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CONSTRUCTION AND PERFORMANCE TESTS OF PROTOTYPE QUARTER-WAVE RESONATOR AND ITS CRYOMODULE AT RIKEN

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Abstract

This paper describes the development of a superconducting quarter-wave resonator for use in an intense low-β-ion linear accelerator [1]. The prototype cavity was fabricated from bulk Nb, inner cavity surface processing was performed, and vertical testing was carried out. In the vertical test, a Q-value of 8.7×10^8 was obtained with an operating field gradient of 4.5 MV/m at a frequency of 75.5 MHz [2]. Here, we describe the results of the performance tests and various phenomena we experienced during the tests. After the vertical tests, the helium vessel was assembled and the prototype resonator was integrated into a cryomodule. Initial cooldown testing results are described. Performance testing of the cryomodule is continuing. The situation of upgrade of the RIKEN heavy-ion RIKEN Linac (RILAC) [3,4] is also reported.

INTRODUCTION

Since 2015, the accelerator group of Nishina Center joined the ImPACT program, led by Dr. Fujita, to develop a system for processing so-called long-lived fission products (LLFPs) via nuclear reactions and transmutations induced by ion beams provided by a particle accelerator [5]. As a part of this program, a superconducting (SC) resonator and its cryostat were proposed and accepted, and we began to research its feasibility and manufacturability and design it for performance in a high-power continuous-wave linear accelerator (linac). Linac energy and ion species will be optimized by extensive simulations and new data for nuclear reactions conducted under the ImPACT program.

The developed superconducting cavity was based on the structure of a quarter-wave resonator (QWR) (Fig. 1) for optimum β as low as 0.08. The schematic of the prototype is shown in Fig. 1. The planned operating acceleration gradient is 4.5 MV/m with a Q-factor of 8.9×10^8 estimated by using 3D simulation package Micro Wave Studio (MWS) [6]. The refrigeration capacity is set at 8 W for cavity wall loss.

Based on what we have learned with the development of the QWR, we are proceeding with the upgrade of the RILAC. Two cryomodules, each of which will hosts 4 QWRs with a frequency of 73 MHz.

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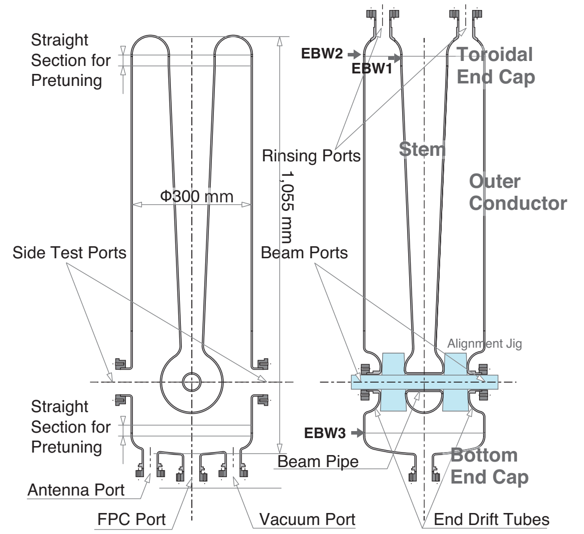

Figure 1: Schematic of the prototype QWR cavity (75.5 MHz).

MANUFACTURING OF PROTOTYPE Nb QWR CAVITY

Fabrication of Cavity

The prototype cavity is made of pure Nb sheets with a residual resistance ratio of 250 provided by Tokyo Denkai Co., Ltd. (TD), and hard Nb (so-called grade 2 Nb) provided by ULVAC is used for port flanges instead of NbTi. The pipes of the beam ports and the beam pipe were machined from bulk Nb (provided by TD). Frequency tuning during manufacturing and interior surface processing are major technical issues in the fabrication of a SC cavity. The main cavity components consist of a top toroidal end cap, an inner conductor (the so-called stem), an outer conductor with beam ports, and a bottom end cap. These parts have two straight sections near the top and bottom for frequency tuning. Note that the prototype cavity does not use a liquid He refrigerator, so it was not required to have a license from the High Pressure Gas Safety Institute of Japan. Before joining the parts by electron beam welding (EBW), the amount of material to cut from the straight sections was carefully determined from measurement of the resonance frequency by pre-assembling the cavity and accounting for shrinkage by the EBW process. Most of the difficulty in pre-tuning comes from the fact that the upper part (indicated as EBW1 and 2 in Fig. 1) must be

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welded first, but the sensitivity of the cut at the upper part, $\Delta f/\Delta x = +58$ KHz/mm, is much larger than that of the cut at the lower part, or EBW3 ($\Delta f/\Delta x = -7.3$ kHz/mm). For the frequency measurements, indium wire with a thickness of 1 mm provided good contact between the parts. In order to ensure accuracy of the measurement, a pair of wedge-shaped spacers indicated as alignment jig in Fig. 1 , which fit into the gaps of the stem and beam ports, were used to align the stem part together with a cylindrical rod for centering the beam pipes. Before the final welding of EBW3, the interior surface was carefully inspected.

Surface Treatment

After assembling the cavity, we performed surface treatment according to a fairly standard procedure:

BCP1 → Annealing → BCP2 → HPR → Baking.

All the facilities for these processes shown in Fig. 2 were developed by MHI [7]. The buffered chemical polishing (BCP) process removes contaminants from the surface of niobium. BCP1 polishes at about 150 μm, while BCP2 polishes at about 20 μm. The polish grit size was determined by accounting for the frequency change. After polishing, the interior surface was inspected again (Fig. 3). The high-pressure rinsing (HPR) utilizes ultra-pure water. A rotating jet nozzle scans the interior surface of the SC cavity in a predetermined pattern, as indicated in Fig. 2. After HPR, vacuum baking was performed at 120°C for 48 hr.

The surface processing was performed four times, as summarized in Tableßtab:process. Preparation for vertical test installing pickups, blank flanges and baking were made in the clean booth at MHI Mihara [8] and a vertical test was performed at KEK after each cycle.

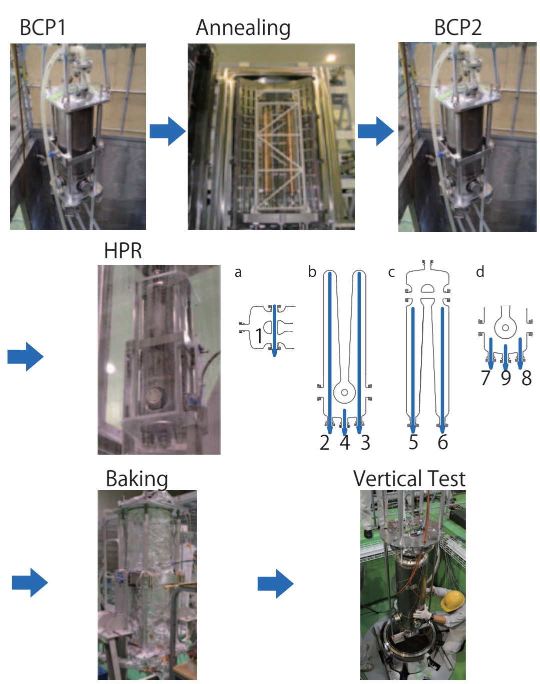

Figure 2: Procedure for surface treatment.

The frequency change was measured during these processes, and the change rate was +0.19 kHz/μm, while the estimation by simulation was 0.1 kHz/μm.

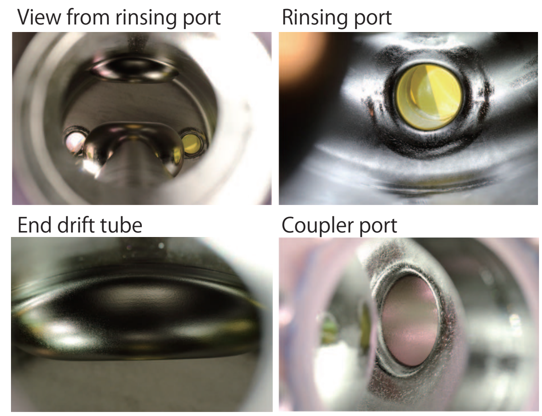

Figure 3: Photos taken after surface processing of the prototype.

Table 1: Surface Treatment Parameters for Each Vertical Test

VT #	BCP1 [μm]	Annealing	BCP2 [μm]	HPR	Baking
VT1	n/a	n/a	19.5	yes	120°C, 48 hr
VT2	97.7	750°C, 3 hr	23.0	yes	120°C, 48 hr
VT3	n/a	n/a	21.9	yes	120°C, 48 hr
VT4	n/a	n/a	n/a	yes	120°C, 48 hr

Vertical Tests

Cavity performance tests, so-called vertical tests, were carried out at the test facility we prepared at the AR-Higashi experimental building at KEK. The Q-value for the cavity was measured as a function of the acceleration field gradient E_{acc} by cooling the cavity with 4.5 K liquid helium using a cryostat chamber equipped with a magnetic shield. Details of the measurement are described elsewhere [2]. All the results of the Q measurements are shown in Fig. 4 together with X-ray emission level monitored by an X-ray detector installed on the top flange of the cavity hanger. In the figure, the constant wall losses for 4 W and 8 W are indicated by dashed lines.

During the first vertical test (VT1), we had trouble with a power coupler and measurement was unsuccessful. For VT2, we made some modifications to the coupler antenna and its driving mechanism. In Fig. 4, the result of Q measurement as a function of field gradient is shown by blue, red, and light green dots. The obtained Q_0 was 8.7×10^8 at E_{acc} = 4.5 MV/m. This value corresponds to surface resistance (Rs) of 27 nΩ. No X-ray emission was observed below 9 MV/m. These results support a conclusion that manufacturing and processing of the prototype cavity were successful.

We aimed at a higher Q_0 by repeating the surface treatment as indicated in Table 1 as VT3. This time, blank flanges for

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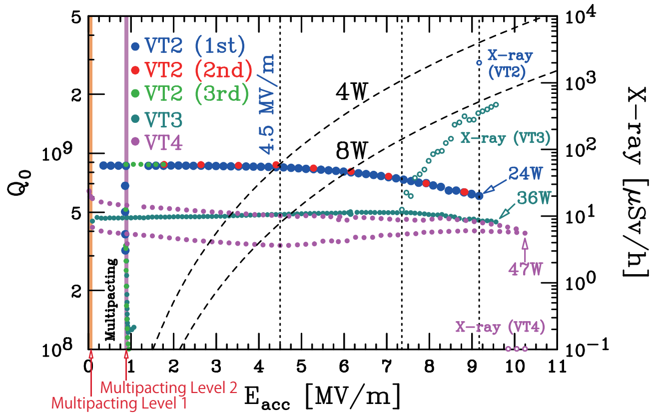

Figure 4: Q_0 as a function of E_{acc} for vertical tests 2, 3, and 4.

the test port, which are made of grade 2 Nb, were polished using the BCP2 solution. As shown in Fig. 4 by green dots, Q_0 fell to 4.7×10^8 at E_{acc} of 4.5 MV/m. The cavity wall loss at this Q_0 value became as large as 7 W. In addition, X-ray emission was observed at 7.5 MV/m. This might have been due to contamination caused by replacing a vacuum seal (U-TIGHTSEAL [9]) to address vacuum leakage at the pickup-port flange, which occurred after HPR. For VT4, after the cavity was enfolded in a He jacket, HPR and baking were aimed at reducing the X-ray emission. This time vacuum leakage did not occur. As shown in Fig. 4 by purple dots, Q_0 did not recover, but the X-ray emission was successfully suppressed.

In the Q_0 measurements, multipacting phenomena were carefully observed. Two levels of multipacting were found, identified as levels 1 and 2 in Fig. 4, which were evident at field gradients E_{acc} of about 0.05 MV/m and 0.9 MV/m, respectively. At level 2, a temperature increase around the toroidal end cap was observed. When E_{acc} reached 0.9 MV/m, the thermometer installed inner side of the toroidal end cap reacted first, and then the thermometer on the outer edge of the toroidal cap showed a temperature rise. This multipacting was ordinarily conditioned in 30 minutes.

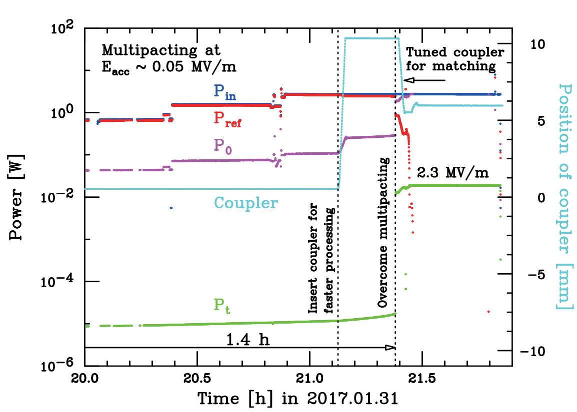

Figure 5: Demonstration of multipacting conditioning during VT4.

When we started the measurement after cooldown of the cavity, we encountered heavy multipacting at level 1 (about 0.05 MV/m) every time. At level 1, the temperature around the acceleration gap slightly increased. It took a few hours to overcome. At VT4, we try to condition the multipacting at level 1 by making the power coupler overcoupled. As shown in Fig. 5, the conditioning of the multipacting was made within 1.4 hr since rf power was turned on.

PROTOTYPE CRYOMODULE

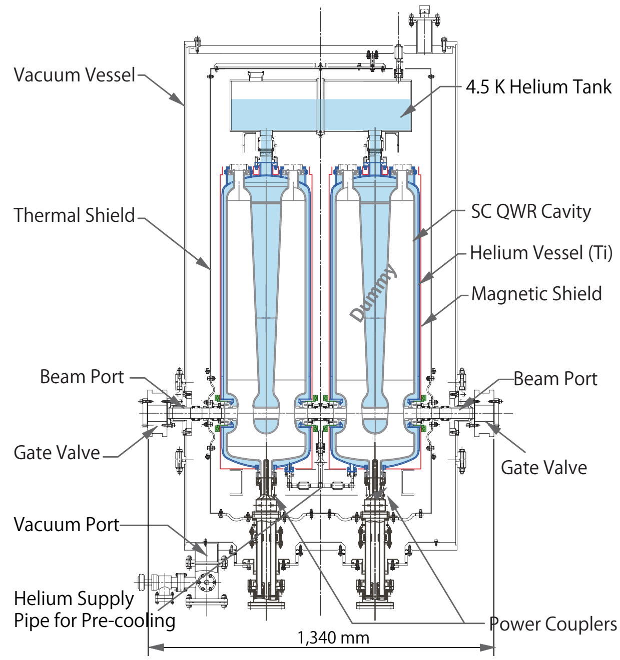

Figure 6: Schematic of the prototype cryomodule.

The prototype cryomodule, which can host two QWRs, is shown in Fig. 6. The manufactured prototype cavity was installed together with a dummy cavity. The cavity was enfolded in a He jacket made of titanium, super-insulators were installed around the helium jacket, and then a magnetic shield was fixed onto the jacket.

The operating temperature of the SC cavity is 4.5 K. The prototype cryomodule can adopt a 4-K GM-JT cryocooler (V316SLCR) [10]. The volume of the He buffer tank is 77 L.

The cryostat vacuum vessel is equipped with a thermal shield, which is cooled by a CH-110 77-K Cryocooler [11] instead of liquid nitrogen. A pair of fundamental power couplers was developed to accept 10 kW radiofrequency (rf) power [12]. The couplers, beam pipes, cavity supports, and a tuner [12] connected between room temperature and the 4.5 K cavity are equipped with anchors to the thermal shield, as shown in Figs. 6 and 7.

After the SC cavity was successfully cooled down to 4.5 K, its resonance frequency was 75.510 MHz with the tuner off, while the frequency tuning range estimated by simulation [1] of the tuner [12] was between 0 and -10 kHz. The loaded Q_L was 1.5×10^6. The SC cavity was excited in the self-excited loop mode and generator-driven mode up to 4.5 MV/m with

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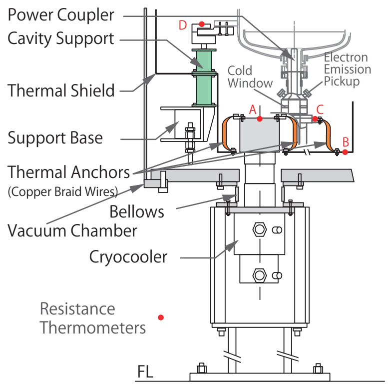

Figure 7: Schematic of the thermal shield showing thermometers and thermal anchors.

X-ray emission below 1 μSv/h, as measured at the end of the beam port. By observing the signal from the pickup antenna, modulation with a frequency of 7~8 Hz was observed. It appeared that the resonant frequency oscillated with a frequency of 7~8 Hz. Wall loss of the SC cavity was measured by observing the drop rate of the helium level in the buffer tank, and it was estimated at 13 W at 4.5 MV/m. Though the cryocooler CH110 has a refrigeration power of 70 W at 40 K, the thermal shield connected to the cold head of the cryocooler by copper braid wires was about 70 K, while the cold temperature of the cold head was below 40 K. No mechanical vibration effects were observed.

The wall loss of 13 W is almost two times larger that the value observed during VT4. Furthermore, an electron emission at the coupler was observed by using a pickup electrode, which was installed to monitor the cavity side surface of the cold window (Kyocera 479B). This electron emission occurred even at low rf power and caused unexpected temperature rise at the power coupler, as shown by thermocouple c in Fig. 7. Further investigation is underway.

UPGRADE OF THE RIKEN LINAC

The RILAC [3, 4] upgrade is going to provide intense heavy-ion beams for super-heavy-element search experiments. Ions with a charge-to-mass ratio larger than 1:5 will be accelerated to more than 6 MeV/u.

The RILAC consists of an electron cyclotron resonance ion source, a radiofrequency quadrupole accelerator, and 12 drift tube linac (DTL) tanks. Among them, the last four DTL tanks will be replaced by two cryomodules, each of which will hosts 4 QWRs with a frequency of 73 MHz instead of 75.5 MHz. The size of the resonator cavity was modified according to this frequency change, and the side test ports and the bottom center port were removed (See Fig. 8). The fabrication of 10 QWRs is planned, but first a prototype cavity is being built and tested. The purpose of the prototype is to verify manufacturing processes, such as assembly by electron beam welding (EBW), frequency tuning, and interior surface processing (Fig. 9).

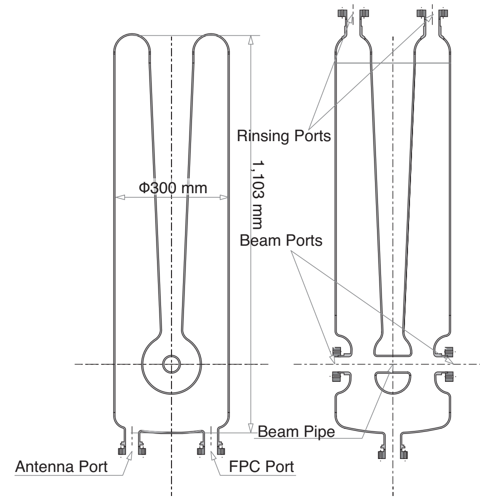

Figure 8: Schematic of the prototype 73-MHz cavity for vertical tests.

Figure 9: Niobium subassemblies for the prototype.

SUMMARY

This paper described the fabrication and testing of a prototype cryomodule based on a QWR SC cavity. The QWR SC cavity was formed from Nb components joined by EBW after frequency tuning. After assembly, surface treatment was applied to the interior until the cavity met objectives for frequency, Q-value, multipacting, and emissions. During the vertical tests, though a Q_0 consistent with the original design was obtained at the first measurement, after that, Q_0 became small. Cryomodule cooldown tests are currently underway, after which additional frequency tuning will be performed by differential BCP to polish the upper surfaces of the SC cavity.

The cryomodules for upgrade of the RILAC is designed on the basis of various data obtained by the development of prototype cryomodule and is now in construction phase.

Design of the accelerator for processing LLFPs is also in progress.

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