Elliptical (TM110) vs. Loaded Structures

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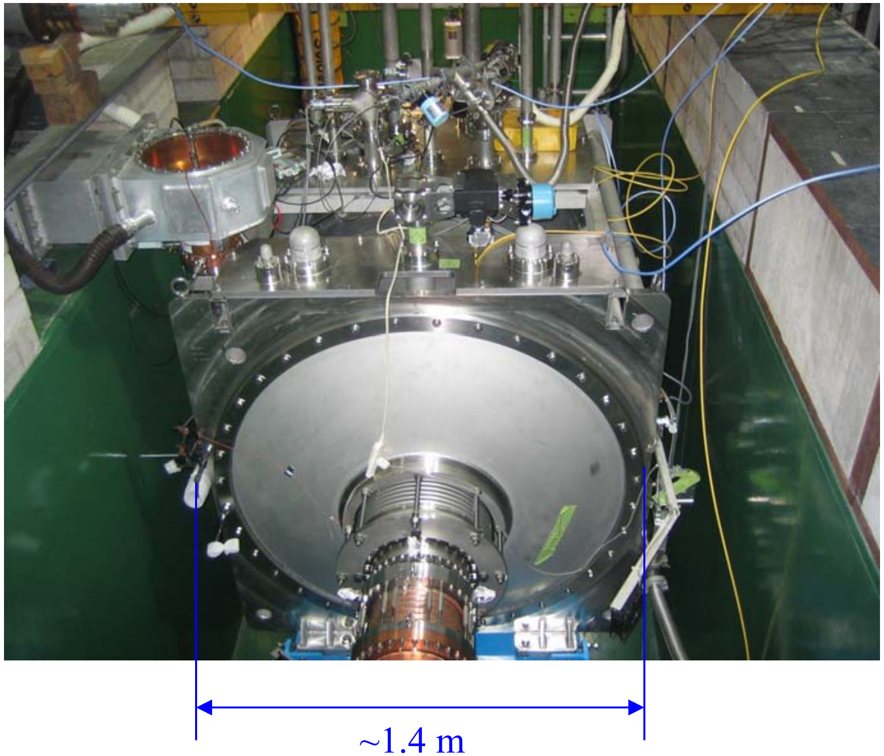
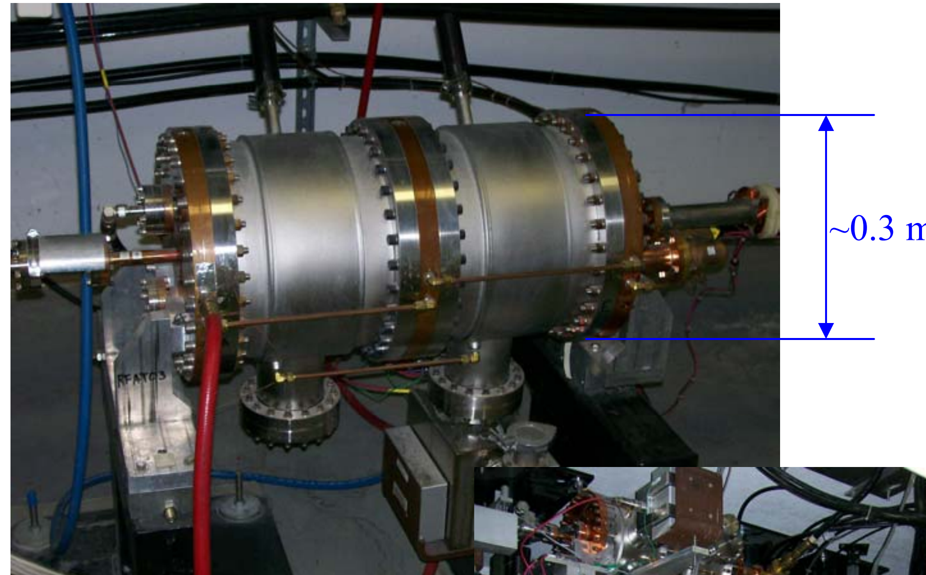
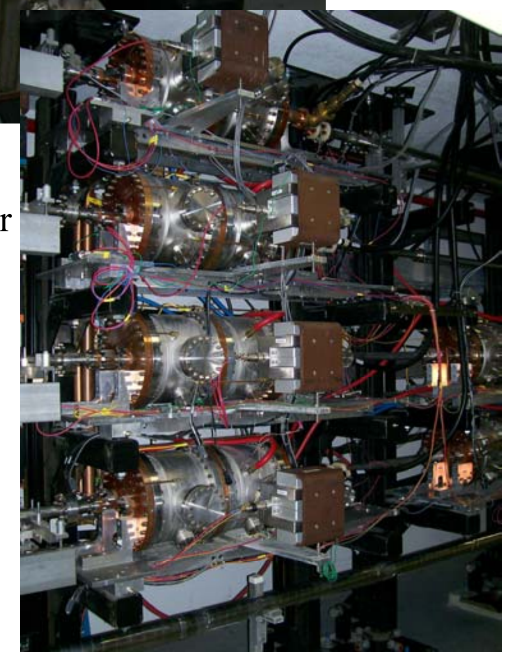
Transverse dimension is most constraint for LHC crab cavity



KEK elliptical crab type cavity, 508.9MHz, Superconducting Nb, in KEKB operation.





JLab two-rod type separator cavity, 499 MHz, Normal conducting Te-Cu alloy rods, end flanges Cu platted, SSTL cylinder, in CEBAF operation.

Two-rod type (loaded) structure takes much less room, but what about efficiency…?

Principle of TM110 dipole mode Deflection of a RF cavity

Panofsky-Wenzel Theorem:

$$P_{\perp} = \left(\frac{e}{v}\right)\int_0^d \left[\mathbf{E}_{\perp} + \left(\mathbf{v}\times\mathbf{B}\right)_{\perp}\right]dz = \left(\frac{e}{\omega_0}\right)\int_0^d (-i)\nabla_{\perp}E_z dz$$

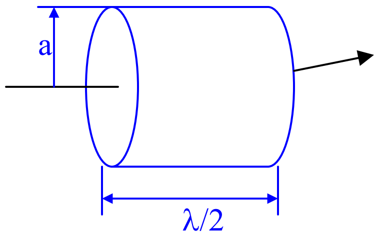
W. K. H. Panofsky and W. A. Wenzel, Review of Scientific Instruments, Nov. 1956, p967.
also M. J. Browman, LANL, PAC93, May 17-20, 1993, Washington D.C. USA.

- Panofsky's theorem implies for any given RF mode, no matter who (E or B) deflecting the beam, there is must an non-zero transverse gradient of longitudinal component of the electric field.
- TM110 is one of such modes. ¼ wavelength transmission line (two rod type, TEM) mode is another one.
- For a best efficiency of a deflecting RF cavity. Cavity shape optimization parameters should be used differently from a normal conducting cavity to a superconductiong cavity.

- Normal conducting cavity optimize:
  Transverse shunt impedance $R_t = V_{def}^2/P$ or R_t/Q for minimum copper wall loss. Because the integrated loss is high comparing to beam power.
- Superconducting cavity optimize:
  V_{def}/B_{max} or $(Rt/Q)(\omega U/\mu_0 H_{max})$ due to fundamental limit of critical magnetic field. Because the integrated loss is low comparing to beam power.
- Transverse verses longitudinal impedance based on Panofsy's:
  $R_t/Q \cong (R_{//}/Q)/(ka)^2$ $k=\omega/c$ a=off-axis distance where to assess the $R_{//}$.

Scaling laws of RF deflecting cavities

Cylindrical pillbox



TM110 mode

$$\frac{R_\perp}{Q} = \frac{1920}{\pi[u_{11}J_2(u_{11})]^2}\left[\frac{J_1(\alpha)}{\alpha} - J_2(\alpha)\right]^2 \qquad [\Omega]$$

Here $\alpha = u_{11}r/a$, $u_{11}=3.832$, is root of J_1, J_1/J_2 is first/second order of Bessel function.

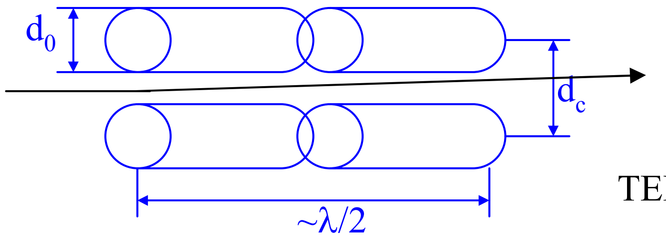
for $r \to 0$, $R_\perp/Q =$ 64.16 Ω
which is wavelength independent.

$$\frac{\omega U}{H_{\max}^2} = \left(7.5\pi u_{11}^2\right)\lambda^2 = 346\lambda^2 \qquad [\Omega m^2]$$

For a 800 MHz cavity,

$$\left(\frac{R_\perp}{Q}\right)\left(\frac{\omega U}{H_{\max}^2}\right) = 64.16 \times 48.59 = 3117.4 \qquad [\Omega m]^2$$

Two-rod transmission line



TEM dipole mode

Reference: C. Leemann and C. G. Yao, LINAC 1990, Albuquerque, NM, p233.

$$\frac{R_\perp}{Q} = \frac{960\lambda^2}{\pi^3}\frac{\ln\left(d_c/d_0\right)}{b^2\ln^2\left(\frac{b+a}{b-a}\right)} \qquad [\Omega]$$

$$b = 0.5\sqrt{d_c^2 - d_0^2} \qquad a = 0.5(d_c - d_0)$$

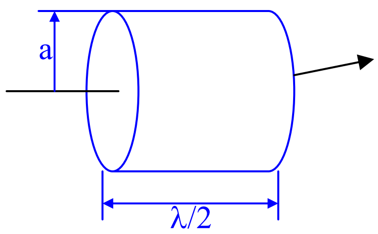
for a 800MHz cavity, d_0=2cm, d_c=5cm $R_\perp/Q$= 3091.2 Ω
which is wavelength dependent.

$$\frac{\omega U}{H_{\max}^2} = 30\pi^3 \frac{\ln\left(d_c/d_0\right)}{\left(\frac{1}{d_0} + \frac{1}{d_0+d_c}\right)^2} \qquad [\Omega m^2]$$

$$\left(\frac{R_\perp}{Q}\right)\left(\frac{\omega U}{H_{\max}^2}\right) = 3091.2 \times 4.85 = 637.5 \qquad [\Omega m]^2$$

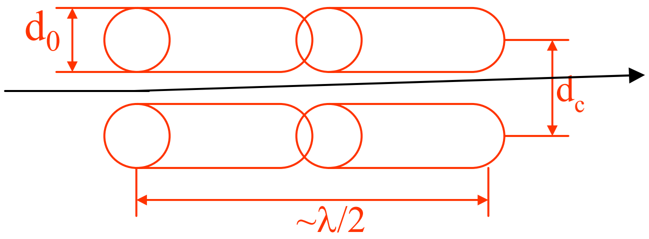
Scaling laws of RF deflecting cavities

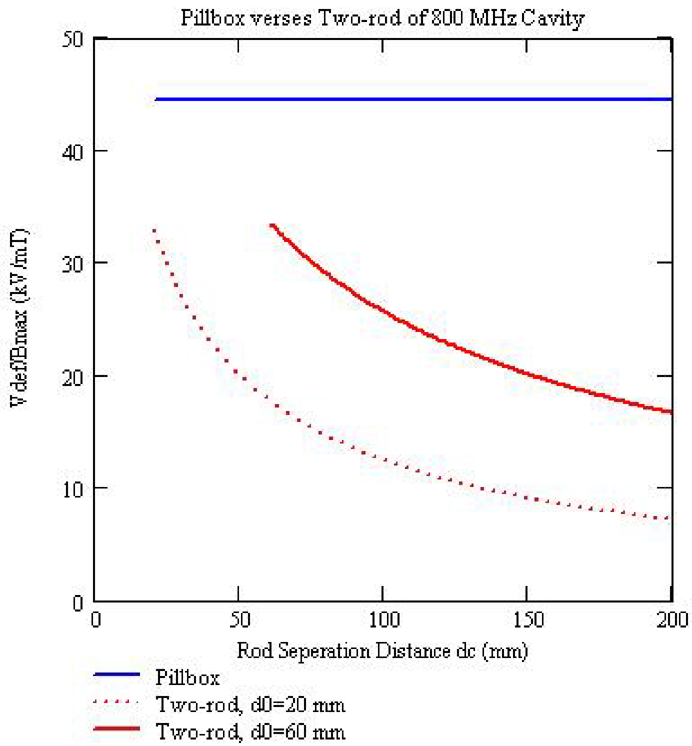
Cylindrical pillbox



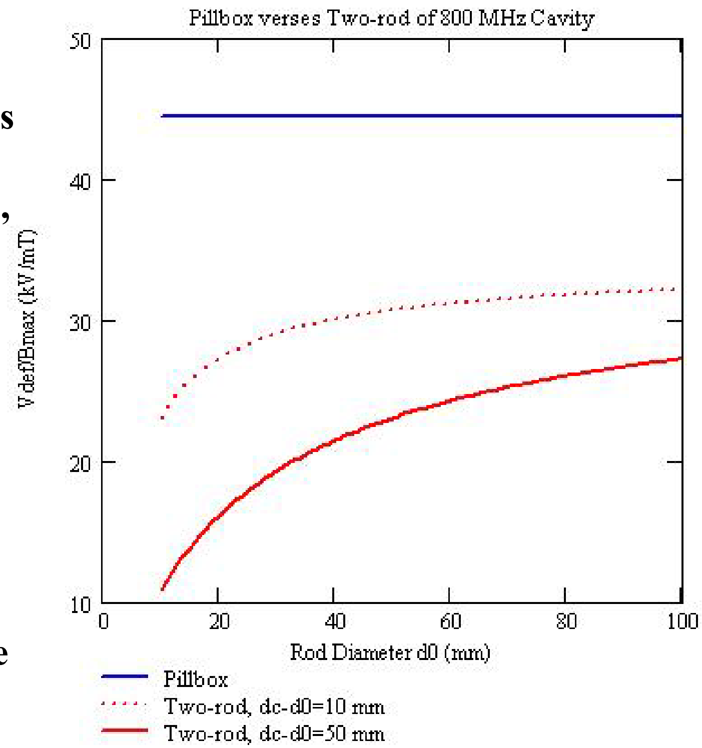
$$\frac{V_{def}}{B_{max}} = \frac{1}{\mu_0}\sqrt{\left(\frac{R_\perp}{Q}\right)\left(\frac{\omega U}{H_{max}^2}\right)}$$

Two-rod transmission line

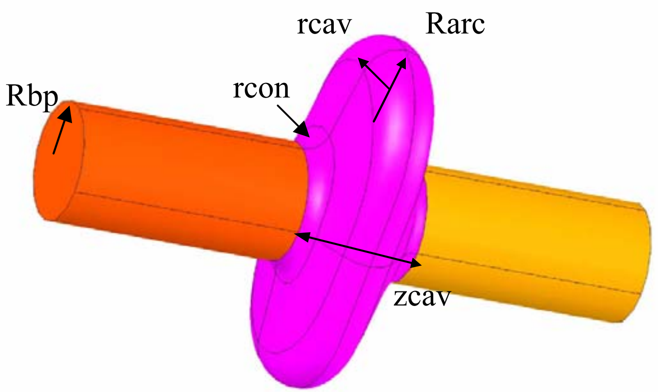




For a 800 MHz cavity with a 50mm beam aperture, two–rod type is only about 60% in efficiency of pillbox type, and even less than the elliptical cavity. But its transverse dimension is 55% or less than the pillbox type.
Squashing elliptical cavity in transverse dimension is in wrong direction for the transverse kick (will give vertical kick instead).



Elliptical squashed SRF cavity R&D for APS

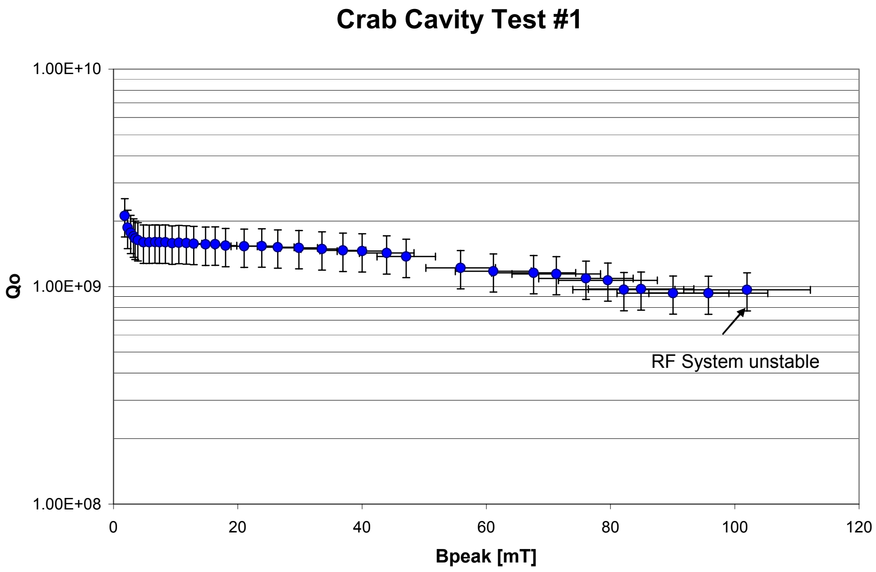


optimized squashed dimensions:

Rarc	44 mm
Rbp	25 mm
rcav	14 mm
rcon	9 mm
zcav	53.24 mm
yline	33.66 mm

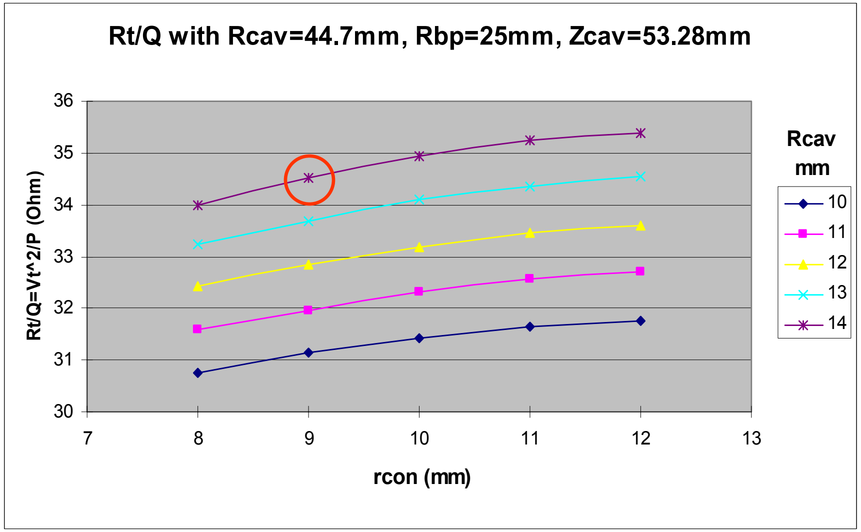
First time vertical test achieved design gradient!

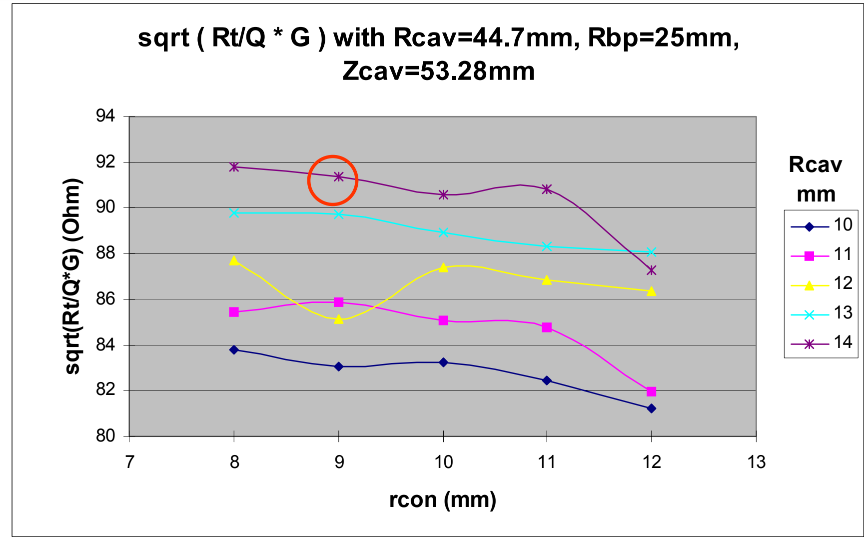
Single-cell 2.815GHz Nb crab cavity



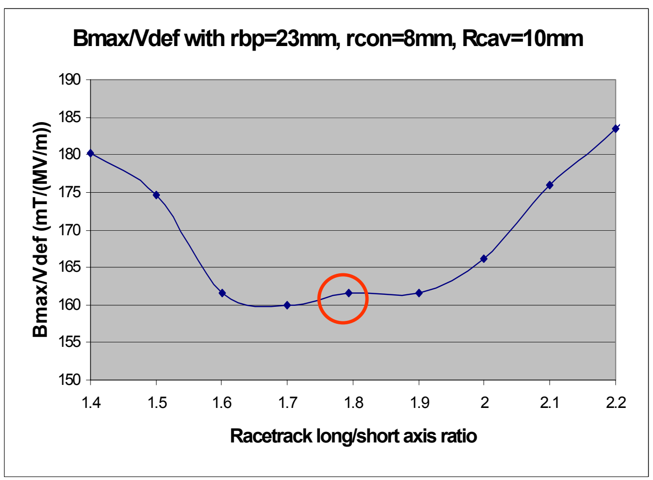
Single-cell structure with beam pipes		
TM110-y mode frequency	MHz	2815.76
Rt/Q include TTF (Rt=Vt^2/P)	Ohm	35.27
Geometry factor G	Ohm	232.29
sqrt((Rt/Q)*G)	Ohm	90.51
Bsmax/Vt	mT/MV	157.15
Esmax/Vt	1/m	75.60
Transverse Gradient Et=Vt/d		
Bsmax/Et	mT/(MV/m)	8.367
Esmax/Et		4.025
cavity effective gap d	mm	53.24
BCS surface resistance Rbcs of Nb at 2K	nOhm	51.29
Residual resistance R0	nOhm	20.00
Q0 at 2K		3.3E+09
BCS surface resistance Rbcs of Nb at 4.2K	nOhm	2498.33
Q0 at 4.2K		9.2E+07

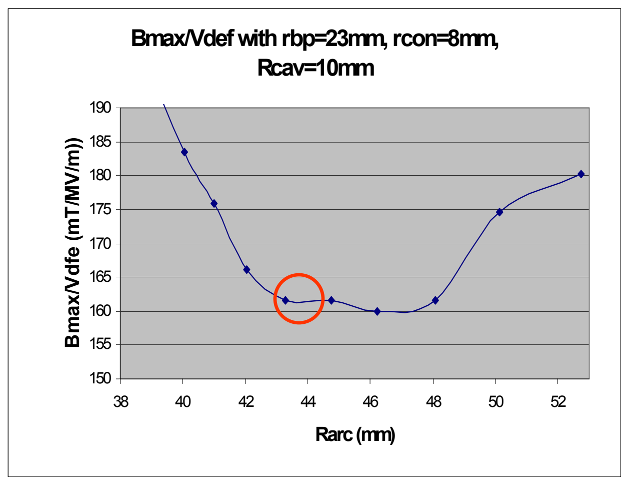
Squashed elliptical cavity shape optimization

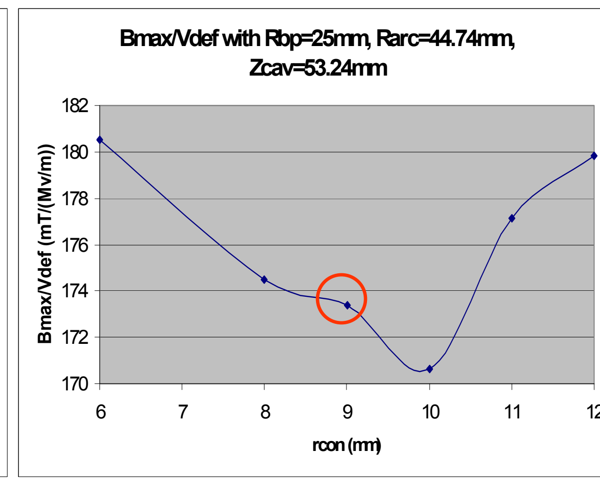




MWS ,ANSYS, HFSS and Gdfidl simulation by Jiarun and Geoff







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

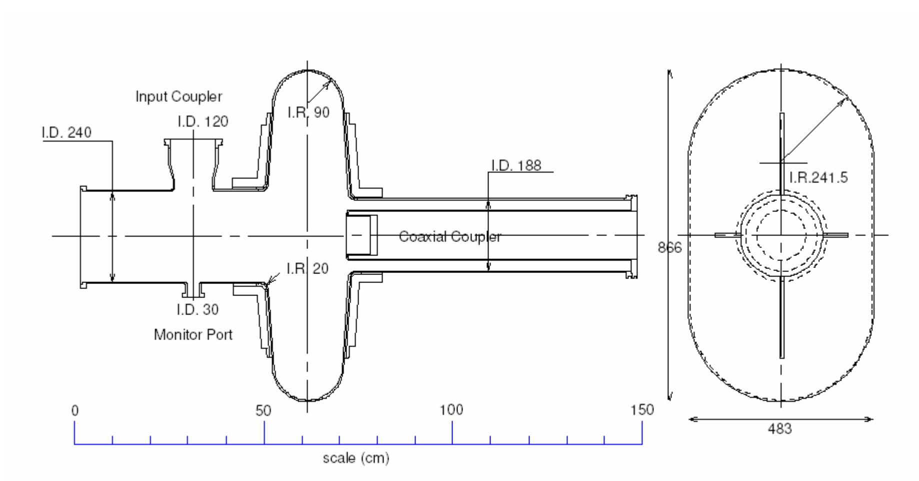
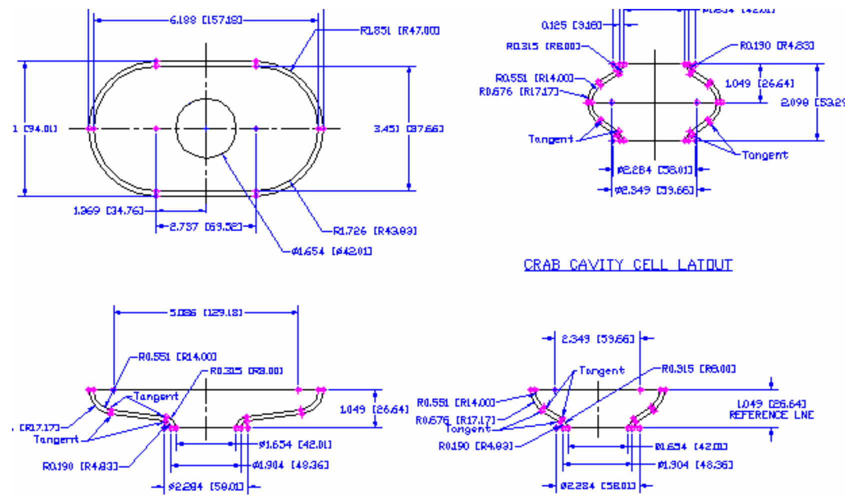
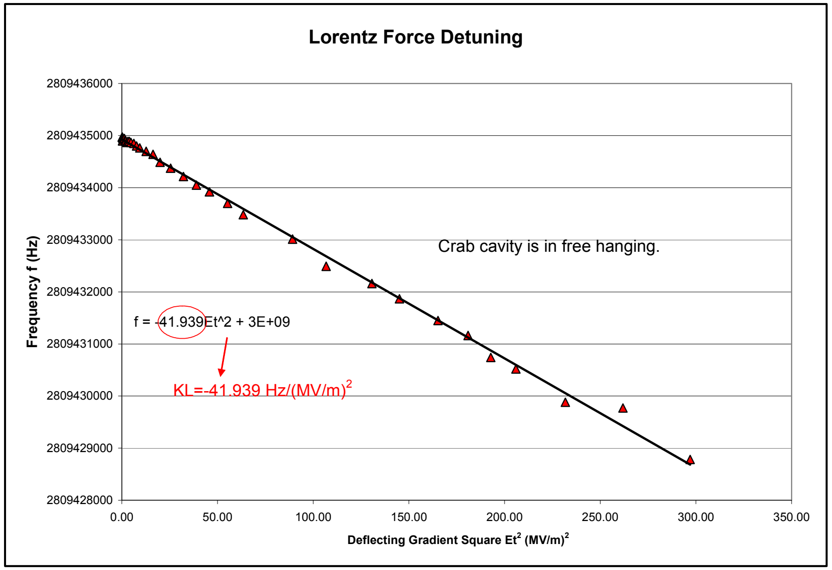
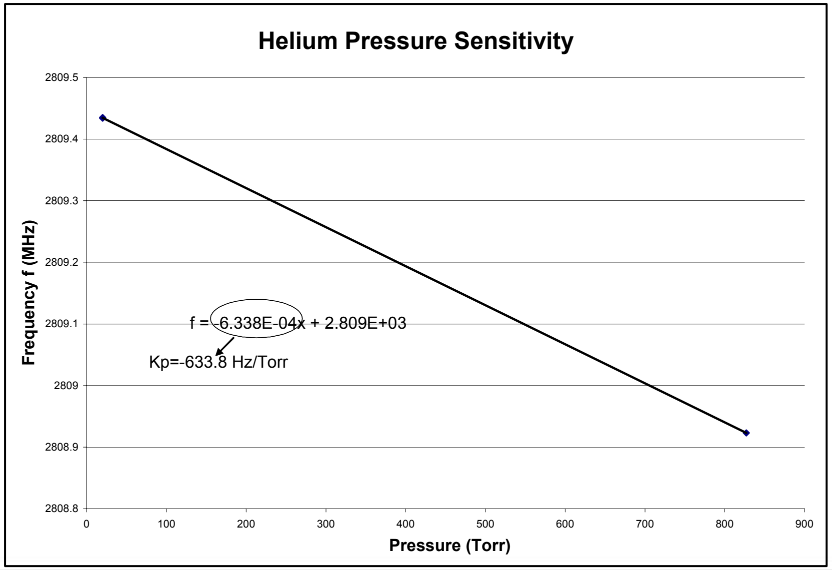


Figure 4: KEKB crab cavity with a model coaxial coupler.

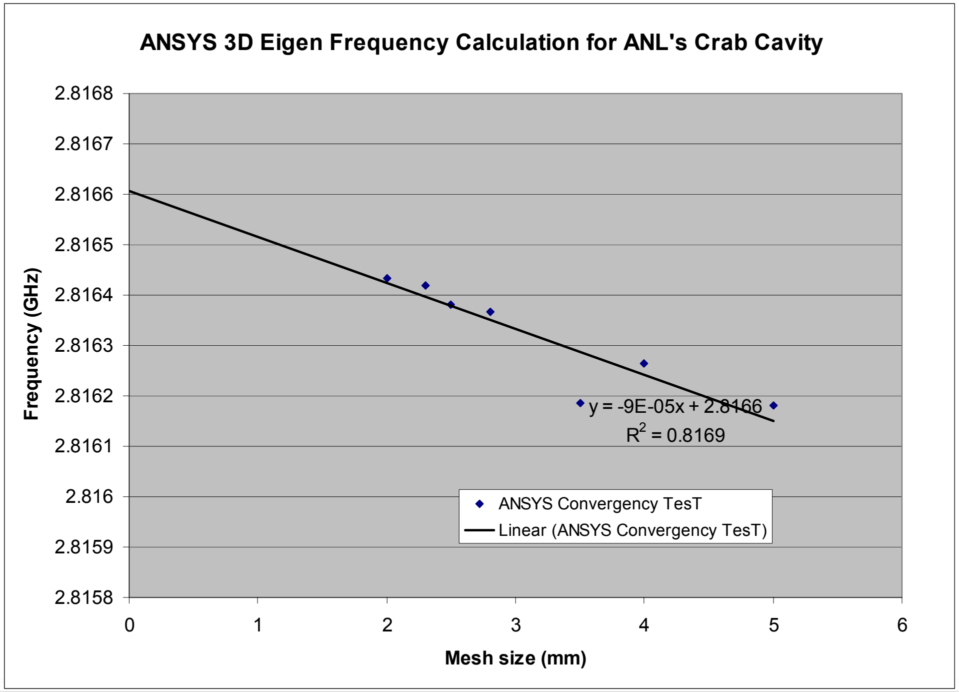


Lorentz force detuning on ANL's crab cavity



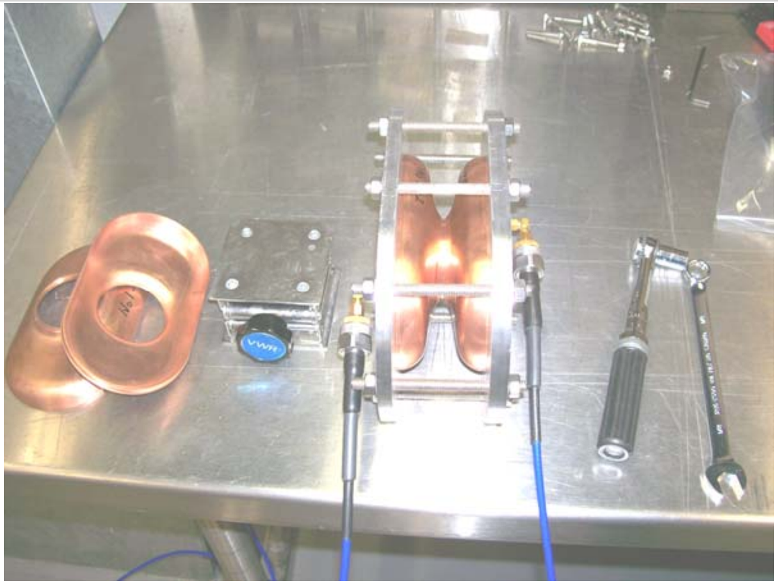


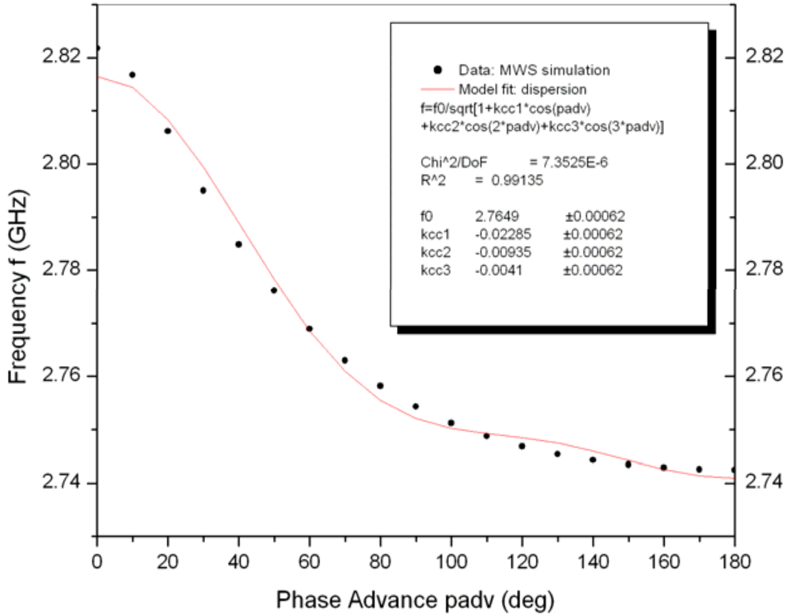
- Single cell cold test gave the LFD -42 Hz/(MV/m)^2 in free state.
- ANSYS gives the calculation result -8.1~9.6 Hz/(MV/m)^2.
- ANSYS Frequency convergence is in first order only.
- Force application to 3D shell structure in ANSYS needs to study to make sure to get the consistent result.
- RF-structural simulation combining Omega-3P with ANSYS might be needed.
- Large LDF number caused the RF PLL unstable during the VTA test in high gradient.
- If this LFD value is true or can not be reduced in the constrained structure with a fixture or tuner. The stiffening ring on this cavity is needed.
- Helium pressure sensitivity is also high comparing with regular elliptical cavities. This also suggested a stiffening ring on this shape cavity.

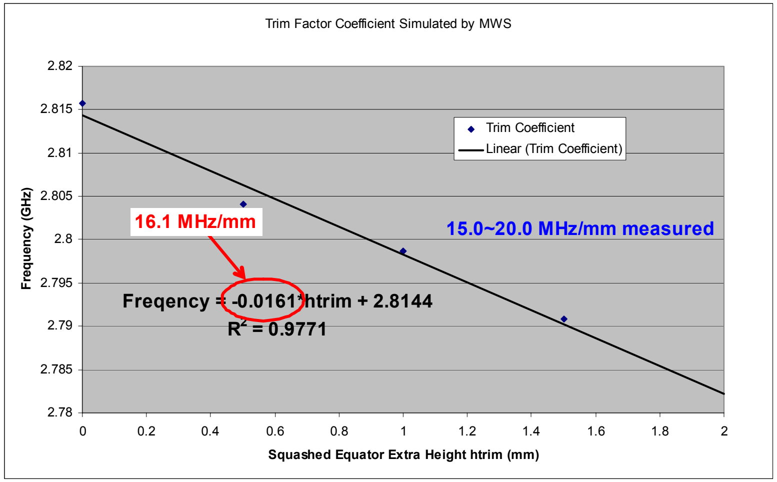


Dumb bell measurement on ANL's crab cavity

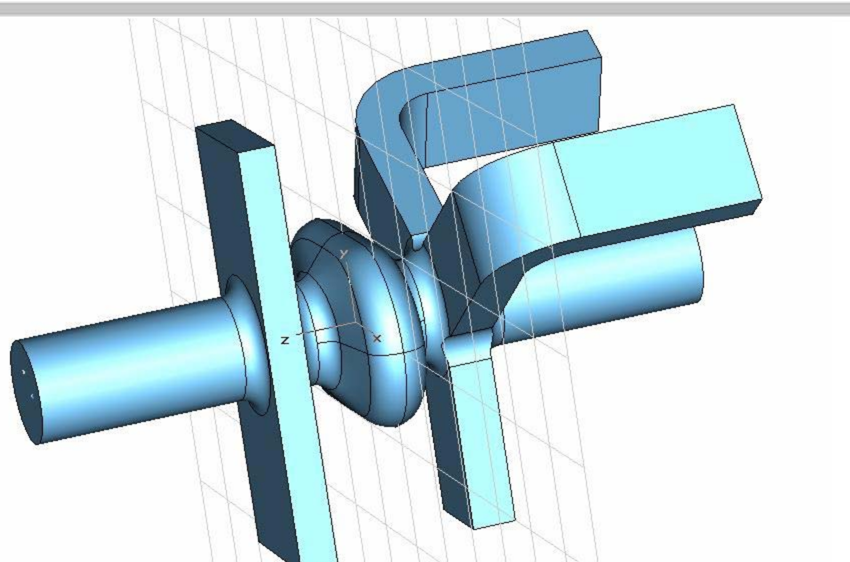
- For a multi-cell structure, the coupling through crab cavity irises is magnetic. The dispersion curve from MWS is abnormal from regular side coupling structure.
- It has an opposite tuning direction to the TM010 mode.
- The measured trimming coefficient on cavity's equator is 14.97 to 19.65 MHz/mm. MWS calculated value is 16.10 MHz/mm.
- If a multi-cell structure is desired (for ANL case, two-cell structure is maximum due to the HOM damping requirement), the frequency recipe and coupling coefficient related to the field flatness need to be studied further.

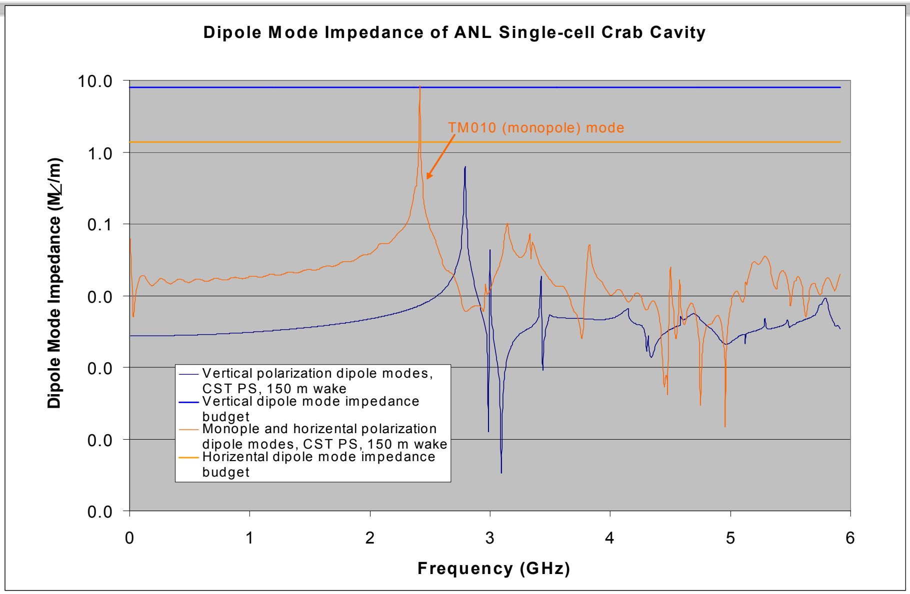




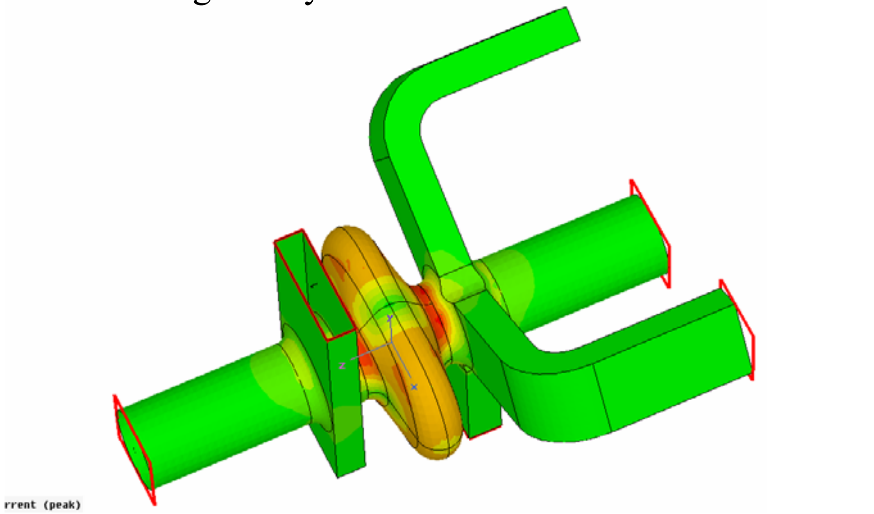


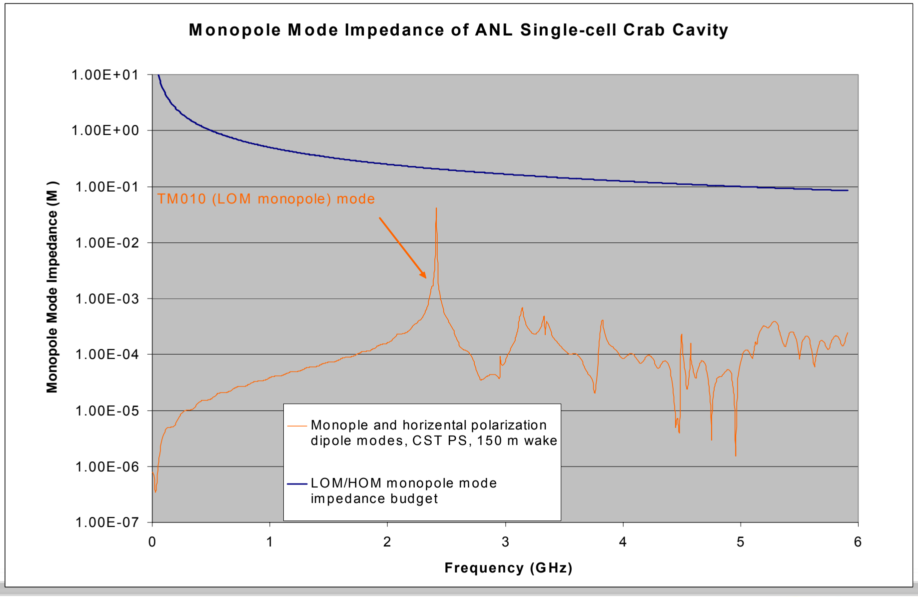
Waveguide HOM damped cavity structure for APS





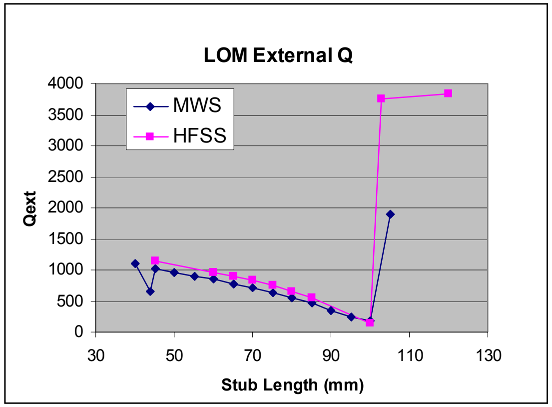
Simulations using CST's MWS and PS solvers. More detail result will be given by D. Li's talk tomorrow.



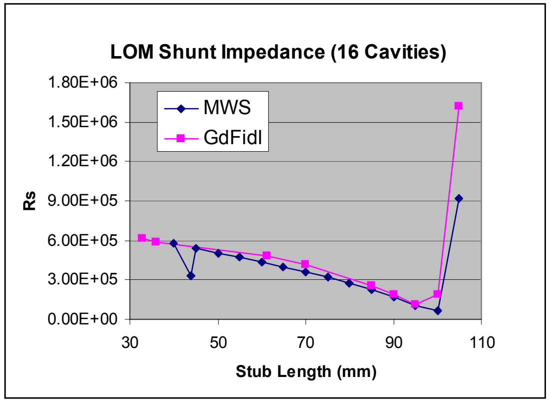


Waveguide HOM damped cavity structure for APS

- LOM waveguide stub length optimization for LOM damping is critical for the design. It was also studied by Geoff, ANL. The conclusion is the same that using ~0.4λg long stub will minimize the LOM Qext.
- Not more than two cells/per unit, 8 cells/per cryomodule could be designed.
- Deflecting mode power coupler could be either combined with LOM or one of HOM waveguides. Qext could be in 10^7 or higher.
- Field enhancement due to the end group waveguide connection needs to be further studied. A better simulation code (like Omega-3P) or Nb structure prototype is preferred.
- LOM/HOM loads could use room temperature ceramic material based on JLab's high current project experience.
- The prototyping the copper cavity with waveguide damping structure is under the way.
- The design can be scaled to LHC's crab cavity based on damping requirement.

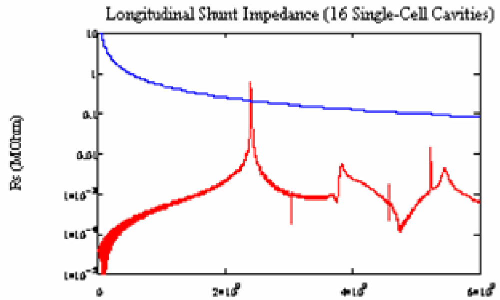


(a

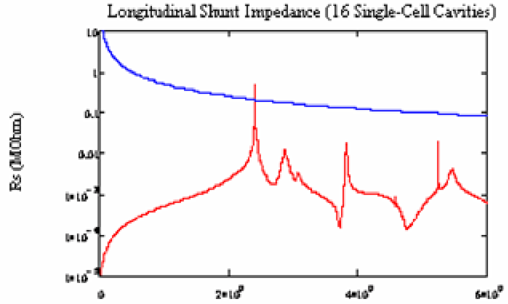


(b

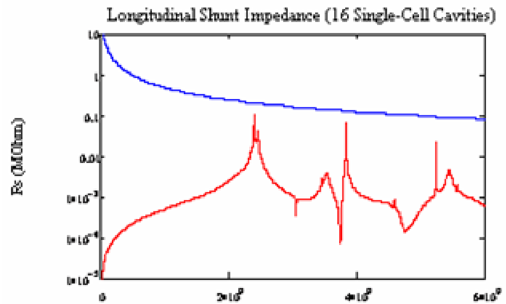
Figure 2: The effect of varying the waveguide stub length on (a) Qext, and (b) shunt impedance for the LOM.



(a) d = 32.8



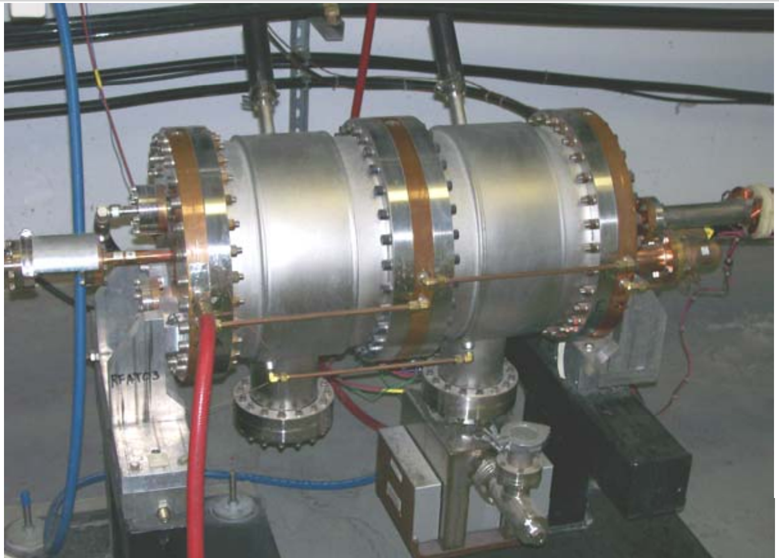
(b) d = 61.2 mm

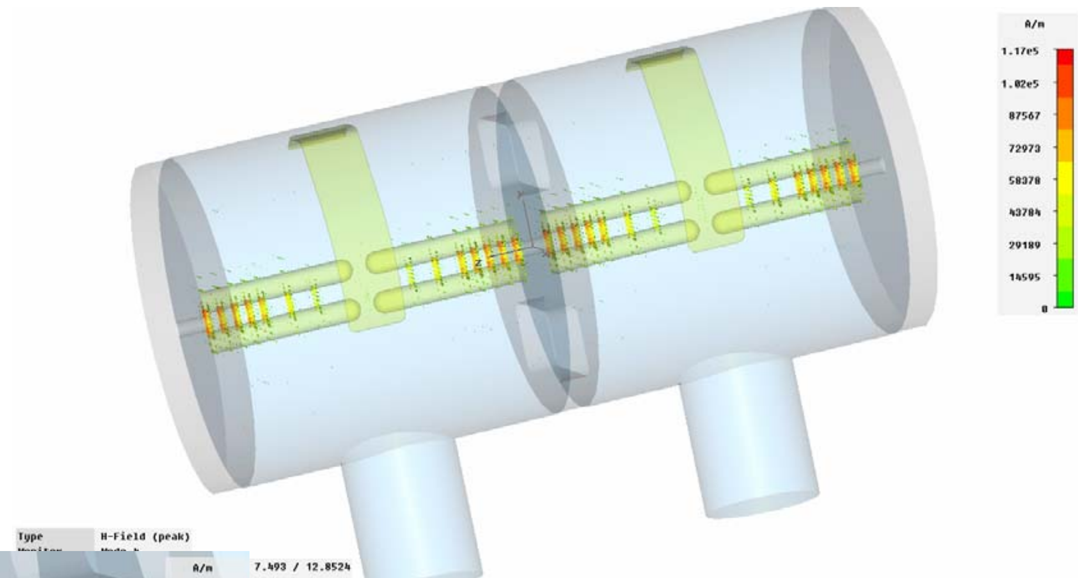


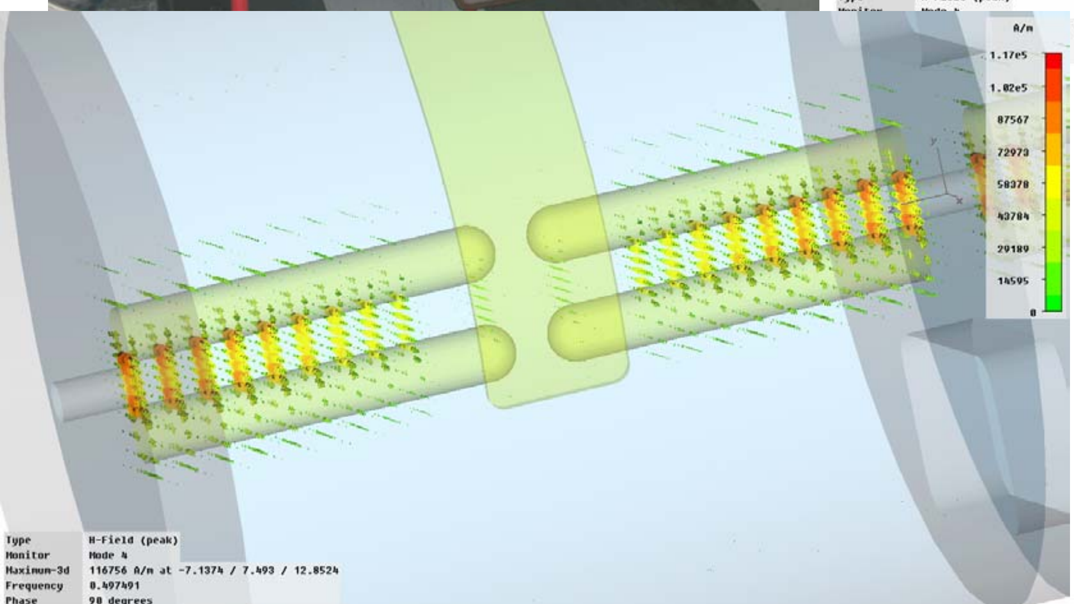
(c) d = 95

Figure 3: GdFidl broadband impedance results (for geometry in figure1) from wakefield simulations for various stub lengths, 'd', and a

CEBAF Normal Conducting Separator Cavity



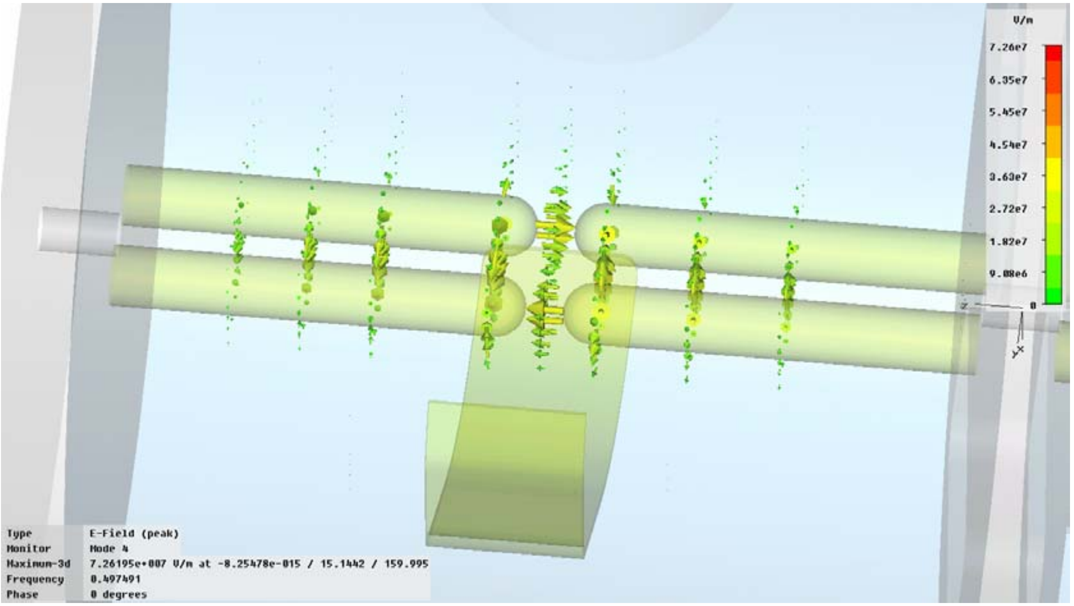


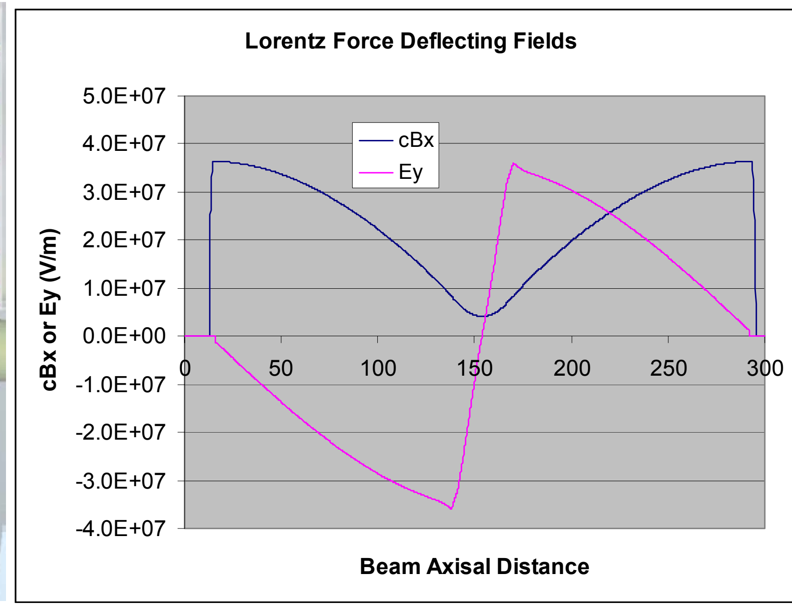


Quick fact and number:

- Q_{cu} is only ~5000 (structure wise), the stainless steel cylinder only takes less than 5% of total loss.
- Each cavity is two-cell, ~λ long, can produce 400kV deflecting voltage with 1.5kW input RF power.
- The maximum surface magnetic field at the rod ends is ~14.3mT.
- You need water cooling on the rods.
- If you can make this cavity in superconducting Nb, the Vdef is equivalent to KEK's crab cavity.

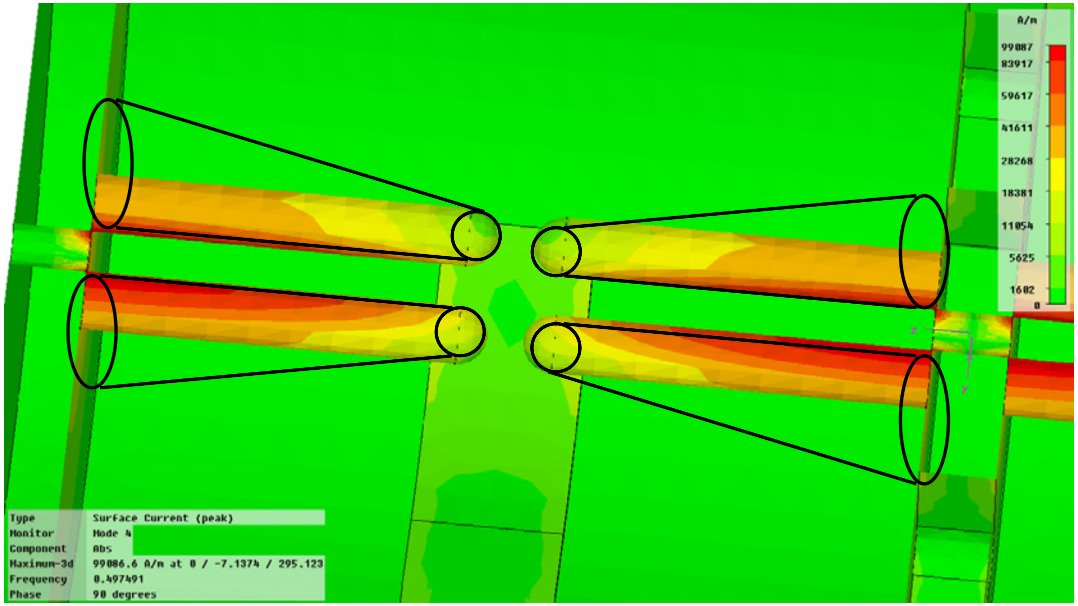
More fact about two-rod separator cavity





- There are both magnetic and electric fields doing the deflecting kick.
- Electric kick is about same in strength with magnetic kick.
- The longitudinal electric field in transverse gradient between the four rods satisfies the Panofsky's theorem.
- The cavity tuner is in low field region. No field enhancement there.
- As the rod separation goes up, the B_x and E_y field drop quickly.
- If the cavity is two cells coupled together, there is a "0" mode in lower frequency.
- We have to use "π" mode for separating three beams in CEBAF.
- Could we make it into Superconducting cavity?
- No Low Order Mode damping is needed since the deflecting mode is the fundamental mode.

How can we make the two-rod cavity better for superconducting?



• Could we reduce the surface magnetic field at the rod ends? Probably not much, you need high magnetic/ electric field near the beam path.

• The cone shape electrodes can certainly reduce rod vibration.

• Microphonics was an issue when we developed superconducting RFQ at SUNY, Stony Brook in 1992.

• Since there is a low loss on the cylinder can, could we make cavity cylinder in low RRR Nb, but rods in high RRR Nb?

Summary

- Transverse dimension is a major constraint (20cm beam-beam separation) for a low frequency LHC's crab cavity design.
- We need V_{def}/B_{max} parameter to optimize the cavity shape not by R_t/Q.
- Two-rod type cavity could be equivalent to pillbox type. Saved transversal space has to be compensated back in longitudinal in order to have a same deflecting efficiency.
- JLab-ANL-LBNAL-Tsinghua's optimized elliptical squashed cavity shape turned out being closed to the KEK's crab cavity shape.
- The prototype and test results of ANL's 2.8GHz's cavity proof that JLab can quickly design and build a superconducting crab cavity including HOM damping and cryostat structures.
- JLab's two-rod type normal conducting cavity can be redeveloped into a superconducing crab cavity with numbers of advantages.
- We need impedance budget to design the HOM damping structure for any crab cavity scheme.
- We should also explore other exotic schemes, like two beam shared in a same cavity: TM010 mode off-axis or TM012 mode sideway.