Status of the superconducting cavity development at RISP.

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I. Introduction
What is the accelerator?

- An accelerator is a machine that accelerates the charged particles by applying the electromagnetic fields.
- To transfer the energy to the particles, the electric field must be applied along the designated beam line.
- The accelerator is essentially the capacitor.
• The modern accelerators use the RF (radio frequency) technology and superconductors

Alternating accelerating voltage makes the high energy acceleration available.

\[ V = V_0 \sin(\omega t + \phi) \]

The frequency reaches radiofrequency (microwave frequency, in particular) as the particle velocity increases

• Superconductor introduces the cryogenic system into the accelerator.

Extremely low resistance of the superconductor enables the much more efficient acceleration with the smaller heat loss
Superconducting linac

High vacuum @ $10^{-9}$ Torr

LHe @ 2 or 4 K

Solid state amplifier

Power coupler

Helium vessel

Cavity

Slow tuner

Beam axis
RAON: The heavy ion accelerator at RISP

- The design is based on the acceleration of the uranium U+33 and U +34 from 0.5 MeV/u to 200 MeV/u with the current 8.3 pμA.
- For efficient acceleration, charge stripper section is inserted in the midway, dividing driver linac into SCL1 and SCL2.
- For more efficient acceleration, SCL1,2 are further divided into the subsections of SCL11,SCL12 and SCL21, SCL22, respectively.
- SCL3 (Post Accelerator) has the same structure as SCL1.
In each subsection, the ions are accelerated by a different kind of the SC with associated nominal beta as determined by beam dynamics study.

<table>
<thead>
<tr>
<th>subsection</th>
<th>cav.type</th>
<th>cav/cm</th>
<th>cm no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCL11</td>
<td>QWR</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>SCL12</td>
<td>HWR</td>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td>SCL21</td>
<td>SSR1</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>SCL22</td>
<td>SSR2</td>
<td>6</td>
<td>23</td>
</tr>
</tbody>
</table>
Superconducting cavities of the RISP

Parameters of the resonators

<table>
<thead>
<tr>
<th>parameters</th>
<th>QWR</th>
<th>HWR</th>
<th>SSR1</th>
<th>SSR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$ (MHz)</td>
<td>81.25</td>
<td>162.5</td>
<td>325</td>
<td>325</td>
</tr>
<tr>
<td>$\beta_g$</td>
<td>0.047</td>
<td>0.12</td>
<td>0.3</td>
<td>0.53</td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>20</td>
<td>20</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>$E_{peak}$ (MV/m)</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Temp. (K)</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
2. Design of the HWR
Performance of the Superconducting cavity: Figures of merit

- Efficient machine, i.e., maximum accelerating gradient with the minimum power supplied.
- The efficiency is characterized by three quantities, i.e. $Q_0$, $R/Q_0$, $TTF$

$$Q_0 = \frac{\omega U}{P_{wall}}, \quad R/Q_0 = \frac{V_{acc}^2}{\omega U}, \quad T(\beta) = \frac{\int \vec{E} \cdot \vec{v} dt}{\int \vec{E} \cdot d\vec{l}}$$

- Once the efficiency is established, one could power up to obtain the maximum gradient, but there is a limit

$$E_{peak}, B_{peak}$$
Electromagnetic design

- Beam dynamics study determines the approximate no. of cavities and the accelerating gradients. For example, SCL12 needs ~120 HWR with the accelerating voltage ~1.3 MV.
- The frequency roughly determines the height of the cavities

\[
Z_I = Z_0 \frac{Z_L + iZ_0 \tan k(z_l - z_i)}{Z_0 + iZ_L \tan k(z_l - z_i)},
\]

\[
H_{cav} = \frac{\lambda}{2}
\]

- Beta and the frequency roughly determines the gap to gap distance of the cavities

\[
d = \frac{\beta \lambda}{2}
\]
• EM design is done by 3D FEA (Finite element analysis) code that optimizes the figures of merit while sweeping the design parameters

**R_{bottom} sweep**

**R_{out} sweep**

**R_{top} sweep**

**R_{ring} sweep**
$H_{cav}$ sweep

TTF vs. beta
Final specification of the HWR

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>Value (mm)</th>
</tr>
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<tbody>
<tr>
<td>$H_{\text{cav}}$</td>
<td>920</td>
</tr>
<tr>
<td>$R_{\text{outer}}$</td>
<td>120</td>
</tr>
<tr>
<td>$d$</td>
<td>100</td>
</tr>
<tr>
<td>$g$</td>
<td>35</td>
</tr>
<tr>
<td>$R_{\text{top}}$</td>
<td>45</td>
</tr>
<tr>
<td>$R_{\text{bottom}}$</td>
<td>21</td>
</tr>
<tr>
<td>$R_{\text{ring}}$</td>
<td>60</td>
</tr>
<tr>
<td>$R_{\text{nose}}$</td>
<td>60</td>
</tr>
</tbody>
</table>

Perspective view of the HWR  Design parameters of the HWR
Electromagnetic fields of the HWR

Electric field distribution

Magnetic field distribution

Longitudinal field distribution of the HWR
• Asymmetry of the transverse (quadrupole) component of the E-field was investigated by obtaining $E_z - E_y$ at 10mm away from the beam axis, which must be zero if the transverse field were symmetric. The difference is about 1% of the longitudinal component.
Optimal figures of merit of the HWR

<table>
<thead>
<tr>
<th>figures of merit</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_0$</td>
<td>$4.10E+09$</td>
</tr>
<tr>
<td>$R/Q_0$</td>
<td>316.2 Ohm</td>
</tr>
<tr>
<td>TTF</td>
<td>0.89</td>
</tr>
<tr>
<td>$E_p$</td>
<td>35 MV/m</td>
</tr>
<tr>
<td>$B_p$</td>
<td>52.2 mT</td>
</tr>
<tr>
<td>$V_{acc}$</td>
<td>1.4 MV</td>
</tr>
<tr>
<td>$P_w$</td>
<td>1.5 W</td>
</tr>
</tbody>
</table>

Figures of merit (HWR)

The peak field values are sensitive to the meshing and thus determined by a larger number of the meshes with the use of 3 symmetry planes.
Error study

Axial component of the accelerating gradient

Beam axis

1% error

6 mm

1% error

2 mm

1% error

1 mm

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Only one gap (RHS) is deformed

Transverse (Vertical) component of the accelerating gradient

0.1 mm

10%

0.12 mm

10%
Multipactation

Electron source

Multipacting electrons

Schematic of the multipaction

- The enlarging the flat region may spread the electrons disrupting the resonance
- Increased $R_{\text{top}}$ from 50 mm to 45 mm.

Multipacting factor vs. gradient scale factor

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Interface to the Coupler

In over-coupling, the power needed to maintain the constant accelerating voltage is given by

\[
P = \frac{V_{\text{acc}}^2}{4 R Q Q_{\text{ext}}} \left[ \left( 1 + \frac{R}{Q} Q_{\text{ext}} \frac{I_b}{V_{\text{acc}}} \cos \phi_b \right)^2 + \left( 2 Q_{\text{ext}} \frac{\Delta f}{f_0} + \frac{R}{Q} Q_{\text{ext}} \frac{I_b}{V_{\text{acc}}} \sin \phi_b \right)^2 \right].
\]

where \( I_b \) is the beam current, \( \phi_b \) is the accelerating phase.

With the bandwidth \( 2\Delta f=80 \) Hz, \( R/Q_0=317 \), \( Q_{\text{ext}}=2.03e6 \), \( I_b\sim0.7 \) mA, and \( \phi_b \), the power is computed as \( P=1.5 \) kW.
Mechanical design

- As a RF device with a narrow bandwidth, SC is very sensitive to the mechanical deformation.

Fabrication

- Clamp-up
- Trimming (in clamp-up)
- Welding
- BCP
- Evacuation
- (plastic) Tuning

Operation

- Cool down
- Lorentz detuning
- Tuner implementation
- Helium pressure fluctuation
Trimming/welding shrinkage

- Frequency shift rate = 272 kHz/2mm

Trimming of the straight section

Frequency vs. trimming

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Polishing

- frequency shift rate = 48.4 kHz/0.1 mm
- The polishing is done by 0.15 mm

Polishing the inner surface

Frequency vs. etch depth
Pressure sensitivity

The stiffeners were introduced and optimized for the minimum deformation against the pressure.

The doubler

The gussets

Frequency shift: 0.27 kHz/bar

B.C: fixed ports

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Cool down

To overcome the thermal contraction difference between cavity (Nb) and the helium vessel (SS 304L), the bellows were introduced.

As an approximation, fixed b.c applied.

The deformation due to cooldown from room temp. to 2K

Maximum deformation of 1.1mm @ toroids

The first principal stress due to cooldown from room temp. to 2K

Maximum stress of 533MPa @ beam ports

Frequency shift: 2.7kHz
Interface to the tuning system
3. Fabrication of the HWR
Fabrication procedure

Material Acceptance

Forming

Welding

Polishing

Evacuation

RF test

Deep drawing, 3D measurement

Machining, (Part) Polishing, (Part) Welding, Clamp-up test, Final welding, Leak check, RF test

BCP, RF test, High temperature annealing, Light etching, Rinsing, HPR

Assembling, Leak check, HPR, Evacuation, RF test

Low temperature baking, (plastic) RF tuning
Anomalous behavior of the cavity

• The origins of these anomalous behaviors trace mostly back to the fabrication imperfections.
The field emitters

Microscopic particles

C, O, Na, In, Al, Si

Geometrical defects

Pit diameter ~ 400 μm

Chemical contaminant

N, O, S, Fe

The quenchers

Normal conducting impurity

Geometrical defects (pit)

Courtesy R.L. Geng
Inspection

<table>
<thead>
<tr>
<th>Grain size</th>
<th>&lt;4 ASTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRR</td>
<td>&gt;300</td>
</tr>
<tr>
<td>Recrystallization</td>
<td>100</td>
</tr>
</tbody>
</table>

Specifications of Nb

Grain structure of Nb

DI (deionized) water dipping

Rust
Forming

Pressing the outer conductor

Pressing the re-entrant nose

Press jig for re-entrant nose

Pressing jig for the upper toroid

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Formed parts of the cavities

Re-entrant nose

Ring

Inner conductor

Outer conductor
EBW (Electron beam welding)

Front bead of the outer housing

Back bead of the outer housing

The ring fixed in welding jig

Front bead of the ring

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Beam Size</th>
<th>Frequency</th>
<th>Focus</th>
<th>Distance</th>
<th>Feed rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 kV</td>
<td>1 × 0.5</td>
<td>4999 Hz</td>
<td>-120 mA</td>
<td>641 mm</td>
<td>5 mm/s</td>
</tr>
</tbody>
</table>

Current of welding

Ø138 Radian (21 mA → 20.5 mA)

Welding condition for the ring welding

Front bead of the ring
RRR test after welding

Welding at $2 \times 10^{-6}$ Torr

- 9% Reduction at $2 \times 10^{-5}$ [At lowest value]
- 5% Reduction [Avg value]

3mm Nb with $\text{RRR} > 300$

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Clamp-up test of Copeer QWR

Frequency shift = -71 kHz/mm  
(Simulation)

Before trimming  
80.734 MHz

After trimming (6.5 mm)  
81.272 MHz

After Upper end welding  
81.363 MHz

After Lower end welding  
81.32 MHz

Frequency shift = -83 kHz/mm  
(Experiment)

Frequency (Mhz) vs. cavity height (mm)
BCP (Buffered chemical polishing)

- Standard chemical composition
  \[ \text{HF: HNO}_3 : \text{H}_3 \text{PO}_4 = 1:1:2 \text{ (volume)} \]
- Etching rate= 1 micron/min @ 20C

Spoke before BCP

Spoke after BCP

- We plan to polish the surface by 20 µm before the welding, 150 µm for bulk polishing and again 10 µm for the light etching.
4. Test in preparation......
Bakcups
Lorentz detuning
Brazed ports