Advances in SRF for Low $\beta$ Ion Linacs

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Disclaimer

This review is covering a wide range of low beta ion cavities developments for several applications, excepted high energy physics and neutron sources:

Refer to these 2 others talks to have a complete picture:

- *SRF Development for High Energy Physics*, Mark Champion
- *Advances in SRF for Neutron Sources*, Sang-Ho Kim
Outlook

- Facility upgrades
  - ATLAS (ANL)
  - HIE-ISOLDE (CERN)
  - Re A3 (MSU)
  - ISAC-II (TRIUMF)

- New projects
  - SPIRAL-2 (GANIL, CEA Saclay, IPN Orsay)
  - SARAF (SOREQ)
  - FRIB (MSU)
  - IFMIF (CEA Saclay)

- Other low beta SC cavities R&D
**Project objectives:** Replace the 3 existing 97 MHz split-rings by a new cryomodule to increase beam transport efficiency (↗ acceptance & ↘ emittance growth)

**Cavity type:** Quarter-wave resonators, f=72 MHz, $\beta=0.077$

**Goal:** Voltage = 2.5 MV (Eacc ~ 7.5 MV/m with $\text{Leff} = \beta \lambda$)

**Parameter** | **Value** | **Units**
---|---|---
Frequency | 72.750 | MHz
Peak Beta | 0.077 | 
QRs | 26.4 | Ohm
R/Q | 576 | Ohm
$\beta \lambda$ | 31.75 | cm
Design Voltage | 2.5 | MV
$\Delta f / \Delta E_{\text{acc}}$ | -1.9 | Hz/(MV/m)$^2$
$\Delta f / \Delta P$ | -2.6 | Hz/Torr
Tuning Sensitivity | ~8 | kHz/mm

**EM design:** a conical-shape outer housing reducing by 20 % the ratio Bpk/Eacc
Cavity preparation:

- 150 µm removed by EP (12 hours total EP time) on the new ANL EP system
- HPR and assembly in a class 100 clean room

RF test of the first prototype:

A max $E_{acc} = 13.4$ MV/m obtained!

Cryomodule design: 17.5 MV in 5.2 m

Clean cavity string (separate vacuum)
**Cold Tuning System**

- Cavity wall deformation by piezo

**Power coupler**

- Design for 4 kW CW - Variable
- 2 RF disc windows (96% Alumina)
- Bellow: copper plated with 20 µm

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**To know more:** THIOB04 by M.P. Kelly
Project objectives: post-accelerate the RIB beam coming from REX-ISOLDE up to 10 MeV/u (intermediate phase at 5.5 MeV/u).

Cavity type: Quarter-wave resonators, Nb/Cu, f=101.28 MHz

- SC-linac between 1.2 and 10 MeV/u
- 32 SC QWR (20 cavities @ $\beta = 0.1$ and 12 cavities @ $\beta = 0.06$)

Performances goal: $E_{acc} = 6$ MV/m and 7 W max of dissipated power

Objectives based on past experience at INFN-Legnaro on sputtered cavities developed for ALPI
CERN: HIE ISOLDE (2)

Cavity features:

- Cavity substrate: OFE copper, 10 mm thick, cold worked; deep drawing and EB welding at CERN. A new design and fabrication process is under study.
- Specially studied beam aperture shapes (racetrack) to minimize the beam steering effect of QWR.
- Op. T° 4.2 K, LHe only on the cavity top and in the stem.

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Low β</th>
<th>high β</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Cells</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>f (MHz)</td>
<td>101.28</td>
<td>101.28</td>
</tr>
<tr>
<td>$\beta_0$ (%)</td>
<td>6.3</td>
<td>10.3</td>
</tr>
<tr>
<td>Design gradient $E_{acc}$ (MV/m)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Active length (mm)</td>
<td>195</td>
<td>300</td>
</tr>
<tr>
<td>Inner conductor diameter (mm)</td>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td>Mechanical length (mm)</td>
<td>215</td>
<td>320</td>
</tr>
<tr>
<td>Gap length (mm)</td>
<td>50</td>
<td>85</td>
</tr>
<tr>
<td>Beam aperture diameter (mm)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>$U/E_{acc}^2$ (mJ/(MV/m)$^2$)</td>
<td>73</td>
<td>207</td>
</tr>
<tr>
<td>$E_{pk}/E_{acc}$</td>
<td>5.4</td>
<td>5.6</td>
</tr>
<tr>
<td>$H_{pk}/E_{acc}$ (Oe/MV/m)</td>
<td>80</td>
<td>100.7</td>
</tr>
<tr>
<td>$R_{sh}/Q$ (Ω)</td>
<td>564</td>
<td>548</td>
</tr>
<tr>
<td>$\Gamma = R_S \cdot Q_0$ (Ω)</td>
<td>23</td>
<td>30.6</td>
</tr>
<tr>
<td>$Q_0$ for 6MV/m at 7W</td>
<td>$3.2 \cdot 10^8$</td>
<td>$5 \cdot 10^8$</td>
</tr>
<tr>
<td>TTF max</td>
<td>0.85</td>
<td>0.9</td>
</tr>
<tr>
<td>No. of cavities</td>
<td>12</td>
<td>20</td>
</tr>
</tbody>
</table>

 Courtesy M. Pasini

New mechanical design, for a 3D fabrication from a billet
Sputtering: 2 techniques are studied: bias diode and magnetron sputtering

First prototype

First RF test on the prototype: an accelerating field of 3 MV/m reached, with an important slope on the $Q_0$.

Optimization of deposition parameters are undergoing (first main goal: increase the RRR of the Nb film)
CERN : HIE ISOLDE (4)

**Cryomodule**: common cavity/cryomodule vacuum, superconducting solenoid

**MOBILE COUPLER**

**COUPLER POSITIONNER**

**PROTOTYPE SOLENOID**

**Nb3Sn (TE/MSC)**

**TUNER**

**MOTORISATION**

*Courtesy O. Capatina*

**To know more:**

**THOB07**: M. Pasini: HIE Isolde QWR

**TUP 0067**: G. Lanza, S. Calatroni et al.: QWR sputtering
**Project objectives**: Upgrade of ISAC II (Phase 2)

**Cavity type**: 20 more quarter-wave resonators, beta 0.11 @ 141 MHz.

Specifications: P<7 W/cavity and voltage = 1.08 MV. All cavities fabricated by local company PAVAC.

**Performances**:

- Individual cavity testing: Almost all cavities above specs. (average Epk=32 MV/m)
- All cryomodules are installed since March 2010 and have accelerated beam with Epk=26 MV/m in average. Some studies are ongoing to increase cavity performances.

**More information**: Talk by R. Laxdal on Thursday THIOB06 Poster by D. Longuevergne MOPO017
**Project objectives:** construction of a 40 MeV deuterons accelerator (which can also accelerate q/A = 1/3 and 1/6) as a driver for RIB production
Low beta cavities (“A” type): developed by CEA Saclay: QWR with dismountable copper bottom flange

12 over 13 cavities received – 1 under repair

Courtesy P. Bosland
High beta cavities ("B" type): developed by IPN Orsay: QWR with welded Nb bottom flange, Titanium He tank (4 mm), SS cavity flanges.

Total produced: R&D phase: 1 prototype +2 pre-series
Series production: 16 (made by Research Instruments)
Performance Goal: 6.5 MV/m and 10 W max.

- Preparation: standard BCP, HPR @ 100 bar, class 10 clean room assembly
- All cavities exhibit multipacting. MP Barriers above 1 MV/m are easily processed. FE level and onset is variable, but when present, it is always processed in VT.
- Low $\beta$ cavities: cavities tested so far are in the spec. Some have $E_{acc} > 10$ MV/m!
- High $\beta$ cavities: all series cavity tested and in the spec with important margins!
High beta cavities: baking effect

- After 72h drying -> 48 h baking @ 120°C
- “Forced” air flow inside the helium vessel + heater on the cavity bottom
- Cavity wrapped in a foil blanket

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Losses @ 6.5 MV/m [W]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No baking</td>
<td>With baking</td>
</tr>
<tr>
<td>MB01</td>
<td>8.5</td>
<td>3.7 (-56%)</td>
</tr>
<tr>
<td>MB02</td>
<td>6.9</td>
<td>4.1 (-41%)</td>
</tr>
<tr>
<td>MB03</td>
<td>7.0</td>
<td>4.4 (-47%)</td>
</tr>
<tr>
<td>MB04</td>
<td>8.4</td>
<td>3.6 (-58%)</td>
</tr>
<tr>
<td>MB05</td>
<td>7.2</td>
<td>3.5 (-51%)</td>
</tr>
<tr>
<td>MB06</td>
<td>7.5</td>
<td>4.8 (-36%)</td>
</tr>
<tr>
<td>MB07</td>
<td>6.9</td>
<td>3.4 (-51%)</td>
</tr>
<tr>
<td>MB08</td>
<td>X</td>
<td>4.0</td>
</tr>
<tr>
<td>MB09</td>
<td>8.9</td>
<td>3.9 (-56%)</td>
</tr>
<tr>
<td>MB10</td>
<td>7.1</td>
<td>3.5 (-51%)</td>
</tr>
<tr>
<td>MB11</td>
<td>X</td>
<td>3.1</td>
</tr>
<tr>
<td>MB12</td>
<td>X</td>
<td>3.8</td>
</tr>
<tr>
<td>MB13</td>
<td>X</td>
<td>3.0</td>
</tr>
<tr>
<td>MB14</td>
<td>X</td>
<td>4.0</td>
</tr>
<tr>
<td>MB15</td>
<td>X</td>
<td>3.1</td>
</tr>
<tr>
<td>MB16</td>
<td>X</td>
<td>3.9</td>
</tr>
<tr>
<td>Mean value</td>
<td>7.6</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Heater (not shown) glued onto the copper cap

Input ~120°C

Losses divided by ~2 @ Eacc=6.5 MV/m

Output ~110°C

Heater ~110°C

Courtesy G. Olry
GANIL, CEA, IPNO : SPIRAL-2 (5)

**Low $\beta$ Cold tuning system**

Mechanical tuner, push system

- Good linearity: 0.15 Hz/motor step
- Sensitivity: ~28 kHz/mm
- Full range: +25 kHz

**High $\beta$ Cold tuning system**

Tuning by insertion of an Nb rod

- 2 ports on the top of the cavity:
  - a) One static plunger
  - b) One moving plunger

- Sensitivity ~1 kHz/mm with Ø 30 mm plunger
- Introducing one plunger by 50 mm(Ø 30 mm)
- First “coarse” tuning: + 50 kHz
- then fine tuning: +/- 4 kHz
Low $\beta$ Cryomodule

- Magnetic field
- Cryo connections
- MLI
- Tuner
- Beam valves
- 60 K thermal screen

High $\beta$ Cryomodule

Two different layout, but both have separated vacuum (clean string assembly)

Power couplers: developed by LPSC Grenoble: see FRIOA04 by Y. G. Martinez
Project objectives: Produce RIB using a 400 kW CW heavy ion driver linac (p to U) up to 200 MeV/u.

Cavity type: Quarter-wave resonators (80.5 MHz) and half-wave resonators (322 MHz), bulk niobium for a total of 344 cavities and 52 cryomodules.

Courtesy Q. Zhao, R. York
**Cavity type**: Quarter-wave resonators (80.5 MHz) and half-wave resonators (322 MHz), bulk niobium for a total of 344 cavities and 52 cryomodules

<table>
<thead>
<tr>
<th>Type</th>
<th>λ/4</th>
<th>λ/4</th>
<th>λ/2</th>
<th>λ/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>β_{opt}</td>
<td>0.041</td>
<td>0.085</td>
<td>0.29</td>
<td>0.530</td>
</tr>
<tr>
<td>f(MHz)</td>
<td>80.5</td>
<td>80.5</td>
<td>322</td>
<td>322</td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>V_a (MV)</td>
<td>0.81</td>
<td>1.62</td>
<td>1.90</td>
<td>3.70</td>
</tr>
<tr>
<td>E_p (MV/m)</td>
<td>30.0</td>
<td>31.5</td>
<td>31.5</td>
<td>31.5</td>
</tr>
<tr>
<td>B_p (mT)</td>
<td>53</td>
<td>71</td>
<td>75</td>
<td>77</td>
</tr>
<tr>
<td>T(K)</td>
<td>4.5</td>
<td>4.5</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

4 cavity types and 2 frequencies
Cavity study status:

- Developments for ReA3: a FRIB technology “prototype” : $\beta=0.041$ QWR cavities successfully accelerates beam at ReA3; tested for FRIB gradients (first accelerated beam by the cryomodule in May 2011)
- $5 \beta=0.53$ HWR prototypes fabricated and 3 tested

Tests in March 2011

Study of Q-disease
Cavity study status:

• Test of $\beta = 0.085$ QWR prototype

(C)avity tests performed at 2K and 4.2 K

Improved tuner design under progress
Study of alternatives:

• Feb 2011: Down selection between 161 and 322 MHz -> 322 MHz chosen
• April 2011: Down selection between single spoke & HWR -> HWR chosen
• An optimized $\beta=0.29$ HWR prototype as an potential alternative will be studied by ANL.

More information on FRIB: Poster MOPO009 by M. Leitner et al.

More information on ReA3: Talk THIOB03 by D. Leitner
Project objectives: characterization of materials with intense neutrons flux (10^{17} n/s) for the future Fusion Reactor DEMO (~150 dpa). Based on two CW 40 MeV deuterons SC linac, 125 mA each.

Cavity type: Half-wave resonators

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Target Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>175</td>
<td>MHz</td>
</tr>
<tr>
<td>β value</td>
<td>0.094</td>
<td></td>
</tr>
<tr>
<td>Accelerating field $E_a$</td>
<td>4.5</td>
<td>MV/m</td>
</tr>
<tr>
<td>Unloaded Quality factor $Q_0$ for $R_s=20$ nΩ</td>
<td>$1.4\times10^9$</td>
<td></td>
</tr>
<tr>
<td>Freq. range of HWR tuning syst</td>
<td>± 50</td>
<td>kHz</td>
</tr>
<tr>
<td>Max. transmitted RF power by coupler (CW)</td>
<td>200</td>
<td>kW</td>
</tr>
<tr>
<td>External quality factor $Q_{ex}$</td>
<td>$6.3\times10^4$</td>
<td></td>
</tr>
</tbody>
</table>
Prototyping status: 2 prototypes have been fabricated and are under testing phase. Preliminary results shows strong MP barriers.

More information:
F. Orsini talk on Thursday (THIOB02)
**Project objectives:** SARAF phase 1: a 2 mA protons and deuterons beam up to 4 MeV (resp. 5 MeV).

**Cavity type:** 6 Half-wave resonators / module; beta 0.09 @ 176 MHz.

Specifications: $P < 10 \text{ W/cavity} @ E_{pk} = 25 \text{ MV/m} (E_{acc} = 5 \text{ MV/m})$

**PSM Cryomodule test:**
- Each of the cavities individually reached stable operation at its specified field ($E_{pk}$ of 25 MV/m, corresponding to a voltage of 840 kV).
- FE: Improvement after He processing (a few $10^{-5}$ mbar)
- Difficulties with stable simultaneous operation of all cavities at nominal field due to cavity high sensitivity to He pressure variations ($60 \text{ Hz/mbar}$).
  - $\rightarrow$ difficult to compensate with the tuner (strong hysteresis)
- Increase of available RF power from 2 to 4 kW to compensate

**More information:** Poster by A. Perry, MOPO011
Other R&D on low $\beta$ SC cavities

**IPN Orsay:** Triple spoke development for EURISOL. Reference solution to accelerate the p beam between 60 and 140 MeV.

-> Prototype fabricated (352 MHz, $\beta$ 0.35), BCP, HPR and assembly done. To be tested in vertical cryostat in september 2011.

**IAP Frankfurt:** SC CH structure (MYRRHA & CW ion linac). High real-estate gradients for acceleration at low velocities

-> A new prototype fabrication has started, 325 MHz, 7 gaps, beta 0.16.

*More information: poster by M. Amberg MOPO035*
Conclusion

• SC RF developments for low beta ion accelerators is very active worldwide; many projects are under study or construction and drive intense R&D programs on such accelerating structures.

• There are many issues faced by all projects for these structures: field emission, multipacting, tuning capabilities, and all required a dedicated study because all cavities are different (cavity type, beta, coupling or tuning solutions)...

• Progress done are tremendous, and in some cases, peak fields achieved start to be comparable with the ones obtained on electron cavities.
THANK YOU FOR YOUR ATTENTION!

Acknowledgment

Many thanks to all people who provided me material for this presentation