Development Progress of the Single Spoke Resonator in High-Energy Linac Front-End at the Rare Isotope Accelerator (RAON)

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1. Introduction

The rare isotope accelerator (RAON) utilizes a superconducting linac (SCL) to accelerate heavy-ion beams over a wide velocity range. In the high-energy linac, single spoke resonator (SSR) is adopted to provide efficient acceleration in the low to medium beta region while maintaining high radio frequency (RF) efficiency and mechanical stability. [1] At major international laboratories such as FRIB and Fermilab, extensive efforts have been devoted to SSR fabrication and surface treatment, including electropolishing (EP) and rotational buffered chemical polishing (BCP), to enhance frequency performance and reliability. [2]

The development of the SSR1 cavity for the RAON high-energy linac front-end began in 2023, encompassing design, prototype fabrication, and performance validation. Technical expertise has been accumulated in electron beam welding (EBW), heat treatment, surface preparation, and ultrapure water (UPW). In the current pre-R&D program, systematic improvements in fabrication processes are being pursued, focusing on minimizing welding distortion, controlling RF deviations, and optimizing surface uniformity. This paper reports the RF design, fabrication process, and frequency control strategy of the SSR1 cavity for the RAON high-energy linac.

2. RF Design Parameters of SSR1 Cavity

The RF parameters of superconducting cavities for RAON is listed in Table I. The SSR1 cavity is designed for medium velocity heavy-ion acceleration with an optimum beta of 0.32 and operates at 325 MHz, the same frequency used in the SSR2 cavity of the high-energy linac rear end. The effective cavity length is 298.2 mm, providing an accelerating voltage of 2.36 MV at a nominal accelerating gradient of 7.9 MV/m. The peak field ratios, E_{pk}/E_{acc}=4.1 and B_{pk}/E_{acc}=6.9, are optimized to mitigate field emission and magnetic quench while sustaining high accelerating performance. SSR1 is designed to ensure stable velocity matching between the HWR (β = 0.13) and SSR2 (β = 0.51) sections.

Table I: Radio frequency (RF) parameters of quarter wave resonator (QWR), half wave resonator (HWR), single spoke resonator SSR cavities in the RAON

Parameters	QWR	HWR	SSR1	SSR2
Optimum beta, β_0	0.051	0.13	0.32	0.51
f [MHz]	81.25	162.5	325	325
L_{eff}(=$\beta_0\lambda$) (mm)	186.5	236.3	298.2	470.8
R/Q	474	298	233	252
E_{pk}/E_{acc}	6.0	5.5	4.1	3.7
B_{pk}/E_{acc}	10.8	9.6	6.9	9.0
E_{acc} [MV/m]	5.7	6.2	7.9	8.7
V_{acc} [MV]	1.07	1.47	2.36	4.10
QRs [ohm]	18.1	37.1	92.2	123.0

3. Fabrication process of SSR1

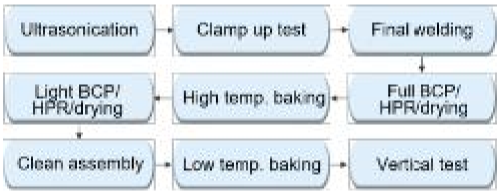

Fig. . Fabrication flow diagram of the SSR1 cavity

Figure 1 shows the fabrication process of the SSR1 cavity, which consists of cleaning, welding, surface treatment, heat treatment, assembly, and performance verification. After subparts fabrication, a clamp-up test is conducted to confirm alignment prior to final EBW. Following welding, a full BCP process with an etching depth of approximately 150 μm is applied to remove surface contamination, the mechanically damaged layer, and surface oxide layers. High-pressure rinsing (HPR) is subsequently performed to eliminate contamination. The cavity then undergoes high-temperature heat treatment at 350°C for 10 h followed by 600°C for 12 h to degas hydrogen and enhance its superconducting properties. To remove surface precipitates and residual contamination formed during heat treatment, additional light BCP is carried out. Cleanroom assembly is subsequently performed, followed by low-temperature baking at 120°C for 48 h. This modifies the surface oxide composition from Nb_2O_5 to NbO_2, thereby reducing BCS surface resistance and high-field Q-drop. [3] Finally, the RF performance of the cavity is evaluated through a vertical test.

4. Advancement of the fabrication process

4.1. Frequency Control

To ensure precise frequency control, it is essential to accurately determine the three-dimensional geometry of subcomponents such as the collar, spoke, and shell. Since dimensional deviations directly affect the resonant frequency, the geometries were measured using a 3D scanner. Fabrication processes including EBW, BCP, evacuation, and cryogenic cooldown can also induce geometric changes, resulting in frequency shifts. These effects were predicted in advance through structural and electromagnetic simulations using ANSYS and CST Studio. Based on the results, the target frequency at the clamp-up stage was set to achieve the final operating frequency of 325 MHz, making this strategy critical for stable cavity performance.

Table II: Simulated frequency change during post process of SSR1

Process	Δf [MHz]	f [MHz]
Clamp-up test		323.82
Half shell welding	– 0.04	323.78
Spoke – collar welding	+ 0.2	323.98
Spoke – shell welding	+ 0.16	324.14
BCP (150μm)	– 0.002	324.14
Vacuum evacuation	+ 0.09	324.23
2K cooldown	+ 0.84	325.07
Tuner	– 0.07	325.00

4.2. Rotational BCP Process

The conventional BCP process, typically performed over several hours, does not sufficiently suppress reaction heat, leading to localized temperature rises and NO_x induced bubble formation on the Nb surface. [4] These bubbles promote non-uniform etching and cause surface streaks, which degrade the intrinsic quality factor (Q_0). To mitigate this, cooling water was applied to control the etchant temperature, and the cavity was rotated during BCP to reduce bubble adhesion and improve etching uniformity. As a result, bubble-induced surface streaks were effectively suppressed.

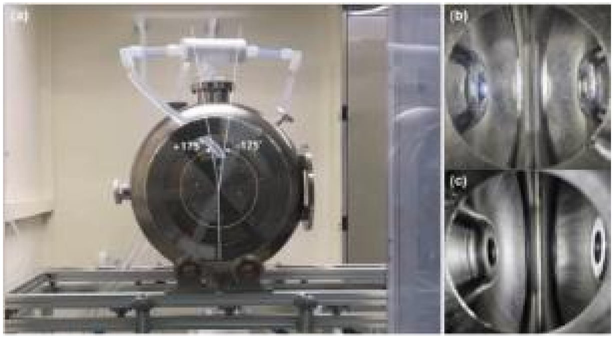

Fig. . (a2) Rotational buffered chemical polishing (BCP) system with a rotation range of ±175° at a speed of 1 rpm, and photographs of the inner surface of the SSR1 cavity after (b) conventional BCP and (c) rotational BCP.

5. Vertical test of SSR dressed cavity

The cavity was evaluated through a vertical test at cryogenic temperature. The measurements were sequentially performed at 4 K and 2 K, where Q_0 was evaluated as a function of accelerating gradient. This test enables the evaluation of superconducting RF performance, including characterization of field emission, quench limits, and Q-slope behavior. Through improvements in the surface treatment process, both the residual resistance (R_{res}) and field emission were reduced, leading to a noticeable enhancement in Q_0. The results demonstrate that the cavity meets the design requirements for high-gradient acceleration up to 7.9 MV/m.

6. Conclusion

The SSR1 cavity for the front-end of the RAON high-energy linac has been successfully designed and fabricated through systematic improvements in fabrication and surface treatment processes. A frequency control strategy based on three-dimensional geometric measurements and coupled structural–electromagnetic simulations enabled precise prediction of frequency shifts induced by welding, surface treatment, vacuum evacuation, and cryogenic cooldown, thereby ensuring accurate achievement of the final operating frequency of 325 MHz.

Furthermore, the introduction of a rotational BCP system with cooling effectively suppressed bubble streak formation. These improvements contributed to enhanced surface quality and are expected to positively impact RF stability and Q_0 performance. The results of this study establish a reliable foundation for fabrication process control and future series production of SSR1 cavities for the RAON high-energy linac.

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