Low-β Superconducting Cavity Design

Tutorial

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Preface

This tutorial is an introduction to superconducting cavities for low velocity beams.

It is intended for non-specialists.

Specialists, however, will find much of their material in the following slides: I thank them all.

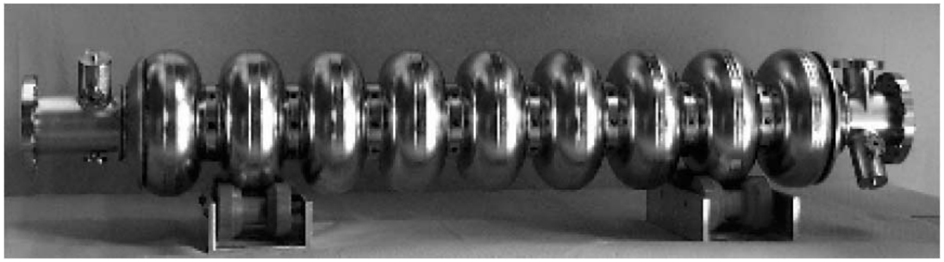
1. Introduction

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

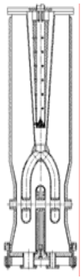
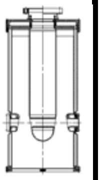
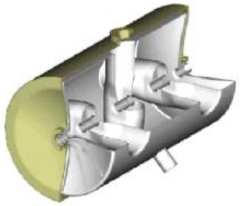
β=1 superconducting
resonator:
"elliptical" shapes



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

More definitions…

The definition changes according to the community

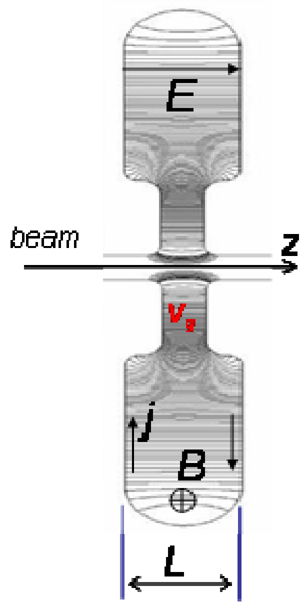
(Approximate) definition	low β	medium β	high β
Heavy ion boosters (usually coupled to electrostatic accelerators)	<0.06 	0.06÷0.12 	>0.12 
Proton linacs Heavy ion drivers	<0.2 	0.2÷0.8 	>0.8 

Important parameters in accelerating cavities

Avg. accelerating field	$E_a=V_gT(\beta_0)/L$	*MV/m*
Stored energy	U/E_a^2	*J/(MV/m)²*
Shunt impedance	$R_{sh}=E_a^2L/P$	*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

constants

$$\vec{E}=\vec{E}(x,y,z)\cos(\omega t)$$
$$\vec{B}=\vec{B}(x,y,z)\sin(\omega t)$$



where:

R_s=surface resistance of the cavity walls

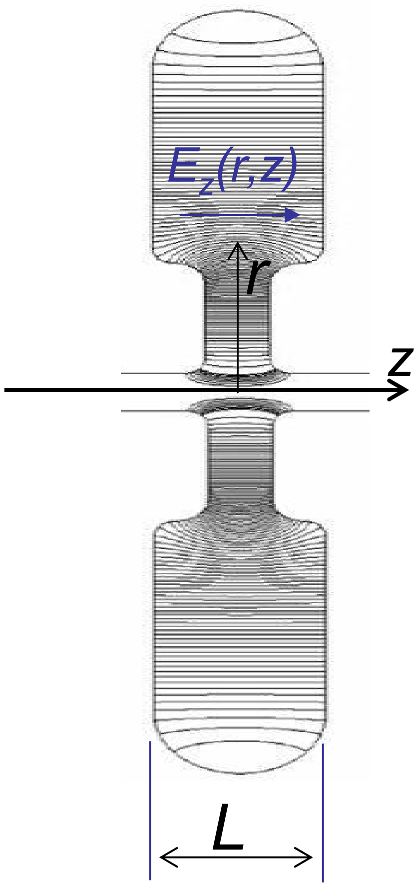
P =rf power losses in the cavity, proportional to R_s

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* $E_z(z)\cos(\omega z/\beta c+\varphi)$.



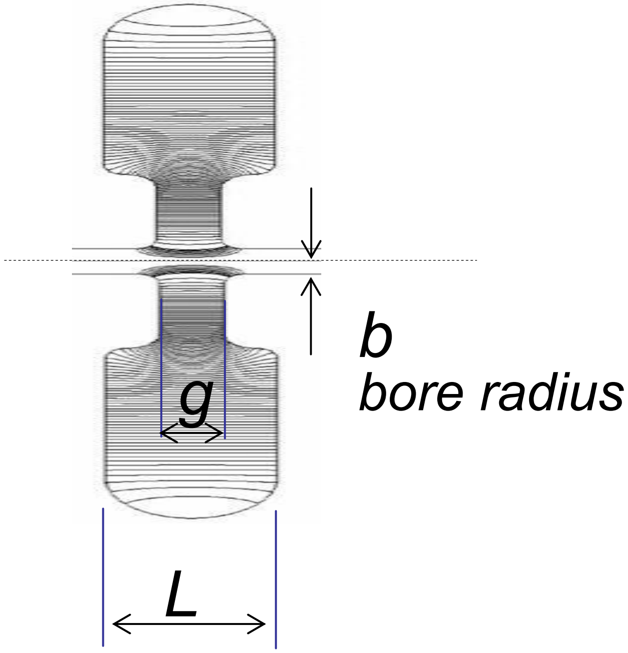
Transit time factor: $$T(\beta) = \frac{\int_{-L/2}^{L/2} E_z(z)\cos\left(\frac{\omega z}{\beta c}\right)dz}{\int_{-L/2}^{L/2} E_z(z)\,dz}$$

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

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

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



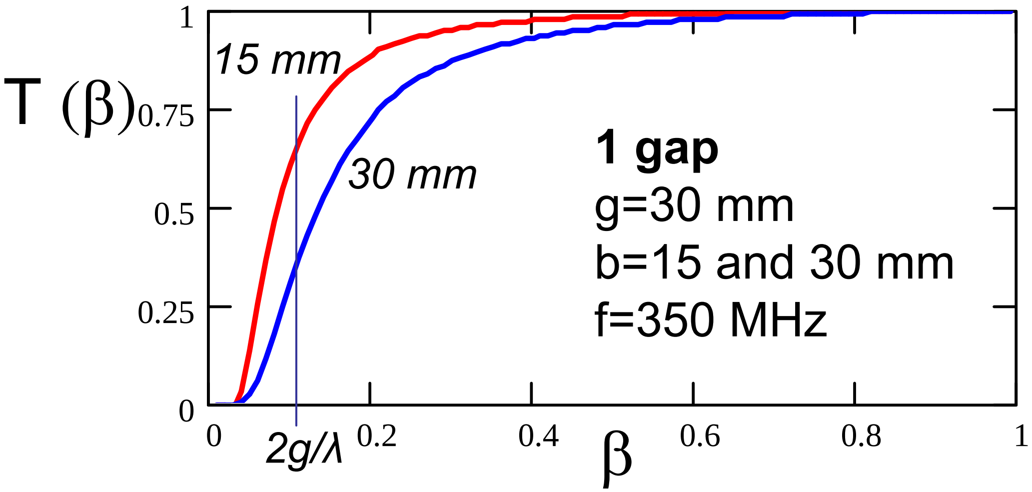
$$T(\beta) \cong \frac{\sin\left(\frac{\pi g}{\beta\lambda}\right)}{\left(\frac{\pi g}{\beta\lambda}\right)}$$

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:

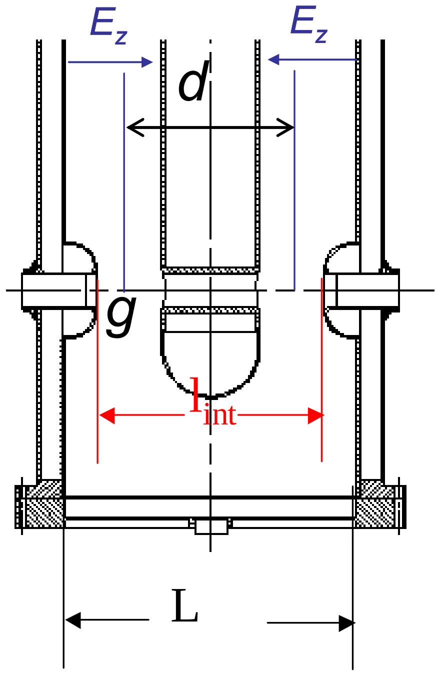
$$g_{eff} \approx \sqrt{g^2 + (2b)^2}$$

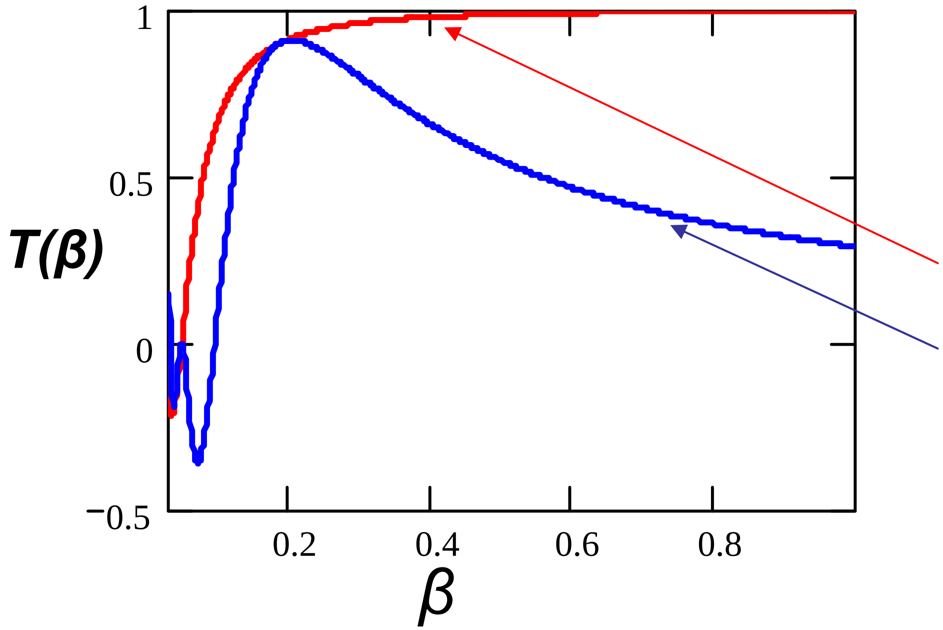


T(β) for 2 gap (π mode)

(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: 1+2 gap effect → $d\sim\beta\lambda/2$

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

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

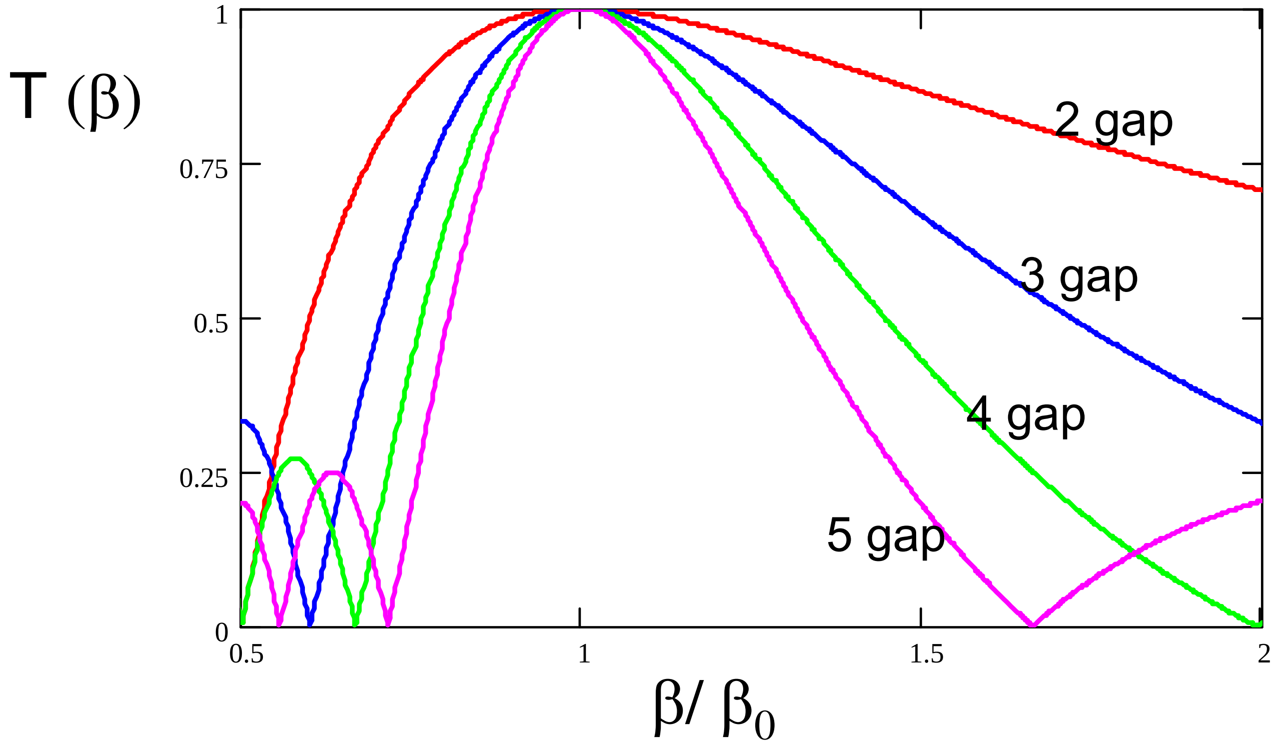
Avg. accelerating field: $E_a^* = E_a T(\beta_0)$

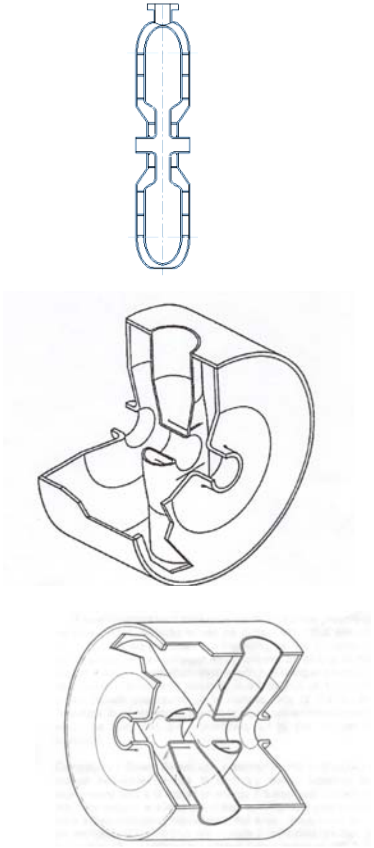
where $\beta_0 \equiv \beta / T(\beta_0) = \max\{T(\beta)\}$ *and* $T^*(\beta_0) = 1$

and the energy gain definition does'nt change

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

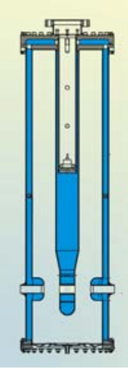
Transit time factor curves (normalized)

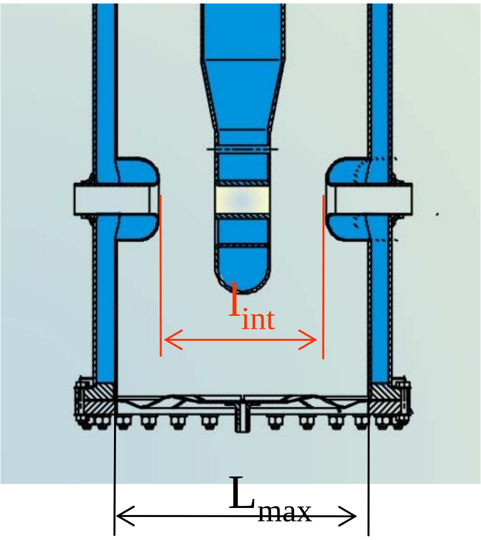




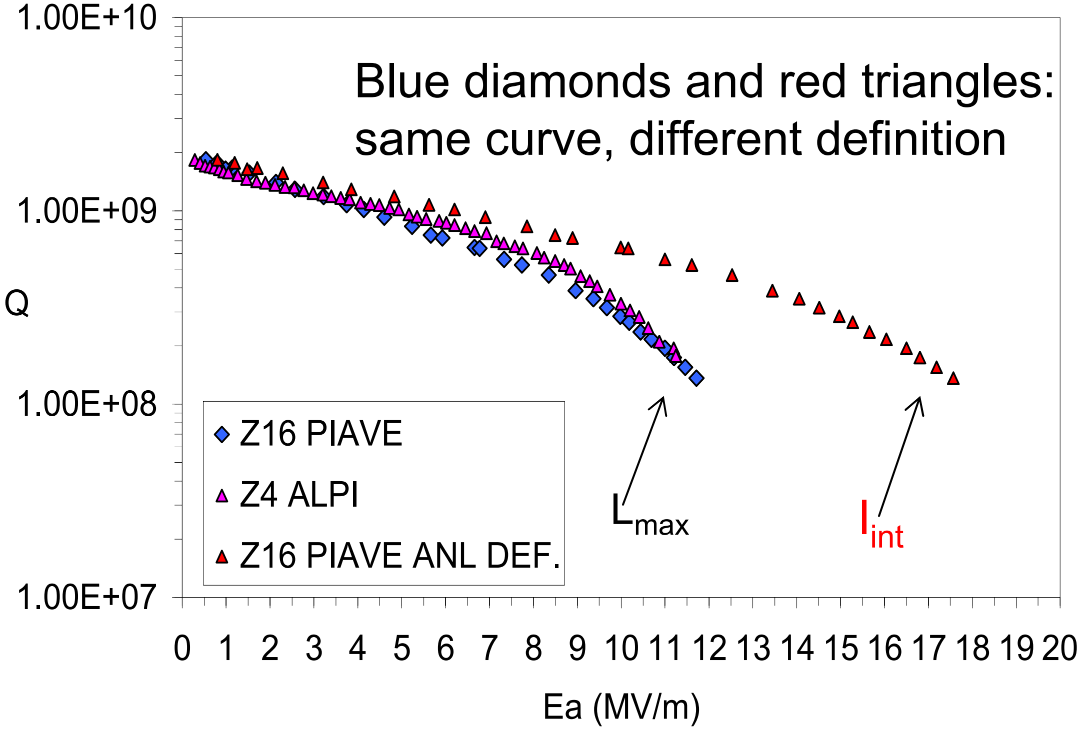
Normalized transit time factor curves vs. normalized velocity, for cavities with different number of gap

Remark: different definitions of gradient





← $n\beta\lambda/2$ →
n *gap N.*



Blue diamonds and red triangles: same curve, different definition

- Sometimes difficult to decide on the definition of 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

Low-β resonators basic requirements

To be efficient at low-β: **This implies:**

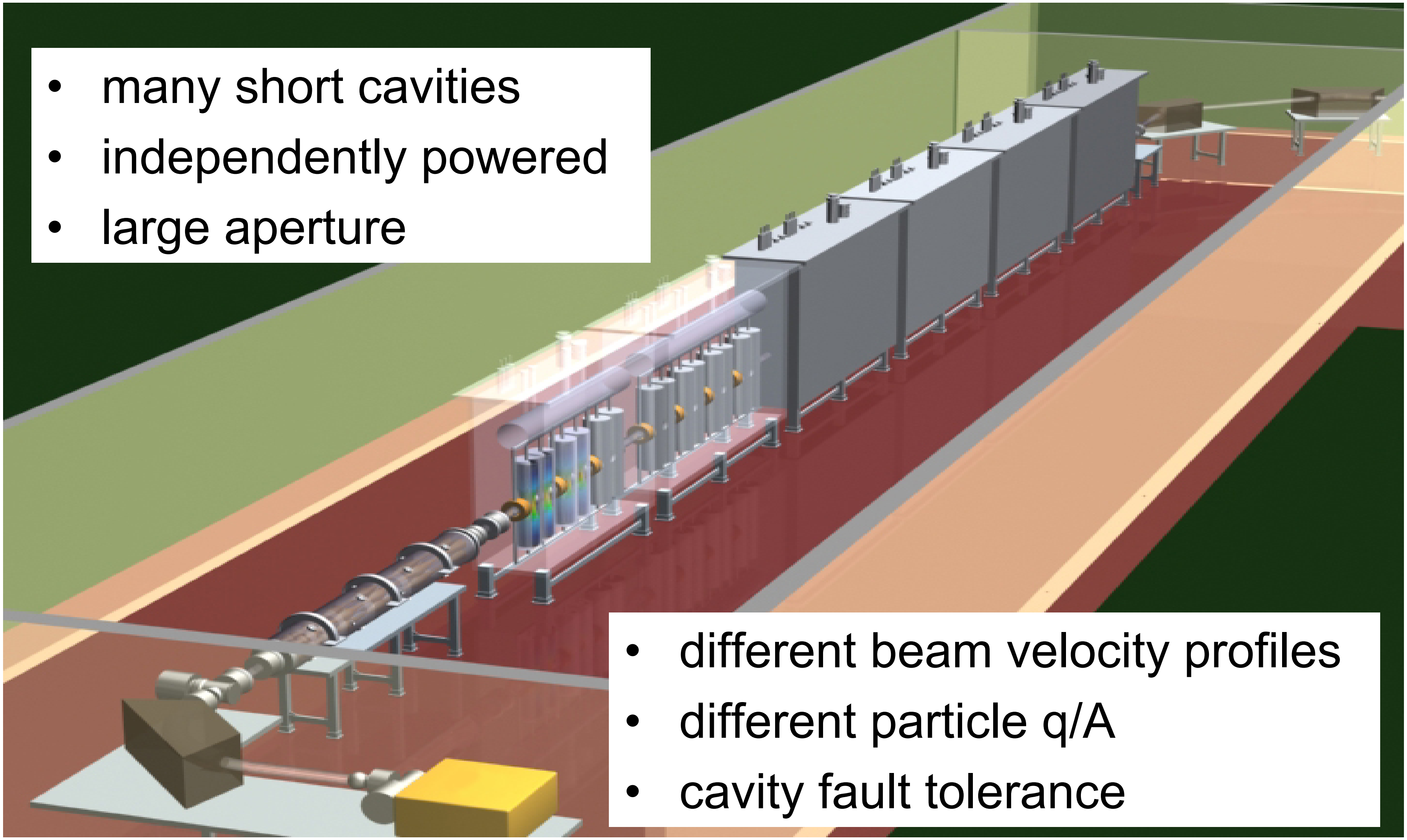
- short gap length
  → High peak fields, low energy gain
- low rf frequency
  → Large resonators, complicated shapes
- small bore radius
  → Low transverse acceptance

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

Low-β SC cavities peculiarities

- Low frequency
  - Large size
  - complicated geometries
  - High peak fields E_p, B_p
- Many different shapes
  - many different EM modes
- Short cavities
  - Many independent cavities in a linac (ISCL)
- Only a few accelerating gaps
  - Large velocity acceptance
- Mostly working at 4.2 K

Superconducting low-β linacs



- many short cavities
- independently powered
- large aperture

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

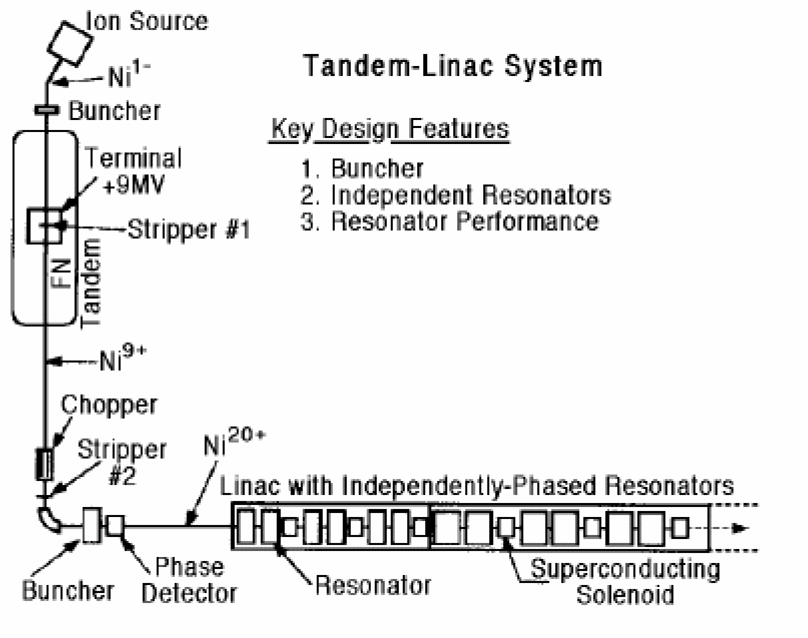
2. Some history

The first low-β SC cavities application

HI boosters for electrostatic accelerators

First and ideal application of SC technology:

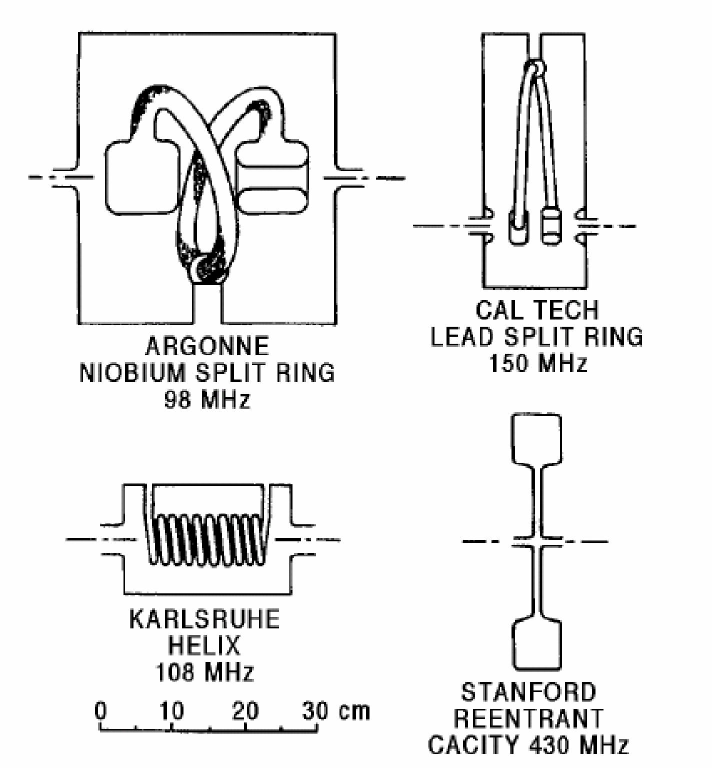
- Low beam current: all rf power in the cavity walls
- 2÷3 gap: wide β acceptance
- High gradient, cw operation
- Hardly achievable with Normal Conducting (NC) cavities



Tandem-booster system

New problems: very narrow rf bandwidth, mechanical instabilities

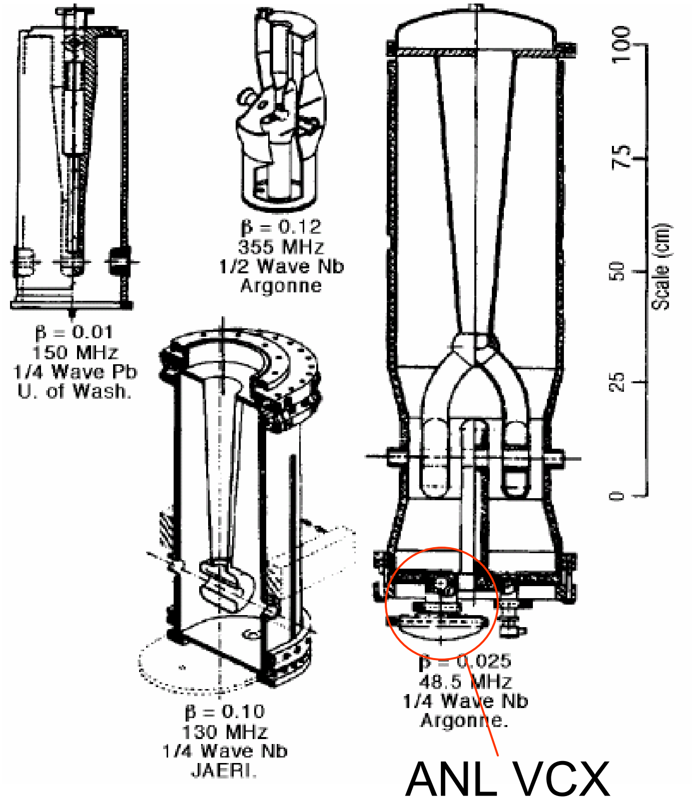
Early resonators: 70's



Low-β cavities in operation from the 70's

- Tandem boosters for light ions 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



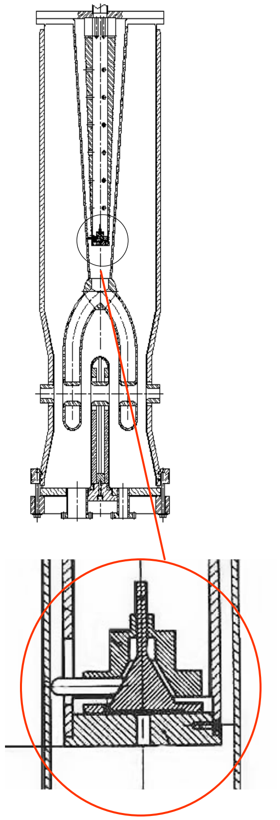
ANL VCX

Low-β cavities in operation from the 80’s

- At ANL Tandem replaced by the first low-β SC Positive Ion Injector, **β~0.001 ÷0.2**
- Heavy ions up to U
- 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**

HI SC low-β resonators: 90’s

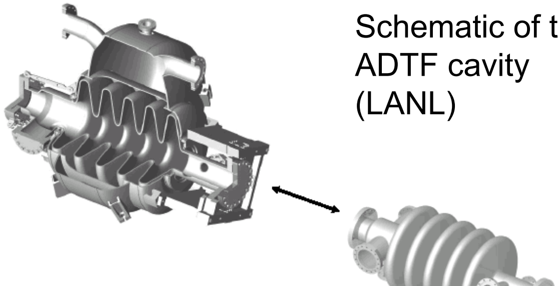
Low-β cavities from the 90’s



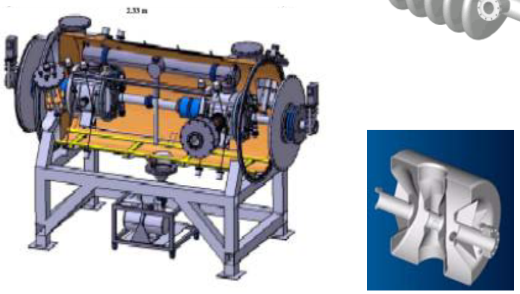
LNL damper

- **β~0.001 ÷0.2**
- New materials:
  - **Sputtered Nb on Cu**
- Linac project with SC RFQs starts at LNL
- Mechanical stability problems solved also by mechanical damping
- E_a typically 3 ÷4 MV/m; first operation at **6 MV/m**

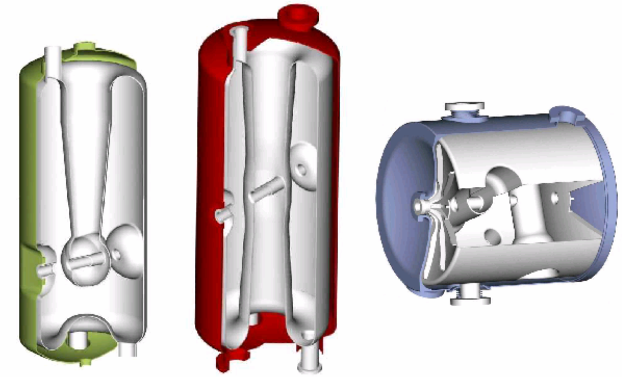
HI SC low-β resonators: present



Schematic of the
ADTF cavity
(LANL)



2-gap spoke cavity and cryomodule (IPNO)



ANL cavities for RIA

- **β~0.001 ÷ 0.8**
- material: mainly **Bulk Nb**
- high intensity proton SC accelerators under construction
- Development for RIB facilities
- Mechanical stability problems solved also by mechanical piezo tuners
- 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**	~ 0.3	1 ÷ 2	~1÷10 mA
High Power Proton Accelerators	~ 0.9	1	~10÷100 mA
High Power Deuteron Accelerators for material irradiation	~ 0.3	2	~100 mA

3. Low-β cavities design

What is a good SC low-β resonator?

It must fulfill the following principal 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/performance ratio

Preliminary choices

- beam energy → β_0, gap length
- velocity acceptance → n. of gaps
- beam size, transv. → bore radius
- beam long. size & f → rf frequency
- beam power → rf coupling type

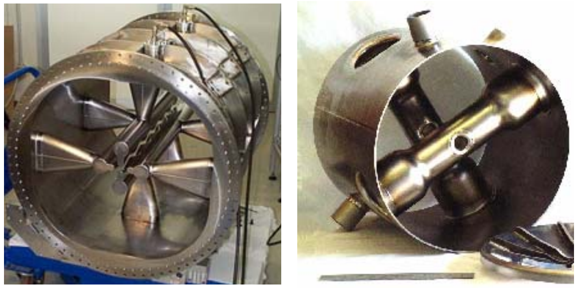
beam specs

- gradient, efficiency → geometry
- cw, pulsed → mech. design
- cost → technology
- …

techn. choices

Choice of the SC technology

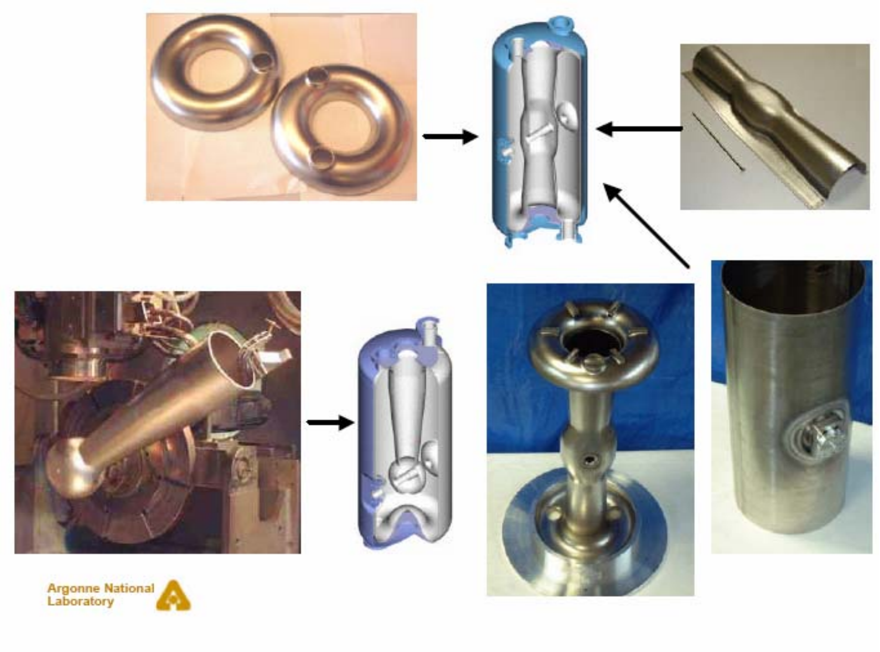
- Bulk Nb (by far the most used)
  - highest performance, many manufacturers, any shape and *f*
    - *performance* **** *cost* **

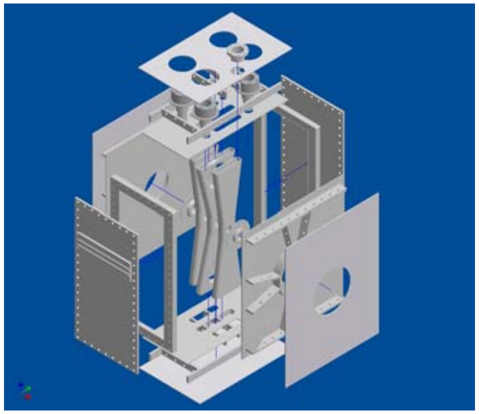


- Sputtered Nb on Cu (only at LNL)
  - high performance, lower cost than bulk Nb in large production, simple shapes
    - *performance* *** *cost* ***

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

Niobium bulk



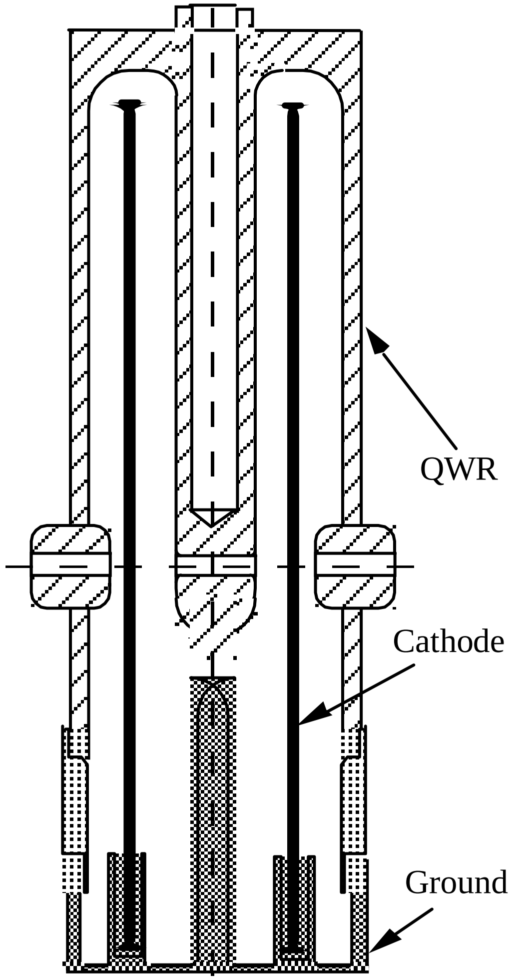


The design must allow:

- 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

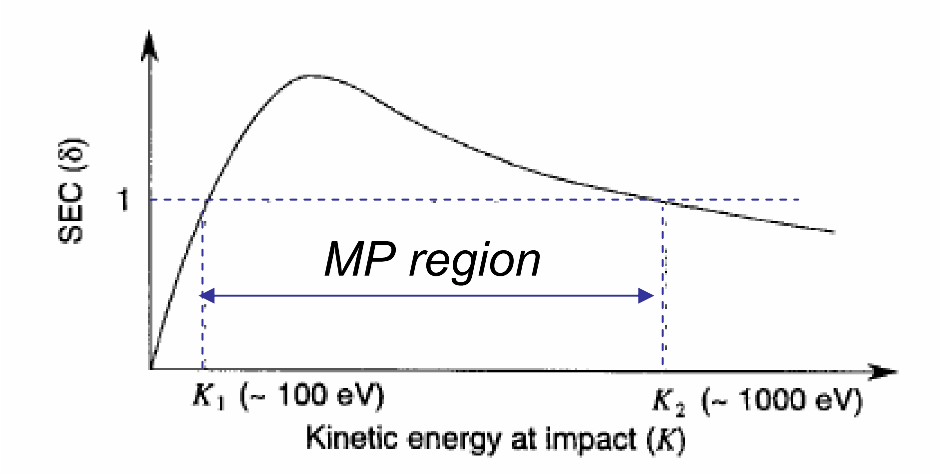
practically suitable mainly for QWRs

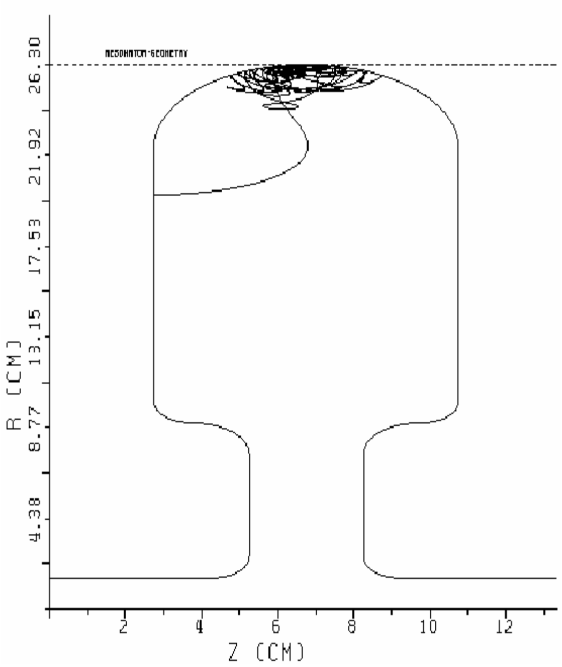
Nb properties – design specifications limits

- 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_s surface resistivity $=R_{BCS}+R_{res}$
  - R_{res} achievable: ~1 nΩ
  - reliable specs <10 n Ω
- Maximum rf power density on the cavity walls
  - ~*1W/cm*^{2} at 4.2K
- Critical temperature
  - · $T_c = 9.2\sqrt{1 - B/200}$

E_a performance limitations : Multipacting

- Multipacting: resonant field emission of electrons
- Conditions:
  1. stable trajectories ending on cavity walls +
  2. secondary emission coefficient >1 +
  3. initial electron impinging the right surface at the right field and phase to start the process





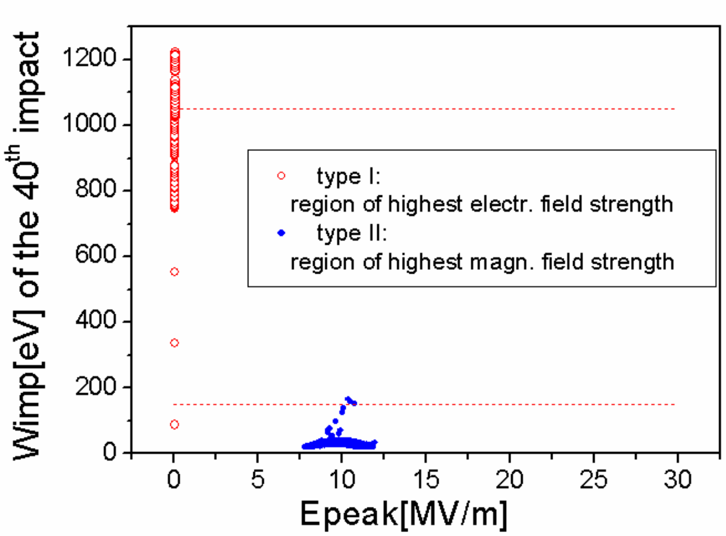
Multipacting in low-β cavities - examples

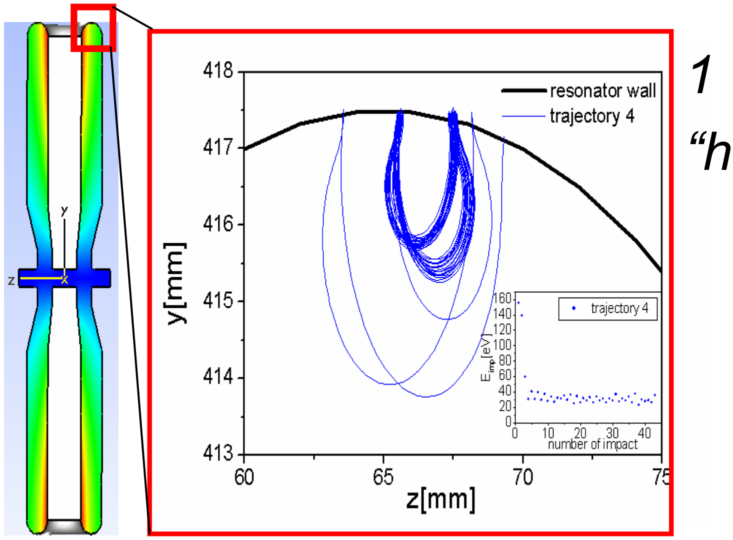
2-point MP in a HWR

1 wall MP: ***E*+*B***

2 walls MP: mainly ***E*.**

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



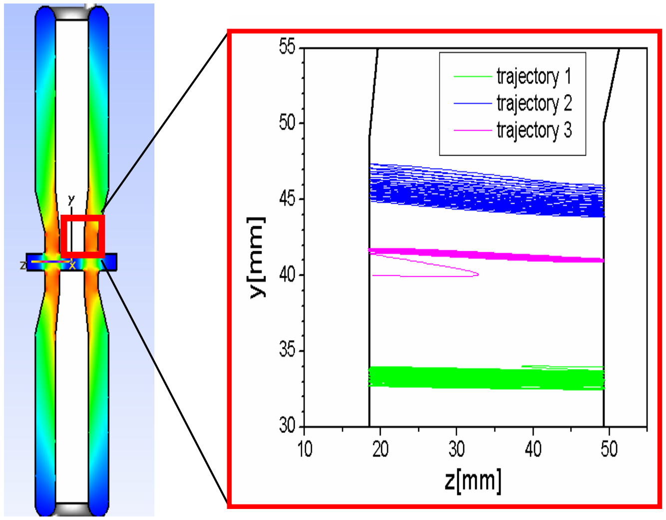


1 wall MP

"horseshoe"

Courtesy of ACCEL

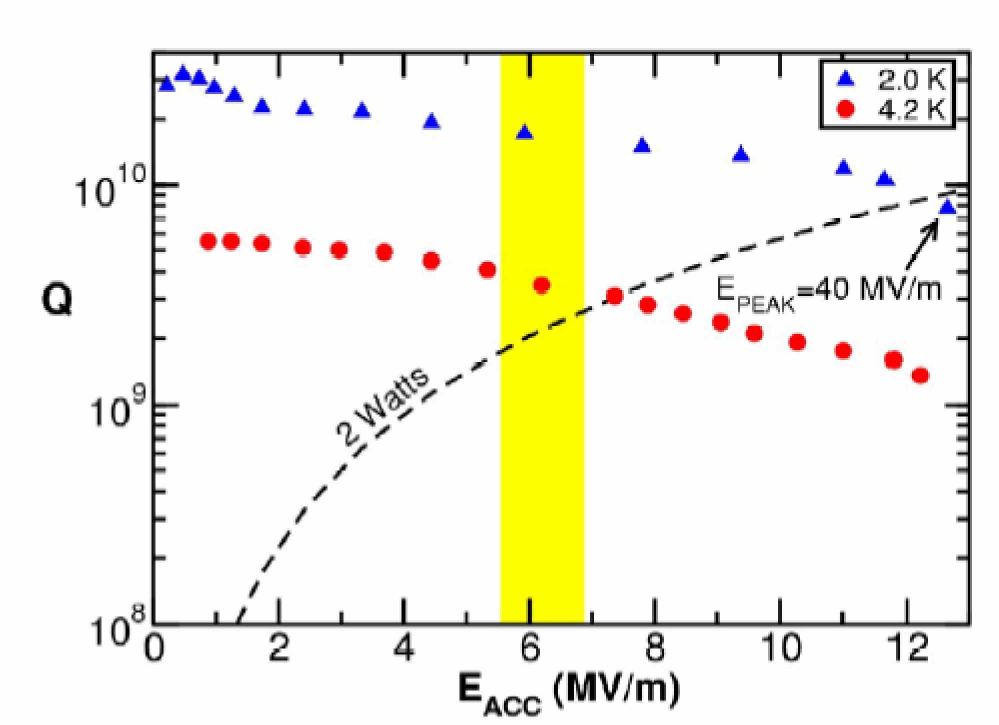
2-walls MP



performance limitations: Q slope

(we will consider only clean and well prepared resonators)

- Surface resistance, especially at 4.2 K, usually decreases at increasing field (not fully understood): the Q curve has usually a slope that must be taken into account



EM design

minimize:

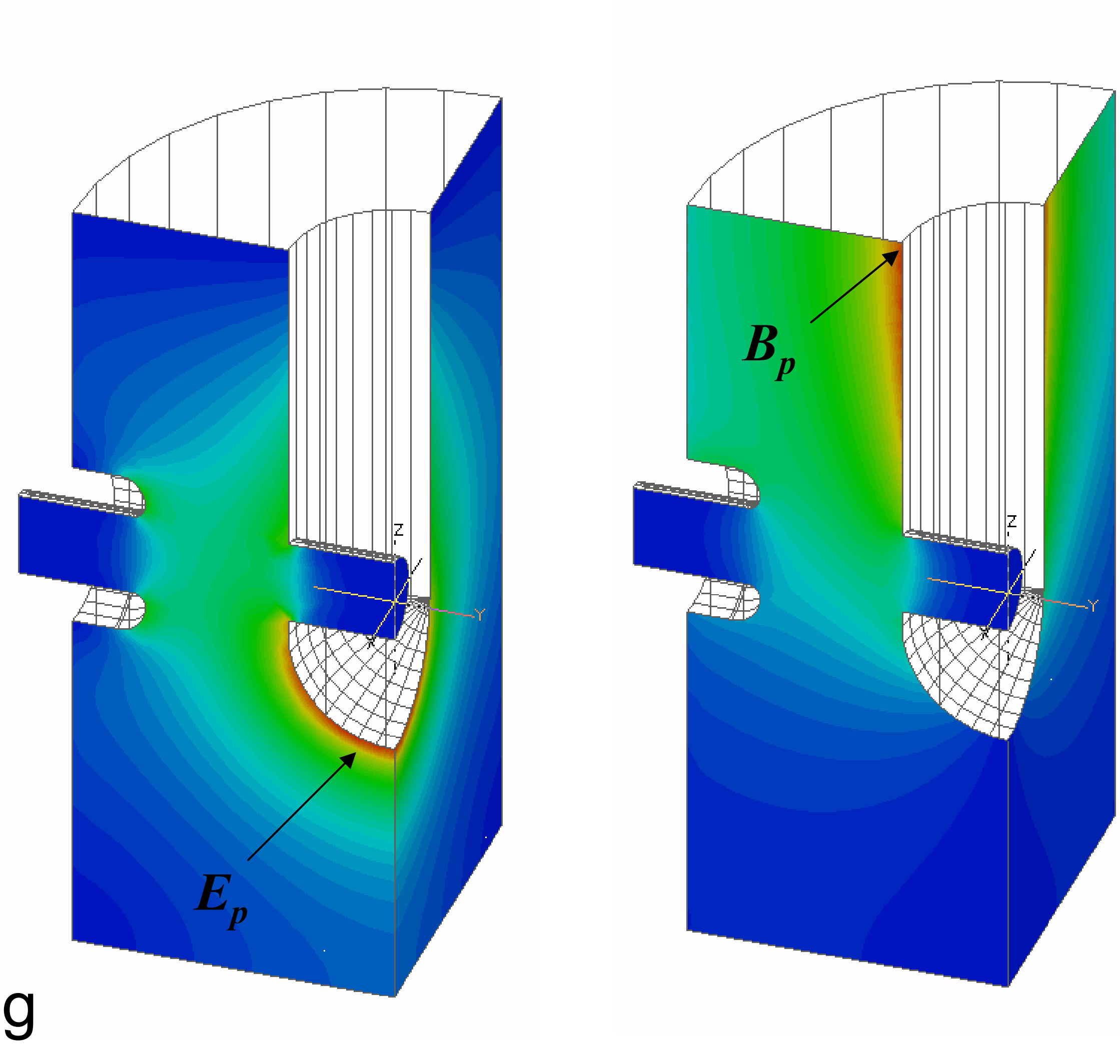
- E_p/E_a
- B_p/E_a

maximize:

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

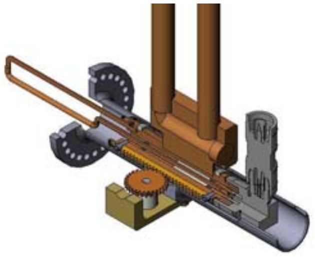
optimize:

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



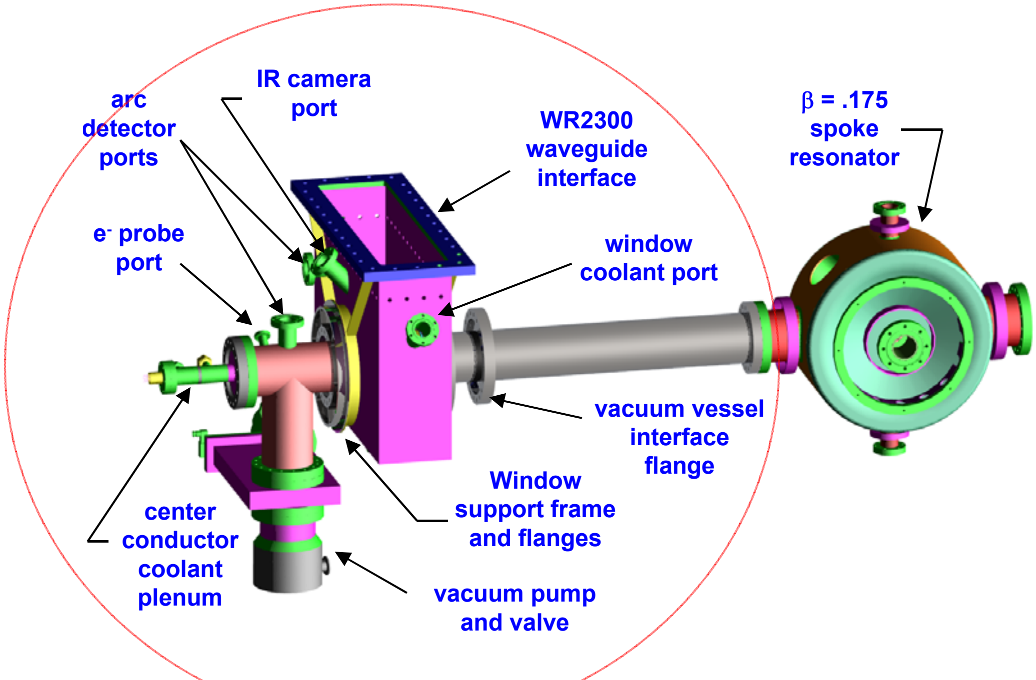
Rf couplers

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



Inductive coupler (TRIUMF)

Capacitive coupler (LEP type)



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

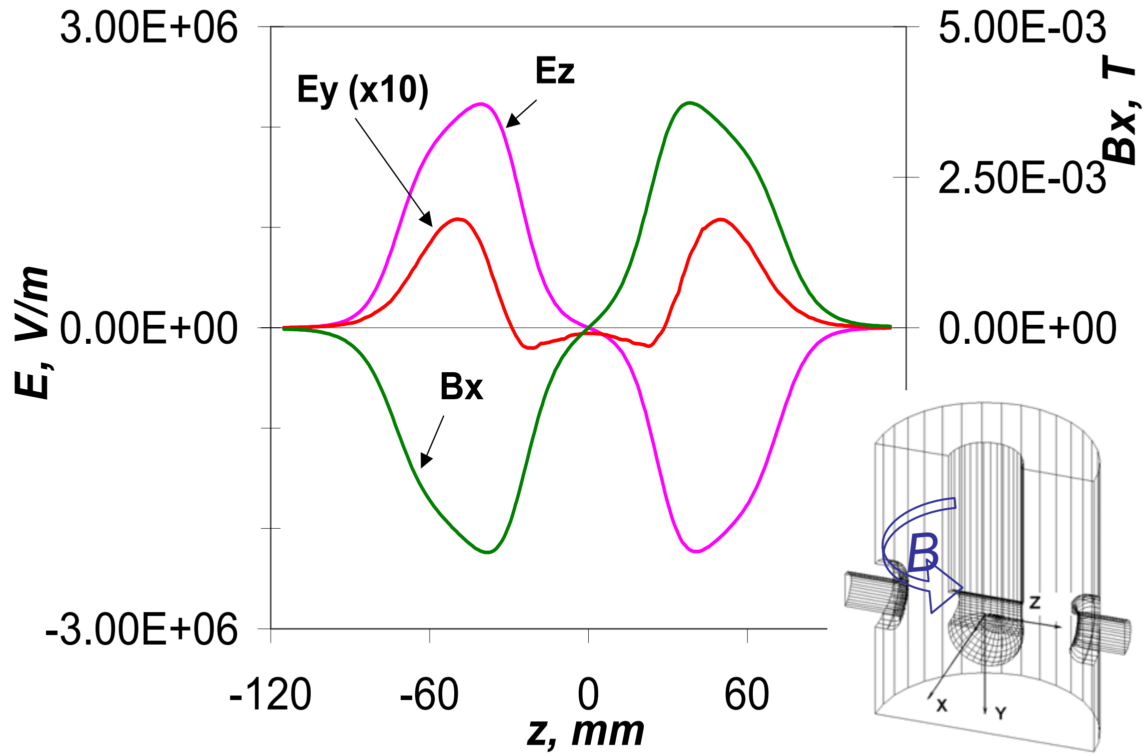
EM design: Beam steering

- Non symmetric cavities can produce beam steering
- The magnetic field gives usually the dominant contribution
- especially in QWRs with large aspect ratio (i.e. approximately L/λ> 1/10) this can give serious beam dynamics problems
- QWRs above ~100 MHz often need some correction
- Transversal kick:

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

QWRs Beam steering

On-axis field components in QWRs

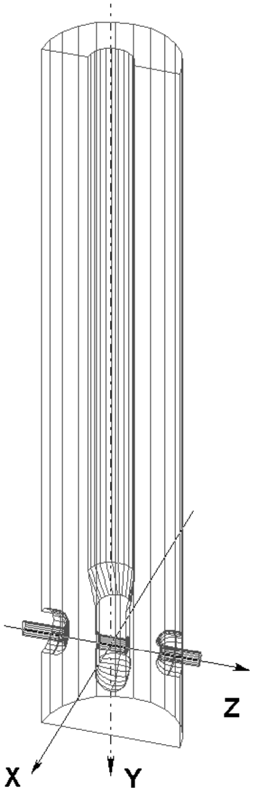


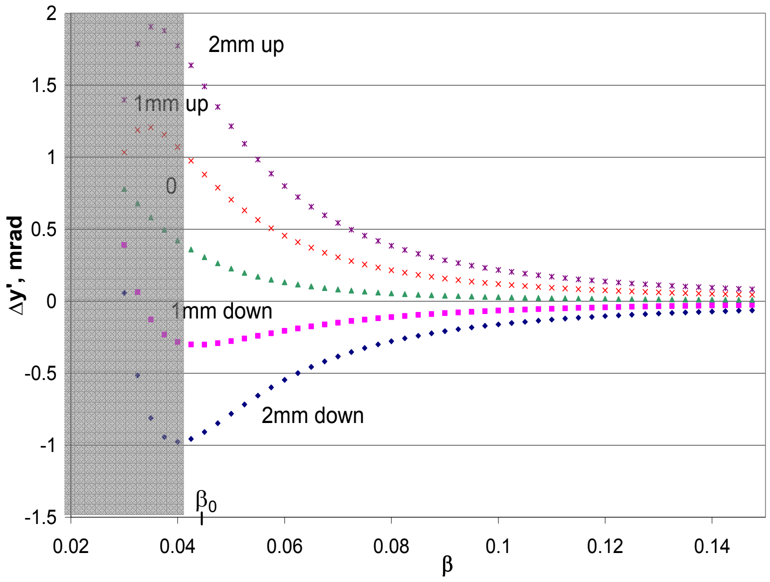
- E_y is symmetric: it cancels in the 2 gap
- B_x is antisymmetric: it adds in the 2 gap
- E_y and $B_x$are 90° out of phase
- B is generally dominant

QWR steering compensation: axis displacement

$$\Delta y' = \frac{\Delta U}{\gamma m c^2 \beta} tg\varphi \left(\frac{\cos\left(\frac{\pi d_y}{\beta\lambda}\right)}{\beta \sin\left(\frac{\pi d}{\beta\lambda}\right)} K_{EY}(y) - c K_{BX}(y) \right)$$

QWR steering on axis analytical formulation

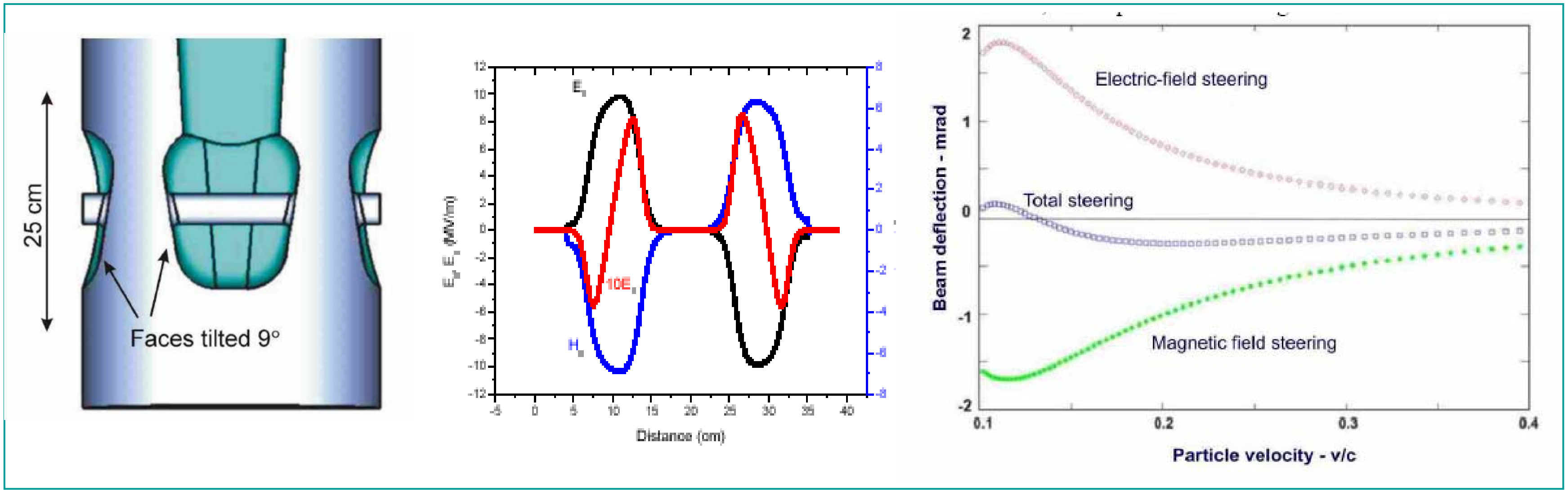




Steering compensation by displacement from the beam axis in 80 MHz QWRs

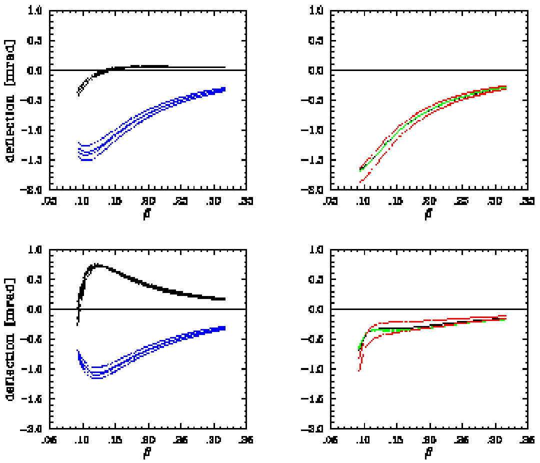
- The QWR steering is similar to the rf defocusing effect in misaligned cavities
- In many low-β resonators, a slight displacement of the beam aperture axis can remove most of the steering

QWR steering compensation by gap shaping



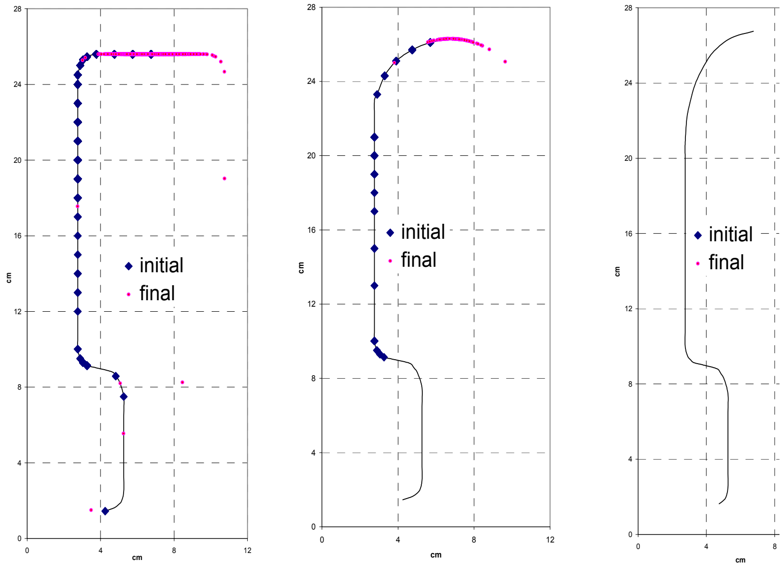
The magnetic steering can be compensated by an artificial enhancement of the electric deflection

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



Multipacting simulations

- cavity design with no stable MP trajectories, or with impact energy out of the $\delta>1$ region



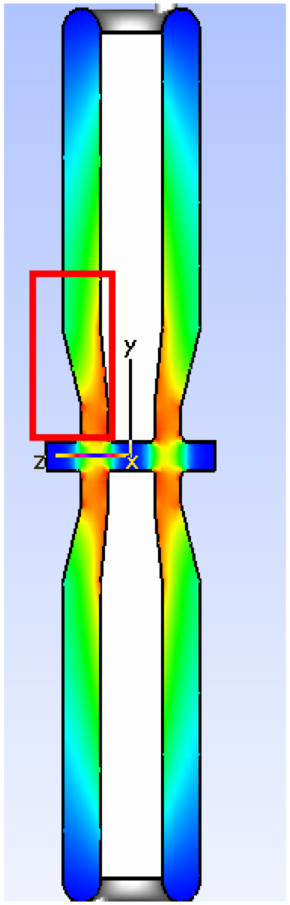
Example of simulation:

- code TWTRAJ (courtesy of R.Parodi, INFN Genova)
- ~60000 Runs
- 0.005 MV/m steps in Ea
- 5 mm steps in e- starting position

Results:

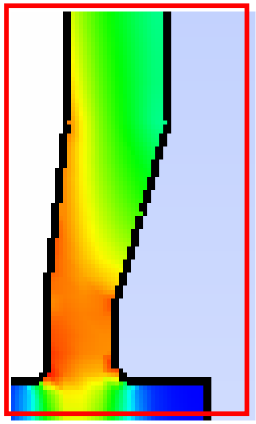
- MP negligible near the gap
- All levels at the equator: the equator profile is critical
- **Ellipsoidal shape 1.5:1 free of MP**

Example: redesigned HWR for MP removal

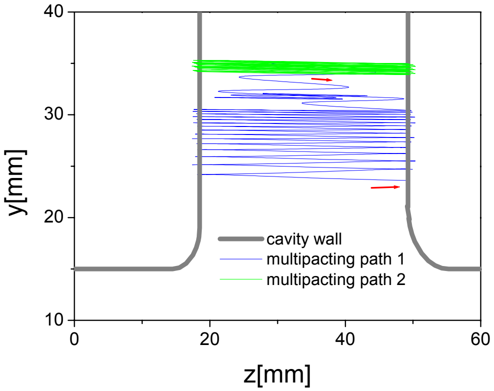


Courtesy of ACCEL

cavity now:

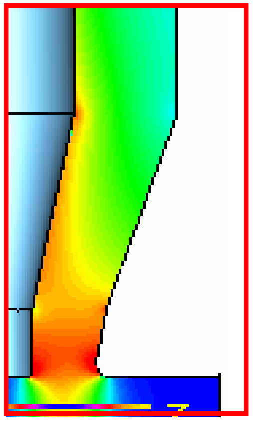


multipacting at E_{peak}=0.1MV/m



redesign A:

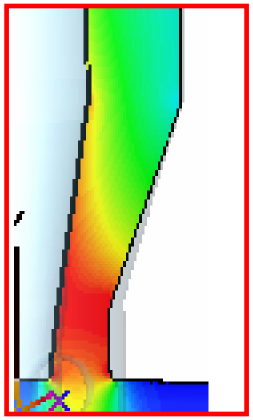
outer wall inclined



no multipacting

redesign B:

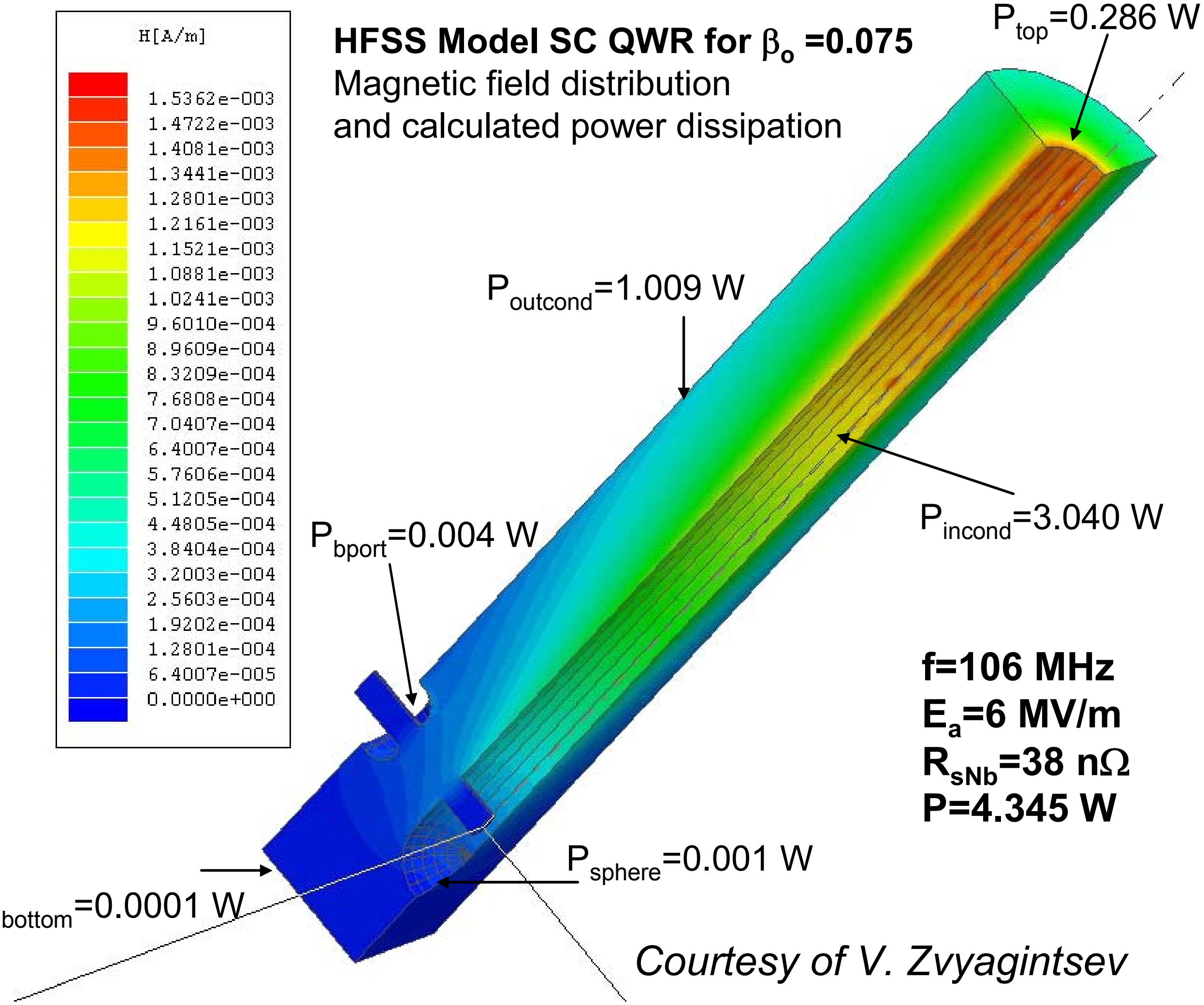
inner wall inclined



no multipacting

EM design: Rf losses calculations

- Maximum allowed power density for cooling reasons: ~1 *W/cm²* at 4.2K
- Large safety margin required: local defects can increase power losses significantly
- high power density must be avoided



HFSS Model SC QWR for β_o =0.075
Magnetic field distribution
and calculated power dissipation

P_{top}=0.286 W

$P_{outcond}$=1.009 W

P_{incond}=3.040 W

P_{bport}=0.004 W

P_{sphere}=0.001 W

P_{bottom}=0.0001 W

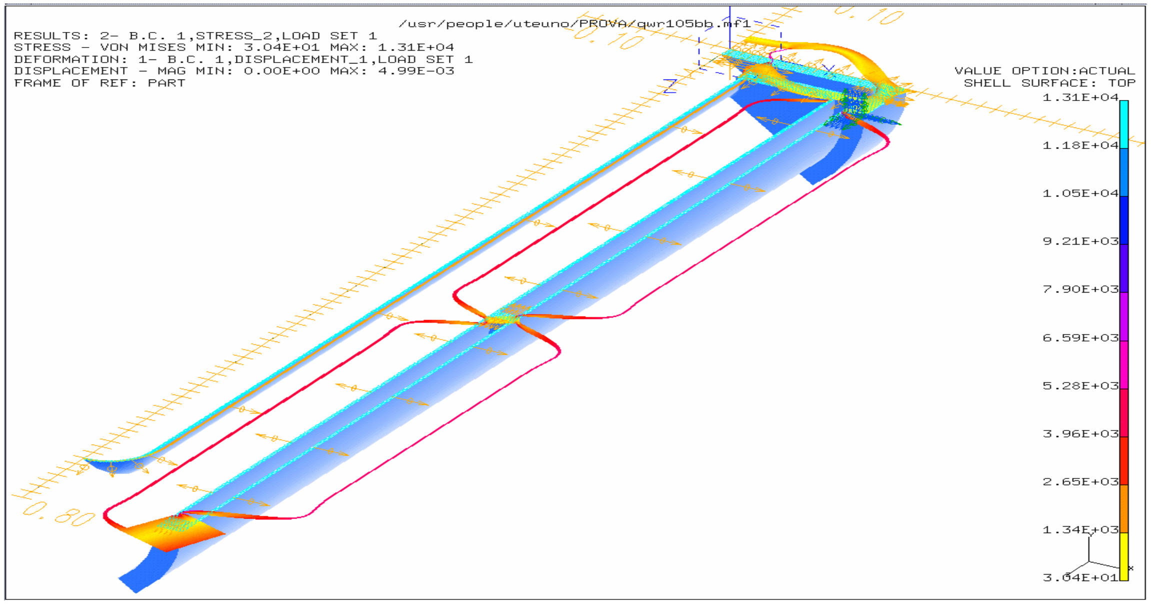
f=106 MHz
E_a=6 MV/m
R_{sNb}=38 nΩ
P=4.345 W

Courtesy of V. Zvyagintsev

Mechanical design

Mechanical design:

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



```
/usr/people/uteuno/PROVA/qwr105bb.mf1
RESULTS: 2- B.C. 1,STRESS_2,LOAD SET 1
STRESS - VON MISES MIN: 3.04E+01 MAX: 1.31E+04
DEFORMATION: 1- B.C. 1,DISPLACEMENT_1,LOAD SET 1
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 4.99E-03
FRAME OF REF: PART
```

Niobium properties: note on the RRR choice

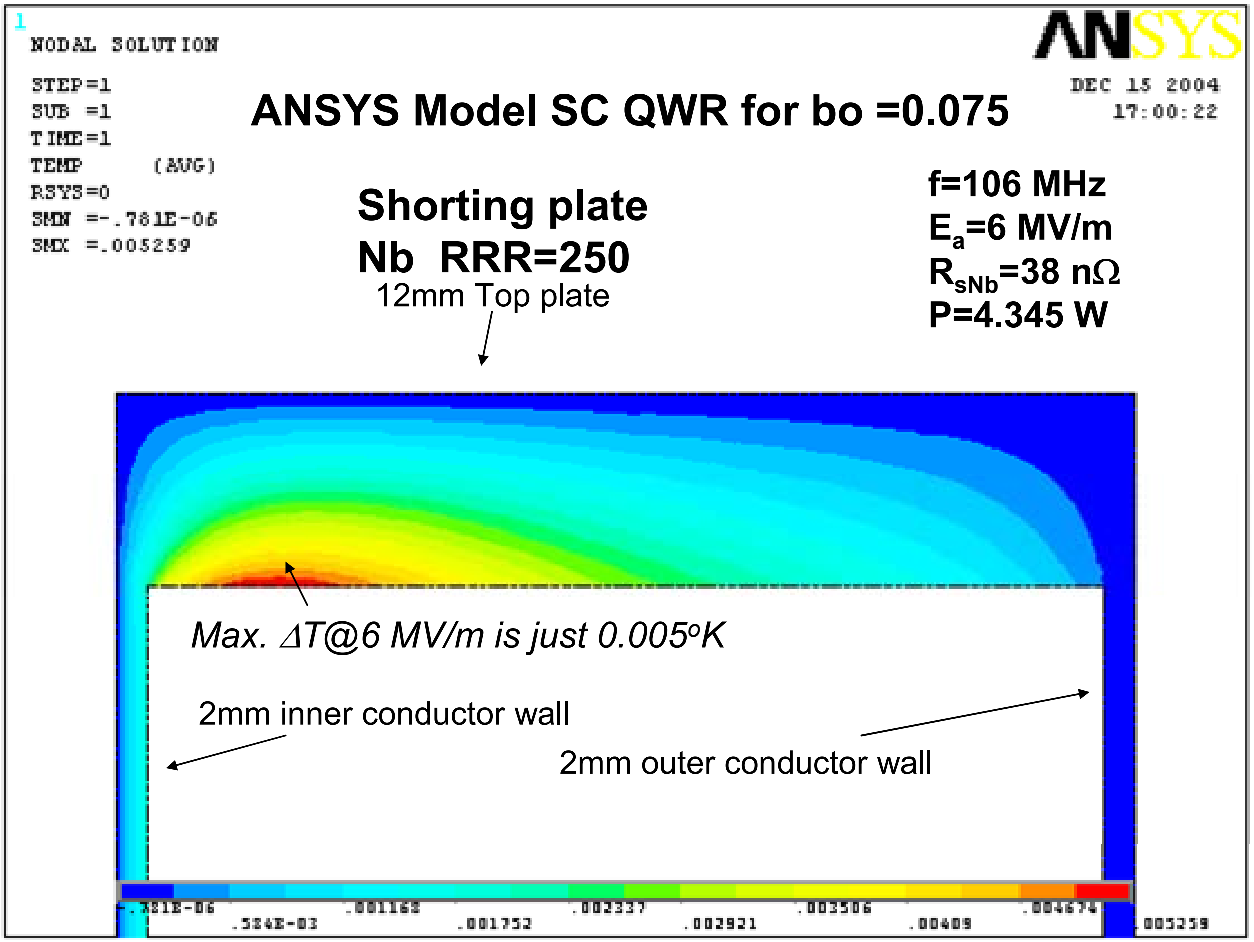
- Thermal conductivity at 4.2 K:

$$\kappa = RRR/4 \quad (W/m)/K$$

- high RRR required, which have poorer mechanical properties compared to normal grade Nb (RRR~40) and higher cost
- typical good choice for rf cavities: RRR~200÷300

Temperature distributions

- Maximum allowed power density on the cooled surface: ~1 W/cm^2 at 4.2K
- Provide good ways for liquid He transport and for gas He removal



ANSYS Model SC QWR for bo =0.075

Shorting plate
Nb RRR=250
12mm Top plate

f=106 MHz
E_a=6 MV/m
R_{sNb}=38 nΩ
P=4.345 W

Max. ΔT@6 MV/m is just 0.005°K

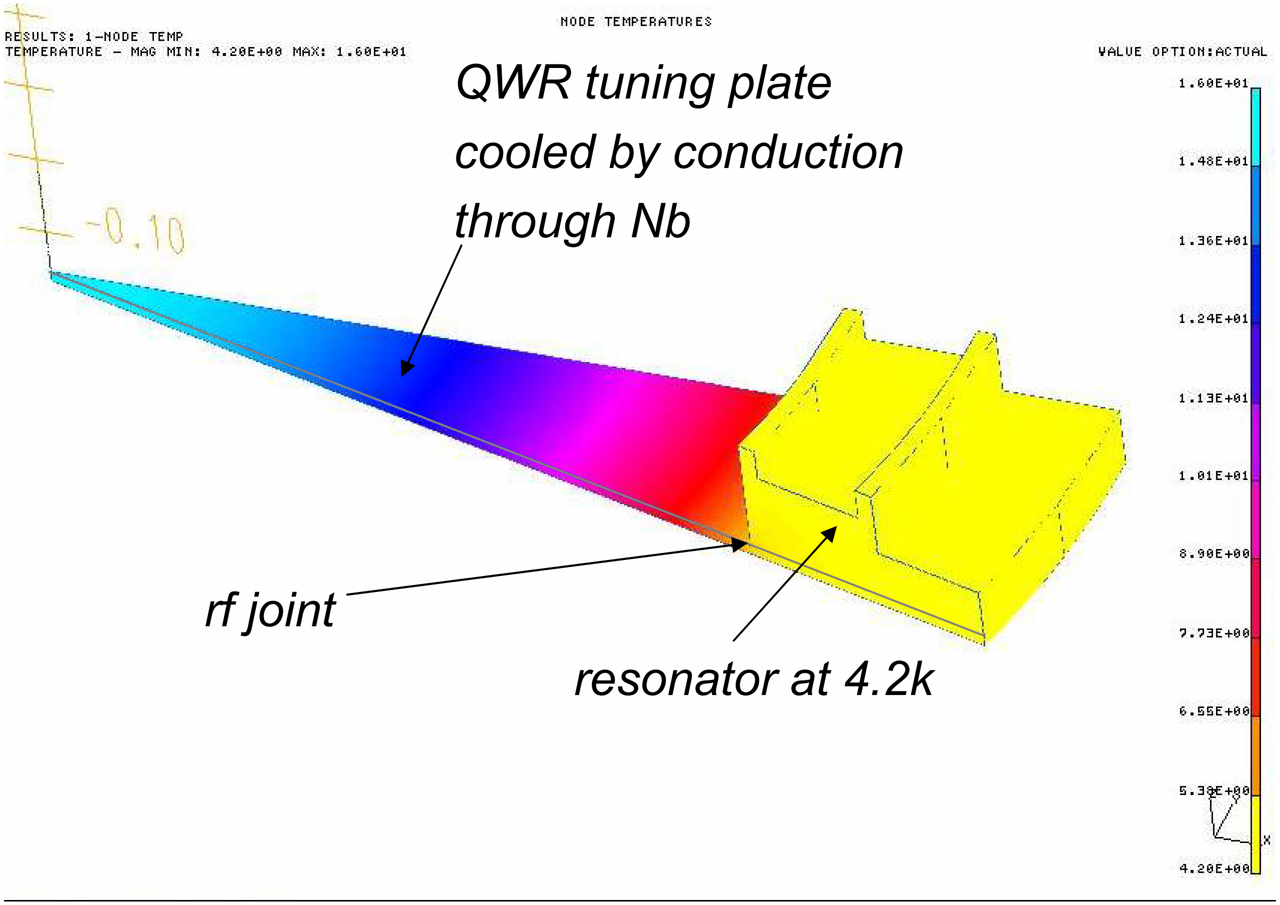
2mm inner conductor wall

2mm outer conductor wall

Courtesy of V. Zvyagintsev

Temperature distributions

- Low-power density surfaces (e.g. tutning plates) can be cooled by thermal conduction through an rf joint
- Don’t exceed a few mT magnetic field on rf joints
- Check the effect of a possible super- to normal-conducting transition in such regions: sometimes it is not critical



QWR tuning plate cooled by conduction through Nb

rf joint

resonator at 4.2k

Courtesy of V. Zvyagintsev

Mechanical tuners

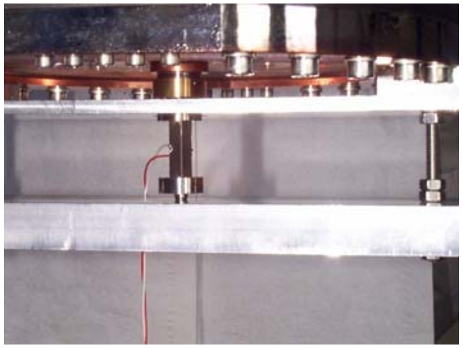
wall displacement toward: $\begin{cases} \text{high } \boldsymbol{E} & \rightarrow \quad f \textbf{ down} \\ \text{high } \boldsymbol{B} & \rightarrow \quad f \textbf{ up} \end{cases}$

Slow- For center frequency tuning and helium pressure compensation

TRIUMF Mechanical tuner

ANL superconducting bellows tuner

Slow and Fast



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

Detuning from mechanical instabilities

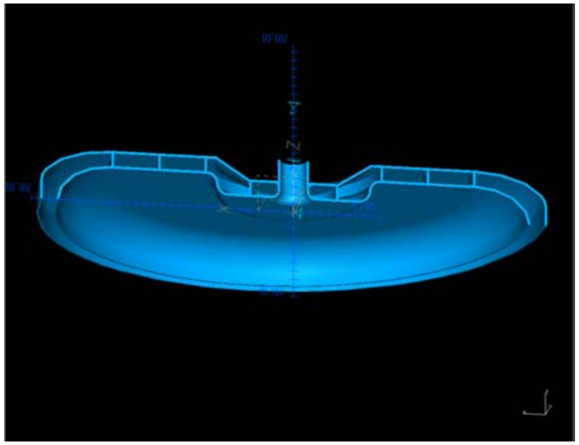
Source:	***Solution:***
Helium pressure variations	mechanical tuning in feedback, mechanical strengthening
Lorentz Force detuning	slow tuning and rf feedback
microphonics	fast tuners, mechanical design, noise shielding, etc.
resonant vibrations	mechanical damping

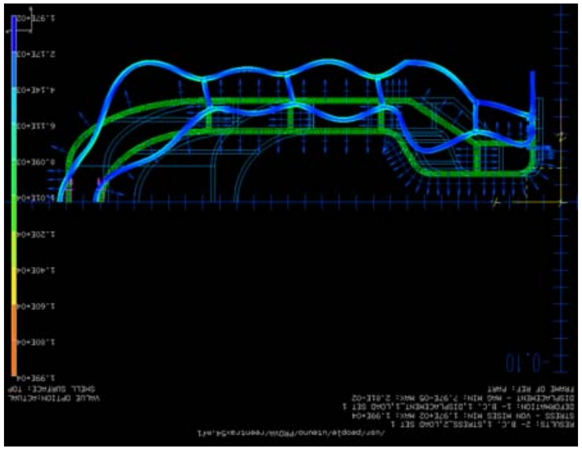
Slow detuning: He pressure fluctuations

$$df\mathrm{R}\ dP$$

- Example:
  - 80 MHz Nb cavity: df/dP ~ 1 Hz/mbar
  - cryosystem: up to 100 mbar/minute observed
- “Natural” solutions
  - Design your resonator strong and your cryosystem stable in pressure
  - use the **mechanical tuner in a feedback loop**
- “Clever” solution:
  - **design a “self-compensating” resonator**

Mechanical reinforcement: double wall





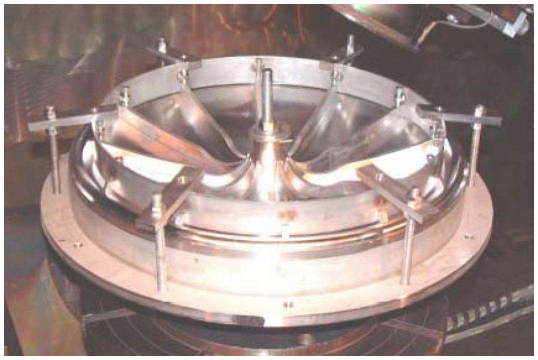
The double wall structure allows to null the net force of the He pressure

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

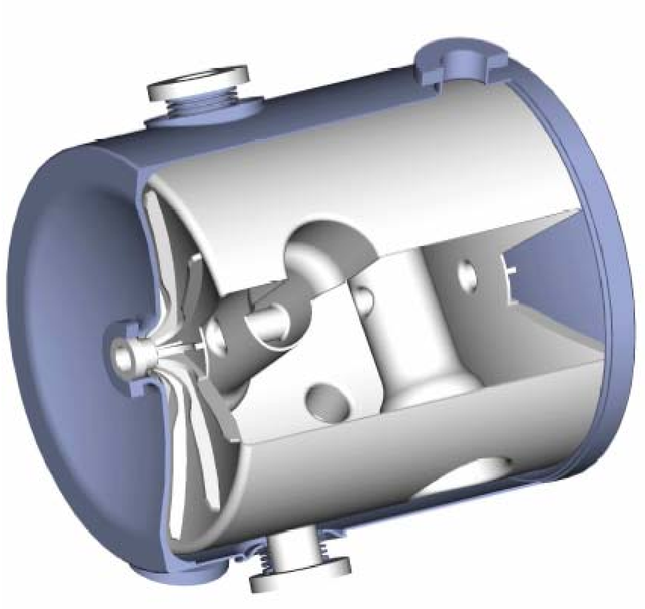
a careful design can minimize df/dP

Self-compensating design

Since it is impossible to eliminate completely deformations caused by He pressure fluctuation, the resonator can be designed in order to produce displacements with opposite effects to the frequency, to obtain a balance.

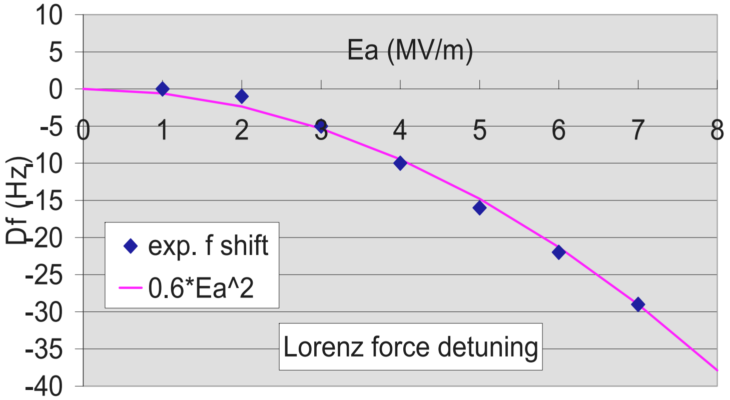


ANL 3-Spoke resonator end-plate with self-compensating design for minimum df/dP

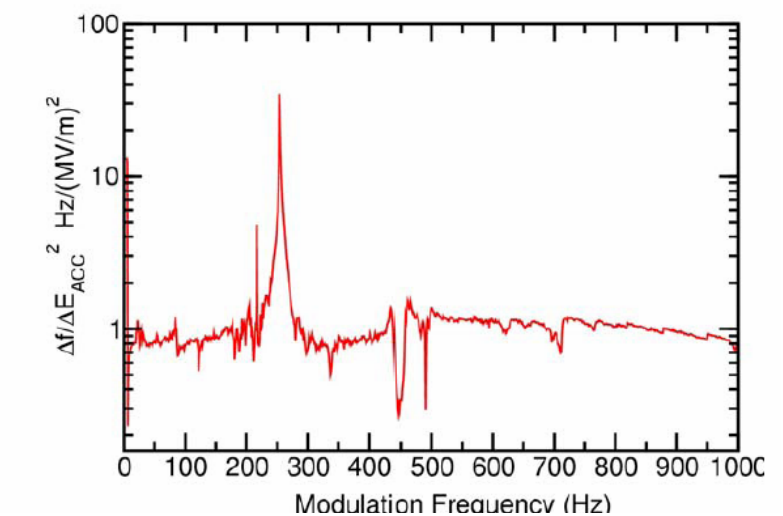


Lorentz Force detuning

Effect of radiation pressure



Lorenz Force detuning measured in a 80 MHz QWR



The amplitude of the Lorentz force transfer function in a 109 MHz. QWR. Amplitude modulations at the peak frequency can excite a mechanical mode

Lorentz force gives a quadratic detuning with field

$$df\, R\, -d(E_a^2)$$

- *solution: strong mechanical structure, tuning*

Resonant vibrations: mechanical modes

- Most dangerous: a small vibration can cause large deformation → large detuning that can exceed the resonator rf bandwidth
- 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**
2. Make the detuning range narrower
    - **careful design**
    - **mechanical damper**

Example: stem vibration in a QWR

Mechanical modes:

~50÷60 Hz most critical

<150 Hz dangerous

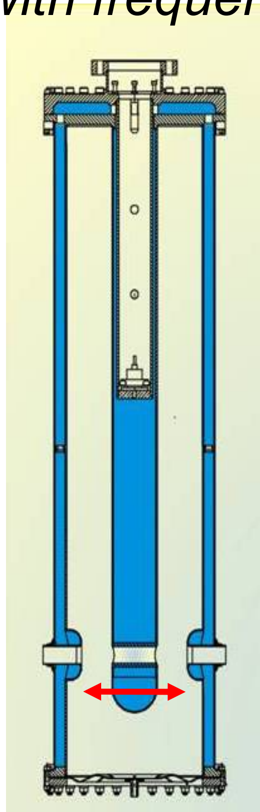
criticity decreasing with frequency

Lowest mode frequency of a 106.08 MHz Nb QWR:

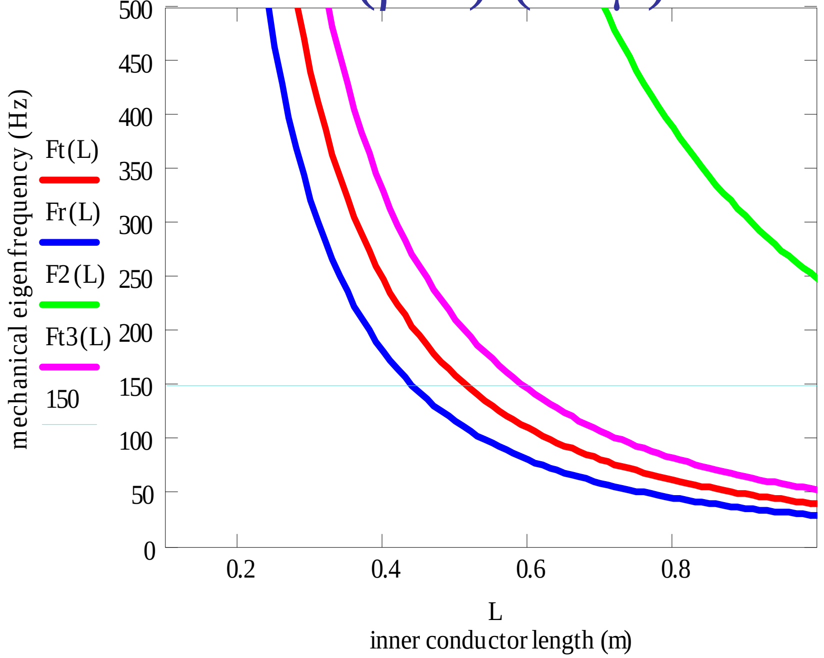
Simulation: 81 Hz

Analytical: 83 Hz

Measured: 78



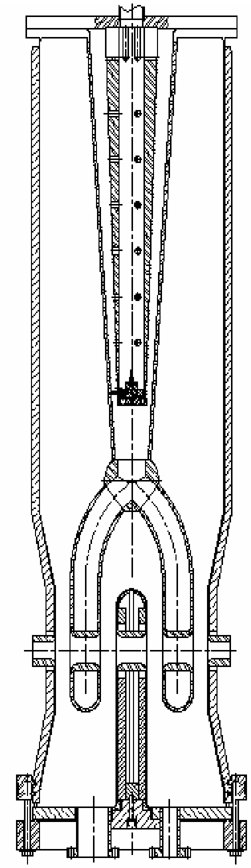
$$\omega=(\beta/L)^2(EI/\mu)^{1/2}$$



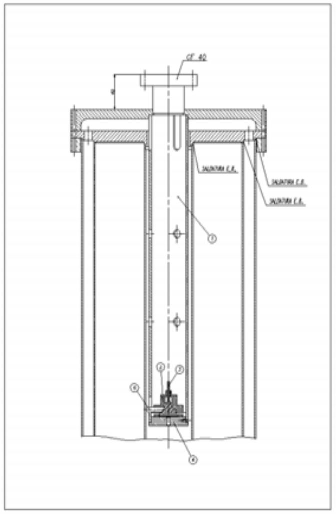
Mechanical frequency vs inner conductor length in LNL type QWR’s (analytical results).
red: 2mm Nb tube; blue: full Cu rod;
Green: 2nd mode. Mag: 80 mm dia tube

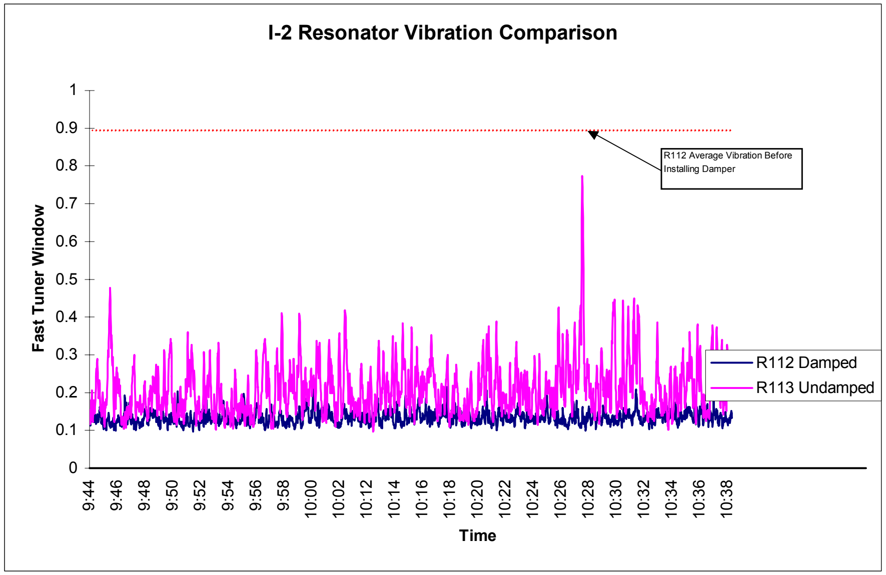
Mechanical vibration dampers

4-gap, 48 MHz QWR with vibration damper



80 MHz QWRs with vibration damper





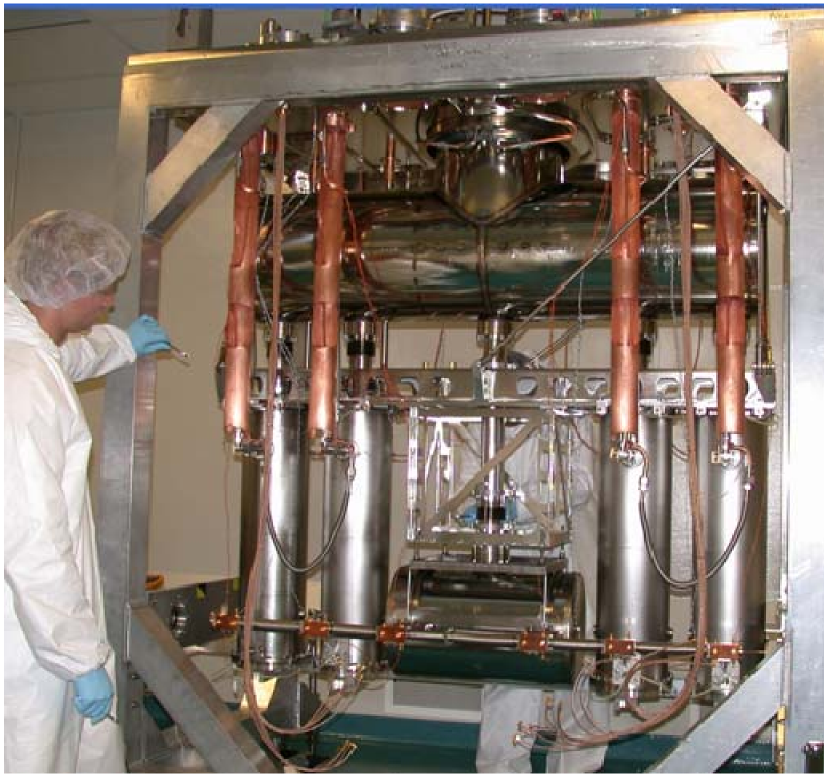
Approx. ×10 attenuation of the vibration amplitude

Vibration dampers are cheap and effective

Cavity integration in cryostats

Design objectives:

- easy installation and maintenance
- stable and reliable operation



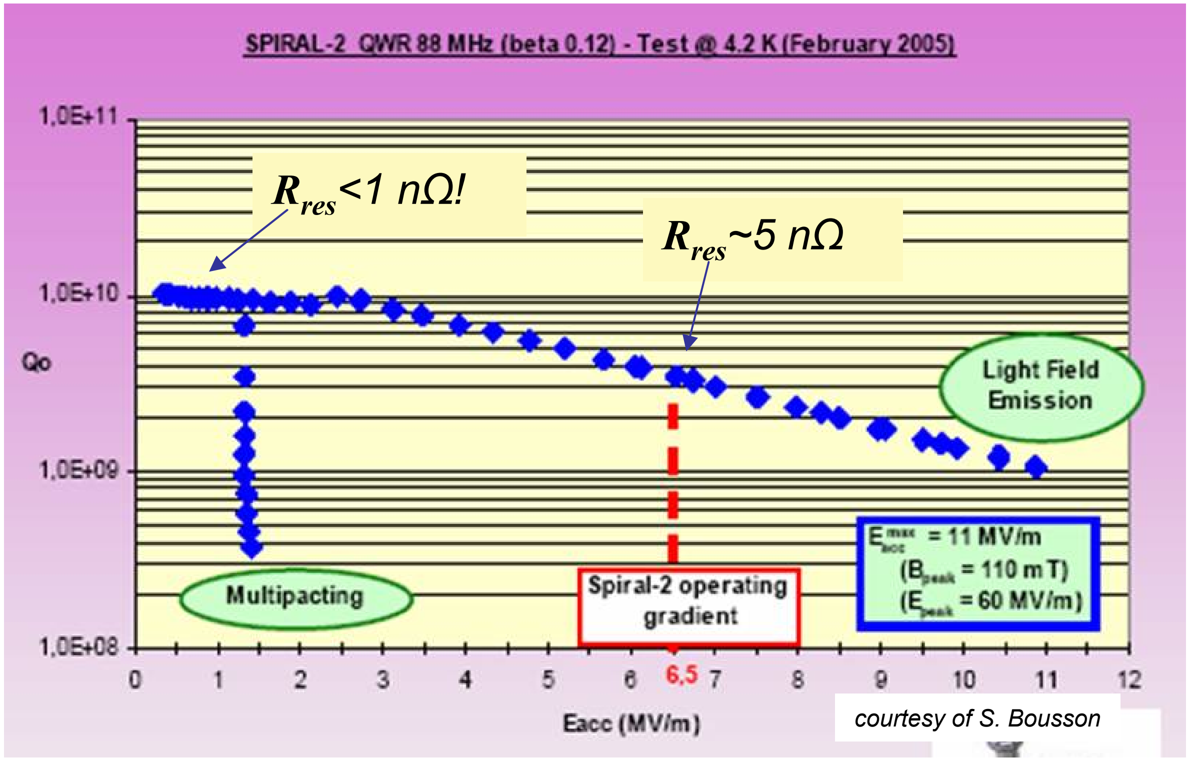
Common vacuum cryostat (TRIUMF)

Common or separate vacuum?

- *In many low-β cryostats the vacuum inside and outside the resonators is not separated*
- *In spite of that, very high Q can be maintained for years in on-line resonators*
- *Q degradation seems to happen only when the cryostat is vented from outside the resonators*
- ***Provide clean venting!***
- *most specialists are anyhow in favour of separate vacuum, considering it safer*

Low-β resonators performance

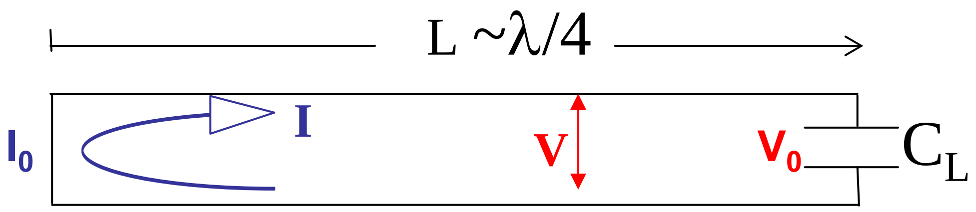
- **achieved >60 MV/m and >120 mT peak fields, and <1 nΩ residual resistance at 4.2K**
- Even if geometries are not favorable for surface preparation (numerous welds, small apertures, etc), the maximum ***E*****,*****B*** fields are not far from the ones of β=1 cavities
- The recent application to low-β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

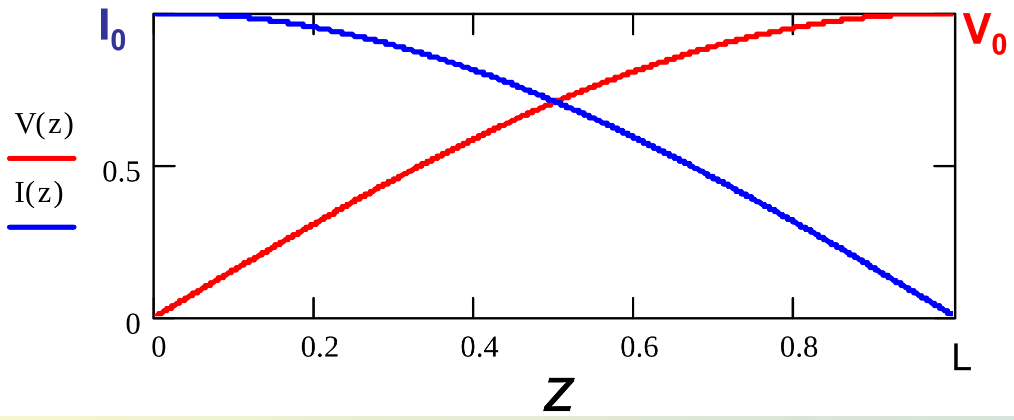


courtesy of S. Bousson

4. Low-β cavity types and characteristics

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





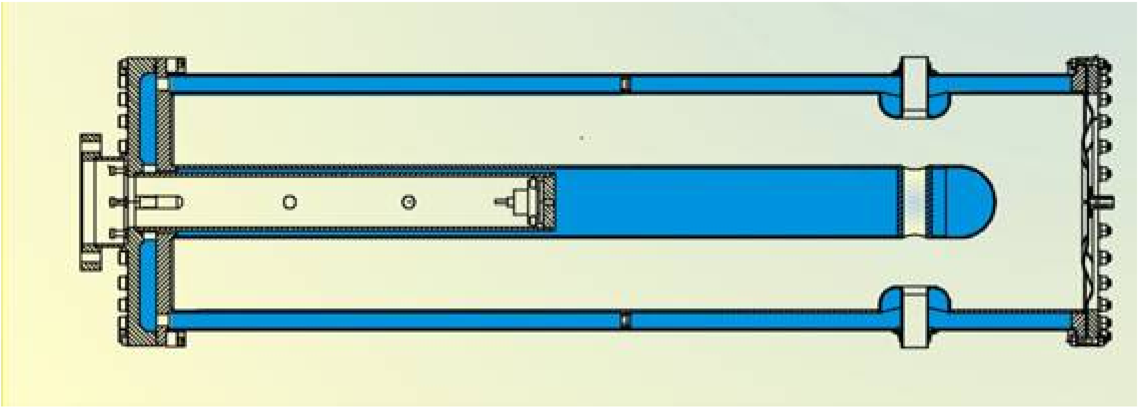
$Z_0 = V_0/I_0$ characteristic impedance

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

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

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

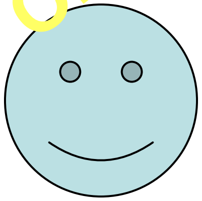
$I \sim I_0 \cos(\omega z/c)\cos(\omega t)$



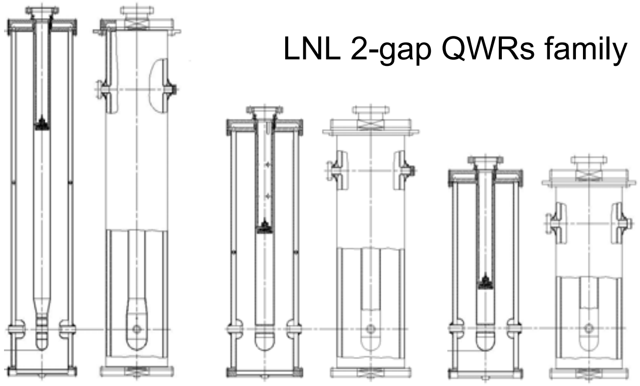
Quarter-Wave resonators

OPERATING

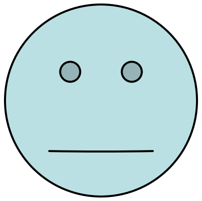
$48 \le f \le 160$ MHz, $0.001 \le \beta_0 \le 0.2$



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

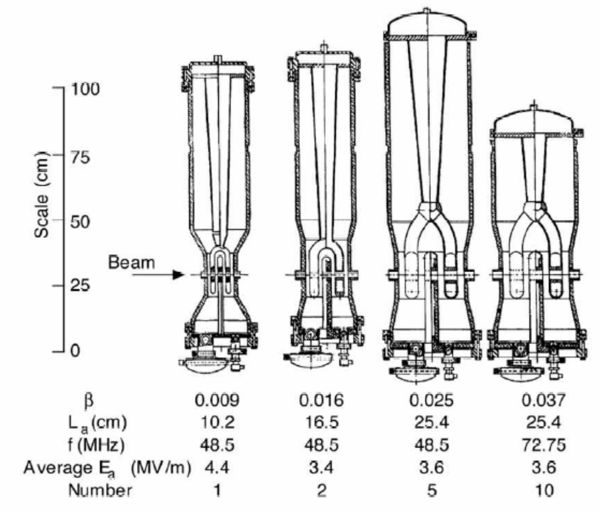


LNL 2-gap QWRs family



- Dipole steering above ~100 MHz
- Mechanical stability below ~100 MHz
- (Quadrupole steering)

Very successful



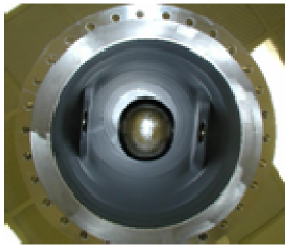
β	0.009	0.016	0.025	0.037
L_a (cm)	10.2	16.5	25.4	25.4
f (MHz)	48.5	48.5	48.5	72.75
Average E_a (MV/m)	4.4	3.4	3.6	3.6
Number	1	2	5	10

ANL 4-gap QWR family

Some of the QWR worldwide

TRIUMF

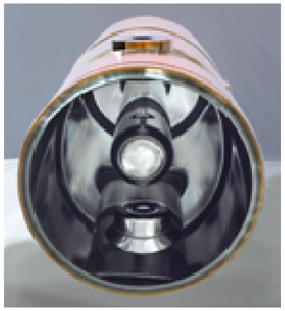
INFN LNL-MSU



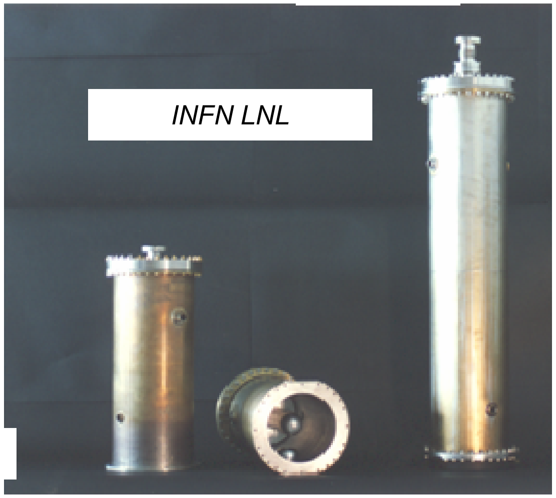
MSU

New Dehli

ANL

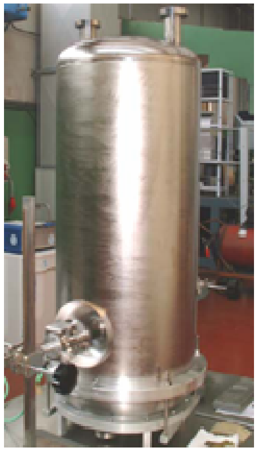


INFN LNL (sputtered)



INFN LNL

Saclay



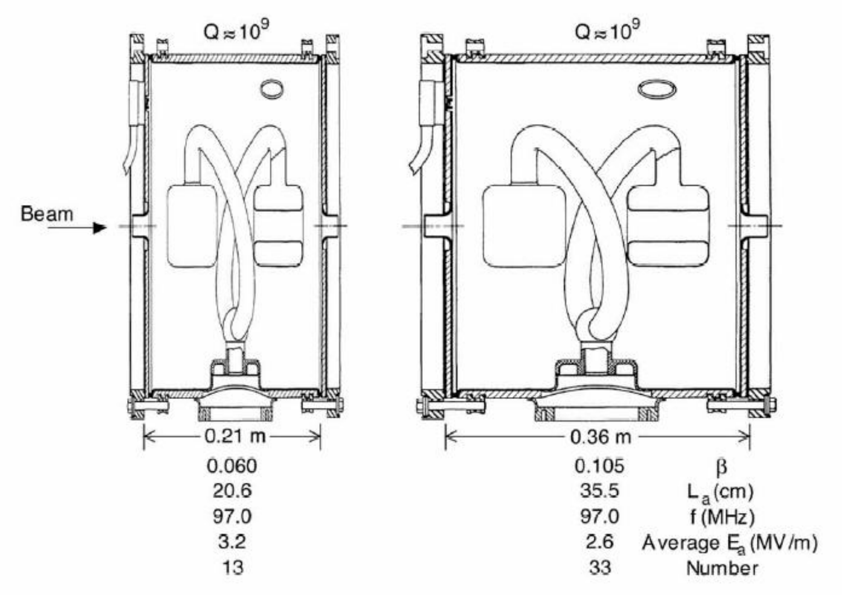
IPNO

Split-ring resonators

OPERATING

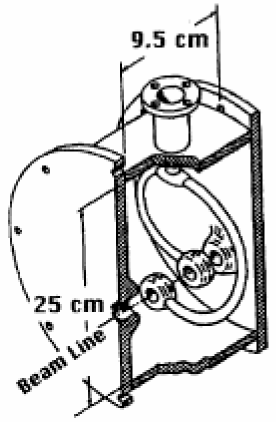
$90 \leq f \leq 150$ MHz, $0.05 \leq \beta_0 \leq 0.15$

- **relatively large energy gain**
- good efficiency



0.21 m	0.36 m	
0.060	0.105	β
20.6	35.5	L_a (cm)
97.0	97.0	f (MHz)
3.2	2.6	Average E_a (MV/m)
13	33	Number

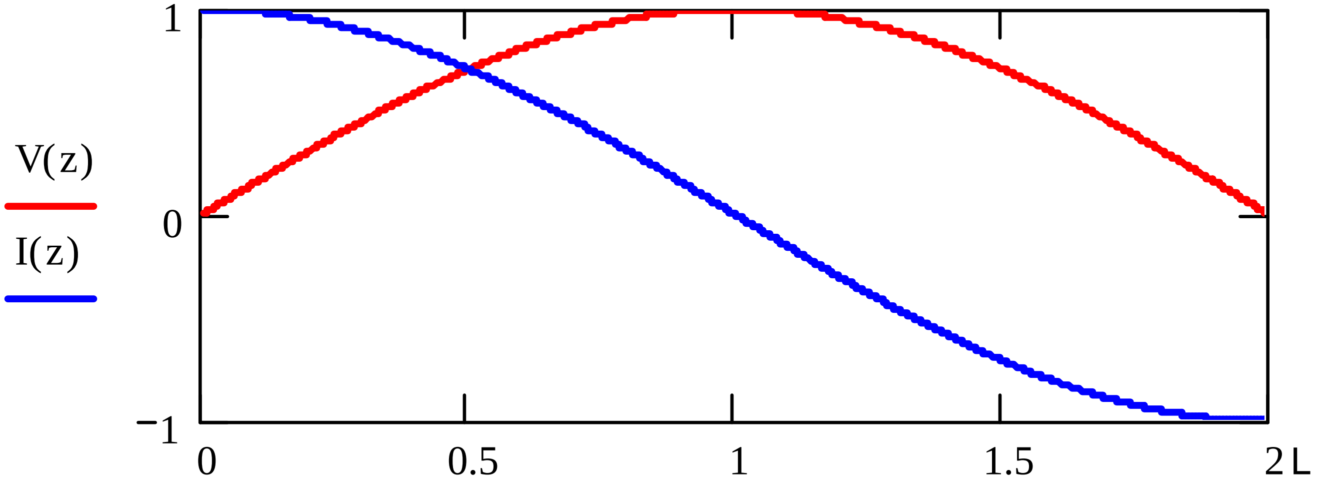
- **mechanical stability**
- beam steering
- **high peak fields**
- more expensive and difficult to build than QWRs

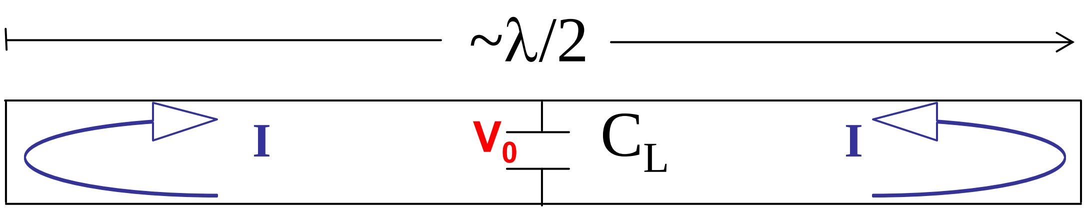


In use for many years

but not developed anymore

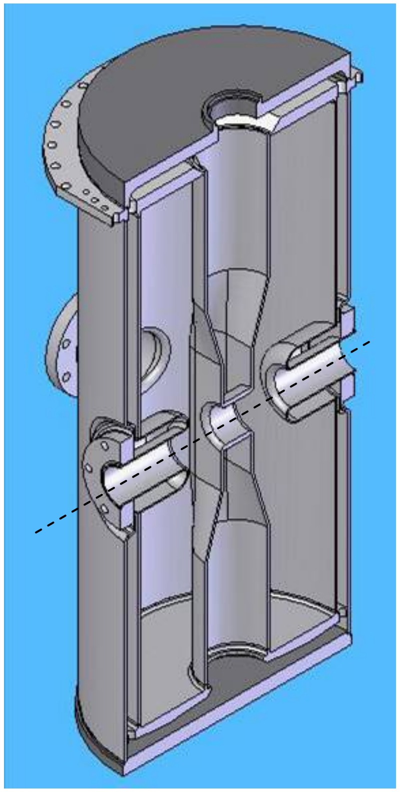
Half-wave structures





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

$$\boxed{P(\lambda/2) \sim 2 P(\lambda/4)}$$

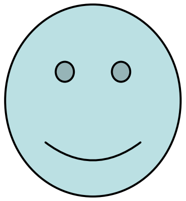


- A half-wave resonator is equivalent to 2 QWRs facing each other
- The same accelerating voltage is obtained with about 2 times larger power

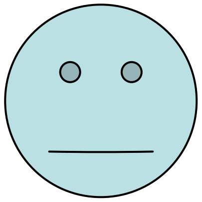
Half-Wave resonators

TESTED

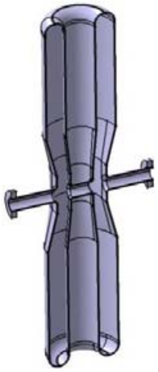
$160 \leq f \leq 352$ MHz, $0.09 \leq \beta_0 \leq 0.3$



- **No dipole steering**
- High performance
- Lower E_p than QWRs
- Wide beta range
- Very compact

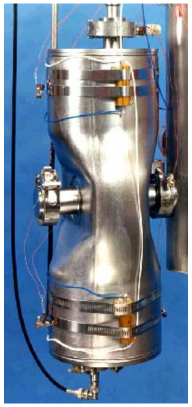


- Not easy access
- Difficult to tune
- **Less efficient than QWRs**
- (Quadrupole steering)



best use around 200 MHz

MSU 322 MHz $\beta=0.28$



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

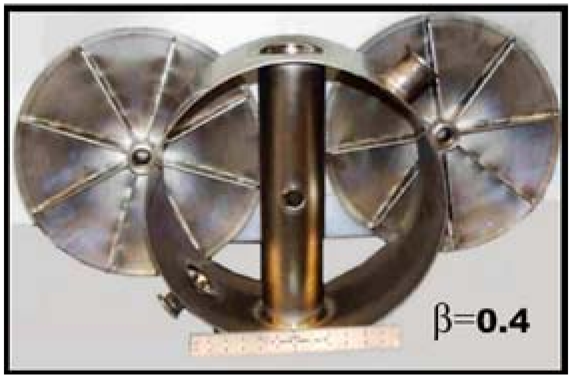
ACCEL 176 MHz SC HWR $\beta=0.09$

Single-SPOKE resonators

TESTED

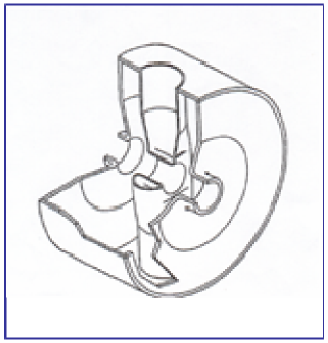
345≤f≤805 MHz, 0.15 ≤ β_0≤ 0.62

- No dipole steering
- High performance
- **Higher R_{sh} than HWRs**
- Wide beta range



LANL β=0.2
SPOKE

- Not easy access (but better than HWRs)
- Difficult to tune
- Larger size than HWRs
- More expensive than HWRs
- (Quadrupole steering)



IPNO SPOKE, β=0.35
352 MHz

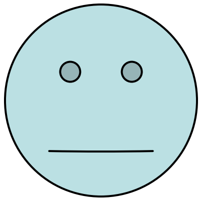
the preferred choice at 350 MHz

Ladder SC cavities

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

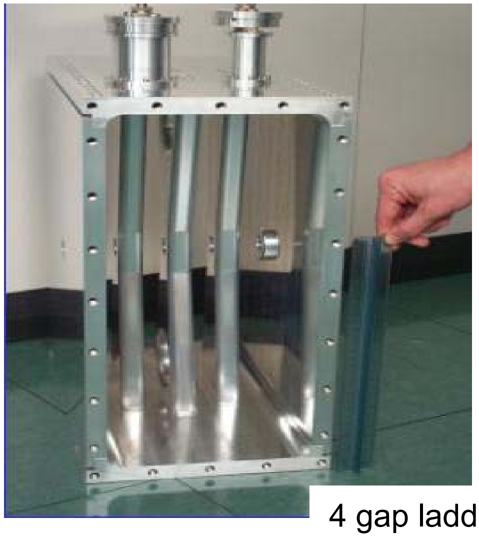
UNDER DEVELOPMENT

- Efficient
- large energy gain
- They can be made for rather low β

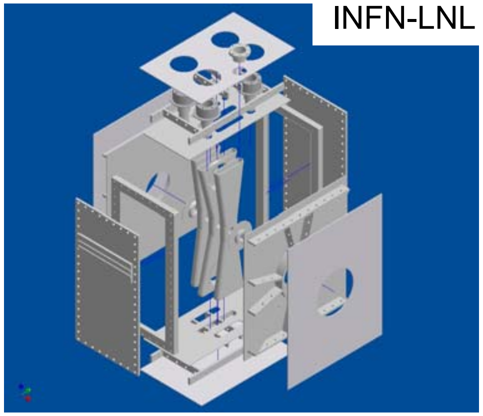


- β acceptance
- small aperture
- not easy to build
- not yet tested
- multipacting?

promising after RFQs



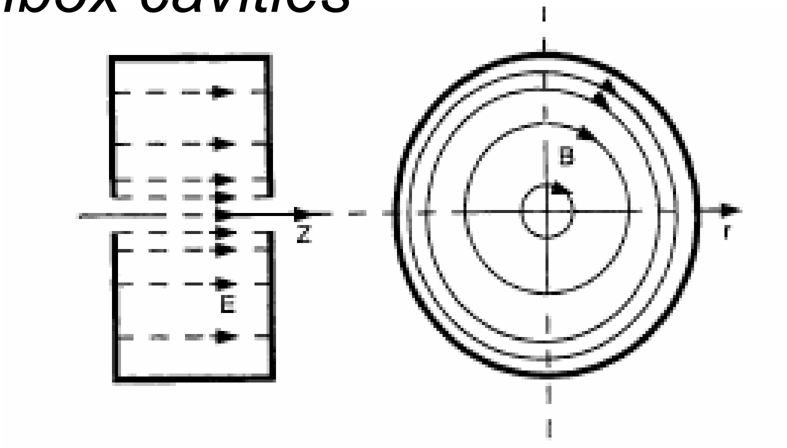
4 gap ladder
352 MHz, β=0.12
INFN-LNL

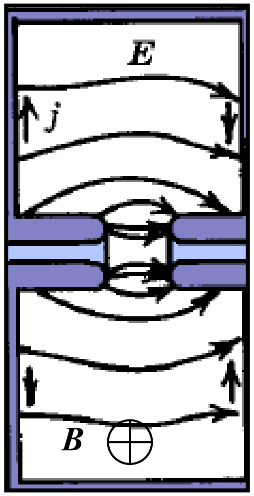


TM mode cavities

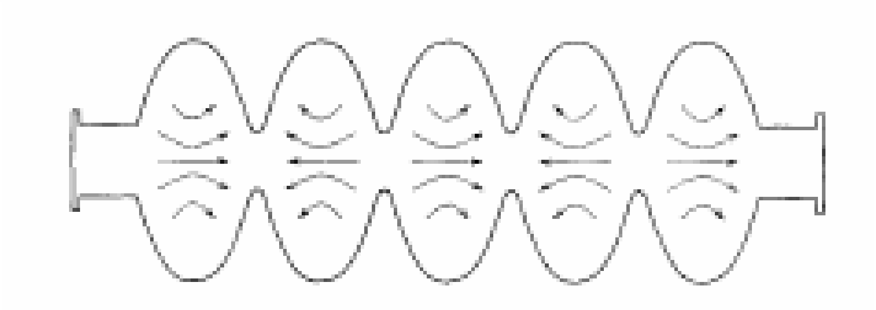
- TM_{010} (Transverse Magnetic) mode
- ***B*** always perpendicular to the EM wave propagation axis (and to the beam axis)

pillbox cavities





nose cavities

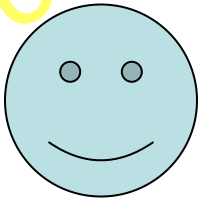


elliptical cavities

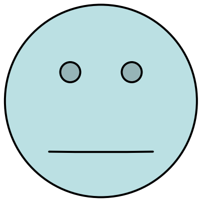
Elliptical resonators

OPERATING

$352 \leq f \leq 805$ MHz, $0.47 \leq \beta_0 \leq 1$



- **Highly symmetric field**
- High performance
- Low E_p and B_p
- Multi cell possibility
- **Large aperture**



- Not suitable for $\beta<0.4$
- Mechanical modes

Very successful

INFN Milano 700 MHz, $\beta=0.5$

CERN
352 MHz
$\beta=0.8$
Nb on Cu

SNS

$\beta=0.81$

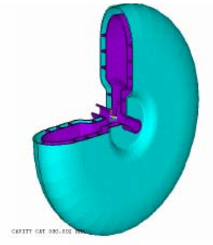
$\beta=0.61$

Reentrant cavities

TESTED

$352 \le f \le 402$ MHz, $0.1 \le \beta$

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



The first reentrant cavities - SLAC

- short accelerating length, little E gain
- single gap only
- mechanical stability
- inductive couplers only

for special applications

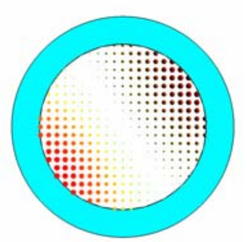
LNL 352 MHz
reentrant cavity

IH and CH multi-gap structures

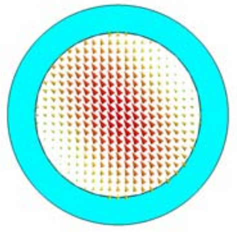
IH-RFQ

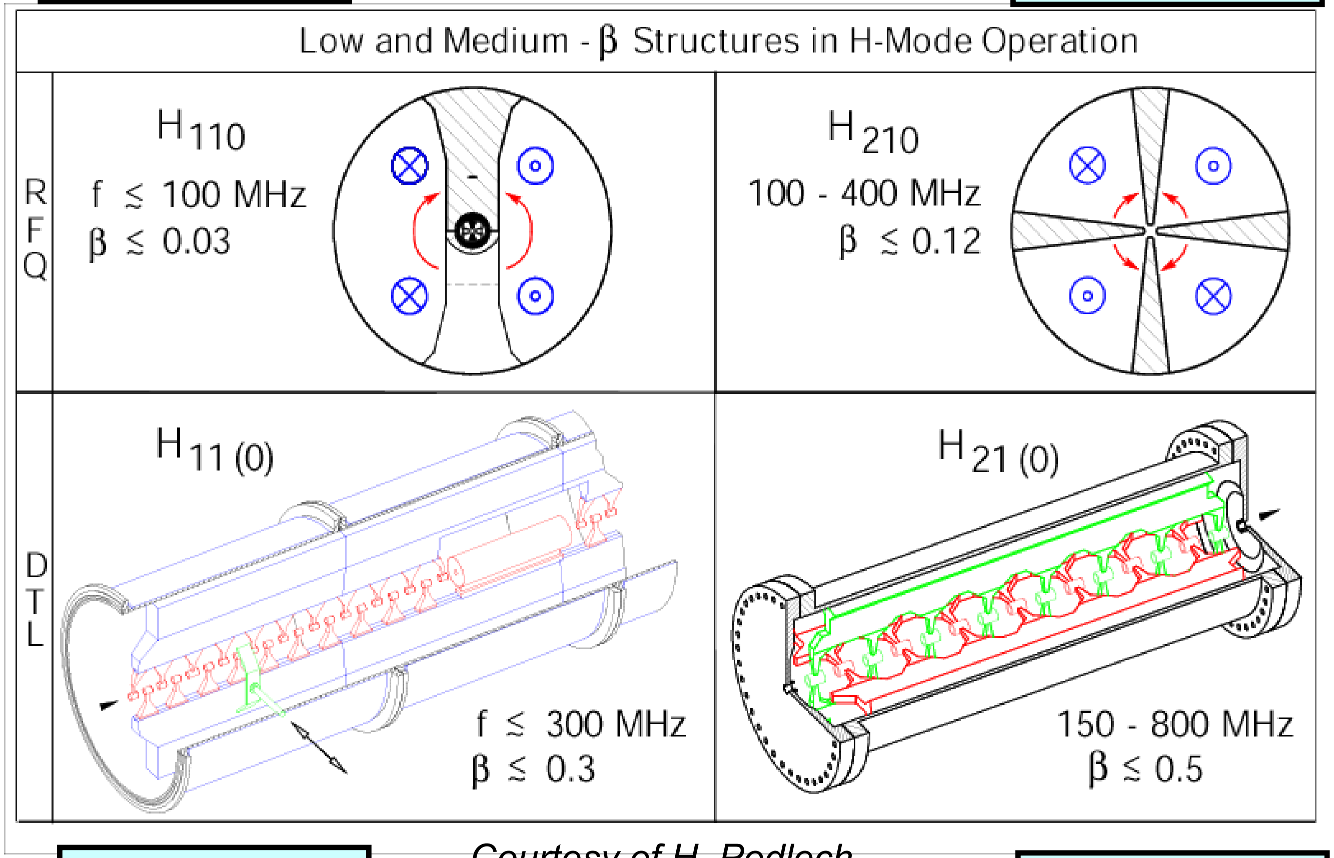
4-vane RFQ

B-Field



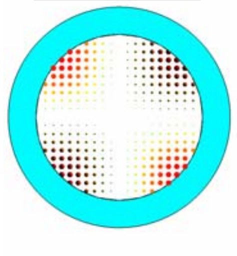
E-Field



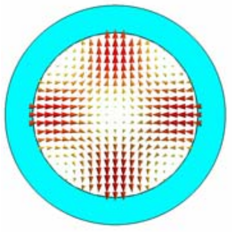


Courtesy of H. Podlech

B-Field



E-Field



IH-Structure

CH-Structure

Superconducting RFQ's

OPERATING

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

☺

- Compact
- CW operation
- High efficiency
- Down to very low beta
- large acceptance

😐

- Mechanical stability
- Not easy to build
- MP and FE
- Cost

LNL SRFQ2, A/q=8.5

technologically challenging

Multi-SPOKE resonators

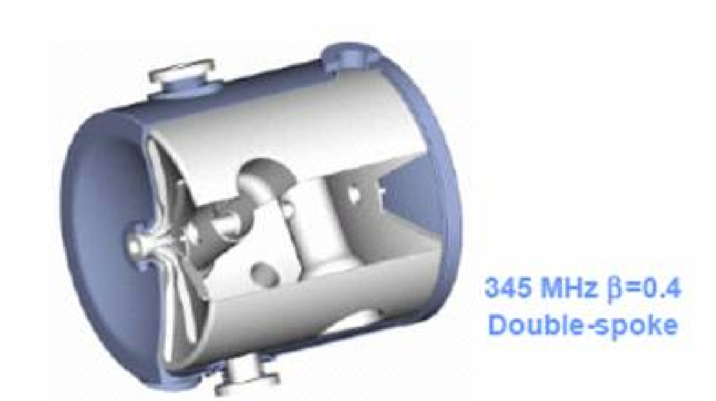
TESTED

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

ANL β=0.4
Double SPOKE

🙂

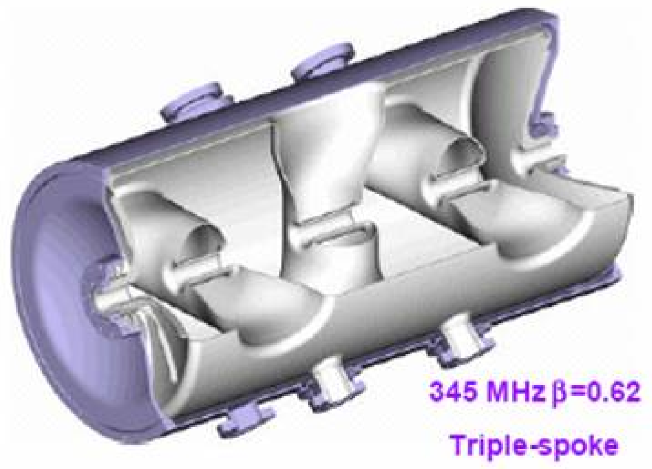
- **High performance**
- **High efficiency**
- **Large energy gain**
- Lower frequency than elliptical
- Mechanically more stable than elliptical



345 MHz β=0.4
Double-spoke

😐

- Large size
- Not easy access
- Difficult to tune
- smaller aperture than elliptical
- More expensive than elliptical



345 MHz β=0.62
Triple-spoke

very promising, esp. for β~0.5

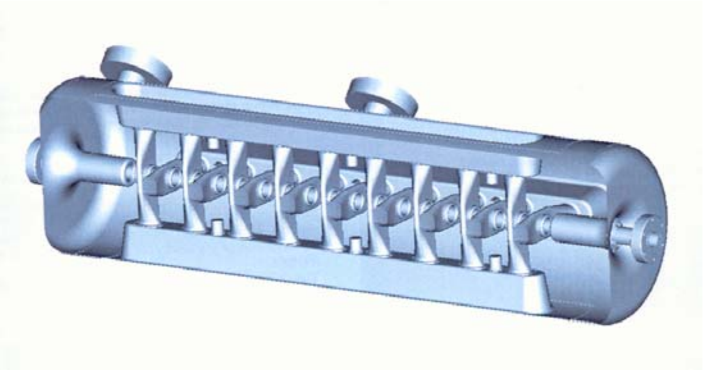
CH multi-gap SC cavities

$174 \le f \le 800$ MHz, $0.1 \le \beta_0 \le 0.3$

UNDER DEVELOPMENT

🙂

- Very efficient
- large energy gain
- They can be made for rather low β



19 gap CH, β=0.1
352 MHz, IAP Frankfurt

😐

- β acceptance
- Difficult to have large aperture
- not easy to build
- cost

β=0.2
784 MHz
IKF Juelich

Promising for fixed velocity profile

Conclusions

- Great interest at present in superconducting low-β resonators
- many applications, old and new
- high perfomance reached, not far from β=1 cavities one
- numerous projects, some funded
- large variety of resonators and new inventions coming
- still open problems: new ideas are welcome!