HOM Damping Efficiency of various SRF Coupler Schemes (work in progress)

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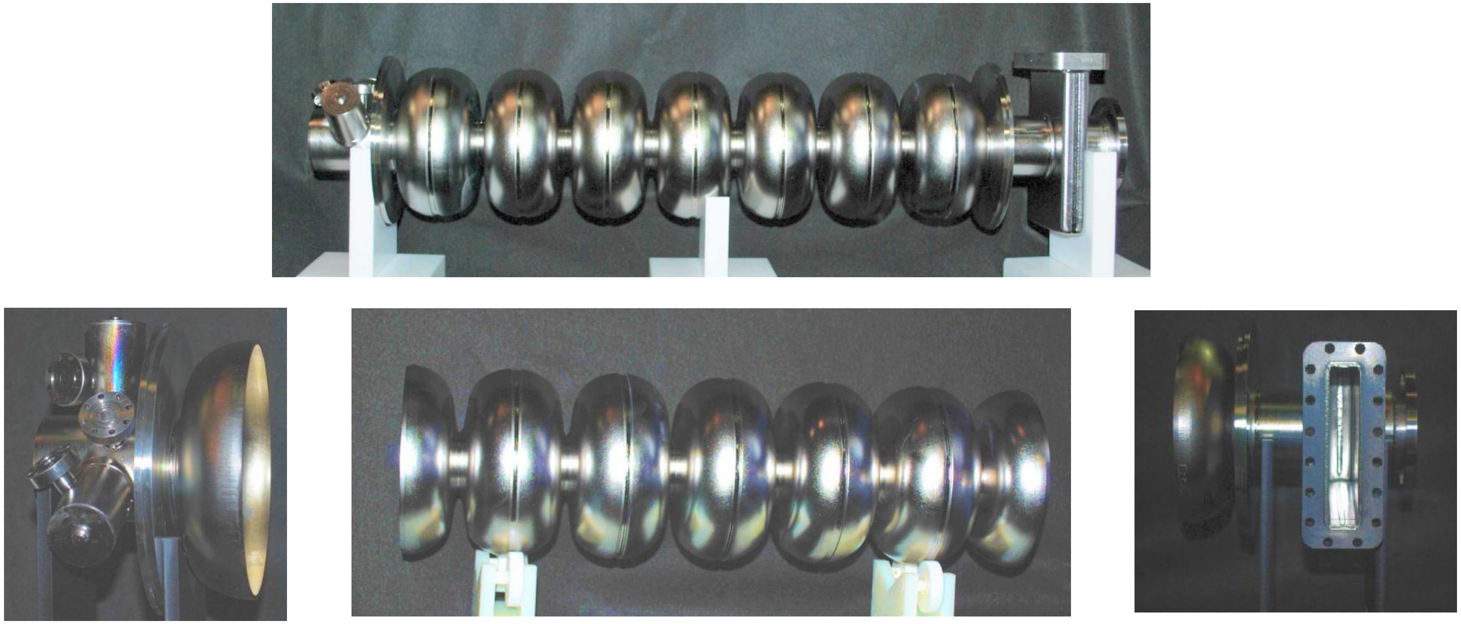
HOM-Damping Workshop in SRF Cavities
11-13. October 2010

Idea

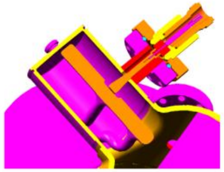
- ☐ analyze HOM coupling schemes independent of given cavity structure
- ☐ idea:
  1) get rid of cavity cells
  2) study broadband damping efficiency of remainder



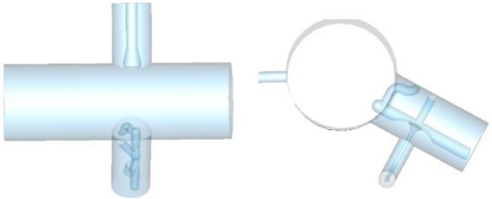
Overview of various existing/considered models

Coaxial Couplers

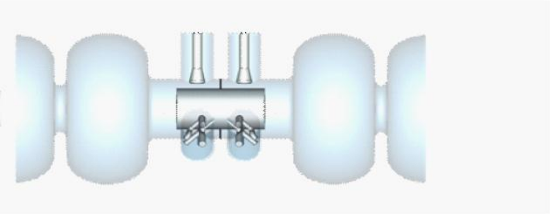
JLAB



TESLA/ILC

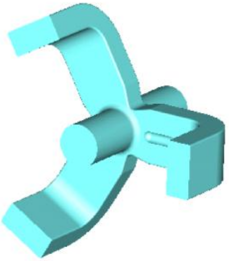


DESY/JLAB

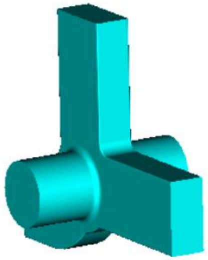


Waveguide Couplers

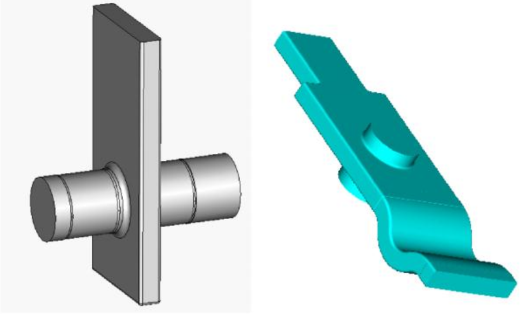
JLAB High Current



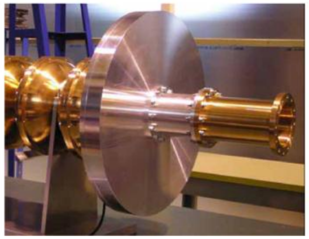
JLAB CEBAF



JLAB CEBAF

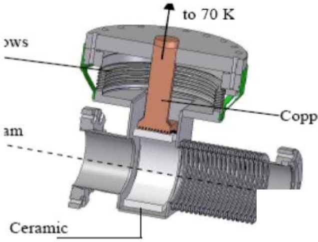


KEK

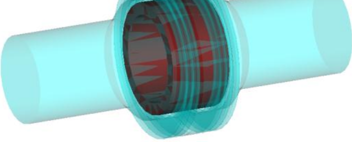


Beam Line Absorbers

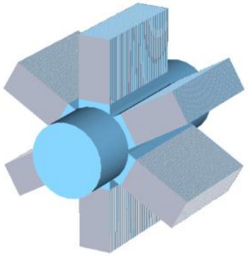
DESY FLASH/X-FEL

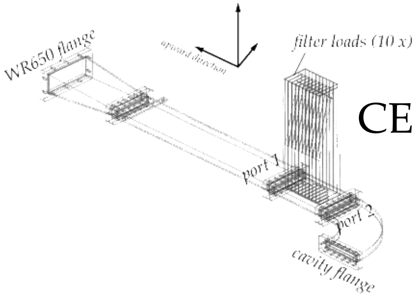


Cornell ERL



DESY

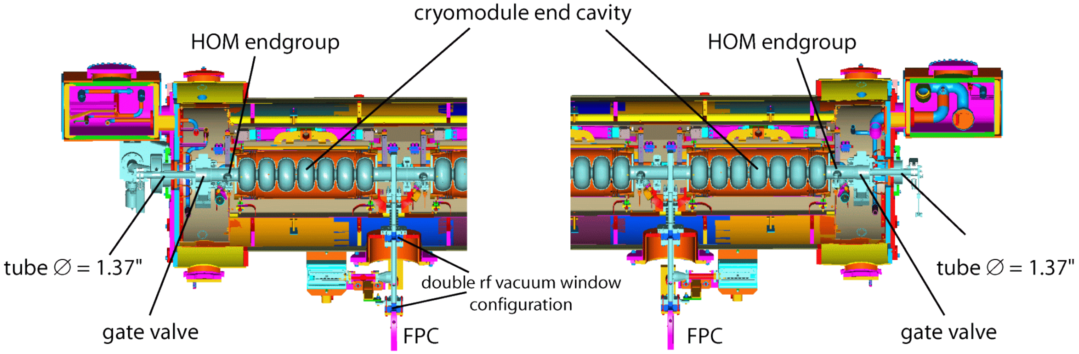




CEBAF filter

Motivation

- ☐ At CEBAF the beam tube steps down at ends of cryomodule (cold-to-warm transition)
  - →no warm beam line absorbers nesessary, HOM power in mW range
- ☐ tube step-down results in lowest cutoff at : 5.1 GHz for TE11 (6.6 GHz TM01, 8.4 GHz TE21)
- ☐ propagating HOMs below 5.1 GHz bounce back within cavity string
- ☐ The HOM-damping efficiency up to this cutoff (apart from trapped modes) is not well understood as it depends on interaction between cavities
  - → full cavity string would be needed for simulation
  - → fabrication tolerances have to be taken into account
  - → extremely hard to predict (or not at all)
  - → also very tedious to measure



CEBAF upgrade cryomodule end configuration

Best example: CEBAF Upgrade cavity design

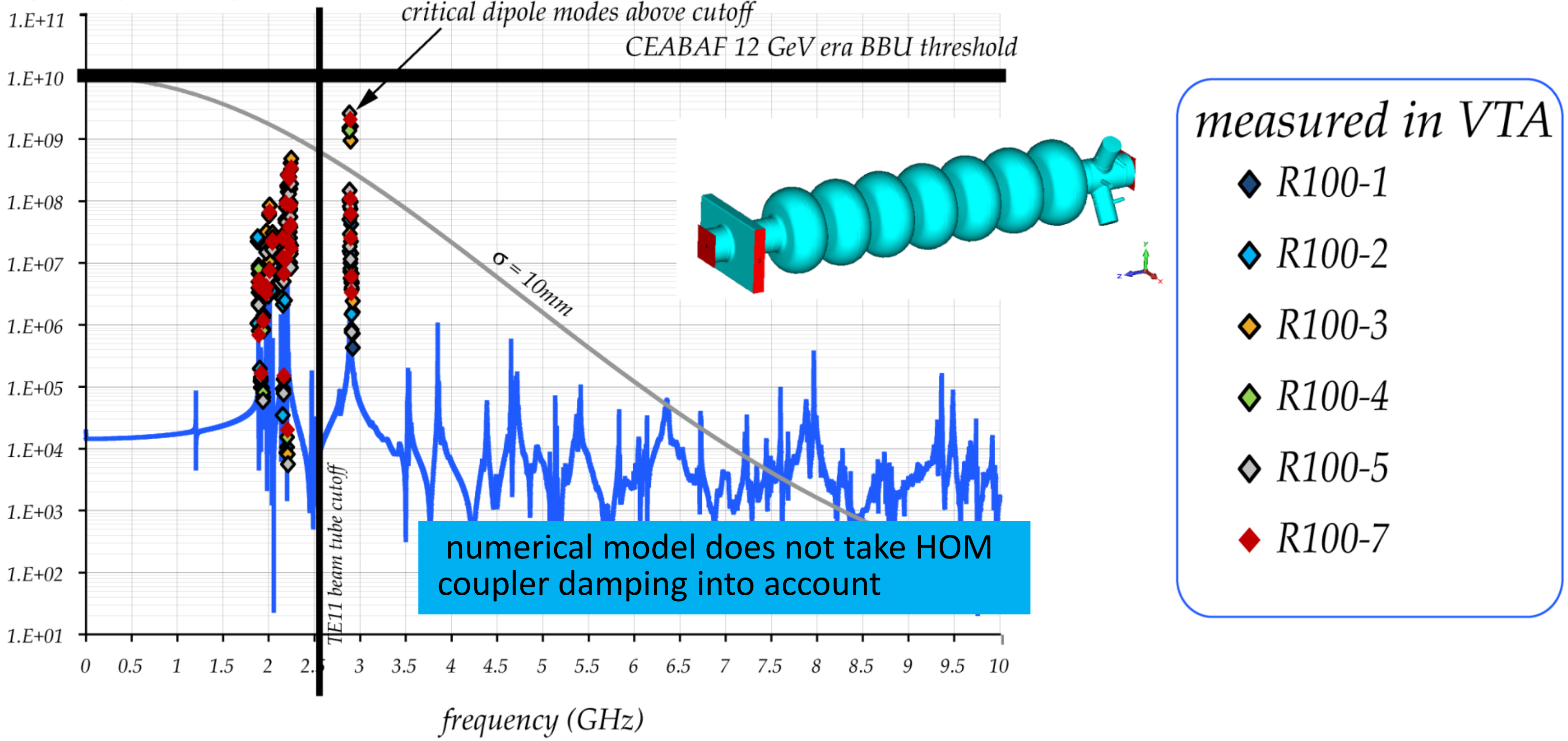
- ☐ **critical dipole modes (400 MHz above cutoff) are BBU limiting modes (more in talk this afternoon)**

LINAC 2010

CRITICAL DIPOLE MODES IN JLAB UPGRADE CAVITIES*

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

dipole impedance spectrum (vertical modes) (Ohm/m)



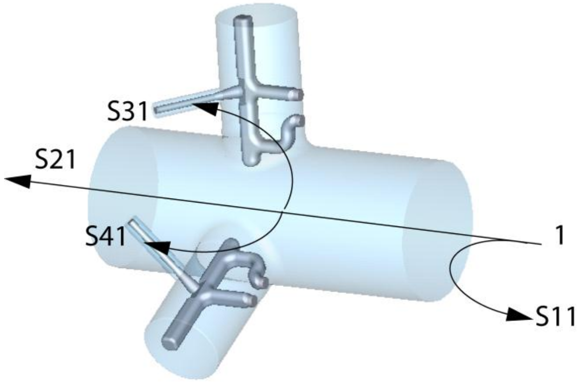
numerical model does not take HOM coupler damping into account

What are numerical alternatives at higher frequencies ?

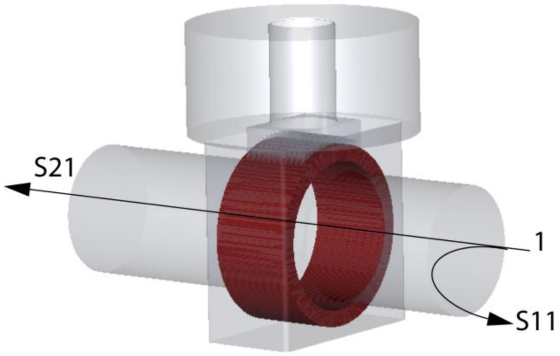
- ☐ the HOM damping efficiency can be characterized fully by S-Parameters by RF energy
  a) transmitted through HOM ports or b) absorbed in loads
- ☐ examples:

1) coaxial coupler
   →consider: signals transmitted through beam tube (S21) are not reflected
   →i.e. no reflection from an adjacent cavity (creating standing waves), but a short can be included
   →ideally one wants to extract as much HOM energy as possible
2) beam line absorber
3) „dead-end“ absorbers

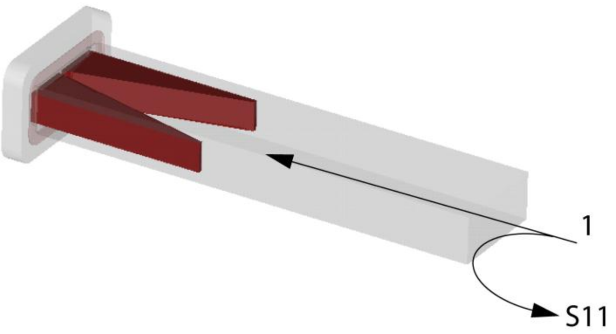
total energy transmitted:
$S31^2 + S41^2$



total energy absorbed:
$1-S11^2 - S21^2$

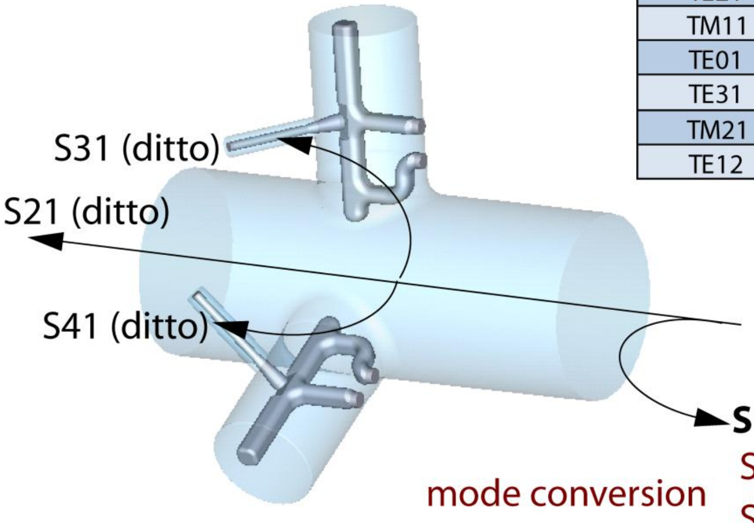


total energy absorbed:
$1-S11^2$



More Ways

total energy transmitted:
$S31^2 + S41^2$ (ditto)



tube cutoffs for 35mm radius

mode type		cutoff frequency GHz
TE11	dipole	2.51
TM01	monopole	3.28
TE21	quadrupole	4.16
TM11	dipole	5.22
TE01	monopole	5.22
TE31	sextupole	5.73
TM21	quadrupole	7.00
TE12	dipole	7.27
⋮		

mode conversion

TE11	TM01	
S1(1),1(1)	S1(1),1(2)	
S1(2),1(1)	**S1(2),1(2)**	• • •
S1(3),1(1)	S1(3),1(2)	
⋮		

Limits and Chosen Constraints

❑ if resonances occur in structure, it seems like energy absorbed (not flowing out of strucure)
  → in this case narrow spikes should be visible in spectrum
  → rather a problem for an HOM damping structure

❑ calculations restricted to above cutoff regime
    → some extrapolation to below cutoff frequencies might be possible
    → the associated energy throughput however critically depends on chosen dimensions/tube lengths

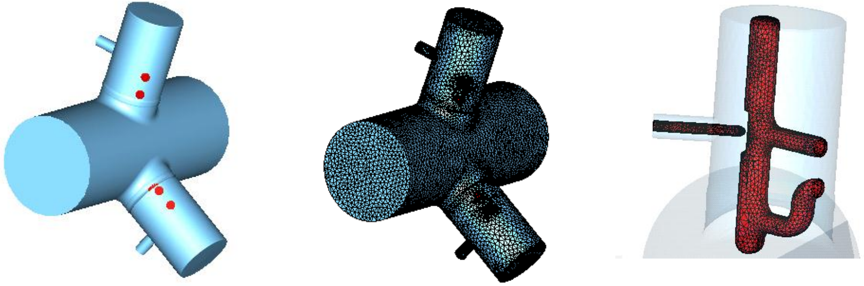
❑ higher order tube and waveguide modes have been limited to
    1) TE11 horizontal (H) and vertical (V) polarization
    2) TM01

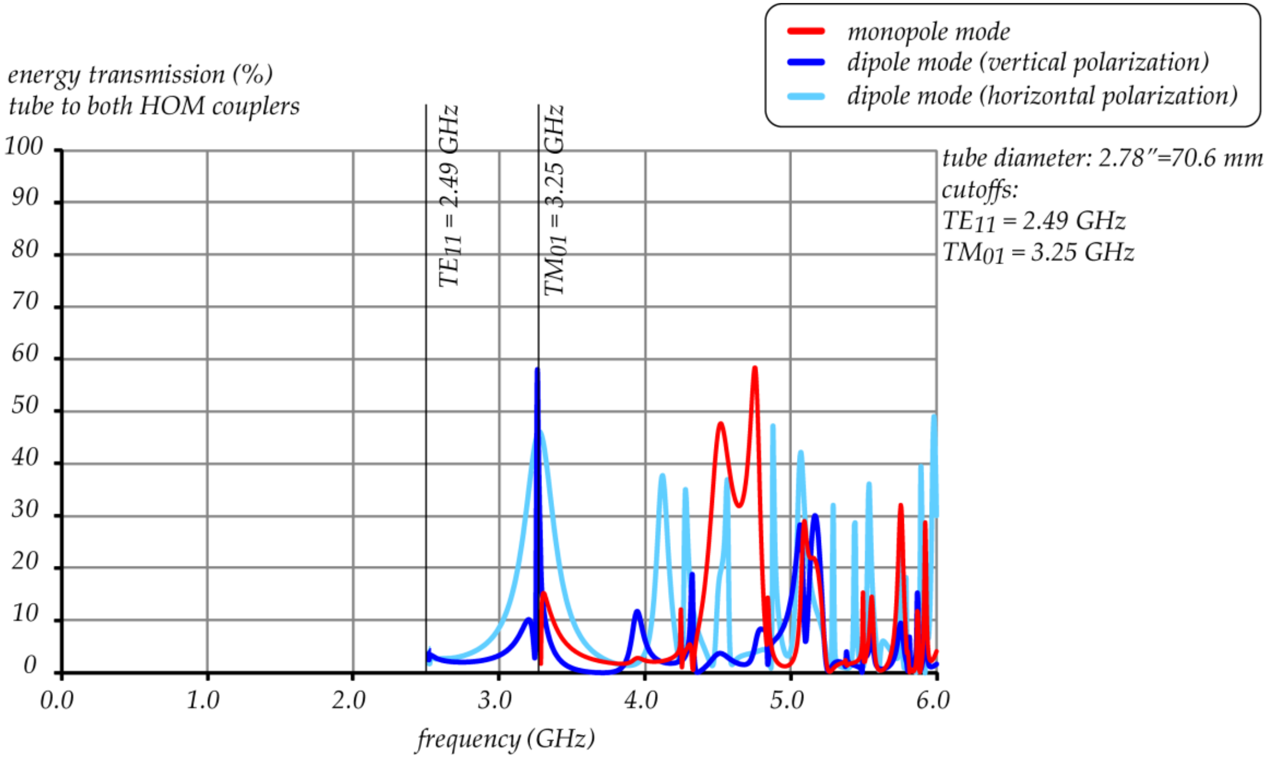
❑ in rectangular waveguides
    1) TE10
    2) TE20

❑ chosen frequency range: first tube cutoff → 6 GHz
    → covers „gray zone“ of quasi trapped HOMs with high impedance

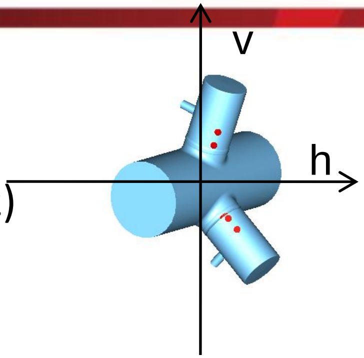
CEBAF Upgrade TESLA-Type Coaxial Dampers Prototype used in *Renascance* Cryomodule

- ☐ will always show model and meshing
- ☐ color code used (bluish – dipole modes, red – monopole mode)

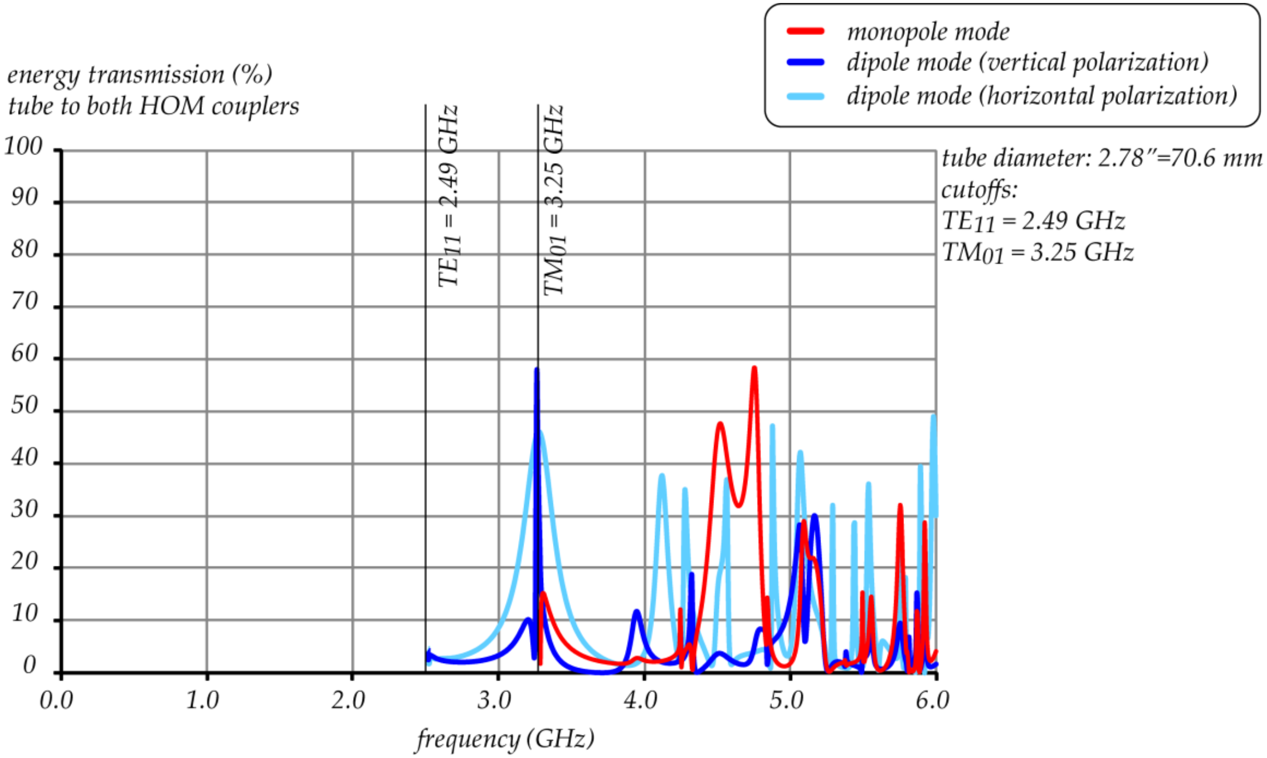




CEBAF Upgrade TESLA-Type Coaxial Dampers Prototype used in *Renascance* Cryomodule



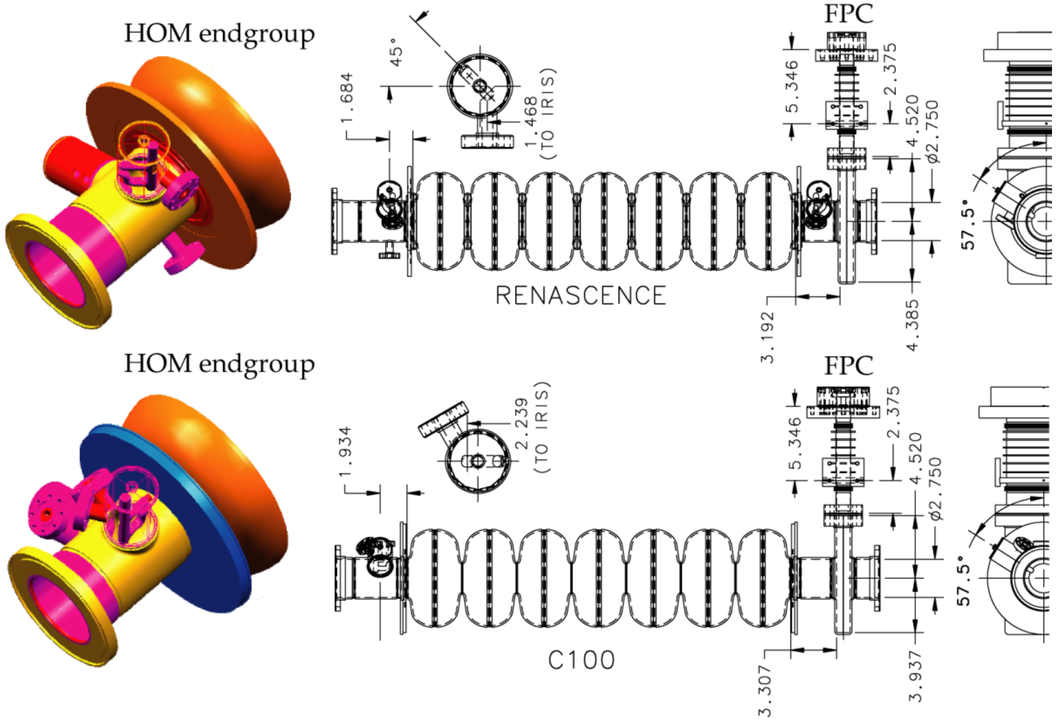
❑ one may ask: what information can be extracted ?
1) imbalance between horizontal and vertical dipole mode damping (not good)
2) best throughput not optimized for HOM frequencies (dipole modes at 2.9 GHz)

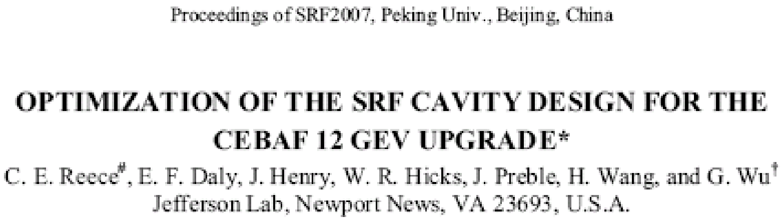


CEBAF Upgrade TESLA-Type Coaxial Dampers

❑ actually changes have been made towards final CEBAF upgrade cavity design:

1) 1 HOM endgroup completely removed (2 couplers out of 4) from power coupler side of cavity due to elevated heat from FPC body
2) remaining HOM endgroup relocated away from cavity (similar heat issue, H of fundamental)
3) coupler hooks-re orientated to improve dipole mode damping
4) probe ports re-oriented to make space for upgrade type tuner brackets
5) probe tip changed from “needle“ to “trombone“ to improve damping



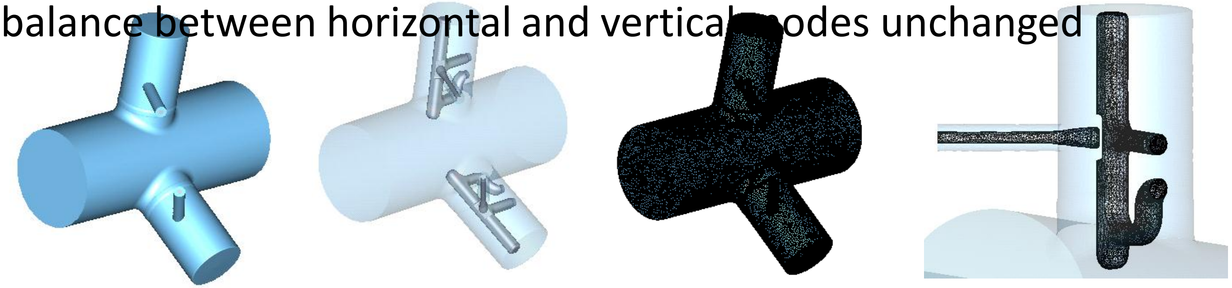

Proceedings of SRF2007, Peking Univ., Beijing, China

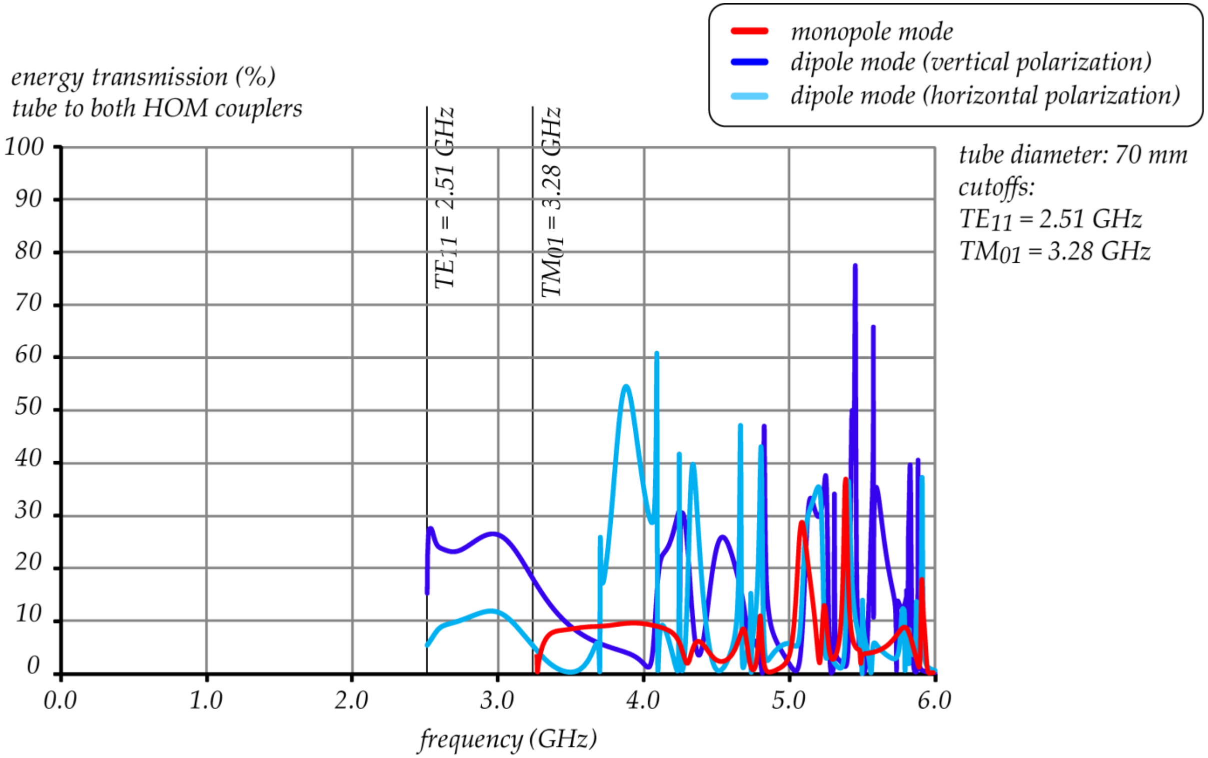
OPTIMIZATION OF THE SRF CAVITY DESIGN FOR THE CEBAF 12 GEV UPGRADE*

C. E. Reece#, E. F. Daly, J. Henry, W. R. Hicks, J. Preble, H. Wang, and G. Wu†
Jefferson Lab, Newport News, VA 23693, U.S.A.

CEBAF Upgrade TESLA-Type Coaxial Dampers

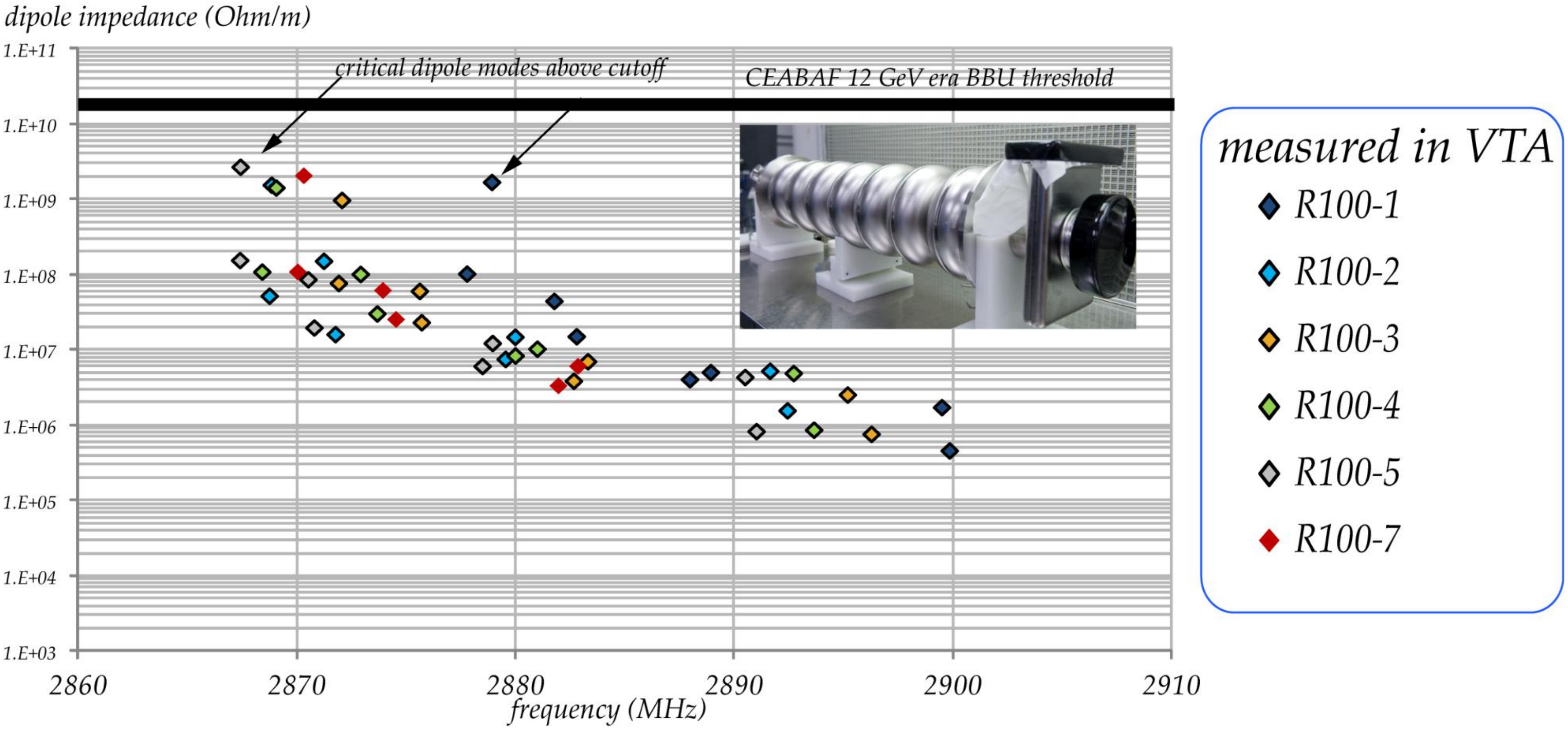
- improvements visible
- imbalance between horizontal and vertical modes unchanged





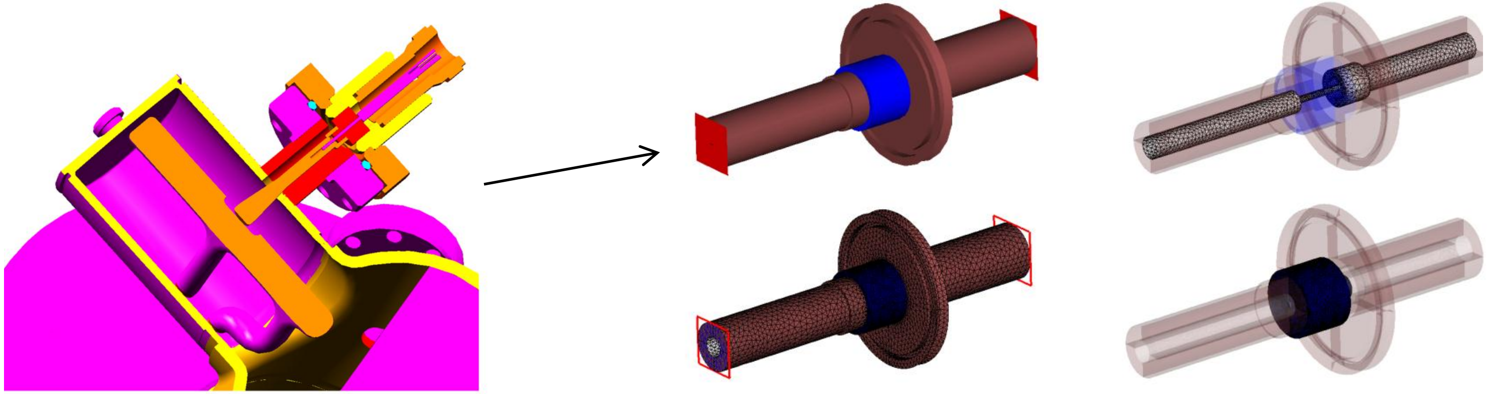
Experimental Proof

- clear difference between horizontally and vertically polarized dipole modes

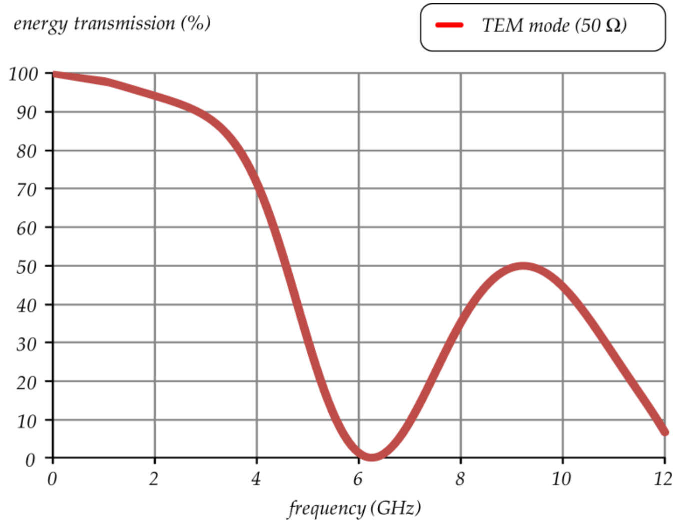


What about RF Feedthroughs?

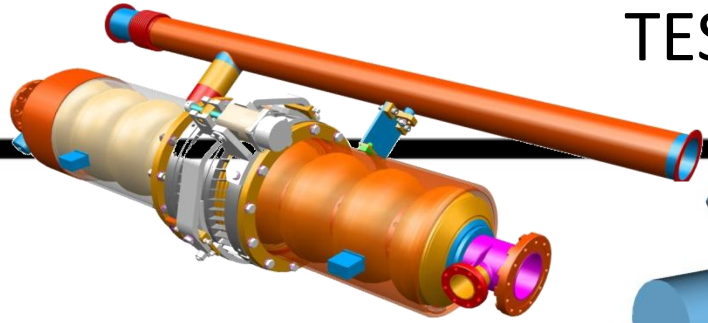
- ☐ what is the broadband performance of the Sapphire RF window at the HOM output port ?
- ☐ model created to calculate throughput

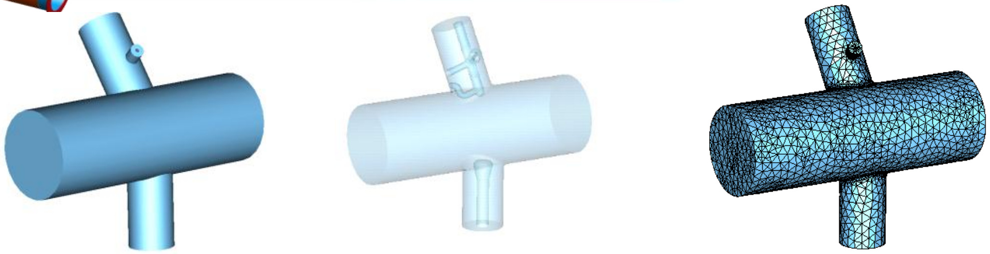


anisotropy of Sapphire taken into account

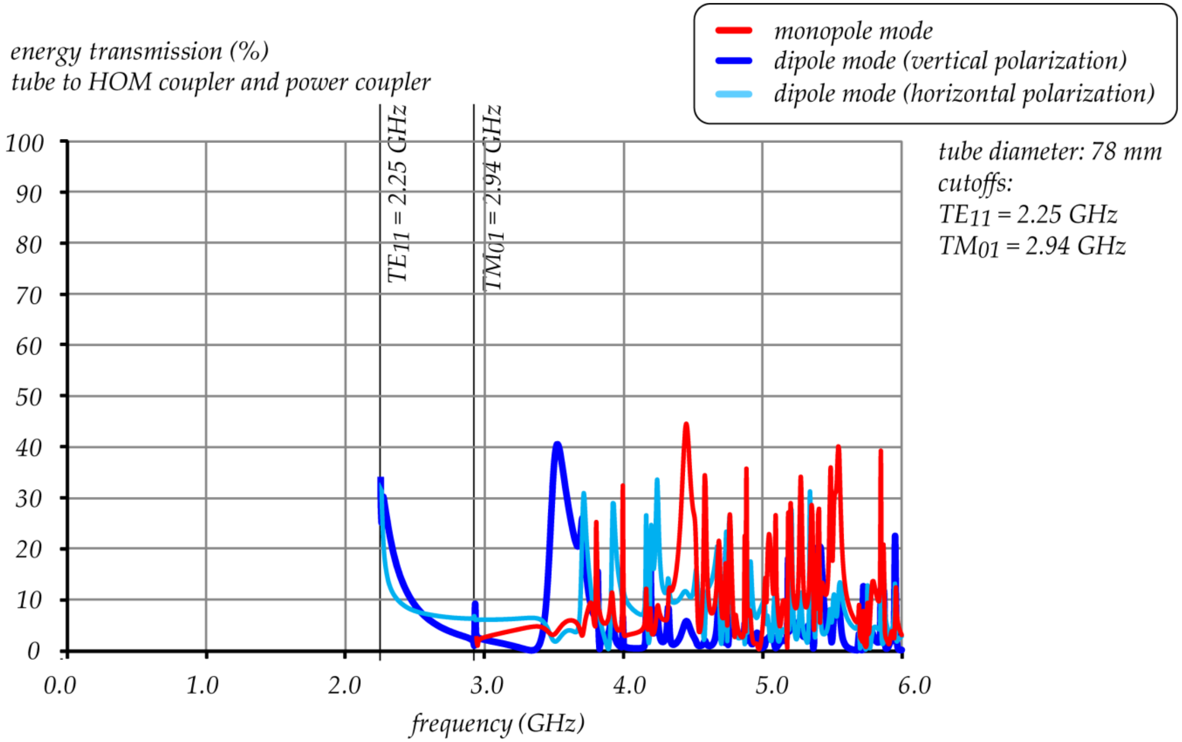


TESLA/ILC Cavities

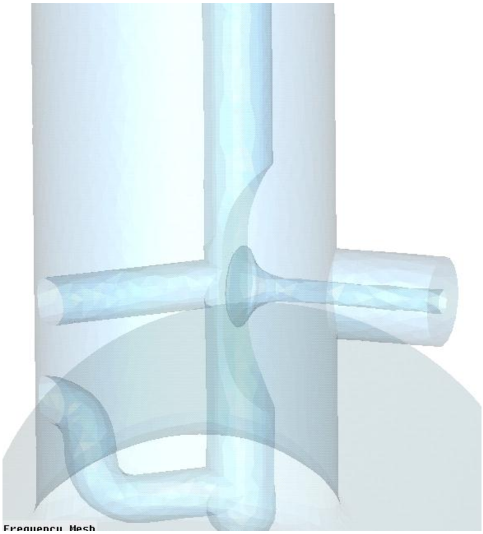




power coupler
actually horizontal

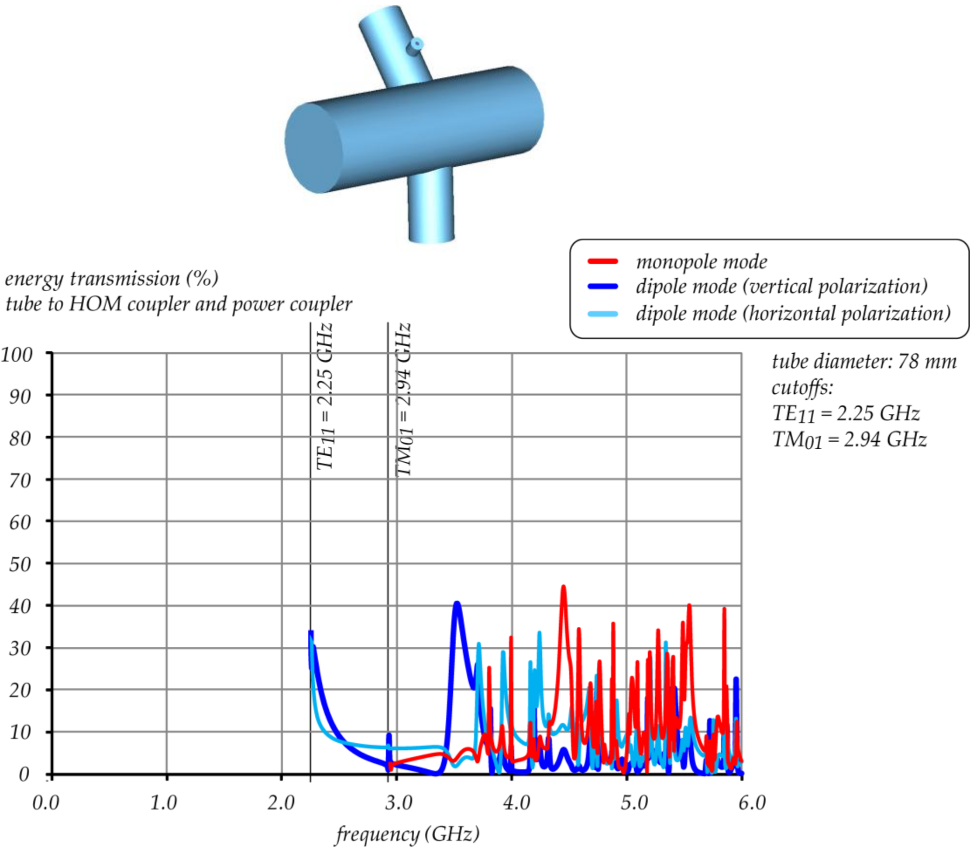


tube diameter: 78 mm
cutoffs:
TE_{11} = 2.25 GHz
TM_{01} = 2.94 GHz



TESLA/ILC Cavities

- ☐ this damping endgroup includes damping via input power coupler
- ☐ no benefit over JLAB HOM endgroup visible (but these are two couplers at one end)



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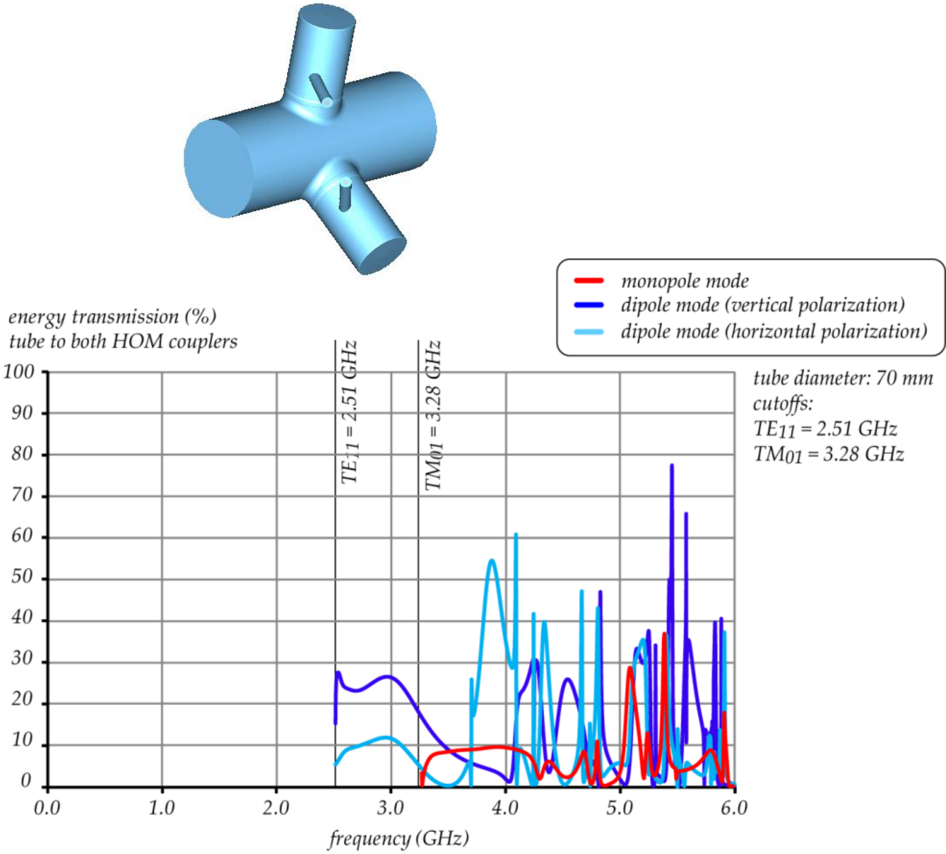
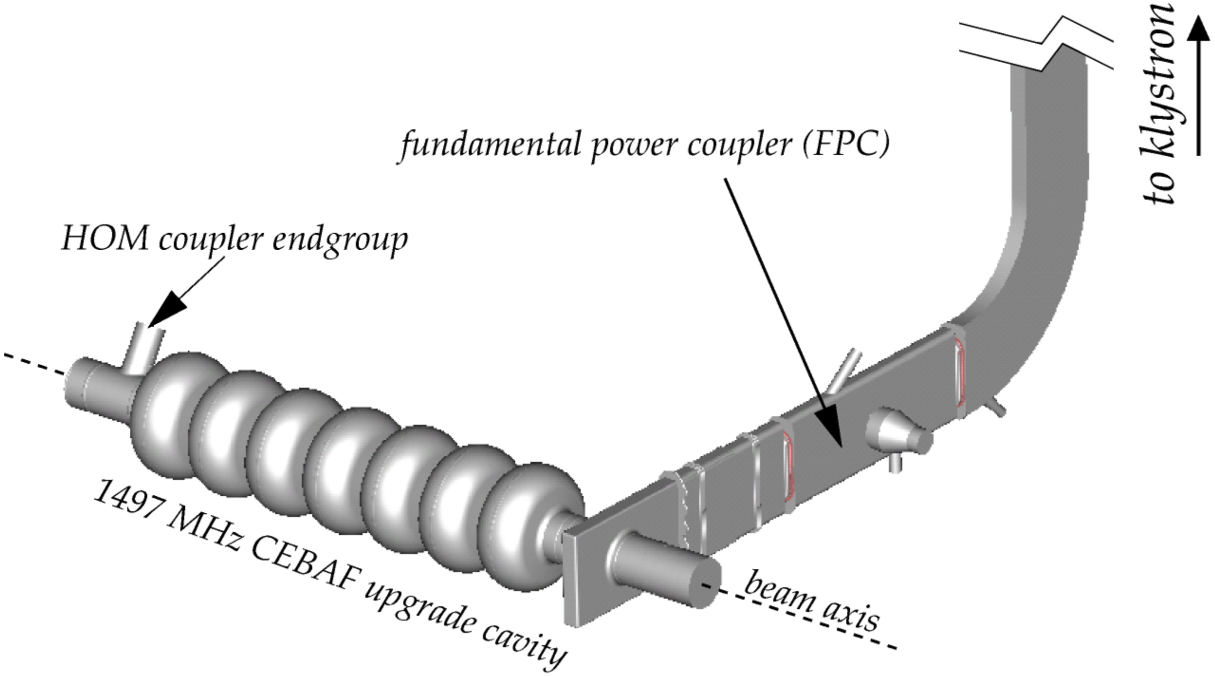


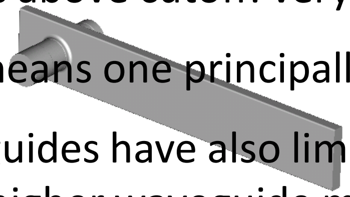
tube diameter: 70 mm
cutoffs:
TE_{11} = 2.51 GHz
TM_{01} = 3.28 GHz

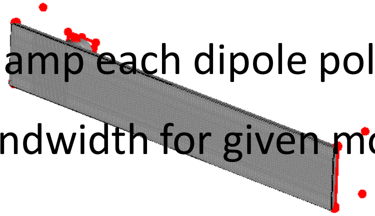
CEBAF Fundamental Power Coupler Waveguide as HOM Dampers (FPC)

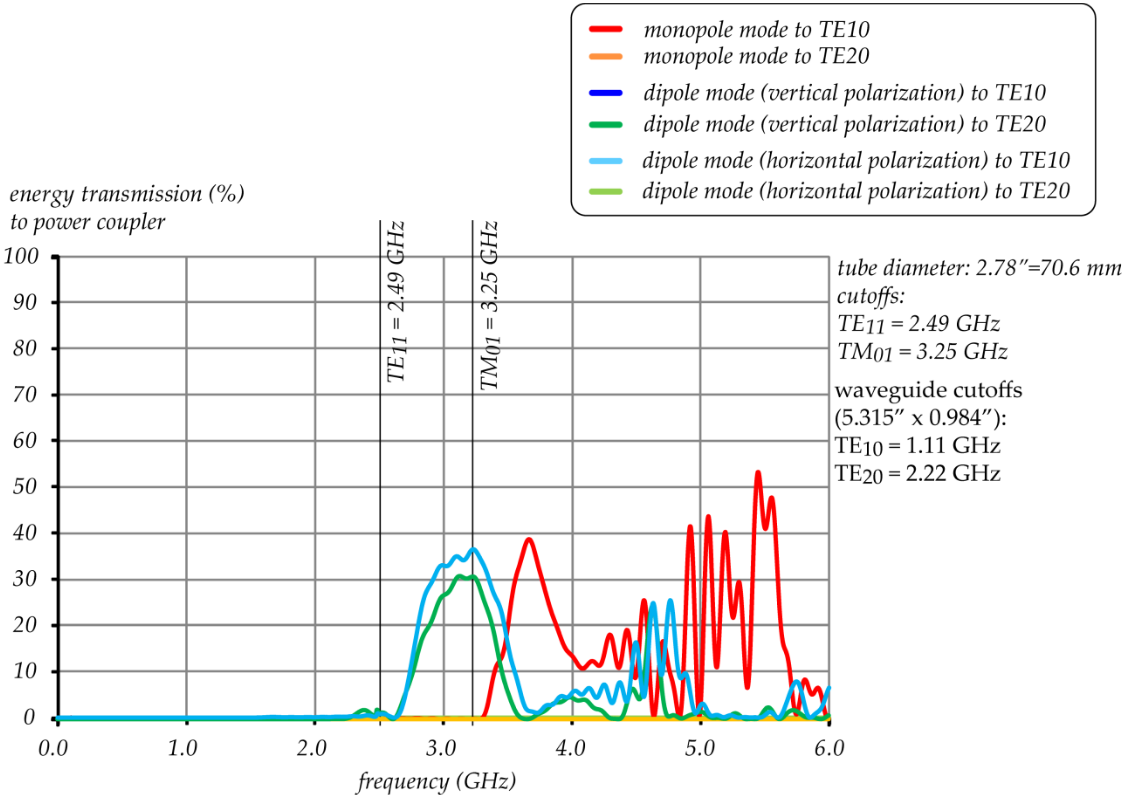


CEBAF Fundamental Power Coupler Waveguides as HOM Dampers (FPC)

- results above cutoff: very effective damping equally for both modes
- that means one principally can damp each dipole polarization with one waveguide effectively
- waveguides have also limited bandwidth for given mode (more later) but one can make use of all higher waveguide modes







tube diameter: 2.78"=70.6 mm
cutoffs:
TE_{11} = 2.49 GHz
TM_{01} = 3.25 GHz

waveguide cutoffs
(5.315" x 0.984"):
TE_{10} = 1.11 GHz
TE_{20} = 2.22 GHz

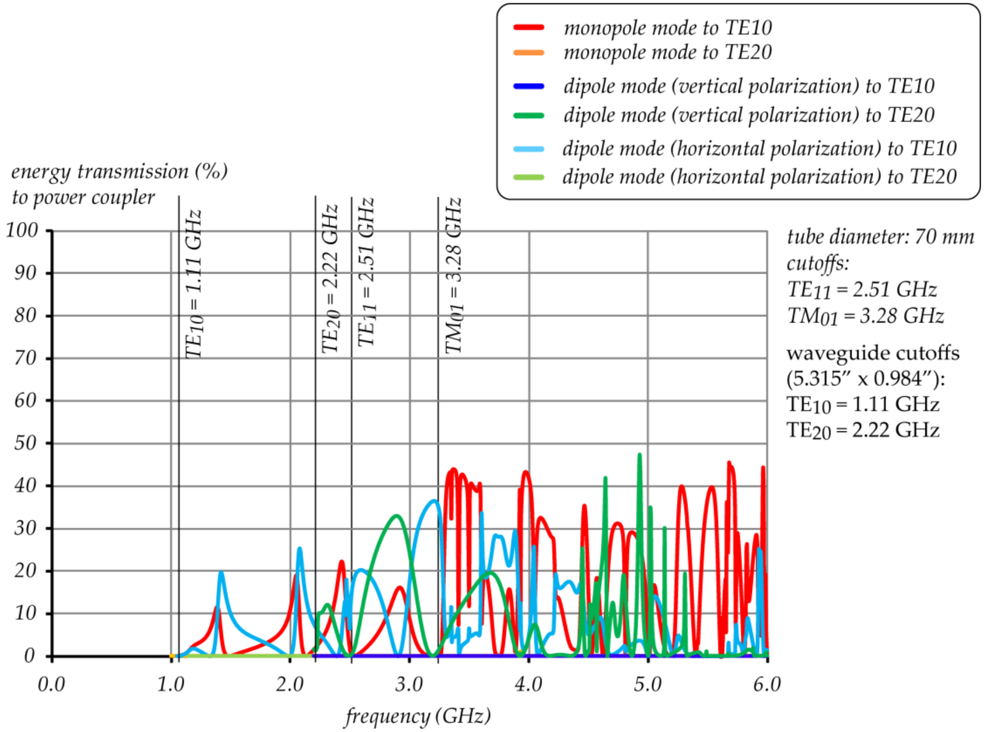
CEBAF FPC cutoffs

mode type	cutoff frequency GHz
TE10	1.115
TE20	2.230
TE30	3.345
TE40	4.460
TE50	5.575
TE11	6.088

⋮

CEBAF Fundamental Power Coupler Waveguides as HOM Dampers (FPC)

- ☐ CEBAF Original Cornell FPC with dogleg chicane to shield window (only refurbished cryomodules)

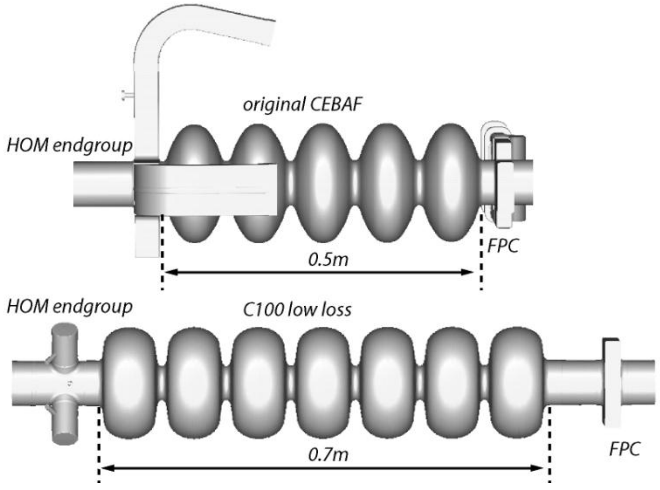


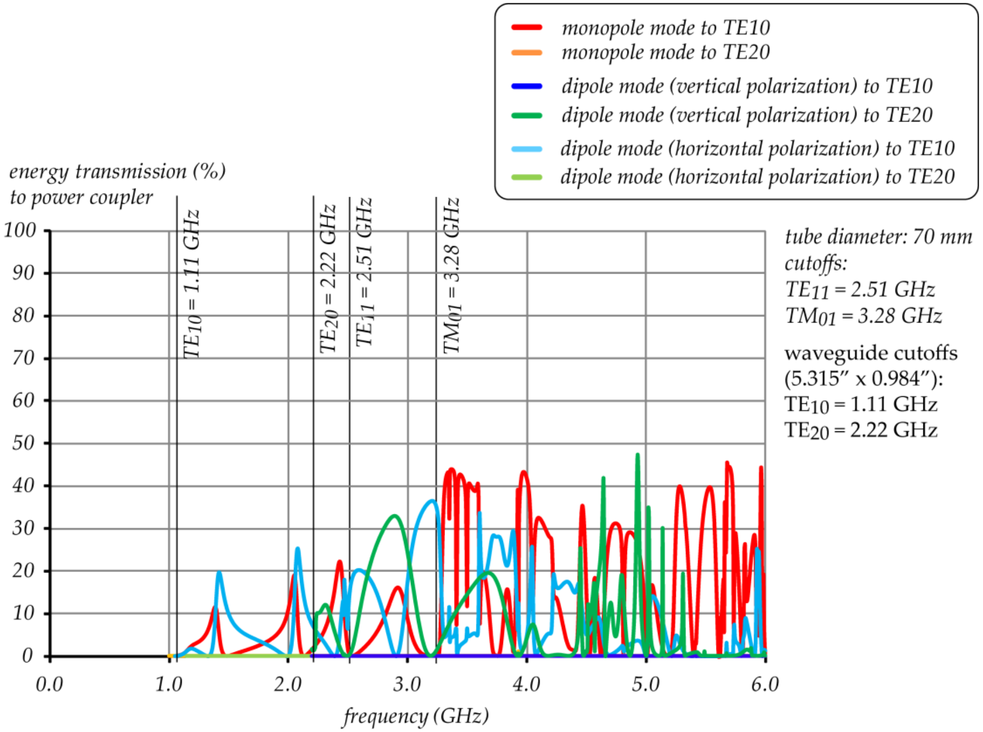
tube diameter: 70 mm
cutoffs:
$TE_{11} = 2.51$ GHz
$TM_{01} = 3.28$ GHz

waveguide cutoffs
(5.315″ x 0.984″):
$TE_{10} = 1.11$ GHz
$TE_{20} = 2.22$ GHz

CEBAF Fundamental Power Coupler Waveguides as HOM Dampers (FPC)

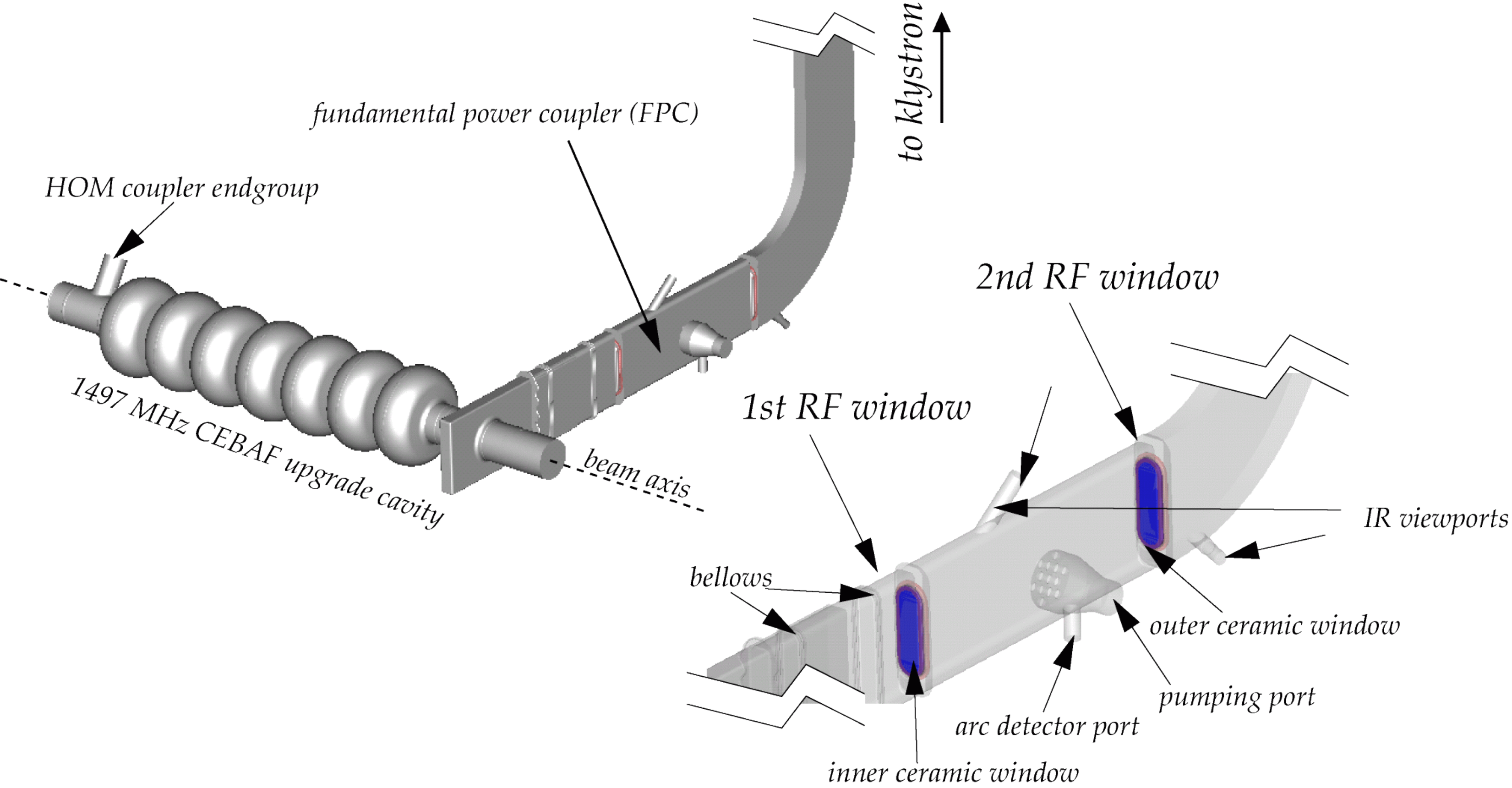
- CEBAF Original Cornell FPC with dogleg chicane to shield window (only refurbished cryomodules)
- leakage visible of energy through coupler below tube cutoff, much more than in upgrade coupler
- reason: FPC much closer to end cell, distance matters





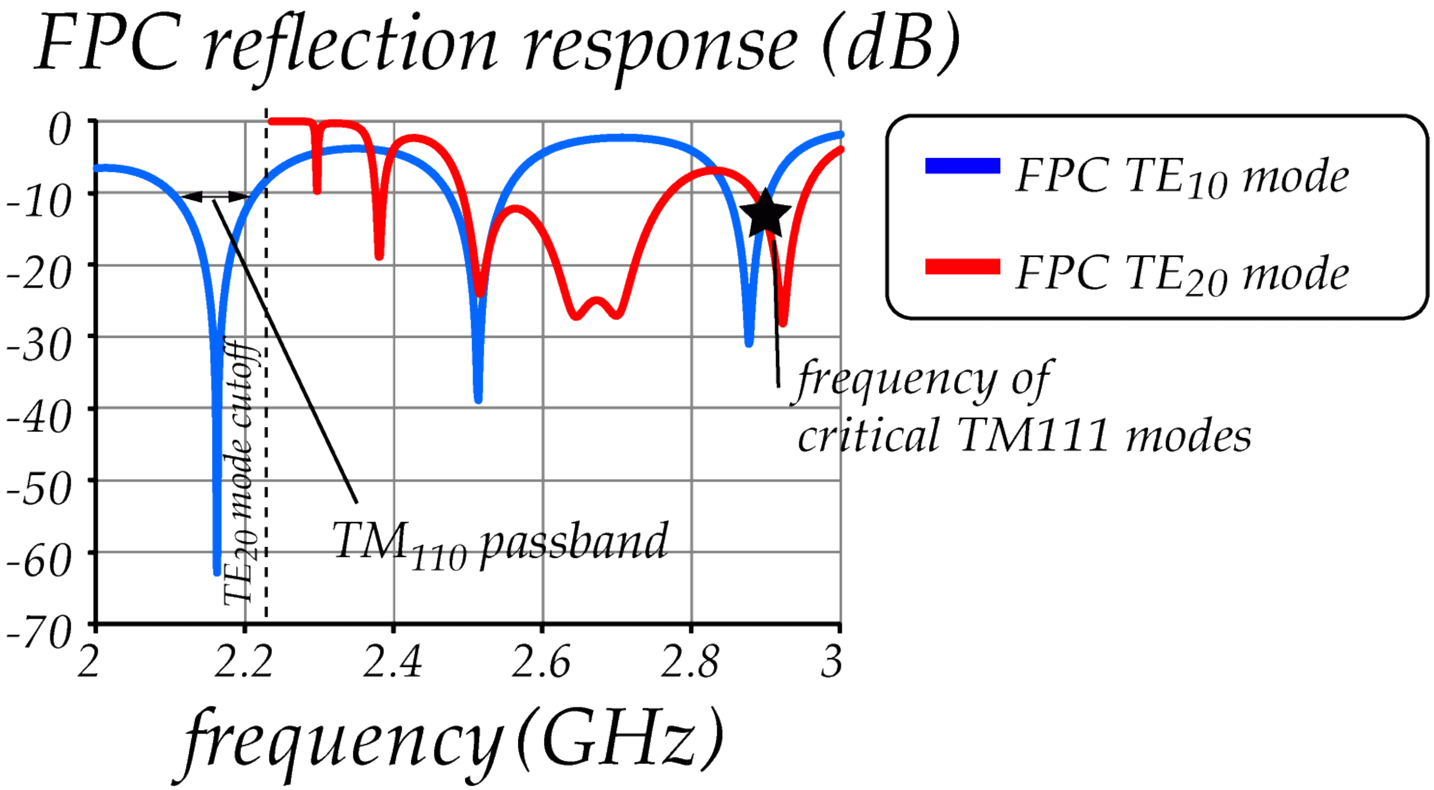
CEBAF Fundamental Power Coupler Waveguides as HOM Dampers (FPC)

- ☐ one issue if coupler is need as HOM damper: RF window(s),is/are limited in bandwitdh

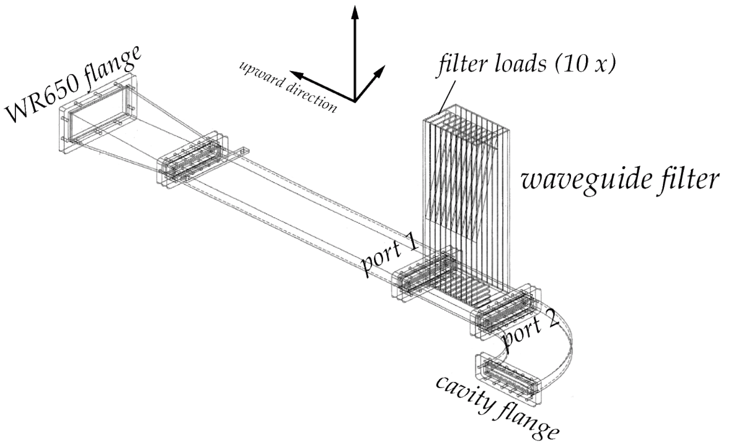


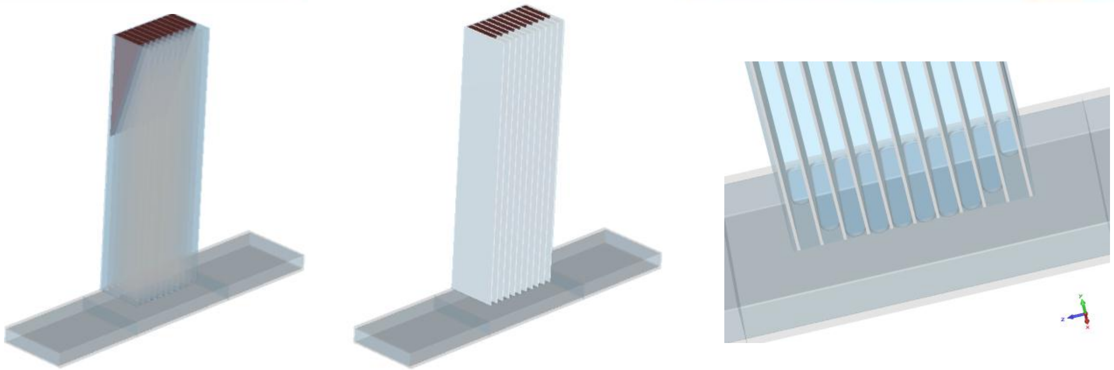
CEBAF Fundamental Power Coupler Waveguides as HOM Dampers (FPC)

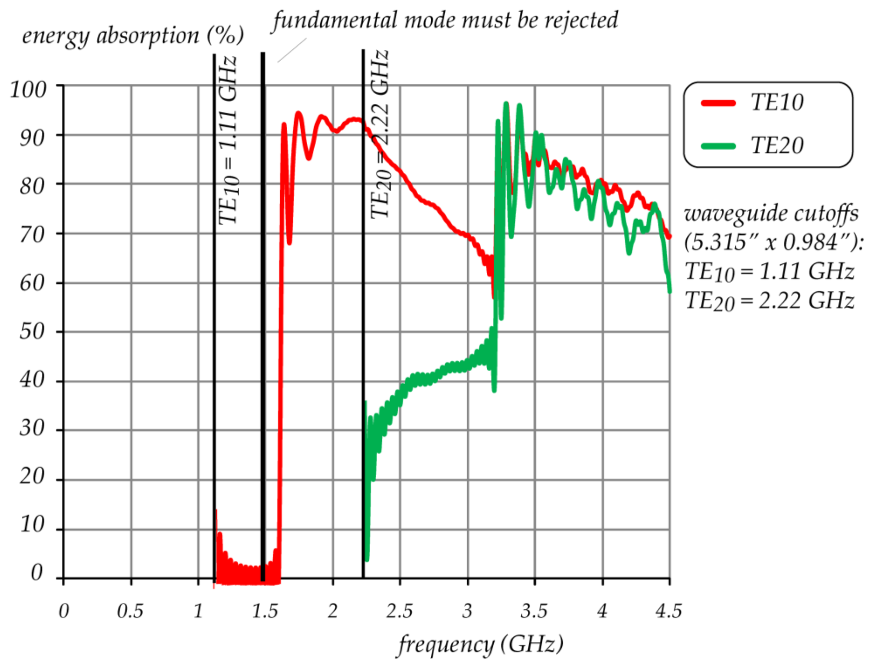
- ☐ window separation has been optimized to optimize throughput of TE10 and TE20 waveguide modes at desired HOM frequencies
- ☐ **where does energy go to ?**



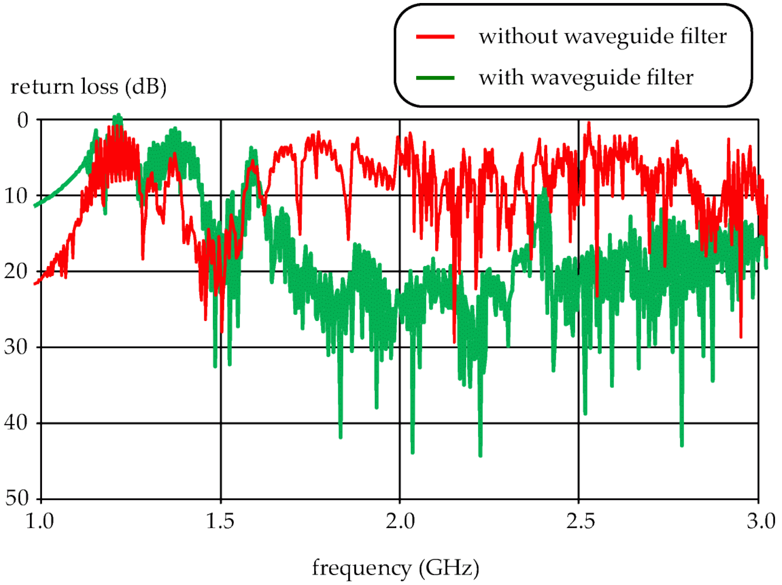
External filter to absorb HOM Energy





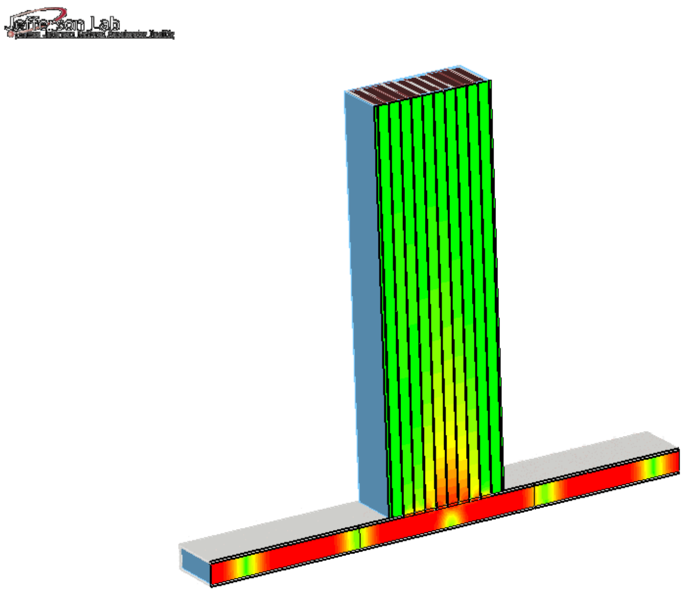


- ☐ measured return loss in TE10 mode

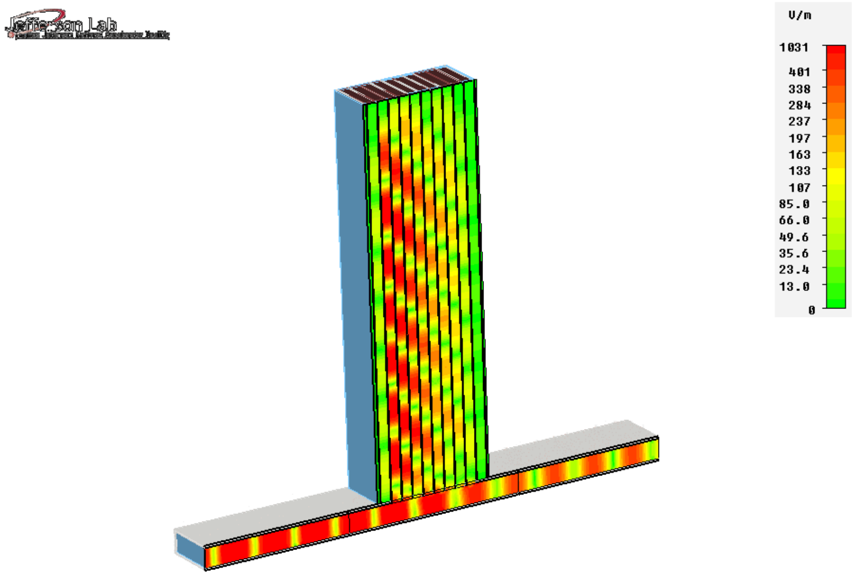


External filter to absorb HOM energy and Klystron Harmonics

@ 1.497 GHz (TE10)

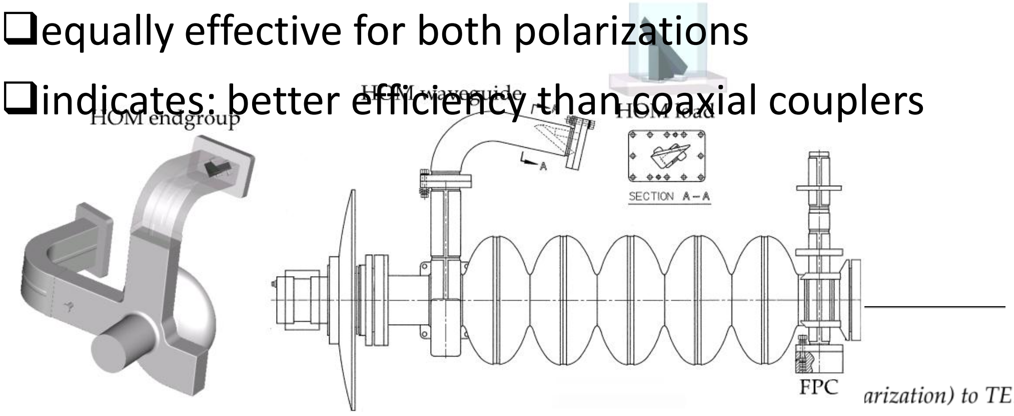


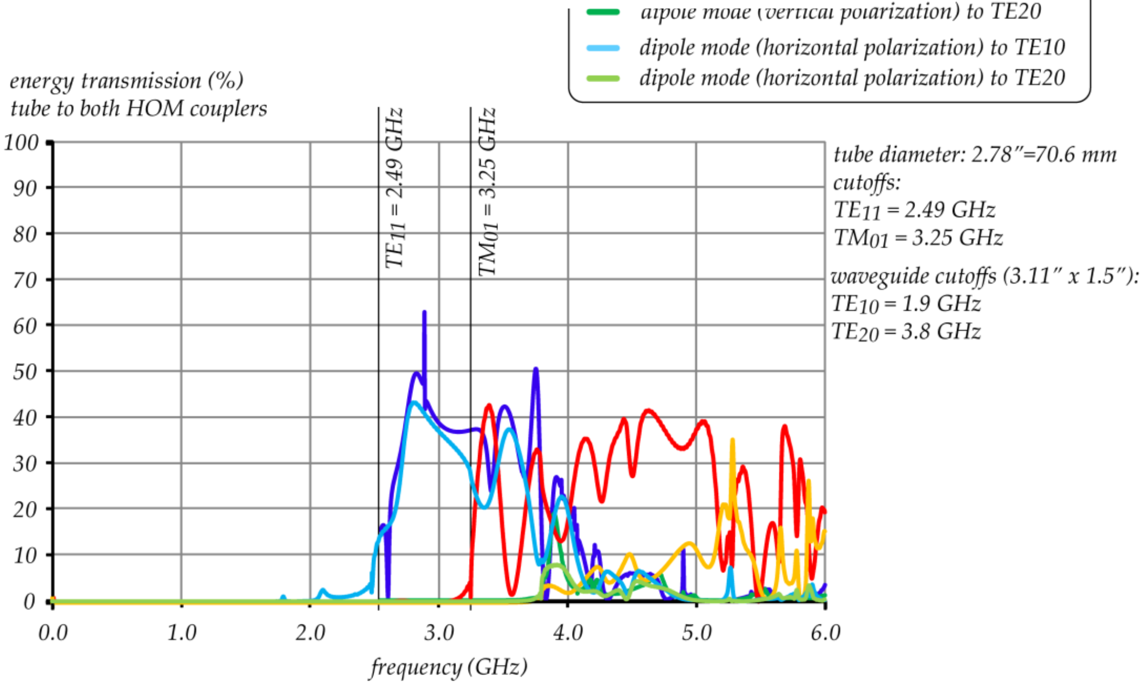
@ 2.9 GHz (TE10)

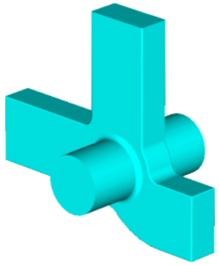


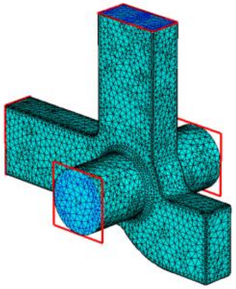
CEBAF Original Cornell Cavity Waveguide Dampers

- CEBAF Original Cornell
- equally effective for both polarizations
- indicates: better efficiency than coaxial couplers









JLAB High Current Cavity Waveguide Damper Design

- ❑concepts for 750 MHz (1A beam current) and 1.5 GHz (10-100 mA) developed
- ❑Strong HOM damping required
  - → Two 3-folded waveguide endgroups (6 damping waveguides, one is also FPC)

Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

CONCEPTS FOR THE JLAB AMPERE-CLASS CW CRYOMODULE *

R. Rimmer, E.F. Daly, W.R. Hicks, J. Henry, J. Preble, M. Stirbet, H. Wang, K.M. Wilson, G. Wu,

JLab, Newport News, VA 23606, USA

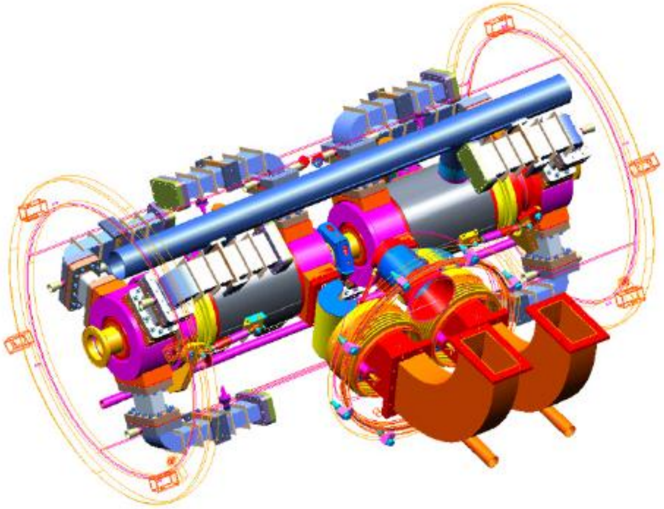


Figure 1: 3D CAD view inside a 1497 MHz high-current cavity pair cryomodule under development.

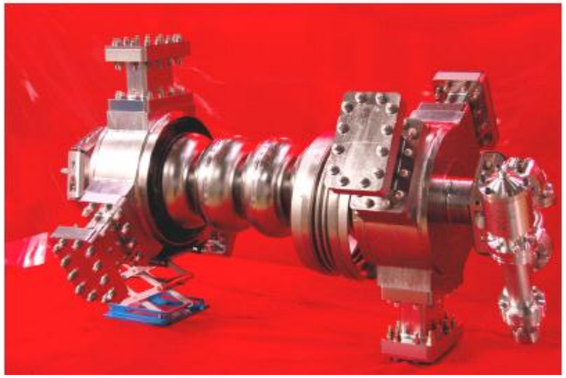
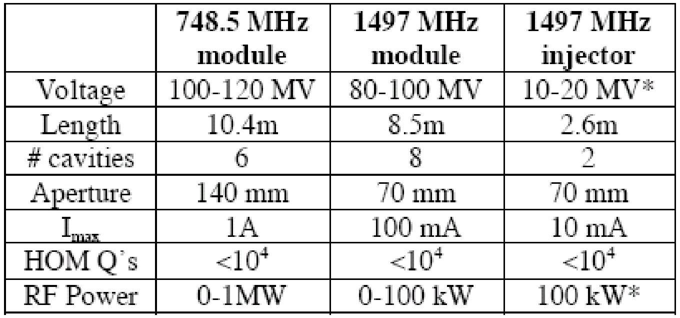


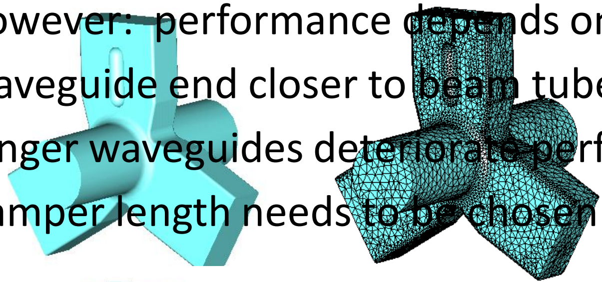
Table 1: JLab high-current cryomodule parameters.



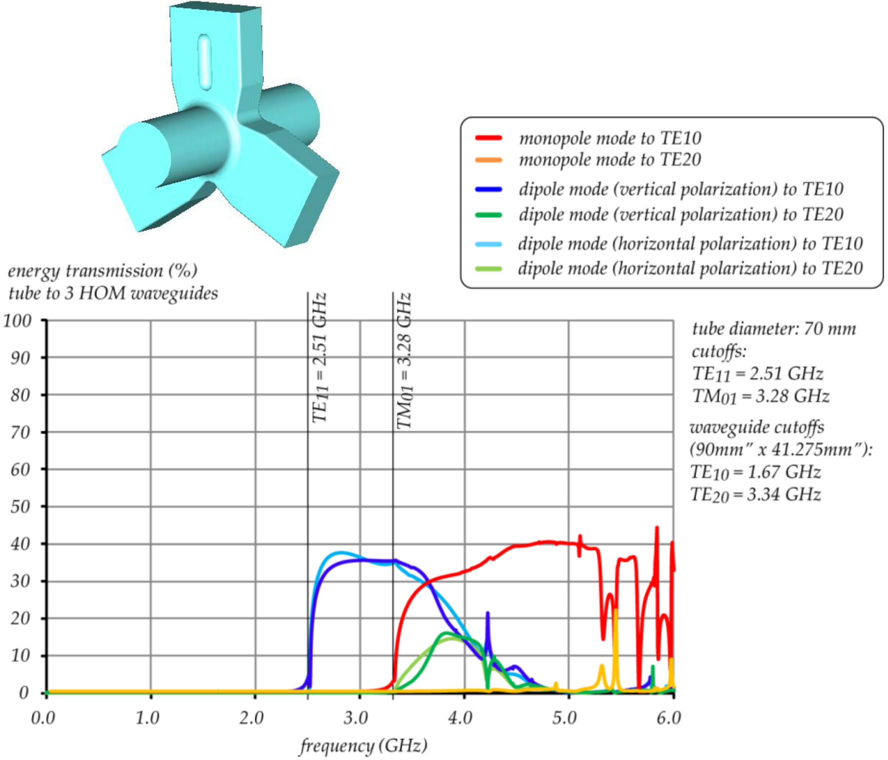
	748.5 MHz module	1497 MHz module	1497 MHz injector
Voltage	100-120 MV	80-100 MV	10-20 MV*
Length	10.4m	8.5m	2.6m
# cavities	6	8	2
Aperture	140 mm	70 mm	70 mm
I_{max}	1A	100 mA	10 mA
HOM Q's	$<10^4$	$<10^4$	$<10^4$
RF Power	0-1MW	0-100 kW	100 kW*

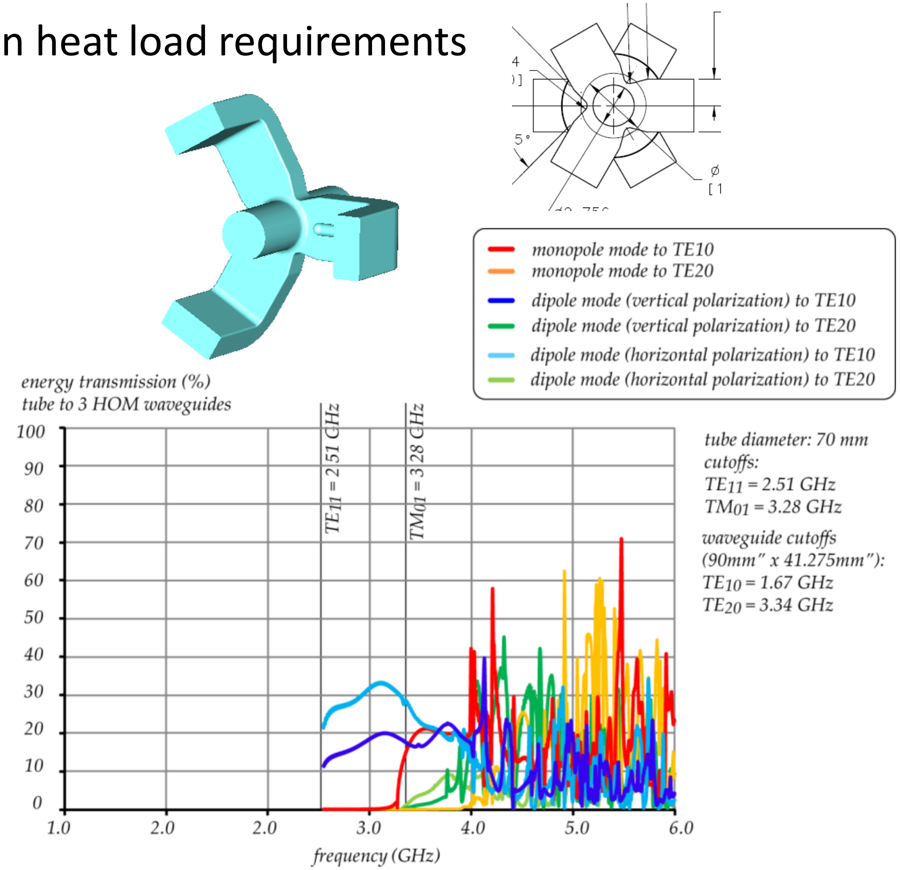
*RF power limited, injector not energy recovered

High Current Waveguide Dampers



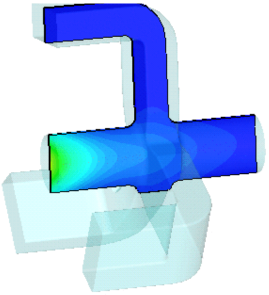
- ☐ results: very effective, smooth and broadband performance
- ☐ however: performance depends on waveguide length
- ☐ waveguide end closer to beam tube will absorb more leaking fields
- ☐ longer waveguides deteriorate performance, but **fundamental mode has to be decayed sufficiently**
- ☐ damper length needs to be chosen also based on heat load requirements



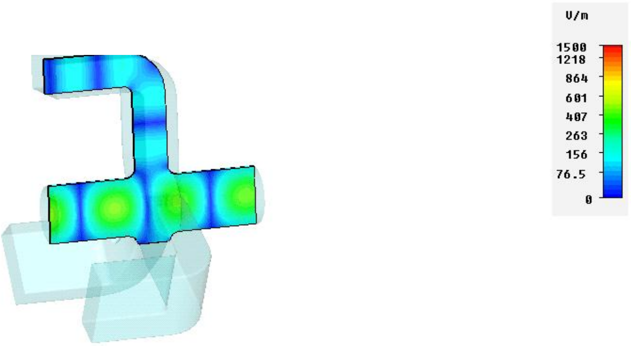


Why not broadband for given mode (here TE10) ?

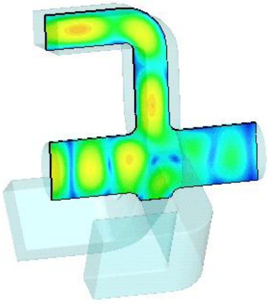
@ 2 GHz (below cutoff)



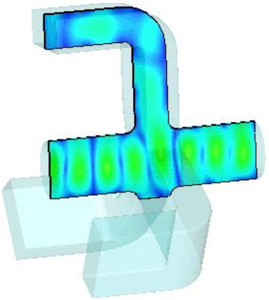
@ 3 GHz



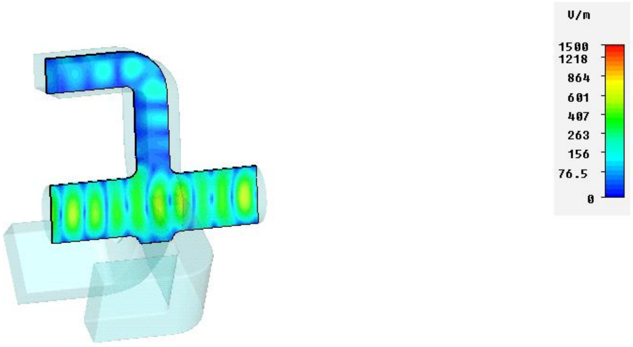
@ 4 GHz



@ 5 GHz



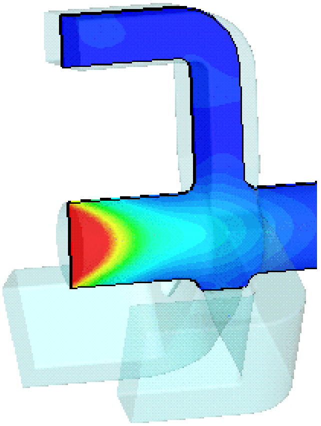
@ 6 GHz



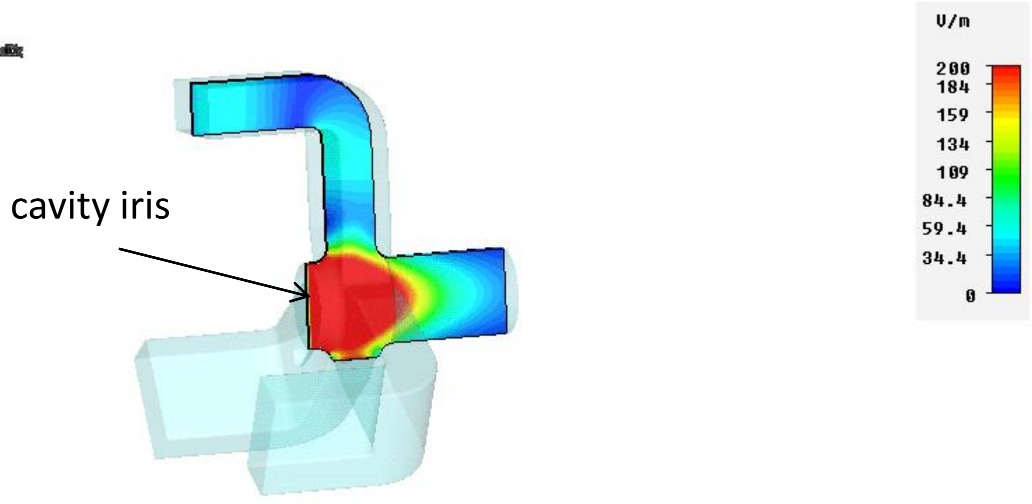
Trapped modes below cutoff improved damping by location close to cavity

- ❑distance to cavity matters

- ❑ 2 GHz (below cutoff)

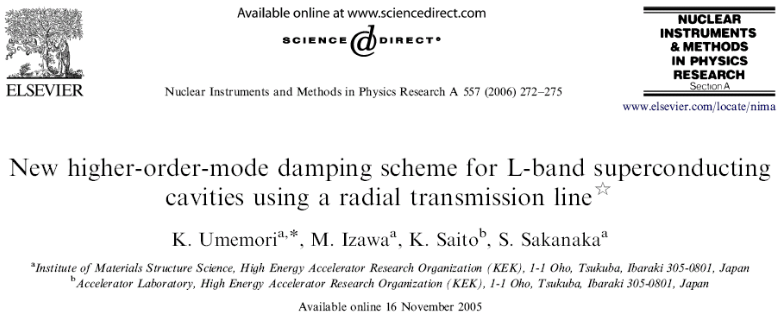


TE10 cutoff = 1.67 GHz



TE10 cutoff = 1.67 GHz

Radial Transmission Line (KEK Design)



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Nuclear Instruments and Methods in Physics Research A 557 (2006) 272–275

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

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New higher-order-mode damping scheme for L-band superconducting cavities using a radial transmission line ☆

K. Umemori[a,]*, M. Izawa[a], K. Saito[b], S. Sakanaka[a]

[a] *Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*
[b] *Accelerator Laboratory, High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*

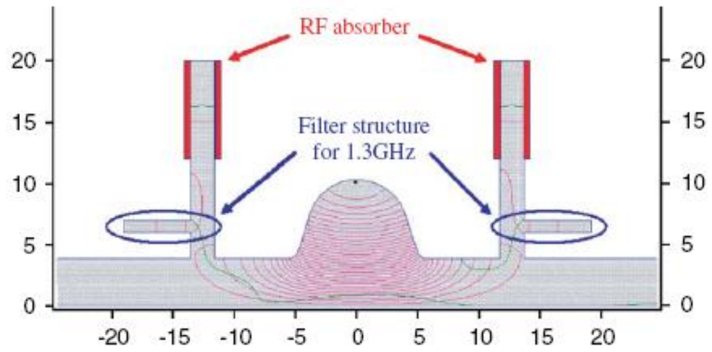


Fig. 1. Conceptual design of the radial-line HOM damper for a single-cell TESLA-type cavity.

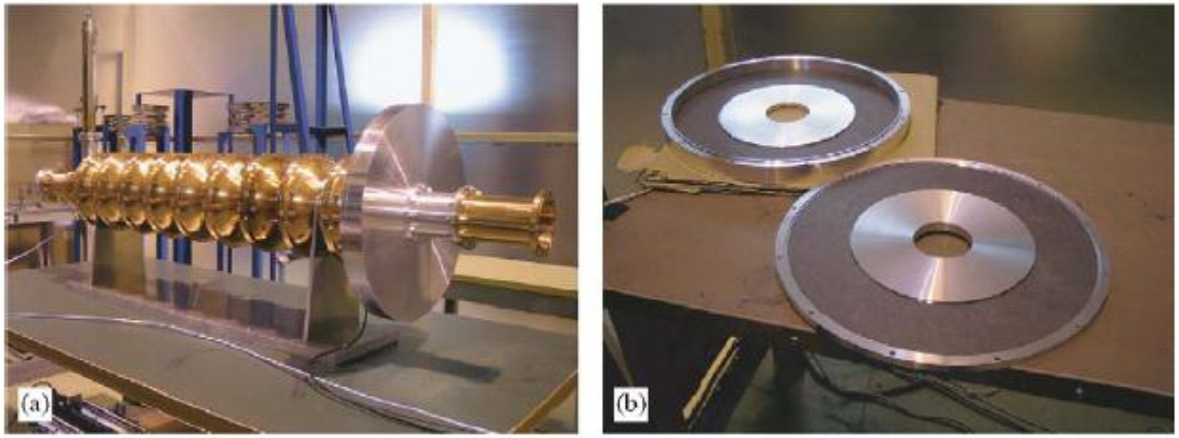
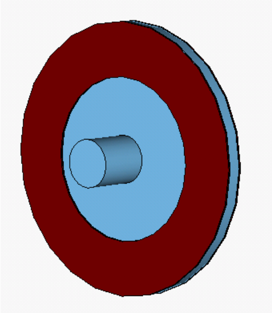
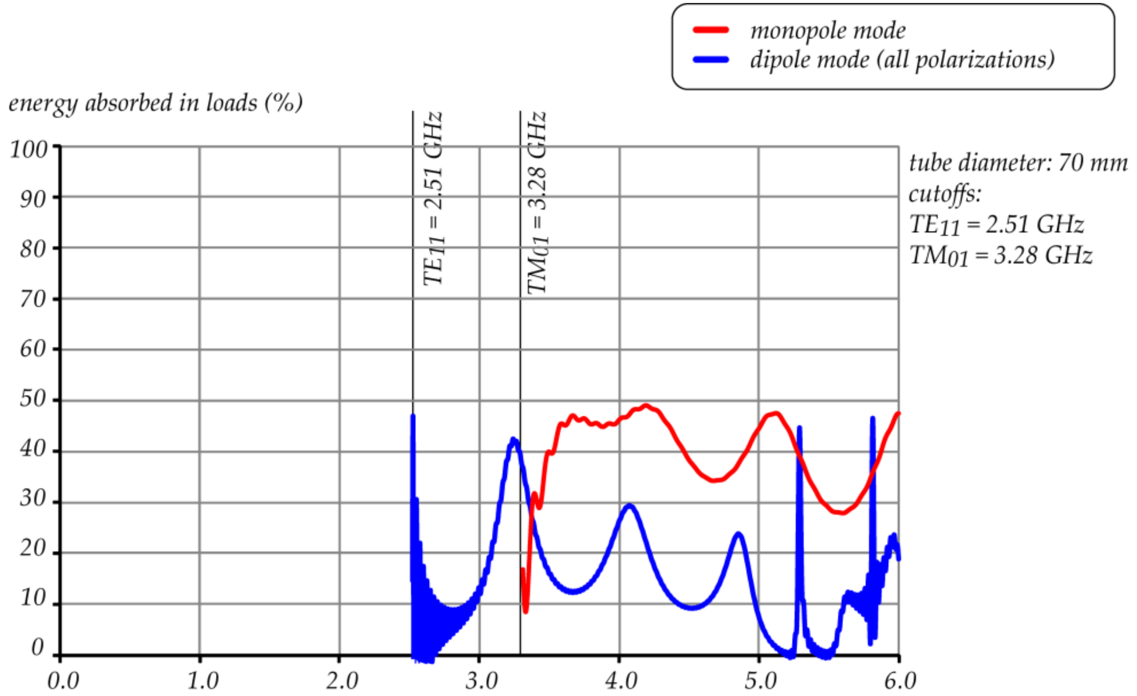


Fig. 2. (a) Low-power model of a 9-cell TESLA type cavity equipped with a radial-line HOM damper and (b) inside the radial-line HOM damper.

Radial Transmission Line (KEK Design)

- ☐ good performance, but “wavy” for dipoles
- ☐ benefit: independent on mode polarization
- ☐ again: performance below cutoff depends strongly on distance to cavity
- ☐ fundamental mode choke filter may be required (problem ?)



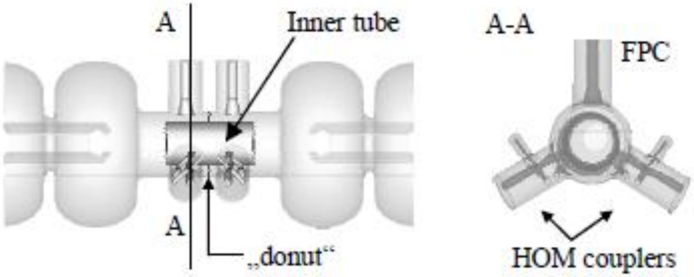


Coaxial Coupler (CC) Scheme for TESLA/ILC-Type Cavities

Proceedings of IPAC'10, Kyoto, Japan THPEC021

COAXIAL COUPLING SCHEME FOR TESLA/ILC-TYPE CAVITIES

J. Sekutowicz, DESY, 22603 Hamburg, Germany
P. Kneisel, TJNAF, Newport News, 23606 Virginia, USA



Proceedings of LINAC08, Victoria, BC, Canada THP044

COAXIAL COUPLING SCHEME FOR FUNDAMENTAL AND HIGHER ORDER MODES IN SUPERCONDUCTING CAVITIES*

J. Sekutowicz, P. Kneisel, G. Ciovati, TJNAF, Newport News, 23606 Virginia, USA
L. Xiao, SLAC, Menlo Park, 94025 California, USA

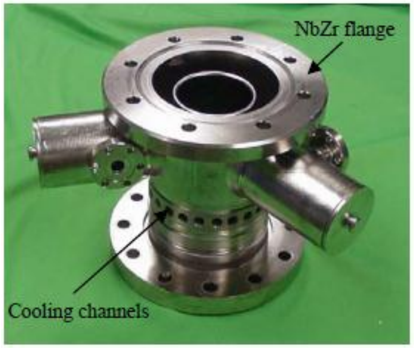
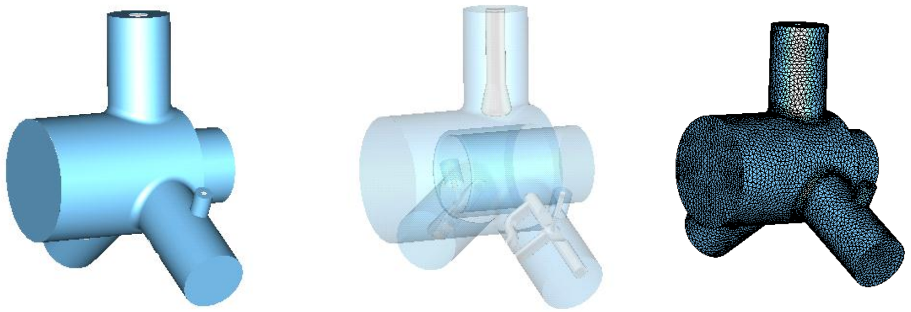


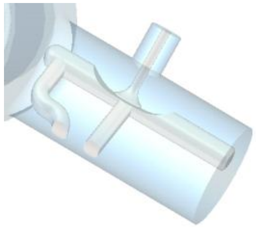
Figure 2: Prototype of the coaxial coupling.

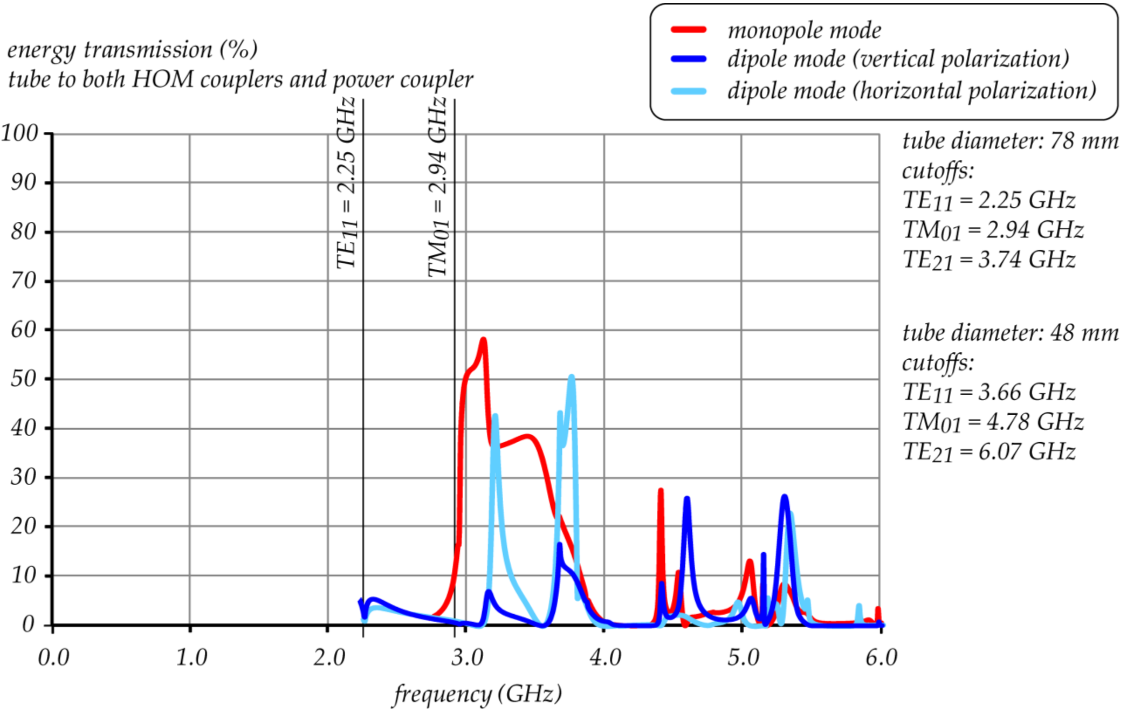
- ☐ benefits:
- ☐ flangable coupler, magnetic flux < 3mT at connection (E_{acc}=34MV/m, 150mT)
- ☐ saves beamline space
- ☐ coupler configuration yields less field asymmetries (coupler kicks)

Coaxial Coupler (CC) Scheme for TESLA/ILC-Type Cavities



DESY/ILC type hook/probe design



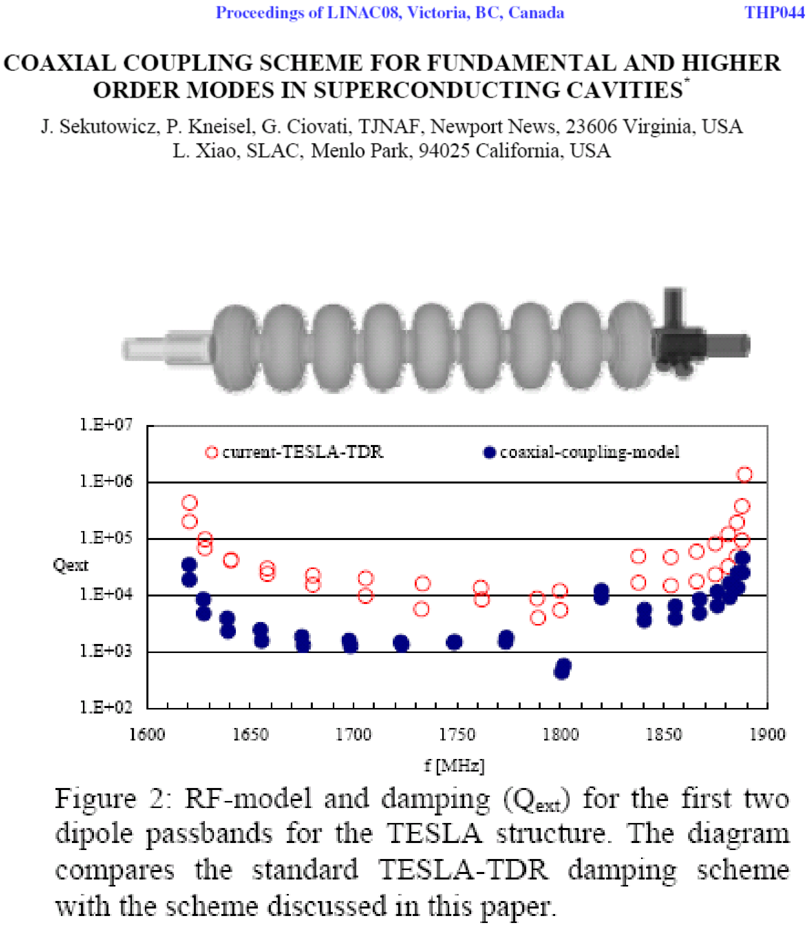


tube diameter: 78 mm
cutoffs:
TE_{11} = 2.25 GHz
TM_{01} = 2.94 GHz
TE_{21} = 3.74 GHz

tube diameter: 48 mm
cutoffs:
TE_{11} = 3.66 GHz
TM_{01} = 4.78 GHz
TE_{21} = 6.07 GHz

Coaxial Coupler (CC) Scheme for TESLA/ILC-Type Cavities

- ☐ seems to work nice for HOMs below cutoff



Proceedings of LINAC08, Victoria, BC, Canada THP044

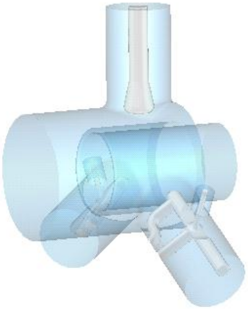
COAXIAL COUPLING SCHEME FOR FUNDAMENTAL AND HIGHER ORDER MODES IN SUPERCONDUCTING CAVITIES*

J. Sekutowicz, P. Kneisel, G. Ciovati, TJNAF, Newport News, 23606 Virginia, USA
L. Xiao, SLAC, Menlo Park, 94025 California, USA

Figure 2: RF-model and damping (Q_{ext}) for the first two dipole passbands for the TESLA structure. The diagram compares the standard TESLA-TDR damping scheme with the scheme discussed in this paper.

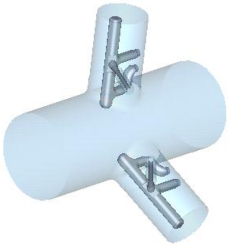
A comparison (above cutoff)

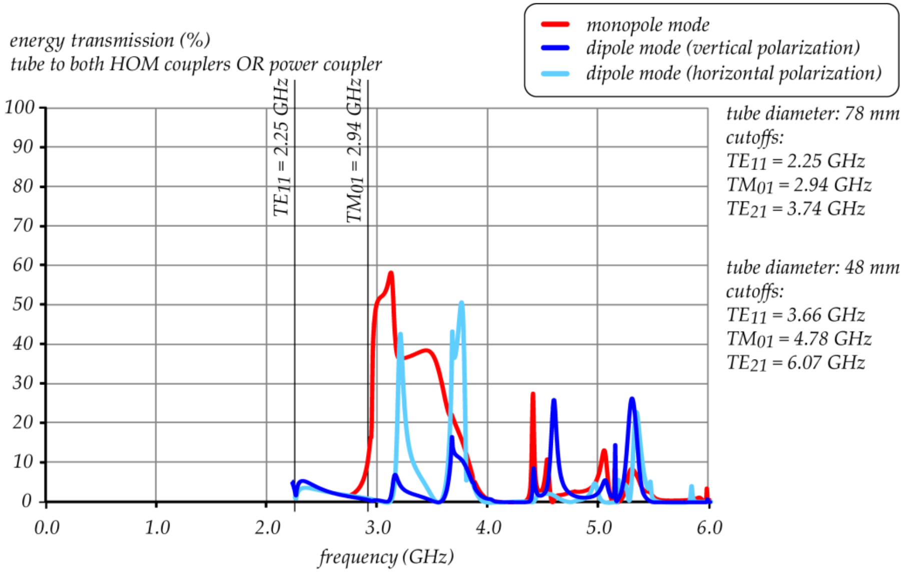
new design

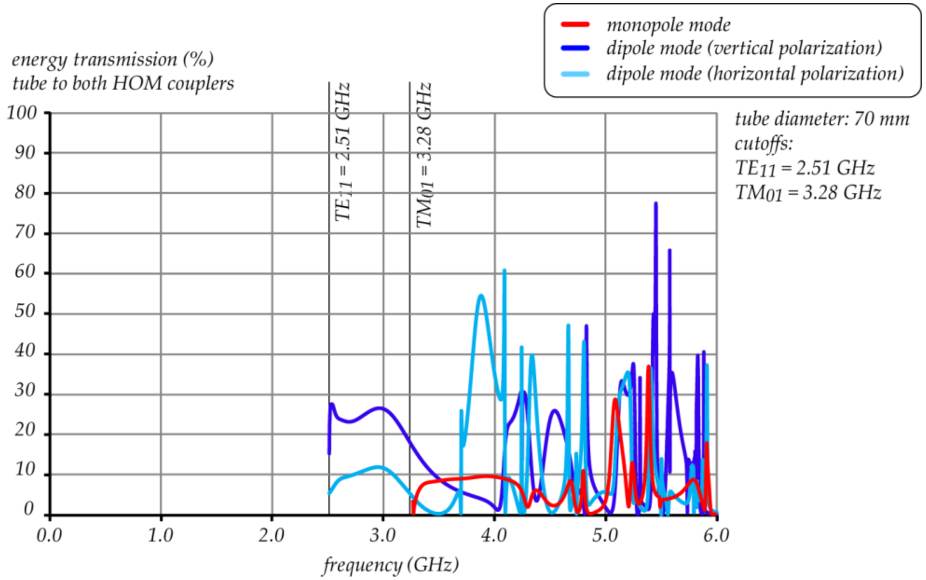


includes damping by FPC

JLAB

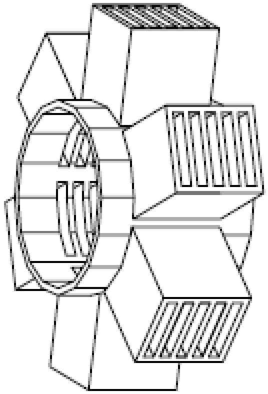






Waveguide Array Absorber (DESY Idea)

- ☐ TESLA proposal (LINAC98)



DESIGN OF A HOM BROADBAND ABSORBER FOR TESLA

M. Dohlus, A. Jöstingmeier, N. Holtkamp and H. Hartwig, DESY, D-22607 Hamburg, Germany

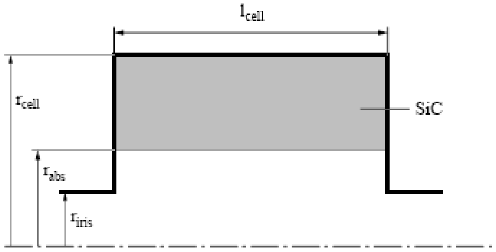


Figure 2: Solid SiC absorber.

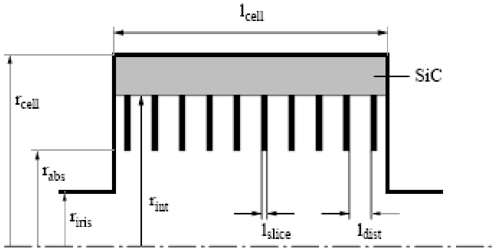


Figure 4: Combined absorber.

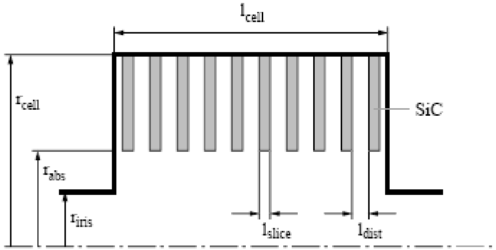


Figure 3: Laminated SiC absorber.

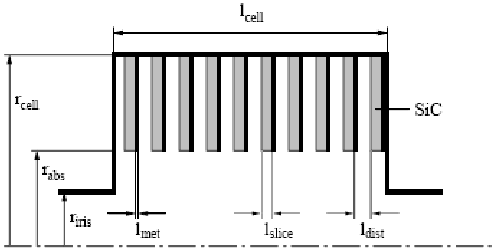
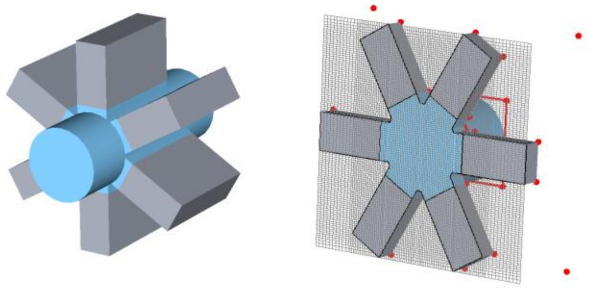


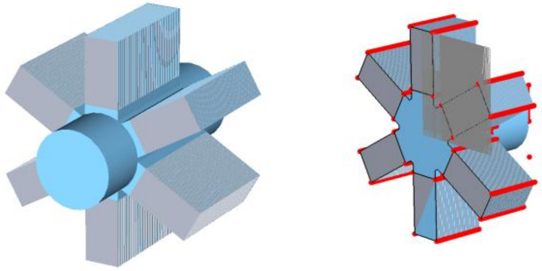
Figure 5: Metallized laminated SiC absorber.

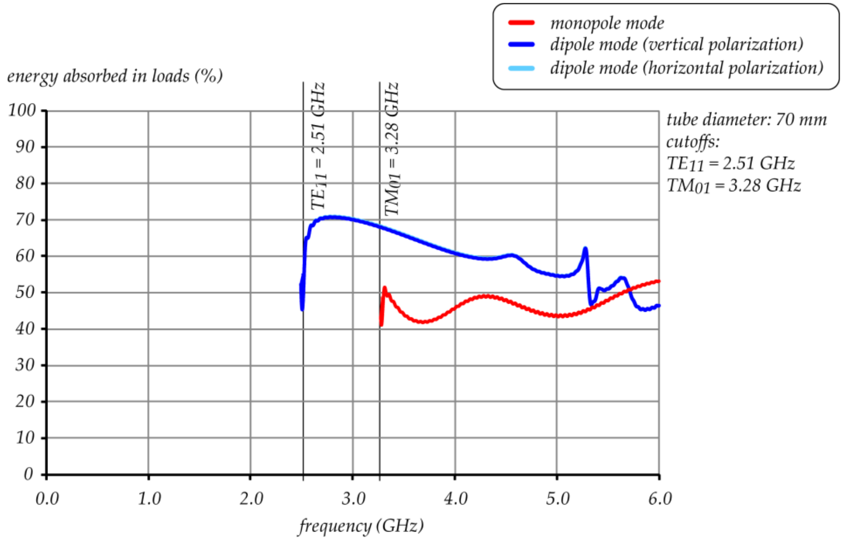
Waveguide Array Absorber (DESY Idea)

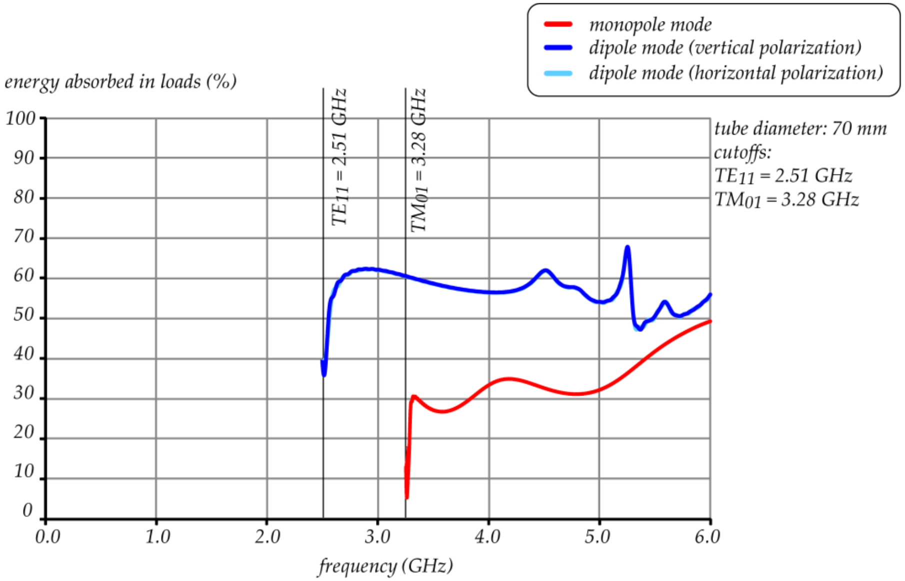
❑ solid absorber



❑ laminated absorber



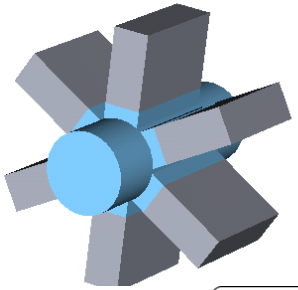


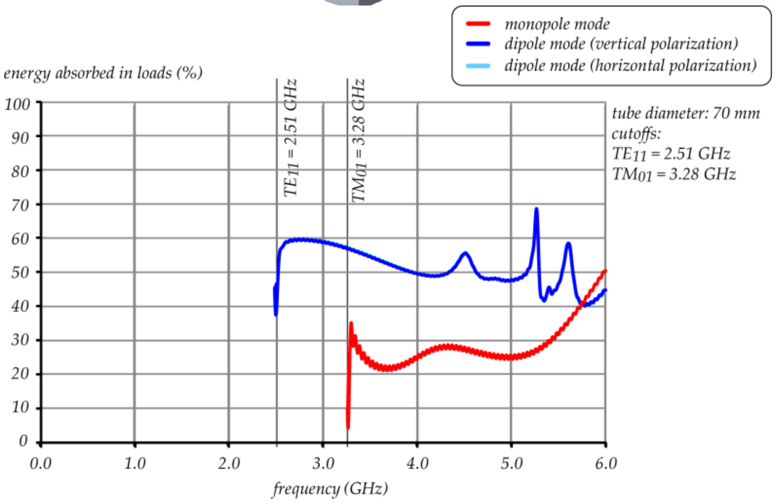


Waveguide Array Absorber (DESY Idea)

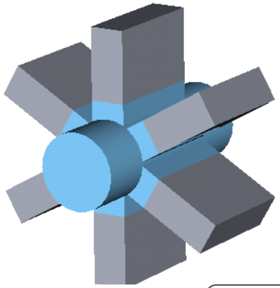
- ❑ outcome: excellent performance
- ❑ probably technically too complicated (and never realized ?)
- ❑ and: rather beamline absorber which benefits from loads being placed so close to the beam tube

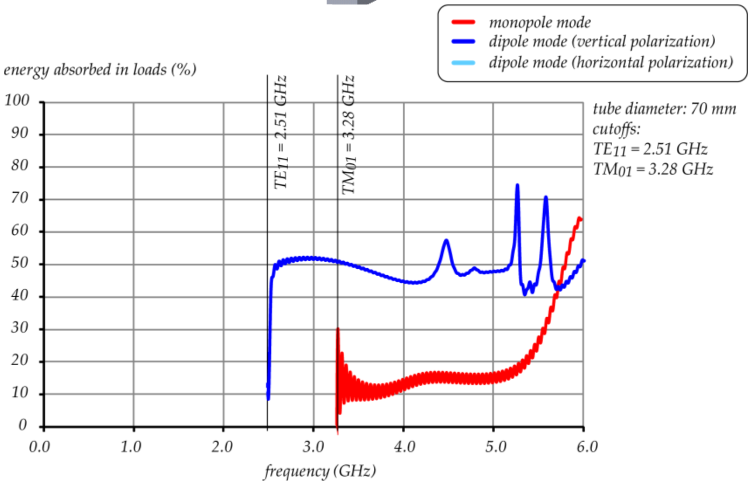
❑ 5mm waveguide added



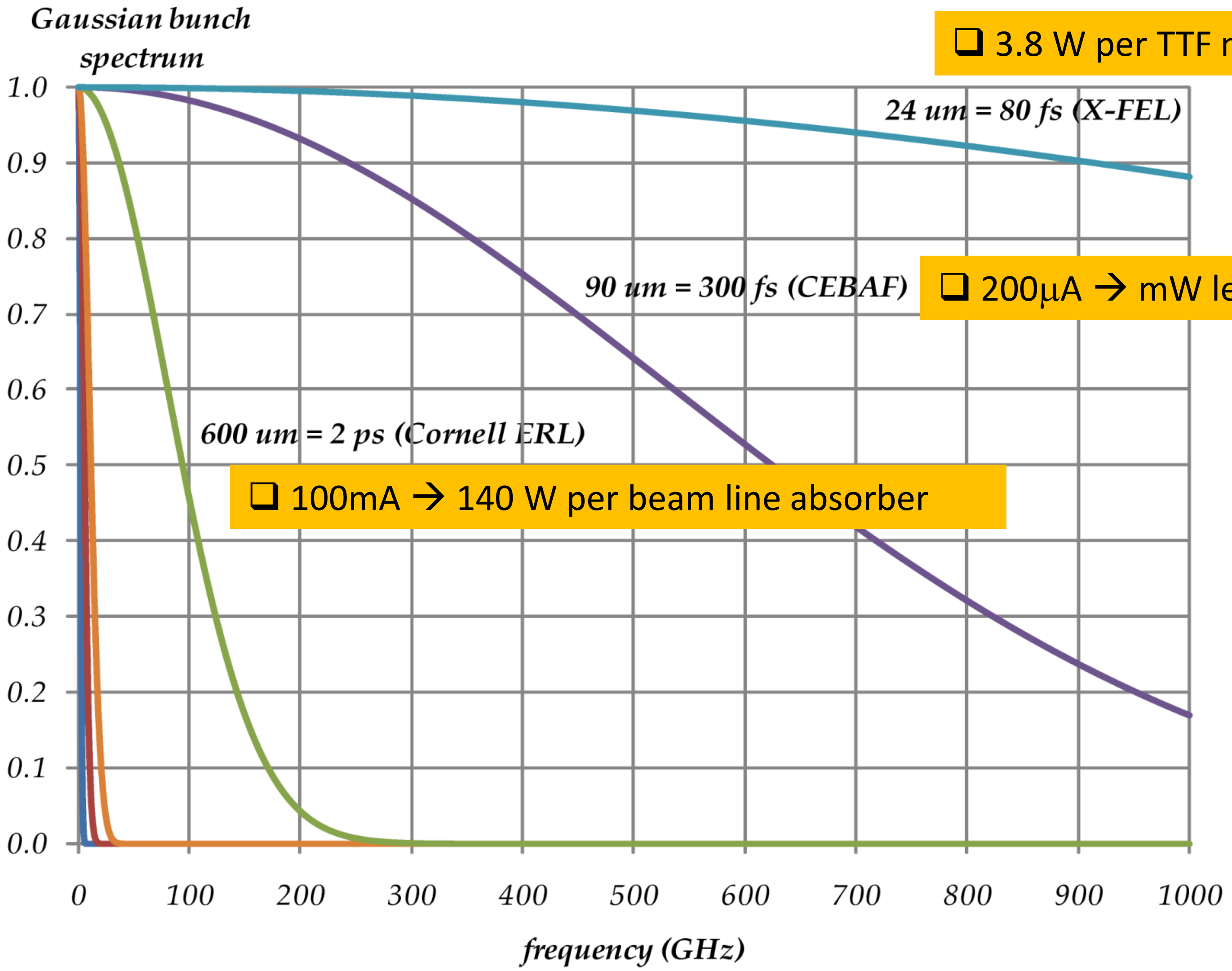


❑ 10 mm waveguide added





Beam Liner Absorbers: HOM Power Levels



- ☐ 3.8 W per TTF module
- ☐ 200µA → mW level
- ☐ 100mA → 140 W per beam line absorber

DESY 70 K Beam Line Absorber (BLA)
for propagating mode absorption in CM interconnections

THPEC022 Proceedings of IPAC'10, Kyoto, Japan

BEAM TESTS OF HOM ABSORBER AT FLASH

J. Sekutowicz, A. Gössel, N. Mildner, M. Dohlus
DESY, Notkestrasse 85, 22607 Hamburg, Germany

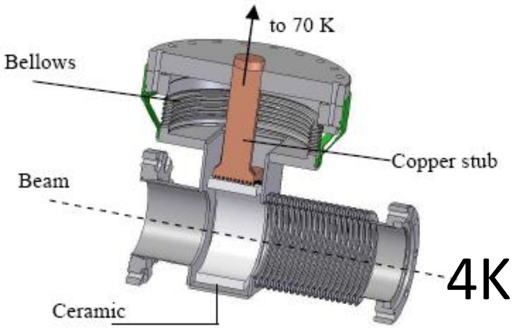


Figure 2: Layout of the beam line absorber.

Figure 3: parts of the BLA prototype: (left) damping ceramic ring welded to the copper stub and (right) housing made of stainless-steel.

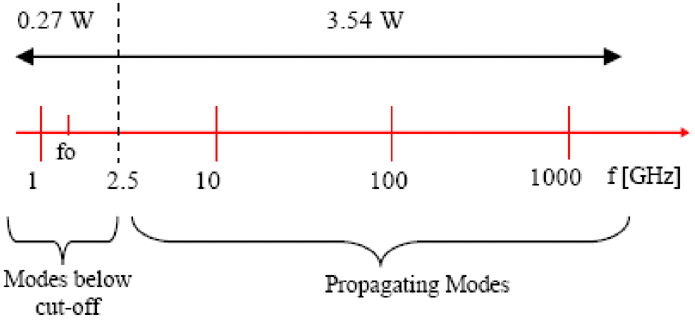
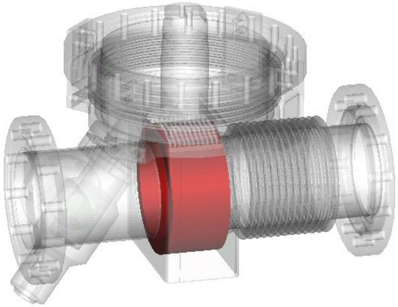
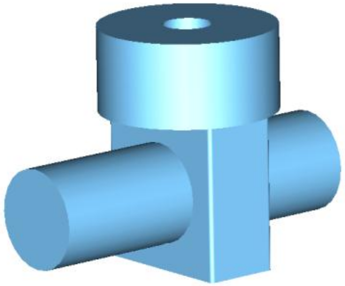


Figure 1: HOM power distribution for XFEL cryomodule vs. frequency for the nominal pulse operation.

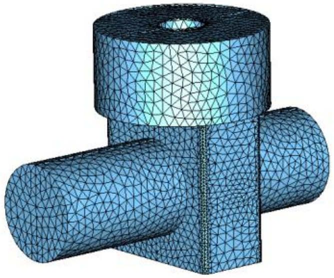
power capacity specified to 100W

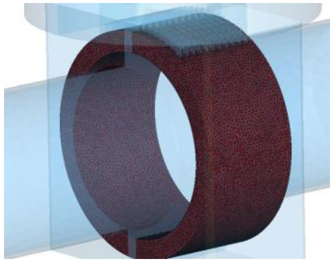
Ceradyne Ceralloy CA-137 used (3 data points 1-10 GHz)



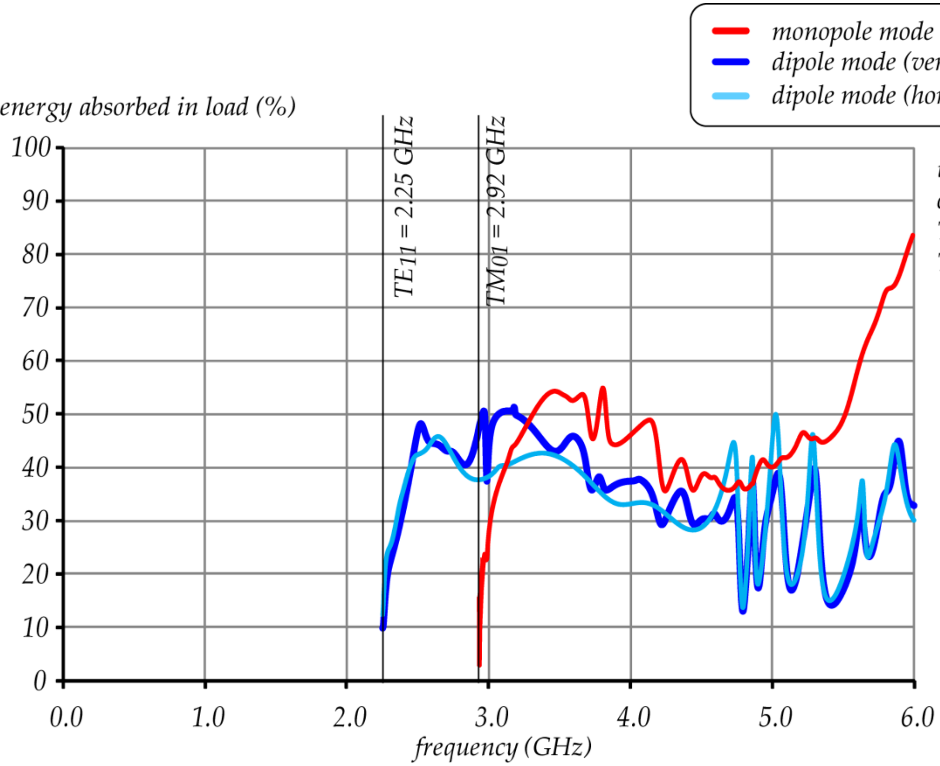


simplified model





absorber length = 76.8mm



tube diameter: 78.5 mm
cutoffs:
TE_{11} = 2.24 GHz
TM_{01} = 2.92 GHz

Artificial Absorber Material

- ☐ electric losses

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \frac{1}{\varepsilon_0}\left(\varepsilon' + i\varepsilon''\right) \qquad \delta_\varepsilon = \frac{\varepsilon''}{\varepsilon'}$$

- ☐ magnetic losses

$$\mu_r = \frac{\mu}{\mu_0} = \frac{1}{\mu_0}\left(\mu' + i\mu''\right) \qquad \delta_\mu = \frac{\mu''}{\mu'}$$

- ☐ electric losses

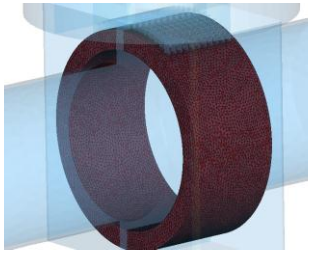
$$\varepsilon_r = \mu_r = 0.6 + 0.8i \longrightarrow \delta_{\varepsilon,\mu} = 1.33$$ very lossy!

$$\left|\varepsilon_r\right| = \left|\mu_r\right| = \sqrt{0.36 + 0.64} = 1$$

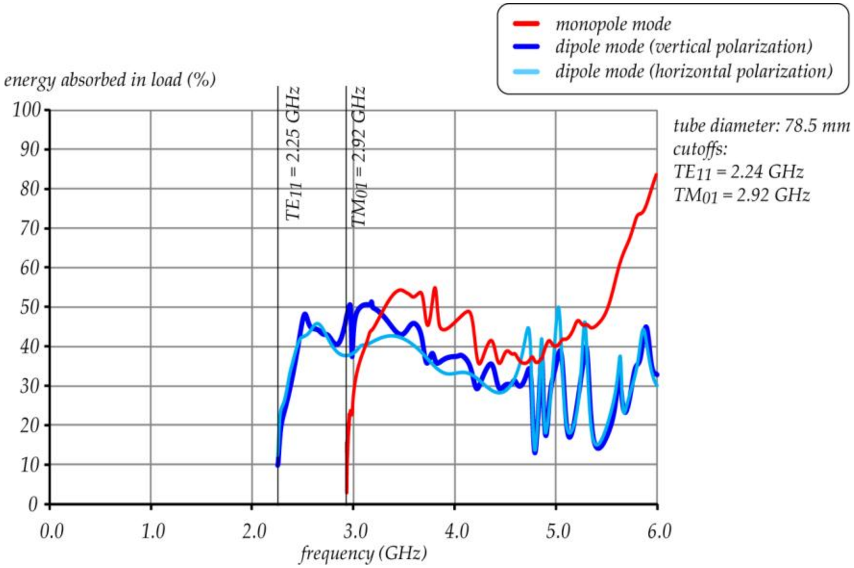
- ☐ benefits:
  - → almost ideal absorber
  - → saves tremendous number of mesh cells!

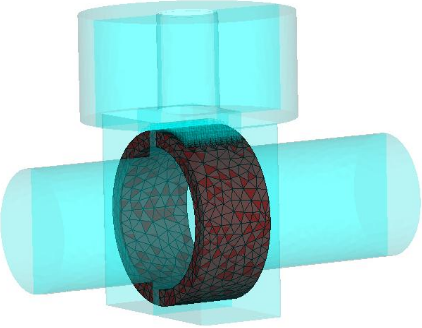
Artificial Absorber Material

- ☐ design has potential to yield much better absorption by finding/using appropriate materials
- ☐ or: with “ideal absorber” one may concentrate to optimize surroundings quickly for better absorption (if required)

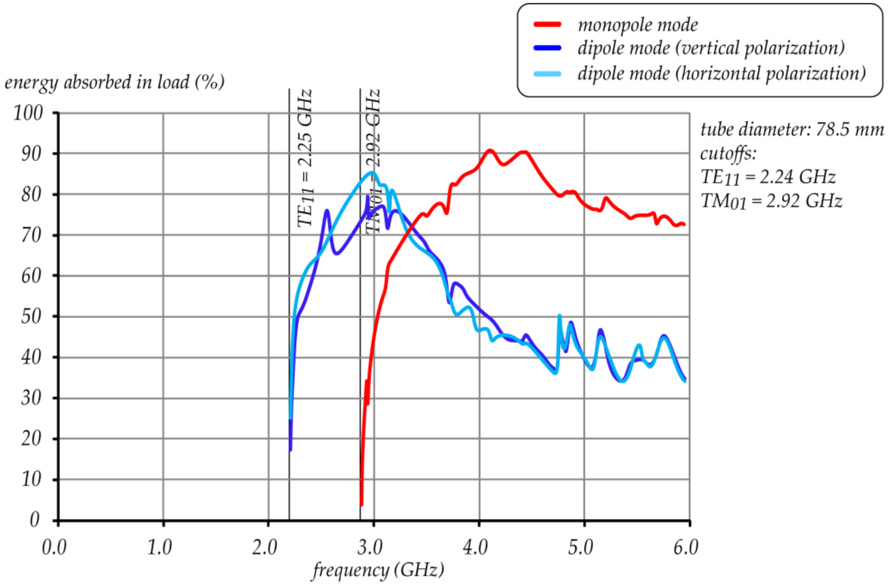


CPU time: 1hr 20 min

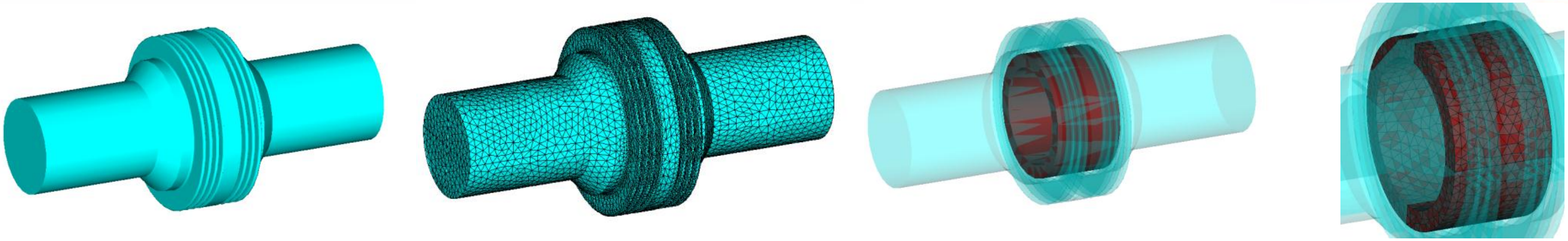




CPU time: 7 min

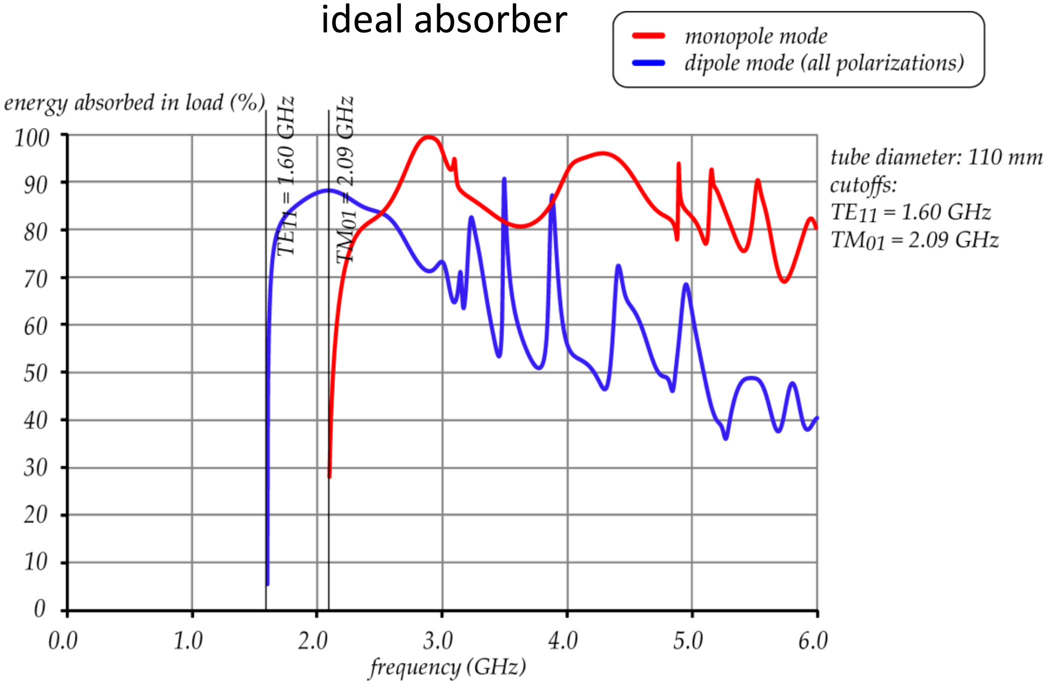


Cornell ERL Beam Line Absorber



absorber length = 76.8mm

ideal absorber



Thank You !

Backup Slides

What are numerical alternatives at higher frequencies ?

❑ the HOM damping efficiency can be characterized fully by S-Parameters and characterized by the energy a) transmitted through HOM ports or b) absorbed in loads

❑ examples:

1) coaxial coupler
   - →consider: signals transmitted through beam tube (S21) are not reflected
   - →i.e. no reflection from an adjacent cavity (creating standing waves), but a short can be included
   - →ideally one wants to extract as much HOM energy as possible
2) beam line absorber
3) „dead-end“ absorbers

❑ benefits:

→numerical S-Parameter calculations fast and accurate

→ can use stand-alone workstation (not every user has access to supercomputers)

→ complex material properties can be taken into account

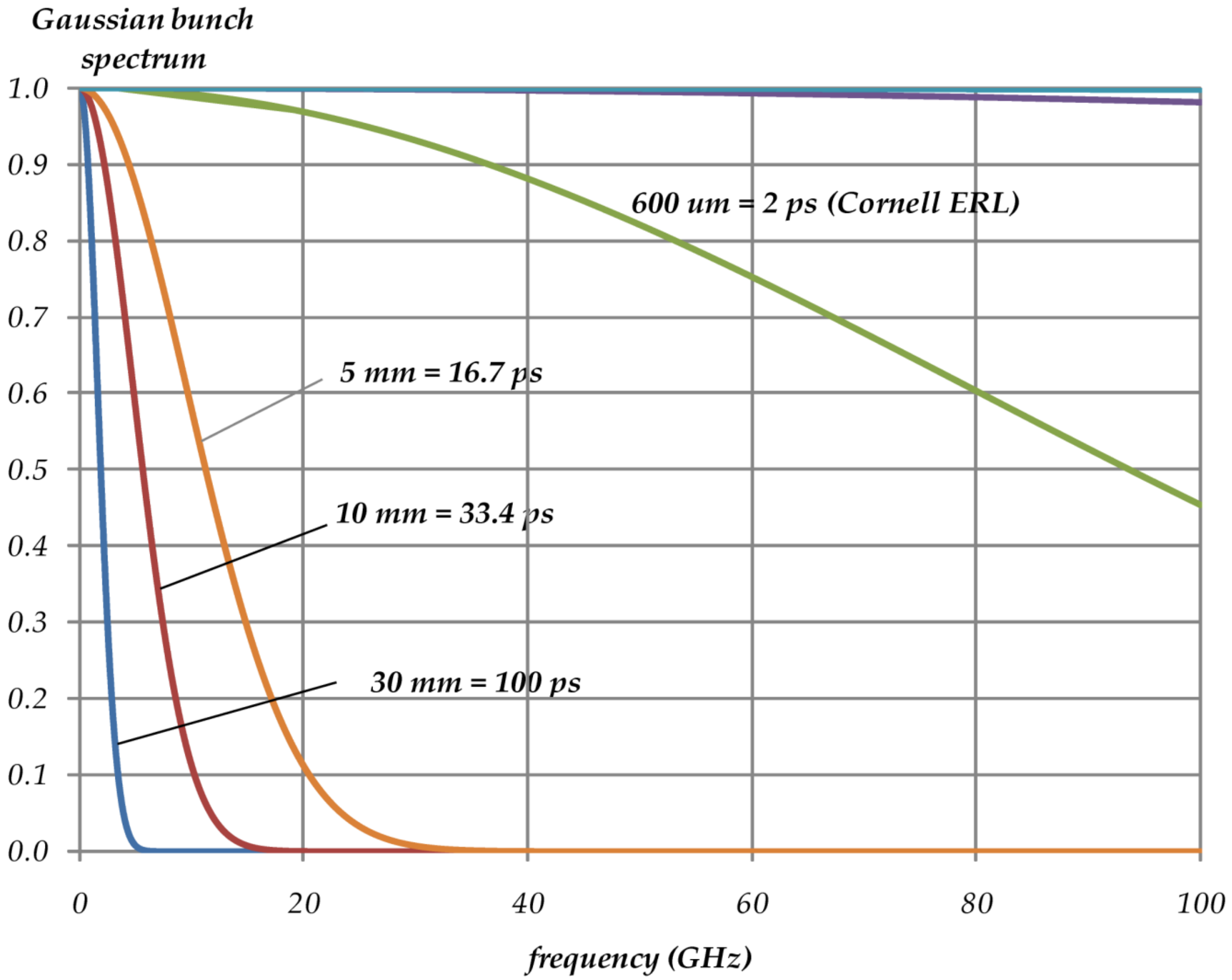
→ covers easily „gray zone“ of quasi trapped HOMs with high impedance sometimes forgotten in cavity design (e.g. CEBAF)

→problem size is handy, allows to mesh complex structures (e.g. DESY type coaxial couplers), which Eigenmode and wakefield solvers with staircase meshing can not allow for

→ full problem even not easy to mesh and run with FEA codes (SLAC‘s Omega3P running on NERSC supercomputers) in this frequency range

→ allows to distinguish between different waveguide modes, such to analzye coupling to monopole, dipole, quadrupole modes etc.)

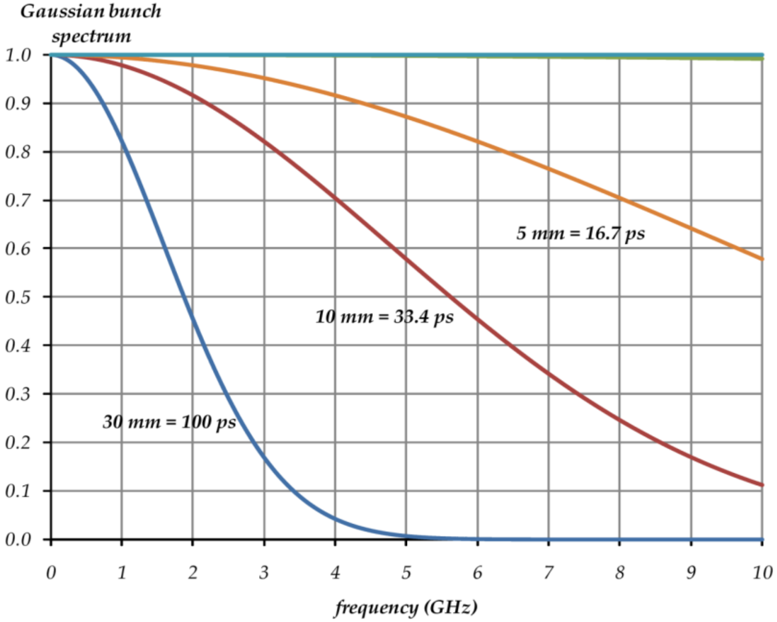
HOM Frequency Regime vs. Bunch Length



Numerical Assessment of HOMs in 3D

coupling impedance spectra, field pattern, loaded and externals Qs, R/Qs, loss factors

- ☐ for 3D SRF cavity structures (operating in L-Band, S-Band) the covered frequency range to fully characterize HOMs is limited to a few GHz
  - →utilizing stand-alone workstations
  - →or small number computers running parallel (e.g. distributed computing in networks)
- ☐ not considered is massive parallel computing resources (e.g. supercomputers/Petascale computer = 10^{15} operations/sec)
  - →i.e. not every user has readily access to supercomputers and massive parallel codes ?
  - →e.g. SLAC's suite of codes accessible only through the US Department of Energy's under the SciDAC program (Scientific Discovery through Advanced Computing)



frequency range typically accessible numerically with reasonable effort/time

Numerical Assessment of HOMs in 3D

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- ☐ for 3D SRF cavity structures (operating in L-Band, S-Band) the covered frequency range to fully characterize HOMs is limited to a few GHz
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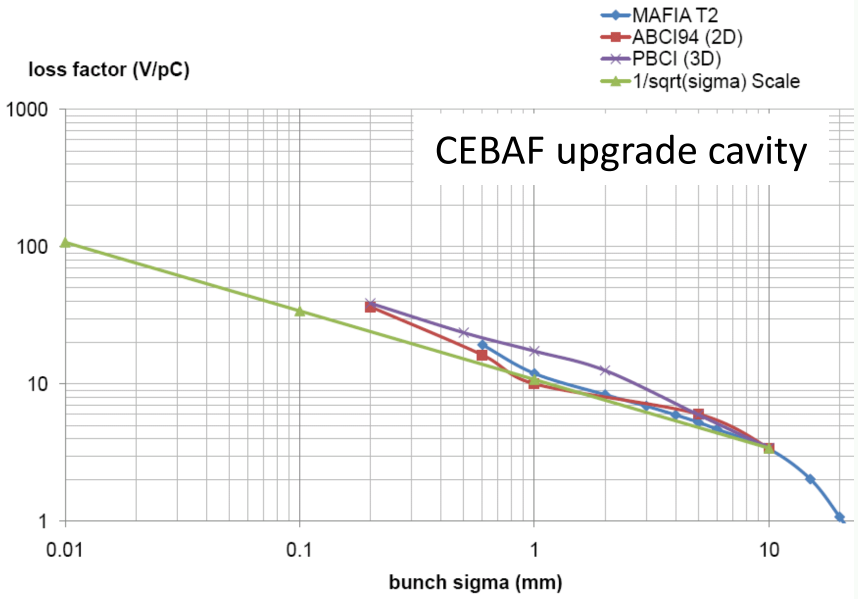
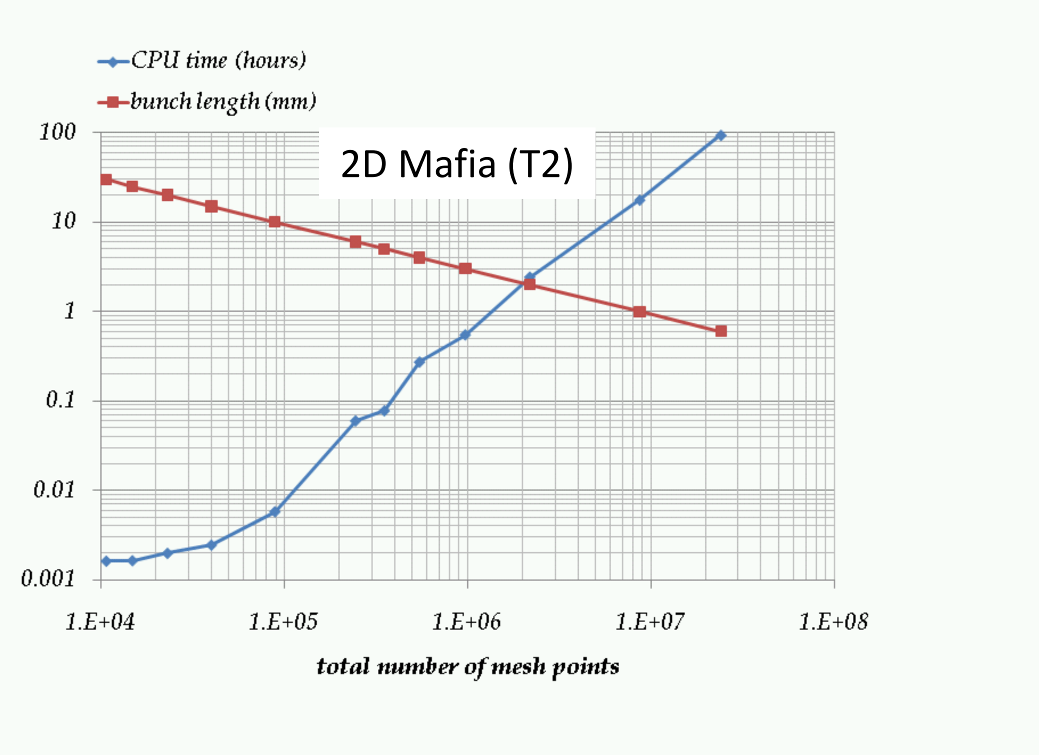
  - →e.g. SLAC‘s suite of codes accessible only through the US Department of Energy‘s under the SciDAC program (Scientific Discovery through Advanced Computing)
- ☐ some constraints in 3D then are:
  - → still relatively large CPU time
  - → limited RAM (32-bit processors only 2^32 = 4.2 billion (4 GByte or lower OS limit))
  - → software codes in use may not be able to handle few GBytes of RAM internally
  - → complex structures can not be meshed easily (or at all)
  - → code may not run on multiple cores, multi-threaded or parallel

Numerical Assessment (Small Scale Computing)

loss factors





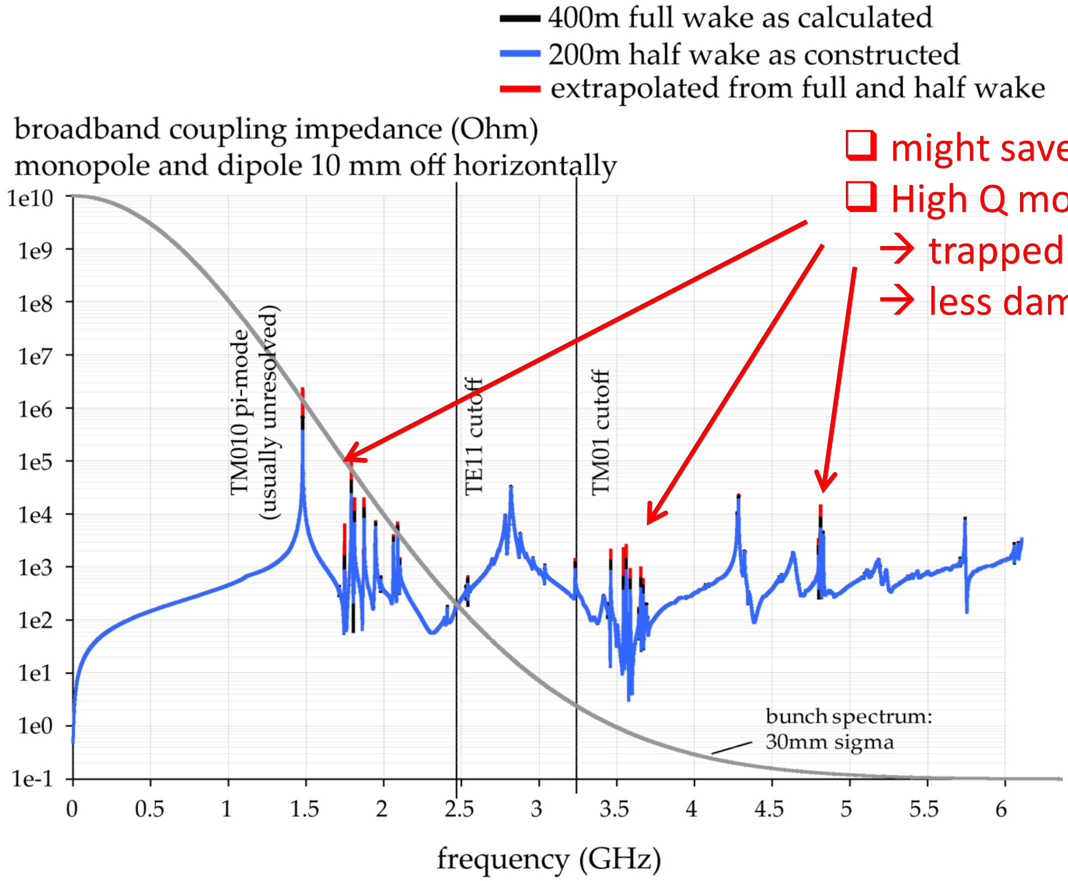
frequency range typically accessible numerically with reasonable effort/time

CPU Time Saving Trick to Resolve High Q Modes

Proceedings of PAC09, Vancouver, BC, Canada FR5PFP094

ENHANCED METHOD FOR CAVITY IMPEDANCE CALCULATIONS*

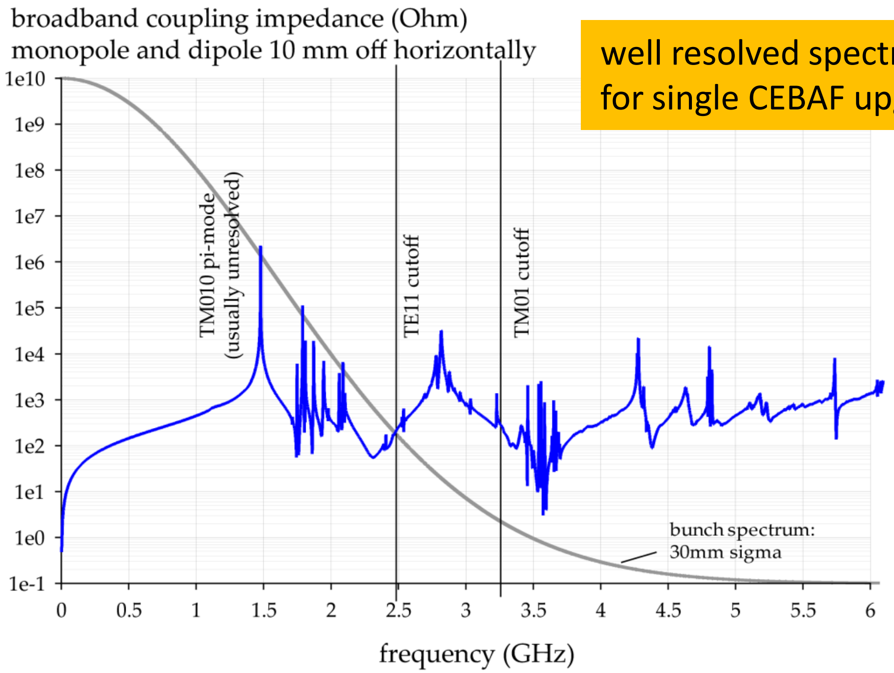
F. Marhauser, R.A. Rimmer, K. Tian, H. Wang, JLab, Newport News, VA 23606, U.S.A



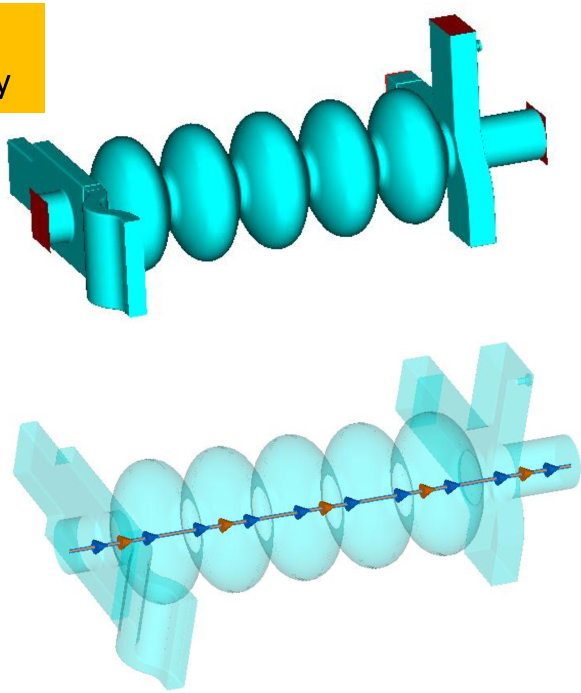
- ☐ might save days/weeks of CPU time
- ☐ High Q modes can be identified immediately
  - → trapped modes
  - → less damped modes, also above cutoff!

Small Scale Computing (Single Cavity)
coupling impedance spectra

- ☐ Example: **wakefield solver** for **Original Cornell/CEBAF cavity with waveguide dampers**
  - → waveguide dampers are easy to model/mesh
  - → waveguide ports are ideal absorbers
  - → broadband cavity coupling impedance accurately predicted
  - → CST Particle Studio: 400m and σ = 30 mm (1.5 M cells) resulted in a **CPU time=18.5 hrs** (8 threads used on Dual Quad Core Nehalem 3.2 GHz, 24 GByte (64 bit Win XP Pro)



well resolved spectrum
for single CEBAF upgrade cavity

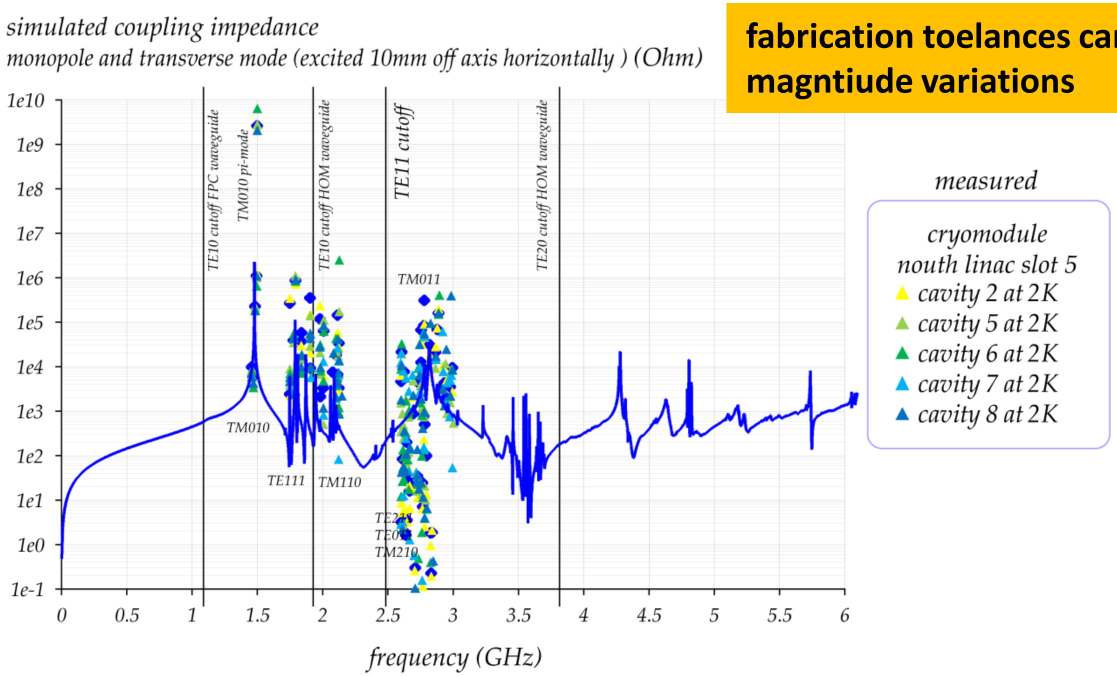


Simulations vs. Measurement (in Cryomodule)

- ☐ Measured Impedance relies on simulated R/Q
  - → 3D is important for mode identification (and R/Q)
  - → will become extremely difficult at higher frequencies
  - → measurement in crymodule also very tedious and limited to small amount of modes above cutoff

$$R = \left(R/Q \right)_{r,\mathrm{simulated}} \cdot Q_{\mathrm{measured}}$$

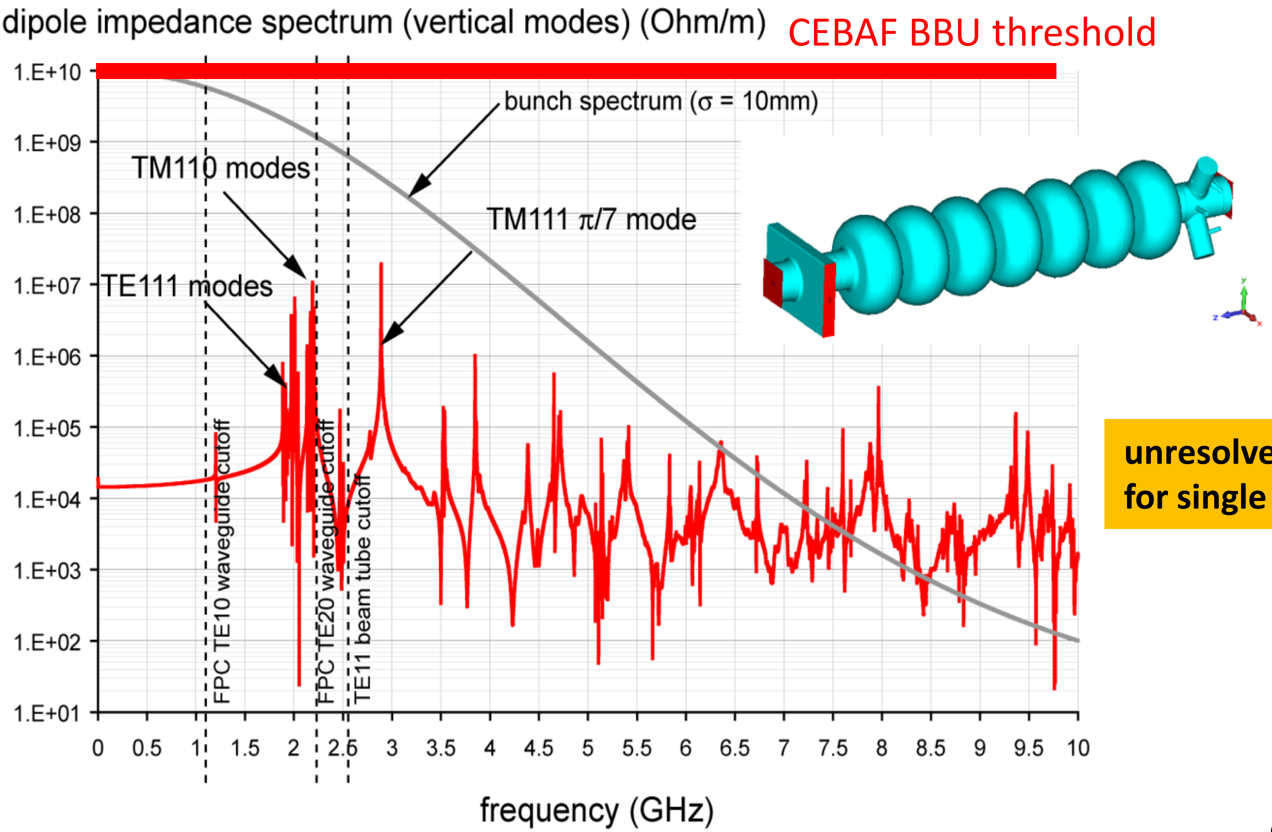
fabrication toelances can contribute to >1 order of magntiude variations



Numerical Assessment of HOMs in 3D

coupling impedance spectra, loaded and externals Q, R/Qs, loss factors

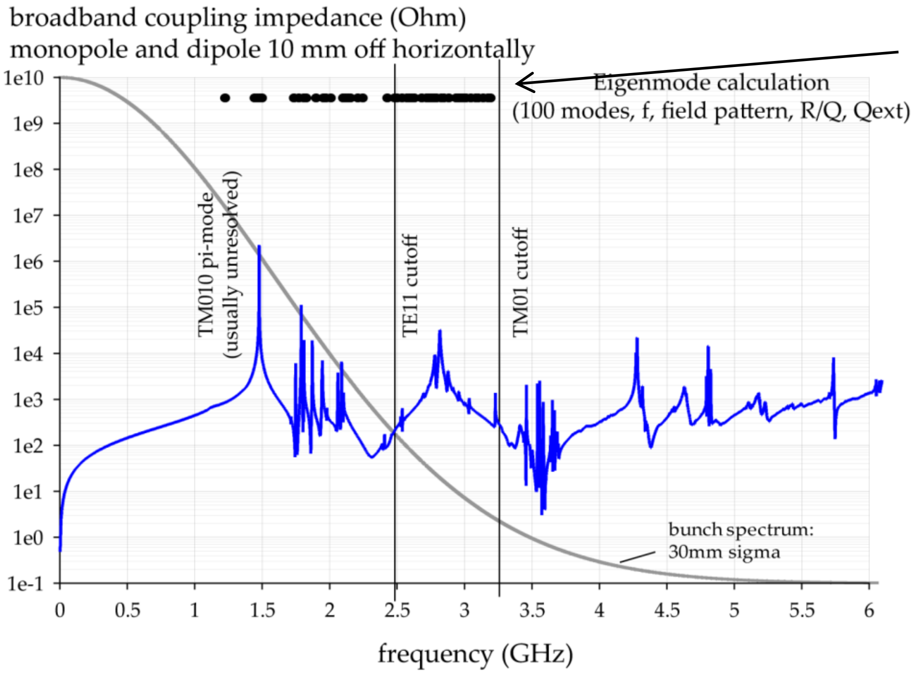
- ❑ what about more complex structures ? e.g. **DESY/TESLA-type coaxial HOM couplers**
- ❑ commercially available codes (HFSS, MAFIA, CST Studio Suite, GDfidL etc.) usually do not succeed to characterize a fully damped SRF cavities with such couplers
  - →e.g. **CST Particle Studio: HOM-couplers too complex**
  - →damping through power coupler and beam tubes only



unresolved spectrum for single CEBAF upgrade cavity

Small Scale Computing

☐ Example: **wakefield solver** for **C50 cavity with waveguide dampers**
  - → waveguide dampers are easy to model/mesh
  - → waveguide ports are ideal absorbers
  - → broadband cavity coupling impedance accurately predicted
  - → CST Particle Studio: 400m and σ = 30 mm (1.5 M cells) resulted in a **CPU time=18.5 hrs** (8 threads used on Dual Quad Core Nehalem 3.2 GHz, 24 GByte (64 bit Win XP Pro)



☐ **Eigenmode solver may take longer**
  - → Here: 100 modes cover ~ 3.1 GHz
  - → **CPU time: 2 days** CST Microwave Studio

☐ CST internal memory handling problem
  - → did not calculate Q_{ext}

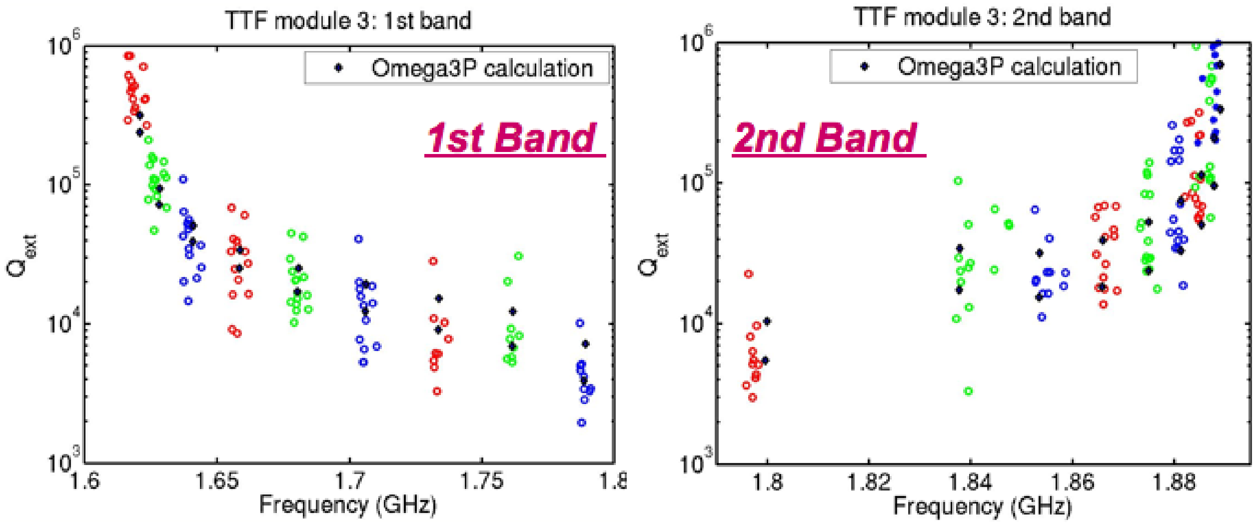
☐ CPU time increases non-linearly with number of modes
  - → mesh density increases
  - → spectrum becomes very dense
  - → not able to compute to much higher frequency

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

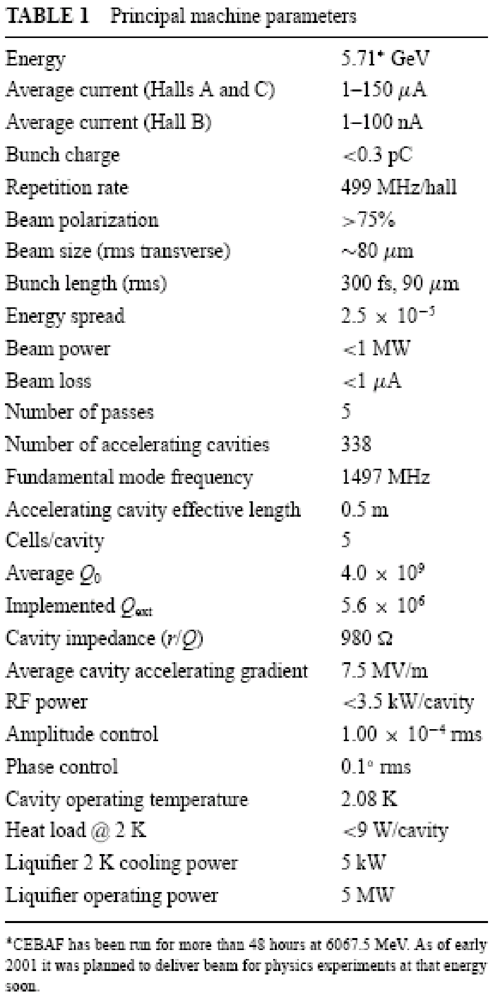


TABLE 1 Principal machine parameters

Energy	5.71[*] GeV
Average current (Halls A and C)	1–150 μA
Average current (Hall B)	1–100 nA
Bunch charge	<0.3 pC
Repetition rate	499 MHz/hall
Beam polarization	>75%
Beam size (rms transverse)	~80 μm
Bunch length (rms)	300 fs, 90 μm
Energy spread	2.5×10^{-5}
Beam power	<1 MW
Beam loss	<1 μA
Number of passes	5
Number of accelerating cavities	338
Fundamental mode frequency	1497 MHz
Accelerating cavity effective length	0.5 m
Cells/cavity	5
Average Q_0	4.0×10^9
Implemented Q_{ext}	5.6×10^6
Cavity impedance (r/Q)	980 Ω
Average cavity accelerating gradient	7.5 MV/m
RF power	<3.5 kW/cavity
Amplitude control	1.00×10^{-4} rms
Phase control	0.1° rms
Cavity operating temperature	2.08 K
Heat load @ 2 K	<9 W/cavity
Liquifier 2 K cooling power	5 kW
Liquifier operating power	5 MW

[*] CEBAF has been run for more than 48 hours at 6067.5 MeV. As of early 2001 it was planned to deliver beam for physics experiments at that energy soon.

Experienced HOM Probe Sapphire RF Feed-Through Issues