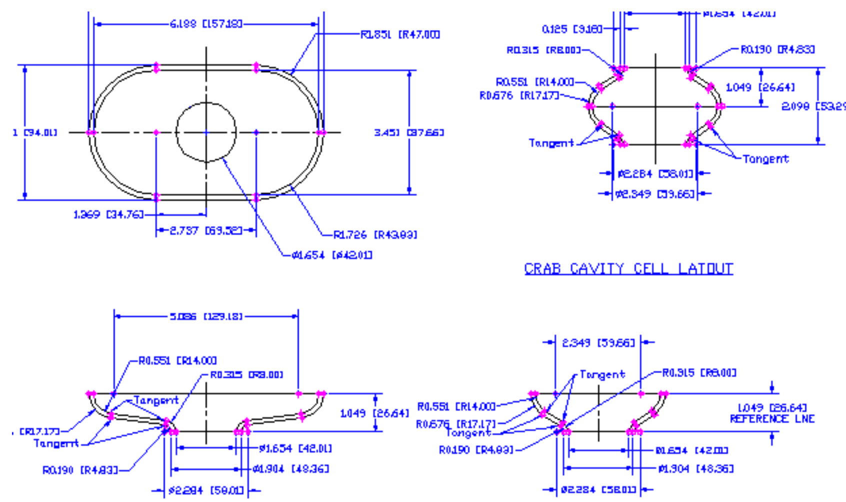
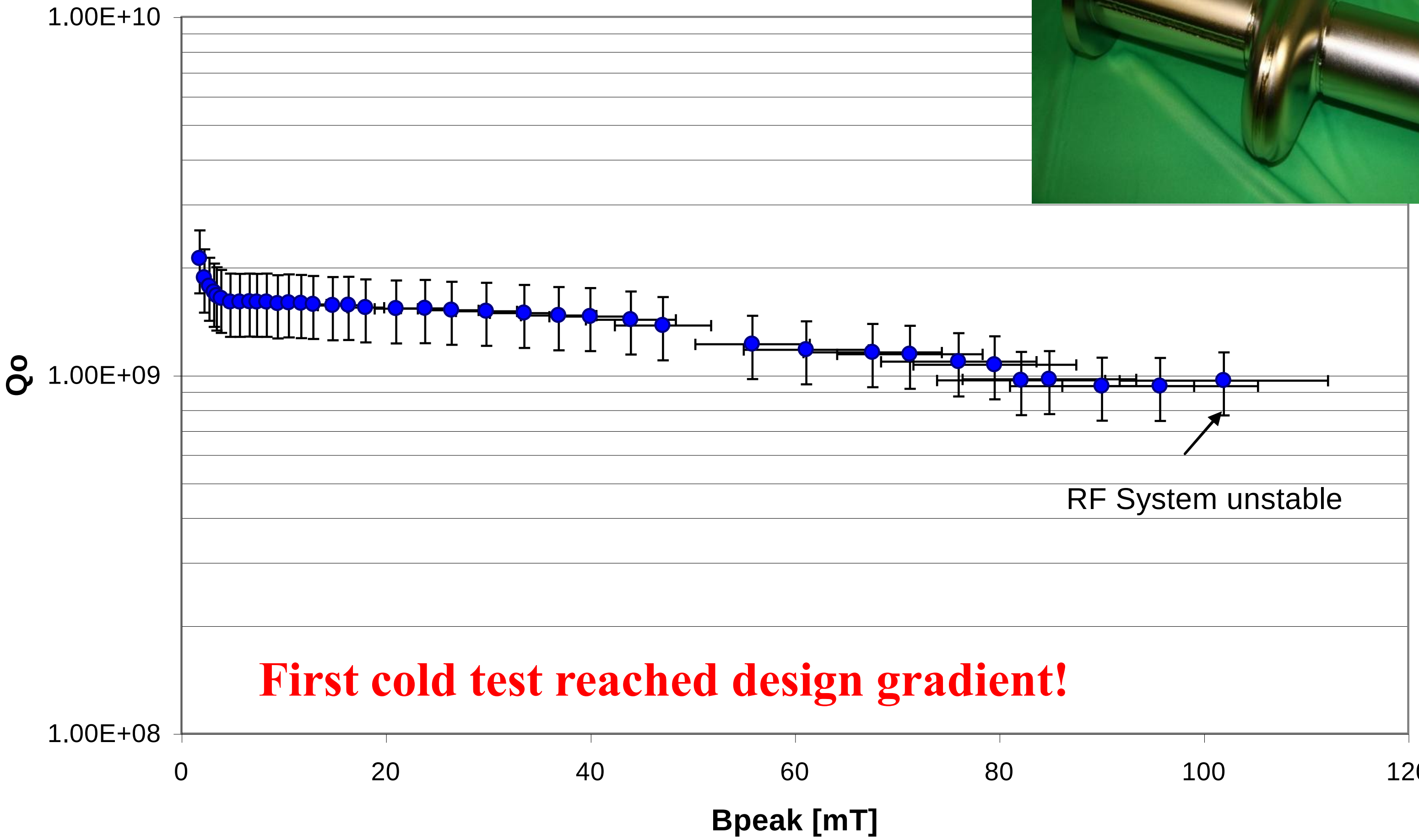


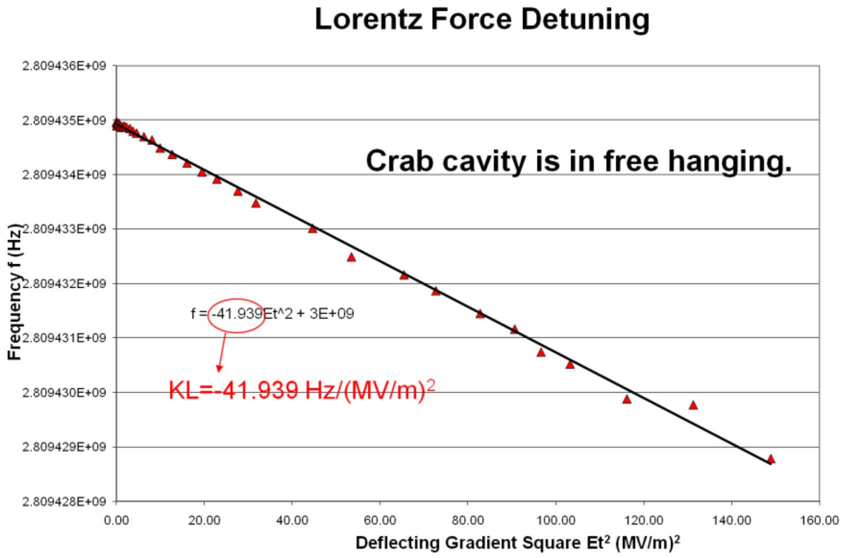
Figure 4: KEKB crab cavity with a model coaxial coupler.

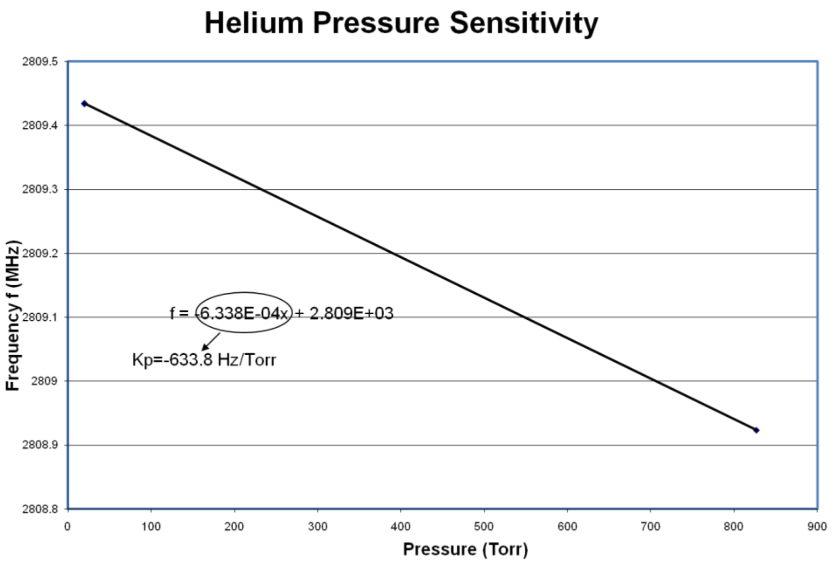


First Cold Single-Cell Crab Cavity Test at 2.1K in 2007



Lorentz Force Detuning on ANL's Crab Cavity

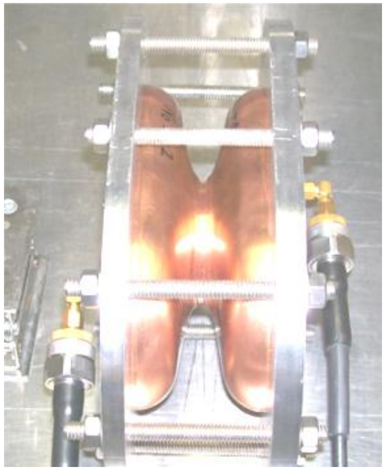


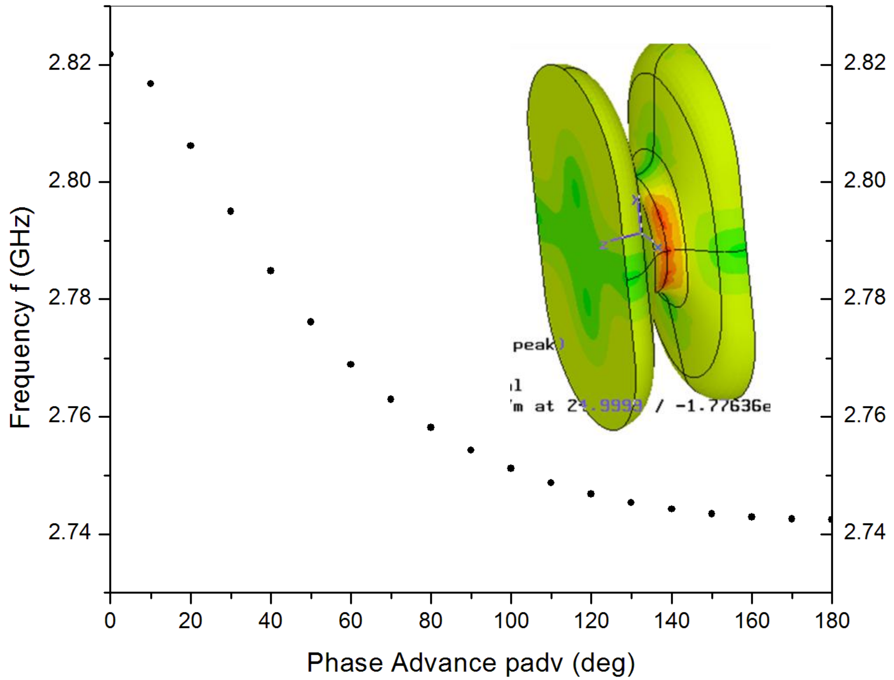


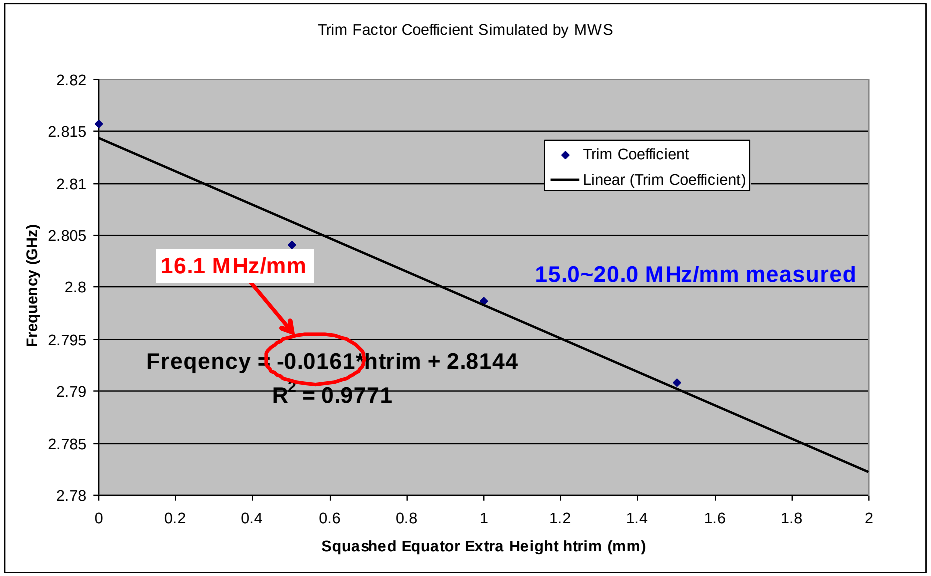
- Large LDF number caused the RF PLL unstable during the VTA test in high gradient.
- LFD is a few Hz/(MV/m)^2 in regular acceleration elliptical cavities.
- With HOM Y and LOM waveguide groups, this number should be reduced down.

Dumb Bell Measurement and Cell-to-Cell Coupling, first reported in ICFA Shanghai Workshop, April 2008

- Dispersion curve has backward direction and has an opposite tuning direction to the TM010 mode.
- Double-chain model can explain this abnormal dispersion curve. Cell-to-cell coupling has both TM110 mode magnetic and TE111 mode electric couplings.
- Magnetic filed enhancement on the iris in pi mode is a constraint going to multi-cell structure. The field direction is crossing the broader wall of the iris when the H field flipping the sign between the adjacent cells.

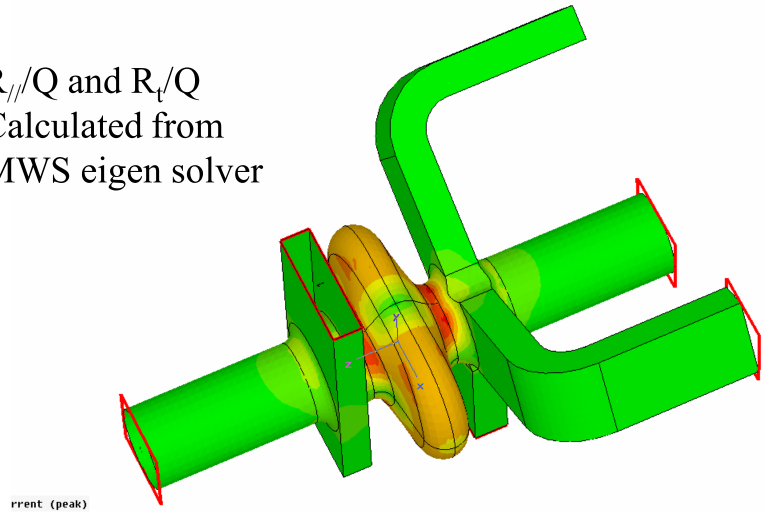


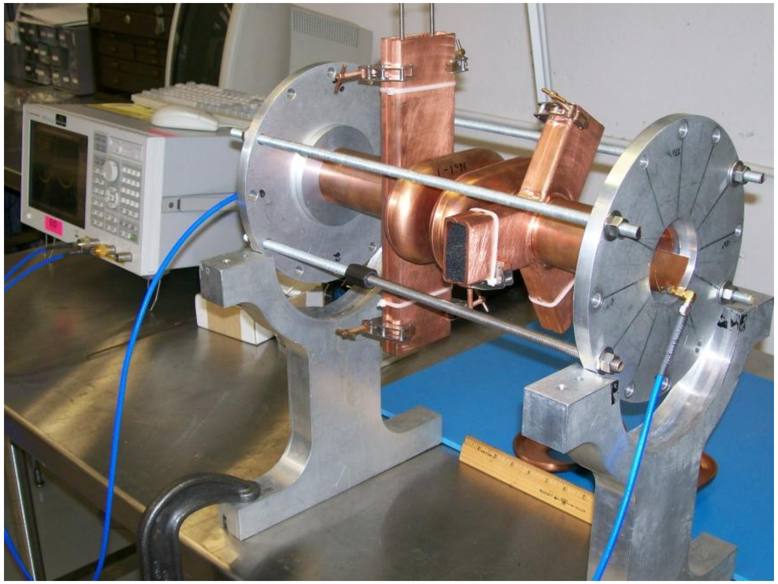


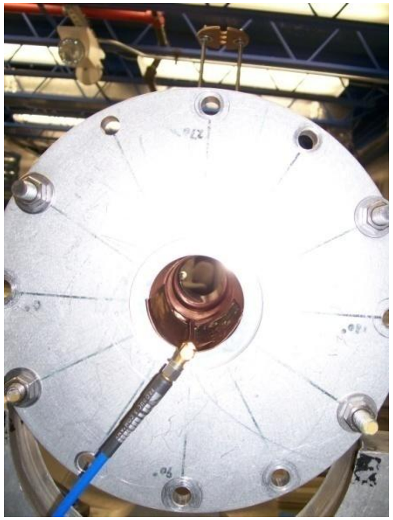


Copper structure prototype, first reported in ICFA Shanghai Workshop, April, 2008

$R_{//}/Q$ and R_t/Q
Calculated from
MWS eigen solver

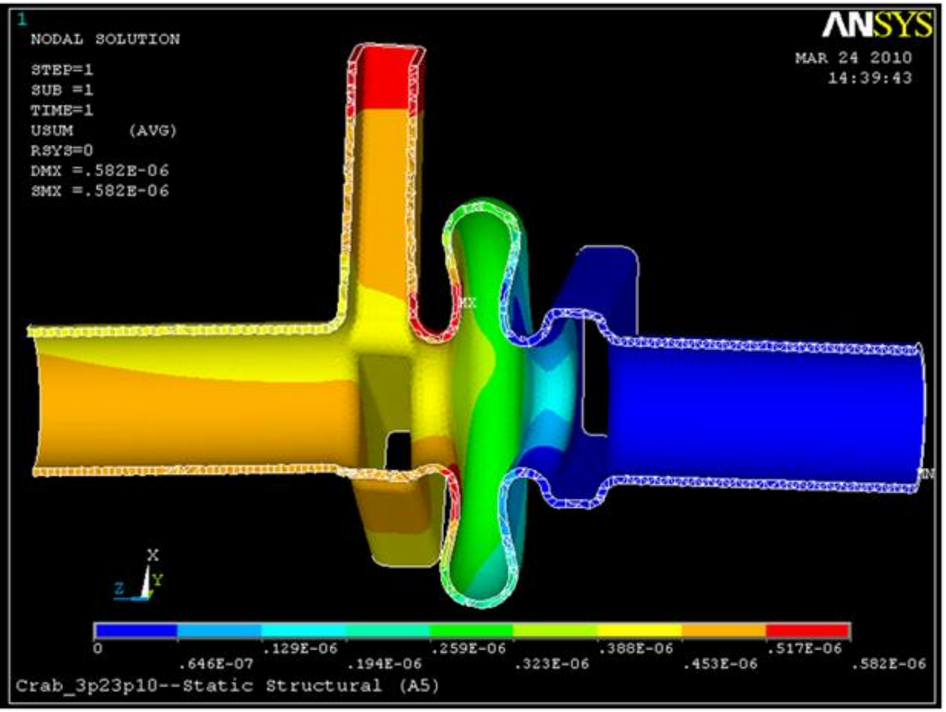


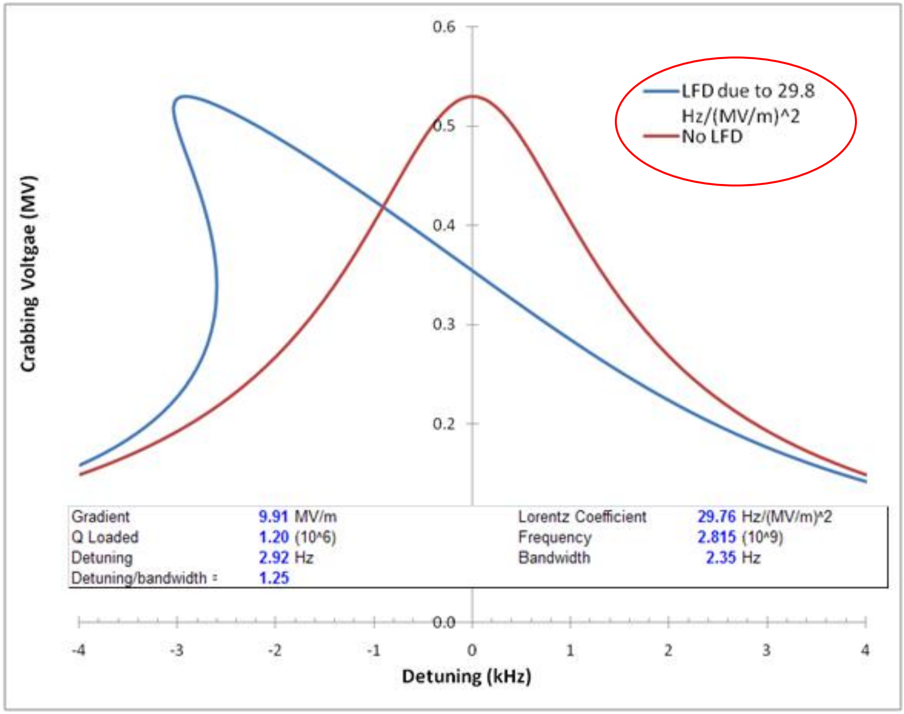




Bench Qext measurement by using
- RF absorbers on WG ports
- Clamping copper parts (low contact loss)
- Weak coupling to VNA
- Rotatable antennas to suppress the unwanted modes.

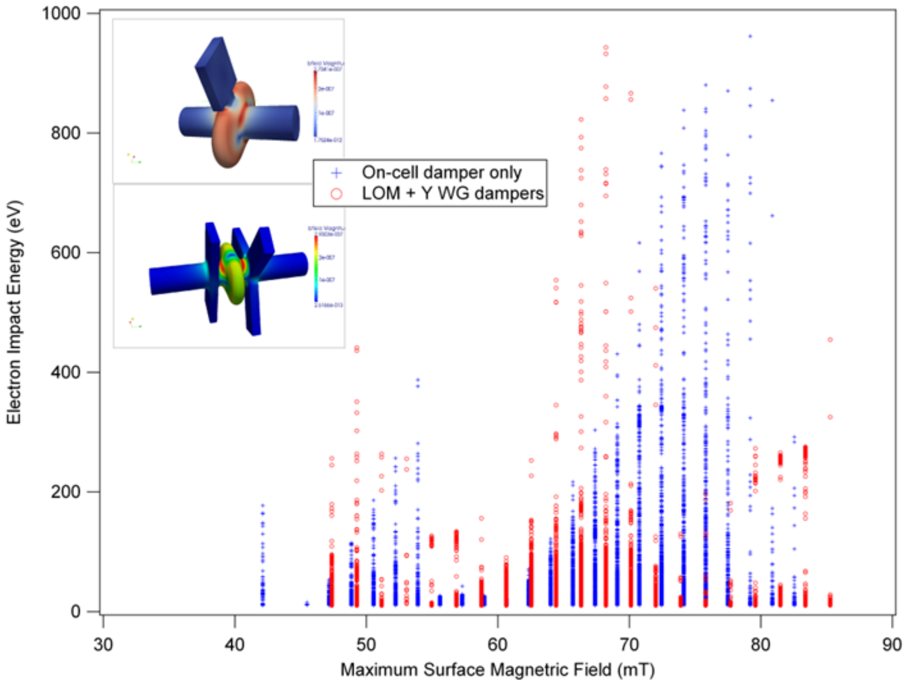
Lorentz Force Detuning Simulation by ANSYS

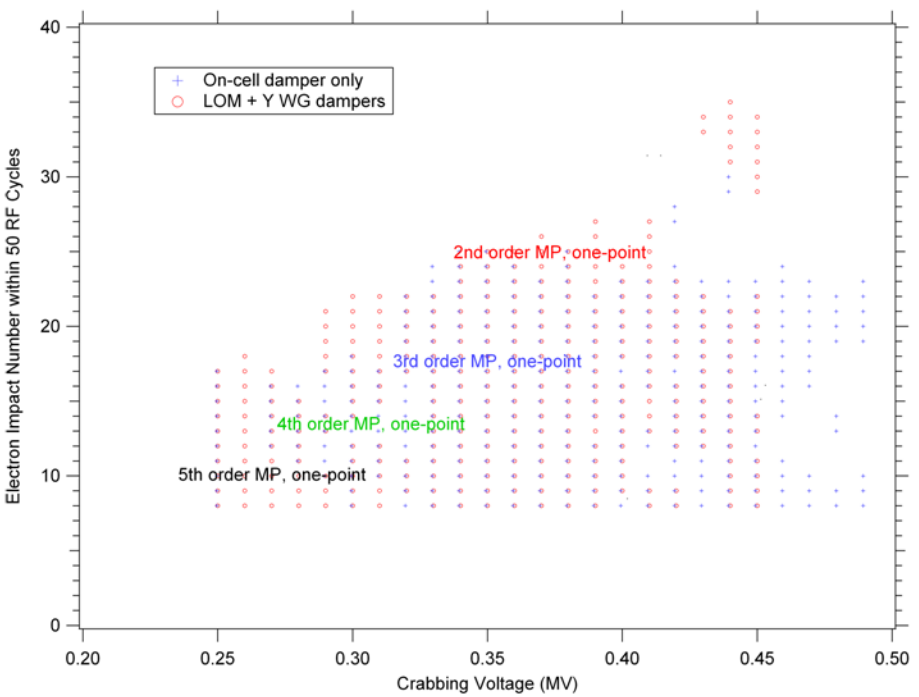




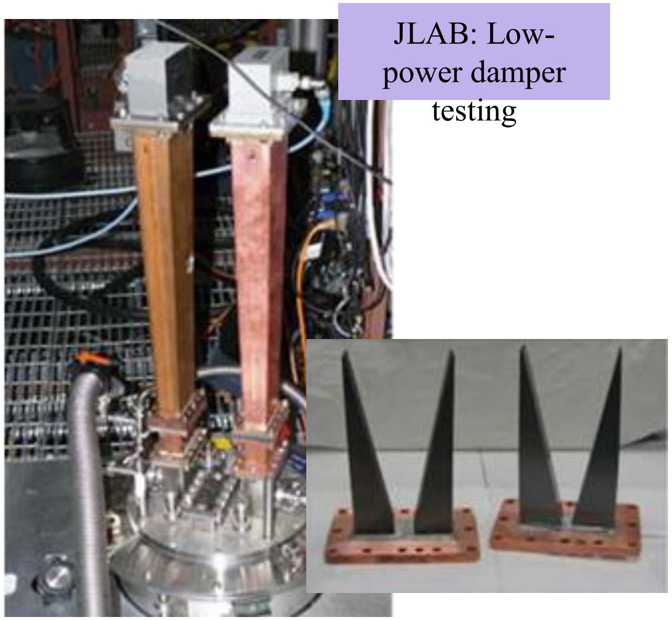
Multipactoring simulation and experiment confirmation

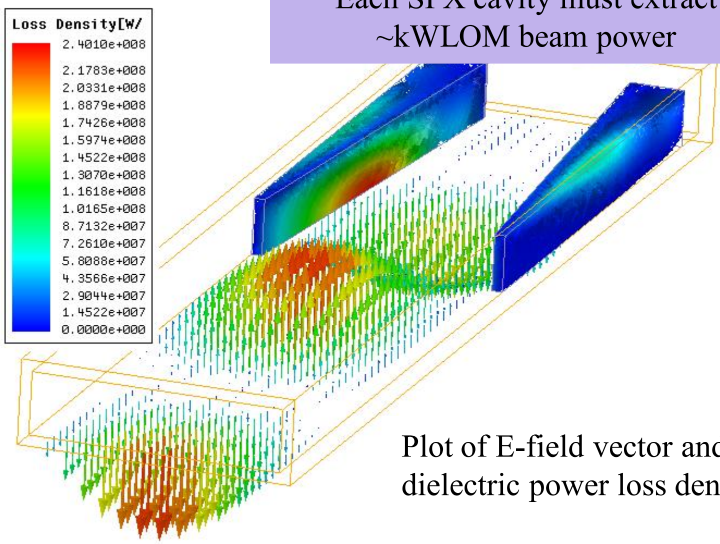
Simulations using SLAC ACD's Omega3P/Track3P



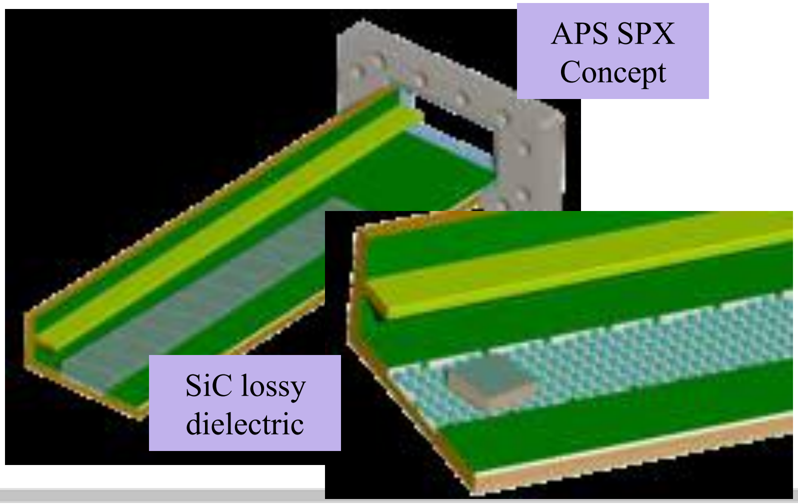


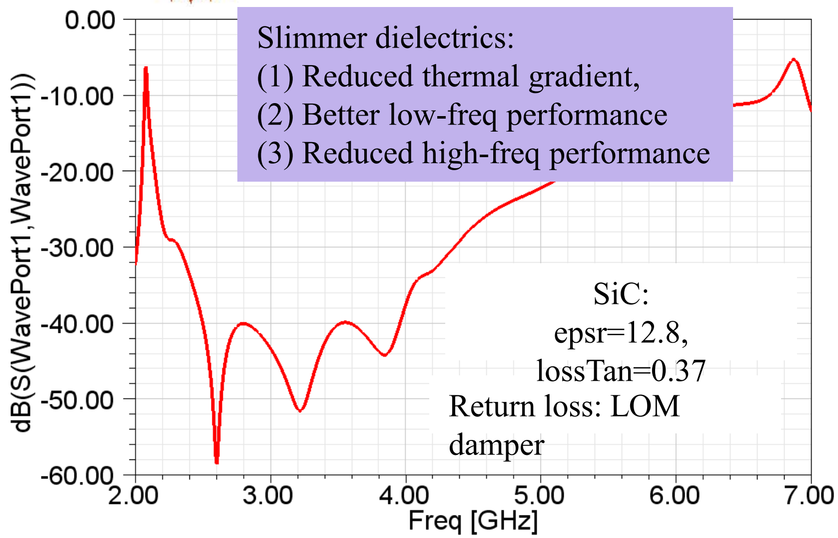
LOW/High power LOM/HOM load designs and tests





Plot of E-field vector and dielectric power loss density



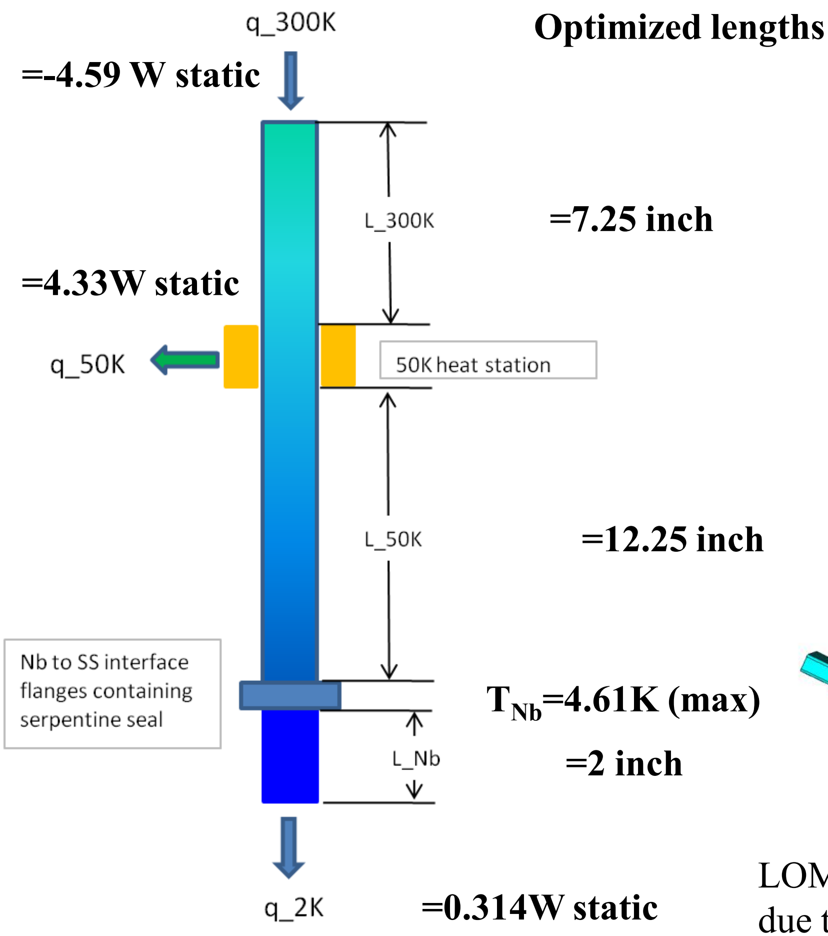


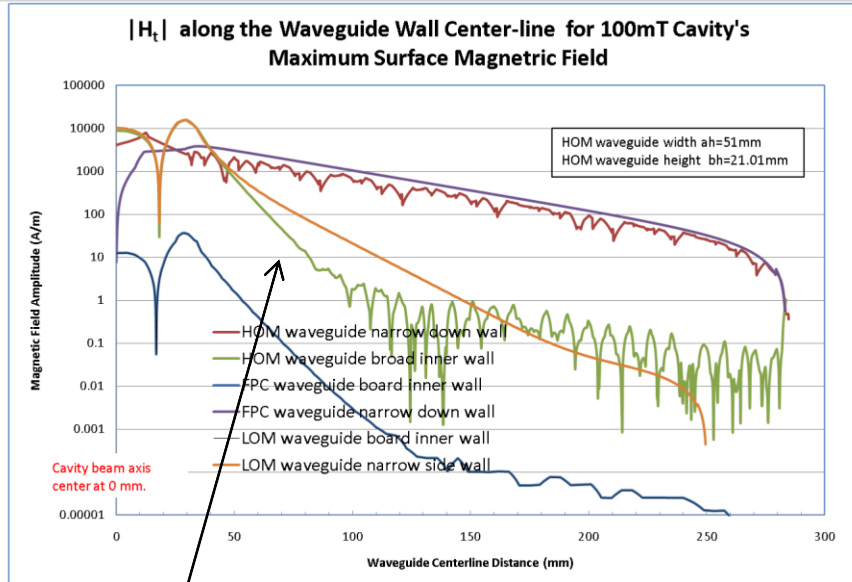
F. Marhauser. “Investigations on Absorber Materials at Cryogenic Temperatures”

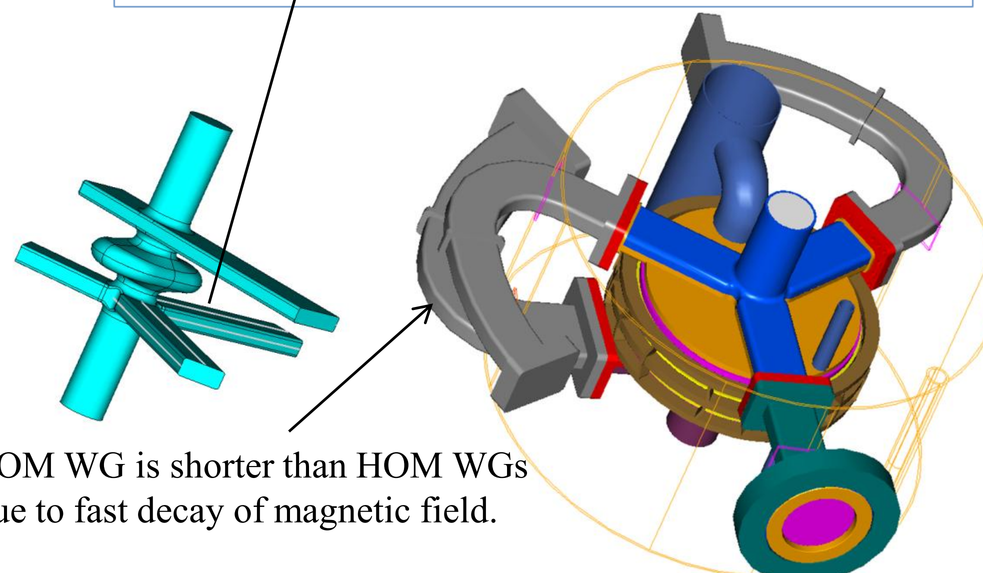
G. Chang: High-Power Damper Concept

Single-cell cavity LOM/HOM WG damper cryostat solution update

1-D RF-thermal model with SS WG, flange interface (AlMg seal) and heat station for HOM waveguides





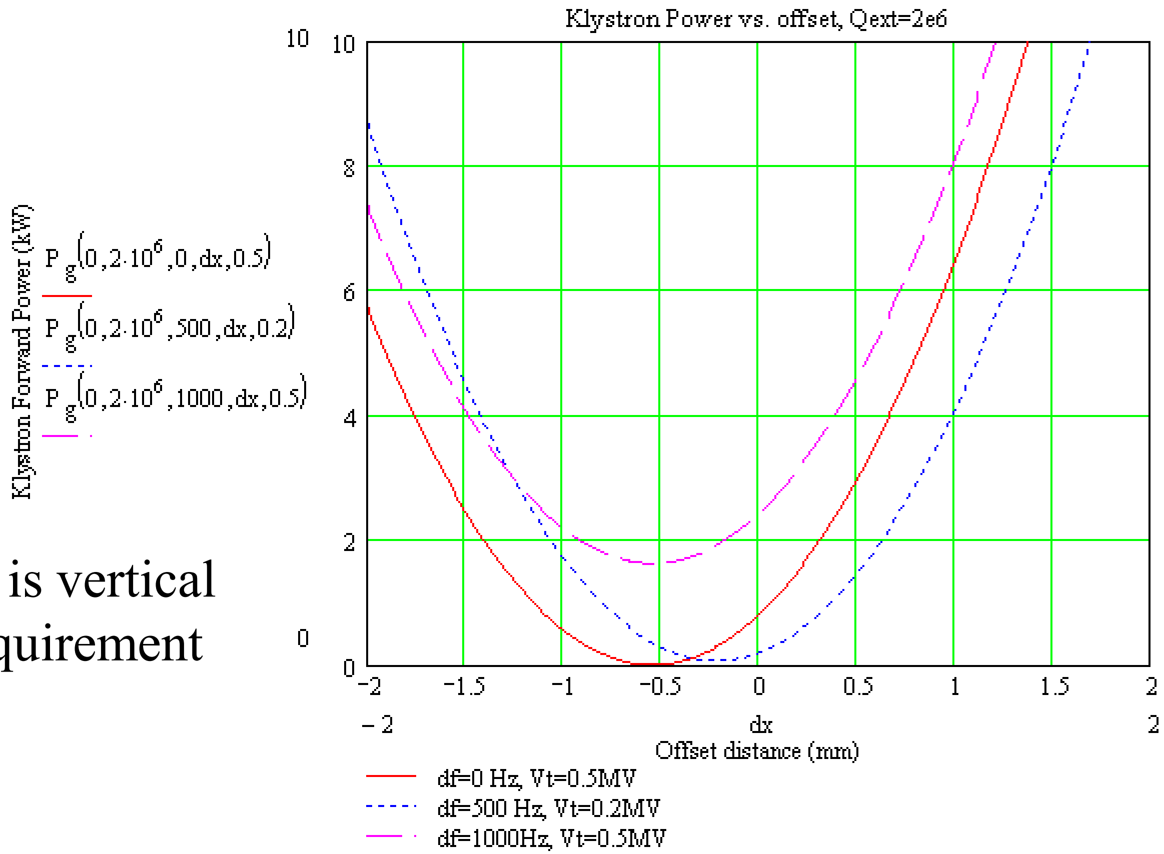


LOM WG is shorter than HOM WGs due to fast decay of magnetic field.

Beam loading issue related to alignment tolerance

$$b\left(\Psi_b, dx, Vt\right) := \frac{I_0 \cdot RoQ(dx) \cdot Q_0}{V_c(Vt, dx)} \cdot \cos\left(\Psi_b \cdot \frac{\pi}{180}\right)$$

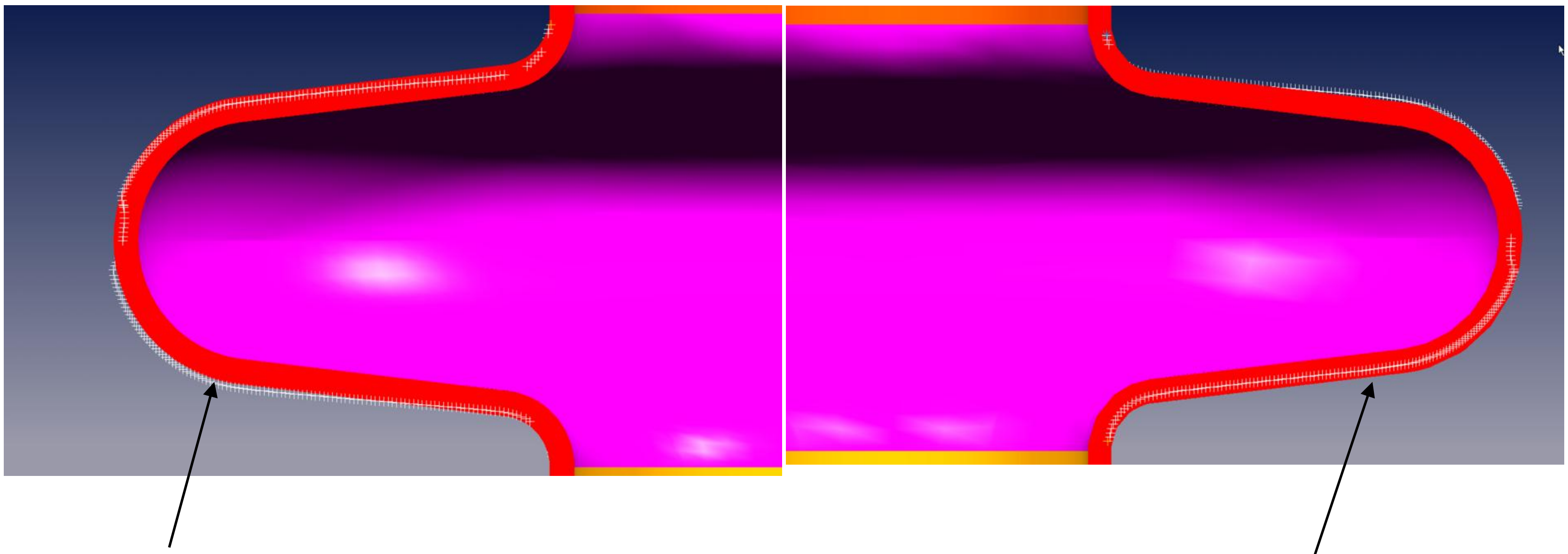
$$P_g\left(\Psi_b, Q_{ext}, \delta f, dx, Vt\right) := \frac{P_c(Vt, dx) \cdot 0.001}{4 \cdot \beta\left(Q_{ext}\right)} \cdot \left[\left(1 + \beta\left(Q_{ext}\right) + b\left(\Psi_b, dx, Vt\right)\right)^2 + \left[\left(1 + \beta\left(Q_{ext}\right)\right) \cdot \left(-2 \cdot \frac{\delta f}{f_0}\right) \cdot \frac{1}{\frac{1}{Q_0} + \frac{1}{Q_{ext}}} - b\left(\Psi_b, dx, Vt\right) \cdot \tan\left(\Psi_b \cdot \frac{\pi}{180}\right)\right]^2\right]$$



dx= ±0.3mm is vertical alignment requirement

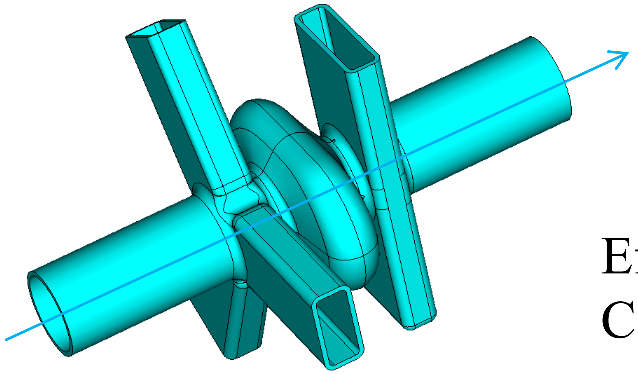
Crab cavity shape deviation from ideal die model

Courtesy to Ben Hall and Brain Carpenter



Shape of crab cavity contour deviated from the ideal design shape. Could it cause the electrical center changed? If yes, CNC machining from niobium bulk is a solution. We are studying on the cost verses accuracy issue with small (16) quantity of crab cavity production for the on-cell damper structure.

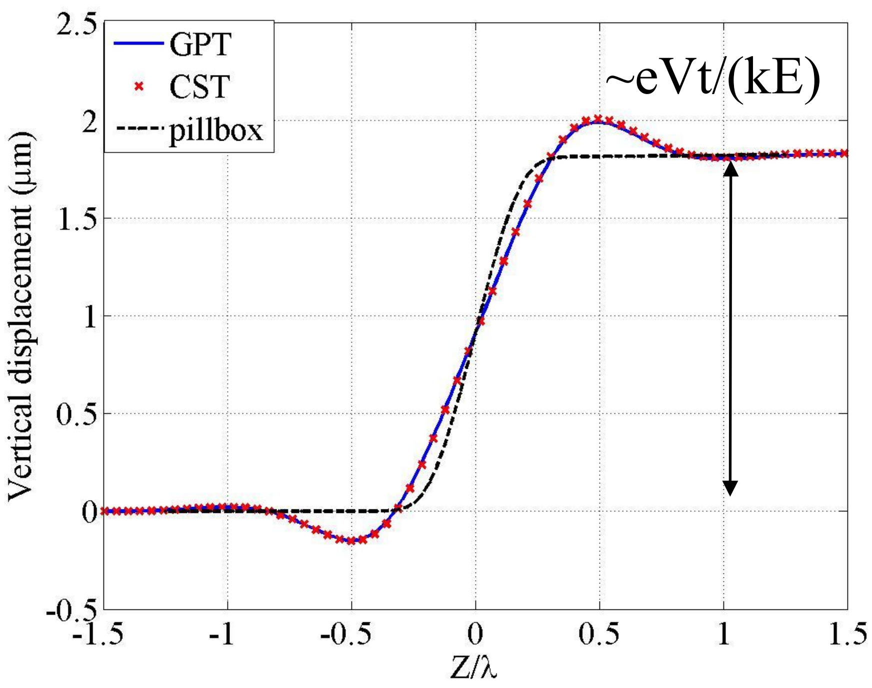
Electrical center simulation study by particle tracking codes

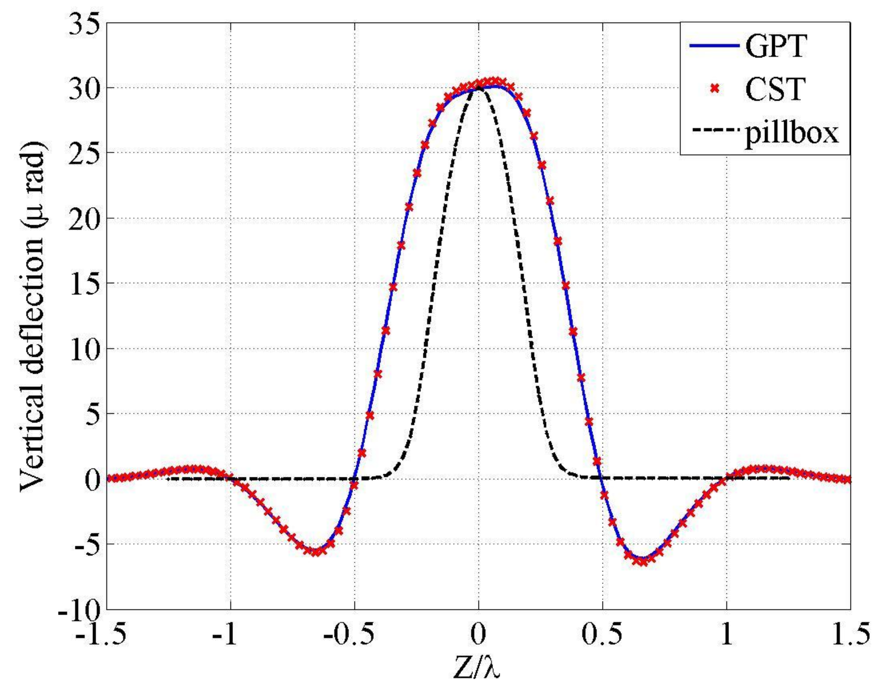


Vt=0.5MV
E=7GeV

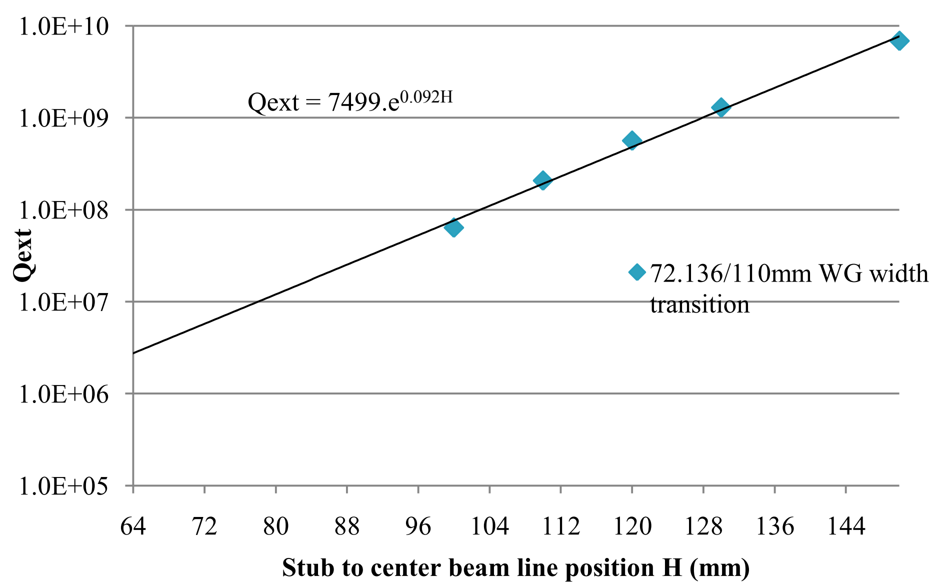
Courtesy to Dr. Shahid Ahmed in CASA, JLab

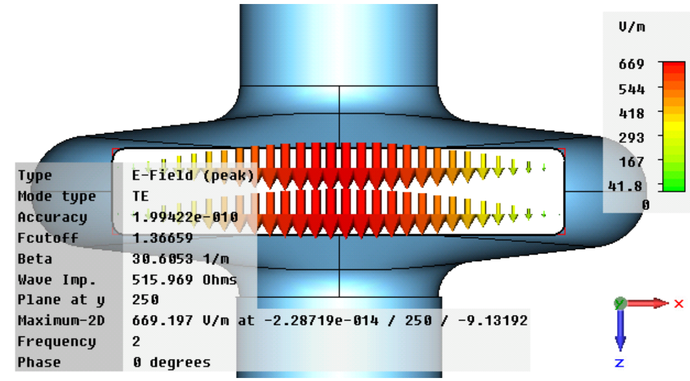
Effect of RF kick/tilt due to LOM /HOM Couplers is very small to the reference particle with "zero" crabbing phase.



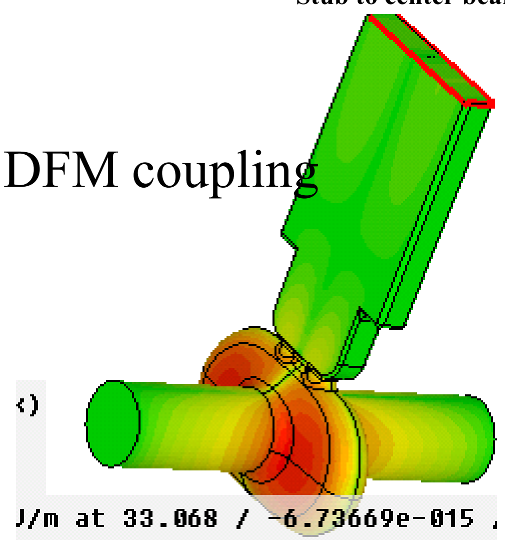


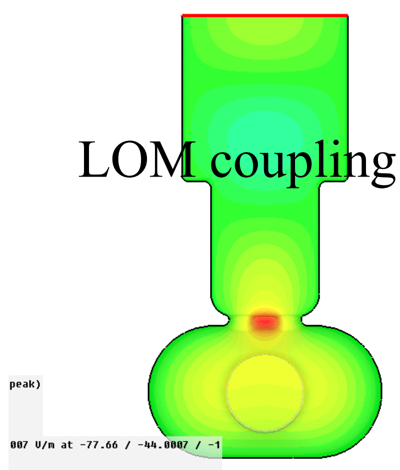
Combine LOM/DFM coupling into one high power coupler

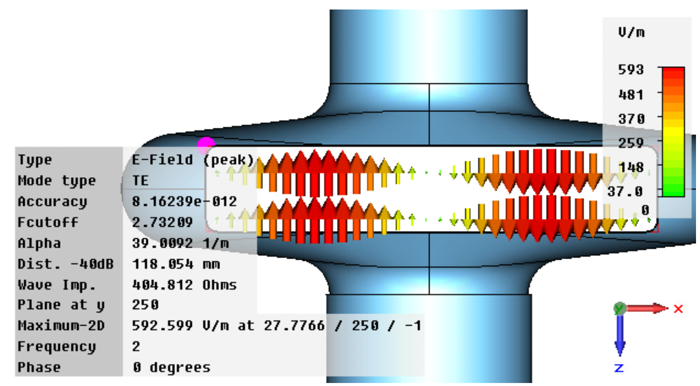




LOM WG on-cell damper (bottom) through TE10 mode. F_{cutoff}=2.087GHz, but =4.172GHz for TE20 mode

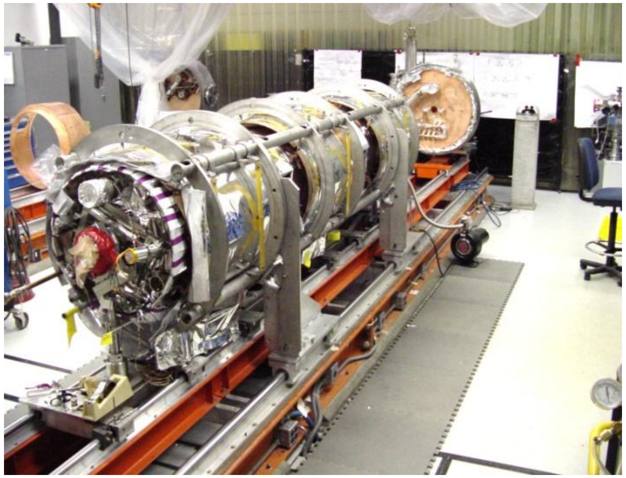


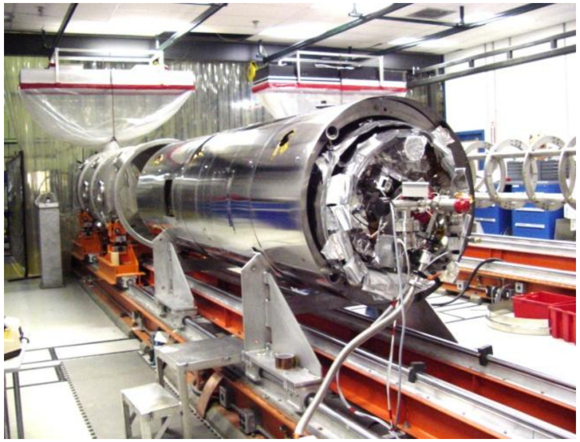




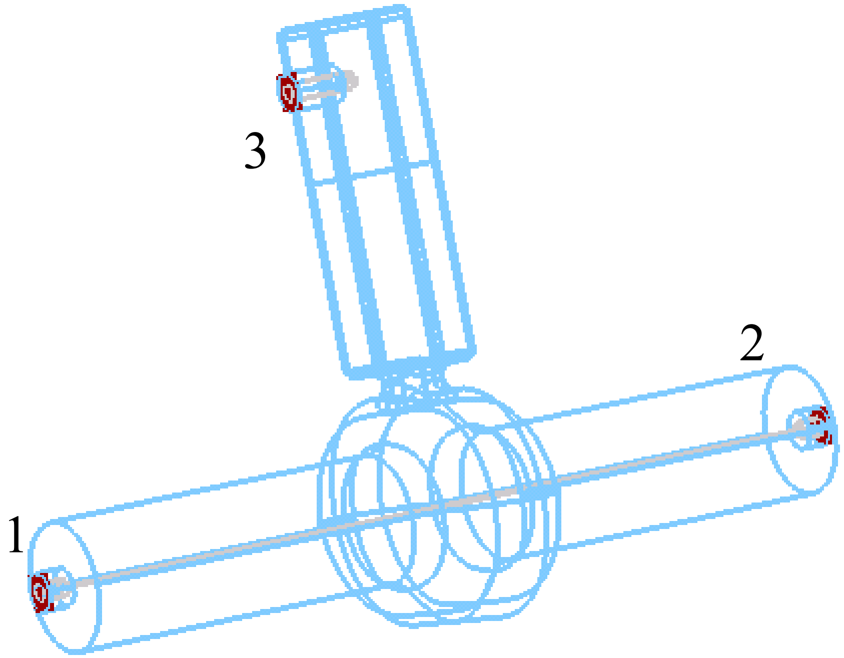
DFM WG on top after stub transition F_{cutoff}=2.732GHz, for TE20 mode.

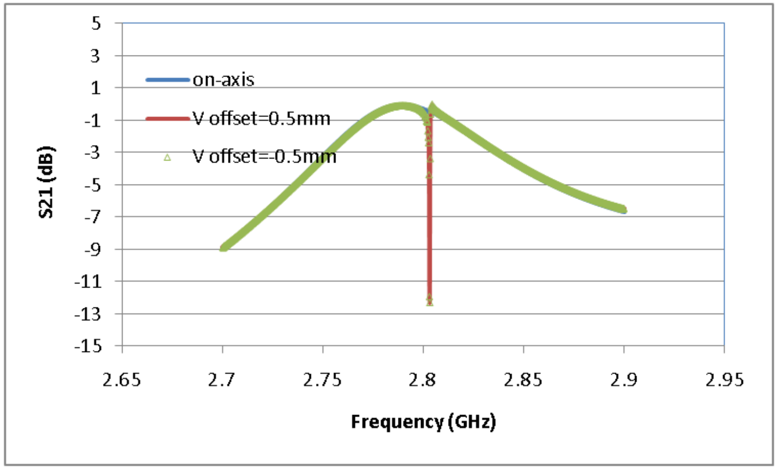
Cryomodule assembly sequence: when alignment is done?

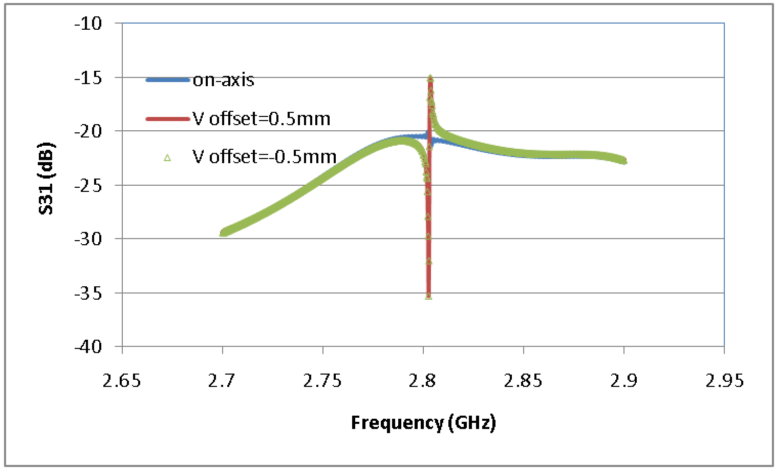


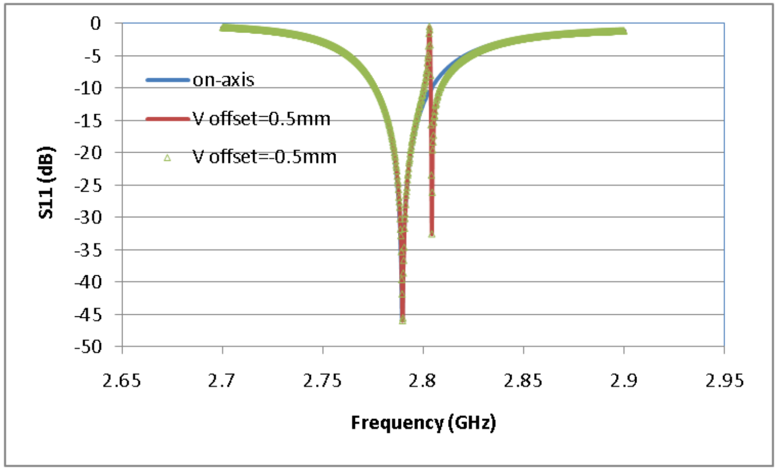


Proof of principle using wire stretching for pre-alignment in clean room



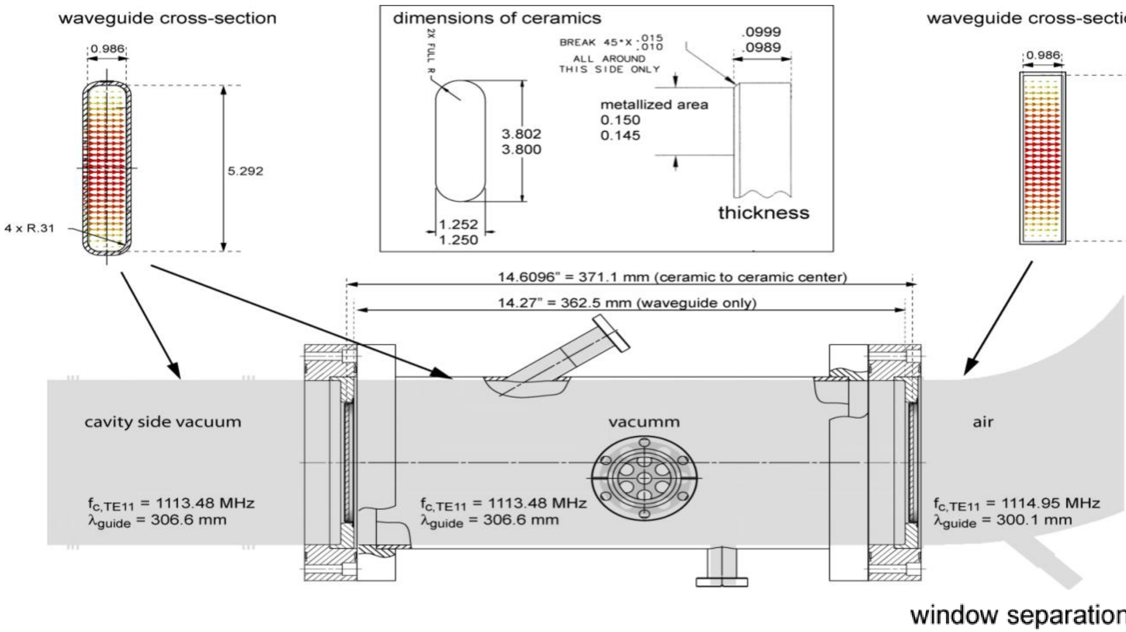




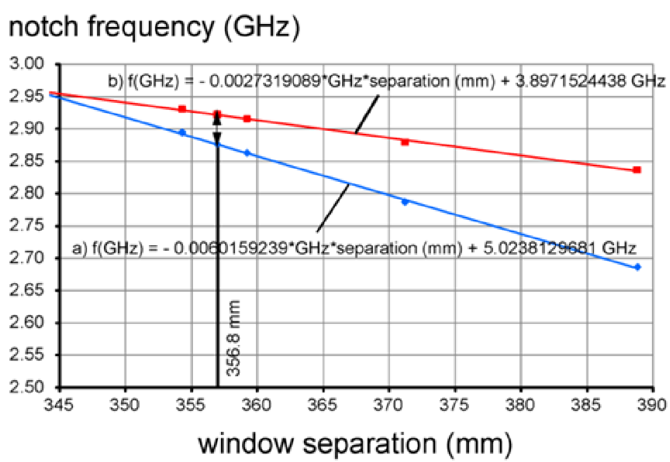


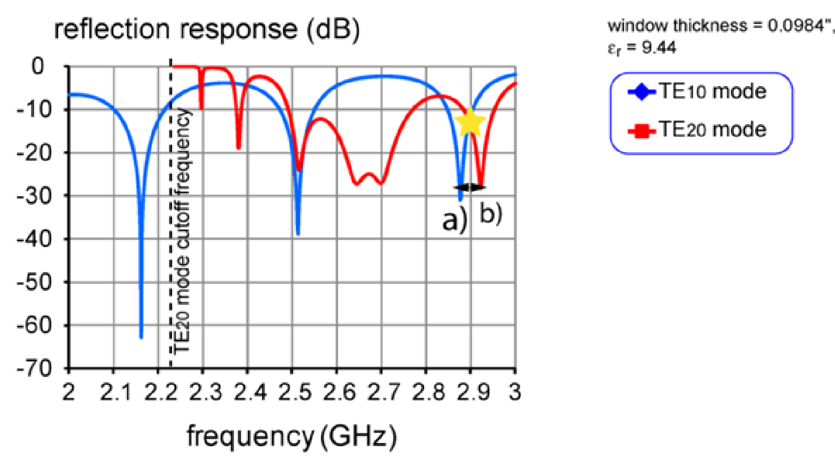
- RF signal sensitivity is 20dB/0.5mm, good enough for clean room warm alignment.
- A vertical mover to align individual cavity at cold stage is still needed.

Double window design for combined LOM/DFM coupler

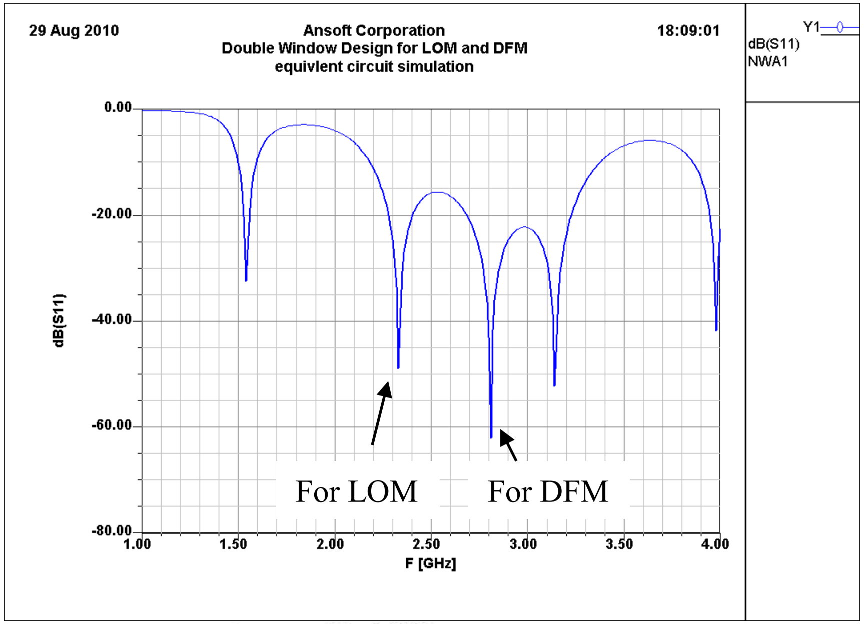


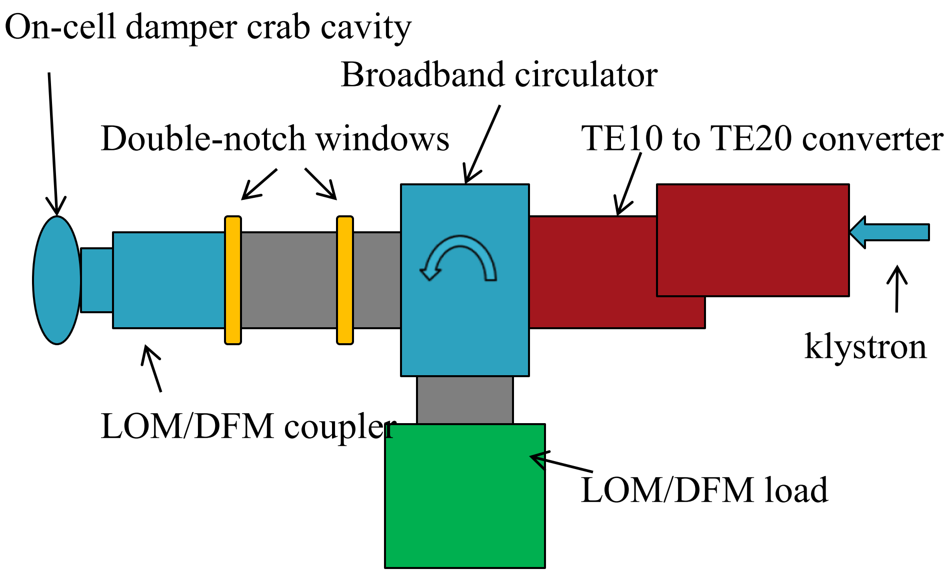
Example:
CEBAF 12GeV double window design by L Phillips , G, Wu and recently modified by F. Marhauser and H. Wang
For triple functions.
FPC/TM111-7/pi mode trans./2nd Harmo. block

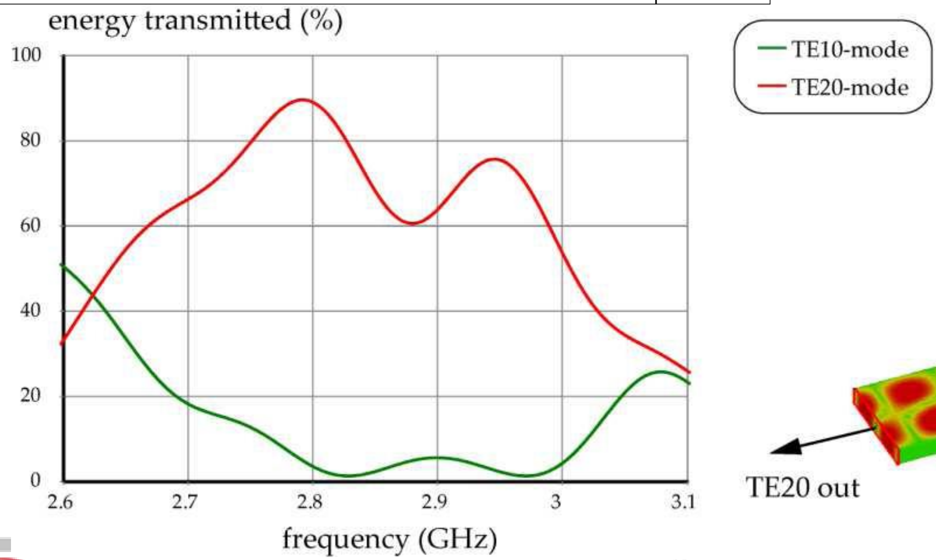


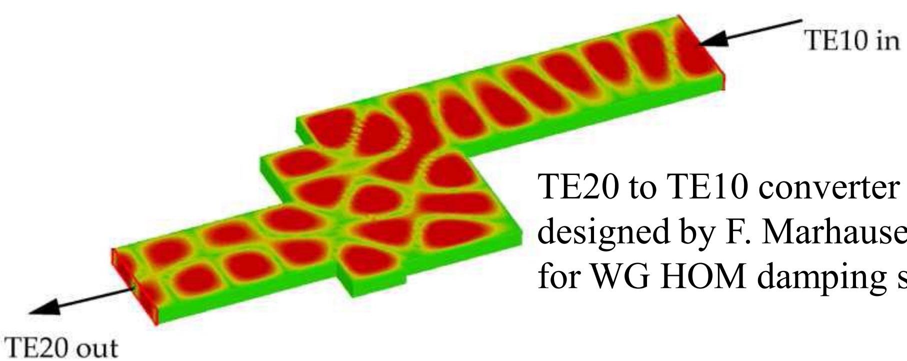


Double window design for combined LOM/DFM coupler



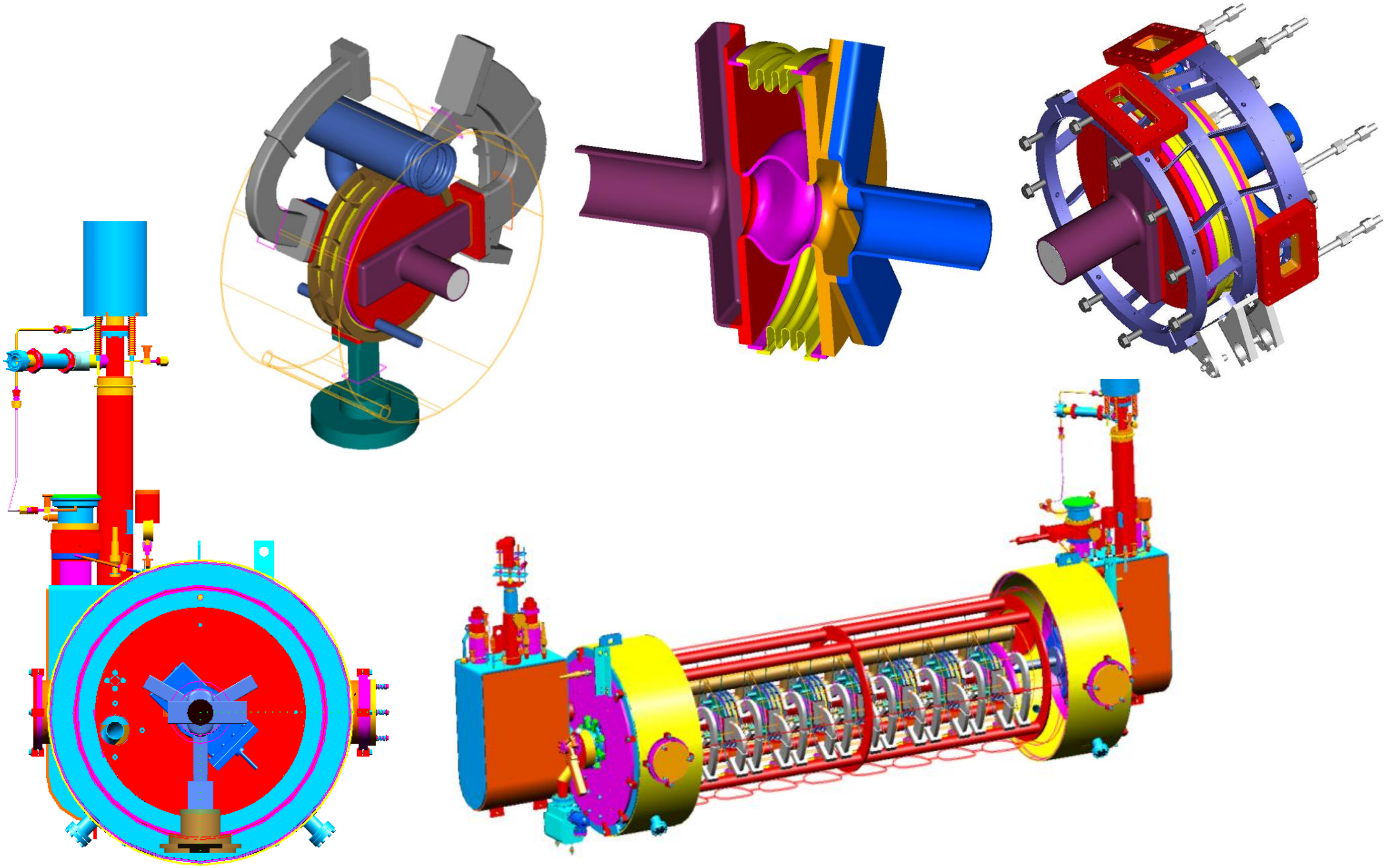






TE20 to TE10 converter
designed by F. Marhauser
for WG HOM damping study

Cryomodule carton design for Baseline cavities



Cavity, Crymodule Specification Update

Parameter	Value	Unit
Basline Cavity		
Frequency	2.815488	GHz
Cavity Type	elliptical	
Fundamental Mode	TM110-y-0	vertical kick
Rt/Q including TTF	35.8	Ω
Crabbing Voltage Vt at Bs=100mT	0.5	MV
Peak Surface Bs Field/Vt	195.6	mT/MV
Peak Surface Es Field/Vt	82	1/m
Geometry Factor	227.5	Ω
Material Thickness	3	mm Nb
Cavity Iris Radius	25	mm
Cavity Active Gap Distance	53.24	mm
Operational Q0	>1.0E+09	at 2K
Cell Number	1	
HOM + FPC Couplers	3	"Y" WGs
LOM Coupler	1	WG+stub
TM110-x Mode	3.56	GHz
Lorentz Force Detune (cal. max.)	10.5	$kHz/(MV)^2$
Tuner Coarse Range, +/-	200	kHz
Tuner Fine Range, +/-	25	kHz
Tuner Fine Resolution	4	Hz, w/o pieco

Cryomodule	Value	Unit
Operational Crabbing/decrabing Voltage	4	MV
Module Number	2	
Cavity Number per module	8	
Qext, TM110-y-0	1.2E+06	
Klystron Power per Cavity	10	kW
Microphonic Amp. Limit +/- 6σ	100	Hz
Cavity Stiffener	may not need if using fast LLRF	
50K Static Heat Load (FPCs+Shield)	27+180	W
50K Dynamic Heat Load (FPCs+Shield)	76+108	W
2K Static Heat Load per Cavity	2.4	W
2K Dynamic Heat Load per Cavity	7	W
Magnetic Field due to Rebar	<0.1	mT
Axial Magnetric Shielding Factor	>100	
HOM Longitudinal Impedance Upper Limit R (monopole HOMs, Rs=V^2/(2P))	<0.5	MΩ-GHz
HOM Horizontal Impedance Upper Limit Rt (dipole x-HOMs)	<1.4	M Ω/m
HOM Vertical Impedance Upper Limit Rv (dipole y-HOMs)	<4.5	MΩ/m

Summary

• Collaboration between ANL, JLab and LBL on SRF crab cavity design, prototype and R&D tests, cryomdule concept design have been worked well since 2007 and in good progress..

• So far no show stopper on our "Baseline" and "Alternate "designs of SRF crab cavities and cryomodule concept.

• The "Alternate" cavity with on-cell damper feature gives us more safety margin on the LOM/HOM impedance budget.

• Alignment challenge is manageable but need more R&D.

• The combination of LOM and DFM couplers reduces the high power coupler into one and their associated cost. The double notch window and TE mode converter are technical feasible.

• We need to confirm our experimental results and demonstrate the "Baseline" cavity's performance by the end of this year.

• We need also proof the Alternate cavity toward integrated Engineering design in a short term and delivery one (or two) test cryomodule (s) in 2.5 years.