

SRF2015 – Whistler, BC, Canada

Tutorial n.7

**Non-Elliptical Resonators
Part I**

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INFN/LNL and FRIB/MSU

Preface

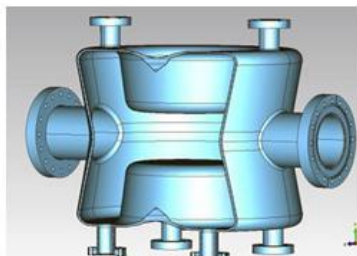
- *This is a tutorial. Its aim is not to be fully exhaustive and rigorous in all aspects, but to transmit key points and fundamental concepts in the field. The material is presented in a way that should be understandable without difficulties by physicists, engineers and also students in these disciplines who are beginners in SRF.*
- *This presentation includes material taken from many sources, and also from previous SRF tutorials which contain additional information and points of view in some specific parts. Their reading, having in mind that technology evolves with time, is recommended too (especially of the last ones: Delayen 2011, Kelly 2013)*

The zoo of Non-Elliptical SRF resonators

$\beta \sim 1$ SC accelerating cavities:
mostly “elliptical” shapes



$\beta < 1$ resonators, from very low ($\beta \sim 0.01$) to very high ($\beta \sim 1$):
many different shapes and sizes, mostly non-elliptical



$\beta = 1$ compact deflecting cavities: non-elliptical shapes

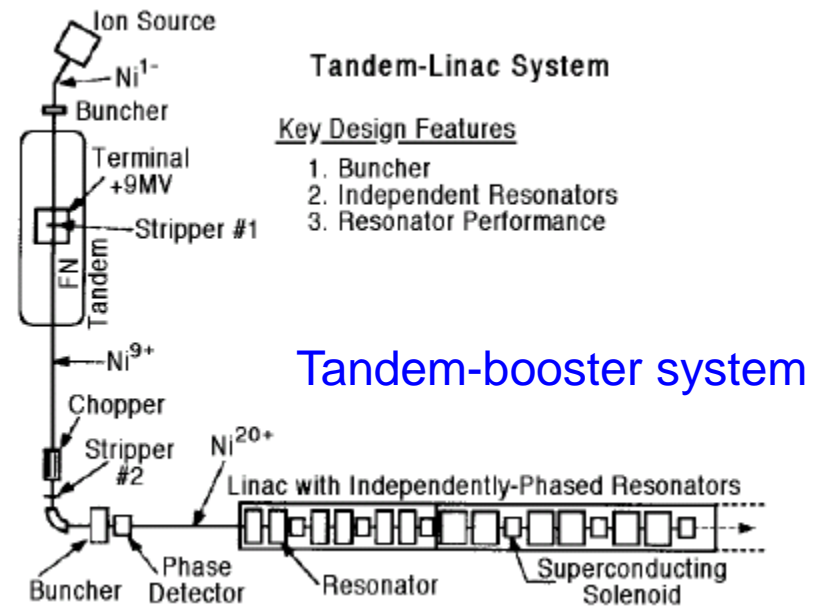
How did we get there?

Some history

The first low- β SC cavities application

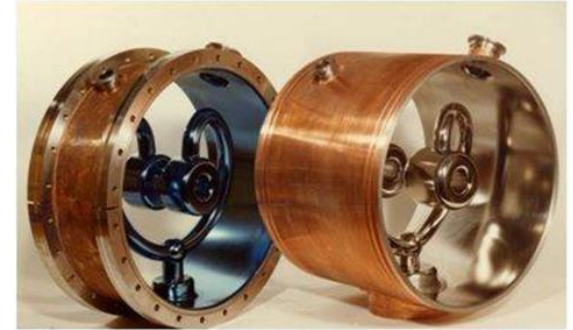
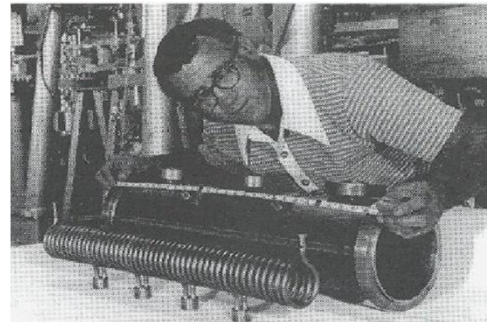
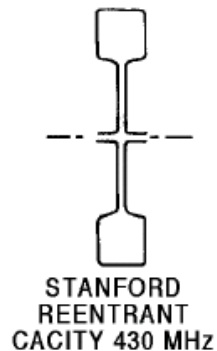
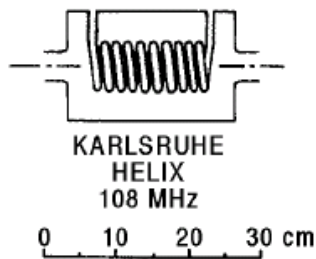
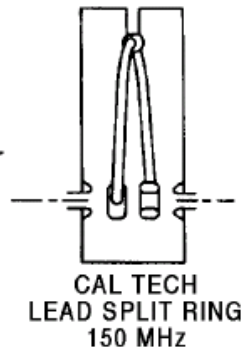
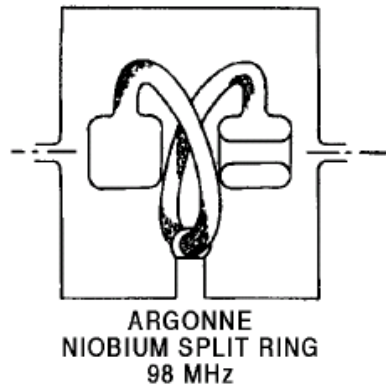
HI boosters for electrostatic accelerators: first and ideal application of SC technology, hardly achievable NC cavities

- Low beam current: all rf power in the cavity walls
- 2÷3 gap: wide β acceptance for different ion energies
- Cw operation



New problems: very narrow rf bandwidth, mechanical instabilities

Early resonators: 70's pioneers



• $\beta \sim 0.1$

• Materials:

• Bulk Nb

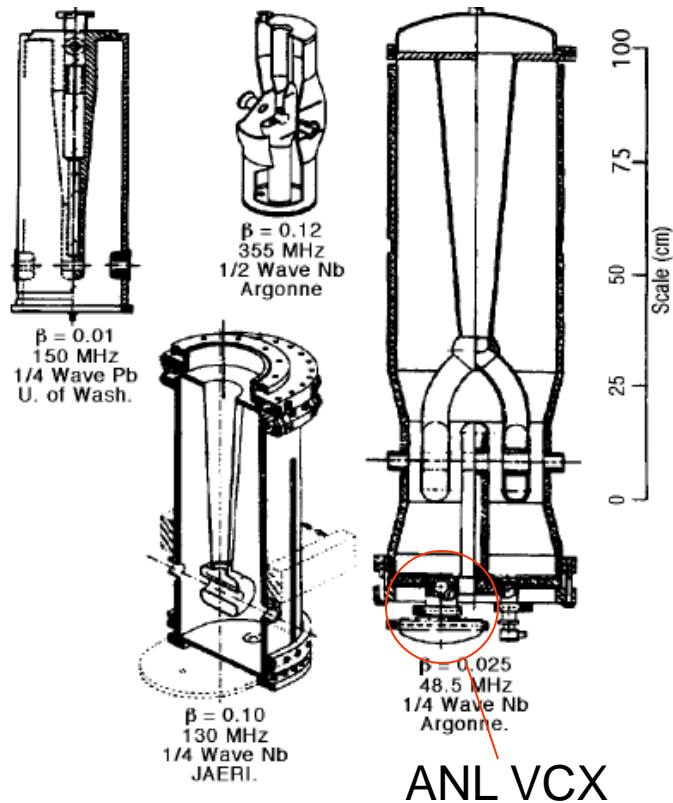
• Pb plated Cu

• E_a typically 2 MV/m

• Mechanical stability problems solved by the **first electronic fast tuners** for Helix resonators

Low- β cavities for ion boosters developed in the 70's

SC low- β resonators : 80's



- First low- β SC Positive Ion Injector at ANL:
 $\beta \sim 0.001 \div 0.2$
- All ion masses
- New materials:
 - **Explosive bonded Nb on Cu**
- Mechanical stability problems solved by electronic fast tuners VCX at ANL
- E_a typically **3 MV/m**; first operation above **4 MV/m**

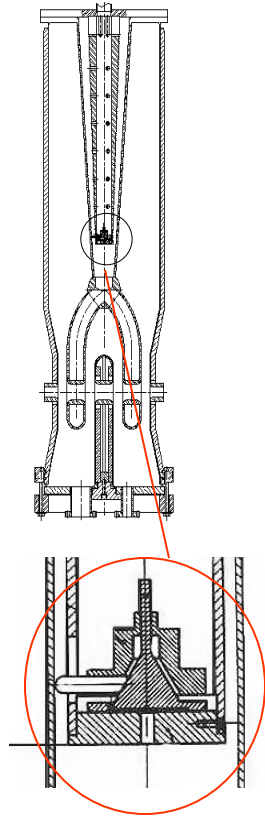
Low- β cavities in the 80's



HI SC low- β resonators: 90's



Low- β cavities
in the 90's

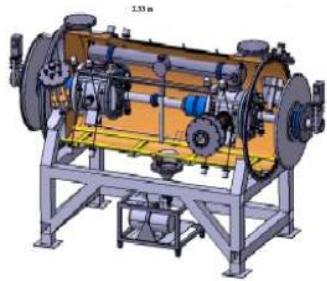
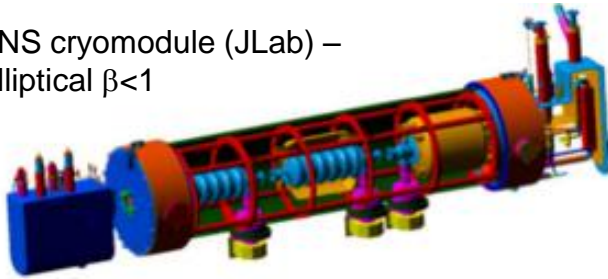


LNL damper

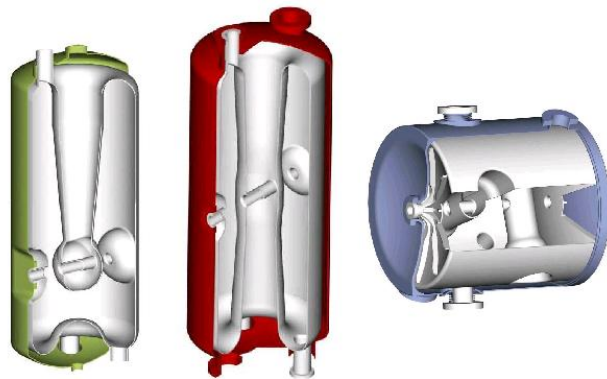
- $\beta \sim 0.001 \div 0.2$
- New materials:
 - **Sputtered Nb on Cu** at LNL
- Linac project with **SC RFQ** starts at LNL
- Mechanical stability problems solved also by mechanical damping
- E_a typically 3-4 MV/m; first operation at **6 MV/m** after introducing HPR (High Pressure Water Rinsing)
- Development of $\beta \sim 0.3 \div 0.6$ Spoke cavities starts at ANL

P,D and HI SC low- β resonators: the millennials

SNS cryomodule (JLab) –
Elliptical $\beta < 1$



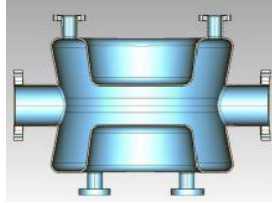
2-gap spoke cavity and cryomodule (IPNO)



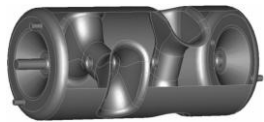
QWR, HWR and Spoke cavities (ANL)

- $\beta \sim 0.001 \div 0.8$
- material: mainly **Bulk Nb**, but also **sputtered**
- Electropolishing (EP) adopted as standard surface treatment for low- β cavities at ANL
- First high intensity SC low- β linacs started construction
- Development for RIB facilities, neutron spallation sources, Accelerator Driven Systems...
- Design E_a typically **6 \div 8 MV/m**, up to 15 for multicell elliptical resonators

SC non-elliptical resonators: present



Crab cavities (ODU and BNL)



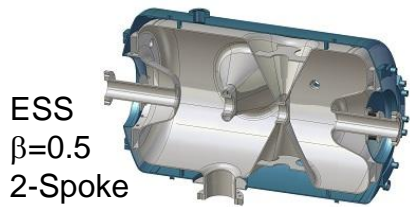
Proposed $\beta=1$,
2gap spoke (ODU)



FRIB $\beta=0.53$ & 0.29 HWRs



ANL $\beta=0.077$
QWR



ESS
 $\beta=0.5$
2-Spoke

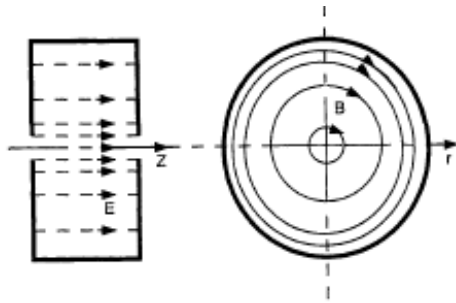
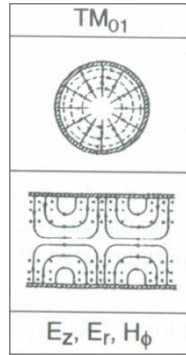
- **Non-elliptical cavities (former “low- β ”): $\beta \sim 0.001 \div 1$**
- New geometries for $\beta=1$ SRF deflecting cavities
- Spoke cavities developed also for $\beta=1$
- Winning geometries: QWR and HWR (incl. Spoke)
- material: mainly **Bulk Nb**, but also **sputtered QWRs**
- New treatment: N-Doping increasing Q (FNL)
- First beams from high intensity SC low- β linacs
- Design E_a up to above **10 MV/m**
- Several large projects ongoing worldwide: RIB facilities, neutron spallation sources, Accelerator Driven Systems, Synchrotron injectors upgrades, luminosity upgrades

And many more...

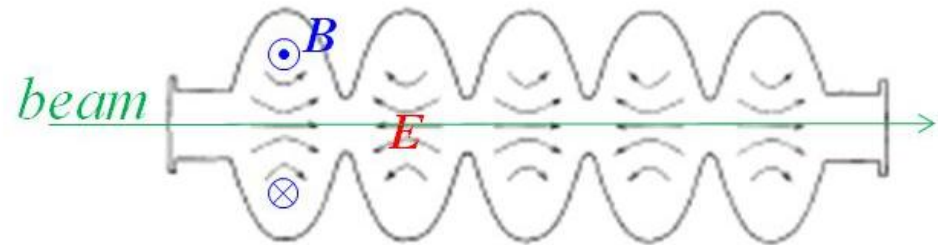
Basic principles of TM and TEM cavities

TM mode cavities – Symmetric around beam axis

- TM_{01} (Transverse Magnetic) mode
- B perpendicular to the EM wave propagation axis (and to the beam axis)
- On the beam axis $B=0$, E_z is maximum: ideal for particle acceleration



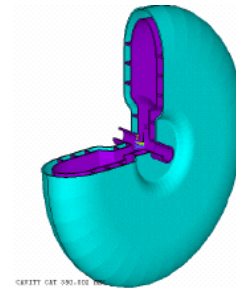
pillbox cavities (Normal-Conducting)



Elliptical SC cavity working in π mode



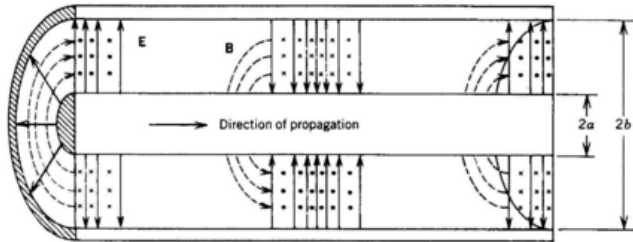
*NC "nose" and SC "reentrant"
Short gap for low- β beams*



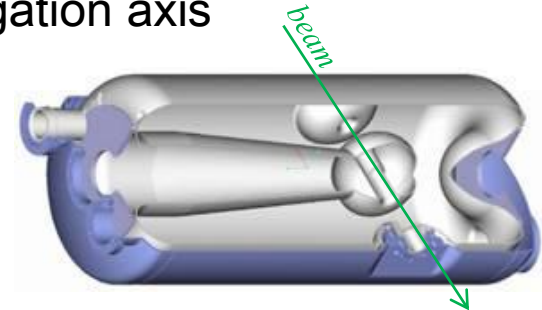
See tutorial "RF principles and TM mode cavity"

TEM mode cavities

- TEM (Transverse Electro Magnetic) mode (related to the cavity symmetry axis)
- B and E are perpendicular to the EM wave propagation axis
- The beam axis is perpendicular to the wave propagation axis



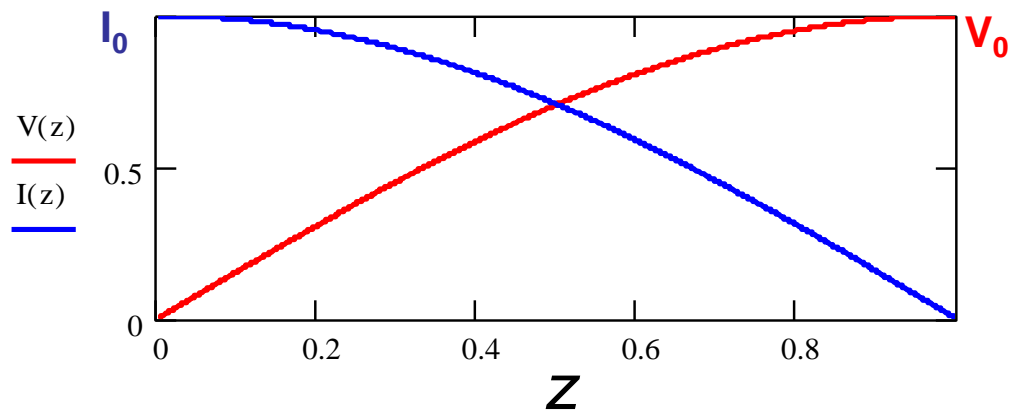
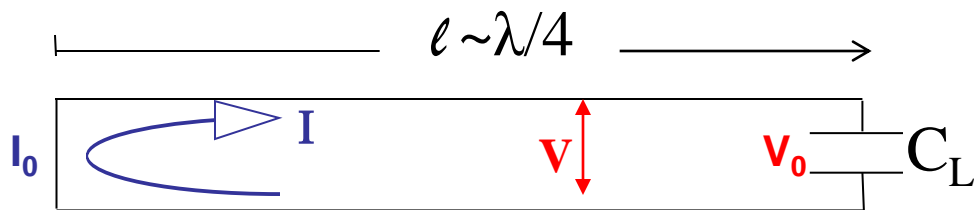
TEM propagating wave in a coaxial line



TEM cavity example: QWR

- Only waveguides with ≥ 2 conductors and homogeneous cross section can have pure TEM modes: any change in cross section introduces longitudinal components
- Traditionally (maybe not fully correctly) we call TEM structures also the non homogeneous ones which result from modifications of standard TEM structures (e.g.: tapered coaxial lines)
- Practical “TEM” cavities are not pure TEM: the field is shaped to build the needed components in the right place for the beam

Quarter-wave structures



TEM modes (Transverse Electro-Magnetic)

$$Z_0 = V_0/I_0 \quad \text{characteristic impedance}$$

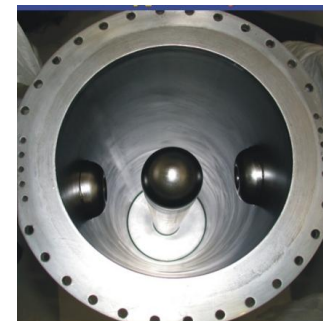
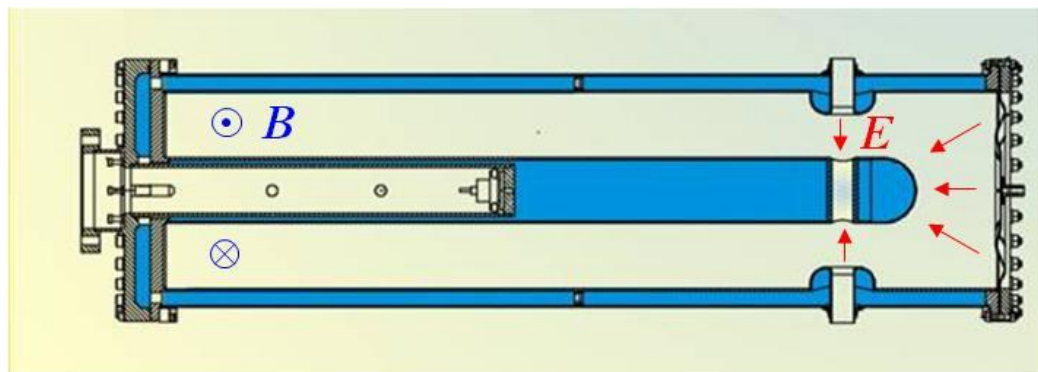
$$\text{Tg}(\omega l/c) \sim 1/(\omega l C_L Z_0)$$

$$U \sim \pi V_0^2 / (8\omega Z_0) \quad \text{stored energy}$$

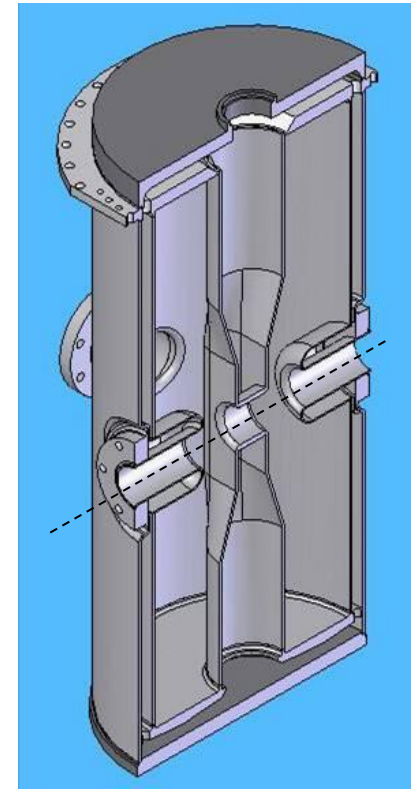
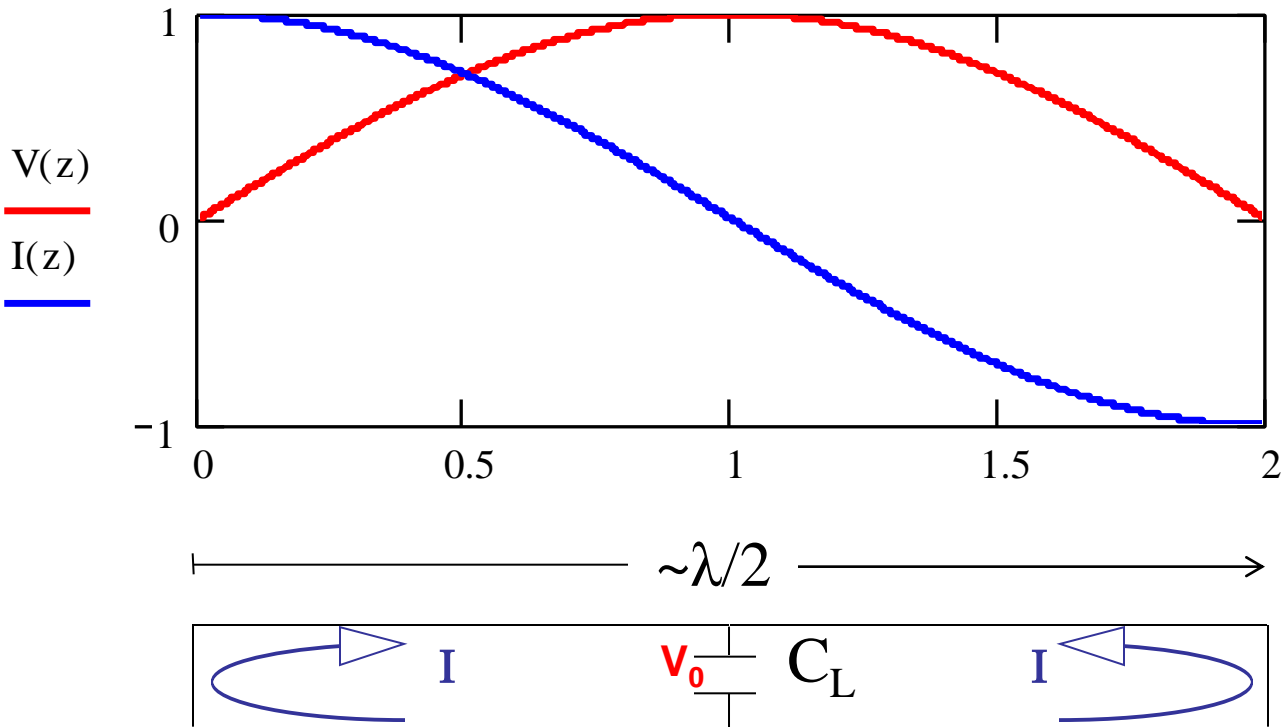
$$V \sim V_0 \sin(\omega z/c) \sin(\omega t)$$

$$I \sim I_0 \cos(\omega z/c) \cos(\omega t)$$

See also J. Delayen, TEM –class cavity design, Tutorial at SRF2011



Half-wave structures



$$U \sim 2\pi V_0^2 / (8\omega Z_0)$$

$$P_{\text{HWR}} \sim 2 P_{\text{QWR}}$$

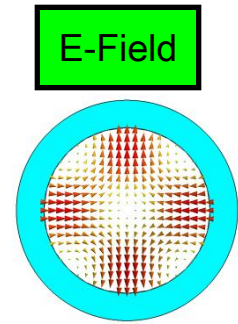
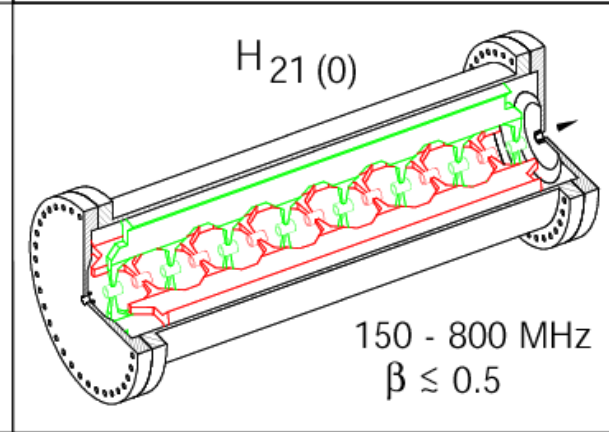
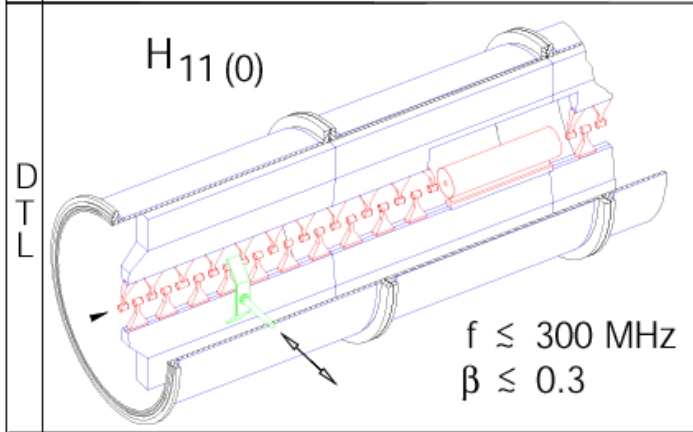
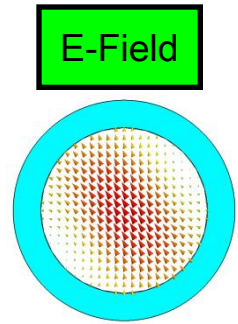
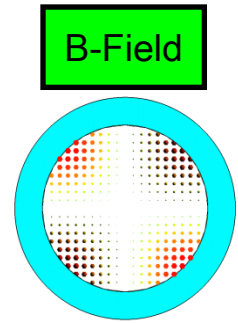
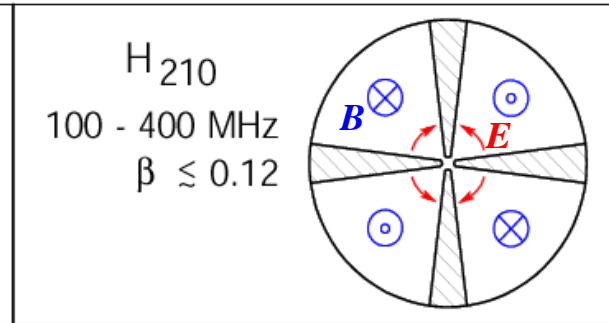
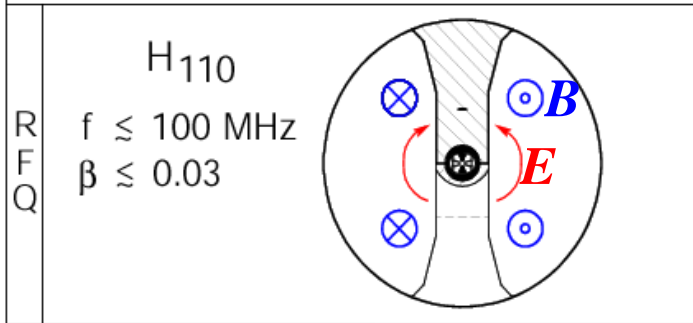
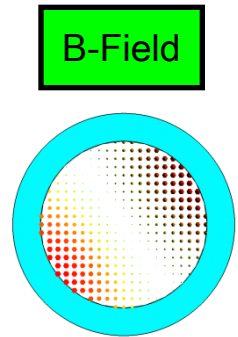
- A half-wave resonator is equivalent to 2 QWRs facing each other and connected
- The same accelerating voltage is obtained with about 2 times larger power

TE mode cavities: IH and CH multi-gap

IH 4-rod RFQ

4-vane RFQ

Low and Medium - β Structures in H-Mode Operation

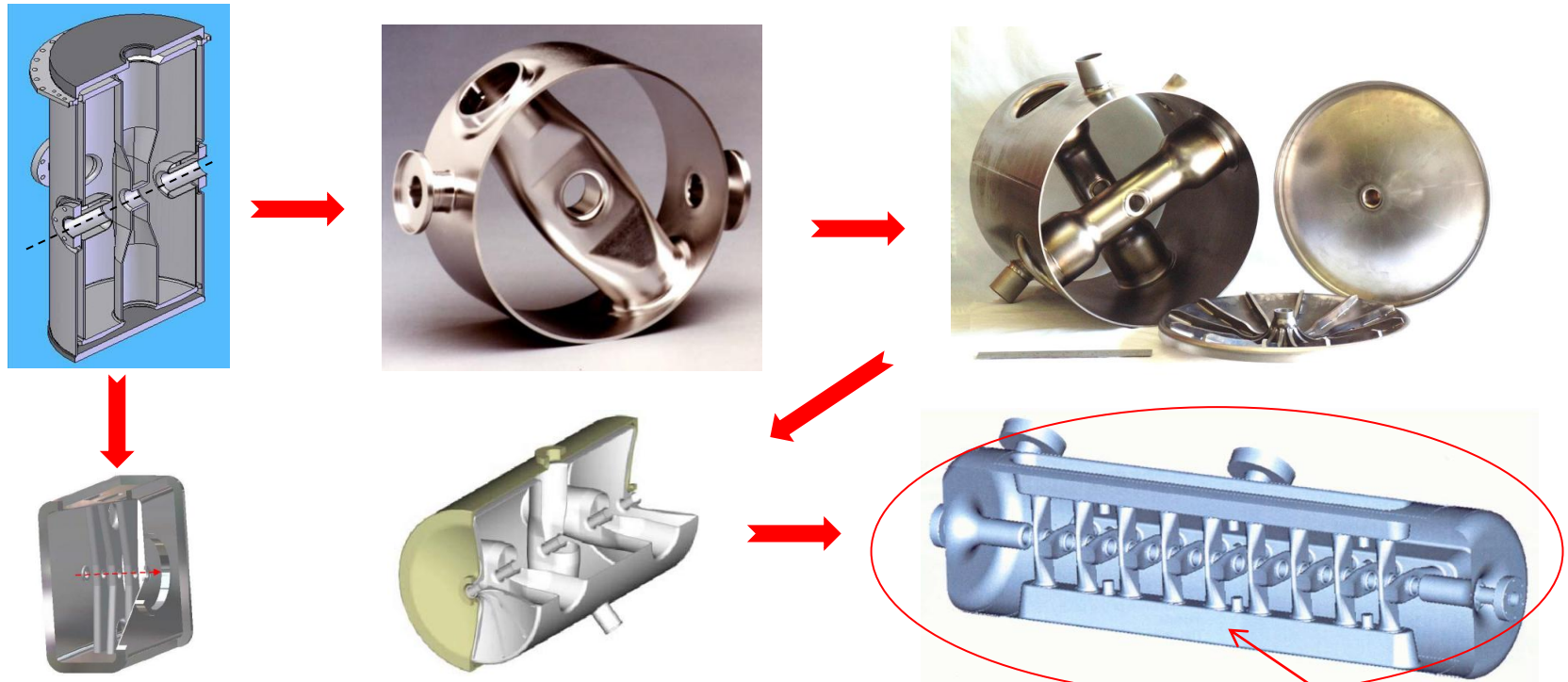


IH-Structure

Courtesy of H. Podlech

CH-Structure

Half-wave structures – spoke and multi-spoke



*mode
stabilizing
ridge*

- Spoke can be still considered “TEM-like” HW cavities with respect to the spoke axis
- Multi-spoke have a similar TEM-like mode when each cell is considered individually, however some of them are closer to CH cavities

Characteristic parameters

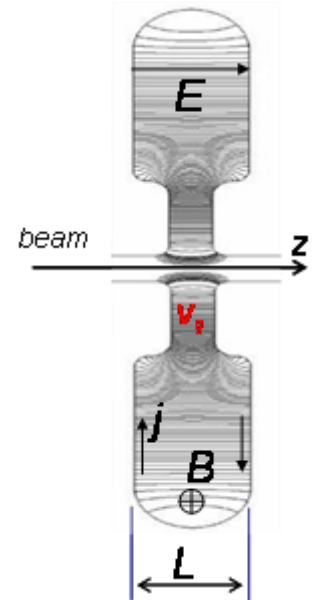
Important parameters in accelerating cavities

Avg. accelerating field	$E_a = V_g T(\beta_0) / L$	MV/m	} constants
Stored energy	U / E_a^2	J/(MV/m) ²	
Shunt impedance per meter	$R_{sh} = E_a^2 L / P$	MΩ/m	
Quality Factor	$Q = \omega U / P$		
Geometrical factor	$\Gamma = Q R_s$	Ω	
Peak electric field	E_p / E_a		
Peak magnetic field	B_p / E_a	mT/(MV/m)	
Optimum β	β_0		
Cavity length	L	m	

where:

R_s = surface resistance of the cavity walls

P = rf power losses in the cavity, proportional to R_s



Energy gain, TTF, gradient

Energy gain:
$$\Delta W_p = q \int_{-L/2}^{L/2} E_z(z_p, t) dz_p$$

In a resonator $E_z(r, z, t) = E_z(r, z) \cos(\omega t + \varphi)$. (For simplicity, we assume:
 1) to be **on axis** so that $r=0$, and $E_z(0, z) \equiv E_z(z)$; 2) $\beta \sim \text{constant}$).

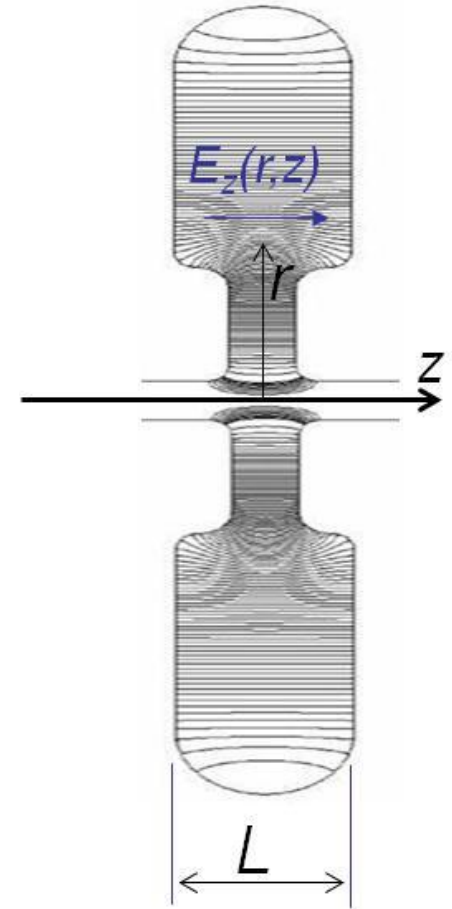
A particle with velocity βc , which crosses $z=0$ when $t=0$, sees a field $E_z(z) \cos(\omega z / \beta c + \varphi)$.

Transit time factor:
$$T(\beta) = \frac{\int_{-L/2}^{L/2} E_z(z) \cos\left(\frac{\omega z}{\beta c}\right) dz}{\int_{-L/2}^{L/2} E_z(z) dz}$$

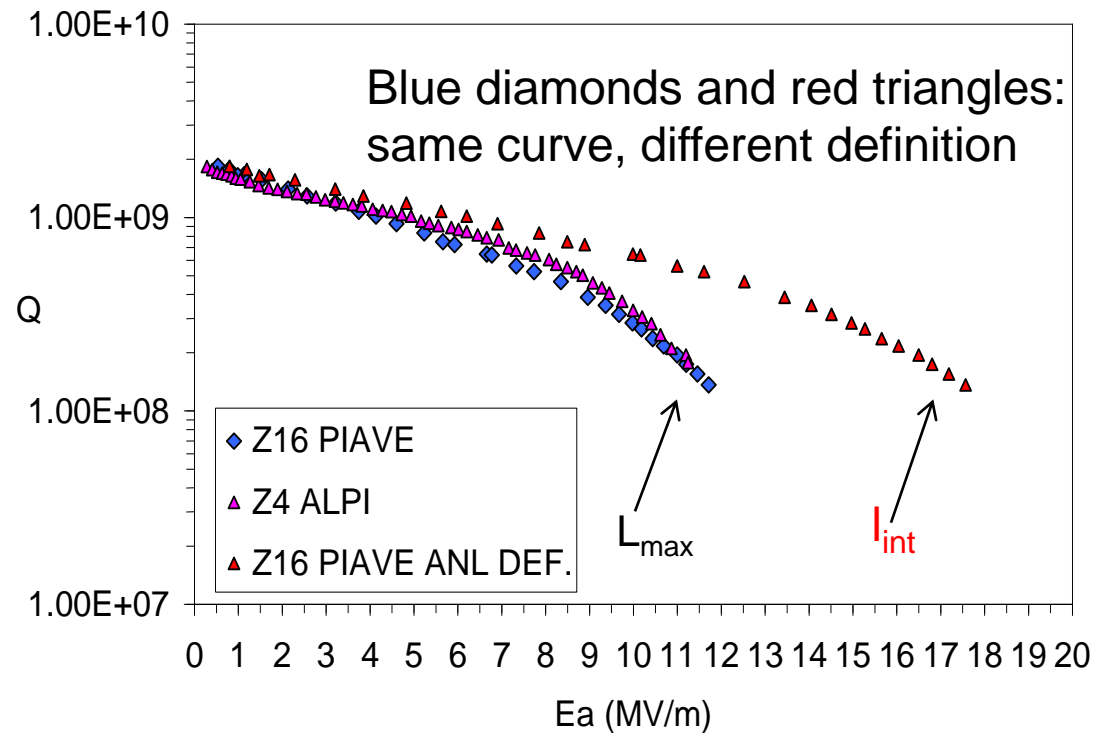
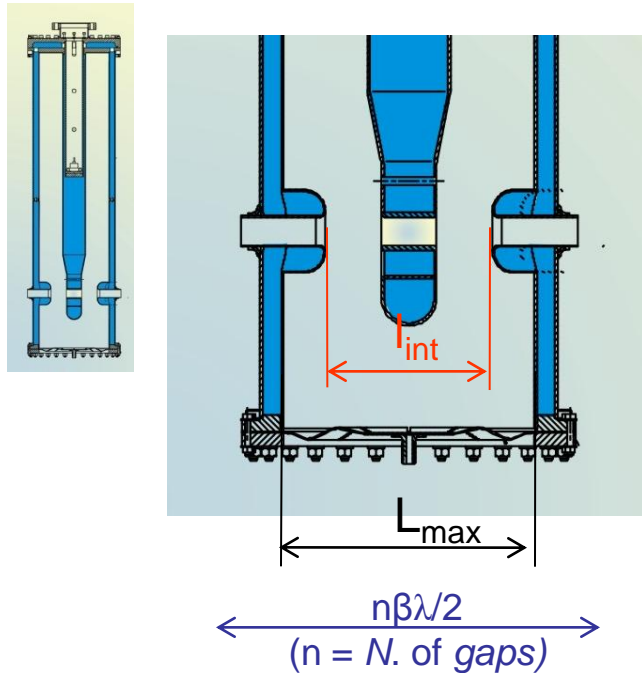
Avg. accelerating field:
$$E_a = \frac{1}{L} \int_{-L/2}^{L/2} E_z(z) dz$$

We obtain a simple expression for the energy gain

$$\Delta W_p = q E_a L T(\beta) \cos \varphi$$

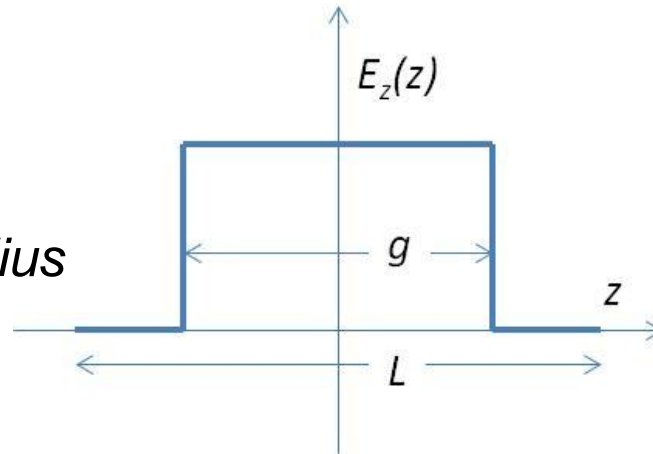
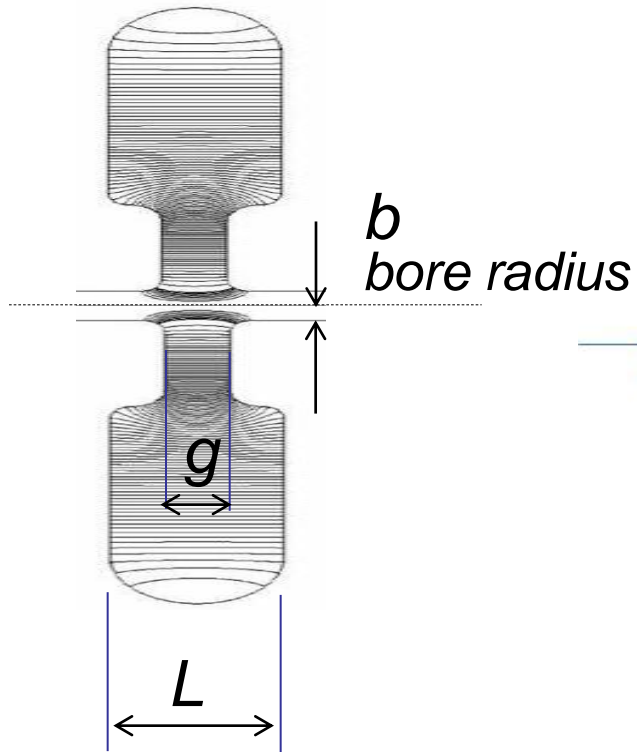


Remark: different definitions of gradient E_a



- In QWR and HWRs it is difficult to define L : l_{int} , L_{max} or even $n\beta\lambda/2$
- The shorter L is defined, the larger E_a appears in Q vs. E_a graphs
- The energy gain, however, is always the same and all definitions are consistent
- **Nowadays most popular:** $L_{eff} = n\beta\lambda/2$

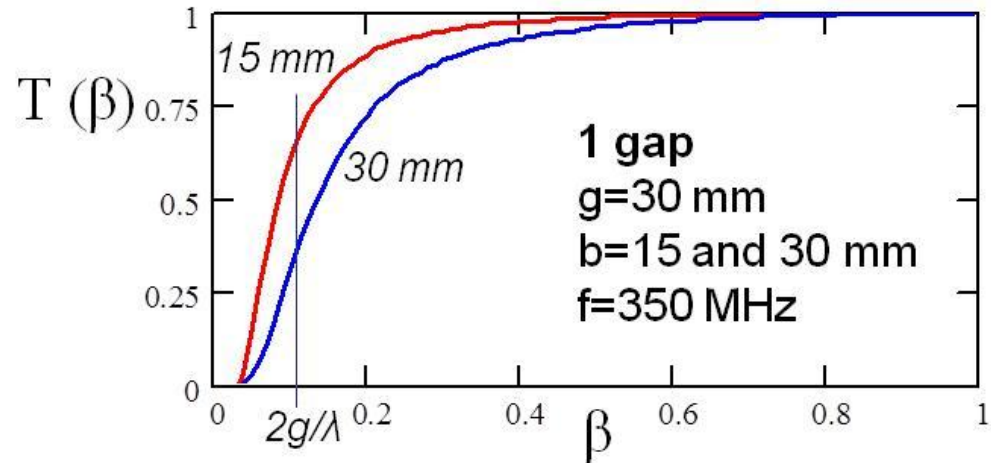
$T(\beta)$ for 1 gap (constant E_z approximation)



$$T(\beta) \cong \frac{\sin\left(\frac{\pi g}{\beta\lambda}\right)}{\left(\frac{\pi g}{\beta\lambda}\right)}$$

Aperture b contributes to the effective gap length:

$$g_{\text{eff}} \approx \sqrt{g^2 + (2b)^2}$$



Rule of thumb: $g_{\text{eff}} < \beta\lambda/2 \rightarrow T(\beta) > 0.63$

Limitation of TM mode cavities for low beta

In summary, to combine:

- **low** β of the beam,
 - large aperture for good beam transmission,
 - reasonably long gap for sufficient energy gain, and
 - $g_{\text{eff}} < \beta\lambda/2$ for high transit time factor,
- we need large λ , thus **low frequency**.

TM elliptical cavities transverse size $\sim\lambda$

- prohibitively large at low frequency

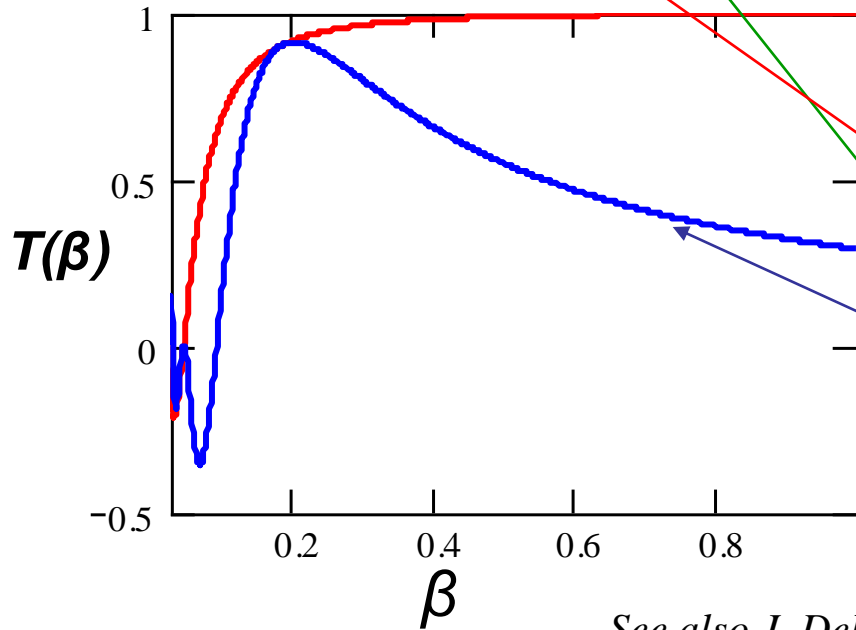
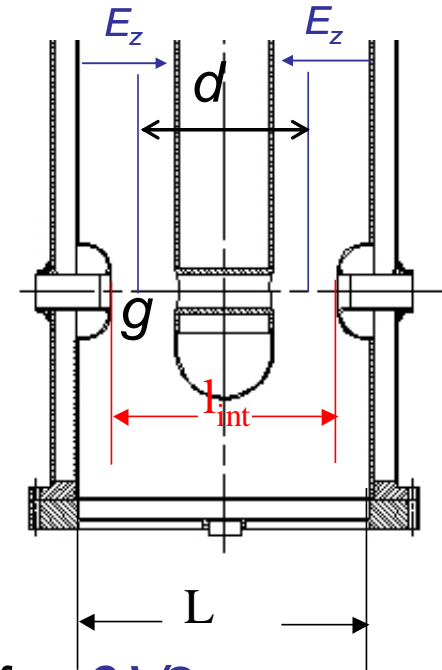
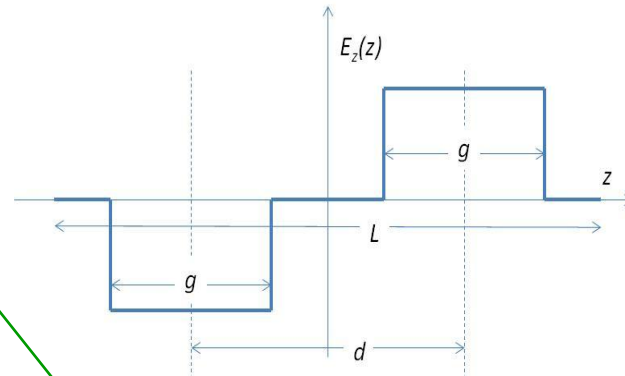
TEM resonators size: $\sim\lambda/2$ and $\sim\lambda/4$

- suitable for low frequency and thus for low- β

T(β) for 2 gap (π mode)

$$T(\beta) \cong \frac{\sin\left(\frac{\pi g}{\beta\lambda}\right)}{\left(\frac{\pi g}{\beta\lambda}\right)} \sin\left(\frac{\pi d}{\beta\lambda}\right)$$

(constant E_z approximation)



1-gap term, high if $g < \beta\lambda/2$

2 gap term, high if $d \sim \beta\lambda/2$

resulting TTF curve

(For more than 2 equal gaps in π mode, only the 2° term changes)

See also J. Delayen, TEM –class cavity design, Tutorial at SRF2011

Transit time factor (normalized)

It is usually convenient to use the **normalized transit time factor** and include the gap effect in the accelerating gradient:

Normalized Transit time factor: $T^*(\beta) = \frac{T(\beta)}{T(\beta_0)}$

Avg. accelerating field: $E_a^* = T(\beta_0)E_a$

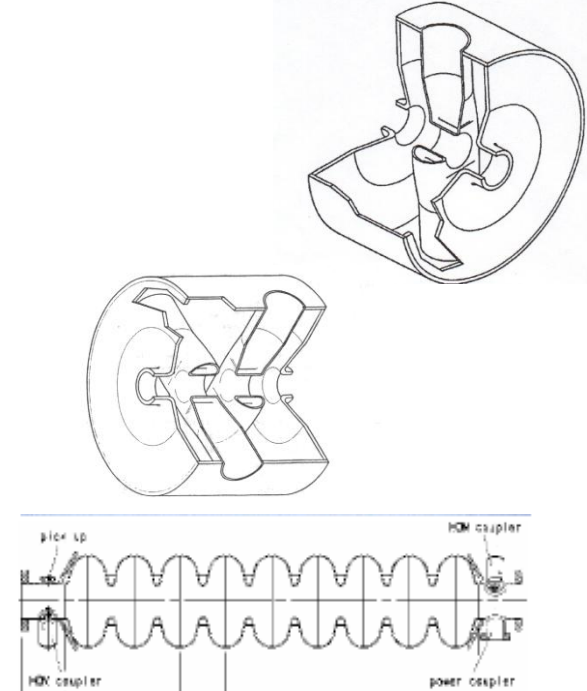
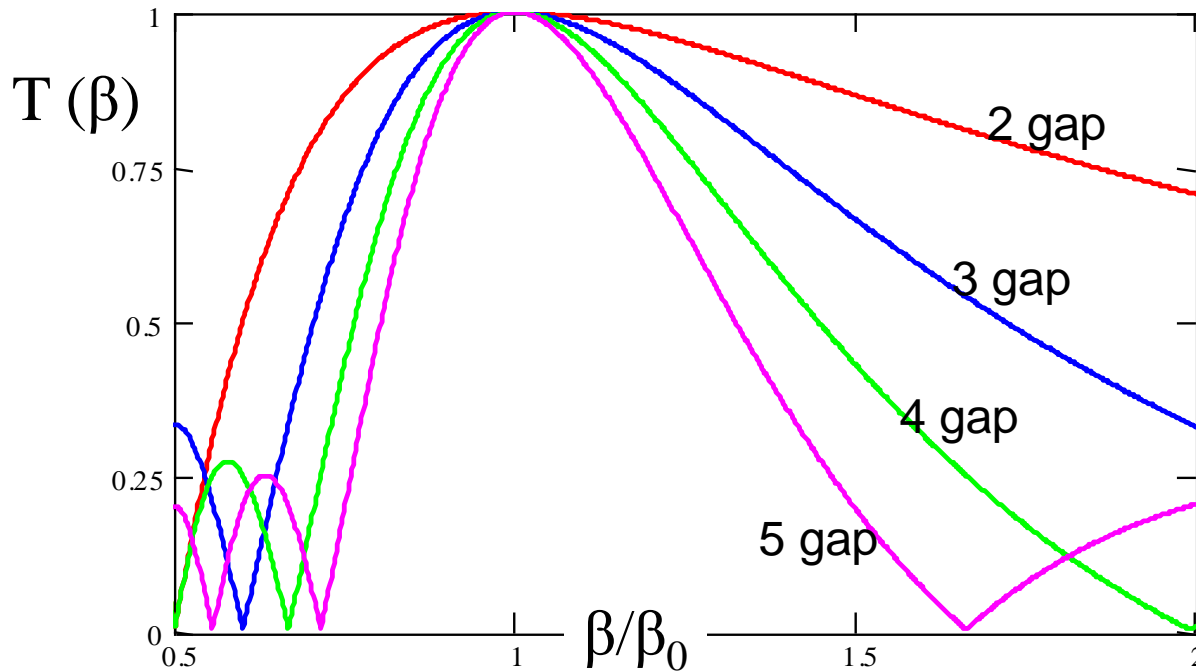
where $\beta_0 \equiv \beta / T(\beta_0) = \max\{T(\beta)\}$ and $T^*(\beta_0) = 1$

and the energy gain definition doesn't change.

$$\Delta W_p = qE_a^* L T^*(\beta) \cos \varphi$$

This is the common definition which we will use from now on, omitting the asterisks

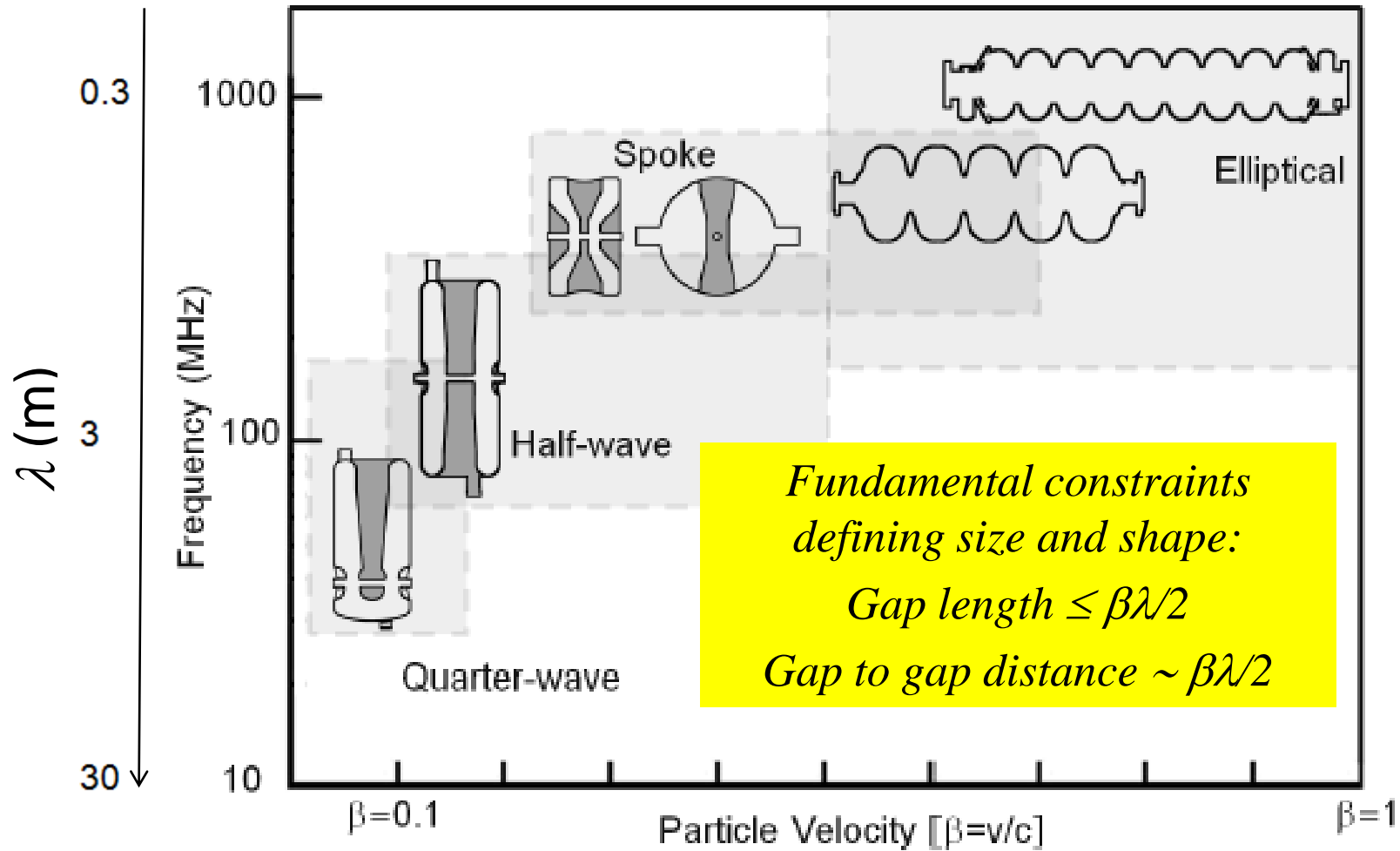
Transit time factor curves vs. gap number n



Normalized transit time factor curves vs. normalized velocity, for cavities with different number of gap

- the larger the gap n., the larger the energy gain at a given gap voltage V_g
- *BUT* the larger the gap n., the narrower the velocity acceptance
 - *~ constant β calls for large n*
 - *fast varying β calls for small n*

Common SRF cavities geometries vs. beam β



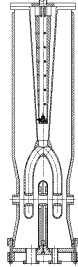

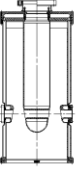

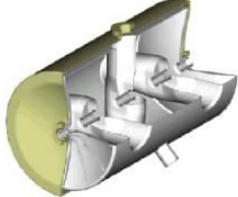

(From M. Kelly's Tutorial at SRF2013)

Non-elliptical SRF cavities main applications

Type	β_{\max}	Beam (A/q)	Max current
HI linacs for nuclear physics research	~ 0.2 (0.5)	ions (7 ÷ 66)	$\sim 1 \mu\text{A}$
HI drivers for RIB facilities and ADS	$\sim 0.3 \div 0.9$	ions ($\sim 1 \div 10$)	$\sim 0.1 \div 30 \text{ mA}$
<i>p, d</i> linacs for radioisotope production	~ 0.3	<i>p, d</i> (1 ÷ 2)	$\sim 1 \div 10 \text{ mA}$
Proton Accelerators for neutron spallation sources	~ 1	<i>p</i> (1)	$\sim 10 \div 100 \text{ mA}$ pulsed
Deuteron Accelerators for material irradiation	~ 0.3	<i>d</i> (2)	$\sim 100 \text{ mA cw}$
High-β linacs with size limitations (proposed)	1	<i>e</i>	$\sim 1 \text{ mA}$
$\beta \sim 1$ deflecting and crabbing	1	<i>e, p(1)</i>	$\sim 1 \text{ A}$

Some definitions in use

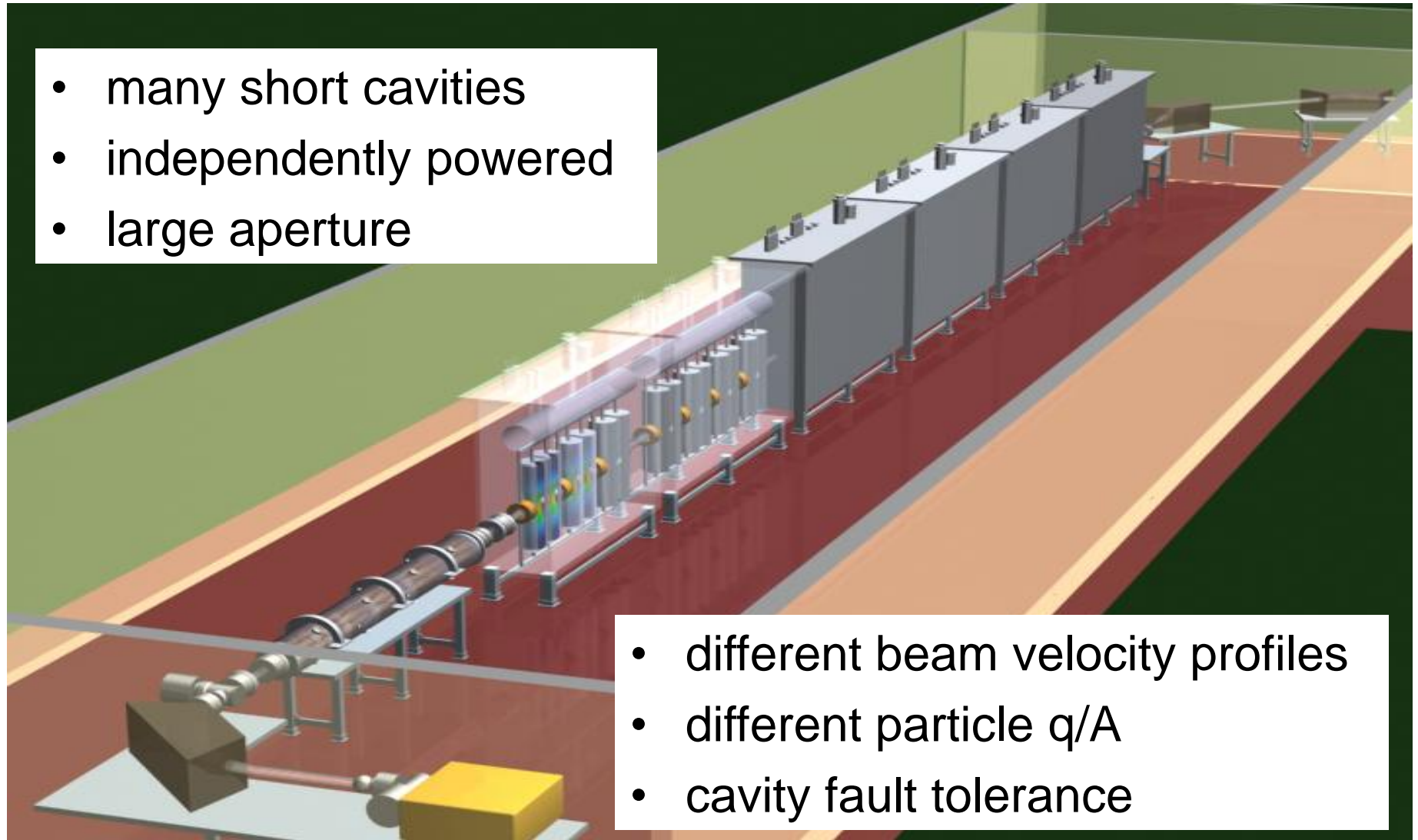
The definition changes according to the community

(Approximate) definition	low β	medium β	high β
Heavy ion accelerators for nuclear physics research $E_{\text{beam}} < 20 \text{ MeV/A}$	< 0.06 	$0.06 \div 0.12$ 	> 0.12 
Proton linacs Heavy ion linacs with $E_{\text{beam}} > 20 \text{ MeV/A}$	< 0.2 	$0.2 \div 0.8$ (“Intermediate”) 	> 0.8 

Typical superconducting low- β linacs

- many short cavities
- independently powered
- large aperture

- different beam velocity profiles
- different particle q/A
- cavity fault tolerance



Cavity design

What is a good SC low- β resonator?

A good resonator must fulfill the following principal (rather general) requirements:

1. Large energy gain
2. Low power dissipation
3. Easy and reliable operation for a long time
4. Easy installation and maintenance
5. Low cost-to-performance ratio

Preliminary choices

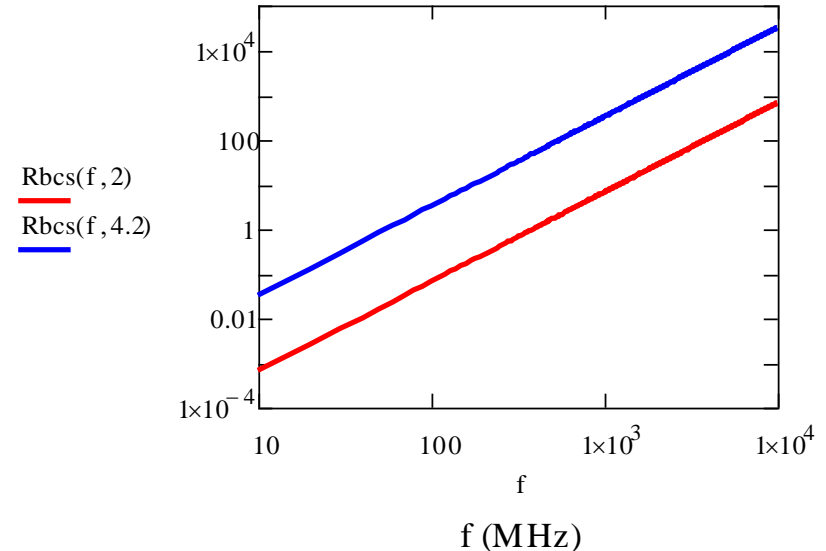
• beam energy	→	β_0 , gap length	} specifications	beam
• velocity acceptance	→	n. of gaps		
• beam size, transv.	→	bore radius		
• beam long. size & f	→	rf frequency		
• beam power	→	rf coupling type		
• gradient, efficiency	→	geometry	} choices	technological
• cw, pulsed	→	mech. design		
• cost, reliability	→	technology		
• ...				

Some useful numbers and rules of thumb to have in mind

- Maximum peak fields, electric E_p and magnetic B_p
 - achieved (cw) ~ 90 MV/m and ~ 150 mT
 - reliable specs ~ 40 MV/m and ~ 75 mT (depending on your “bravery factor”)
- R_{BCS}
 - $R_{BCS} (Ohm) = 2 \times 10^{-4} \frac{1}{T} \left(\frac{f(GHz)}{1.5} \right)^2 \exp\left(-\frac{17.67}{T}\right)$
- R_{res} residual resistance = $R_s - R_{BCS}$
 - Achievable < 1 n Ω
 - reliable specs < 10 n Ω
- Rf power density on the cavity walls
 - Achievable ~ 1 W/cm 2 at 4.2K; ~ 5.6 W/cm 2 at 2K
 - Reliable: much below (related also to cooling system)
- Critical Temperature vs. magnetic field
 - $T_c = 9.2\sqrt{1 - B / 200}$

2K or 4.2K?

- $R_s = R_{BCS}(T, f) + R_{residual}$
- R_{BCS} increases with f^2
- 2K is more expensive than 4.2K: it appears convenient only if $R_{BCS}(4.2) > R_{residual}$
- Nowadays reliable R_{res} is below $\sim 10\text{n}\Omega$: so the (blurry) border seems to be around 200 MHz
- However:
 - 2K systems provide better He pressure stability
 - 2K allows higher gradients than 4.2K
 - Large linacs often need a 2K system for high- β cavities anyhow



f (MHz)	80	160	320	640	1280
Rs(4.2K)	2.02	8.07	32.3	129	516
Rs(2K)	0.04	0.17	0.67	2.7	10.6

After overall optimization, 2K systems can be the best choice also for low frequency cavities, especially in large linacs

Electromagnetic design

EM design optimization

provide since the beginning:

- Suitable openings for processing, pumping and installation of all required accessories

optimize:

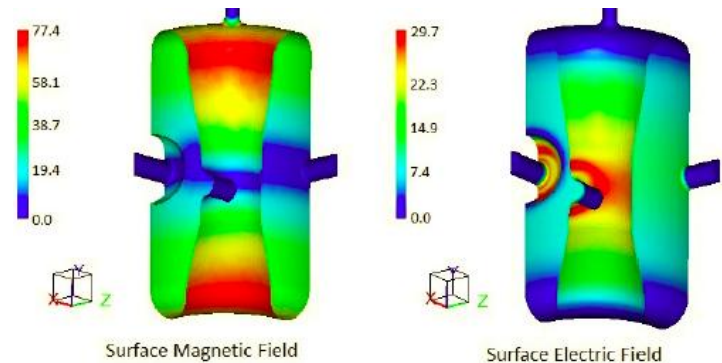
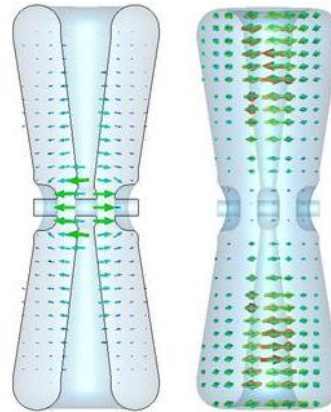
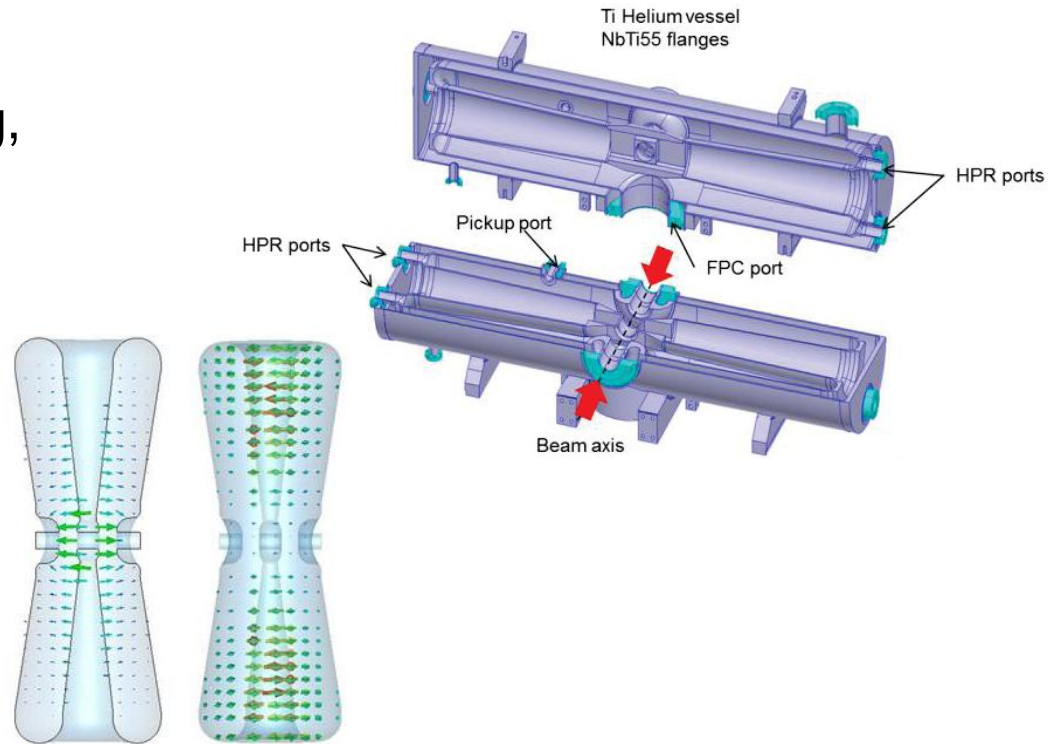
- E , B for beam dynamics
- geometry for low MP
- geometry for good coupling and tuning

maximize shunt impedance:

- $E_a^2 / (P/L)$

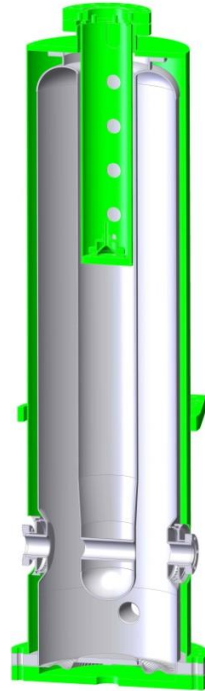
minimize peak fields:

- E_p/E_a
- B_p/E_a
- (Good choice: $B_p/E_p \sim 1.5 \div 2$)



Remark on overall geometry optimization

- Have in mind the overall scope when optimizing
- Optimization of the cavity influences complexity and cost
- Shape refinements should be pursued as far as needed by accelerator and beam dynamics requirements



Cost effective geometry, optimized for a large linac section operating at intermediate gradient ($B_p/E_p \sim 2$)

$\sim 45\%$ Larger OD and ID to obtain
 $\sim 45\%$ Lower B_p/E_a

Larger volume for
Higher R_{sh}/Q

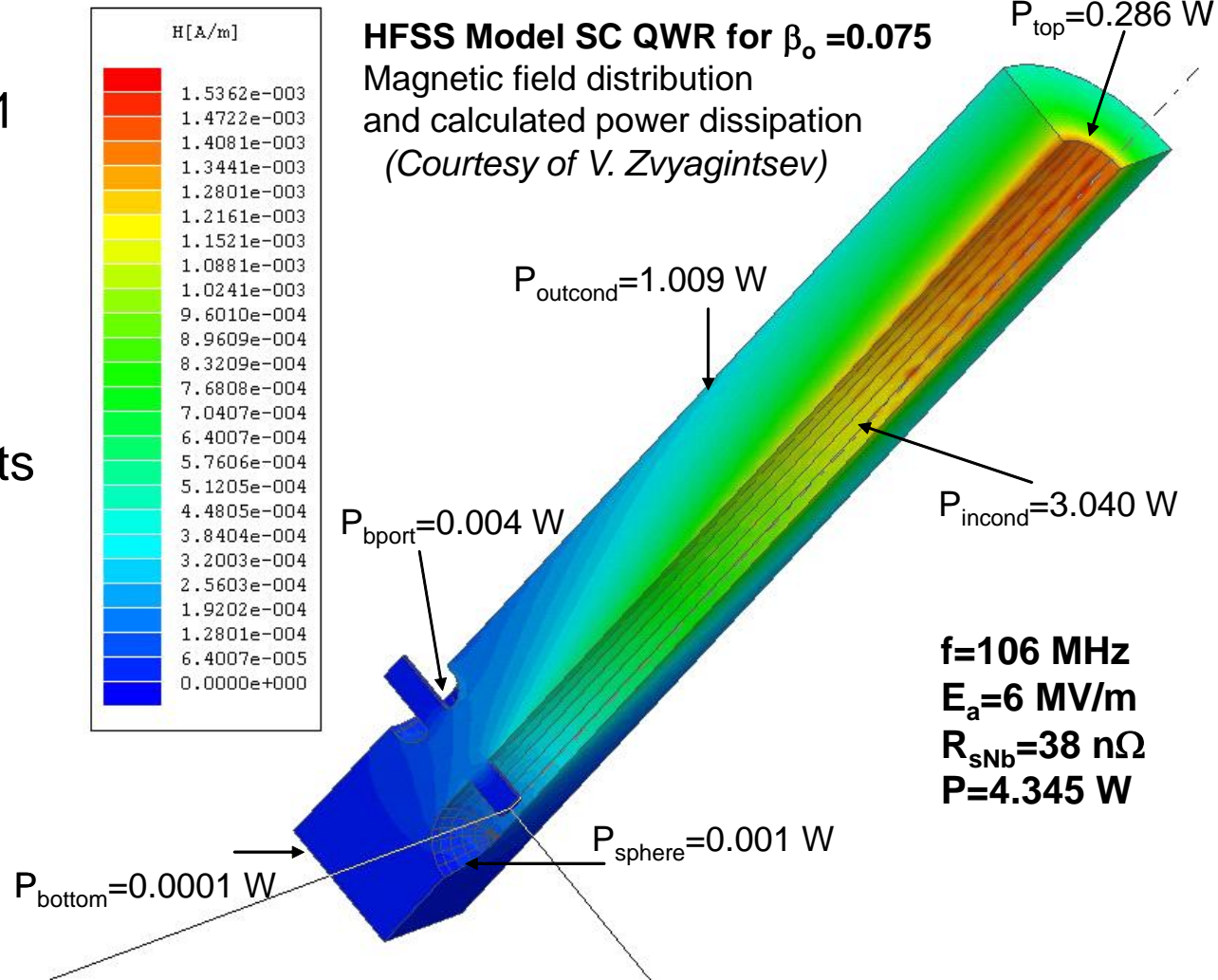
Larger r for
15% Lower E_p/E_a

Same β , more complex geometry, optimized for operation at highest gradient ($B_p/E_p \sim 1.5$)

See also M. Kelly, TEM –class cavity design, Tutorial at SRF2013

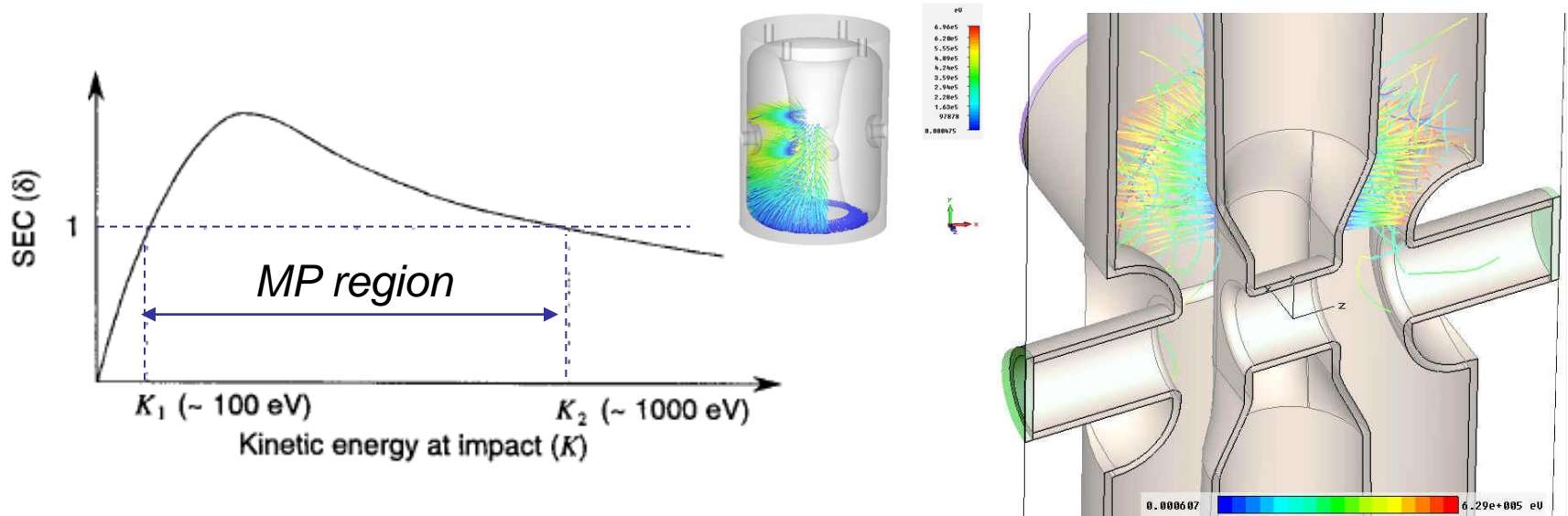
EM design: hints on Rf losses

- Keep maximum rf losses well below ~ 1 W/cm^2 at 4.2 K and ~ 5.6 W/cm^2 at 2K
- Large safety margin required: local defects can increase power losses significantly



EM design: Multipacting

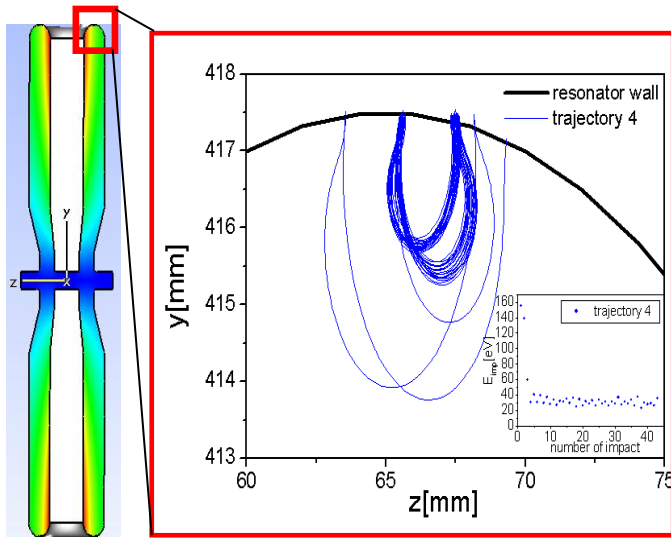
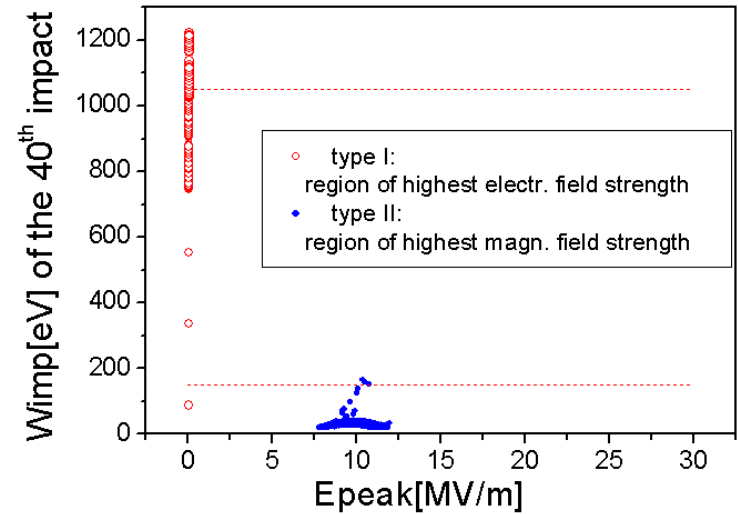
- Multipacting: resonant field emission of electrons under the action of the EM field
- 3 simultaneous conditions to start MP:
 1. stable trajectories ending on cavity walls (cavity geometry) +
 2. secondary emission coefficient >1 (surface preparation) +
 3. initial electron impinging the right surface at the right field and phase to start the process (vacuum, presence of free electrons)
- Initial electrons can be originated and captured far from the resonant trajectory (cavity geometry)



Multipacting in low- β cavities - examples

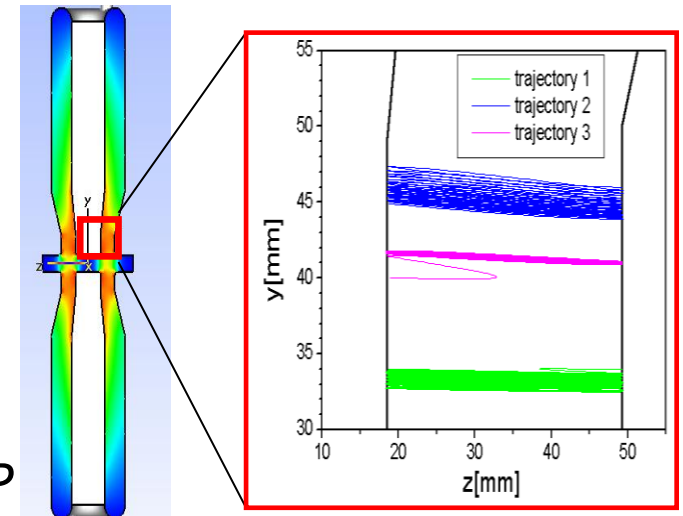
2-point MP in a HWR

- 1 wall MP: $E+B$ to turn the trajectory
- 2 walls MP: mainly E
- B can be used to displace electrons away from the MP area



1 wall MP
“horseshoe”

Courtesy of ACCEL



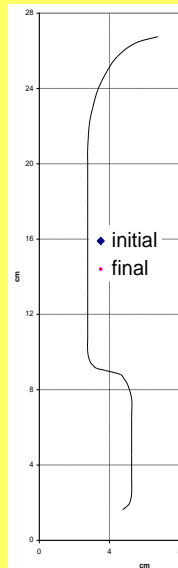
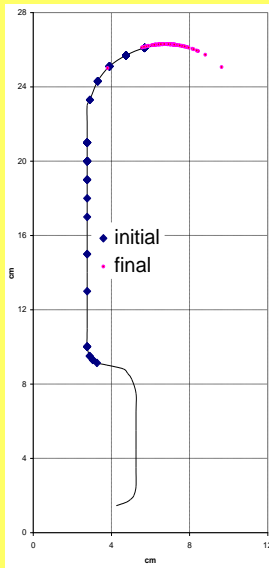
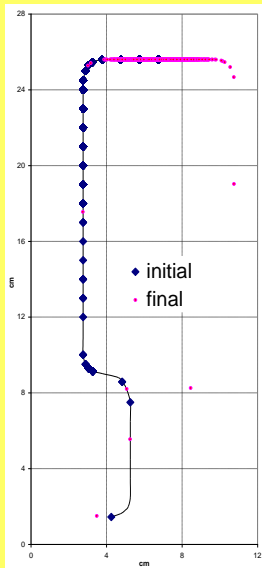
2-walls MP

Multipacting calculations

- It is common experience that MP could always be conditioned in a low- β cavity, if clean and in a good vacuum. However, this may take a long time (days). This is not acceptable when operating an accelerator
- MP can be minimized with an appropriate choice of the cavity shape
- Several powerful 3D codes are nowadays available for MP particles tracking. Some are included in packages for 3D EM and mechanical design of cavities.
- Simulations are very powerful but they might miss some of the all possible modes

Avoiding multipacting

- cavities must be designed with no stable MP trajectories, or with impact energy out of the $\delta > 1$ region
- Accumulation points, which collect electrons from a large volume and position them in a stable trajectory, should be removed by geometry
- Levels at high E_a are more dangerous than levels at low E_a
- it is often impossible to eliminate levels completely; to make them tolerable, the volume in which the electrons are captured must be small

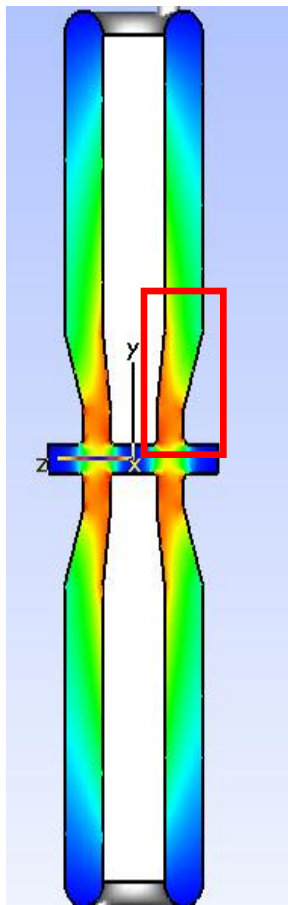


Example: simple 350 MHz, 2D geometry

Results:

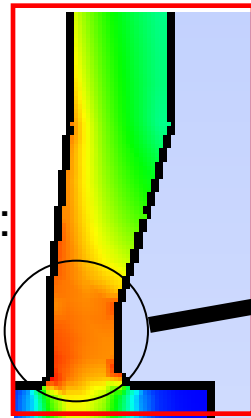
- A sharp step in the “nose” removed an accumulation point near the beam gap which was present in a conical nose
- Ellipsoidal shape 1.5:1 removed all MP trajectories at the equator
- MP negligible in the final shape (confirmed by SRF test)

3D example: redesigned HWR for MP removal

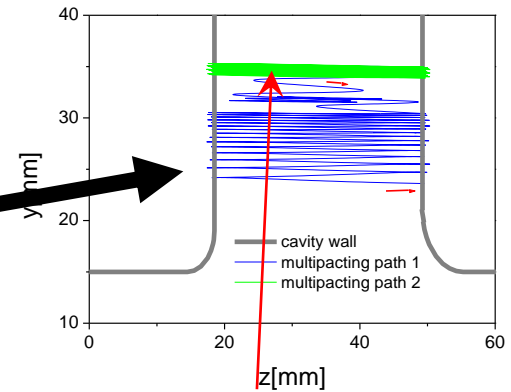


SARAF HWR
(Courtesy of ACCEL)

first design:

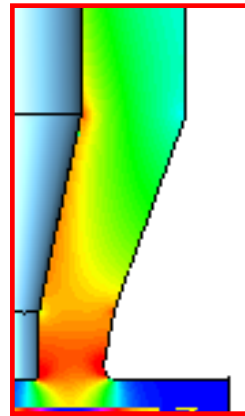


multipacting at
 $E_{\text{peak}}=0.1\text{MV/m}$



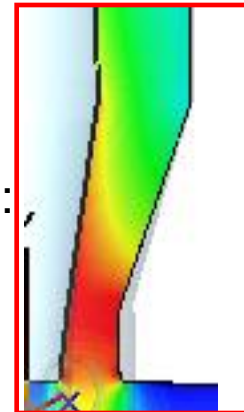
Accumulation point

redesign A:
outer wall
inclined



no multipacting

redesign B:
inner wall
inclined

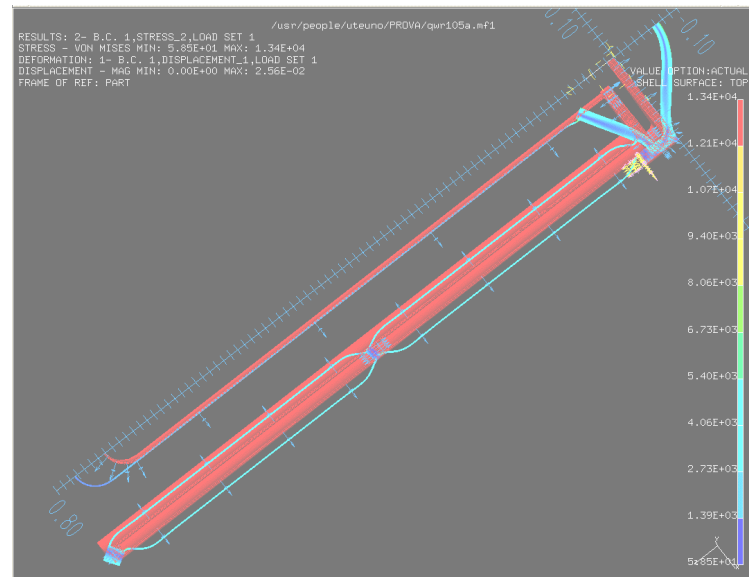
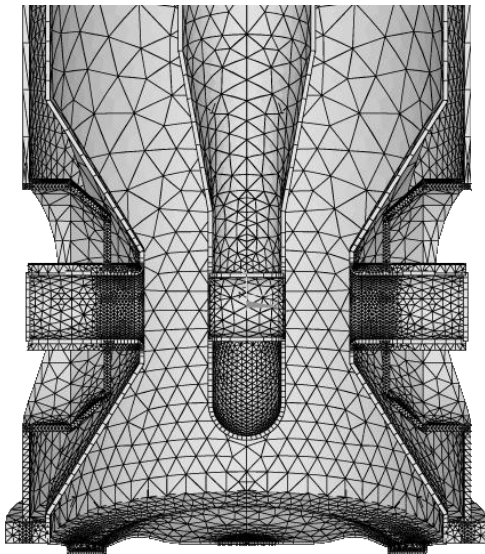


no
multipacting

Mechanical design

Mechanical design

- realizes the optimized EM design and provides whatever necessary to make it work properly (cooling, alignment fixtures, tuning...)
- Statical analysis (He pressure, Lorentz force detuning, tuning range, stress, plastic deformation limits,...)
- Dynamical analysis (mechanical modes...)
- Thermal analysis (cooling, T distributions,...)
- Construction procedure

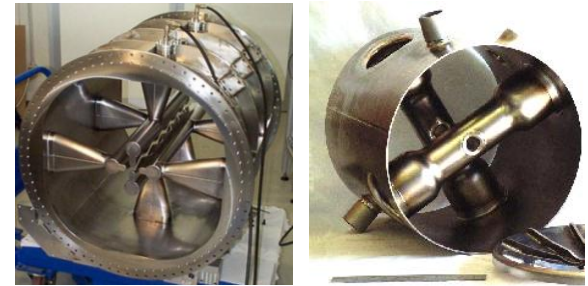


Choice of the SC technology

- Bulk Nb (by far the most used)

- highest performance, many manufacturers, any shape and f

- *performance* ***** *cost* **



- Sputtered Nb on Cu (only on QWRs)

- good performance, lower cost than bulk Nb in large production, simple shapes

- *performance* *** *cost* ***

[See dedicated tutorial “Beyond bulk niobium”](#)



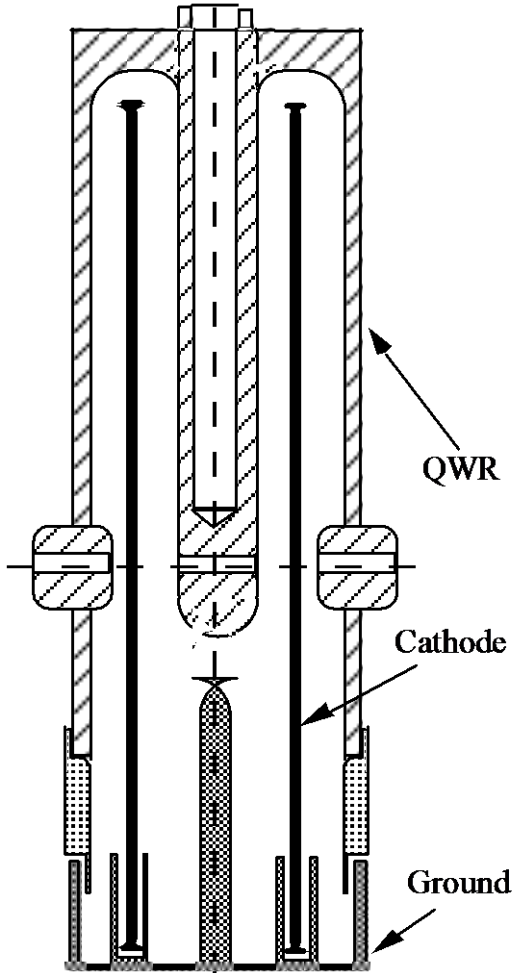
- (Plated Pb on Cu - abandoned

- lower performance, cheap and affordable also in a small laboratory

- *performance* * *cost* *****)



Note on design of Nb sputtered on Cu QWRs



The design must allow:

- OFHC Cu substrate
- no brazing
- rounded shape optimized for sputtering
- no holes in the high current regions
- Only shapes with large openings for cathode insertion and large volumes to maintain sufficient distance between cathode and cavity walls

Among non-elliptical cavities, practically suitable only for QWRs

DC biased diode

See dedicated tutorial “Beyond bulk niobium”

Niobium properties: note on the RRR choice

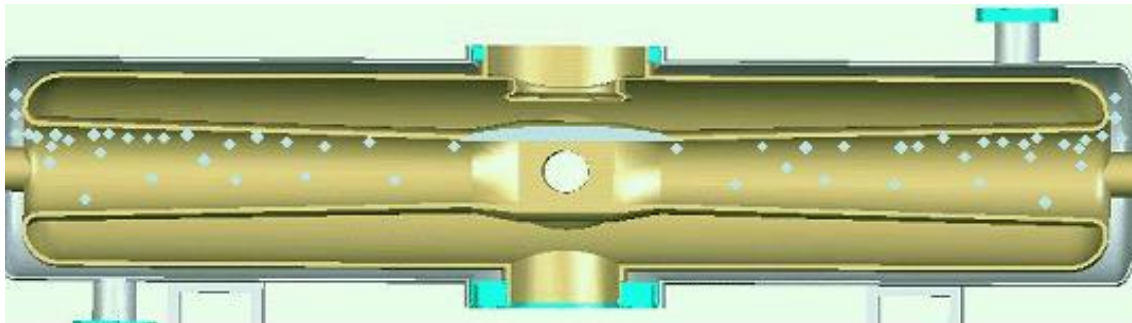
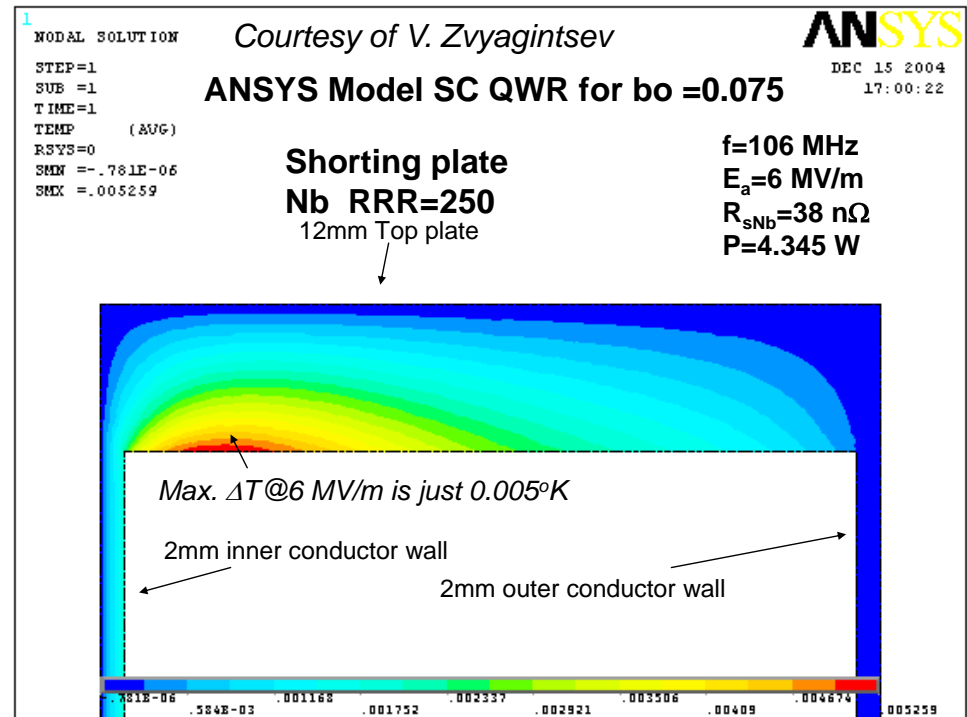
- Thermal conductivity at 4.2 K:

$$k = \text{RRR}/4 \quad (\text{W/m})/\text{K}$$

- high RRR required, which have higher cost and poorer mechanical properties compared to normal grade Nb (RRR~40)
- Nowadays typical good choice for low- β cavities: RRR~250 , almost a standard for Nb vendors

Mechanical design: hints on cooling

- Keep T well below T_c
- provide good ways for He flow
- avoid gas trapping
- Keep due clearance for He gas and heat flow
- At 2K check that thermal paths in superfluid He allow $T < T_\lambda$ at the Nb walls

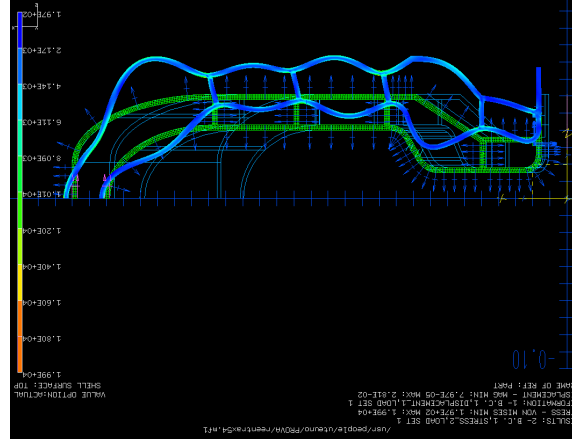
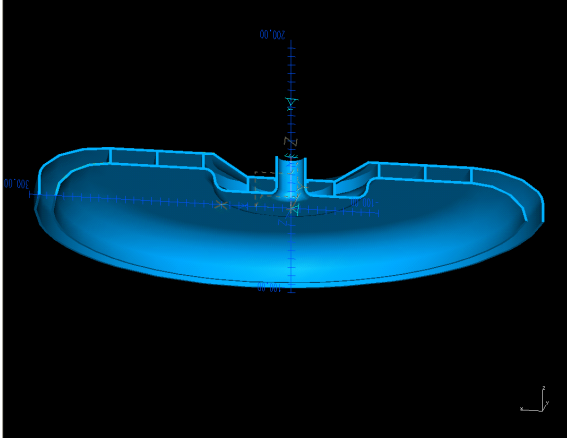


IFMIF HWR working in horizontal position. Gas He pockets had been Eliminated for better cooling

Helium vessel

- Most non-elliptical cavities are built with integrated He vessel, which performs also structural functions
- Practical materials for He vessels:
 - **Stainless steel**
 - cost effective, excellent mechanical properties, TIG weldable in air
 - Different thermal contraction from Nb: bellows required
 - Not weldable with Nb: transition SS to Nb parts required (explosive bonded, brazed...)
 - Not suitable for HT baking: to be added to the cavity after 800 °C baking
 - **Titanium**
 - Excellent mechanical properties, weldable with Nb (EBW), TIG weldable in inert atmosphere, suitable for HT baking
 - Thermal contraction similar to Nb
 - Material cost higher than SS
 - **Nb, NbTi**
 - Perfect matching and weldability (by EBW) with Nb, good mechanical properties
 - Thermal contraction same as Nb, suitable for HT baking
 - High cost compared to SS and Ti

Mechanical reinforcement: double wall



The double wall structure allows to null the net force of the He pressure

It is possible to expose to He pressure large surfaces without making them collapse

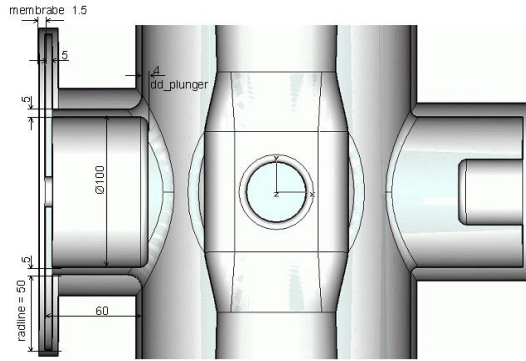
a careful design can minimize df/dP



Cavity accessories

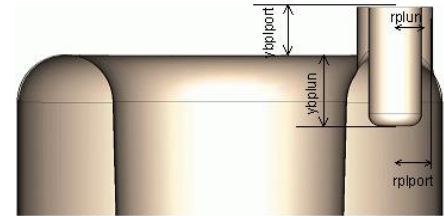
Frequency tuning

wall displacement toward: $\left\{ \begin{array}{l} \text{high } E \rightarrow f \text{ down} \\ \text{high } B \rightarrow f \text{ up} \end{array} \right.$



(images from IFMIF HWR studies)

Capacitive tuner in a high E region (by far the more used)



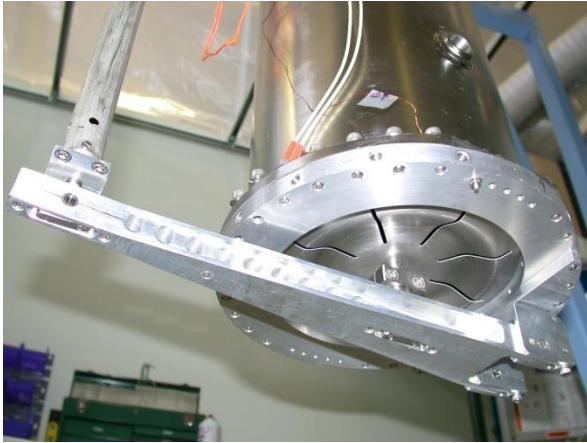
Inductive tuner in a high B region

Unwanted mechanical deformations cause detuning during cavity operation: He pressure fluctuations are a primary cause

Mechanical tuners

Slow tuners

For center frequency tuning and helium pressure compensation



Mechanical tuner with Nb slotted plate (TRIUMF)

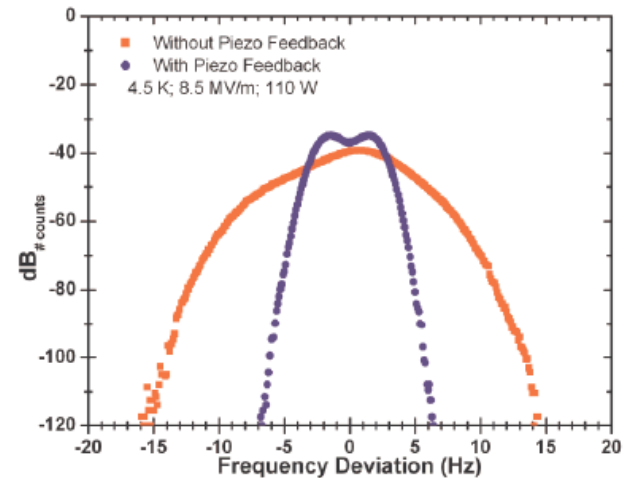


SC bellows tuner (ANL)

Fast tuners



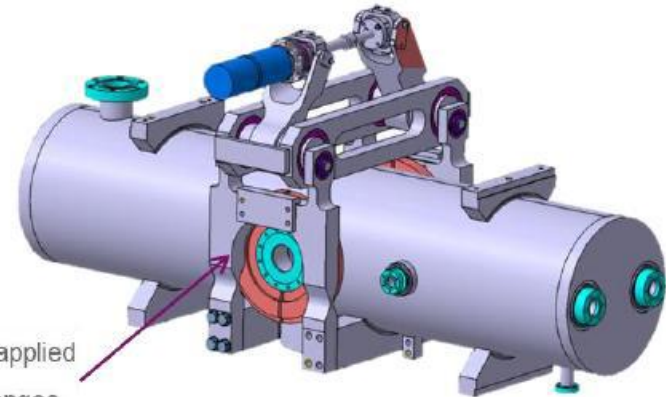
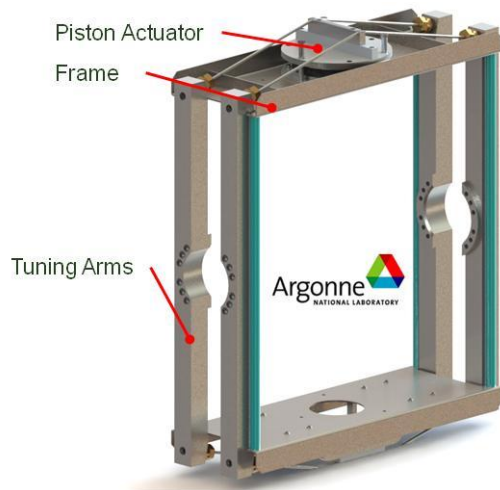
Piezoelectric tuner actuator. Suitable for fast tuning and also for high precision slow tuning.



Tuners for closed cavities



Pneumatic tuner (ANL)



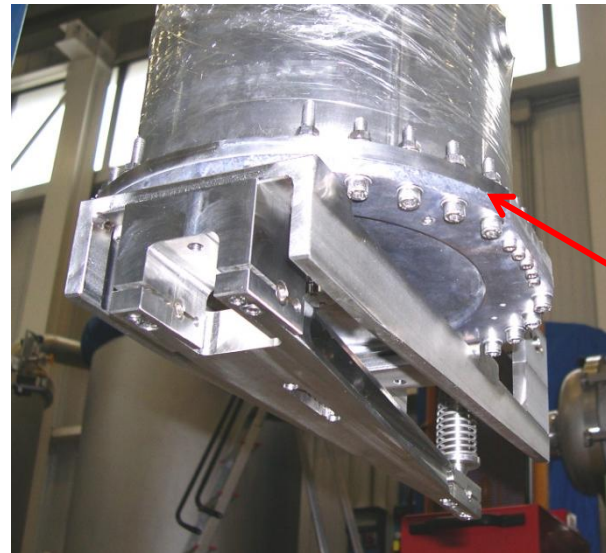
Tuning system applied
on the nose flanges

Motor driven tuner (IFMIF)

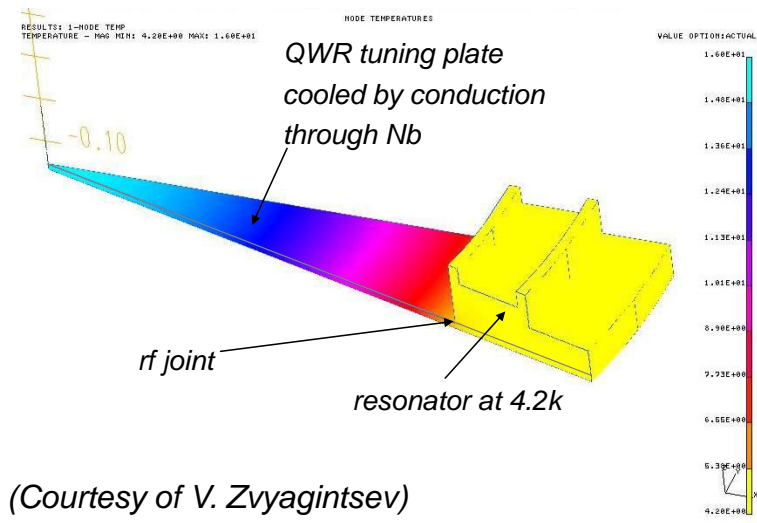
- Tuning by cavity deformation
- Pneumatic (also for QWRs): fast, strong and cost effective, but always requiring gas flow and frequency tracking to keep the position
- Motor driven: slow and bulky, but stable after setting its position

Remarks on RF joints

- Low rf power density surfaces (e.g. capacitive tuning plates) can be cooled by thermal conduction through an rf joint
- Don't exceed a few mT magnetic field on rf joints. 1 mT is usually safe
- Check the temperature distribution on the plate in operation
- Check the effect of a possible super-to normal-conducting transition in such regions: sometimes it is not critical, leading to some increase of rf power losses but not to a cavity quench



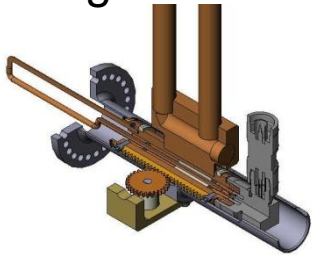
SC rf joint



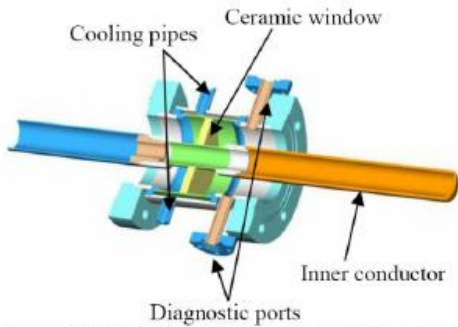
(Courtesy of V. Zvyagintsev)

Rf power coupling in TEM cavities

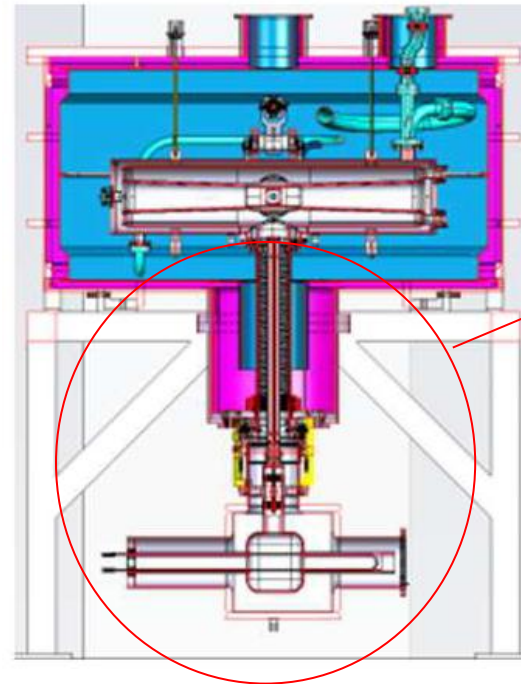
- Inductive couplers at low P (<1 kW) and low f (<300 MHz)
- Capacitive couplers above ~ 1 kW and ~ 300 MHz
- High power couplers can be larger than their resonators and require a well integrated design



500 W Inductive coupler (TRIUMF)



20 kW Capacitive coupler (IPNO)

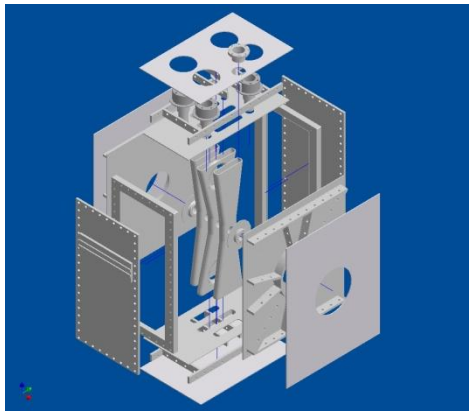
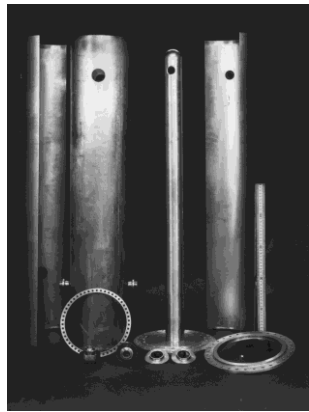
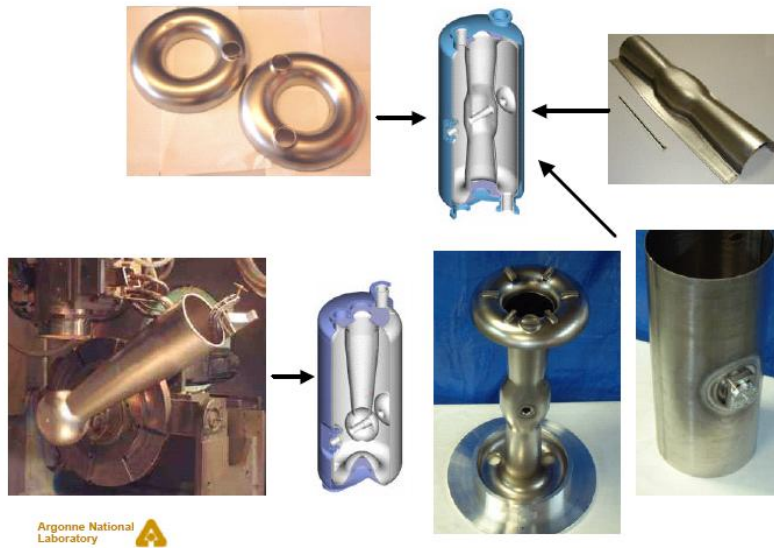


100 kW power coupler for 125 mA beam (IFMIF/EVEDA)

See dedicated tutorial “Fundamental Power couplers and HOM couplers for SC application”

Fabrication, tuning, processing

SRF cavities typical construction steps



- parts obtained by machining and forming of Nb sheets, rods, plates,...
- Parts joined before welding (“stack-up”), 1st frequency test and dimensional adjustment
- Cleaned Nb parts joined by electron beam welding in HV ($<10^{-5}$ mbar)
- 2nd frequency adjustment, He vessel assembly
- surface treatment: chemical polishing, electropolishing (barrel polishing,...)
- HT baking at $600\div 800$ °C, (N doping+EP/CP)
- high pressure water rinsing
- (120 °C baking)

Nowadays several vendors possess all these technological capabilities and can deliver “turn-key” the cavities you designed

Rf frequency setting before EBW (coarse): stack up

- In TEM cavities coarse tuning is made by modifying either inner conductor length or loading capacitance.
- The parts are stacked together for frequency measurement before welding
- Welding shrinkage must be taken into account



Cut to right length
before welding:

1. To change length
2. To change load capacitance (beam ports, tuning pucks, tuning plate reference planes...)



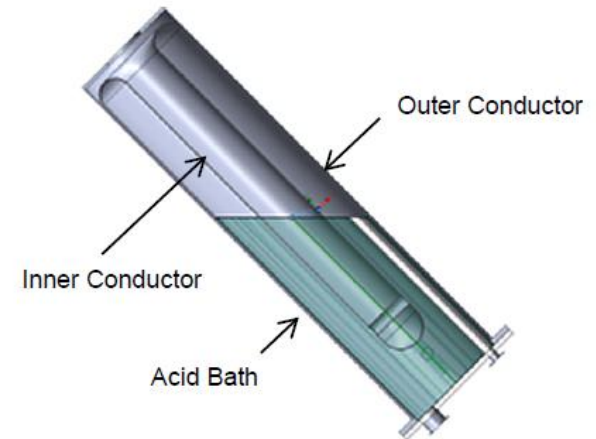
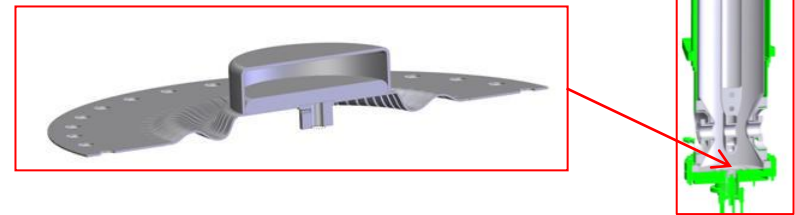
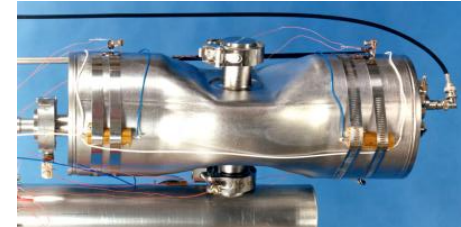
Rf frequency correction after welding (coarse)

- After welding tuning operations are more limited and correction range is smaller

- Some of the main methods:

1. Plastic deformation (usually to change load capacitance)
2. Puck insertion (QWRs removable plate): adjusting the puck length it is easy to adjust the frequency
3. Differential etching: removes material selectively to increase length or load capacitance

1. New entry 2015: virtual welding...

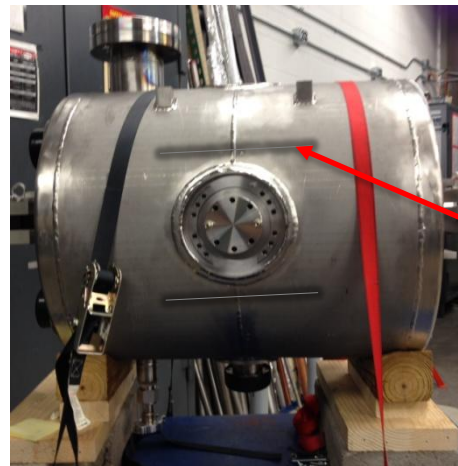
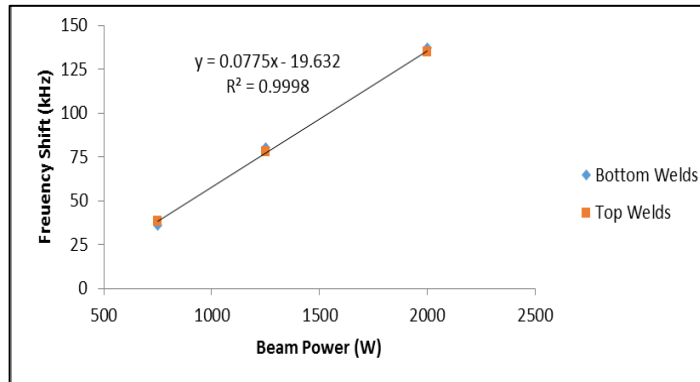


Virtual EB and TIG Welding

1. **Virtual EBW:** applied not to join two parts, but only to cause controlled contraction of the Nb metal in strategic positions, thus obtaining controlled frequency shifts. Very precise and reproducible

2. **Virtual TIG:** similar operation on the He vessel, done in inert atmosphere

“Virtual” EB welds on Nb reducing cavity length (frequency up)



“Virtual” TIG welds on Ti vessel: reducing vessel circumference, beam ports are pushed in (frequency down)

Cavity processing

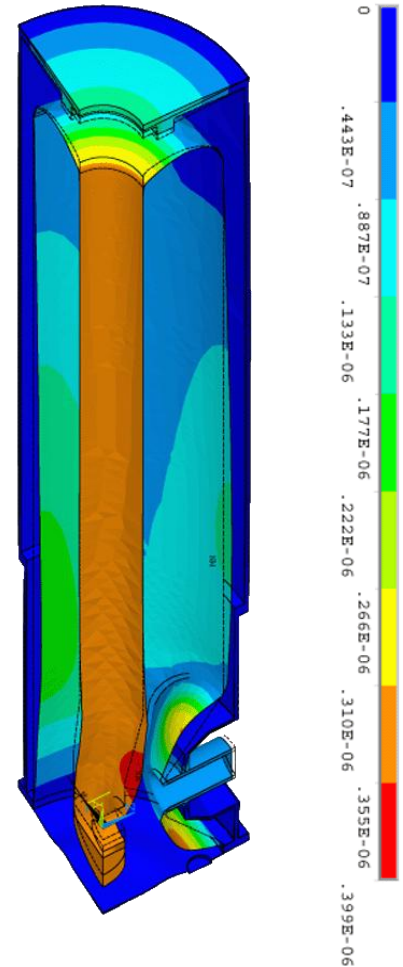
- Cavity processing is nowadays similar for elliptical and non-elliptical cavities ([See dedicated tutorial “Clean room techniques and cavity preparation”](#))
- Typical sequence (summary of main steps):
 - Electropolishing (**EP**) and/or Chemical polishing (**CP**) – to remove $\sim 150 \mu\text{m}$ of Nb and produce a clean and smooth surface of pure Nb
 - $600\div 800 \text{ }^\circ\text{C}$ **baking** in high vacuum - mostly to eliminate Q-disease
 - (**N doping** during $800 \text{ }^\circ\text{C}$ baking – to reduce R_s and increase Q. New technique, not yet implemented in operating linacs but in future ones)
 - **Light etch** (a few μm of CP or EP, if needed) – to remove possible contamination from furnace (or to reach the right depth in Nb after N doping)
 - High pressure water rinsing (**HPR**), clean drying – to remove any residual particle from the rf surface
 - **Low T baking** $80\div 120 \text{ }^\circ\text{C}$ baking (if needed) – to outgas and improve vacuum ($120 \text{ }^\circ\text{C}$ baking in addition can reduce R_{BCS} , but it can also increase R_{res})
 - RF processing in the cryostat: multipacting conditioning, high power rf processing, Helium processing (if needed)

Operational issues

Slow detuning: He pressure fluctuations

$$df \propto dP$$

- “Natural” solutions
 - Design your resonator strong
 - Build your cryosystem stable in pressure, with low dP/dt : **<5 Hz/min** achievable without big efforts
 - use the **mechanical tuner in a feedback loop**
- “Clever” solution:
 - design a **“self-compensating” resonator**

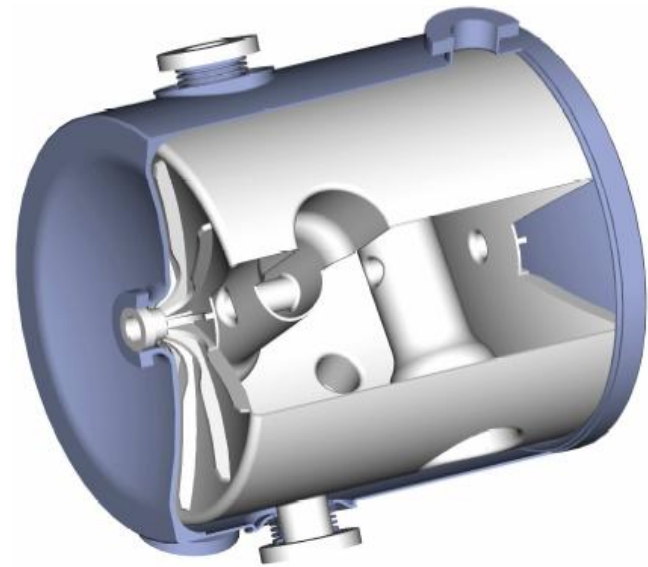


Self-compensating design

resonators can be designed in order to produce displacements with opposite effects to the frequency, to obtain a balance.



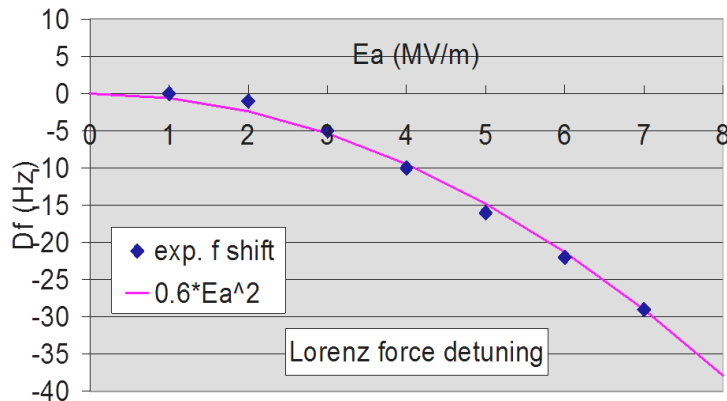
ANL 3-Spoke resonator end-plate with ribs calibrated for minimum df/dP



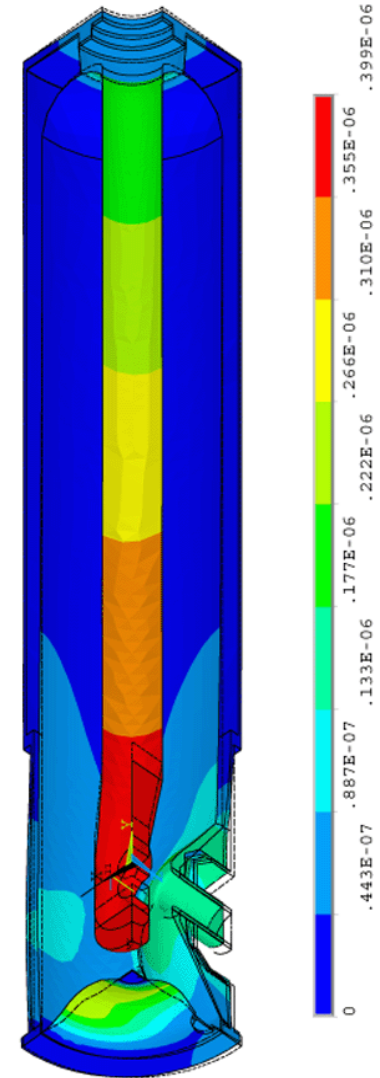
Lorentz Force detuning (LFD)

$$\delta f \propto -\delta(E_a^2)$$

- Lorentz force (radiation pressure) gives a typical quadratic detuning with field, always down
- solutions: strong mechanical structure, symmetric design (IC centering), tuning in feedback

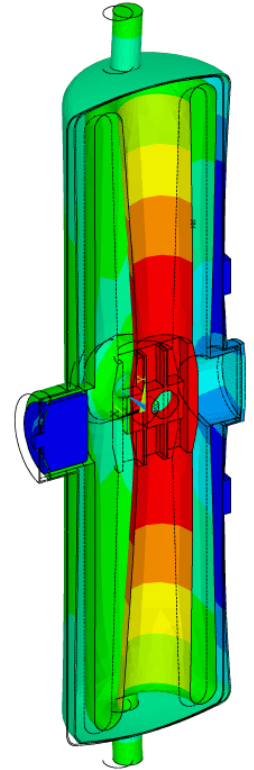


Lorentz Force detuning measured in a 80 MHz QWR



Resonant vibrations: mechanical modes

- Most dangerous: a small vibration can cause large deformation
→ large detuning that can exceed the resonator rf bandwidth
- Excited by:
 - pressure waves in the He
 - mechanical noise from environment (pumps, compressors,...)
 - mechanical disturbances from cryostat accessories (tuners, valves, stepper motors...)
 - Lorentz force detuning coupling to amplitude fluctuations
- The deformation is usually too fast to be recovered by mechanical tuners (however, the piezo technology is available)
- Solutions:
 1. Make the rf bandwidth wider
 - **overcoupling**
 - **electronic fast tuner**
 - **piezoelectric tuner** (only for low mechanical f)
 2. Make the detuning range narrower
 - **careful design**
 - **inner conductor centering**
 - **mechanical damping**
 - **(electronic damping by properly exciting Lorentz forces)**



Example: stem vibration in a QWR

Mechanical modes:

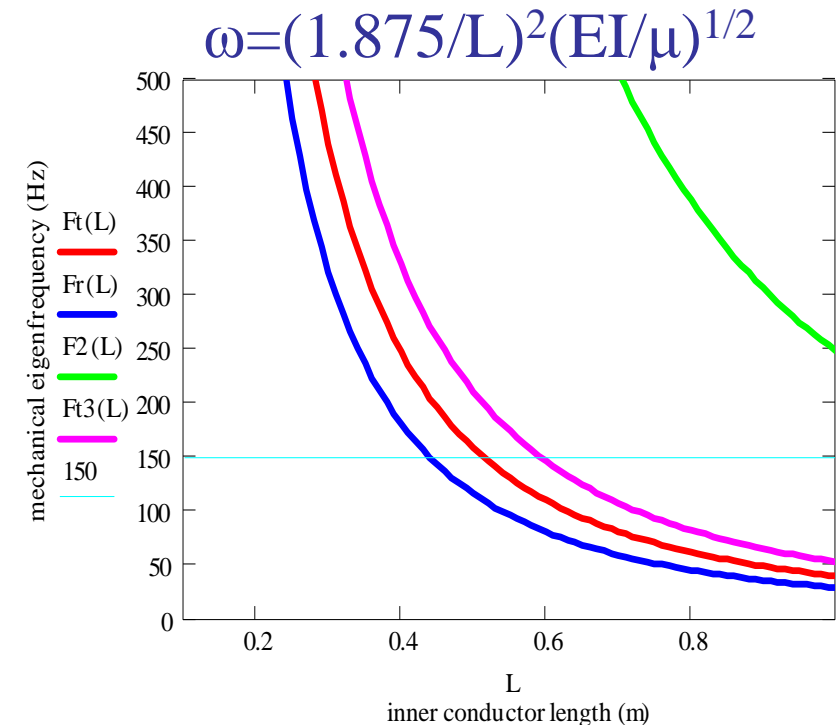
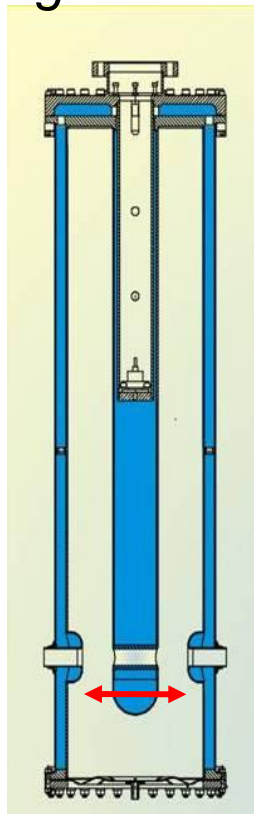
- *~50-60 Hz most critical*
- *< ~ 150 Hz dangerous*
- *criticality decreasing with increasing frequency*

Lowest mode frequency of a 106.08 MHz Nb QWR:

Simulation: 81 Hz

Analytical: 83 Hz

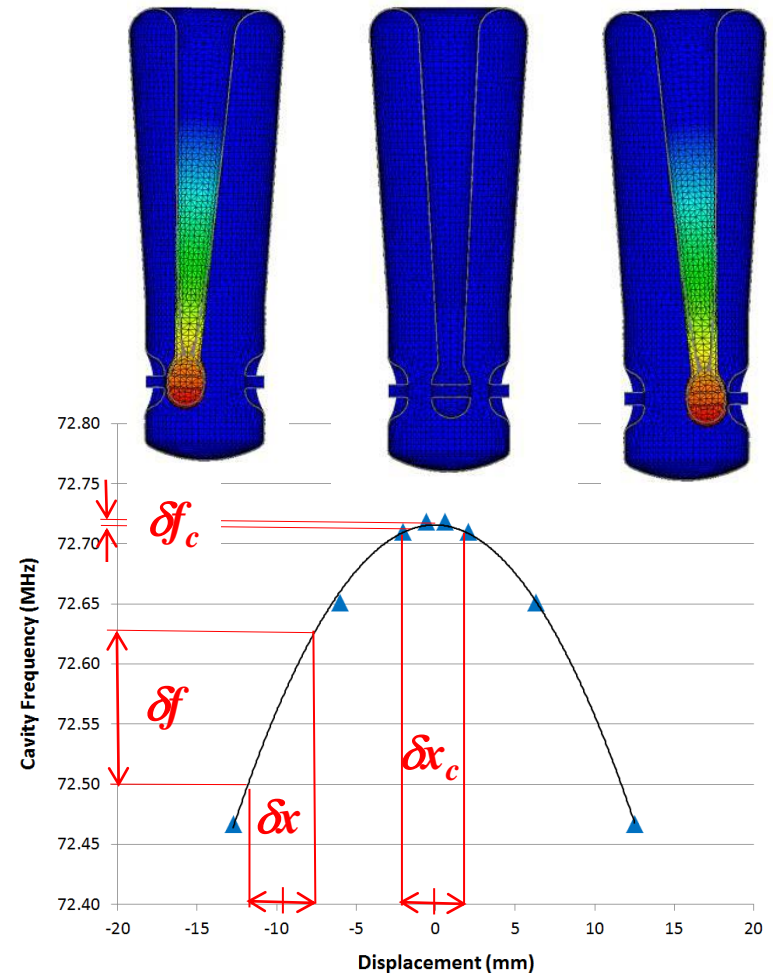
Measured: 78



QWR mechanical frequency vs length of the inner conductor ($\varnothing=60$ mm, analytical results).
 red: 2mm thick, Nb tube; blue: full Cu rod;
 magenta: 80 mm dia tube. Green: 2nd mode.
 (E =Young modulus; I = geometrical moment of inertia of the i.c. tube cross section; μ =mass per unit length of the i.c. tube)

Importance of inner conductor centering

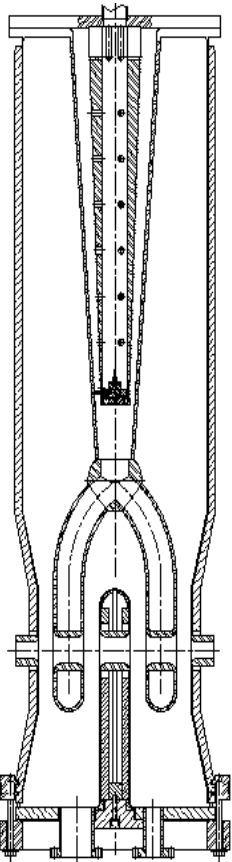
- In coaxial QWRs and HWRs any displacement δr of the inner conductor from the EM center lowers the cavity resonance frequency.
- When the IC is centered ($\delta r=0$), the frequency $f(\delta r)$ has a maximum and its derivative is zero $df/d(\delta r)=0$
- Detuning in response to vibrations or Lorentz forces causing IC displacement will be minimum if the IC starts from the center
- It is possible (not always easy) to plastically deform the cavity and center the IC: the effective EM center is found by looking for maximum rf frequency
- **We look for low detuning rather than for extreme stiffness**



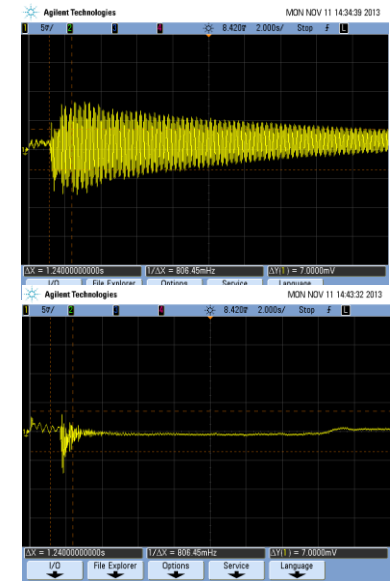
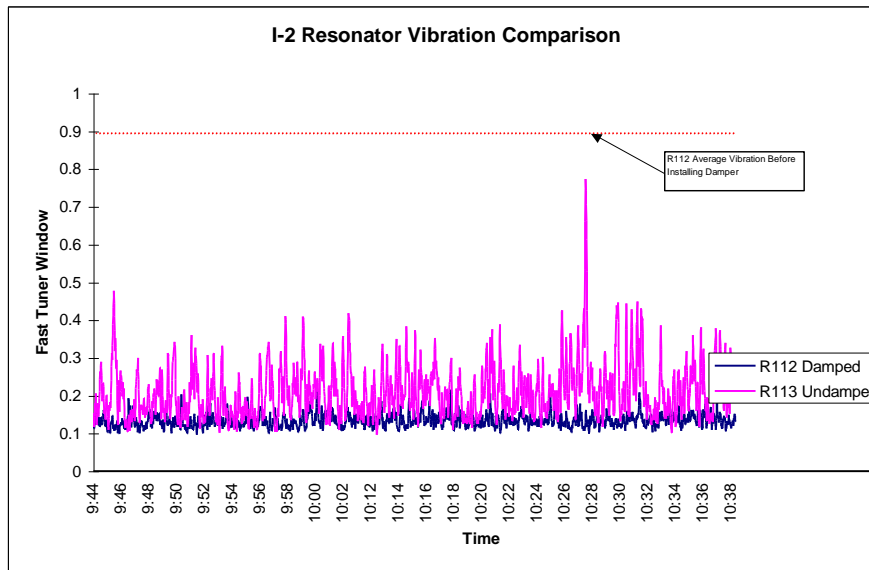
δf vs. δr from QWR IC displacement
(From M. Kelly's Tutorial at SRF2013)

Mechanical vibration dampers

4-gap, 48 MHz
QWR with vibration
damper



Self-adjusting, 4-points of contact vibration damper



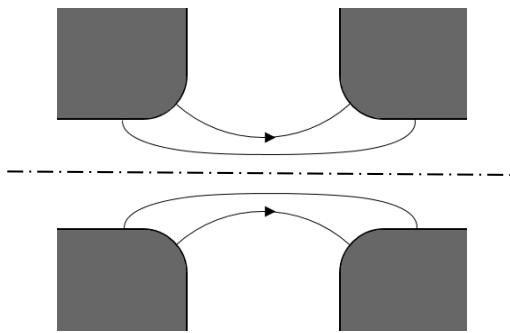
Detuning decay time without (top) and with damper in a 80.5 MHz FRIB QWR

Dampers attenuate the vibration amplitude by approx. a factor of 10

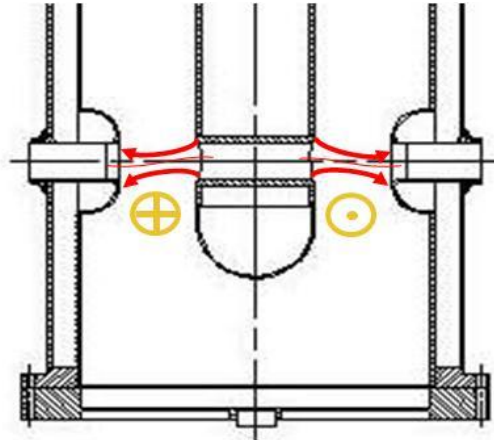
Vibration dampers in QWRs are cheap and effective

Beam Steering in QWRs

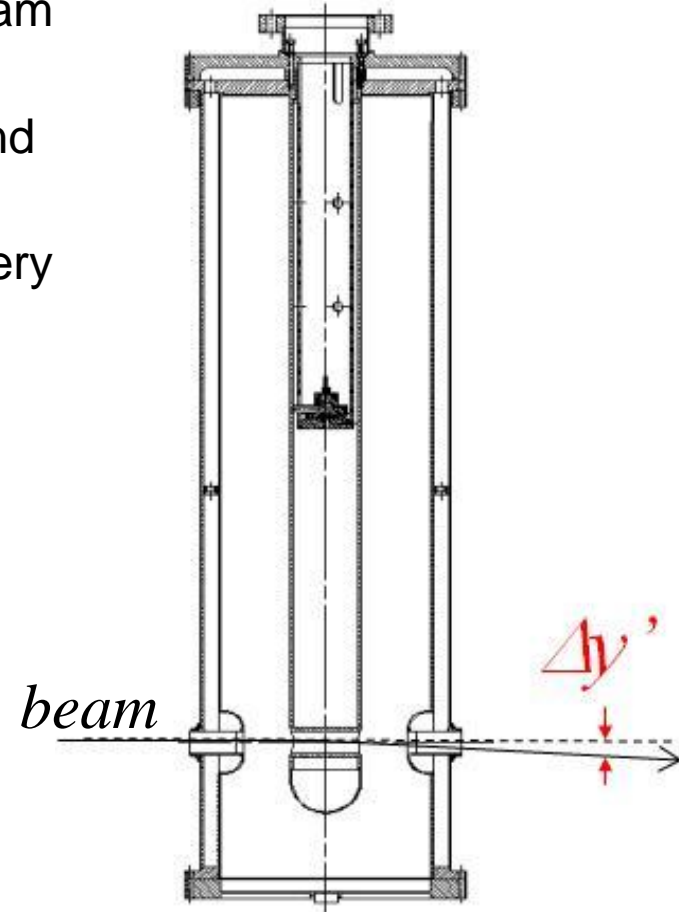
- Lack of symmetry in QWRs can produce transverse E and B fields along the beam axis. This can cause beam steering and serious problems in beam transport
- Unwanted field components have different shapes and time dependence compared to accelerating field
- Steering adds to the rf defocusing which given by every accelerating gaps to beams out of axis



Ideal rf gap: \mathbf{E} and \mathbf{B} cylindrically symmetric; on axis only \mathbf{E}_z with no transverse components



QWR rf gaps: on axis both \mathbf{E}_y and \mathbf{B}_x are present



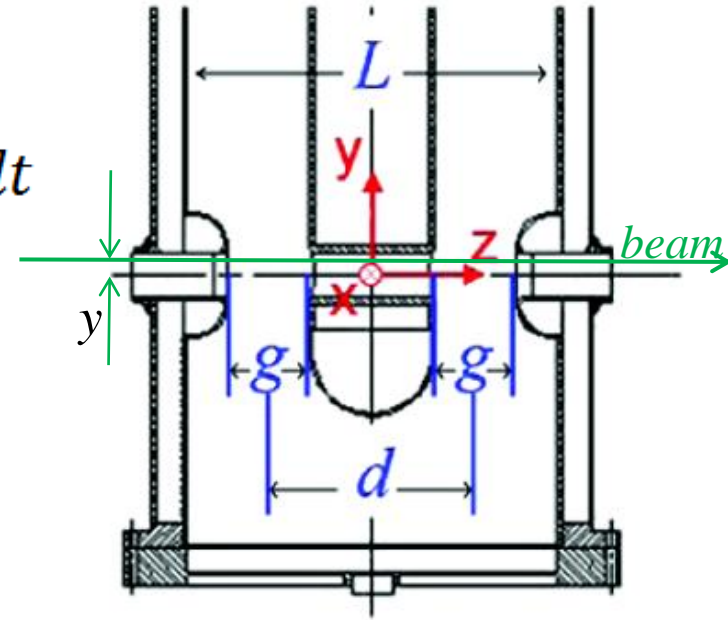
Transverse kick

Vertical kick Δp_y from E_y and B_x :

$$\Delta p_y = qe \int_{t(-L/2)}^{t(L/2)} E_y(z, t) + \beta c B_x(z, t) dt$$

The resulting steering angle $\Delta y'$ is simply:

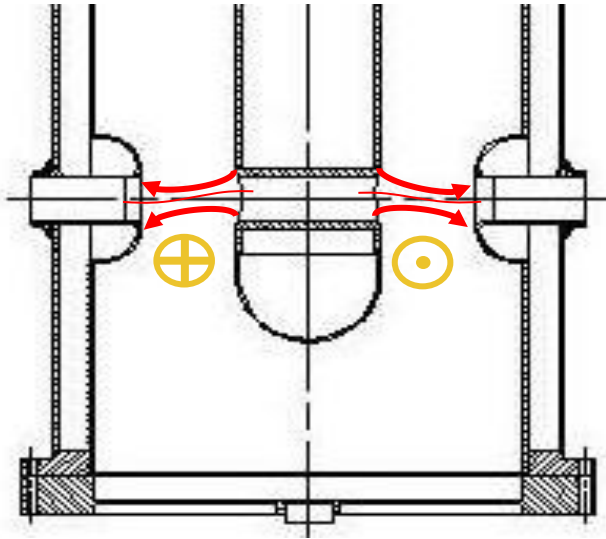
$$\Delta y' = \frac{\Delta p_y}{p_z}$$



However, out of axis there is always rf defocusing proportional to r .
In the y direction it adds to the steering when $y \neq 0$

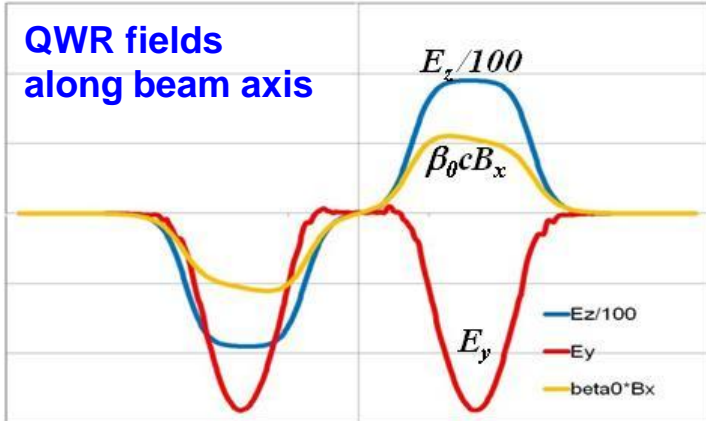
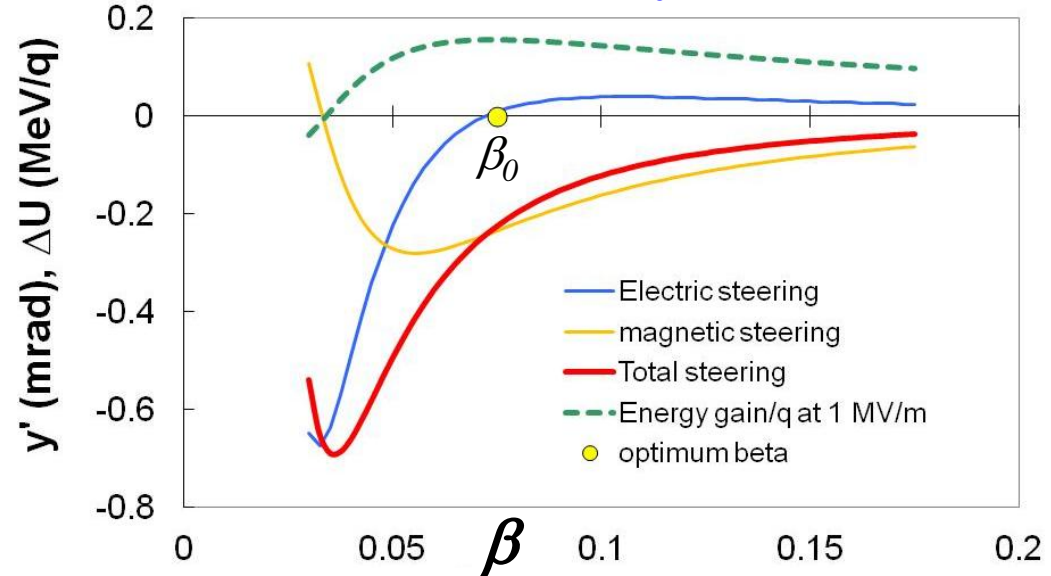
$$\Delta y'_{\text{rf}}(\beta) = - \frac{\omega}{2\beta^3 \gamma^3 m_0 c^3} \frac{q}{A} e E_a L T(\beta) y \sin \phi.$$

On axis steering at typical acceleration $\phi = -30^\circ$



- Electric steering is 0 at β_0 and small above β_0
- Magnetic steering is nearly maximum at β_0
- E_y and B_x are comparable and $\sim 1\%$ the accelerating field

Steering in a coaxial $\beta_0=0.075$ QWR



QWR Steering general formula

- Working out the previous formulas we find: (*Phys. Rev. ST Accel. Beams 14, 070101 (2011)*)

$$\Delta y'(\beta, y) \sim \frac{qeE_a L \sin\phi}{\beta\gamma A m_0 c^2} \left\{ \underbrace{G_{Bx} T_{Bx}(\beta)}_{\text{magnetic}} + \underbrace{\frac{G_{Ey}}{\beta} T_{Ey}(\beta)}_{\text{electric}} + \underbrace{\frac{\omega(1-\beta^2)}{2c\beta^2} T(\beta) \cdot y}_{\text{Rf defocusing}} \right\}$$

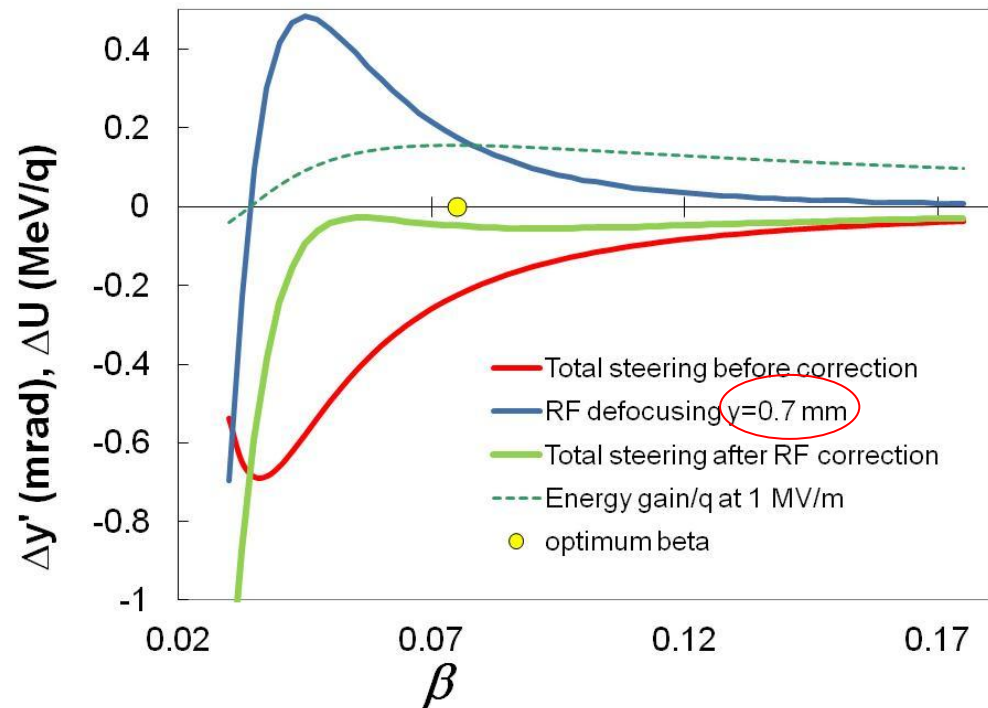
All terms :

- are proportional to acceleration gradient and equally depending on the beam phase
 - have different transit time factors $T(\beta)$ and different optimum β_0 's
 - have different geometrical factors G
 - have different dependance on $1/\beta^n$
 - The rf defocusing term gives a vertical steering proportional to the vertical distance y of the beam from the geometrical beam tubes axis
- Playing with the cavity geometry and with the beam axis position – all terms inside brackets - we can perform **steering correction**
 - This correction will work at any gradient E_a and phase ϕ !**

1st Correction Method: beam axis displacement

$$\Delta y'(\beta, y) \sim \frac{qeE_a L \sin\phi}{\beta\gamma A m_0 c^2} \left\{ G_{Bx} T_{Bx}(\beta) + \frac{G_{Ey}}{\beta} T_{Ey}(\beta) + \frac{\omega(1-\beta^2)}{2c\beta^2} T(\beta) \cdot y \right\}$$

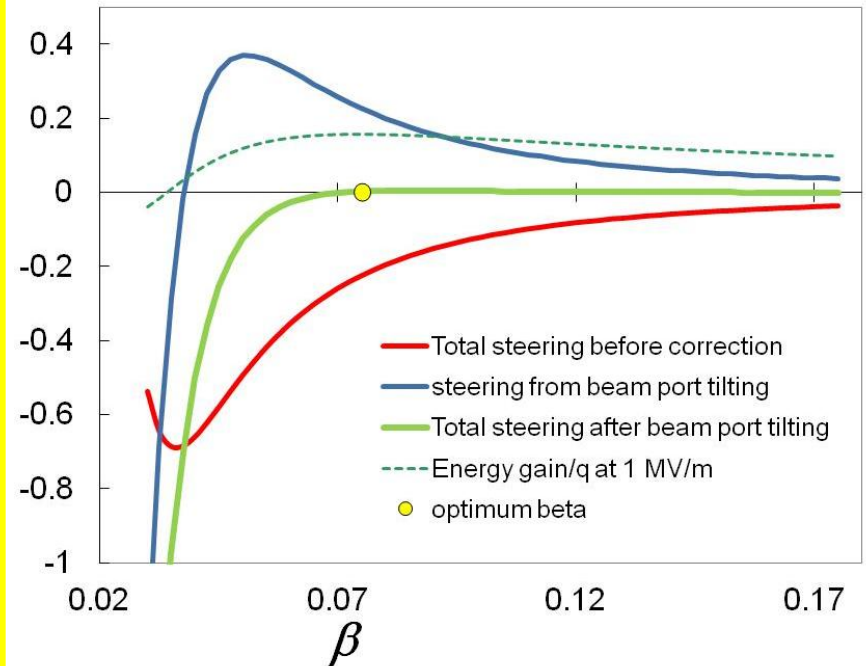
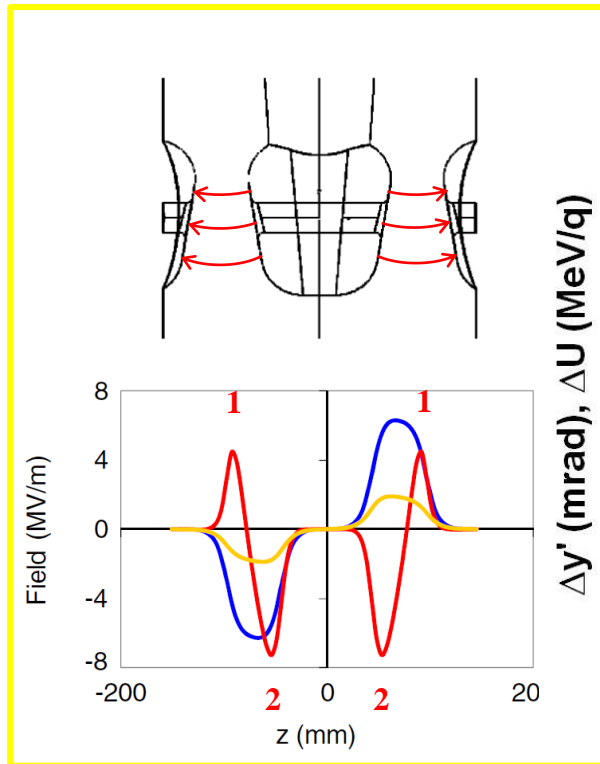
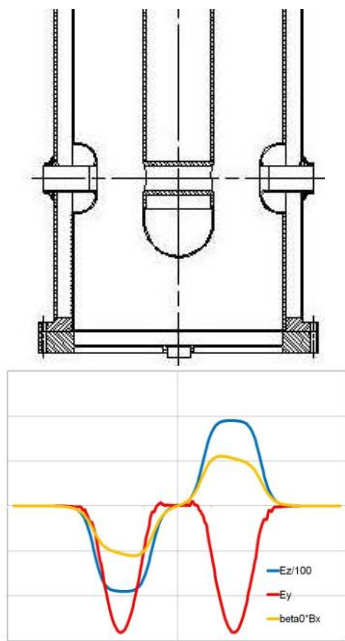
- B steering and rf defocusing have a rather similar TTF and shape.
- By shifting the input beam up (thus at a positive y) by an appropriate amount, it is possible to cancel steering
- This is particularly effective especially at lower β , where steering it is stronger



2nd Correction Method: Beam Port Tilting

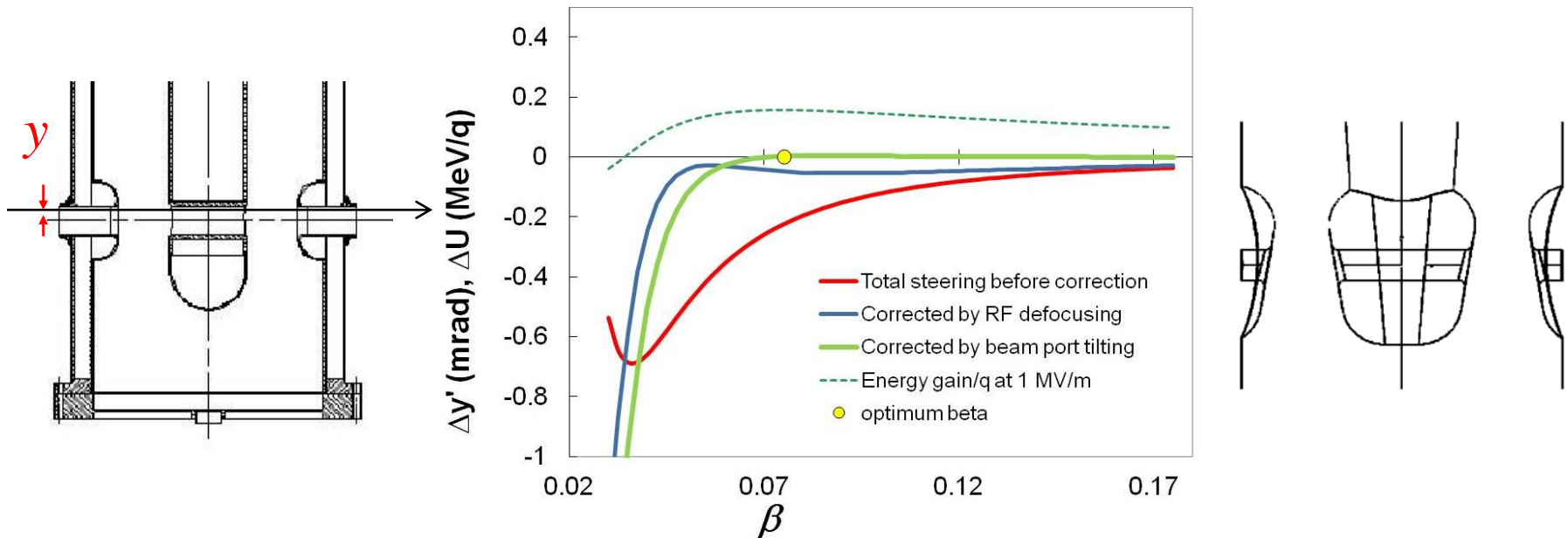
$$\Delta y'(\beta, y) \sim \frac{qeE_a L \sin\phi}{\beta\gamma A m_0 c^2} \left\{ G_{Bx} T_{Bx}(\beta) + \left[\frac{G_{Ey}}{\beta} T_{Ey}(\beta) \right]_1 + \left[\frac{G_{Ey}}{\beta} T_{Ey}(\beta) \right]_2 + \frac{\omega(1-\beta^2)}{2c\beta^2} T(\beta) \cdot y \right\}$$

- Beam port tilting creates additional E_y steering terms which can be properly shaped to cancel steering almost completely near and above β_0



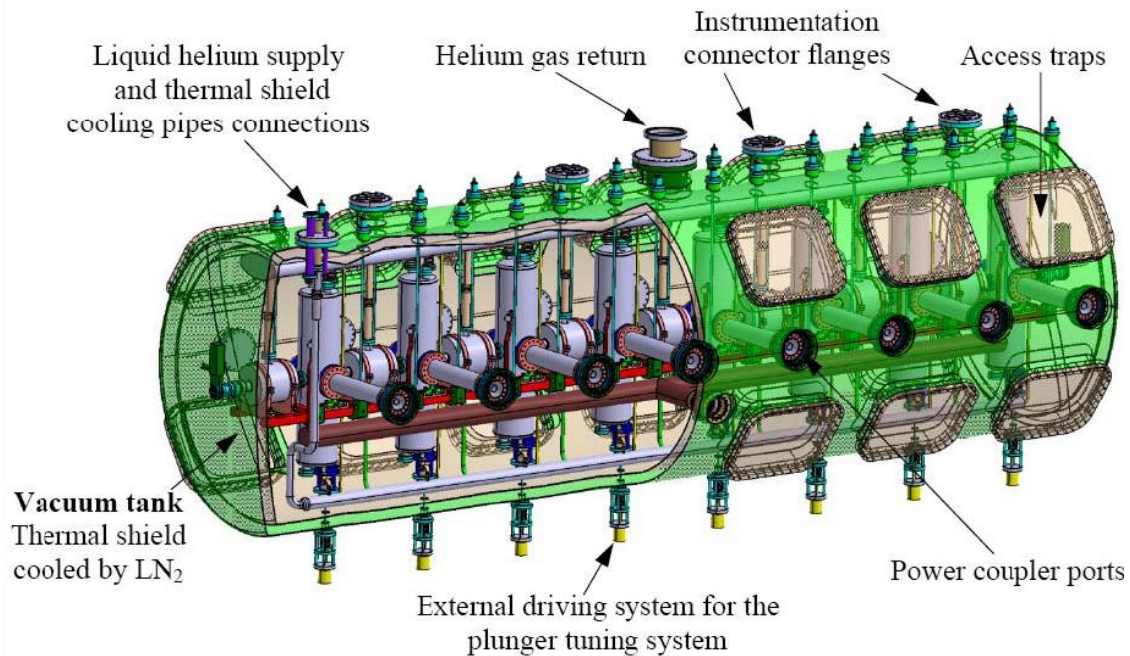
Comparison of the two methods

- Both methods are very effective
- Beam displacement is easy in lower β_0 QWRs requiring small y
- In higher beta cavities ($\beta_0 \gg 0.1$) the required axis displacement y becomes larger, causing loss of effective aperture: in this case beam port tilting is preferable
- Above $\beta_0 \sim 0.2$, the tilting angles become too large, affecting cavity performance: steering free geometries like HWRs are needed

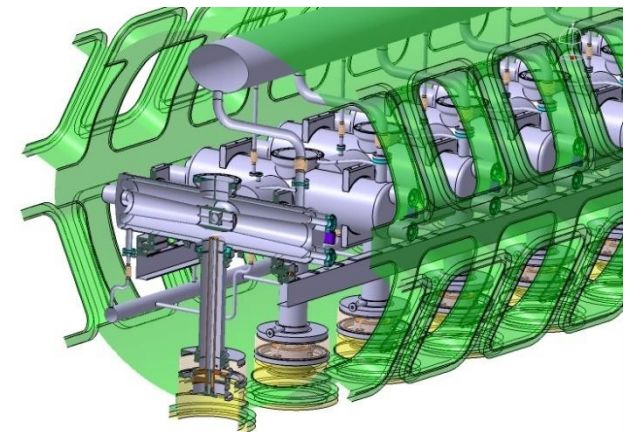


Non-elliptical cavities integration in cryomodules

Some remarks on cryomodules for NE cavities



Early design studies for the IFMIF/EVEDA cryomodules, in the two versions with vertical or horizontal cavity orientation. Finally, the horizontal HWR orientation was chosen



- Non-elliptical cavities require more complicated cryomodule structures compared to elliptical ones
- Much larger diversity in NE cryomodules than in elliptical
- Different solutions exploited for the same cavity types
- Couplers, tuners and rf lines are often dominant ingredients, especially in high rf power cryomodules

Vacuum scheme in low- β cryomodules

Design objectives in every accelerator cryostat: cryogenic efficiency, easy installation and maintenance, stable and reliable operation



Common vacuum cryostat (TRIUMF)

Many low- β cryostats working at 4.2K have only one common vacuum inside and outside the resonators

- cryostat design and assembly simplified*
- possible contamination of rf surfaces from outside the resonator*
- In spite of that, very high Q can be maintained for years in on-line resonators*
- Q degradation only when the cryostat is vented from outside the resonators*
- Provide clean venting, and common vacuum will be (nearly) as reliable as separate one (at least at 4.2K)!***

Top-down and bottom-up low- β cryomodules

- Top down: cavities and cryogenics hang from the top plate of the cryostat (well established approach)
- Bottom-up: cavities and cryogenics sit on the cryomodule base plate (recent development)
- Advantages and disadvantages in both solutions, both work. Especially in long and heavy cryomodules the bottom up solution can facilitate assembly and reliable alignment.



Top-down cryomodule (ANL)



Bottom-up cryomodule (FRIB/MSU)

Non-Elliptical Resonators

End of Part I

Thank you

(and see you tomorrow for Part II)

SRF2015 – Whistler, BC, Canada

Tutorial n.7

**Non-Elliptical Resonators
Part II**

A. Facco

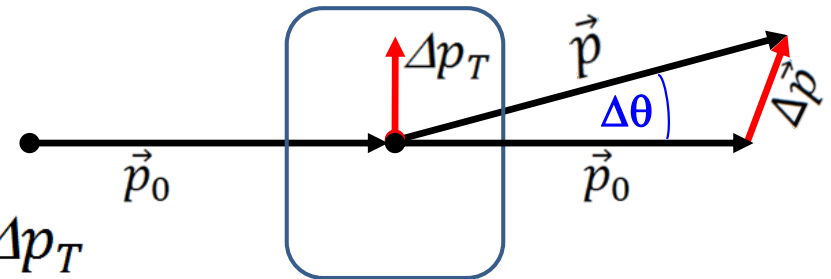
INFN/LNL and FRIB/MSU

SRF Deflecting Cavities

Basic definitions in beam deflection

- Cavities do not only accelerate and bunch, they can also deflect the beam: the change $\Delta\vec{p}$ of particle momentum in a cavity under the action of the fields \vec{E} and \vec{B} can have all components:

$$\Delta\vec{p} = qe \int (\vec{E} + \vec{v} \times \vec{B}) dt$$



- The deflecting angle is

$$\Delta\theta = \frac{\Delta p_T}{p_L}$$

- $p_L \sim p_0$ is the longitudinal beam particle momentum

- Δp_T is the projection on the transverse plane x,y of $\Delta\vec{p}$

- when treating deflection, in most formulas the beam velocity is assumed to be constant: $p_L \cong |\vec{p}_0| \cong |\vec{p}|$

Voltage and Gradient in Deflecting Cavities

For deflecting cavities it is useful to define a “**deflecting voltage**” V_T

In typical cavities deflecting the beam in the x-z plane,

$$V_T = \int_{-L/2}^{+L/2} \left[E_x(z) \cos\left(\frac{\omega z}{\beta c}\right) + \beta c B_y(z) \sin\left(\frac{\omega z}{\beta c}\right) \right] dz$$

Starting from V_T , if L is the cavity effective length, a deflecting field (or gradient) can be defined:

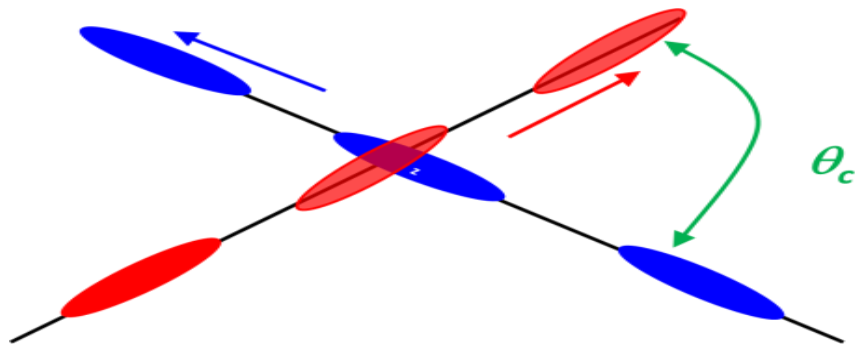
$$E_T \equiv \frac{V_T}{L}$$

To maximize the time under the deflecting field (1/2 rf cycle), $L = \frac{\beta \lambda}{2}$
This way deflection simply becomes

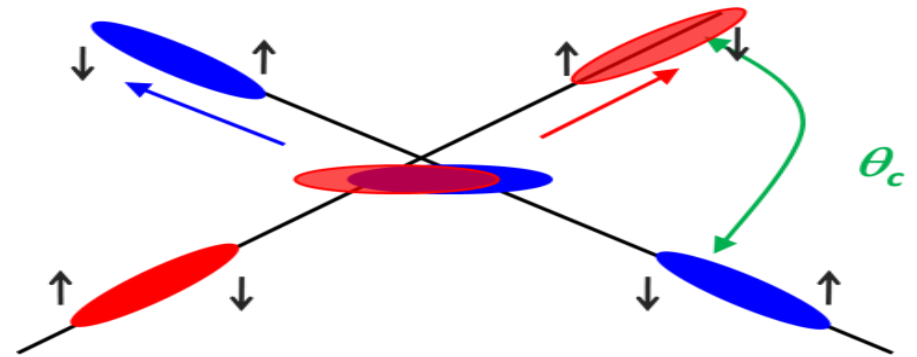
$$\Delta\theta = \frac{qeE_T \lambda \cos \phi}{2\beta\gamma m_0 c^2} = \frac{qeV_T \cos \phi}{\beta\gamma m_0 c^2}$$

Motivation for SRF

- Needed to deflect the beam at high β , where usual normal-conducting deflectors are ineffective or too expensive
- Main use:
 - Chopping and beam rf separation at high β
 - **Crabbing**: bunch rotation in colliding beams to increase luminosity. head and tail of the bunch must be deflected at different angles



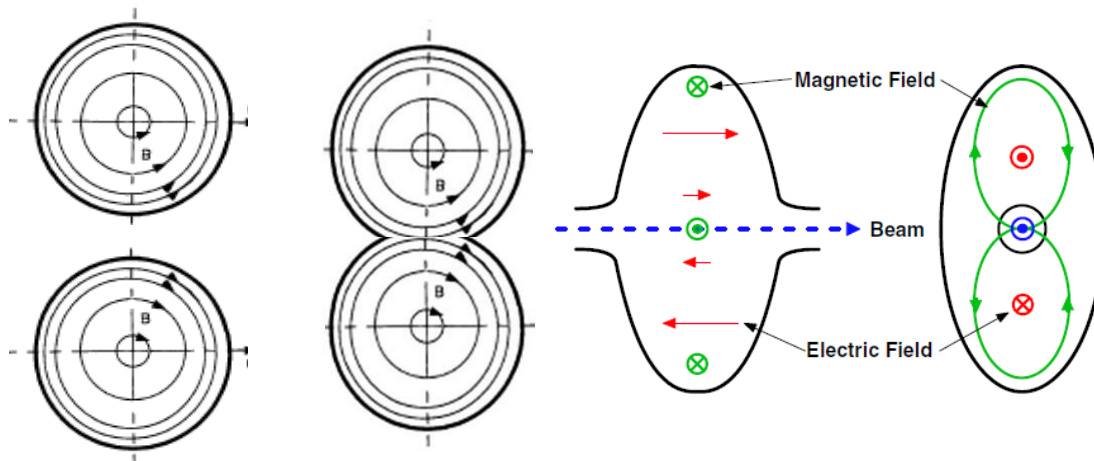
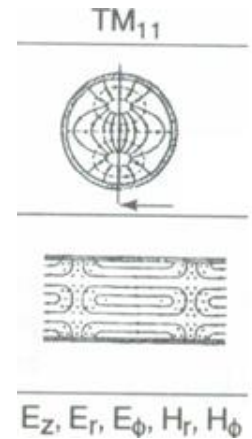
No bunch rotation: limited overlap between colliding beams



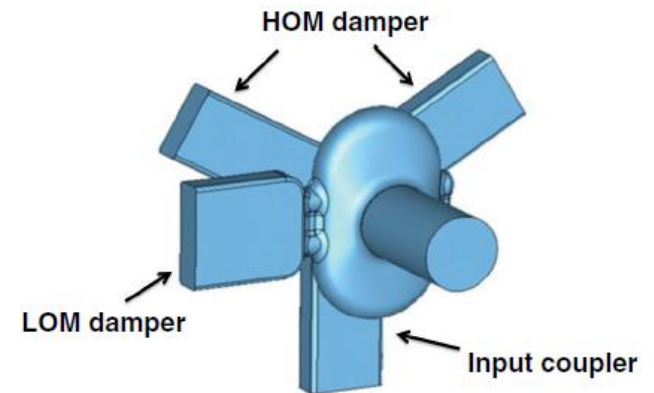
Crabbing: maximum overlap between colliding beams, increasing luminosity

Limits of elliptical deflectors

- Elliptical deflector typically use only magnetic field
- Deflection can be increased by using multicell cavities
- Elliptical cavities can have an elongated shape in order to remove degeneracy of the TM₁₁ mode
- However, their **transverse size** ($\sim \lambda$) depends on rf frequency and cannot be reduced



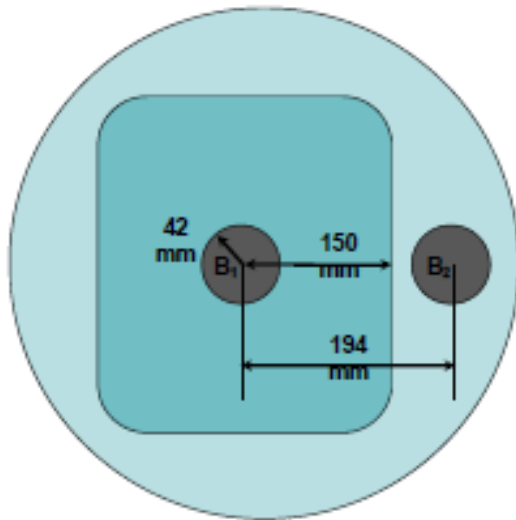
Sketch of elliptical deflector with TM₁₁ mode, in analogy to connecting two TM₀₁ cavities with opposite phase



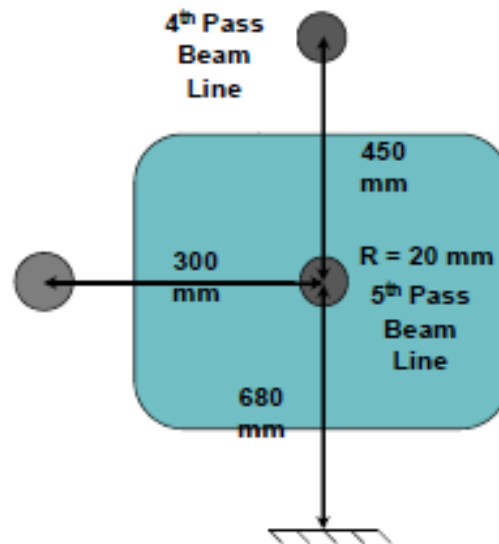
The APS deflecting cavity geometry

Quest for compact deflecting cavities

- New applications – e.g. crabbing at LHC – require compact resonators working at low frequency with low transverse dimensions to fit the limited space between beam lines
- A new generation of TEM (and TE) type deflecting resonators with small transverse size has been developed



400 MHz LHC
crabbing system

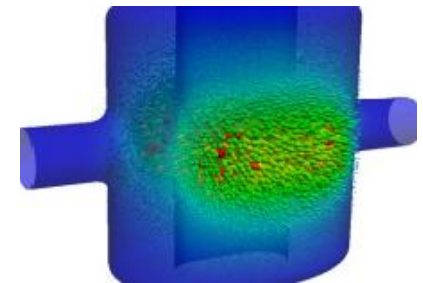
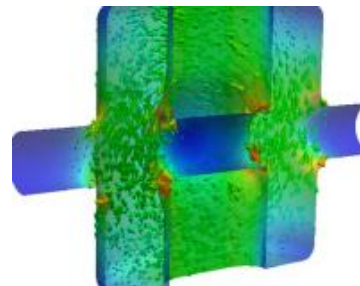
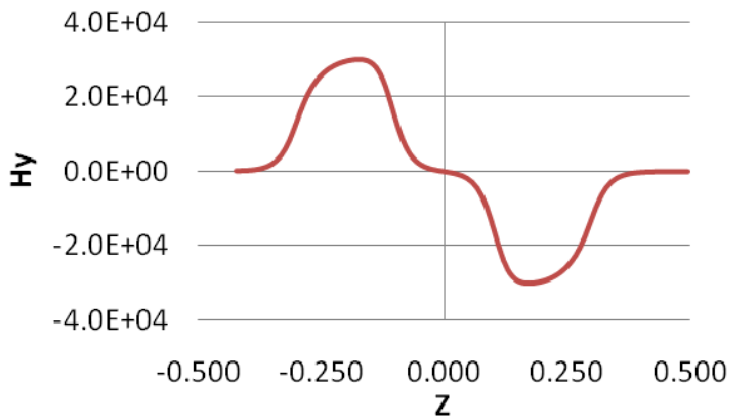
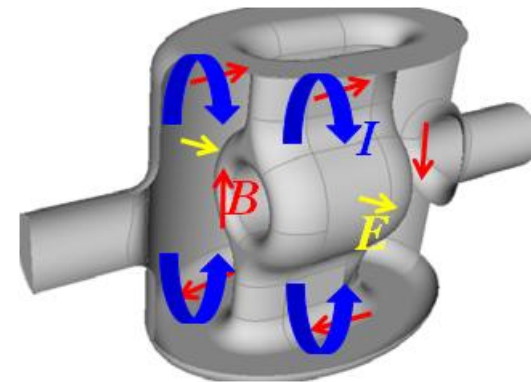
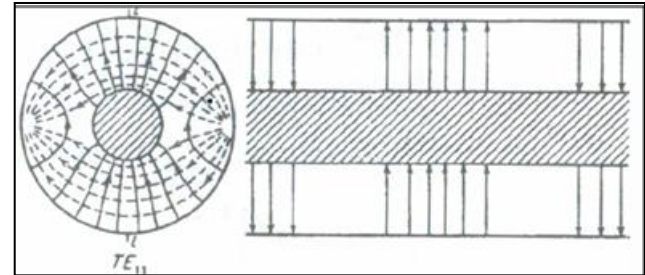


499 MHz JLAB Upgrade
deflecting system

Dimensional constraints for deflecting systems under construction.

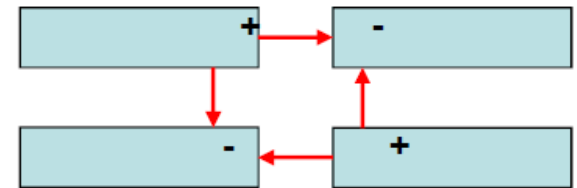
The SLAC 400 MHz crab HWR

- Although looking like an HWR it is used in the TE₁₁ mode which possess a strong B_y on axis
- B_y gives a deflection $\Delta x'$
- Very compact in x, it is $\sim \lambda/2$ long in y (~ 375 mm)

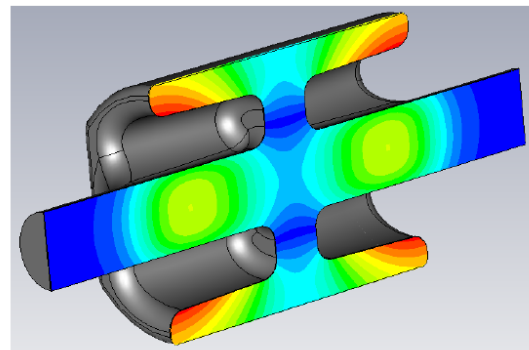
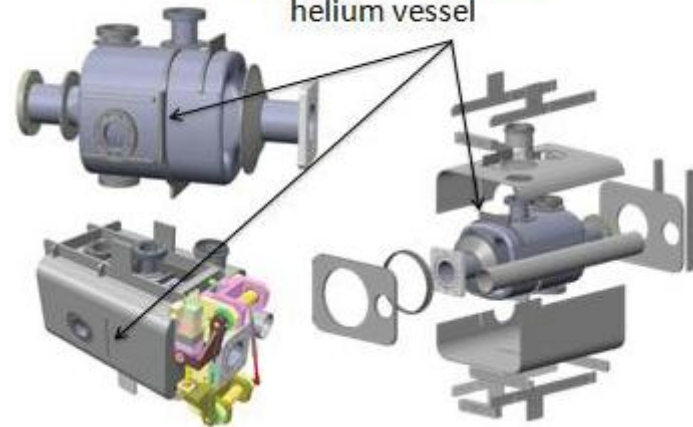


The UK/JLAB 400 MHz 4-rod cavity

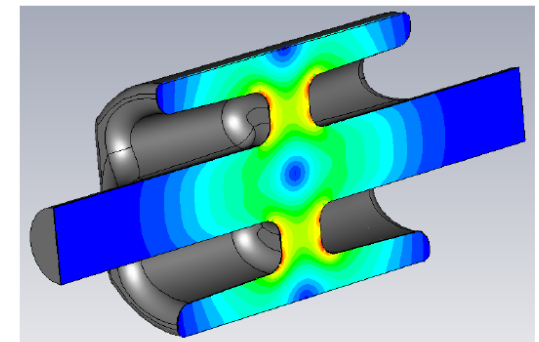
- 4 QWRs working in push-pull mode
- Both E_x and B_y giving deflection
- Transverse radius < 150 mm
- Built and tested to $V_T \sim 3.3$ MV, close to the LHC crab cavity goal



Ribs welded to cavity and helium vessel



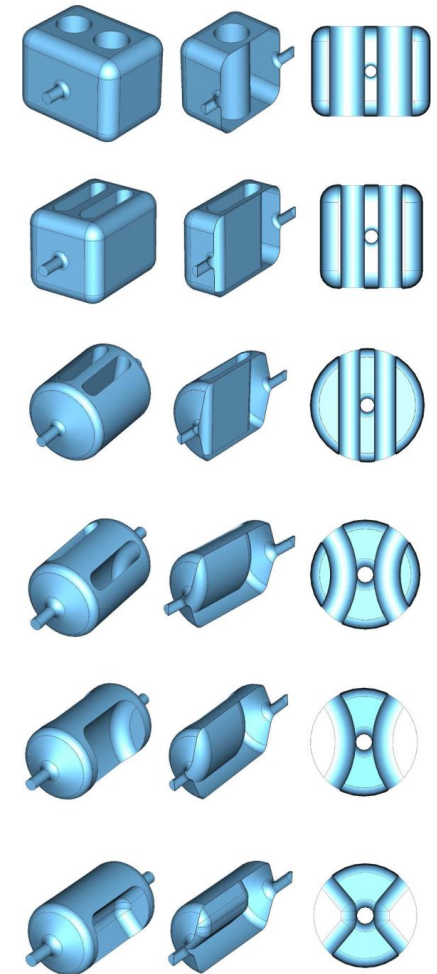
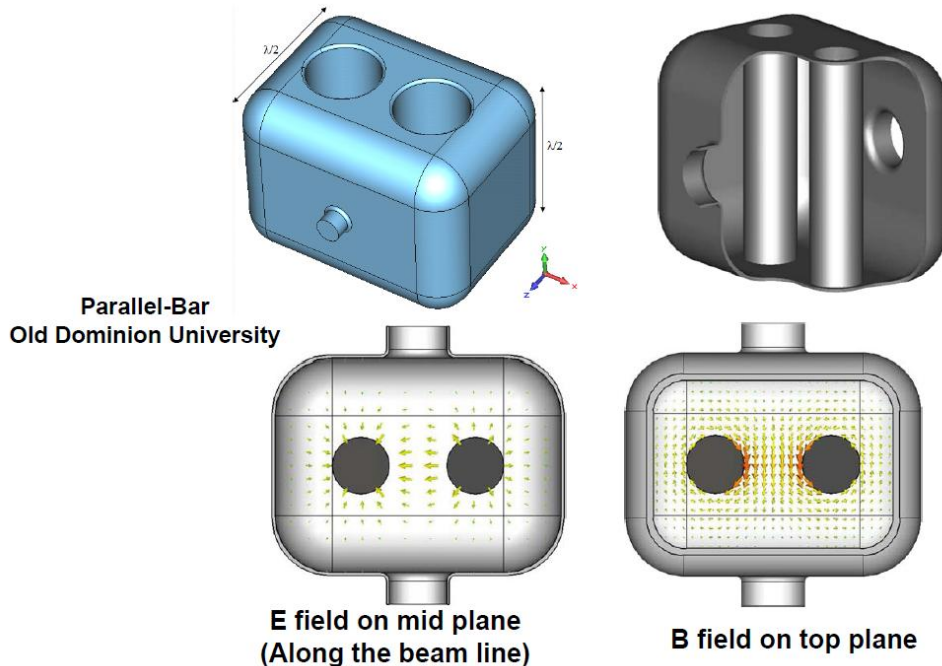
B field



E field

The Parallel-Bar 400 MHz crab HWR

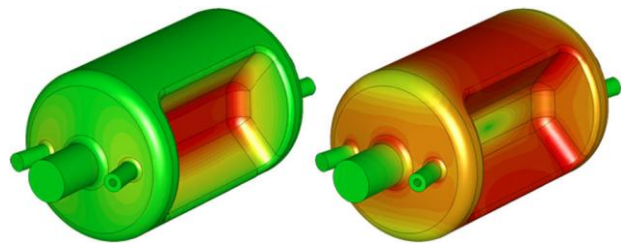
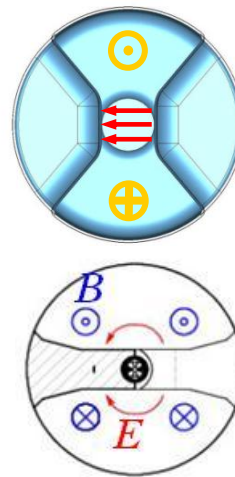
- Double HWR working in TEM π mode
- Deflecting field: E_x
- Good SRF parameters, but transverse size > 150 mm: geometry evolved to fit LHC crabbing limits



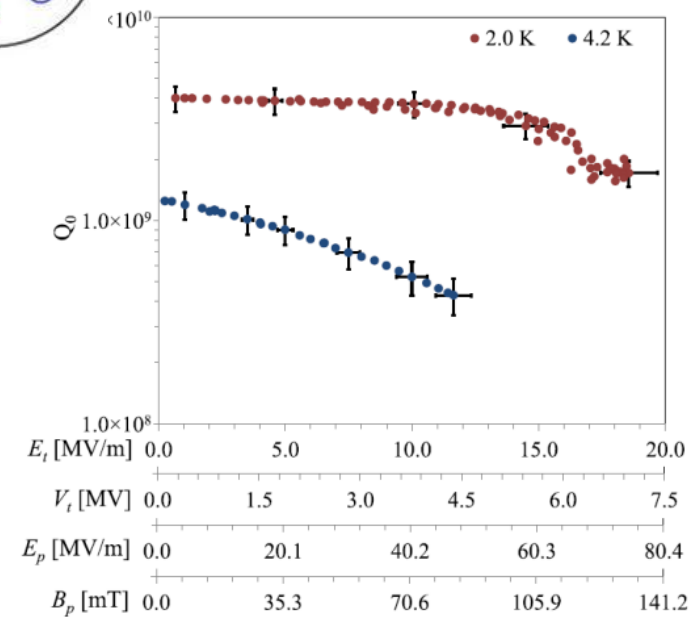
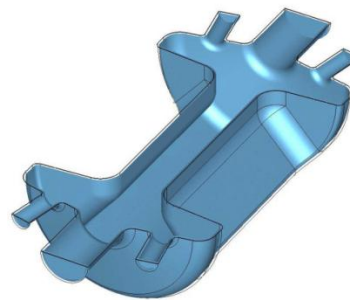
Parallel-Bar cavity evolution

The ODU Rf-Dipole 400 MHz crab cavity

- Ultimate evolution from Parallel-Bar geometry: TEM mode became similar to the TE one of an IH structure, or even to the TEM of a QWR
- Deflecting field: E_x
- Size fitting LHC crab system
- Prototype built and tested to $V_T > 7$ MV (LHC goal: > 3.34 MV)

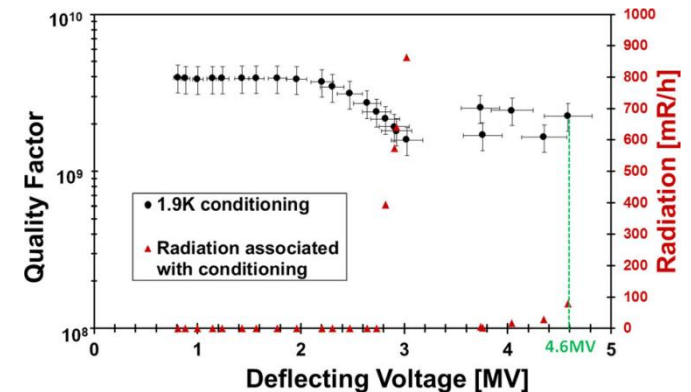
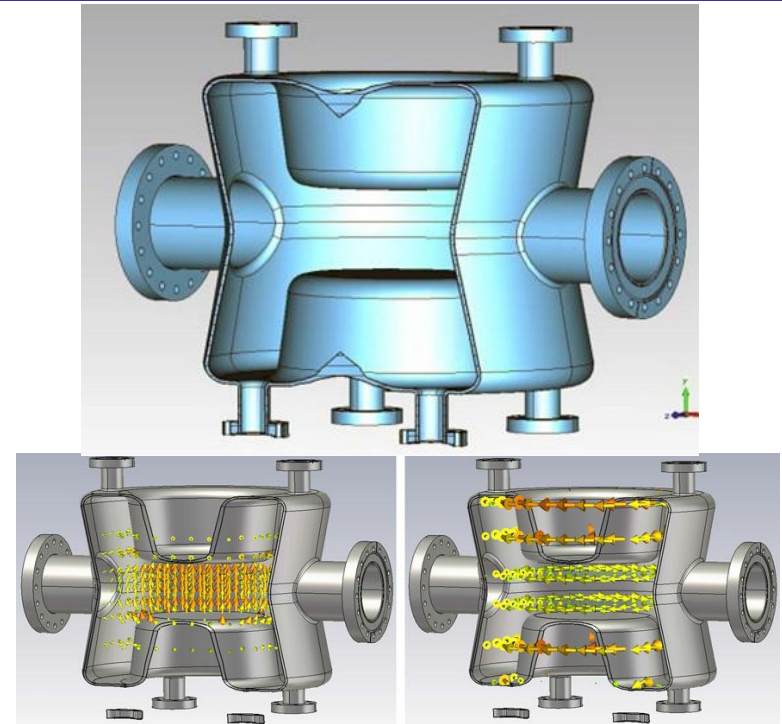


Surface E and B distribution



The BNL 400 MHz double QWR

- Double QWR operated in push-pull mode
- Deflecting field: E_x
- Transverse size fitting LHC crab cavity limits
- Proof of principle prototype built and tested cw to $V_T > 3\text{MV}$ limited by rf power; $V_T > 4.5$ in pulsed mode (LHC goal: $> 3.34\text{ MV}$)
- 2° generation prototype under construction



State of the art in Non-Elliptical cavities

Design, Construction and Treatments

- **Design.** Powerful tools – mainly simulation codes - exist for cavity design optimization in all aspects (RF, mechanical, thermal, magnetic,...). These tools are challenged even more in Non-Elliptical cavities than in Elliptical ones, due to their intrinsic complexity and variety
- **Construction.** Construction and welding technology is steadily improving, thus the quality and reproducibility of the final cavities produced. The quality of commercially available high-RRR Nb is nowadays very high
- **Processing.** All treatments and techniques developed for elliptical cavities and bringing record performance are now applied also in non elliptical ones
- **Large scale production.** All state-of-the-art procedures and treatments for Nb cavities once limited to a few research laboratories can now be handled by industry

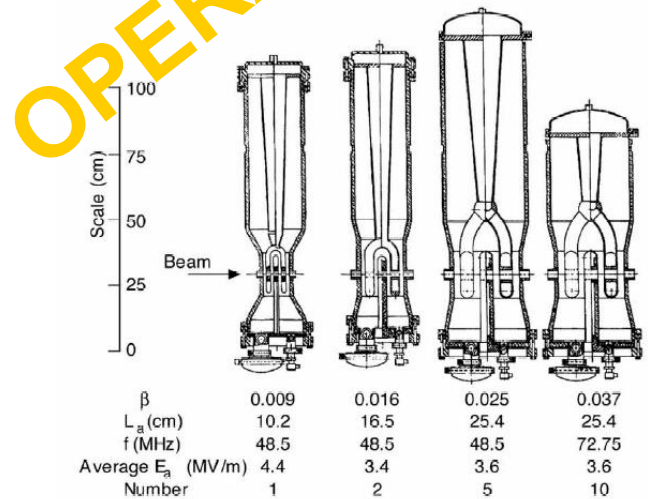
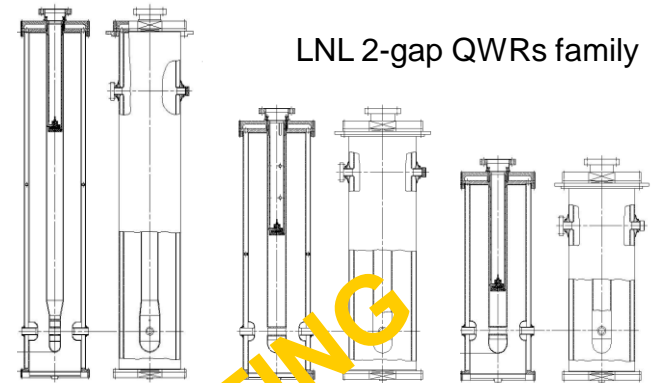
Quarter-wave structures: Quarter-Wave resonators

$$48 \leq f \leq 162 \text{ MHz}, 0.001 \leq \beta_0 \leq 0.2$$

- + Compact
 - + Modular
 - + High performance
 - + Relatively low cost
 - + Easy access (in the open ones)
 - + Down to very low beta
- Dipole steering for higher β QWRs
 - Mechanical stability for lower f QWRs

Very successful

Largest family in operation

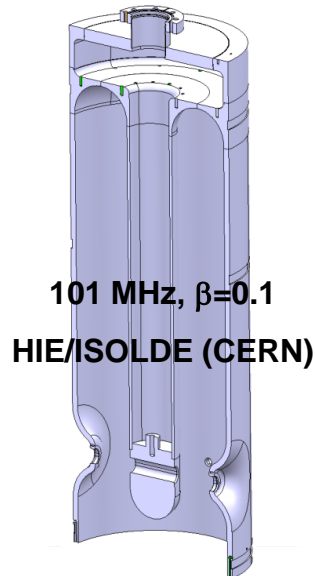


ANL 4-gap QWR family

Some of the QWRs worldwide...



TRIUMF



101 MHz, $\beta=0.1$
HIE/ISOLDE (CERN)



New Dehli



$\beta_0 = 0.041$ $\beta_0 = 0.085$
72 MHz, (FRIB/MSU)



160 MHz, $\beta=0.12$
INFN LNL
(sputtered)



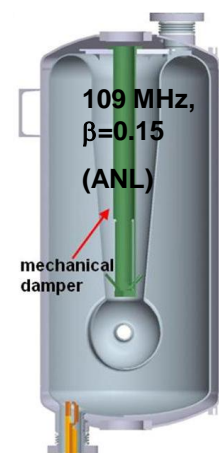
INFN LNL



Saclay



IPNO



109 MHz,
 $\beta=0.15$
(ANL)

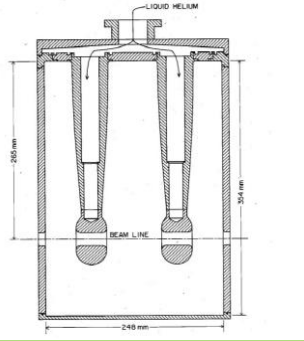
mechanical damper



72 MHz,
 $\beta=0.077$
(ANL)

Quarter-wave structures: Split-ring resonators

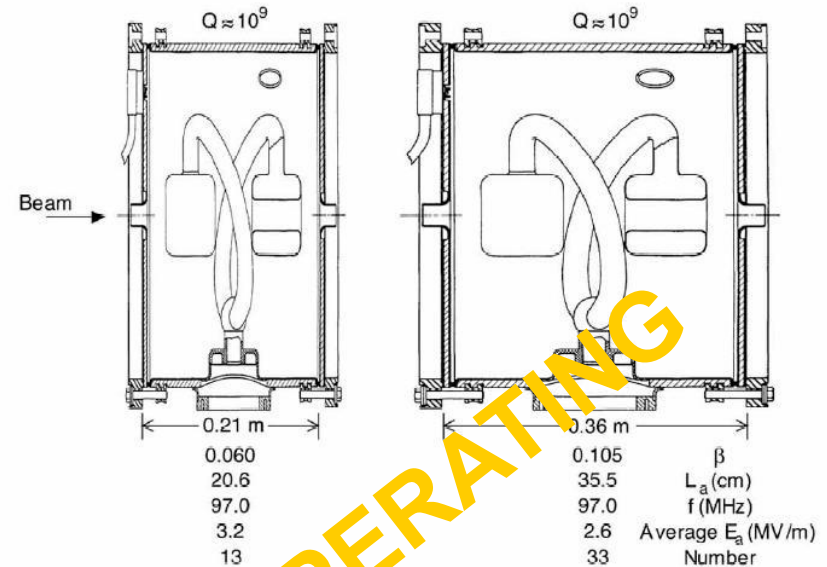
Double QWR,
(prototyped in the
80's). Its push-pull
operation mode is
similar to the split-
ring's one



$$90 \leq f \leq 150 \text{ MHz}, \quad 0.05 \leq \beta_0 \leq 0.15$$

- + relatively large energy gain
- + compact
- + good efficiency
- - mechanical stability
- beam steering
- high peak fields
- more expensive and difficult to build than QWRs

Successful resonators in use for many years, now obsolete



OPERATING



Half-wave structures: **Half-Wave resonators (coaxial)**

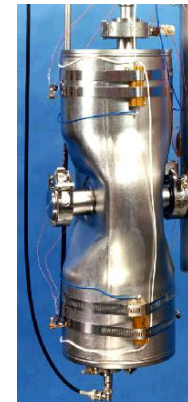
$$160 \leq f \leq 352 \text{ MHz}, 0.09 \leq \beta_0 \leq 0.53$$

- + Most of the QWRs virtues
- + + **No dipole steering**
- + Lower E_p than QWRs



- Not easy access
- Difficult to tune (but new techniques coming)
- **Less efficient than QWRs**

Very successful
Ideal around 150÷300 MHz
competing with single Spoke



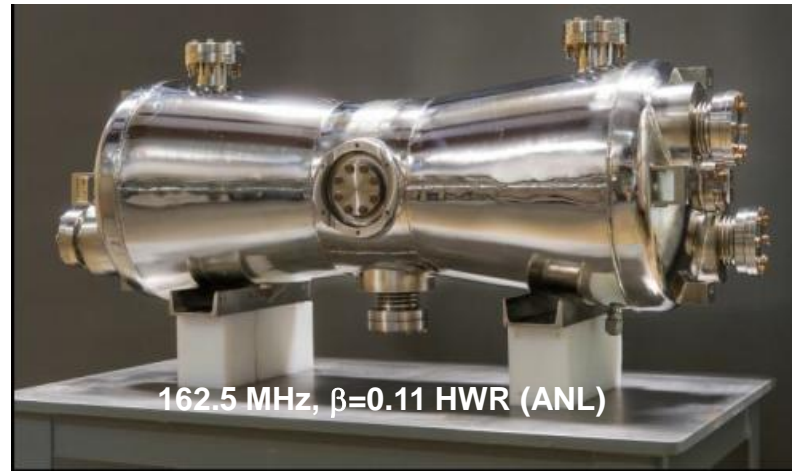
The first 355 MHz SC HWR
ANL - $\beta=0.12$

OPERATING



SARAF/ACCEL
176 MHz, $\beta=0.09$
The first SC HWR in
an operating linac

Some of the HWRs worldwide...



Half-wave structures: **Single-SPOKE resonators**

$$345 \leq f \leq 805 \text{ MHz}, 0.15 \leq \beta_0 \leq 0.62$$



LANL $\beta=0.4$
SPOKE

- + All virtues of coaxial HWRs
- + they can work at higher frequency than coaxial HWRs
- + they can be stacked in multi-gap cavities

- Larger size than HWRs, too large below ~ 350 MHz
- More expensive than HWRs

very successful R&D

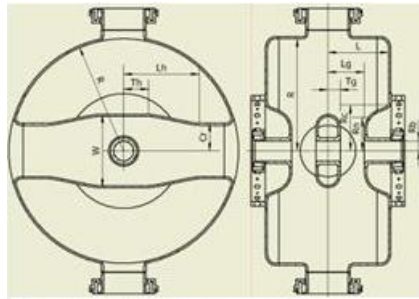
***the most prototyped around 350 MHz,
will be soon used in accelerators***



IPNO SPOKE, $\beta=0.35$
352 MHz

READY FOR OPERATION

Some of the Single SPOKE worldwide...



CH structures: Multi-SPOKE resonators

$$345 \leq f \leq 805 \text{ MHz}, 0.15 \leq \beta_0 \leq 1$$

- + High performance
- + High efficiency
- + Large energy gain
- + Lower frequency and β than elliptical
- + Mechanically stable

- Not easy access
- Smaller aperture than elliptical
- More expensive than elliptical
- More difficult to build and tune than elliptical

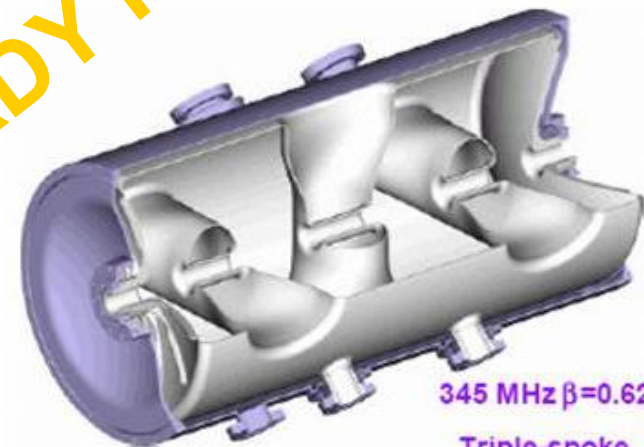
***very successful R&D,
Especially for $\beta \sim 0.3 \div 0.6$***



The first Double SPOKE, ANL $\beta=0.4$



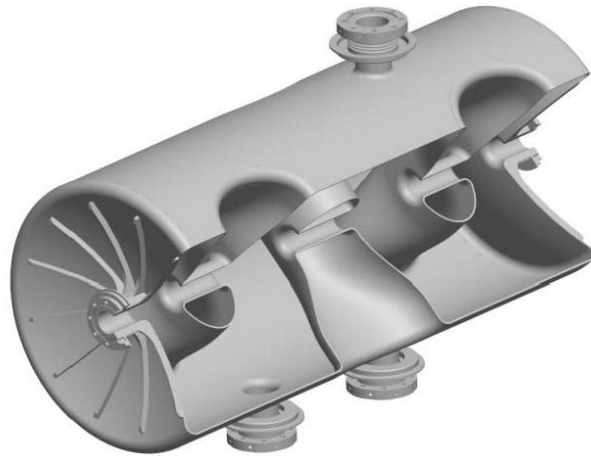
345 MHz $\beta=0.4$
Double-spoke



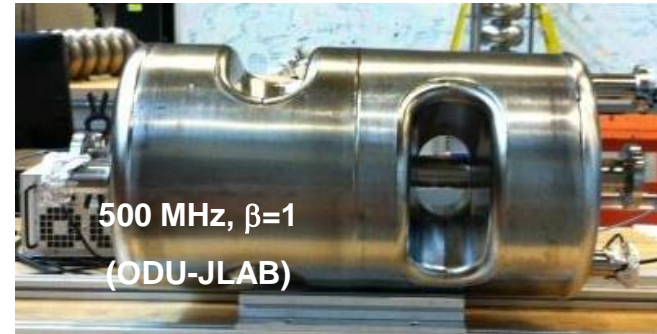
345 MHz $\beta=0.62$
Triple-spoke

READY FOR OPERATION

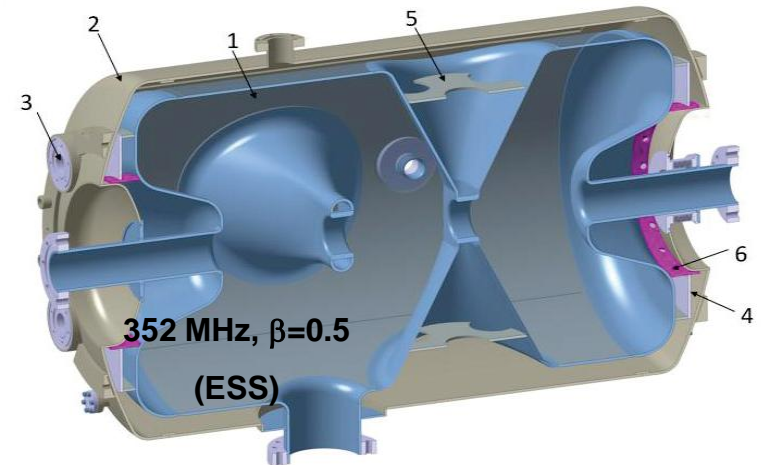
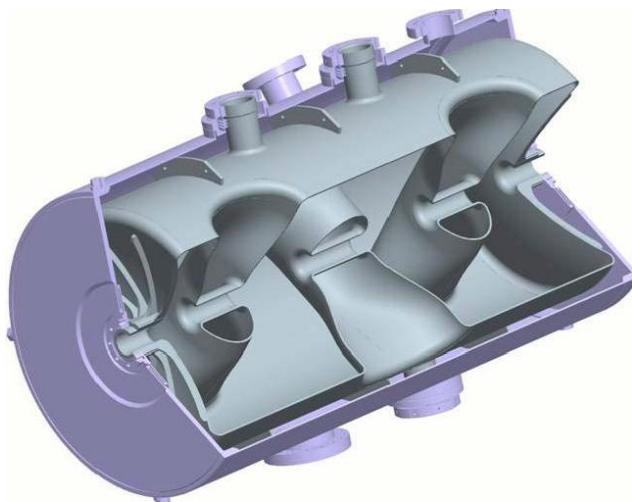
Some of the Multi-Spoke structures worldwide...



345 MHz, $\beta=0.5$ & $\beta=0.63$ (ANL)



500 MHz, $\beta=1$
(ODU-JLAB)



352 MHz, $\beta=0.5$
(ESS)

CH structures: **Superconducting RFQ**

80 MHz, $0.001 \leq \beta_0 \leq 0.035$

- + Compact
- + CW operation
- + High efficiency
- + Down to very low beta
- + large acceptance
- Mechanical stability, powerful fast tuners required
- Not easy to build
- strong MP and FE
- Cost



INFN/LNL SRFQ2, $A/q=8.5$

Efficient but challenging alternative to NC cw RFQs.

Unique development: only 2 units operating in couple

CH structures: CH multi-gap SC cavities

$$174 \leq f \leq 800 \text{ MHz}, 0.1 \leq \beta_0 \leq 0.3$$

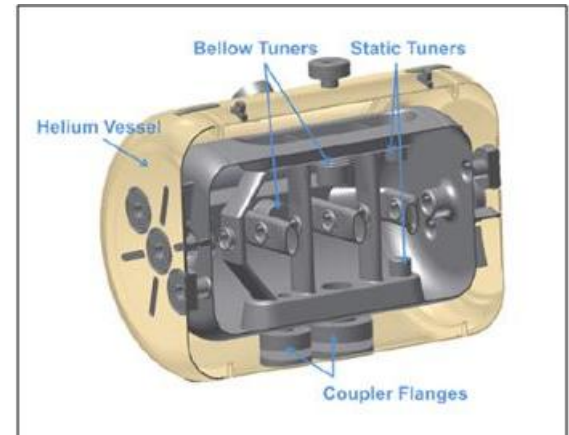
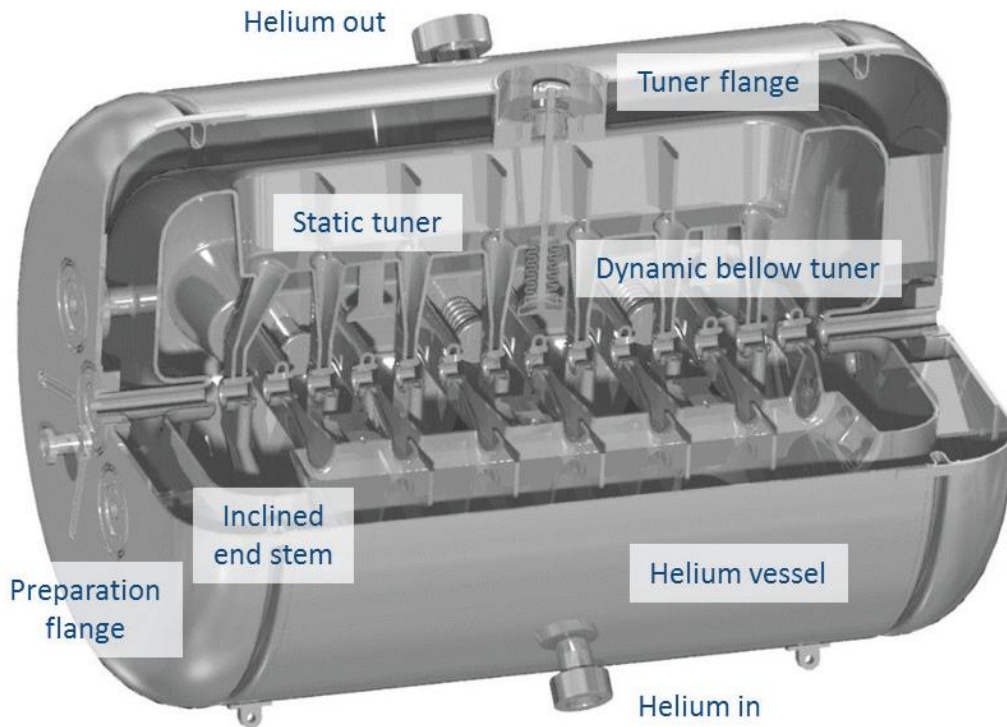
- + Very efficient
- + **large energy gain**
- + feasible also for very low β
- β acceptance
- Difficult to have large aperture
- not easy to build and tune
- ancillaries not yet fully developed
- cost (...but possibly good cost/MV in a linac)



Developed successfully – the future for fixed β profile?

Some of the CH structures worldwide...

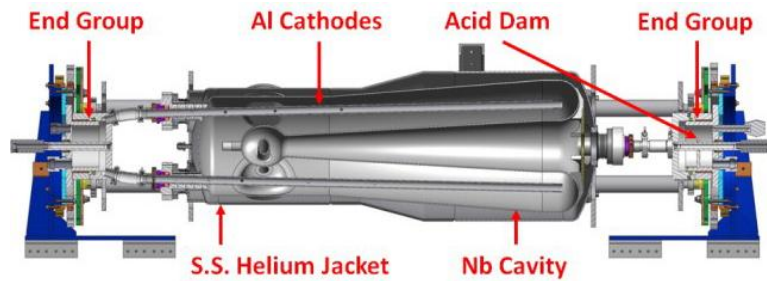
217 MHz ,15 gap CH, $\beta=0.059$ (IAP)



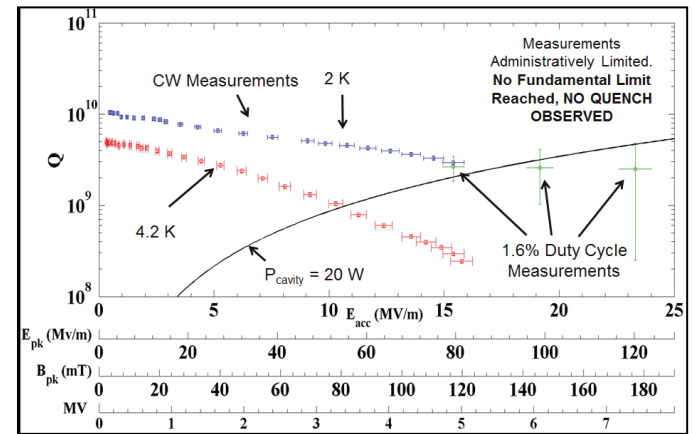
Open issues

- Many old problems solved. Still open issues:
 - Q-slope problems, especially at 4.2K, but also at 2K at high field (HFQS). TM cavities results not yet achieved
 - Mechanical stability: in some cavities still large LFD and df/dP , and mechanical modes requiring large bandwidths
 - Performance reproducibility: still below elliptical cavities. This imposes by design a large safety margin between operational specifications and prototypes performance
- Non-Elliptical geometries are more complicated than elliptical ones and produce more complex behavior. It is more difficult to obtain perfect cavities, but results are getting closer and closer

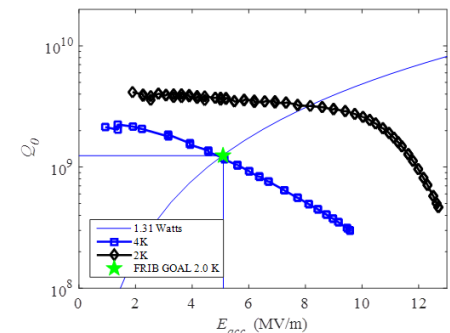
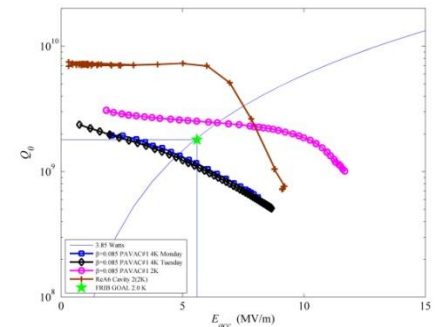
QWR “typical best” performance examples



ANL EP setup for bi-conical QWR



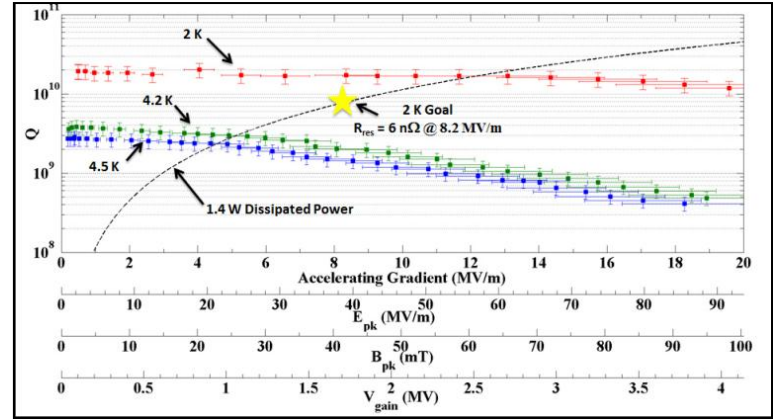
- Electropolished ,72 MHz QWR with low B_p/E_p (ANL)
 - Max $E_p \sim 80$ MV/m (~ 120 MV/m pulsed)
 - Max $B_p \sim 120$ mT and (~ 175 mT pulsed)
- BCP'ed 80.5 MHz QWRs (MSU)
 - Max $E_p \sim 80$ MV/m ($\beta=0.041$)
 - Max $B_p \sim 150$ mT ($\beta=0.085$)
- (Note that all above QWRs have different B_p/E_p)



HWR “typical best” performance examples



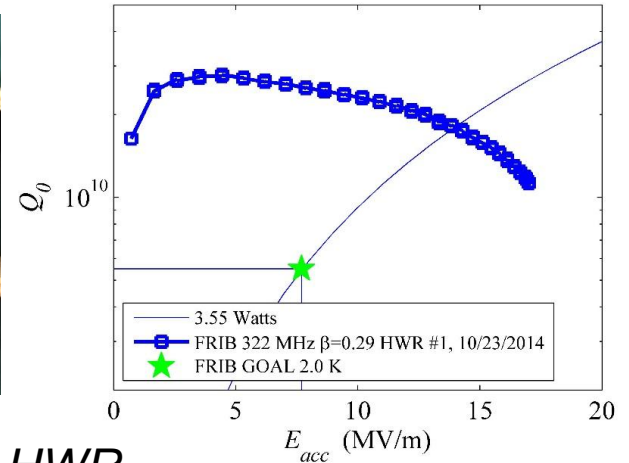
ANL for bi-conical HWR under EP



- Electropolished ,162.5 MHz HWR with low B_p/E_p (ANL)
 - Max $E_p \sim 90$ MV/m
 - Max $B_p \sim 100$ mT
- BCP'ed 322 MHz HWR (MSU)
 - Max $E_p \sim 73$ MV/m
 - Max $B_p \sim 130$ mT



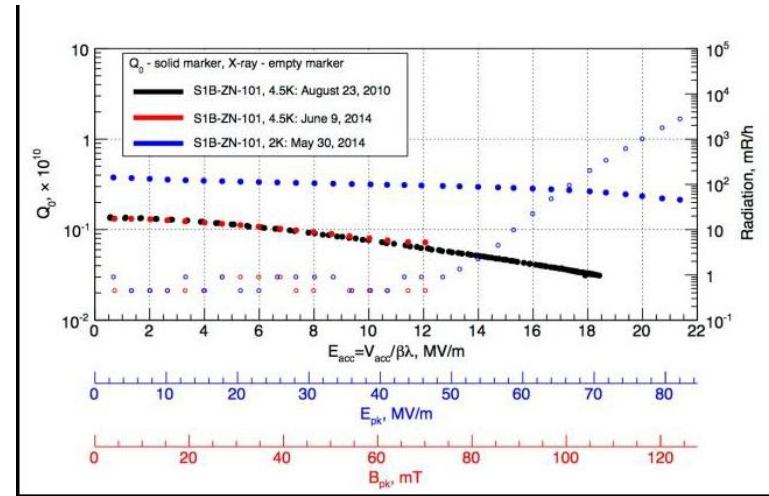
MSU 322 MHz HWR



SPOKE “typical best” performance examples

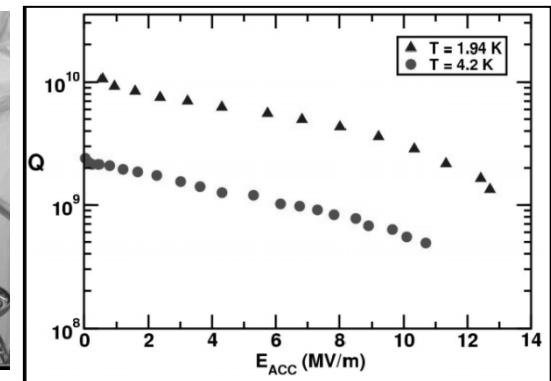


FNAL 325 MHz Single Spoke cavity



- BCP'ed, 325 MHz Single Spoke (FNAL)
 - Max $E_p \sim 85$ MV/m
 - Max $B_p \sim 125$ mT

- Electropolished, 345 MHz Triple-Spoke (ANL)
 - Max $B_p \sim 117$ mT



Non-Elliptical cavities: final remarks

- Non elliptical cavities are becoming as widespread as elliptical ones, built and treated with similar techniques and in a large scale.
- Several ambitious projects of high intensity p , d and heavy ion CW linacs prompted low- β SRF technology to step from “artists’ creations” to industrial hi-tech production aiming at performance and reliability
- Recent developments: high current, crabbing, and $\beta=1$ spoke cavities
- Some new large projects chose 2K to increase operation Q and E_a
- Best performance are approaching elliptical TM ones; the required SRF technology is now industrially available
- Still open issues: Q-slope and best performance reproducibility
- Recent great achievements of “Nitrogen doping” technique might further raise the bar in high Q and E_a also for non-elliptical cavities

This is a growing technology: there is still a lot to do

New good ideas will be welcome!

Thank you

*Thanks also to all people who have
contributed in the field and have provided
precious material for this tutorial*