Low- and Intermediate-β Cavity Design

Tutorial introduction to superconducting resonators for acceleration of ion beams with β<1.

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What are low-β superconducting resonators?

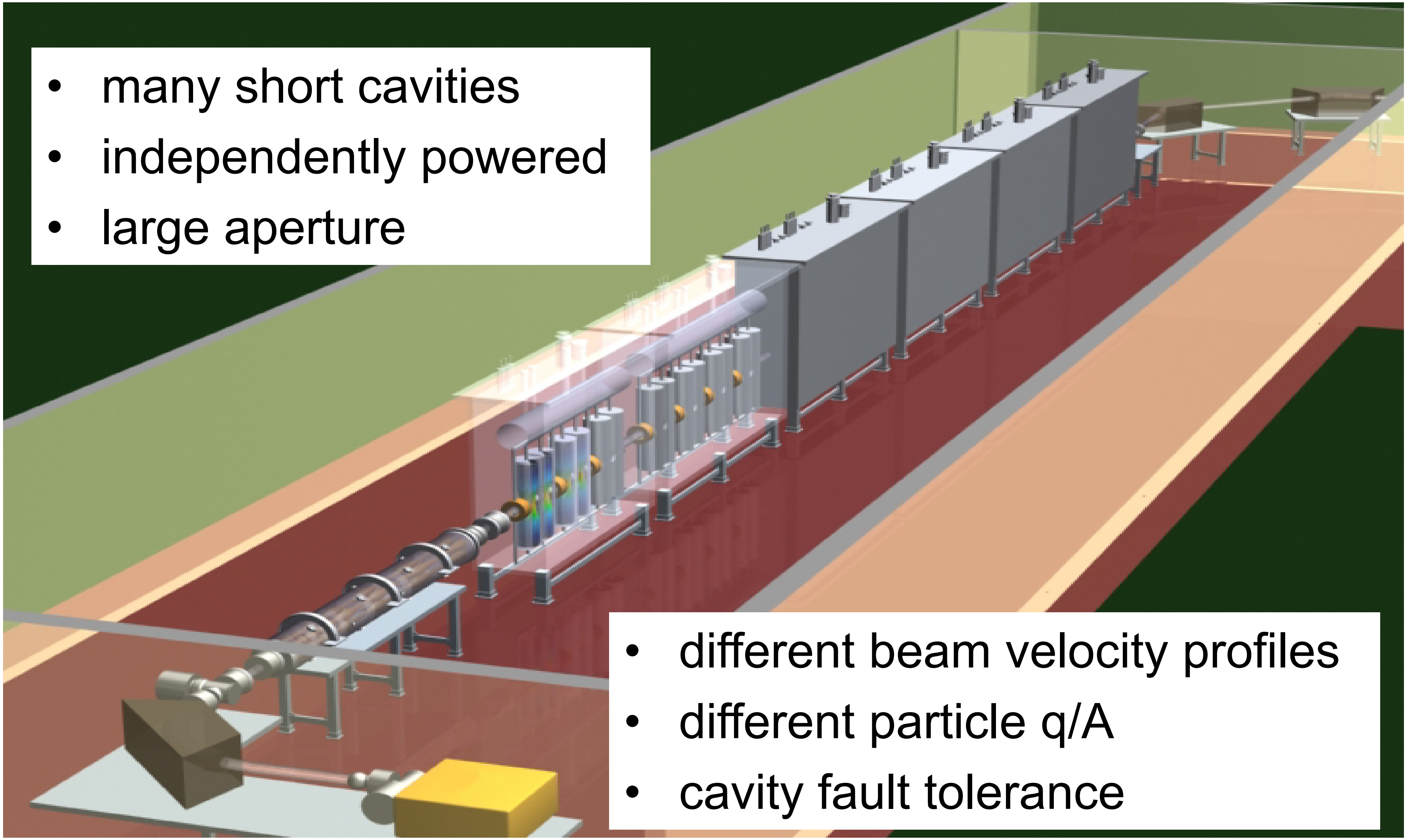
low-β cavities: **Just cavities that accelerate efficiently particles with β <1…**

low-β cavities are often further subdivided in low-, medium-, high- β

β=1 SC resonators:
"elliptical" shapes

β<1 resonators, from very low (β~0.03) to intermediate (β~0.5):
many different shapes and sizes

Typical superconducting low-β linacs



- many short cavities
- independently powered
- large aperture

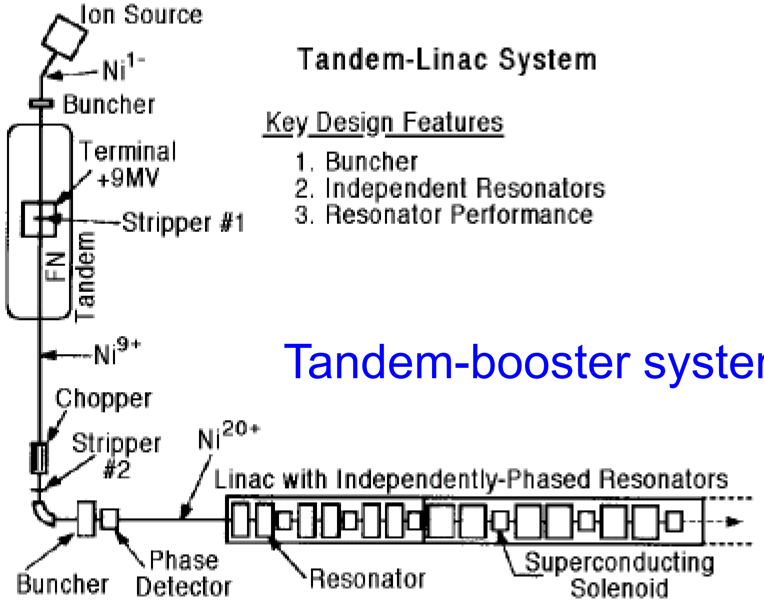
- different beam velocity profiles
- different particle q/A
- cavity fault tolerance

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

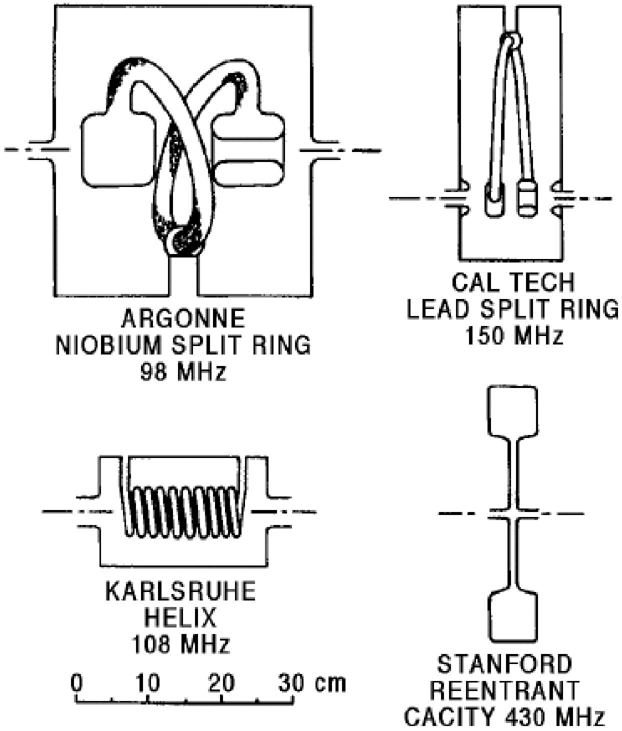
- Low beam current: all rf power in the cavity walls
- 2÷3 gap: wide β acceptance for different ion energies
- Cw operation



Tandem-booster system

New problems: very narrow rf bandwidth, mechanical instabilities

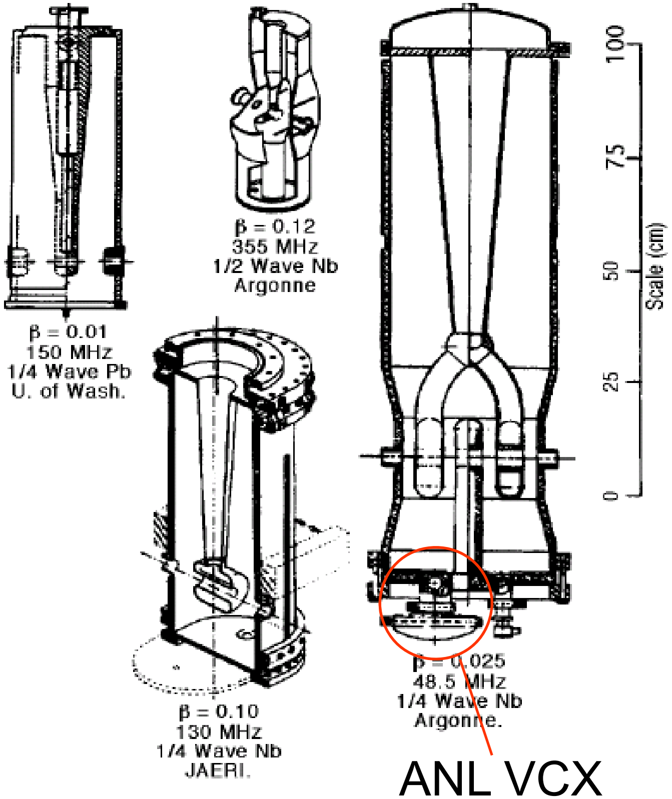
Early resonators: 70's



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

- **β~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

SC low-β resonators : 80's

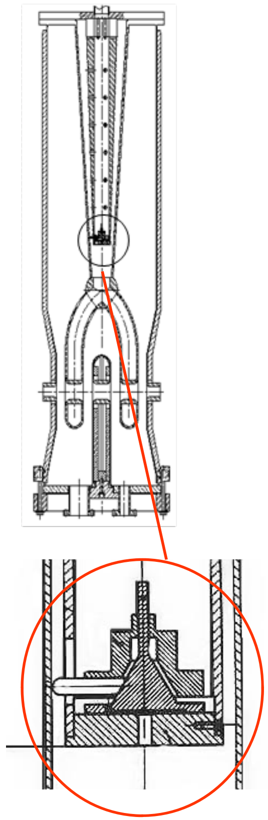


- First low-β SC Positive Ion Injector at ANL: **β~0.001÷0.2**
- All ion masses
- New materials:
    - **Explosive bonded Nb on Cu**
- Mechanical stability problems solved by electronic fast tuners VCX at ANL
- E_a typically **3 MV/m**; first operation above **4 MV/m**

Low-β cavities in the 80's

HI SC low-β resonators: 90's

Low-β cavities in the 90's

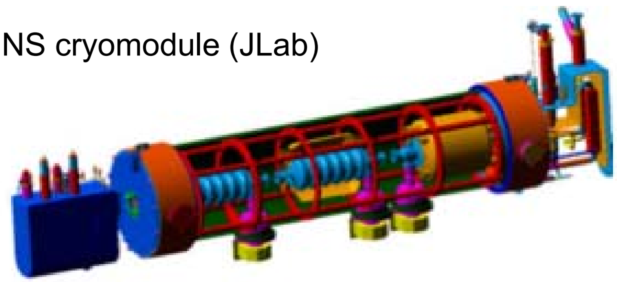


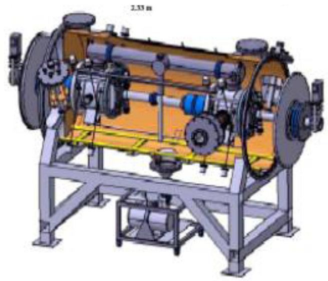
LNL damper

- **β~0.001÷0.2**
- New materials:
  - **Sputtered Nb on Cu**
- 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**
- Development of β~0.3÷0.6 Spoke cavities starts

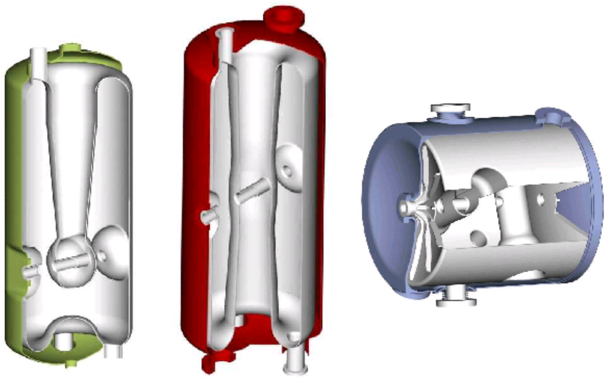
HI SC low-β resonators: present

SNS cryomodule (JLab)





2-gap spoke cavity and cryomodule (IPNO)



QWR, HWR and Spoke cavities (ANL)

- **β~0.001 ÷ 0.8**
- material: mainly **Bulk Nb,** but also **sputtered**
- high intensity SC low-β linacs under construction
- Development for RIB facilities, neutron spallation sources, Accelerator Driven Systems…
- Design E_a typically **6 ÷8 MV/m**, up to 15 for multicell elliptical

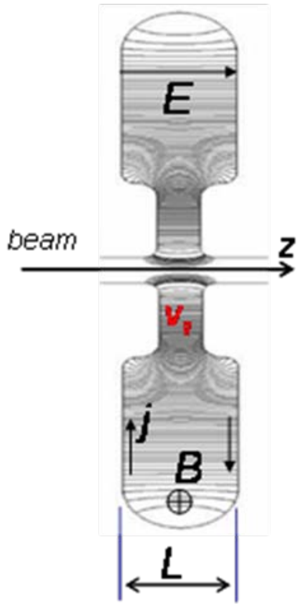
Low-β cavities: new applications

Type	β_{max}	A/q	current
Post-accelerators for RIB facilities	~ 0.2 (0.5)	7÷ 66	< 1 nA
HI drivers for RIB facilities	~ 0.3÷0.9	~ 1 ÷ 10	~0.1÷10 mA
***p*,*d* linacs for radioisotope production**	~ 0.3	1 ÷ 2	~1÷10 mA
High Power Proton Accelerators for neutron spallation sources	~ 0.9	1	~10÷100 mA pulsed
High Power Deuteron Accelerators for material irradiation	~ 0.3	2	>100 mA cw

Low-β cavity definitions

Important parameters in accelerating cavities

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



where:

R_s=surface resistance of the cavity walls

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

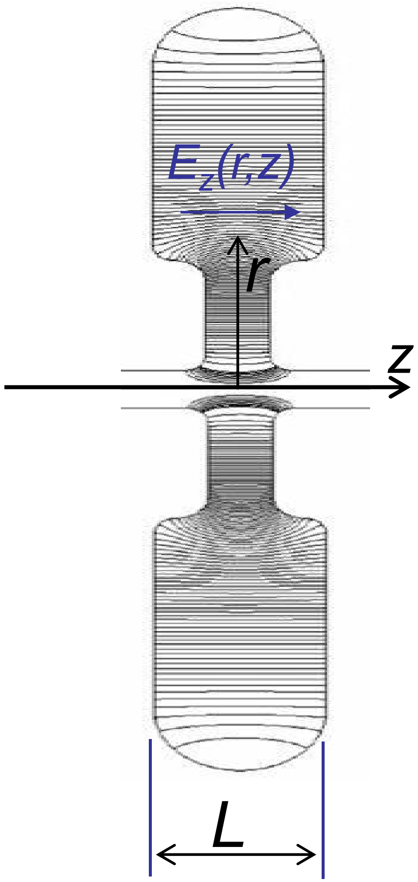
Energy gain, TTF, gradient

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 to be on axis so that $r=0$, and $E_z(0,z) \equiv E_z(z)$).

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 espression for the energy gain

$$\Delta W_p = qE_a LT(\beta)\cos\varphi$$

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: $T^*(\beta) = \dfrac{T(\beta)}{T(\beta_0)}$

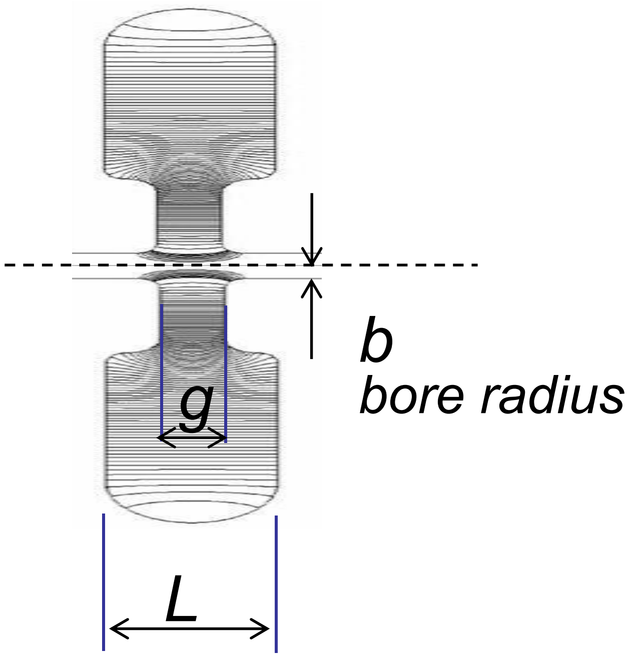
Avg. accelerating field: $E_a^* = T(\beta_0)E_a$

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

and the energy gain definition does'nt change

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

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



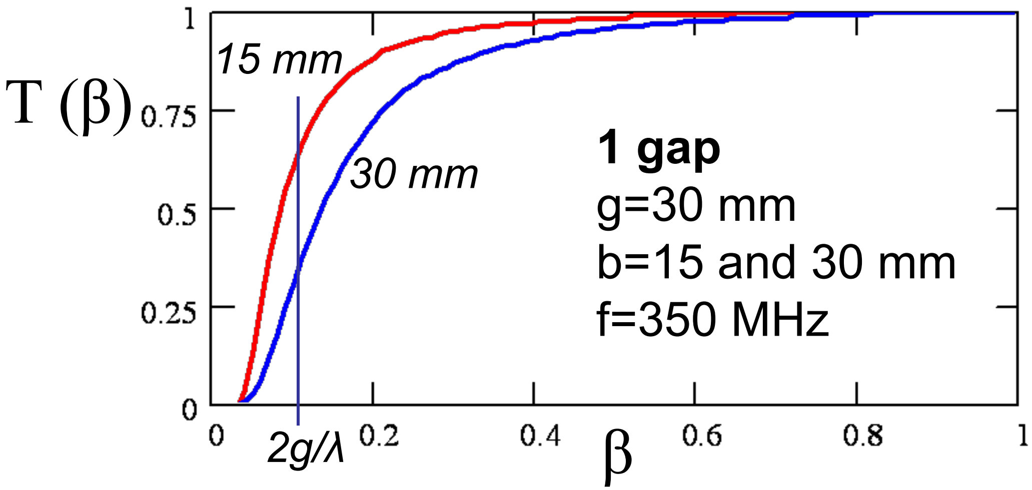
$$T(\beta) \cong \frac{\sin\left(\frac{\pi g}{\beta\lambda}\right)}{\left(\frac{\pi g}{\beta\lambda}\right)}$$

To be efficient at low-β it is necessary to decrease rf frequency and gap length

Rule of thumb: $g<\beta\lambda/2$

The bore radius, however, contributes to the effective gap length:

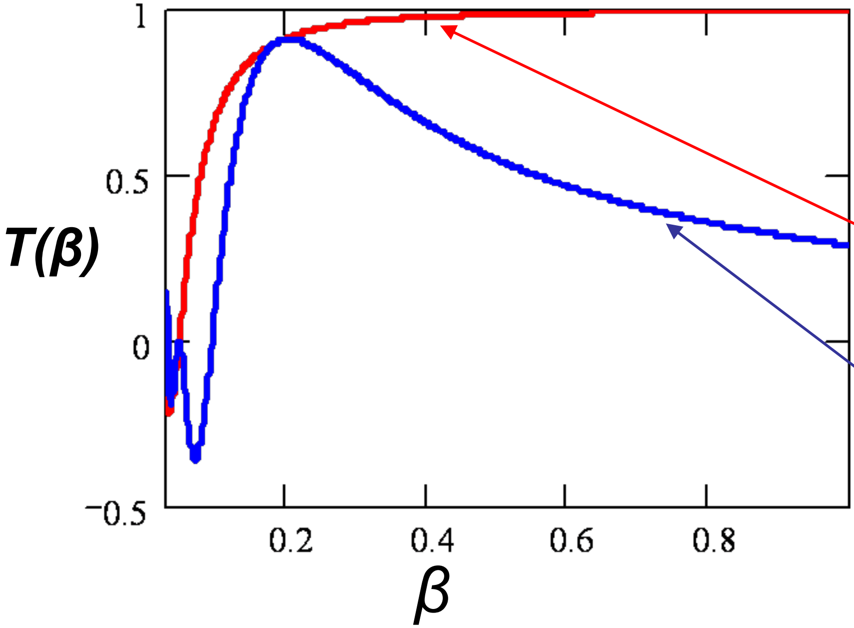
$$g_{eff} \approx \sqrt{g^2 + (2b)^2}$$

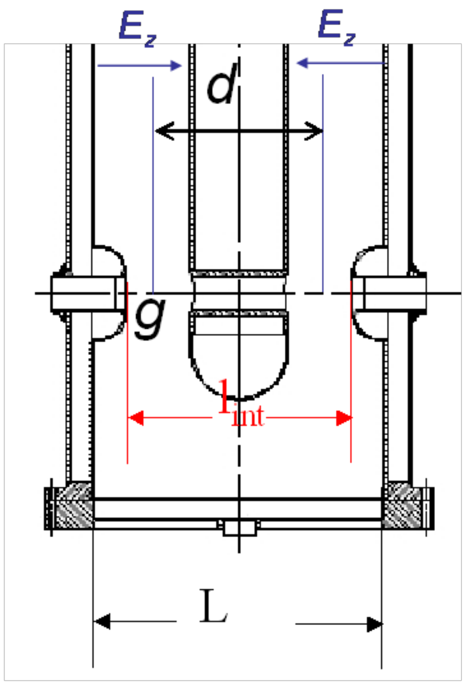


T(β) for 2 gap (π mode)

(constant E_z approximation)

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





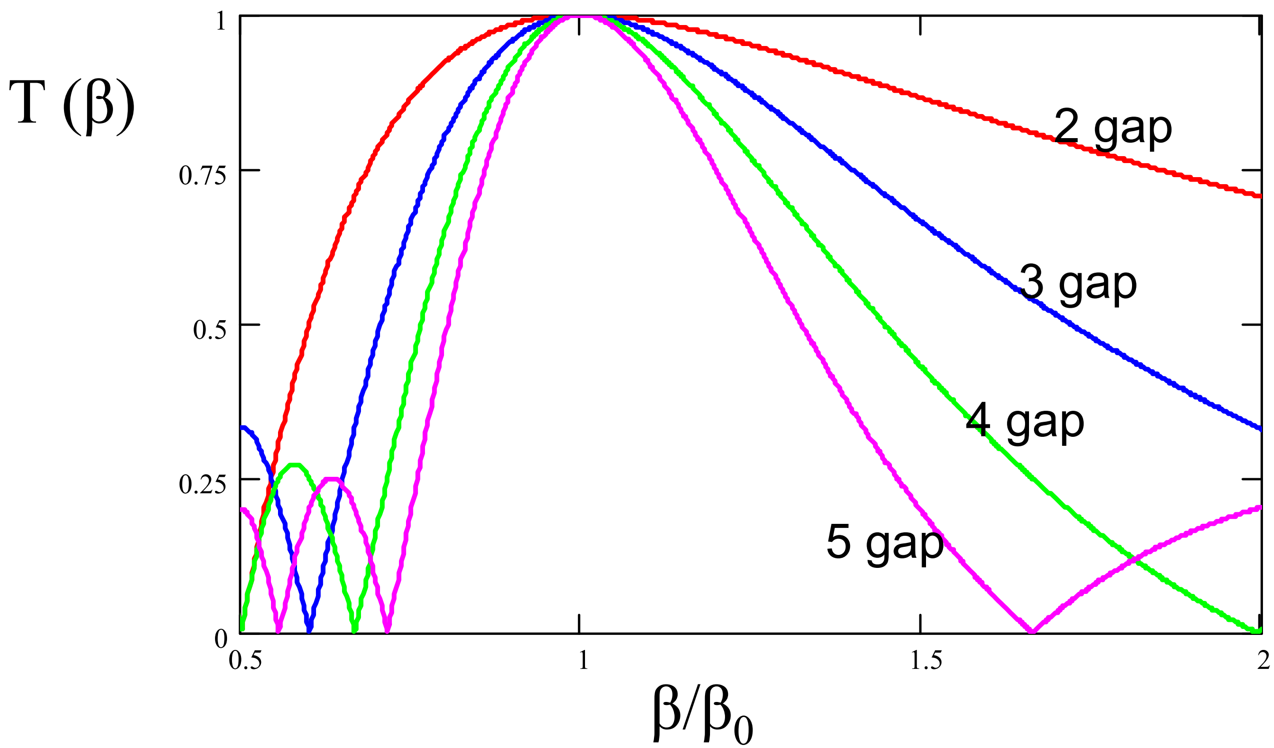
1° term: 1-gap effect → *$g<\beta\lambda/2$*

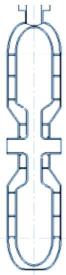
2° term: 2 gap effect → *$d\sim\beta\lambda/2$*

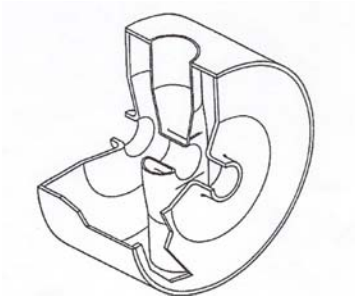
1°+ 2° term TTF curve

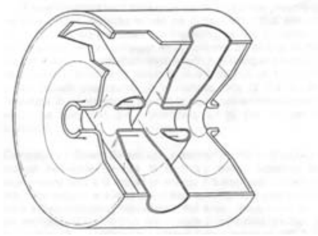
(For more than 2 equal gaps in π mode, the formulas change only in the 2° term)

Transit time factor curves (normalized)





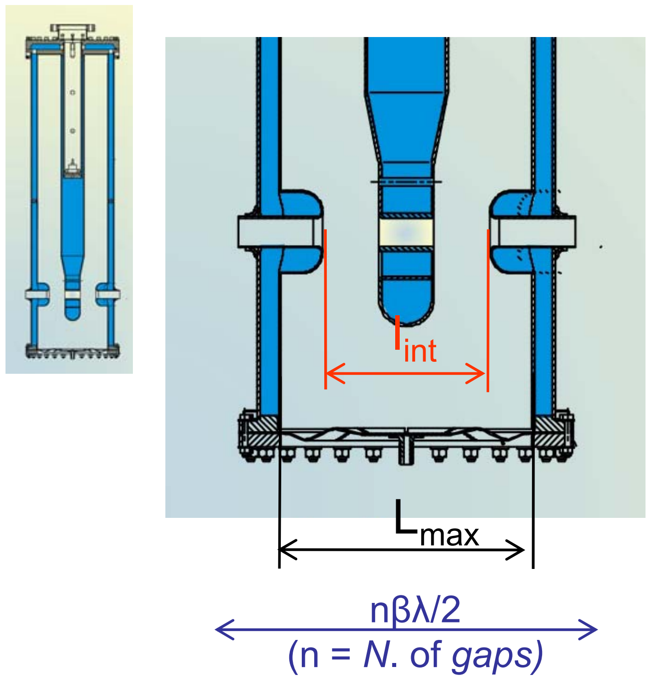


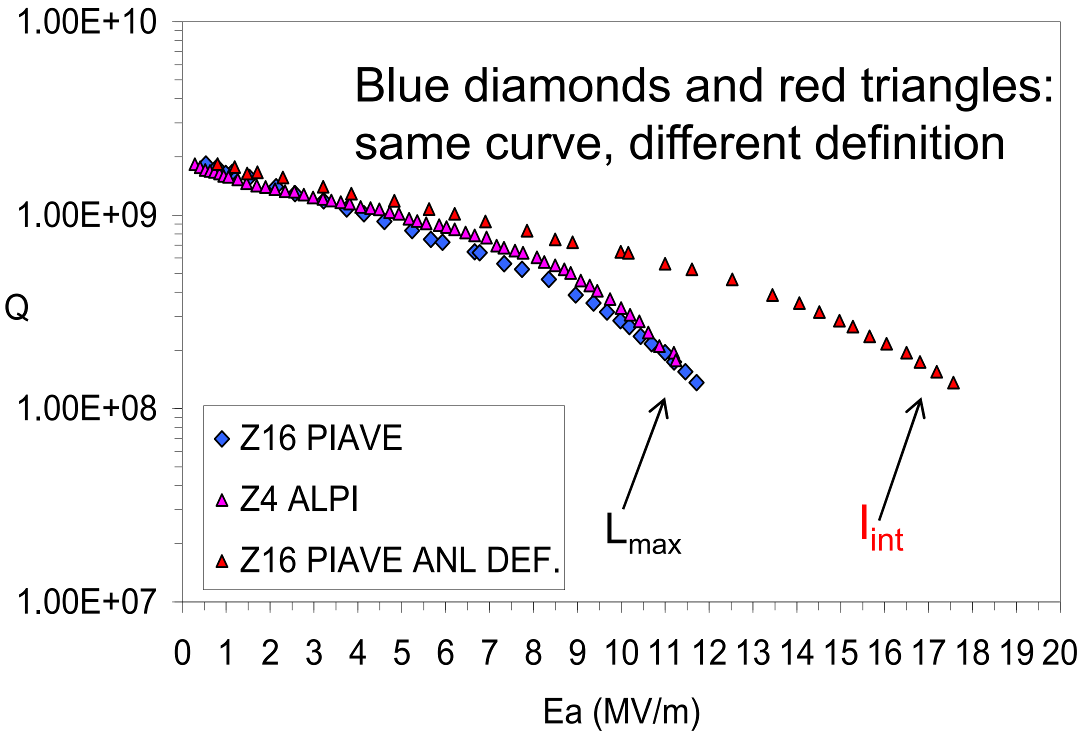


Normalized transit time factor curves vs. normalized velocity, for cavities with different number of gap

- the larger the gap n., the narrower the velocity acceptance

Remark: different definitions of gradient





- Sometimes difficult to decide on the definition of L: ***l_{int}*, *L_{max}*** or even ***nβλ/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

Low-β resonators basic requirements

To be efficient at low-β:

however, this implies:

- short gap length
  → High peak fields, low energy gain
- low rf frequency
  → Large resonators, complicated shapes
- small bore radius
  → Low transverse acceptance

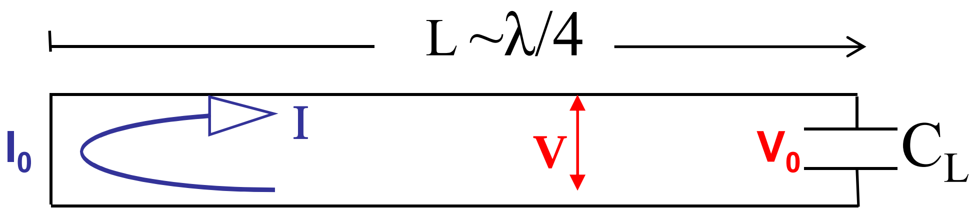
Superconductivity, with high fields and low power dissipation, allows to overcome most of these drawbacks

Low-β cavity types

Low-β SC cavities peculiarities

- Low frequency
  - Large size
  - complicated geometries
  - High peak fields E_p, B_p
  - efficient operation at 4.2 K
- Short cavities
  - Few accelerating gaps-Large velocity acceptance
  - Many independent cavities in a linac (ISCL)
- Many different shapes
  - several different EM modes

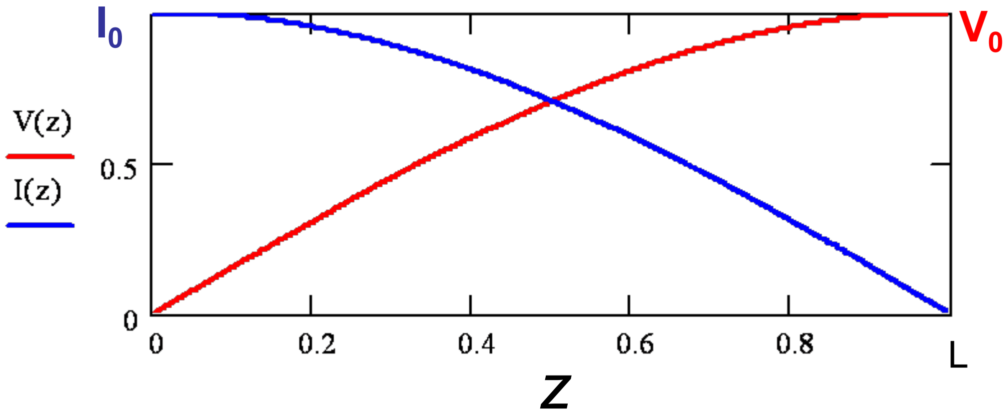
Quarter-wave stuctures: small g/λ, small size



$Z_0 = V_0/I_0$ characteristic impedance

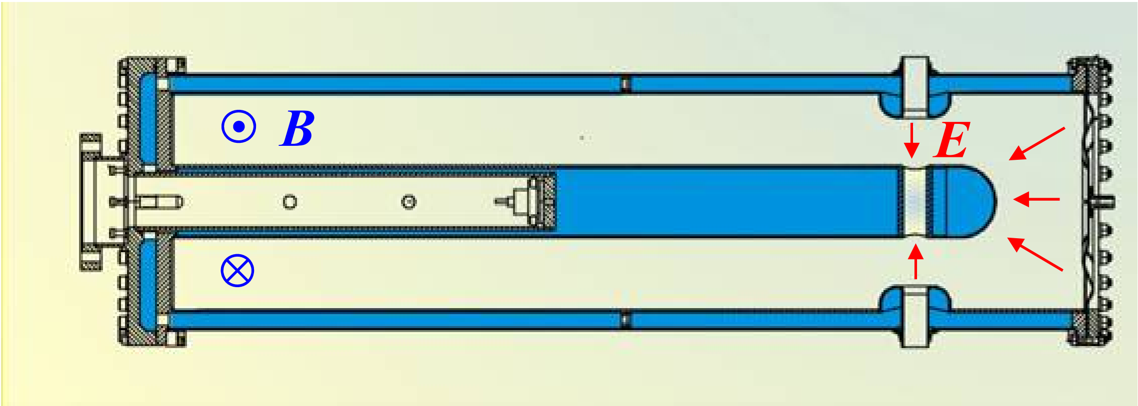
$Tg(\omega L/c) \sim 1/(\omega C L Z_0)$

$U \sim \pi V_0/(8\omega Z_0)$ stored energy

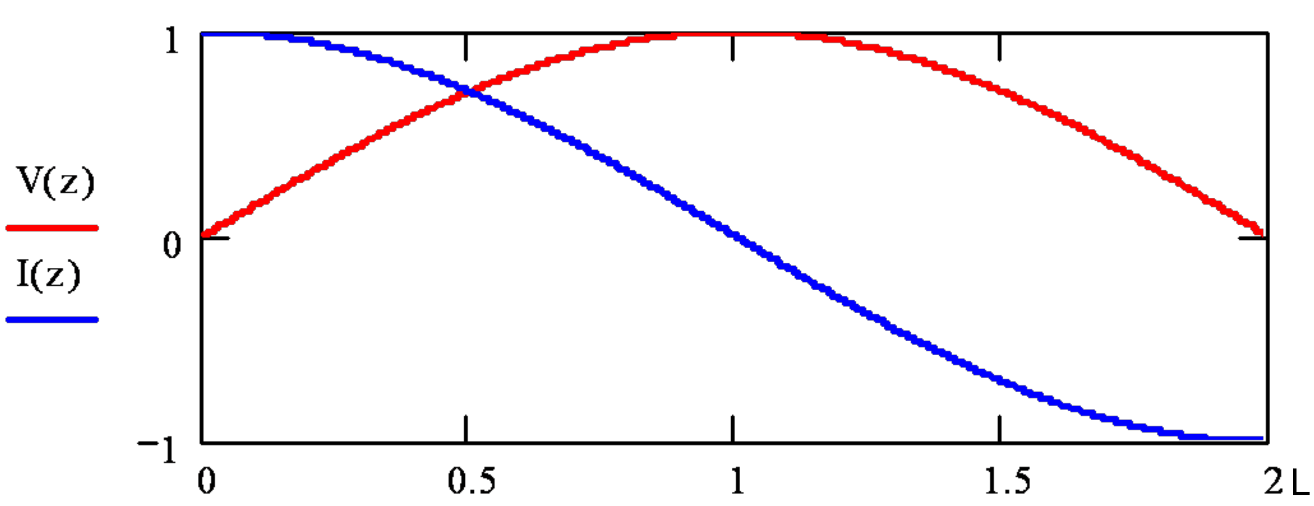


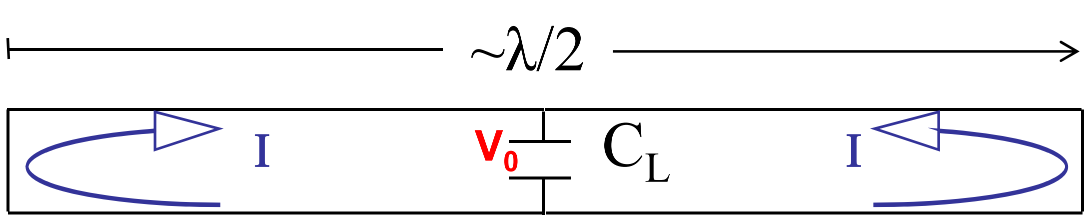
$V \sim V_0 \sin(\omega z/c)\sin(\omega t)$

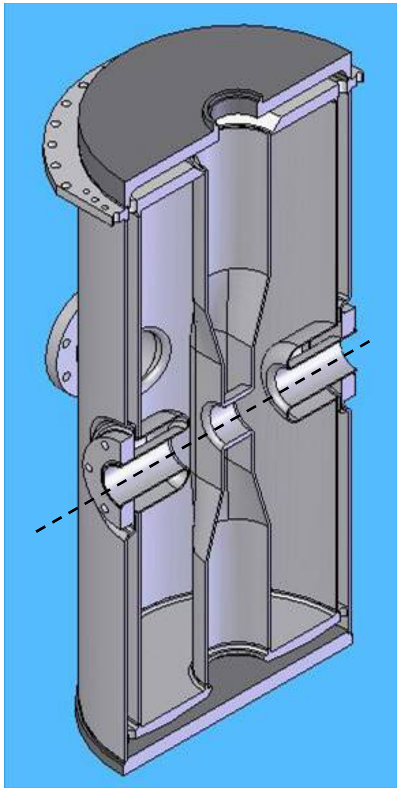
$I \sim I_0 \cos(\omega z/c)\cos(\omega t)$



Half-wave structures – more symmetry







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

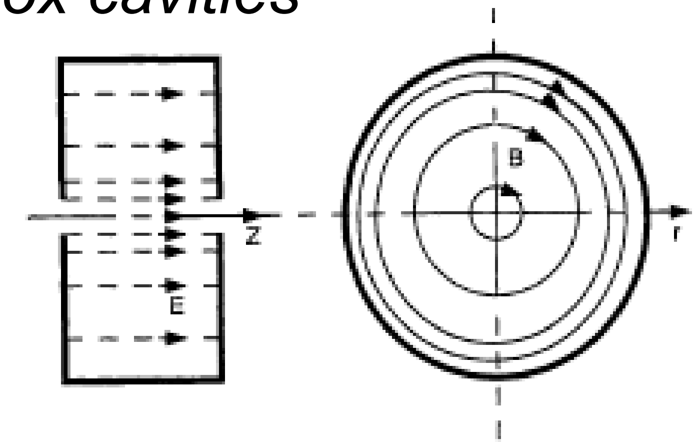
$$P_{HWR} \sim 2\, P_{QWR}$$

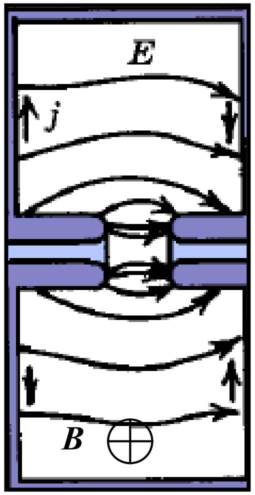
- A half-wave resonator is equivalent to 2 QWRs facing each other and connected
- The same accelerating voltage is obtained with about 2 times larger power

TM mode cavities – axial symmetry

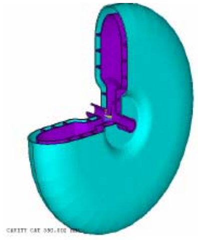
- TM_{010} (Transverse Magnetic) mode
- B is always perpendicular to the EM wave propagation axis (and to the beam axis)

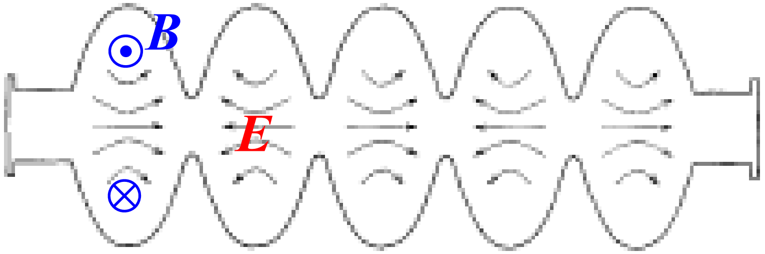
pillbox cavities





"nose" and "reentrant" cavities





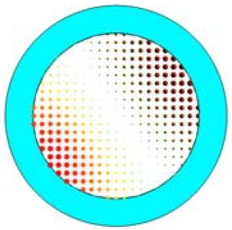
elliptical cavities

IH and CH multi-gap structures

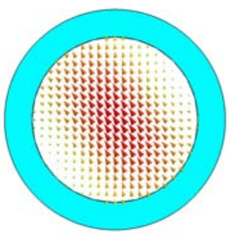
IH 4-rod RFQ

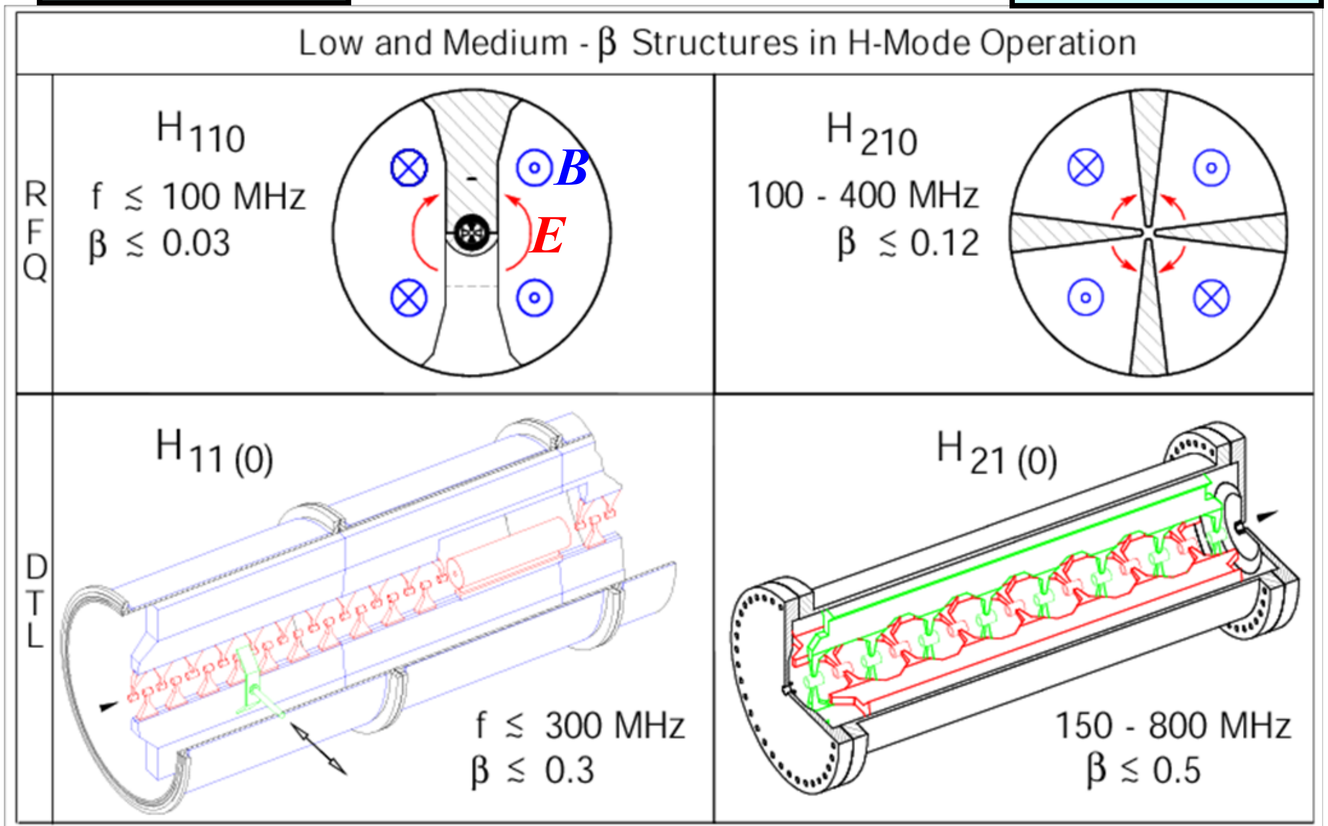
4-vane RFQ

B-Field



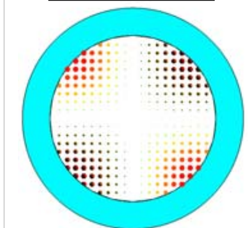
E-Field



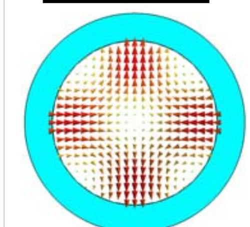


Courtesy of H. Podlech

B-Field



E-Field



IH-Structure

CH-Structure

Low-β cavities design issues

What is a good SC low-β resonator?

It must fulfill the following principal (rather general) requirements:

1. large E_a (energy gain)
2. large R_{sh} (low power dissipation)
3. easy and reliable operation
4. easy installation and maintenance
5. low cost-to-performance ratio

Preliminary choices

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

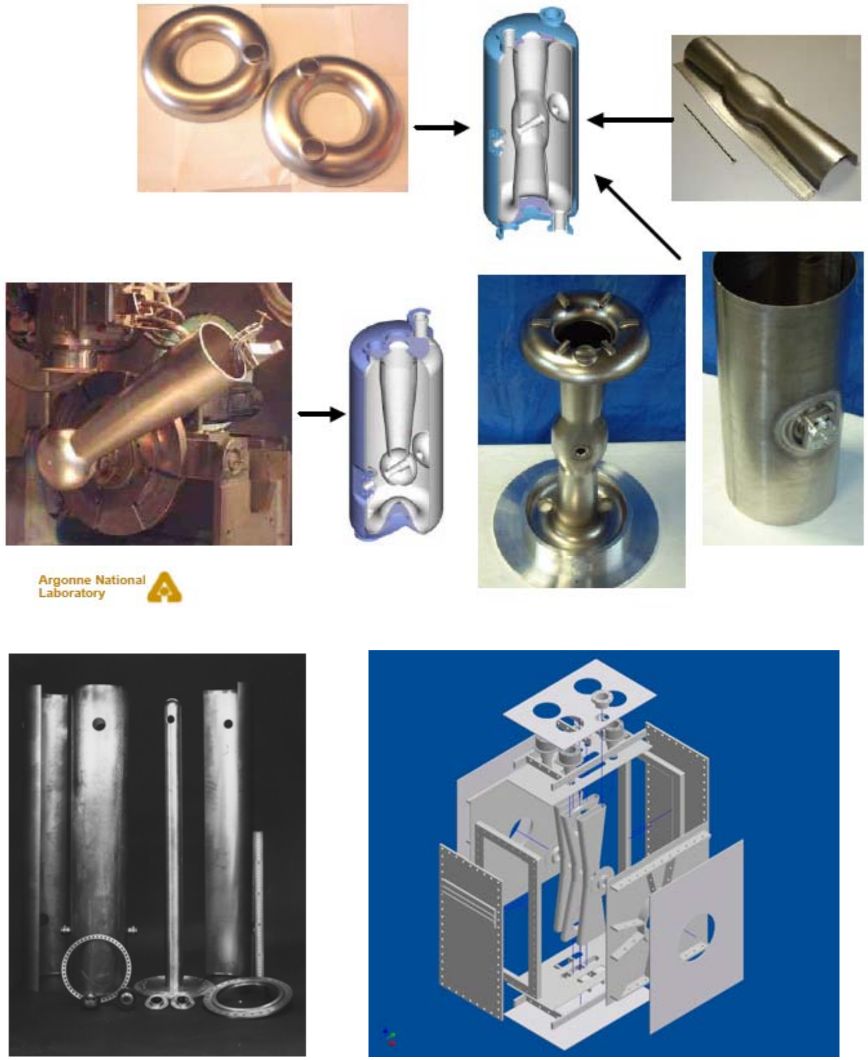
Choice of the SC technology

- Bulk Nb (by far the most used)
  - highest performance, many manufacturers, any shape and *f*
    - *performance* **** *cost* **


- Sputtered Nb on Cu (only on QWRs)
  - high performance, lower cost than bulk Nb in large production, simple shapes
    - *performance* *** *cost* ***

- Plated Pb on Cu (being abandoned)
  - lower performance, lowest cost, affordable also in a small laboratory
    - *performance* ** *cost* ****

Niobium bulk

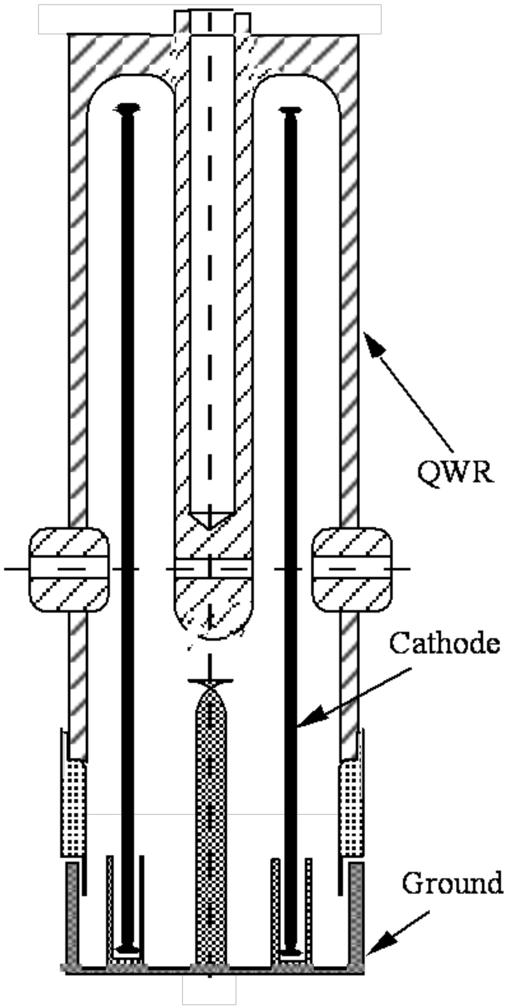


The design must allow:

- parts obtained by machining of Nb sheets, rods, plates,…
- required excellent electron beam welding
- required excellent surface treatment (large openings for chemical polishing or electropolishing, high pressure water rinsing…)

A large variety of cavity shapes can be obtained

Niobium sputtering on copper



DC biased diode

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 cathod insertion and large volumes to maintain sufficient distance between cathode and cavity walls

practically suitable only for QWRs

Numbers to keep in mind in low-β cavities design

- Maximum peak electric field E_p
  - Achievable: > 60 MV/m
  - Reliable specs 30÷35 MV/m
- Maximum peak magnetic field B_p
  - Achievable >120 mT
  - reliable specs 60÷70 mT
- R_{res} residual resistance= R_s- R_{BCS}
  - achievable: ~1 nΩ
  - reliable specs <10 n Ω
- Maximum rf power density on the cavity walls
  - *~1W/cm*^{2} at 4.2K
- Critical Temperature
  - $T_c = 9.2\sqrt{1 - B/200}$

EM design

minimize:

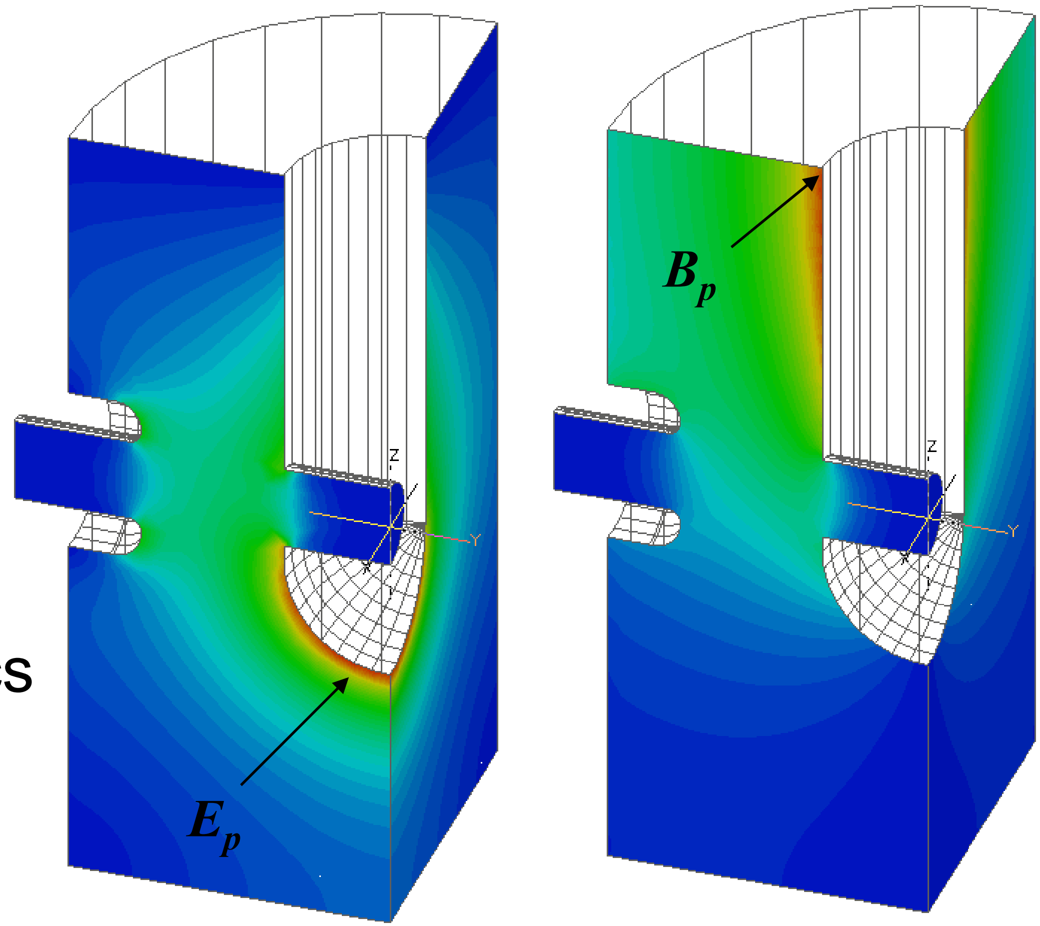
- E_p/E_a
- B_p/E_a

maximize:

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

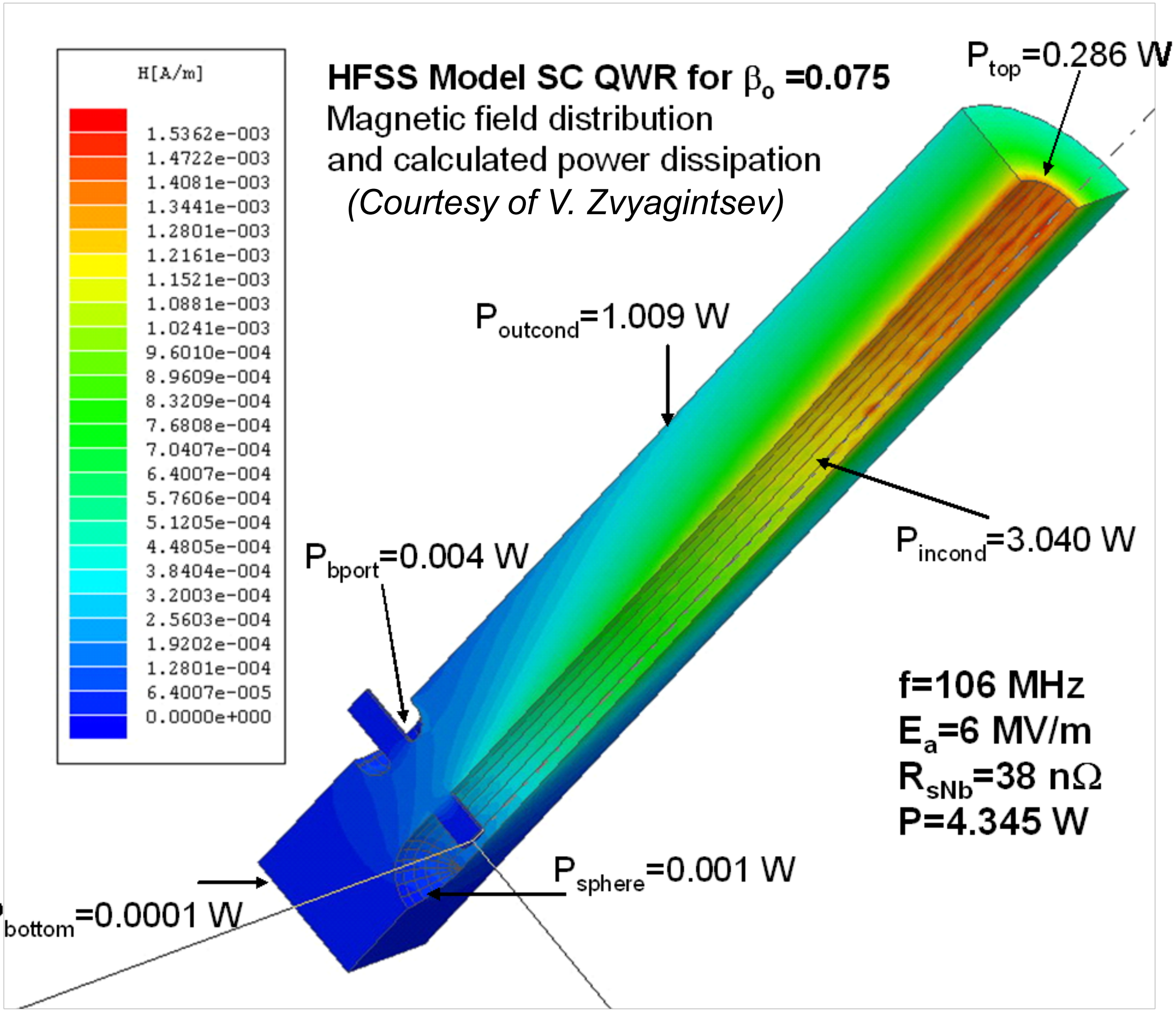
optimize:

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



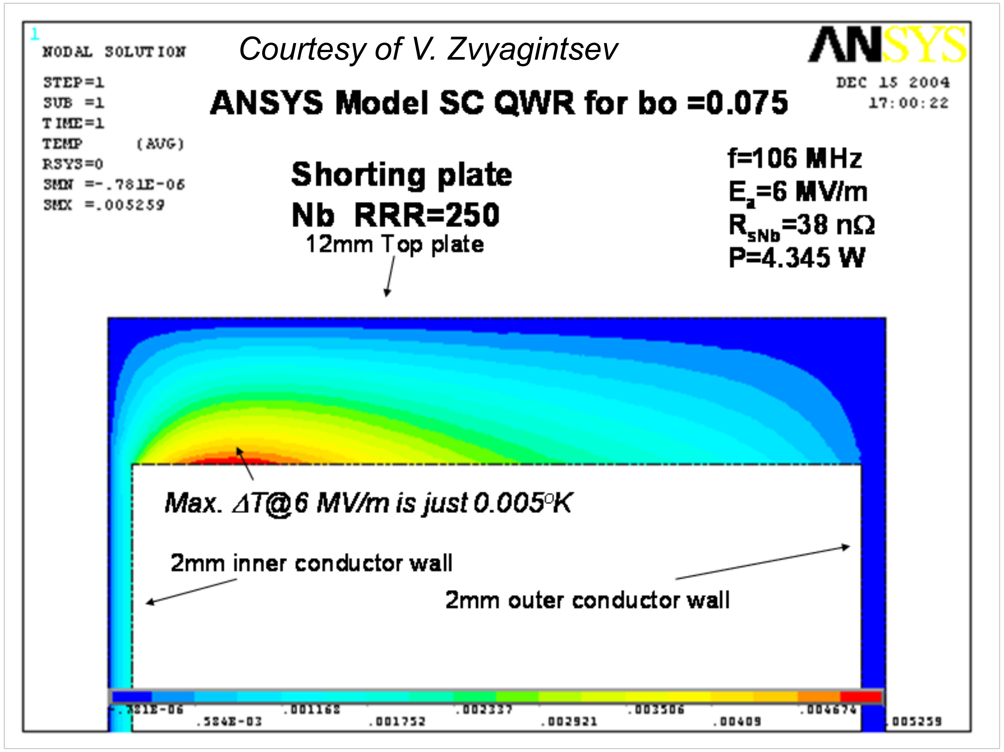
EM design: Rf losses calculations

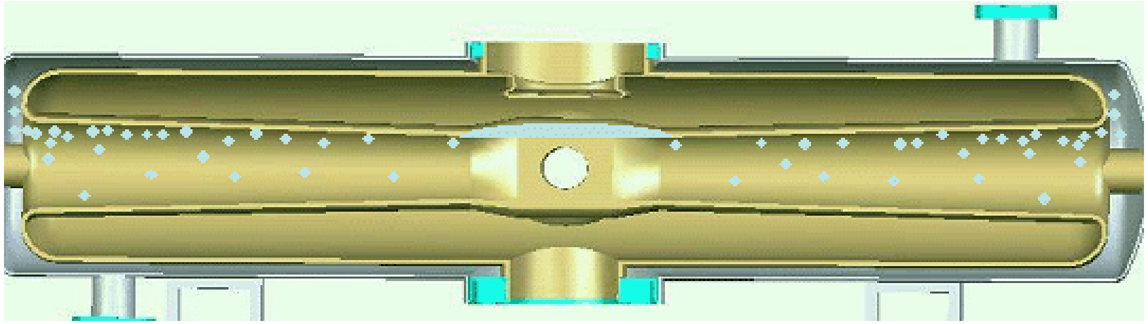
- Keep power density well below ~1 W/cm^2 at 4.2K
- Large safety margin required: local defects can increase power losses significantly



Temperature distributions

- Keep T well below the critical value
- Thick walls are not always an issue with high RRR Nb
- provide good ways for liquid He flow
- avoid gas trapping

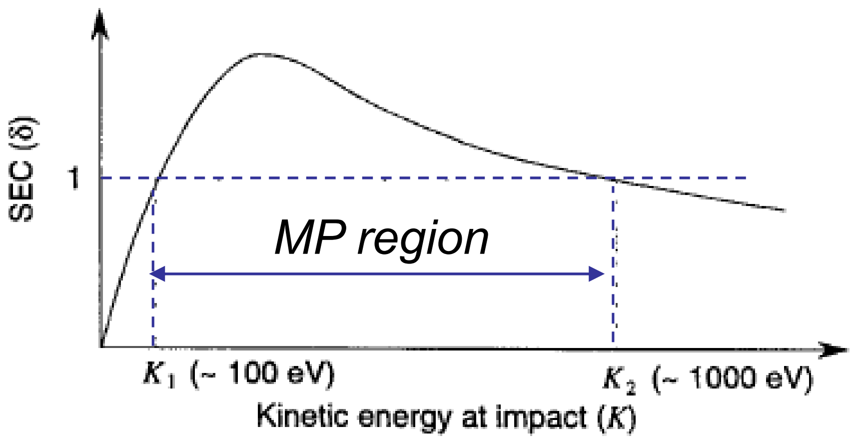


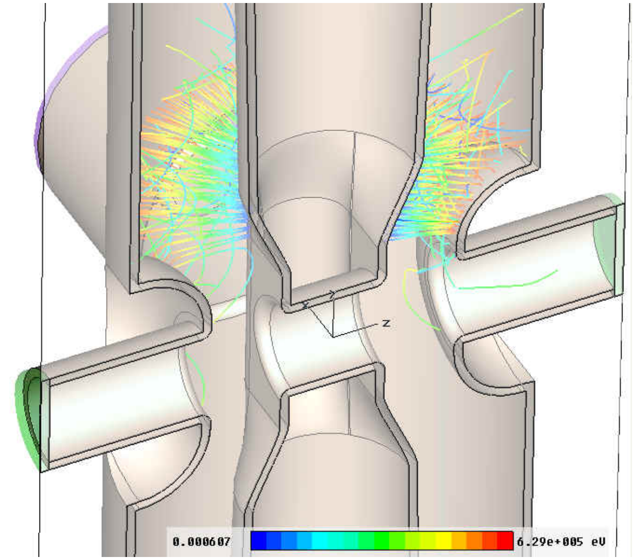


IFMIF HWR working in horizontal position. Gas He pockets had been be eliminated.

EM design: Multipacting

- Multipacting: resonant field emission of electrons under the action of the EM field
- Conditions:
  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 (presence of free electrons)
- Initial electrons can be originated and captured far from the resonant trajectory (cavity geometry)



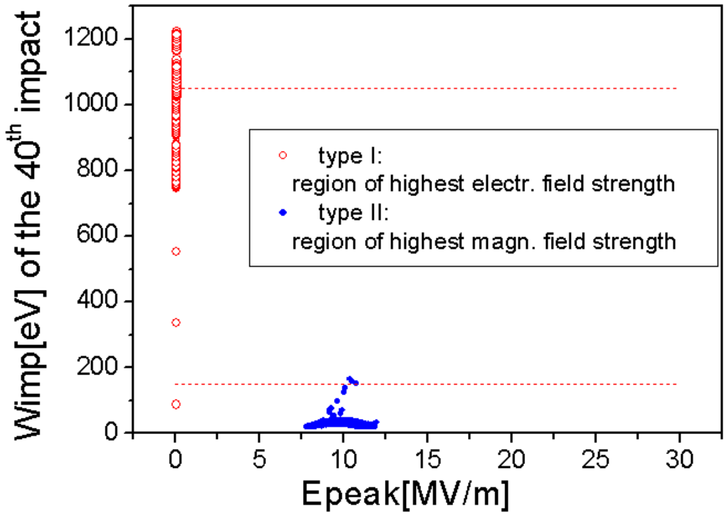


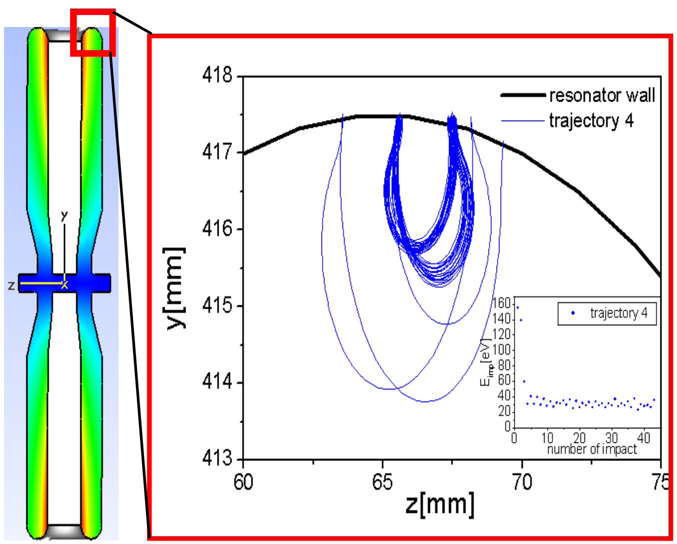
Multipacting in low-β cavities - examples

2-point MP in a HWR

- *1 wall MP: E+B*
- *2 walls MP: mainly E ;*

  B can be used to displace electrons away from the MP area



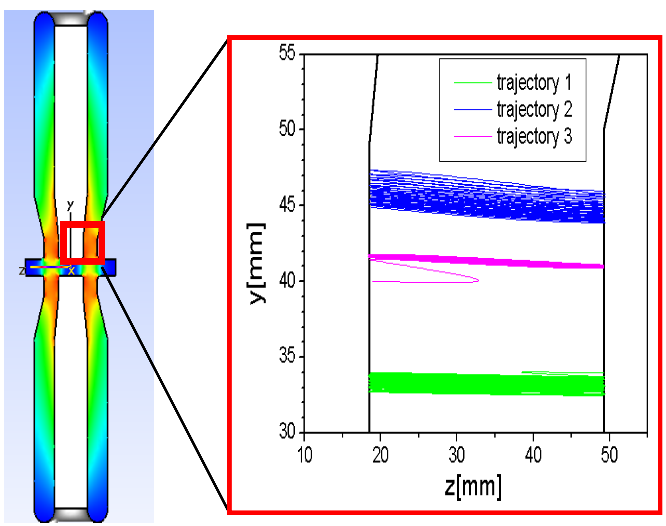


1 wall MP

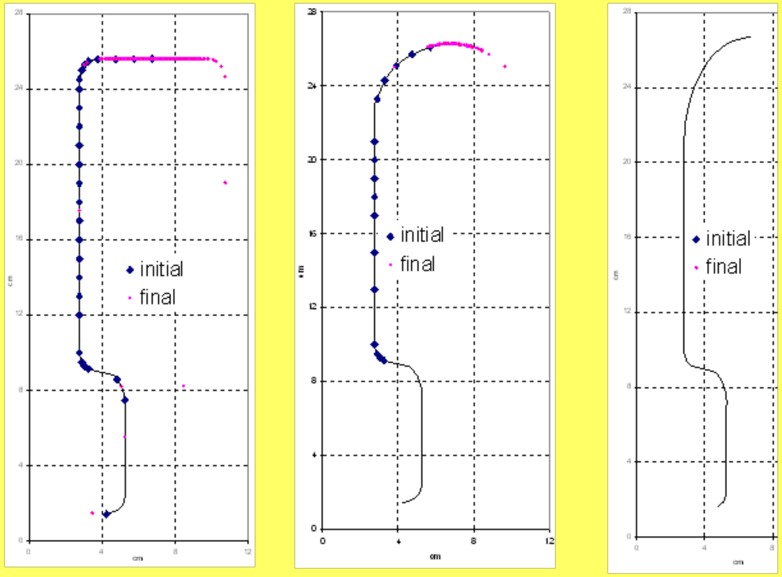
"horseshoe"

Courtesy of ACCEL

2-walls MP



Avoiding multipacting



Example for a simple geometry:

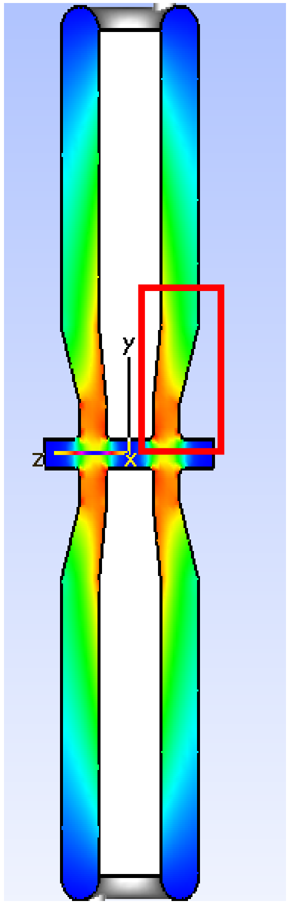
- code TWTRAJ (one of the first ceated for this scope - courtesy of R.Parodi)
- ~60000 Runs
- 0.005 MV/m steps in Ea
- 5 mm steps in e- starting position

Results:

- MP negligible near the gap
- Levels at the equator: its profile is critical
- **Ellipsoidal shape 1.5:1 free of MP**

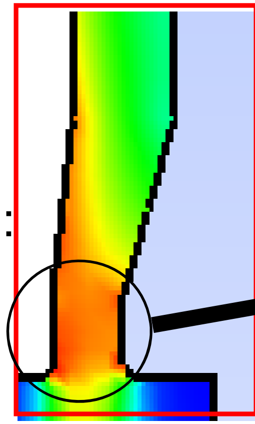
- cavities must be designed with no stable MP trajectories, or with impact energy out of the δ>1 region
- it is often impossible to eliminate levels completely; to make them tolerable, the volume in which the electrons are captured must be small
- powerful codes are nowadays available for MP particles tracking, also as part of packages for EM and mechanical design of cavities

Example: redesigned HWR for MP removal

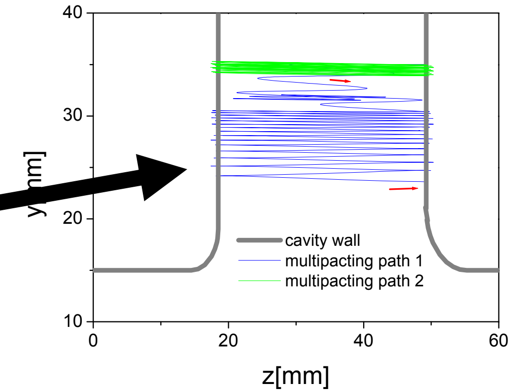


SARAF HWR
(Courtesy of ACCEL)

first design:

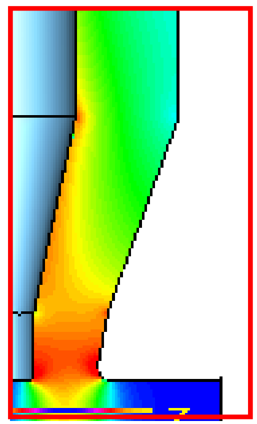


multipacting at E_{peak}=0.1MV/m



redesign A:

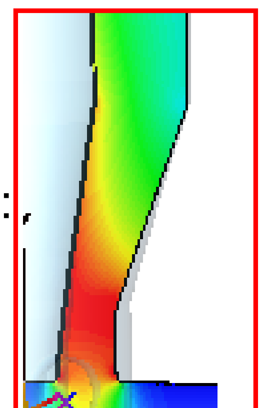
outer wall inclined



no multipacting

redesign B:

inner wall inclined



no multipacting

EM design: Beam steering

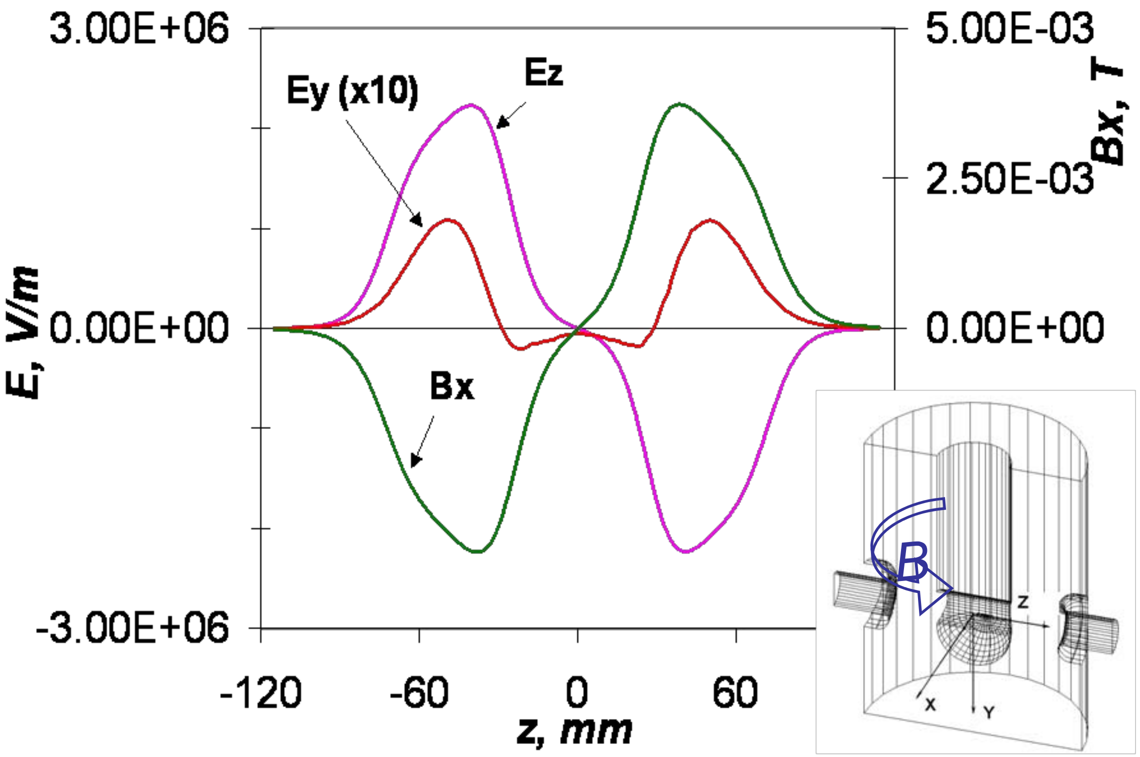
- Non symmetric cavities can produce beam steering
- Transversal kick:

$$\Delta p_y = q\int\left(E_y(z,t) + \beta c B_x(z,t)\right)\cdot dt$$

- The magnetic field gives usually the dominant contribution
- This can give serious beam dynamics problems, especially with high current beams in QWRs with large aspect ratio (approximately for $\beta_0 > 0.1$).

Beam steering in QWRs

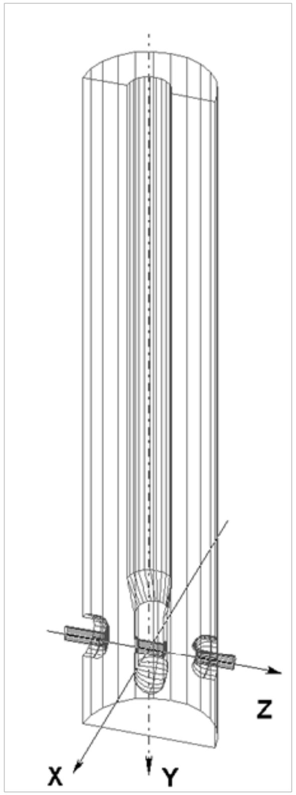
On-axis field components in QWRs



- E_y is symmetric: at β_0 it cancels in the 2 gap
- B_x is antisymmetric: it adds in the 2 gap
- B_x has 90° phase delay from E_y
- B is generally dominant

QWR steering : homogeneous gap approximation

if E and B are constant in the gap, and null outside (square functions):



$$\Delta y' = \frac{qE_a LT(\beta)}{\gamma m \beta c} \sin\phi \left(\frac{K_{EY}}{\beta c \cdot tg\left(\frac{\pi d}{\beta \lambda}\right)} - K_{BX} \right)$$

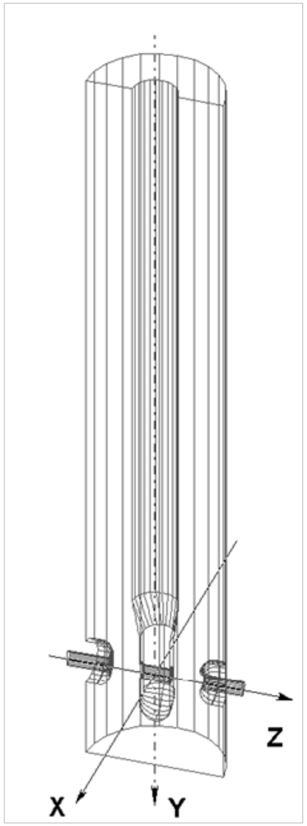
where $K_{Ey}=E_y/E_z$ *and* $K_{Bx}=B_x/E_z$

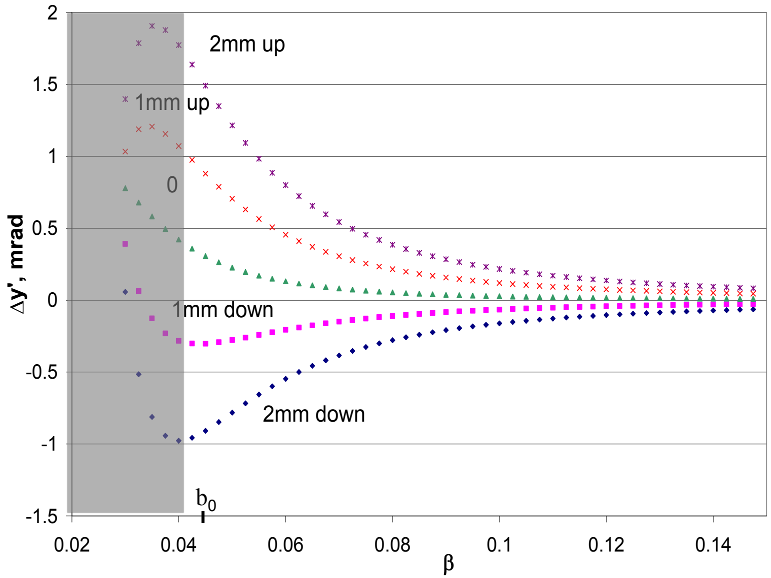
- steering is (of course) proportional to E_a
- E_y steering goes as $1/\beta^2$, B_x steering goes as $1/\beta$
- near optimum β, E_y steering goes as $(\beta-\beta_0)/\beta^2$
- Φ =0 (max. acceleration): no steering
- Φ=±90 (bunching-debunching): maximum steering

QWR steering compensation: axis displacement

rf defocusing in the y direction:

$$\Delta y' = \frac{\pi}{\lambda} \cdot \frac{qE_a LT(\beta)}{mc^2 \beta^3 \gamma^3} \sin\phi \cdot y$$

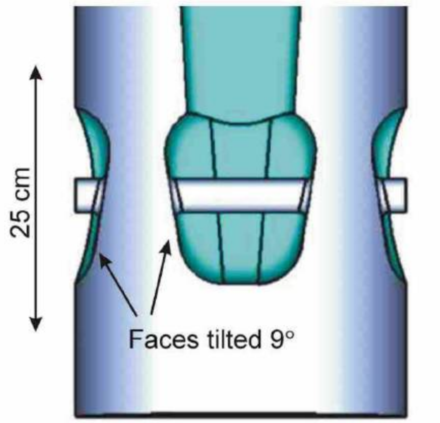


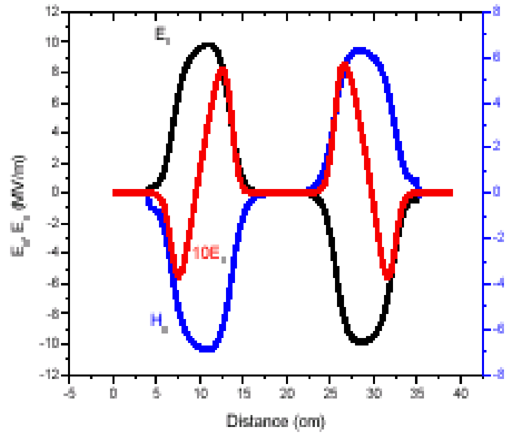


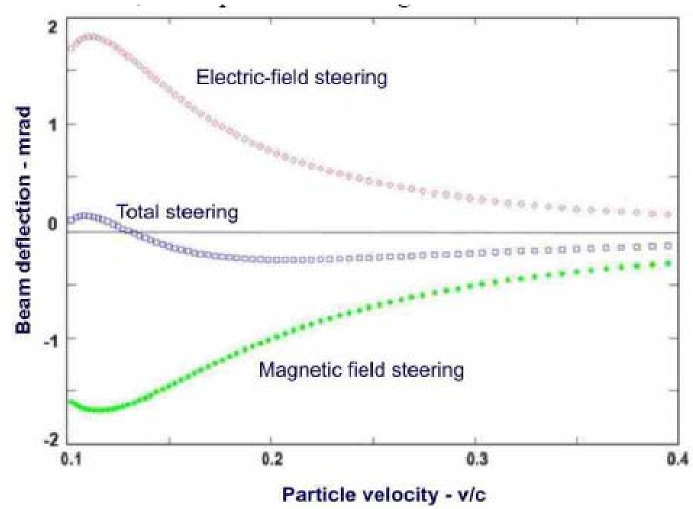
Steering compensation by displacement from the beam axis in 80 MHz QWRs

- The QWR steering has many similarities with the rf defocusing effect in misaligned cavities
- In many low-β resonators, a slight displacement in y of the beam aperture axis can remove most of the steering

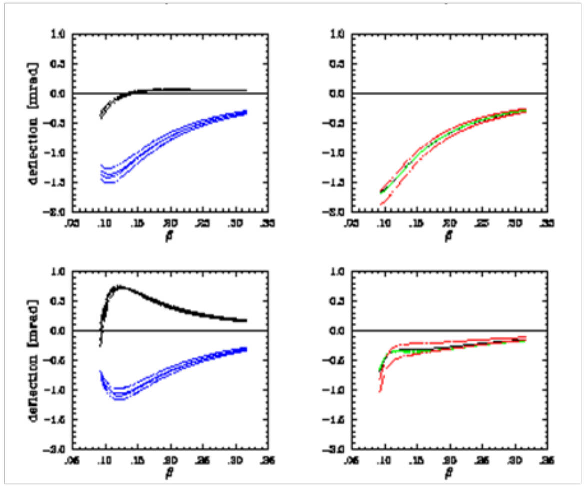
Steering compensation by gap shaping







Magnetic steering can be compensated by properly shaping E_y

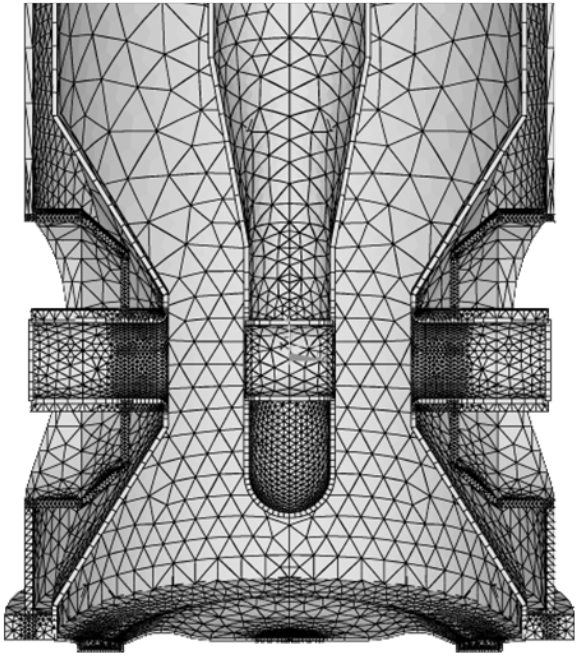


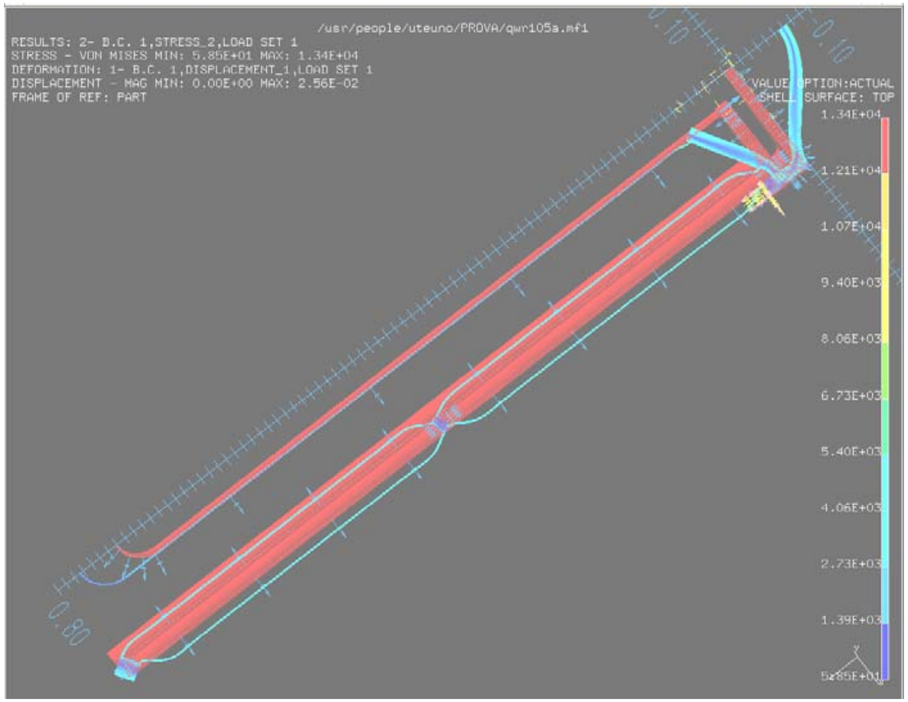
QWR steering :
161 MHz standard shape (top)
161 MHz corrected

Mechanical design

Mechanical design:

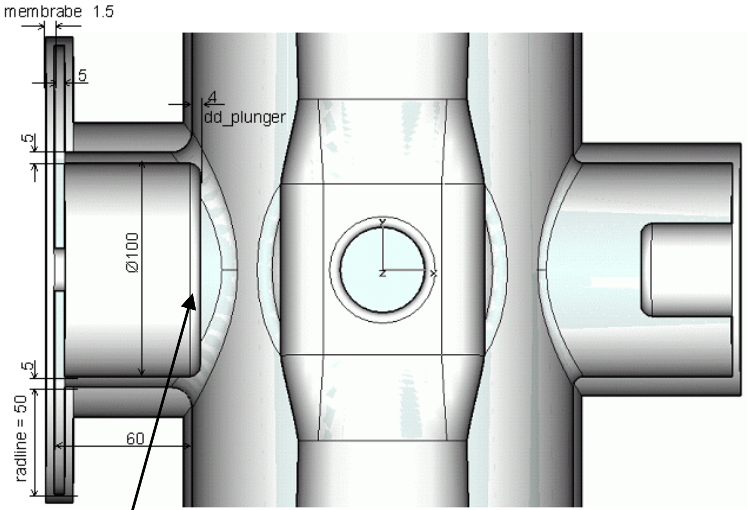
•Statical analysis (He pressure…)
•Dynamical analysis (mechanical modes…)
•Thermal analysis (cooling, T distributions,…)
•Construction procedure

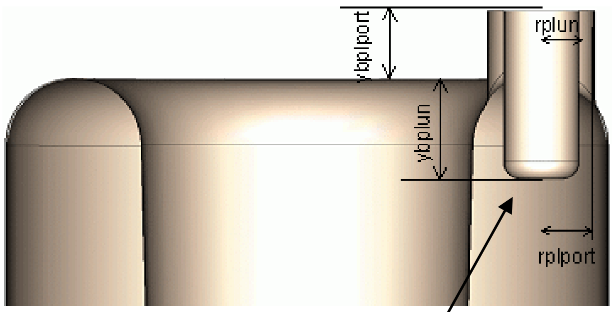




Frequency tuning

wall displacement toward: $\begin{cases} \text{high } E & \rightarrow \quad f \textbf{ down} \\ \text{high } B & \rightarrow \quad f \textbf{ up} \end{cases}$





(IFMIF HWR studies)

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

Inductive tuner in a high B region

Mechanical tuners

Slow tuners

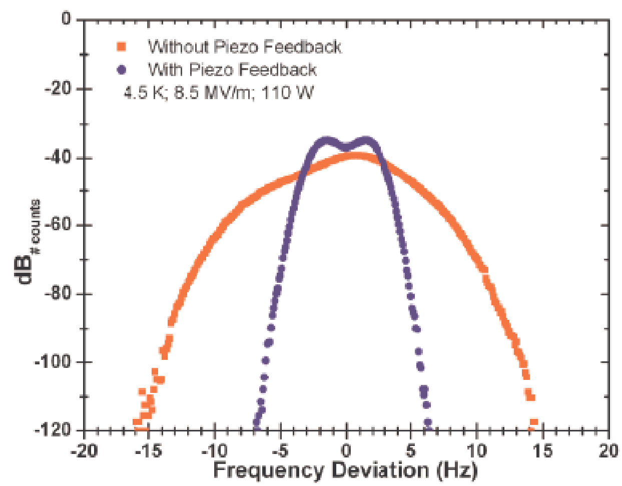
For center frequency tuning and helium pressure compensation

Mechanical tuner with Nb slotted plate (TRIUMF)

SC bellows tuner (ANL)

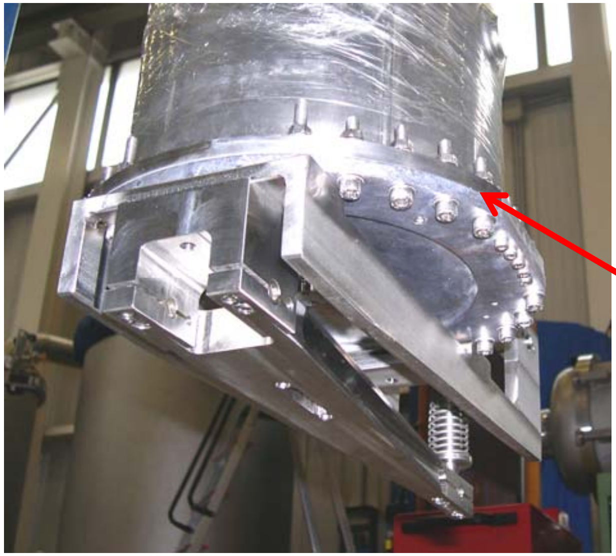
Fast tuners

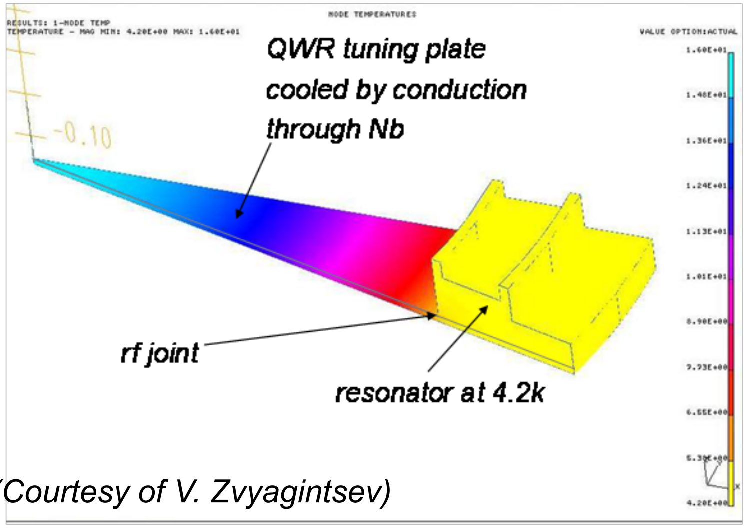
Piezoelectric tuner actuator. Suitable for fast tuning and also for high precision slow tuning.



RF joints in SC mechanical tuners

- 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. <u>1 mT</u> is 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





(Courtesy of V. Zvyagintsev)

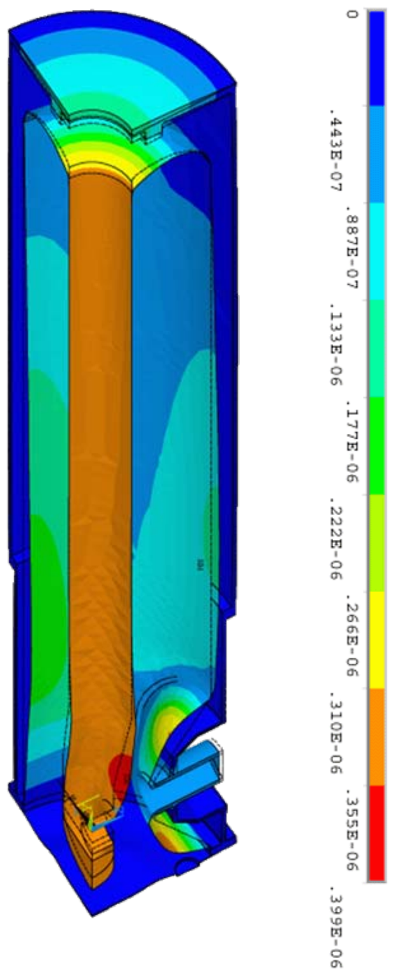
Detuning from mechanical instabilities

Source:	***Solution:***
Helium pressure variations	mechanical tuning in feedback, mechanical strengthening
Lorentz Force detuning	slow tuning and rf feedback
microphonics	fast tuners, mechanical design, noise shielding, etc.
resonant vibrations	mechanical damping, electronic damping

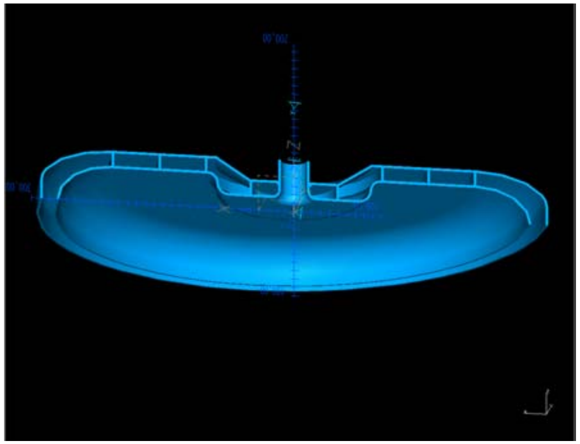
Slow detuning: He pressure fluctuations

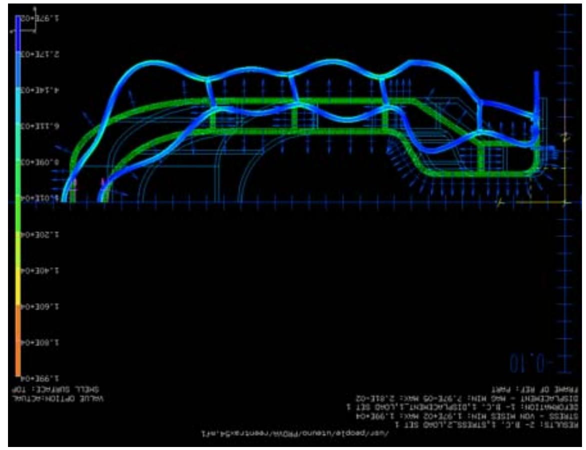
$$df \propto dP$$

- “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**



Mechanical reinforcement: double wall





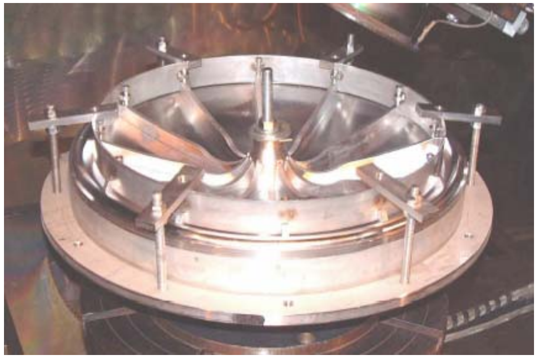
The double wall structure allows to null the net force of the He pressure

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

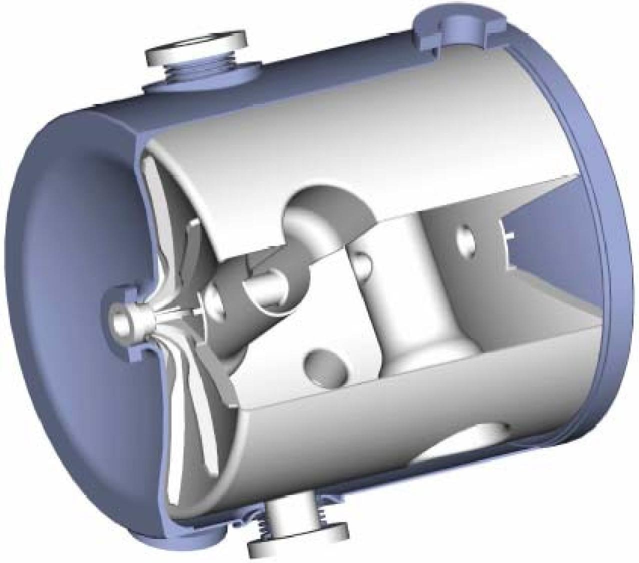
a careful design can minimize df/dP

Self-compensating design

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



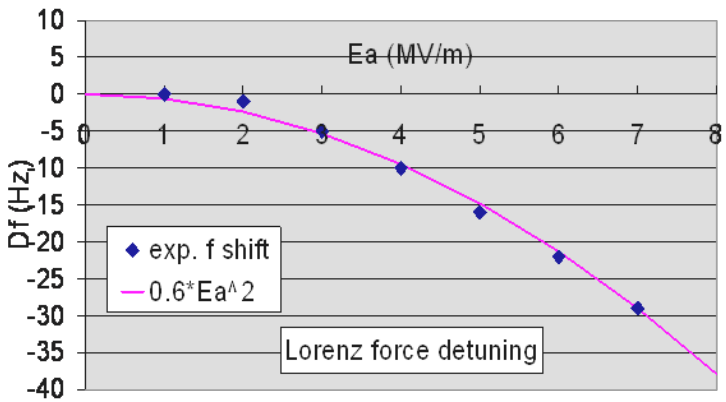
ANL 3-Spoke resonator end-plate with ribs calibrated for minimum df/dP



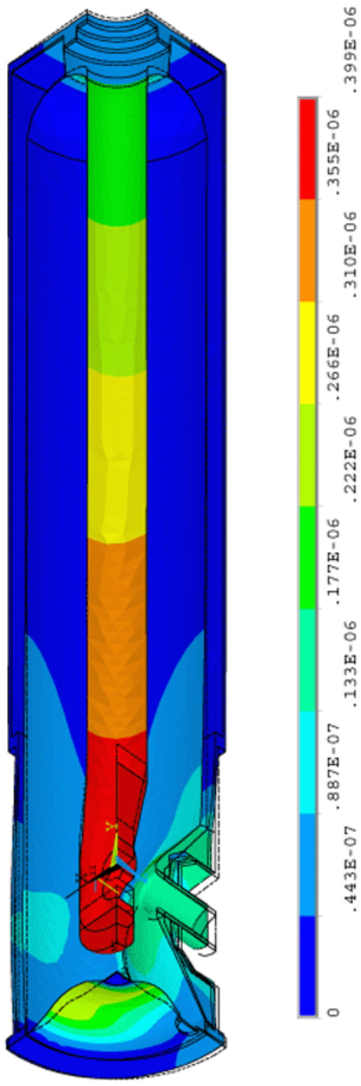
Lorentz Force detuning

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

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

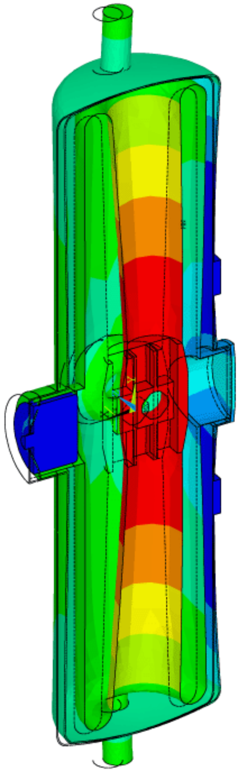


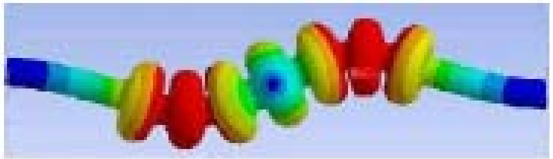
Lorenz Force detuning measured in a 80 MHz QWR



Resonant vibrations: mechanical modes

- Most dangerous: a small vibration can cause large deformation $\rightarrow$ 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 progressing)
- 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**
     - **mechanical damping**
     - **electronic damping by properly exciting Lorentz forces**





Example: stem vibration in a QWR

Mechanical modes:

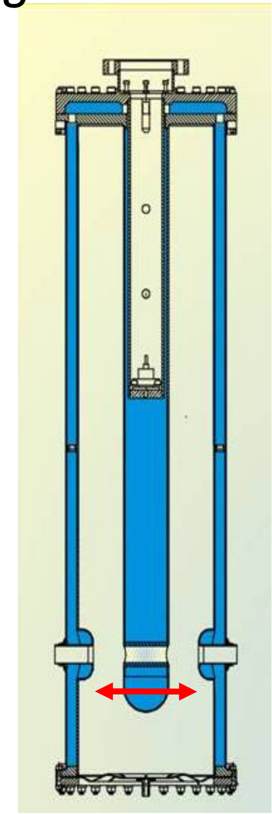
- *~50-60 Hz most critical*
- *<150 Hz dangerous*
- *criticity decreasing with frequency*

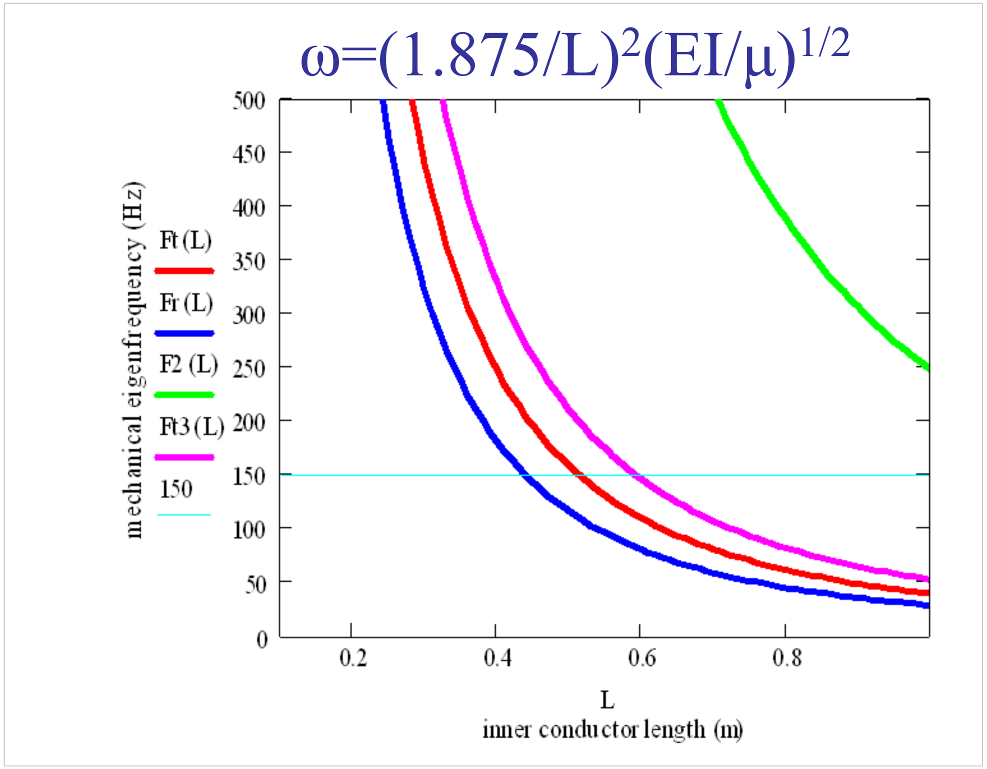
Lowest mode frequency of a 106.08 MHz Nb QWR:

Simulation: 81 Hz

Analytical: 83 Hz

Measured: 78

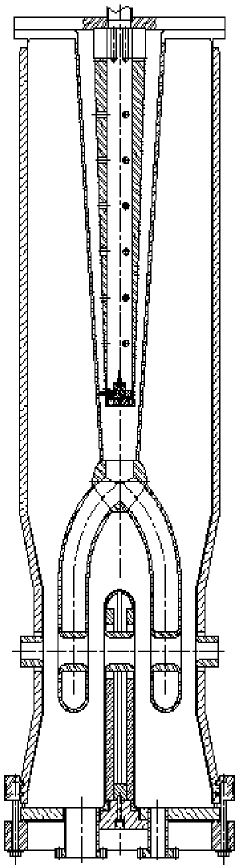




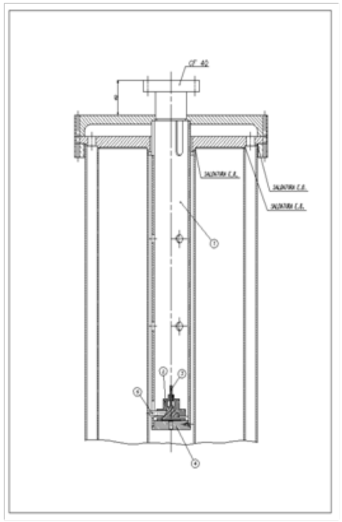
QWR mechanical frequency vs length of the inner conductor (Ø=60 mm, analytical results).
red: 2mm thick, Nb tube; blue: full Cu rod; magenta: 80 mm dia tube. Green: 2nd mode.
(E=Young modulus; I= geometrical moment of inertia of the i.c. tube cross section; μ=mass per unit length of the i.c. tube)

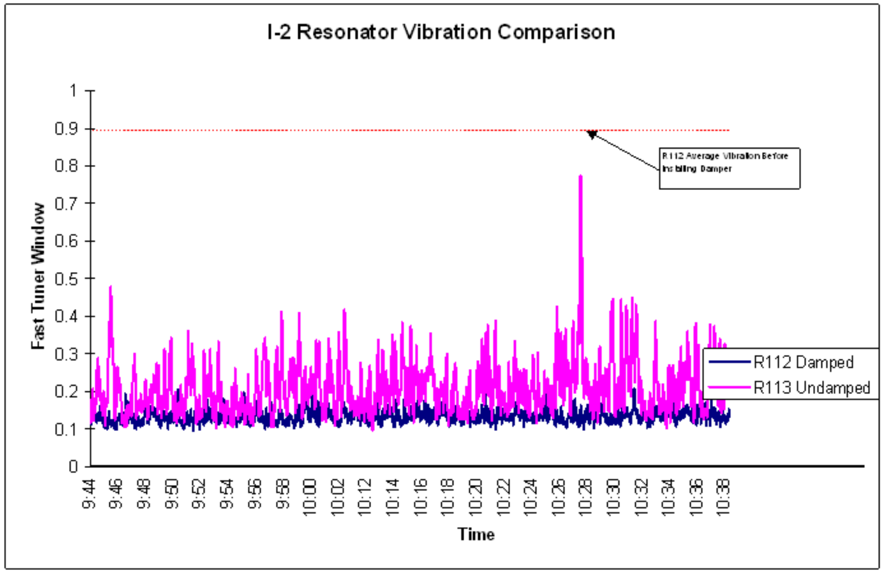
Mechanical vibration dampers

4-gap, 48 MHz QWR with vibration damper



80 MHz QWRs with vibration damper



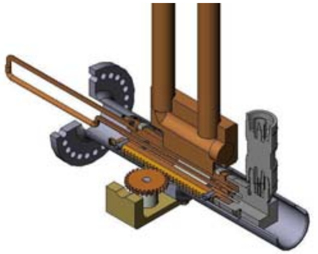


attenuation of the vibration amplitude by approx. a factor of 10

Vibration dampers are cheap and effective in QWRs

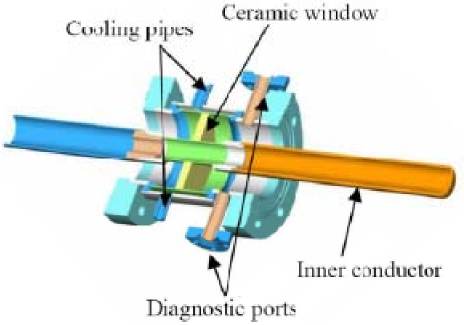
Rf power coupling

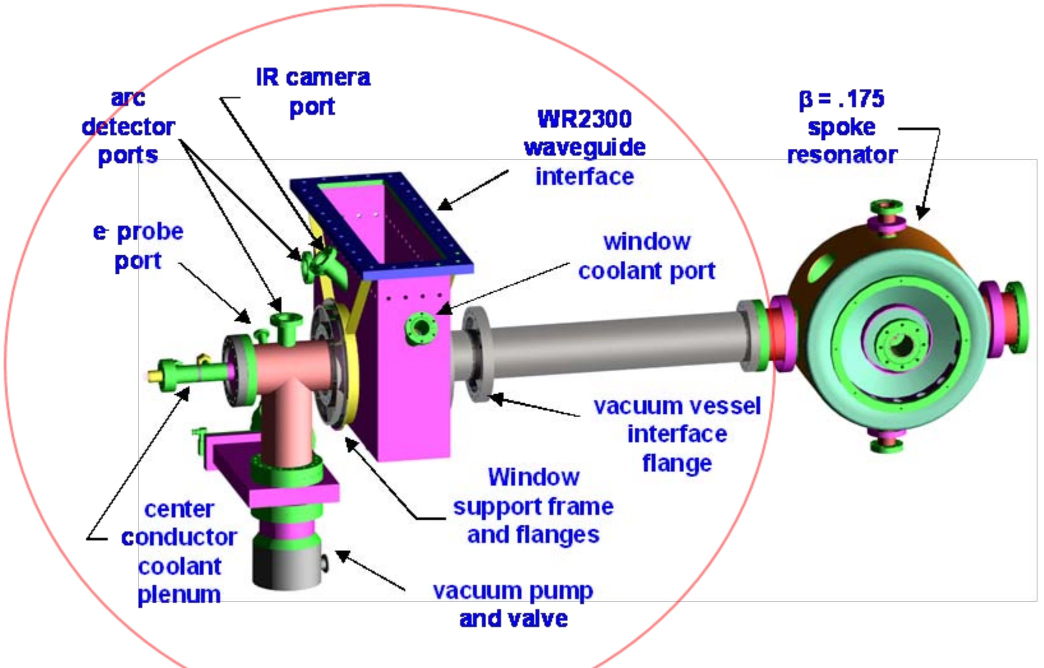
- Inductive couplers at low *P* (<1 kW) and low *f* (<300 MHz)
- Capacitive couplers above ~1 kW and ~ 300 MHz
- High power couplers can be very large and require a well integrated design



500 W Inductive coupler (TRIUMF)

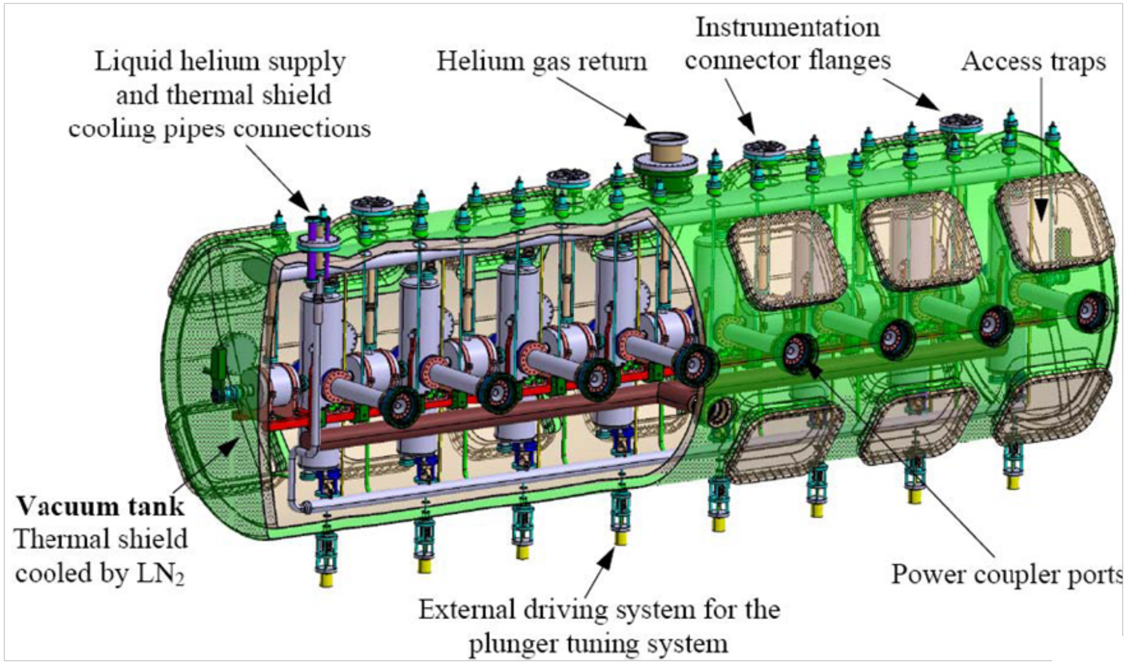
20 kW Capacitive coupler (IPNO)





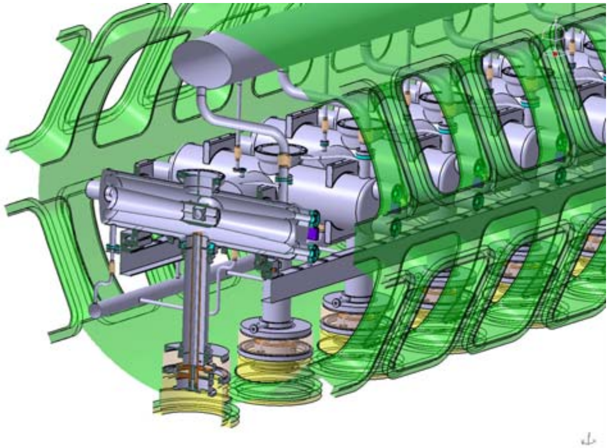
103-mm, 200 kW power coupler design for 100 mA beam (LANL)

Cavity integration in cryostats



IFMIF separate vacuum cryostats, in the two versions with vertical or horizontal cavity orientation

- Different solutions can be exploited for the same cavity types
- Couplers, tuners and rf lines are often dominant ingredients, especially in high rf power cryostats



Vacuum scheme in low-β cryostats

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

Common vacuum cryostat (TRIUMF)

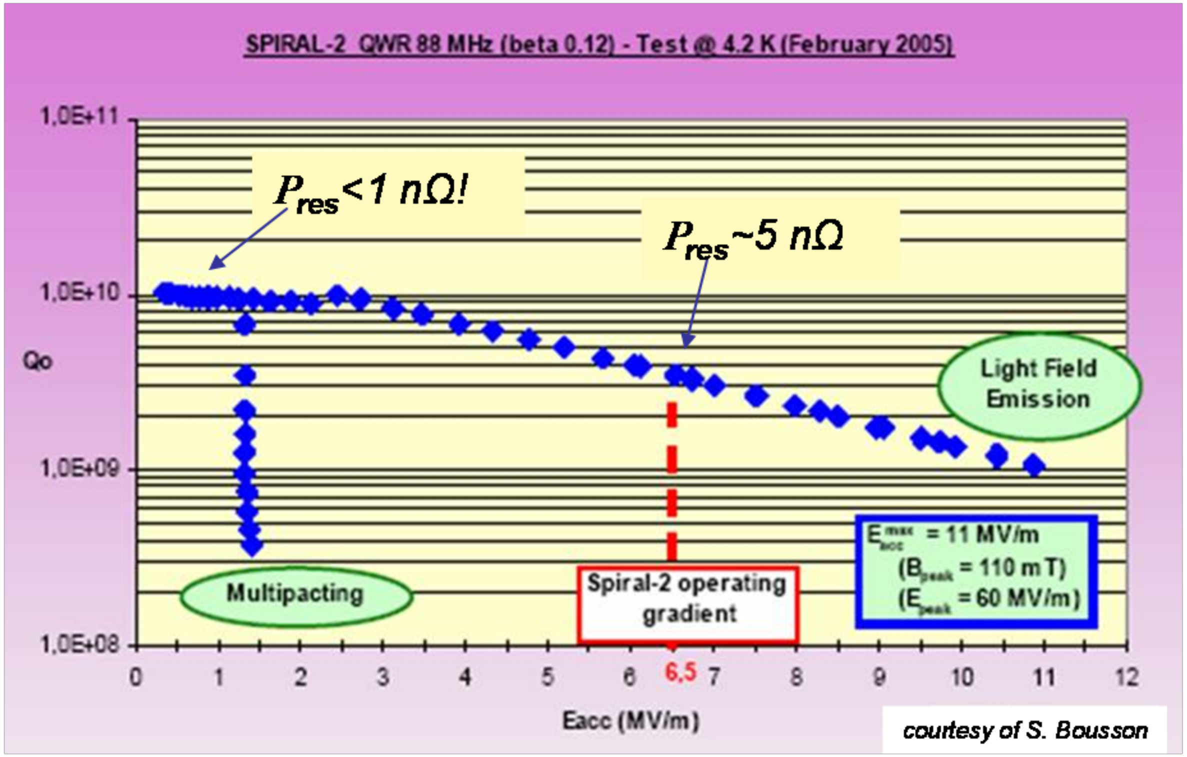
Typical problem in low-β cryostats: choice between common and separate vacuum.

- *In many low-β cryostats the vacuum inside and outside the resonators is not separated*
- *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!***

State of the art

Low-β resonators performance

- **achieved >60 MV/m and >120 mT peak fields, and <1 nΩ residual resistance at 4.2K**
- Even if geometries are not favorable for surface preparation (numerous welds, small apertures, etc), the maximum ***E,B*** fields are not too far from the ones of β=1 cavities
- However, a larger safety margin must be kept
- The recent application to low-β of the most advanced preparation techniques had raised also low-field *Q's* to extremely high values
- Still problems with Q-slopes and Q-switches



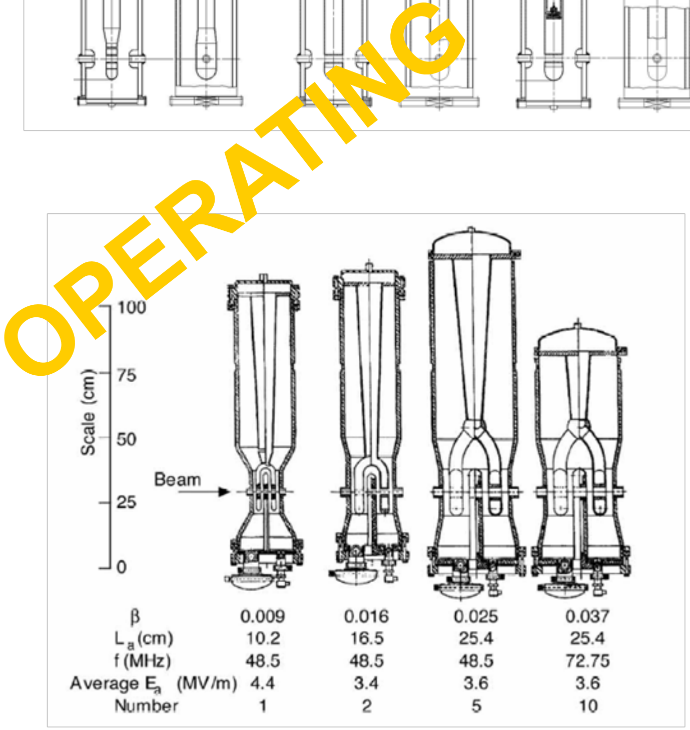
Quarter-wave stuctures: **Quarter-Wave resonators**

48≤f≤160 MHz, 0.001≤β_0≤0.2

- ✚ Compact
- ✚ Modular
- ✚ **High performance**
- ✚ **Low cost**
- ✚ **Easy access**
- ✚ Down to very low beta

- − Dipole steering for higher β QWRs
- − Mechanical stability for lower f QWRs

Very successful

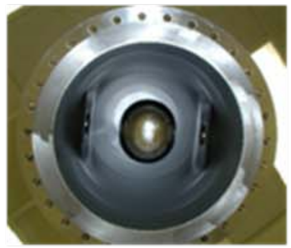


ANL 4-gap QWR family

Some of the QWR worldwide

TRIUMF

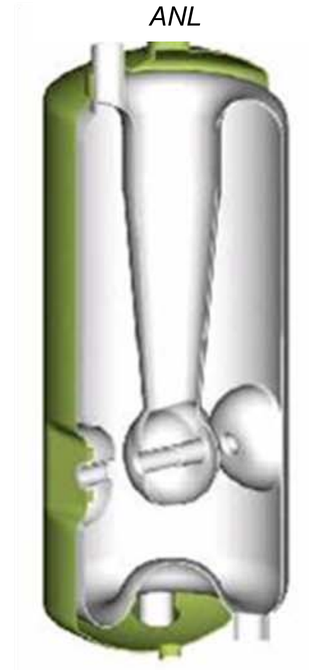
INFN LNL-MSU



MSU

New Dehli

ANL



INFN LNL (sputtered)

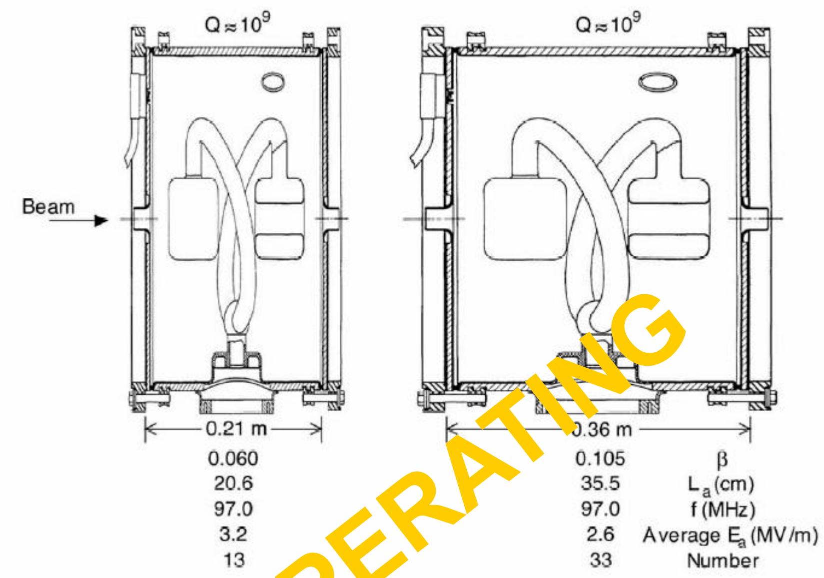
INFN LNL

Saclay

IPNO

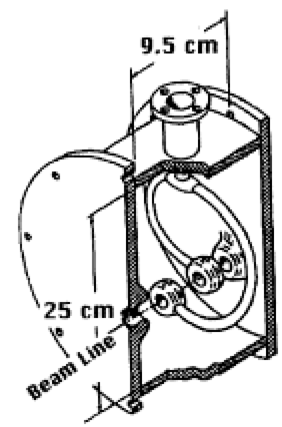
Quarter-wave stuctures: **Split-ring resonators**

$90 \leq f \leq 150$ MHz, $0.05 \leq \beta_0 \leq 0.15$



+ **relatively large energy gain**
+ good efficiency

- - **mechanical stability**
- beam steering
- high peak fields
- more expensive and difficult to build than QWRs



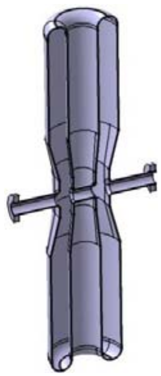
In use for many years

being replaced by QWRs

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

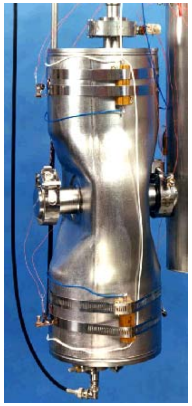
$160 \leq f \leq 352$ MHz, $0.09 \leq \beta_0 \leq 0.3$

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



MSU 322 MHz β=0.28

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



The first 355 MHz SC HWR ANL - β=0.12

OPERATING

ACCEL 176 MHz SC HWR β=0.09

Ideal around 150÷300 MHz

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

$345 \le f \le 805$ MHz, $0.15 \le \beta_0 \le 0.62$

- \+ All virtues of coaxial HWRs
- \+ Higher R_{sh} than (coaxial) HWRs
- \+ larger aperture than HWRs

LANL β=0.4
SPOKE

READY FOR OPERATION

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

IPNO SPOKE, β=0.35
352 MHz

the favorite 2-gap choice around 350 MHz

Half-wave structures: **Ladder resonators**

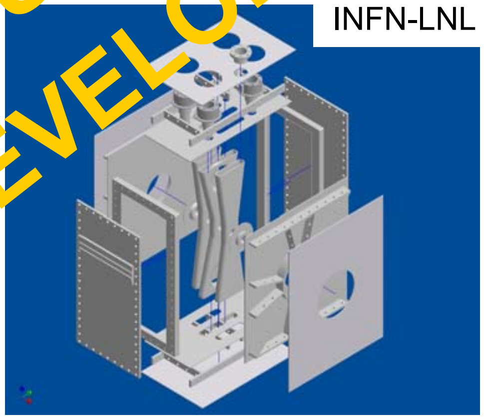
350 MHz, $0.1 \leq \beta_0 \leq 0.3$

- + large energy gain
- + they can be made for rather low β
- + + easy access (removable side walls)

- small aperture
- not easy to build
- strong field emission
- ancillaries not yet fully developed

promising for beam boosting just after an RFQ

4 gap ladder
352 MHz, β=0.12
INFN-LNL



TM mode cavities: **multi-cell Elliptical resonators**

352≤f≤805 MHz, 0.47≤ β_0≤ 1

- + + **Large energy gain**
- + Highly symmetric field
- + taking profit of the wide β=1 experience
- + Low E_p and B_p
- + **Large aperture**

- - Not suitable for β<0.5
- - Dangerous Mechanical modes
- - Dangerous Higher Order Modes

Very successful

TM mode cavities: **single-cell Reentrant cavities**

352≤f≤402 MHz, β >0.1

- \+ Highly symmetric field
- \+ Very Compact
- \+ Low E_p and B_p
- \+ Widest velocity acceptance
- \+ Possibility of large aperture

- \- little E gain
- \- mechanical stability
- \- inductive couplers only
- \- ancillaries not yet fully developed

for special applications

The first reentrant cavities - SLAC

TESTED OFF LINE

LNL 352 MHz
reentrant cavity

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

LNL SRFQ2, A/q=8.5

Efficient alternative to standard RFQs for cw beams

CH structures: **Multi-SPOKE resonators**

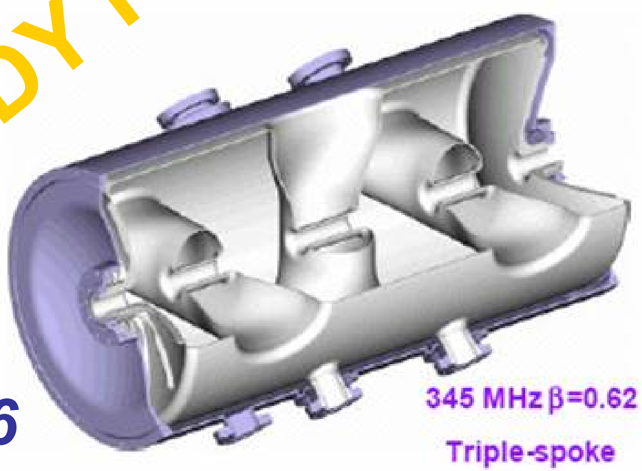
345≤f≤805 MHz, 0.15 ≤ β_0≤ 0.62

The first Double SPOKE, ANL β=0.4

- **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

READY FOR OPERATION

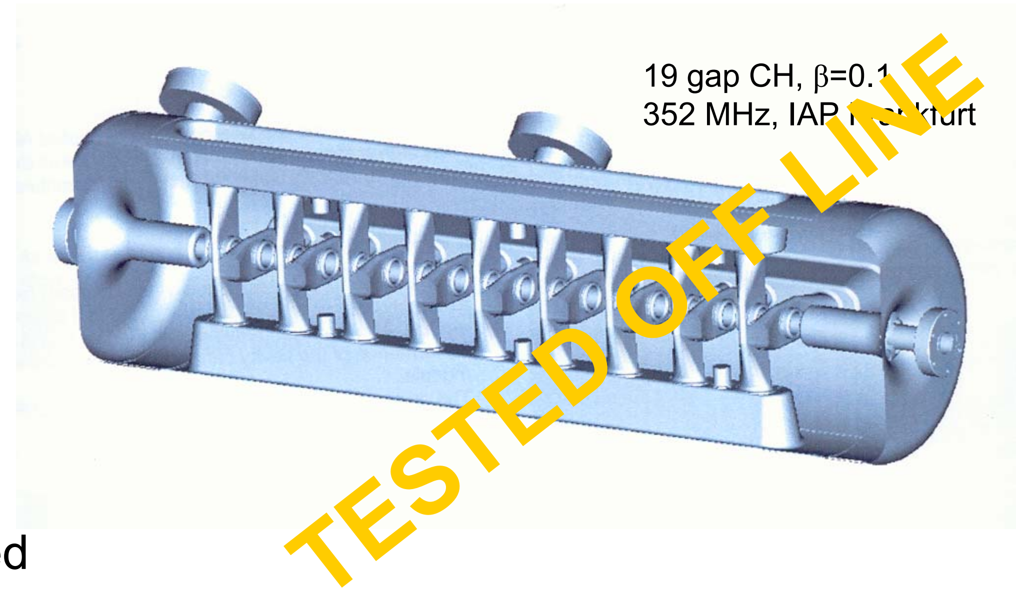


very successful, esp. for β~0.3÷0.6

CH structures: **CH multi-gap SC cavities**

174≤f≤800 MHz, 0.1≤ β_0≤ 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)

The future for fixed velocity profile ?

Conclusions

- SC technology: becaming the 1st choice also at low-β
- high performance reached, specifications still moving up
- new applications: very high current beams
- large variety of resonators operating, or ready for operation
  - today: QWRs, HWRs and elliptical
  - tomorrow: SPOKE
  - future: CH?
- numerous ongoing projects

…still a lot to do in the field…!

Thank you

Thanks also to all people who have contributed in the field