SUPERCONDUCTING TWIN QUARTER WAVE RESONATOR FOR ACCELERATION OF LOW VELOCITY HEAVY IONS

H. Kabumoto, S. Takeuchi, M. Matsuda, N. Ishizaki, Y. Otokawa,

Japan Atomic Energy Agency (JAEA), Tokai, Ibaraki, Japan

Abstract

We have designed and fabricated a superconducting twin quarter wave resonator (Twin-QWR) for the acceleration of low velocity heavy ions. The resonator has 2 inner conductors and 3 acceleration gaps which give a resonant frequency of 129.8 MHz and an optimum beam velocity of 6 % of the light velocity. Each inner conductor resonates like in a coaxial quarter-wave line resonator. The resonator was designed to have a separatable structure so that we could treat the inner conductor part fully made of high purity niobium apart from the outer conductor made of niobium and copper. We obtained the quality factor Q_0 of 9×10^8 at 4.2 K at a low electric field, and the acceleration field gradient E_{acc} of 5.8 MV/m at an RF power input of 4 W.

INTRODUCTION

The tandem accelerator of Japan Atomic Energy Agency (JAEA-Tandem accelerator) was built for basic science researches with heavy ions, such as nuclear physic, nuclear chemistry, atomic/molecular physics, solid state physics and material science. This is a 20UR Pelletron of a maximum voltage of 20 MV. Its steady operation for research began in 1982. Its superconducting linac was built as a booster in 1994 to advance these studies [1]. Since 2005, we have been operating an ISOL-based radioactive nuclear beam facility called Tokai Radioactive Ion Accelerator Complex (TRIAC) [2].

The superconducting booster consists of 40 acceleration resonators and 10 cryostats [3-5]. Every resonator is a coaxial quarter wave resonator (QWR) of which frequency is 129.8 MHz, and optimum beam velocity is 10 % of the light velocity. The acceleration field gradients are about 5 MV/m at 4.2 K at an RF power input of 4 W on average. The RF power dissipation of 4 W for each resonator is determined from the cooling capacity of the helium refrigerator. The acceleration field gradient of 5 MV/m corresponds to an acceleration voltage of 0.75 MV for each resonator, and total acceleration voltage is 30 MV.

We have been considering a plan of re-accelerating the radioactive ion beams from the TRIAC to an energy of 5-8 MeV/u by superconducting booster. In order to inject the beams into superconducting booster, we need a pre-booster which is capable of acceleration from 1.1 MeV/u to 2.0 MeV/u. The present Twin-QWR was designed for such a pre-booster.

DESIGN AND FABRICATION

Outline

Figure 1 shows a cutaway view of the Twin-QWR. It has 2 drift tubes and 3 acceleration gaps. The resonant frequency is 129.8 MHz, which is the same for existing QWRs in the superconducting booster. The optimum beam velocity β_{opt} ($=v_{opt}/c$) is 0.06. There has been once the work of building one like this Twin-QWR by J. Delayen and J. Mercerean at Caltec, aiming at high velocity heavy ions [6-7]. Aiming at this low beta of 0.06 with Twin-QWR structure is a challenge that needs careful consideration in the design because the resonator is vertically very long compared to the acceleration gaps.

The inner conductor part, which includes two inner conductors terminated with drift tube and the top end plate, is made of pure niobium, and it is directly cooled with liquid helium. The outer conductor is made from explosively bonded niobium-copper composite plates, and the niobium surface is cooled with help of thermal conduction via thick copper layer. The top part of the outer conductor is cylindrical, the cross section in the middle part gradually changes to oval as it goes lower and the bottom part has flat surfaces perpendicular to the beam axis so that axially symmetric accelerating fields are generated in the resonator.

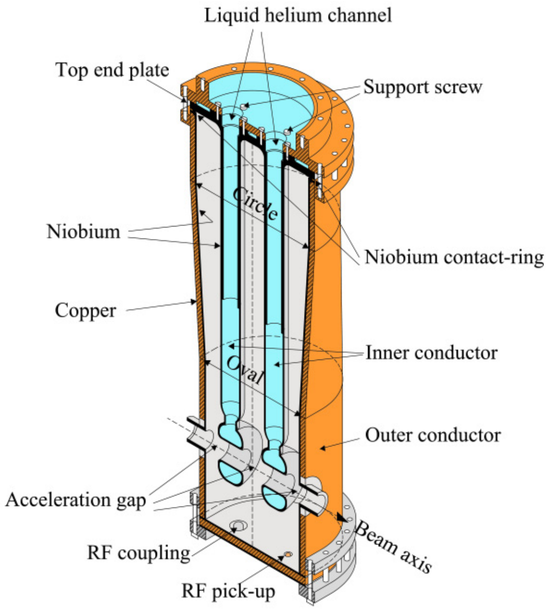

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Figure 1: Cutaway view of Twin-QWR.

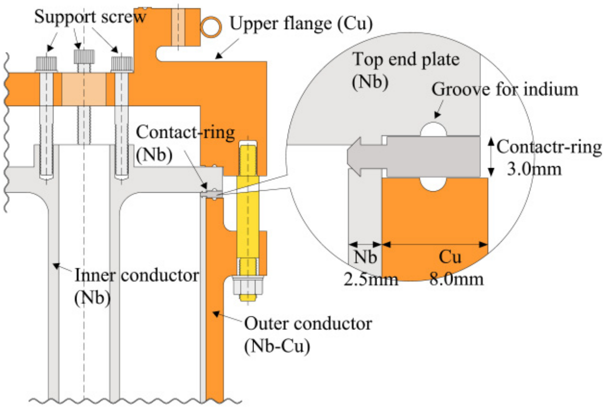

Figure 2: Schematic drawing of the niobium contact-ring.

Niobium contact-ring

The inner conductor part and outer conductor are connected by sandwiching a superconducting contact-ring made of pure niobium. A schematic drawing of the superconducting niobium contact-ring is shown in figure 2. This contact-ring has sharp knife-edges which can be firmly stuck into the niobium surfaces of the top end plate and cut end of niobium outer conductor by bolting these parts together so that superconducting current flows across the niobium contact-ring at the least surface resistance [8]. There are grooves for putting indium wires for thermal conduction.

The main reason for having such a separatable structure is to give the purely-niobium made inner conductor part a heat-treatment at a temperature higher than 600 ℃ in case the niobium is polluted with hydrogen heavily, because the degradation of the resonator Q is very serious in that case [9]. But, such a heat-treatment is not applicable to the outer conductor part made from niobium-copper composite plates. And such pollution to the outer conductor dose not affect very much on the resonator Q, because the current density on the wall is much less than that on the inner conductor walls.

Designing

We fabricated a normal conducting model resonator with aluminum, and carried out a bead perturbation measurement. We also calculated electromagnetic field in the Twin-QWR using MAFIA. Figure 3 shows the electric field profiles measured and calculated along the beam axis at the acceleration field gradient E_{acc} of 1 MV/m.

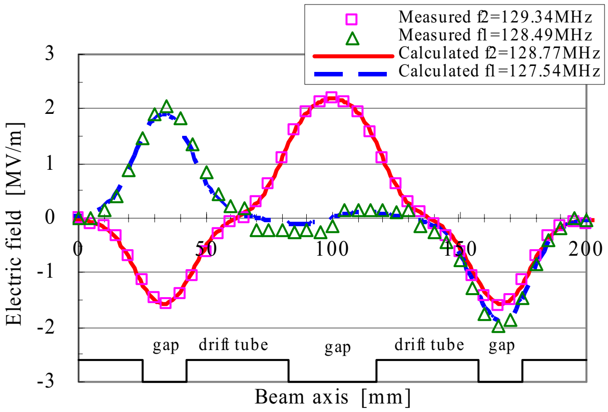

Figure 3: Electric field profiles which are measured and calculated along the beam axis at E_{acc} = 1 MV/m.

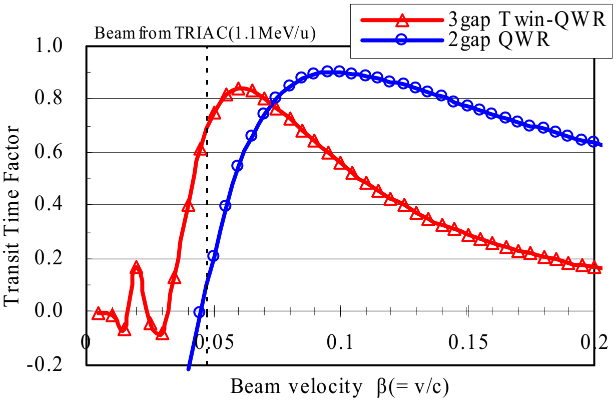

Figure 4: Transit time factors of Twin-QWR and QWR as a function of beam velocity.

The calculated resonant frequency agree with measured one in the accuracy of 0.5-0.8 %, and the calculated profiles of electromagnetic fields also agree with measured ones. The lowest resonant frequency obtained in the measurement is 128.49 MHz, in which case there is no electric field in the center acceleration gap, call it symmetric phase mode. The second one is 129.34 MHz, in which case there are a strong field in the center acceleration gap and opposite fields in the both side gaps, call it anti-symmetric phase mode, and this is the mode for acceleration. The measured frequency separation between two modes is about 0.86 MHz, which is enough for stable operation. Table 1 presents the main parameters of the present Twin-QWR obtained from the measurement and calculation.

Figure 4 shows the transit time factors of Twin-QWR and QWR as a function of beam velocity. The optimum beam velocity β_{opt} of Twin-QWR is 0.06, and β_{opt} of QWR is 0.10. The beams accelerated by the TRIAC have the velocity of about 0.048×c (=1.1 MeV/u), and Twin-QWR can accelerate such beams efficiently.

Frequency stability

In the design of the inner conductor part, it is important to hinder frequency instability. The frequency instability is mainly caused by a deformation of the top end plate by a helium pressure change in this case of Twin-QWR. The pressure of liquid helium deviates about 0.005 MPa at maximum under a turbulent condition in our refrigerator. The 2 inner conductors largely swing, compared to a single center conductor in a QWR, and it results in large electric capacity changes or large frequency deviations. For this reason, the top end plate needs to be screwed to the upper flange of the resonator just above the upper inner conductors as is shown in figure 2.

Table 1: Main Parameters of Twin-QWR

		Measurement	Calculation
Optimum beam velocity	β_{opt} (=v/c)	0.06	
Frequency [MHz]	f_0	129.34	128.49
RF stored energy [J/(MV/m)^2]	U_0/E_{acc}^2	0.039	0.037
Peak surface electric field	E_p/E_{acc}	4.3	4.2
Peak surface magnetic field [mT/(MV/m)]	H_p/E_{acc}	12.5	12.3
Acceleration gap length [m]	L_g	0.0175, 0.035, 0.0175	
Drift tube length [m]	L_D	0.04, 0.04	
Reference acceleration length [m]	L	0.15	

Frequency instability is also caused by mechanical vibrations due to vacuum pumps, helium gas, and other mechanical vibration. The thickness of inner conductors in the upper half section is 4.5 mm, and it is larger than that of lower one of 2.5 mm. The drift tube is designed as light as possible for suppressing the amplitude of mechanical vibration. With such a structure, the calculated mechanical eigenfrequency of the inner conductor was 82 Hz, which seems to be high enough for stable operation.

Fabrication and Assembling

Figure 5 shows the fabricated main parts and assembled the resonator. The resonator mainly consists of (a) inner conductor part, (b) superconducting niobium contact-ring, (c) outer conductor. The (d) open side of the resonator was finally closed with bottom end plate, and under that an RF coupler and RF pick-up were set up.

The inner conductor part and contact-ring were made of high purity niobium which Residual Resistance Ratio (RRR) was 180-220. The outer conductor and bottom end plate were made from explosively bonded niobium-copper composite plates. The outer conductor has a so complicated shape that we chose a pair of well suited combinations for electron beam welding after bending several plates into the shape of a half part of the outer conductor by machine.

Surface treatments were done after mechanical processing. We did an 80-100 μm electro-polishing for the contact-ring. High purity niobium absorbs hydrogen in the process of electro-polishing, and it causes degradation of resonator Q-values. We gave 600 ℃ 1.5 hours heat treatment to inner conductor and contact-ring for the purpose of outgassing hydrogen.

After these treatments, the inner conductor part and outer conductor were joined together with superconducting niobium contact-ring, and bolted all together by the force on about $3\text{-}4\times10^5$ N (estimated).

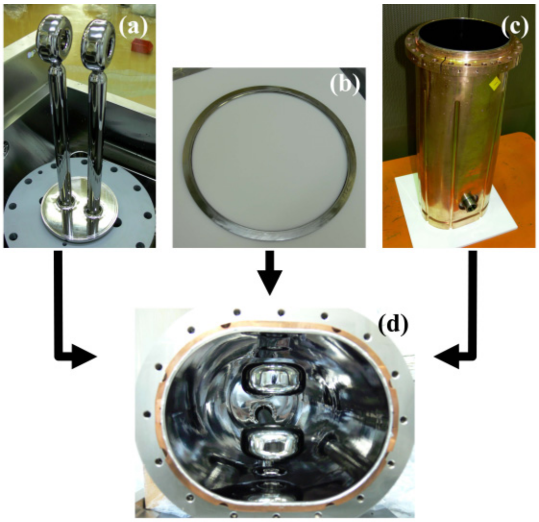

Figure 5: Main resonator parts and assembled Twin-QWR.

The niobium layer of the outer conductor was so thin (2.5 mm) that we needed to set the contact-ring accurately.

High Pressure Water Jet Rinsing

After that, we did a high pressure water jet rinsing (HPWR). A very clean surface is necessary in superconducting resonator. Even a small contamination causes an electron field emission which limits the acceleration field gradient [10]. Our high pressure water jet rinsing procedure was as follows.

First, we rinsed the resonators using methanol for the purpose of washing contaminations, like oil and other chemical pollutions. Then, we did high pressure water jet rinsing for 2-3 hours. The water was pressurized to 7-8 MPa by mechanical compressor, and sprayed on the surface of the niobium. After HPWR, we rinsed the resonator again using methanol for the purpose of quick drying. Finally, we carried out mild baking at 120 ℃ for 2 days in high vacuum.

In the test case of using ultra-pure water of 18 MΩ・cm, the surface of niobium was anodized a little probably due to a generation of plasma or electrostatic current. We could prevent this anodizing using CO_2-dissolved water which electric resistivity was lowered to 0.03 MΩ・cm.

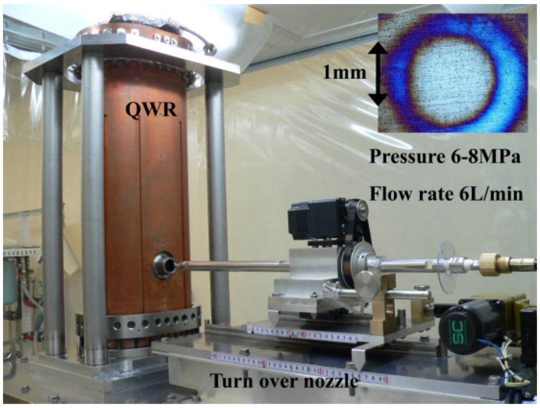

Figure 6: Schematic view of high pressure water jet rinsing (HPWR) and anodized niobium sample.

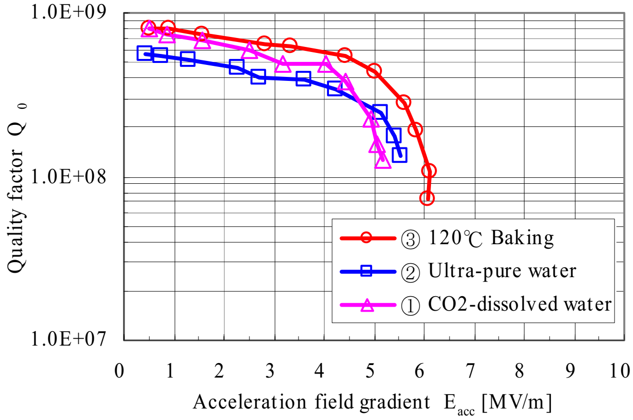

Figure 7: Effect of HPWR and mild baking with QWR.

We carried out series tests of comparing the different water and mild baking with spare QWR of booster. We did HPWR with ①CO$_2$-dissolved water (no baking) at first. The resonator Q_0-values at 4.2 K at low electric field was 7.9×10^8. After the HPWR using ②18 MΩ・cm ultra-pure water (no baking), the Q_0-values was degraded a little to 5.6×10^8. And then, we gave ③mild baking to the resonator, the Q_0-values was improved to 8.1×10^8. The electron field emissions were occurred in every test. There would be a projection on the surface of this QWR. From such experience, we gave the HPWR using CO$_2$-dissolved water and mild baking to the Twin-QWR.

RESULT OF OFF-LINE TESTS

Resonator Performance

We carried out off-line performance tests at the temperature of liquid helium (4.2 K). In the first test, temperature rising was observed around the niobium contact-ring, and the quality factor Q_0 at low electric field was 2×10^8, the acceleration field gradient E_{acc} was 2.8 MV/m at an RF power input of 4 W.

We disassembled the resonator, and found that the contact-ring was partly dislocated by 0.4 mm and not completely in contact with outer conductor. We made an alignment holder of contact-ring to prevent dislocation, and assembled the resonator with a new contact-ring.

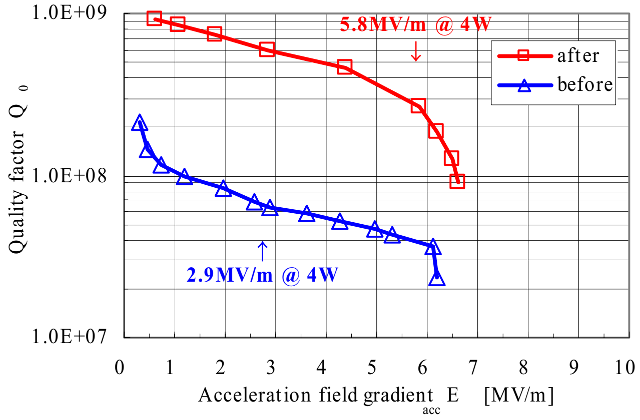

Figure 8: Resonator Q_0-values at 4.2K before and after changing the niobium contact-ring.

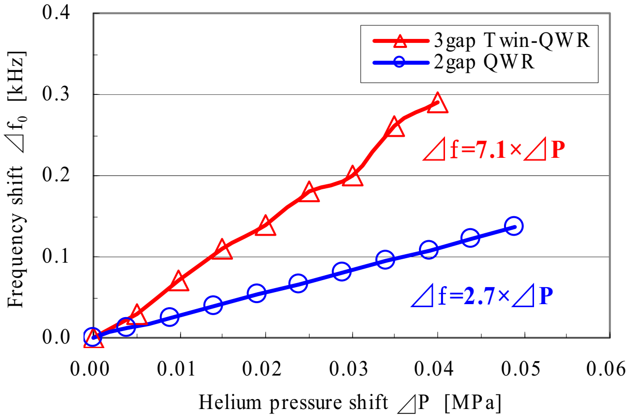

Figure 9: Frequency shift due to the helium pressure.

Figure 8 shows the resonator Q_0-values at 4.2 K before and after changing the contact-ring. Resonator Q_0-values at low electric field was improved to 9×10^8, and the acceleration field gradient E_{acc} was 5.8 MV/m at an RF power input of 4 W. The Q_0-values degraded slightly around 6.0 MV/m without an electron field emission, and thermal breakdown was observed at 6.5 MV/m.

We also measured the frequency stability against the helium pressure (Figure 9). The frequency shift with changing helium pressure was 7.1 kHz/MPa, and it was 2.6 times as large as our QWR's 2.7 KHz/MPa. The pressure of liquid helium deviates about 0.005 MPa when our refrigerator is very turbulent. For stable operation of the Twin-QWR, we will have to set the RF coupling stronger to get a band width of 40-50 Hz, while the existing QWRs have been operated within about 20 Hz.

SUMMARY AND OUTLOOK

A low beta superconducting resonator was developed for acceleration of low velocity heavy ions of $0.045<\beta<0.10$. What we have designed and fabricated is a twin quarter wave resonator (Twin-QWR). In the off-line performance tests, we obtained the quality factor Q_0 of 9×10^8 at 4.2 K at low electric field, and the acceleration field gradient E_{acc} of 5.8 MV/m at an RF power input of 4 W. A superconducting niobium contact-ring worked as a good superconducting current contact between the inner conductor part and outer conductor. The frequency shift with helium pressure was measured, and we found that stable beam acceleration will be secure from a sudden change of helium pressure by setting the RF coupling at a band width of 40-50 Hz.

We have designed the present Twin-QWR as a prototype resonator for a pre-booster of re-accelerating the radioactive ion beams from the TRIAC, and it has been confirmed that the Twin-QWR has high performances enough for such a purpose.

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