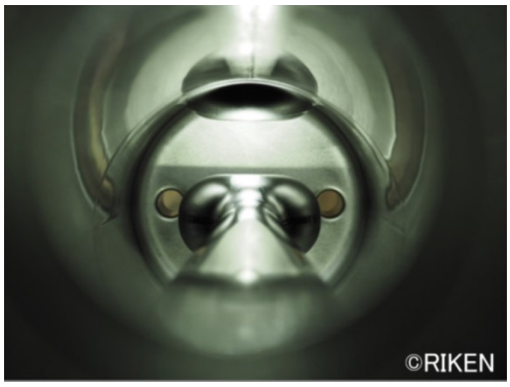
Manufacturing Techniques of Superconducting RF Cavities for Heavy Ions



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The 113th element, nihonium, named for Japan, was listed in the periodic table in November 2016.

In response, The Institute of Physical and Chemical Research (RIKEN) launched a project to increase the beam intensity and energy of the existing heavy ion linac to allow it to further investigate new super-heavy elements.

In order to realize this enhancement in a limited space, it is indispensable to introduce superconducting radio frequency cavities, but those made of pure niobium for heavy ions had not been developed in Japan. Mitsubishi Heavy Industries Machinery Systems, Ltd. (MHI-MS) worked with RIKEN on the development of superconducting radio frequency cavities for heavy ions utilizing its technology for manufacturing superconducting radio frequency cavities for electrons and has succeeded in manufacturing 10 actual units. This report describes the manufacturing technology that realized high-performance superconducting radio frequency cavities for heavy ions.

1. Introduction

A heavy ion accelerator is a particle accelerator that accelerates heavy ions, which usually refer to ions of elements heavier than carbon, to a high energy level. Research activities using heavy ion accelerators include nuclear physics (such as research on synthesis of elements), elementary particle physics (such as high-energy heavy ion collision experiments), radiotherapy (such as heavy ion radiotherapy, etc.), research on radiation damage to materials, etc.

RIKEN decided to introduce superconducting radio frequency cavities into a heavy ion linac, RILAC, in the Radioactive Isotope Beam Factory (RIBF) at the RIKEN Nishina Center to increase beam intensity and energy.

Figure 1 shows a schematic diagram of the RILAC upgrade plan. One of the features of the superconducting radio frequency cavity is that it can perform CW (continuous-wave) acceleration at a high accelerating gradient (in V/m).

The purpose of this RILAC upgrade was to perform CW acceleration with a high acceleration voltage (in V) within a limited length (in m).

In order to achieve this, it was indispensable to apply superconducting radio frequency cavities[(1)].

A superconducting radio frequency cavity for heavy ions has a complicated shape. Globally, its development is being carried out at accelerator laboratories in the United States and France. On the other hand, in Japan, the Japan Atomic Energy Agency has operated a tandem booster using a niobium/copper clad material, but a product made of pure niobium has not been developed.

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Since the late 1980s, we have accumulated technologies to manufacture superconducting radio frequency cavities made of pure niobium for electrons that achieved both a high acceleration gradient and a high Q value, which is a performance index for high frequency loss in cavities (the higher the Q value, the smaller the ratio of high frequency loss).

In recent years, these performances we offer have satisfied the required specifications of the International Linear Collider (ILC) project.

Utilizing these accumulated technologies, we worked on the production of 10 superconducting radio frequency cavities for heavy ions in a short period from 2017 to 2018.

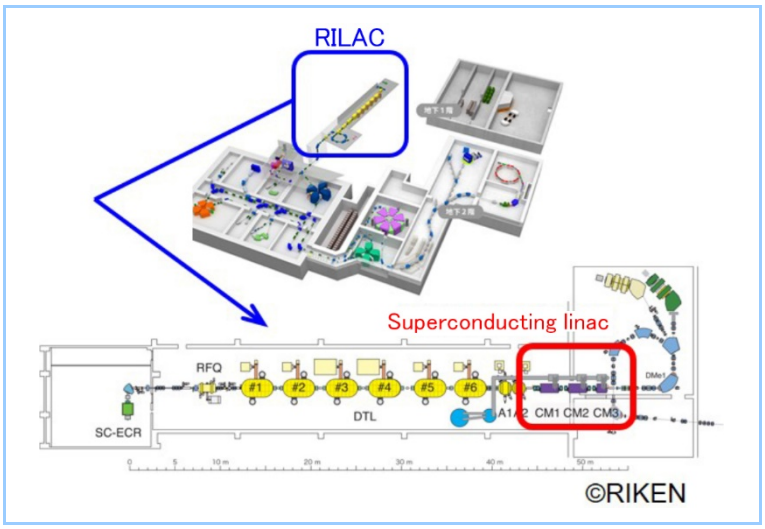

Figure 1 Schematic diagram of RILAC upgrade plan

2. Outline of superconducting radio frequency cavity for heavy ions

2.1 Configuration

A superconducting radio frequency cavity has a double-vessel structure composed of a vessel made of a superconducting material (niobium) and a vessel covering the outside thereof.

An electric field is formed inside of the niobium cavity by high-frequency power input from the outside and heavy ions get energy from the electric field and accelerate.

Between the vessels, liquid helium is stored and cooled to 4.5 K.

Since the niobium cavity becomes superconducting, the power loss during operation due to electrical resistance can be minimized.

Superconducting radio frequency cavities are assembled (modularized) with input couplers for inputting high frequency power, tuners for adjusting the resonance frequency of the superconducting radio frequency cavities, magnetic shields for shielding magnetism that affects superconducting properties, thermal shields for reducing heat load on the superconducting radio frequency cavities, vacuum chambers for adiabatic retention of superconducting radio frequency cavities, etc., which are then installed in a beam line. We also designed, manufactured and assembled these module components. **Figure 2** presents the configuration of the superconducting radio frequency module for RILAC.

Figure 3 illustrates the superconducting radio frequency cavities for heavy ions being modularized.

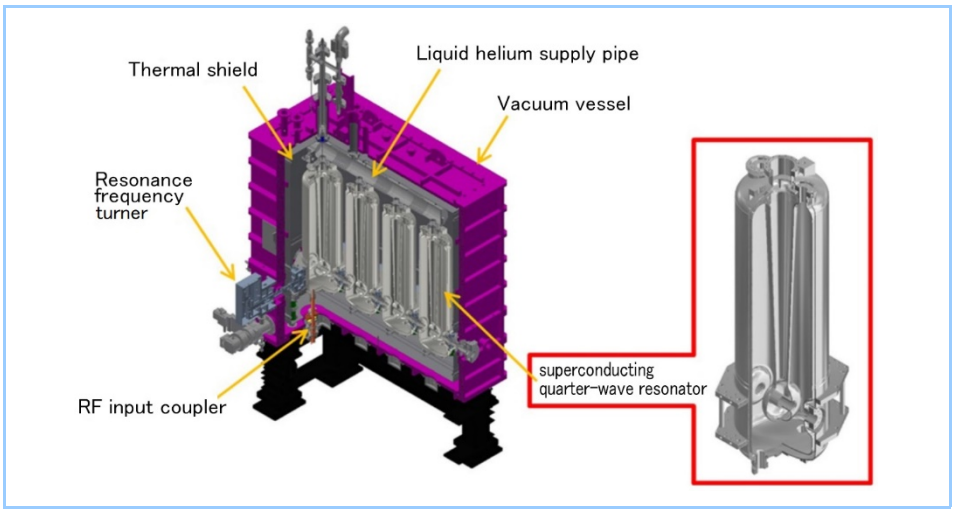

Figure 2 Configuration of superconducting radio frequency module for RILAC

Figure 3 Superconducting radio frequency cavities for heavy ions being modularized

2.2 Design of superconducting radio frequency cavity for heavy ions

The typical shapes of superconducting radio frequency cavities are classified according to the resonance frequency and the velocity of the accelerating particles. **Figure 4** gives the classification of typical shapes of superconducting radio frequency cavities[(2)].

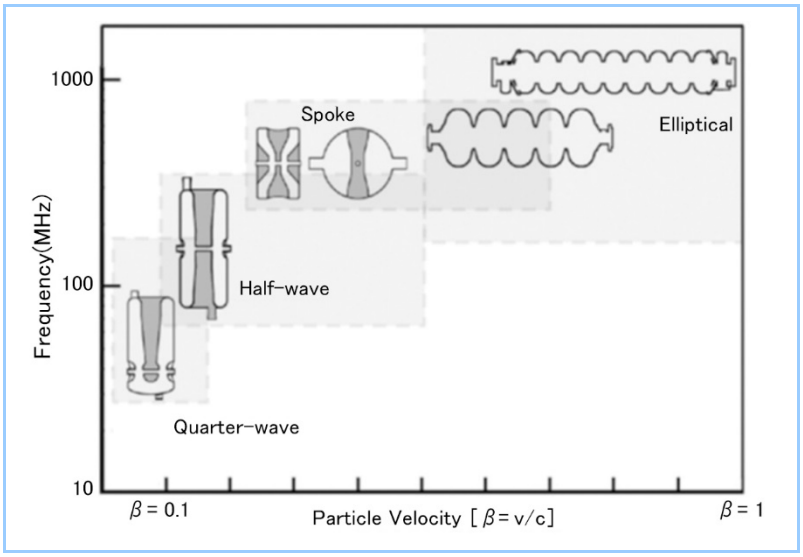

Figure 4 Classification of typical shapes of superconducting radio frequency cavities[(2)]

The superconducting radio frequency cavity for RILAC is called a quarter-wave resonator (QWR) and the radio frequency design was carried out by RIKEN.

Table 1 shows the design parameters of the superconducting radio frequency cavity for

RILAC[3].

Table 1 Design parameters of superconducting radio frequency cavity for RILAC[3]

Item	Design value	
Resonance frequency (4.5 K)	73.0	[MHz]
Accelerating gradient E_{acc}	6.75	[MV/m]
Particle velocity β_{opt}	0.078	
Performance index for high frequency loss Q_0	1.0×10^9	

Since superconducting radio frequency cavities store liquid helium, they are subject to the High Pressure Gas Safety Act. There was a problem in that the evaluation formulas of applicable laws and regulations could not be used due to the special materials and shape, but criteria for the safety evaluation of the material strength and structural strength were defined through the detailed standard pre-evaluation system of the High Pressure Gas Safety Institute of Japan, and the structural design was carried out after obtaining the approval of the relevant ministries and agencies.

Figure 5 presents an exploded view of the superconducting radio frequency cavity for RILAC.

The major parts were shaped from pure Nb sheets (purity 99.85% or more) of 3.5 mm or 4.0 mm in thickness by press-forming.

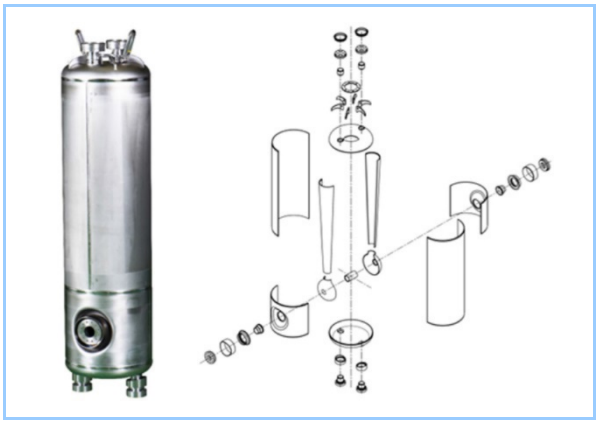

Figure 5 An exploded view of the superconducting radio frequency cavity for RILAC

3. Superconducting radio frequency cavity manufacturing technology that achieves high acceleration gradient and high Q value

3.1 Electron beam welding (EBW)

Impurities on the inner surface of a superconducting radio frequency cavity become heat sources and lead to deterioration of the superconducting characteristics.

Such impurities include not only particulate matter such as grit and dust, but also gas components such as oxygen and nitrogen.

Therefore, it is necessary to assemble parts in a cleanroom and to perform welding in vacuum.

In order to meet this requirement, we have a shop dedicated to accelerator manufacturing, which has an ISO Class 7 (formerly Class 10000) cleanroom with a 10-kw low-voltage electron beam welder.

Since defects in the welding process cause suppression of the performance of the superconducting radio frequency cavity to be restrained, a wide variety of items are managed, such as the thickness, gaps and steps of welding grooves, the cleanliness of welding groove surfaces, the cleanliness of assembly areas and the stability of welding parameters.

This time, all of the welding processes were performed from one side and a smooth weld

bead is formed on both the front and back sides without mechanical polishing. **Figure 6** shows an example of a weld bead.

3.2 Frequency tuning

The resonance frequency of a superconducting radio frequency cavity is determined depending on the shape of its inner surface but may deviate from the design value depending on the manufacturing accuracy during the manufacturing process.

The frequency was measured during the manufacturing process and the part length was adjusted.

As a result, the error of the resonance frequency at the completion of welding assembly was kept within a few kHz.

This is equivalent to processing and welding assembly with an accuracy of 1000 mm for the total length of the superconducting radio frequency cavity of about 0.1 mm. **Figure 7** shows the resonance frequency measurement performed at room temperature.

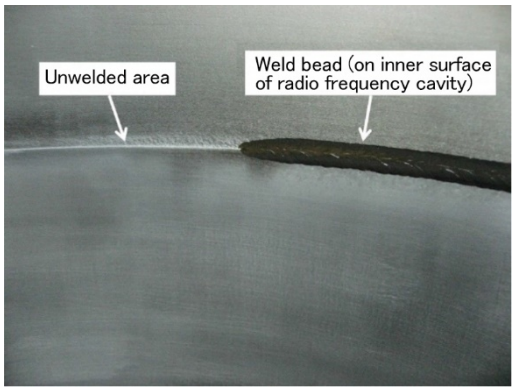

Figure 6 Example of weld bead

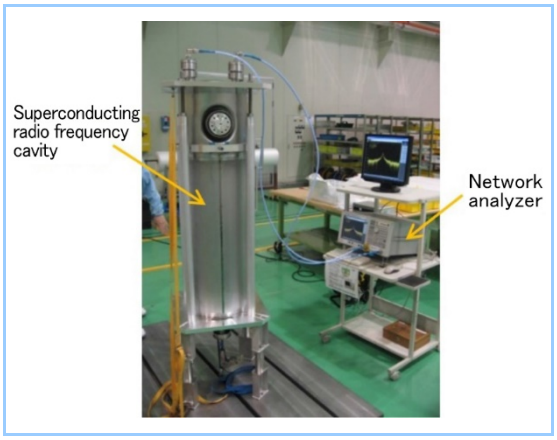

Figure 7 Resonance frequency measurement (at room temperature)

3.3 Buffered chemical polishing (BCP)

The surface treatment of superconducting radio frequency cavities is a very important process that affects the performance thereof. In order to finish the inner surface smoothly, electro-polishing or buffered chemical polishing is usually performed.

This time, we introduced in-house surface treatment equipment for buffered chemical polishing.

As the buffered chemical polishing solution, we adopted a mixed solution of nitric acid (HNO_3) that oxidizes the niobium surface, hydrofluoric acid (HF) that dissolves the niobium oxide film (Nb_2O_5) and phosphoric acid (H_3PO_4) that suppresses the polishing rate. It should be noted that in the buffered chemical polishing of niobium, the polishing speed rises sharply when the liquid temperature increases due to the heat of the polishing reaction and polishing with the residual chemical solution progresses if it takes time to drain the liquid after polishing. Therefore, we constructed a circulation system to control the liquid temperature and flow rate. As shown in the **title photograph**, the inner surface of a superconducting radio frequency cavity after surface treatment resulted in a semi-mirror finish unique to buffered chemical polishing.

3.4 Vacuum heat treatment

Vacuum heat treatment is the process of removing hydrogen occluded in niobium material during buffered chemical polishing. Exposing the superconducting radio frequency cavity with residual hydrogen to a temperature of about 100 K for a long time increases the surface resistance and causes its performance to be restrained. We carried out vacuum heat treatment for 3 hours in the large vacuum heat treatment furnace owned by our company depicted in **Figure 8**.

3.5 High-pressure rinse (HPR)

High-pressure rinse is the process of injecting high-pressure ultrapure water on to the inner surface of a superconducting radio frequency cavity after buffered chemical polishing to obtain a clean surface. Foreign matter (particulate matter and chemical residue) remaining on the inner surface of the superconducting radio frequency cavity becomes the basis of field emission.

This time, we introduced in-house high-pressure rinse equipment.

Based on the results of superconducting radio frequency cavity for electrons, the specifications of high-pressure rinse were set to a water pressure of 8 MPa and an electrical conductivity of 18 MOhm-cm or more

The flange assembly after high-pressure rinsing was carried out in a cleanroom adjacent to the high-pressure rinsing equipment.

In consideration of installation cost, maintainability and assemblability, an openable ceiling system and a horizontal clean air flow system were adopted for the specifications of the clean room.

As a result, the cleanliness performance of ISO Class 4 (formerly Class 10) was obtained, which is comparable to the performance of general methods that use HEPA filters in the outlets, and walls, ceilings, or floors as suction ports.

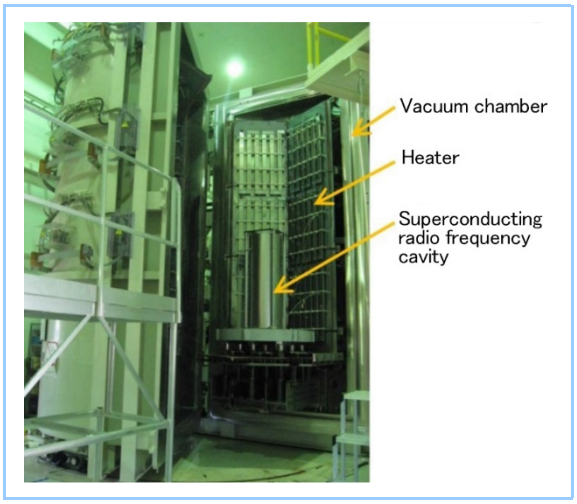

Figure 8 Large vacuum heat treatment furnace

4. Performance of superconducting radio frequency cavity for heavy ions

RIKEN has confirmed the performance of 10 superconducting radio frequency cavities that had completed the welding process.

As shown in **Figure 9**, each of the superconducting radio frequency cavities was placed in a vertical test stand constructed at the RIKEN campus. They were then cooled to 4.2 K with liquid helium and a low power radio frequency was input to measure the accelerating gradient and the Q value.

Figure 10 shows the results of the vertical performance test [(3)].

Stable performance exceeding the specification value was obtained in all 10 superconducting radio frequency cavities for heavy ions, and RIKEN evaluated this result as follows [(1)].

- The integrity and validity of the series of manufacturing processes (machining, welding and surface treatment) of the superconducting radio frequency cavities were confirmed.
- The surface conditions of superconducting radio frequency cavities that were very close to ideal were realized.

Figure 9 Installation of bulk superconducting cavity into the test cryostat for vertical testing (VT).

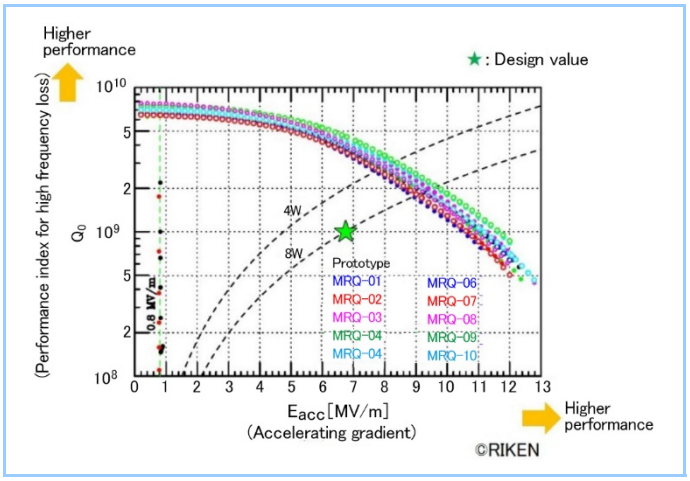

Figure 10 The results of the vertical performance test [3]

5. Conclusion

By utilizing and developing our technology for manufacturing superconducting radio frequency cavities, we succeeded in manufacturing Japan's first superconducting radio frequency cavity made of pure niobium for heavy ions. All 10 of the superconducting radio frequency cavities were installed in the subsequent stage of RIKEN heavy ion Linac (RILAC) and are currently being operated day and night in order to synthesize 119th element and other new elements. Heavy ion accelerators are being built or planned in various places around the world, and are also being considered as next-generation accelerators in Japan. We will contribute to the technological development thereof.

References

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