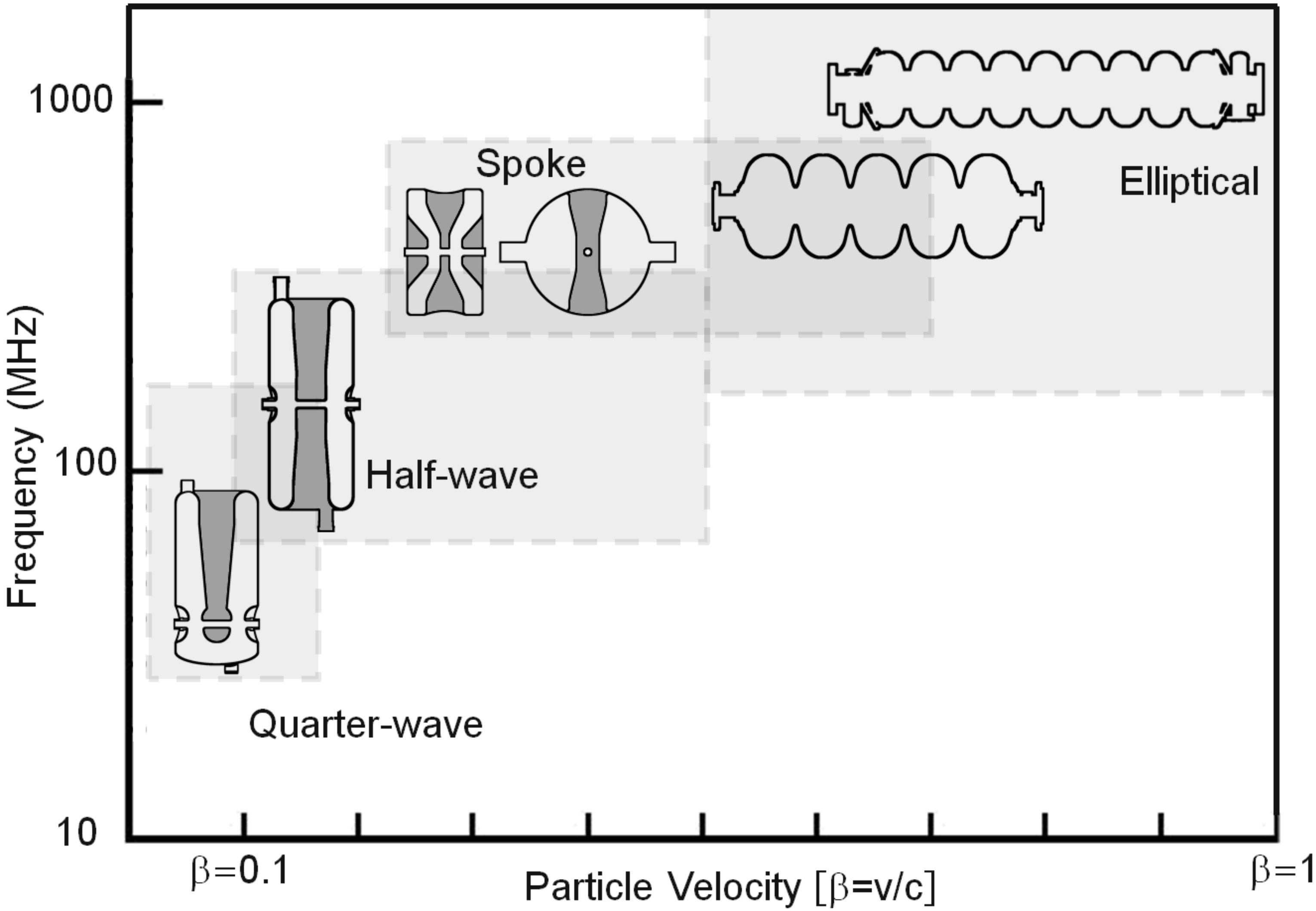
TEM-class Cavity Design

SRF 2013 Tutorial Program
Sept. 19-21
Ganil, Caen

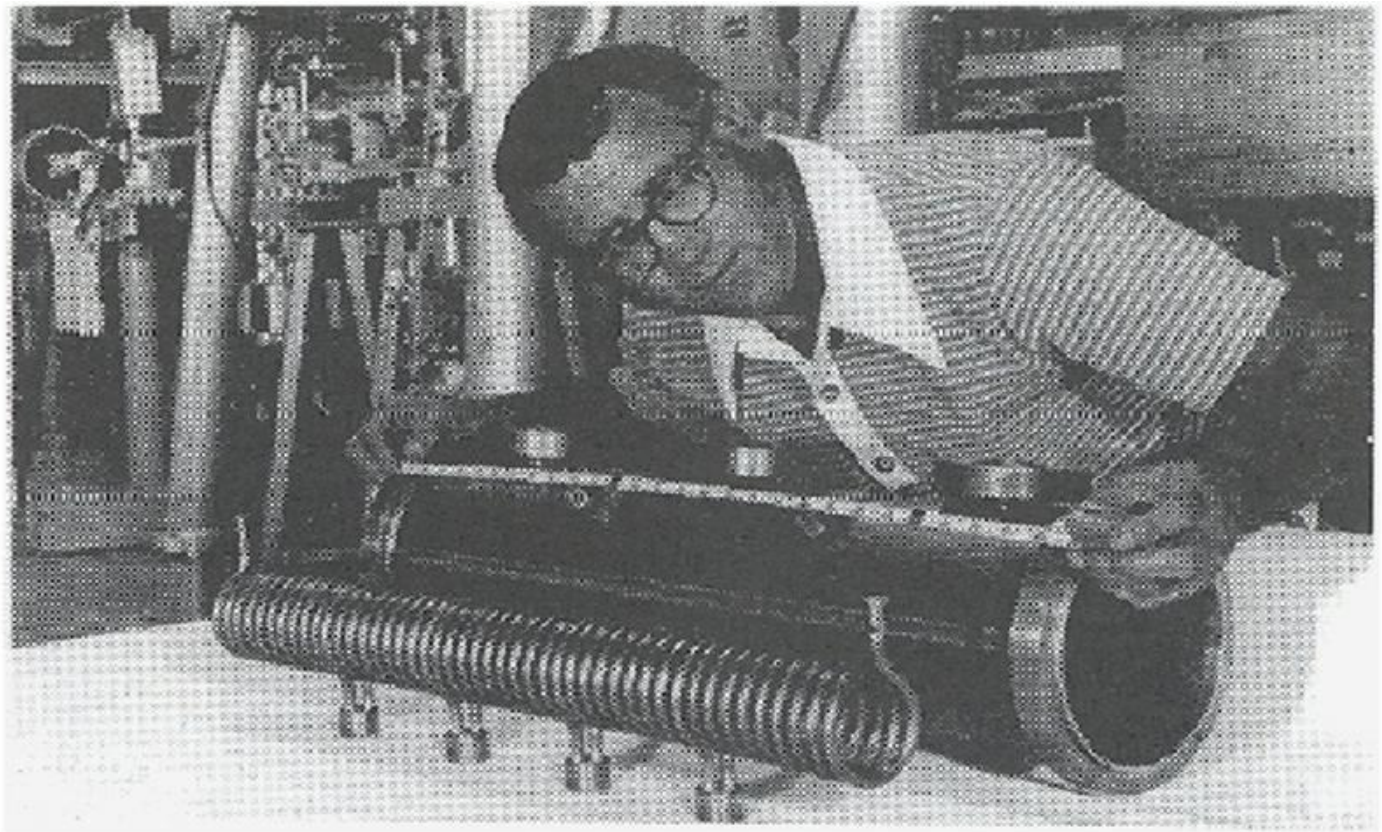
Speaker: Mike Kelly

Special Acknowledgements:
Ken Shepard
Jean Delayen
Alberto Facco
Zack Conway

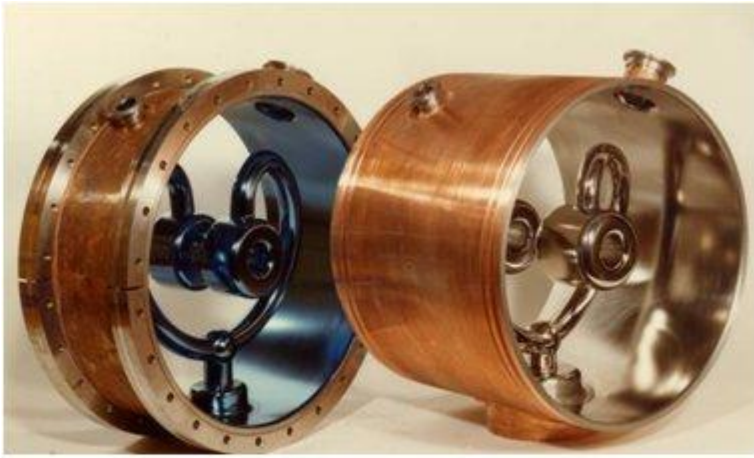
Practical Superconducting Cavity Geometries Spanning the Full Range of Velocities

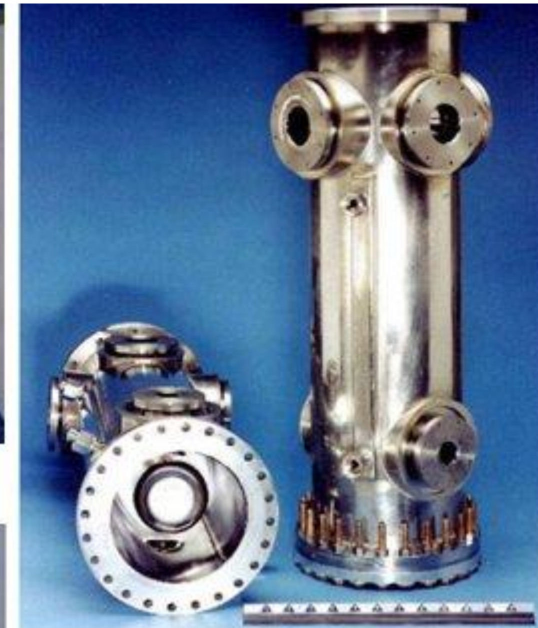


Helical Niobium Resonator for a Heavy-ion Linac



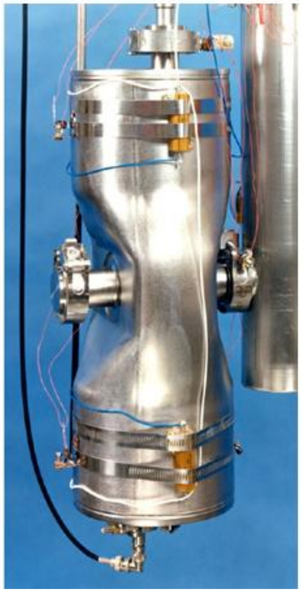
Quarter-wave Cavities






Half-wave Cavities

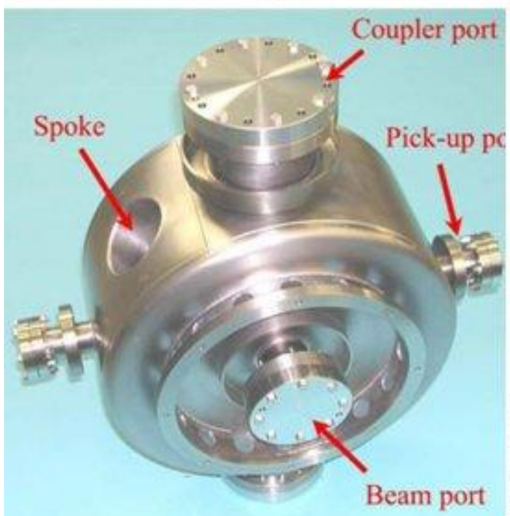



Spoke Cavities








A Few General Words on TEM Cavities

- Heavy-ions require acceleration by many cavities to reach velocities approaching speed of light
- Cavities with are designed for specific regions of velocity
- TEM cavities are most efficient for heavy ions with v $\leq$ 0.5c
- Low frequency cavities have large accelerating gaps
- Coaxial design optimum (only through 3D simulations)
- Common question: Why not high beta QWR? – physically large, strong magnetic steering on beam axis

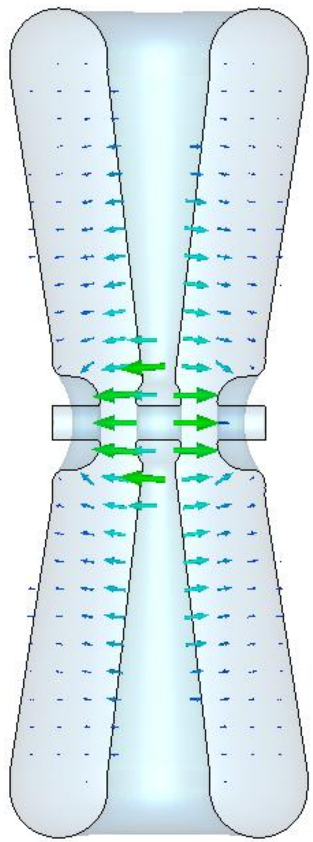
TEM-cavity Topics

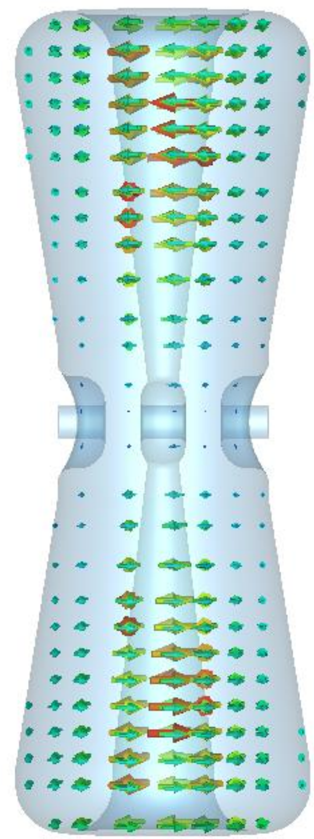
- Ion acceleration in a 2-gap RF structure
  - Cavity models
- Cavity Design
  - Electromagnetic design
  - Mechanical design
- Cavity Fabrication
  - Examples for modern structures
- Performance and Applications

TEM Cavity Fields

Example: Lowest mode of a $\lambda/2$ resonant line

Electric Field





Magnetic Field

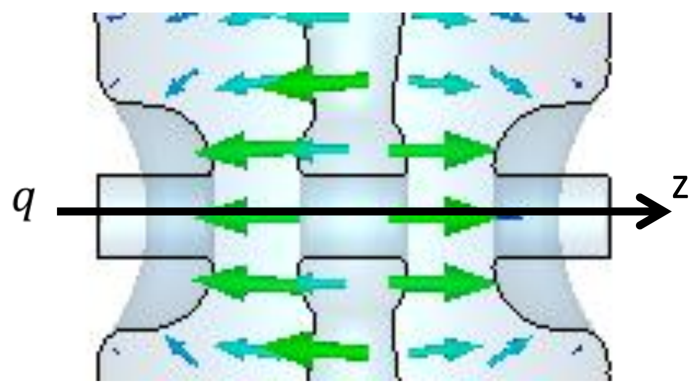
Strong coupling of fields means that accelerating fields are insensitive to small changes in the geometry. Higher order excitations are well separated from the fundamental mode.

Acceleration in a 2-gap Cavity

Charged Particle Acceleration in a 2-gap Accelerating Cavity

Energy gain of a particle, charge q, moving along the z-axis through a sinusoidally varying electric field. φ is the phase of the field as the particle moves through z=0.

$$\Delta W = q \int_{-\infty}^{+\infty} E(z)\cos(\omega t + \varphi)\, dz$$



Constant Velocity Approximation

If the particle does not change its velocity substantially:

$$z(t) = \beta c t$$

(Valid except for very low beta cavities running at high gradient)

$$\Delta W = q \int_{-\infty}^{+\infty} E(z) \left(\cos\left(\frac{\omega z}{\beta c}\right) \cos\varphi - \sin\left(\frac{\omega z}{\beta c}\right) \sin\varphi \right) dz$$

$$\Delta W = q \cos\varphi \int_{-\infty}^{+\infty} E(z) \cos\left(\frac{\omega z}{\beta c}\right) dz$$

(For the case where E(z) symmetric with respect to the cavity center)

Particle Energy Gain in Terms of Velocity, Transit Time, and Maximum Possible Energy Gain

$$\Theta = \frac{\int_{-\infty}^{+\infty} E(z) \cos\left(\frac{\omega z}{\beta_0 c}\right) dz}{\int_{-\infty}^{+\infty} |E(z)| dz}$$

Reduction in energy gain due to time varying e-field, “Transit time factor”

$$\mathrm{T}(\beta) = \frac{\int_{-\infty}^{+\infty} E(z) \cos\left(\frac{\omega z}{\beta c}\right) dz}{\int_{-\infty}^{+\infty} E(z) \cos\left(\frac{\omega z}{\beta_0 c}\right) dz}$$

Reduction in energy gain due to non-optimal velocity, “Velocity acceptance factor”

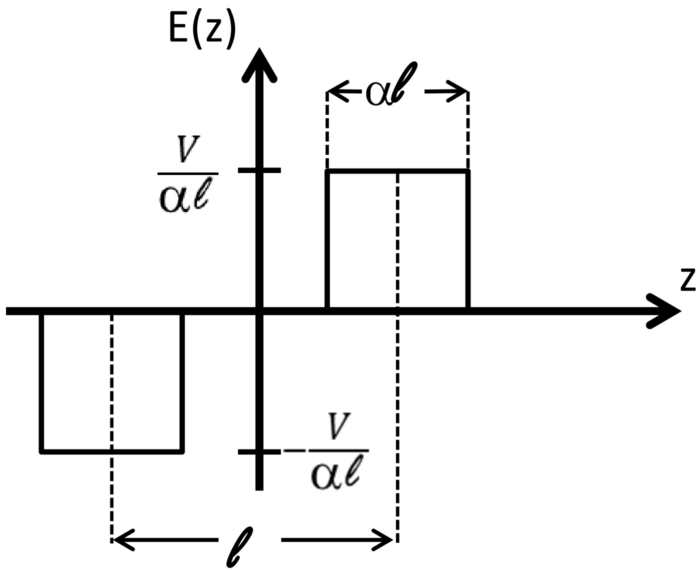
$$\Delta W_0 = \Theta \int_{-\infty}^{+\infty} |E(z)| dz$$

Energy gain by a synchronous particle (φ=0) of unity charge (q=1) and $\beta=\beta_0$

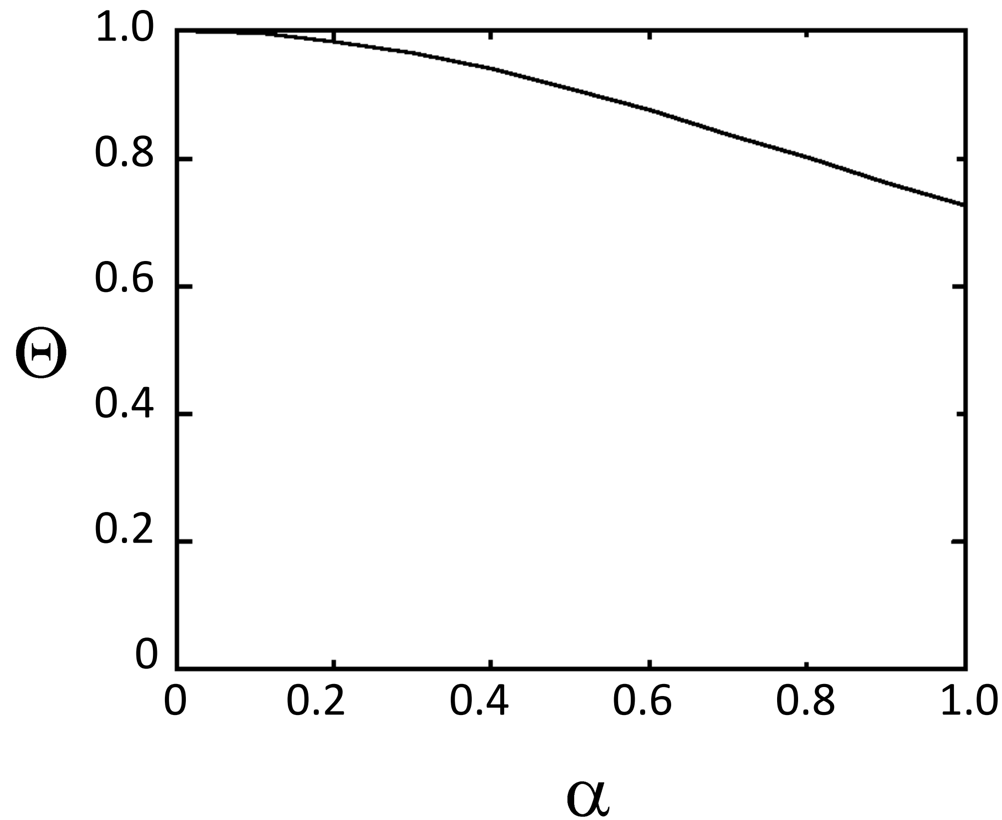
$$\Delta \boldsymbol{W} = \boldsymbol{q}\ \boldsymbol{cos}\,\boldsymbol{\varphi}\ \Delta \boldsymbol{W}_{\mathbf{0}}\ \mathrm{T}(\beta)$$

J. R. Delayen

Reduction in Energy Gain Due To Time Varying Field

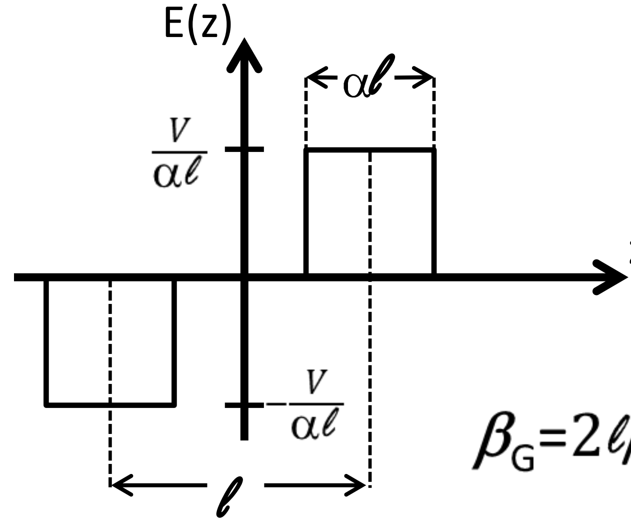


Idealized electric field profile in a 2-gap accelerating cavity



Geometrical β_G and Optimal β_0

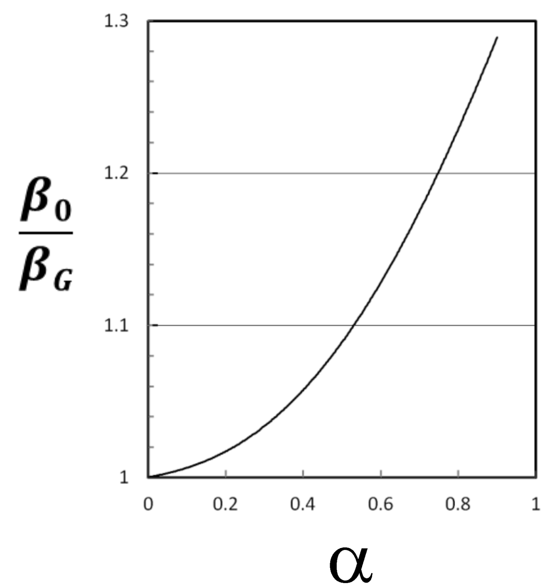
$$T(\beta) = \frac{\beta}{\beta_0} \frac{\sin\left[\frac{\omega}{\beta c}\frac{\alpha \ell}{2}\right] \sin\left[\frac{\omega}{\beta c}\frac{\ell}{2}\right]}{\sin\left[\frac{\omega}{\beta_0 c}\frac{\alpha \ell}{2}\right] \sin\left[\frac{\omega}{\beta_0 c}\frac{\ell}{2}\right]}$$



$\beta_G = 2\ell/\lambda$

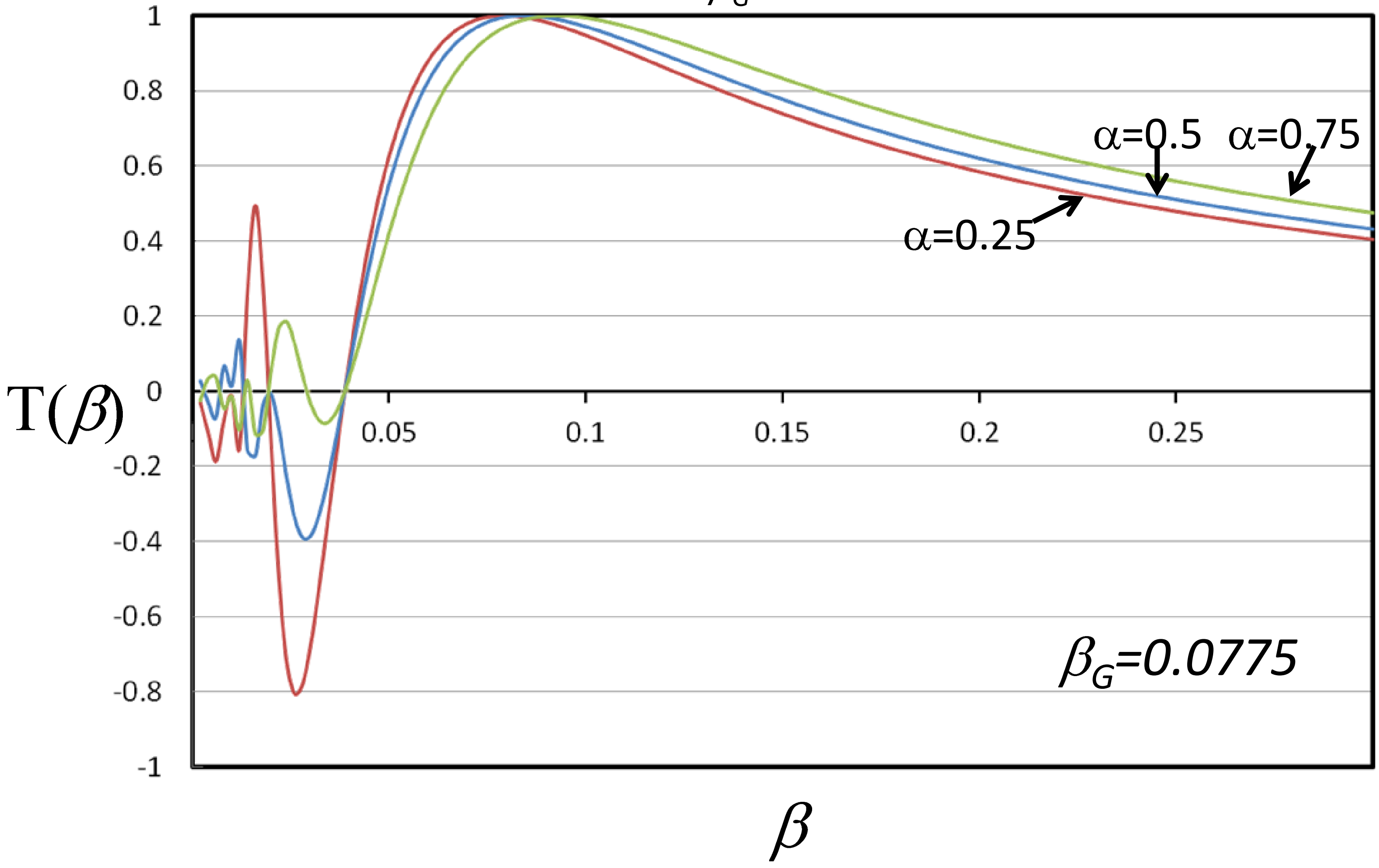
$$T(\beta) = \frac{\beta}{\beta_0} \frac{\sin\left[\frac{\beta_0}{\beta}\frac{\pi \alpha}{2x_0}\right] \sin\left[\frac{\beta_0}{\beta}\frac{\pi}{2x_0}\right]}{\sin\left[\frac{\pi \alpha}{2x_0}\right] \sin\left[\frac{\pi}{2x_0}\right]}$$

$$\textit{where } x_0 = \frac{\beta_0 \lambda}{2\ell} = \frac{\beta_0}{\beta_G}$$



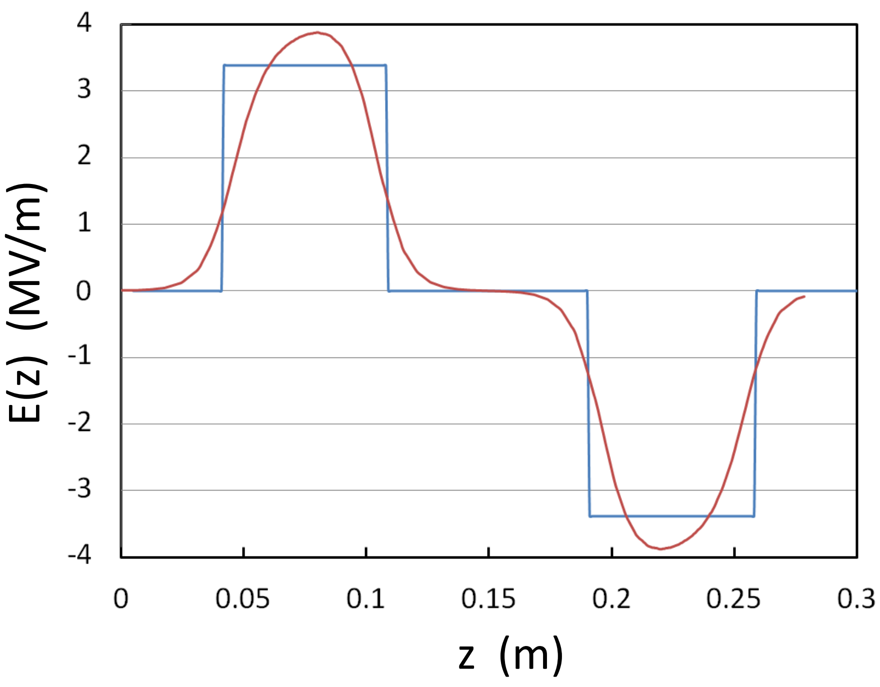
Velocity Acceptance

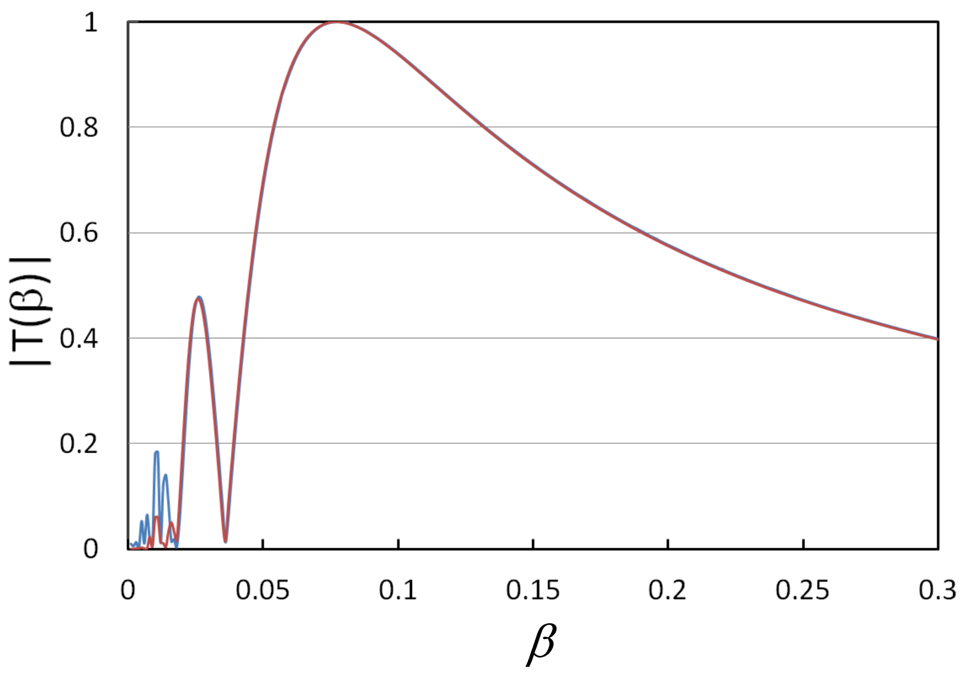
Example of velocity acceptance for three values of the filling factor and β_G=0.0775



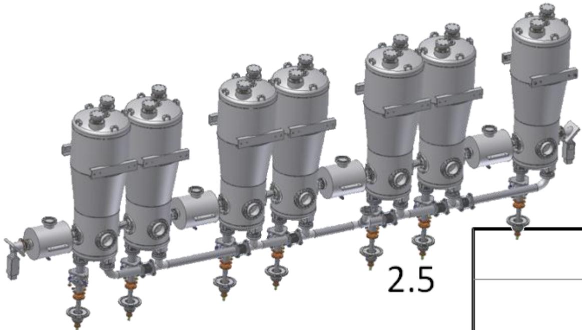
Realistic Field Profile

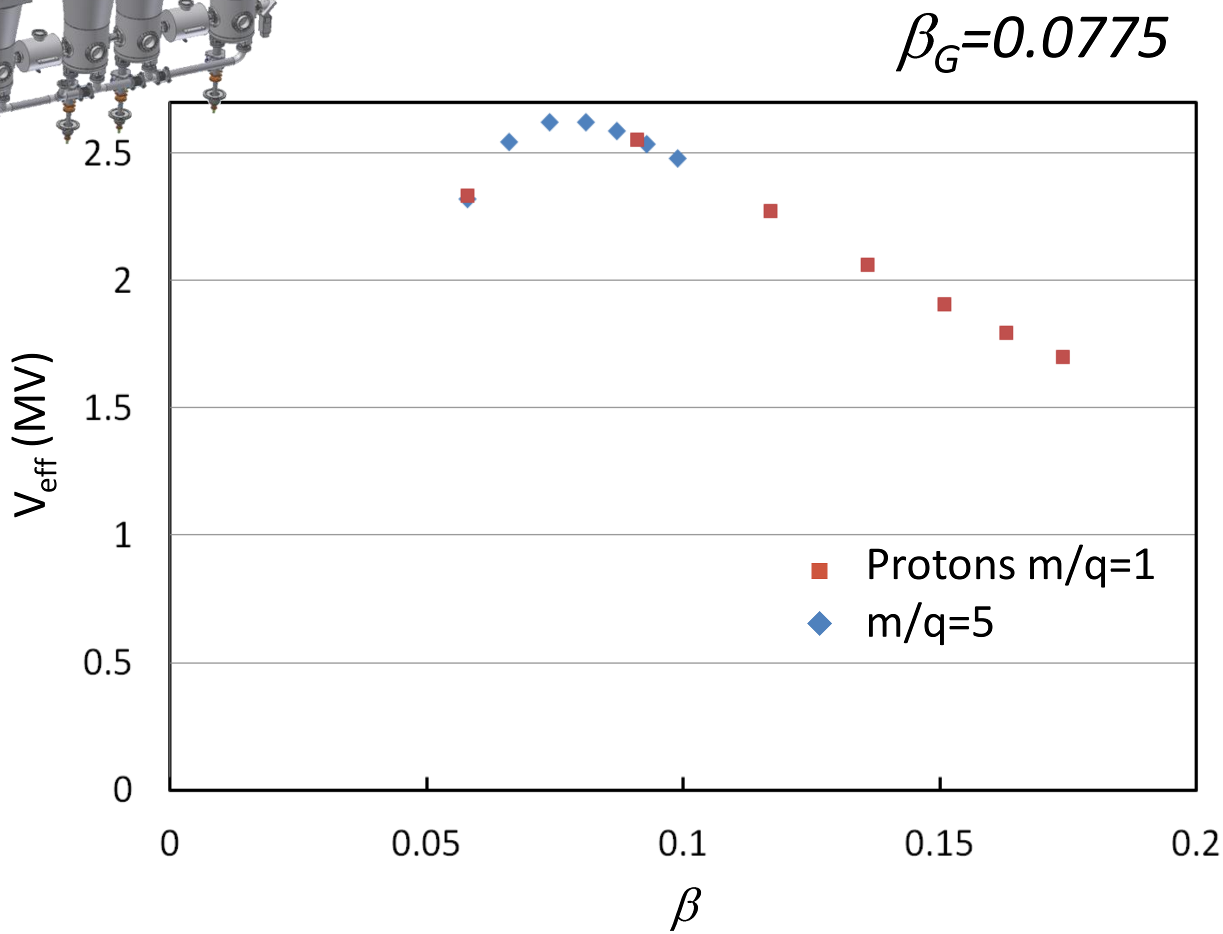
- Fields in the gaps penetrate into the beam tube aperture in real cavities
- Velocity acceptance function insensitive to this effect





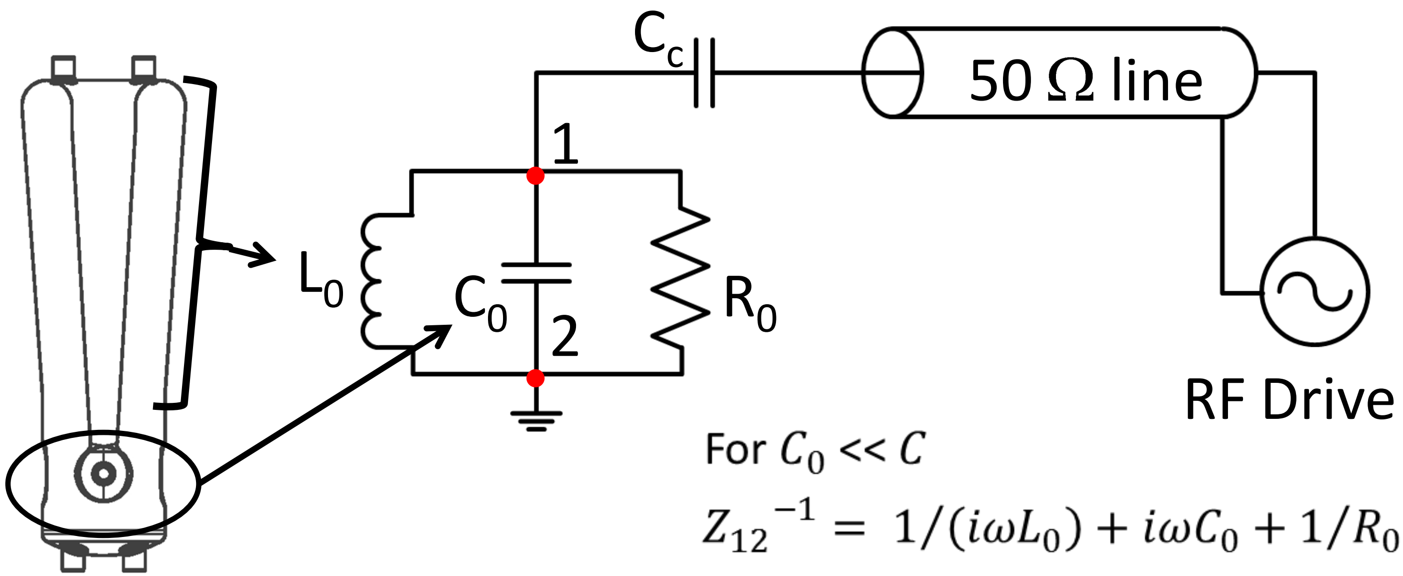
Energy Gain and m/q





Equivalent Circuit Model of a Cavity

Cavity behavior can be modeled as a lumped inductance, capacitance and resistance
Useful to analyze cavity properties (stored energy, decay time) or
Complex problems such as cell-to-cell coupling in multi-gaps(cells)



For $C_0 << C$

$$Z_{12}{}^{-1} = 1/(i\omega L_0) + i\omega C_0 + 1/R_0$$

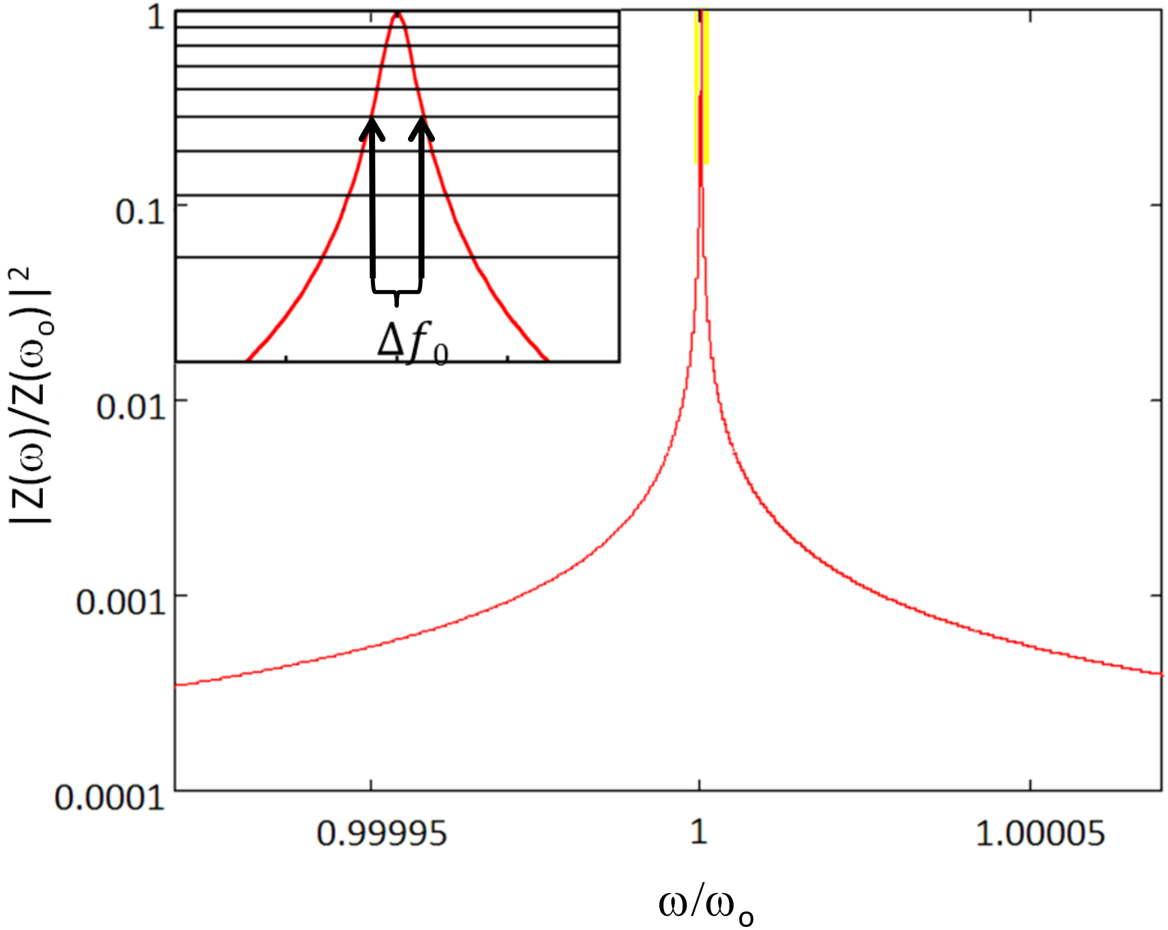
$$|Z_{12}|^{-2} = (\omega C_0 - 1/\omega L_0)^2 + 1/R_0{}^2$$

$$|Z_{12}| = \frac{1}{\sqrt{\left(\omega C_0 - \frac{1}{\omega L_0}\right)^2 + \frac{1}{R_0{}^2}}}$$

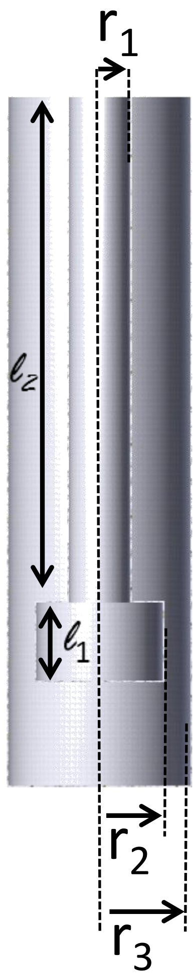
Resonance Behavior from Circuit Model

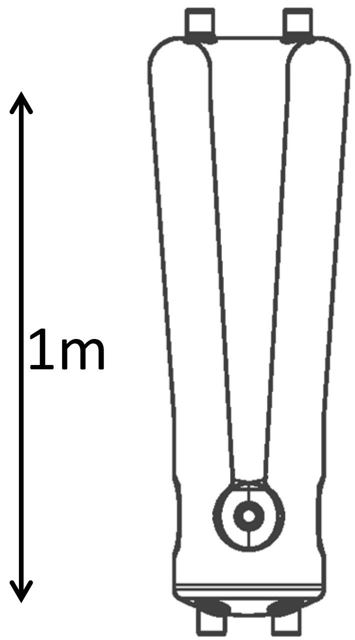
$$\frac{1}{\sqrt{L_0 C_0}} \equiv \omega_o = \text{maximum of } |Z(\omega)|$$

$$Q \equiv \frac{f_0}{\Delta f_0} = \frac{U}{\Delta U} = 1/\text{fractional energy dissipated per RF period}$$



Quarter-wave Cavity as a Capacitively Loaded Quarter-wave Line





	Loaded Quarter-wave Line	3D EM Simulation (CST Studio)
L_0 (nH)	206	161
C_0 (pF)	25	30
f_0 (MHz)	70	**73**
U_0 (J)	0.32	**0.38**

$$L_0 \approx \frac{\mu_0}{2\pi} \ln\frac{r_3}{r_1} \cdot \ell_2 \qquad C_0 \approx \frac{2\pi\epsilon_0}{\ln\frac{r_3}{r_1}} \cdot \ell_1$$

Electromagnetic Design

Cavity Design Considerations

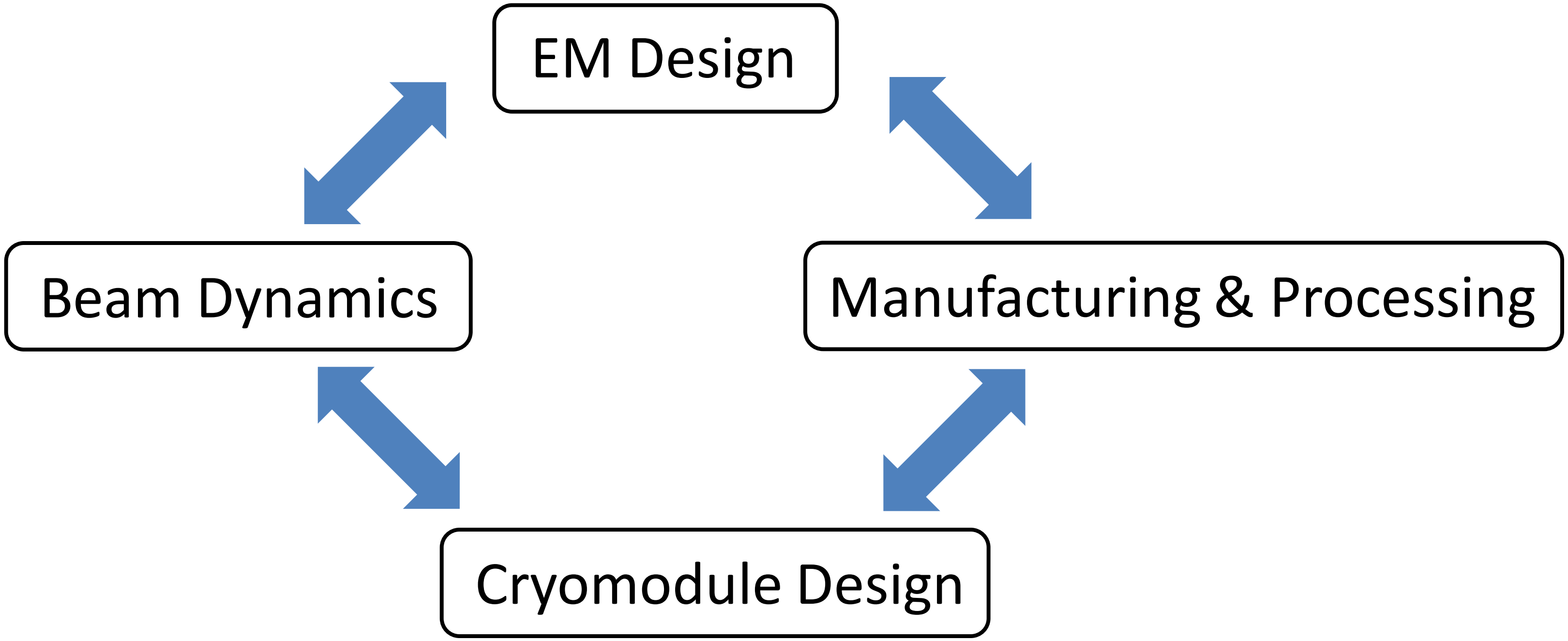
Beam transport/Beam dynamics

- Energy gain
- Velocity acceptance
- Beam loss requirements

Practical Issues

- Microphonics, cw or pulsed operation
- Power dissipation
- Tuning
- Fabrication, pressure vessel
- Chemical processing, cleaning, assembly

Electromagnetic Design Informed by Beam Dynamics and Practical Considerations



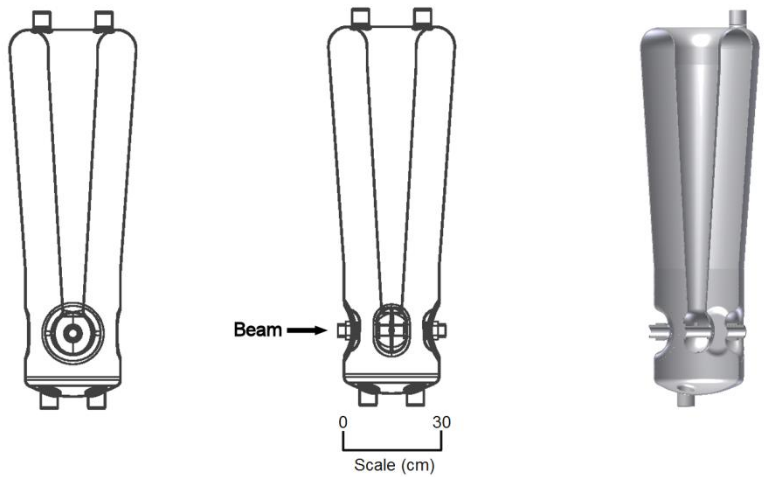
- Cavity EM design (i.e. shape) must simultaneously incorporate:
  - Requirements from beam physics; e.g. cavity acceptance and beam aperture
  - Manufacturing, processing, operation
- Manufacturing considerations include:
  - Number and location of ports for coupling and effective processing
  - Cavity tuning cuts (coarse tuning, fine tuning, slow tuning in operations)
  - Cost and complexity

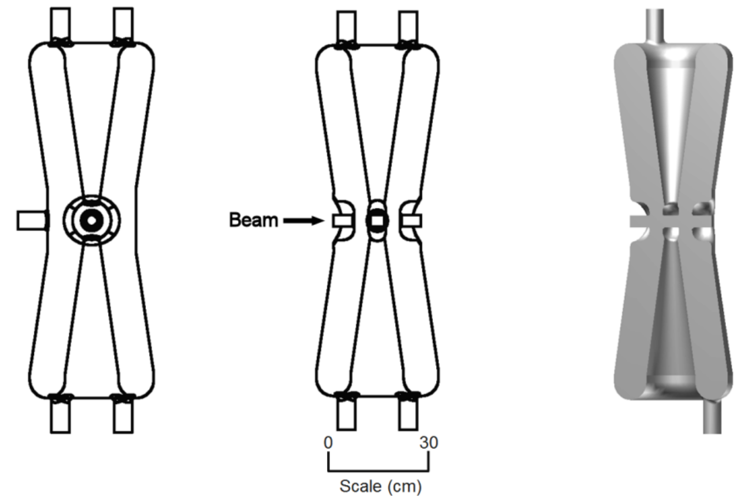
B. Mustapha

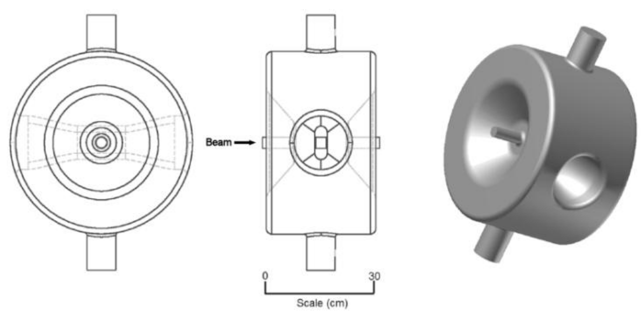
‘Figures of Merit’ for EM Design

- E_{PEAK}: Minimize peak surface electric field to reduce field emission (normalized to E_{ACC})
- B_{PEAK}: Minimize peak magnetic field to maximize achievable accelerating voltage (normalized to E_{ACC})
- $R_{SH}/Q = V^2_{ACC}/\omega U$: Maximize R/Q to produce more accelerating voltage (V_{ACC}) for a given stored energy in the cavity (U)
- $G = Q \cdot R_s$: Maximize the geometry factor to increase the cavity effectiveness of providing accelerating voltage (shape alone)

Recent Geometries for Two-gap Quarter-wave, Half-wave and Spoke Cavities





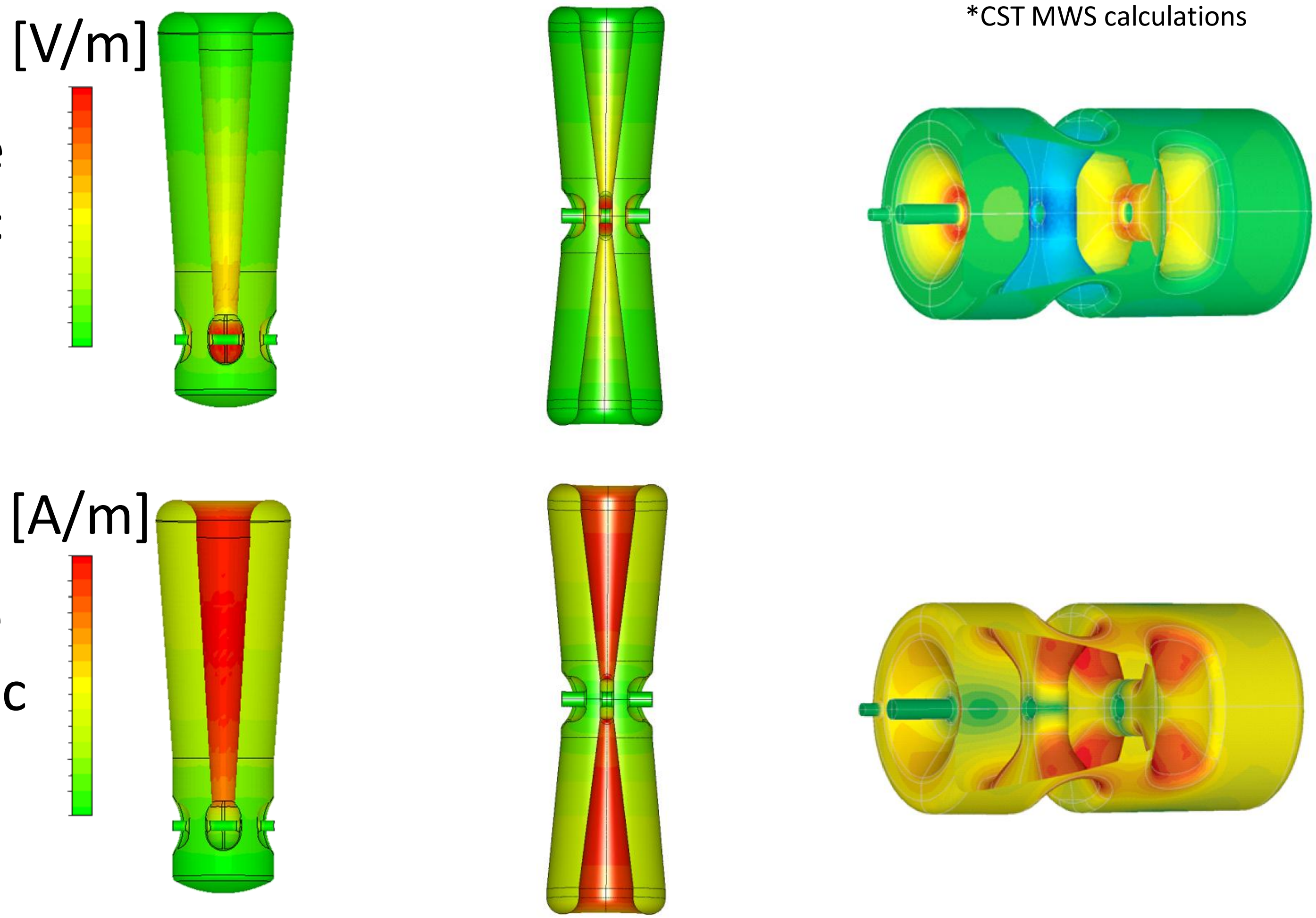


Optimizing Cavity EM Design for Surface Fields*

*CST MWS calculations

Surface Electric Fields

Surface Magnetic Fields

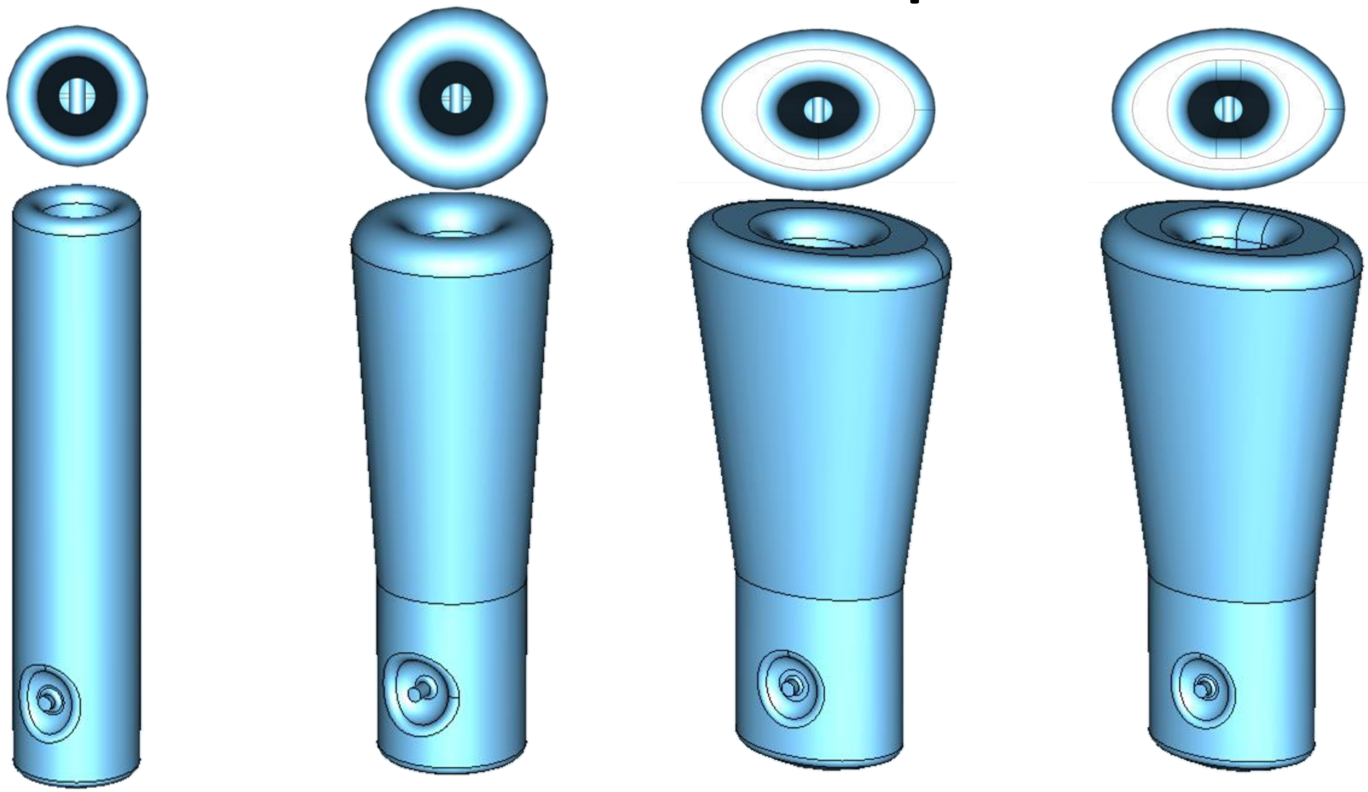


Quarter-wave

Half-wave

Double-spoke (C.S. Hopper J.R. Delayen)

QWR EM Design Optimization: Possible Shapes



Cylinders Conical Elliptical Race-track

Increasing complexity, lower surface fields

QWR EM Design Optimization: An Example

Some primary cavity geometrical parameters:

Cavity Top Diameter (D1)

Stem Top Diameter (D2)

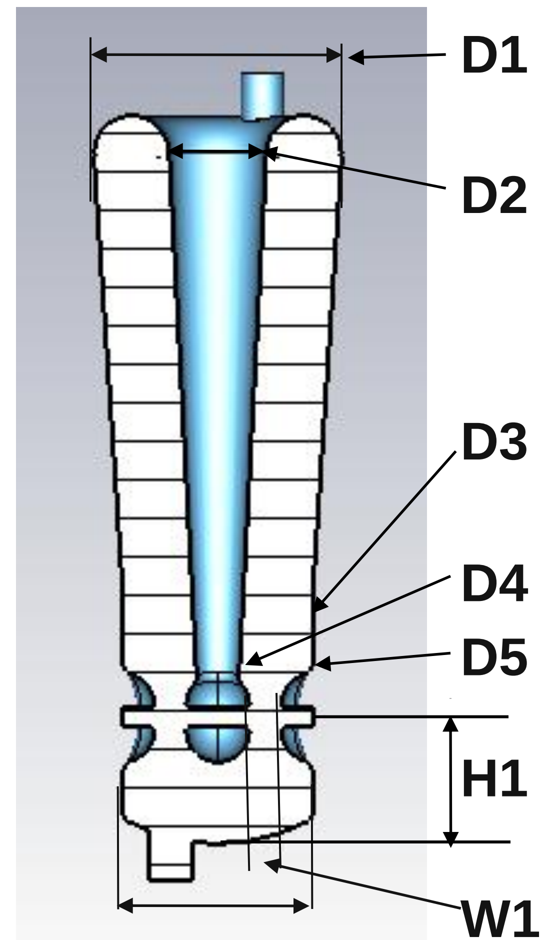
Cavity Lower Diameter (D3)

Stem Bottom Diameter (D4)

Drift Tube Outer Diameter (D5)

Drift Tube Gap Width (W1)

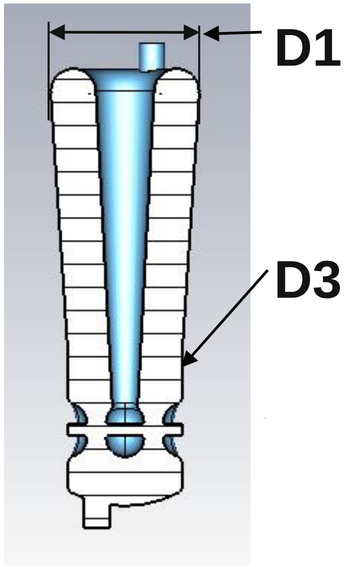
Cavity Bottom Height (H1)

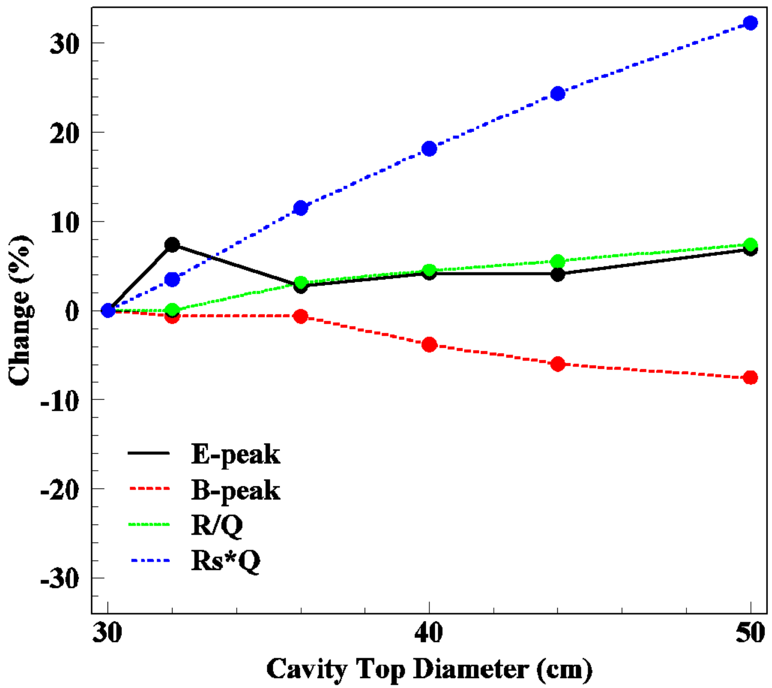


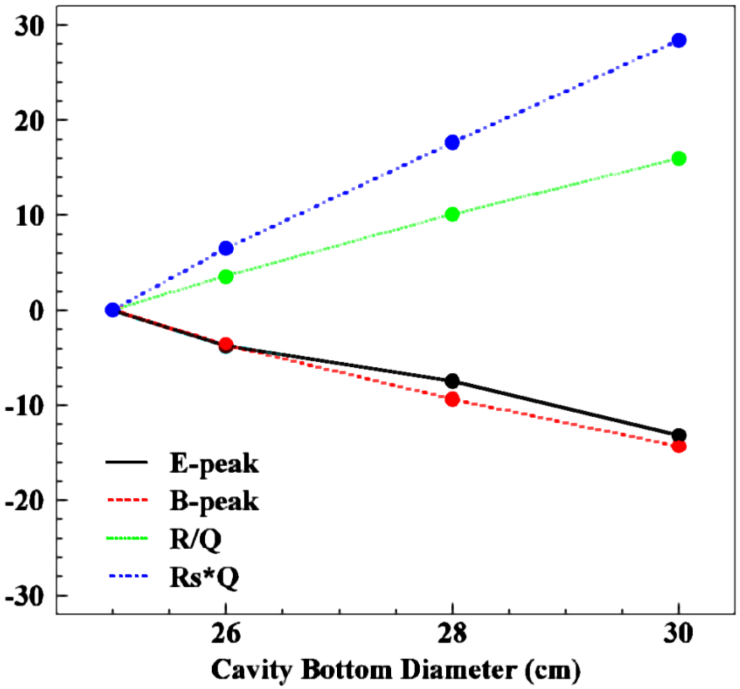
Some important considerations:

- Sections of both the inner and outer conductors should be a right angle cylinders for coarse tuning during fabrication
- Cavity optimization that adversely impact ‘real estate gradient’ not useful (increase D1 within limits)
- The cavity height/width largely determine the cryomodule dimensions (*e.g.* optimize H1 within limits)

QWR EM Design Optimization: An Example

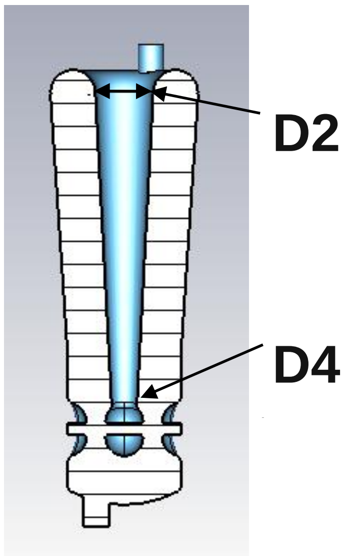


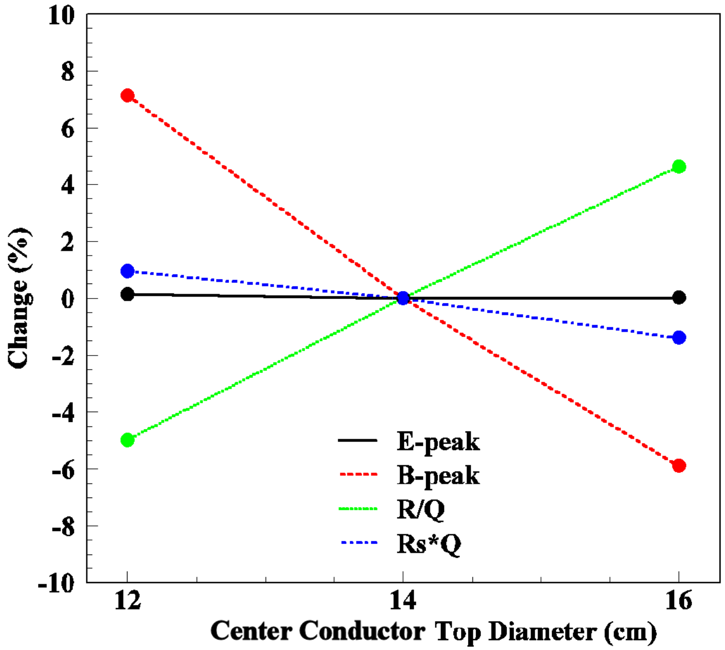


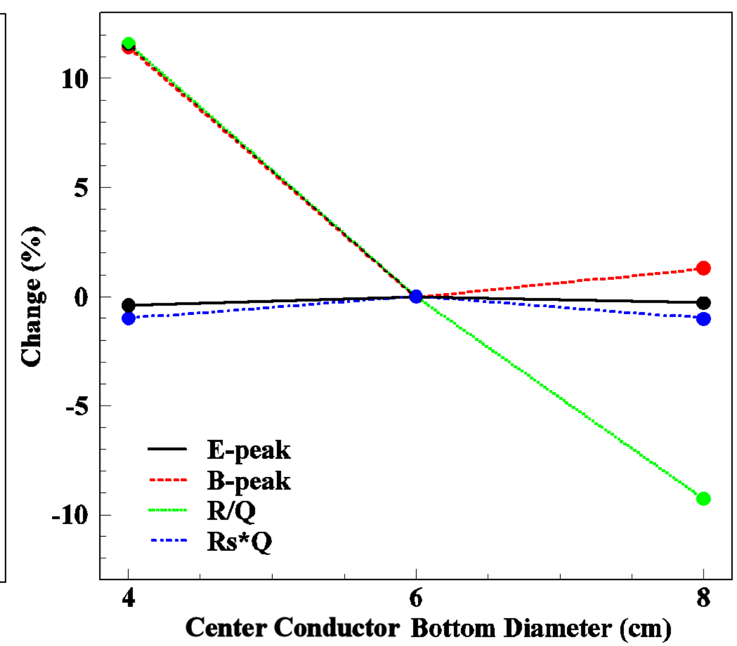


Electromagnetic design parameters improve continuously as the outside diameter increases. The limit is determined by physical size constraints.

QWR EM Design Optimization: An Example

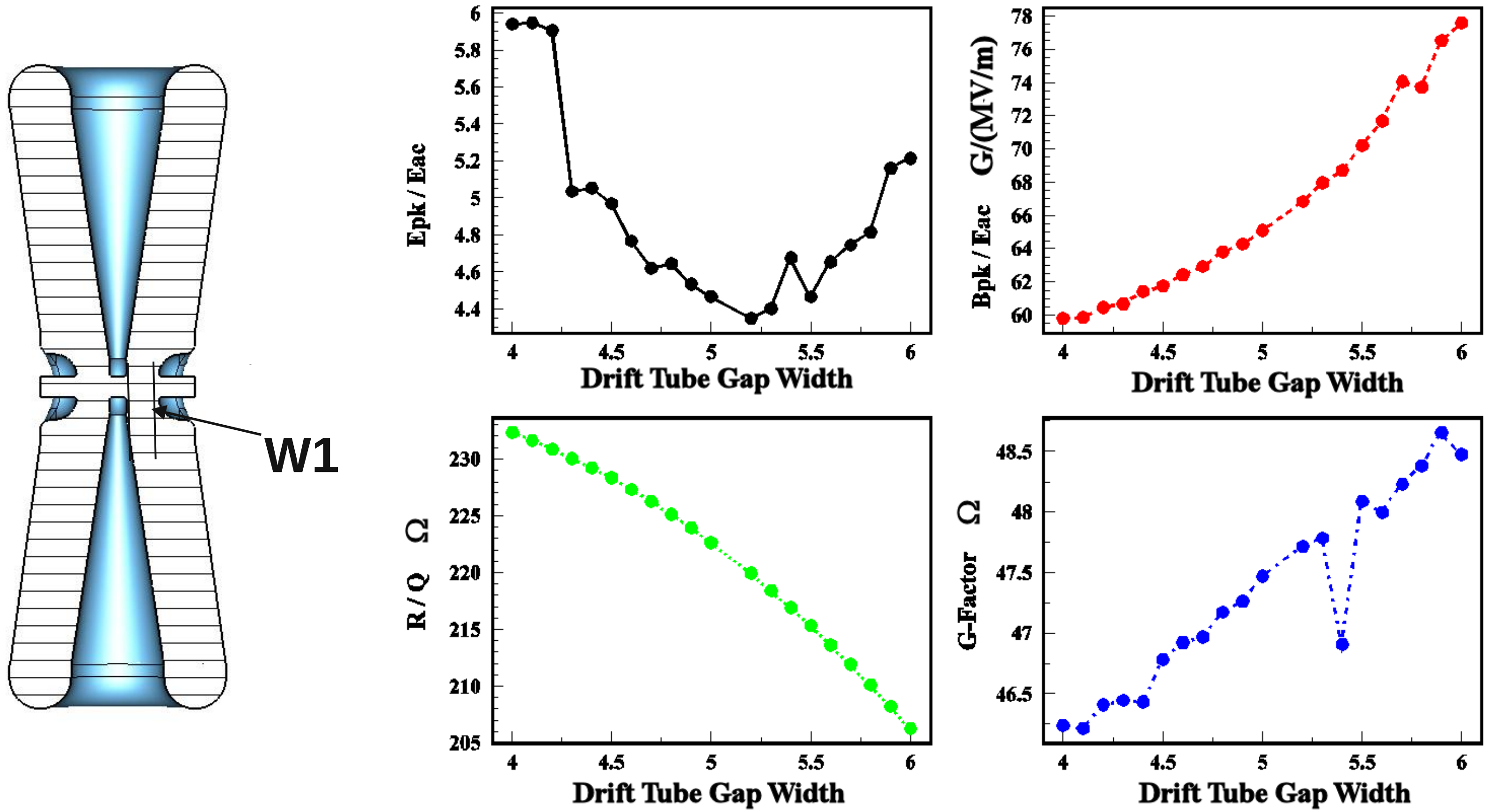






Minimizing B_{peak} often has beneficial effects for R/Q and geometry factor

HWR EM Design Optimization: An Example



(has an equivalence to drift tube length and nose length)

B. Mustapha

QWR EM Design Optimization: Two Possible Geometries

Cylindrical

Tapered

EM Design Parameters

Parameter	Cylinder	Tapered	Unit
E-peak*	5.9	5.1	MV/m
B-peak*	10.2	7.6	mT
R/Q	515	575	Ohm
QR_S	16.8	26.4	Ohm

*For E_{ACC}=1 MV/m

$\ell_{EFF} = n \cdot \beta\lambda = 0.32$ m

Summary: Some EM Parameters for Recent TEM-cavities

Parameter	QWR	HWR	Single Spoke	Units
Frequency	72.5	162.5	325	MHz
Beta	0.08	0.11	0.2	v/c
E-peak*	5.1	4.6	3.8	MV/m
B-peak*	7.6	5.4	5.8	mT
R_{SH}/Q	575	262	242	Ohm
QR_S	26.4	48	84	Ohm

*For E_{ACC}=1 MV/m

$\ell_{EFF} = n \cdot \beta\lambda$

Optimizing Cavity Design for RF Losses

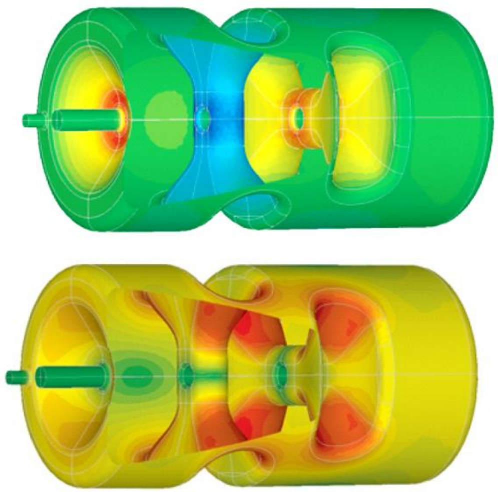
$$P_{in} = \frac{V^2_{ACC} \cdot R_s}{(R_{SH}/Q)(Q \cdot R_s)}$$

The dissipated power in terms of cavity design parameters (shunt impedance and geometry factor) and cavity performance parameters

$$P_{IN} = \frac{\left(\frac{B_{PEAK}}{B_{PEAK}/E_{ACC}} \cdot \ell_{eff}\right)^2 [R_{BCS}(T,\omega) + R_{Res}]}{(R_{SH}/Q)(Q \cdot R_s)}$$

A possible strategy for optimization for the CW SRF cavity for losses: Choose reasonable values for B_{PEAK}, $R_{Res,}$ then optimize E_{ACC}, T, ω, R_{SH}, QR_S to minimize P_{IN}

Optimizing Cavity Design for RF Losses

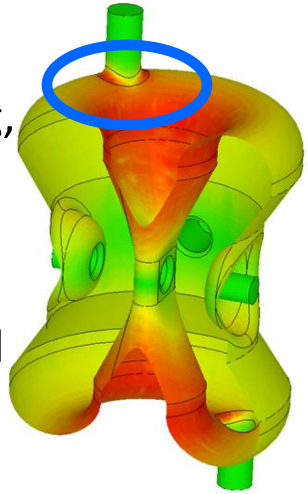


Double-spoke
(C.S. Hopper
J.R. Delayen, PRSTAB)

Parameter	Double Spoke Surface Fields	Double Spoke RF Losses	Units
Frequency	352	352	MHz
Beta	0.82	0.82	v/c
E-peak*	3.7	4.3	MV/m
B-peak*	7.05	7.8	mT
R_{SH}/Q	642	647	Ohm
QR_S	158	173	Ohm
$R_{SH}/Q*QR_S$	$1.0x10^5$	$1.1x10^5$	Ohm^2

Detailed Aspects
Electromagnetic Design

Impact of Cavity Ports



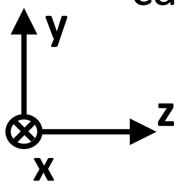
- Ports into the RF volume are required at beam aperture, for RF coupling, vacuum pumping and surface processing (QWR's, HWR's, Spokes)
- Usually possible introduce suitable ports without adverse impact on performance
- Improperly designed ports-> RF losses (port length too short), increased surface fields, trapped gas bubble in 4 K operation
- Example: Blend radius on 50 mm port chosen to reduce peak magnetic field

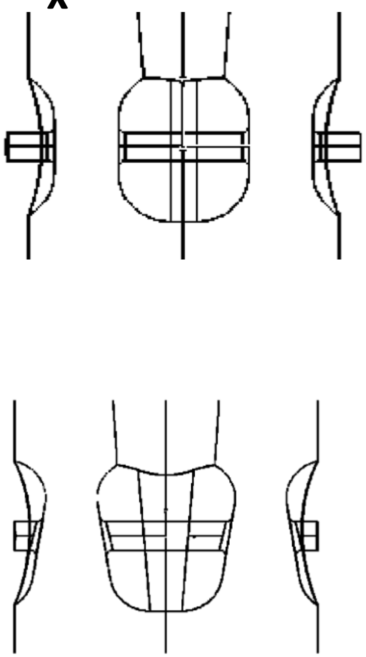
Port Blend Radius	Mesh Cells	Freq. MHz	β_opt	Epeak	Bpeak mT	R/Q Ω	QRs Ω
No Port	1.41 M	322.05	0.297	4.166	6.94	199.91	95.04
1/4"	3.76 M	320.70	0.298	4.307	10.2	198.12	96.19
2/5"	3.76 M	320.65	0.298	4.307	8.47	198.13	96.24
1/2"	3.74 M	320.60	0.298	5.033	7.91	198.13	95.94
3/4"	3.66 M	320.48	0.298	4.286	7.43	198.16	95.61
1"	3.80 M	320.33	0.298	4.368	7.08	198.19	95.52

Beam Steering in Quarter-wave Cavities

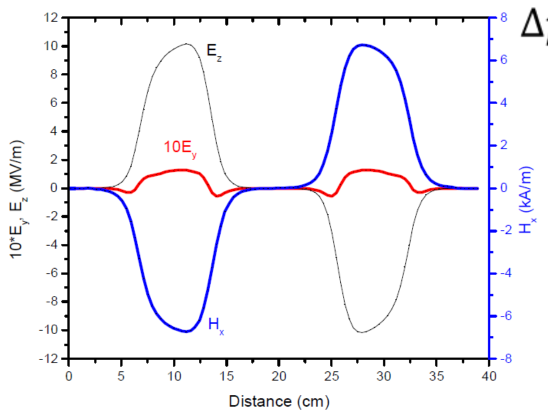
Beam steering due to unavoidable magnetic field on the beam axis when $\phi \neq 0$

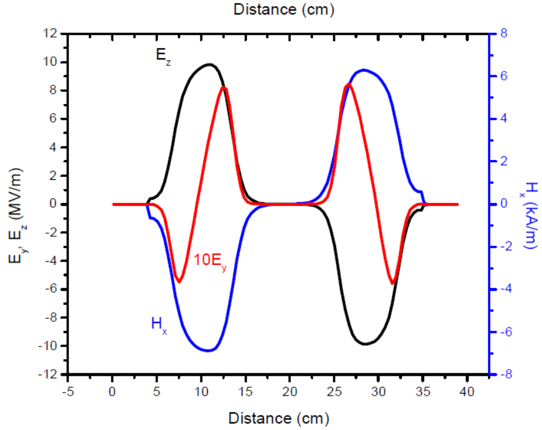
One remedy: The vertical field E_y, ‘normally’ small, may be modified by the cavity geometry to cancel magnetic steering due to H_x

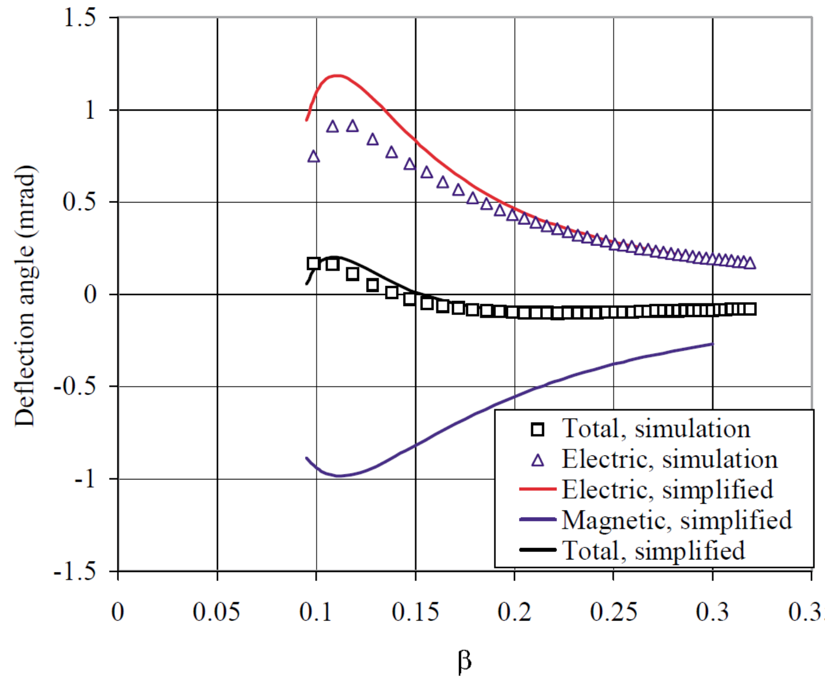




$$\Delta p_y \sim \frac{1}{\beta^2} \int_{L/2}^{-L/2} E_y \cos(kz+\varphi) + \beta c \cdot B_x \sin(kz+\varphi) dz$$





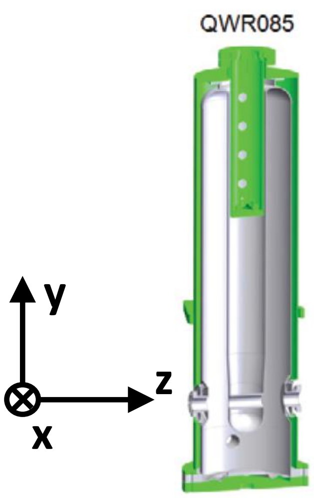


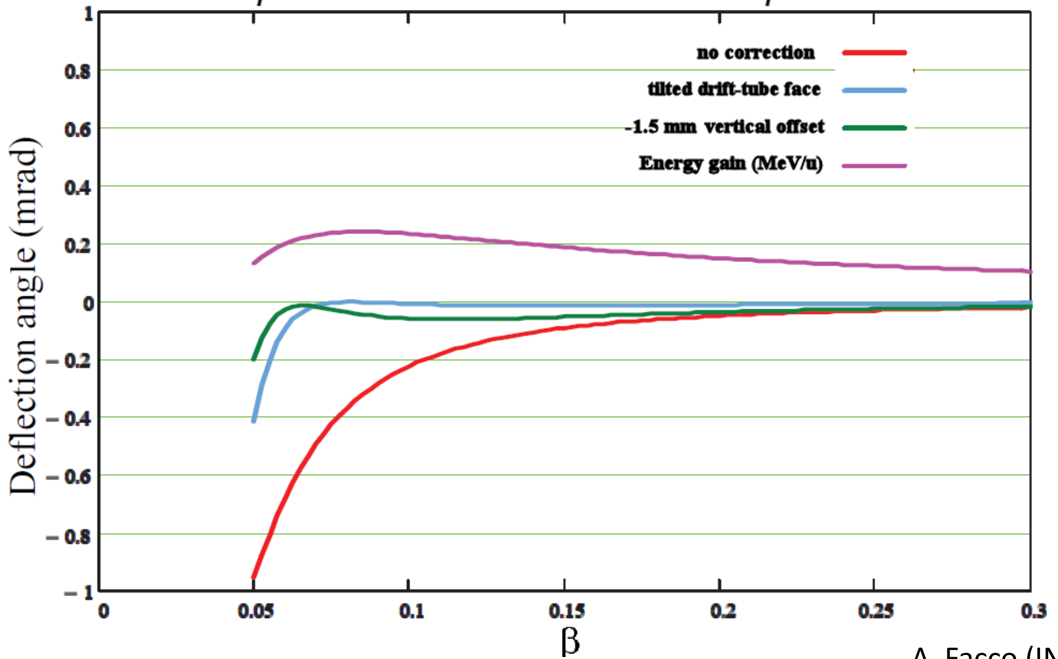
Beam Steering in Quarter-wave Cavities

The cavity may be shifted downward by an amount, y_0, to cancel magnetic steering due to B_x

$$\Delta p_y \sim \frac{1}{\beta^2}\int_{L/2}^{-L/2} \frac{y_0}{2}\frac{\partial E_z}{\partial z} cos\left(\frac{\omega z}{\beta c}+\varphi\right) + \beta c \cdot B_x\, sin\left(\frac{\omega z}{\beta c}+\varphi\right) dz$$

Note $\frac{\partial E_z}{\partial z} \sim \frac{1}{\beta}$ so defocussing term $\sim \frac{1}{\beta^3}$

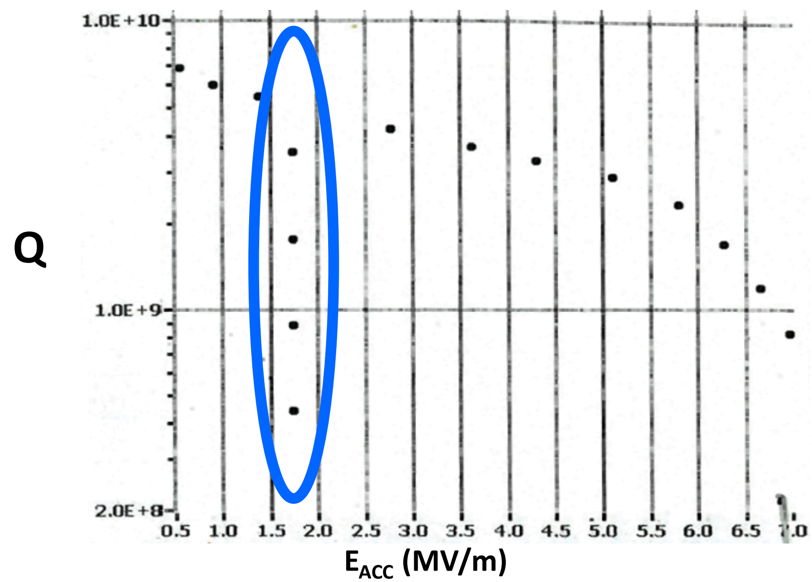




A. Facco (INFN) et al, IPAC12

Multipacting in TEM Cavities

- Multipacting: Secondary electron emission in resonance with cavity RF electromagnetic fields; leads to exponential electron multiplication



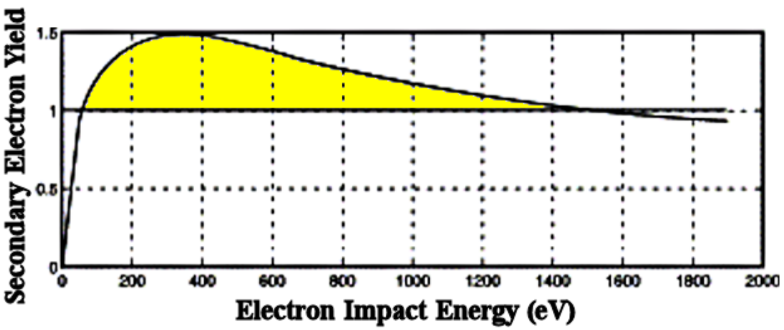
Example of 'multipacting barrier' in a 72 MHz QWR at E_{ACC}~1.7 MV/m; multipacting is distinct from field emission at higher fields

- Primarily a function of the cavity shape and properties of the surface

Multipacting in TEM Cavities

Niobium Surface

Example of a secondary electron spectrum for a wet-prepared niobium surface

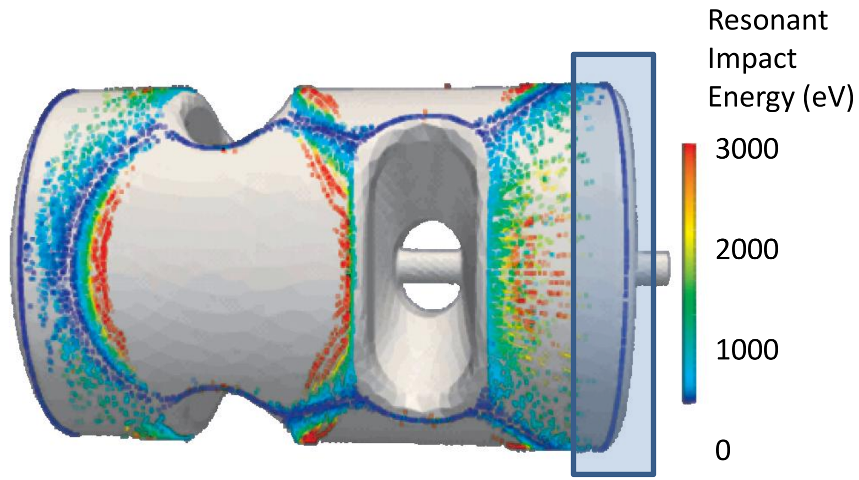


(Shemelin et al., NIM, V496)

Secondary emission in real cavities is a physical phenonmenon that depends on the work function of a complex niobium oxide and the detailed history of the surface treatment

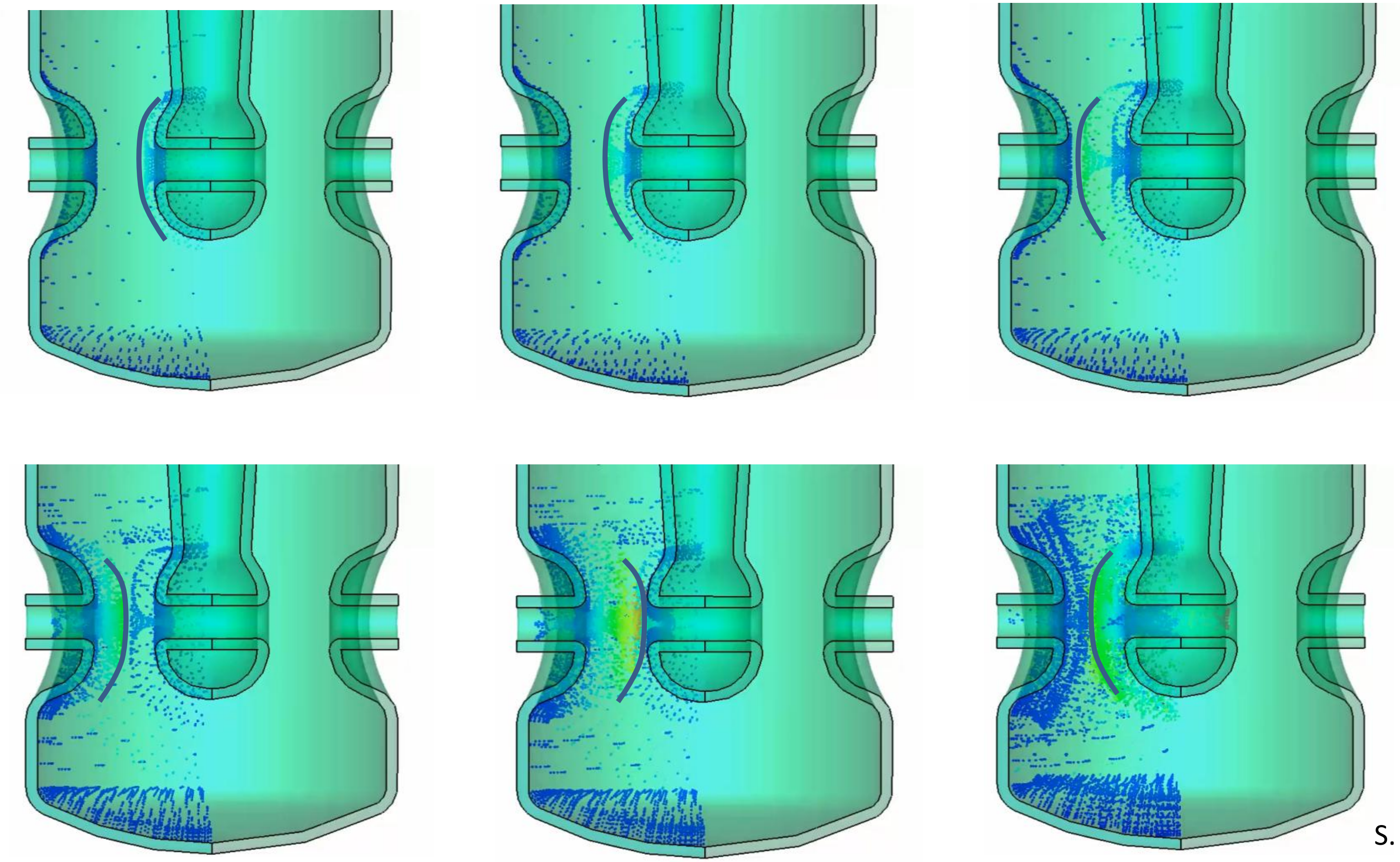
Geometry

End wall blend radius chosen to remove the resonant trajectories; however many regions still expected to produce resonant trajectories



C.S. Hopper
J.R. Delayen (ODU), PRSTAB

Multipacting in TEM Cavities
Example: 2 Point Multipacting in a QWR with E_{ACC}=8 kV/m



S. Kutsaev (ANL)

Transit time for electrons between gaps ~ one half cavity period = 7 nS

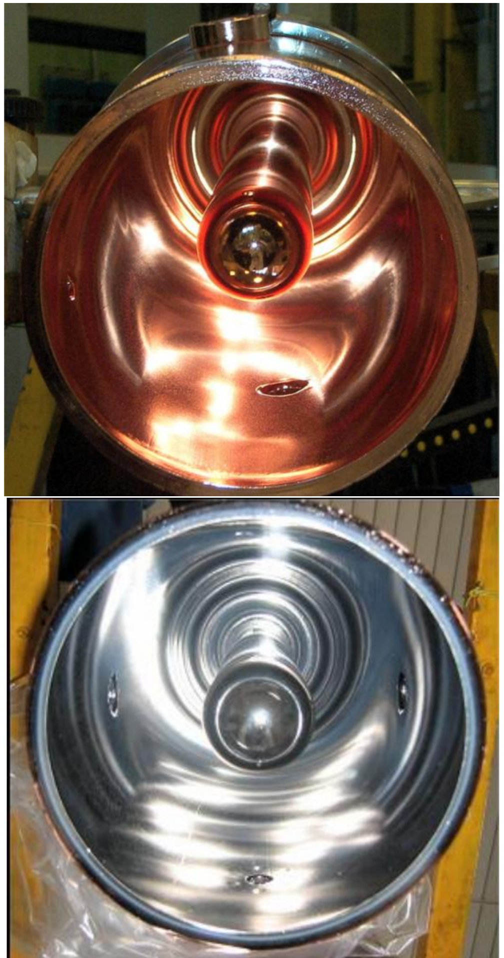
General Statements, Systematic Effects and TEM-cavity Design

- Parametric studies are effective to optimize EM properties within the bounds of an assumed geometry
- Geometrical improvements are almost always possible but may require increased complexity (cost)
- Quarter-wave cavities ($\lambda/4$) geometries are compact and have high shunt impedance; these are often the optimal choice for gradient and RF losses when v/c~0.1
- Half-wave and spoke cavities ($\lambda/2$) geometries have low surface fields; these are often the optimal choice in the range of 0.15 < v/c < 0.5; may be useful in applications up to v/c~1
- Surface fields can be 'traded off' to improve RF losses (possible gains appear to be ~ +/- 10%)
- Multipole fields can cause steering or defocussing; there are known mitigation techniques
- Multipacting effects can be reduced, but not eliminated, by design

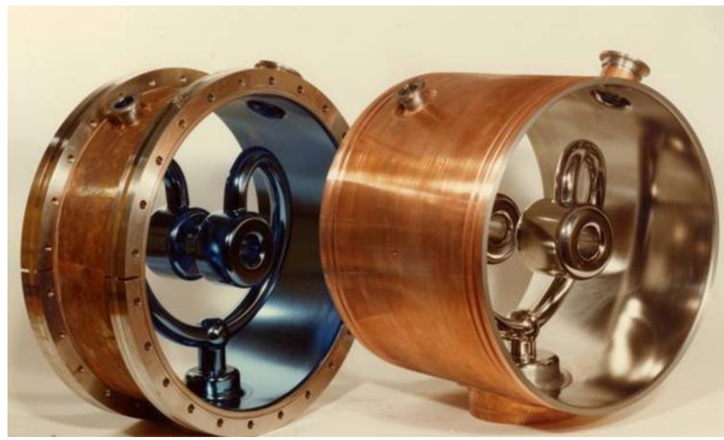
Mechanical Design

Mechanical Design for TEM-cavities

Technological Approaches Over the Years for Fabrication



Niobium sputtered onto copper



Niobium explosively bonded onto copper

'Bulk' niobium inside a helium vessel

Mechanical Design for TEM-cavities

Mechanical design considerations:

- Stresses in niobium and helium vessel under possible conditions of temperature and pressure
- Mechanical frequencies of the system
- Response of the cavity frequency to external pressure changes
- Needs for mechanical tuners or ‘coarse’ tuning during fabrication
- Response of the cavity to changes in the cavity field (Lorentz detuning)
- Interfaces (ports) for TEM-cavities

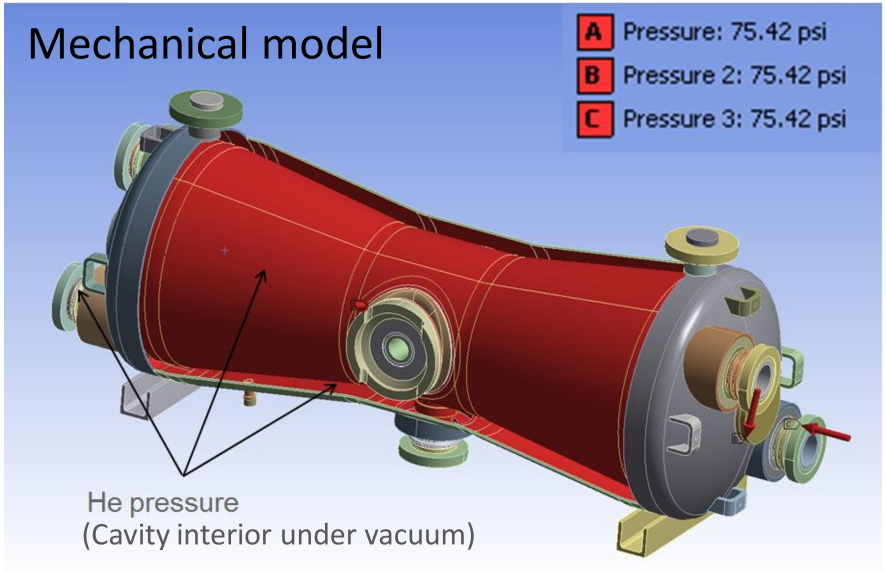
Mechanical Design for TEM-cavities

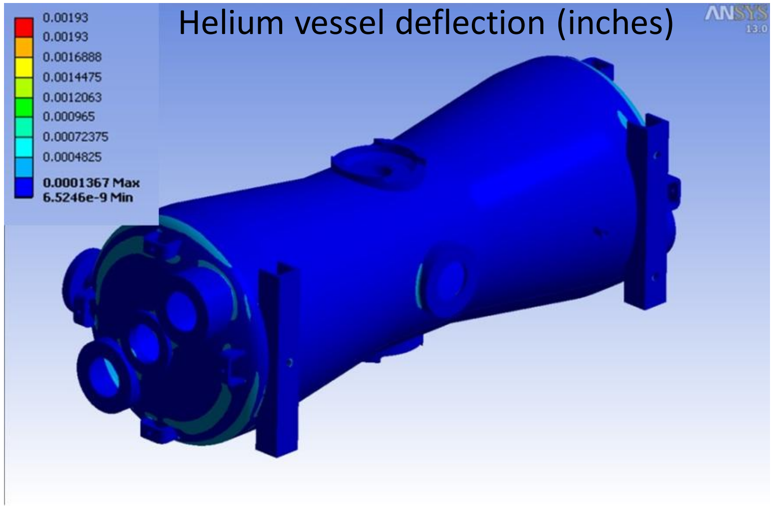
Other Comments:

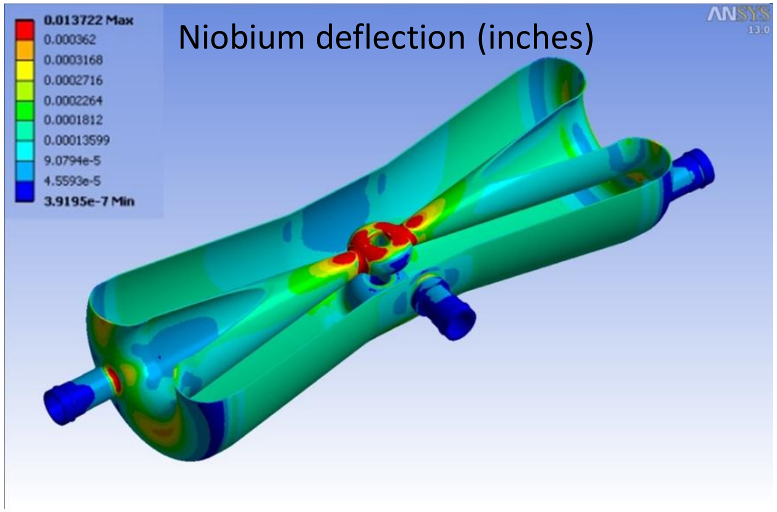
- Cavity should not collapse or detune during fabrication or operation
- May need to be designed and built in compliance with local pressure vessel regulations (ASME B&PV Code, Japanese High Pressure Gas Safety Regulations (HPGSR)
- Finite Element Analysis (FEA) and field testing are standard

(Combined expertise on SRF cavities and advanced mechanical engineering required to address all of these issues)

Design for Helium Pressure in Cavities with Double-wall

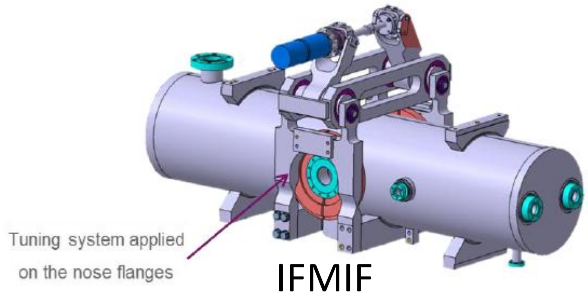






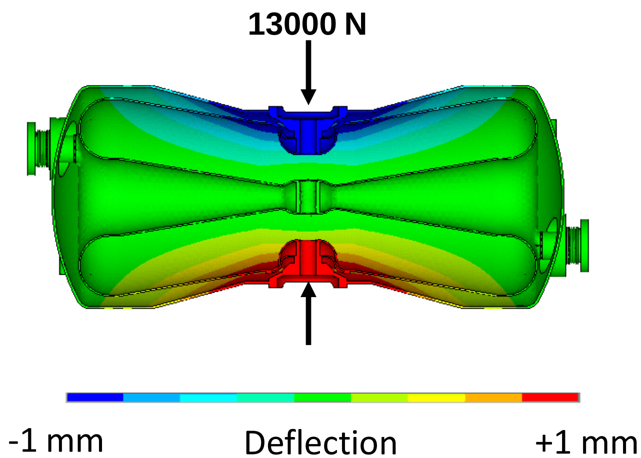
1. Physical model & boundary conditions
2. Material properties at room and cryogenic temperatures (*e.g.* niobium, titanium, stainless steel using elastic/perfectly plastic model)
3. Forces/pressures
4. Convergence to a stable solution predicts no plastic collapse (may still exceed yield)
5. Compliance with code may require other calculations for local failure, buckling and cyclic loading

Cavity Response to a Mechanical Tuner



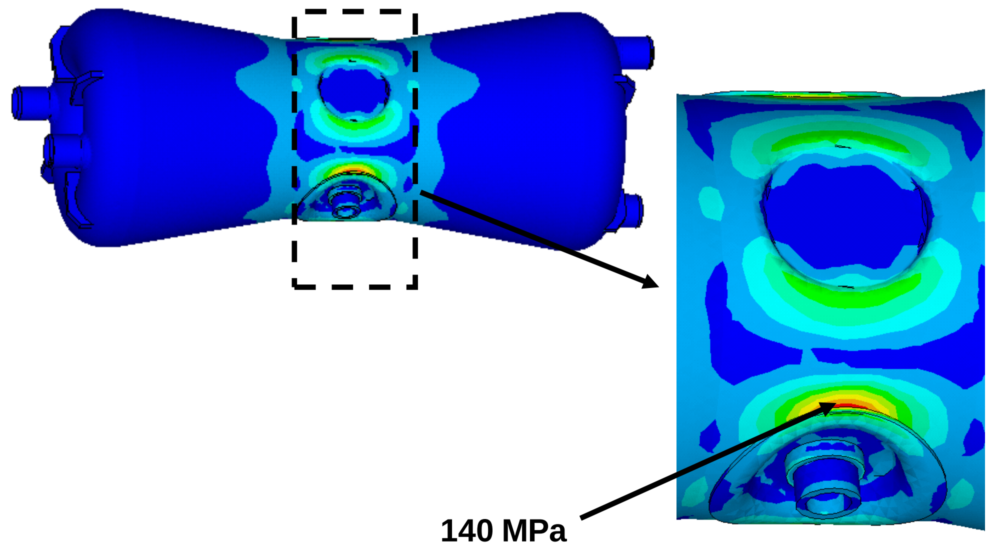
Force applied by two types of external tuners

Deflection and Frequency Response



(Δf=140 kHz @ 176 MHz and 4 K from coupled EM simulations)

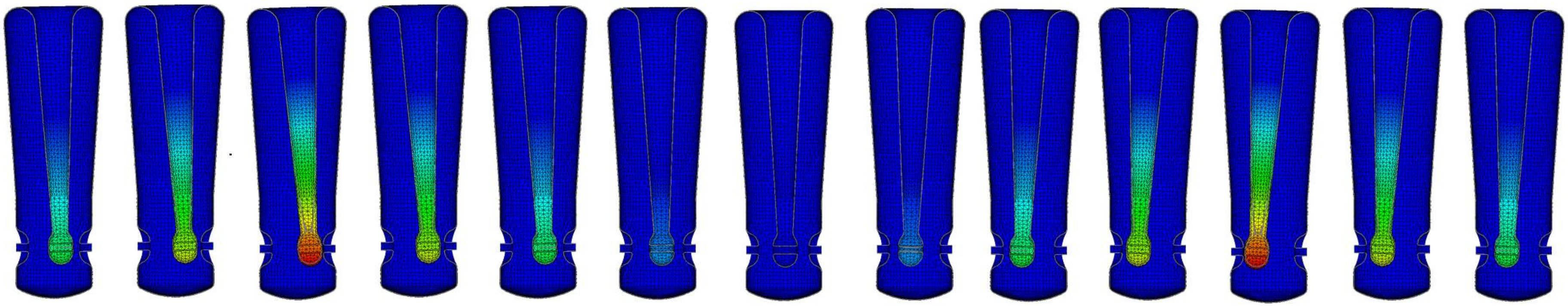
Material Stresses



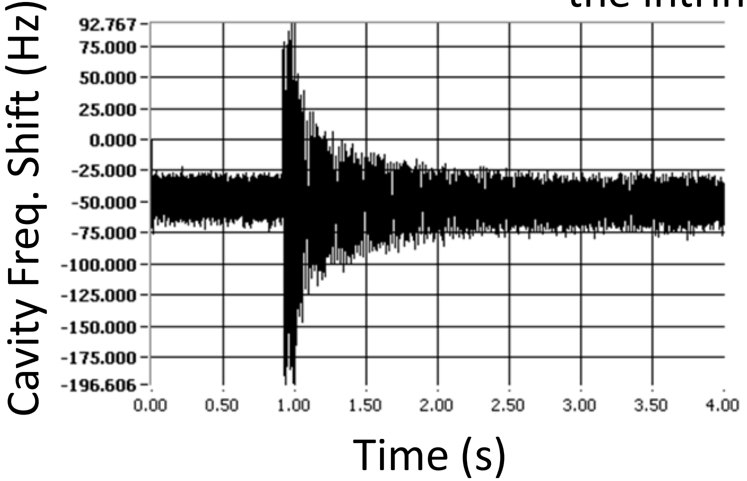
Common for local stress to exceed niobium yield (~50 MPa) at room temperature;
Slow tuner may not be able to run full stroke at room temperature

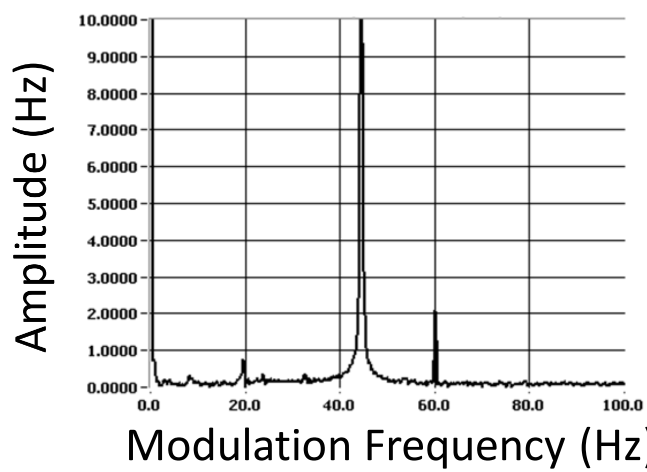
Mechanical Vibrations and Frequency Detuning

Quarter-wave cavities have a pair of degenerate mechanical eigenmodes, with relatively low frequency ~30-60 Hz (~100 Hz for HWR)

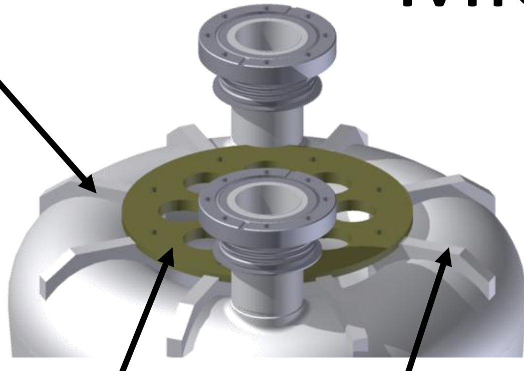


The amplitude of frequency modulations from external disturbances is many times the intrinsic cavity bandwidth





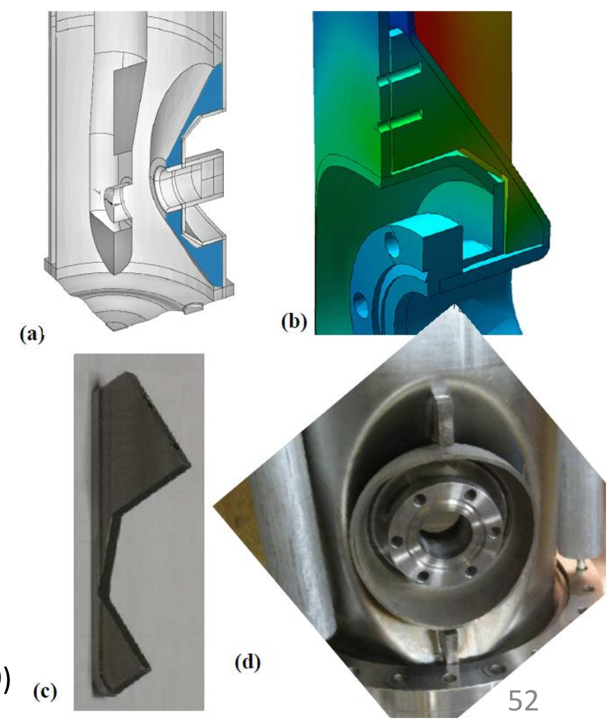
Cavity Mechanical Design and Microphonics

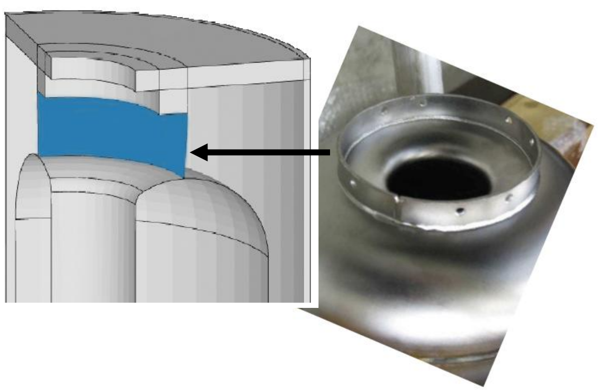


1 cm thick Titanium plate

1-1/4 cm thick niobium ribs

Mechanical stiffening for a β=0.077 QWR in magnetic field region (left) reduces $\Delta f/\Delta P$ and raises pendulum mode frequency (~50 Hz up to 67 Hz)





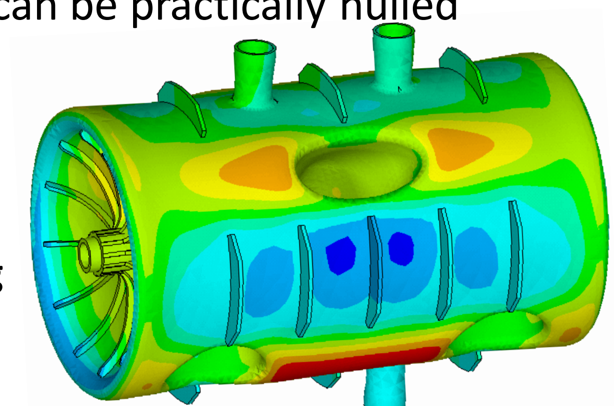
Mechanical stiffening for a β=0.041 QWR in magnetic field region (left) and electric field region (right) reduces $\Delta f/\Delta P$ and K_L

(Zaplatin, SRF 2009)

Response of the Cavity Frequency to External Pressure Changes

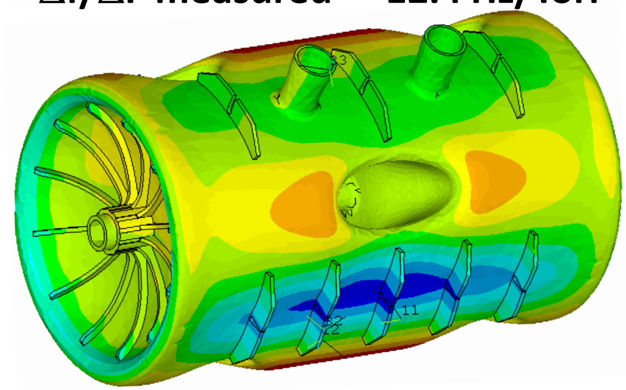
- Can be dominant contribution to frequency shifts in 4 Kelvin operation
- Inward pressure in E-field and H-field regions produce frequency shifts in opposite directions
- Example: Support ribs in E-field and H-field to ‘balance’ deflections so that $\Delta f/\Delta p$ can be practically nulled

Before Machining Ribs



$\Delta f/\Delta P$ measured = -12.4 Hz/Torr

After Machining Ribs



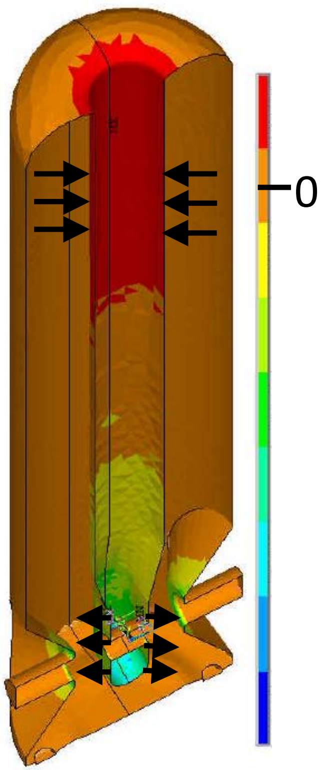
$\Delta f/\Delta P$ = -0.5 Hz/Torr

β=0.5 triple-spoke w/ support ribs

Shepard, Z. Conway (ANL)

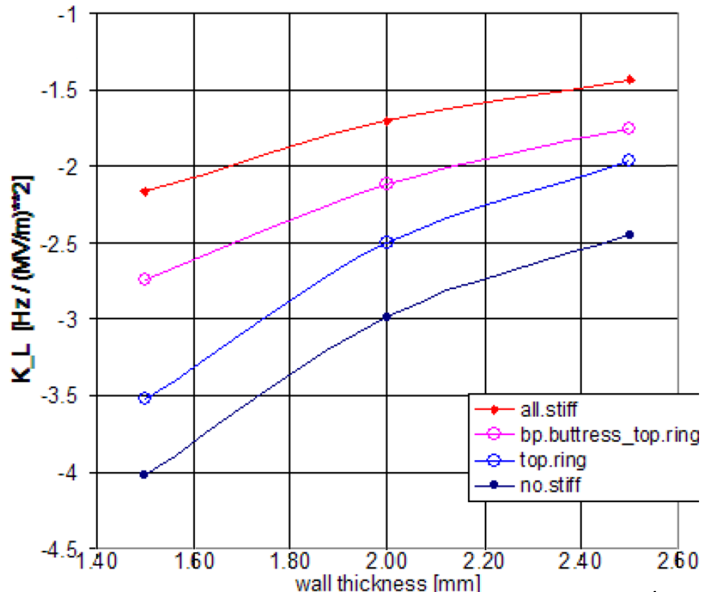
Response of the Cavity Frequency to RF Field Level (Lorentz Detuning)

- RF fields exert forces on the cavity wall proportion to square of surface fields
- Less important for CW operation
- Frequency can couple to field amplitude changes and contribute to microphonics (frequency variations producing phase instability)
- Shift is always negative; typical K_L values are between 1.5 and ~5 Hz/(MV/m)^2



EM force on walls of a QWR

$$\Delta F = K_L \cdot E_{ACC}^{\;2}$$



(Zaplatin, SRF 2009)

Cryogenic Design Issues for TEM Cavities

- Gravity fed cryogenic access port at the top of cavity helium vessel with area ~10 cm^2 ; Cavity RF losses~10 Watts or 1/2 gm/s at 4.2 Kelvin
  - (Trapped) helium bubbles a consideration at 4 Kelvin
- Cooling of the cavity RF surface through thin (3 mm) high RRR niobium to helium bath not a design constraint

$$\text{Heat Transfer (RRR} = 250\text{) Q} = \frac{1\ cm^2}{0.3\ cm} \int K(T)dT \approx 10 \frac{Watt}{cm^2}$$

(Large heat loads can be tolerated over a limited area)

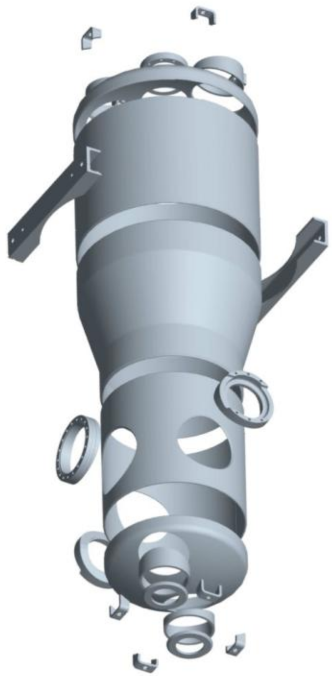
- However, TEM cavities often incorporate conduction cooled components or use thicker niobium material
  - Conducting cooled parts require study and conservative design

Fabrication

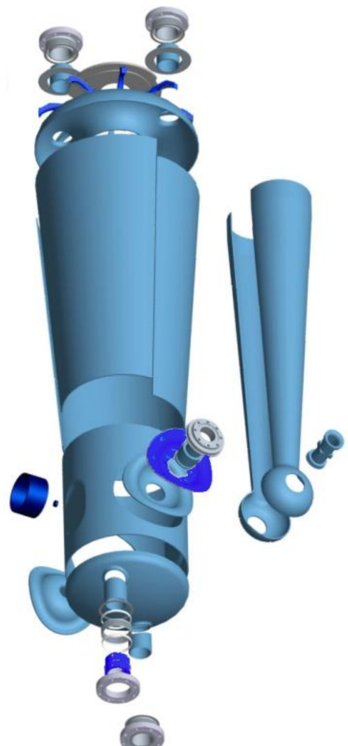
TEM-cavity Fabrication

- High-purity fine grained Niobium is commonly used for both TEM- and elliptical-cell cavities
  - Available commercially from several vendors
  - It is formable, weldable, and machinable
- Established and commercially available fabrication techniques exist. These have been developed through several decades of experience.
  - Hydroforming and deep drawing
  - Electron beam welding
  - Machining and electric discharge machining (EDM)
  - Brazing
  - *Details in the literature are sparse – often these are closely held by a particular industry (or person within industry)*
- Obvious statement: All fabrication steps involving niobium cavity are critical; fabrication is done in industry or scientific labs, however, all techniques require knowledge of the requirements for good SRF performance

TEM-cavity Fabrication
Quarter-wave Parting

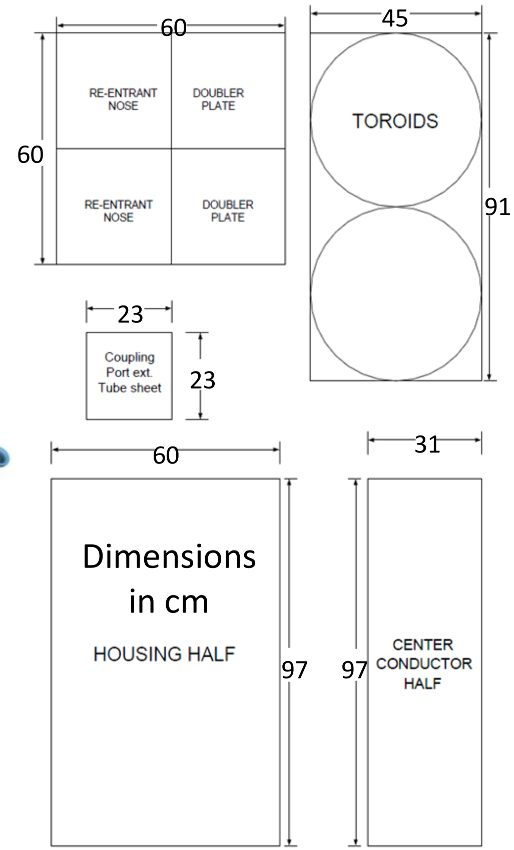


Helium vessel (stainless steel - gray)



Niobium - blue

Geometry of subcomponents matched to material size/properties and vendor capabilities



Major niobium subcomponents parted from 3 mm niobium sheet

Major niobium subcomponents formed from 3 mm niobium sheet

Fabrication: An Example of Coarse Tuning

Purpose: To adjust cavity dimensions during fabrication in order that the (cold) cavity frequency is sufficiently close to target (master oscillator) and within the range of a ‘slow tuner’.

Example for a QWR:

Master Oscillator Clock	12,125	kHz
↓ Cavity Harmonic	6	
↓ Target Frequency Cold in Cryomodule	72,750	kHz
↓ Slow Tuner Frequency Range	20	kHz
↓ Target Frequency Cold (Slow tuner off)	72,760	kHz

A General Tuning Approach: Begin with the target frequency and track backwards though each operation that affects the cavity frequency

Fabrication: Tuning

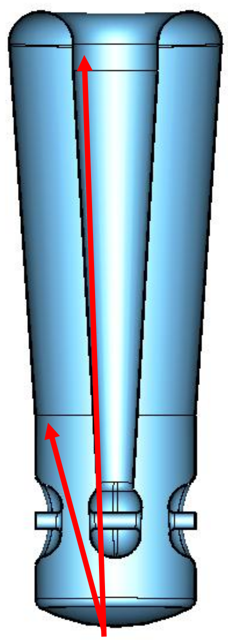
Example of 2 Primary Stages for Adjusting Cavity Frequency

Calculations for initial tuning cuts*

Length	Frequency (kHz)	ΔFrequency (kHz)
-5 mm	73,132	273
-4 mm	73,077	218
-3 mm	73,021	162
-2 mm	72,968	109
-1 mm	72,914	55
Reference	72,859	0
+1 mm	72,804	-55
+2 mm	72,750	-109
+3 mm	72,698	-161
+4 mm	72,641	-218
+5 mm	72,589	-270

High Sensitivity +55 kHz/mm

*CST MWS

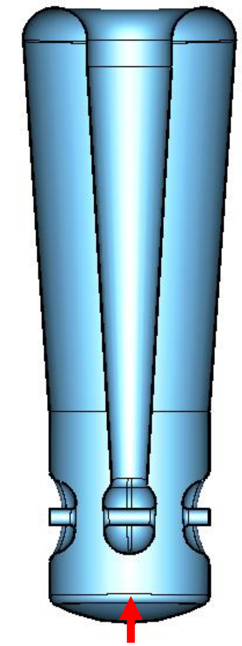


Trimming Locations

Calculations for final tuning cuts*

Length	Frequency (kHz)	ΔFrequency (kHz)
-5 mm	72.846	-13
-4 mm	72.847	-12
-3 mm	72.852	(-7)
-2 mm	72.851	-8
-1 mm	72.856	-3
Reference	72.859	0
+1 mm	72.862	3
+2 mm	72.863	4
+3 mm	72.868	9
+4 mm	72.869	10
+5 mm	72.873	14

Lower Sensitivity -3 kHz/mm



Trimming Location

Fabrication: Tuning

	Frequency Tuning Table	Δ Frequency (kHz)	Frequency (kHz)
0)	**Cavity frequency cold in operation**		72,750.0
1)	1/2 of slow tuner frequency shift	10	72,760.0
2)	Lower Helium Pressure from 1.3 to 1.0 Bar	0.4	72,760.4
3)	Warm cavity up to room temperature	-104.1	72,656.3
4)	Vent rf space from vacuum to 1 Bar	1.19	72,657.5
5)	Δfrequency due to dielectric constant of air	-22.4	72,635.1
6)	Electropolish cavity (250 micron)	-28.5	72,606.6
7)	Add weld shrinkage for bottom dome: 0.7 mm	2.1	72,608.7
8)	Indium wire thickness clamping bottom dome 0.25 mm	0.8	72,609.5
8)	Add back 0.635 cm bottom dome cut	16.5	72,626.0
9)	Add Tapered housing weld shrinkage top: 0.7 mm	4.2	72,630.2
10)	Add Tapered housing weld shrinkage bottom: 0.7 mm	2.8	72,633.0
11)	Add tapered housing (top) Indium wire: 0.25 mm	1.5	72,634.5
12)	Add tapered housing (bottom) Indium wire: 0.25 mm	1	72,635.5
13)	Add center conductor weld shrinkage: 0.5 mm	-30.5	72,605.0
14)	Add center conductor indium wire: 0.25 mm	-15.2	72,589.8
15)	Add back center conductor/cylinder cuts: 1.25 cm	-690.9	71,898.9
16)	Add back center conductor/cylinder cuts: 1.25 cm	-690.9	71,208.0
17)	Add back in material cut from bottom of cylinder: 3.175 cm	53	71,204.0

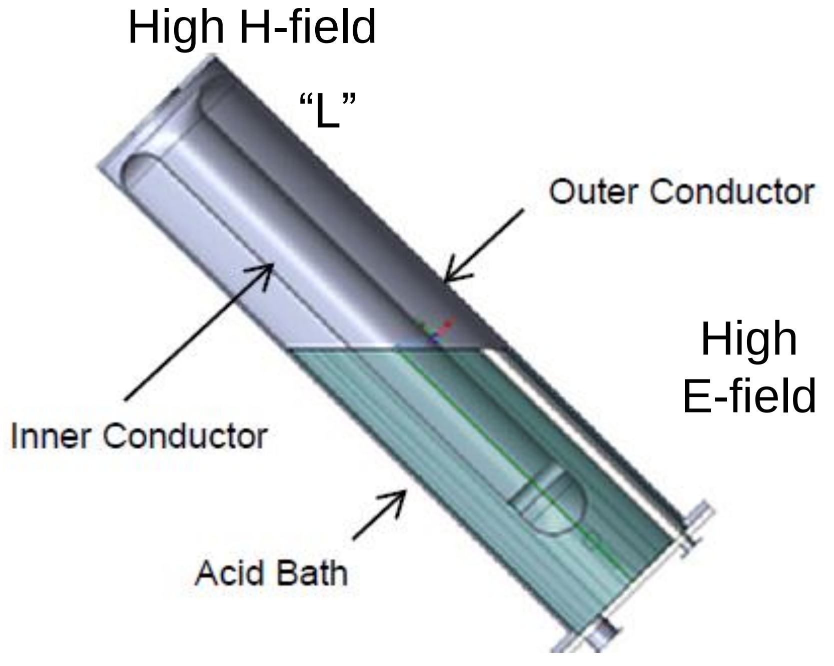
Time sequence

This represents the first time that the cavity is clamped together as an assembly

For a couple of steps, experimental error versus predicted turned out to be a large fraction of slow tuner range

→ **Need to prototype**

Fabrication: Tuning by Chemistry



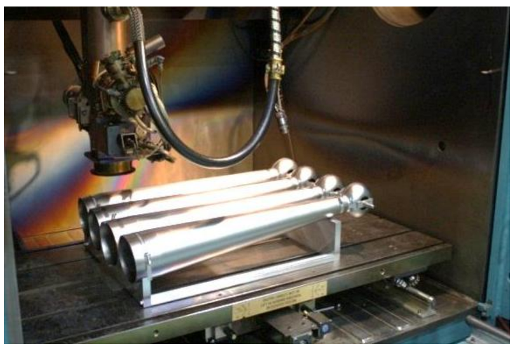
- Preferential removal from the RF surface by chemistry to lower the effective capacitance and raise the frequency
- Tilt and rotation prevent formation of a sharp step
- Effective tuning range ~ 100 kHz

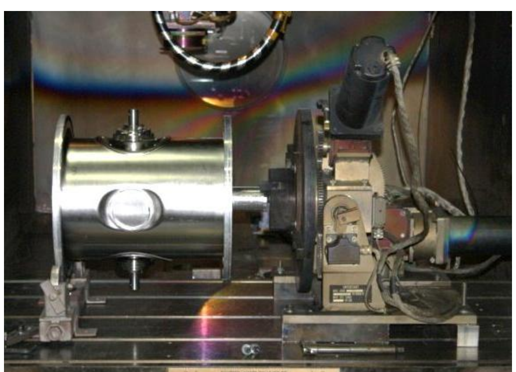
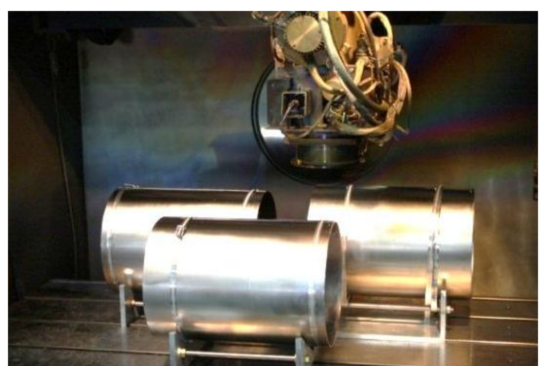
K. Saito (FRIB)

Fabrication: Assembly by Electron Beam Welding

The variety of geometrically complex welds for modern TEM-cavities (relative to e-cell) usually require:

- Large high-vacuum welding chamber
- Programmable electron gun with multiple axes
- Engineered fixtures to hold or manipulate cavity parts
- Weld development on test samples for new geometries (Parameters include: beam current and focus, beam oscillation, beam speed with respect to part, gun-to-work distance)



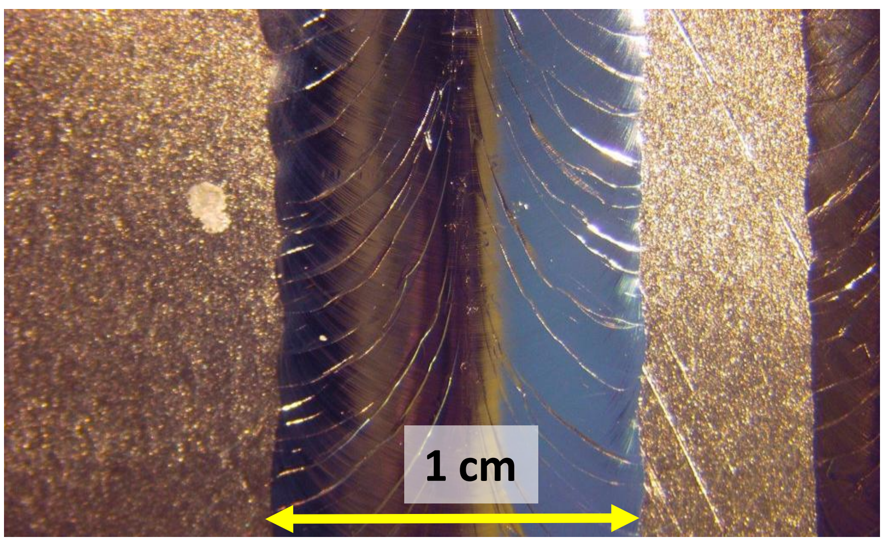




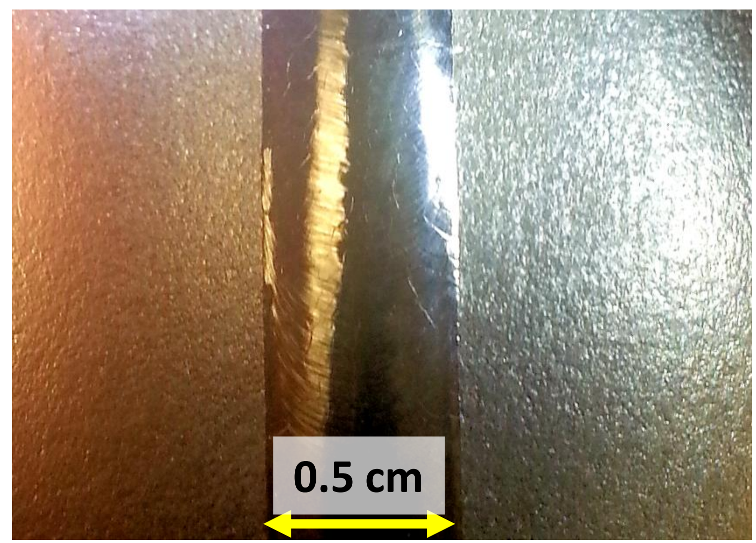

Fabrication:
Details on Electron Beam Welding

TEM-cavity using two weld types: 'Through welds' from the helium side or 'Keyhole' welds from the RF side; differences include:

- ~4 times more heat and larger heat affected zone for through welds than for keyhole welds
- Weld shrinkage 0.7 mm (for 3 mm sheet) for through weld, 0.5 mm for keyhole weld
- 100 micron grain step sizes for through welds; much less for keyhole after 'cosmetic pass'
- Though welds very sensitive to orientation with respect to the direction of gravity
- Keyhole welds suitable for very thick material (1 cm or more); Through welds good to ~3 mm

'Keyhole welds' have several advantages; both types well demonstrated where good SRF performance in a high field region is required

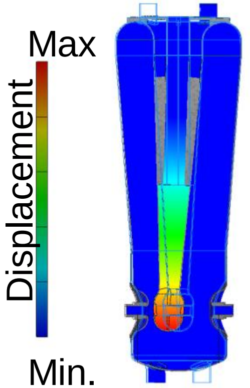




Fabrication: Alignment of Central Conductor

Mechanically bending the center conductor to maximize the frequency practically eliminates microphonics from pendulum mode (frequency shifts are 2nd order with respect to position)

- Performed for displacements parallel and perpendicular to the beam axis
- In practice, no position measurement needed; only a frequency measurement (network analyzer) and a method to impart displacement



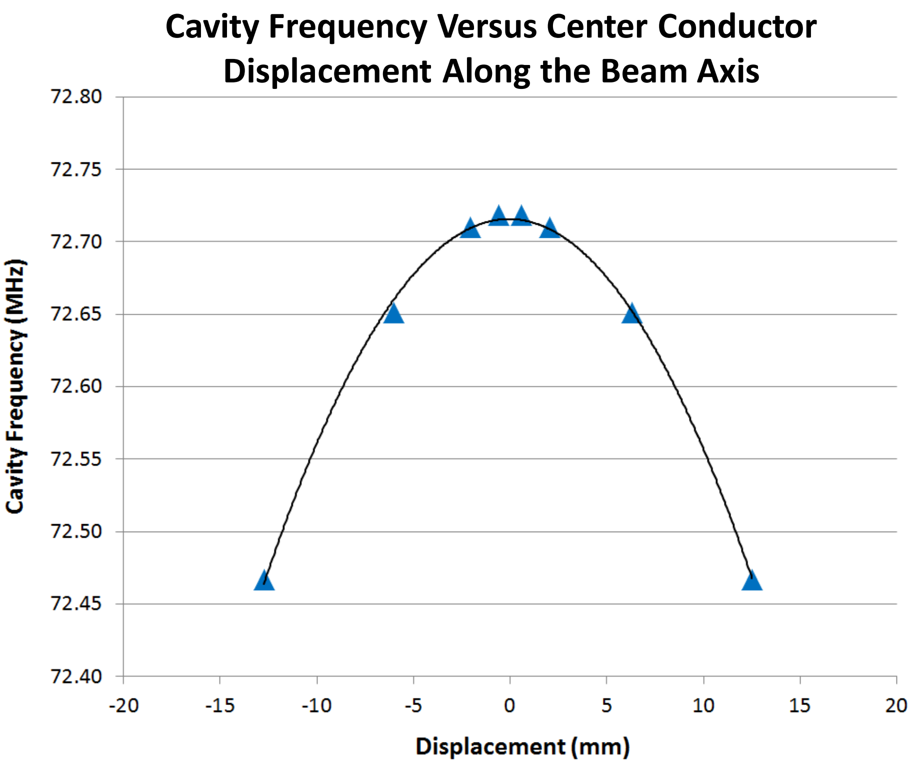
Freq. vs. displacement $f(x) = -1.643x^2 - 0.831x$

Change in Freq. vs. displacement

$$\frac{\partial(f)}{\partial x} = -3.286x - 0.831$$

Minimum given by:

$$\frac{\partial(f)}{\partial x} = 0 \qquad x_0 \cong 0.25 \text{ mm}$$



Fabrication: Helium Vessel Designs

Technical Considerations:

- Many effects on the niobium cavity during fabrication, tuning, cooling down to cryogenic, and operations
- Pressure and cryogenic requirements
- Cavity beam axis alignment

Technical Solutions:

- Stainless steel – large industrial base; brazed to niobium; need to consider differential contraction with niobium
- Titanium – thermal contraction similar to niobium; electron beam welded to niobium through an intermediate niobium-titanium alloy or direct to niobium
- Niobium – 'Reactor' grade; no material transitions; superconducting so may provide benefits of a Meissner shield

Stainless steel

Titanium

Niobium

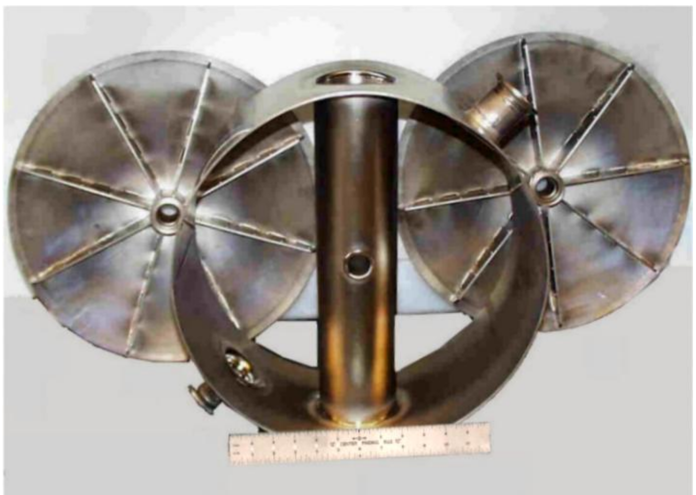
TEM Cavities and Surface Processing/Cleaning

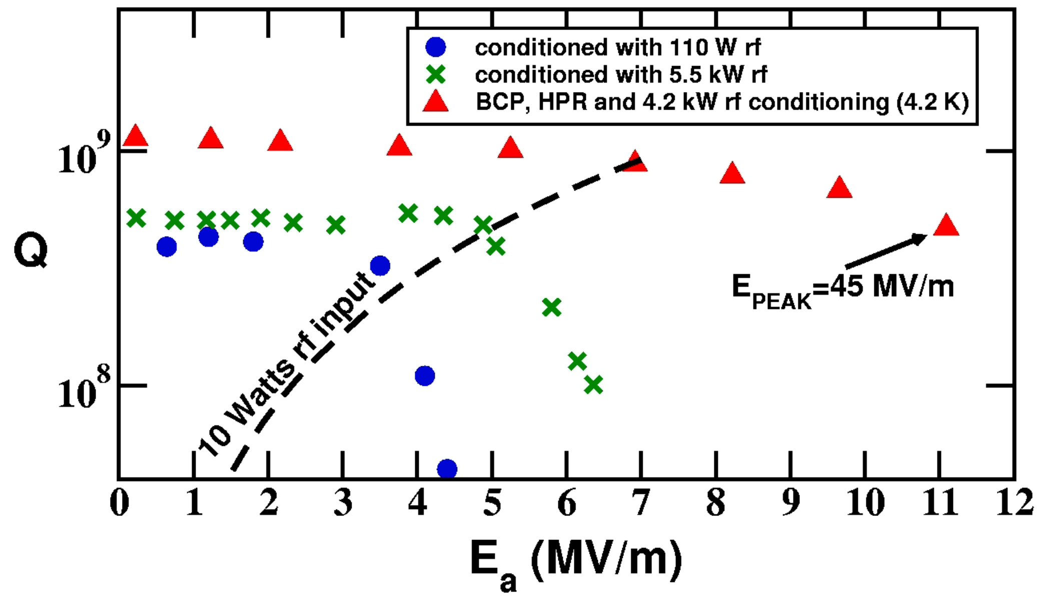
Similar as for elliptical cavities…

- Pre-cleaning (*e.g.* ultrasonic cleaning)
- Heavy removal of niobium from the RF surface, *e.g.* 100 μm
- Remove hydrogen by baking in a high temperature vacuum furnace
- Final mechanical tuning (center conductor alignment)
- Light removal of niobium from RF surface, *e.g.* 20 μm
- High-pressure water rinsing in a low particle clean room area
- Assembly, evacuation and low temperature baking

Issues specific to TEM cavities are associated with some more complicated geometries and the size and location of access ports

Early Spoke Cavity and the Use of Clean Assembly

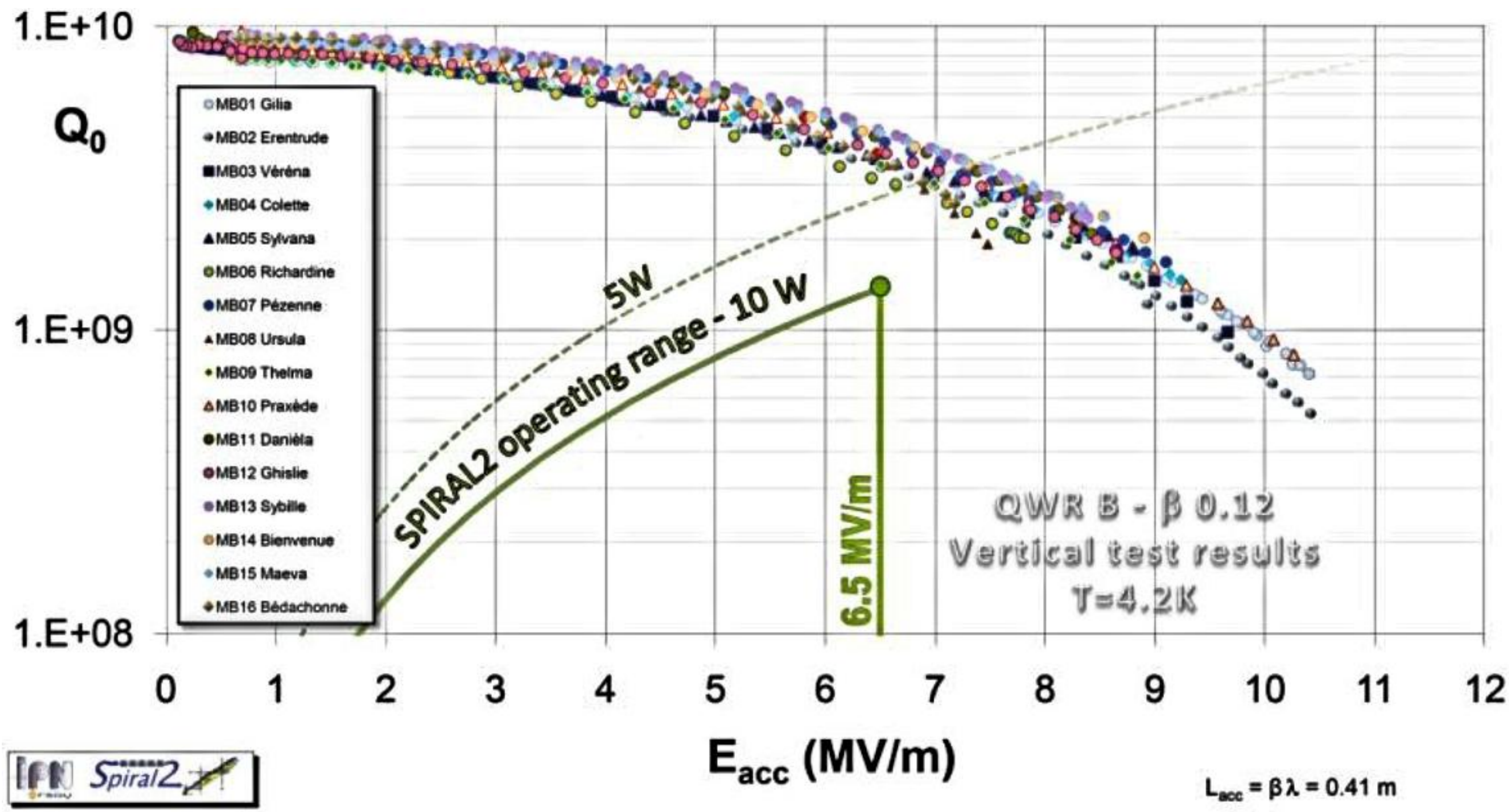




High-pressure water rinsing and pulsed processing used to improve cavity field performance

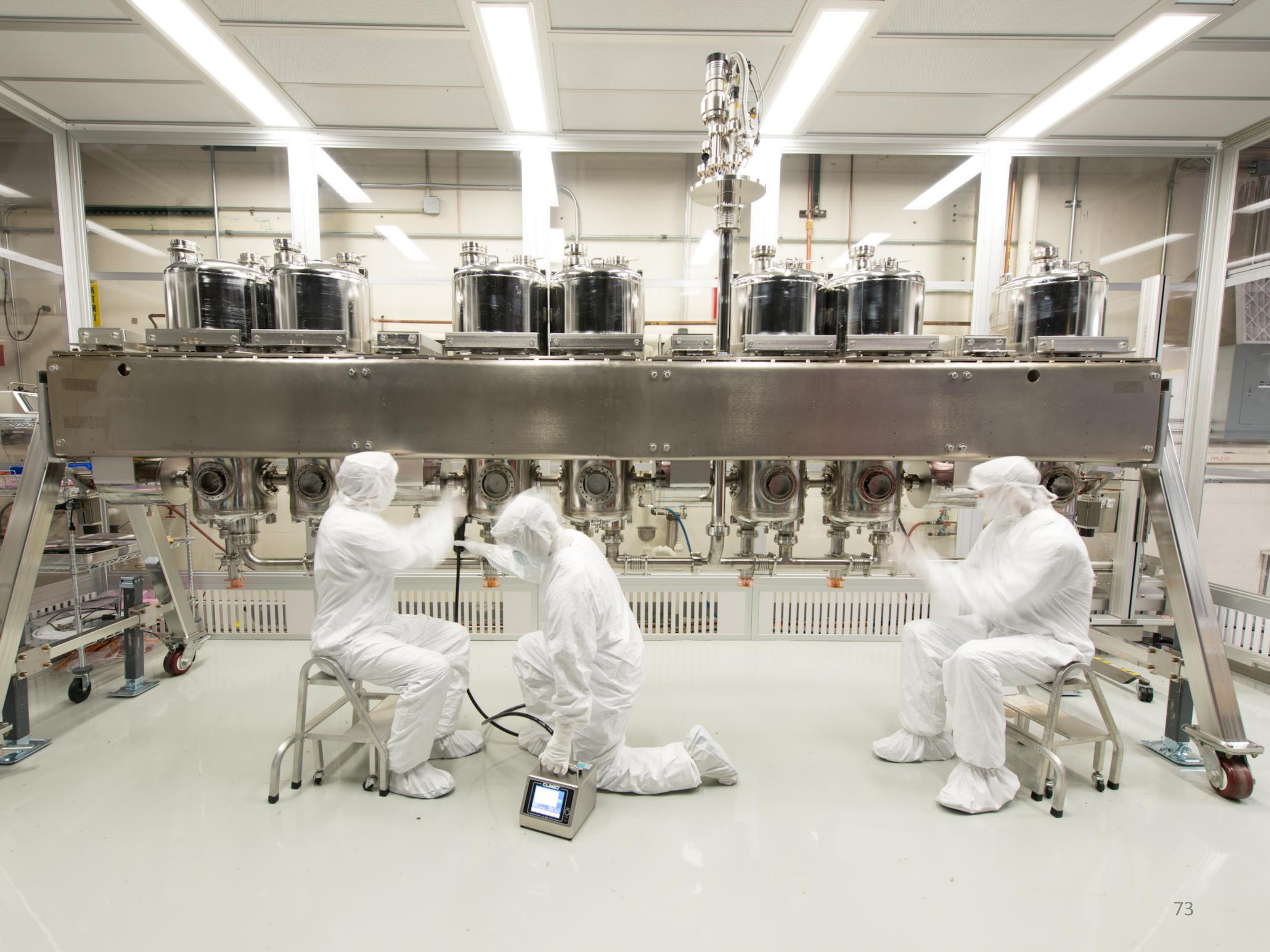
M. Kelly 2001 (ANL)

Performance Curves for 8 Quarter-wave Cavities



Some Recent Hardware


IPN
orsay
SUPRATech



Last Comments

Nothing magical about TEM cavities

A large variety of technical solutions to the many problems have been developed over four decades

The area of reduced beta SRF is particularly dynamic and there is lots of room for new good ideas

The number and variety of machines requiring TEM cavities is larger than ever, so,

Survey the field, build hardware, test hardware, build some more – ***Thank you***