Status of RAON accelerator system

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Institute for Basic Science

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RAON site

Project period: 2011.12-2021.12 (10 years 1 month)
Site area: 952,066 m²
Budget: 382M$(Acc.), 299M$(Land), 519M$(Bld.)
# RAON Layout and Beam Parameters

<table>
<thead>
<tr>
<th>Particle</th>
<th>Driver Linac</th>
<th>Post Acc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>H⁺</td>
<td>O⁺₈</td>
<td>Xe⁺₅₄</td>
</tr>
<tr>
<td>Beam energy (MeV/u)</td>
<td>600</td>
<td>320</td>
</tr>
<tr>
<td>Beam current (µA)</td>
<td>660</td>
<td>78</td>
</tr>
<tr>
<td>Power on target (kW)</td>
<td>&gt; 400</td>
<td>400</td>
</tr>
</tbody>
</table>
Progress of Accelerator Systems
**Injector specification**

- **ECR-IS**
  - Output norm (rms) emittance: $0.12 \, \pi \, \text{mm-mrad}$
  - Beam current: $400 \, \text{euA}$ for $^{238}\text{U}^{33+} + ^{238}\text{U}^{34+}$
  - Output beam energy: $10 \, \text{keV/u}$
  - RF frequency: $28+18 \, \text{GHz}$
  - Magnets: Fully superconducting NbTi

- **LEBT**
  - Pre-bunchers: Multi-harmonic buncher, Velocity equalizer
  - Two Bends: $90 \, \text{deg.}$

- **RFQ**
  - RF frequency: $81.25 \, \text{MHz}$
  - Output beam energy: $500 \, \text{keV/u}$
  - 4 Vane types

- **MEBT**
  - 3 Re-bunchers RF freq.: $81.25 \, \text{MHz}$
**28 GHz ECR Ion Source**

- Superconducting sextupole and solenoid prototypes were tested in 2013.
- Superconducting magnet assembly (6 sextupoles + 4 solenoids) was completed in 2014.
- Cryostat fabrication and assembly was done in 2014.
- Beam test is in progress.

**B**<sub>inj</sub> = 3.5 T, **B**<sub>ext</sub> = 2.2 T,
**B**<sub>r</sub> = 2 **B**<sub>ecr</sub>, **B**<sub>min</sub> = 0.7 T

**Six 4K cryocoolers,**
One single stage cryocooler

28GHz Gyrotron
### Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field</td>
<td>70% of the designed value</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>8.4e-8 @ injection chamber (not in plasma chamber)</td>
</tr>
<tr>
<td>Microwave power</td>
<td>28GHz, 1 kW</td>
</tr>
<tr>
<td>Bias disk voltage</td>
<td>-50 V</td>
</tr>
<tr>
<td>Electrode structure</td>
<td>Triode structure</td>
</tr>
<tr>
<td>Extraction voltage</td>
<td>20 kV, -0.5kV, 0V</td>
</tr>
<tr>
<td>Extraction current</td>
<td>2.1 mA</td>
</tr>
<tr>
<td>Electrode distance</td>
<td>24 mm – 15 mm</td>
</tr>
</tbody>
</table>

![ Radiation Shielding Block](image1)

![ Inside Shielding Block](image2)

![ Beam current [uA]](image3)

- O1+
- O2+
- O3+
- O4+
- O5+
- O6+
- O7+
- O8+ & H2+

Q/A 0.0 0.1 0.2 0.3 0.4 0.5 0.6
<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam Properties:</strong></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>81.250 MHz</td>
</tr>
<tr>
<td>Particle</td>
<td>H(^{+1}) to U(_{238}^{+33})</td>
</tr>
<tr>
<td>Input Energy</td>
<td>10 keV/u</td>
</tr>
<tr>
<td>Input Current</td>
<td>0.4 mA</td>
</tr>
<tr>
<td>Input Emittance: transverse (rms, norm)</td>
<td>0.012 .cm. mrad</td>
</tr>
<tr>
<td>Output Energy</td>
<td>0.507 MeV/u</td>
</tr>
<tr>
<td>Output Current for 0.4mA in.</td>
<td>~0.39 mA</td>
</tr>
<tr>
<td>Output Emittance: transverse (rms, norm)</td>
<td>0.0125 .cm. mrad</td>
</tr>
<tr>
<td>Output Emittance: longitudinal (rms)</td>
<td>~26 keV/u-Degree</td>
</tr>
<tr>
<td><strong>Transmission</strong></td>
<td>~98 %</td>
</tr>
<tr>
<td><strong>Structures and RF:</strong></td>
<td></td>
</tr>
<tr>
<td>Peak surface Field</td>
<td>1.70 Kilpatrick</td>
</tr>
<tr>
<td>Structure Power (for U(_{238}^{+33}))</td>
<td>92.4 kW</td>
</tr>
<tr>
<td>Beam Power (for 0.2mA each U(_{238}^{+33}+34))</td>
<td>1.44 kW</td>
</tr>
<tr>
<td><strong>Total Power</strong></td>
<td>94 kW</td>
</tr>
<tr>
<td>Duty Factor</td>
<td>100%</td>
</tr>
<tr>
<td>RF Feed</td>
<td>1 Drive loops</td>
</tr>
<tr>
<td><strong>Mechanical:</strong></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>4.94 meter</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>TBD Degree C</td>
</tr>
</tbody>
</table>
RFQ Prototype

- RFQ Design (2013.08)
- Design review (2013.11)
- RFQ Prototype
  - vane machining and 3D measurement
  - The 1st brazing failed (2014.04)
  - Assessed the related issues
  - Brazing procedure modified (2014.05)
  - Confirmed brazing procedure (2014.06)
  - RFQ prototype fab. completed (2014.09)

- RFQ Prototype test
  - 15kW SSA, coupler, RCCS are installed

RFQ coupler Leak test
Sample brazing test
Prototype RFQ – RF conditioning

- 15 kW RF power amp.
- Repetition rate: 1 Hz, 100 μsec
- RF power range: 1 W – 15 kW
RFQ Fabrication

RFQ Fabrication: delivered in 2016.08
- RAON SCL is designed to accelerate high intensity beams.
- Focusing by NC quad doublets rather than SC solenoids.
- Optimized geometric beta of SC cavities (0.047, 0.12, 0.30, 0.51).
- Employs larger aperture to reduce beam loss (40 mm and 50 mm aperture).
- Prototyping of SC cavities and cryomodules is done.
### Layout of Driver Linac

<table>
<thead>
<tr>
<th>ECR</th>
<th>LEBT</th>
<th>RFQ</th>
<th>MEBT</th>
<th>SCL11</th>
<th>SCL12</th>
<th>STRIP</th>
<th>SCL21</th>
<th>SCL22</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>QWR (81.25MHz)</td>
<td>HWR (162.5MHz)</td>
<td>SSR1 (325MHz)</td>
<td>SSR2 (325MHz)</td>
<td></td>
</tr>
</tbody>
</table>

- **CAV** | **QF** | **QD** | 22 cryomodules | Output 2.7 MeV/u
  - 22 $\beta=0.047$ QWRs, 44 quadrupoles

- **CAV** | **CAV** | **QF** | **QD** | 13 cryomodules | Output 6.0 MeV/u
  - 98 $\beta=0.12$ HWRs, 64 quadrupoles

- **CAV** | **CAV** | **CAV** | **CAV** | **QF** | **QD** | 19 cryomodules | Output 18.5 MeV/u

- **C** | **C** | **C** | **C** | **QF** | **QD** | 23 cryomodules | Output 56.5 MeV/u
  - 69 $\beta=0.30$ SSR1, 46 quadrupoles

- **C** | **C** | **C** | **C** | **C** | **QF** | **QD** | 23 cryomodules | Output 200 MeV/u
  - 138 $\beta=0.51$ SSR2, 46 quadrupoles

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Stripper: charge state 33, 34 → 77, 78, 79, 80, 81 for Uranium

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Total 331 cavities, 100 cryomodules, 196 quadrupoles, 122m (LEL,CSS), 181m (HEL)
Design of SC Cavity

Optimization of Cavity Parameters

Multipacting analysis

Mechanical analysis

Frequency shift

<table>
<thead>
<tr>
<th>Frequency shift</th>
<th>QWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant Frequency</td>
<td>81.25MHz</td>
</tr>
<tr>
<td>Cavity length(upper)</td>
<td>-67.1kHz/mm</td>
</tr>
<tr>
<td>Cavity length(lower)</td>
<td>+1.3kHz/mm</td>
</tr>
<tr>
<td>Welding (0.58mm shrink)</td>
<td>+38.2kHz</td>
</tr>
<tr>
<td>EP/BCP (125um)</td>
<td>+267kHz</td>
</tr>
<tr>
<td>External pressure(Vacuum, L-He)</td>
<td>-4.6Hz/mbar</td>
</tr>
<tr>
<td>Cool down(293K→2K)</td>
<td>+203kHz</td>
</tr>
<tr>
<td>Lorentz Detuning</td>
<td>-1.7Hz/(MV/m)^2</td>
</tr>
</tbody>
</table>
## Superconducting cavity

### Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>QWR</th>
<th>HWR</th>
<th>SSR1</th>
<th>SSR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_g$</td>
<td>-</td>
<td>0.047</td>
<td>0.12</td>
<td>0.30</td>
<td>0.51</td>
</tr>
<tr>
<td>$F$</td>
<td>MHz</td>
<td>81.25</td>
<td>162.5</td>
<td>325</td>
<td>325</td>
</tr>
<tr>
<td>Aperture</td>
<td>mm</td>
<td>40</td>
<td>40</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$QR_s$</td>
<td>Ohm</td>
<td>21</td>
<td>42</td>
<td>98</td>
<td>112</td>
</tr>
<tr>
<td>$R/Q$</td>
<td>Ohm</td>
<td>468</td>
<td>310</td>
<td>246</td>
<td>296</td>
</tr>
<tr>
<td>$V_{acc}$</td>
<td>MV</td>
<td>0.9</td>
<td>1.3</td>
<td>1.9</td>
<td>3.6</td>
</tr>
<tr>
<td>$E_{peak}/E_{acc}$</td>
<td></td>
<td>5.6</td>
<td>5.0</td>
<td>4.4</td>
<td>3.9</td>
</tr>
<tr>
<td>$B_{peak}/E_{acc}$</td>
<td></td>
<td>9.3</td>
<td>8.2</td>
<td>6.3</td>
<td>7.2</td>
</tr>
<tr>
<td>$Q_{calc}/10^9$</td>
<td>-</td>
<td>1.7</td>
<td>4.1</td>
<td>9.2</td>
<td>10.5</td>
</tr>
<tr>
<td>Temp.</td>
<td>K</td>
<td>4.5</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

**EM design optimization: Parameters sweeping**
SC Cavity Prototyping

- CAVITY Manufacturing Process

1. MATERIAL INSPECTION
2. DEEP DRAWING
3. MACHINING
4. 3D SCAN (CMM)
5. BCP
6. EBW
Buffered Chemical Polishing

**Figure 3:** SEM Images of Nb samples (x5000), (a) surface of undeformed Nb, (b) cross-section of undeformed Nb, (c) surface of deformed Nb, (d) cross-section of deformed Nb, (e) surface of undeformed Nb with 1:1:1 BCP treated for 50 min, and (f) cross-section of undeformed Nb with 1:1:1 BCP treated for 50 min.

(Courtesy of TRIUMF)
Vertical test of QWR cavity

$Q_0$

$E_{acc} [MV/m]$

$B_{peak} [mT]$

$E_{peak} [MV/m]$

Target

4K-1st
4K-2nd
4K-Bake
2K
Vertical test of HWR cavity

- HWR in HPR
- $Q_{\text{ext}}$ calibration
- RF system
- Leak check
RF coupler prototyping

High power test: TW 16kW, SW 5kW

Frequency: 162.5 MHz
Nominal RF power: 5kW
Q_{ext}=2 \times 10^6

High power test: TW 16kW, SW 5kW
Frequency: 325 MHz
Nominal RF power: 20 kW
Q_{ext}=6 \times 10^6 \sim 7 \times 10^6

High power test in progress
Cryomodule design (QWR)

- **Level gauge**
- **Safety valve**
- **Feed-through**
- **View port**
- **Gate valve**
- **Coupler**
- **Reservoir**
- **4K module line**
- **Chamber**
- **Magnetic shield**
- **Thermal shield**
- **Support part**
- **Dummy cavity**

### Stress (Condition: Vacuum)
- **Type:** Static Structural
- **Equivalent Stress**
- **Unit:** MPa
- **Max:** 78.14
- **Time:** 1
- **Colors:**
  - 78.14 Max
  - 69.49
  - 60.775
  - 52.094
  - 43.411
  - 34.729
  - 26.047
  - 17.365
  - 8.6823
  - 2.8715e-6

### Displacement (Condition: Vacuum)
- **Type:** Static Structural
- **Total Deformation**
- **Unit:** mm
- **Max:** 0.00769
- **Time:** 1
- **Colors:**
  - 0.00769 Max
  - 0.00495
  - 0.00298
  - 0.00191
  - 0.00095
  - 0.00047
  - 0.00018
  - 0.00009
  - 0.00000

- **Material:**
  - 4K He line
    - STS316L
    - Pipe inlet Size: 3/8" Tube
    - Gasket: VCR fitting
  - 40K He line
    - Material: Cu
    - Pipe inlet Size: 65A Sch5S
    - Gasket: Helicoflex
  - Safety line
    - Material: STS316L
    - Pipe inlet Size: 65A Sch5S
    - Gasket: Helicoflex
Cryomodule development

QWR Cryomodule (LHe/LN test)

HWR Cryomodule (LHe/LN test)

SSR1 Cryomodule (LN test)

SSR2 Cryomodule (LN test)
Static load of cryomodule

- QWR static load: 3.9 W (expectation: 3.2 W)
- HWR static load: 13.5 W (expectation: 14.7 W)
- Install Helium Liquefier (New & Old)
- Install Warm Pump for 2K-module and 2K-module testing
- Remodeling of the facility is under way

[SRFTF Layout]

[Control System Logic]

[Table]

<table>
<thead>
<tr>
<th>MAJOR MILESTONE WORK ITEM</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRF Test Facility</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Report on Strategy of Constructing the Cryoplant of RAON were submitted.
HRS Capacity options, HRS/HDS Construction Budgets were included.

**Cryoplant Capacity**
- Option 1: 3.5 kW 13 kW 3.5 kW
- Option 2: 13 kW 7 kW
- Option 3: 20 kW

<table>
<thead>
<tr>
<th>Load (kW)</th>
<th>SCL 1</th>
<th>SCL 2</th>
<th>SCL 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>1.5</td>
<td>3.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Dynamic</td>
<td>1.95</td>
<td>9.0</td>
<td>1.95</td>
</tr>
<tr>
<td>Total</td>
<td>19.8  kW @ 4.5 K</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Cryogenic System Building**
- ColdBox (HEX, JT-V/V, CC)
- Distribution Box (DB)
- LHe Dewar
- Control Room (CR)

**Comp. Station Building**
- LP, HP Comps / ORS
- HGMS
  - Rec-Comps / Gas Bags
  - Purifier
  - Pure & Impure Buffers (Yard)
  - He Storage Vessels (Yard)
- LN2 Tanks (Yard)
Helium Distribution System

- Helium Distribution Flow: Cryoplant $\rightarrow$ DB (Distribution Box) $\rightarrow$ TL (Transfer Line) $\rightarrow$ VB (Valve Box) $\rightarrow$ CM (Cryomodule)
RAON RF Systems

- RF Systems: Supplying RF Power to Cavity
  - LLRF: RF Power Control
  - HPRF: High Power Amp., Transmission Line
  - RF Distribution

**LLRF Control Stability**
- Amplitude: ± 1%
- Phase: ± 1°

![Diagram of RF Systems](image-url)
HPRF test (QWR/HWR/SSR/RFQ SSPA)

- **2 kW SSPA unit test**

  - Gain
  
  ![Graph showing gain vs. input dBm for different units]

  - Efficiency
  
  ![Graph showing efficiency vs. output power (dBm) for different units]

- **7 kW full power test**

  - Output power vs. input dBm
  
  ![Graph showing relationship between output power in watts and input dBm for different units]
LLRF+HPRF+Nb cavity test

**Setup**

- 163.272592 MHz
- LLRF → Amp. → Powermeter → SC HWR → Oscilloscope
- Operation range: under 50 W, HPRF output power (T/L limitation)
- CW operation: 1 H

**Result**

- Optimization of P and I coefficients

<table>
<thead>
<tr>
<th>LLRF</th>
<th>target</th>
<th>QWR</th>
<th>HWR</th>
<th>SSR1</th>
<th>SSR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/o PI FB (%)</td>
<td>±2.6 (1.5)</td>
<td>±58 (7)</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>(amplitude shift (dB))</td>
<td>w/o P &amp; I optimization</td>
<td>±1</td>
<td>±1.1</td>
<td>±7</td>
<td>-</td>
</tr>
<tr>
<td>w/ PI FB (%)</td>
<td>±1</td>
<td>±0.15</td>
<td>±1.05</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>w/o P &amp; I optimization</td>
<td>±1</td>
<td>±0.15</td>
<td>±1.05</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Prototyping of major accelerator parts has been in progress since 2013 through domestic vendors.
- ECR ion source cryostat was fabricated (2014.09)
- RFQ prototype fabricated successfully (2014.10)
- SC cavity prototypes were delivered for test (since 2014.05)
- Cryomodule prototypes were delivered for test (since 2014.12)

Some prototypes are in testing stage.
- ECR ion source, RFQ, MEBT buncher
- Superconducting cavities and cryomodules (QWR, HWR)

SRF test facility is under installation and will be ready in Feb. 2016.
Thank you!