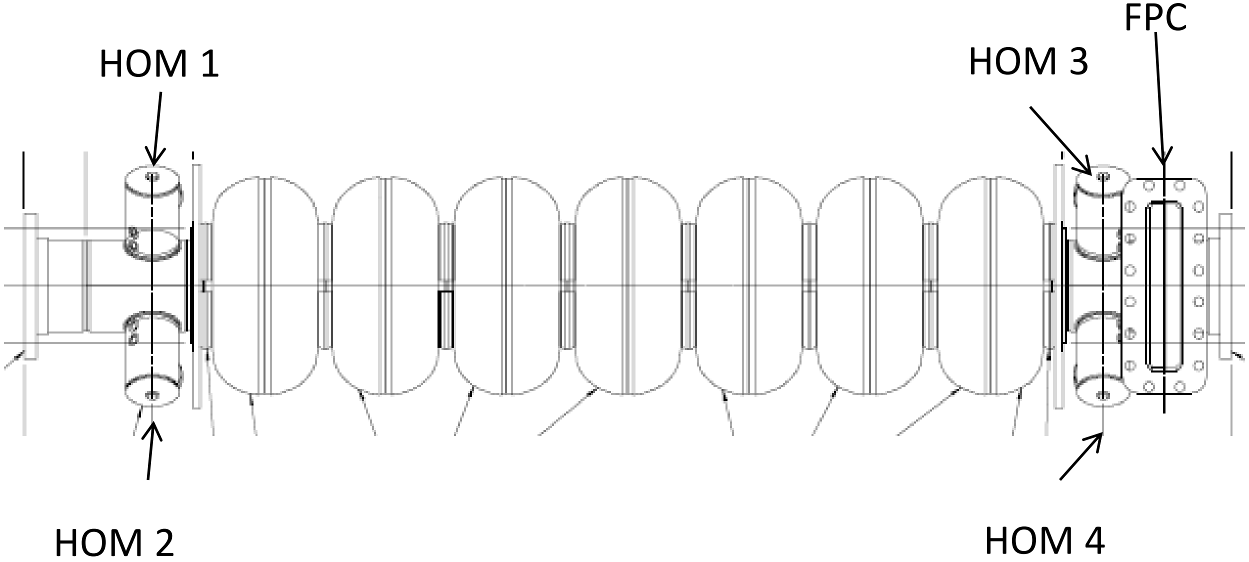
HOM Damping Sensitivity in SRF Cavities (as seen at JLAB)

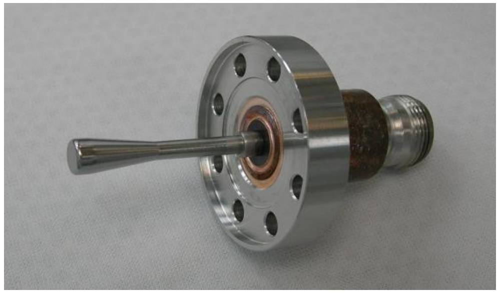
F. Marhauser
Jefferson Lab, Newport News, Virginia 23606, USA

HOM-Damping Workshop in SRF Cavities
11-13. October 2010

History: CEBAF upgrade cavity HOM damping concept

- CEBAF upgrade prototype cavities were originally equipped with four DESY/type coaxial couplers (2 each end) in so-called **Renascence** cryomodule prototyping 5 High Gradient (HG) and 3 Low Loss (LL) cavities in same cryomodule
- heating problems arised during the test period in the HOM coupler feedthroughs
  → resulted in premature cavity quenches when Nb probe tips went normal conducting





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- heating issue was resolved by utilizing Sapphire feedthroughs and improved thermal anchoring

WEP32 Proceedings of SRF2007, Peking Univ., Beijing, China

PERFORMANCE OF THE CEBAF PROTOTYPE CRYOMODULE *RENASCENCE* *

C. E. Reece, E. F. Daly, G. K. Davis, M. Drury, W. R. Hicks, J. Preble, H. Wang[#]
Jefferson Lab, Newport News, VA 23606, USA

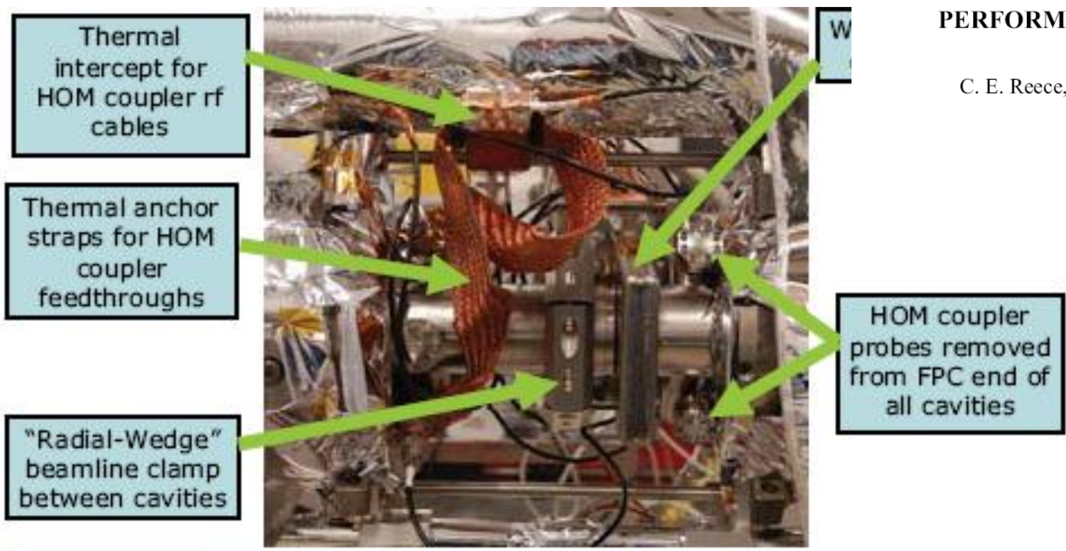

Figure 10. Final configuration of HOM probes and thermal anchoring in *Renascence*.

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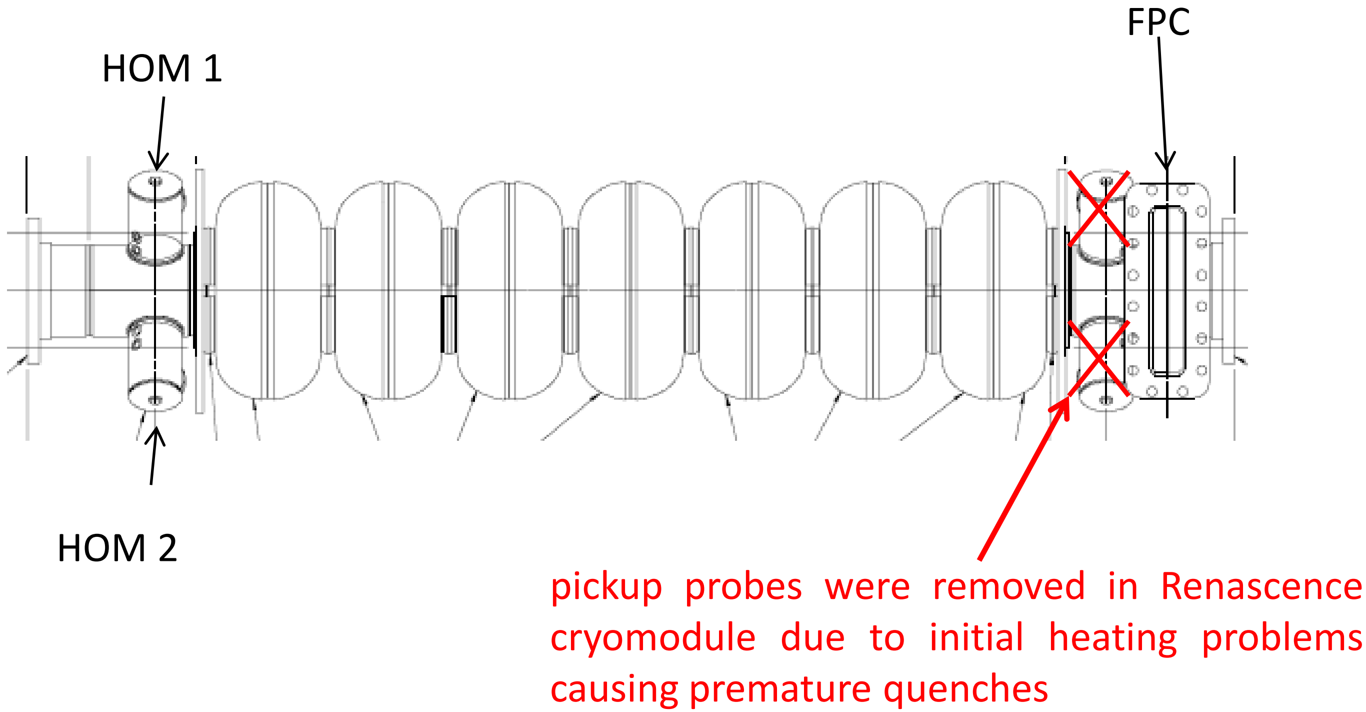

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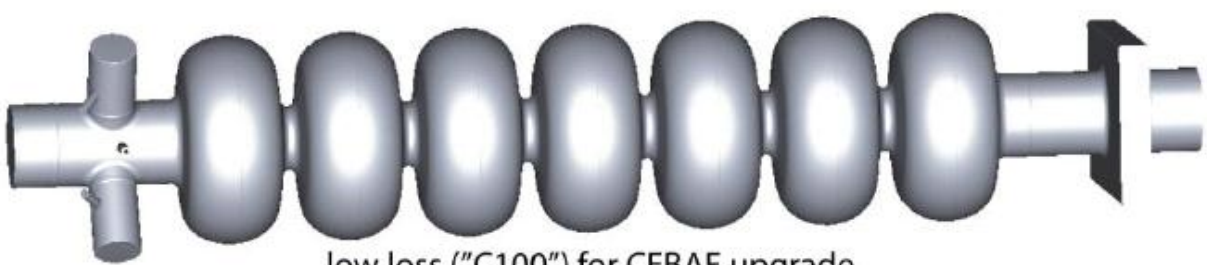
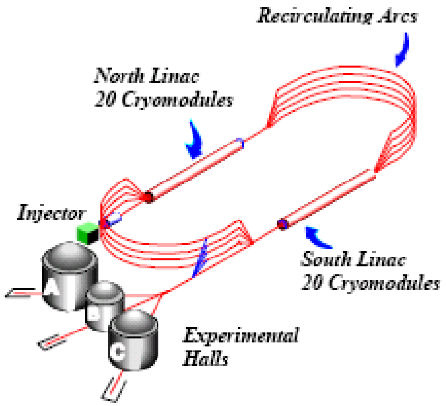
- heating issue was resolved by utilizing Sapphire feedthroughs and improved thermal anchoring
- however: **as a precaution the HOM probe tips on the FPC side were removed**
- it was relyed on adequete damping based on measurements (**however in non-final configuration**)
- for the final CEBAF LL upgrade cavity design it was decided to use the same damping concept
- **it it obvious that any HOM tilting effect (e.g. due to fabrication tolerance) can have tremendous consequences on mode damping**

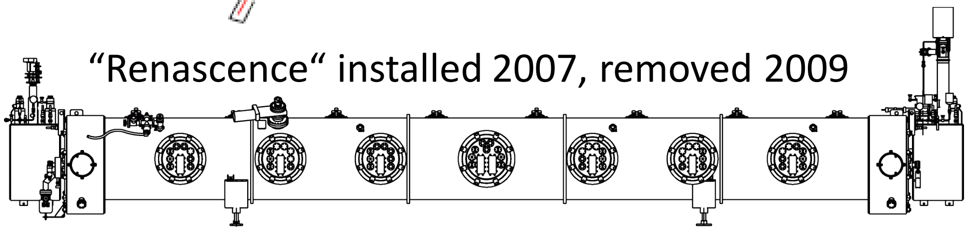


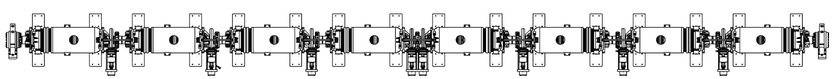
low loss ("C100") for CEBAF upgrade

Lesson Learned from Renascence
BBU in Upgrade Prototype Cryomodule



“Renascence“ installed 2007, removed 2009





EPAC 2008

OBSERVATION AND MITIGATION OF MULTIPASS BBU IN CEBAF*

R. Kazimi, A. P. Freyberger, C. Hovater, G. A. Krafft, F. Marhauser, T. E. Plawski, C. E. Reece, J. Sekutowicz, C. Tennant, M. G. Tiefenback, H. Wang,
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, U.S.A.

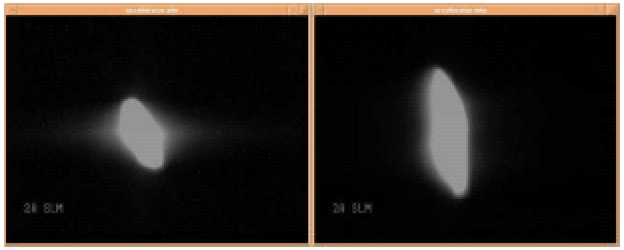


Figure 2: Beam spot well below BBU limit (left) and very close to BBU limit (right) on the SLM.

$$I_{th} = \frac{-2 p_1 c}{e k (R/Q) Q M \sin(\omega T_r)}$$

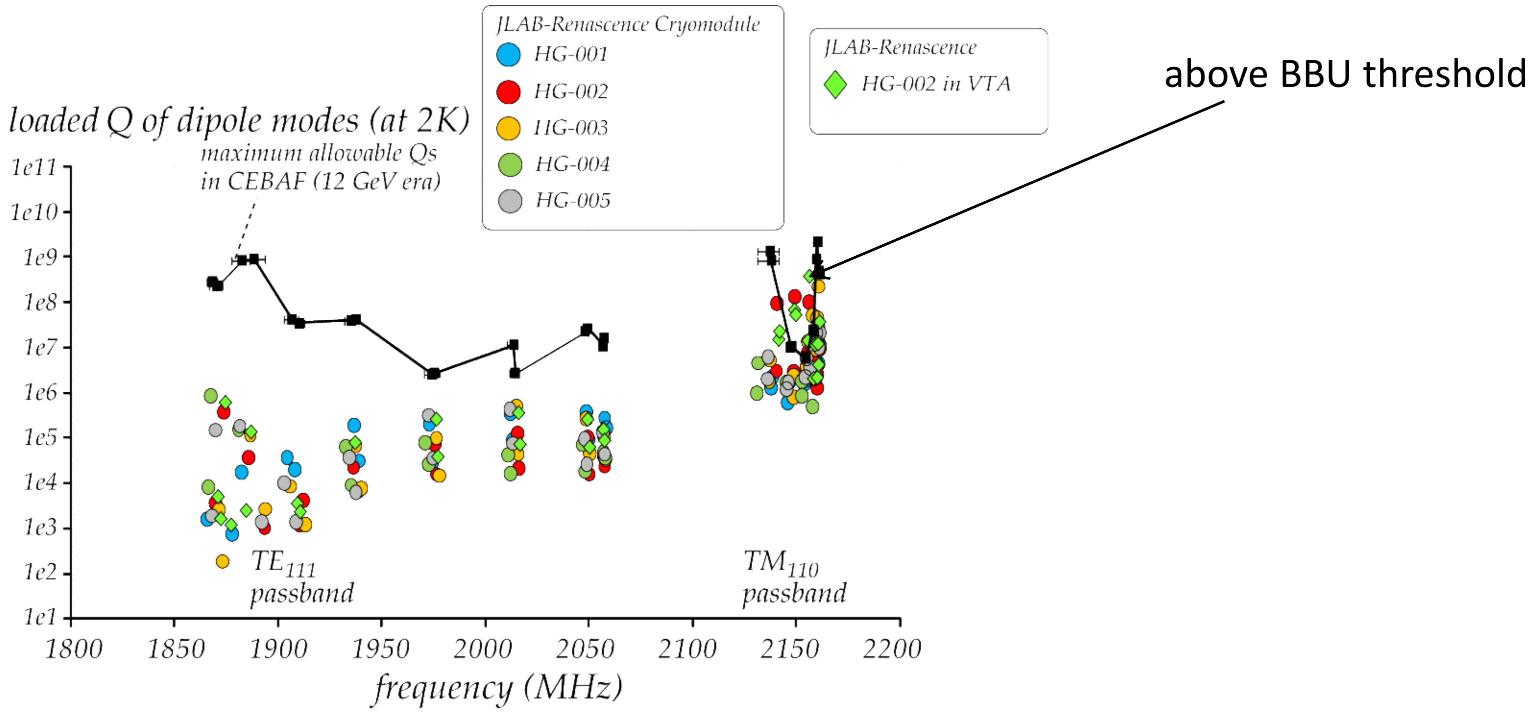
multiple passes:

$$M \sin(\omega T_r) \rightarrow \sum_{j}^{N} \sum_{i<j} M^{ij} \frac{p_1}{p_i} \sin(\omega T_r^{ij})$$

- ❑ culprit: single deformed cavity (**reason: fabrication tolerances/errors**)
- ❑ BBU I_{th} as low as 40 µA injected beam (CEBAF design 200 µA peak, expected BBU threshold 20 mA)
- ❑ only good thing: BBU theory has been verified for the first time

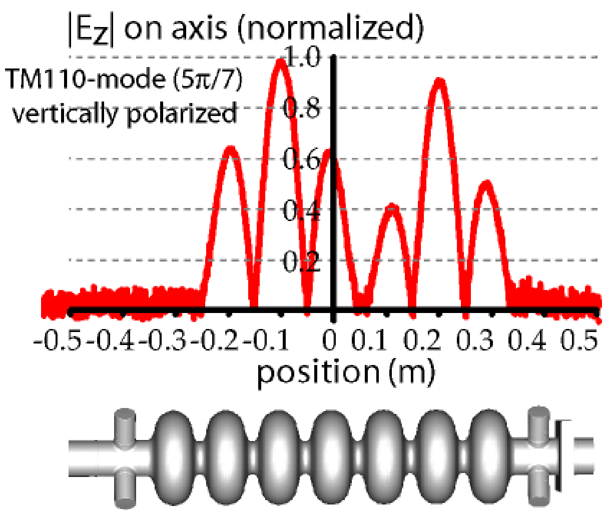
What happened to cavity HG002 ?

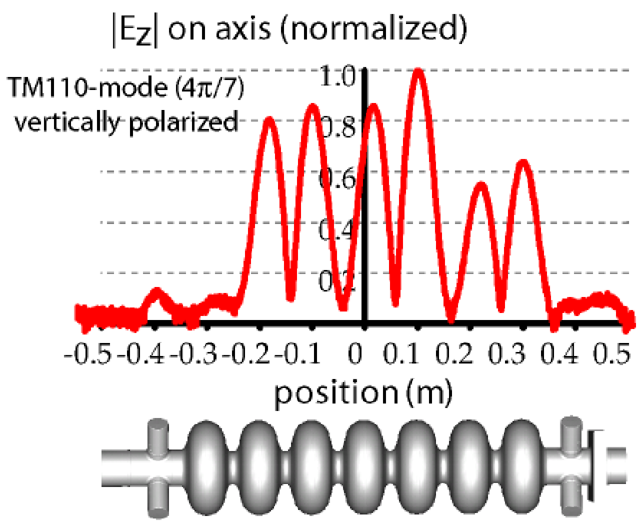
- single HG cavity (HG002) has received 2nd beam weld to repair equator hole → cell shrunk further
  - → initial fundamental mode field was very unflat
  - → required heavily tuning to achieve field flatness, especially the at shrunk cell
- effect on HOMs were not considered and cavity was installed in cryomodule
- loaded Q measurements were performed in aftermath of BBU
  - → **revealed ~3 orders of magnitude higher Qs** than expected
  - → Qs of trapped TM110 modes above BBU threshold



What happened to cavity HG002 ?

- Renascence was removed from CEBAF in 2009 and cavities were inspected
- field profile measurements were done on HG002
- **outcome: deformed cell created tilted HOM fields with essentially no field at HOM couplers**
  → two dipole modes (formerly TM110, 4π/7 and 5π/7) caused **vertical** BBU





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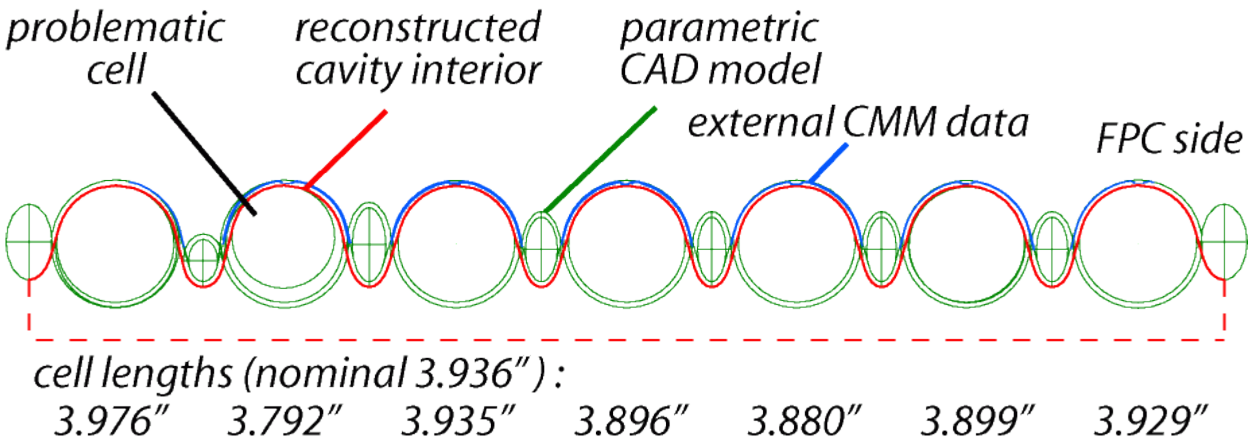

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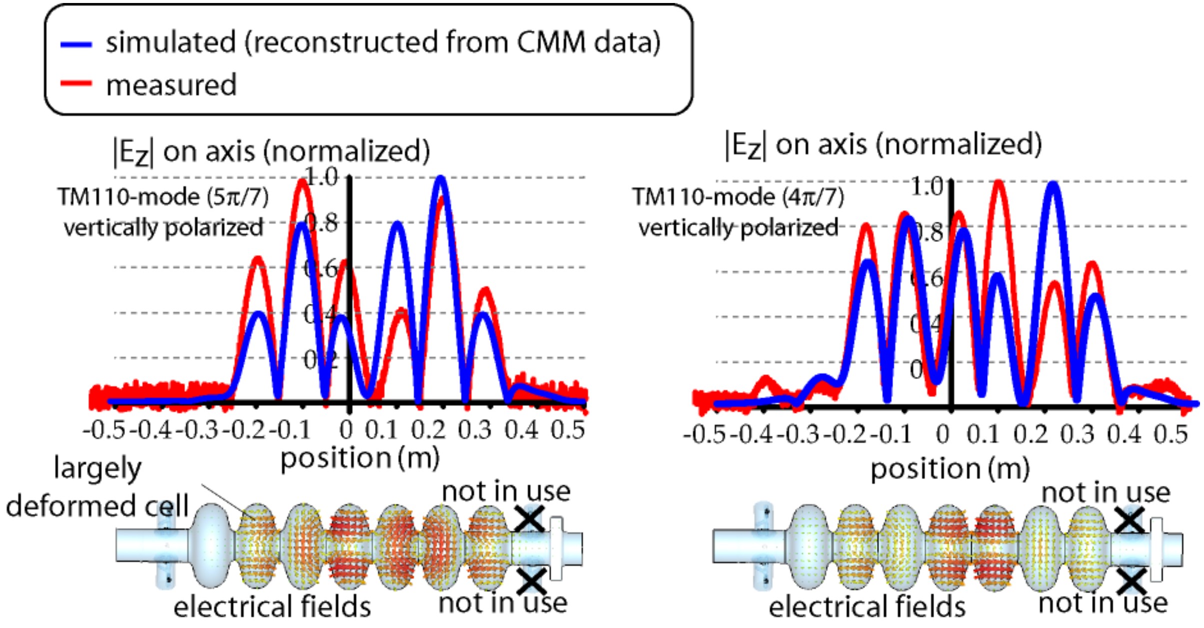

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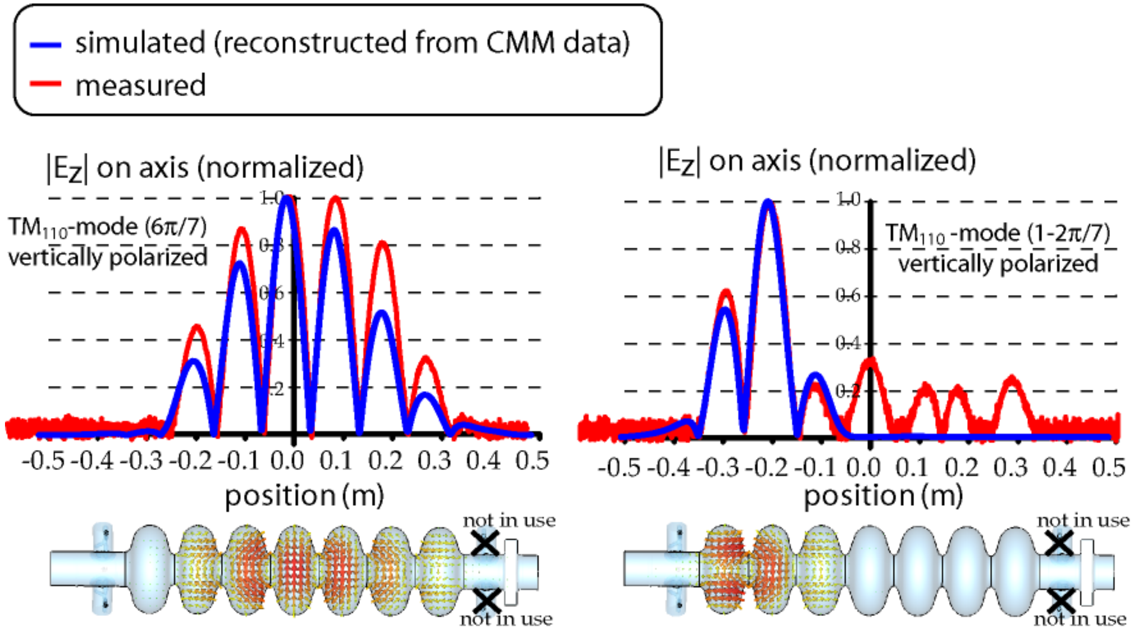
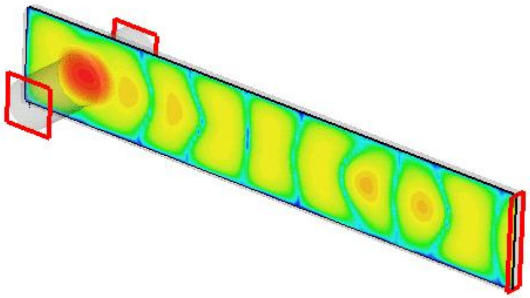
- the deformed cavity shape was reconstructed (outer cell contour measured by CMM) for numerical modeling
  →well agreement with experimental findings
  →many other modes tilted as well



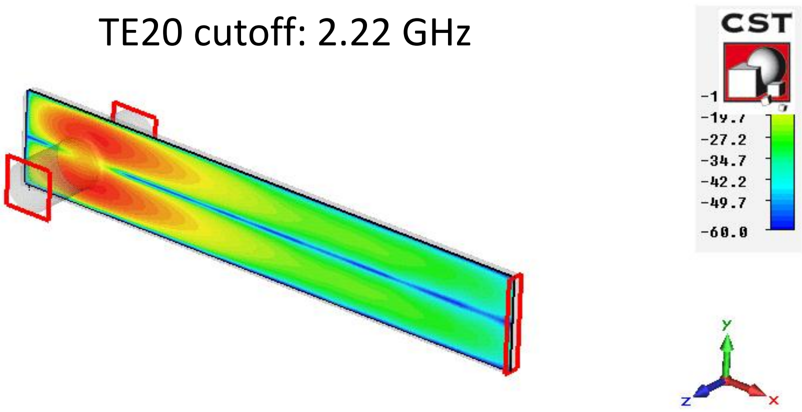
Beneficial help of fundamental power coupler (FPC)

- all horizontally polarized modes were tilted in same manner, could as well excite BBU, why not?
- power coupler points in horizontal direction
- **horizontally polarized dipole modes couple to TE10 waveguide mode**
- **vertically polarized dipole modes couple to TE20 waveguide mode**
- **BBU modes resonate at 2.15 GHz just below TE20 mode cutoff**
  → vertical modes cannot be damped adequately in this case

TE10 cutoff: 1.11 GHz



TE20 cutoff: 2.22 GHz



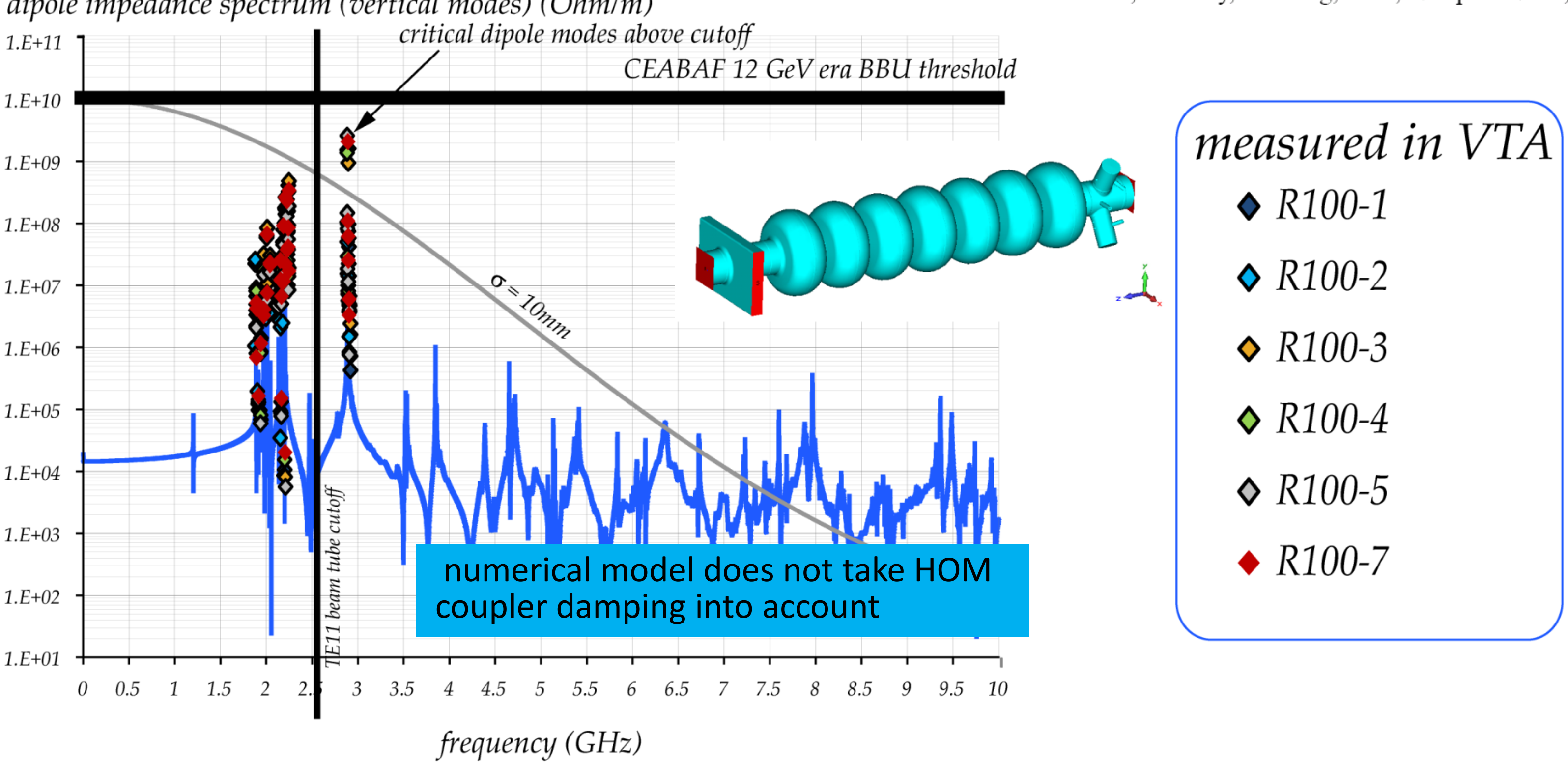
How sensitive are other modes ?

- ❑ **critical dipole modes (400 MHz above cutoff) are BBU limiting modes**
- ❑ damping depends strongly on boundary conditions
- ❑ fabrication tolerances can easily "melt down" **margin to BBU threshold**
- ❑ **how to control this issue?**

LINAC 2010

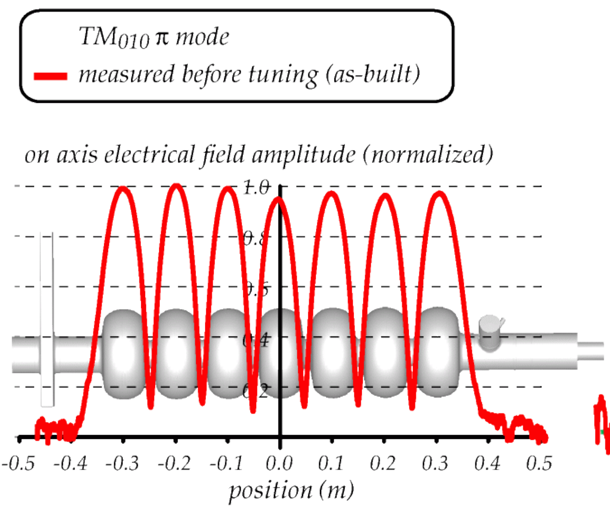
CRITICAL DIPOLE MODES IN JLAB UPGRADE CAVITIES*

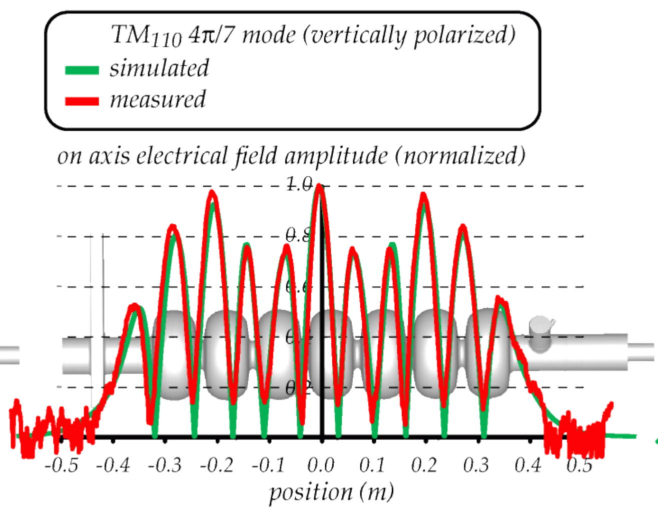
F. Marhauser, J. Henry, H. Wang, JLab, Newport News, Virginia, U.S.A

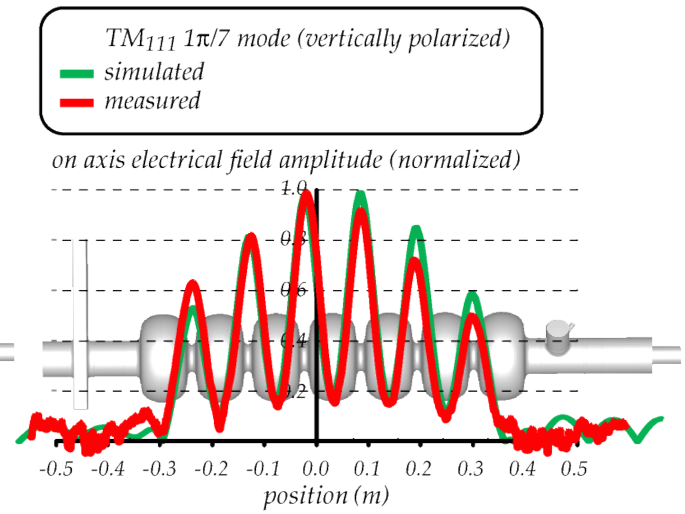


In the BBU aftermath more effort spent on critical modes

- **critical dipole modes (400 MHz above cutoff) are BBU limiting modes**
- damping depends strongly on boundary conditions
- fabrication tolerances can easily "melt down" **margin to BBU threshold**
- **how to control this issue?**
- these "R100" CEBAF upgrade type cavities are latest in-house fabrication
  1) **built very field flat and close to tune at the same time**
  2) **built with caution to obtain symmetric fields to avoide tilted HOM fields as far as possible**
- example: R100-1 as built fundamental mode and most critical dipole HOMs

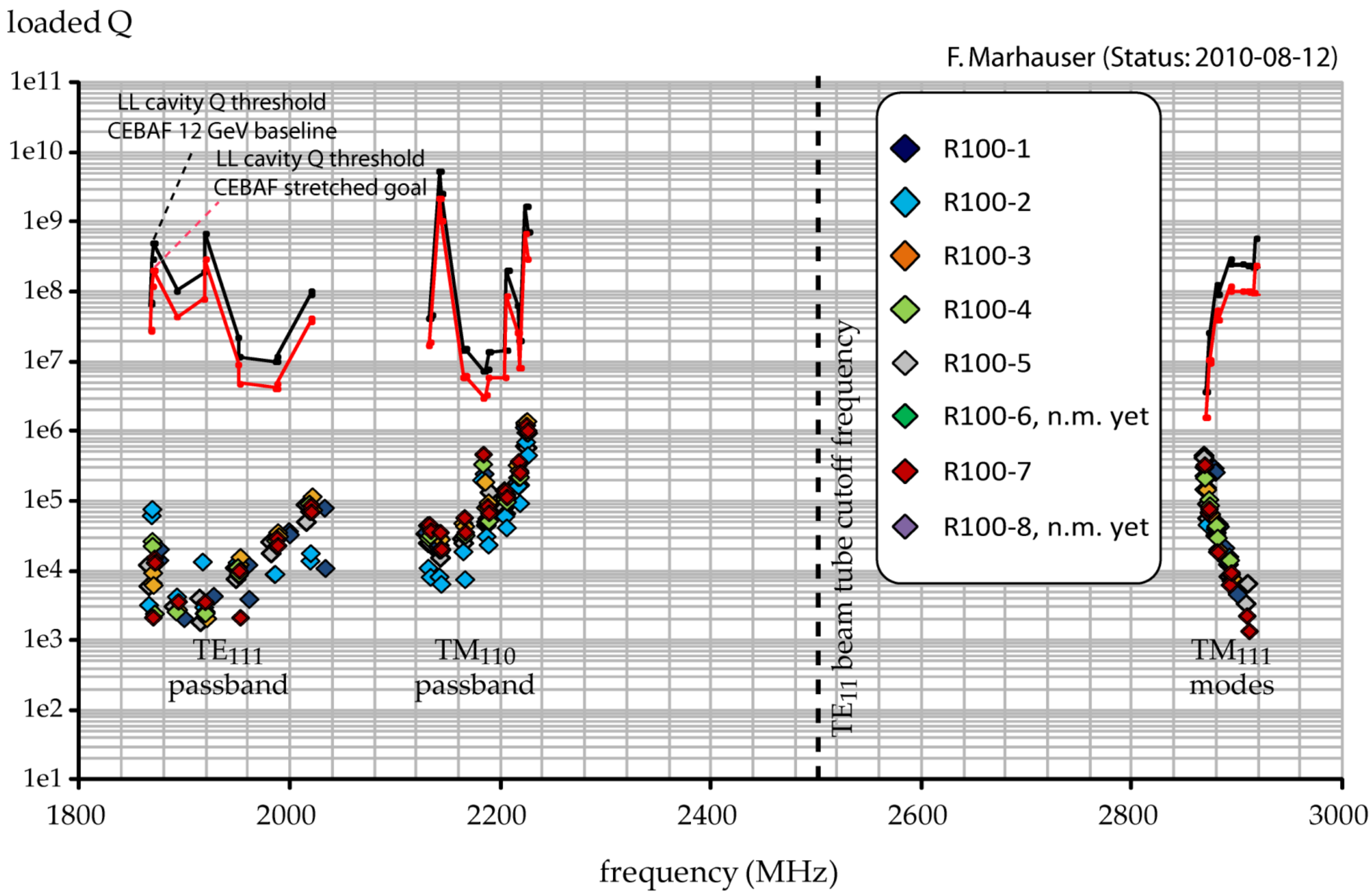






Controlled HOM damping among R100 cavities due to thourough cavity fabrication

❑ benefit: guarentees more repetitive damping performance

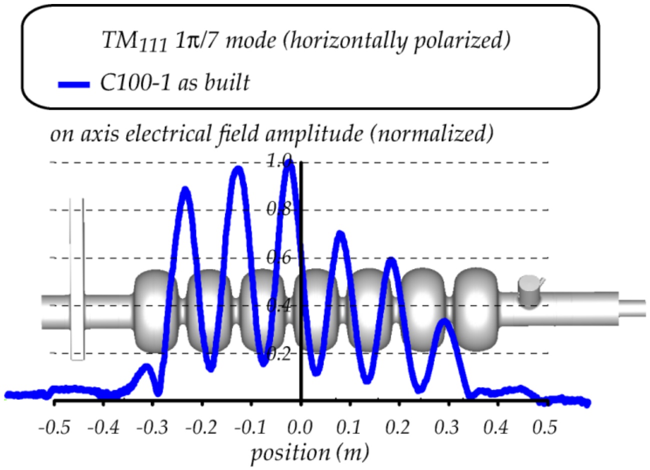


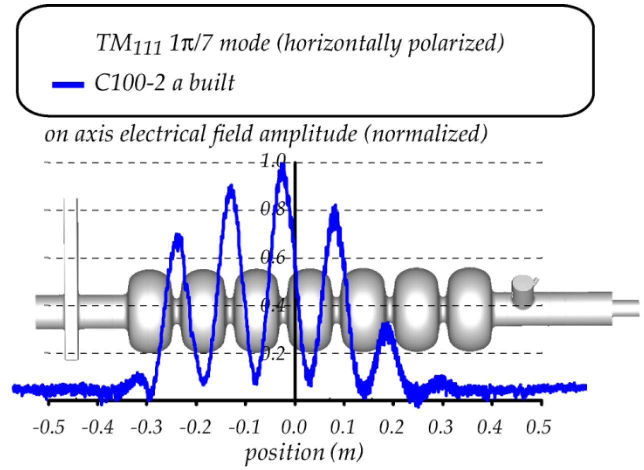
CEBAF Upgrade Type Cavities “R100“ built in-house

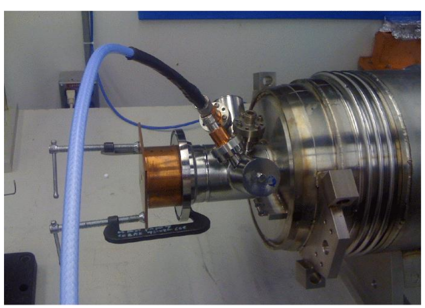
CEBAF Upgrade Type Cavities R100	**deviation from warm target frequency (MHz)**	**as-built field flatness in % from average**
R100-1 1st cavity used for frequency calibration of following sequence	1.58	-2.8/2.5
R100-2	-0.03	-6.4/3.5
R100-3	0.07	-3.8/2.8
R100-4	0.10	-5.5/12.6
R100-5	-0.04	-5.8/7.1
R100-6	0.22	-4.7/10.1
R100-7	0.05	-7.5/5.1* after chemistry
R100-8	0.32	-3.4/2.7 * after chemistry

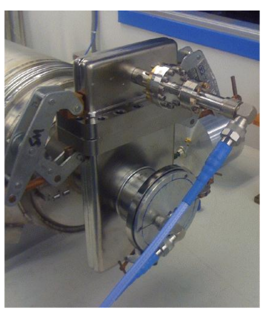
What if fabrication is not well controlled?

- first two in-house built cavities C100-1 and C100-2 showed tilted dipole modes at 2.9 GHz



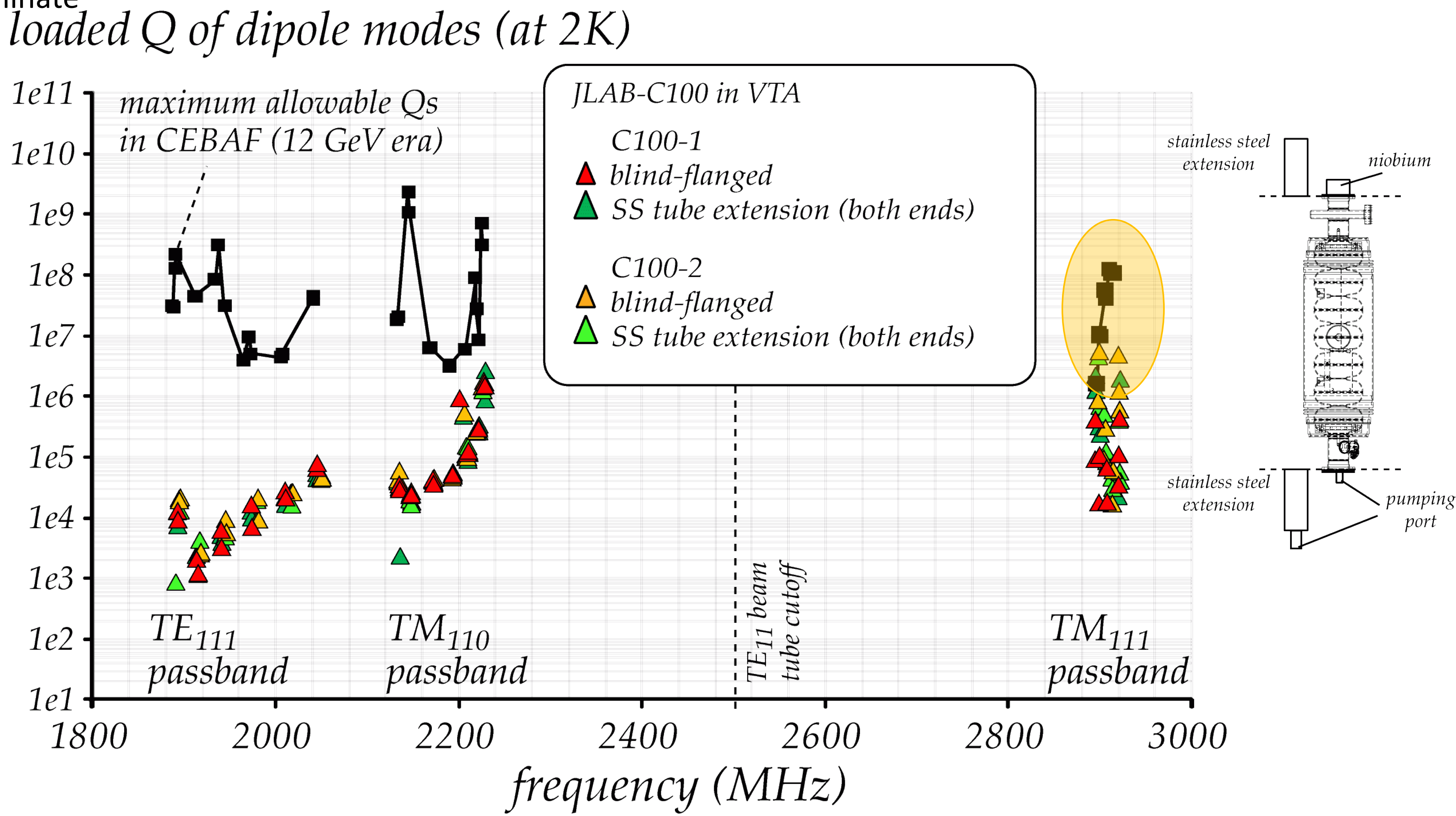






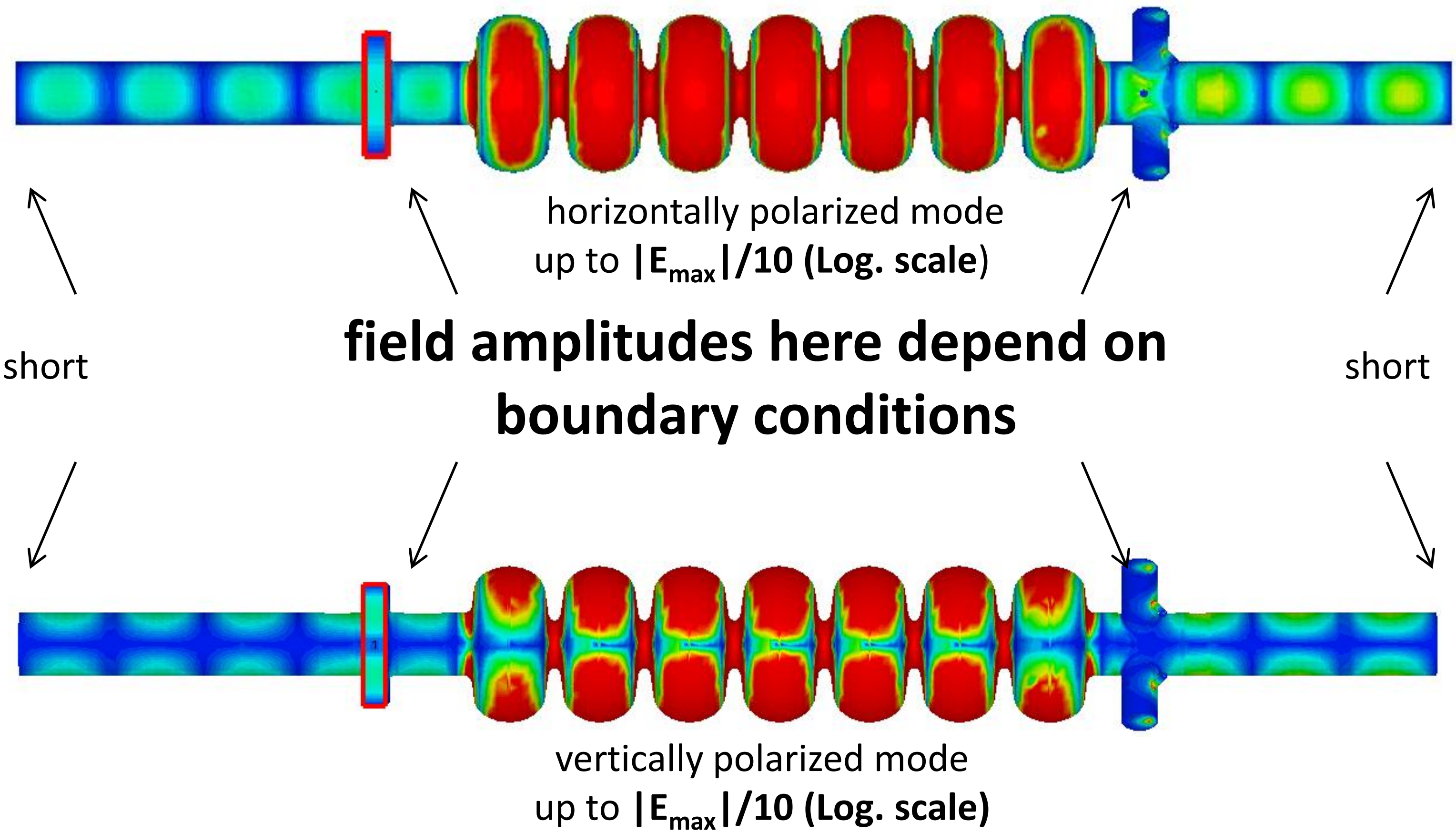
What if fabrication is not well controlled?

- the 2nd HOM survey with normal conducting (SS) tubes showed no remedy → wall losses do not dominate



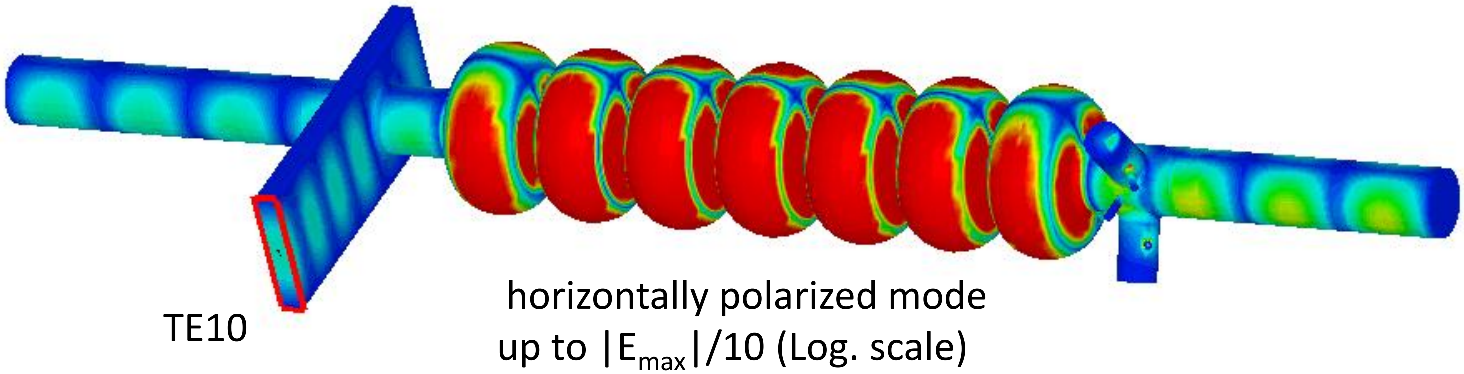
Eigenmode simulations for critical propagating TM111 π/7-mode fields

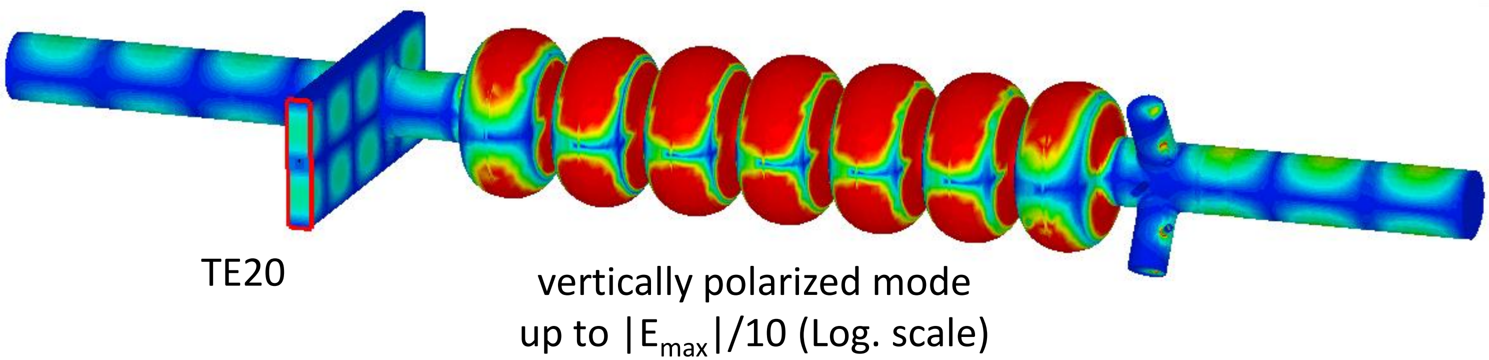
- beam tube boundaries play important role on how fields couple to both the HOM couplers and the FPC



Eigenmode simulations for critical propagating TM111 π/7-mode fields

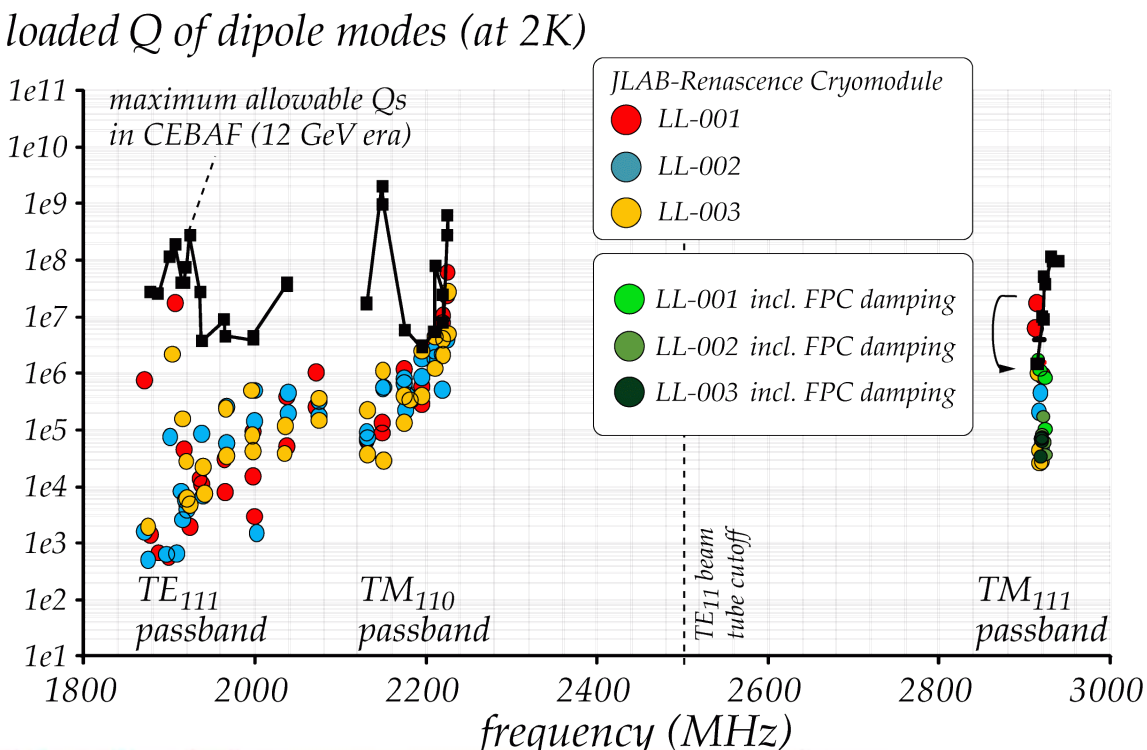
- from a different angle: **coupling through FPC may become very important when coaxial HOM couplers are not efficient**

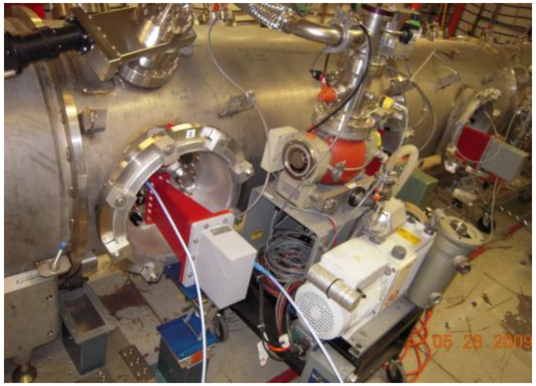




Now we know that bounday conditions matter: What may happen in string of cavities/cryomodule?

- HOM survey in full upgrade type cryomodule "Renascence" performed
- large fluctuations in damping found even for trapped modes (up to 2 orders of magnitude)
- **many critical HOMs found in LL cavities (not only HG002)**
- **LL-001 (end in string) shows elevated Qs**





adapter on FPC waveguides used for measurements

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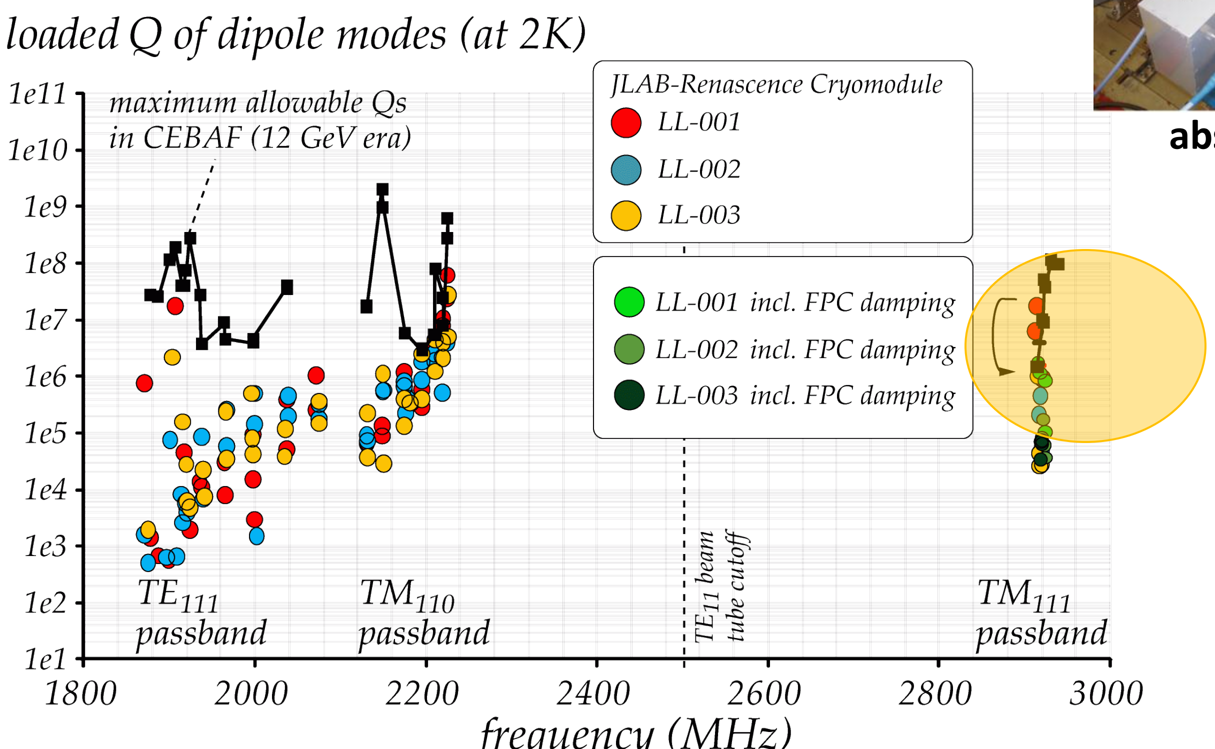
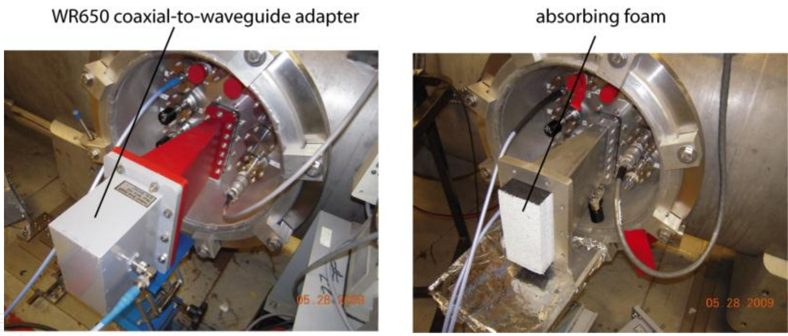
- large fluctuations in damping found even for trapped modes (up to 2 orders of magnitude)
- **many critical HOMs found in LL cavities (not only HG002)**
- **LL-001 (end in string) shows elevated Qs**
- abersorber was placed in FPC waveguide
  →verified damping via FPC is crucial

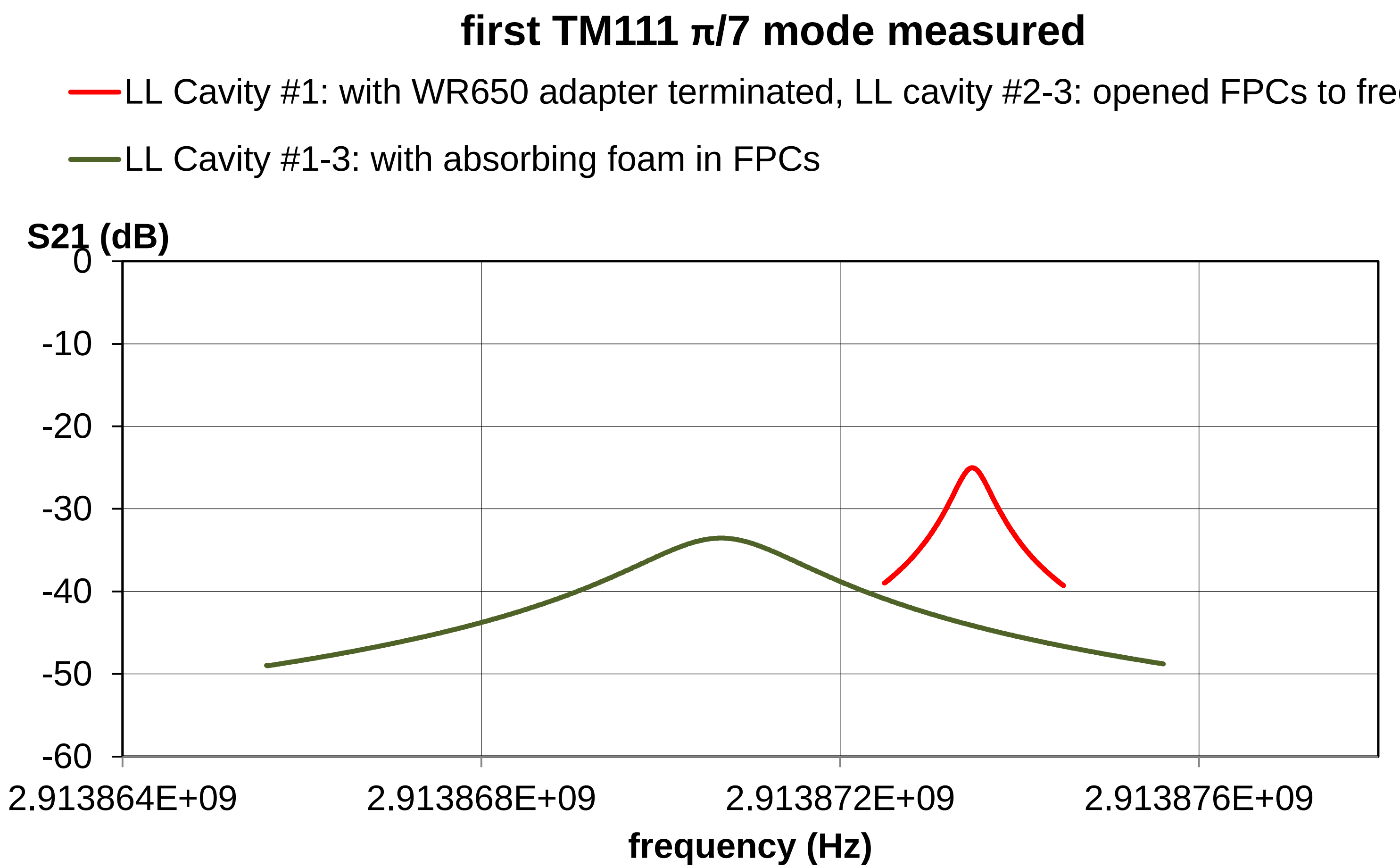




absorber placed in FPC waveguide

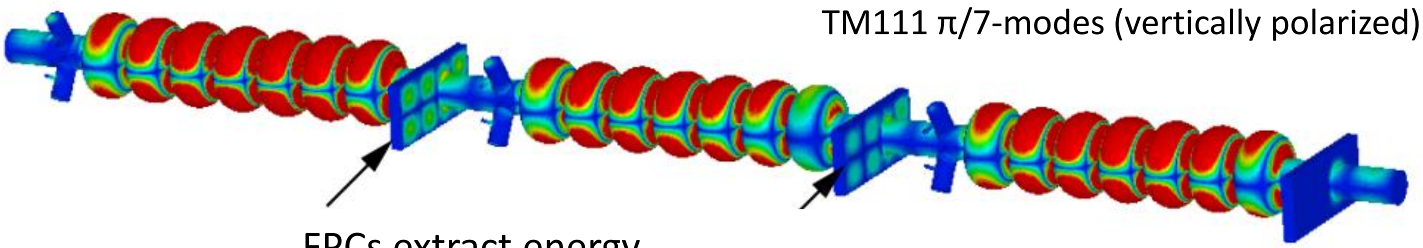
modes now just below BBU threshold

Renaissance cavity measurements
- problematic mode above cutoff w/o and with foam in FPC -

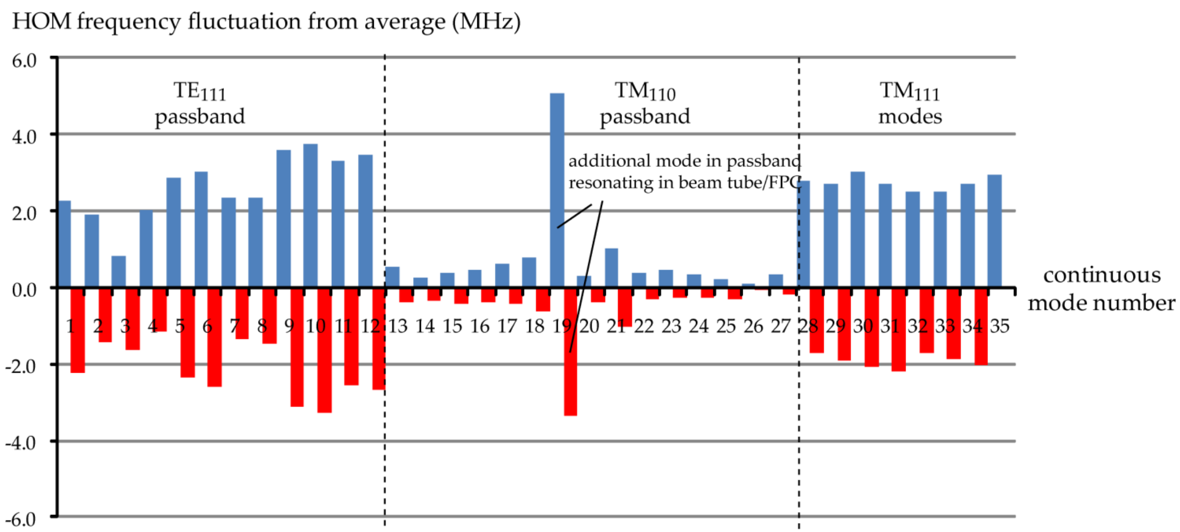


Trying to resemble real world, i.e. simulations for a short string

- "**resonant case**" for critical propagating TM111 modes:
  → every cavity same resonance is highly very unlikely

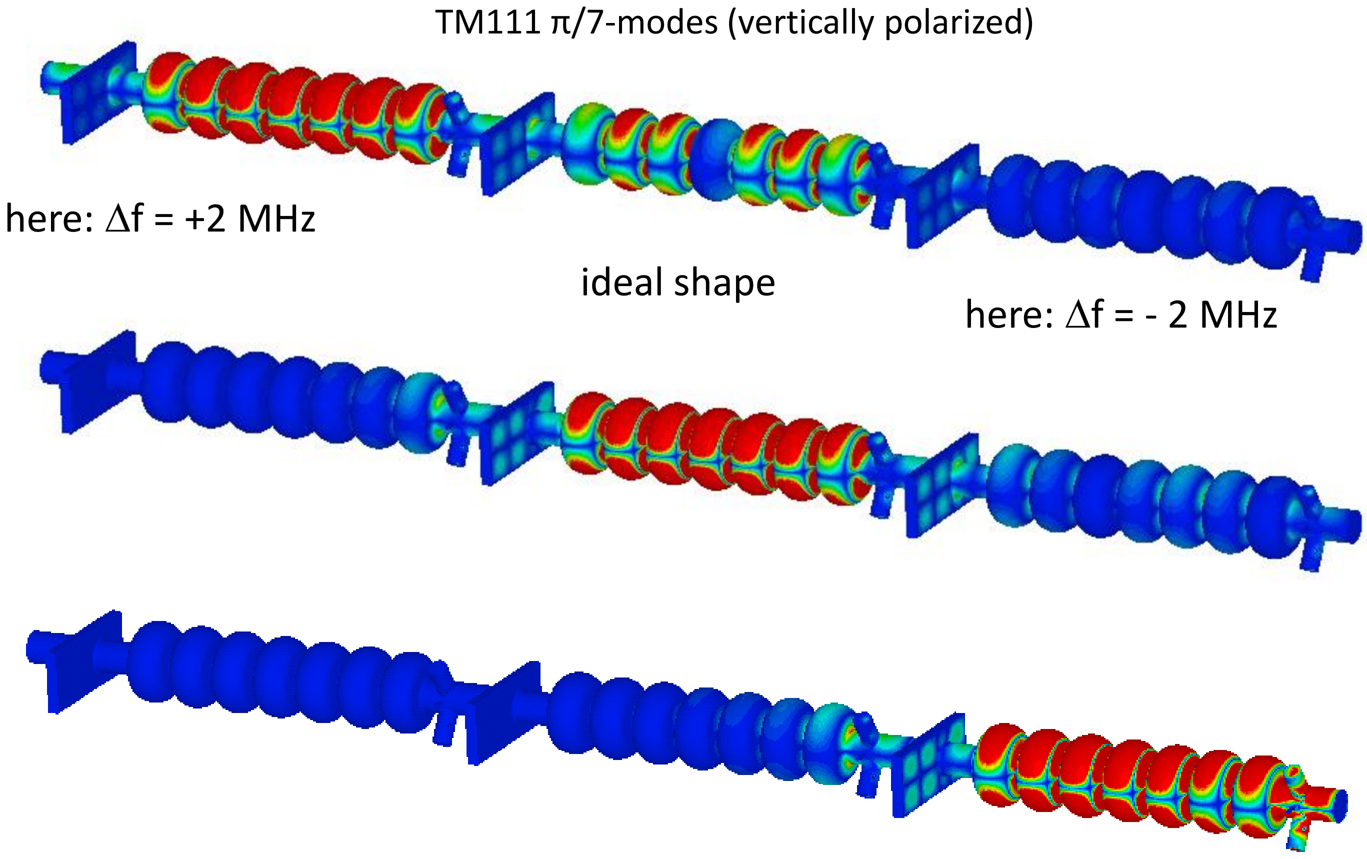


- **cavity frequency variation measured among individual R100 cavities**



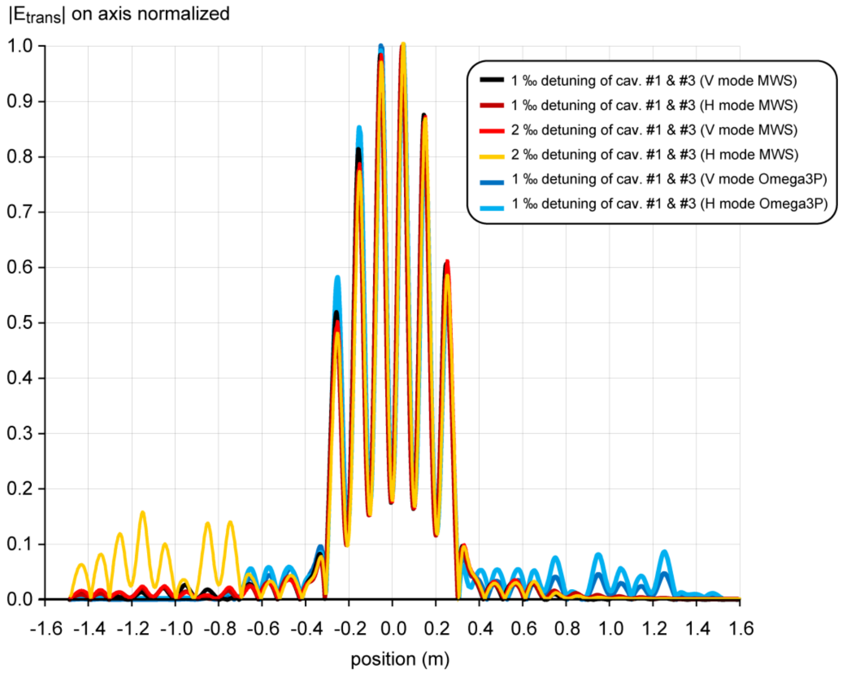
Trying to resemble real world, i.e. simulations for a short string

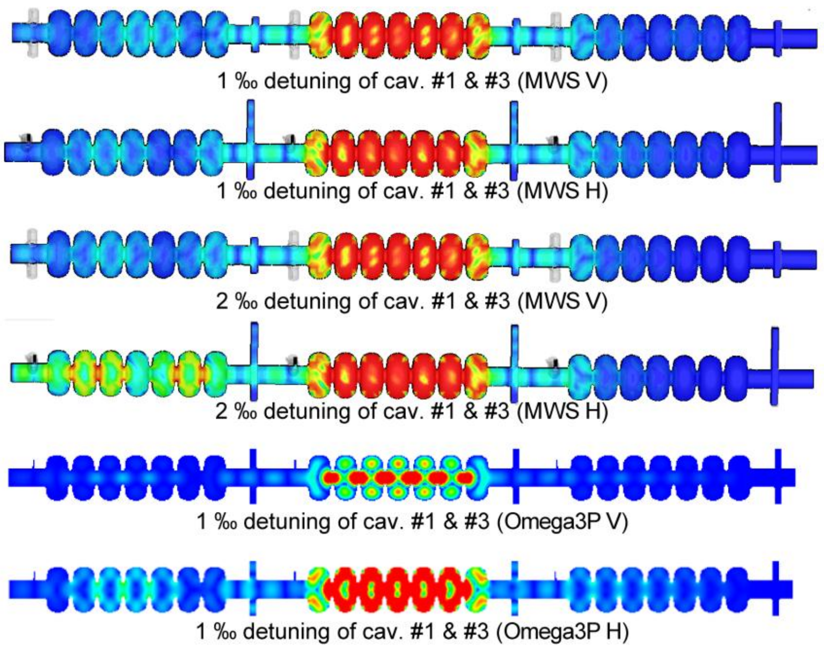
- ❑ "**detuned case**" for critical propagating TM111 modes:
  → detune outer cavities by realistcal 2 MHz with respect to center cavity



Fields for sandwiched cavity

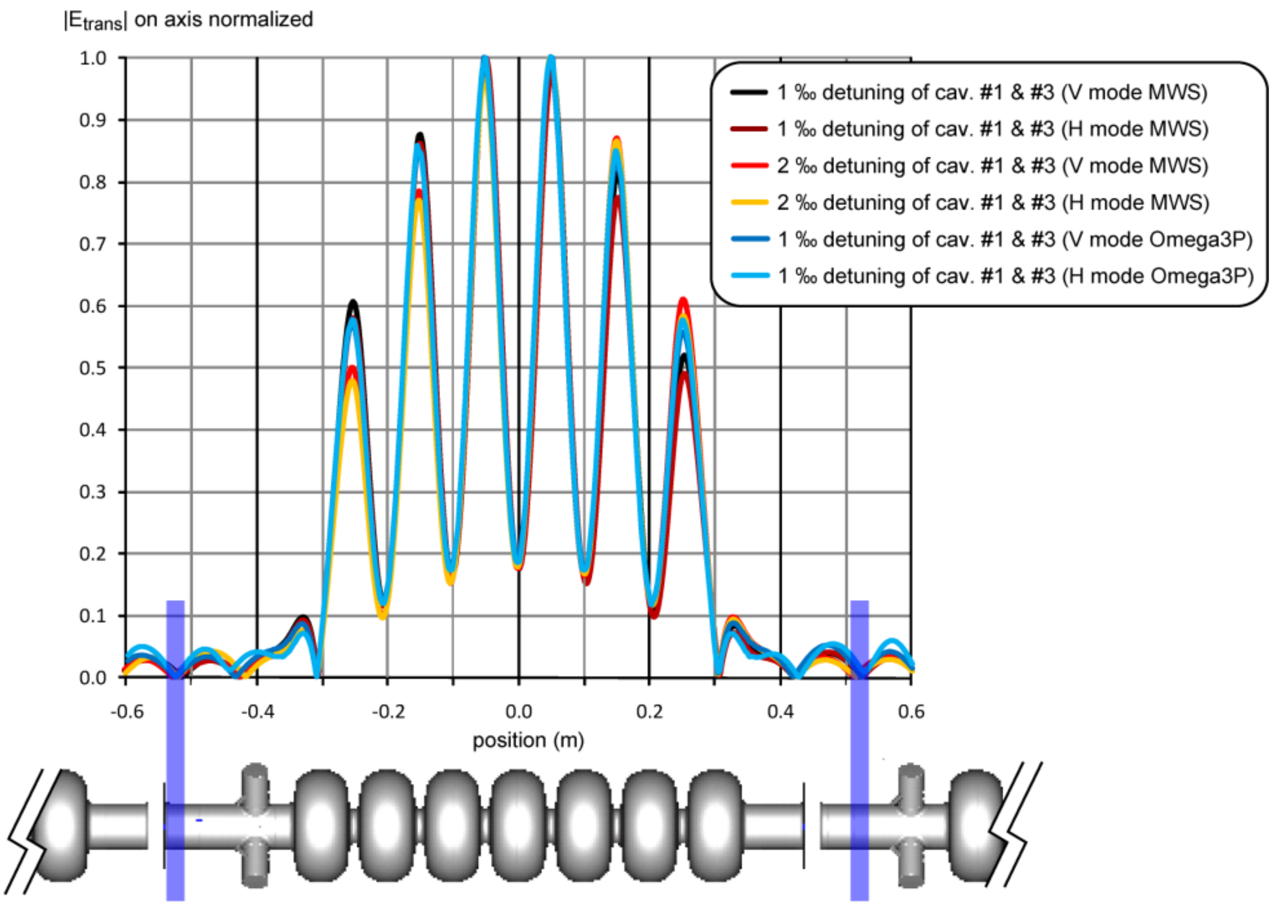
- **standing wave pattern** are forming in interconnecting beam tube **depending on detuning of cavities**
- this can alter HOM damping efficiency at HOM coupler locations





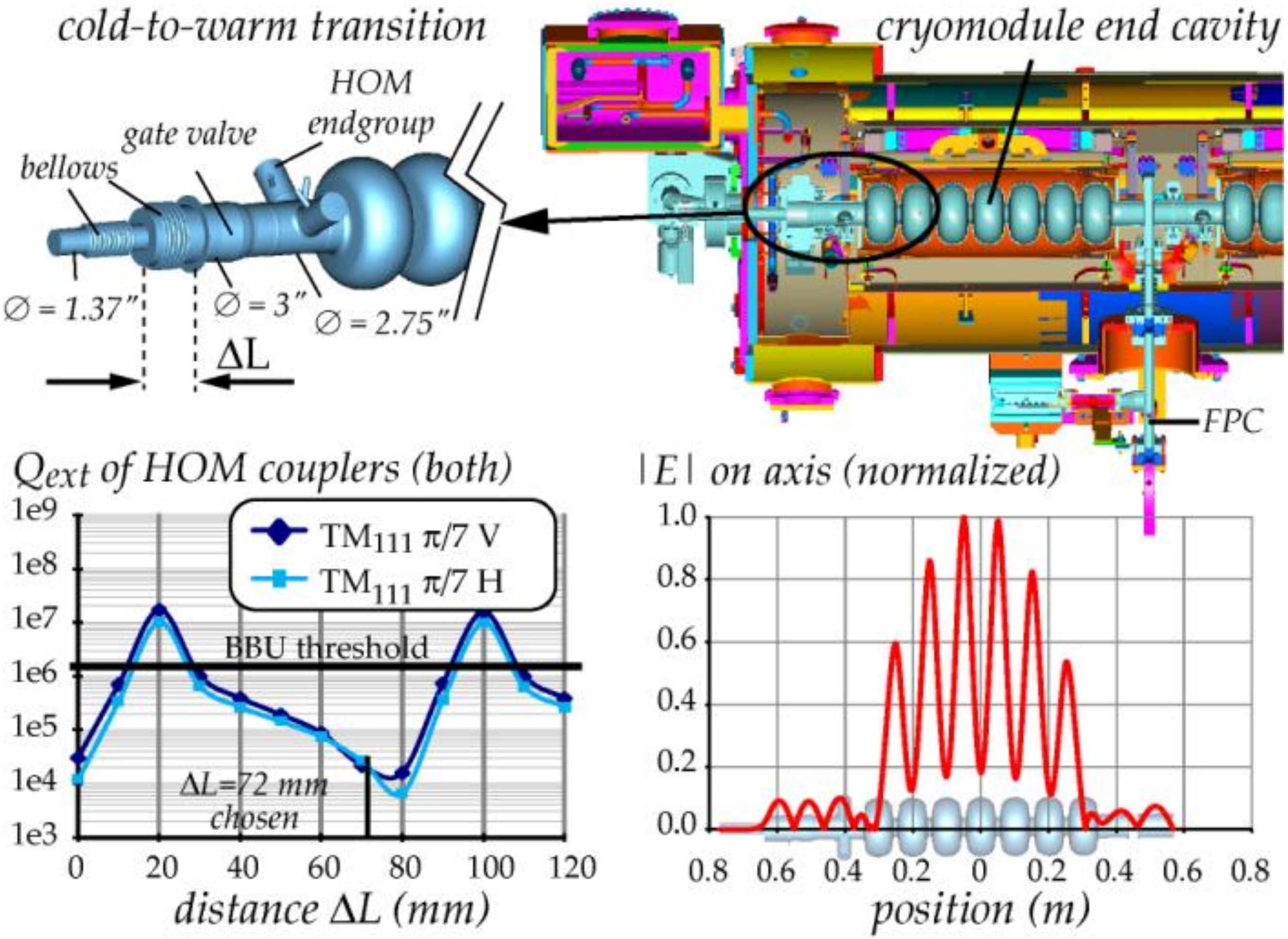
Fields for sandwiched cavity

- closer look: the variation of the standing wave minima/maxima is ~ ±1cm in this case



How to use this for our benefit?
- at least for cavities at end of cryomodule -

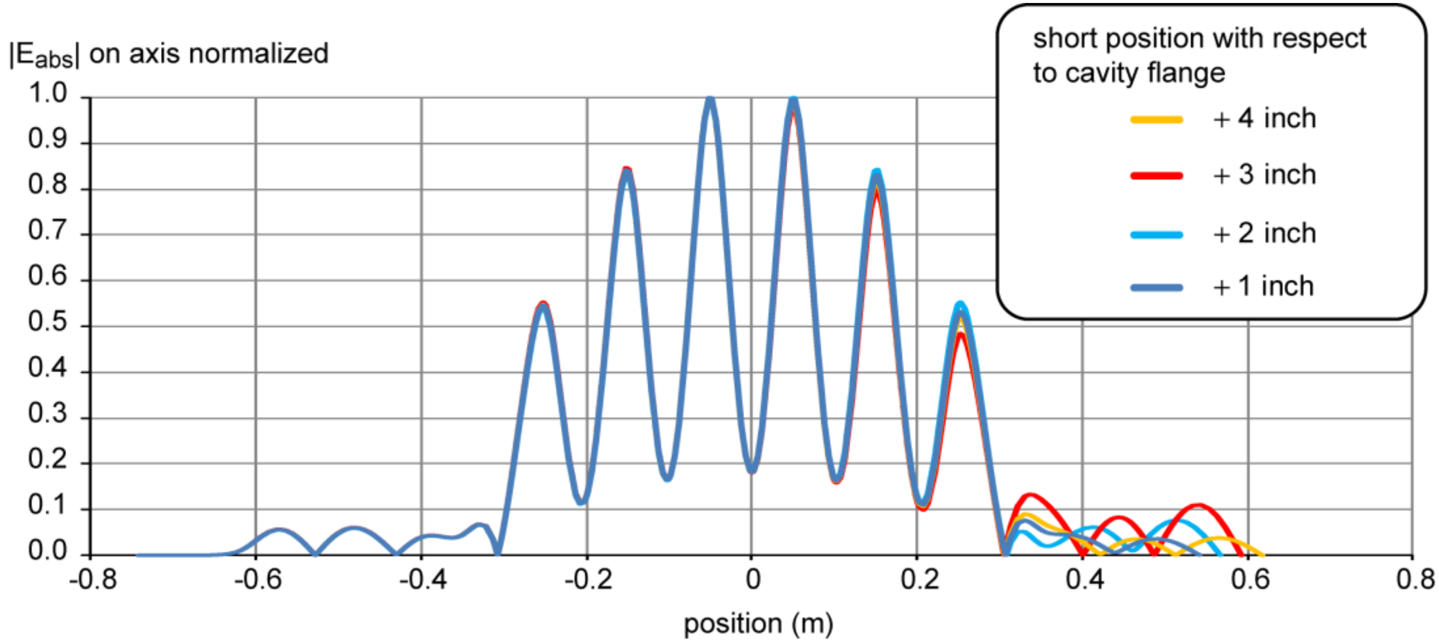
- ❑ end tube length was optimized to maximize HOM coupling (SLAC's Omega3P used on supercomputer)
- ❑ **note: Q_{ext} spans 3 order of magnitude**



How to use this for our benefit?
- at least for cavities at end of cryomodule -

- ❑ it was verified that variations on inner side (adjacent cavity) do not alter conditions on end
- ❑ scheme supposed to work (proven in VTA)
- ❑ it is unknown though what happens if fields are tilted in cavity due to fabrication errors

→ a new quality assurance has been established to check all 80 (+6 spares) CEBAF upgrade type cavities currently in production for tilted HOMs and avoid installation of any problematic cavity
→ 12 already delivered, some already show tilted fields and need Q measurements in VTA...



Other Example: ILC HOM coaxial coupler optimization

SLACs Advanced Computation Department

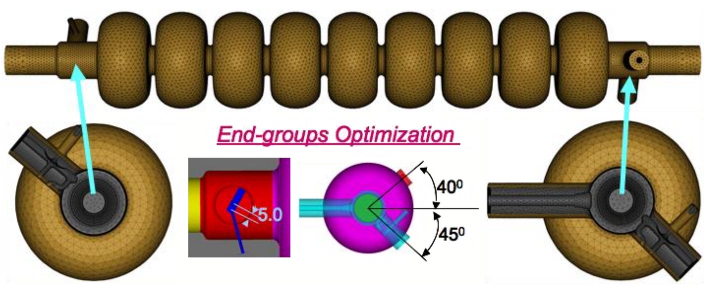
http://www.slac.stanford.edu/grp/acd/omega3p.html

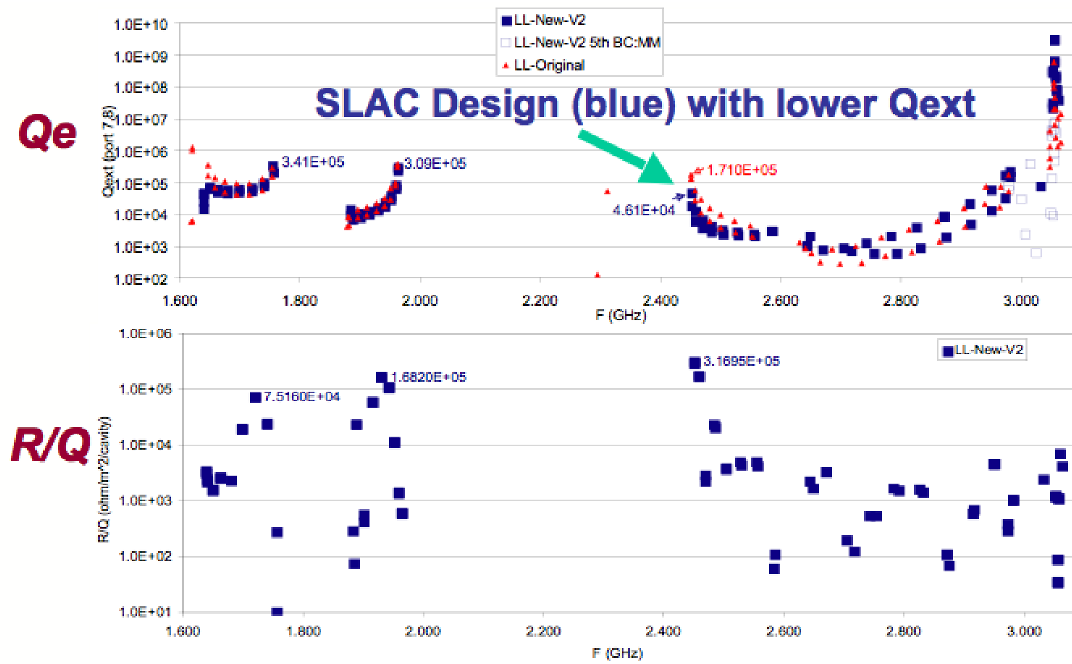
- ❑ Endgroup optimization for Low-Loss ILC cavity design

→ **direct use of High-Order-Mode (HOM) couplers provide inadequate HOM damping**

→ several dangerous modes found in the 3rd dipole band from high-resolution simulations using Omega3P

1.3 GHz ILC cavity

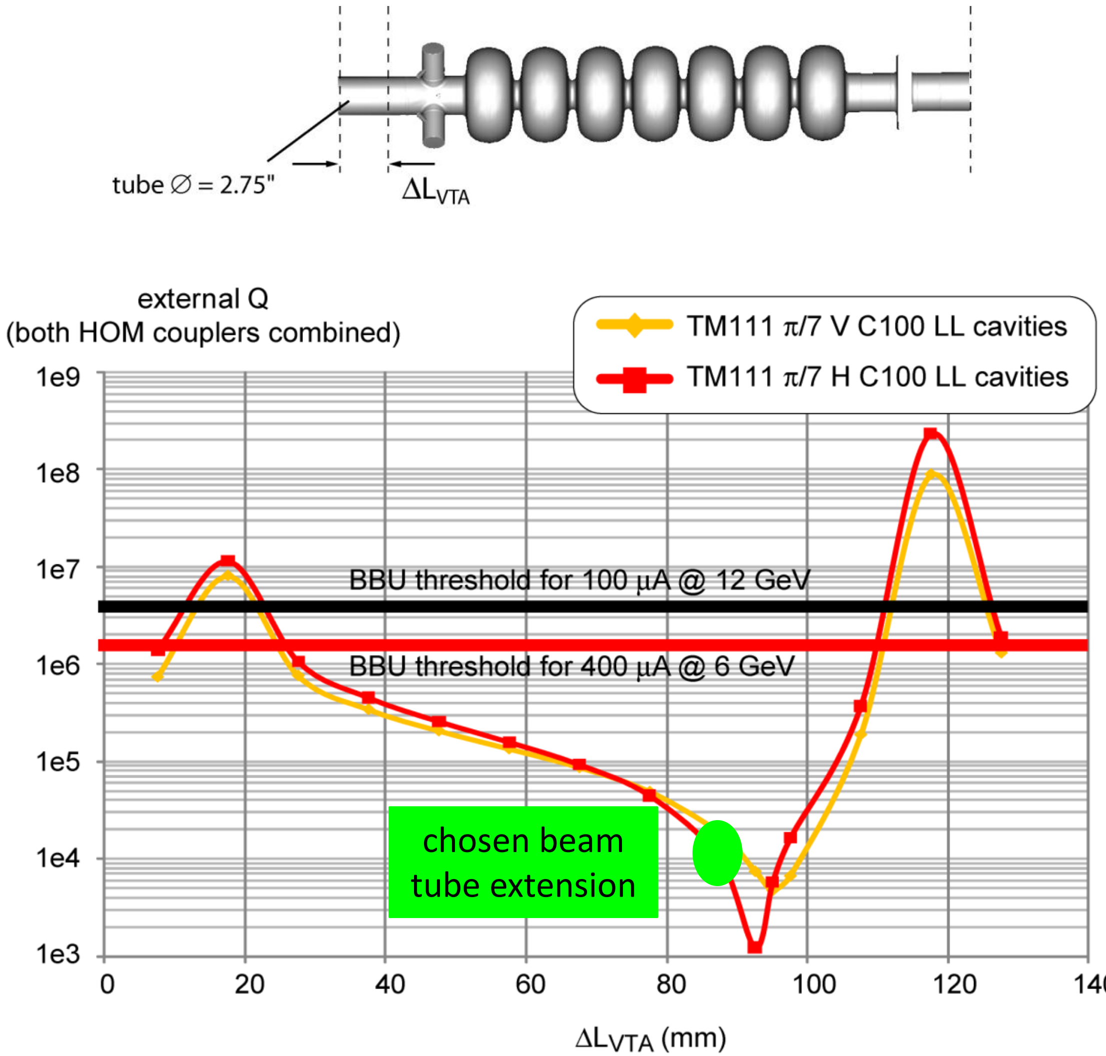




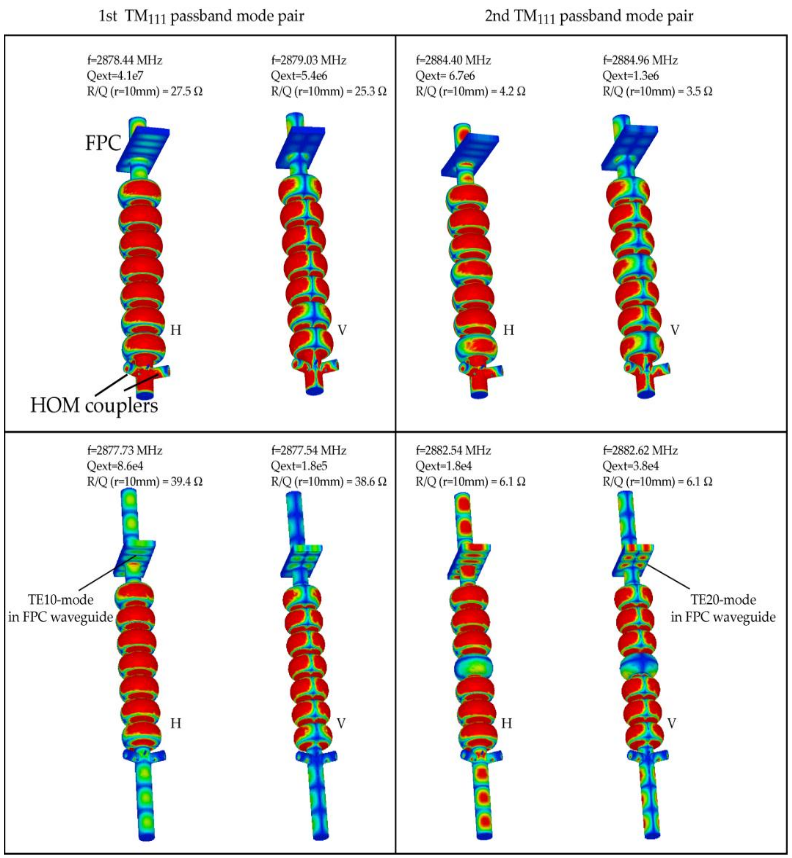
Thank You !

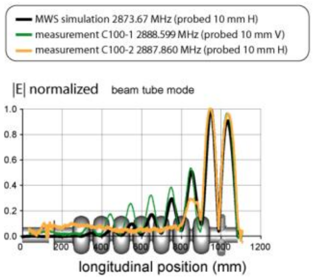
Backup Slides

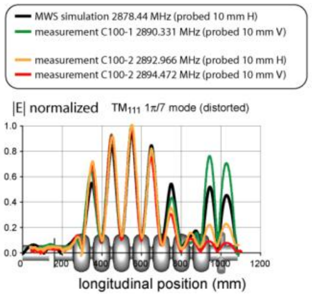
Optimized Tube length for VTA measurements

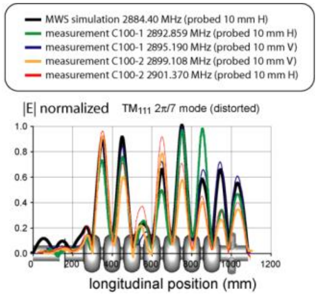


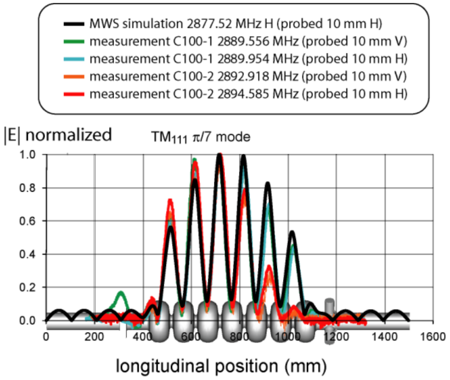
Eigenmode simulations for critical propagating TM111 π/7-mode fields



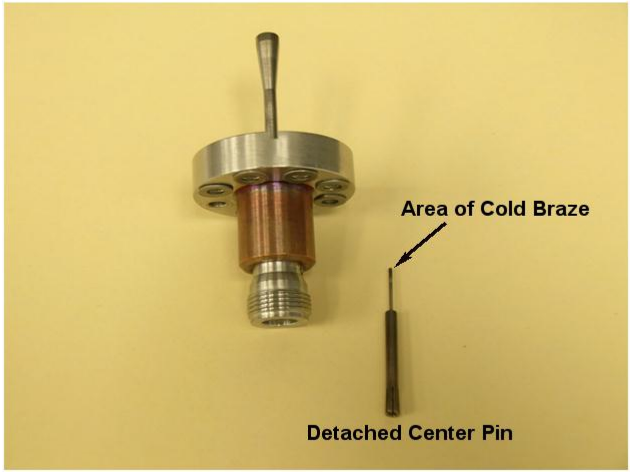








Experienced HOM Probe Sapphire RF Feed-Through Issues

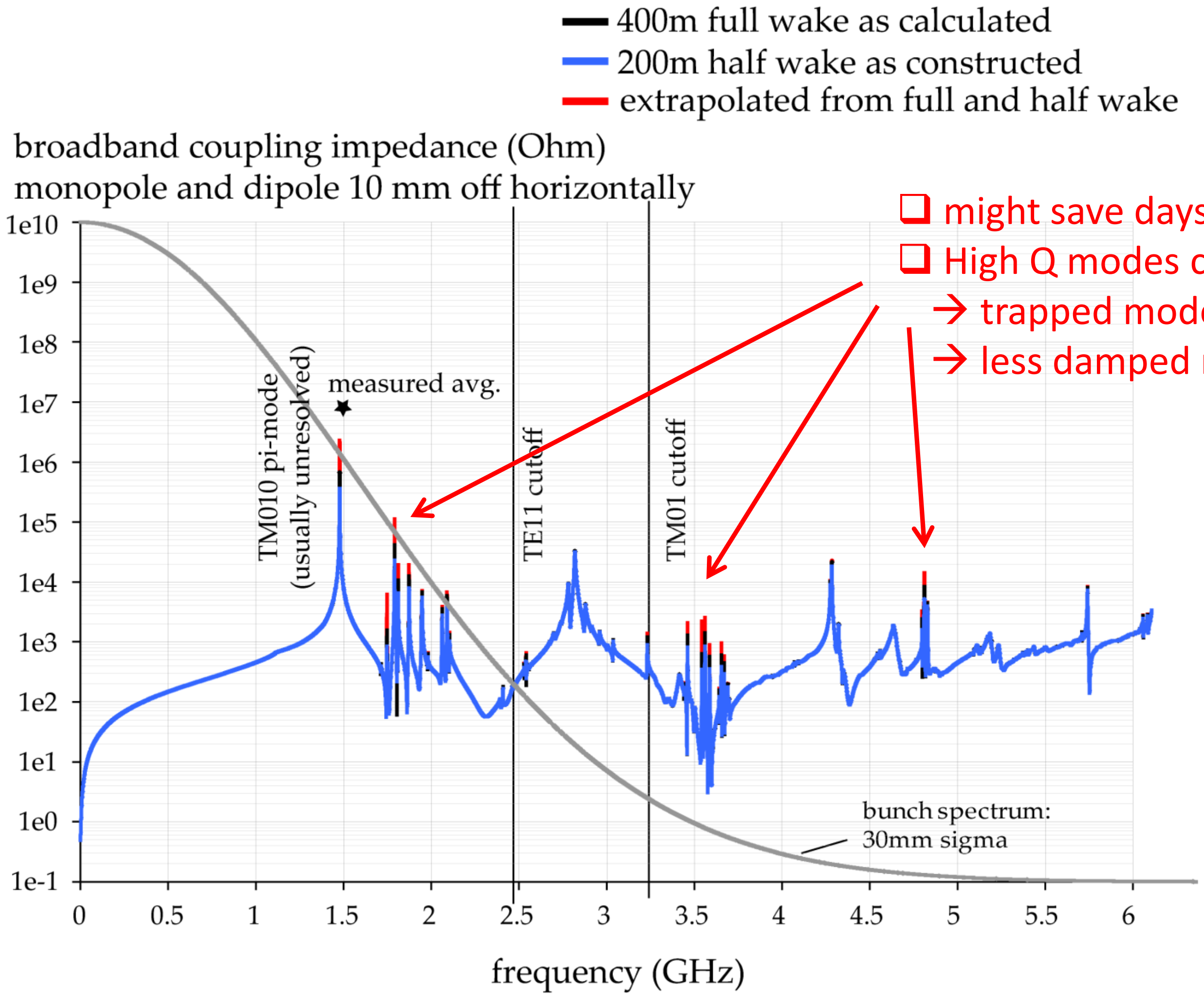


CPU Time Saving Trick to Resolve High Q Modes

Proceedings of PAC09, Vancouver, BC, Canada FR5PFP094

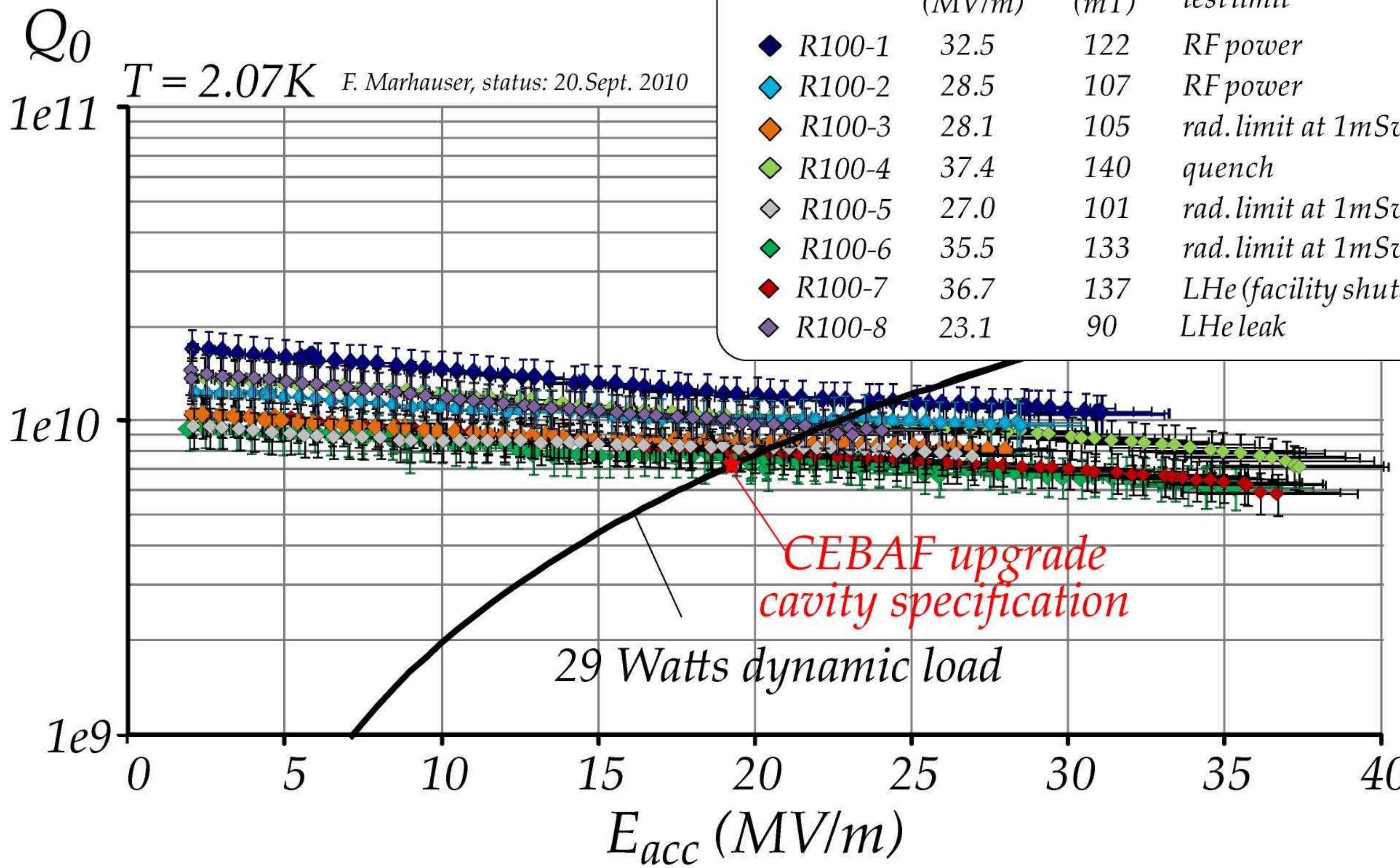
ENHANCED METHOD FOR CAVITY IMPEDANCE CALCULATIONS*

F. Marhauser, R.A. Rimmer, K. Tian, H. Wang, JLab, Newport News, VA 23606, U.S.A



- might save days/weeks of CPU time
- High Q modes can be identified immediately
  - → trapped modes
  - → less damped modes, also above cutoff!

R100 vertical RF high power test performance at 2K



	max. E_{acc} (MV/m)	B_{peak} (mT)	test limit
R100-1	32.5	122	RF power
R100-2	28.5	107	RF power
R100-3	28.1	105	rad. limit at 1mSv/hr
R100-4	37.4	140	quench
R100-5	27.0	101	rad. limit at 1mSv/hr
R100-6	35.5	133	rad. limit at 1mSv/hr
R100-7	36.7	137	LHe (facility shutdown)
R100-8	23.1	90	LHe leak

BBU Threshold Specification for Dipole Impedances
What Q is acceptable in that Frequency Range ?

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

- BBU dipole impedance threshold to support 12 GeV baseline physics up to 100 µA :

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

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

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

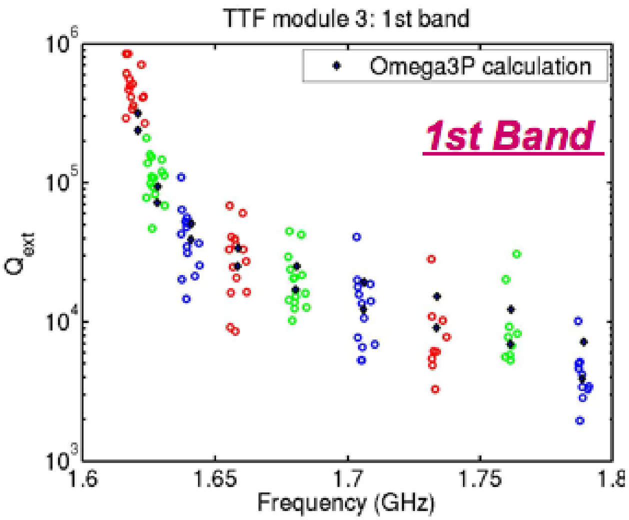
f (MHz)	$k \cdot r^2$ (m) @ r = 10 mm	R/Q (Ohm) @ r = 10 mm	$R/Q_\perp$ (Ohm/m)	$R_{\perp,\mathrm{threshold}}$ (Ohm/m)	maximum allowable Q
3000	6.08E-03	40	6.58E+03	1.0E+10	1.6E+06
3000	6.08E-03	40	6.58E+03	2.4E+10	3.8E+06

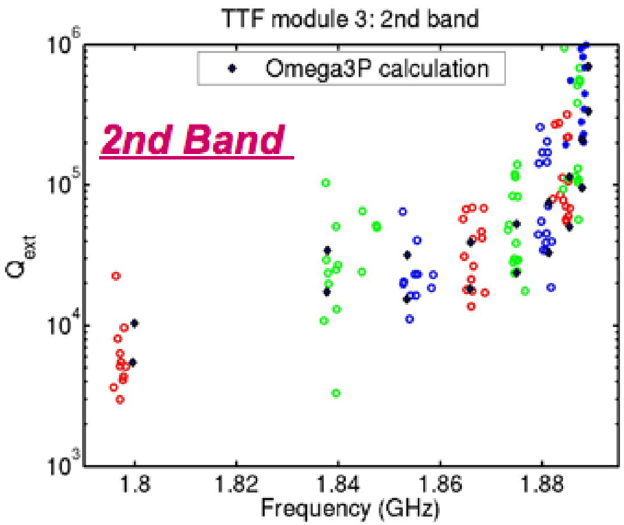
Today's High End Computation Capabilities

SLACs Advanced Computation Department

http://www.slac.stanford.edu/grp/acd/omega3p.html

- Using the complex eigensolver in **Omega3P, the first ever direct calculations of the dipole mode spectrum (1.3 GHz fully equipped TESLA cavity**) have been obtained on NERSC in 2005
  - → e.g. 531K high-order tetrahedral elements with 2nd order basis functions
  - → resulted in about 3.5 million DOFs (**2 hrs** with 512 CPUs & aggregated 300GB memory)

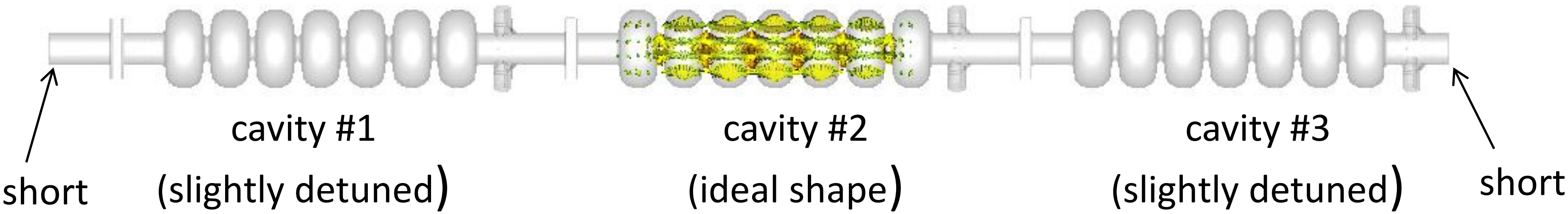




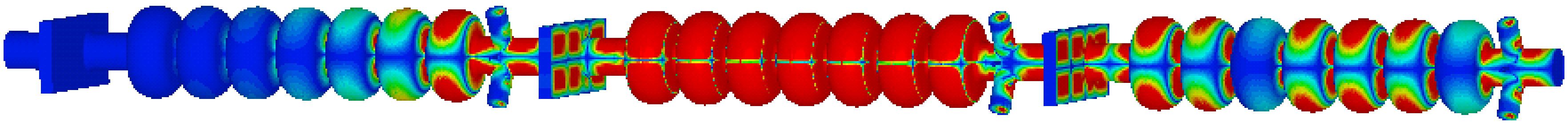
calculation vs. measurements, data scatter due to cavity cell fabrication tolerances

CST Microwave Studio Eigenmode Solver Simulations (MWS)
- Trying to resemble real World -

- ❑ 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)

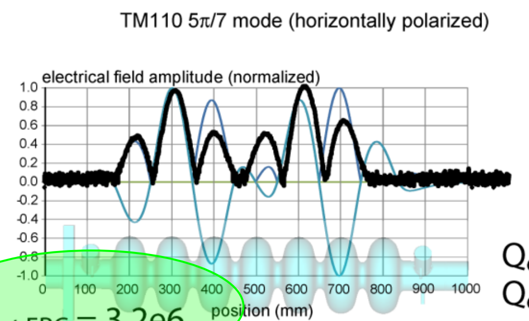


vertically polarized mode
up to $|E_{max}|/10$ (Log. scale)

Beneficial help of fundamental power coupler (FPC)

- experimental proof seen: horizontal modes have at least an order of magnitude lower Q_{ext} FPC
- in either case: HOM couplers rather useless

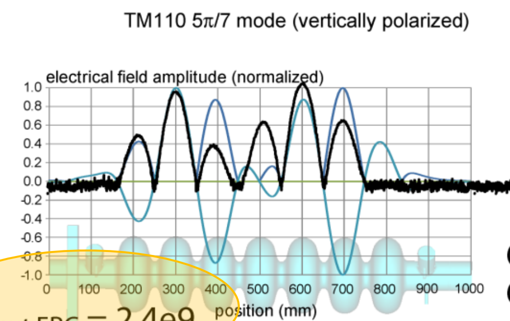
horizontal modes	vertical modes



$Q_{ext,FPC} = 3.2e6$

$Q_{ext,HOM\ up} = 2.5e8$
$Q_{ext,HOM\ down} = 8.8e8$

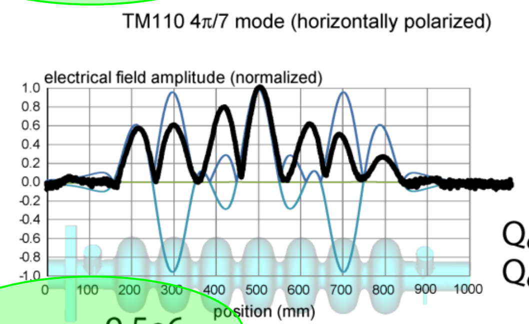
field sampled on axis
- |E| MWS
- E_r MWS, $E_z = 0$
- |E| measurement (spherical ceramic)



BBU

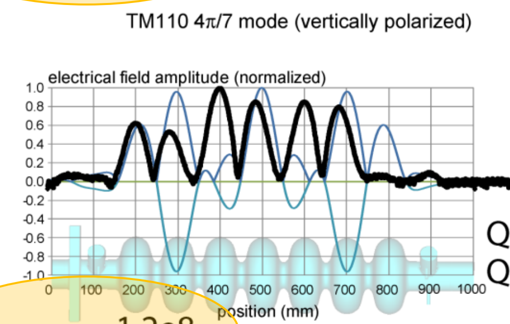
$Q_{ext,FPC} = 2.4e9$

$Q_{ext,HOM\ up} = 4.7e8$
$Q_{ext,HOM\ down} = 7.3e8$



$Q_{ext,FPC} = 9.5e6$

$Q_{ext,HOM\ up} = 6.5e7$
$Q_{ext,HOM\ down} = 1.7e8$



BBU

$Q_{ext,FPC} = 1.2e8$

$Q_{ext,HOM\ up} = 4.2e9$
$Q_{ext,HOM\ down} = 1.1e10$