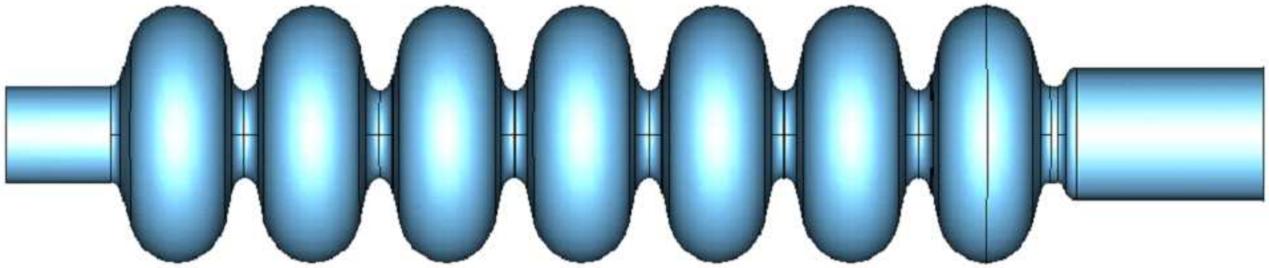
Accelerating (S)RF Cavities

Matthias Liepe



- **RF Cavity Design**
  - Design objectives
  - Numerical Eigenmode solver
  - Design examples:
    - NC vs. SC
    - SC cavity center cell shape
    - Number of cells of SC cavities
    - SC cavity end cell optimization
- **Higher order modes**
  - Introduction: HOMs and excitation by a beam
  - HOM damping schemes
  - HOM damping examples and results

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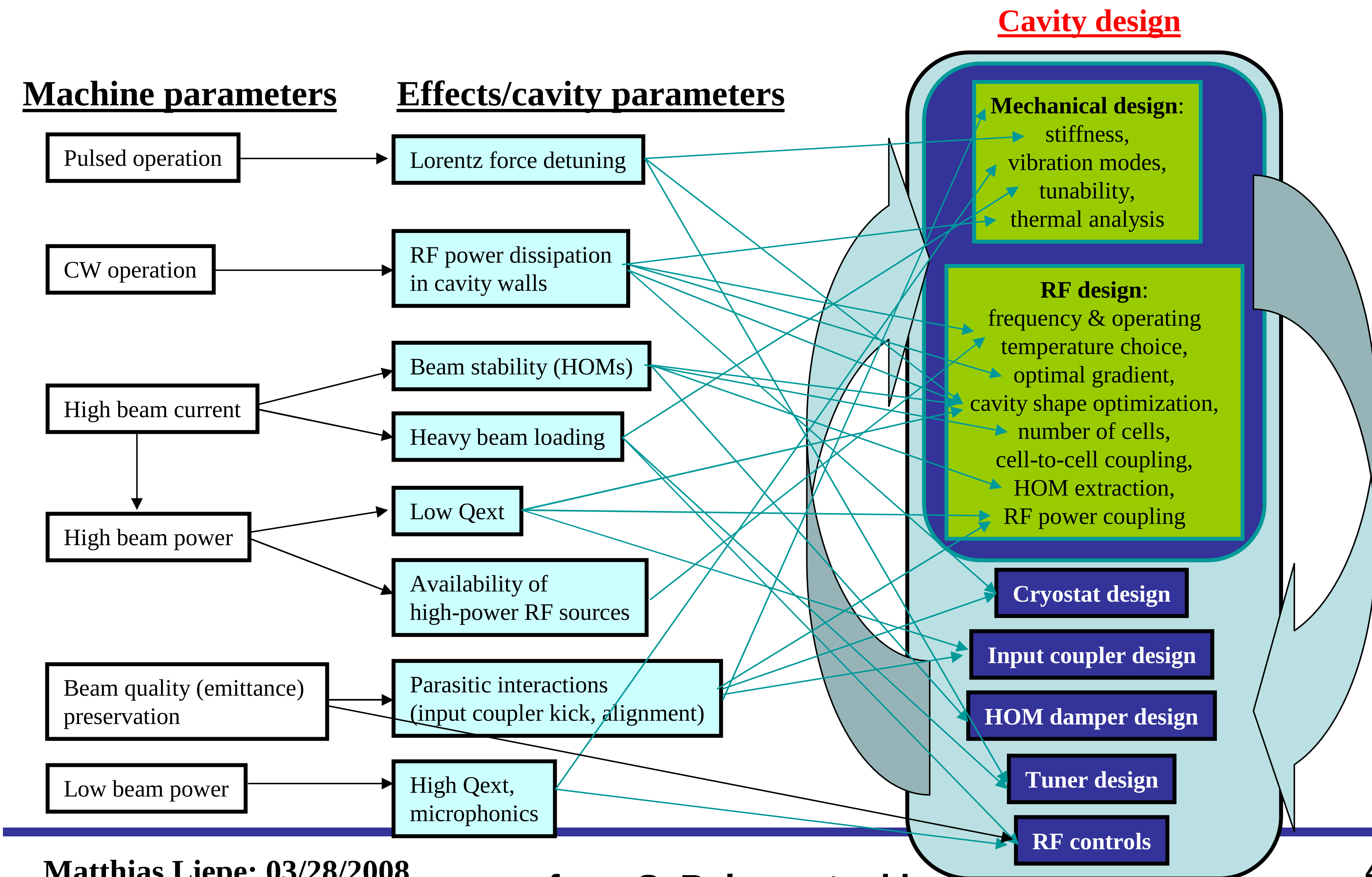
Cavity Design Objectives



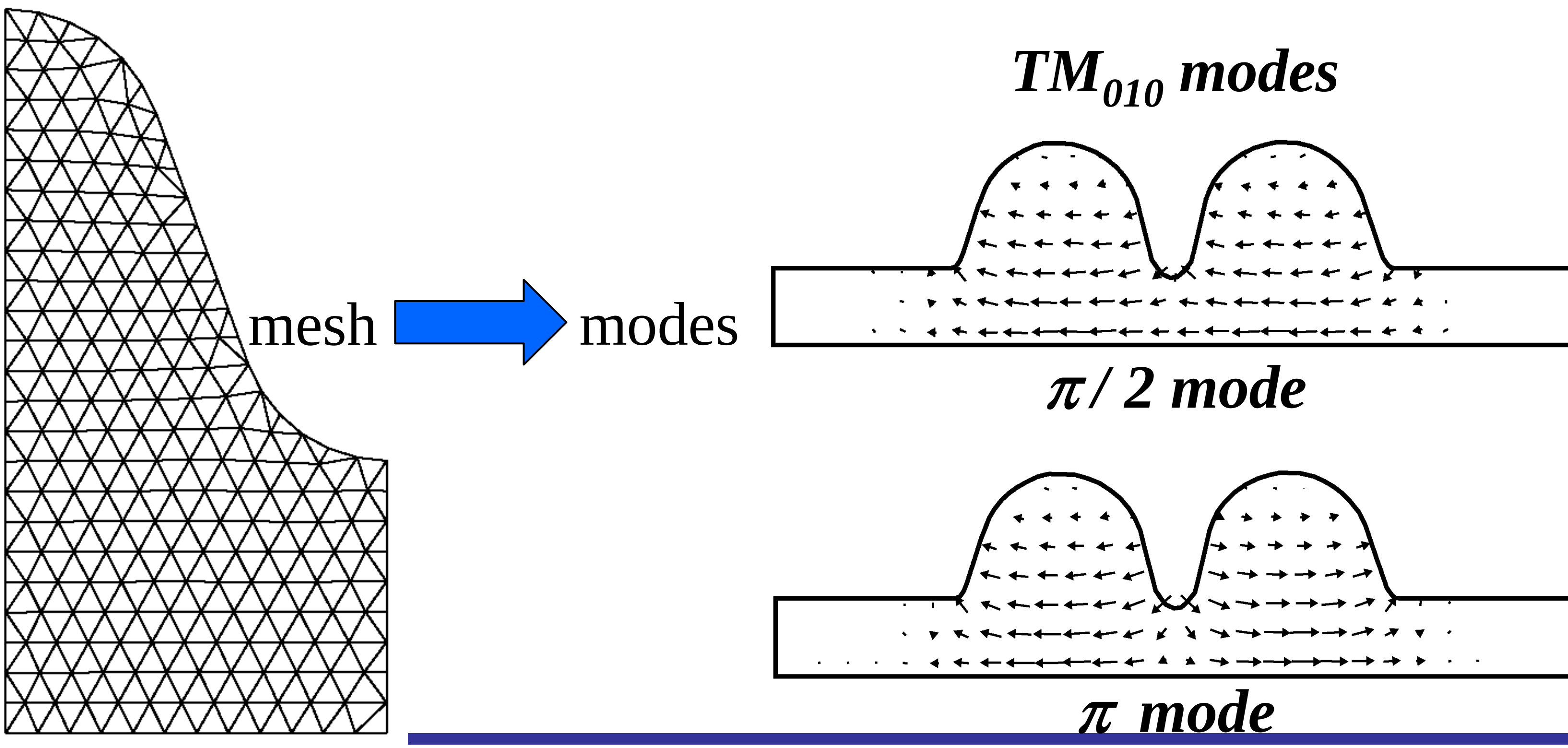
from S. Belomestnykh

Cavity Design Parameters

- Choice of material (impacts losses and operating gradient)
- Frequency (impacts size of cavity, cost, surface resistance, assembly technique …)
- Number of cells (impacts field flatness, tunability, HOM extraction, pulsed operation …)
- Aperture size (impacts beam stability, peak fields, HOM damping …)
- Cavity shape (impacts peak surface fields at a given E_{acc}, power dissipation at a given E_{acc}, multipacting …)
- …

The modes in real cavities (with beam tubes,…) cannot be calculated analytically.

⇒ Use numerical codes (like MAFIA, Microwave studio, SLANS, Superfish,…).

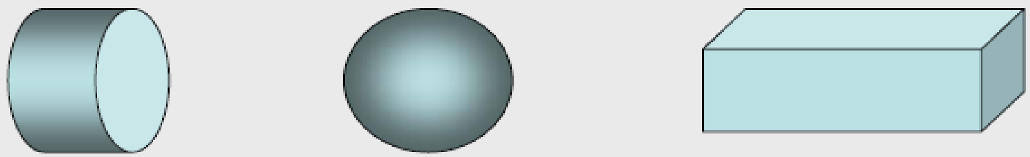


Tools for RF Design

Usually the design of an elliptical cavity is performed in two steps "2D" and "3D" :

- "2D" is fast and allows to define geometry of a cylindrical symmetric body (inner and end-cells) of the cavity.
- "3D" is much more time consuming but necessary for modeling of full equipped cavity with FPC and HOM couplers and if needed to model fabrication errors. Also coupling strength for FPC and damping of HOMs can be modeled only 3D.

The solution to 2D (or 3D) Helmholtz equation can be analytically found only for very few geometries (pillbox, spherical resonators or rectangular resonator):



We need numerical methods:

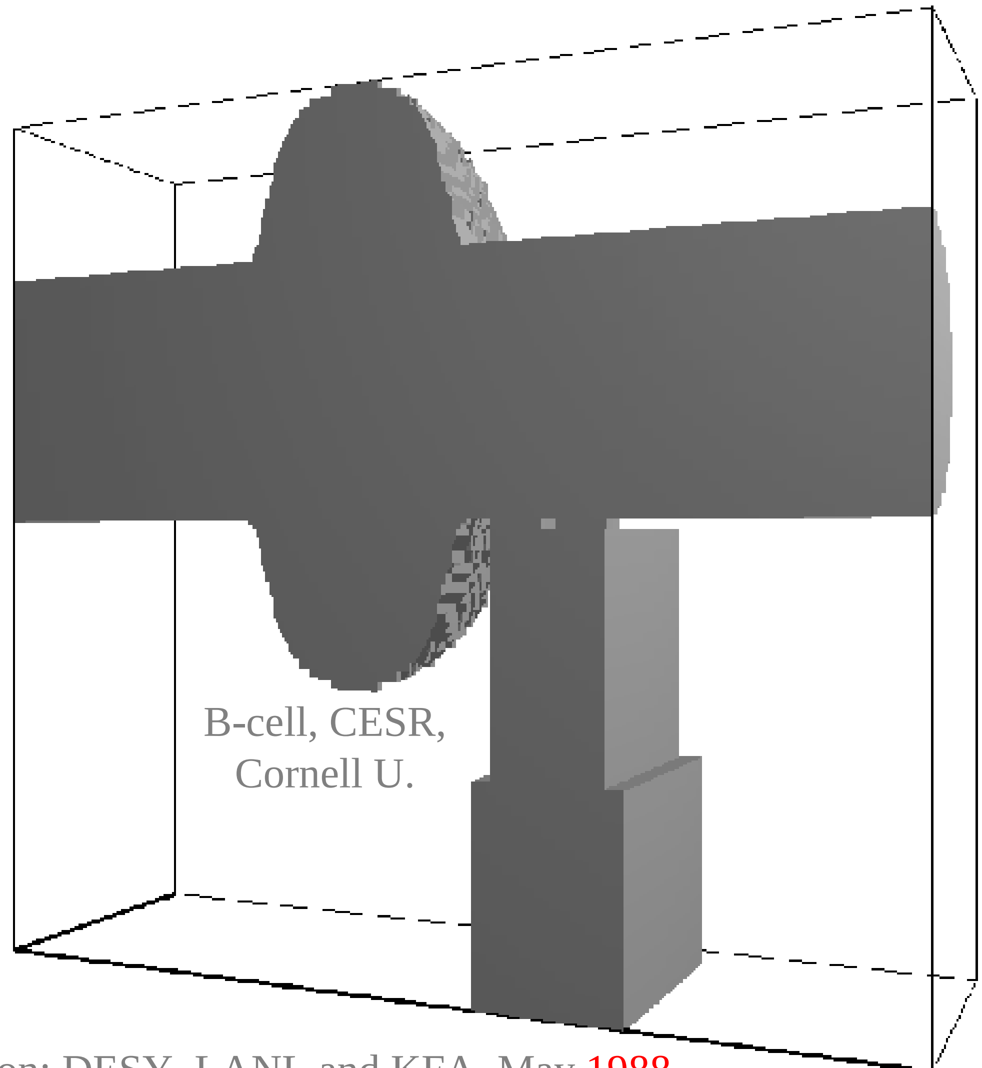
$$(\nabla^2 + \omega^2 \varepsilon\mu)A = 0$$

Approximating operator
(Finite Difference Methods)

Approximating function
(Finite Element Methods)

Examples - MAFIA

MAFIA is a 3D simulation code used for the design of RF cavities and other electromagnetic structures, including electrostatic and magnetostatic devices. It is an acronym for the solution of **MA**xwell's equations using the **F**inite **I**ntegration **A**lgorithm. MAFIA uses a rectangular mesh generation routine which is flexible enough to model even the most complex geometries. The routine allows the user to specify the "coarseness" of the mesh in a particular area of interest.



V. Shemelin, S. Belomestnykh. Calculation of the B-cell cavity external *Q* with MAFIA and Microwave Studio. Workshop on high power couplers for SC accelerators. Newport News, VA, 2002.

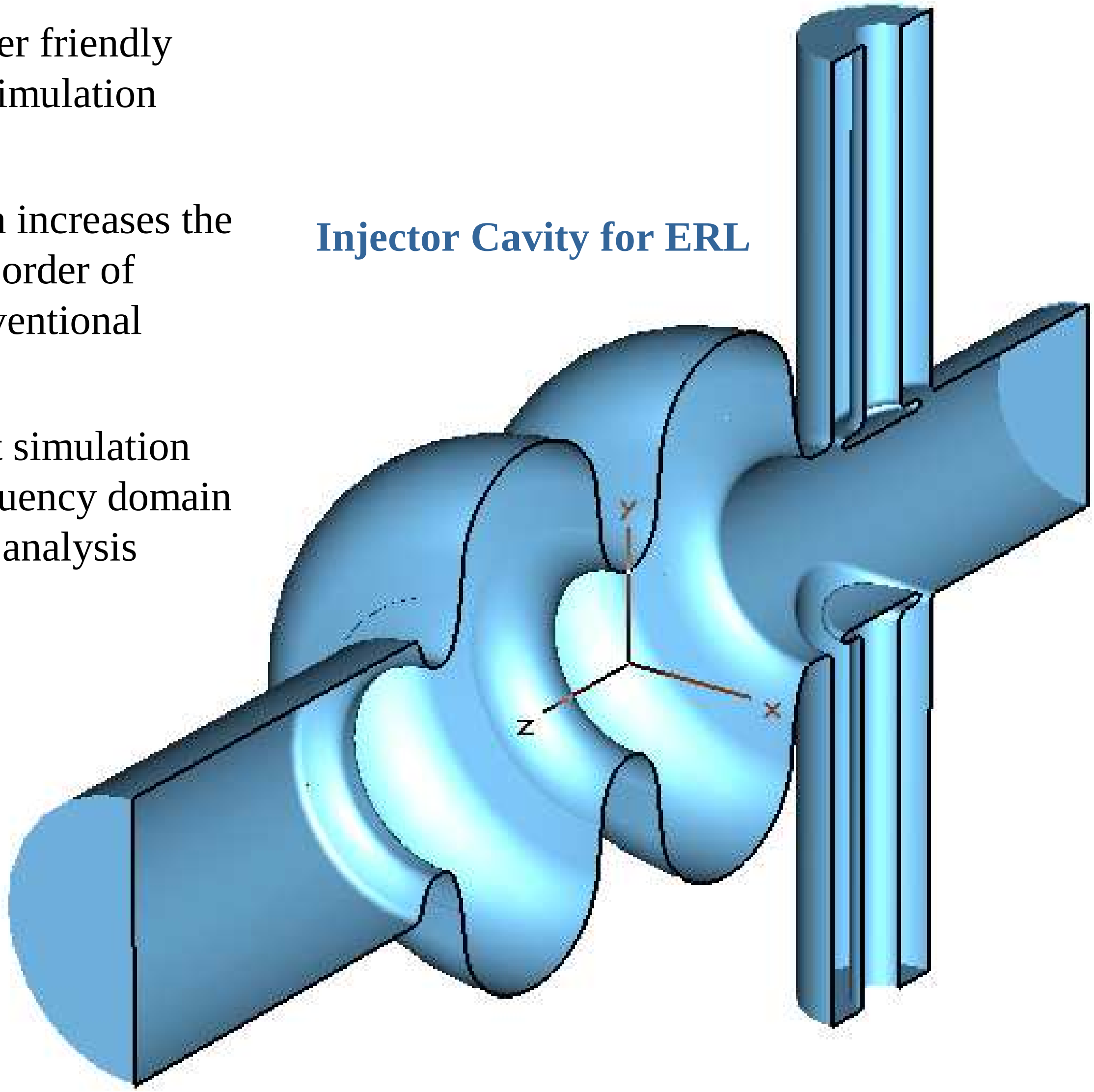
MAFIA User Guide, The MAFIA Collaboration: DESY, LANL and KFA, May 1988.

The program combines both a user friendly interface (Windows based) and simulation performance.

Perfect Boundary Approximation increases the accuracy of the simulation by an order of magnitude in comparison to conventional simulators.

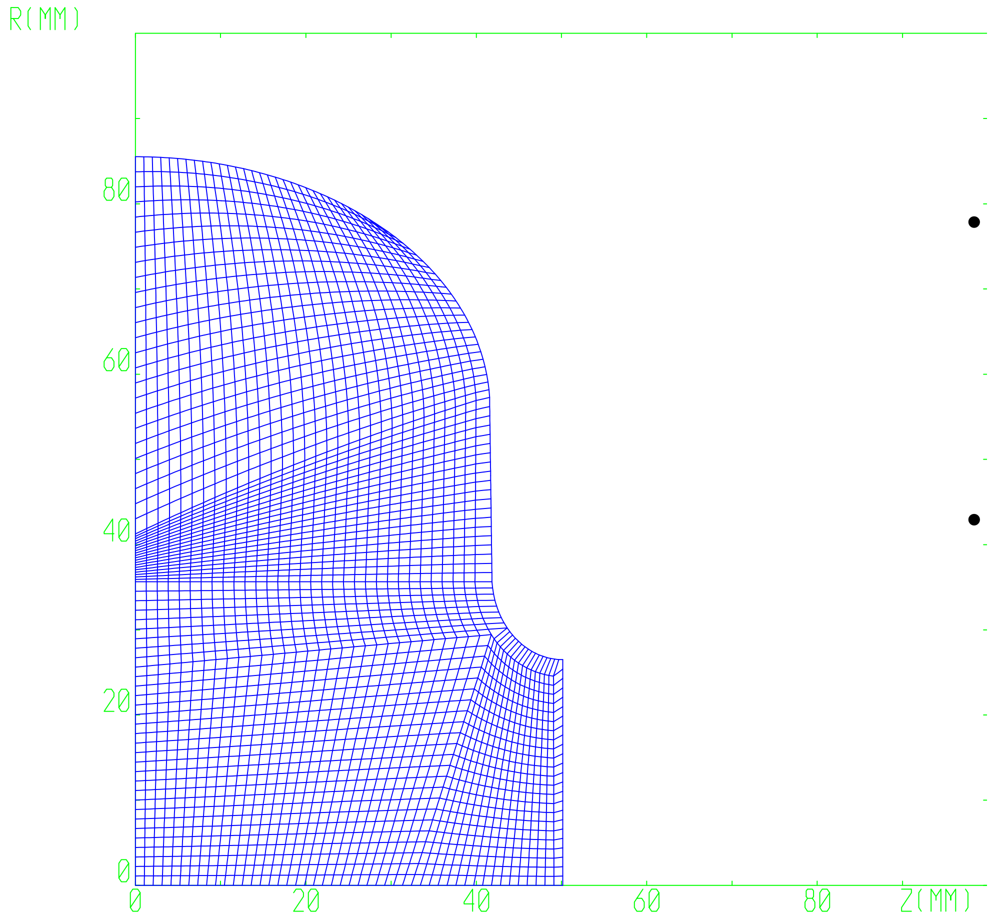
The software contains 4 different simulation techniques (transient solver, frequency domain solver, eigenmode solver, modal analysis solver).

Injector Cavity for ERL



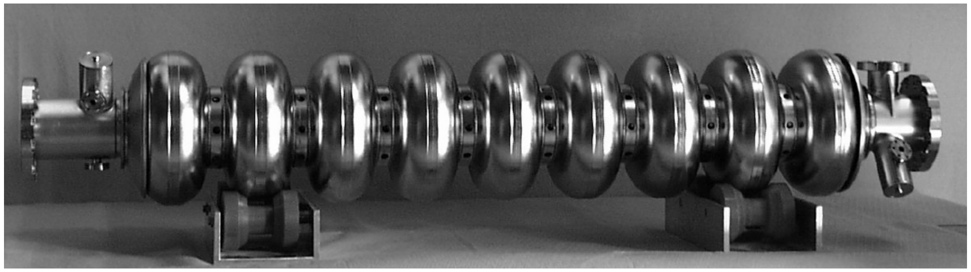
CST Microwave Studio, User Guide, CST GMbH, Buedinger Str. 2a, D-64289, Darmstadt, Germany.

Examples-SuperLANS / CLANS



- **SuperLANS (or SLANS) is a computer program designed to calculate the monopole modes of RF cavities using a finite element method of calculation and a mesh with quadrilateral biquadratic elements.**
- **SLANS has the ability to calculate the mode frequency, quality factor, stored energy, transit time factor, effective impedance, max electric and magnetic field, acceleration, acceleration rate, average field on the axis, force lines for a given mode, and surface fields.**
- **Later versions, SLANS2 and CLANS2, calculate azimuthally asymmetric modes, and CLANS and CLANS2 can include into geometry lossy dielectrics and ferromagnetics.**

Design Example 1: Normal conducting vs. Superconducting RF



Power dissipated into the wall:

$$P_{diss} = \frac{1}{2} R_s \int_S \left| \vec{H} \right|^2 ds = \frac{V_{acc}^2}{R/Q \cdot G} R_S$$

Example:

- **Accelerating voltage: let's take only 1 MV**
- **Constant R/Q (depends on cell shape): 1000 Ω**
- **Geometry constant: 270 Ω**
- **Surface resistance: $R_{s,copper}$ = 10 mΩ $R_{s,Nb}$= 10 nΩ**

⇒ $P_{diss,copper}$ = 37 kW $P_{diss,Nb}$ = 37 mW

⇒ Copper is not the best choice for a ILC shape cavity…

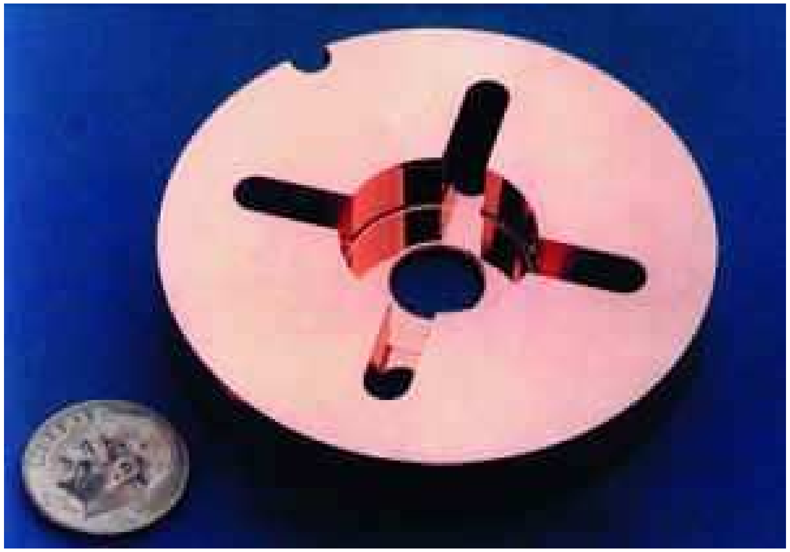
Minimize surface resistance!
⇒ Superconducting cavities.
mΩ (copper) ⇒ nΩ

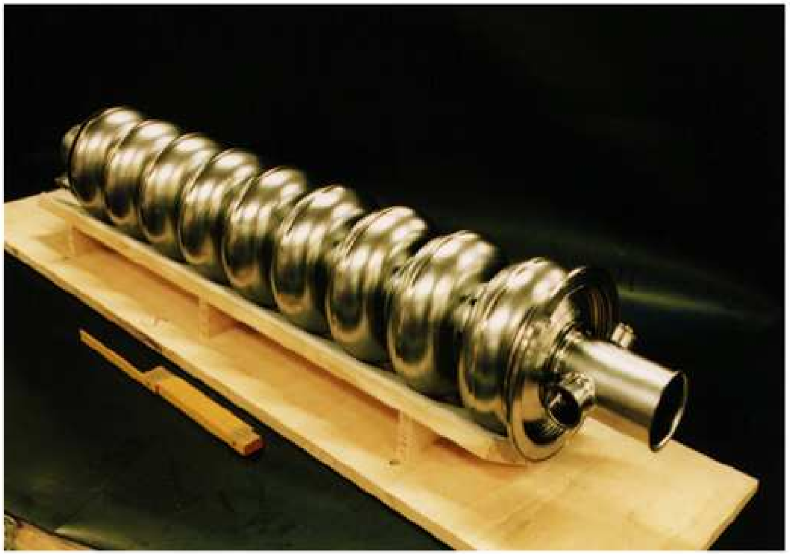
$$P_{diss} = \frac{1}{2} R_s \int_S \left|\vec{H}\right|^2 ds = \frac{V_{acc}^2}{R/Q \cdot G} R_S$$

~~**Depend only on cavity geometry.**~~
~~**⇒ Maximize for copper cavities.**~~

Less important for SRF cavities!

RF Cavities for Linacs





- one cell from NLC
- normal conducting cavity
- copper
- 11.4 GHz
- water cooled

- TESLA
- superconducting cavity
- niobium
- 1.3 GHz
- 2 K (LHe)

Fundamental differences due to difference in wall losses.

Superconducting Cavities: Advantages

- Can operate at a higher voltage in cw operation or long pulse operation because of low losses.
- Power consumption is less. $\Rightarrow$ Operating cost savings, better conversion of ac power to beam power.
- Power dissipation is not the primary concern! Can tailor design to a given accelerator application.

Superconducting Cavities: Advantages (cont.)

- **Freedom to adapt design better to the accelerator requirements allows, <u>for example</u>, the beam-tube and the cell iris size to be increased:**

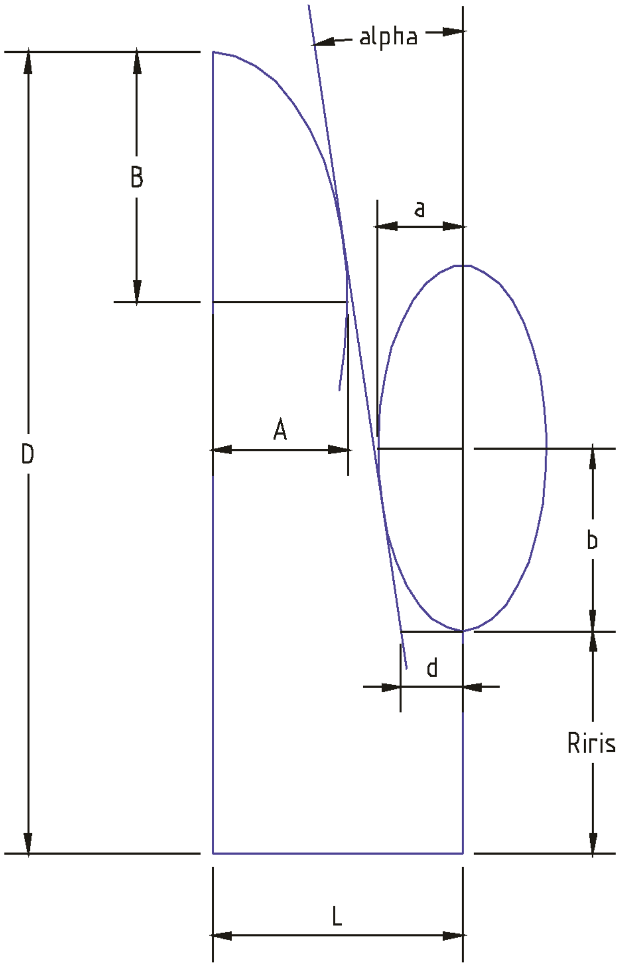
  - **Reduces the interaction of the beam with the cavity.**
    (scales as iris radius$^{2 \text{ to } 3}$) $\Rightarrow$ The beam quality is better preserved.
    Important for, e.g., FELs.

  - **HOMs are removed more easily. Better beam stability.**
    $\Rightarrow$ More current accelerated.
    Important for, e.g., B-factories.

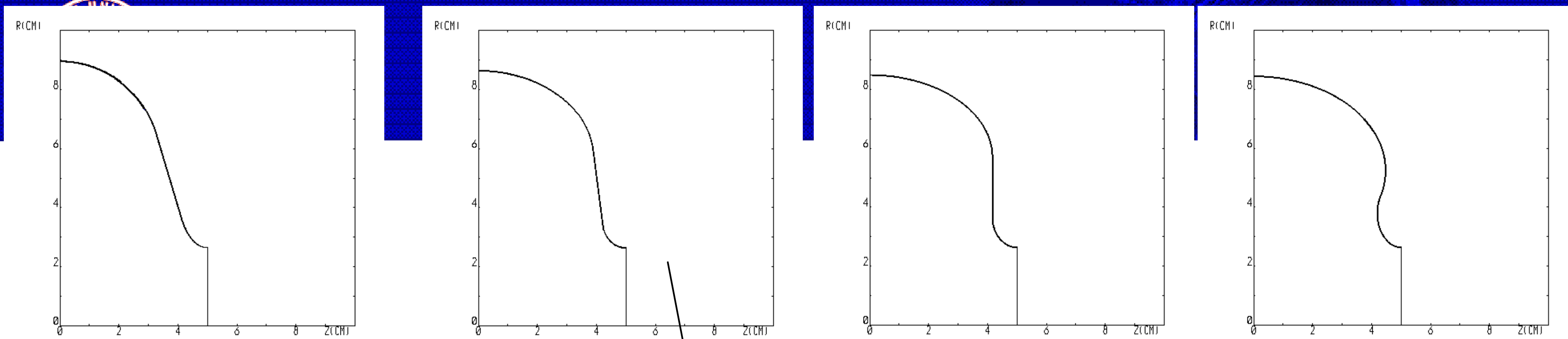
  - **Reduce the amount of beam scraping. $\Rightarrow$ Less activation in, e.g., proton machines.**
    Important for, e.g., SNS, Neutrino factory.

  - **Allows more coupling between cells in multicell structures.**
    $\Rightarrow$ Better energy exchange between cells.
    Important for e.g., high-energy machines.

Design Example 2: Center Cell Shape of an SRF Cavity



- The **cell length (L)** determines the cavity geometrical beta value.
- The **cell iris radius (R_{iris})** is mainly determined by the cell-to-cell coupling requirements and cavity impedance limitations.
- The **iris ellipse ratio (r=b/a)** is primary determined by the local optimization of the peak electric field.
- The **cell radius (D)** is used for the frequency tuning without modifying any electromagnetic or mechanical cavity parameter.
- The **side wall inclination (α)** and **B** and **A** can be use to minimize relative surface peak fields.
- **Usual design goal: Maximize R/Q*G / minimize peak magnetic surface field for given wall angle, maximum peak electric field and minimum iris radius**



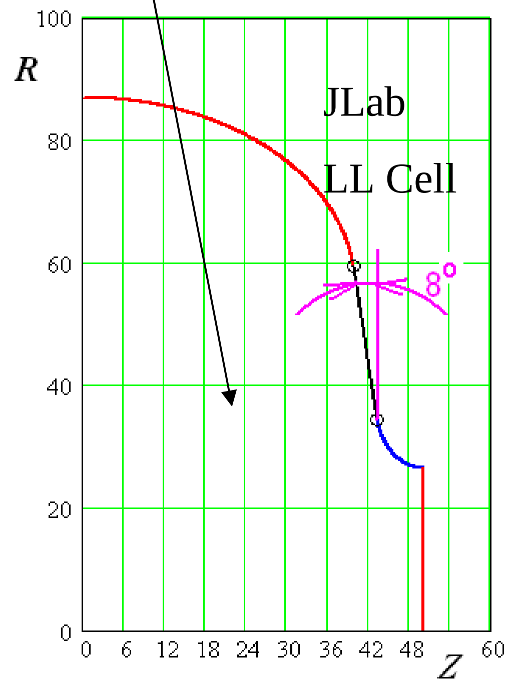
G*R/Q, relative units:

0.90 (75deg) **1.00 (82deg)** **1.02 (90deg)** **1.042 (105 deg)**

If one rejects the limitation of the angle we can further improve the value of *G*R/Q*

JLab's optimized shape was designed under restriction that the angle of the wall slope is not less than 8 deg. This angle is useful to let liquid easily flow from the surface when chemical treatment or rinsing are performed.

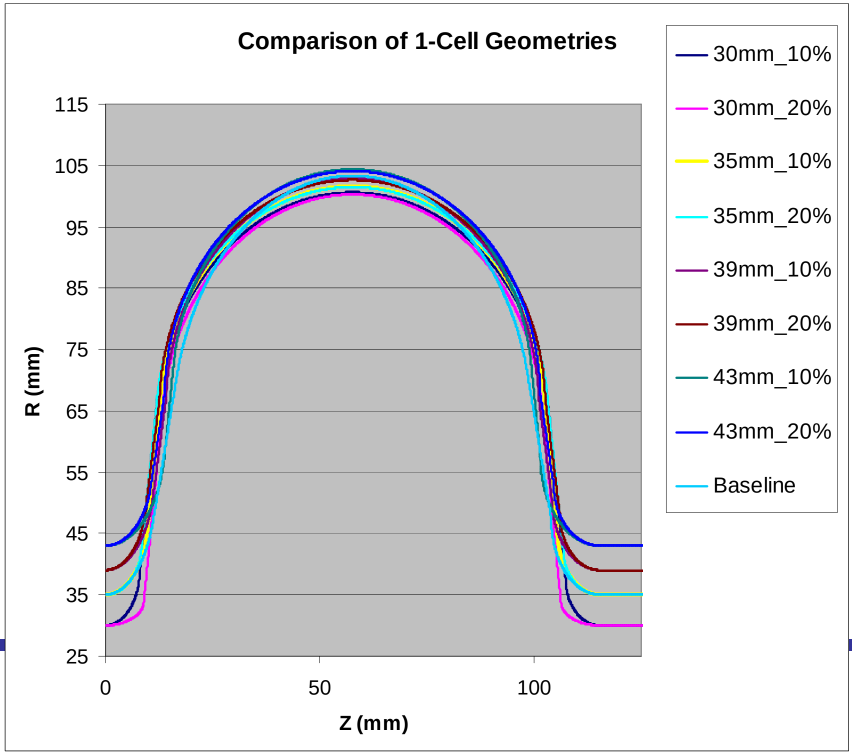
This shape is also more mechanically strong.

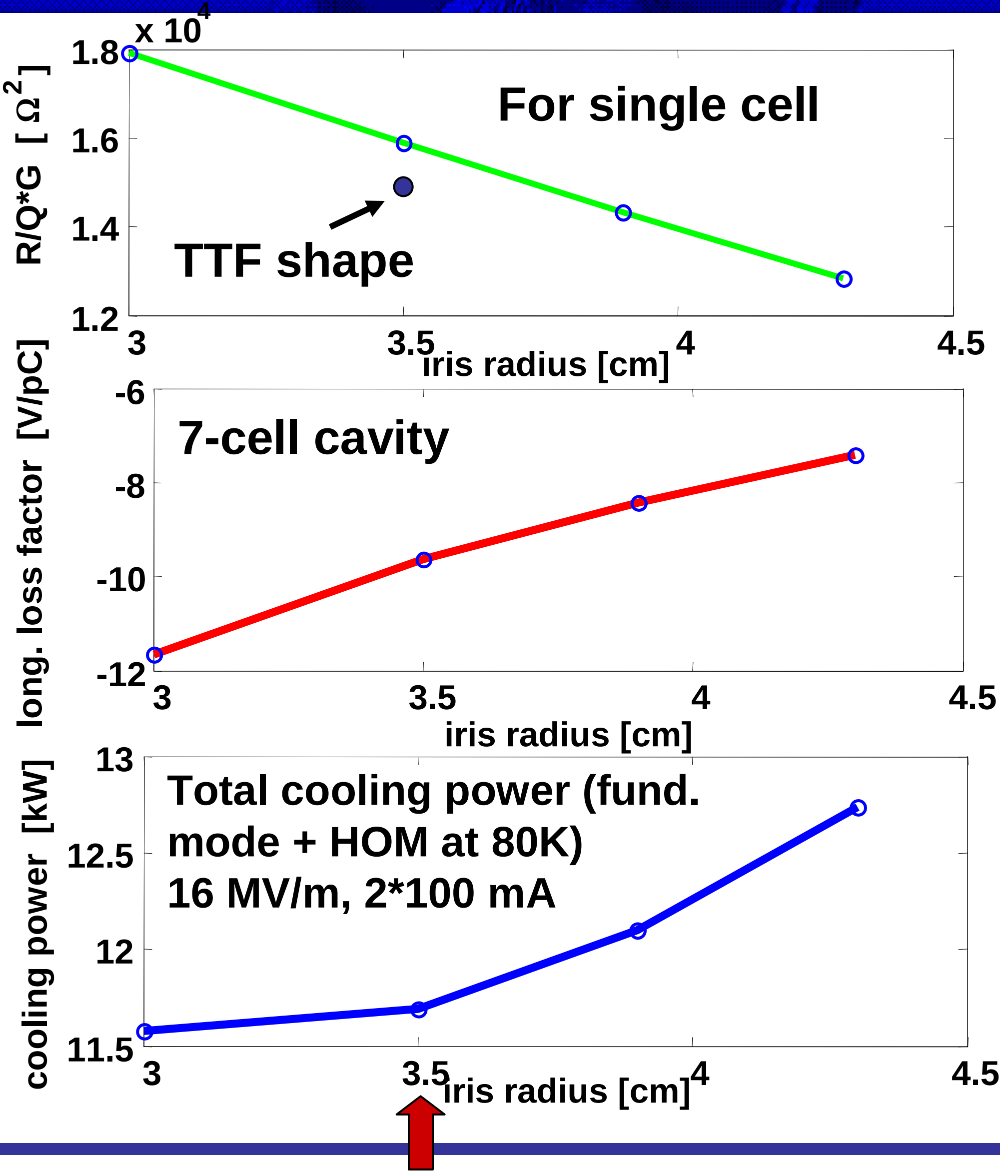


Cavity Cell Shape and R/Q*G and Loss Factor

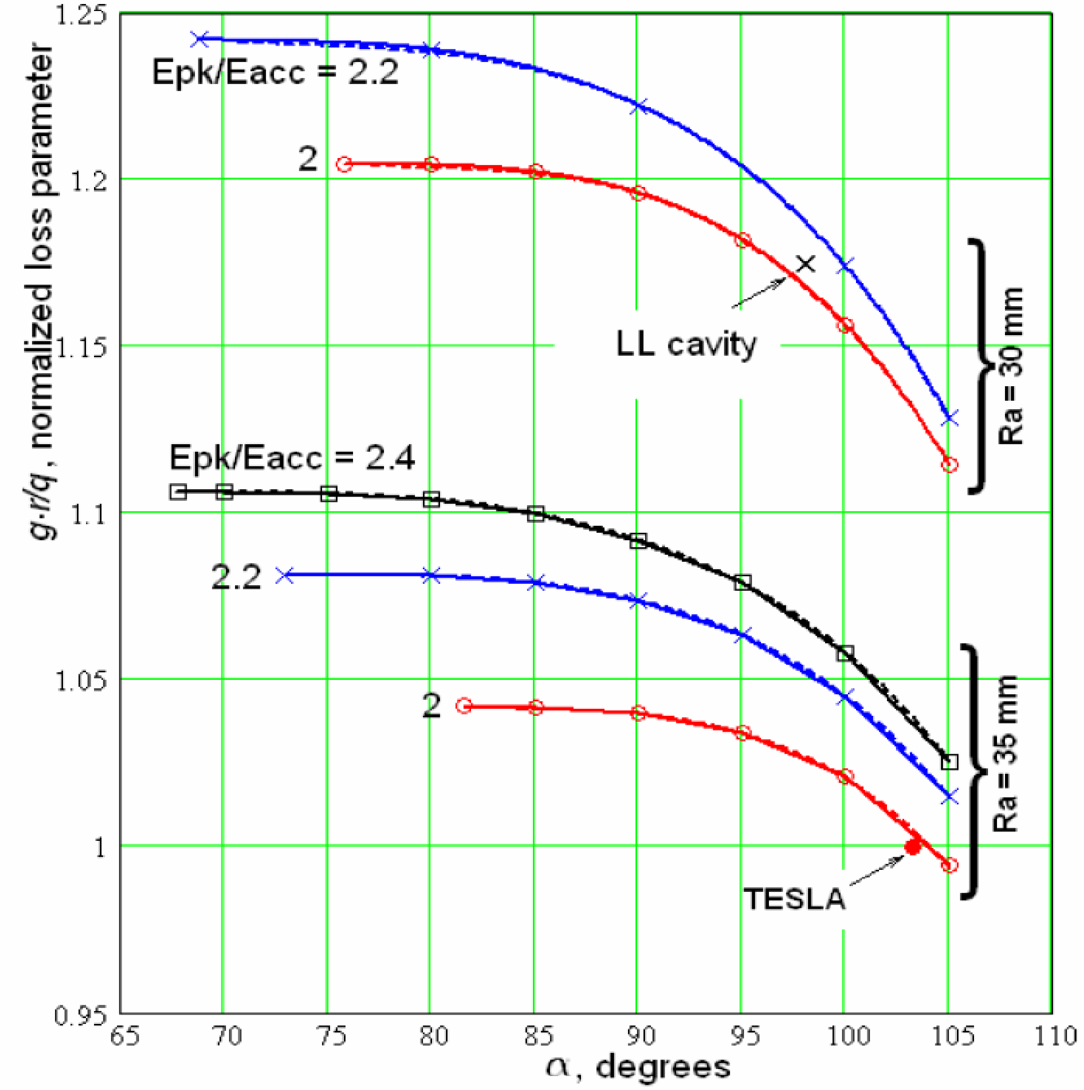
1.3 GHz center-cell:

- Cells optimized for fixed side wall angle (82 deg) and electric peak field (E/E_{acc}=2.2)



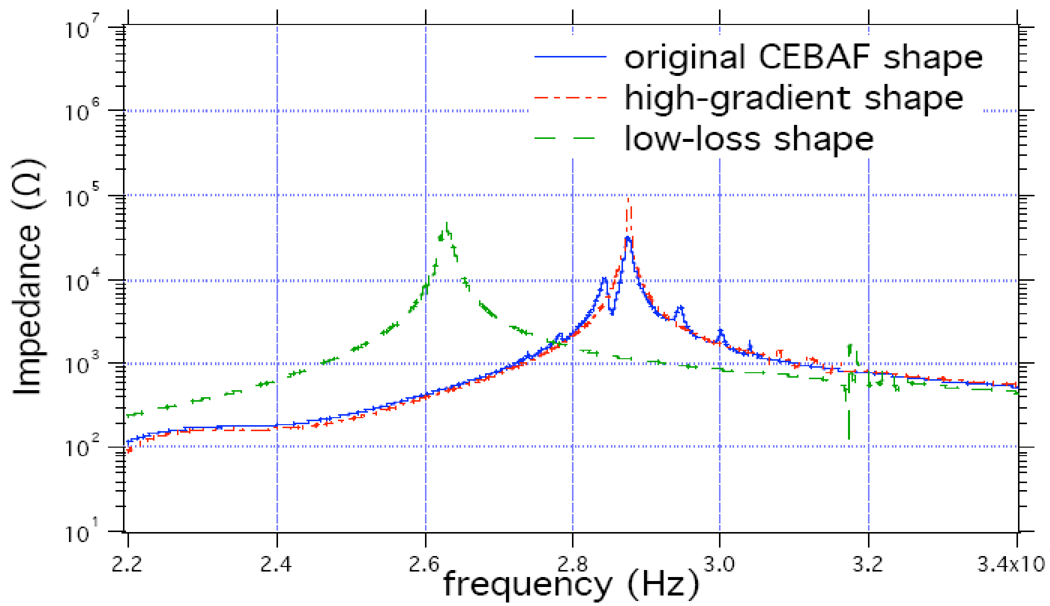


Wall Angle, Peak Field and R/Q*G



from V. Shemelin

Impact of Cell Shape on HOM Impedances (I)



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

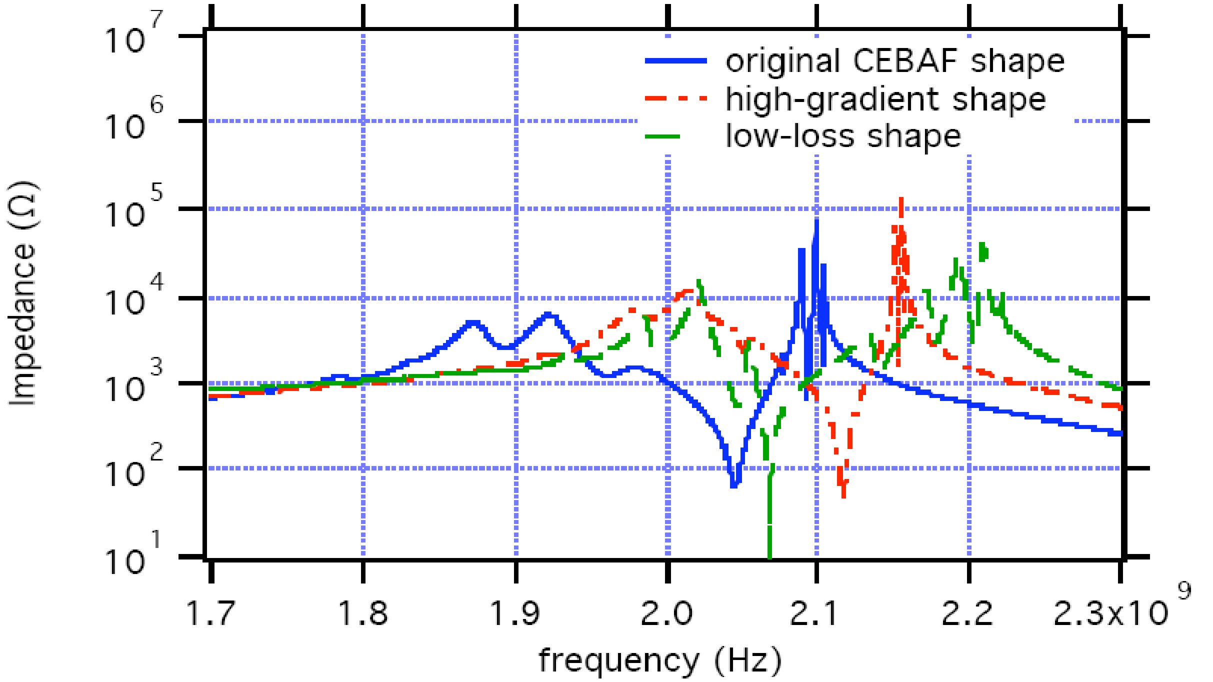
TM_{011} mode data for multi-cell cavities.

	#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. $^{\dagger}R=V^2/2P$

from Bob Rimmer

Impact of Cell Shape on HOM Impedances (II)



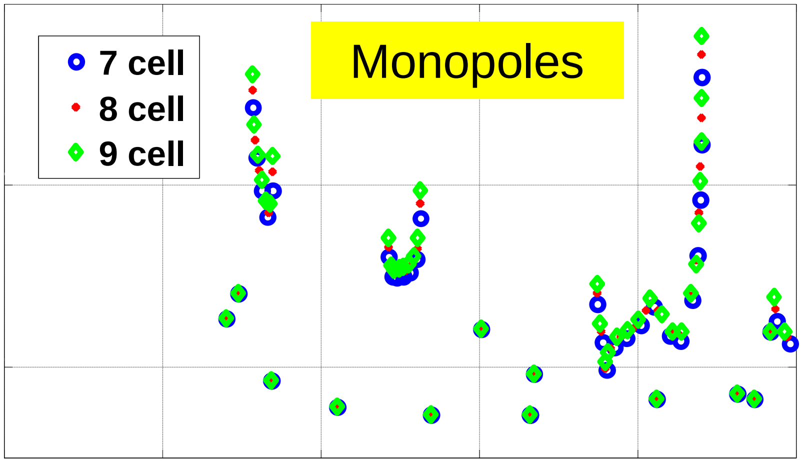
7-cells, OC, HG, LL shapes, TE_{111}/TM_{110} dipole, beam-pipe damping

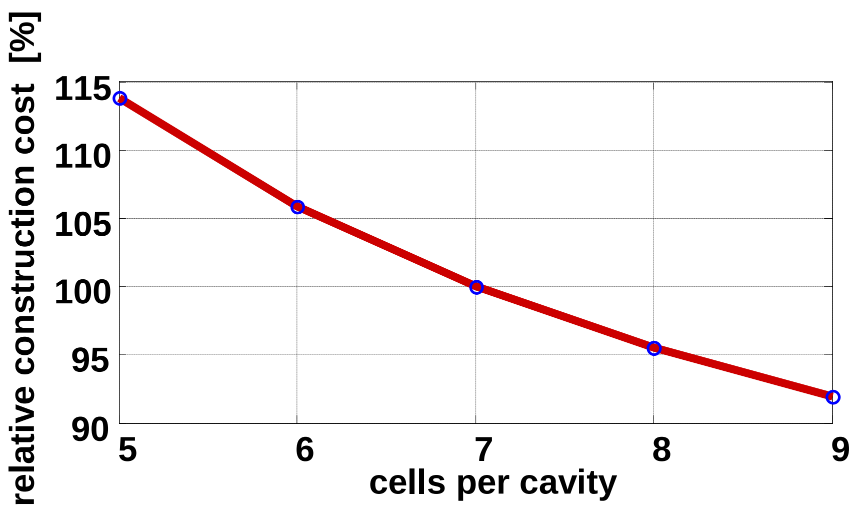
TE_{111}/TM_{110} mode data for multi-cell cavities.

	# 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.

Design Example 3: Number of Cells per SC Cavity





F. Marhauser at al. PAC 1999

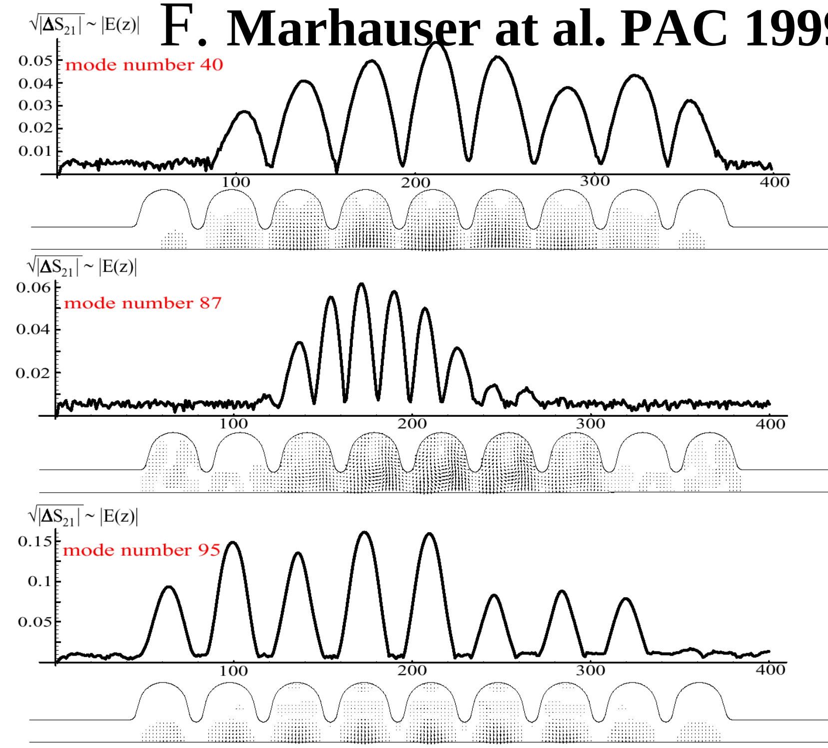


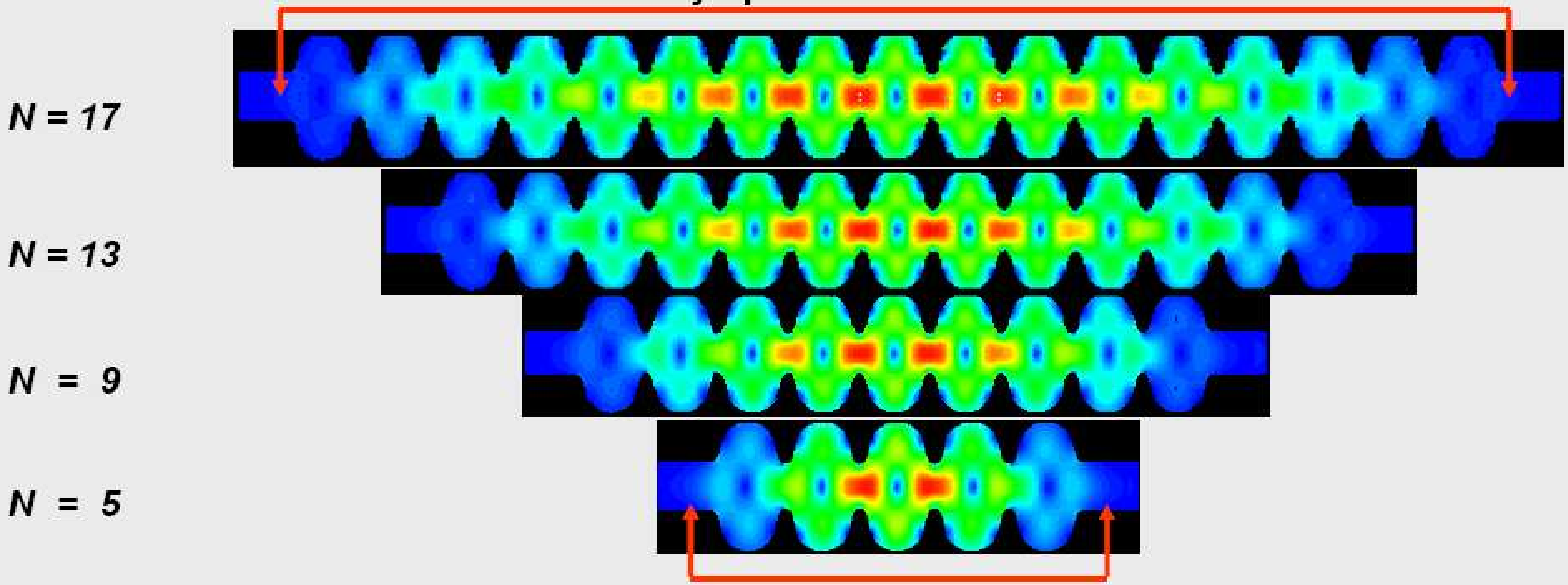
Figure 5: Trapped dipole mode (comp. Figure 4) no. 40 (f = 3.084 GHz MAFIA; 3.078 GHz meas.), mode no. 87 (f = 4.323 GHz MAFIA; 4.314 GHz meas.) and mode no. 95 (f = 4.426 GHz MAFIA; 4.421 GHz meas.).

- **Risk of trapped modes increases with number of cells**

Trapped Modes

Example: how N influences strength of the E-H fields at HOM couplers locations

no E-H fields at HOM couplers locations (trapping), which are always placed at the end beam tubes



E-H fields at HOM couplers locations

Less cells in a structure helps always to reach low Qs of HOMs.

HOM strength (number of Cells)

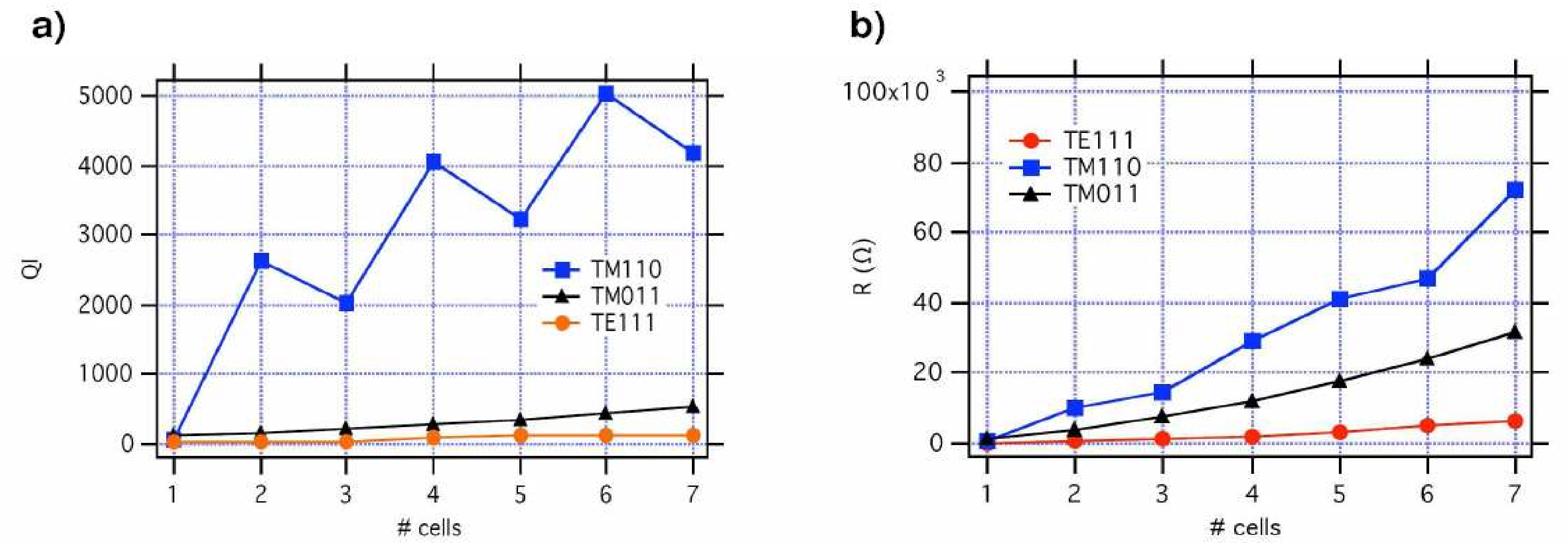
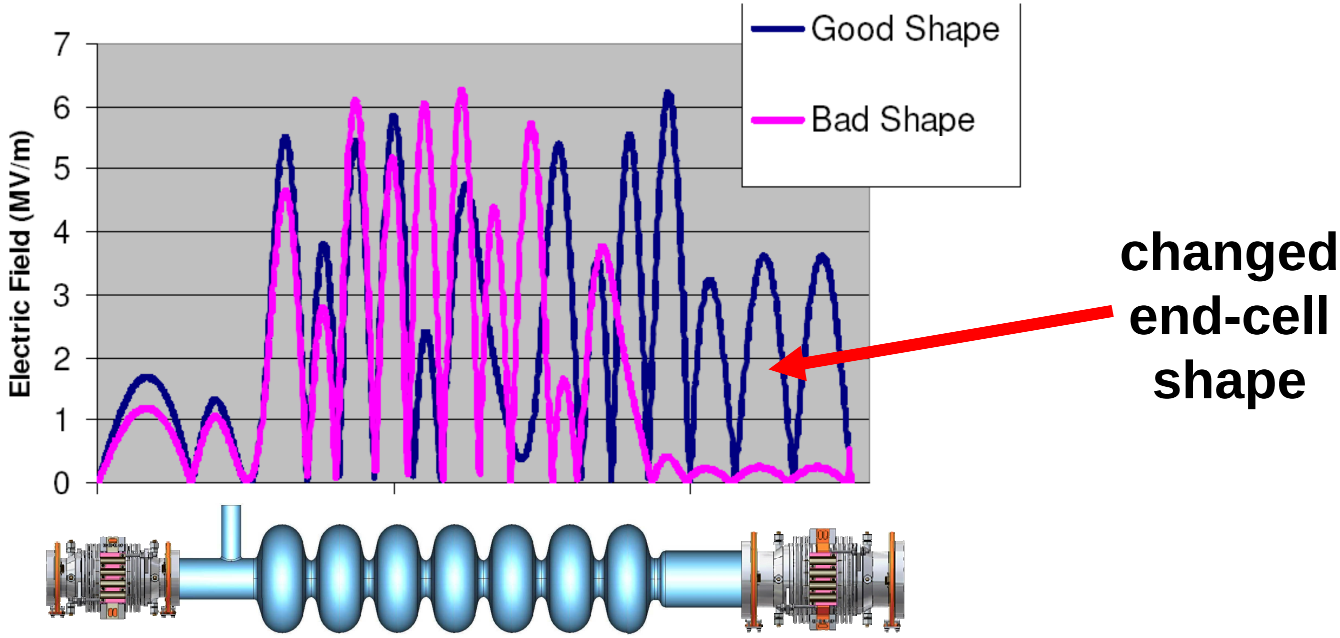


Fig. 11. Impact of number of cavity cells on HOM impedance (TM011, TE111 and TM110 passband modes with beam pipe damping). a) Loaded Q vs. number of cells. b) Impedance vs. number of cells (dipoles at 25 mm transverse offset). Courtesy of B. Rimmer.

Design Example 4: 7-Cell SRF Cavity End-Cell Design

- **End cell shape has significant impact (example HOM):**



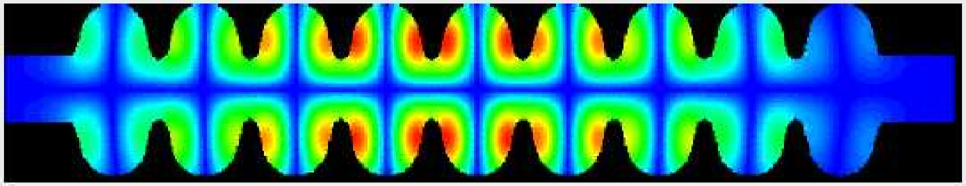
- **Can fine-tuning of end cell to**
  - Increase damping of most dangerous HOM(s)
  - Avoid strong monopole modes at beam harmonics
  - Note: Can optimize end cell shape only for a few selected modes!!

End Cell Optimization: ILC Cavity

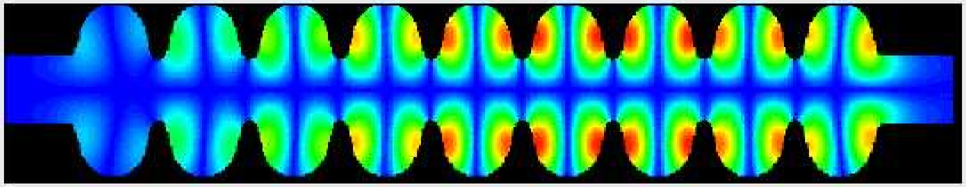
2. Tailor end-cells to equalize HOM frequencies of inner- and end-cells.

Example: TESLA 9-cell cavity, which has two different end-cells (asymmetric cavity)

The lowest mode in the passband
f_{HOM} = 2382 MHz



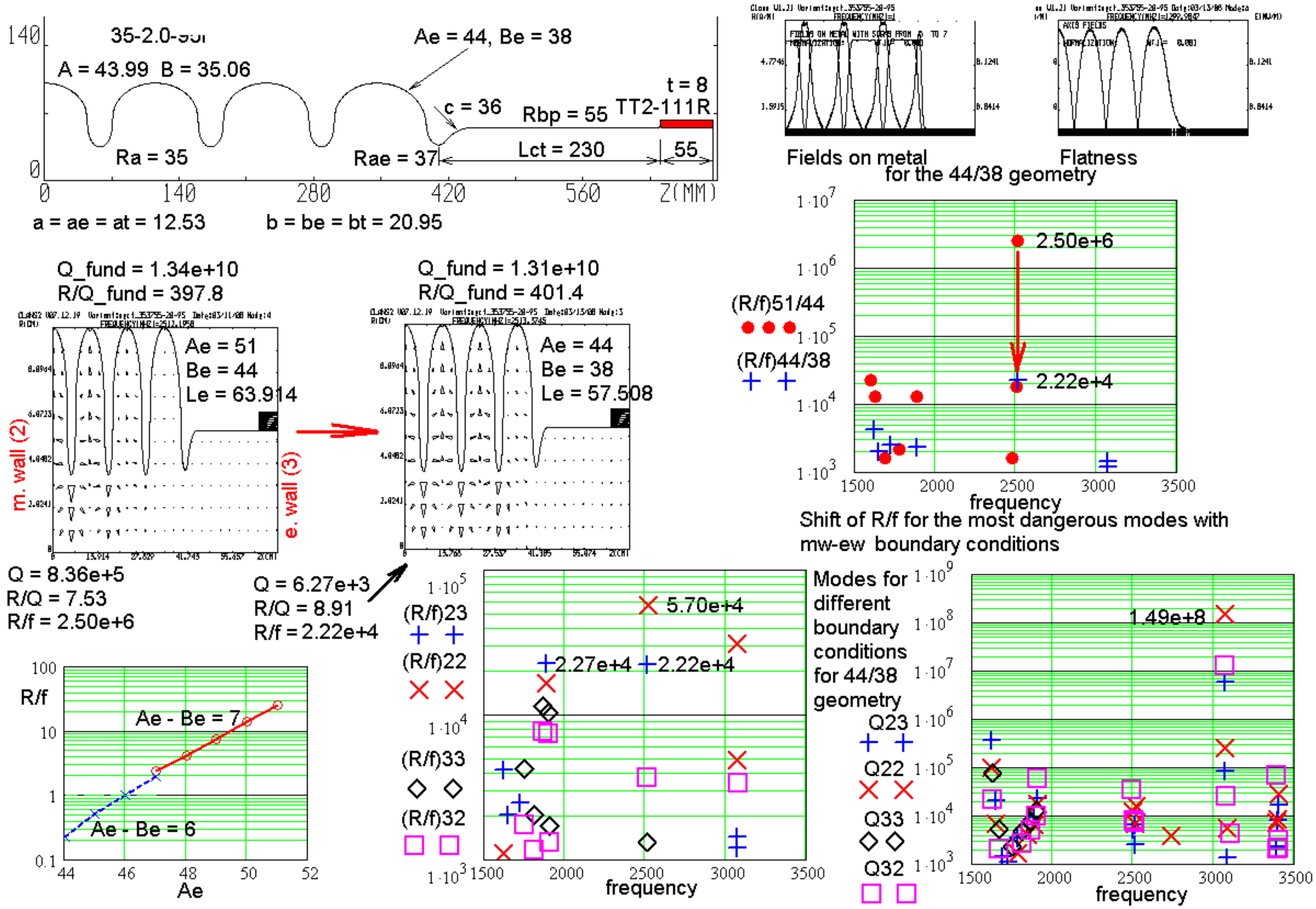
The highest mode in the passband
f_{HOM} = 2458 MHz



The method works for very few modes but keeps the (R/Q) value high of the fundamental mode.

7-Cell SRF Cavity End-Cell Design

II. Cavity with Epk/Eacc = 2.0. Suppression of the worst Dipole (2513 MHz).



Cavity Examples: SRF High beta Cavities

The "heart" of all mentioned facilities are sc standing wave (usually multi-cell) accelerating structures.

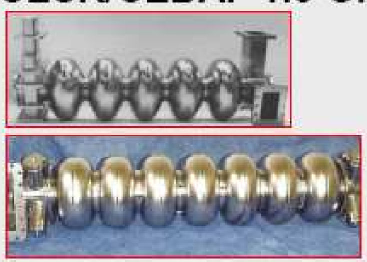
FERMI 3.9 GHz

TESLA/ILC 1.3 GHz

S-DALINAC 3 GHz

SNS ß=0.61,0.81, 0.805 GHz

CESR/CEBAF 1.5 GHz



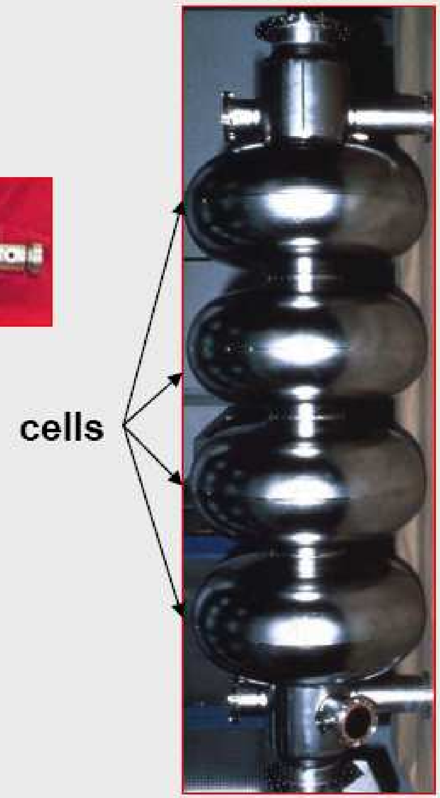
HERA 0.5 GHz

HEPL 1.3 GHz

KEK-B 0.5 GHz

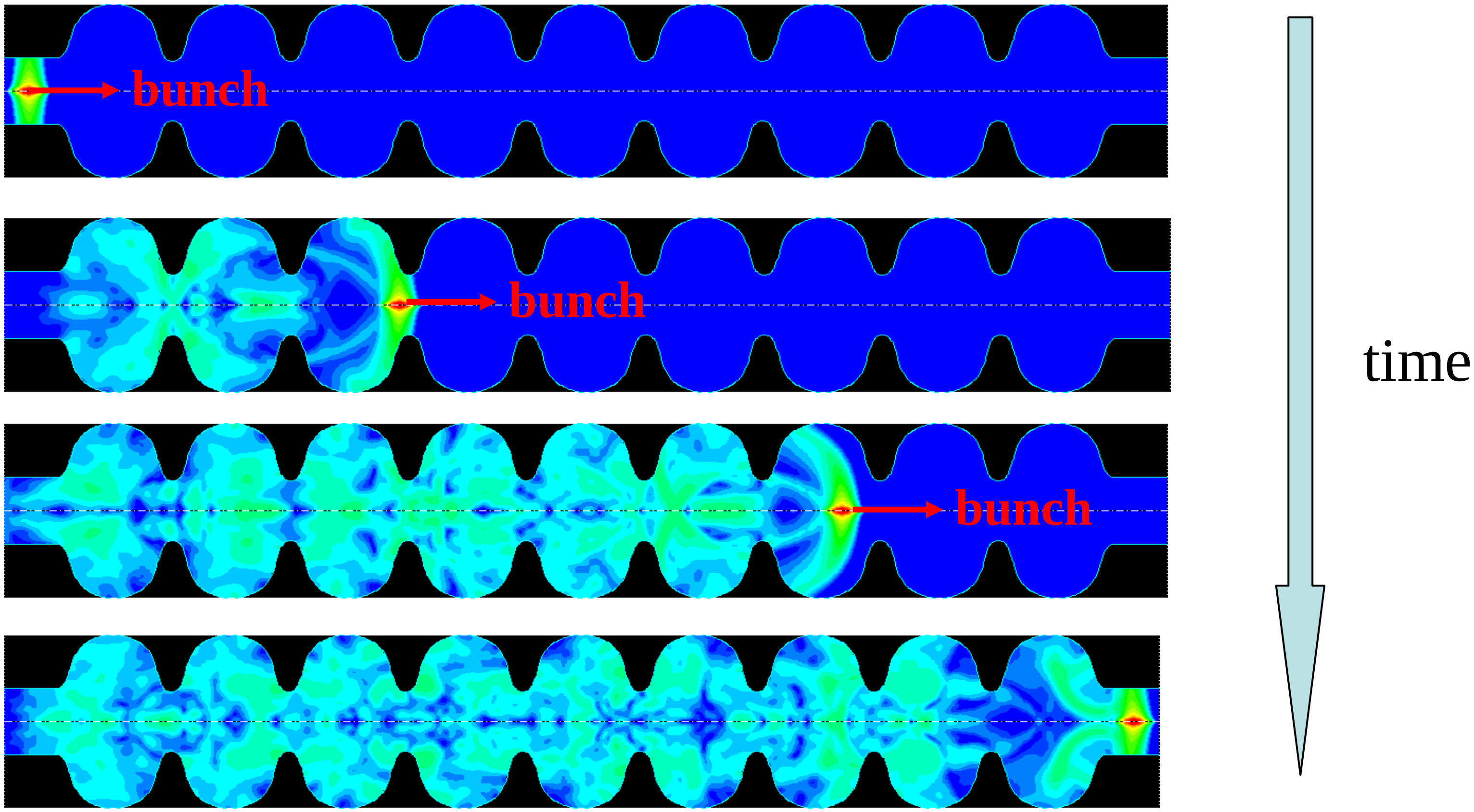
CESR 0.5 GHz

LEP 0.352 GHz



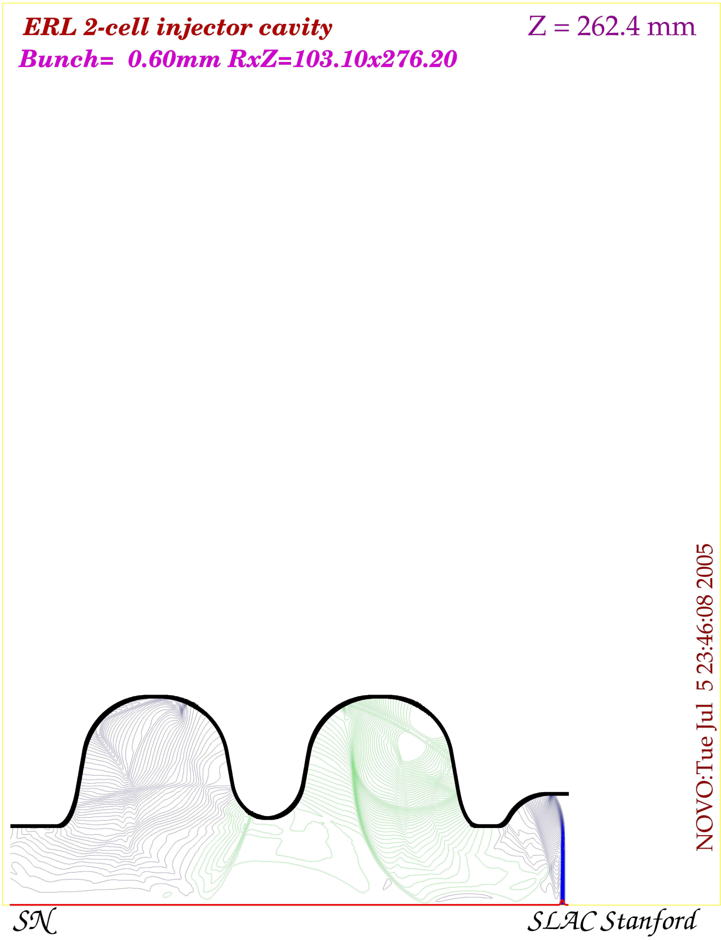
- **Higher order modes**
  - Introduction: HOMs
  - HOM excitation by a beam
  - HOM damping schemes
  - HOM damping examples and results

HOM Excitation by a Bunch



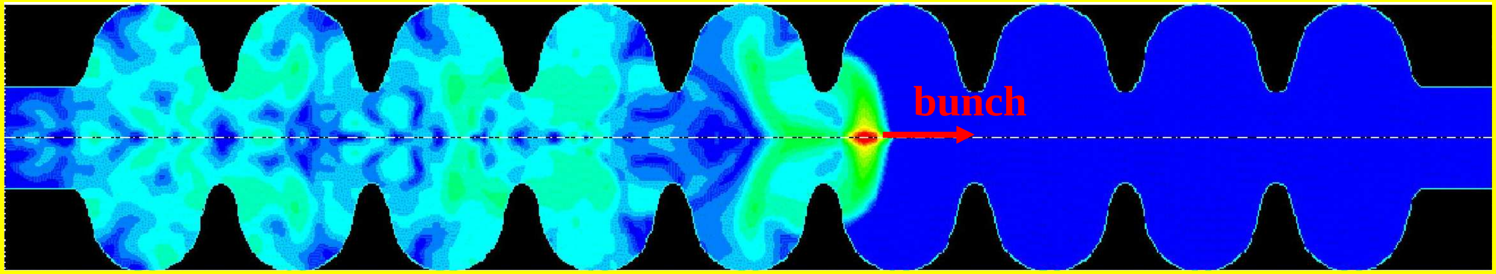
The bunched beam excites higher-order-modes (HOMs) = wakefields = electromagnetic fields in the cavity.

- **Bunch traverses a cavity**
- **⇒ deposits electromagnetic energy, which is described as wakefields (time domain) or higher-order modes (HOMs, frequency domain)**
- **Subsequent bunches are affected by these fields and at high beam current one must consider instabilities**



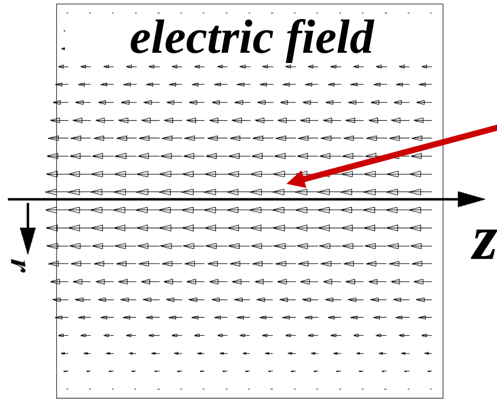
Single Bunch Monopole Losses: Wake Potential of a Point-Charge

The beam excites higher-order-modes (HOMs) in a cavity:



- **When a charge passes through a cavity, it excites HOMs.**
- **If it passes exactly an axis, it will only excite monopole modes.**
- **For a point charge, the HOM excitation depends only on the bunch charge and the cavity shape.**
- **The excited field can be described by the wake potential.**

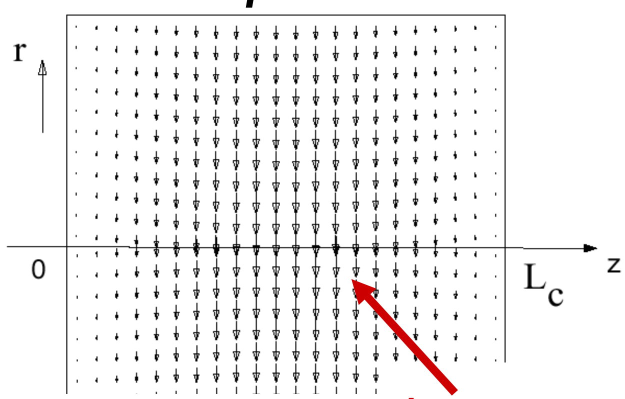
Monopole modes



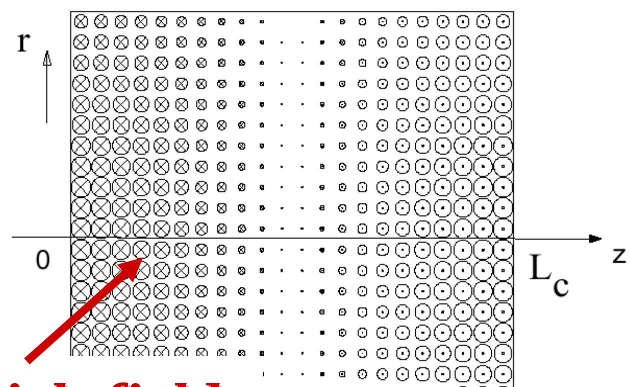
longitudinal electric field on axis

Dipole modes, quadrupole modes,…

electric field



magnetic field



transverse kick-fields

Monopole, Dipole and Quadrupole Modes…

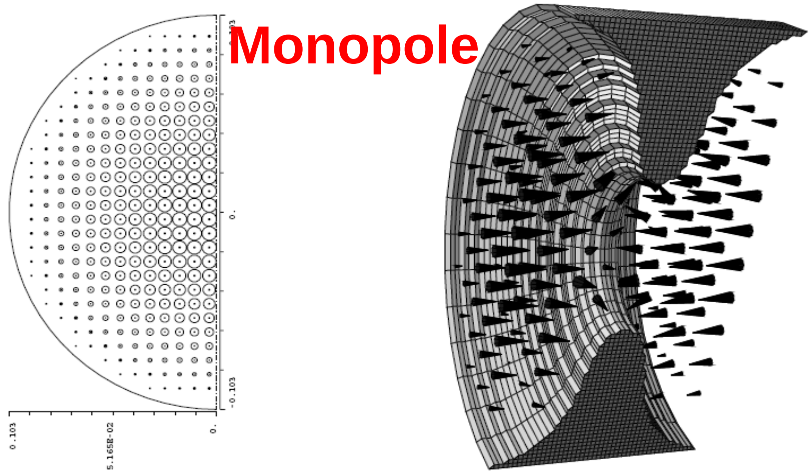


Figure 5: One mid-cell of a TESLA cavity. The electric field of the 1.3 GHz accelerating π-mode is shown. The left graph shows the electric field in a plane perpendicular to the cavity axis.

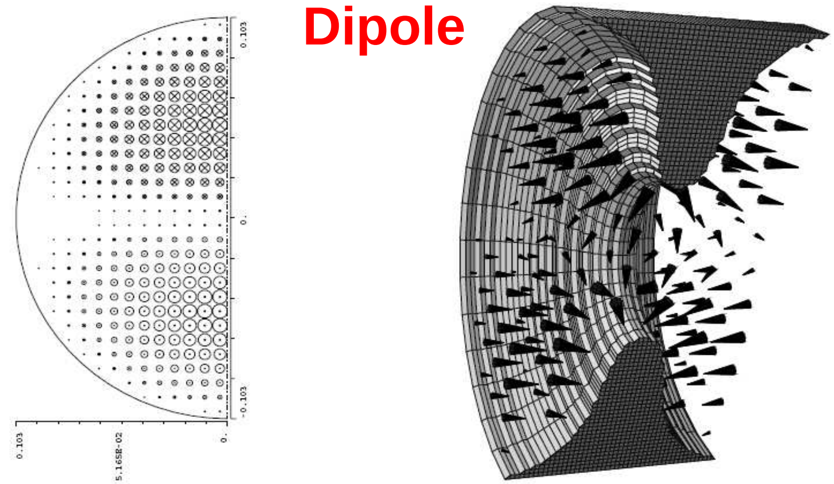


Figure 6: One mid-cell of a TESLA cavity. The electric field of the 1.79 GHz π-mode of the first dipole passband is shown. The left graph shows the electric field in a plane perpendicular to the cavity axis.

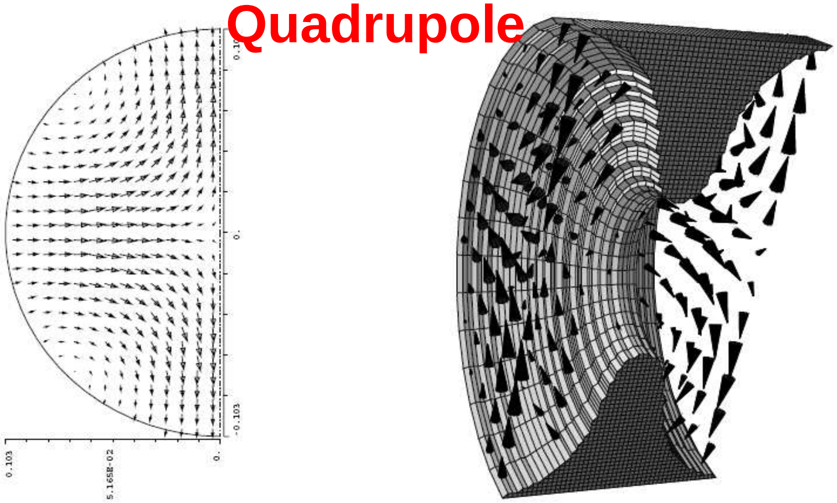


Figure 7: One mid-cell of a TESLA cavity. The electric field of the 2.32 GHz π-mode of the first quadrupole passband is shown. The left graph shows the electric field in a plane perpendicular to the cavity axis.

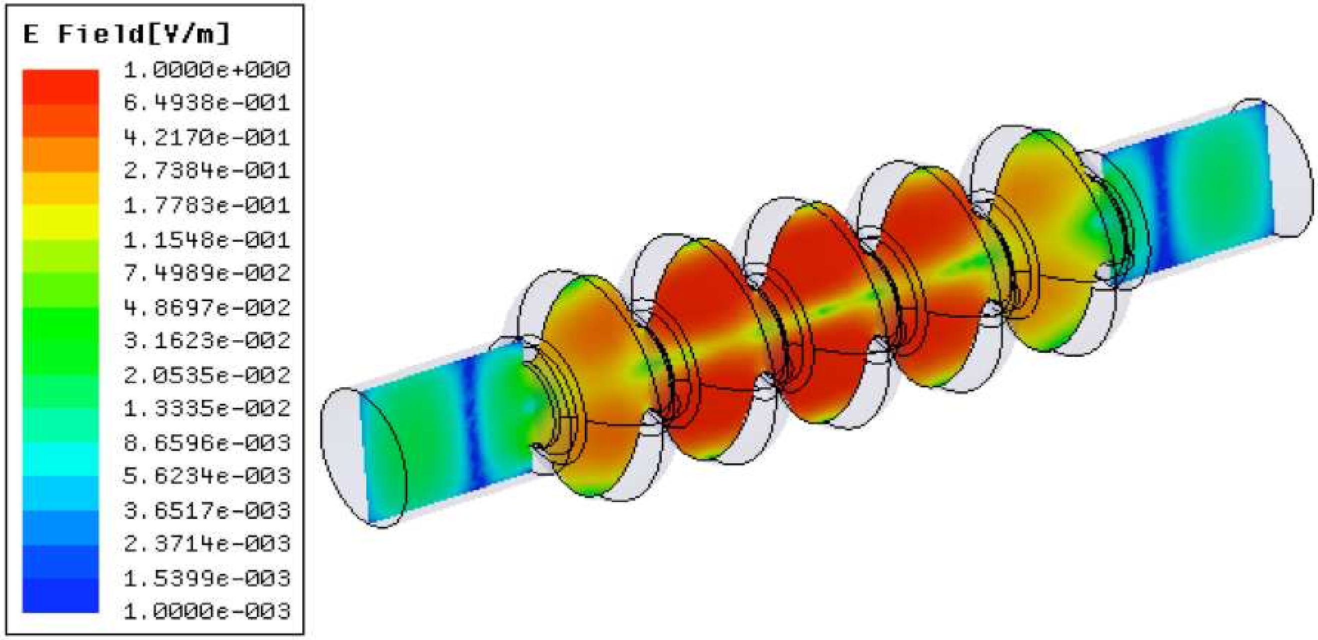
$$\begin{aligned}\widetilde{\boldsymbol{E}}(r,\phi,z) &= \sum_m \Big(\widetilde{E_r^{(m)}}(r,z)\,\cos(m\,\phi)\quad \boldsymbol{e_r} \\ &\quad + \widetilde{E_\phi^{(m)}}(r,z)\,\sin(m\,\phi)\quad \boldsymbol{e_\phi} \\ &\quad + \widetilde{E_z^{(m)}}(r,z)\,\cos(m\,\phi)\quad \boldsymbol{e_z} \Big)\end{aligned}$$

$$\begin{aligned}\widetilde{\boldsymbol{B}}(r,\phi,z) &= \sum_m \Big(\widetilde{B_r^{(m)}}(r,z)\,\sin(m\,\phi)\quad \boldsymbol{e_r} \\ &\quad + \widetilde{B_\phi^{(m)}}(r,z)\,\cos(m\,\phi)\quad \boldsymbol{e_\phi} \\ &\quad + \widetilde{B_z^{(m)}}(r,z)\,\sin(m\,\phi)\quad \boldsymbol{e_z} \Big).\end{aligned}$$

from R. Wanzenberg

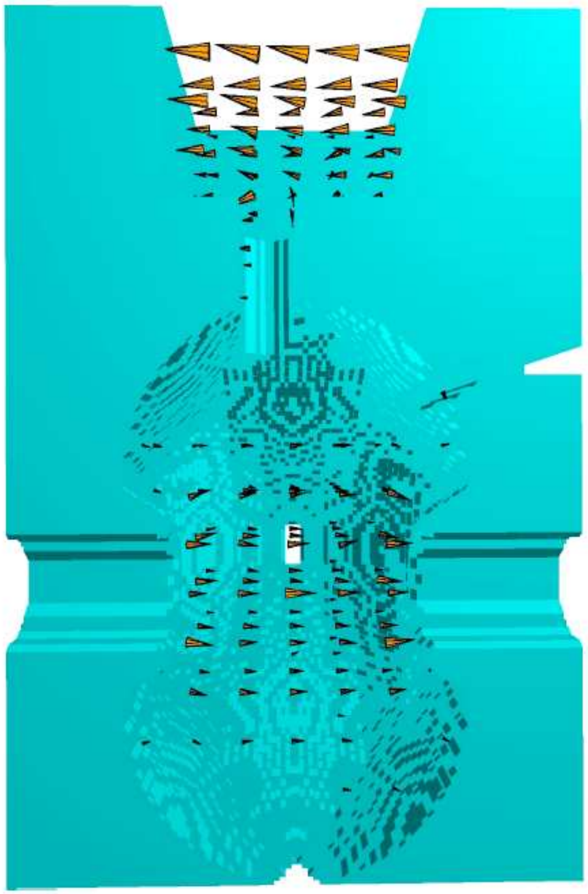
Methods of HOM Calculations: Frequency Domain

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

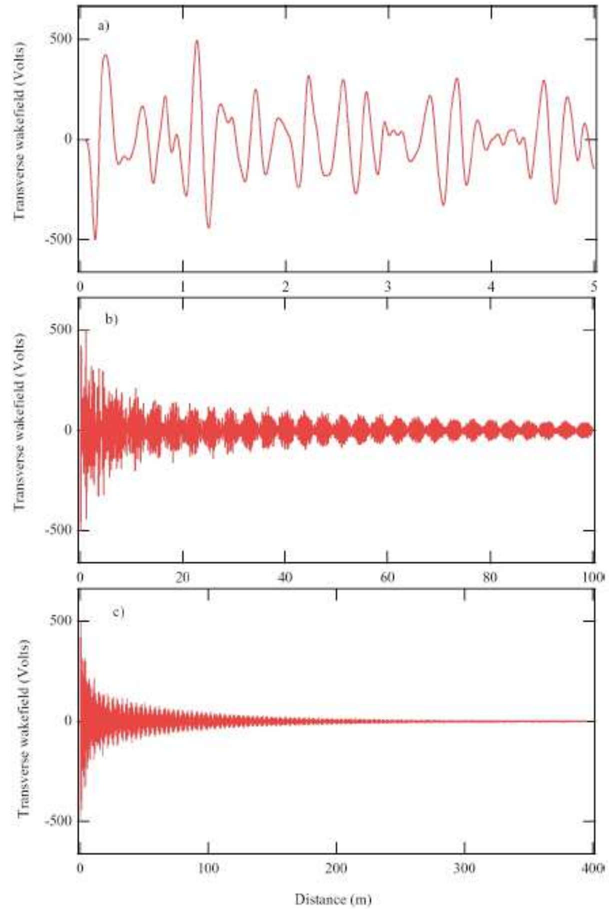


HFSS 3D complex Eigenvalue solution, 5-cell cavity with enlarged beam-pipes.

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



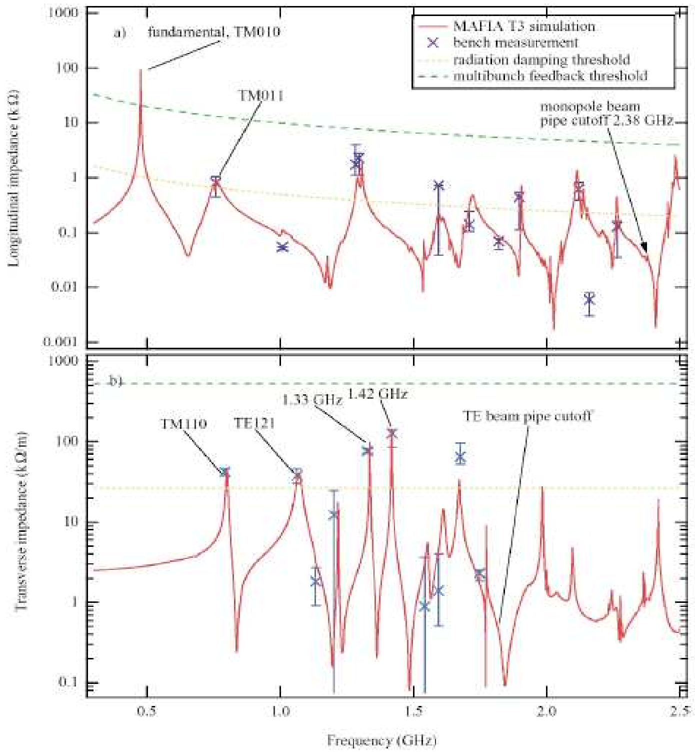
3D MAFIA model of PEP-II cavity.



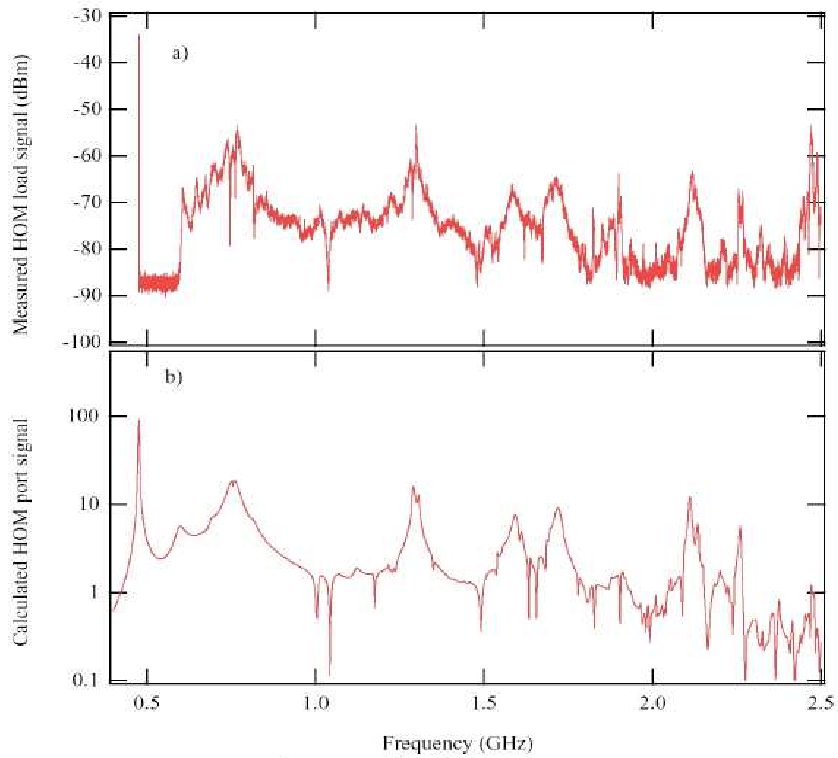
Short-, medium- and long-range wakes*.

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

Time-Domain Method (II)



Calculation vs bead-pull measurements.



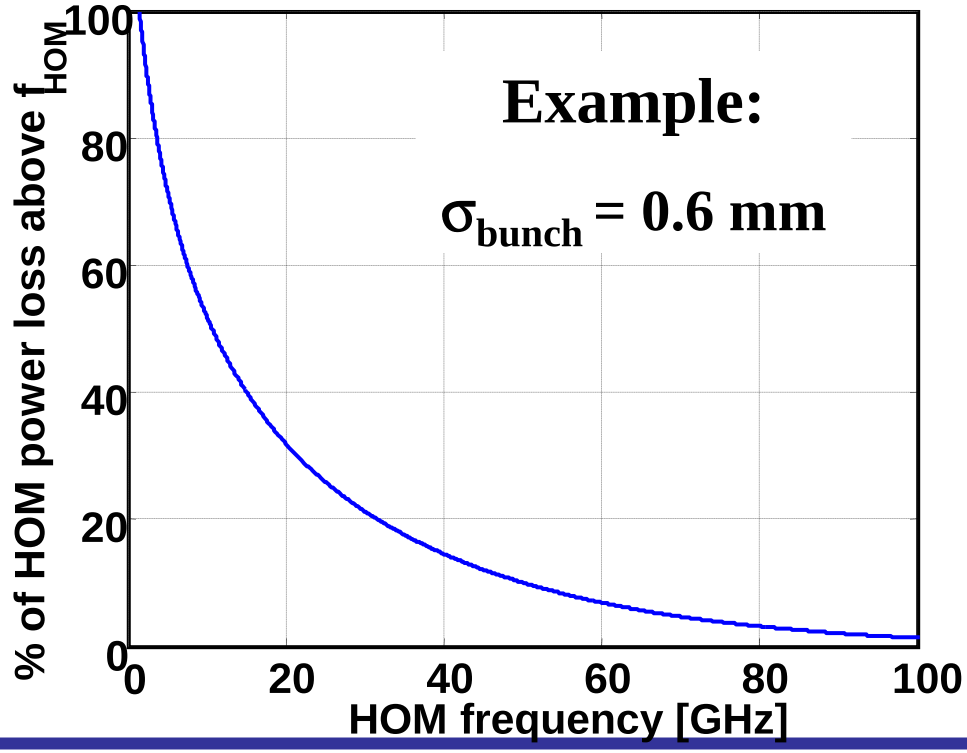
Measured vs calculated HOM spectrum.

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

- **Higher order modes**
  - Introduction: HOMs
  - HOM excitation by a beam
  - HOM damping schemes
  - HOM damping examples and results

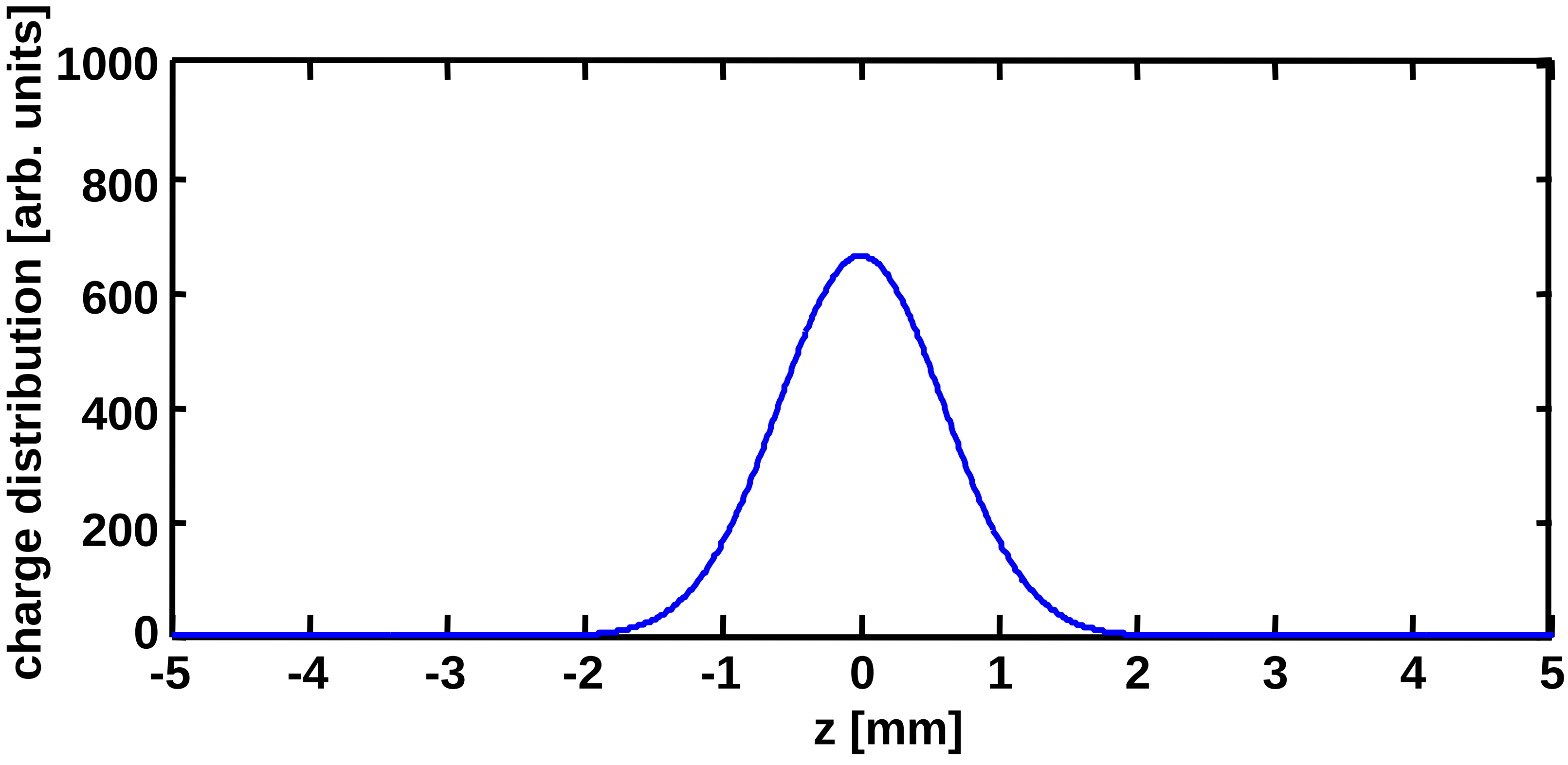
The excited HOM power of a single bunch depends on:

- **the HOMs of the cavity (i.e. their shunt impedance),**
- **the bunch charge ($P_{HOM} \propto q_b^2$),**
- **the bunch length (i.e. the spectrum of a bunch).**



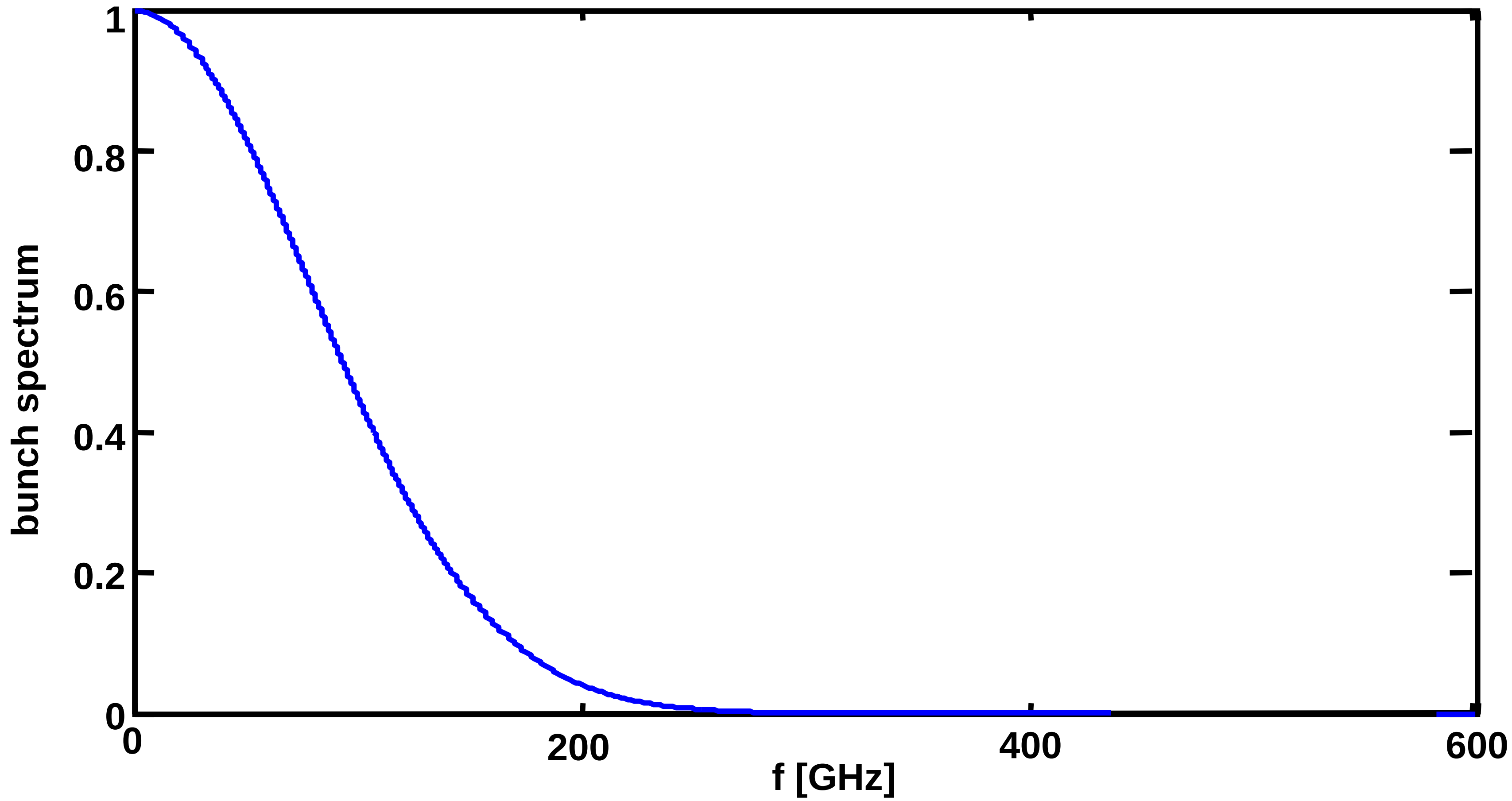
⇒ Short bunches excite very high frequency modes!

Longitudinal charge distribution for a 600 μm bunch:



Single Bunch Monopole Losses: The Bunch Spectrum

Spectrum of a 600 μm bunch:



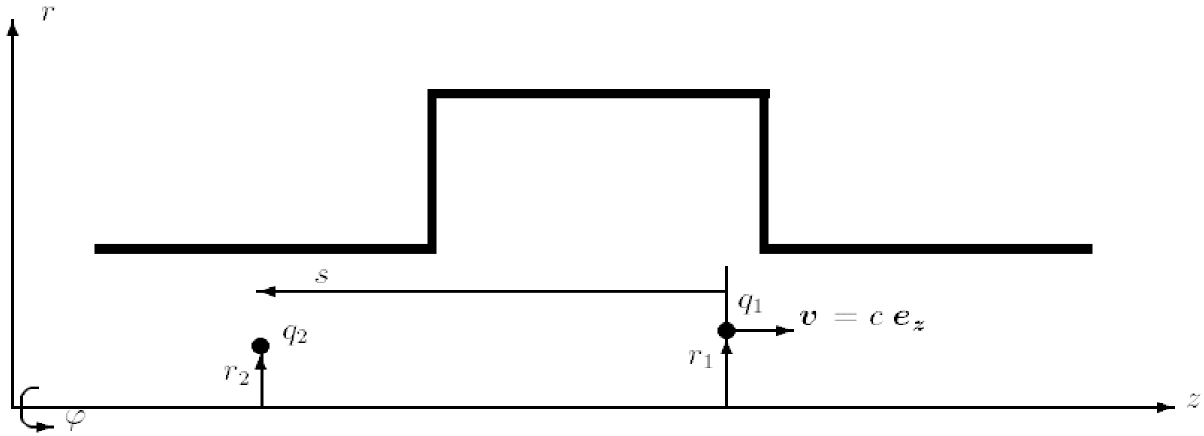
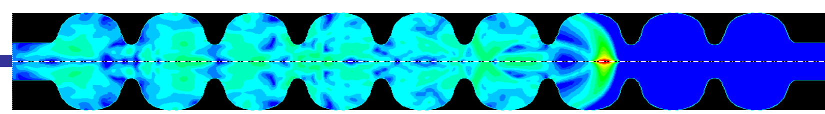


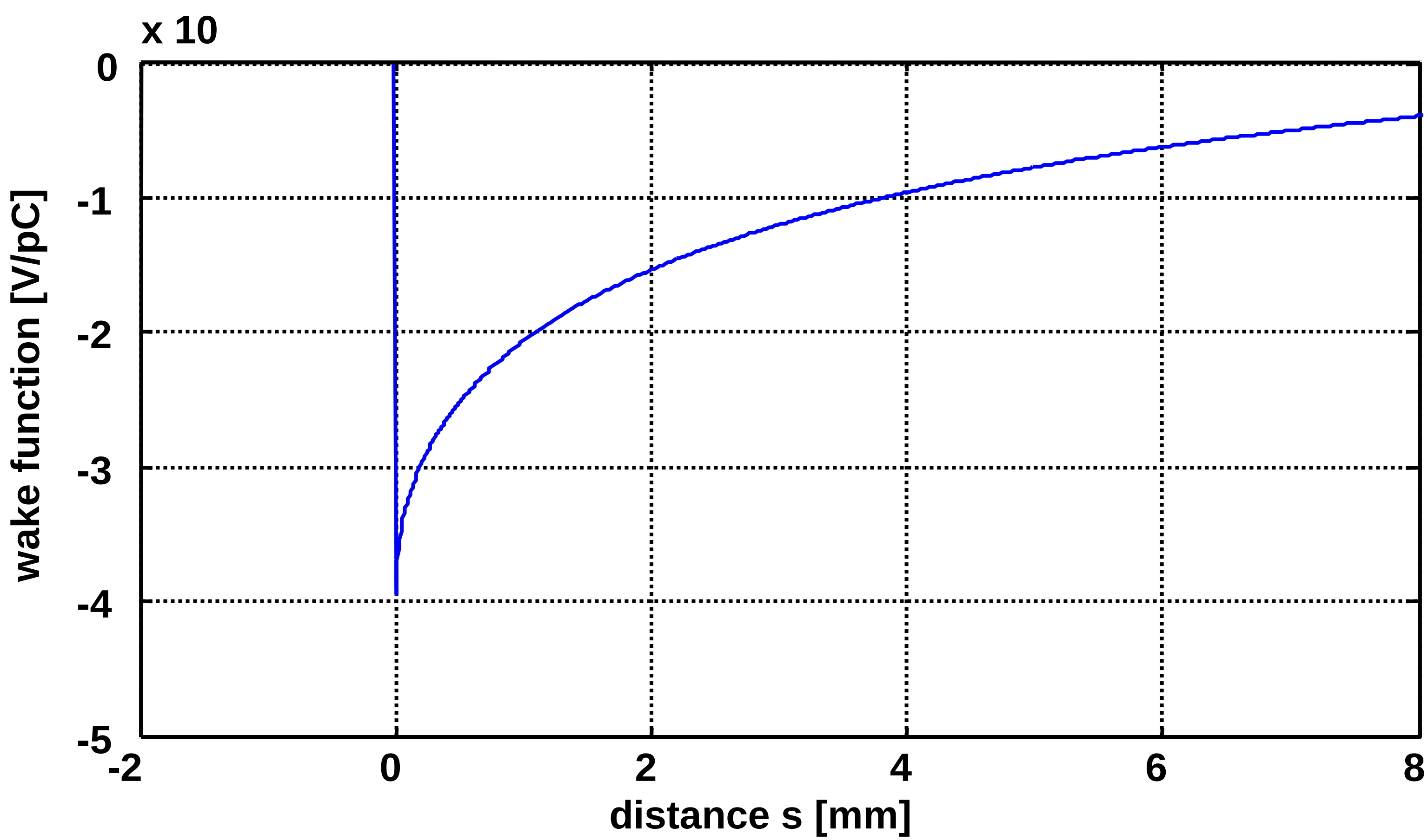
Figure 8: A point charge q_1 traversing a cavity with an offset r_1 followed by a test charge q_2 with offset r_2 .

Lorentz-Forces on test charge: $F = \frac{dp}{dt} = q_2 \left(E + c\, e_z \times B \right).$

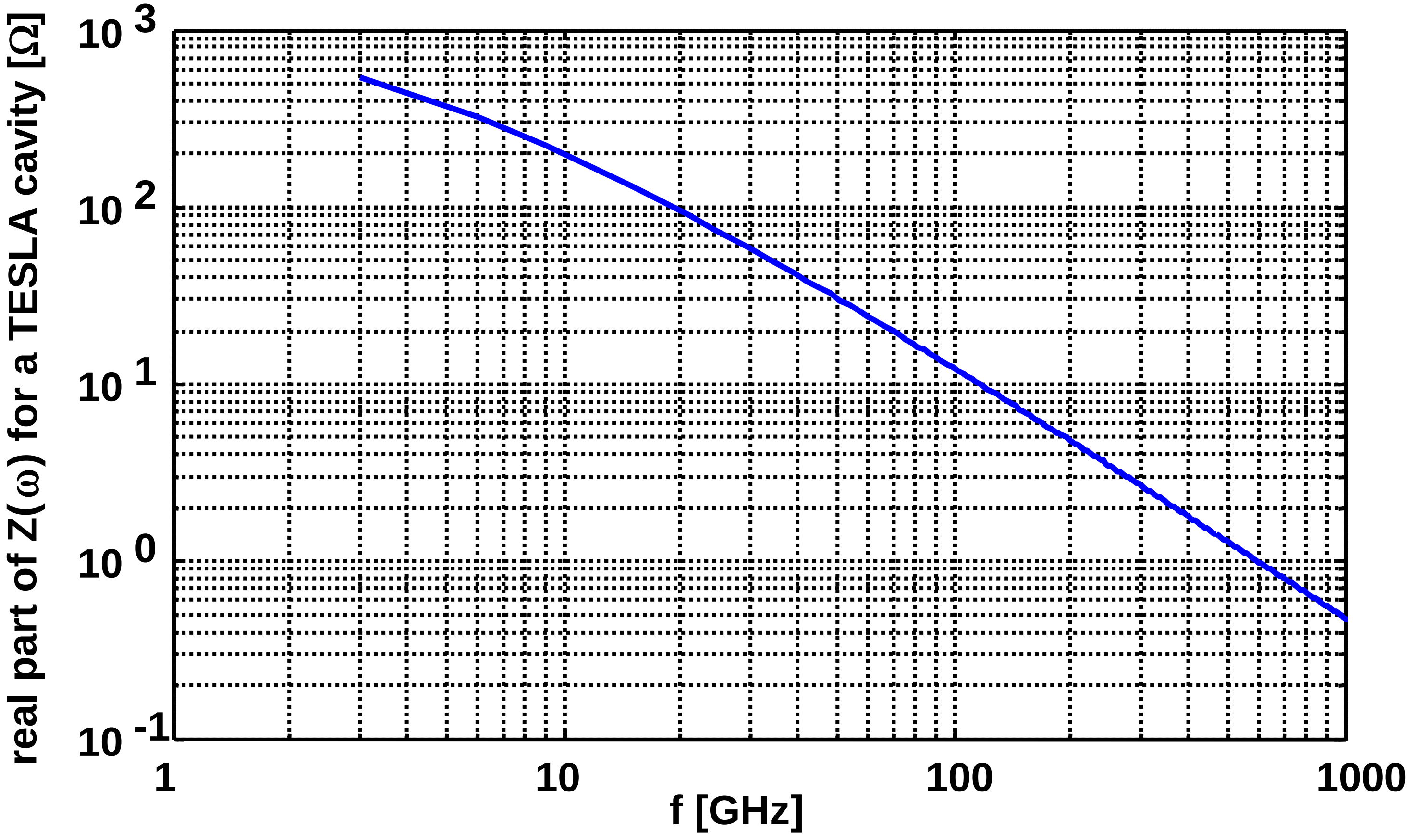
The integrated field seen by a test particle traveling on the same path at a constant distance *s* behind a point charge *q* is the longitudinal wake (Green) function *w(s)*.



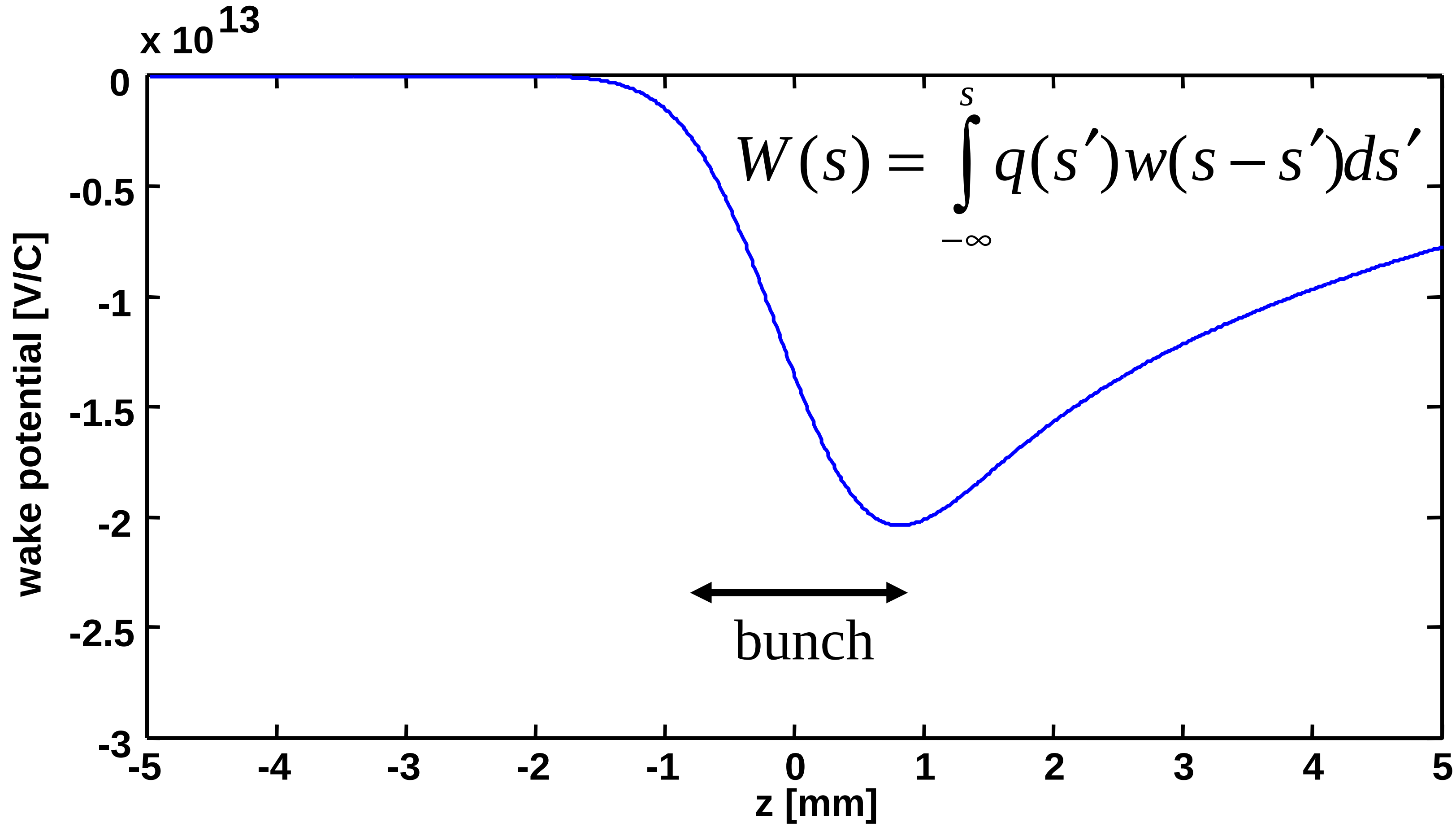
Single Bunch Monopole Losses: Wake Function of a Point Charge after a TESLA Cavity



The fft of the wake function gives the cavity impedance Z(ω):



Single Bunch Monopole Losses: Wake Potential of a Bunch after a TESLA Cavity



$$W(s) = \int_{-\infty}^{s} q(s')w(s-s')ds'$$

The wake potential ***W*** is a convolution of the linear bunch charge density distribution ***q(s)*** and the wake function ***w***

Single Bunch Monopole Losses: Loss Factor

Once the longitudinal wake potential is known, the **longitudinal loss factor**, which tells us how much electromagnetic energy a bunch leaves behind in a structure can be defined as:

$$k = \frac{\Delta U}{q^2} \qquad \boldsymbol{k_{\|} = \int_{-\infty}^{\infty} q(s) W(s) ds}$$

Average power loss:

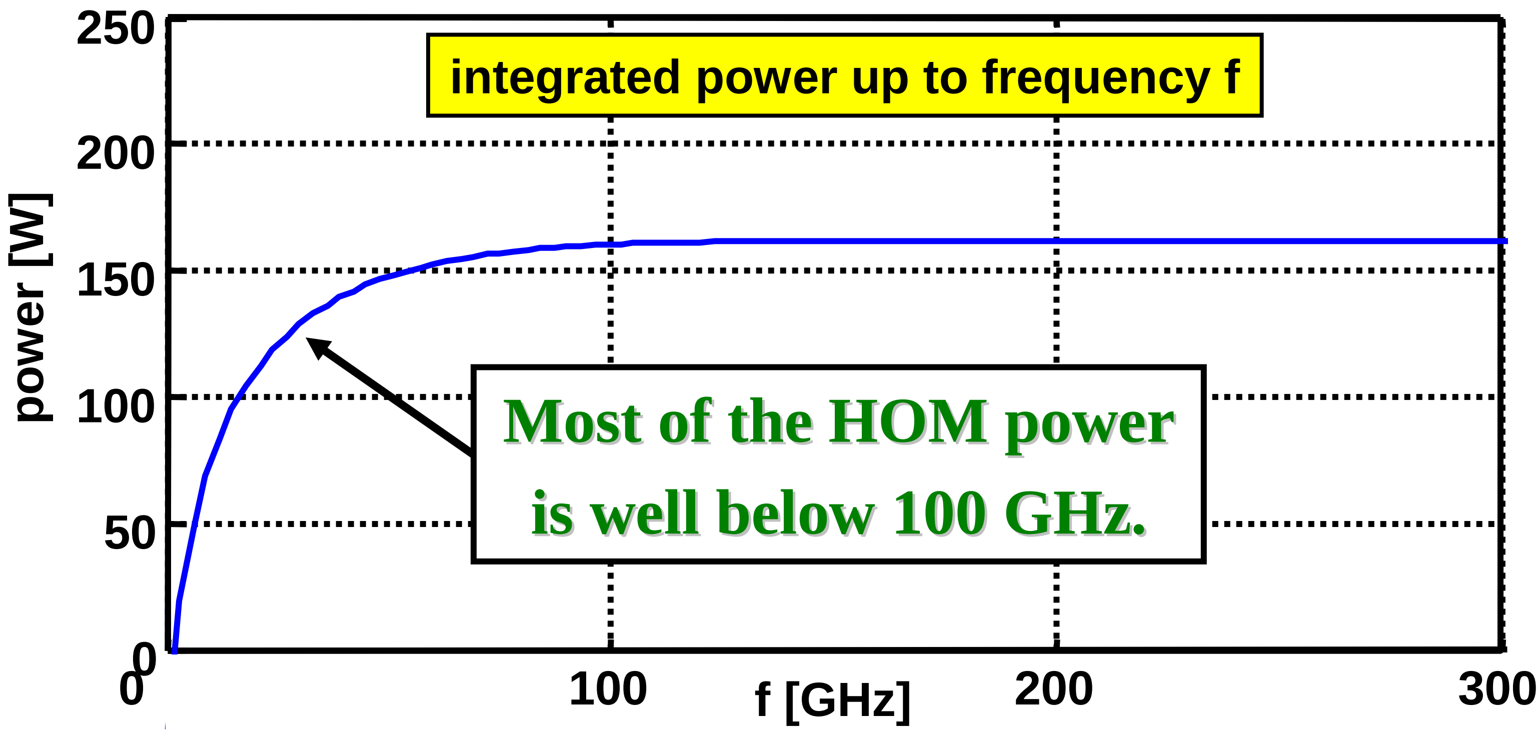
$$P_{\|} = k_{\|} Q_{bunch} I_{beam}$$

- **This is the total energy lost by a bunch divided by the time separation of two consecutive bunches.**
- **This does not include any interaction between bunches (i.e. resonant mode excitation)!!!**

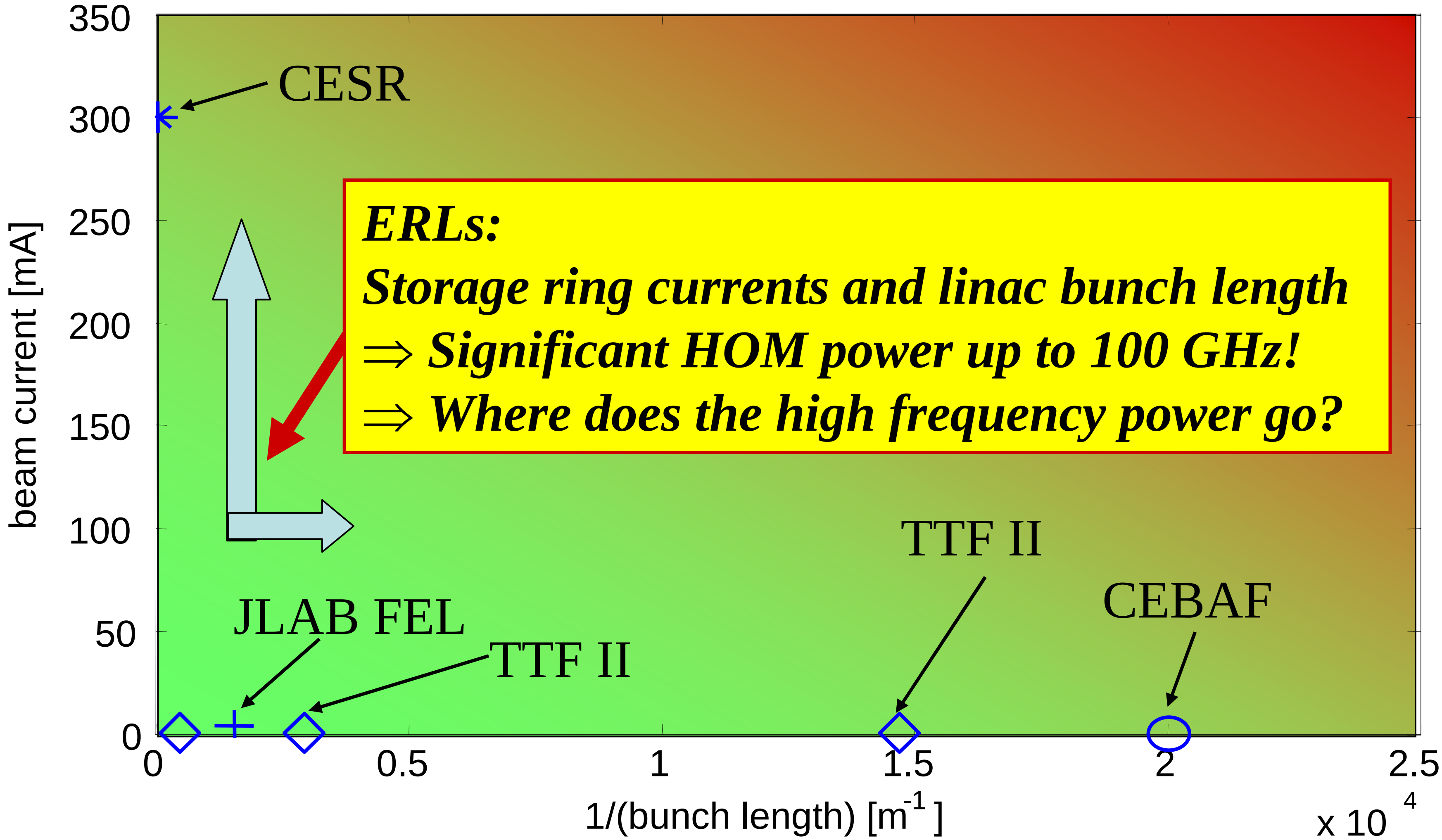
Single Bunch Monopole Losses: HOM Power Frequency Distribution

The frequency distribution of the HOM losses is determined by the bunch spectrum *and* the cavity impedance Z(ω):

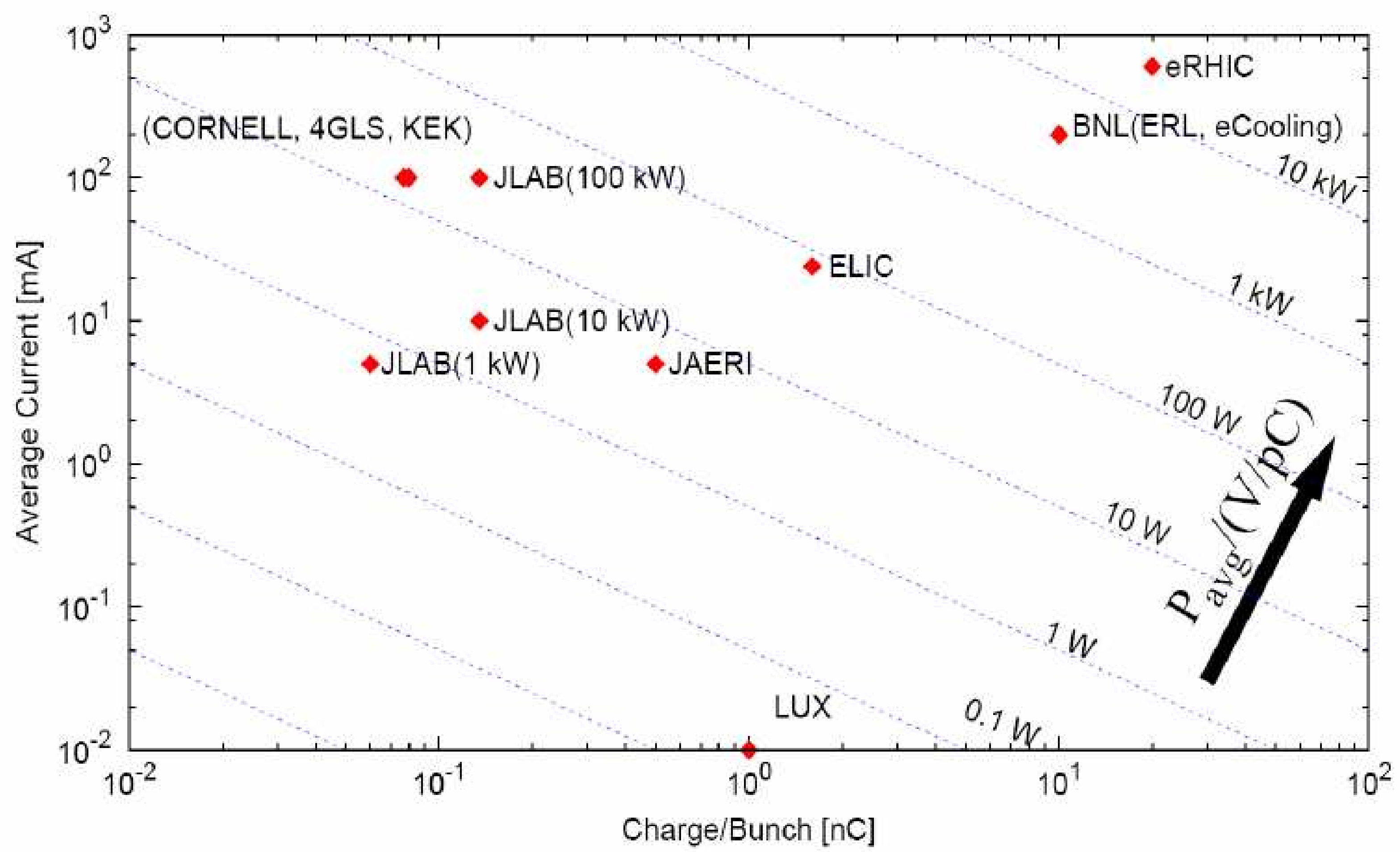
$$P(\omega) \propto Z(\omega)\left[\tilde{q}(\omega)\right]^2$$



High current and short bunches



ERLs:
Storage ring currents and linac bunch length
⇒ Significant HOM power up to 100 GHz!
⇒ Where does the high frequency power go?


eRHIC
BNL(ERL, eCooling)
(CORNELL, 4GLS, KEK)
JLAB(100 kW)
10 kW
ELIC
1 kW
JLAB(10 kW)
JLAB(1 kW)
JAERI
100 W
10 W
1 W
0.1 W
LUX
$P_{avg}/(V/pC)$
Average Current [mA]
Charge/Bunch [nC]
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
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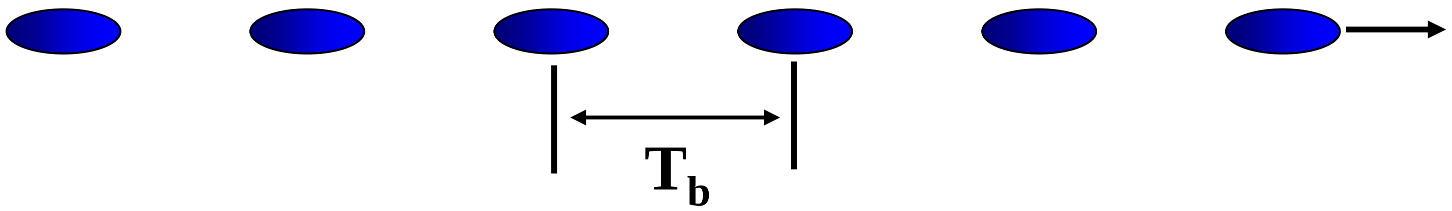
10^{-1}
10^{0}
10^{1}
10^{2}



- **The HOMs excited by a bunch are decaying due to losses,**
- **but: still significant field present in the cavity when the next bunch enters the cavity!**
- **$\Rightarrow$ Resonant excitation of a HOM, if**

$$f_{HOM} \approx N \frac{1}{T_b}$$

HOM Excitation

The excited HOM power of a bunch train depends on:

- **the HOM losses of a single bunch,**
- **the beam harmonic frequencies and the HOM frequencies (resonant excitation is possible!),**
- **the bunch charge and the beam current ($P_{HOM} \propto QI$),**
- **and the external quality factor, Q_{ext} of the modes. Lower Q_{ext} means less energy deposited by the beam:**

$$P_{HOM} \propto Q_{ext}$$

Bunch Trains: The more Complex Picture

In *average* the total HOM losses per cavity are given by the single bunch losses (77 pC bunch charge, 2.6 GHz bunch repetition rate, $\sigma_b = 600\ \mu m$):

$$P_{\|} = k_{\|} Q_{bunch} I_{beam} = 10.4\,\mathrm{V/pC} \cdot 77\,\mathrm{pC} \cdot 0.2\,\mathrm{A} = 160\,\mathrm{W}$$

But: If a monopole mode is excited on resonance, the loss for this mode can be much higher:

$$P = \left(\frac{R}{Q}\right) Q I_{beam}^2$$

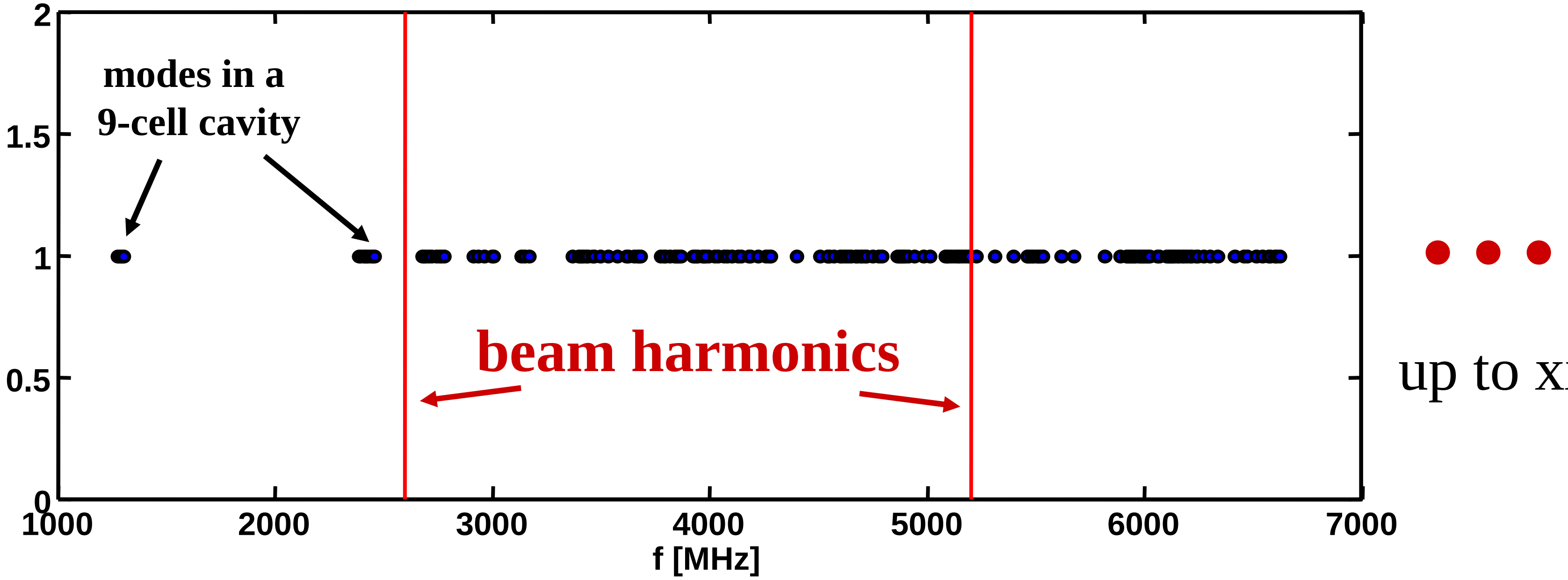
⇒ To stay below 200 W:

- **achieve (R/Q)Q < 5000,**
- **or avoid resonant excitation of the mode.**

Example: Cornell ERL:

$$f_{HOM} = N \cdot 1.3\,\text{GHz in the injector}$$
$$f_{HOM} = N \cdot 2.6\,\text{GHz in the main linac}$$

… so most of the monopole modes in the ERL will not be excited resonantly.



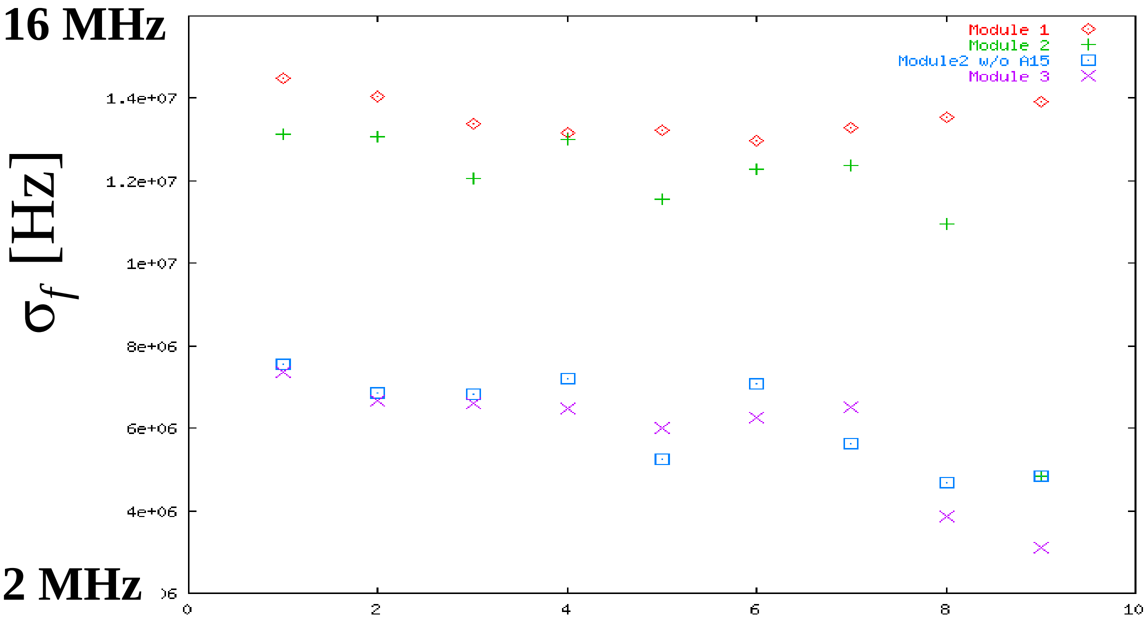
up to xx GHz

Can one design the HOM frequencies such, that non of the modes are excited resonantly?

- **The higher the frequency, the more sensitive is the frequency of a HOM to small perturbations in the cavity shape:**

Simple approximation: $$\frac{\Delta f_{HOM}}{f_{HOM}} = const.$$

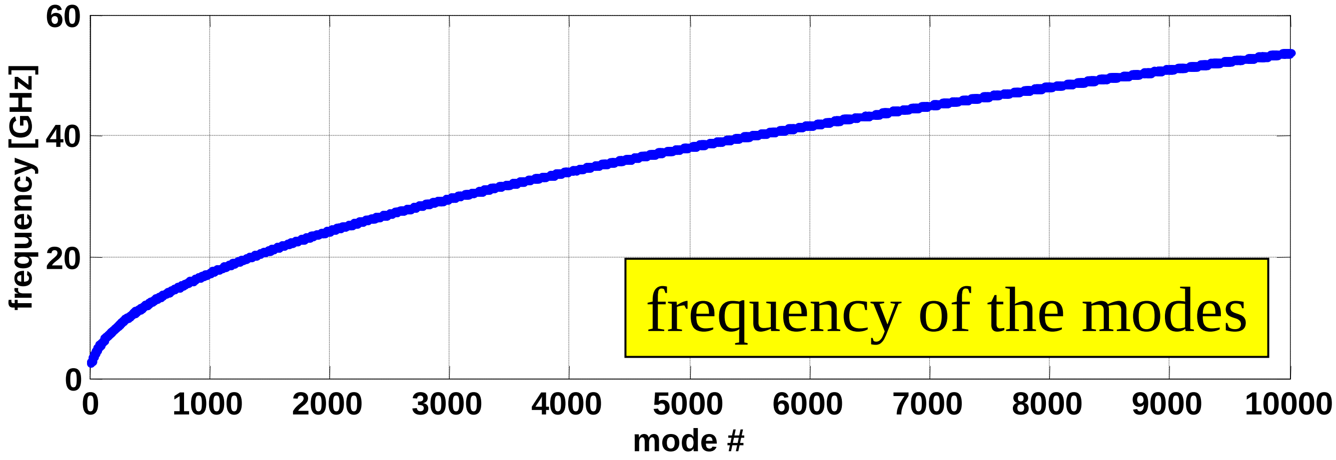
- **How large is "const"? Example: 2.4 GHz modes at TTF**

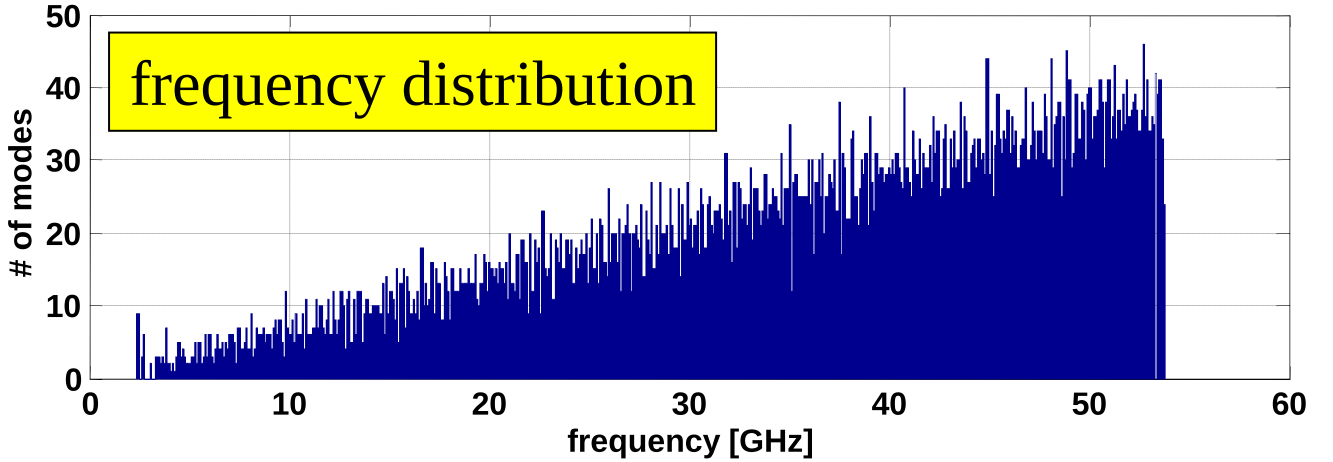


σ_f = 10 MHz
$\Rightarrow$ const = 0.4 %

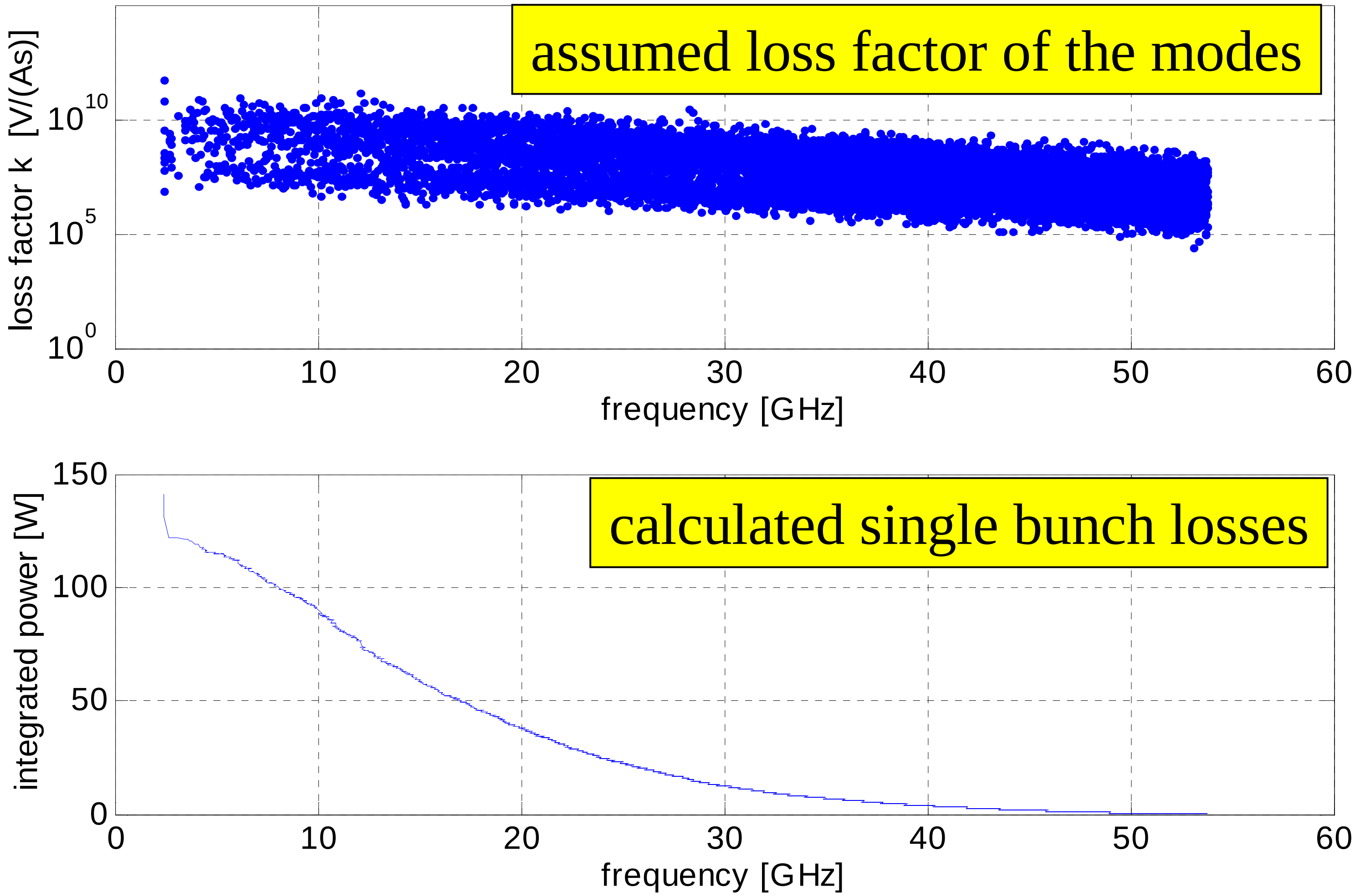
i.e. *σ_f = 20 MHz at 5.2 GHz*
σ_f = 31 MHz at 7.8 GHz
σ_f = 42 MHz at 10.4 GHz
…

Bunch Trains:
A Simple Model: 10000 Monopoles with random f's

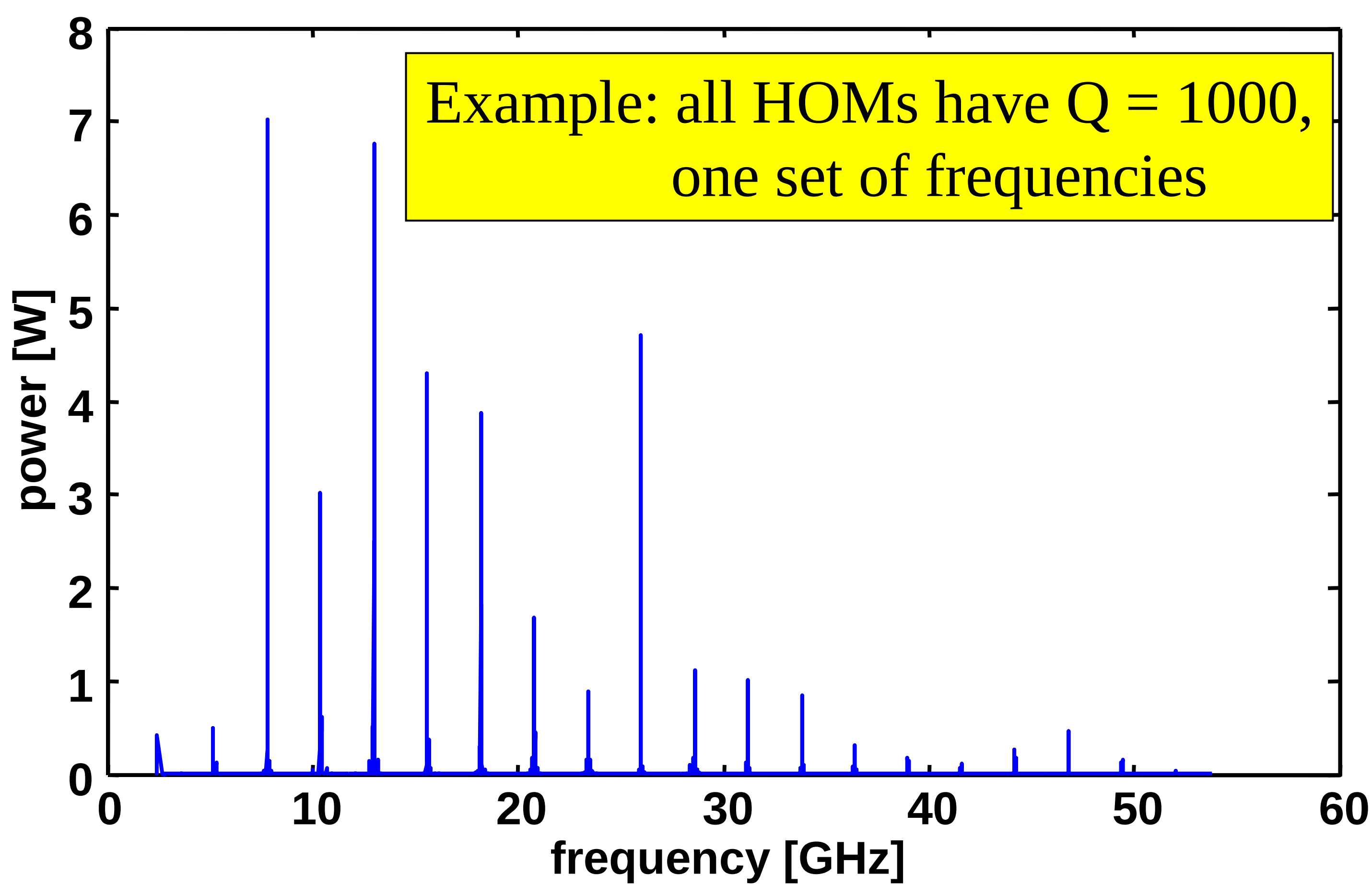




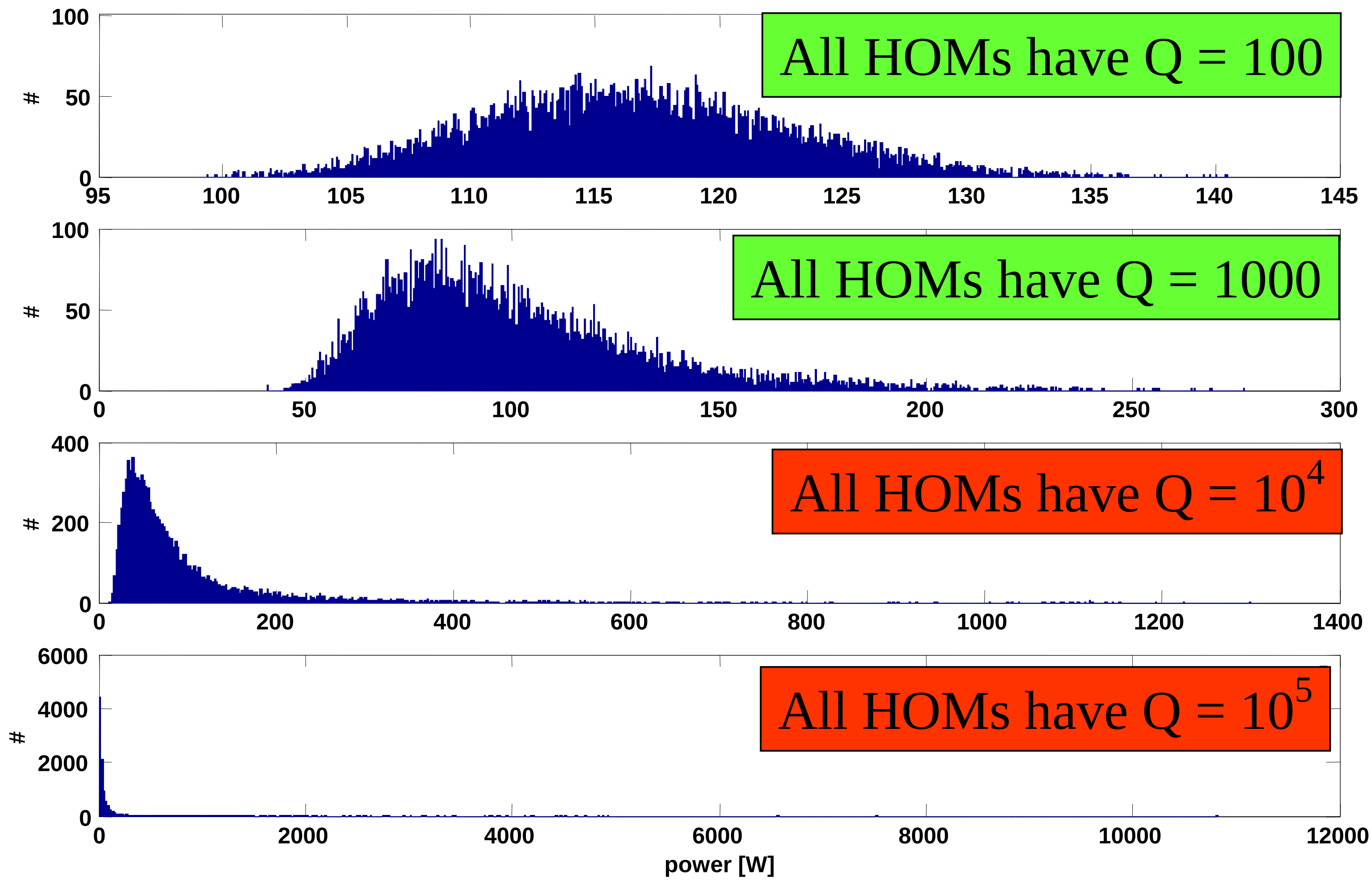
Bunch Trains: A Simple Model: 10000 Monopoles with random f's



Bunch Trains:
A Simple Model: 10000 Monopoles with random f's



A Simple Model: 1000 Monopoles with random f's
Total HOM Monopole Power for random Sets of Frequencies



Parasitic modes excited by the accelerated beam may lead to:

- **degradation of the beam quality (transverse emittance growth due to dipole modes, BBU, energy spread),**
- **additional cryo-losses (wall losses, heating of cables and feedthroughs), mostly due to monopole modes.**

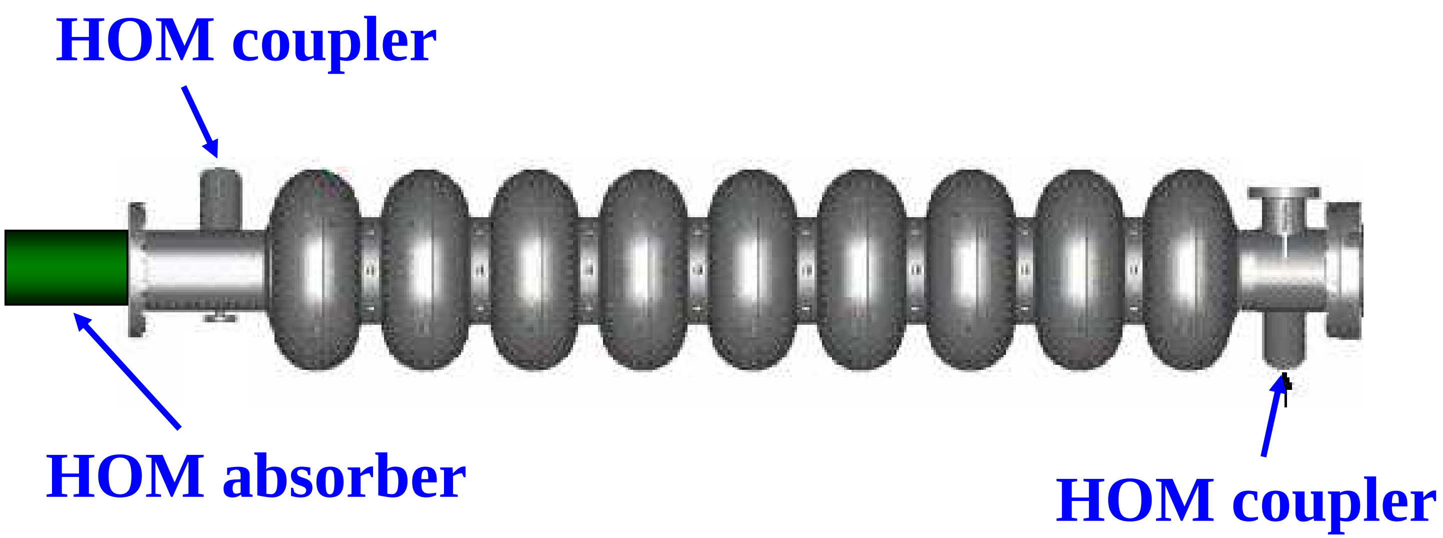
$\Rightarrow$ ***Requirements on the external quality factor, Q_{ext} of the modes.***

Without additional damping the HOMs can have very high quality factors ($Q>10^{10}$)!

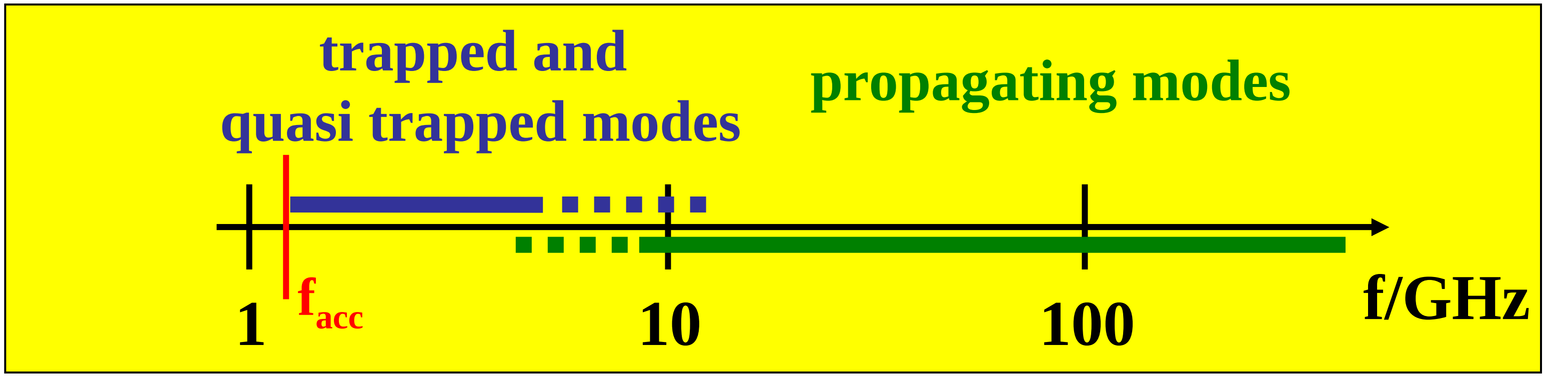
- **Higher order modes**
  - Introduction: HOMs
  - HOM excitation by a beam
  - HOM damping schemes
  - HOM damping examples and results

Solution (for SC Cavities): HOM Couplers and Absorbers

The parasitic e-m fields can be kept below the threshold by means of HOM couplers and HOM absorbers, usually attached to the beam tubes of a s.c. cavity.

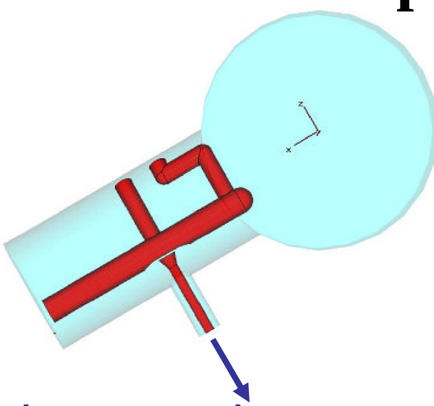


Higher-Order-Mode Couplers and Absorbers



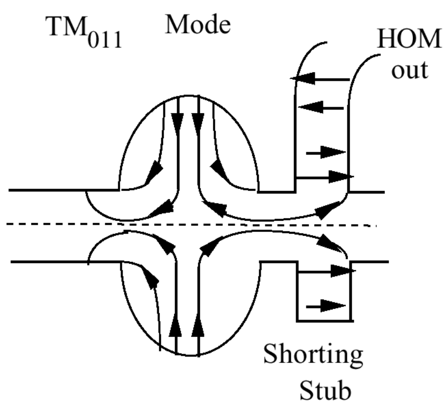
HOM couplers

antenna couplers

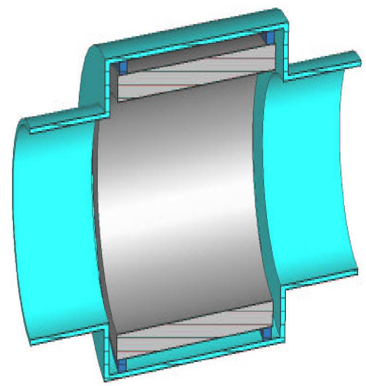


to room temperature load

waveguide couplers



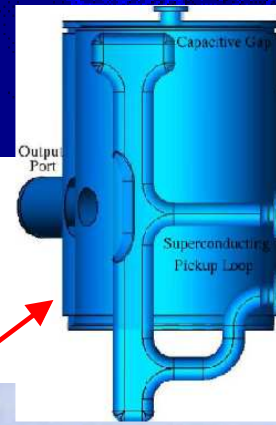
HOM beam-pipe absorber



absorber between cavities temperature level with good cryogenic-efficiency

The frequency where the HOMs start to propagate depends on the beam tube diameter: $\omega_c \propto 1/\text{diameter}$!

HOM Extraction/Damping Schemes



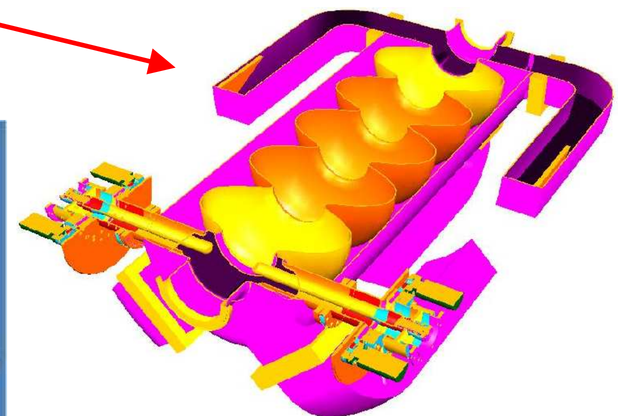
<u>Several approaches are used</u>:

- Loop couplers (several per cavity for different modes/orientations)

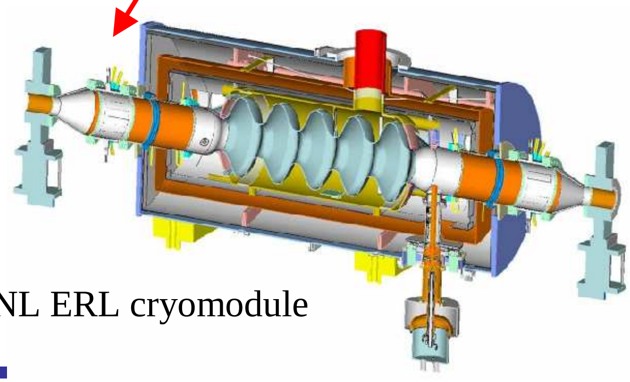
- Waveguide dampers

- Beam pipe absorbers (ferrite or ceramic)

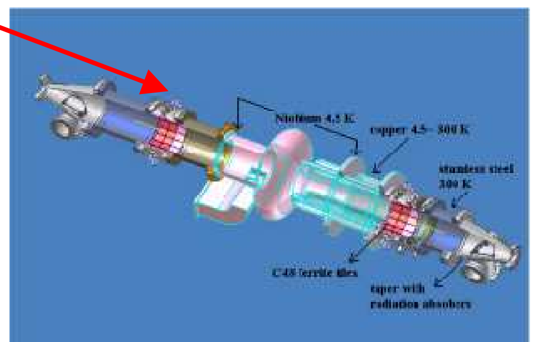
TESLA cavity loop coupler



JLab proposal

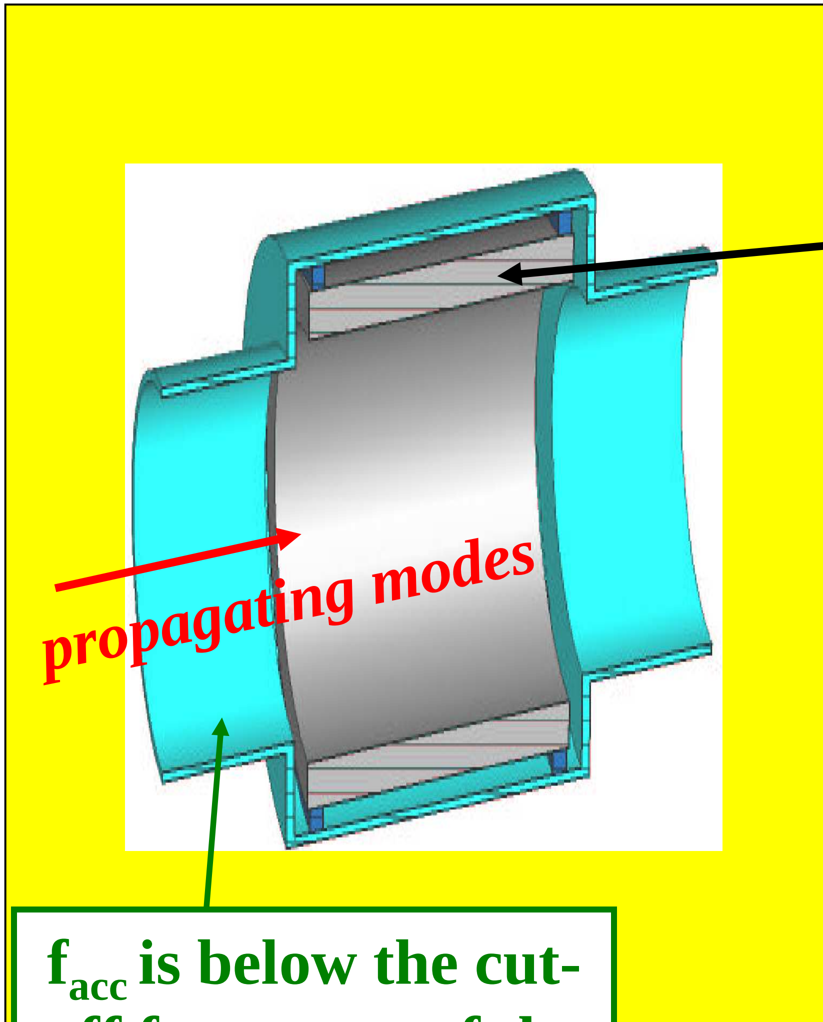


BNL ERL cryomodule



B-cell beam line components (TLS)

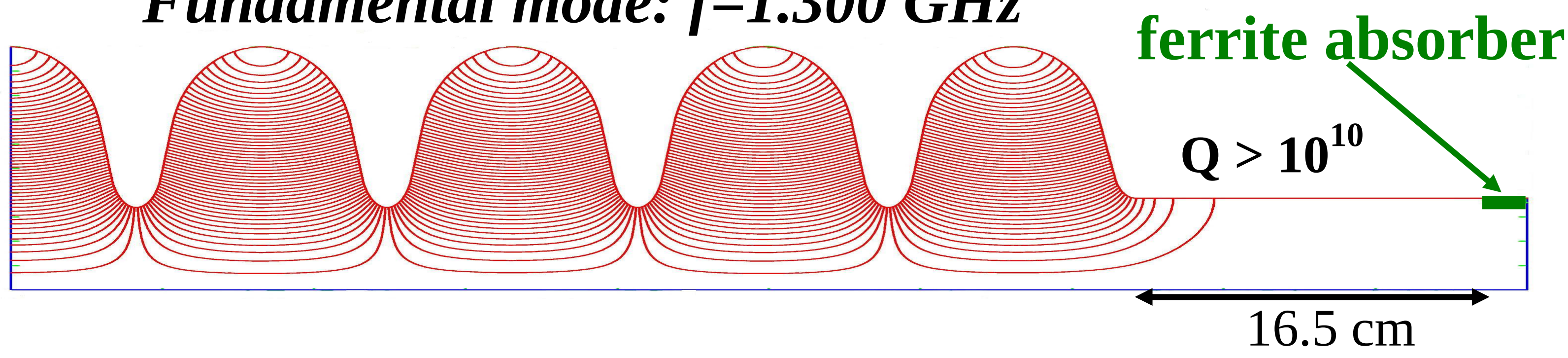
Broadband Beam Pipe RF Absorber



f_{acc} is below the cut-off frequency of the tube

- **High frequency modes propagate out the beam pipe.**
- **RF absorbing material can damp these modes.**
- **Dissipated power will be intercepted by cooling (water, GHe, LN_2).**
- **Candidate absorber materials:**
  - ferrites (used in CESR HOM load)
  - $Zr_{10}CB_5$ CERADYNE (used for CEBAF HOM load)
  - Mo in AL_2O_3
  - …

Fundamental mode: f=1.300 GHz



•Low field at absorber

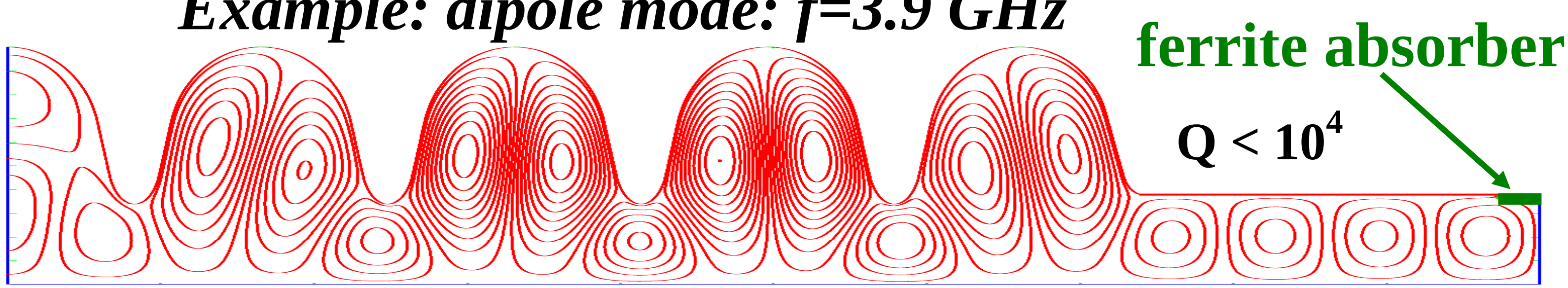
⇒ no significant damping of the fundamental mode

but:

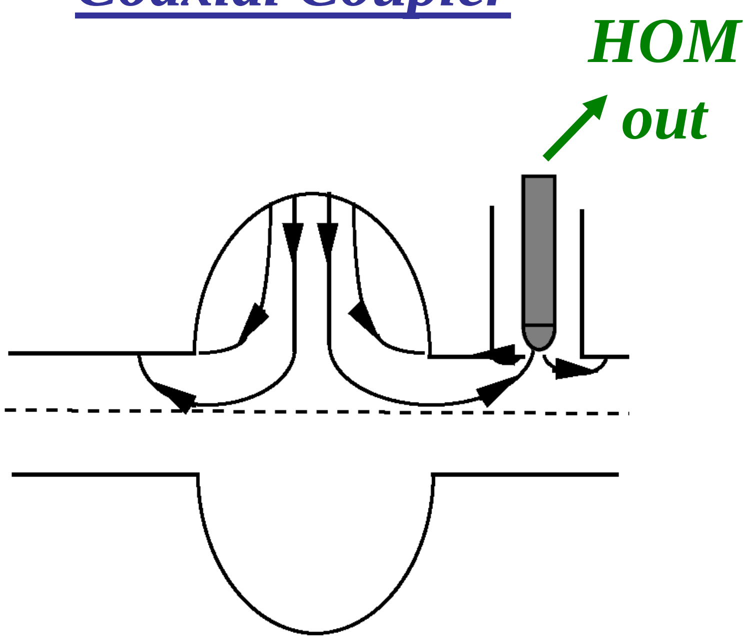
• Propagating modes have higher fields at the absorber

⇒ damping and power extraction!

Example: dipole mode: f=3.9 GHz

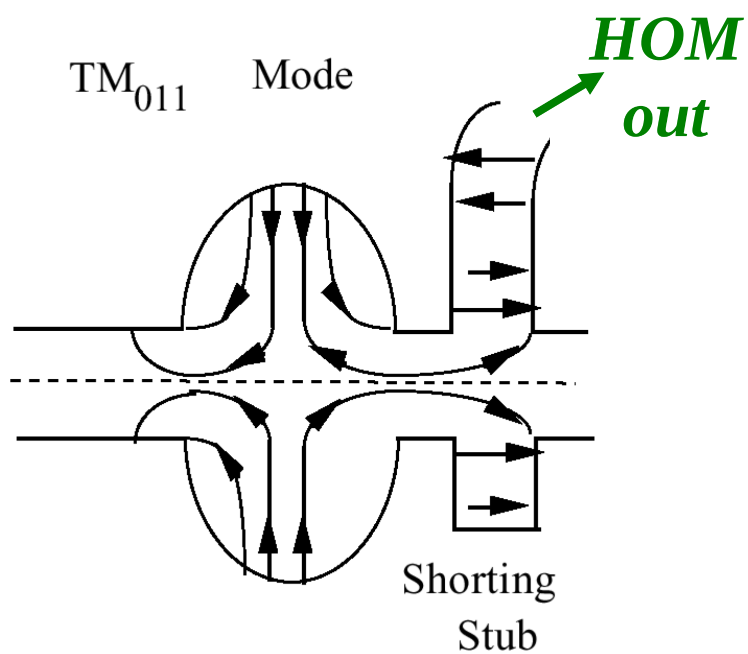


Coaxial Coupler



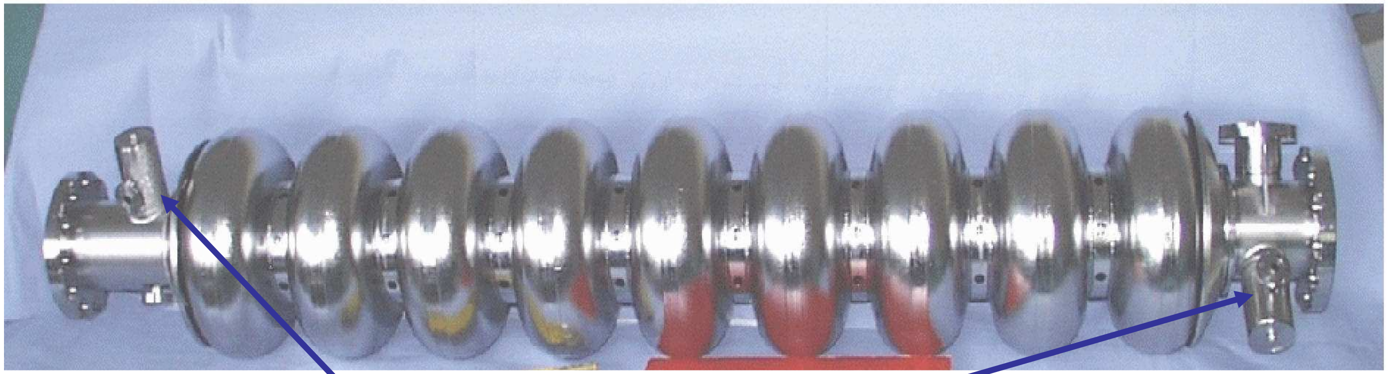
Rejection filter suppresses coupling to the accelerating mode.

Waveguide Coupler

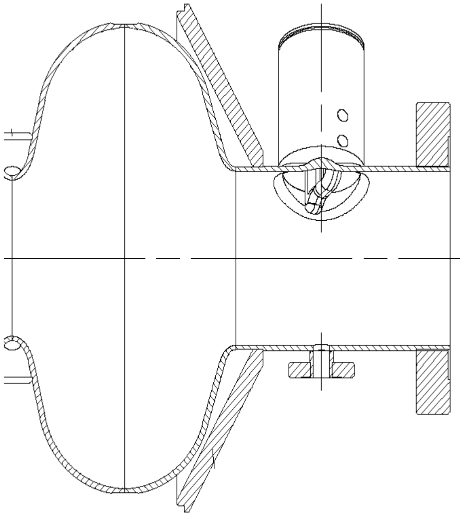


Waveguide cutoff suppresses coupling to the accelerating mode.

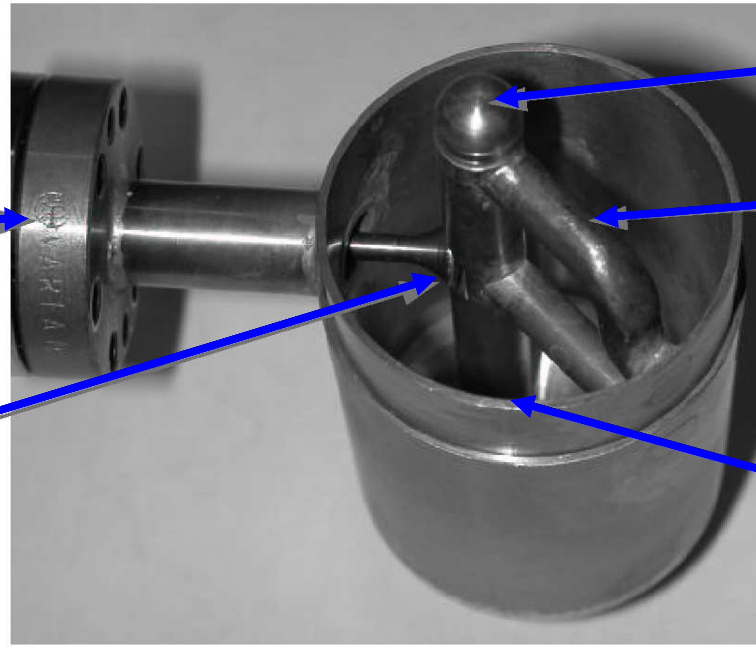
TTF HOM Loop Coupler (1)



HOM coupler at each side of the cavity close to end cell to damp HOMs



Coupler model:

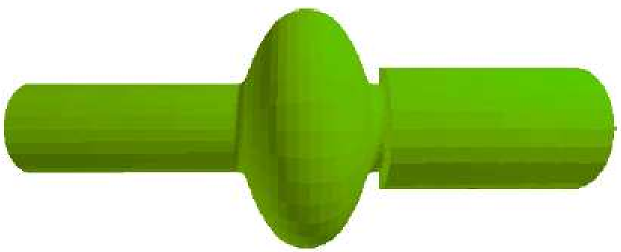


- **Important to reduce Q of non-propagating dipole modes.**
- **Can only handle a few 10 W.**
- **Will work up to a few GHz but not above.**
- **Cooling / heating from fundamental mode issue in cw cavity operation.**

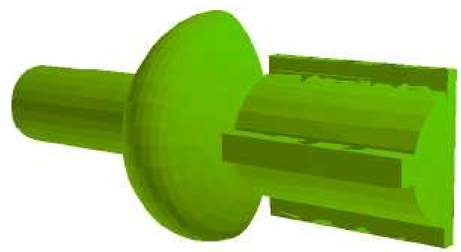
Methods for HOM Damping

Methods of broad-band HOM damping:

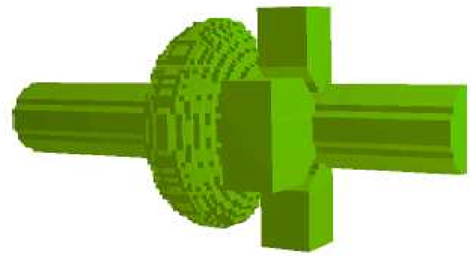
Strong HOM damping has been shown in single-cell cavities, e.g. Cornell and B-factory storage rings. Studies show these methods can be applied to multi-cell cavities. Options include multiple coaxial antennas, beam pipe loads, waveguide loads.



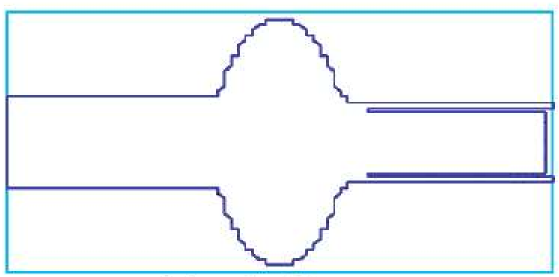
Enlarged beam pipe.
(KEK, BNL, Cornell ERL)



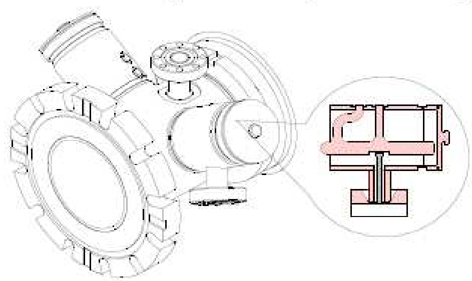
Fluted beam pipe.
(Cornell, CESR)



Waveguide dampers
(CEBAF, PEP-II)



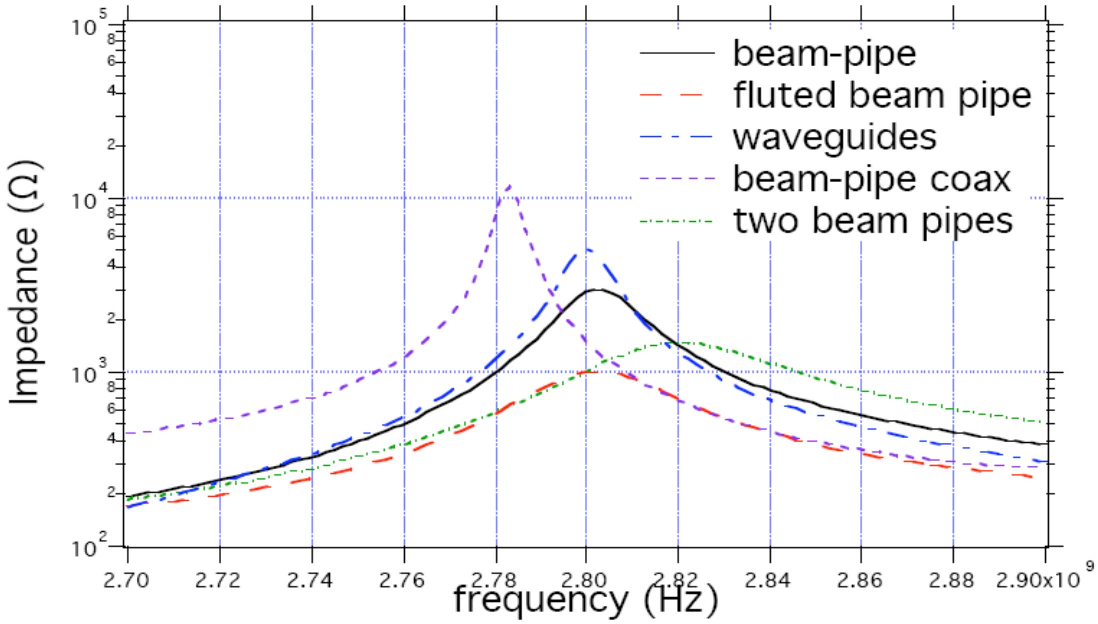
Coaxial/radial beam pipe
(KEK, JAERI)



Multiple coaxial loops
(DESY, CERN)

from Bob Rimmer

Methods for HOM Damping: Effectiveness



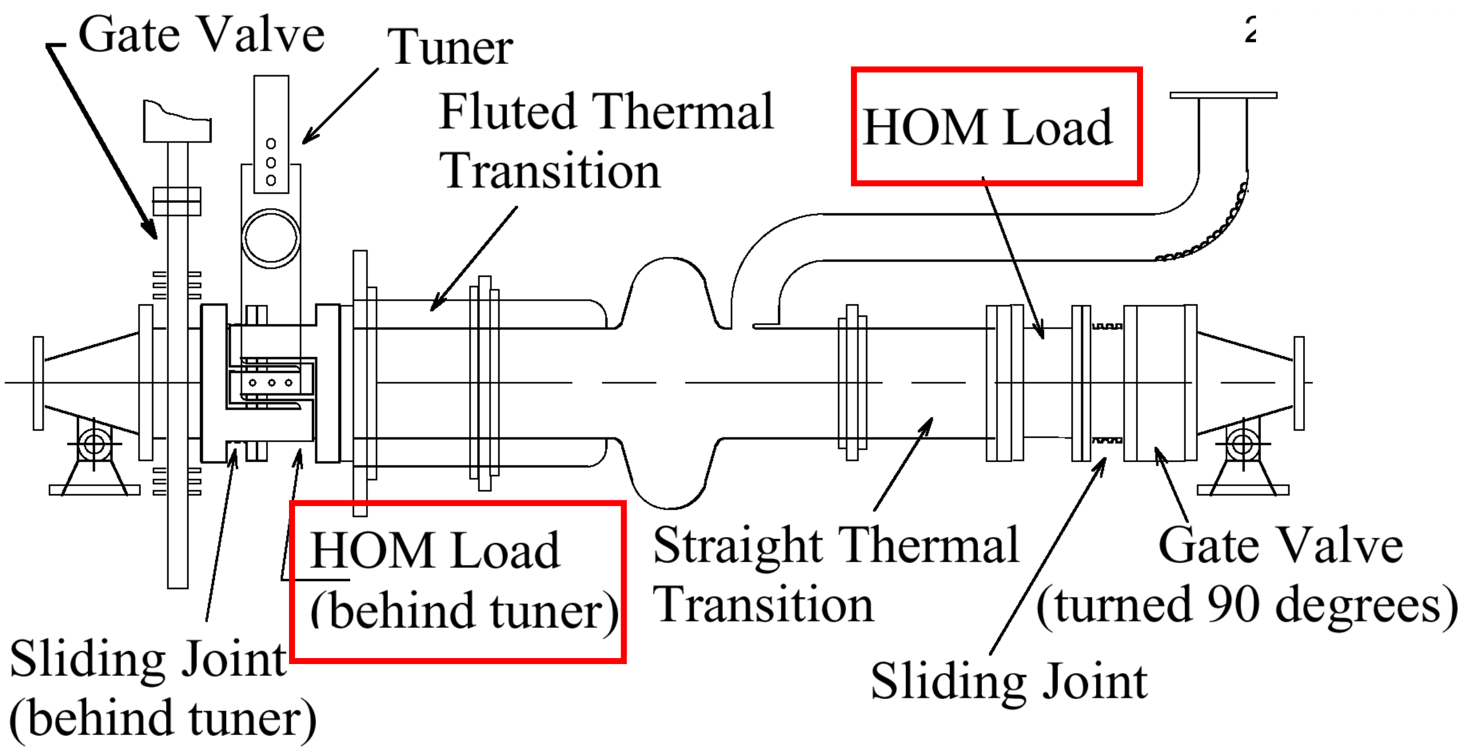
TM_{011} mode with various damping schemes.

	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

*$R=V^2/2P$

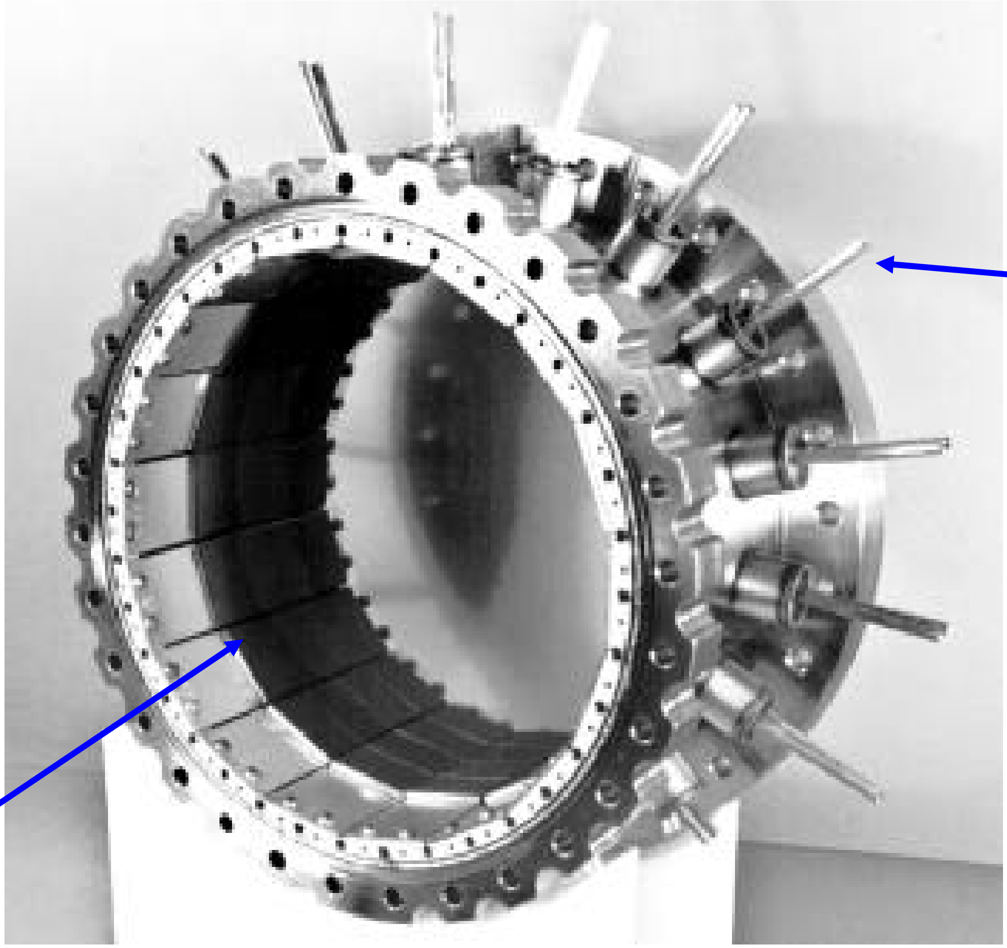
- **Higher order modes**
  - Introduction: HOMs
  - HOM excitation by a beam
  - HOM damping schemes
  - HOM damping examples and results

Example 1: CESR HOM Ferrite Absorber (1)



- **Flute beam pipe ⇒ guide out the first two defecting modes.**
- **Total HOM power: several kW!**
- **$Q_{ext} < 10^3$**

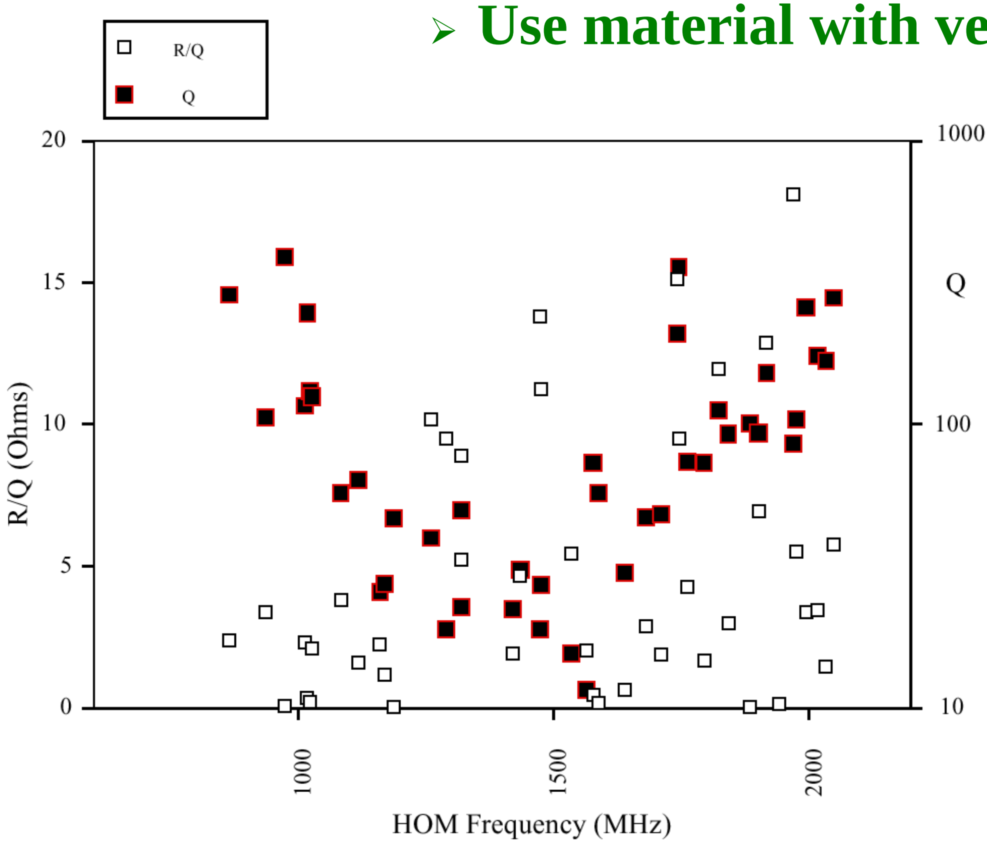
CESR HOM Ferrite Absorber (2)

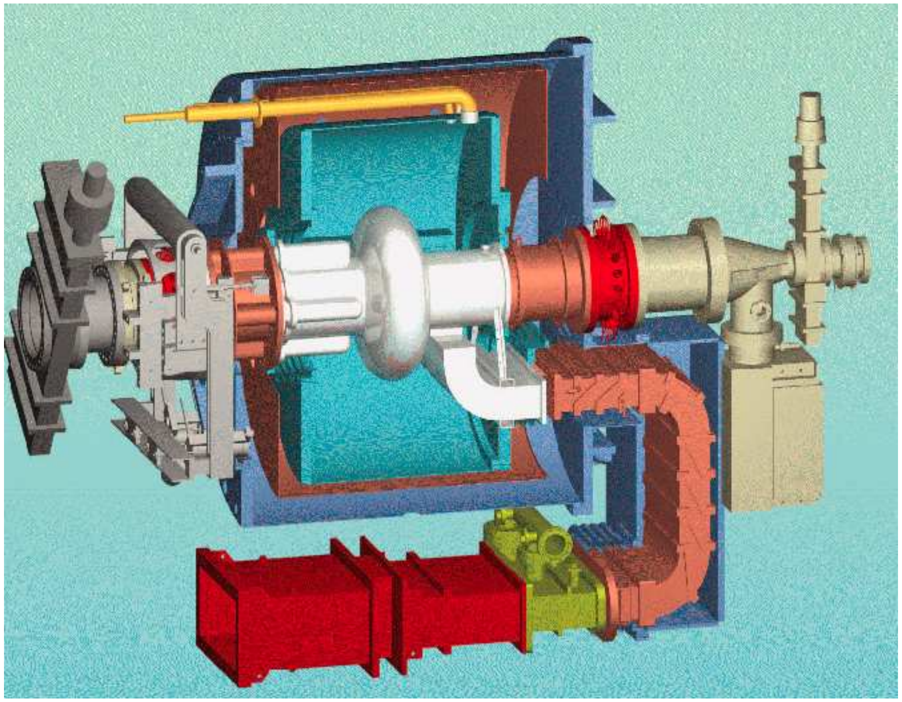


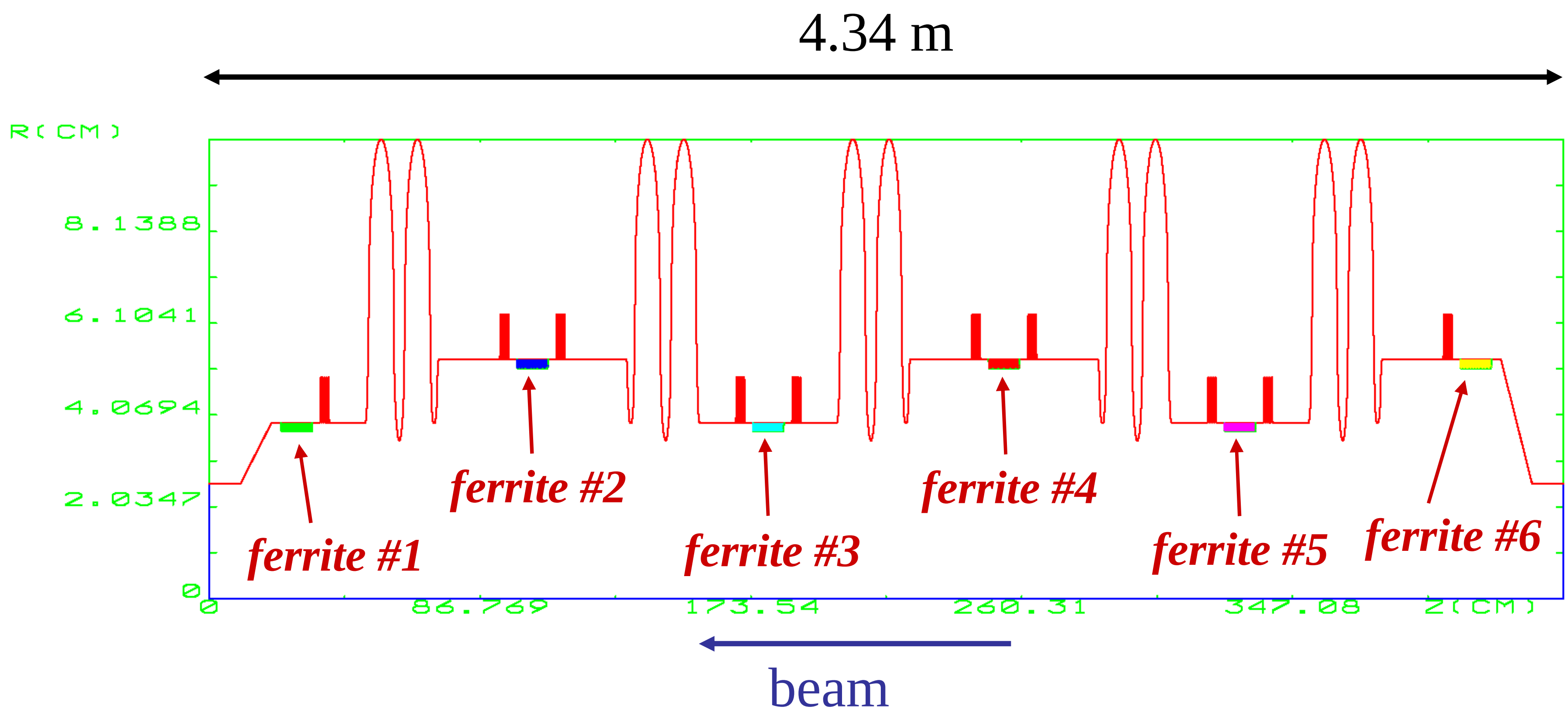
water cooling

ferrite

- Use a single cell (no reflection by irises between cells)
- Open beam tubes so that all modes propagate out the beam tubes!
- Use material with very high RF losses.



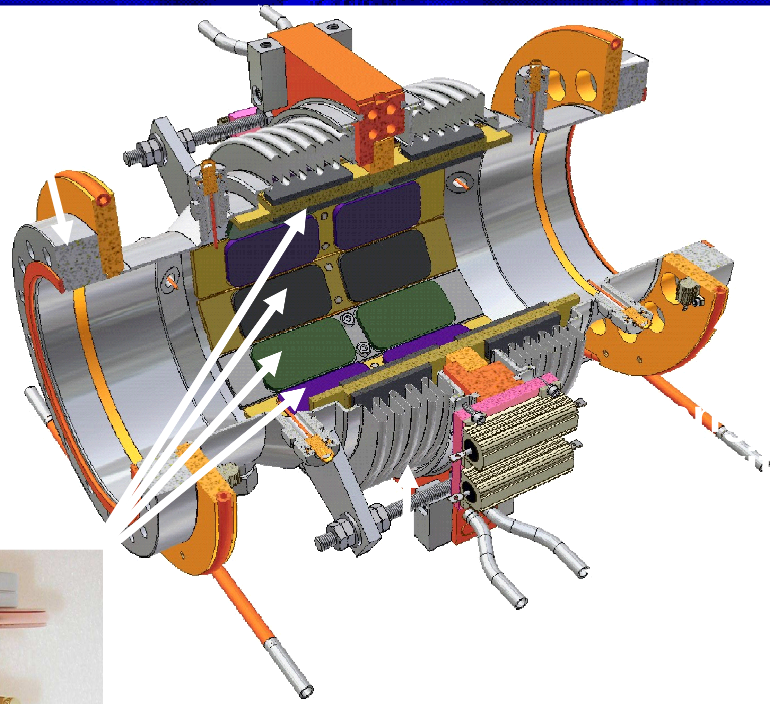


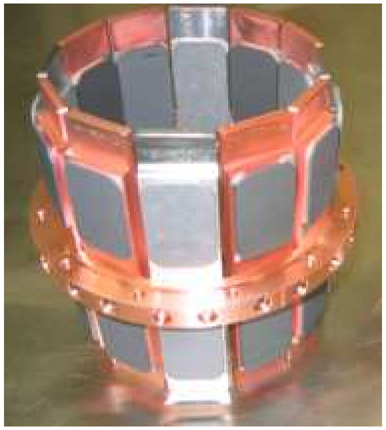


HOM damping concept: Make all TM monopole and all dipole modes propagating by increasing the beam tube diameter (as in CESR).

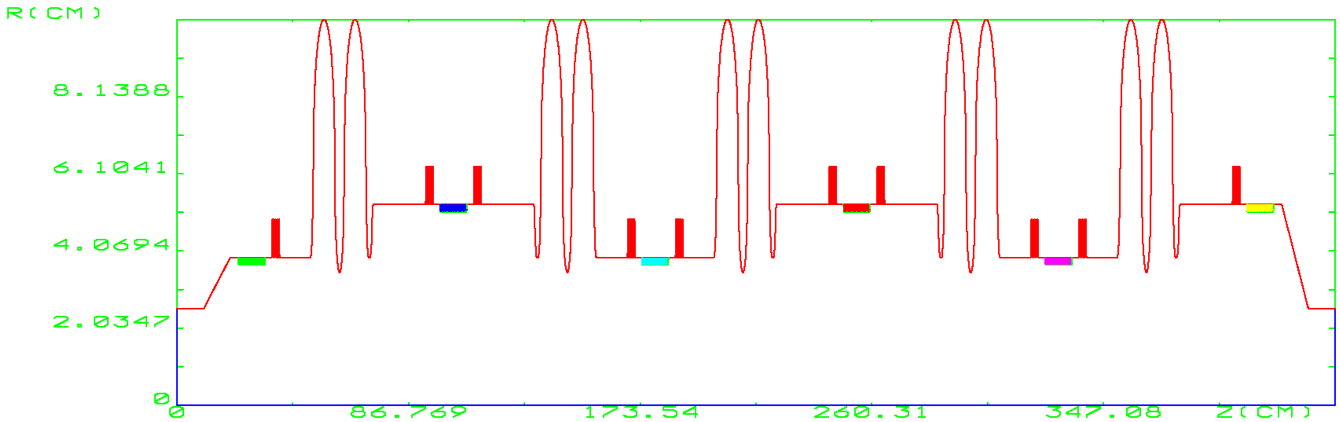
Cornell ERL Beam Line HOM Loads

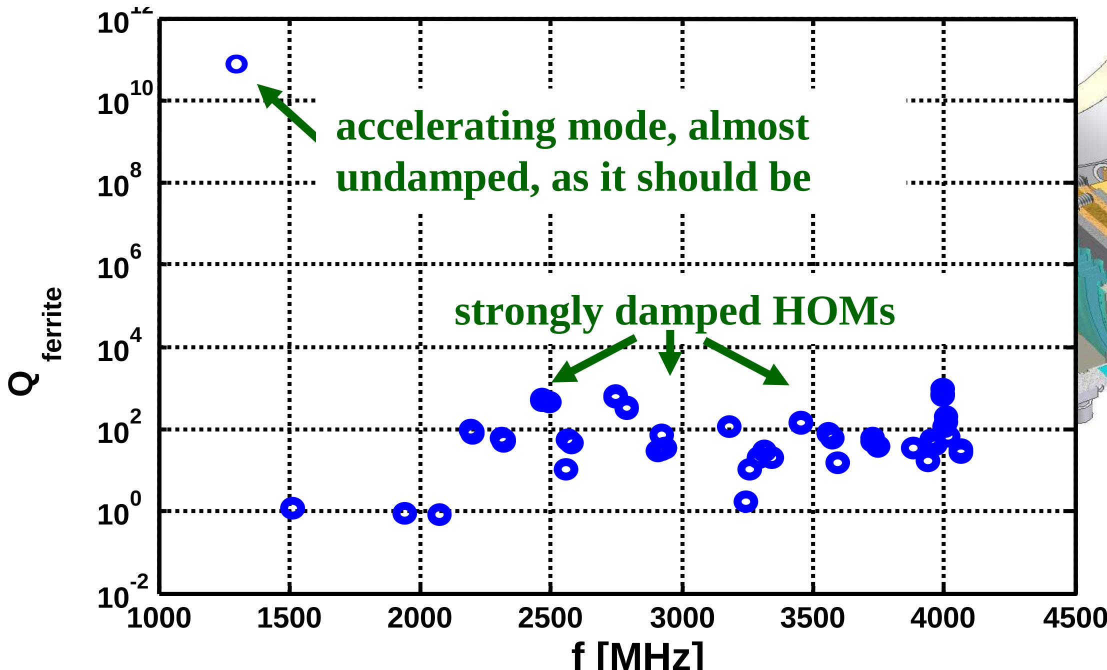
Power per load	**26 W (200 W max)**
HOM frequencies	**1.4 – 100 GHz**
Operating temp.	**80 K**
Coolant	**He Gas**
RF absorbing tiles	**TT2, Co2Z, Ceralloy**

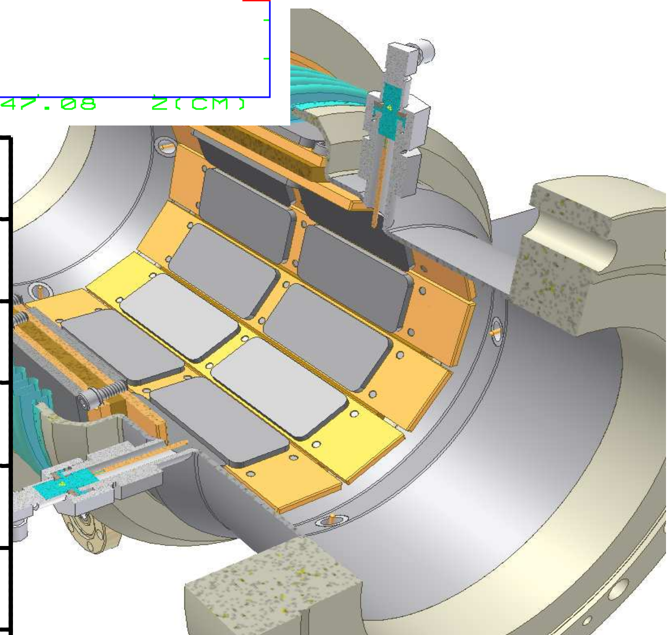




Cornell ERL Beam Line HOM Loads: Damping Calculations

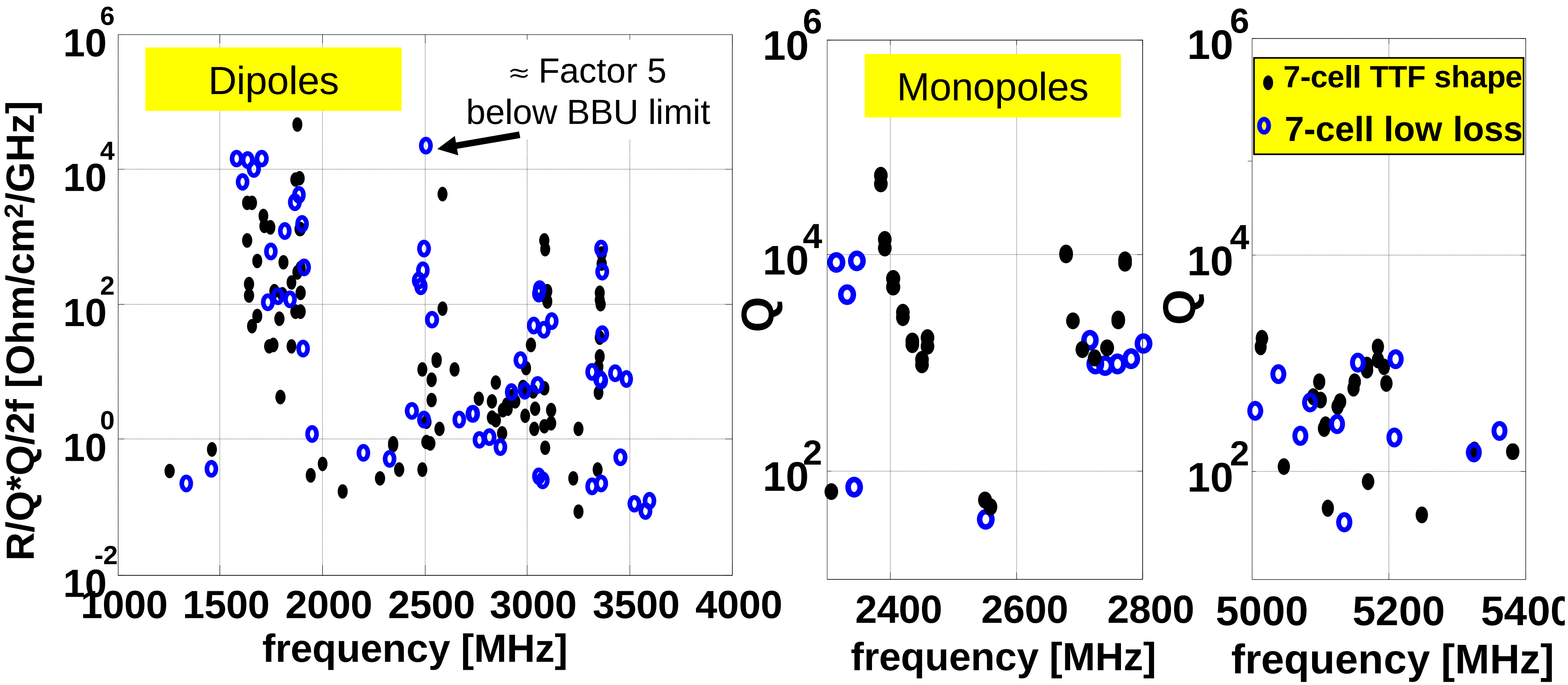


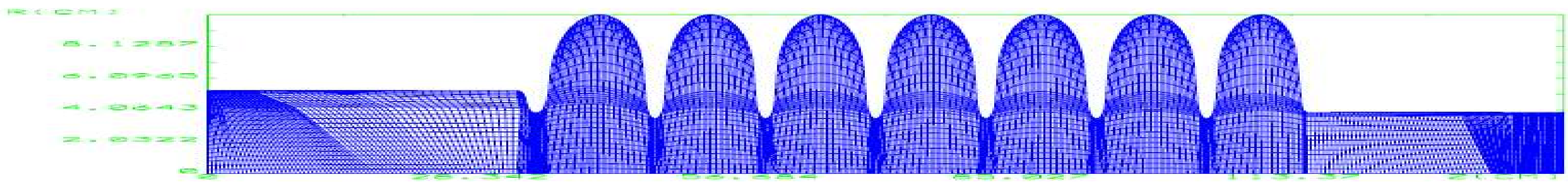




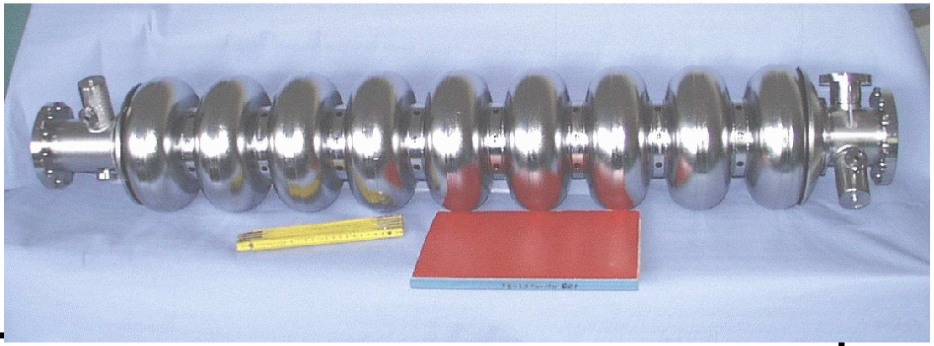
ERL Main Linac HOM Damping Simulations

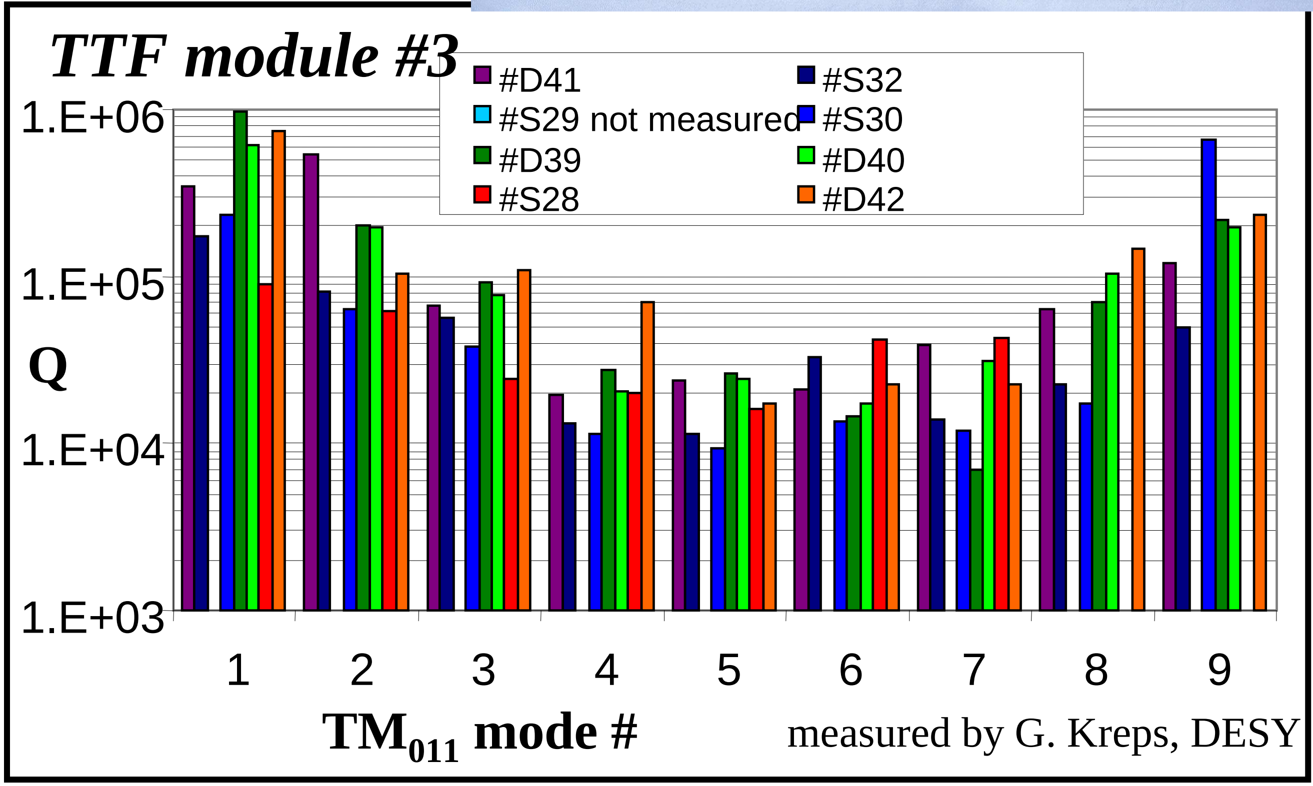
- **CLANS calculations (started 3D Microwave Studio models)**
- **Modes are sufficiently damped for 100 mA operation**

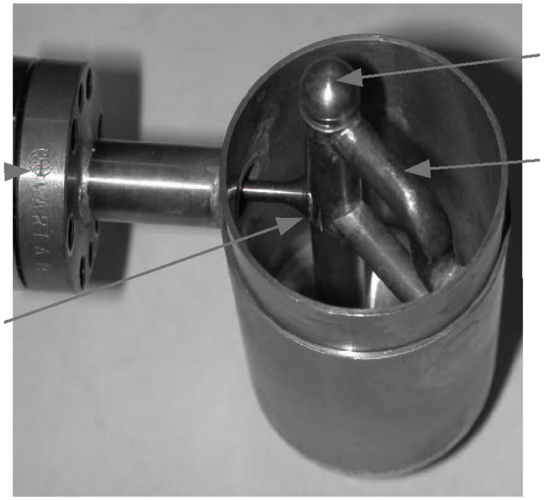




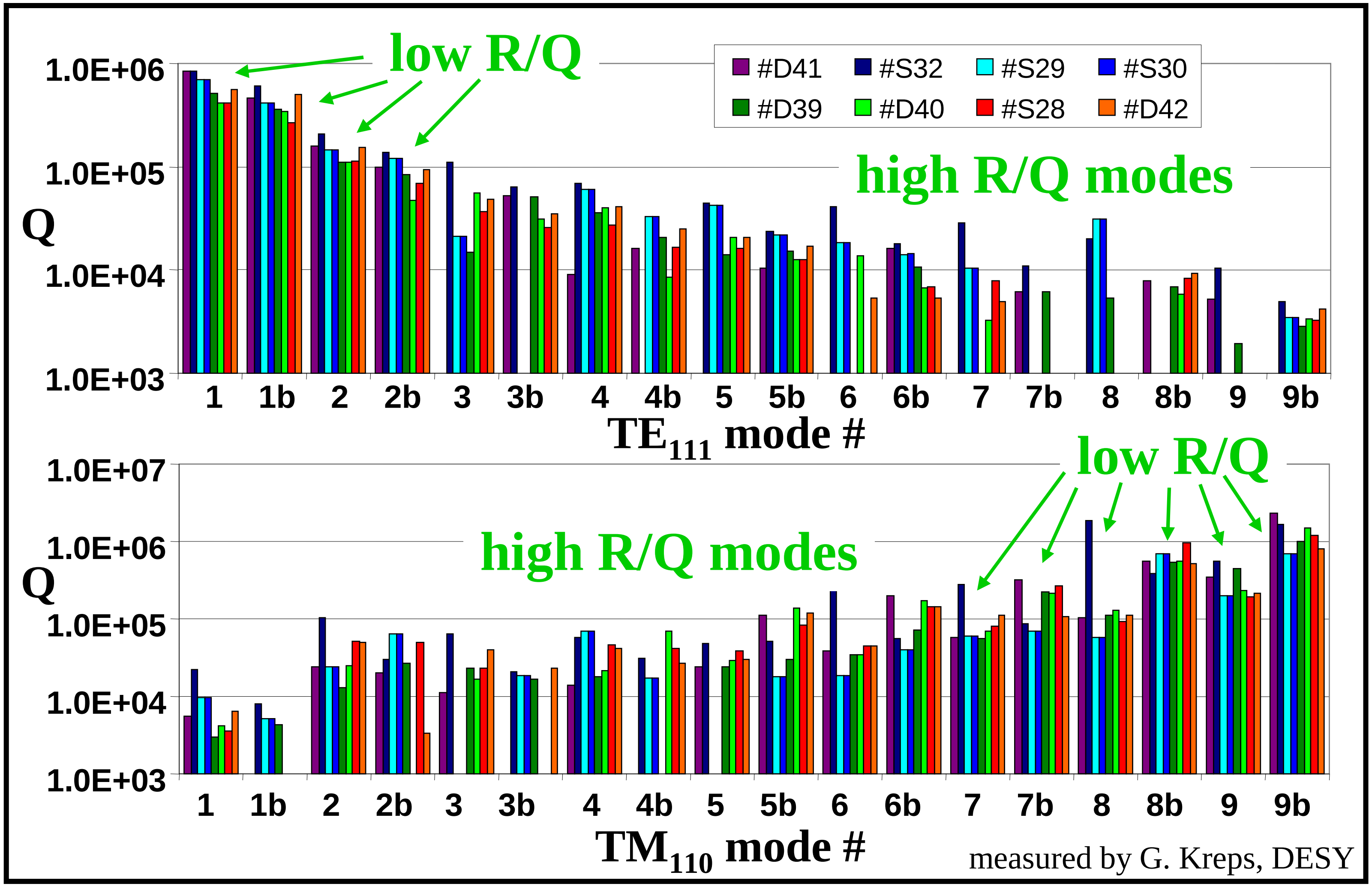
Example 4: ILC Cavity with HOM Loop Couplers





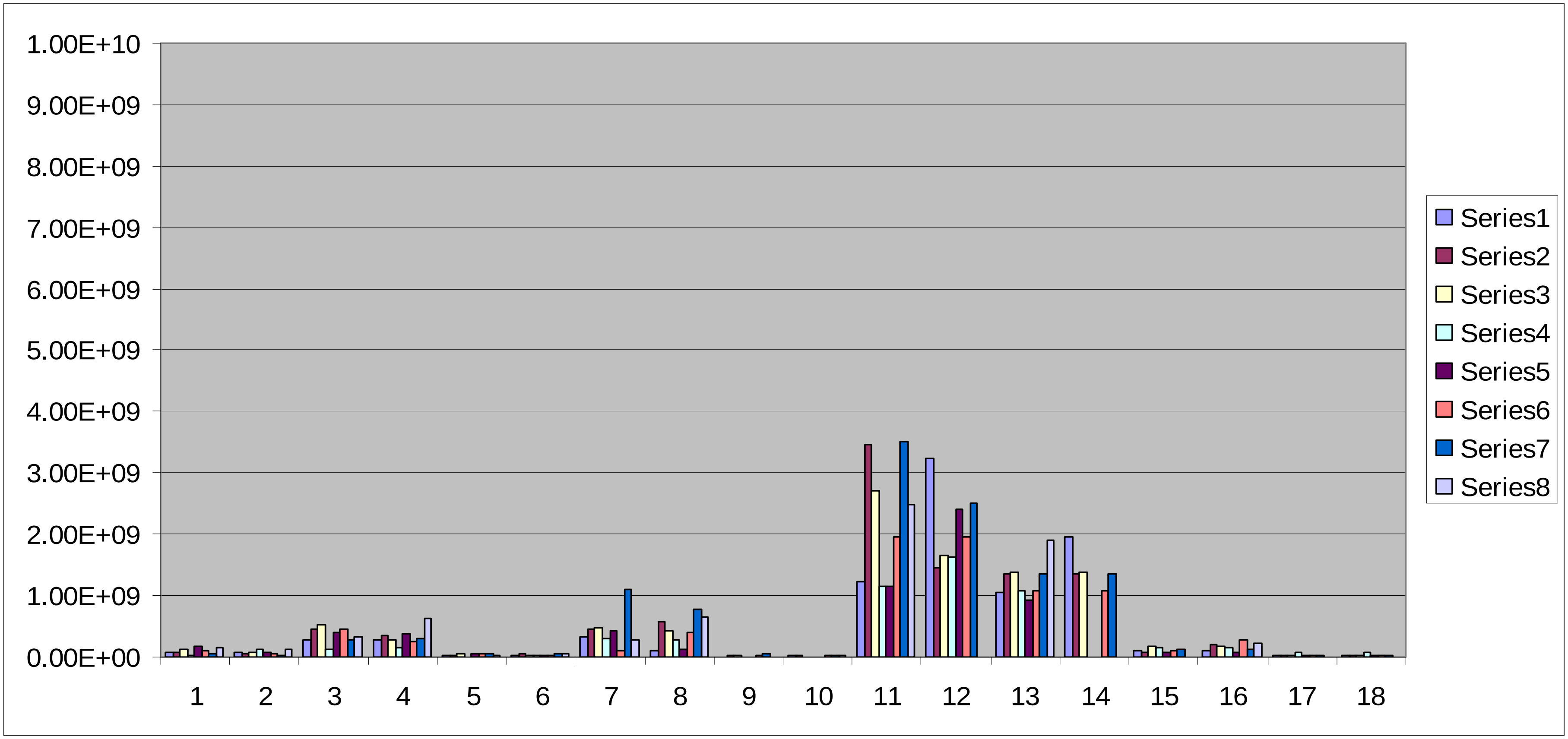


TTF HOM Coupler: Measured Damping of Dipole Modes



9-cell Cavities
TE111 Dipole Modes: TTF Module 2

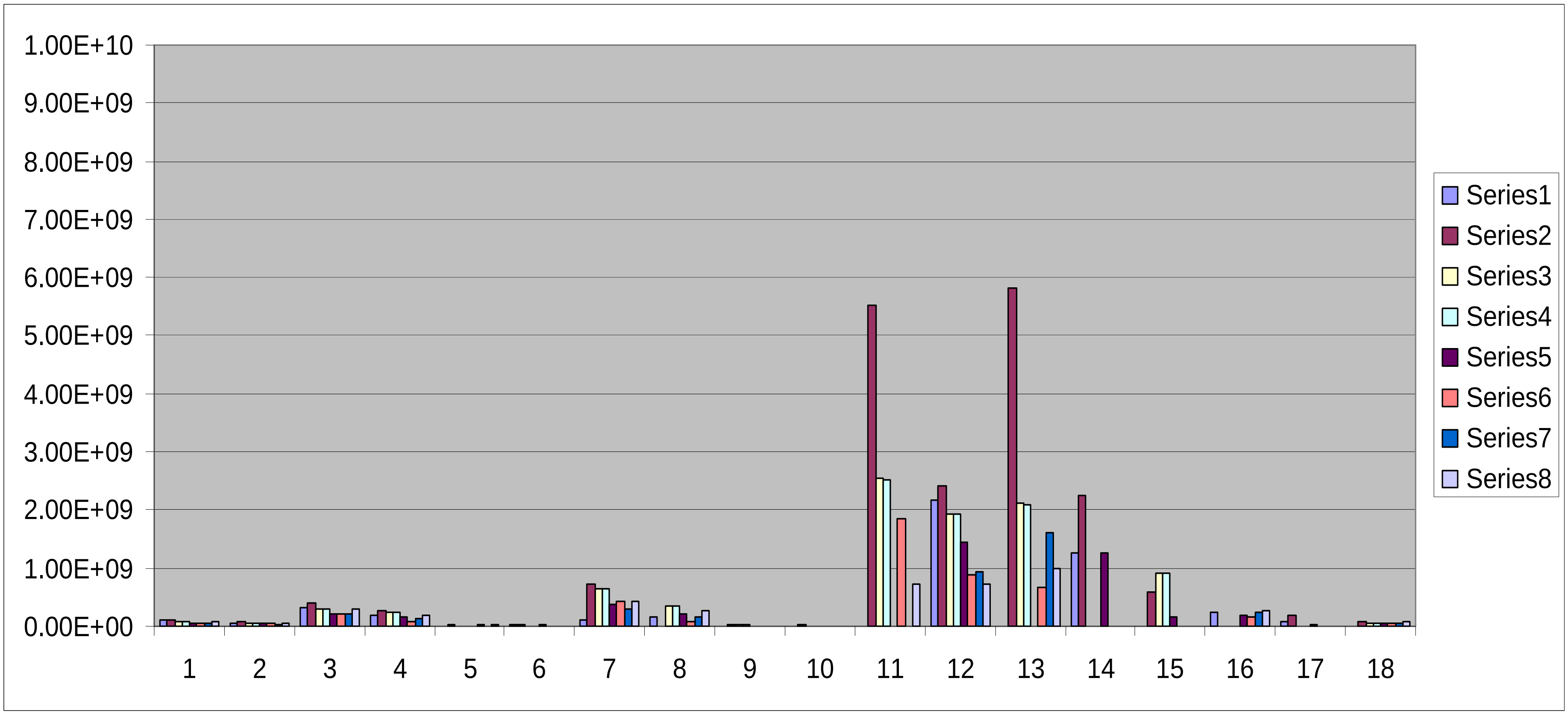
(R/Q)Qf [ΩMHz]



Mode #

9-cell Cavities
TE111 Dipole Modes: TTF Module 3

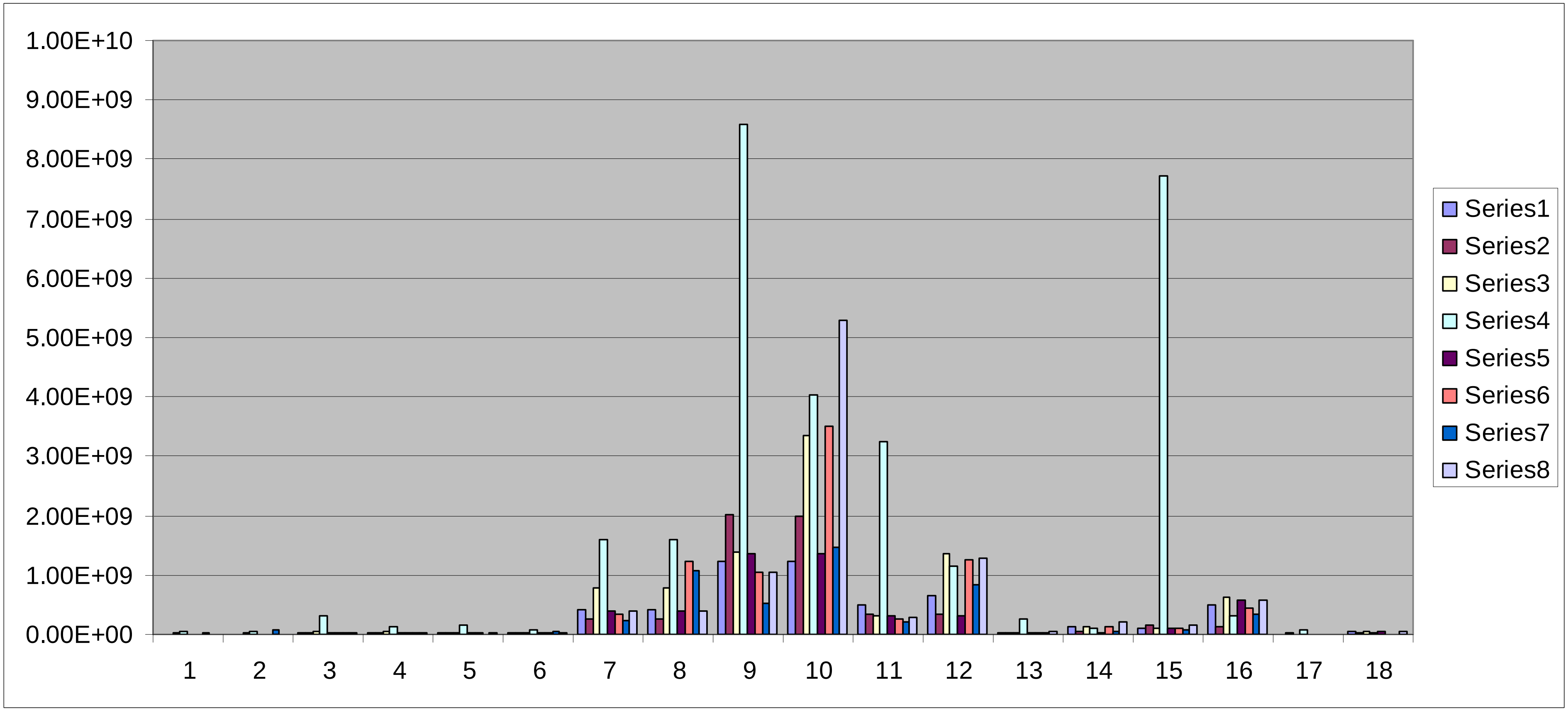
(R/Q)Qf [ΩMHz]



Mode #

9-cell Cavities
TM110 Dipole Modes: TTF Module 2

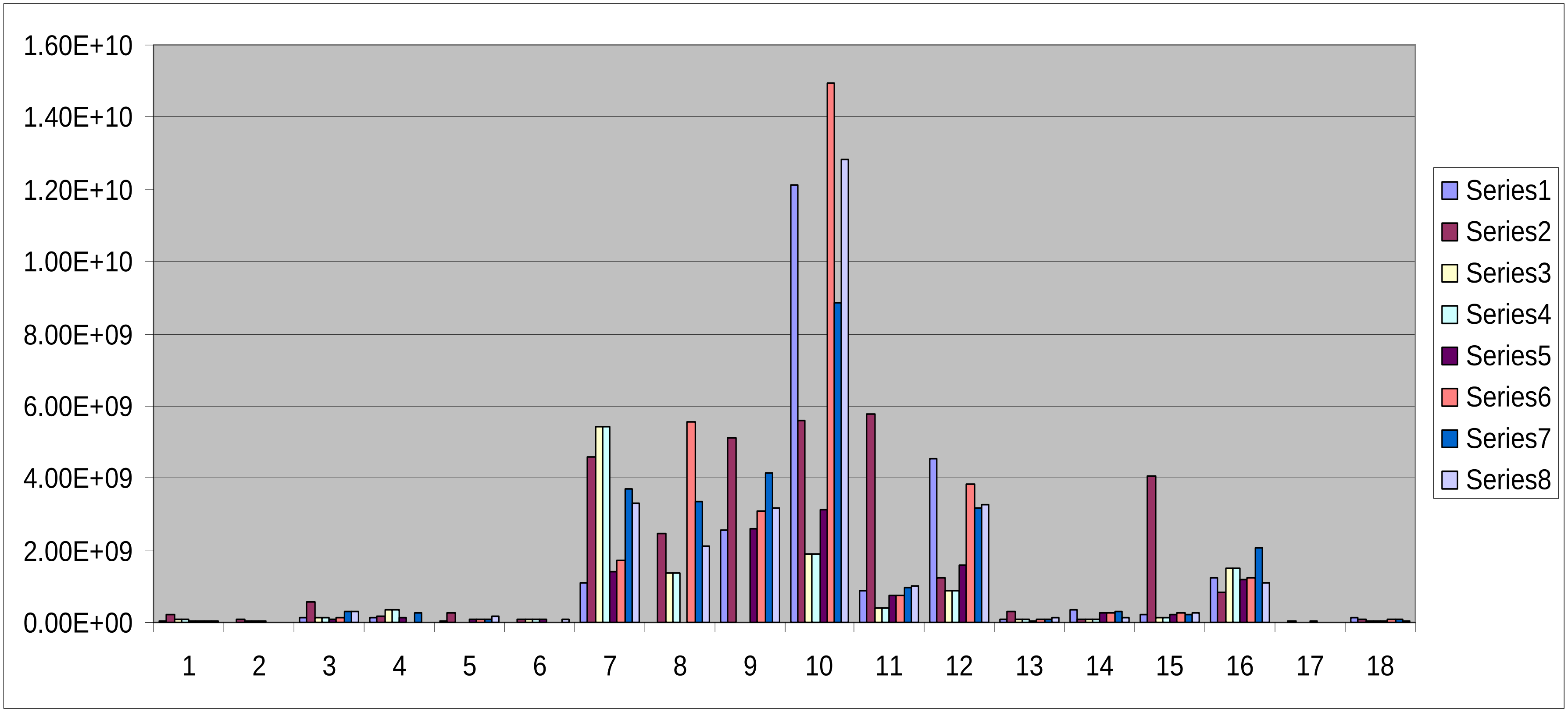
(R/Q)Qf [ΩMHz]



Mode #

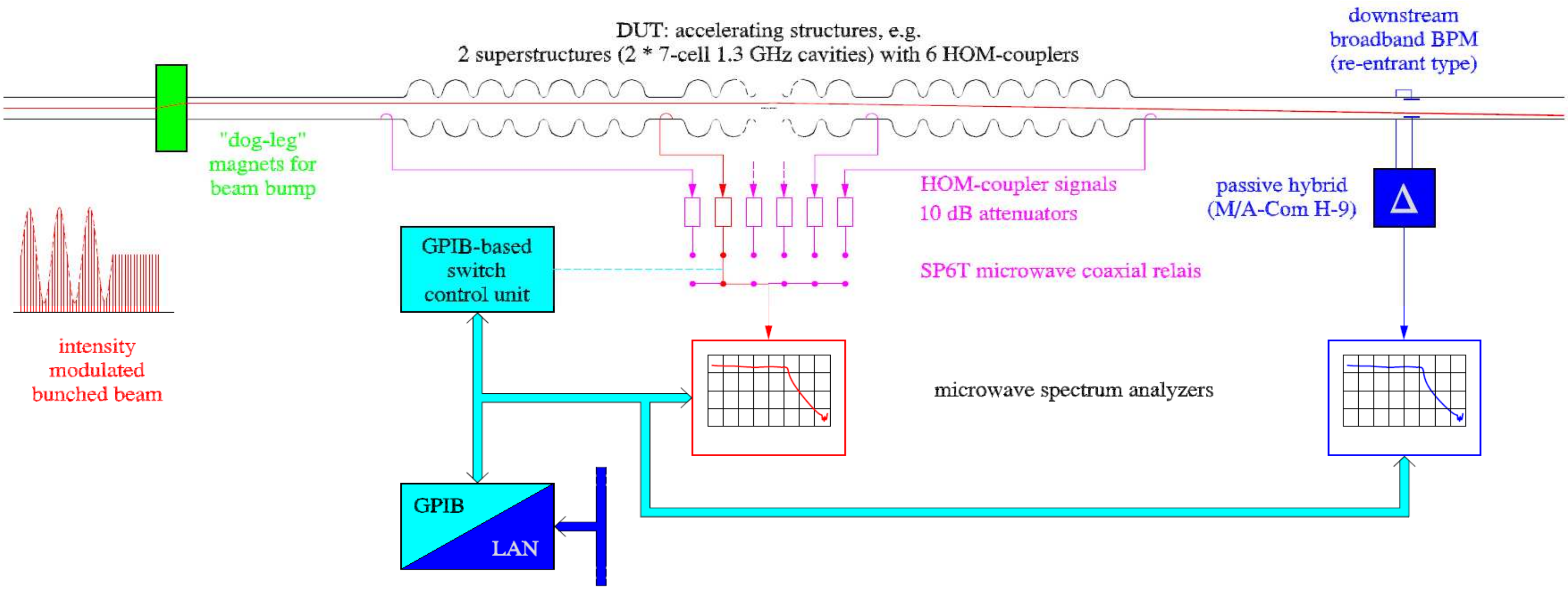
9-cell Cavities
TM110 Dipole Modes: TTF Module 3

(R/Q)Qf [ΩMHz]

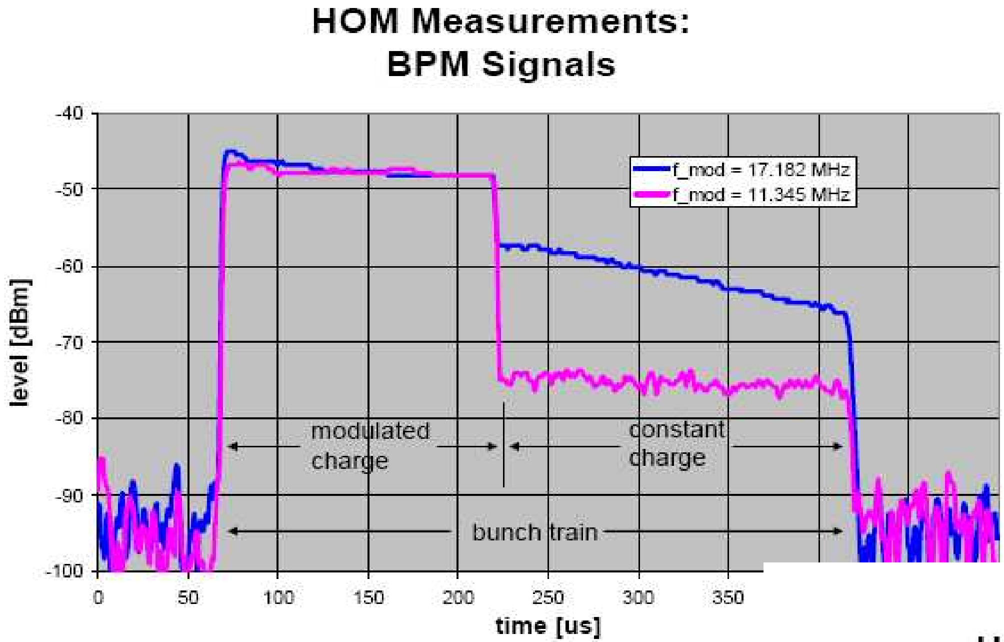


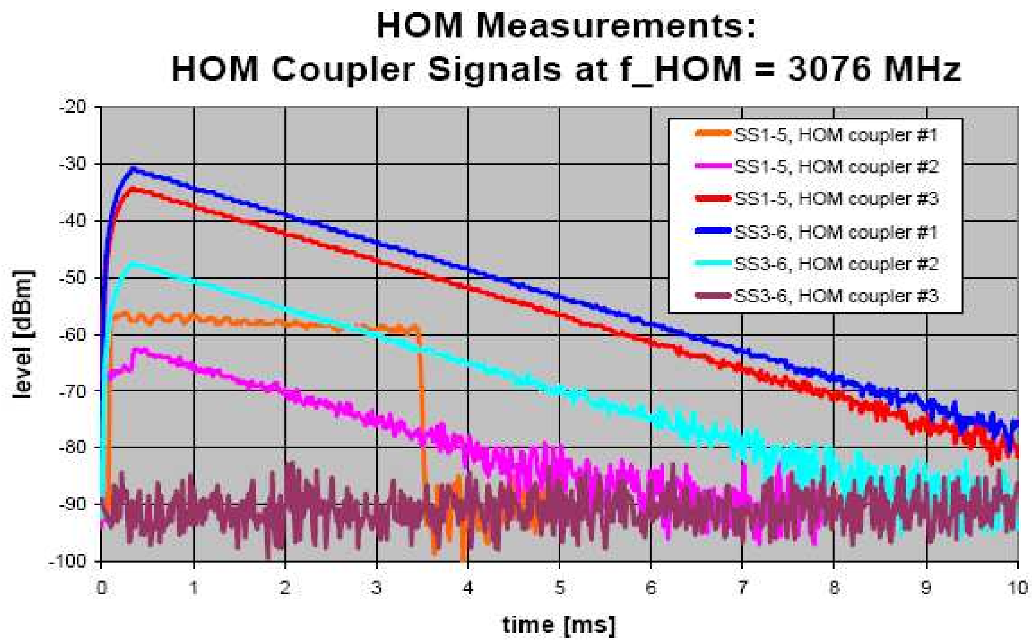
Mode #

Experimental Setup for Beam Based HOM Measurements at TTF/FLASH

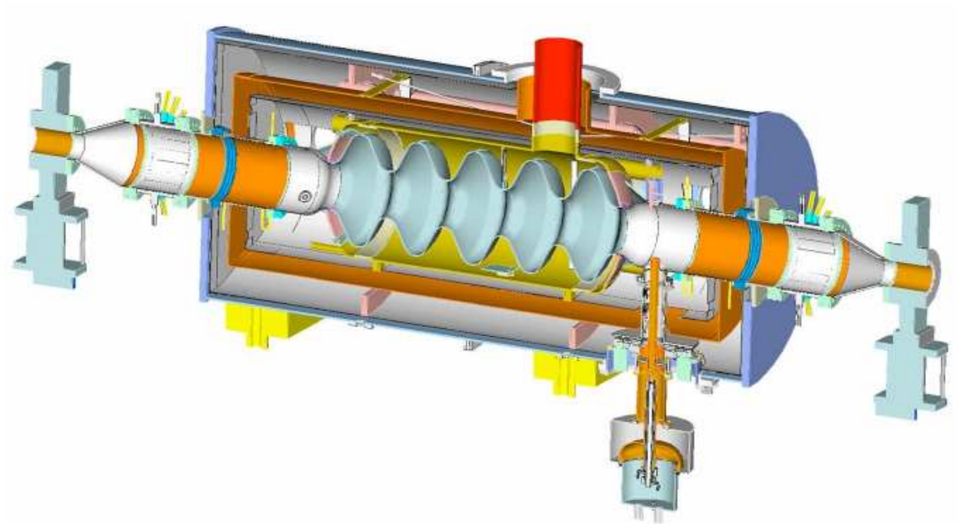


Beam Based HOM Measurements at TTF/FLASH

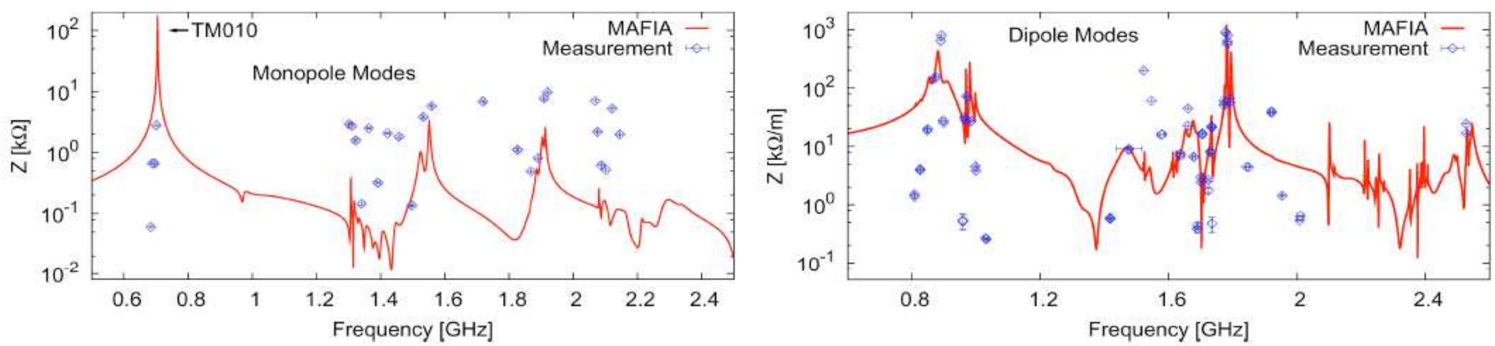




Example 5: BNL ERL Cavity



BNL high current ERL cryomodule concept for electron cooling



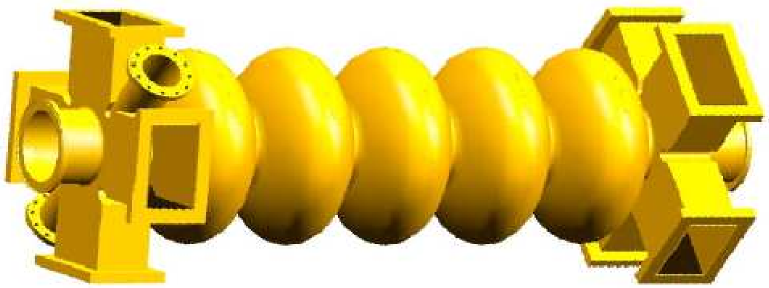
Calculated and Measured HOM spectra. (See Rama Calaga's talk, this working group)

Example 6: TJNAF 1A Cryomodule Design

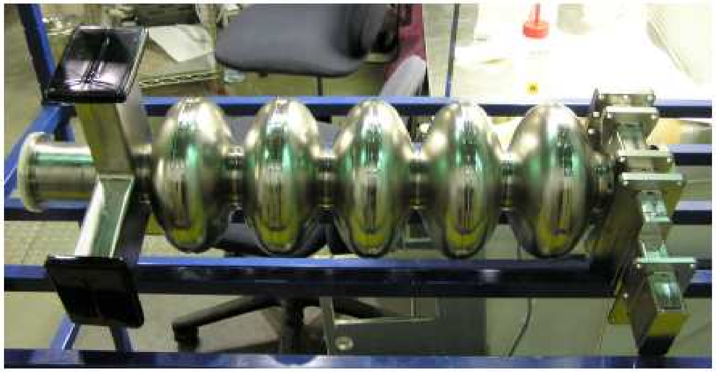
FEL Ampere-class module draft specs.

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

JLab FEL proposal:

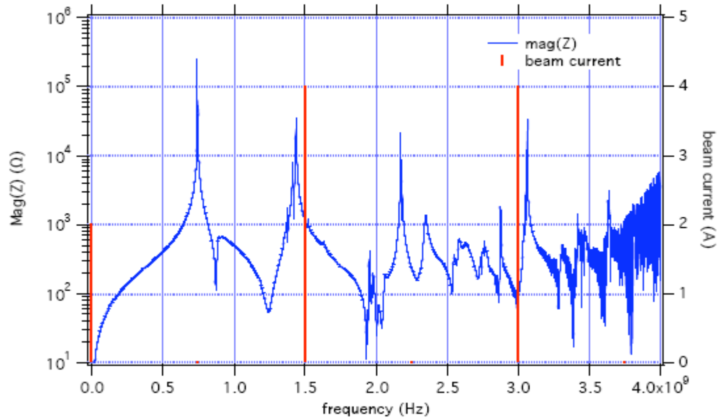


5-cell waveguide damped cavity

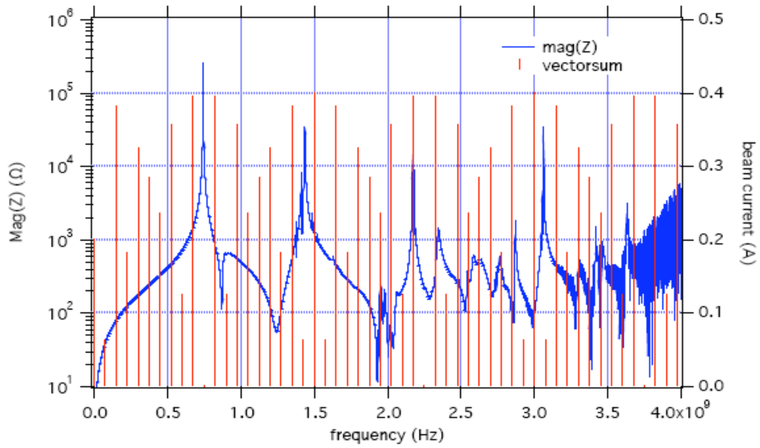


CEBAF cavity

TJNAF 1A Cryomodule Design



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?)