DESIGN STUDIES FOR QUARTER-WAVE RESONATORS AND CRYOMODULES FOR THE RIKEN SC-LINA C

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Abstract

Recently we proposed a plan to upgrade the intensity of uranium beams at the RIKEN RI-Beam Factory [1]. In this plan, a superconducting linac replaces the existing injector cyclotron. The linac’s quarter-wave resonators (QWRs) operate at 73 MHz in the continuous wave mode with $\beta (\equiv v/c)$ as low as 0.055-0.122. A coaxial probe-type RF fundamental power coupler that transmits RF power of 5 kW will be utilized for beam loading at about 1 kW/resonator. Tuning of the resonant frequency will be achieved using a mechanical tuner pressing on the resonator wall in the direction parallel to the beam. In this paper, design studies for a pure Nb QWR and its cryomodule are described. The construction status of the prototype, consisting of a QWR, a coupler, a tuner and a test cryomodule, is also reported.

SC-LINA C FOR RIKEN RI-BEAM FACTORY

Why a Superconducting Linac?

At this time, the RIKEN RI-Beam Factory (RIBF) provides the world’s most intense uranium beams with an energy of 345 MeV/u. However, the beam currents of uranium are still not intense enough to reach the goal of 1 p\(\mu\)A. A schematic of the current method for the acceleration of uranium ions is shown in Fig. 1. As reported in Ref. [2], the injector RILAC2 [3, 4] can accelerate uranium ions with a mass-to-charge ratio of 7 up to 0.67 MeV with an intensity greater than a few p\(\mu\)A. However, the transmission efficiency, defined as the ratio of the beam current bombarding the target to the beam current from the ion source is only a few percent. This is partly due to the low efficiency of charge stripping, indicated by CS in Fig. 1, which occurs twice during acceleration at the energies of 11 MeV/u and 51 MeV/u. Furthermore, the succeeding booster RIKEN Ring Cyclotron [5] (RRC) cannot handle such a high beam current because the acceleration voltage of its double gap resonator is too low [6].

An upgrade of the RIBF is therefore under discussion, the objective being to significantly increase the uranium beam currents. One candidate is a new injector, with a latter part consisting of superconducting resonators, to replace the RRC, which was not designed to handle very high power beams with a high mass-to-charge ratio. The layout of the new injector is shown in Fig. 2.

![Figure 2: Schematic of a new injector.](image)

RIKEN SC-LINA C

The superconducting part of the proposed RIKEN linac, called SRILAC, consists of 14 cryomodules, each of which contains four quarter-wave resonators (QWRs). It is designed to accelerate 1 mA $^{238}\text{U}^{3+}$ from 1.4 MeV/u up to 11 MeV/u. We set moderate goals for the design: The resonator should have a total gap voltage of 1.6 MV with 4.0 W RF power dissipation. The RF of the QWRs will be 73.0 MHz, and a large beam aperture of 40 mm\(\phi\) is chosen for the beam pipes of the drift tubes.

The conceptual design of an accelerator cryomodule is shown in Fig. 3. The QWRs, made from Nb sheets with a thickness of 4 mm, are housed independently in a helium vessel made of titanium. The operating temperature of the helium is 4.5 K. The valve box is separated from the cryomodule which contains four QWRs. In this design top loading is adopted so that the QWRs hang from the top lid of the chamber of the cryomodule. The cryomodule is equipped with a single-stage thermal shield and its temperature is 80 K. The thermal shield provides a thermal anchor to the fundamental power couplers (FPCs). The FPC is designed to handle RF power from 5 kW to the maximum required for operation with $Q_{\text{ext}} \sim 10^6$. Note that $Q_{\text{ext}}$ of the order of $10^5$ is set for beam loading of a few kilowatts and for better RF control. $Q_{\text{ext}}$ must be chosen carefully taking into account the radiation damping of the beam.
into account the unloaded Q-factor ($Q_0$) of the resonator, actual beam loading, the strength of microphonics, and RF control. The coupling strength of the FPC is tunable by sliding in the azimuthal direction and tuning can be made without warming up the cold mass or breaking the vacuum of the cryostat chamber.

Instead of superconducting solenoids, room temperature quadrupole doublets are chosen to allow simple operation and alignment. Details of the design study for the SC-LINAC section, specifically, configuration of the accelerating resonators and quadrupoles and geometrical optimization of the QWRs, have been described elsewhere [7, 8].

**DESIGN STUDIES FOR SC-QWRS FOR THE RIKEN SC-LINAC**

**Resonator**

Details of the former design of the resonator were reported in Ref. [7]. Further optimization of the geometrical design was performed with the 3-D simulation software package CST Microwave Studio (MWS) [9]. By modifying the stem to a conical shape (instead of the original straight cylindrical shape) and making the inner diameter of the resonator larger, as shown in Fig. 4, the distribution of the magnetic field strength along the stem surface was flattened and, as a result, the peak magnetic field was greatly reduced. Its RF power dissipation was also reduced by 20%. The characteristics of the resonator are summarized in Table 1. For the estimation of $Q_0$, an $R_s$ (≡ $R_{BCS} + R_{res}$) of 25 nΩ was used.

**Frequency Tuning**

One of the ways to realize cold tuning of the QWR is to press the beam port azimuthally, reducing the gap length. The advantage of this method is that the frequency change is sensitive to the gap length. A mechanical structure acts on the beam port flange and changes the gap directly. However, installation space between resonators is limited because the resonators are placed as close as possible because the beam dynamics requires strong transverse defocusing at the acceleration gap. The other way to change the gap length is to squeeze the outer cylinder perpendicular to the beam axis [10].

Mechanical simulations of these two methods have been performed. The simulated deformation using ANSYS15.0.7 is shown in Fig. 5. In the simulation model, the thickness of the resonator wall is 4 mm. For physical properties of the Nb at 4.5 K, a Young’s modulus of 125 MPa

<table>
<thead>
<tr>
<th>Table 1: Characteristics of SC-QWRs for the RIKEN SC-LINAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency at 4.5 K [MHz]</td>
</tr>
<tr>
<td>$\beta_{opt}$</td>
</tr>
<tr>
<td>$E_{acc}$ [MV/m]</td>
</tr>
<tr>
<td>$E_{peak}/E_{acc}$</td>
</tr>
<tr>
<td>$B_{peak}/E_{acc}$ [mT/MV/m]</td>
</tr>
<tr>
<td>$R_{sh}/Q_0$ [Ω]</td>
</tr>
<tr>
<td>$V_{acc}$ at $E_{acc}=4.5$ MV/m, $\beta=0.08$</td>
</tr>
<tr>
<td>$G$ [Ω]</td>
</tr>
<tr>
<td>$P_0$ [W]</td>
</tr>
<tr>
<td>Inner diameter [mm$^3$]</td>
</tr>
<tr>
<td>Height [mm]</td>
</tr>
<tr>
<td>Aperture (beam tube) [mm$^3$]</td>
</tr>
<tr>
<td>$Q_0$</td>
</tr>
<tr>
<td>$Q_{ext}$</td>
</tr>
<tr>
<td>Max. beam loading [kW]</td>
</tr>
</tbody>
</table>
and a Poisson ratio of 0.38 are used. The rigidity of the helium vessel is not taken in account. The left and right figures are for pressing the beam ports and pressing perpendicular to the beam axis, respectively. To press the resonator wall perpendicular to the beam axis a set of cylinders (side cylinders) is used. The vertical position of the attached cylinders is at the same height as the beam ports. A load of 5,000 N is applied to the beam ports or side cylinders. The deformations and the resulting the frequency shifts ($\Delta f$) are summarized in Table 2. The bracketed values in Table 2, obtained using MPHYSICS software from CST, which is a 3-D simulation of thermal and mechanical stress analysis, are shown to indicate the consistency between results from different simulation codes. The frequency tuning range must be set so that the maximum stress does not exceed the yield stress at 4.5 K with a mechanical safety factor. The maximum stress can be reduced further by adding ribs or modifying the corner radius between the connected parts.

**Table 2: Simulation of Deformation of the Cold Tuner**

<table>
<thead>
<tr>
<th>Load</th>
<th>Beam Ports</th>
<th>Side Cylinders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Deform. [mm]</td>
<td>0.375(0.380)</td>
<td>0.448(0.450)</td>
</tr>
<tr>
<td>Max. Stress [MPa]</td>
<td>116(123)</td>
<td>205(233)</td>
</tr>
<tr>
<td>$\Delta f$ [kHz]</td>
<td>-9.40</td>
<td>6.23</td>
</tr>
<tr>
<td>Sensitivity [kHz/mm]</td>
<td>-24.75</td>
<td>13.84</td>
</tr>
</tbody>
</table>

**Correction of Steering Effect by RF Magnetic Field**

Due to the vertical asymmetry of the QWR structure, the accelerated beams are kicked downward by the RF magnetic field. To counteract this steering effect it is proposed to have a tilt between the faces of neighboring drift tubes [11]. This modification of the drift tube shape produces a vertical component in the electric field to correct the steering of the accelerated beams. To choose the tilting angle, beam orbits were obtained numerically (Runge-Kutta-Gill method) for electric and magnetic RF fields with tilting angles $\theta_c$. The simulation was made for the first cryomodules because the steering effect is significant for low beta particles. The RF fields were obtained by interpolating the gridded data from MWS with third order spline functions. As shown in Fig. 6, $\theta_c = 2.3^\circ$ minimizes the vertical shift due to steering effect at the exit of the cryomodule.

**Beam Loading Simulation**

A simulation of RF power with beam loading was made via a lumped circuit model. The resonator equivalent circuit model with beam loading shown in Fig. 7 was used. In the figure, $Q$ is the quality factor of the unloaded resonator, $i_{beam}$ is the fundamental Fourier component of the beam current (in this case $i_{beam} = -2 \times I_{beam} \times TTF$), $i_{gen}$ is the current output of the generator, $V_{gen}$ is the output voltage of the generator, $Z_0$ is the output impedance of the generator (50 Ω), $Z_{in}$ is the input impedance seen from the coupler, $Z_{cav}$ is the impedance of the cavity (resonator), $i_{FPC}$ is the forward current through the capacitive coupler, $i_{cav}$ is the current flowing into the resonator, $V_{cav}$ is the resonator voltage and $i'_{load}$ is the reflected current flowing into the dummy load. By adjusting the capacitance of the FPC ($C_{FPC}$) zero reflection current can be obtained. In this case, a power output from generator and the sum of the power dissipation of the resonator wall and the beam loading become balanced. $Q_{ext}$ is determined by the ratio of RF power transmitted into the FPC to the power stored in the resonator and depends on $C_{FPC}$. The loaded quality factor $Q_{loaded}$ is obtained from the resonance curve of the stored energy with no beam loading as the ratio of the resonant frequency to FWHM and then $Q_{ext}$ is extracted from the relation $1/Q_{loaded} = 1/Q_0 + 1/Q_{ext}$. The obtained values of $Q_{ext}$ are plotted in Fig. 8.

The beam-loading effect can be simulated by an additional current source $i_{beam}$, as shown on the right-hand side
of Fig. 7. Here the beam frequency was assumed to be a subharmonic of the RF frequency. With beam loading, the RF current which flows into the resonator $i_{cav}$ is represented as sum of the currents:

$$i_{cav} = i_{cav}^{gen} + i_{cav}^{beam}.$$  

The currents $i_{cav}^{gen}$, $i_{cav}^{beam}$ are obtained according to Kirchhoff’s law. The amplitude and phase of the output current of the generator $i_{gen}$ is controlled so that the amplitude of the cavity voltage and its phase $\phi_s$ with respect to the beam phase stay constant:

$$V_{cav}^{gen} = Z_{cav} \cdot i_{cav}^{gen} = V_{cav} \cdot \exp(j\phi_s) - V_{cav}^{beam} i_{gen},$$

$$i_{gen} = Z_0 + Z_{FPC} + Z_{cav} i_{cav}^{gen}.$$  

The output RF powers of the power source are calculated as $P_{gen} = \text{real} \left( V_{gen} \cdot i_{gen}^{*} / 2 \right) = Z_0 \cdot |i_{gen}|^2 / 2$ and are plotted as a function of the difference between RF frequency and resonant frequency for various values of $C_{FPC}$ in Fig. 8. Here $a^*$ denotes a complex conjugate of $a$.

**External Q of the Fundamental Power Coupler**

To determine the tuning stroke of the antenna of the FPC, $Q_{ext}$ is calculated as a function of the coupler antenna insertion. Values of $Q_{ext}$ are obtained according to the method proposed by Balleyguier [12]. Following this method, the ratio of the volume integral of $|E|^2 (H^2)$ to the surface integral of $|E|^2 (|H|^2)$ at the port set at the end of the FPC (see Fig. 9) gives $Q_{ext}$:

$$Q_{ext} = Q_1 + Q_2 = \frac{\omega_1}{c} \frac{\int \int \int \text{cavity} |E|^2 \, dV}{\int \int \text{port} |E|^2 \, dS} + \frac{\omega_2}{c} \frac{\int \int \text{cavity} |H|^2 \, dV}{\int \int \text{port} |H|^2 \, dS}.$$  

The suffixes 1 and 2 indicate that calculations were made with the boundary conditions at the port being open and short, respectively. As plotted in Fig. 9, a ±5 mm stroke of the coupling antenna changes $Q_{ext}$ by a factor of 10.

**Prototype**

Prototyping of the SC-QWR for low β heavy-ions such as deuteron, alpha, carbon started this year. A design study of a SC-QWR and its test cryomodule is also in progress. Fabrication of the first SC-QWR will be completed in Q1 of 2016 and vertical tests will subsequently be conducted. The project plans to make acceleration tests of very intense beams with an energy of 6 MeV/u from the RIKEN linac booster [13].

**Design of the Prototype Resonator**

The frequency of the resonator is chosen to be 75.5 MHz, which is the frequency of the RIKEN linac booster. The shape of the resonator for the RIKEN SC-LINAC, whose frequency is 73.0 MHz, was modified to meet this requirement.

Cross-sectional views of the prototype resonator are shown in Fig. 10. The shape of the resonator was modified considering not only local stresses caused by atmospheric pressure and pressing by the tuner but also convenience of fabrication. The prototype will be manufactured from pure Nb (residual resistivity ratio, RRR > 250) sheets with a thickness of 4 mm. The end drift tubes, stem, upper toroidal part, bottom cover and the outer cylinder will
be formed by deep drawing and joined by electron-beam welding (EBW) [14]. In Fig. 10, blue lines indicate boundaries between these parts. The faces of the drift tubes are tilted by 2.3°. Pre-tuning is supposed to be done by cutting the straight section of the stub and the outer cylinder.

The prototype resonator has 9 ports. The two ports on the upper toroidal part are cleaning ports. The center port at the bottom is for the FPC and the other two ports are for pickup antennas. In the median plane, the resonator is equipped with two beam ports and two test ports. The test ports are for future R&D of a plunger type tuner. As the material for the flanges of these ports Grade-2 Nb is chosen instead of NbTi, and flanges utilizing HELICOFLEX gaskets are used for the vacuum seal. After the vertical tests of the resonator, a He jacket made of Ti, whose thermal expansion coefficient is similar to that of Nb, will be mounted by EBW.

**Mechanical Study of the Resonator**

Investigation of the rib structure mounted on the upper toroidal part to suppress the vertical deformation and mechanical vibration of the stem (pendulum modes) is now in progress. The QWR resonator has pendulum vibration modes that are azimuthal (mode 1) and perpendicular to the beam (mode 2). Table 3 summarizes estimates made by ANSYS of deformation with a uniform pressure of 0.1313 MPa and the frequencies of vibration modes with and without a rib structure (Fig. 11) similar to that of the SPIRAL2 β = 0.07 resonator [10]. The maximum deformation occurs at the inward edge of the flanges of the two clean ports on the upper toroidal part which incline inwardly in the radial direction accompanied with a downward displacement of the stem. As the model number indicated in the first row of Table 3 increases, stiffness increases and deformation becomes smaller. Also the stiffer the toroidal part, the higher the frequency of the vibration modes becomes. It is crucial to avoid the situation in which the frequency of the vibration mode is 50 Hz which matches the frequency of commercial electric power.

### Table 3: Deformation and the Frequencies of Vibration Modes Estimated by ANSYS Simulation

<table>
<thead>
<tr>
<th>Model</th>
<th>t1 mm</th>
<th>t2 mm</th>
<th>t3 mm</th>
<th>δZ mm</th>
<th>f_{mode1} Hz</th>
<th>f_{mode2} Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>0.254</td>
<td>32.5</td>
<td>33.5</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>0.073</td>
<td>45.7</td>
<td>47.2</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>0.067</td>
<td>48.2</td>
<td>49.4</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>0.051</td>
<td>54.3</td>
<td>55.2</td>
</tr>
</tbody>
</table>

**Surface Treatment**

The 9 ports of the resonator will be utilized for surface cleaning. The planned surface treatment procedure is

Light BCP → HPR → Annealing → BCP → HPR.

With the second BCP process we will try to pre-tune to the resonant frequency. For the HPR process a new system dedicated to the QWRs will be installed in the class 1 clean room [15].

**Cryostat**

A plan view of the test cryomodule is shown in Fig. 12. The resonator vacuum must be separate from the vacuum of the cryostat chamber to maintain the high cleanliness of the resonator surface. The FPCs have a variable coupling mechanism that can be tuned without warming up the cold mass or breaking the vacuum of the cryostat. A room temperature magnetic shield is employed to minimize the effects of geomagnetism. The single-stage thermal shield is designed to be cooled by using a small cryo-cooler. To minimize the heat flow into the 4 K cold mass and the thermal shield from the parts at room temperature, transition parts are attached to beam pipes and the outer conductors of the FPCs.

![Figure 11: Rib structure for the upper toroidal part of the prototype resonator.](image1)

![Figure 12: Plan view of the test cryomodule.](image2)
The dynamic and static heat loads from the FPC were estimated using MWS and MPHYSICS. The estimated thermal flow is summarized in Table 4. The values in this table are based on the following assumptions. The FPCs are coaxial and handle a maximum RF power of 10 kW. Double vacuum windows are adopted. The antennas of the FPCs are made of bulk copper and are cooled by heat conduction through the cold window. The outer conductor is made of copper-plated stainless steel and its RRR is assumed to be 30. The placement of the warm and cold ceramic disk-type windows and the thermal anchors are optimized [16]. Since the optimum placement of the ceramic windows and thermal anchor is sensitive to the effective RRR of copper-plated conductors, it is important to know the RRR of the real material before the placement is decided. The design of the mechanical structure to deform the resonator wall in the azimuthal direction has not yet been completed. So the heat load from mechanical tuner is not included in the estimation.

**SUMMARY**

The construction of a superconducting linac to upgrade the intensity of uranium beams at the RIKEN RIBF has been proposed. Design studies for a superconducting cryomodule for the low \( \beta \) section, including the QWR, fundamental power coupler and cold tuner, have been conducted. This year the prototyping of an SC-QWR for a very intense ion accelerator was started. Manufacturing of the QWR is in progress and the vertical test of the resonator is planned for March 2016. A test cryomodule which is capable of containing two resonators will be manufactured in 2016 and a cool down test will be performed in March 2017.

**ACKNOWLEDGEMENT**

Development of a prototype superconducting resonator and its cryomodule was funded by the ImPACT Program of the Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).

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