DEVELOPMENT OF SC-QWR AND ITS CRYOMODULE FOR LOW-BETA ION ACCELERATORS AT RIKEN RIBF

Naruhiko Sakamoto
RIKEN Nishina Center
Outline

1. Introduction

2. Development of SC-QWR

3. Development of Prototype Cryomodule

4. RIKEN Linac Upgrade (SRILAC)

Summary
(1) New Injector SC-Linac for RIBF (K. Yamada, SRF2013)

- SC-Linac (73.0 MHz), 14 cryomodules, L=43 m
- 1.4 MeV/u
- 11 MeV/u
- 56 SC-QWRs (73.0 MHz)/14 CMs
- \(^{238}\text{U}^{35+}\) 11 MeV/u, 1 mA
- Cyclotrons
SC-LINAC PROJECTS AT RIBF

(1) New Injector SC-Linac for RIBF (K. Yamada, SRF2013)

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(2) ImPACT Program (N.S., SRF2015, 2017)

- Nuclear transmutation via nuclear reaction
- Prototype CM
  SC-QWR(75.5 MHz)

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3/July/2019
SC-LINAC PROJECTS AT RIBF

(1) New Injector SC-Linac for RIBF (K. Yamada, SRF2013)

- 1.4 MeV/u SC-Linac (73.0 MHz), 14 cryomodules, L=43 m
- 11 MeV/u

14 cryomodules

Rebuncher

RFQ

SC-ECRIS

Cyclotrons

RT-cavities (36.5 MHz)

(2) ImPACT Program (N.S., SRF2015, 2017)

Nuclear transmutation via nuclear reaction

Prototype CM

SC-QWR (75.5 MHz)

(3) SRILAC (N.S., LINAC2018)

Super Heavy Element synthesis (Z>118)

10 SC-QWRs (73.0 MHz)/3 CMs

A/q=6 6.5 MeV/u, 10 pμA

2016-

2014-2019

2013-
Prototype SC-QWR(75.5 MHz)

- Quarter-Wave resonator with an optimum β 0.08
- Slow tuner compressing the acceleration gaps
- Side test ports for block tuner
- BCP for surface processing (RRR 250 TD): $Q_0 \times 10^8$

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>75.5 (CW)</td>
</tr>
<tr>
<td>Optimum $\beta$</td>
<td>0.08</td>
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<tr>
<td>$R_{sh}/Q_0$ (Ω)</td>
<td>578</td>
</tr>
<tr>
<td>$G$ (Ω)</td>
<td>23.5</td>
</tr>
<tr>
<td>$V_{acc}$(MV)</td>
<td>1.44</td>
</tr>
<tr>
<td>$E_{acc}$ (MV/m)</td>
<td>4.5</td>
</tr>
<tr>
<td>$E_{peak}/E_{acc}$</td>
<td>6.2</td>
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<tr>
<td>$B_{peak}/E_{acc}$ (mT/(MV/m))</td>
<td>9.7</td>
</tr>
<tr>
<td>Operating Temperature(K)</td>
<td>4</td>
</tr>
<tr>
<td>Target $Q_0$(Rs=25 nΩ)</td>
<td>$\times 10^8$</td>
</tr>
</tbody>
</table>

Diagram:
- Quarter-Wave resonator with an optimum $\beta$ 0.08
- Slow tuner compressing the acceleration gaps
- Side test ports for block tuner
- BCP for surface processing (RRR 250 TD): $Q_0 \times 10^8$

3/July/2019 SRF’19 @Dresden
Surface processing (BCP, Annealing, HPR) facility has been developed by MHI-MS.
## Performance of Cavity

- BCP(100 μm) → Annealing(750°C, 3hr) → BCP(20 μm) → Baking(120°C, 48hr)

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Measurement was performed at KEK.

![View of Test Facility](image_url)
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<tr>
<td>VT4</td>
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<td>-</td>
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→ Cavity was assembled to the test cryomodule.
  - Cool-down test
  - RF Test (Reported in SRF’17)

Study of cavity performance was continued.
→ Cavity was disassembled from the test cryomodule.
→ Design modification was made to the SRILAC cavities.
1. Introduction

2. Development of SC-QWR

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Summary
Why the cavity got degraded?

- During conditioning of multipacting temperature rise of the blank flange of the test port was observed.
Why the cavity got degraded?

- During conditioning of multipacting temperature rise of the blank flange of the test port was observed.
- Vacuum seal of the side test port (U-TIGHTSEAL) was found seriously damaged after VT4.
Performance of Cavity

- BCP(100 μm) → Annealing(750°C, 3hr) → BCP(20 μm) → Baking(120°C, 48hr)

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<td>D26.5 +21.5</td>
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- Clean up the flange surfaces
- Exchange U-TIGHTSEAL
- Differential Etching + BCP2+HPR+Baking

Measurements were performed at KEK.
Performance of Cavity

BCP(100 μm) → Annealing(750°C, 3hr) → BCP(20 μm) → Baking(120°C, 48hr)

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- Clean up the flange surfaces
- Exchange U-TIGHTSEAL
- Differential Etching + BCP2+HPR+Baking

The cavity yielded Q₀ 4.5 times of that of VT2

Measurements were performed at KEK.
Differential Etching

- Frequency tuning during fabrication is time-consuming.
- One effective way of frequency tuning is differential etching.

L. Popielarske et al., Linac’12, MOPB071

- The frequency shift was estimated by MWS simulations.

Differential etching of 26 μm increased the frequency by 12.6 kHz at 4K.
Side Test Ports for Frequency Tuning

- Frequency tuning during fabrication requires a lot of attention.
- Cold tuner adjusts the frequency at 4.5 K with an order of 0 to -10 kHz squeezing beam ports with 5,000 N.
- During operation, cold tuner trims frequency detuning due to variation of He pressure, microphonics, Lorentz force detuning, beam loading, and etc. within a bandwidth of ±60 Hz.

![Illustration of Side Test Ports](image)

- A pair of plug lowers the frequency with an order of a few 10 kHz.
- Plugs machined with high precision can adjust the frequency within 1 kHz.
- Possibility as a dynamic tuner: $\Delta f/\Delta t = $ a few kHz/mm.
Performance of Cavity

BCP(100 μm)→Annealing(750°C, 3hr )→BCP(20 μm)→Baking(120°C, 48hr)

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<td>1.9x10⁸</td>
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</table>

Measurements were performed at KEK.

Plug tuner degrades $Q_0$ to 1/10 of that of VT5

Observed frequency shift 27.2 kHz while the estimation was 23.4 kHz.
Design modification of the cavity for the SRILAC.
Frequency 75.5 MHz → 73.0 MHz
Removal of the side test ports

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<tr>
<th>Parameters</th>
<th>Prototype</th>
<th>SRILAC</th>
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<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>75.5 (CW)</td>
<td>73.0 (CW)</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Height [mm]</td>
<td>1055</td>
<td>1103</td>
</tr>
<tr>
<td>Optimum $\beta$</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>$L_{cav}$ (mm)</td>
<td>318</td>
<td>320</td>
</tr>
<tr>
<td>$E_{peak}/E_{acc}$</td>
<td>6.0</td>
<td>6.2</td>
</tr>
<tr>
<td>$B_{peak}/E_{acc}$(mT/(MV/m))</td>
<td>9.5</td>
<td>9.79.6</td>
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<tr>
<td>$R_{sh}/Q_0$ (Ω)</td>
<td>578</td>
<td>579</td>
</tr>
<tr>
<td>$G$ (Ω)</td>
<td>23.5</td>
<td>22.4</td>
</tr>
<tr>
<td>$V_{acc}$(MV)</td>
<td>1.44</td>
<td>2.16</td>
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<tr>
<td>$E_{acc}$ (MV/m)</td>
<td>4.5</td>
<td>6.8</td>
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<tr>
<td>$Q_0@E_{acc}$</td>
<td>$2.3\times10^9$</td>
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<tr>
<td>$P_0@E_{acc}$ (W)</td>
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</tr>
<tr>
<td>$Q_{pickup}$</td>
<td>$2.8\times10^{11}$</td>
<td></td>
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Measurements were performed at KEK.
# Modification of the cavity design

- **Design modification of the cavity for the SRILAC.**
  - Frequency $75.5 \text{ MHz} \rightarrow 73.0 \text{ MHz}$
  - Removal of the side test ports

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Measurements were performed at KEK.

![Diagram showing cavity design and parameters](image)

**Diagram:**
- **Prototype**
- **SRILAC**

**Side Test Ports:**
- **Prototype Target**
- **SRILAC Target**

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

- **VT5**
- **Prototype**
- **SRILAC**
All the ten SC-QWRs showed almost comparable performances in terms of the prototype cavity for the SRILAC.
History of Frequency Tuning

1. Jacketing
2. FPC
3. Vacuum
4. Cooldown
5. Helium Pressure
6. Tuner

Frequency [kHz]

-5 kHz

Pretuning

MOP055: K. Suda et al.

Δf/ΔL = ~18 kHz/mm
1. Introduction

2. Development of SC-QWR

3. Development of Prototype Cryomodule

4. RIKEN Linac Upgrade (SRILAC)

Summary
Prototype Cryomodule

- The operating temperature is **4K**.
- The cavity is enfolded in the helium jacket made of titanium.
- Local magnetic shield is attached on the helium jacket.
- A pair of fundamental power couplers with double window was developed to accept 10 kW rf power.
- The cryostat vacuum vessel is equipped with a thermal shield cooled by CH-110 77K Cryocooler instead of utilizing liquid nitrogen.
- Propping up structure: Cavities are mounted on the common frame.

After the series study, the prototype cavity was integrated to the prototype cryomodule again.
Cryomodule Assembly (ISO Class 1)
Cool-down and RF Test

- Cryomodule was cooled with liquid helium supplied from helium dewars.
- Long-term operation was attempted at the cave of the linac bldg.
Long-Term RF Test

- 12 hr operation at 4.75 MV/m
- Liquid helium was supplied from 1000 l dewar.
- Frequency of the signal generator was manually tuned.
- Newly developed LLRF based on FPGA
- Solid state amplifier (4.5 kW)
Long-Term RF Test

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- Long term stability of pickup level (Pt) was within ±0.1%
- Phase error observed was within ±1 deg.
- X-ray level was about 0.8 μSv/h

Reliability with a criteria $\frac{\Delta E_{\text{acc}}}{E_{\text{acc}}} \leq \pm 0.1\%$ was 95%
Observation of Microphonics

- Vibration of the cryo-cooler excited the mechanical vibration.
- Microphonics are clearly observed as phase oscillation.

40 Hz : Predicted
250 Hz: Other part?

TUP042: O. Kamigaito et al.
Slow Tuner

- Frequency is lowered by squeezing accelerating gaps.
- $\Delta f/\Delta L = 20$ kHz/mm
- Frequency shift vs. rotation number of the handle was measured at 4K.

Mechanical loss was rather large $\rightarrow$ New design for SRILAC cavities
1. Introduction

2. Development of SC-QWR

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4. RIKEN Linac Upgrade (SRILAC)

Summary
Upgrade of RIKEN Linac

- For 113 experiment $^{70}\text{Zn}^{14+}$ ($A/q = 5$) was accelerated to 5 MeV/u.
- The RILAC is going to have upgrade aiming to continue super heavy element (SHE) search experiment challenging the 8th row of the periodic table of elements ($A>119$).
- Upgrade goal: Ions $A/q = 6$ will be accelerated up to 6.5 MeV/u.
- The last four RT-DTL tanks were replaced by high-performance superconducting linac based on quarter wave resonator.
- RIKEN SC-ECR provides intense metal ions.
Upgrade of RIKEN Linac

- For 113 experiment $^{70}$Zn$^{14+}$ ($A/q = 5$) was accelerated to 5 MeV/u.
- The RILAC is going to have upgrade aiming to continue super heavy element (SHE) search experiment challenging the 8th row of the periodic table of elements ($A > 119$).
- Upgrade goal: Ions $A/q = 6$ will be accelerated up to 6.5 MeV/u.
- The last four RT-DTL tanks were replaced by high-performance superconducting linac based on quarter wave resonator.
- RIKEN SC-ECR provides intense metal ions.
# Design Modification of Cryomodule

<table>
<thead>
<tr>
<th>ITEMS</th>
<th>Prototype</th>
<th>SRILAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>75.5 (c.w.)</td>
<td>73.0 (c.w.)</td>
</tr>
<tr>
<td>Operating Temp.(K)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>#of cavities</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Length(mm)</td>
<td>1337</td>
<td>2200</td>
</tr>
<tr>
<td>Cold Focusing Element</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Shape</td>
<td>Cylinder</td>
<td>Rectangler</td>
</tr>
<tr>
<td>Material</td>
<td>Stainless Steel</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td>Thermal Shield(K)</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Local Magnetic Shield</td>
<td>On the helium jacket</td>
<td>Inside the jacket</td>
</tr>
<tr>
<td>Thermal Shield Cryo-cooler</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Liquid N2</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Cavity Intervals</td>
<td>420</td>
<td>430</td>
</tr>
<tr>
<td>Static Heat Load(W)</td>
<td>3.6</td>
<td>18</td>
</tr>
<tr>
<td>Cavity Support</td>
<td>Propping up</td>
<td>Propping up</td>
</tr>
<tr>
<td>Platform</td>
<td>Common frame</td>
<td>Bottom plate</td>
</tr>
</tbody>
</table>
Cryomodule for the SRILAC

- Operation temperature is **4K**.
- Cryostat chamber maintain the cold mass which consists of cavities, helium vessel, FPCs, magnetic shields, dynamic tuner 4K with 80 K shield.
- Cavities are supported by four pillars on the rigid **bottom base plate**.

**Static Heat Load** to 4K: **18 W**
- FPC: 6 W
- Helium pipes: 4.5 W
- Tuner: 2.5 W
- Cavity support: 2 W

- Liquid helium cryogenic system using a HELIAL MF refrigerator (Air Liquide) with **600 W** cooling power.
- Carbon steel vessel → Magnetic field shielding
**Cryomodule for the SRILAC**

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- FPC: 6 W
- Helium pipes: 4.5 W
- Tuner: 2.5 W
- Cavity support: 2 W

**Liquid helium cryogenic system** using a HELIAL MF refrigerator (Air Liquide) with 600 W cooling power.

**Height from the floor [m]**
- At Beam Line Level:
  - 1.0: 13.56 (41.08) 10.34 (40.94)
  - 1.2: 12.88 (41.70) 12.47
  - 1.3: 12.32 (41.21) 12.69
  - 1.4: 12.03 (40.00) 12.74
  - 1.6: 11.99 (40.40) 12.36 (39.40)
  - 2.0: 11.83 (39.51) 11.25
  - 2.1: 11.56 (40.34) 10.75
  - 2.2: 11.33 (39.72) 10.46
  - 2.3: 11.23 (39.95) 10.38
  - 2.4: 11.53 (39.85) 10.49

- 1.0 → 2.4 m

**Magnetic Field [μT]**

<table>
<thead>
<tr>
<th>Height from the floor [m]</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>11.53 (39.85)</td>
<td>10.49</td>
</tr>
<tr>
<td>2.3</td>
<td>11.23 (39.95)</td>
<td>10.38</td>
</tr>
<tr>
<td>2.2</td>
<td>11.33 (39.72)</td>
<td>10.46</td>
</tr>
<tr>
<td>2.1</td>
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<td>10.75</td>
</tr>
<tr>
<td>2.0</td>
<td>11.83 (39.51)</td>
<td>11.25</td>
</tr>
<tr>
<td>1.8</td>
<td>12.06 (40.49)</td>
<td>12.00</td>
</tr>
<tr>
<td>1.6</td>
<td>11.99 (40.40)</td>
<td>12.36 (39.40)</td>
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<td>1.0</td>
<td>13.56 (41.08)</td>
<td>10.34 (40.94)</td>
</tr>
</tbody>
</table>

@Beam Line Level
Local Magnetic Shield

- After pre-tuning Ti jacket and μ-metal magnetic shield was installed.
- Local magnetic shield is placed inside the helium jacket
  - Simple structure with a good shielding
  - Easy handling

Frequency Tuner
Fundamental Power Couplers

- Single-RT-window
- Coupling tunable: $Q_{\text{ext}}$: from $1 \times 10^6$ to $4.5 \times 10^6$
- A pair of FPCs were conditioned with 5 kW RF power of CW and traveling wave mode.
- Cleaning of the coupler and assembling to the test resonator were performed in the ISO class 1 clean room.

Photos of FPC  Conditioning Resonator  Schematic of FPC

Warm Window

80 K 10 cm
Cryomodule Assembly at ISO Class 1
Construction Status

✓ Installation and alignment of cryomodules
✓ Installation of helium refrigerator and transfer line
✓ Inspection by Saitama prefecture

Installation of the control system is underway.
First cooling down will be started in August.
Beam pipes and a pair of differential pumping system will be installed in this September.
Summary and Perspective

Prototype Superconducting Linac

- R&D of Superconducting Cavity started since 2013 at RIKEN
- First prototype cavity achieved $Q_0 \ 2 \times 10^9$ successfully.
- Newly developed RF system worked well.

RIKEN Linac upgrade

- RIKEN heavy ion linac will have acceleration voltage and intensity
- Upgrade by introducing a superconducting linac based on high performance SC-QWRs and SC ECR ion-source.
- Ten SC-QWRs were fabricated and processed. All the cavities have a good performance.
- Three cryomodules were assembled and installed to the linac bldg.
- Construction of the control system is underway.
- Cooling test will be made in August.
- SC-ECR will be ready by the end of October.

Beam commissioning is scheduled in the third quarter of FY2019
Related Papers

**Cavity Fabrication-MOP055**: K. Suda *et al.*, RIKEN Nishina Center, “Fabrication and Performance of Superconducting Quarter-Wavelength Resonators for SRILAC”

**Cavity Protection-TUP013**: H. Imao *et al.*, RIKEN Nishina Center, “Non-evaporable Getter-based Differential Pumping System for SRILAC at RIBF”

**Construction Status-TUP037**: K. Yamada *et al.*, RIKEN Nishina Center, “Construction of Superconducting Linac Booster for Heavy Ion Linac at RIKEN Nishina Center”

**Microphonics-TUP042**: O. Kamigaito *et al.*, RIKEN Nishina Center, “Measurement of mechanical vibration of SRILAC cavities”
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Thank you for your attention.