Seamless Quarter-Wave Resonator for HIE-ISOLDE

Silvia Teixeira López
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• The **High Intensity and Energy ISOLDE** (HIE-ISOLDE) project is a major upgrade of the existing ISOLDE and REX-ISOLDE facilities.

• Energy increase of the delivered radioactive ion beam (RIB) **from 3 MeV/u to 10 MeV/u**.

• **SC LINAC based on Quarter Wave Resonators (QWRs).**

• High-β section consists on **4 cryo-modules** with 5 cavities each, installed during the next shut down.
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Quarter-Wave Resonator

- Superconducting Nb/Cu cavity at 4.5 K
- Conduction cooling through the copper substrate (good thermal conductivity of Cu)
- 3D-forged OFE copper
- DC bias sputtering system
- Shrink fit and electron beam welding in the high magnetic field region
- Common vacuum: Beam vacuum = isolation vacuum

<table>
<thead>
<tr>
<th>Frequency</th>
<th>101.28 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{acc}}$</td>
<td>6 MV/m</td>
</tr>
<tr>
<td>$\beta_{\text{optimum}}$</td>
<td>10.9%</td>
</tr>
<tr>
<td>$R/Q$</td>
<td>553 $\Omega$</td>
</tr>
<tr>
<td>$E_{\text{peak}}/E_{\text{acc}}$</td>
<td>5.0</td>
</tr>
<tr>
<td>$B_{\text{peak}}/E_{\text{acc}}$</td>
<td>96 G/(MV/m)</td>
</tr>
<tr>
<td>$G=RsQ$</td>
<td>30.34 $\Omega$</td>
</tr>
<tr>
<td>$U/E_{\text{acc}}^2$</td>
<td>0.207 J/(MV/m)$^2$</td>
</tr>
<tr>
<td>$P_c$ at 6MV/m</td>
<td>10W</td>
</tr>
</tbody>
</table>

- L$^4$He (4.5K)

Superconducting Nb/Cu cavity at 4.5 K

Conduction cooling through the copper substrate (good thermal conductivity of Cu)

3D-forged OFE copper

DC bias sputtering system

Shrink fit and electron beam welding in the high magnetic field region

Common vacuum: Beam vacuum = isolation vacuum

- 300 mm
- 950 mm

July 19th, 2017
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Why a new cavity design?
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A.M. Porcellato, S. Stark, V. Palmieri, F. Stivanello
"Niobium Sputtered QWRs", Proceedings of the 12th International Workshop on RF Superconductivity, Cornell University, Ithaca, New York, USA.

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Features of the previous design

- Inner and outer conductor are welded at the high magnetic field region.

- Beam port noses maximize R/Q, avoid RF leakage through the beam ports and correct the RF defocusing.

- The beam is transversely kicked mainly by the magnetic field. Racetrack-shaped beam ports with an offset from the centre kick it back to the beam axis.
Features of the previous design

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- Beam port noses **maximize R/Q, avoid RF leakage** through the beam ports and **correct the RF defocusing**.

- The beam is **transversely kicked** mainly by the magnetic field. Racetrack-shaped beam ports with an offset from the centre kick it back to the beam axis.

Machining from the bulk = rotational symmetry = no beam port noses
The removal of the noses would cause:

- Dramatic decrease of R/Q.
- Increase of the surface currents at the bottom plate, which increases the RF losses.
- Non-negligible RF leakage through the beam ports.

Wall thickness of only 10 mm at the beam ports.

RF leakage non-negligible.
Seamless design process

- The conical shape on the inner and outer conductor decreases $B_{\text{peak}}$, optimizes $R/Q$ and reduces the RF leakage through the beam ports.
- In order to further reduce RF leakage, extra pieces and shutters have been designed to extend the cut-off length.
- According to a full numerical multi-particle tracking through the whole linac, the vertical steering at high $\beta$ region can be neglected. No need for correction by racetrack.
- As an alternative, beam port tilting was already simulated and it will make the cavity useful at lower $\beta$.

### Table

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Output Energy [MeV/u]</th>
<th>Transmission [%]</th>
<th>Transverse RMS Emittance Growth [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original (a)</td>
<td>14.17</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>high $\beta$ CM (b)</td>
<td>14.2</td>
<td>100</td>
<td>-0.3</td>
</tr>
<tr>
<td>All CM (c)</td>
<td>13.86</td>
<td>85</td>
<td>21.2</td>
</tr>
</tbody>
</table>
RF design

- Full parametrical study.
- Optimization for a higher beta.

The cavity has to be **retuned** after every optimization iteration.

Transition Time Factor (TTF)
Efficiency of acceleration depending on the electric-field structure

\[ V_{\text{acc}} = TTF \times \int_{-\infty}^{\infty} |E_z(z)| \, dz \]

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>QS</th>
<th>QSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [MHz]</td>
<td>101.28</td>
<td>101.28</td>
</tr>
<tr>
<td>( E_{\text{acc}} ) [MV/m]</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>( \beta_{\text{opt}} ) [%]</td>
<td>10.9</td>
<td>12.2</td>
</tr>
<tr>
<td>( R/Q ) at ( \beta_{\text{opt}} ) [Ω]</td>
<td>553</td>
<td>502</td>
</tr>
<tr>
<td>( E_{\text{peak}}/E_{\text{acc}} )</td>
<td>5.0</td>
<td>5.2</td>
</tr>
<tr>
<td>( B_{\text{peak}}/E_{\text{acc}} ) [G/(MV/m)]</td>
<td>96</td>
<td>93</td>
</tr>
<tr>
<td>( G=R_sQ ) [Ω]</td>
<td>30.34</td>
<td>30.1</td>
</tr>
<tr>
<td>( U/E_{\text{acc}}^2 ) [J/(MV/m)^2]</td>
<td>0.207</td>
<td>0.214</td>
</tr>
</tbody>
</table>

The new RF field is broader → Higher TTF at high \( \beta \)

**QSS E-Field**
**QS E-Field**

\( \beta \sim 0.17 \)

→ **Good to use in CM4**
Mechanical design and fabrication

Tolerance study of the geometry determined for an acceptable pre-tuning uncertainty of the resonant frequency.

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<th>Parameters</th>
<th>Sensitivity [kHz/mm]</th>
<th>δ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ_mnt</td>
<td>155</td>
<td>±0.1</td>
</tr>
<tr>
<td>tip gap</td>
<td>16</td>
<td>±0.7</td>
</tr>
<tr>
<td>δ_torus</td>
<td>105</td>
<td>±0.2</td>
</tr>
<tr>
<td>r_taper</td>
<td>28</td>
<td>±0.3</td>
</tr>
<tr>
<td>r_cav</td>
<td>47</td>
<td>±0.2</td>
</tr>
<tr>
<td>δ_tip</td>
<td>105</td>
<td>±0.2</td>
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</tbody>
</table>

The changes to outer dimensions and interfaces were kept to minimum.

New shutters and beam port extensions were designed and manufactured.

A blank test assembly was performed to ensure cavity insertion in the cryomodule.

Cavity manufactured in two steps, first deep drilling, then precise final machining.

A prototype cavity was produced and confirmed the feasibility of the machining with lathe technique.
Cold test (vertical cryostat)
Cold test (vertical cryostat)

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Best cavity in vertical tests since the beginning of the series production!
Future work

• Production of more cavities for a spare cryomodule more statistics.
• Further design optimization.
  • Studies on beam dynamics for the lower energy section of the linac.
  • Low beta version for possible phase 3.
Conclusions

- A seamless QWR has been designed and prototyped, showing the feasibility of machining the cavity out of the bulk.

- The figures of merit of the QSS cavity have been compared to the nominal design (QS) showing a similar performance.

- Trade offs had to be made in terms of RF design, in order to minimize the changes of the interfaces (coating system, handling, cryomodule integration, etc.)

- Due to the increase in cross-section at the cavity top, the conduction cooling was more effective, showing much smaller thermal gradients (uniform cooling).

- The first seamless cavity produced (QSS1) displayed excellent RF performance.

- This cavity will be installed in CM4.
Thank you for your attention.

Questions?