Commissioning and Operation of
RIKEN Heavy Ion
Superconducting Linac

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1. Overview of RIKEN Heavy Ion SC-Linac(SRILAC)

2. Commissioning

3. Operational experience in 2020

Summary
Collaborators


RIKEN Nishina Center

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KEK

- Cavities and cryomodules were constructed by MHIMS
- LLRF and Solid State Amplifiers were developed by Thamway Co.
- He refrigerator and Compressor were from Air Liquide and Maekawa, respectively.
The RIKEN Heavy-Ion Linac (RILAC) upgrade was performed to allow it to further investigate super-heavy elements beyond Nh.

- The new element Nh was synthesized by bombarding a $^{209}$Bi target with an intense $^{70}$Zn$^{14+}$ beam with an energy of $5 \text{ MeV/u}$ accelerated by the RILAC, which was upgraded by adding a booster linac comprising six DTLs.

- The Superconducting RILAC (SRILAC) was introduced by replacing the latter 4 DTLs of the booster linac so that ions (A/q=6) are accelerated to $6.5 \text{ MeV/u}$.

- Construction: 2016—2019
- First cool down: October 2019
- First beam acceleration test: $^{40}$Ar$^{13+}$ 6.2 MeV/u in January 2020

1) O. Kamigaito et al., RSI 76 013306(2005)
SC-ECR

RILAC

Transfer Line

Joint Box and Cold Box

Cryomodules

Courtesy of T. Nagatomo
Overview of SRILAC

- Three Cryomodules host 10 SC-QWRs (CW, 73 MHz).
- RT Quadrupole magnets are located in the MEBT.
- Vacuum pressure of MEBT line is about $1 \times 10^{-8}$ Pa with IP and NEG pumps.
- At the both end of the SRILAC three-stage differential pumping systems (DPS) are introduced to prevent gas flow from RT section where several $10^{-5}$ Pa.

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**Design view of the differential pumping system**

- 1st stage: **TMP**(HiPAce700:Pfeifer) w/ dry roughing pump(NeoDry60E;Kashimaya) + **Cryogenic pump**(CRYOU6H;ULVAC)
- 2nd stage: **ZAO**(Capacitor HV1600;SAES) + **IP**(Valcon Plus 200:Agilent)
- 3rd stage: **UHV ZAO**(Capacitor Z400;SAES)

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- Maximum acceleration gradient : 6.8 MV/m w/ \( \phi_s = -25 \text{ deg.} \)
- Local magnetic shield is placed inside the He vessel.
- The tuner coarsely changes the resonant frequency to 73 MHz ( – 14 kHz) and dynamically compensates the frequency due to He pressure deviation and Lorentz detuning.

\[
\Delta f / \Delta p_{\text{He}} = -2 \text{ Hz/hPa} \quad \Delta f = -35 \text{ Hz} @ E_{\text{acc}} = 6.8 \text{ MV/m}
\]

3) K. Suda et al., TTC2020

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### Performance of QWRs for SRILAC

- Bulk Nb (RRR 250) with BCP based Surface processing
  
  BCP(100 μm)→Annealing(700° C, 3hr)→BCP(20 μm)→Baking(120° C, 48hr)

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>73.0 (c.w.)</td>
</tr>
<tr>
<td>Optimum β</td>
<td>0.08</td>
</tr>
<tr>
<td>$R_{sh}/Q_0$ (Ω)</td>
<td>579</td>
</tr>
<tr>
<td>$G (=R_{sh}/Q_0)$</td>
<td>22.4</td>
</tr>
<tr>
<td>$V_{acc}$ (MV)</td>
<td>2.2</td>
</tr>
<tr>
<td>$E_{acc}$ (MV/m)</td>
<td>6.8</td>
</tr>
<tr>
<td>$E_{peak}/E_{acc}$</td>
<td>6.2</td>
</tr>
<tr>
<td>$B_{peak}/E_{acc}$ (mT/(MV/m))</td>
<td>9.6</td>
</tr>
<tr>
<td>Operating Temperature (K)</td>
<td>4</td>
</tr>
<tr>
<td>Target $Q_0$</td>
<td>$1 \times 10^9$</td>
</tr>
</tbody>
</table>

### Diagram

- No emission!

- $6.8$ MV/m

- $B_{bg} < 10$ mG

- SRILAC Goal

- 4K
Cryomodule for SRILAC

- Operating temperature: **4.5 K**.
- 80 K Thermal shield with Liquid N₂
- He Ports: Pre-cooling port, Supply port, Return-port
- Heat load estimation: 18 W/Cryomodule (not confirmed)
  - FPC: 6 W, Helium pipes: 4.5 W, Tuner: 2.5 W,
  - Cavity support: 2 W
- Liquid helium cryogenic system
  - HELIAL MF (Air Liquide)
  - + MYCOM Compressor (Maekawa)
- Cooling capacity: **700 W@4.5 K**

*Electric power consumption of the compressor is 300 kW Cavity vacuum is separated from isolation vacuum.*

- Cavities are mounted on the bottom base plate
- Single RF window FPC

Opening of the supply valve controls liquid helium level.

Opening of the return valve controls He pressure.
2. Commissioning
First Cooldown Test

Cool-down process was initiated on September 11, 2019 for the first time and the liquid-He level of the CM tanks finally reached the target levels on September 14, 2019 without any serious troubles.

Liquid-He level was controlled by adjusting the supply-valve opening and the absolute pressure of the HE was stabilized to be 125.9 ± 0.3 kPa by controlling the return-valve.

After cool-down test, on November 17, 2019 vacuum leak from coupler window (SC05) occurred before high power RF test. 4) K. Ozeki et al., TTC2020
Q_{ext} and Tuners

- All the cavity had resonant frequency in the tuner range at 4.5 K.

- $Q_{ext}$ was set $1.5-2.0 \times 10^6$ by adjusting the coupler antenna position.

![Diagram of a cavity system with a focus on Q_{ext} and tuners]

- Gear box
- Three stages of gears (each 1:4)
- Total ratio 1:64
- Rotary encoder at the 2nd stage

- Stepping motor
- Drive shaft
- Drive plate
- Support plate (Ti)
- Ti Jacket (Cavity, Mag. shield, Inside)
- Vacuum seal (magnetic fluid)
- Blank flange on beam port
- Wire

4) K. Suda et al., SRF2019, TTC2020
Auto-Tune Control

- Tuners are dynamically driven according to the phase \( \Delta \phi = \phi_{\text{ref}} - \phi_{\text{in}} \).
- Tuning Motor is activated when \( |\Delta \phi| \) exceeds 15 deg.
Microphonics

- Processing of multipacting below 0.1 MV/m was successfully performed.
- Microphonics are observed in pickup signal of the cavity.
- LLRF feedback loop controls amplitude and phase of the cavity RF field well.

![Power spectrum of the cavity pickup signal](image1)

PLL ON

![Power spectrum of the cavity pickup signal with PLL ON](image2)
Before opening gate valves of the both end of the cryomodules for the first time, field emission was measured.

For SC02,06,07,09,10 showed field emission below $E_{\text{acc}}=2.5$ MV/m.
Phase scan (i.e. energy measurement by changing RF phase) was performed.

Ar beam was accelerated to 6.2 MeV/u on January 28, 2020 for the first time.

The correction of the absolute value of the accelerating voltage was within ±10%.
### Correction of pickup ratio

**40Ar^{13+}, 6.2 MeV/u**

Gap voltage calculated with a pickup ratio obtained from VT

<table>
<thead>
<tr>
<th>Cavity</th>
<th>$V_g$ (kV)</th>
<th>$E_{acc}$ (MV/m)</th>
<th>$E_{in}$ (MeV/u)</th>
<th>$E_{out}$ (MeV/u)</th>
<th>$V_{actual}$</th>
<th>Correction</th>
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<tbody>
<tr>
<td>SC01</td>
<td>1130</td>
<td>3.18</td>
<td>3.61</td>
<td>3.91</td>
<td>1064.1</td>
<td>1.06</td>
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<td>SC02</td>
<td>1130</td>
<td>3.18</td>
<td>3.91</td>
<td>4.21</td>
<td>1090.2</td>
<td>1.04</td>
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<td>1130</td>
<td>3.18</td>
<td>4.21</td>
<td>4.50</td>
<td>1130.9</td>
<td>1.00</td>
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<td>SC04</td>
<td>1130</td>
<td>3.18</td>
<td>4.50</td>
<td>4.79</td>
<td>1142.7</td>
<td>0.99</td>
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<td>SC06</td>
<td>1130</td>
<td>3.18</td>
<td>4.79</td>
<td>5.08</td>
<td>1048.9</td>
<td>1.08</td>
</tr>
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<td>SC07</td>
<td>1130</td>
<td>3.18</td>
<td>5.08</td>
<td>5.37</td>
<td>1058.8</td>
<td>1.07</td>
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<tr>
<td>SC08</td>
<td>1130</td>
<td>3.18</td>
<td>5.37</td>
<td>5.65</td>
<td>1103.3</td>
<td>1.02</td>
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<tr>
<td>SC09</td>
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<td>3.18</td>
<td>5.65</td>
<td>5.93</td>
<td>1051.0</td>
<td>1.08</td>
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<tr>
<td>SC10</td>
<td>1130</td>
<td>3.18</td>
<td>5.93</td>
<td>6.21</td>
<td>1130.6</td>
<td>1.00</td>
</tr>
</tbody>
</table>
3. Operational Experience
Scheduled shut down for annual maintenance

Lockdown due to the novel virus
SRILAC Operation in 2020

- Scheduled shut down for annual maintenance
- Leakage from coupler window (SC06)
- Lockdown due to the novel virus

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Leakage from coupler window (SC06)

Liquid Helium level [%]

Beam operation

Jan 1/15
Feb 4/1
Mar 6/11
Apr 7/28
May 9/21
Jun 10/27
Jul 11/24
Aug
Sep
Oct
Nov
Dec

Liquid Helium level [%]

0
20
40
60
80
100

6/24-7/5 7/28
10/13-27 12/7-28
11/25-30
SRILAC Operation in 2020

![Graph showing liquid helium level and operation dates]

- **Liquid Helium level [%]**
- **Beam operation**
- **High Power RF test (X-ray level measurement)**

**Leakage from coupler window (SC06)**

Comparison of Field Emission Levels

- After an impact of SC06 coupler-window-break emission levels of SC07, SC08 became higher than those of the measurement #1.

![Diagram showing comparison of field emission levels before and after one year operation.]

- Before opening the GVs:
  - X-ray [μSv/h] vs. Gap Voltage [MV]

- After one year operation:
  - X-ray [μSv/h] vs. Gap Voltage [MV]

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SC01 and SC10 located at the end of SRILAC section stay still in low emission level. DPS works well so far.
Summary of SRILAC Operation in 2020

- Leakage from coupler window (SC06)
- Beam operation
- High Power RF test (X-ray level measurement)
- Open GVs for the first time

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Summary

- An upgrade of RIKEN heavy-ion linac was successfully conducted by the introduction of a new SC linac-booster that consists of 3 cryomodules based on 10 TEM QWRs made from bulk niobium and c.w. heavy-ion beams.

- A cool-down test and RF test with an operational temperature of 4.5 K were successfully performed without significant trouble, except SC05 encountered a vacuum leakage from the ceramic window of the coupler.

- The $^{40}$Ar$^{13+}$ beam was successfully accelerated to 6.2 MeV/u in the first beam acceleration test. User operation is ongoing.

- The emission levels of SC01 and SC10 are almost maintained through the beam operation. It might be owing to newly developed DPS.

- While the vacuum leakage of the SC05 coupler window did not degrade performance of the other cavities in CM2, the vacuum leakage with SC06 brought serious damage to SC07 and SC08.

- Recovery of damaged couplers of SC05 and SC06 by introducing the outer vacuum window is planned. (see the next presentation by K. Ozeki)
Thank you.
Backups