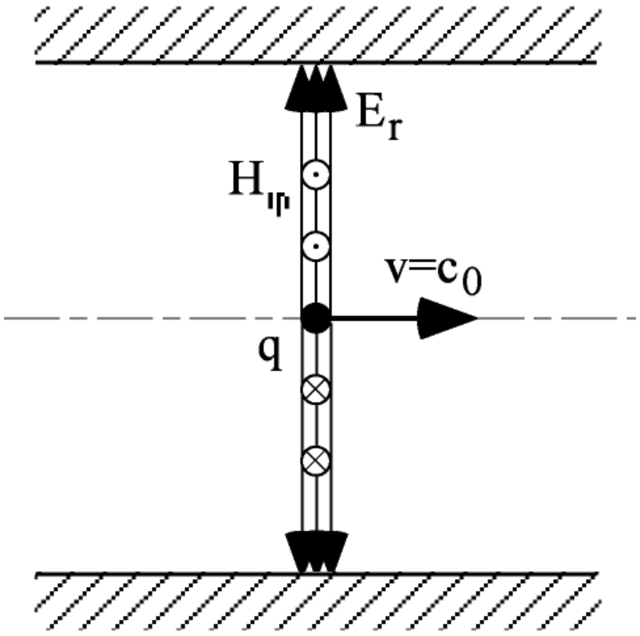
Investigations on Critical Higher Order Modes in CEBAF Upgrade Cavities

F. Marhauser
Thanks also to H. Wang and K. Tian

27. August 2009

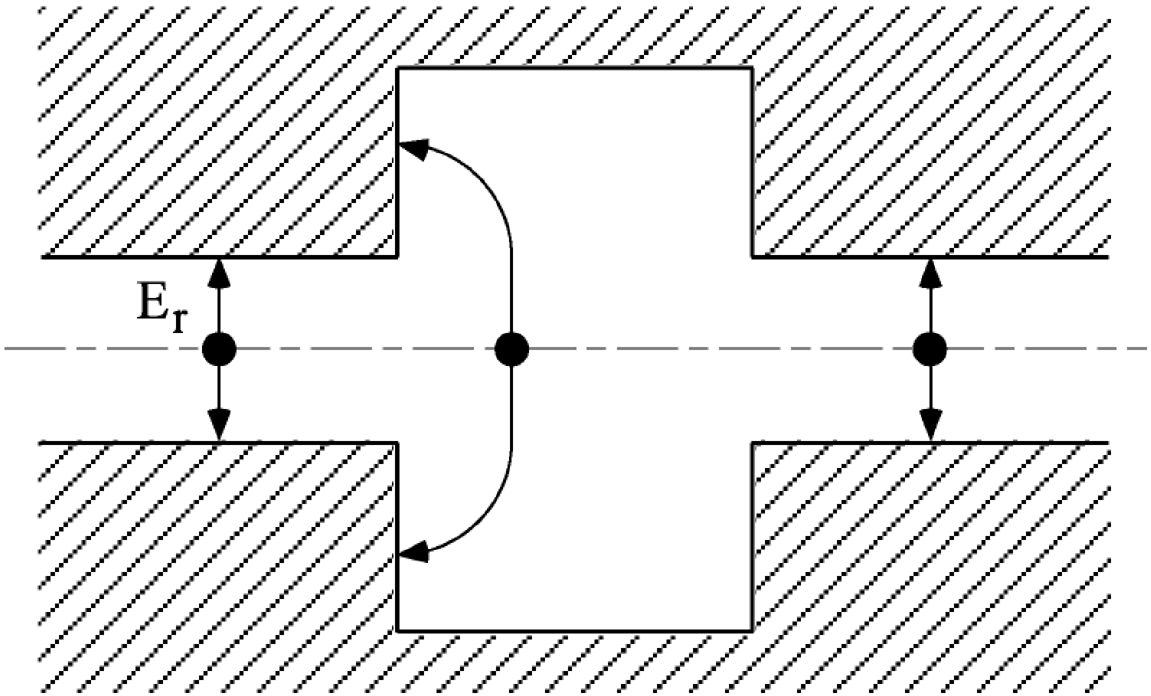
How HOMs are excited and why they are important - Wakefields-

- some basic slides first introducing the subject
- Lorentz-contracted fields of electrons in a smooth pipe for beta=1
- electrons do not "see" each other even at same longitudinal position
- rf losses depend on ohmic wall losses



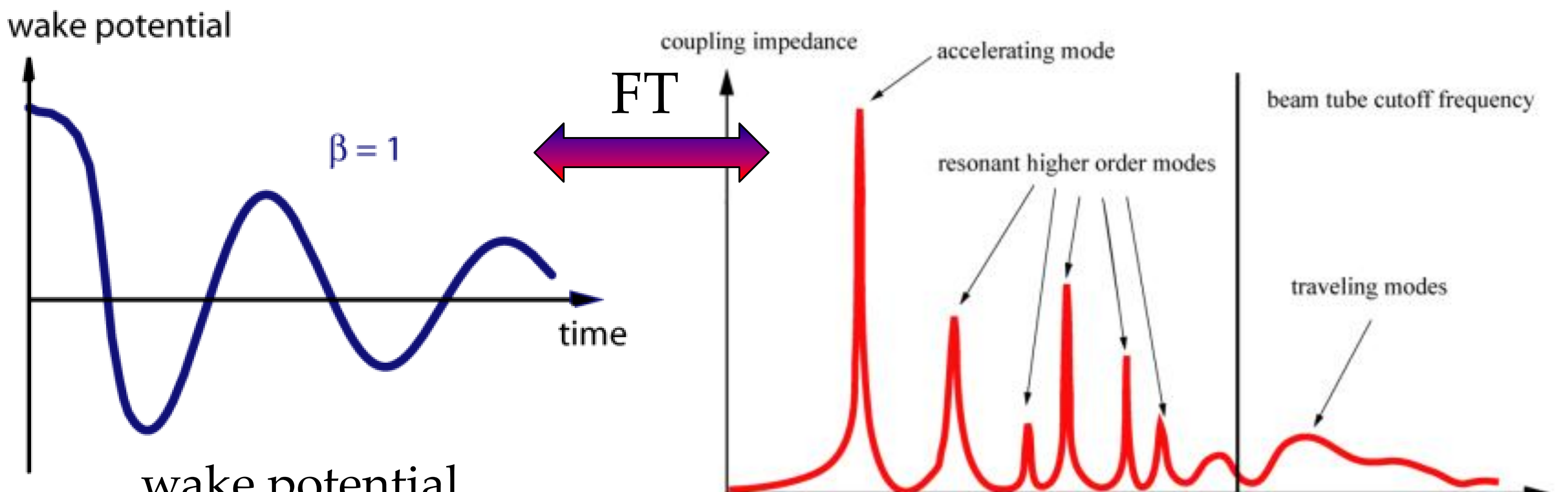
How HOMs are excited and why they are important
- Cavities -

- change in cross-section leaves field behind source (causality)
- when passing the cavity, the electrons leave energy/fields "wakefields"
- wakefields are "stripped off" even without ohmic losses in walls
- resembles Ohm's law: Beam current excites voltage at cavity impedance



How HOMs are excited and why they are important
- Impedances -

- wakefield (in time domain) is superposition of all beam generated Eigenmodes in resonant system (in frequency domain)
- formulation of the wakefield (or wake potential) and impedance interchangeable by applying a Fourier Transform (FT)
- spectrum exhibits Higher Order Modes (HOMs) of high impedance and usually lower impedances above beam tube cutoff



wake potential
(time domain)

cavity broadband coupling impedance
(frequency domain)

How HOMs are excited and why they are important - Operational Instabilities -

- In cavities the ohmic wall losses are small, especially in SRF cavities
- problem in recirculating accelerators: Subsequent beams can still experience the wakefields after several turns
- The decay time of HOMs large described by the (loaded) quality factor

$$Q = \frac{2\pi f_0 W_{stored}}{\overline{P}_{loss}} = \frac{2\pi f_0 W_{stored}}{dW/dt}$$

- stored energy decays exponentially $W(t) = W(t=0) \cdot e^{-\frac{2\pi f_0}{Q} \cdot t}$

  Example: f_0=2 GHz, Q = 1e5

  → **damping length: W(t=0)/exp(1)=2.4 km**

- resonant built-up of instabilities is possible for specific HOMs depending on the optics and circulation time

→ **CEBAF vertical beam break-up (BBU) instability event November 2007 caused by a single dipole mode in a single cavity (Q~1e8 !)**

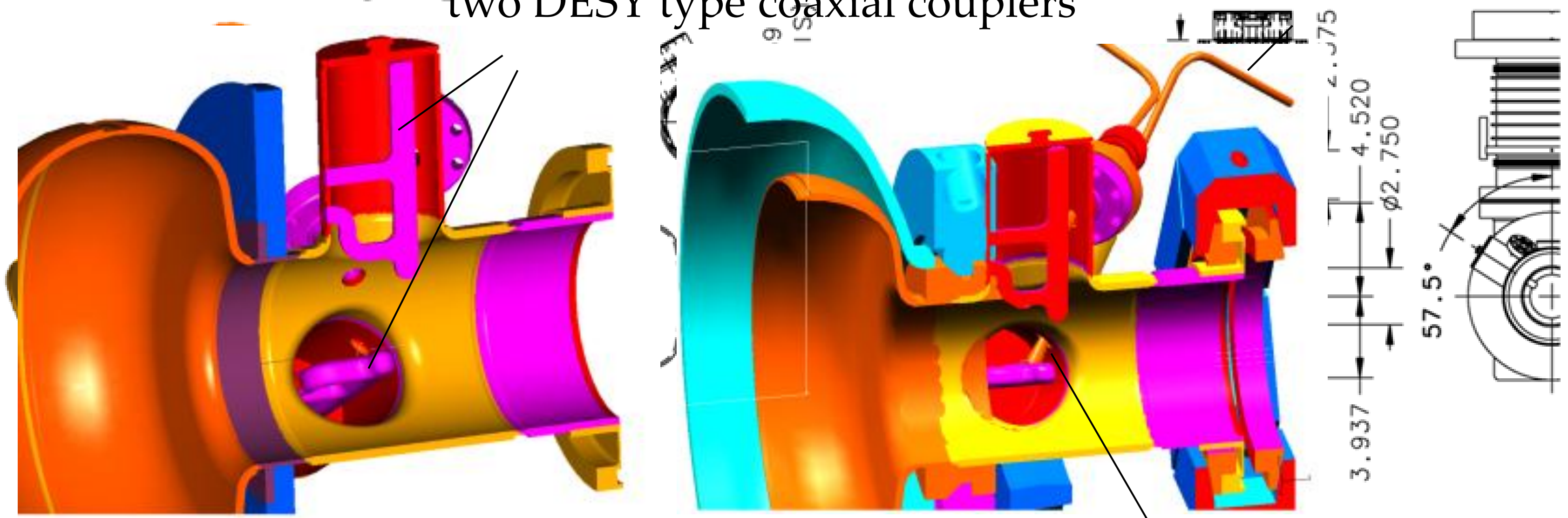
How HOMs are excited and why they are important
- Definition of HOM Dipole Shunt Impedance -

$$R_{\perp,\text{threshold}} = \frac{R_{\perp}}{Q} Q_l k = \frac{R}{Q} \frac{1}{kr^2} Q_l$$

- measure of the parasitic interaction of the beam and the specific HOM, which has to be kept within acceptable limits by design
- R/Q (in Ω) is the characteristic shunt-impedance taken at a radial offset
  - R/Q depends only on the geometry (not losses) → given by cavity
  - **can be easily calculated numerically**
- $R/Q_{\perp} = R/Q/(kr)^2$ (in Ω/m) is transversally normalized dipole impedance
  - wave number k takes into account the frequency dependence of the threshold impedance
- **only way to reduce the impedance is by reducing the quality factor of the cavity capturing fields in external ports (loaded Q_l)**
- $\mathbf{Q_l}$ is figure of merit characterizing the ability to suppress a specific HOM
  - takes into account rf losses in walls (Q_0) and energy dissipated externally
  - **can be measured easily**

CEBAF 12 GeV Era
- Cavity Design -

- cavities needs to be designed to provide sufficiently low Q_l
- HOM coupler(s) are needed to extract mode energy
- have to be broadband to cover the most parasitic HOMs
- should not damp the accelerating mode



New Upgrade Cryomodule "C100"
7-cell Cavity Design
HOM coupler endgroup

CEBAF 12 GeV Era
- BBU Threshold Specification for Dipole Impedances -

- impedance threshold for a given accelerator must not be exceeded to guarantee a stable beam operation
- BBU dipole impedance threshold to support 12 GeV baseline physics up to 100 μA (G. Krafft et al., JLAB-TN-09-015, 2009) :

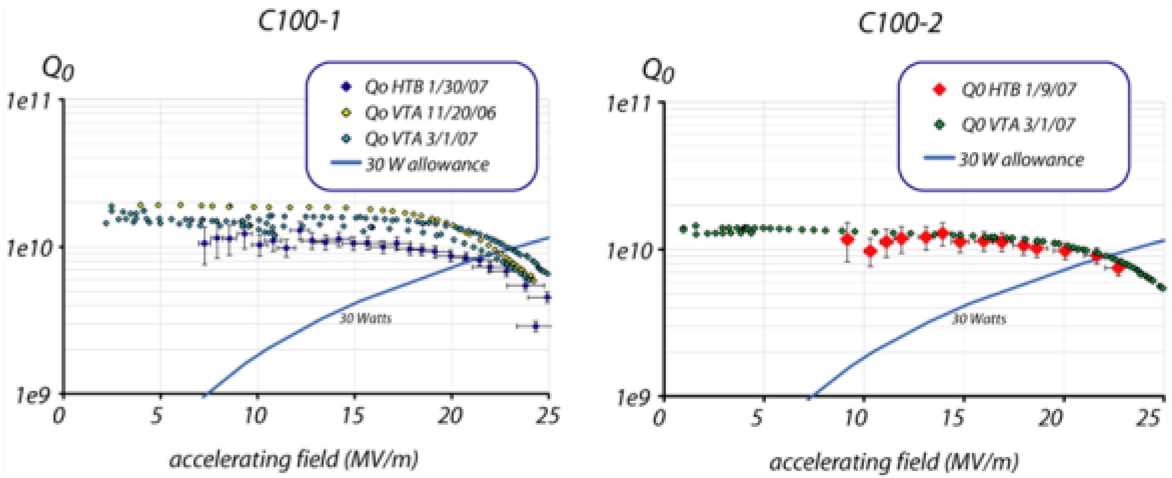
$$R_{\perp,\mathrm{threshold}} \leq 2.4e10 \ \frac{\Omega}{\mathrm{m}}$$

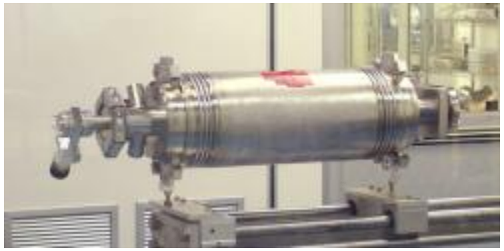
- threshold beyond baseline physics up to 400 μA at lower beam energies :

$$R_{\perp,\mathrm{threshold}} \leq 1.0e10 \ \frac{\Omega}{\mathrm{m}}$$

CEBAF 12 GeV Era
- C100 Cavity Performance for First 2 Prototypes -

- first two C100 cavity prototypes (C100-1 and C100-2) were manufactured during 2006 and high power tested within 2006 and 2007
- Test done in the vertical test area (VTA) and after assembly as a cavity-pair in the horizontal test bed (HTB) cryomodule environment
- Goal of 19.2 MV/m CW at Q_0=8e9 successfully achieved
- **What about HOM damping efficiency ?**

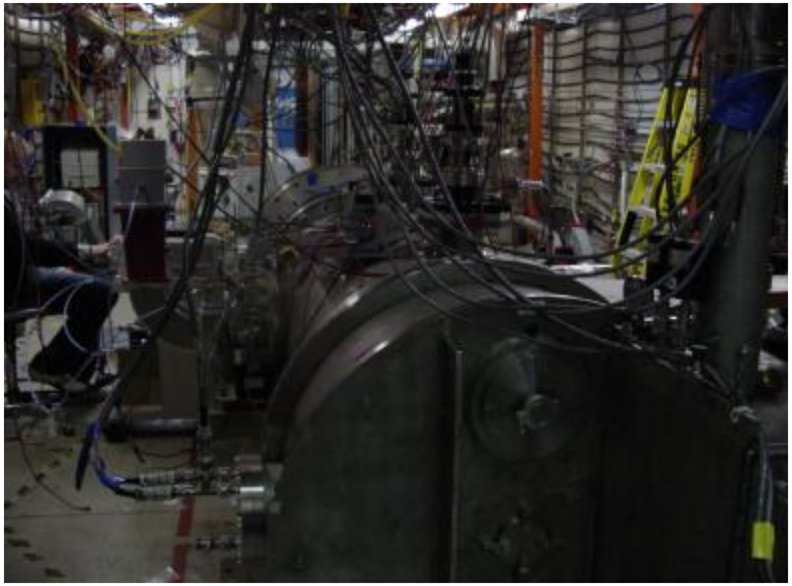




C.E. Reece et al. "Optimization of the SRF Cavity Design for the 12 GeV Upgrade"
13th International Workshop on SRF Superconductivity, Peking University, Beijing, China, 2007, WEP31

CEBAF 12 GeV Era
- Horizontal Test Bed (HTB) -

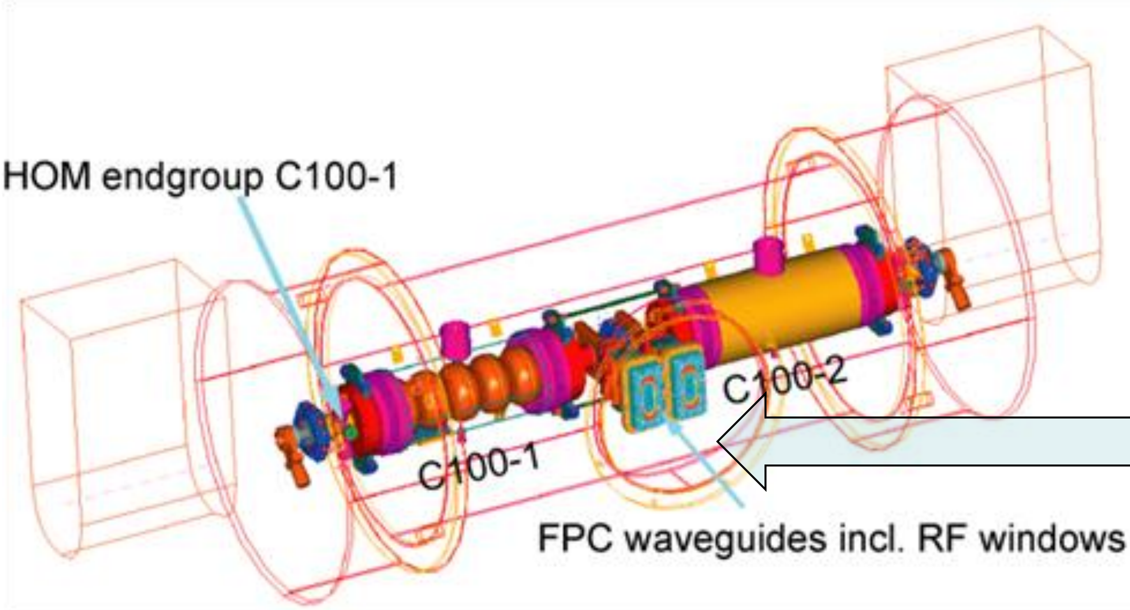
- ❑ performed a detailed HOM survey of C100-1 and C100-2 up to 3 GHz at 2K in HTB
- ❑ HTB is a dedicated upgrade style quarter cryomodule

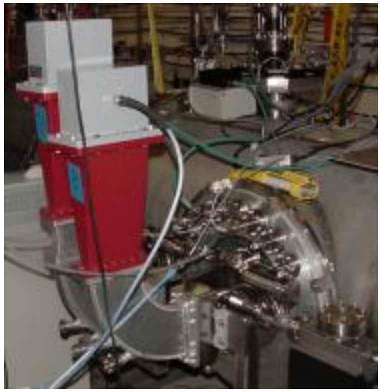


Cryomodule Test Facility (CMTF)

CEBAF 12 GeV Era
- Figure of Merit: Loaded Q of HOMs -

- transmission spectra recorded with Vector Network Analyzer
- signal launched in at FPC via WR650 coaxial-to-waveguide adapter
- picked up signal either at HOM coupler 1 or 2
- loaded Q-measurements: i) $Q_l = \frac{f_0}{\Delta f_{-3dB}}$ ii) $Q_l = \frac{f_0}{2 \times \Delta f_{-3dB,right or left}}$ iii) $Q_l = \frac{f_0}{90 \times \Delta f / \Delta \phi}$

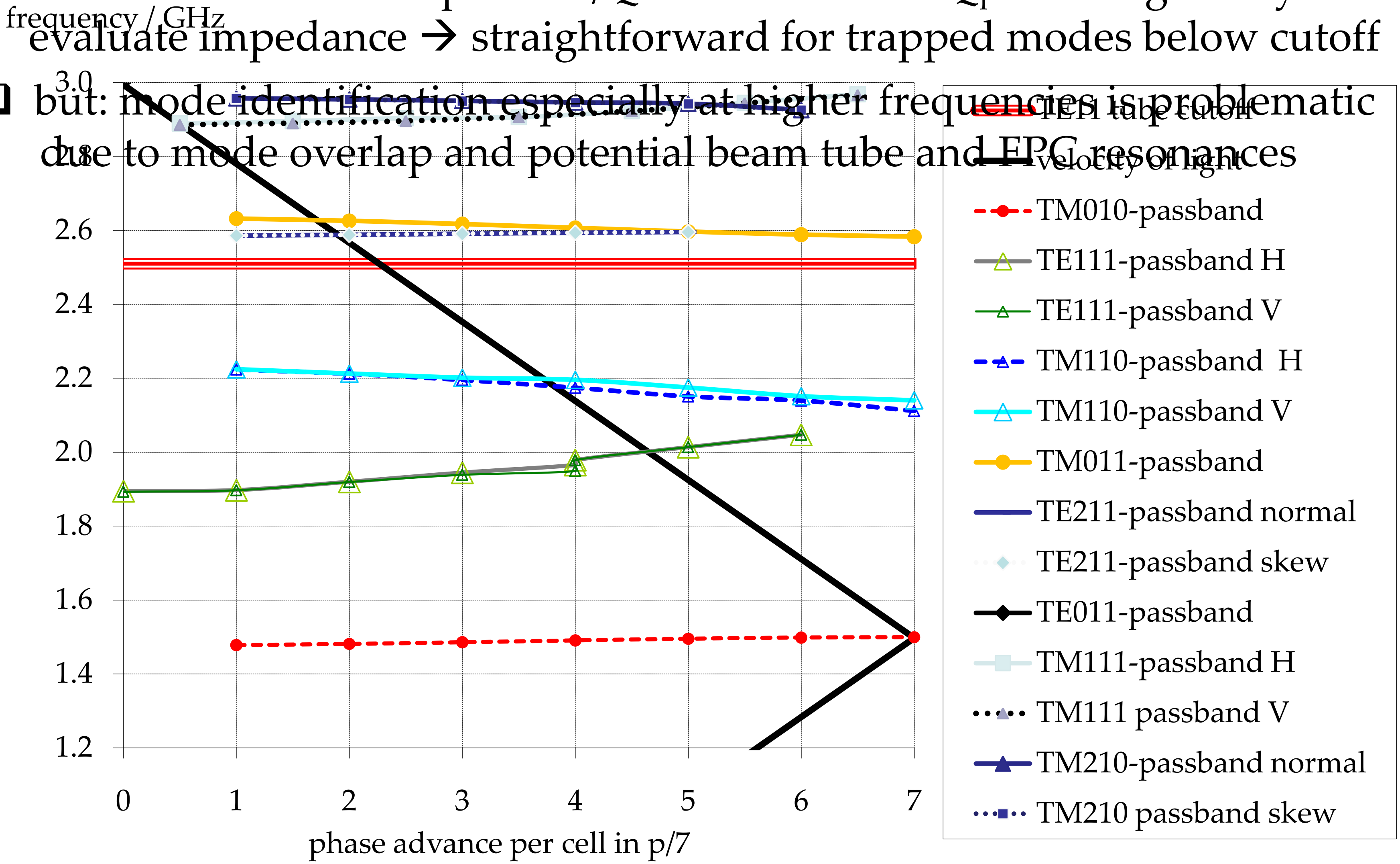




adapters at FPCs for low power measurements

CEBAF 12 GeV Era
- HTB HOM Survey Findings (05/06 2008)-

- need to correlate computed R/Q with measured Q_l unambiguously to evaluate impedance → straightforward for trapped modes below cutoff
- but: mode identification especially at higher frequencies is problematic due to mode overlap and potential beam tube and FPC resonances



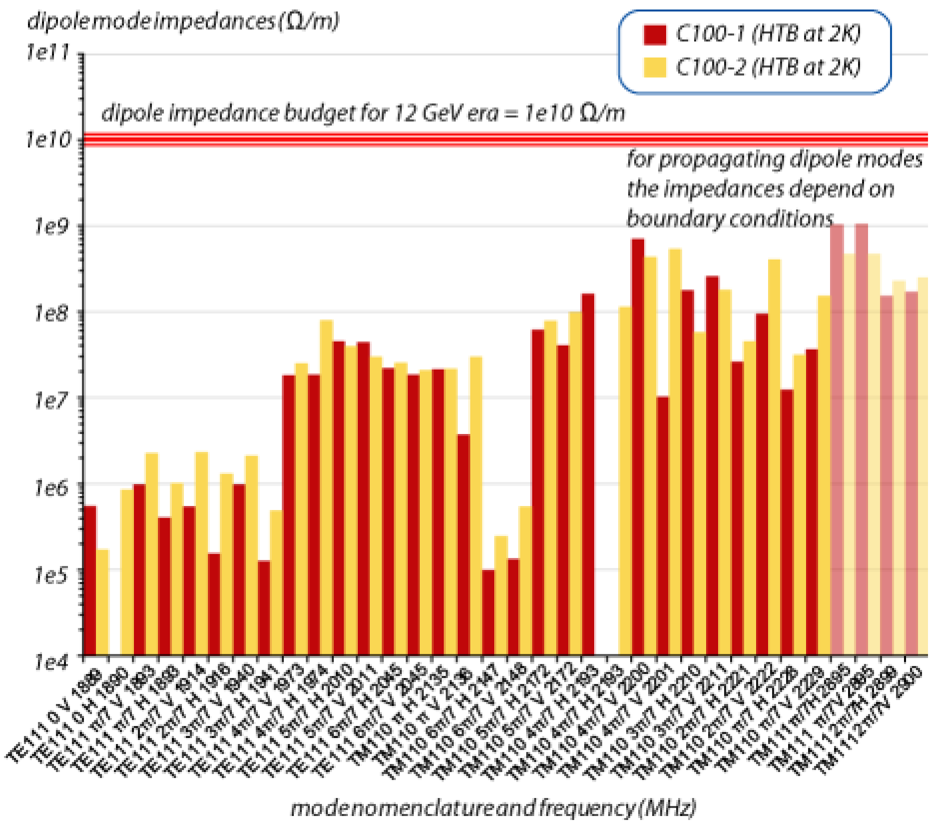
Jefferson Lab

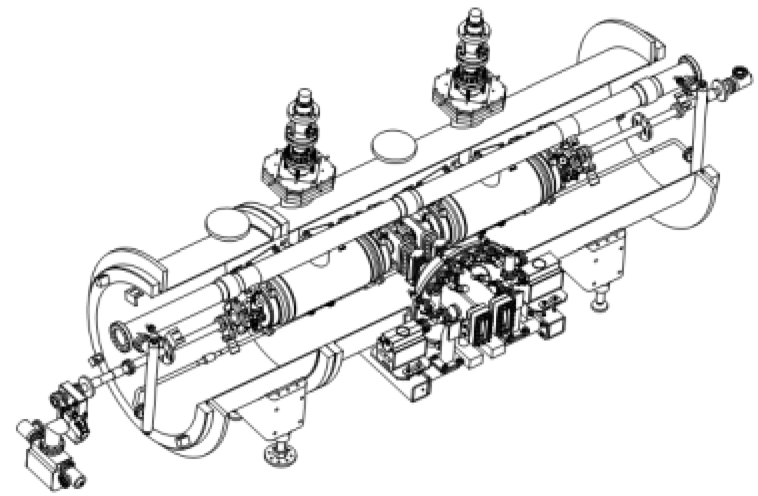
CEBAF 12 GeV Era
- HTB HOM Survey Findings (05/06 2008)-

- results published at PAC 2009

HOM SURVEY OF THE FIRST CEBAF UPGRADE STYLE CAVITY PAIR*

F. Marhauser, E. Daly, G.K. Davis, M.A. Drury, C. Grenoble, J. Hogan, R. Manus,
J.P. Preble, C.E. Reece, R.A. Rimmer, K. Tian, H. Wang, JLab, Newport News, VA 23606, U.S.A

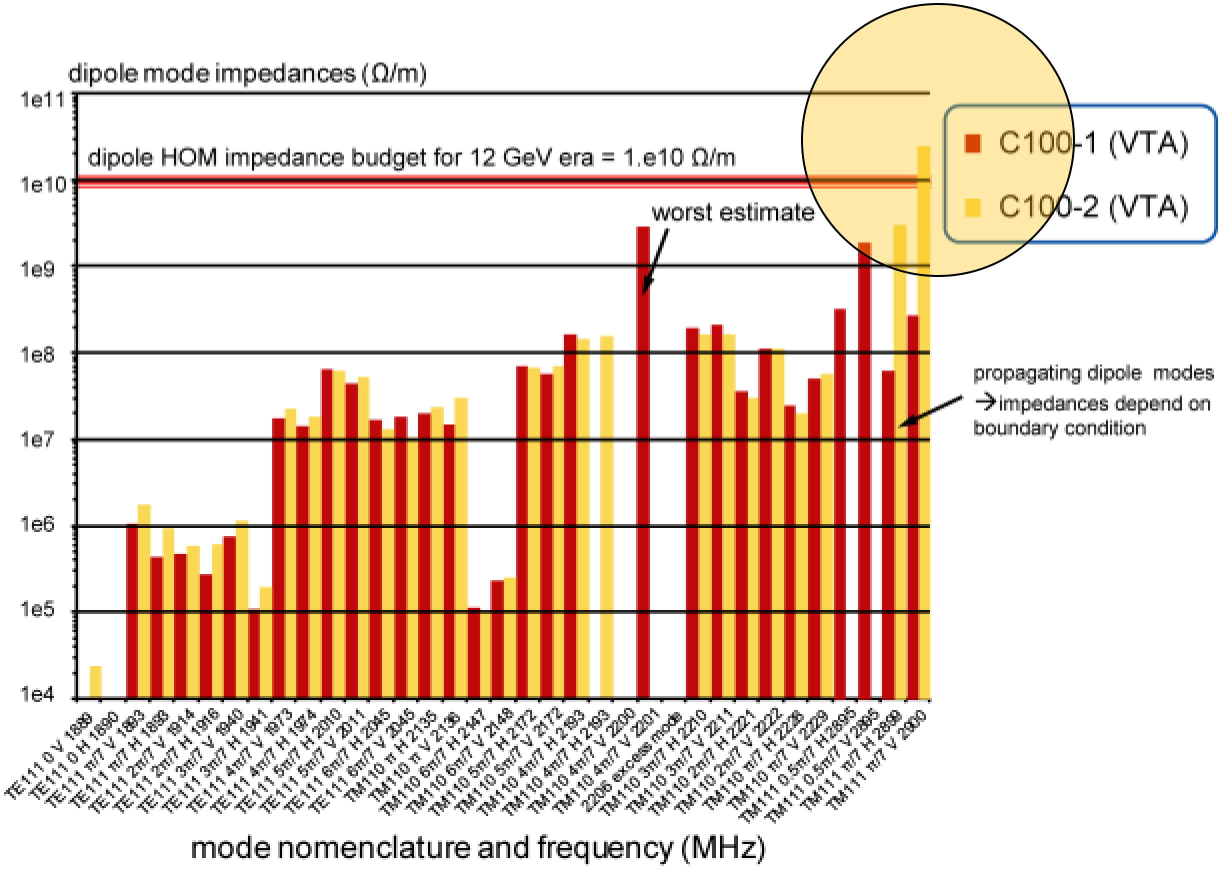


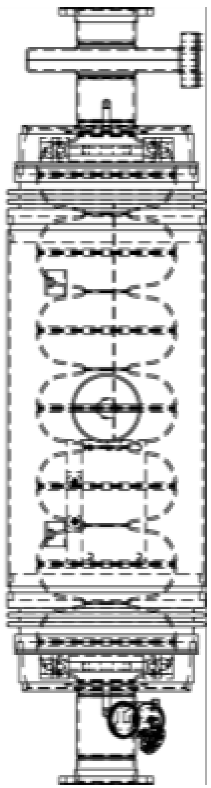


So, what is the problem?

CEBAF 12 GeV Era
- Vertical Test Area (VTA) HOM Survey Findings (07-2008) -

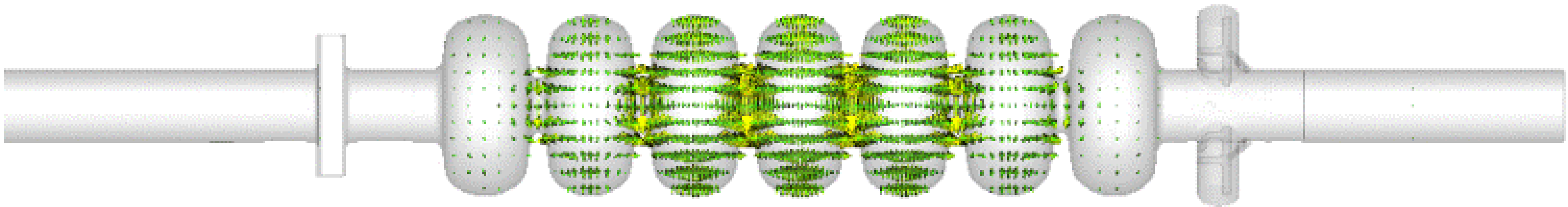
- did similar measurement in VTA after disassembly of cavities
- outcome: good agreement with HTB data for modes below cutoff
- BUT: mode above cutoff "popped" up
- this is first mode (pair) in 3rd TM111 dipole passband





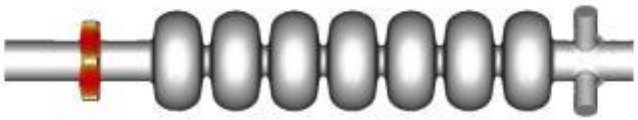
CEBAF 12 GeV Era
- Bad Guy -

TM111 π/7 mode at 2.9 GHz
(here vertical polarization)



CEBAF 12 GeV Era
- Vertical Test Area (VTA) HOM Survey Findings -

- What we have measured in the VTA (July 2008)



original VTA assembly

C100-1	no extensions	
f (MHz)	Ql at 4K	R (Ω/m)
2895.396	8.89E+04	3.11E+08
2895.473	4.02E+05	1.82E+09
2899.319	1.71E+04	6.16E+07
2900.118	1.04E+05	2.58E+08

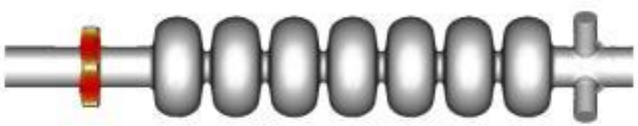
C100-2	no extensions	
f (MHz)	Ql at 4K	R (Ω/m)
2898.458	8.06E+05	2.82E+09
2900.047	5.14E+06	2.32E+10
2904.938	8.96E+04	3.22E+08
2906.840	2.86E+05	7.05E+08

why are some Ql's higher in the VTA?

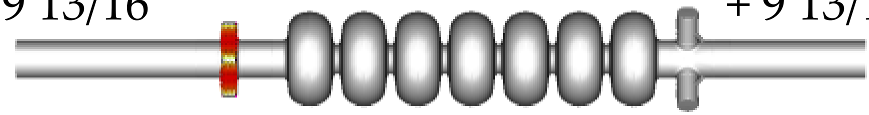
exceeding BBU threshold!

CEBAF 12 GeV Era
- Vertical Test Area (VTA) HOM Survey Findings -

- What we have measured in the VTA (July 2008 and March/April 2009)



original VTA assembly

+ 9 13/16”  + 9 13/16”

VTA assembly with SS tube extensions

C100-1 f (MHz)	no extensions Ql at 4K	R (Ω/m)
2895.396	8.89E+04	3.11E+08
2895.473	4.02E+05	1.82E+09
2899.319	1.71E+04	6.16E+07
2900.118	1.04E+05	2.58E+08
C100-2 f (MHz)	**no extensions Ql at 4K**	**R (Ω/m)**
2898.458	8.06E+05	2.82E+09
2900.047	5.14E+06	2.32E+10
2904.938	8.96E+04	3.22E+08
2906.840	2.86E+05	7.05E+08

C100-1 f (MHz)	SS-extensions Ql at 2K	R (Ω/m)
2895.076	2.0E+06	1.31E+10
2895.419	1.2E+06	7.80E+09
2898.886	2.9E+05	2.77E+08
2889.81	2.3E+05	2.39E+08
C100-2 f (MHz)	**SS-extensions Ql at 2K**	**R (Ω/m)**
2898.369	4.1E+06	2.62E+10
2900.013	6.5E+05	4.22E+09
2904.474	4.8E+05	4.51E+08
2906.600	1.2E+05	1.26E+08

Q’s increased even further!

CEBAF 12 GeV Era
- What Q is acceptable for these TM111 π/7 HOMs -

$$R_{\perp,\mathrm{threshold}} = \frac{R_\perp}{Q} Q_1 k = \frac{R}{Q} \frac{1}{kr^2} Q_1$$

12 GeV baseline:

$$R_{\perp,\mathrm{threshold}} \leq 2.4\mathrm{e}10 \ \frac{\Omega}{\mathrm{m}}$$

stretched goal:

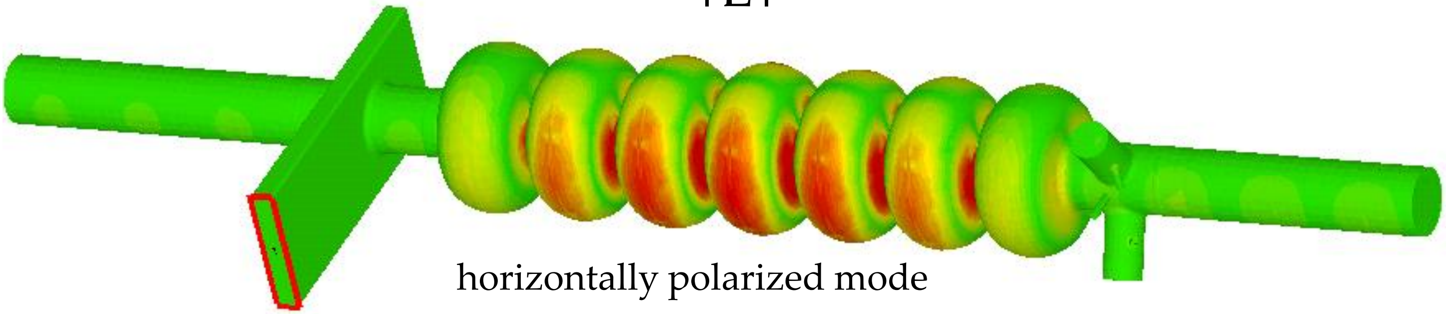
$$R_{\perp,\mathrm{threshold}} \leq 1.0\mathrm{e}10 \ \frac{\Omega}{\mathrm{m}}$$

f (MHz)	R/Q(r=10mm) Ω	$R/Q_\perp$ Ω/m	$R_{\perp,\mathrm{threshold}}$ Ω/m	maximum allowable Q
2900	40	6.58e3	1.0e10	1.6e6
2900	40	6.58e3	2.4e10	3.8e6

CEBAF 12 GeV Era
- VTA with extensions, TM111 π/7-Mode Field Amplitudes -

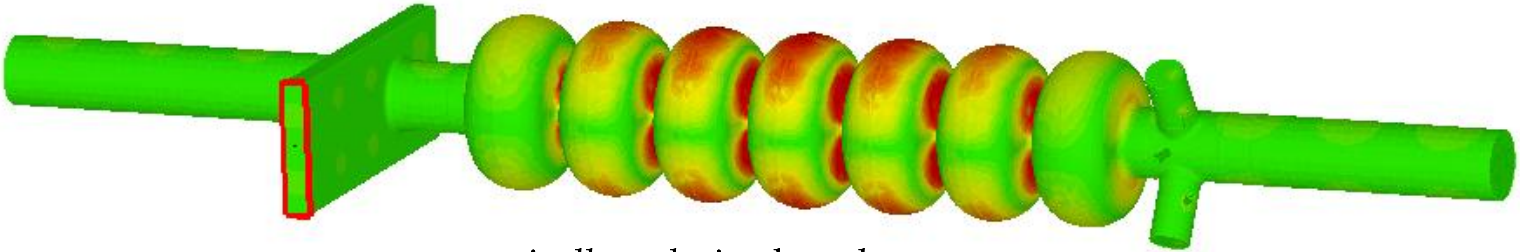
- since field levels are low in beam tubes, how efficient are HOM couplers (P_{loss}~field^2) ?

|E|



horizontally polarized mode

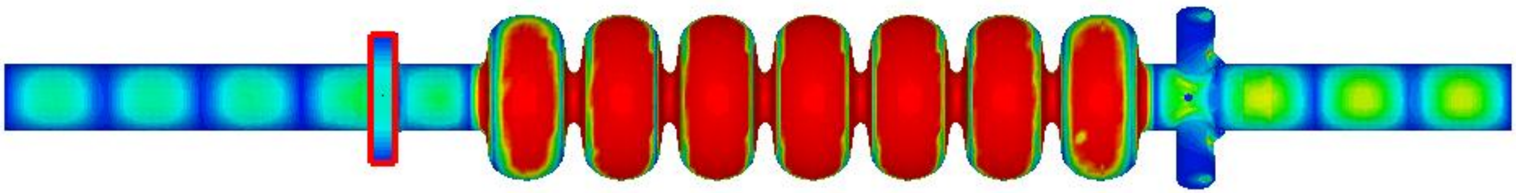
|E|



vertically polarized mode

CEBAF 12 GeV Era
- VTA Configuration, TM111 π/7-mode Field Amplitude -

- beam tube boundaries play important role on how fields couple to both the HOM couplers and the FPC

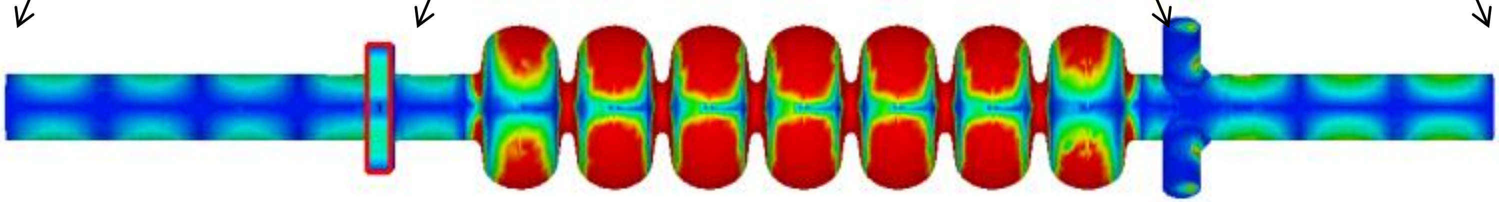


horizontally polarized mode
up to $|E_{max}|/10$ (Log. scale)

short

field amplitudes here depend on boundary conditions

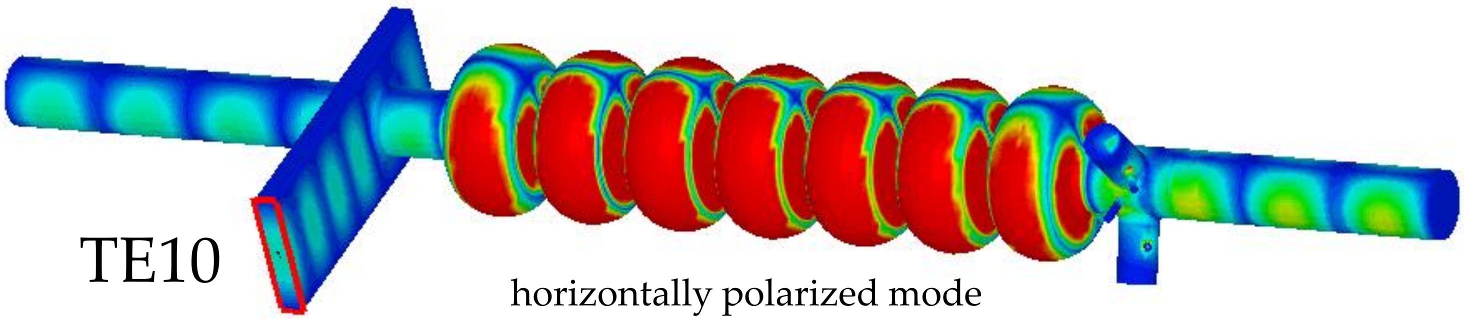
short



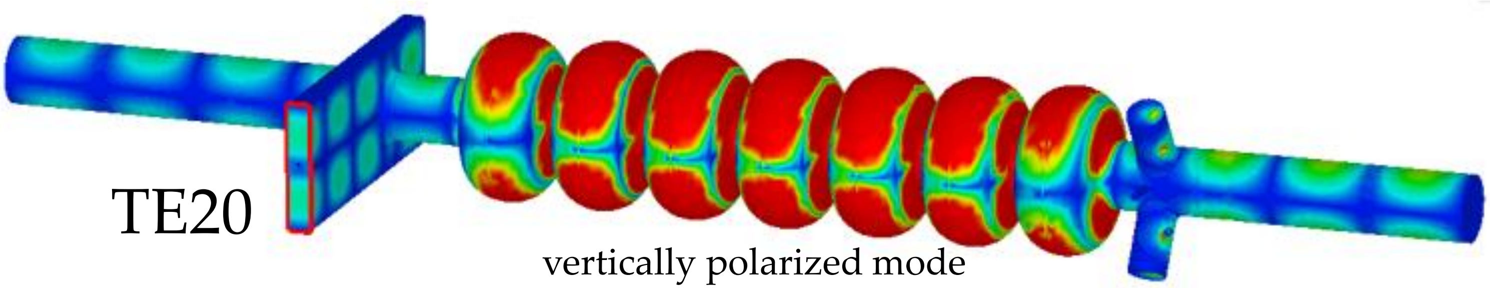
vertically polarized mode
up to $|E_{max}|/10$ (Log. scale)

CEBAF 12 GeV Era
- VTA Configuration, TM111 π/7-mode Field Amplitude -

- coupling through FPC may become very important if HOM couplers do not work are not efficiently enough
- **horizontally polarized mode couples to TE10 FPC mode**
- **vertically polarized mode couples to TE20 FPC mode**



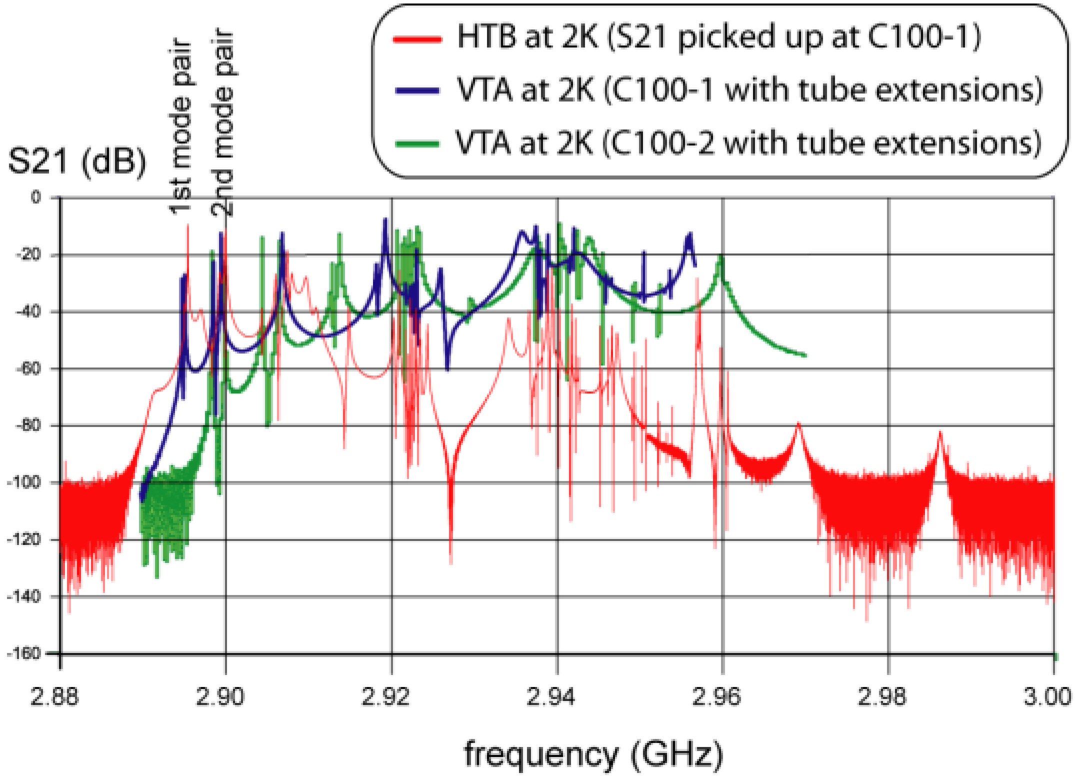
horizontally polarized mode
up to $|E_{max}|/10$ (Log. scale)

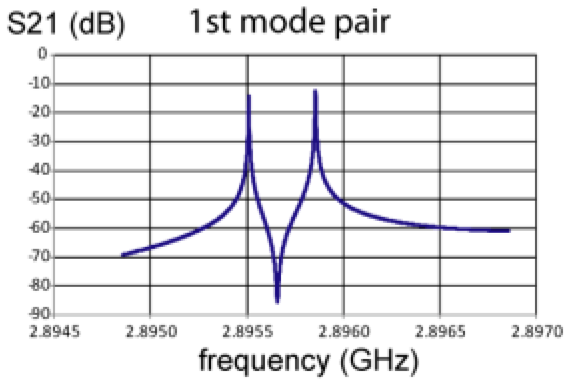


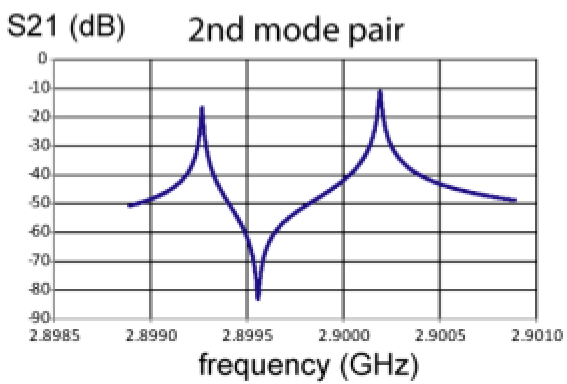
vertically polarized mode
up to $|E_{max}|/10$ (Log. scale)

CEBAF 12 GeV Era
- What is major Difference between VTA and HTB ? -

- ❑ dipole pair more distinctive in individual cavities (VTA) than HTB
- ❑ additional resonances in HTB (beam tube modes, FPC modes)
  → unclear situation
- ❑ **have we measured the correct mode ?**

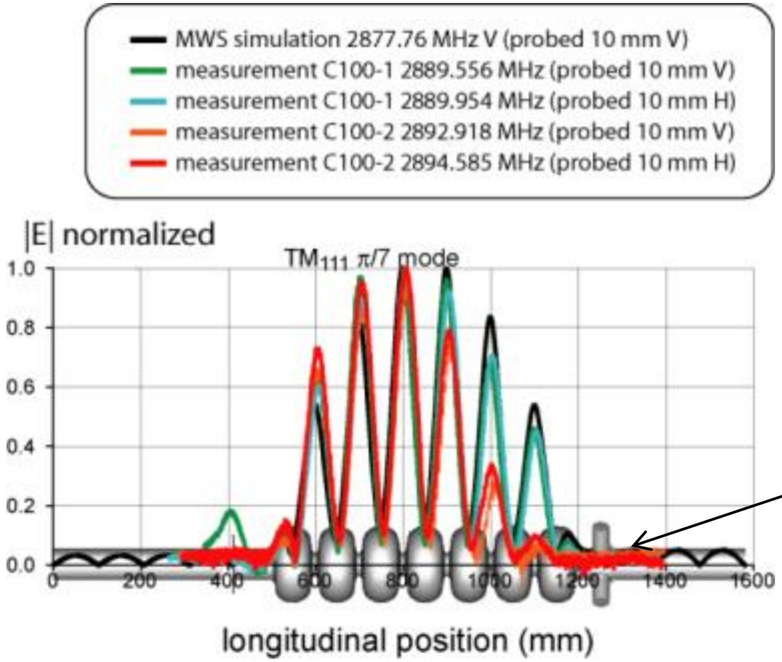






CEBAF 12 GeV Era
- Field Profile ("Bead-Pull" Measurement) -

"bead-pull" measurement setup



BINGO !

low field levels at coupler with minima of standing wave at HOM can position

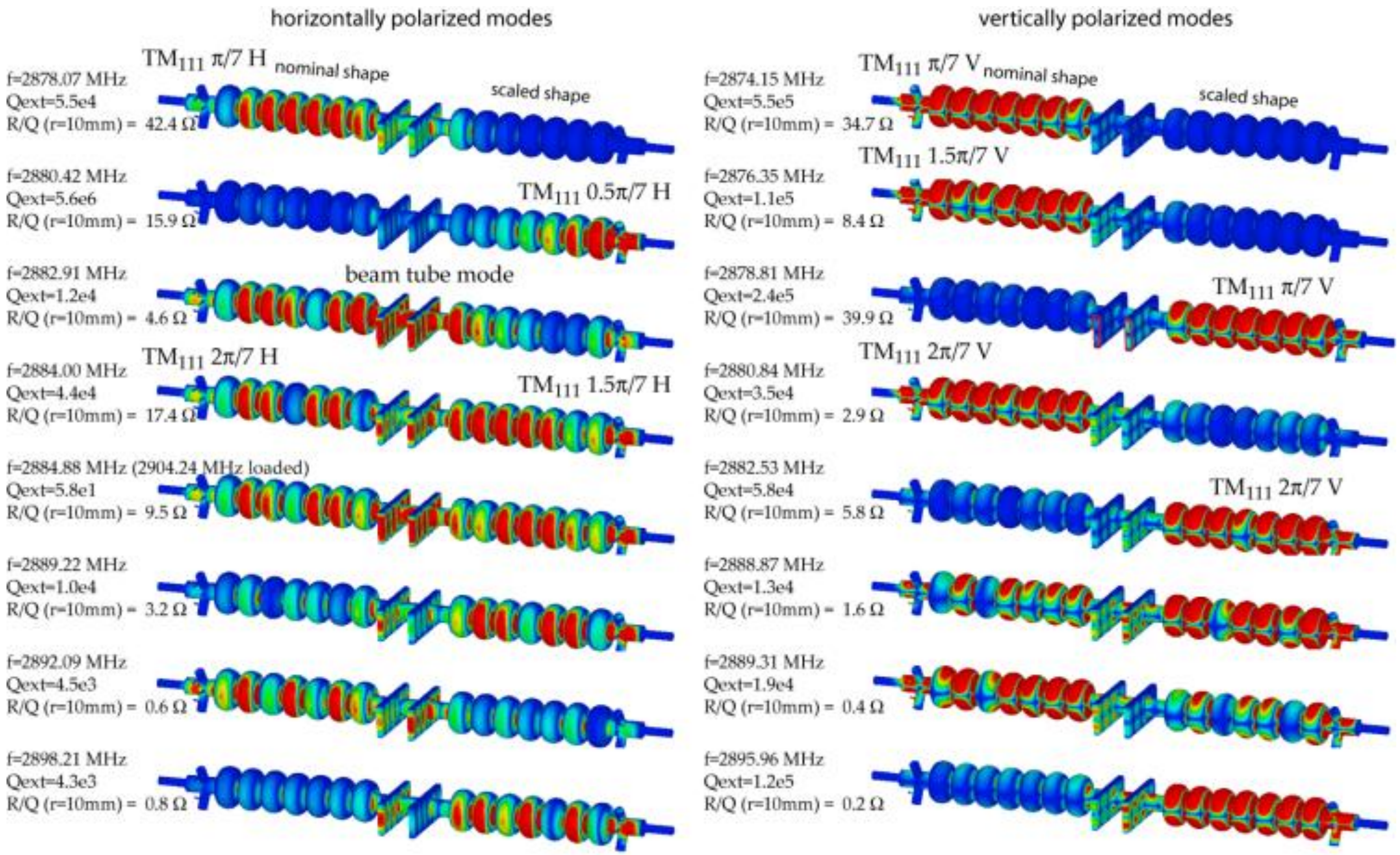
CEBAF 12 GeV Era
- So ???-

- So ? is rather complex to answer (technical report in preparation)
- Explanation combines different effects including
  - beam tube boundaries
  - fabrication tolerances
  - cavity pair coupling effects in HTB
  - mode polarization effects
  - fundamental mode power coupler coupling effects
  - rf characteristics of coaxial-to-waveguide adapters
  - combined external losses
- To summarize :
  Cavity modes in HTB can be damped by a combination of both HOM couplers and both FPCs → lowers the Qs
- The HTB configuration is not fully representative for all cavities in C100 cryomodule string due to symmetry plane
- Q of parasitic modes might be underestimated

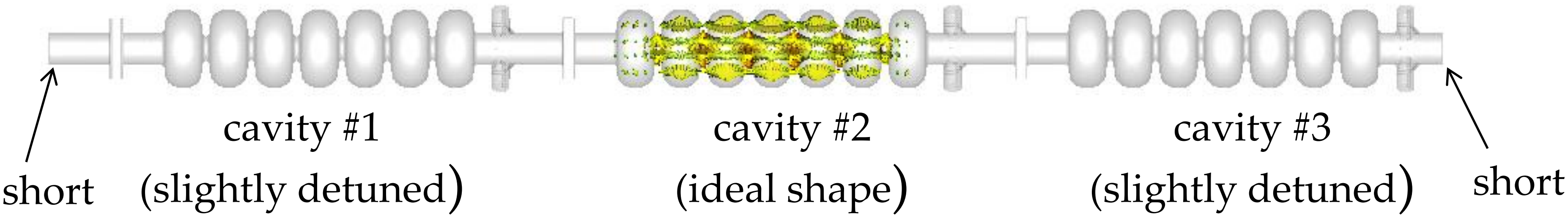
CEBAF 12 GeV Era
- HTB Cavity Pair Simulations -

cavity #1
(ideal shape)

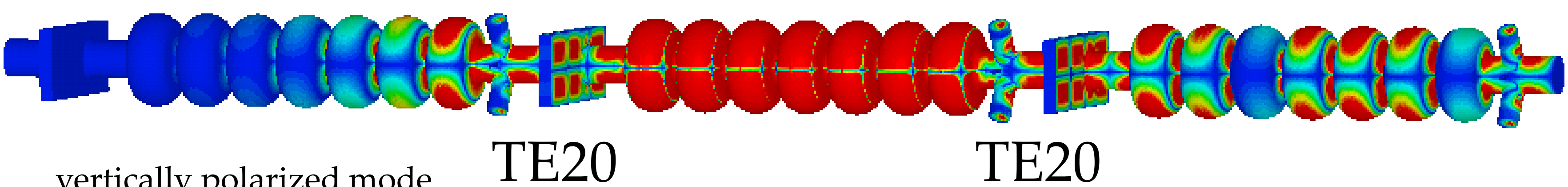
cavity #2
(slightly detuned)



- simulation of cavity string



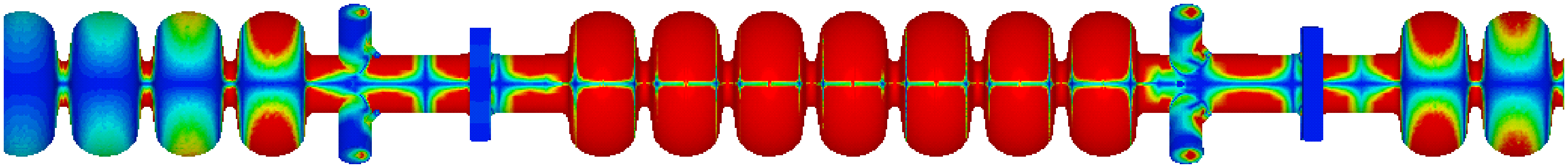
- how far and strong the field propagates in neighboring cavities may depend on detuning ?
- cavities share 2 HOM couplers and 2 FPCs (except for cavity at end of cryomodule!)



vertically polarized mode
up to $|E_{max}|/10$ (Log. scale)

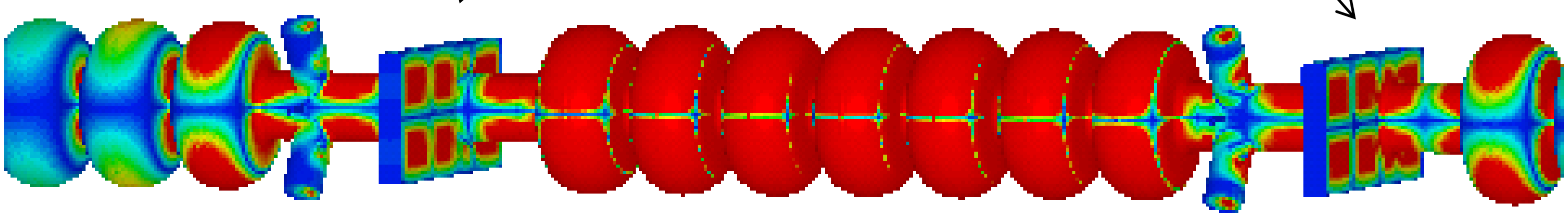
CEBAF 12 GeV Era
- Trying to Resemble Real World -

- ❑ conditions for middle cavity most realistic (representative !?)

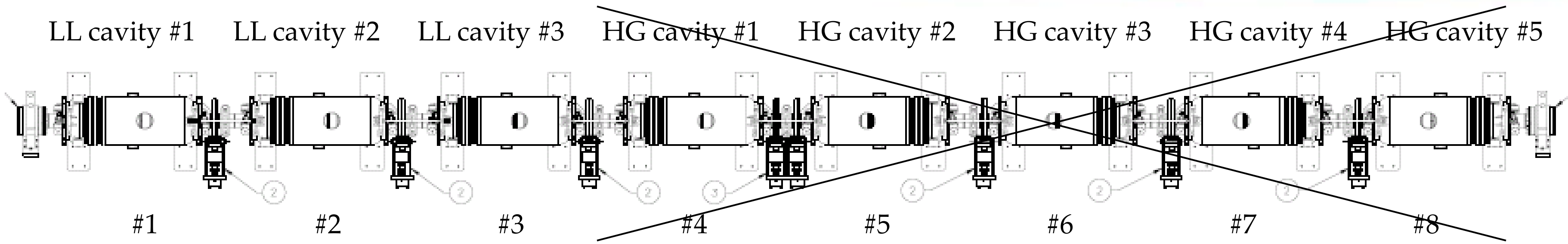


vertically polarized mode
up to $|E_{max}|/10$ (Log. scale)

- ❑ HOM couplers seem to be positioned unfavorable for this mode
- ❑ FPCs may be key-components for damping this mode

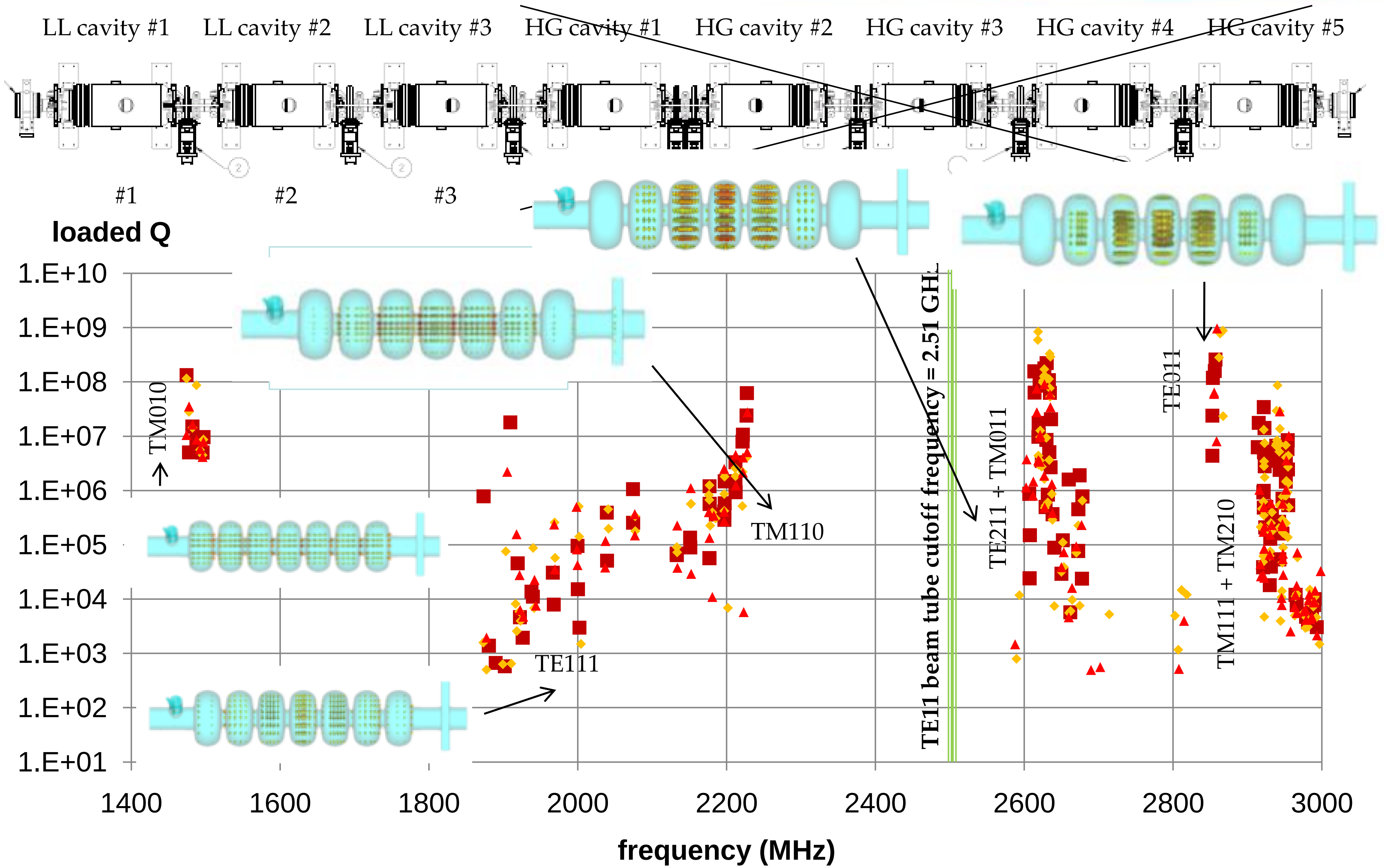


CEBAF 12 GeV Era
- Measured Mode Frequencies in LL cavities + Simulation -

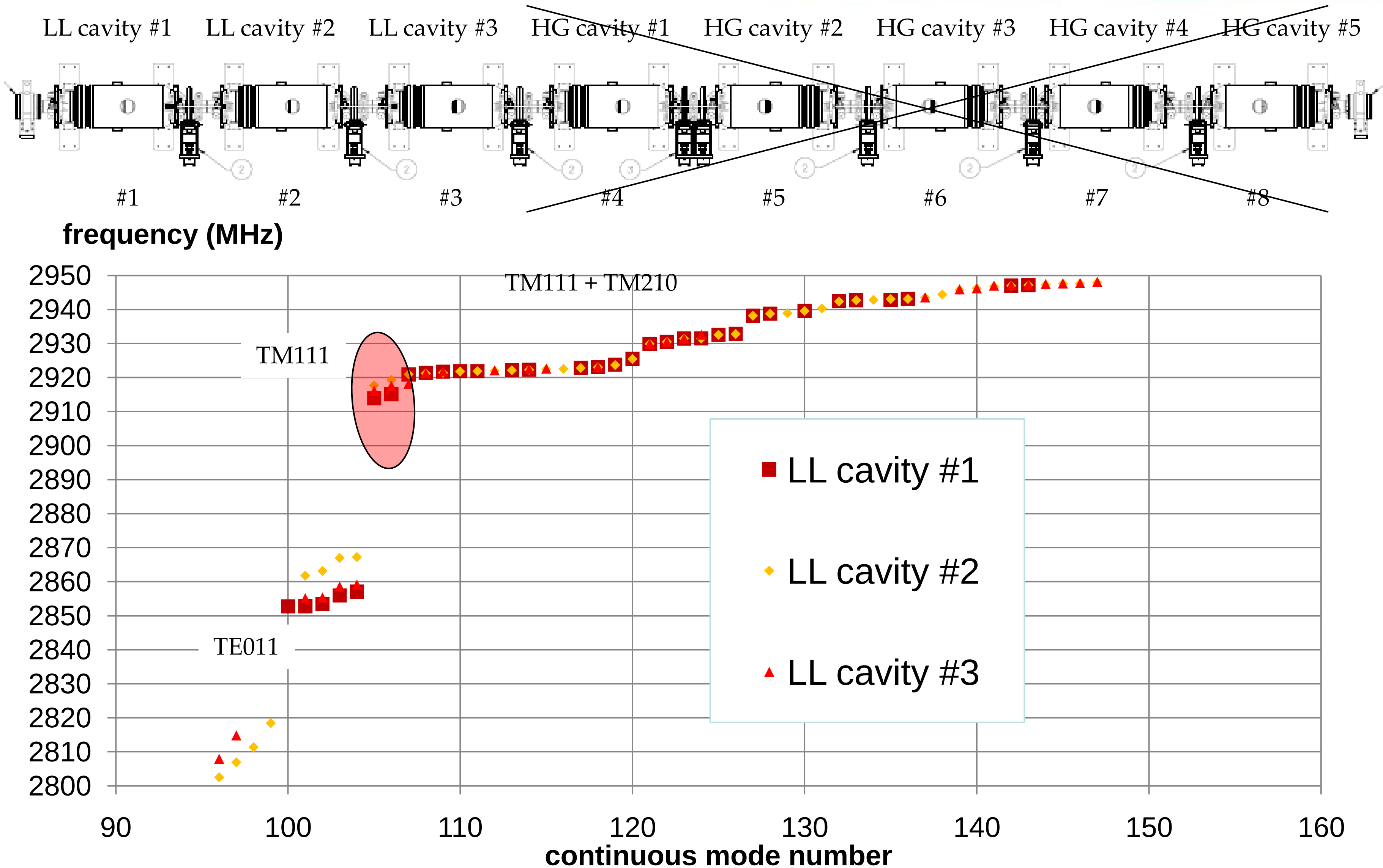


- Renaissance Cryomodule in CMTF after removal from CEBAF 1L04
- HOM survey done for all cavities up to 3GHz at 2K
- concentrated on three LL type cavities as used fro upgrade
- HOM endgroup different than in final C100 cavity design
- we wanted to study the damping effect by the FPC as well

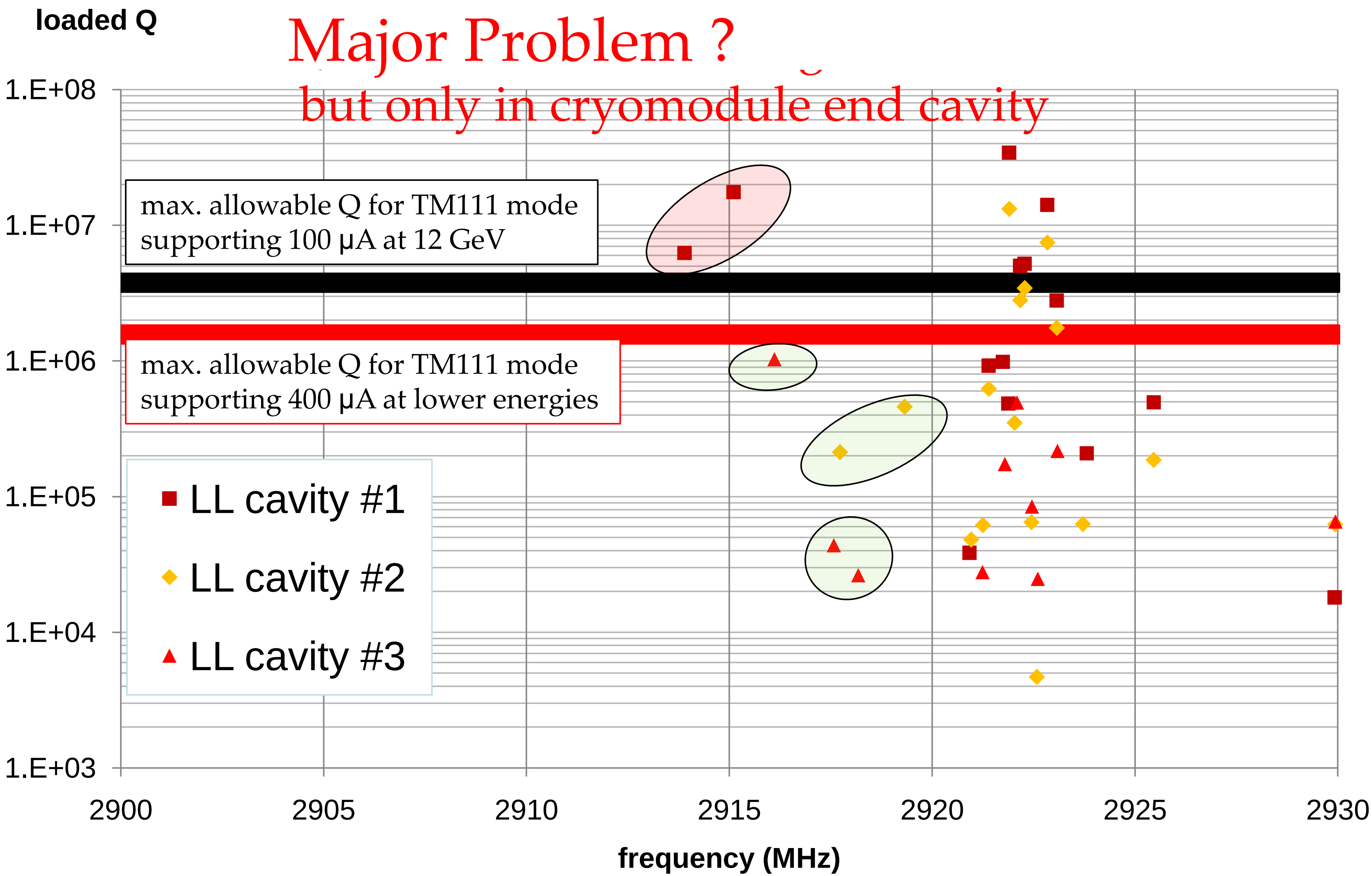
CEBAF 12 GeV Era
- Cavity String Measurements: Loaded Qs -



CEBAF 12 GeV Era
- Measured Mode Frequencies in LL cavities + Simulation -

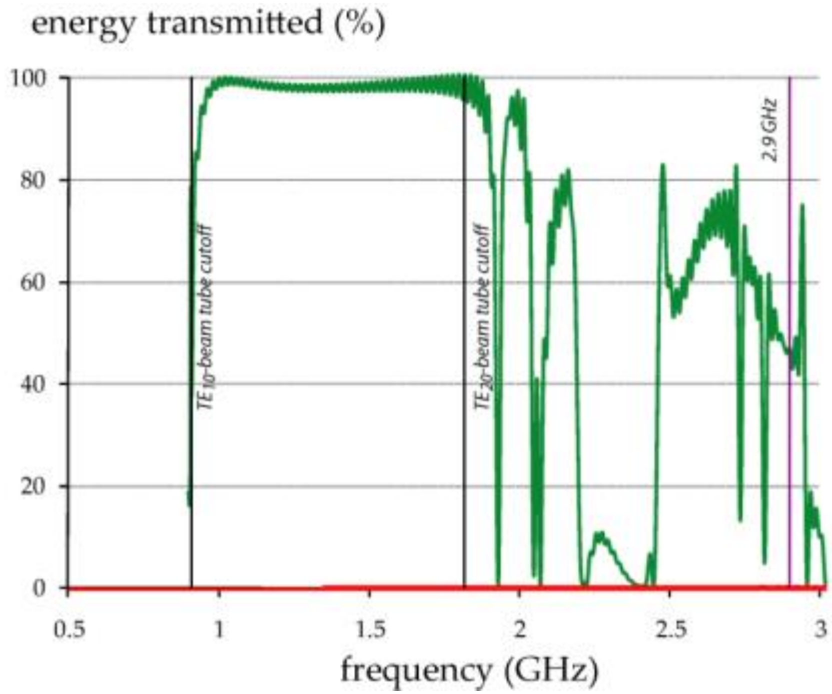


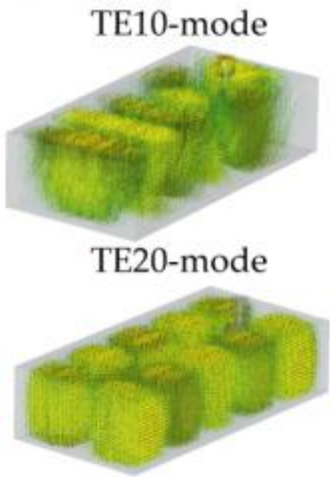
CEBAF 12 GeV Era
- Loaded Qs in LL Cavities -



CEBAF 12 GeV Era
- Limited Performance on Low Power Adapters -

- adapter is no multi-modal device → support only TE10 mode
- TE20 mode mostly reflected

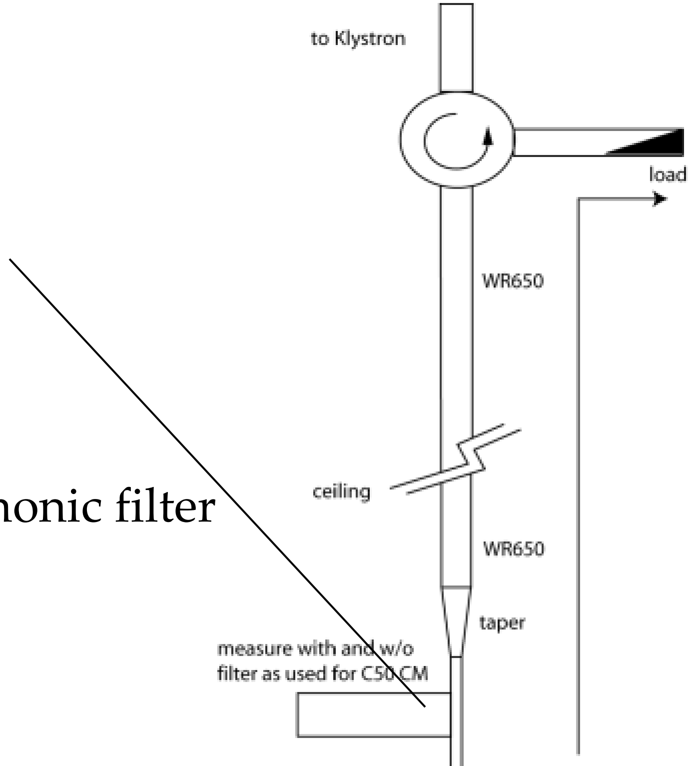


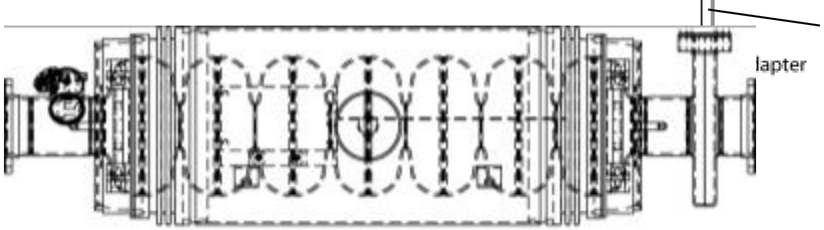


CEBAF 12 GeV Era
- Real High Power Waveguide Setup-

- tunnel measurement at empty "Renaissance" slot 1L04
- measure return loss "shooting upwards"

Klystron 2nd harmonic filter used in CEBAF waveguides





"symmetric "adapter only good for TE10

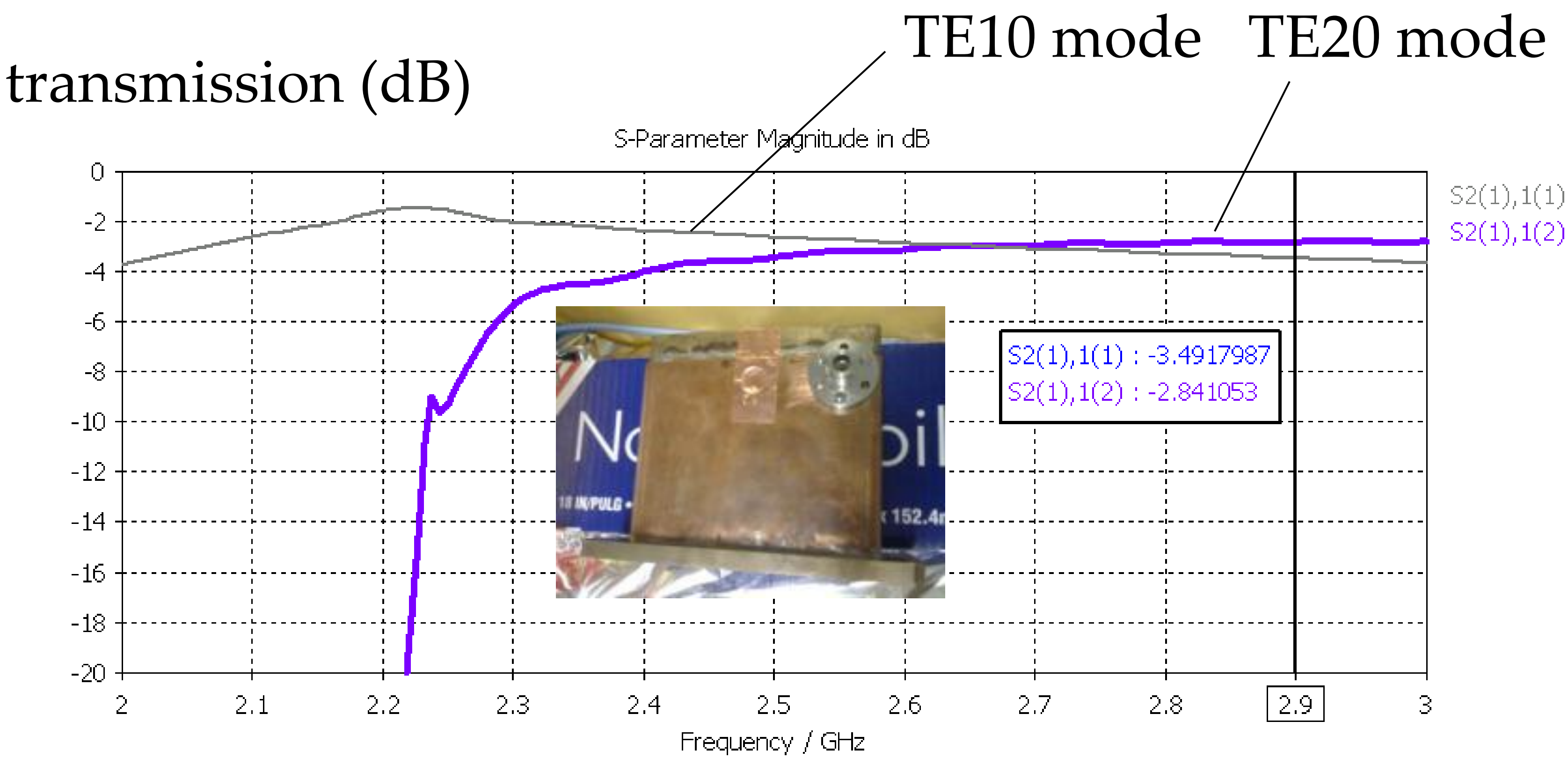
adapter attached close to cavity position

CEBAF 12 GeV Era
- Real High Power Waveguide Setup-

	without HOM filter			**with HOM filter**	
	symmetric adapter			**symmetric adapter**	
f (MHz)	energy transmitted (%)		**f (MHz)**	**energy transmitted (%)**	
2900	91		**2900**	**99.4**	

Co-axial-to Waveguide Adapters used in VTA
- Tunnel Measurement- Empty Slot 1L04 -

- **what about TE20 mode ?**
- to investigate TE20 mode an “asymmetric” adapter has been used
- offset of antenna numerically optimized
- transmits both TE10 and TE20 mode

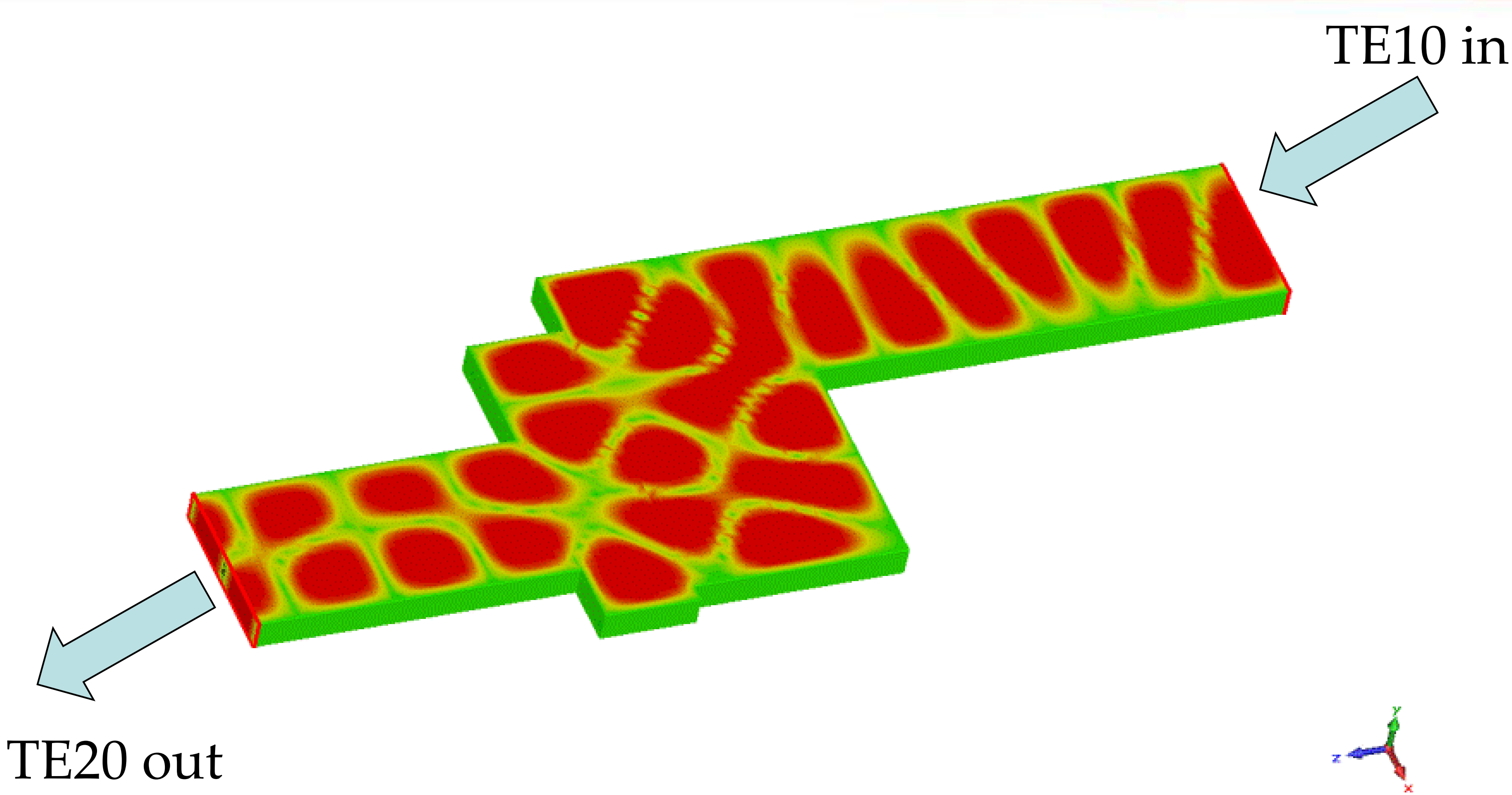


CEBAF 12 GeV Era
- Real High Power Waveguide Setup-

	without HOM filter				with HOM filter	
	symmetric adapter				**symmetric adapter**	
f (MHz)	energy transmitted (%)			**f (MHz)**	**energy transmitted (%)**	
2900	91	84.5		**2900**	**99.4**	**99.7**

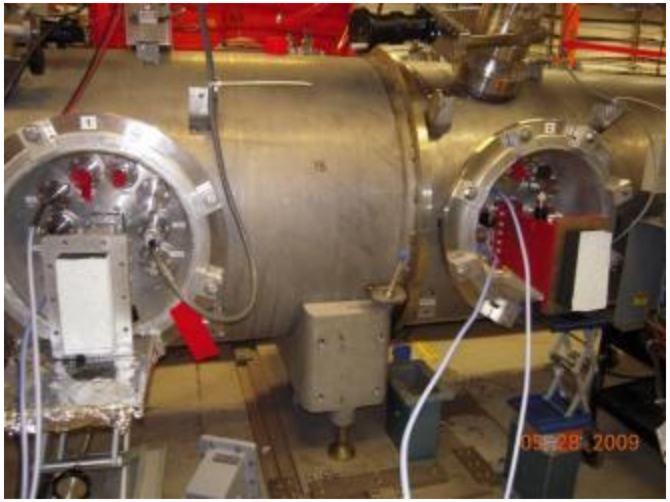
- CEBAF waveguide filter works very well at 2.9 GHz
- however: need pure TE20 measurement!
- TE10 to TE20 mode converter designed for measurements to come

CEBAF 12 GeV Era
- TE10 to TE20 converter to characterize TE20 loss -

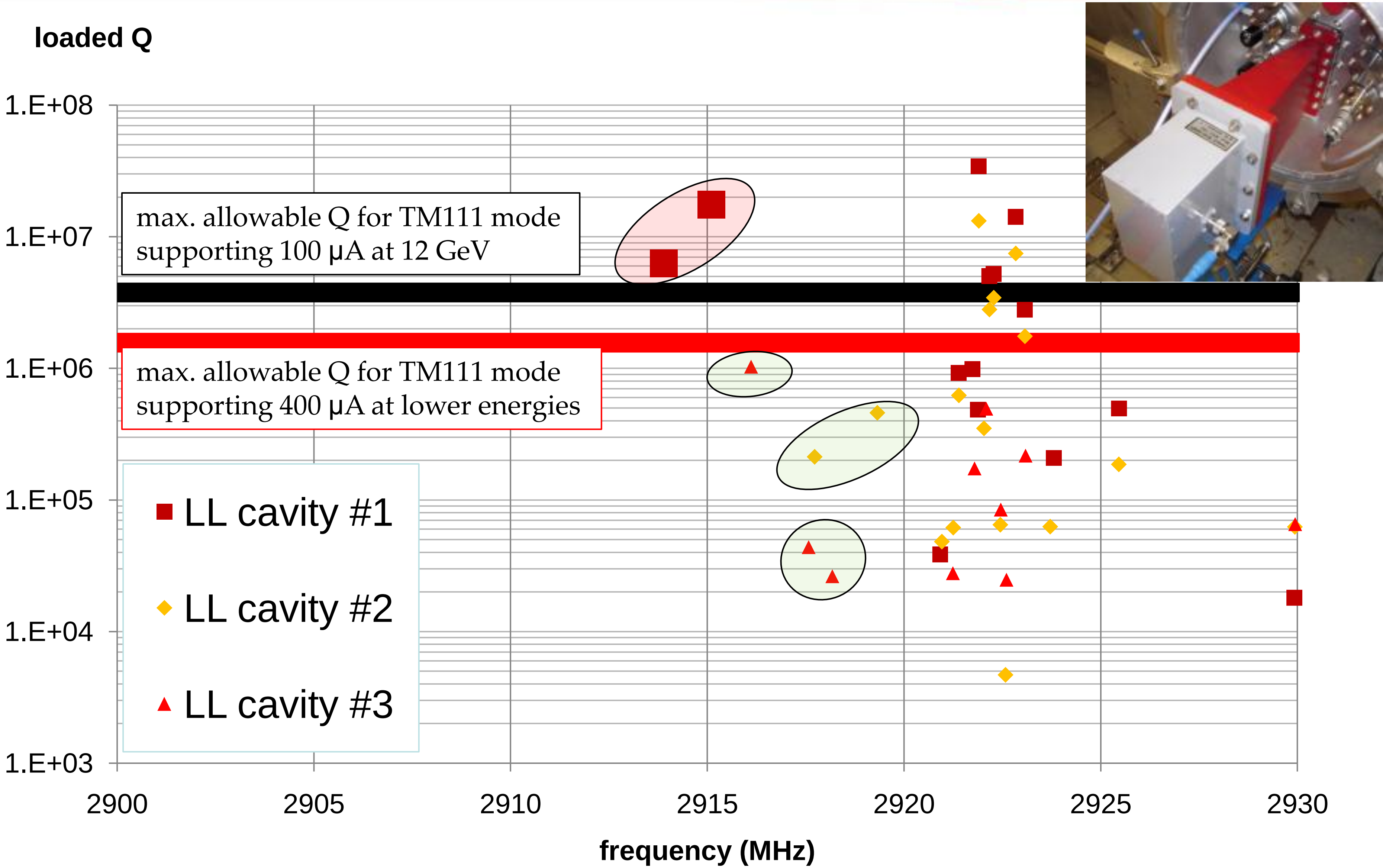


CEBAF 12 GeV Era
- What is effect on HOMs -

- since real waveguide setup provides good absorbing performance around 2.9 GHz, what improvement can we except ?
- instead using adapters we inserted absorbing foam in the FPC (similarly good damping for both TE10 and TE20 modes)
- Q_l measured again launching signal from one HOM coupler of one cavity to HOM coupler of adjacent cavity
- foam placed in cavity 1 through 5

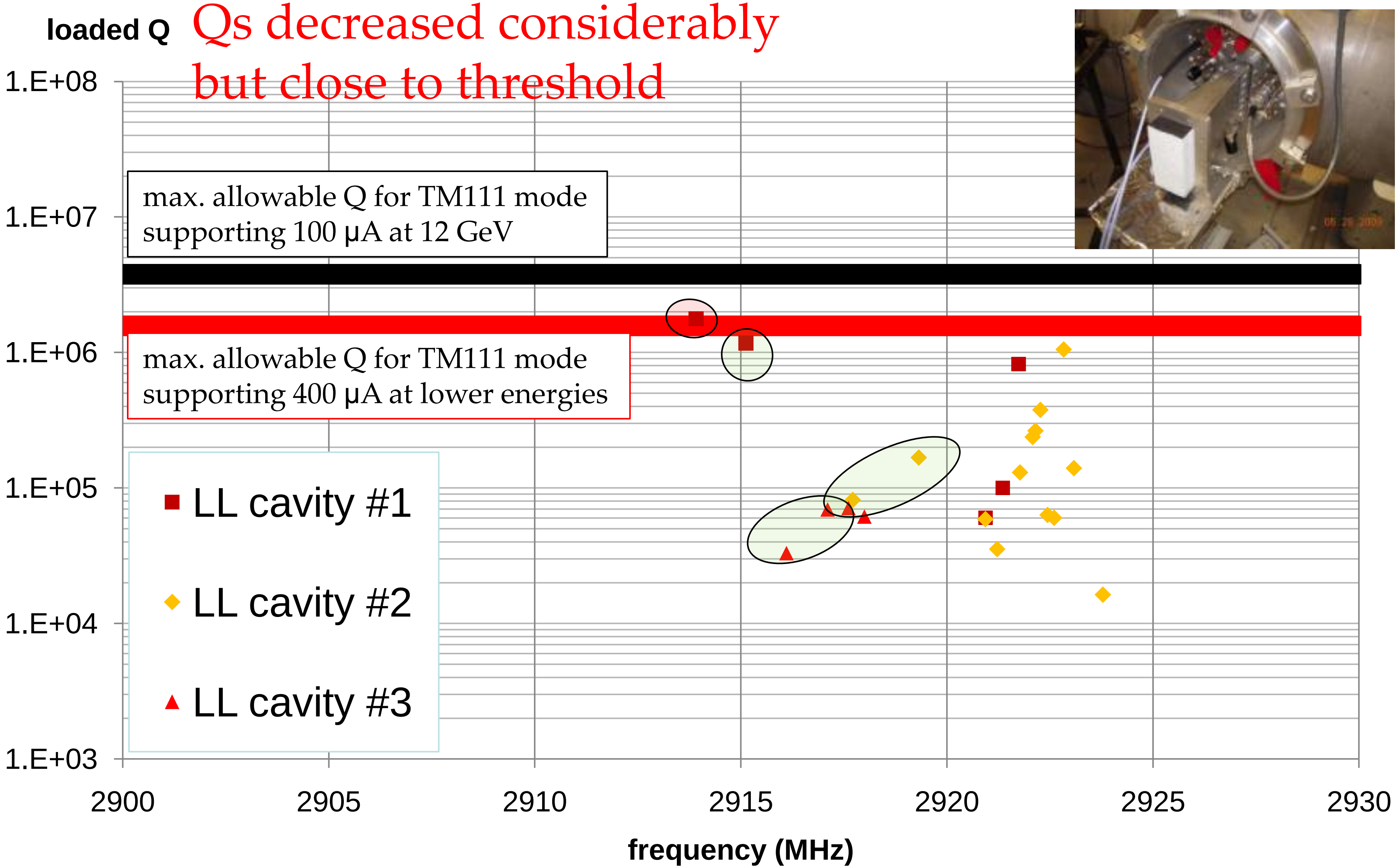


CEBAF 12 GeV Era
- TM111 π/7 mode with FPC Adapter -



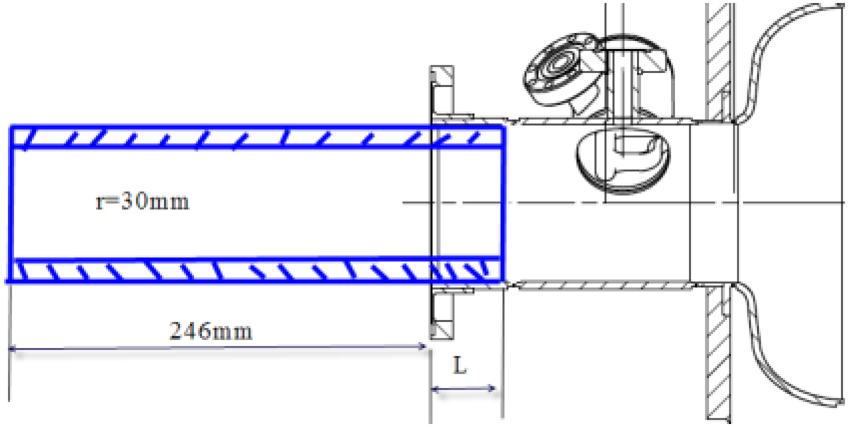
CEBAF 12 GeV Era
- TM111 π/7 mode with FPC Adapter -

Qs decreased considerably but close to threshold

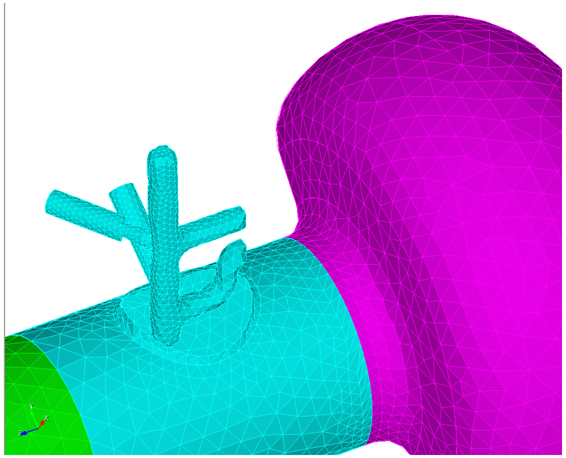


CEBAF 12 GeV Era
- Cryomodule End Cavity -

- Further improvement for cryomodule end cavity without design change ?
- proposal: use insert in beam tubes to adjust reflection favorably for HOM couplers
- needed SLACs massive parallel Omega3P FEA code to model the complex HOM coupler details required use of
- goal: optimize location in beam tube to maximize damping

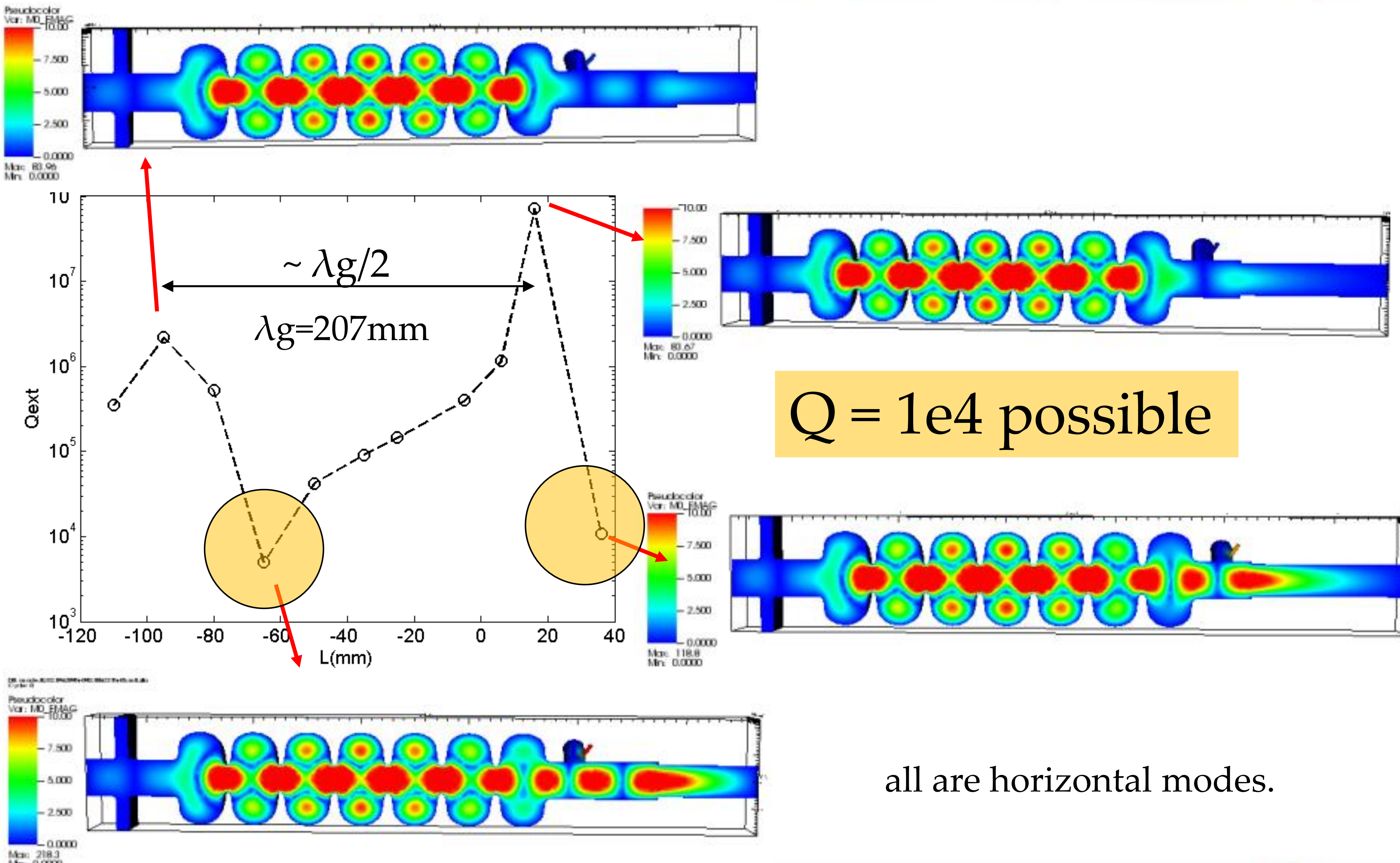


- beam pipe radius: 35mm
  → f_c = 2.51 GHz
- Step-down tube radius:
  → f_c = 2.92 GHz



Omega 3P FE meshing of HOM endgroup

CEBAF 12 GeV Era
- Improvement of HOM TM111 π/7 Mode Damping by Insert -



Q = 1e4 possible

all are horizontal modes.

CEBAF 12 GeV Era
- Summary -

- HOM damping of rather confined propagating mode is involved process, which needs to take into account the adjacent cavities
- tremendous alteration of parasitic mode Q observed depending on boundary conditions in VTA, cavity-pair configuration in HTB and cryomodule cavity position in cavity string
- provided relieving studies for endangered C100 cavity design
- cure in reach without design change
- need to take into account FPC as "HOM damper" doing double-duty as multi-modal absorber (CEBAF waveguide filter good candidate)
- need to check performance for TE20 mode more purely (need to damp vertically polarized mode as well)
- simulation indicates, that performance of cryomodule end cavity can be improved by simple insert