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TESTS OF THE BALLOON SINGLE SPOKE RESONATOR*

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Abstract

A novel balloon variant of the single spoke resonator (SSR) has been designed, fabricated and tested at TRIUMF. The cavity is the β=0.3 325 MHz SSR1 prototype for the Rare Isotope Science Project (RISP) in Korea. The balloon variant is specifically designed to reduce the likelihood of multipacting barriers near the operating point. A systematic multipacting study led to a novel geometry, a spherical cavity with re-entrant irises plus a spoke. The balloon cavity provides competitive RF parameters and a robust mechanical structure. Cold tests demonstrated the principle of the balloon concept. The cold test results will be reported in this paper.

INTRODUCTION

RISP has been proposed as a multi-purpose accelerator facility at the Institute for Basic Science (IBS), Korea, for research in atomic and nuclear physics, material science, bio and medical science, etc. At the heart of RISP is a powerful heavy ion linac [1]. The linac consists of three independently phased superconducting sections. The high energy section SCL2 of the driver linac uses two types of 325 MHz single spoke resonators with geometry β at 0.30 and 0.51 corresponding to SSR1 and SSR2 respectively. TRIUMF has been contracted to design, fabricate and test two of the SSR1 variants.

Figure 1: Bare cavity (left) and jacketed cavity (right) of SSR1 prototype.

The prototype cavity of SSR1 β=0.30 designed by TRIUMF is shown in Fig. 1. The cavity is termed the balloon variant due to the conformal shape of the outer conductor that obviates the need for a central spool. The balloon geometry is proposed to suppress multipacting in the accelerating gradient range of several MV/m [2]. It also provides a more inherently robust mechanical structure. The cavity is designed [3] to operate in continuous wave (CW) mode at 2 K with 35 MV/m peak electric field. The design parameters are listed in Table 1. The SSR1 prototype is fabricated with 3 mm RRR niobium for cavity, and 3 mm 316L stainless steel for flanges and the helium jacket. The details were reported in Ref. [4].

Table 1: Design Parameters of SSR1

Parameters	Value
Frequency	325 MHz
Geometry β	0.30
Geometry factor	93 Ω
R/Q	233 Ω
E_{peak}/E_{acc}	3.84
B_{peak}/E_{acc}	6.07 mT/(Mv/m)
df/dp	-1.6/+1.5 Hz/mbar
Lorentz force detuning	-8.7/-1.4 Hz/(MV/m)^2
Tuning sensitivity	467 kHz/mm
Spring constant	14 kN/mm

CAVITY PROCESSING

Cavity was inspected, and leak checked after fabrication. 200 µm surface layer was re-moved by buffer chemical polishing (BCP) in several steps with flipping cavity orientation. The BCP solution is mixed with HNO_3, HF, H_3PO_4 in the volume ratio of 1:1:2. The cavity is fixed on a support frame via stiffener rings on both end shells. The RF ports are positioned up and down during etching. RF ports are used as acid inlet and outlet. The acid temperature was monitored during etching and controlled below 15 ˚C.

High pressure rinsing (HPR) is done through beam ports on the horizontal rinsing stand and each RF port on the vertical rinsing stand. A dedicated nozzle is designed for this cavity. There are two water jets on each direction from 30˚ to 150˚ off the rinsing wand axis with an increment of 30˚. Two additional water jets are 10˚ off the axis on the top. For each cavity assembly, the cavity was rinsed 3.5 hours on the horizontal stand at 80 bar pressure, and 2 hours on vertical stand via each RF port with 45 bar pressure.

The cavity was degassed after an integrated 200 µm BCP. There were obvious signs of hydrogen Q-disease in the pre-degassing tests. Due to concerns about the copper brazing between niobium and stainless-steel flanges, 600 ˚C for 10 hours degassing recipe was selected. The hydrogen partial pressure was monitored with residual gas analyser (RGA) and reduced by 3 orders of magnitude. Additional 20 µm BCP followed by HPR was completed prior to cold test.

Low temperature baking was applied as the last treatment for the hermitic seal cavity before cold test. Two recipes, 50 ˚C for 2 hours and 120 ˚C for 48 hours, were tested to evaluate the effects on BCS resistance and multipacting conditioning. The cavity was actively pumped during the baking procedure. The cavity vacuum was improved by 2 orders of magnitude during the 120 ˚C bake.

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CRYOGENIC TESTS

Cavity Performance

The bare cavity was tested after each BCP step and hydrogen degassing. The helium jacket was welded after Test #4. Additional 20 µm light BCP was employed to remove the surface contamination in the jacketing procedure. The processing steps and cold test sequence are listed in Table 2. Each cold test was completed at both 4 K and 2 K in bath mode, except Test #6 in jacketed mode. The Q-E_{acc} curves are shown in Fig. 2.

Table 2: Processing and Tests of Bare Prototype Cavity

Test #	BCP	Integrated BCP	Heat treatment
1	60 µm	60 µm	N/A
2	80 µm	140 µm	N/A
3	60 µm	200 µm	50 ˚C
4	20 µm	220 µm	600 ˚C + 120 ˚C
5	20 µm	240 µm	N/A
6	-	240 µm	120 ˚C

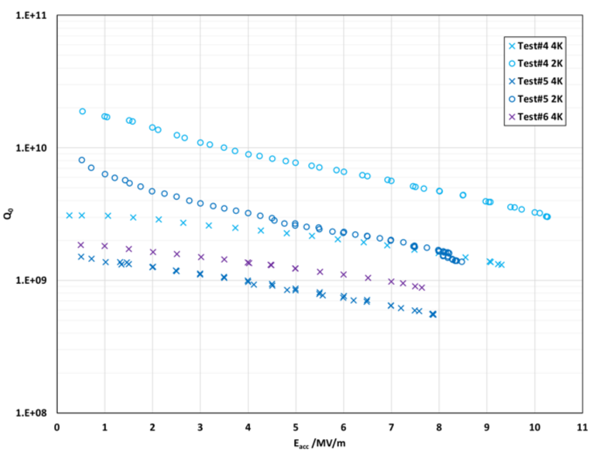

Figure 2: 4K and 2K Q-E_{acc} curves of the prototype SSR1.

The initial Q_0 of bare cavity is 1.9×10^{10} at 2 K. As the BCS resistance is negligible at 2 K for 325 MHz, the residual resistance is 4.9 nΩ. The ambient magnetic field in the cryostat is 35 mG in the vertical direction. Assuming all magnetic flux is trapped in the superconducting transition, the calculated flux sensitivity [5, 6] of SSR1 is 0.12 nΩ/mG. The contribution of trapped flux to residual is estimated at 4.2 nΩ. The 2 K curve has more pronounced Q-slope in the medium field range, which is dominated by the residual resistance. Surface defects in form of either geometry or foreign material are suspected. At the nominal operating gradient, Q_0 is 4.0×10^9 and cavity power dissipation is 6.7 W. Cavity quench limits accelerating gradient at 10.3 MV/m, corresponding to the peak magnetic field of 63 mT, without detectable X-rays.

The jacketed cavity gives declined performance. The BCP after jacketing opened up one or more defects is suspected. The low field Q_0 of unbaked cavity is 8.1×10^9 at 2K. Detectable field emission onset is 7 MV/m. There is Q-switch in the gradient range of above 8.1 MV/m with X-ray dose over 30 µSv/hr at the cavity elevation. Due to TRIUMF's multi-purpose cryostat is not designed for 2K tests in jacketed mode, the 2K curve of Test #6 is missed. However, the 4K results demonstrated baking improves 4K Q.

Cavity inner surface was inspected with high resolution cameras via RF ports. The evidence of bubble trace on cavity shell near RF ports, the small geometry defects on shell, and the imperfect welds at the spoke collar were observed as shown in Fig. 3. It supports the hypothesis of Q-slope, early quench and reduced performance after jacketing.

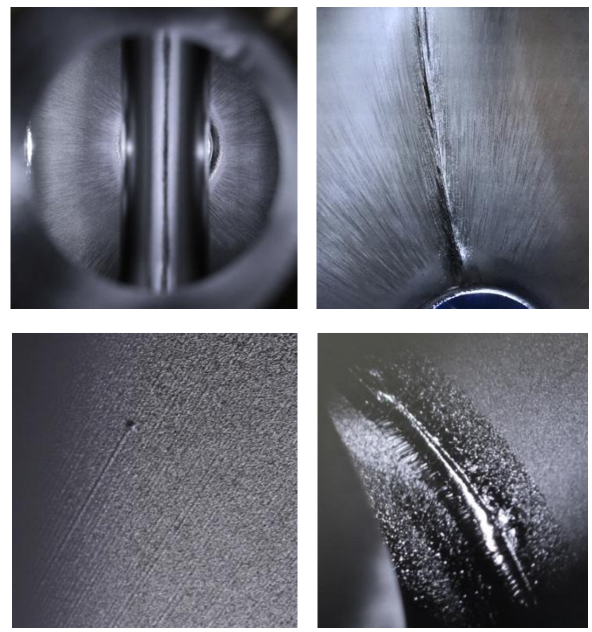

Figure 3: Uneven finish and defects on the RF surface.

The BCS resistance of each test is extracted by measuring Q rise from 4 K to 2 K, shown in Fig. 4. It demonstrates 120 ˚C bake decreases BCS component by a factor of 50% in the low field regime at 325 MHz and mitigates the field dependence of BCS resistance. 120 ˚C baked cavity provides higher Q and less Q-slope at 4 K.

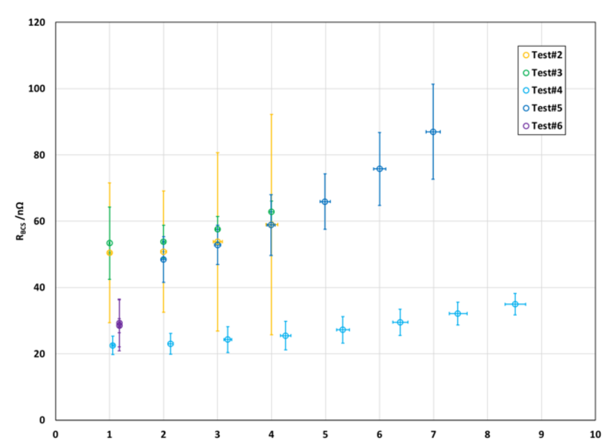

Figure 4: Extracted BCS component of the surface resistance of each cold test at 4K as a function of E_{acc}.

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The cavity resonant frequency at 2 K is 324.995 MHz measured at 1 MV/m in jacketed mode test. Frequency tuning by plastic deformation after fabrication is not needed. The mechanical parameters of the prototype cavity are listed in Table 3. Because of the uneven thinning of the cavity shells in spinning process [4], the cavity rigidity is reduced, and the helium pressure sensitivity is higher than the design specification as expected. As a sequence, the cavity spring constant is also decreased.

Table 3: The Mechanical Parameters of SSR1 Prototype

Parameters	Measured Data
Pressure Sensitivity	-15 Hz/mbar
Lorentz Force Detuning	-7.8 Hz/(MV/m)^2
Tuning Sensitivity	465 kHz/mm
Spring constant	10 kN/mm

Multipacting

The motivation of proposing the balloon variant is to reduce the likelihood of multipacting barriers near the operating gradient. This principle is proved through the prototype cavity cold tests. The comparison of measurement and simulation results is summarized in Fig. 5. The points in the figure represent cavity quality factor with multipacting loading. The lines are the simulated growth rates of the secondary electrons. It indicates multipacting barriers existing if the growth rate is a positive value. The dashed line represents the first order barrier, while the solid line represents the higher order ones (order > 1).

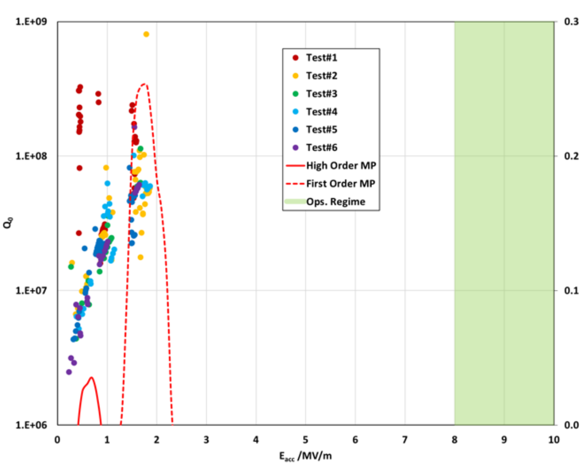

Figure 5: Comparison of measured (Q_0) and predicted (secondary electron growth rate) multipacting barriers of SSR1 prototype.

Some conclusions are obtained as follows. There are no multipacting barriers either around the operational gradient or below 0.1 MV/m. The barriers only exist between 0.2 MV/m and 1.8 MV/m. The measurement results are consistent between tests and they are well predicted by 3D simulation codes, CST MWS and PS [7]. The simulation slightly over estimated the first order barrier in the higher gradient range (1.9 to 2.4 MV/m), while under estimated the higher orders ones (0.2 to 0.4 MV/m and 0.9 to 1.1 MV/m).

Multipacting conditionings were completed at 4 K with a variable RF coupler. Different manners were applied, such as pulse conditioning, amplitude modulation and frequency modulation. Pulse or step function drive provides a chance to jump over multipacting barriers and plunge into the higher gradient range. CW conditioning in self-exited loop was demonstrated as the best setting to clean up barriers. It is found that multipacting is unlikely to reappear after a completed conditioning.

The low temperature baking is verified to mitigate the intensity of multipacting. The baking procedures were performed at 50 ˚C for 2 hours and at 120 ˚C for 48 hours. Both recipes are effective to reduce the conditioning time by about 50 %. Removing the absorbed moisture and residual gas from the RF surface weakens the barriers. Consequently, bake at a lower temperature with a shorter period is more time-efficient for multipacting mitigation purpose.

CONCLUSION

The balloon variant of the single spoke resonator was proposed to mitigate multipacting around operational gradient. The first balloon cavity was designed, fabricated and tested by TRIUMF as the prototype of RISP SSR1. Cold tests demonstrated the principle of the balloon concept. There is no multipacting barrier around the operational gradient. Few barriers exist in the low field regime and are consistent with simulation prediction. Low temperature baking mitigates multipacting intensity. The prototype cavity is processed with BCP, HPR, hydrogen degassing, and low temperature baking. The bare cavity meets the design specifications. Jacketed cavity shows declined performance. Defects in various forms are observed on RF surface. The cavity resonant frequency is 5 kHz off the operating frequency without post-fabrication frequency tuning. Mechanical parameters are also consistent with the design within expected allowance. Further study of eliminating the strong medium field Q-slope and early quench is in progress.

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