Low- and Intermediate-\(\beta\) Cavity Design

Tutorial introduction to superconducting resonators for acceleration of ion beams with \(\beta<1\).

A. Facco - INFN-LNL
What are low-\(\beta\) superconducting resonators?

low-\(\beta\) cavities: Just cavities that accelerate efficiently particles with \(\beta < 1\)...

low-\(\beta\) cavities are often further subdivided in low-, medium-, high- \(\beta\)

\(\beta=1\) SC resonators: “elliptical” shapes

\(\beta<1\) resonators, from very low (\(\beta \sim 0.03\)) to intermediate (\(\beta \sim 0.5\)): 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-$\beta$ 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
- $2\div 3$ gap: wide $\beta$ acceptance for different ion energies
- Cw operation

New problems: very narrow rf bandwidth, mechanical instabilities
Early resonators: 70’s

- $\beta \approx 0.1$
- 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-$\beta$ cavities for ion boosters developed in the 70’s
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
HI SC low-\(\beta\) resonators: 90’s

- \(\beta \approx 0.001\div0.2\)
- 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 \(\beta \approx 0.3\div0.6\) Spoke cavities starts
HI SC low-β resonators: present

- 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

SNS cryomodule (JLab)

2-gap spoke cavity and cryomodule (IPNO)

QWR, HWR and Spoke cavities (ANL)
### Low-\(\beta\) cavities: new applications

<table>
<thead>
<tr>
<th>Type</th>
<th>(\beta_{\text{max}})</th>
<th>A/q</th>
<th>current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-accelerators for RIB facilities</td>
<td>(~ 0.2) ((0.5))</td>
<td>7÷66</td>
<td>&lt; 1 nA</td>
</tr>
<tr>
<td>HI drivers for RIB facilities</td>
<td>~ 0.3÷0.9</td>
<td>~ 1 ÷ 10</td>
<td>~0.1÷10 mA</td>
</tr>
<tr>
<td>(p,d) linacs for radioisotope production</td>
<td>~ 0.3</td>
<td>1 ÷ 2</td>
<td>~1÷10 mA</td>
</tr>
<tr>
<td>High Power Proton Accelerators for neutron spallation sources</td>
<td>~ 0.9</td>
<td>1</td>
<td>~10÷100 mA pulsed</td>
</tr>
<tr>
<td>High Power Deuteron Accelerators for material irradiation</td>
<td>~ 0.3</td>
<td>2</td>
<td>&gt;100 mA cw</td>
</tr>
</tbody>
</table>
Low-\(\beta\) cavity definitions
**Important parameters in accelerating cavities**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
<th>Unit(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. accelerating field</td>
<td>$E_a = \frac{V_g T(\beta_0)}{L}$</td>
<td>MV/m</td>
</tr>
<tr>
<td>Stored energy</td>
<td>$U/E_a^2$</td>
<td>J/(MV/m)$^2$</td>
</tr>
<tr>
<td>Shunt impedance</td>
<td>$R_{sh} = E_a^2 L/P$</td>
<td>MΩ/m</td>
</tr>
<tr>
<td>Quality Factor</td>
<td>$Q = \omega U/P$</td>
<td></td>
</tr>
<tr>
<td>Geometrical factor</td>
<td>$\Gamma = Q R_s$</td>
<td>Ω</td>
</tr>
<tr>
<td>Peak electric field</td>
<td>$E_p/E_a$</td>
<td></td>
</tr>
<tr>
<td>Peak magnetic field</td>
<td>$B_p/E_a$</td>
<td>mT/(MV/m)</td>
</tr>
<tr>
<td>Optimum $\beta$</td>
<td>$\beta_0$</td>
<td></td>
</tr>
<tr>
<td>Cavity length</td>
<td>$L$</td>
<td>m</td>
</tr>
</tbody>
</table>

where:

- $R_s =$ surface resistance of the cavity walls
- $P =$ rf power losses in the cavity, proportional to $R_s$
Energy gain:

$$\Delta W_p = q \int_{-L/2}^{+L/2} E_z(z) \cos \left( \frac{\omega z}{\beta c} + \phi \right) dz$$

In a resonator $E_z(r,z,t)=E_z(r,z)\cos(\omega t+\phi)$. (For simplicity, we assume to be on axis so that $r=0$, and $E_z(0,z) = E_z(z)$.)

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

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

$$\Delta W_p = q E_a L T(\beta) \cos \phi$$
Transit time factor (normalized)

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

\[
T^*(\beta) = \frac{T(\beta)}{T(\beta_0)}
\]

**Normalized Transit time factor:**

Avg. accelerating field: 

\[
E_a^* = T(\beta_0)E_a
\]

where \( \beta_0 = \frac{\beta}{T(\beta_0)} = \max\{T(\beta)\} \) and \( T^*(\beta_0) = 1 \)

and the energy gain definition doesn’t change

\[
\Delta W_p = qE_a^*LT^*(\beta)\cos \varphi
\]
$T(\beta)$ for 1 gap (constant $E_z$ approximation)

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

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

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

Rule of thumb: $g < \beta \lambda / 2$
$T(\beta)$ for 2 gap (π mode)

(constant $E_z$ approximation)

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

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

2° term: 2 gap effect  $\rightarrow d<\beta \lambda/2$

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: \( l_{\text{int}}, L_{\text{max}} \) 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:

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

however, this implies:

Superconductivity, with high fields and low power dissipation, allows to overcome most of these drawbacks
Low-\(\beta\) cavity types
Low-\(\beta\) 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 structures: small $g/\lambda$, small size

\[ Z_0 = \frac{V_0}{I_0} \]  characteristic impedance
\[ T_g(\omega L/c) \sim \frac{1}{(\omega CLZ_0)} \]
\[ U \sim \pi V_0/(8\omega Z_0) \] 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

A half-wave resonator is equivalent to 2 QWRs facing each other and connected

\( U \sim \frac{2\pi V_0^2}{(8\omega Z_0)} \)

\[ P_{\text{HWR}} \sim 2P_{\text{QWR}} \]

- 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

![Diagram of IH and CH multi-gap structures](image)

<table>
<thead>
<tr>
<th>IH 4-rod RFQ</th>
<th>4-vane RFQ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H\textsubscript{110}</strong></td>
<td><strong>H\textsubscript{210}</strong></td>
</tr>
<tr>
<td>(f \leq 100) MHz</td>
<td>100 - 400 MHz</td>
</tr>
<tr>
<td>(\beta \leq 0.03)</td>
<td>(\beta \leq 0.12)</td>
</tr>
</tbody>
</table>

**E-Field**

**B-Field**

**IH-Structure**

**CH-Structure**

*Courtesy of H. Podlech*

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A. Facco - INFN  
Low- and Intermediate-\(\beta\) cavity design  
SRF09 - Dresden, 17/9/2009
Low-β cavities design issues
What is a good SC low-\(\beta\) 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 $\rightarrow \beta_0$, gap length
- velocity acceptance $\rightarrow$ n. of gaps
- beam size, transv. $\rightarrow$ bore radius
- beam long. size & $f$ $\rightarrow$ rf frequency
- beam power $\rightarrow$ rf coupling type
- gradient, efficiency $\rightarrow$ geometry
- cw, pulsed $\rightarrow$ mech. design
- cost, reliability $\rightarrow$ technology

beam specs

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 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

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

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 nΩ
- **Maximum rf power density on the cavity walls**
  - ~1W/cm² at 4.2K
- **Critical Temperature**
  - $T_c = 9.2\sqrt{1 - B / 200}$
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/cm² at 4.2K
- Large safety margin required: local defects can increase power losses significantly

HFSS Model SC QWR for $\beta_0 = 0.075$
Magnetic field distribution and calculated power dissipation
(Courtesy of V. Zvyagintsev)

$P_{\text{top}} = 0.286$ W
$P_{\text{outcond}} = 1.009$ W
$P_{\text{incond}} = 3.040$ W
$P_{\text{bport}} = 0.004$ W
$P_{\text{bottom}} = 0.0001$ W
$P_{\text{sphere}} = 0.001$ W
$f = 106$ MHz
$E_a = 6$ MV/m
$R_{\text{SNB}} = 38$ nΩ
$P = 4.345$ W
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-\(\beta\) 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”

2-walls MP

Courtesy of ACCEL
Avoiding multipacting

Example for a simple geometry:
- code TWTRAJ (one of the first created for this scope - courtesy of R. Parodi)
- ~60000 Runs
- 0.005 MV/m steps in $E_a$
- 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 $\delta > 1$ 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:

redesign A:
outer wall inclined
no multipacting

redesign B:
inner wall inclined
no multipacting

multipacting at $E_{\text{peak}}=0.1\text{MV/m}$
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 $\beta_0$ 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):

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

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 $\beta$, $E_y$ steering goes as $(\beta - \beta_0)/\beta^2$
- $\Phi = 0$ (max. acceleration): no steering
- $\Phi = \pm 90$ (bunching-debunching): maximum steering
QWR steering compensation: axis displacement

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

rf defocusing in the y direction:

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

Steering compensation by displacement from the beam axis in 80 MHz QWRs
Magnetic steering can be compensated by properly shaping $E_y$

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

- Statically analysis (He pressure…)
- Dynamically analysis (mechanical modes…)
- Thermally analysis (cooling, T distributions,…)
- Construction procedure
Frequency tuning

wall displacement toward:

\[ \begin{align*}
\text{high } E & \rightarrow f \text{ down} \\
\text{high } B & \rightarrow f \text{ up}
\end{align*} \]

(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)

**Fast tuners**

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

SC bellows tuner (ANL)

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A. Facco - INFN

Low- and Intermediate-β cavity design

SRF09 - Dresden, 17/9/2009
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. 1 mT 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

<table>
<thead>
<tr>
<th>Source:</th>
<th>Solution:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium pressure variations</td>
<td>mechanical tuning in feedback,</td>
</tr>
<tr>
<td></td>
<td>mechanical strengthening</td>
</tr>
<tr>
<td>Lorentz Force detuning</td>
<td>slow tuning and rf feedback</td>
</tr>
<tr>
<td>microphonics</td>
<td>fast tuners, mechanical design,</td>
</tr>
<tr>
<td></td>
<td>noise shielding, etc.</td>
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<tr>
<td>resonant vibrations</td>
<td>mechanical damping,</td>
</tr>
<tr>
<td></td>
<td>electronic damping</td>
</tr>
</tbody>
</table>
Slow detuning: He pressure fluctuations

\[ df \propto dP \]

- "Natural" solutions
  - Design your resonator strong
  - Build your cryosystem stable in pressure, with low \( \frac{dP}{dt} \): \( <5 \text{ Hz/min} \) achievable without big efforts
  - Use the mechanical tuner in a feedback loop
- "Clever" solution:
  - Design a "self-compensating" resonator
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 → 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 Hz

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.

\[ \omega = \left( \frac{1.875}{L} \right)^2 \left( \frac{EI}{\mu} \right)^{1/2} \]

\( E = \text{Young modulus}; I = \text{geometrical moment of inertia of the i.c. tube cross section}; \mu = \text{mass per unit length of the i.c. tube} \)
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

- 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

IFMIF separate vacuum cryostats, in the two versions with vertical or horizontal cavity orientation
Vacuum scheme in low-β cryostats

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

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 $\beta=1$ 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 structures: **Quarter-Wave resonators**

\[ 48 \leq f \leq 160 \text{ MHz}, \ 0.001 \leq \beta_0 \leq 0.2 \]

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

- Dipole steering for higher \( \beta \) QWRs
- Mechanical stability for lower \( f \) QWRs

**Very successful**
Some of the QWR worldwide
Quarter-wave structures: **Split-ring resonators**

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

\[ 90 \leq f \leq 150 \, \text{MHz}, \ 0.05 \leq \beta_0 \leq 0.15 \]

*In use for many years\* *being replaced by QWRs*
Half-wave structures: **Half-Wave resonators (coaxial)**

\[ 160 \leq f \leq 352 \text{ MHz}, \quad 0.09 \leq \beta_0 \leq 0.3 \]

- 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

**Ideal around 150÷300 MHz**
Half-wave structures: **Single-SPOKE resonators**

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

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

- Larger size than HWRs, too large below \( \sim 350 \text{ MHz} \)
- More expensive than HWRs

**the favorite 2-gap choice around 350 MHz**
Half-wave structures: **Ladder resonators**

\[ 350 \text{ MHz}, \ 0.1 \leq \beta_0 \leq 0.3 \]

- large energy gain
- they can be made for rather low \( \beta \)
- 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**
TM mode cavities: **multi-cell Elliptical resonators**

\[352 \leq f \leq 805 \text{ MHz}, \ 0.47 \leq \beta_0 \leq 1\]

+ + Large energy gain
+ Highly symmetric field
+ taking profit of the wide $\beta=1$ experience
+ Low $E_p$ and $B_p$
+ Large aperture

- Not suitable for $\beta<0.5$
- Dangerous Mechanical modes
- Dangerous Higher Order Modes

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

\[ 352 \leq f \leq 402 \text{ MHz, } \beta > 0.1 \]

- 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**
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

Efficient alternative to standard RFQs for cw beams

LNL SRFQ2, $A/q=8.5$
CH structures: **Multi-SPOKE resonators**

345 ≤ f ≤ 805 MHz, 0.15 ≤ β₀ ≤ 0.62

- 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, esp. for β~0.3÷0.6**
CH structures: CH multi-gap SC cavities

174 ≤ f ≤ 800 MHz, 0.1 ≤ β₀ ≤ 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: becoming 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