Low and Medium-β Superconducting Cavities

A. Facco

INFN-LNL
Definition

low-, medium- and high-\(\beta\): \textbf{Just cavities with }\(\beta<1\ldots\)

The definition, however, changes according to the community

<table>
<thead>
<tr>
<th>(Approximate) definition</th>
<th>low (\beta)</th>
<th>medium (\beta)</th>
<th>high (\beta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy ion boosters</td>
<td>&lt;0.06</td>
<td>0.06 (\div) 0.12</td>
<td>&gt;0.12</td>
</tr>
<tr>
<td>Proton linacs</td>
<td>&lt;0.2</td>
<td>0.2 (\div) 0.8</td>
<td>&gt;0.8</td>
</tr>
<tr>
<td>Heavy ion drivers</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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
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

New problems: very narrow rf bandwidth, mechanical instabilities

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Early resonators: 70’s

- Tandem boosters for light ions $\beta \sim 0.1$
- Materials:
  - Bulk Nb
  - Pb plated Cu
- $E_a$ typically $2 \text{ MV/m}$
- Mechanical stability problems solved by the first electronic fast tuners for Helix resonators

Low-$\beta$ cavities in operation from the 70’s
SC low-β resonators: 80’s

- At ANL Tandem replaced by the first low-β SC Positive Ion Injector, $\beta \approx 0.001 \div 0.2$
- 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-\(\beta\) resonators: 90’s

- \(\beta \sim 0.001 \div 0.2\)
- 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
Present QWR performance example:
LNL bulk Nb, 80 MHz double wall

Maximum fields:
- $E_a = 11.7$ MV/m
- $E_p = 57$ MV/m
- $B_p = 120$ mT

Best ALPI and PIAVE
low beta cavities results

LNL 80 MHz, $\beta = 0.055$ cryostat

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On-line resonators test

E_a at 7 W (MV/m)

of the 12
80 MHz ALPI QWRs
on line
Average ~6.8 MV/m
constant in time

Avg: 3.2 Hz rms

Distributions of the frequency oscillation amplitudes in
a 24 hour record for all low beta cavities in ALPI.

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What do we learn from HI boosters?

All SC low-\(\beta\) cavities presently in operation still belong to the low current, HI linacs category!

- QWRs are a good choice when possible
- \(E_a > 6\) MV/m achievable in operation
- Max \(E_p \sim 60\) MV/m
- Max \(H_p \sim 120\) mT
- Very reliable machines are possible (ANL linac \(\sim6000\) h/y beam on target)
- Mechanical vibrations can be handled

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Remark: different definitions of gradient in different labs

- $E_a$: Energy gain per unit charge at optimum $\beta_0$, divided by the effective length $L$
- $L$ can be: $l_{\text{int}}$, $L_{\text{max}}$ or even $\beta \lambda$ (see figure)
- $E_a$ defined with $l_{\text{int}}$ give larger values than $E_a$ defined with $L_{\text{max}}$
- This discrepancies do not affect the energy gain definition, which is the same

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SC linacs : new trends
# Low-\(\beta\) cavities: new applications

<table>
<thead>
<tr>
<th>Type</th>
<th>(\beta_{\text{max}})</th>
<th>(A/q)</th>
<th>(\text{current})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-accelerators for RIB facilities</td>
<td>(~ 0.2 (0.5))</td>
<td>(7 \div 66)</td>
<td>(&lt; 1 \text{ nA})</td>
</tr>
<tr>
<td>HI drivers for RIB facilities</td>
<td>(~ 0.3 \div 0.9)</td>
<td>(~ 1 \div 10)</td>
<td>(~0.1 \div 10 \text{ mA})</td>
</tr>
<tr>
<td>(p,d) linacs</td>
<td>(~ 0.3)</td>
<td>(1 \div 2)</td>
<td>(~1 \div 10 \text{ mA})</td>
</tr>
<tr>
<td>High Power Proton Accelerators</td>
<td>(~ 0.9)</td>
<td>(1)</td>
<td>(~10 \div 100 \text{ mA})</td>
</tr>
<tr>
<td>High Power Deuteron Accelerators for material irradiation</td>
<td>(~ 0.3)</td>
<td>(2)</td>
<td>(~100 \text{ mA})</td>
</tr>
</tbody>
</table>
Radioactive Ion Beam Facilities

- Driver: from p to U, I~500 µA
- Post-accelerator: variable A/q, I<< 1 nA
- Evolution of HI boosters

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Moving to higher $\beta$ and $I$

**HI cavities**
- $\beta \approx 0.3$
- Low current (~µA)
- Short cavities

**Low-intermediate $\beta$**
- $\beta = 0.1 \div 0.5$
- High current, mA
- Short cavities

**Electron cavities**
- $\beta = 1$
- High current (~mA)
- Long cavities

**High-$\beta$**
- $\beta = 0.5 \div 0.9$
- High current, mA
- Long cavities

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RIA cavities development at ANL

172.5 MHz \( \beta = 0.14 \) HWR

115 MHz \( \beta = 0.15 \), Steering Corrected QWR

345 MHz \( \beta = 0.4 \) Double-spoke

345 MHz \( \beta = 0.5 \) Triple-spoke

345 MHz \( \beta = 0.62 \) Triple-spoke

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RIA cavities development at MSU

• Alternative design of the RIA driver based on 80.5 MHz
• Most of the cavities are ready

\[ \beta_{\text{opt}} = 0.041 \]
80.5 MHz
Legnaro

\[ \beta_{\text{opt}} = 0.085 \]
80.5 MHz
MSU

\[ \beta_{\text{opt}} = 0.285 \]
322 MHz
MSU

\[ \beta_{\text{opt}} = 0.49 \]
805 MHz
MSU/JLAB

\[ \beta_{\text{opt}} = 0.63 \]
805 MHz
SNS

\[ \beta_{\text{opt}} = 0.83 \]
805 MHz
SNS

Courtesy of T. Grimm, MSU
Heavy Ion and Proton linacs

• Low- and intermediate-\( \beta \) SC cavities for Proton linacs are very similar to the ones for Heavy Ions
• The main differences are at \( \beta < 0.3 \):
  • Higher frequency at low beta (from 350 MHz RFQs)
  • Larger rf power couplers, rf ports and beam aperture (from higher beam current)

Example: \( \beta = 0.1 \)

10 mA protons ⇒ 350 MHz cavity (reentrant, spoke, HW…)
10 \( \mu \)A heavy ions ⇒ 100 MHz QWR
LANL $\beta=0.175$ SC spoke resonator for high power proton beams

103-mm (OD) power coupler designed for up to 100 mA beam (212 kW)
High Intensity Superconducting Proton Linacs

• Many applications
  – RIB drivers, ADS systems, spallation neutron sources, …

• Consolidated scheme
  – a proton (H⁺,H⁻) injector and a ~350 MHz, NC RFQ
  – a SC high energy linac with multicell, elliptical cavities
  – A low and intermediate energy linac, either NC (DTL, CCL), SC (low-β elliptical, spoke, half wave coaxial, reentrant…) or both

• Problem: where do we change from NC to SC?

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Where do we change from NC to SC?

No unique answer, many points to consider:

**Beam A/q**
- NC: fixed velocity profile
- SC: ISCL (Independently-phased SC Cavity Linac) with large velocity acceptance

**Pulsed vs. CW**
- NC $E_a$ limited by water cooling: better pulsed
- SC are very sensitive to Lorentz force detuning: better cw

**Beam current**
- High current $\rightarrow$ high beam loading $\rightarrow$ NC high rf losses negligible
- Low current $\rightarrow$ low beam loading $\rightarrow$ SC efficiency is important

**Reliability issues**
- NC large cavities $\rightarrow$ no fault tolerance
- SC short cavities $\rightarrow$ some fault tolerance is possible

**Construction and operation cost**
- From EURISOL studies, 5 mA 5-100 MeV NC and SC proton linacs have comparable construction cost, while SC is cheaper in operation

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Where do we change from NC to SC?

• In **low power heavy ion accelerators**: as soon as possible
• In **high power proton accelerators** the real estate gradient at \( \beta < 0.3 \) can hardly exceed 1 MV/m for beam dynamics constraints: NC solutions can be competitive even in cw mode

**IPHI: NC**
- 5-11 MeV, 100 mA p DTL
- 352 MHz cw
- \( E_a \sim 0.8 \text{ MV/m r.e.} \)

**SC ADS Driver (LANL):**
- 6.7- 43 MeV, 20 mA p linac
- 352 MHz cw
- \( E_a \sim 0.4 \text{ MV/m r.e.} \)
Low- and intermediate-β Resonator geometries and characteristics
Superconducting RFQ’s

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

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

- Mechanical stability (fast tuners required)
- Low beam current only
- Difficult to build
- Expensive

LNL SRFQ2, $A/q=8.5$

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Two superconducting RFQs in one cryostat

- Installation is complete
- Beam transport to the RFQs OK
- Alignment checked to be within ±0.2 mm on the beam axis
- Q values and $E_{s,p}$ exceeding specs (>3x10^8 and > 25 MV/m)
- Stiff vs. mechanical noise: locking with VCX was proven to work, providing a bandwidth of 80 & 200 Hz on SRFQ1 and SRFQ2
- Slow P changes of the refrigerator (TCF50) can be controlled, to a level where the slow f-tuners can follow (~ 20 mbar/min)
- Beam acceleration through SRFQs: planned for October 2004
Quarter-Wave resonators

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

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

- Dipole steering above \(\sim 100\) MHz
- Mechanical stability below \(\sim 100\) MHz
- (Quadrupole steering: could give problems with solenoids)

ANL 48.5 MHz, \(\beta = 0.0016\) QWR

NSCL 97 MHz, \(\beta = 0.08\) QWR

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Superconducting QWRs development at Nuclear Science Centre

- Required 26, $\beta=0.08$, 97 MHz QWRs
- 8 built in collaboration with ANL
- The rest is being built in house. A facility for Nb resonators production has been set up, with:
  - Eb welding
  - EP
  - HPR
  - High vacuum baking at 1200 °C

Courtesy of S. Ghosh, NSCL

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- 46, $\beta = 0.11$ and 8, $\beta = 0.13$, 160 MHz QWRs routinely used for beam acceleration

- Average operational $E_a > 4.4$ MV/m @ 7W, in spite of being produced using the recovered substrates of the previously installed Pb/Cu resonators

- Some of them are reliably locked up to 6.5-7.3 MV/m without necessity of fast or “soft” tuners and/or strong overcoupling. Frequency not affected by changes in the He bath pressure ($\Delta f < 0.01$ Hz/mbar)

*Courtesy of A. Porcellato, INFN-LNL*
## ISAC-II SC QWRs

<table>
<thead>
<tr>
<th>Section</th>
<th>$\beta_0$ (%</th>
<th>$f_{RF}$ (MHz)</th>
<th>No.</th>
<th>$E_a$ (MV/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low $\beta$</td>
<td>4.2</td>
<td>70.7</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Med $\beta$</td>
<td>5.7</td>
<td>106</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>High $\beta$</td>
<td>7.1</td>
<td>106</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>10.4</td>
<td>141</td>
<td>20</td>
<td>6</td>
</tr>
</tbody>
</table>

### Medium Beta Cavities

- **Nominal ($\beta=7.1\%$):**
  - $f_{req}=106.08\text{MHz}$
  - $E_p/E_a \approx 5$
  - $H_p/E_a \approx 100 \text{ G/(MV/m)}$
  - $U/E_a \approx 0.09\text{J/(MV/m)}^2$
  - $\Gamma \approx 19\Omega$

- **Flat ($\beta=5.7\%$):**

**Courtesy of R. Laxdal, TRIUMF**

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ISAC-II QWRs Performance

- 20+1 resonators produced
- All cavities tested up to now meet the specifications of \(6 \text{MV/m @7W}\)
- CP at CERN (5 QWRs) and Jlab
- HPR at TRIUMF

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ISAC-II Medium Beta Cryomodule

First Medium beta cryomodule in assembly

Provide suitable bandwidth by overcoupling

\[ P_f = 200 \text{ W at cavity: } f_{1/2} = 20\text{Hz} \]

at \( E_a = 6\text{MV/m} \) with \( \beta_c = 200 \)

Courtesy of Bob Laxdal, TRIUMF
SPIRAL 2 low-β QWRs

SPIRAL2 HI driver

• 40 MeV, 5 mA SC linac for A/q=2 and 3
• To be built at GANIL as a RIB driver
• CEA Saclay and IPN Orsay are developing the resonators

CEA prototype

• Nb QWR - 88 MHz - β=0.07
• Design goals for operation:
  • Eacc = 6.5 MV/m
  • Epeak = 32 MV/m
• Prototype under construction
SPIRAL 2 medium-\(\beta\) QWRs

IPN Orsay prototype

- Nb QWR - 88 MHz - \(\beta=0.12\)
- Beam tube aperture: \(\Phi 36\) mm
- RF coupling by \(\Phi 36\) mm port
- 6 ports for HPR
- under construction, delivery in October 2004

- Design goals for operation:
  - \(E_{acc} = 6.5\) MV/m
  - \(E_{peak} = 36\) MV/m
  - \(B_{peak} = 66\) mT

- Design of the cryomodule

Preliminary design of the \(\beta\) 0.12 cryomodule

Courtesy of G. Orly, IPNO
MSU- LNL: QWR with steering correction

• 161 MHz, $\beta=0.16$
• separate vacuum is possible
• Extendable to different $f$ and $\beta$
• first preliminary test before HPR
• RIA specifications already fulfilled
QWRs and HWRs for RIA

- Prototypes built and tested
- RIA specifications met
- Cryomodule under construction

80.5 MHz, $\beta=0.08$
322 MHz, $\beta=0.28$
161 MHz, $\beta=0.16$ (MSU-LNL)

$E_p$ [MV/m]

$Q_0$
ANL QWR and HWR prototypes for RIA

- Prototypes constructed and under testing
- The preliminary results are very encouraging and final results will be presented at the LINAC conference

172 MHz
\( \beta = 0.14 \)

115 MHz
\( \beta = 0.15 \)
With steering correction

Courtesy of K. Shepard, ANL
Prototype cryomodule will be completed in summer of 2004
Half-Wave resonators

$160 \leq f \leq 352 \text{ MHz}, \ 0.09 \leq \beta_0 \leq 0.3$

• **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)
ACCEL cavities for SARAF

- ACCEL is currently building a 40 MeV linear accelerator for 2 mA cw protons and deuteron for the SARAF (SOREQ APPLIED RESEARCH ACCELERATOR FACILITY) at SOREQ NRC, Israel;
- 176 MHz superconducting half-wave-resonators
- 2 HWR families: $\beta=0.09$ and $\beta=0.15$

Cryomodule n.1 – $p$ and $d$ from 1.5 MeV/u

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Courtesy of ACCEL
Parameters of $\beta = 0.09$ SARAF HWR

Cavities are produced out of RRR > 250 bulk niobium, design goal: $E_p = 25$ MV/m

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>176</td>
<td>MHz</td>
</tr>
<tr>
<td>Cavity height $h$</td>
<td>835</td>
<td>mm</td>
</tr>
<tr>
<td>Diameter of inner conductor</td>
<td>80</td>
<td>mm</td>
</tr>
<tr>
<td>Diameter of outer conductor</td>
<td>180</td>
<td>mm</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>3</td>
<td>mm</td>
</tr>
<tr>
<td>Cavity volume</td>
<td>17</td>
<td>l</td>
</tr>
<tr>
<td>Accelerating length $L_{acc}$</td>
<td>99</td>
<td>mm</td>
</tr>
<tr>
<td>Optimum beta</td>
<td>9</td>
<td>%</td>
</tr>
<tr>
<td>Geom. constant $G = R_S \times Q_0$</td>
<td>24.5</td>
<td>W</td>
</tr>
<tr>
<td>Shunt Impedance $R/Q$</td>
<td>164</td>
<td>W</td>
</tr>
<tr>
<td>$E_{peak} / E_{acc}$</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>$B_{peak} / E_{peak}$</td>
<td>2.1</td>
<td>mT/MV/m</td>
</tr>
<tr>
<td>$B_{peak} / E_{acc}$</td>
<td>6.2</td>
<td>mT/MV/m</td>
</tr>
</tbody>
</table>

$\beta = 0.09$ prototype

• The 1st prototype is under testing
• The 1st cryomodule is under construction
• The $\beta = 0.15$ prototype and cryomodules will follow

1 Measured from start of the first to the end of the second acceleration gap of the HWR, excluding leakage field in beam tubes

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H-, D- injector

COSY Injector project (temporary suspended)
- 50 MeV with both H- and D- beams
- 2 mA (COSY space charge limit)
- 0.5 ms pulses @ 2 Hz
- 44 HWRs
- 160-320 MHz
- 8 MV/m
- \( \beta = 0.11-0.2 \)

- A first 160 MHz prototype has been built and is presently under testing
- Preliminary results very encouraging

IKF Juelich

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LNL: 352 MHz, $\beta=0.3$ HWR

- **Modular design** for high intensity p and HI linacs (SPES, EURISOL), extendable to different $\beta$ and f
- Very compact and stiff structure including He vessel
- **Side tuner** insensitive to He pressure

\[
E_a L T = 1.2 \text{ MV @ 10W (preliminary)}
\]

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SPOKE resonators

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

- No dipole steering
- High performance
- Higher $R_{sh}$ than HWRs
- Wide beta range
- Multi-cell possibility

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

LANL $\beta=0.2$
SPOKE

ANL $\beta=0.4$
Double SPOKE

IPNO SPOKE, $\beta=0.35$
352 MHz
SPOKE resonators performance example: ANL and LANL 352 MHz cavities

ANL $\beta=0.3$ and $\beta=0.4$ prototypes

LANL $\beta=0.2$ prototypes

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IPNO - $\beta$ 0.35, 352 MHz spoke cavity

New tests in 2004 @ 4.2 K & 2 K

Tests @ 2 K
Eacc max = 16.2 MV/m
No quench
RF power limitation
1. No He processing
2. After He processing

Tests @ 4.2 K
Eacc max = 10 MV/m
No quench
RF power limitation
1. 2. No He processing
3. 4. After He processing

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New $\beta_{0.15}$, 352 MHz spoke cavity design

**RF parameters (MAFIA calculations)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_0$ (@ 4.2K)</td>
<td>$1.4 \times 10^9$</td>
</tr>
<tr>
<td>$r/Q$ [Ω]</td>
<td>88</td>
</tr>
<tr>
<td>$G$ [Ω]</td>
<td>67</td>
</tr>
<tr>
<td>$E_p/E_{acc}$</td>
<td>$3.97^b$</td>
</tr>
<tr>
<td>$B_p/E_{acc}$ [mT/MV/m]</td>
<td>$7.95^b$</td>
</tr>
<tr>
<td>Voltage gain @ $E_p=30$ MV/m [MV]</td>
<td>0.63</td>
</tr>
</tbody>
</table>

\(^a\) assuming a 10 nOhm residual resistance
\(^b\) $L_{acc}=$iris-to-iris length=0.2 m

**Mechanical parameters (COSMOS & MICAV calculations)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum stress under 1 bar [MPa]</td>
<td>&lt; 39</td>
</tr>
<tr>
<td>Stiffness with stiffening rings (without stiffening rings) [N/mm]</td>
<td>6200 (3200)</td>
</tr>
<tr>
<td>Tuning sensitivity (using beam tubes) [kHz/mm]</td>
<td>~1100</td>
</tr>
</tbody>
</table>

- New stiffeners
- RF port bigger and @ 90°/spoke bar
- Nb: RRR250, 3 mm thick

Delivery in September 04

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Double SPOKE $\beta=0.4$

Maximum fields:
- $E_a = 11.5$ MV/m
- $E_p = 40$ MV/m
- $B_p = 79$ mT

Performance Goal:
- $E_{acc} = 9$ MV/m
- Voltage = 3.4 MV
Elliptical resonators

$352 \leq f \leq 805 \text{ MHz, } 0.47 \leq \beta \leq 1$

- Highly symmetric field
- High performance
- Low $E_p$ and $B_p$
- Multi cell possibility
- Large aperture
- Not suitable for $\beta < 0.4$
- Operation at 2K (with one exception)

INFN Milano 700 MHz, $\beta = 0.5$

CERN 352 MHz, $\beta = 0.8$
Sputtered Nb on Cu
β<1 Elliptical resonators examples

- Prototypes successfully developed at JLAB, KEK, JAERI, LANL, CEA Saclay, IPN Orsay, INFN Milano, CERN
- SNS cavities and cryomodules under production, very good performance
Intermediate-\(\beta\) cavities

\textbf{Nb Cavity ( 5-cell 700 MHz \(\beta = 0.65\))}

In collaboration with IPNO

Results Improvement in Vertical Cryostat and Cry-Ho-Lab

\[ Q_0 = 9.10^9 \text{ at } E_{\text{peak}} = 43 \text{ MV/m}, \quad B_{\text{peak}} = 83 \text{ mT} \]

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MSU-JLAB 6-cell elliptical $\beta=0.47$

- $\beta=0.47$ Criomodule built and tested
- Actively damped the 0.47 microphonics using adaptive feedforward
TRASCO/ADS $\beta=0.47$

Test #1 limited by strong field emission

- Z501
- Z502 - before conditioning
- Z502 - after conditioning
- Design Value

$Q_0$

$E_{\text{acc}}$ [MV/m]

Multipacting barriers

Start of electron emission
3-Spoke or 6-cell?

• **3-SPOKE advantages:**
  – lower n. of cavities if $B_p$ of 82 mT in operation is used
  – Higher longitudinal and transverse acceptance
  – 4.2 K instead of 2 K

• **On the other hand:**
  – $B_p$=82 mT in operation is rather challenging
  – 6-cell are well developed, 3-SPOKE not yet
  – 2 K have some advantages in terms of mechanical stability
  – According to MSU calculations both SPOKE and 6 cell have adequate acceptance for RIA, and their cost, using realistic $B_p$, would be the same

• The discussion is still open to new results.
Reentrant cavities

$352 \leq f \leq 402 \text{ MHz, } 0.1 \leq \beta$

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

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

The first reentrant cavities - SLAC

LNL 352 MHz reentrant cavity

A. Facco – EPAC 2004
**LNL β>0.1, 352 MHz Reentrant cavity**

TRASCO 30 mA Fault tolerant Linac with Reentrant Cavities

- 5÷100 MeV
- 230 cavities
- Cavity aperture 30 mm
- Superconducting quadrupole singlets in a FODO lattice
- SC Linac length : 48 m
Other multi-gap SC cavities

$174 \leq f \leq 352 \text{MHz}, \ 0.1 \leq \beta \leq 0.3$

• Very efficient
• Large energy gain
• They can be made for rather low $\beta$

• $\beta$ acceptance
• Difficult to have large aperture
• Difficult to build and expensive
• Not yet demonstrated

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## 19 gap, 352 MHz, $\beta=0.1$

Fixed velocity profile, high energy gain resonator
Under construction

<table>
<thead>
<tr>
<th>Cells</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (cm)</td>
<td>105</td>
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<tr>
<td>Frequency (MHz)</td>
<td>352</td>
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<tr>
<td>$\beta$</td>
<td>0.1</td>
</tr>
<tr>
<td>Material</td>
<td>Bulk Niobium</td>
</tr>
</tbody>
</table>

| $E_0$ (MV/m) | 4 |
| $E_a=ET$ (MV/m) | 3.2 |
| $E_p$ (MV/m) @ 3.2 MV/m | 21.0 |
| $B_p$ (mT) @ 3.2 MV/m | 23.3 |
| $G=R_sQ_0$ (\(\Omega\)) | 56 |
| $R_a/Q$ (\(\Omega\)) (T incl.) | 3220 |
| $(R_a/Q)G$ (\(\Omega^2\)) | 180000 |
| $Q_0$ (BCS, 4K, 352 MHz) | $1.5\times10^9$ |
| $Q_0$ (total $R_s=150$ n\(\Omega\)) | $3.7\times10^8$ |
| $W$ (mJ/(MV/m)^2) | 155 |
| $W$ @ 3.2 MV/m (J) | 1.58 |
| $P$ @ 3.2 MV/m and $R_s=150$ n\(\Omega\) = (W) | 9.5 |
Conclusions

• After two decades of heavy ion SC boosters, new applications for low- and intermediate-β superconducting resonators
• Low- and intermediate-β cavities reach nowadays $E_p \sim 60$ MV/m and $B_p \sim 120$ mT, and approximately half of these values are considered reliable in operation
• Strong development in SC cavities is pushed by new high power proton accelerator and heavy ion linac projects
• Large variety of shapes and characteristics for different applications
• In high current proton linacs, however, NC DTLs choice can be still competitive for $\beta < 0.3$, even in cw
• The time of commercial SC linacs for HPPA is maybe starting