ERL workshop, JLab,
March 19-23, 2005.

"HOM calculations/predictions & overview of damping schemes for ERLs"

Bob Rimmer

JLab.

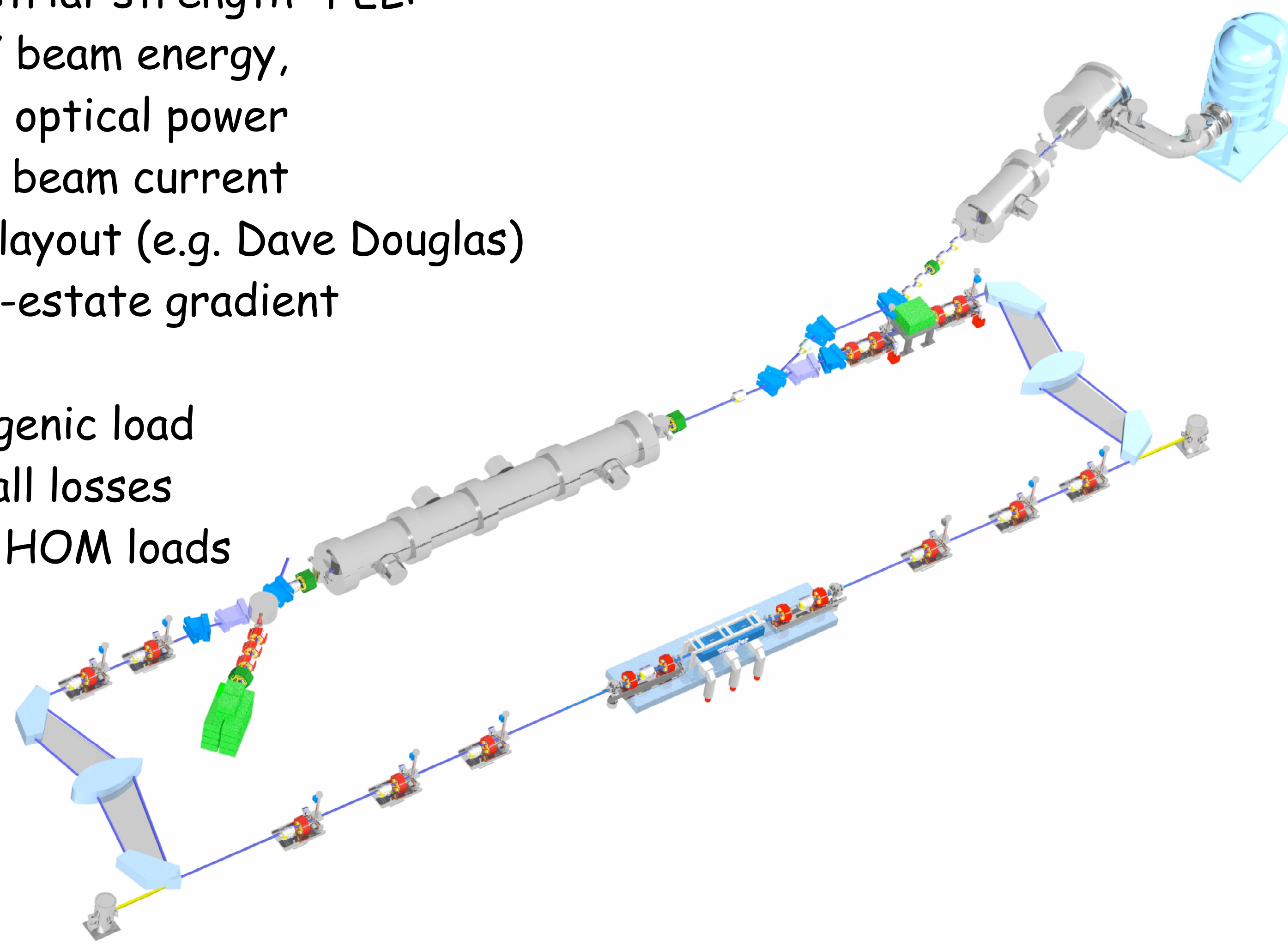
Intro, ERL requirements
Methods of HOM calculation
Methods of broad-band HOM damping
Number of cells
Cell shape/cell-cell coupling.
Example 1: BNL electron cooler CM concept
Example 2: JLab Ampere-class FEL CM concept
HOM power issues
Conclusions

Intro, ERL requirements:

High-average power ERL's face many challenges on the "current" frontier. Some similar to storage ring e+e- colliders, e.g. HOM damping, RF power.

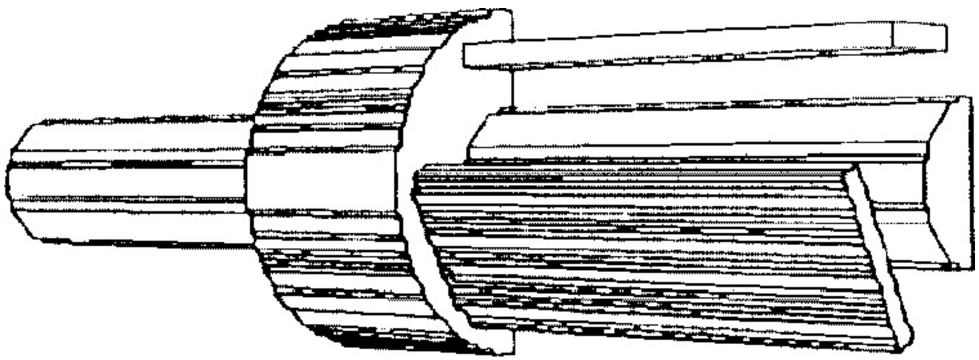
Typical "industrial-strength" FEL:

- ~100MeV beam energy,
- ~100kW+ optical power
- ~100mA+ beam current
- Compact layout (e.g. Dave Douglas)
- High real-estate gradient
- CW
- Low cryogenic load
  - Low wall losses
  - Warm HOM loads

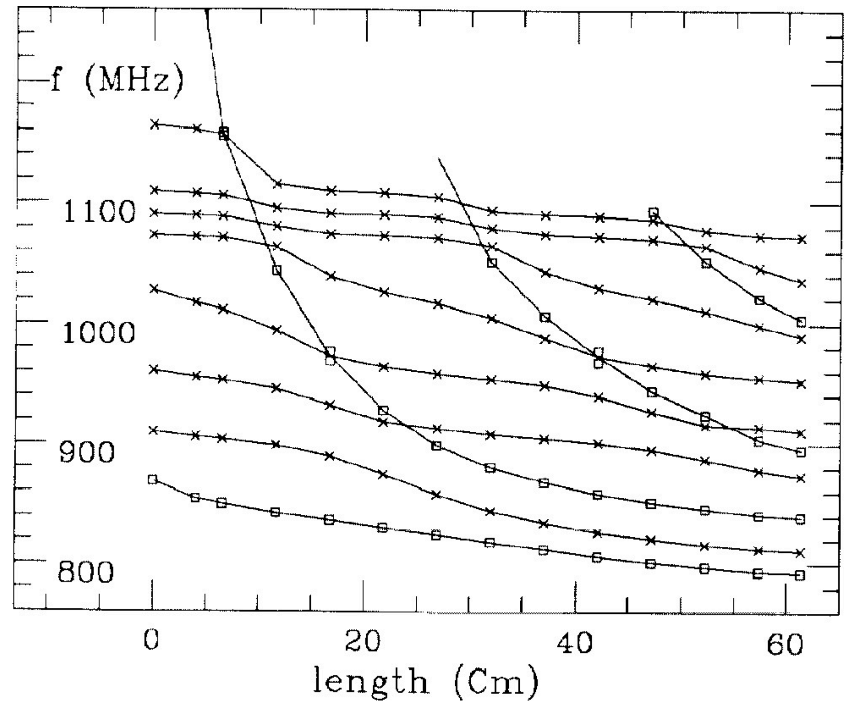


Methods of HOM calculation:

Kroll-Yu/Kroll-Lin method



Pillbox model with waveguide damping.

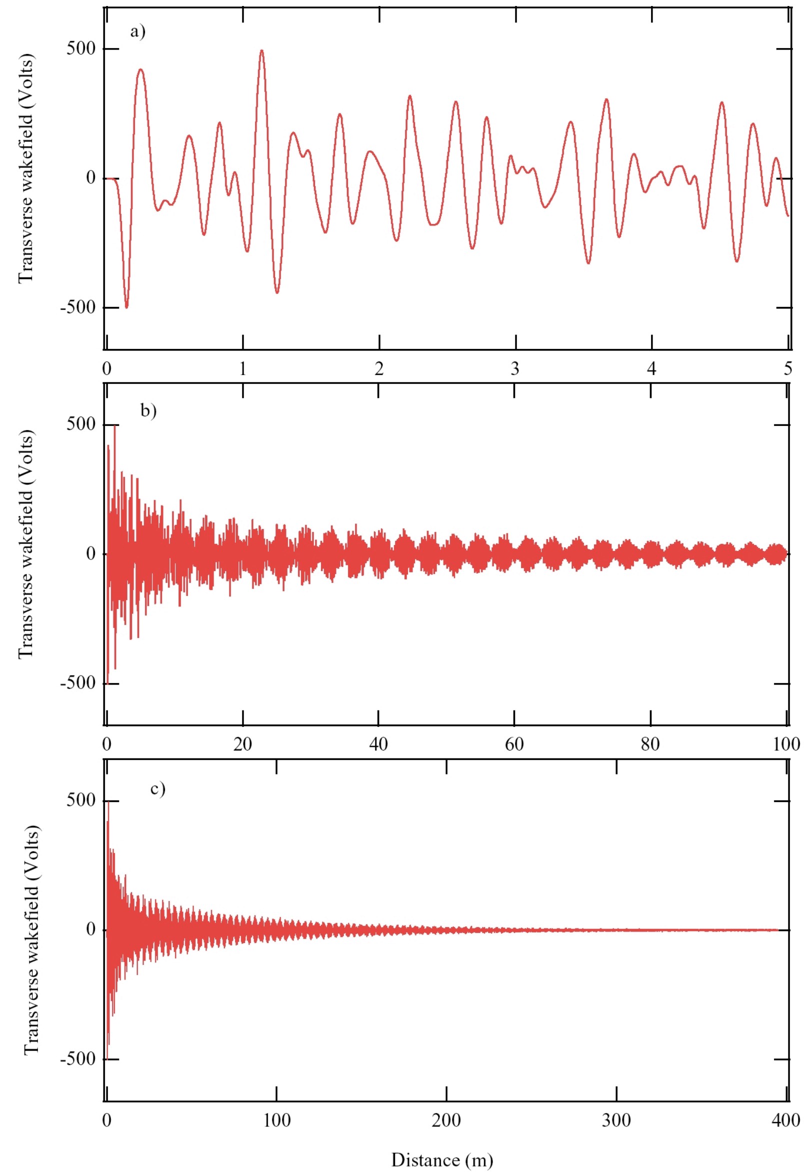


Mode chart vs waveguide length.

Method involves (laborious) calculation of resonant modes with port(s) shorted at various lengths. Frequency variation at "avoided crossings" can be fitted to analytical formulae to get Q_{ext} and coupling factor, □. Works best for strong coupling (□ >> 1).

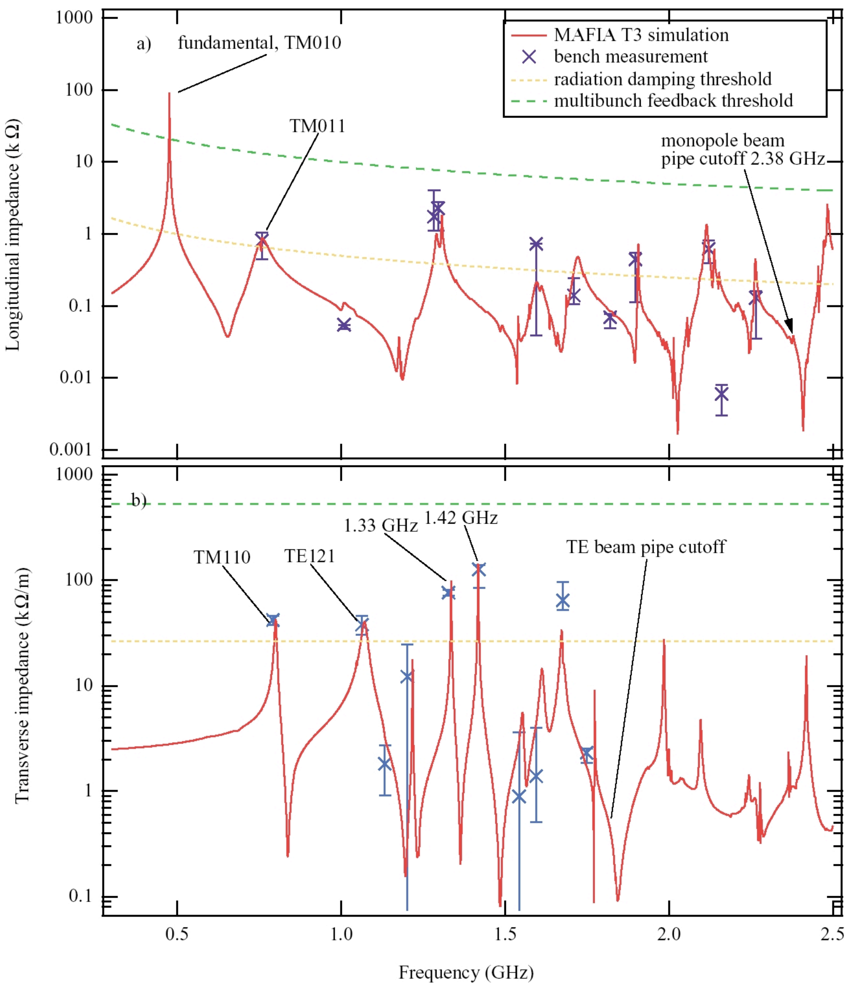
Time domain (FFT) method (developed at SLAC, widely used, ABCI, MAFIA etc.)

3D MAFIA model of PEP-II cavity.

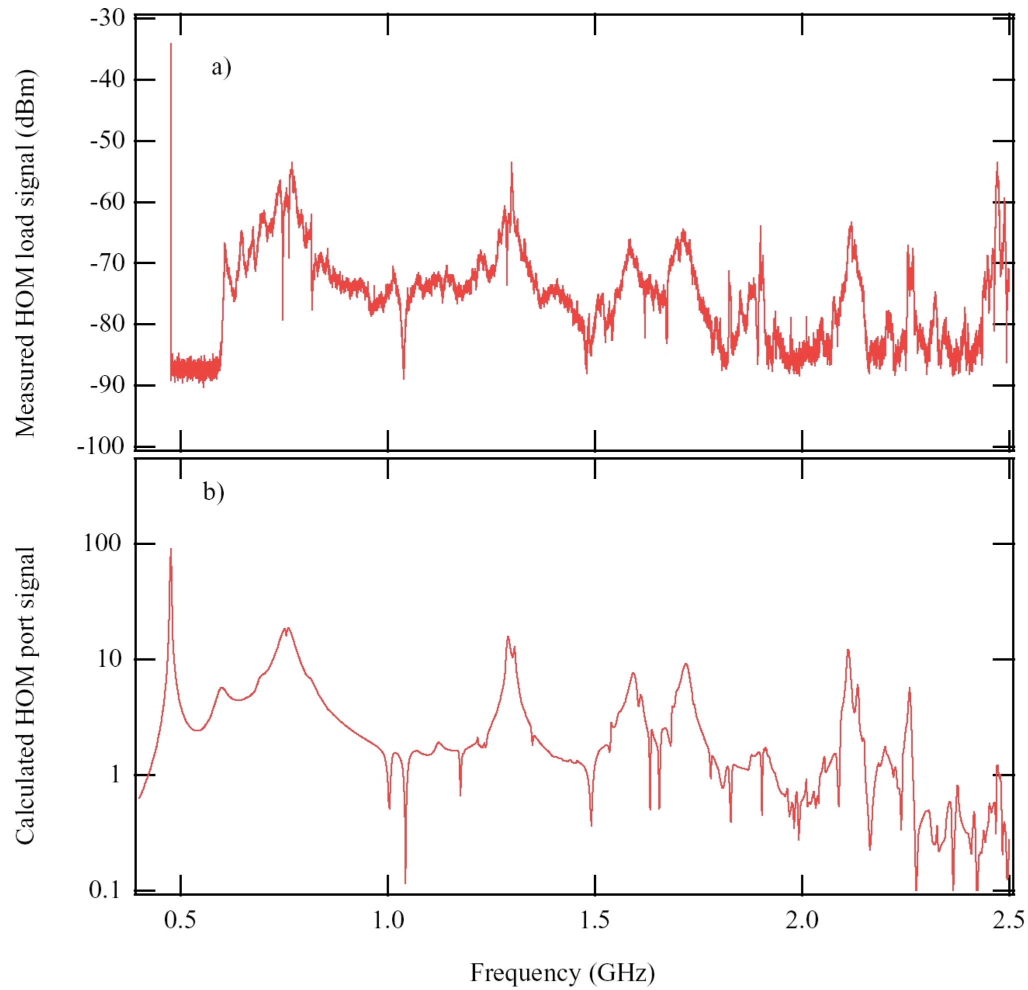


Short-, medium- and long-range wakes*.

*(2000) Physical Review Special Topics – Accelerators and Beams, Volume 3, 102001



Calculation vs bead-pull measurements.

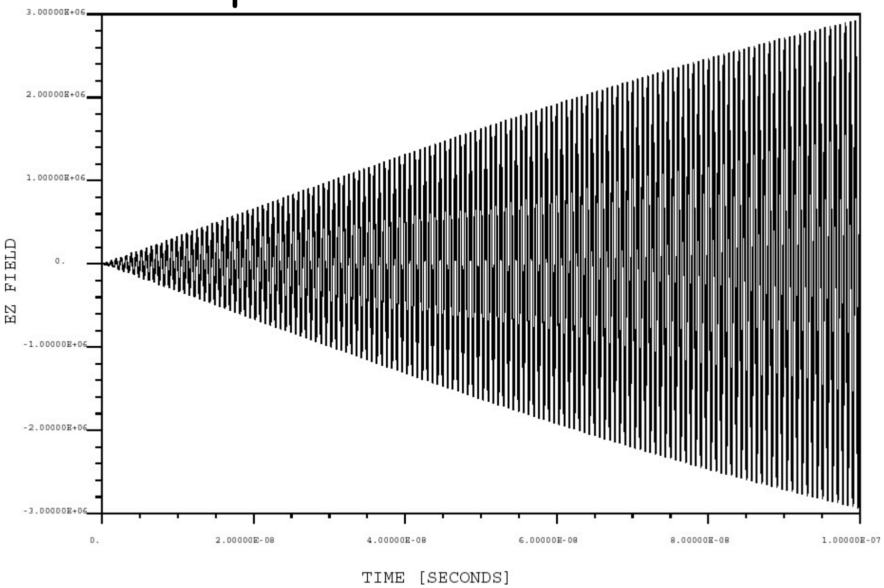


Measured vs calculated HOM spectrum.

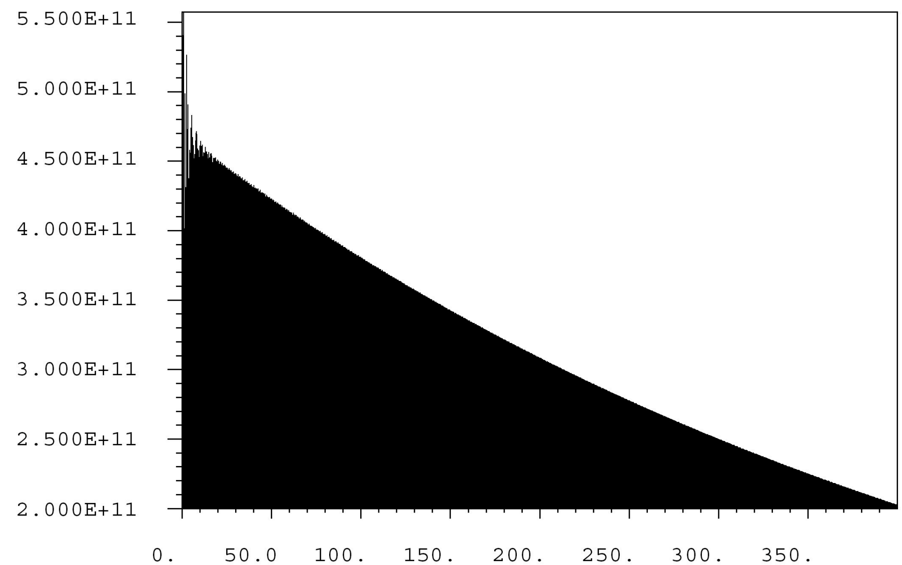
Method uses open boundaries on ports. FFT of long-range wake gives broad-band impedance spectrum in one run. Works best for strong coupling (□ >> 1). Frequency resolution set by wake length, max frequency set by mesh size (typ. ~10 GHz).

Also:

growth/decay method for ~1 or less, in which only beginning of a fill is simulated or a mode is pre-loaded the decay tracked long enough to fit the exponent. One short run per mode.



linear "growth" method (MAFIA)

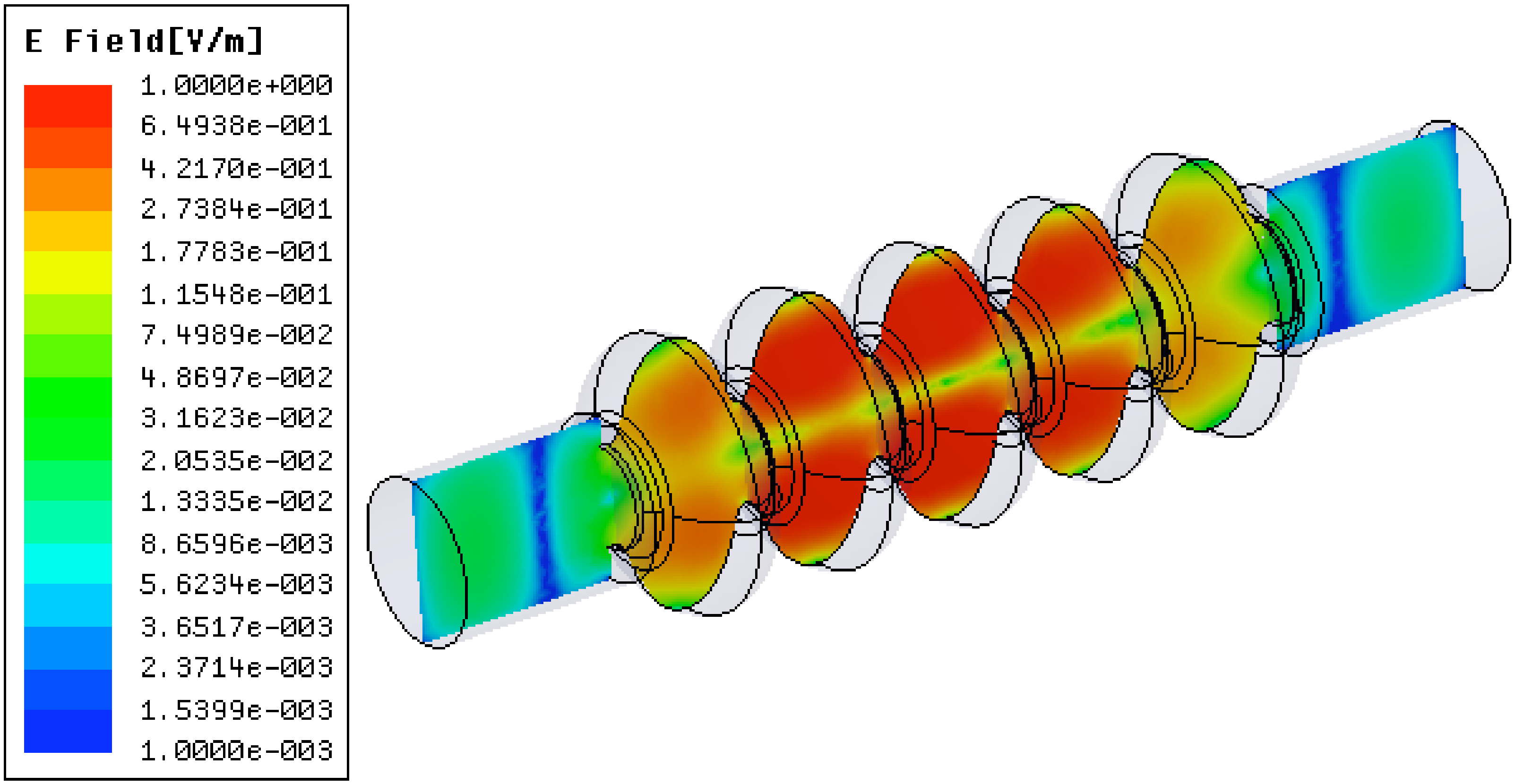


mode decay method (MAFIA)

Poynting method: (time domain).The energy flowing through a section of uniform waveguide is calculated once the port amplitude has reached a steady flow. One short run per mode.

Perturbation method for very high Q_{ext}, e.g. 10^6-10^9. Uses frequency difference between open and short termination to calculate Q_{ext}.

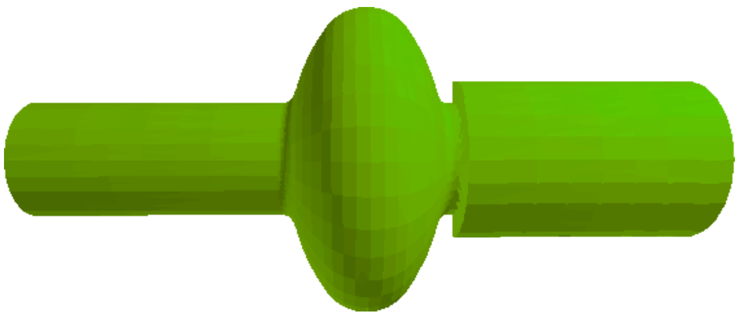
Complex eigenvalue solution (becoming available, SLAC codes, ANSYS beta, HFSS) gives real and imaginary parts of impedance directly, hence R and Q.



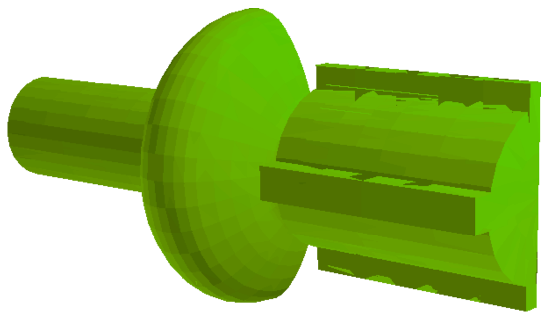
HFSS 3D complex Eigenvalue solution, 5-cell cavity with enlarged beam-pipes.

Methods of broad-band HOM damping:

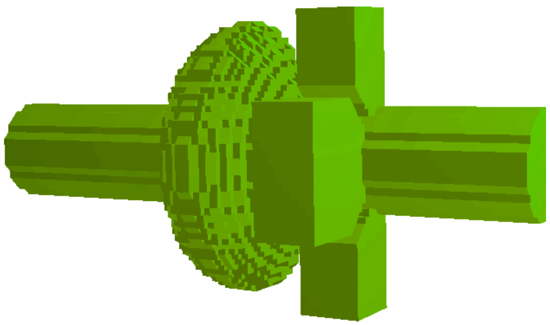
Strong HOM damping has been shown in single-cell cavities, e.g. Cornell and B-factory storage rings. Studies show these methods can be applied to multi-cell cavities. Options include multiple coaxial antennas, beam pipe loads, waveguide loads.



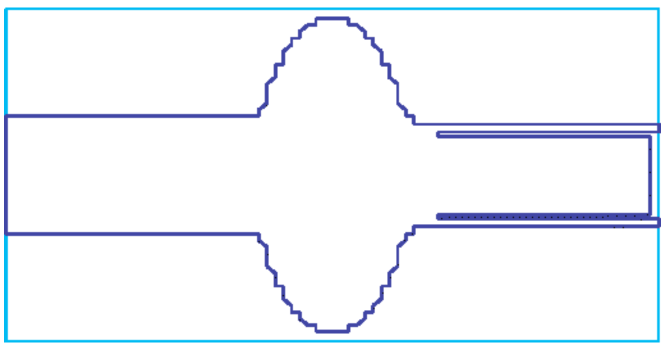
Enlarged beam pipe.
(KEK, BNL, Cornell ERL)



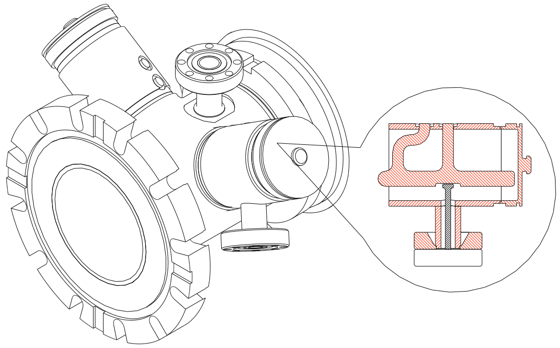
Fluted beam pipe.
(Cornell, CESR)



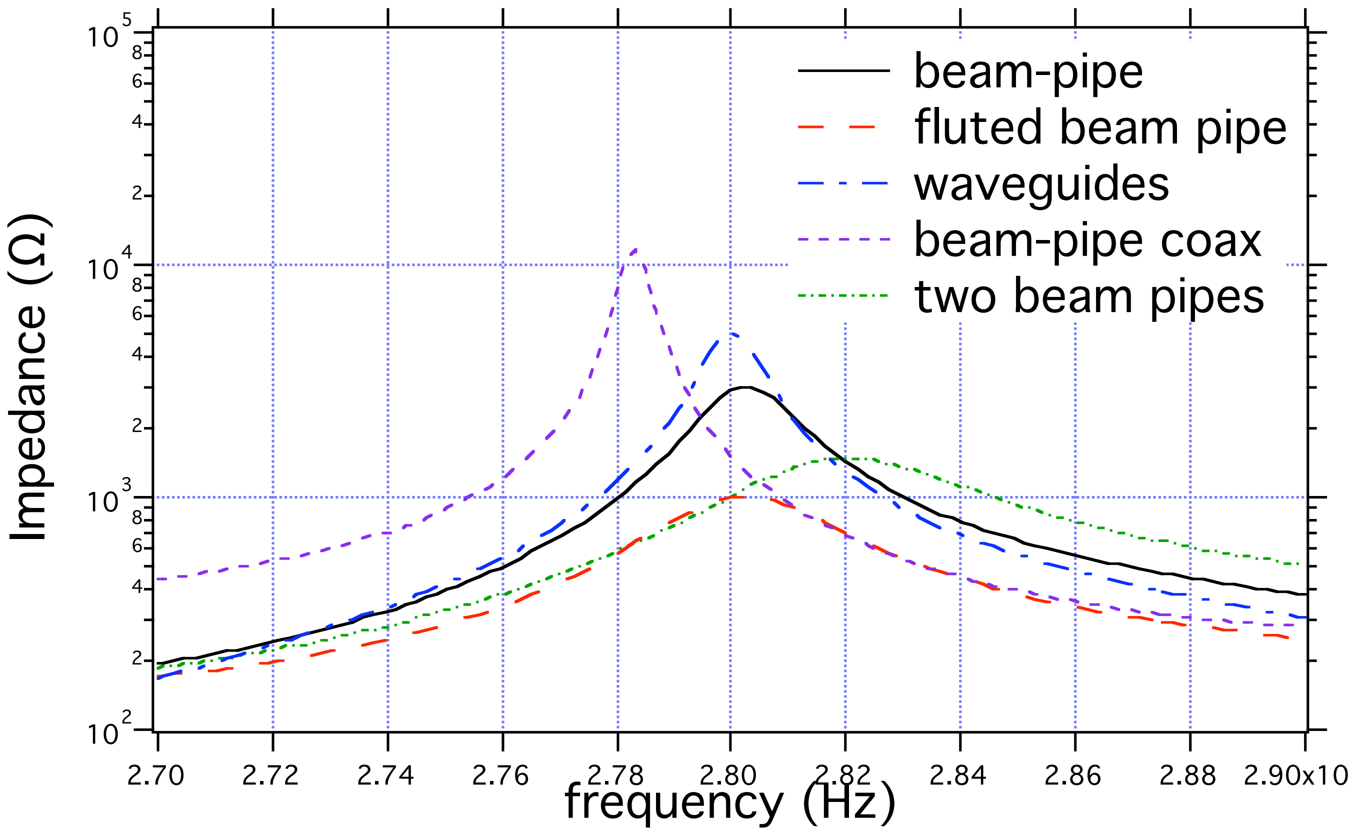
Waveguide dampers
(CEBAF, PEP-II)



Coaxial/radial beam pipe
(KEK, JAERI)



Multiple coaxial loops
(DESY, CERN)

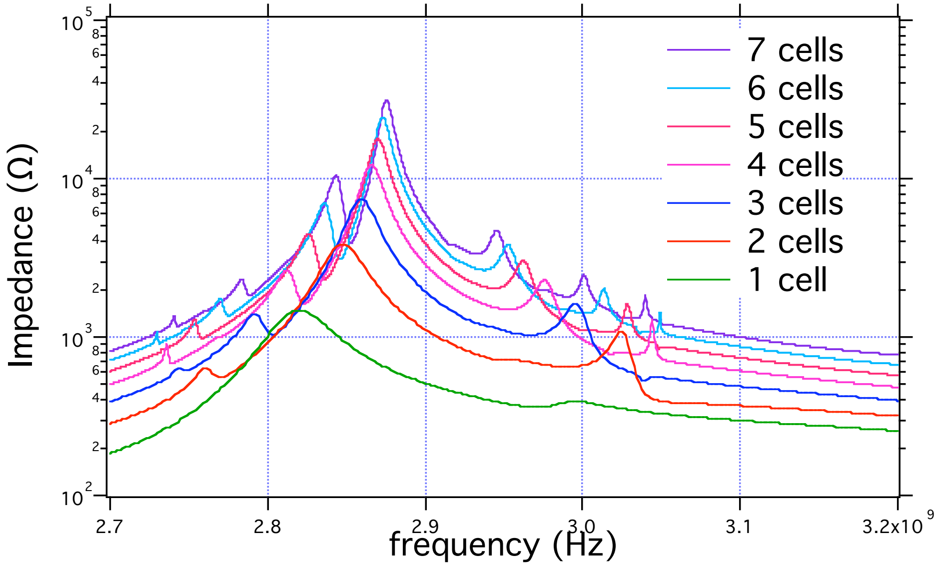


TM_{011} mode with various damping schemes.

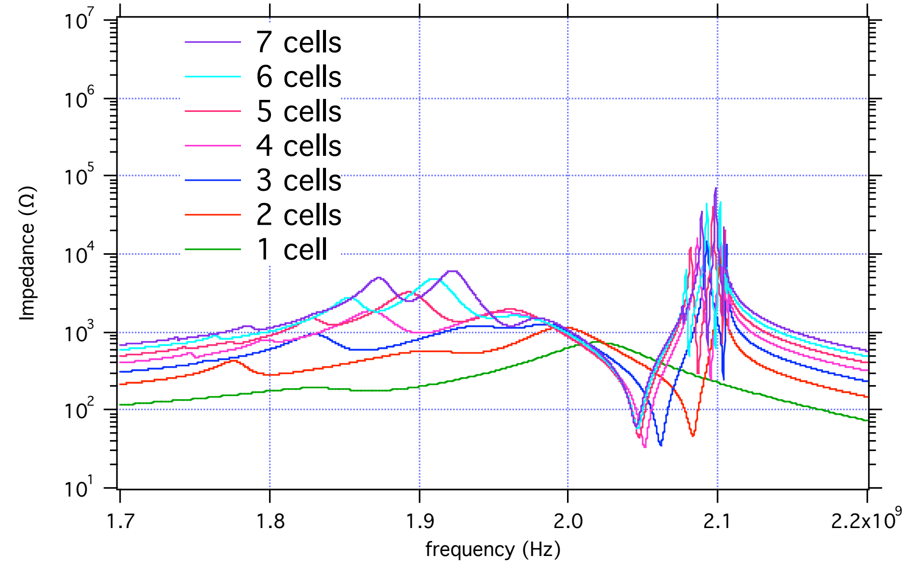
	Freq. MHz	Q_{ext}	R* ( )	R/Q ( )
b-pipe	2803	252	3001	11.9
flutes	2803	137	1010	7.3
w-guide	2800	353	5040	14.3
bp-coax	2783	725	11879	16.4
2xbp	2822	121	1481	12.2

$*R=V^2/2P$

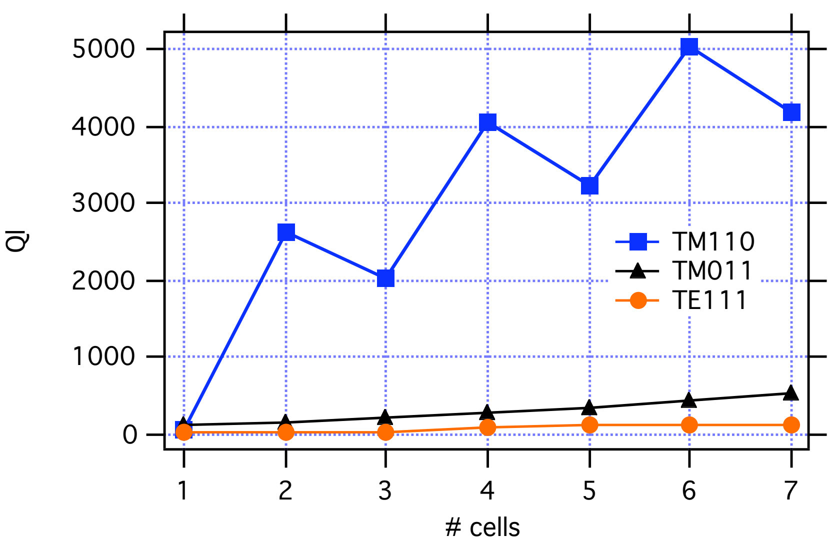
Number of cells:



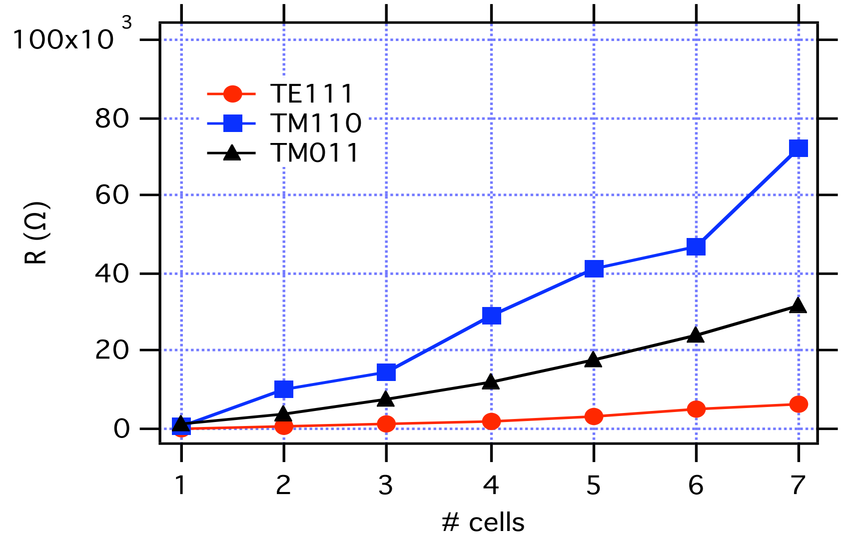
TM_{011} passband mode vs # cells



TE_{111} and TM_{110} passbands.

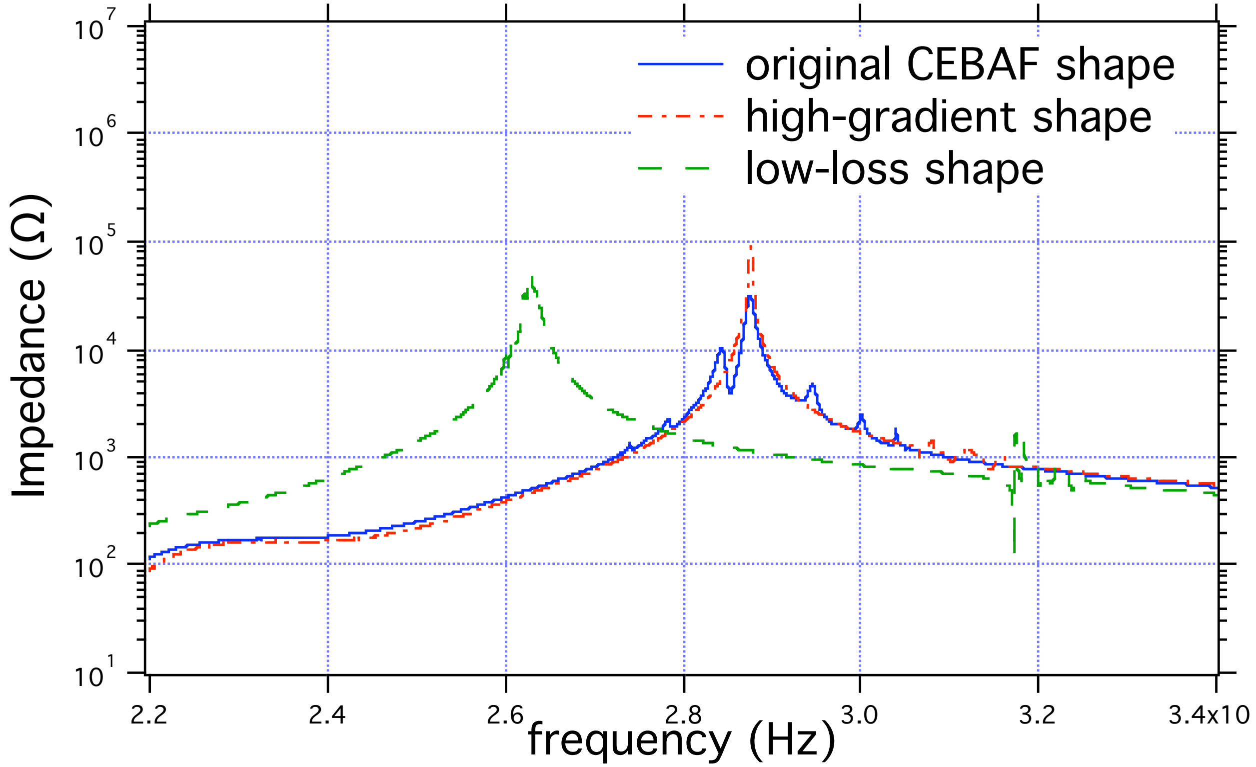


Loaded Q vs # cells, beam-pipe damping



R vs # cells (R @ 25mm for dipoles)

Cell shape/cell-cell coupling:

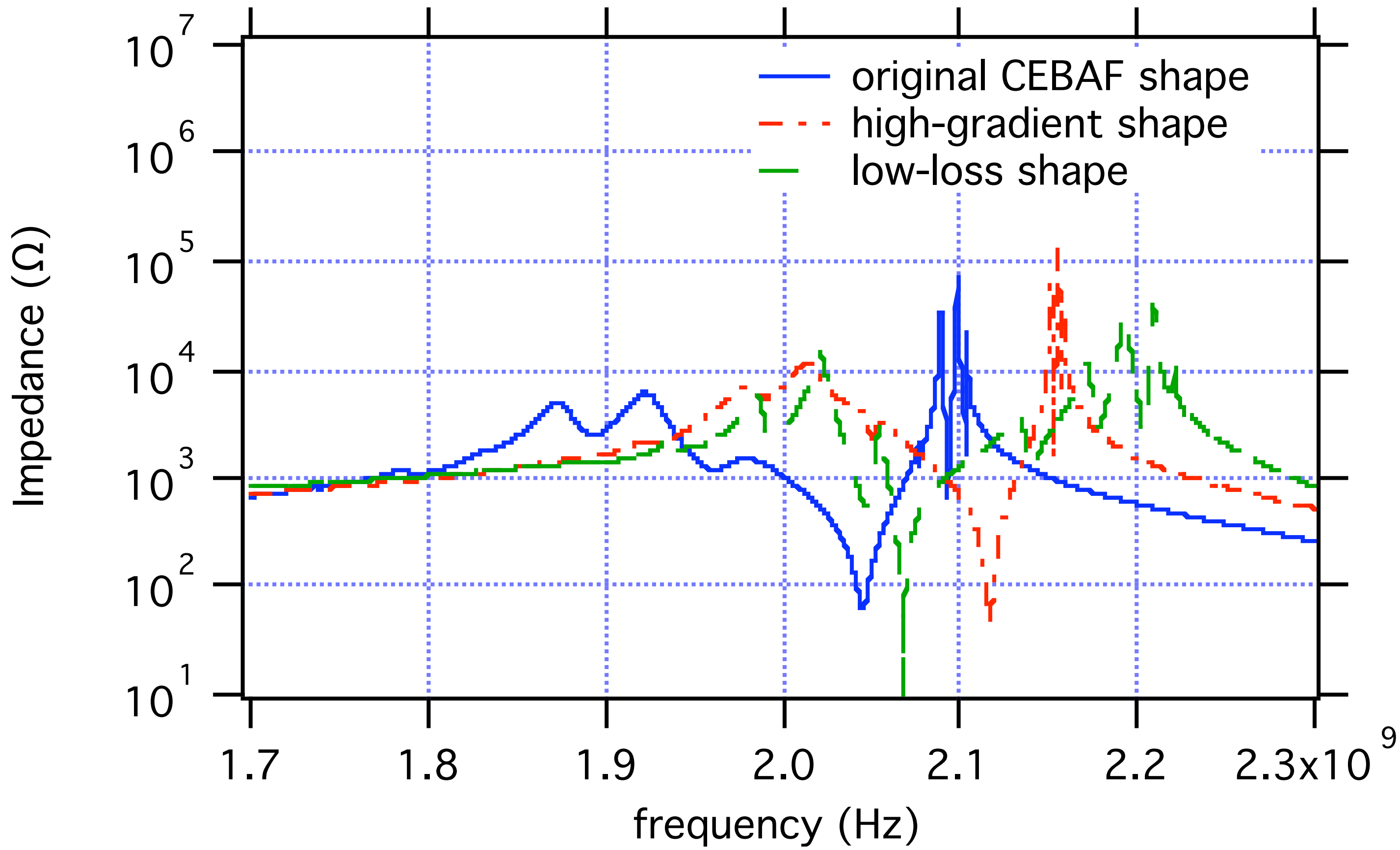


TM_{011} band, *OC*, *HG*, *LL* shapes, 7-cells, beam-pipe damping

TM_{011} mode data for multi-cell cavities.

	#cells	Freq,MHz	Q_{ext}	$R^{\dagger}$ ( )	R/Q ( )
OC	7	2876	527	31463	59.7
HG	7	2876	1348	90380	67.0
LL	7	2629	985	53556	54.4
*OC**	5	2871	707	35453	50.1
DESY**	4	910	600		

*waveguide damped. **500 MHz cavity, meas. Q. $^{\dagger}R=V^2/2P$



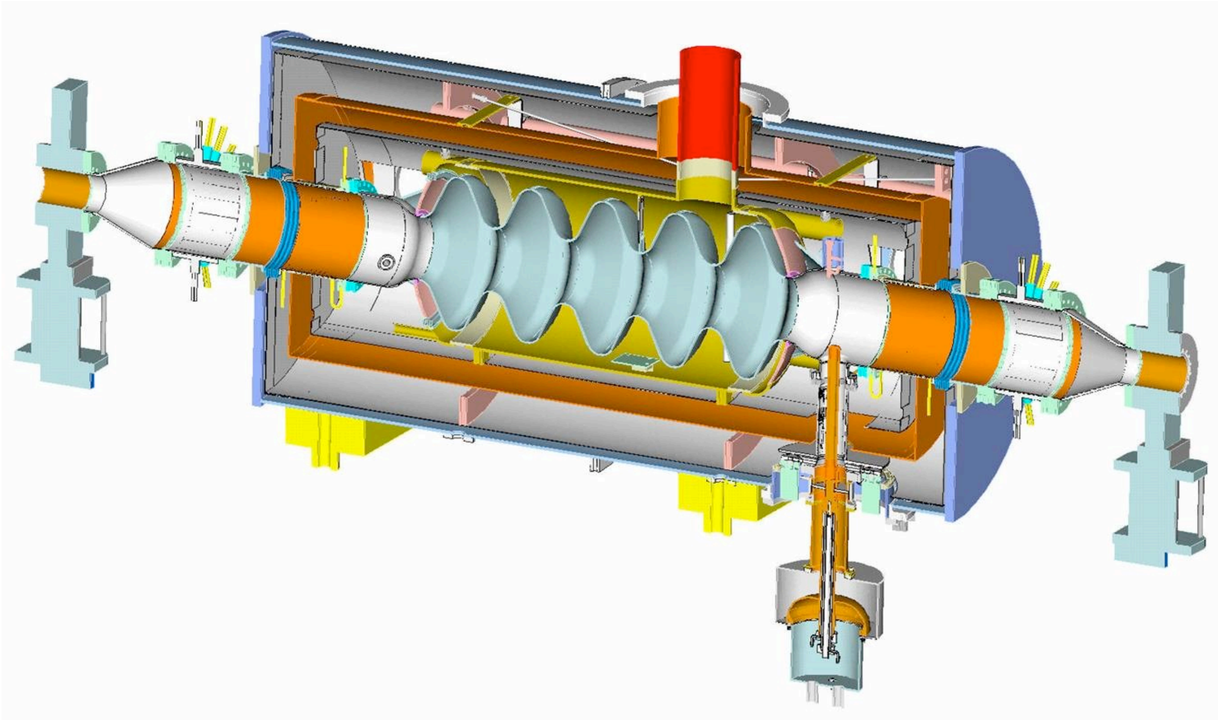
7-cells, OC, HG, LL shapes, TE_{111}/TM_{110} dipole, beam-pipe damping

TE_{111}/TM_{110} mode data for multi-cell cavities.

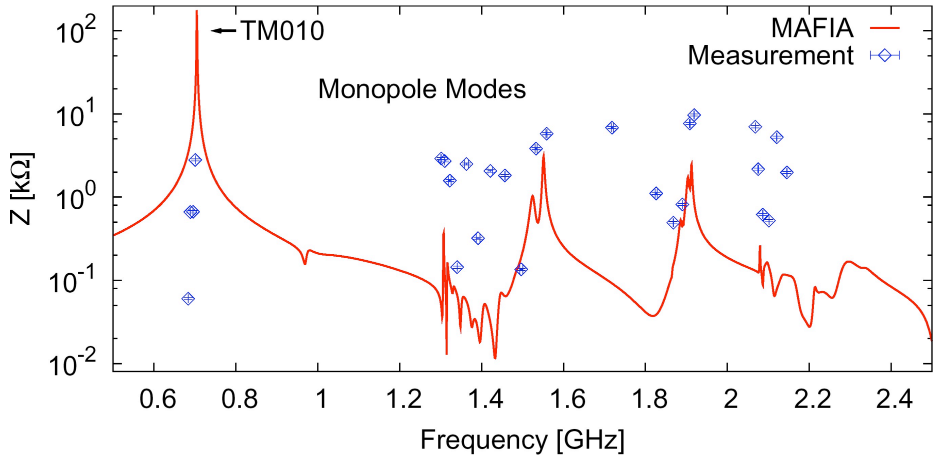
	# cells	TE_{111} f,MHz	TE_{111} Q_{ext}	TE_{111} R†, ( )	TM_{110} f, MHz	TM_{110} Q_{ext}	TM_{110} R† ( )
OC	7	1922	135	6088	2099	4177	72101
HG	7	2014	185	11359	2156	5694	146409
LL	7	2021	490	14107	2209	2071	39510
*OC**	5	1894	956	22949	2103	3274	47064
DESY	4	650	4000		716	6000	

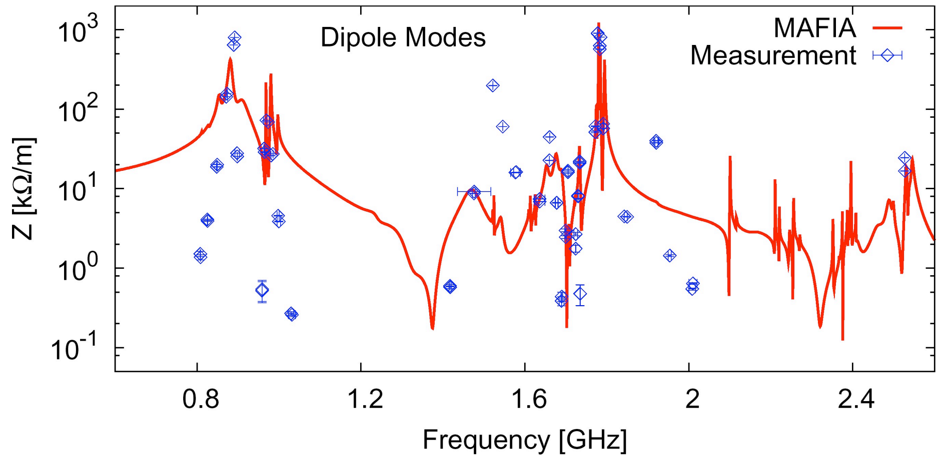
*waveguide damped. †R calculated at 25mm offset in cavity.

Example1: BNL beamline-damped cryomodule



BNL high current ERL cryomodule concept for electron cooling





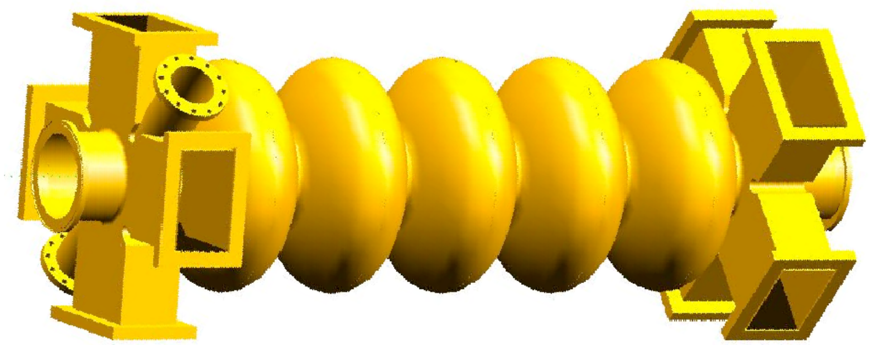
Calculated and Measured HOM spectra. (See Rama Calaga's talk, this working group)

Example 2: JLab Ampere-class CM concept

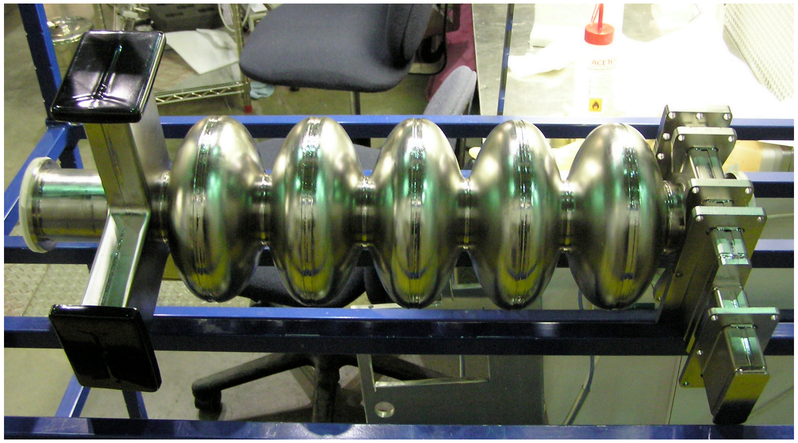
FEL Ampere-class module draft specs.

Voltage	100-120 MV
Length	~10m
Frequency	750 MHz
Beam Aperture	>3"
BBU Threshold	>1A
HOM Q's	$<10^4$

JLab FEL proposal:

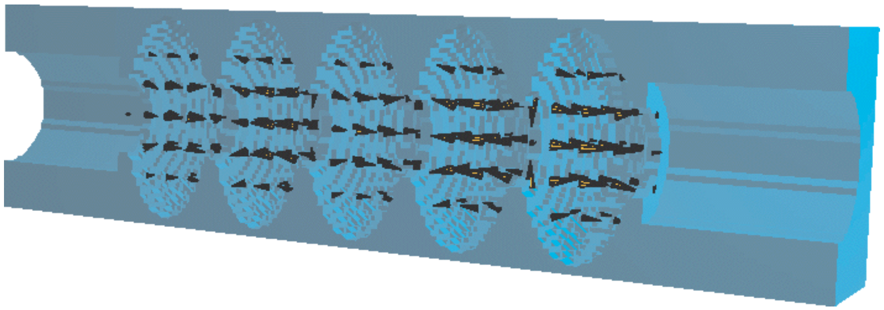


5-cell waveguide damped cavity

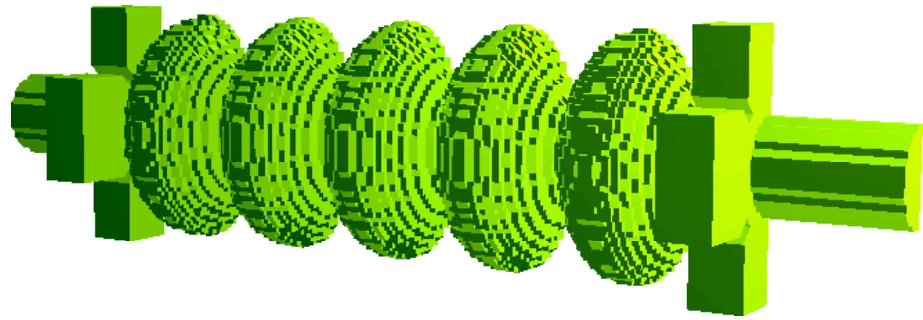


CEBAF cavity

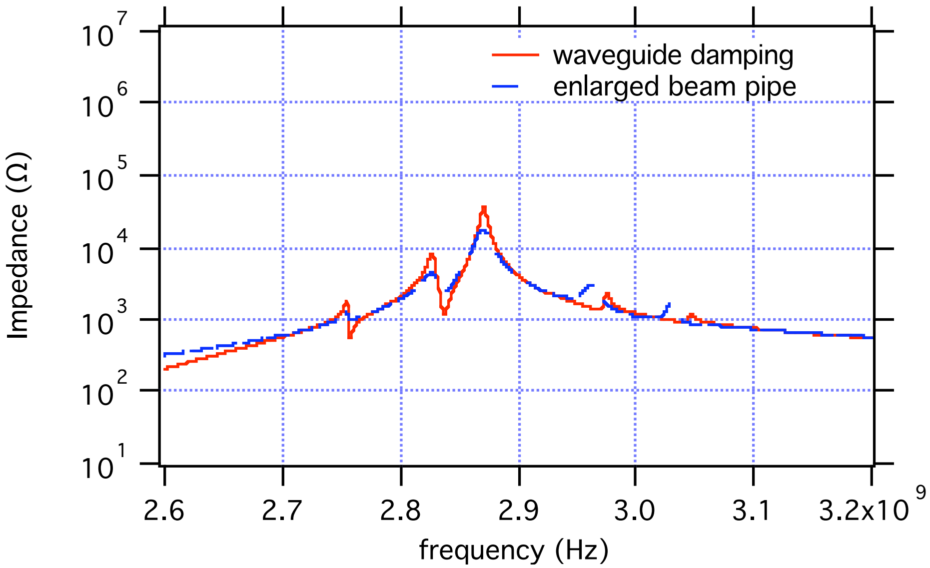
Compare waveguides with beam pipe loading:



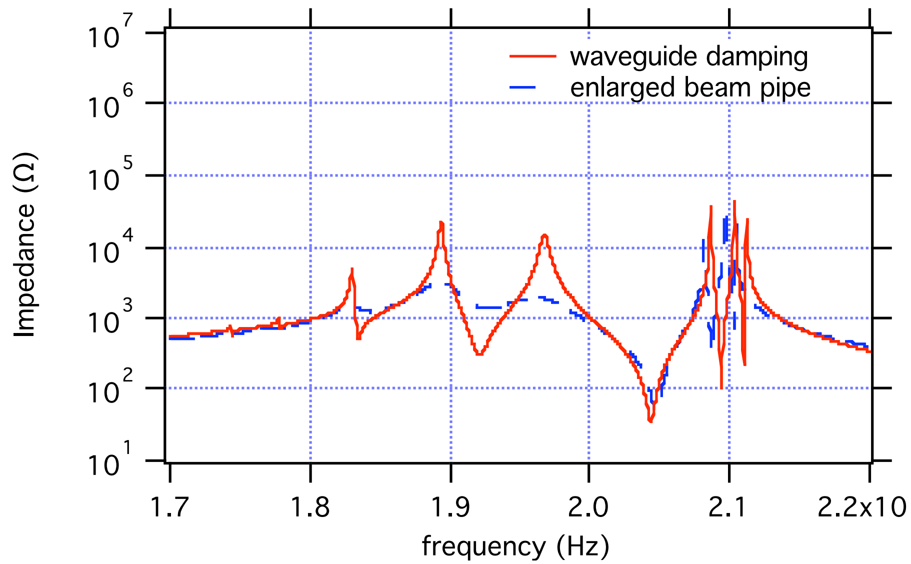
5-cell cavity with beam-pipe loads.



5-cell cavity with waveguide loads.



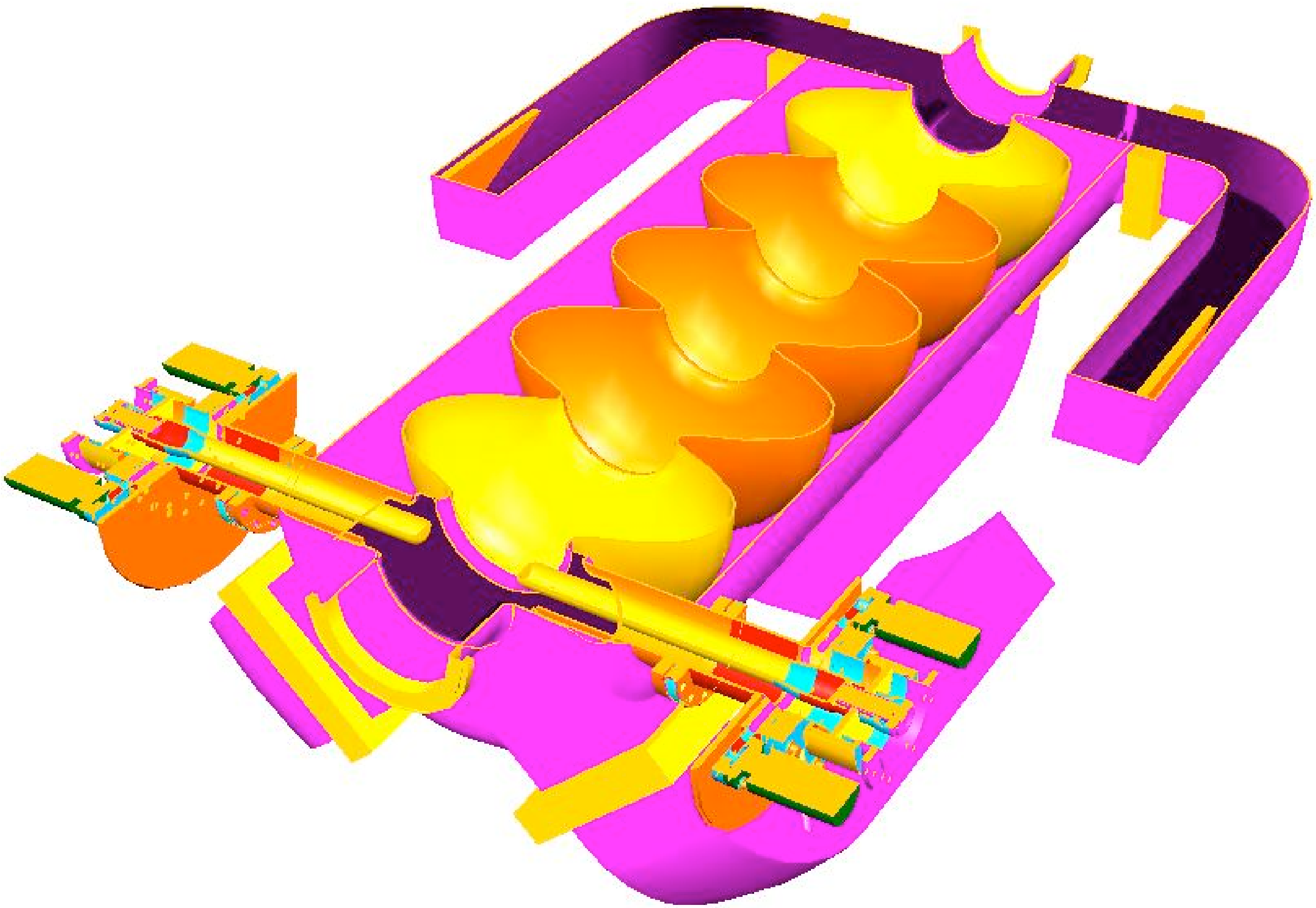
TM_{011}, 5-cells, wg and beam-pipe loads.



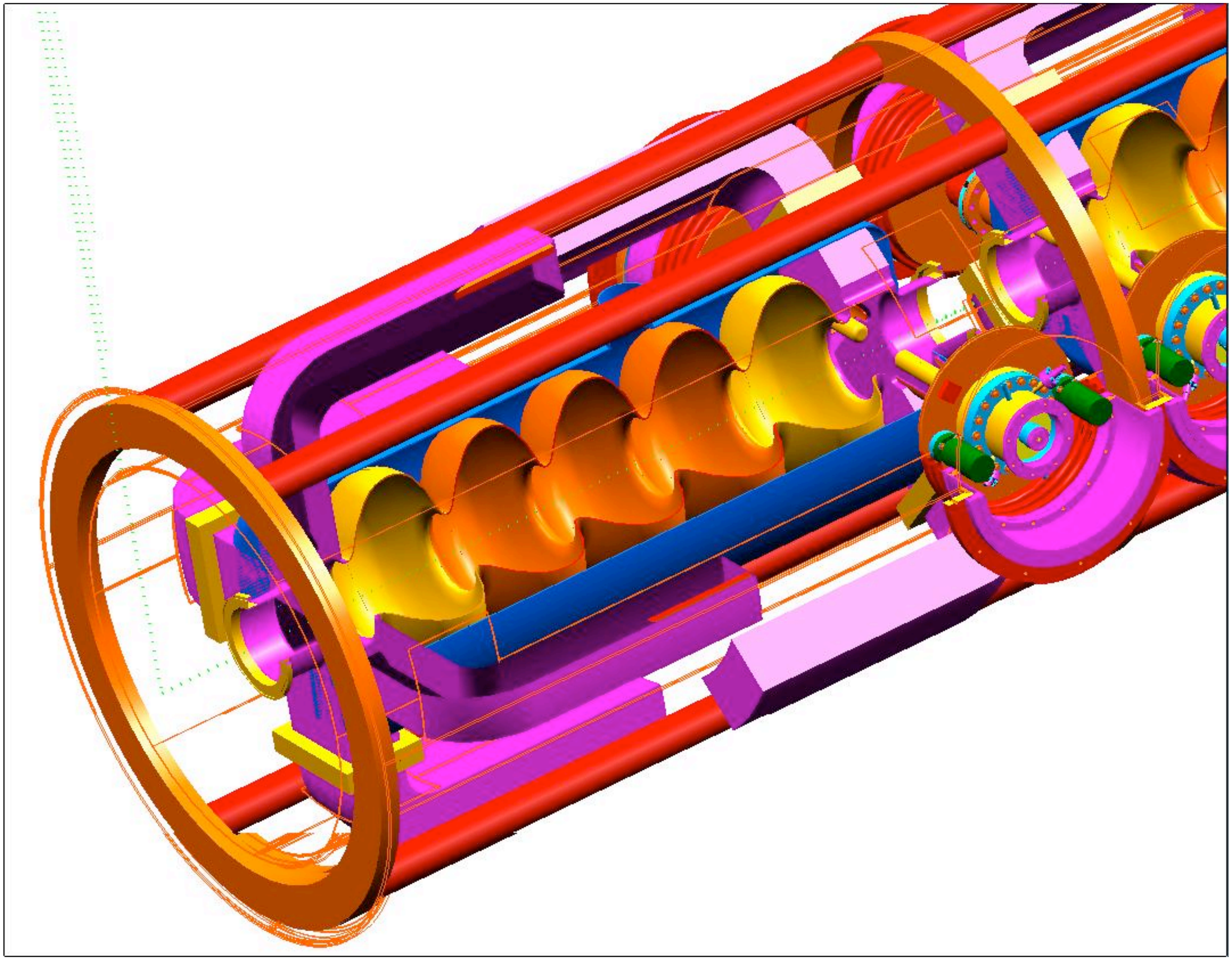
Dipole, 5-cells, wg and beam-pipe loads.

Impedance is good in either case, real estate gradient is better for waveguides.

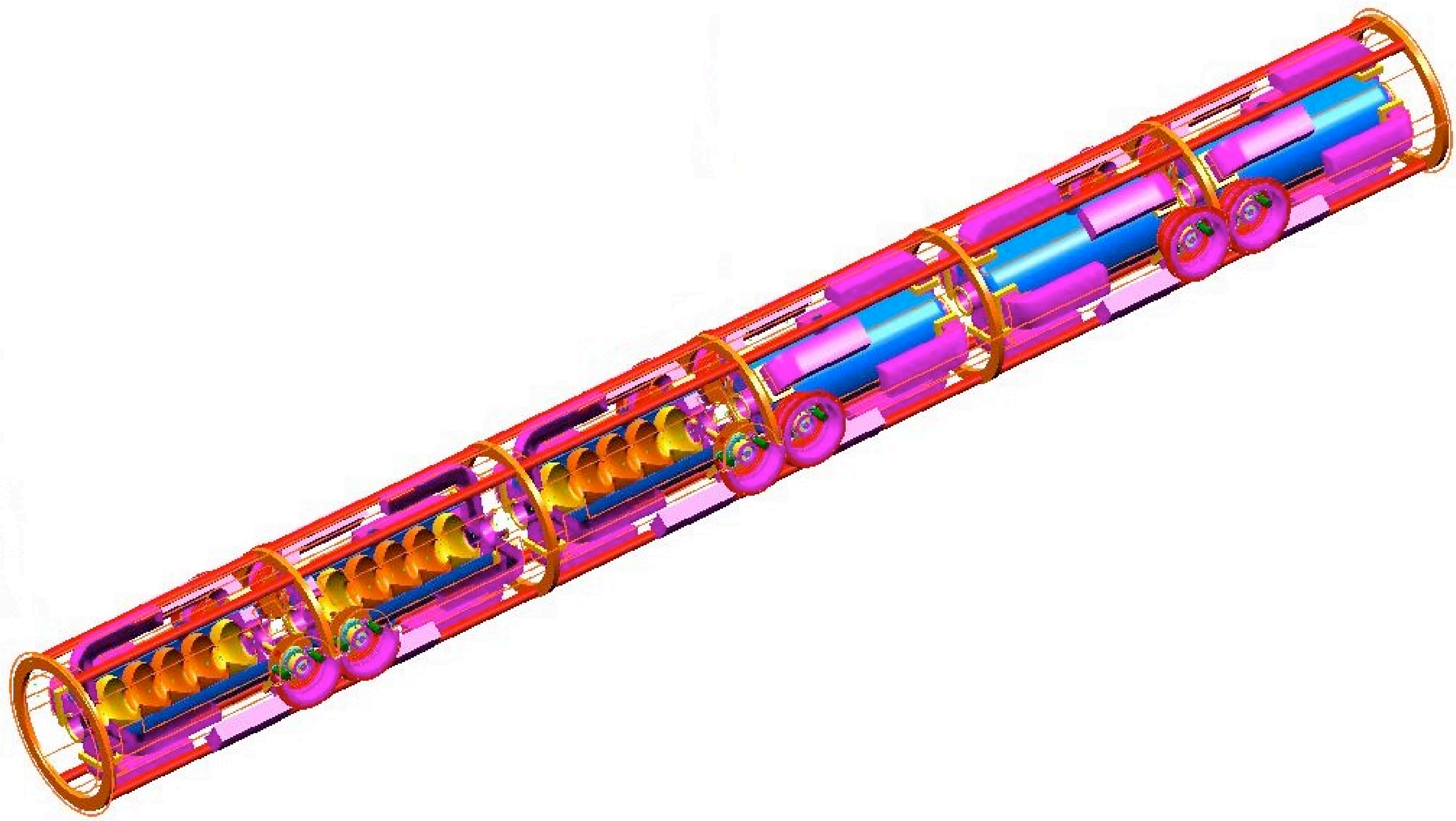
Packaging:



Five cell cavity with helium vessel, waveguide dampers
and two SNS style couplers



Waveguide-damped cavity packaged in SNS-type space frame

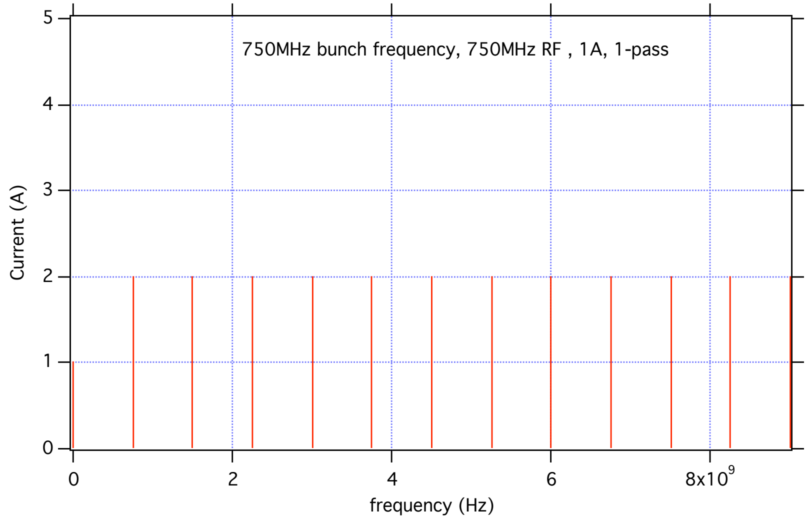


750 MHz cryomodule with six five-cell cavities with waveguide damping

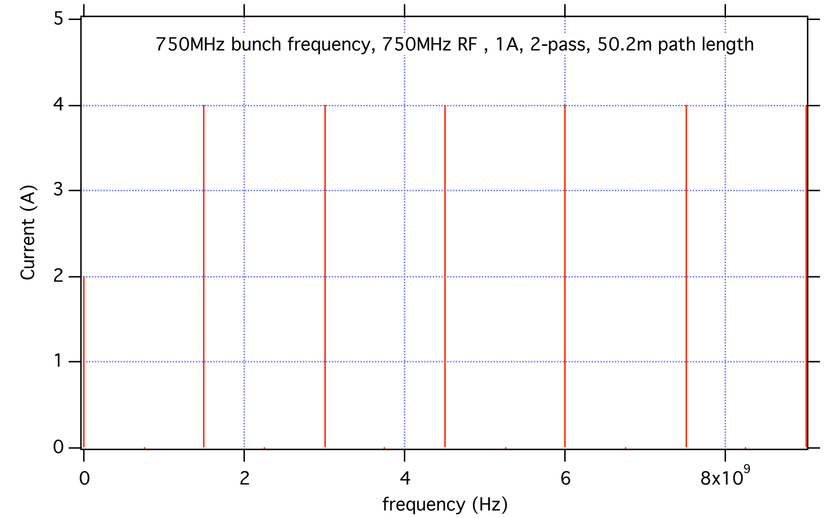
750 MHz cryomodule with six five-cell cavities with waveguide damping

Frequency	750 MHz
# cells	5
Damping Type	Waveguide
Cavity Length	1.4m
Iris Diameter	14 cm (5.5")
# Cavities	6
Min. Module Length	10.4m
Nominal Module Voltage	100 MV (120 MV peak)
Cavity Gradient (Eacc)	16.7 MV/m (20 MV/m max)
Real Estate Gradient	~10 MV/m
TE_{111} freq, Q_{ext}	947 MHz, 9.5e2
TM_{110} freq, Q_{ext}	1052 MHz, 3.3e3
TM_{011} freq, Q_{ext}	1436 MHz, 7.1e2
HOM Power/Cavity	~20 kW(est)
BBU Threshold	>1A

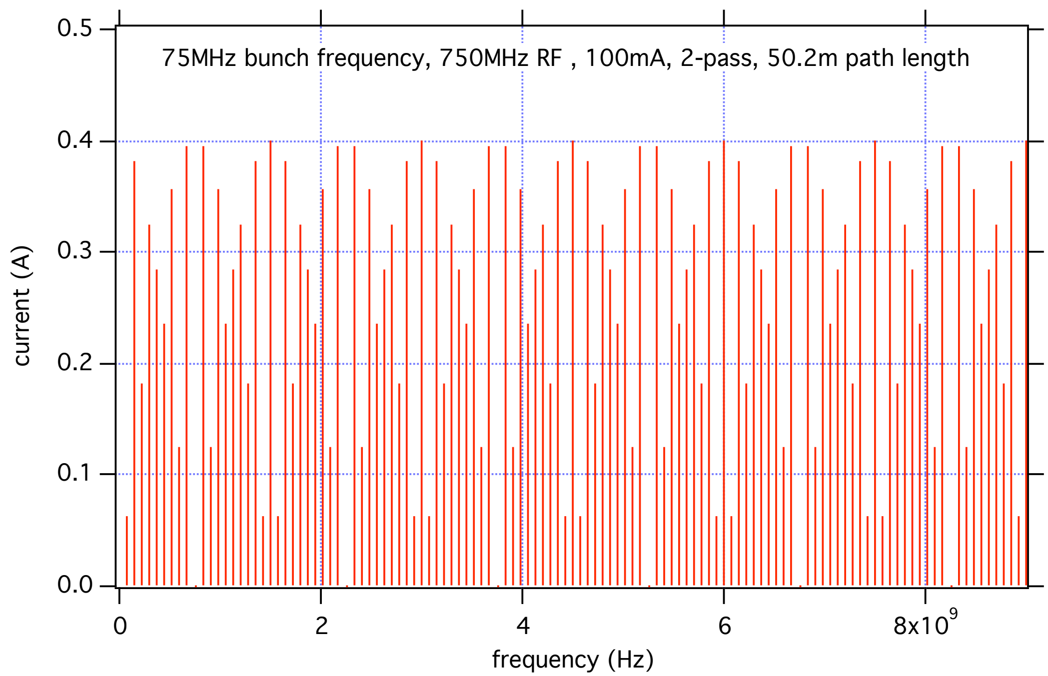
HOM power: Beam spectrum goes out to THz! A lot of power can be extracted.



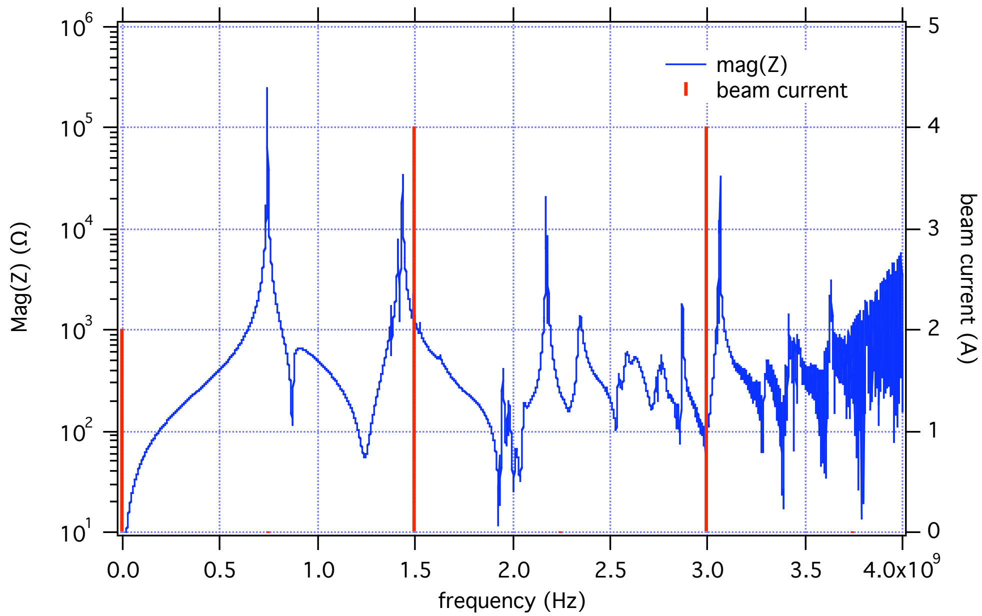
750 MHz, 1A single pass.



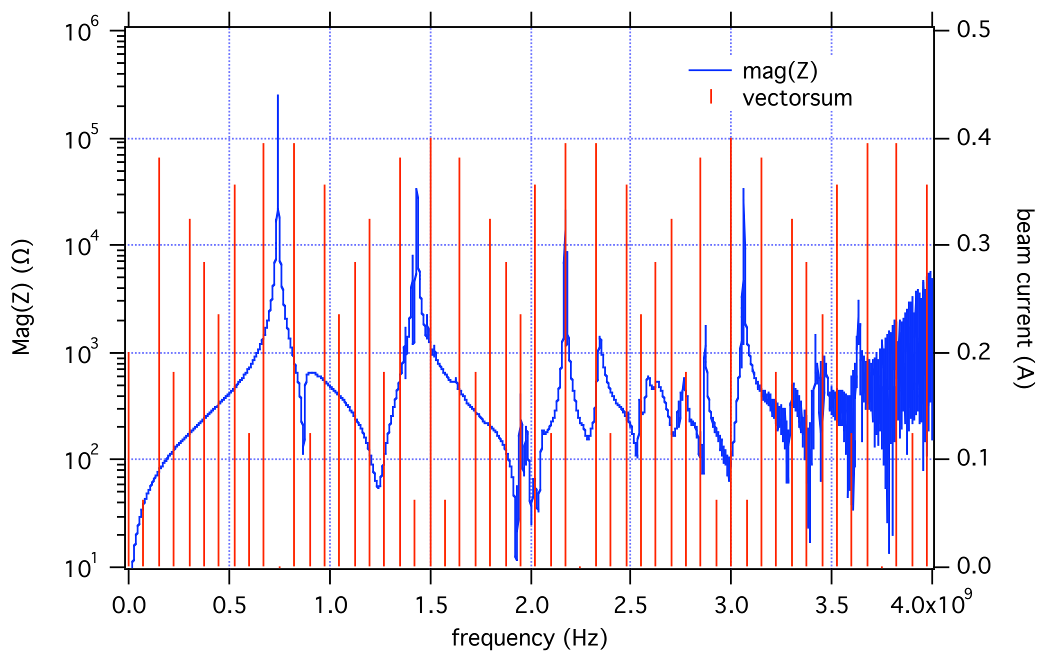
750 MHz, 1A 2 pass, 50.2m path length



Beam spectrum vector sum, 75 MHz, 100mA 2 pass, 50.2m path length



Beam spectrum, 750 MHz, 1A 2 pass, 50.2m path length (~22 kW below cutoff)



Beam spectrum, 75 MHz, 100mA 2 pass, 50.2m path length (>5 kW below cutoff?)

Conclusions:

- A variety of schemes are in use for HOM prediction using many different codes.
- Established methods have been cross-checked with experimental measurements.
- There are several choices for strong HOM damping, all can give good Q's.
- Cell shape and coupling can influence Q's (weakly) and frequencies (strongly).
- High-current tends to push us to fewer cells/cavity, lower frequencies.
- Several high-current cryomodule concepts are being developed.
- Superstructures may be useful to further increase real-estate gradient.
- HOM power may be at least as much of a concern as BBU.