DEWAR TESTING OF BETA = 0.085 QUARTER WAVE RESONATORS AT MSU*

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Abstract

Michigan State University is developing quarter wave resonators (QWRs) for a superconducting linac to reaccelerate exotic ions to 3 MeV per nucleon or higher (ReA3). Eight QWRs with an optimum velocity of $\beta = v/c = 0.085$ and a resonant frequency of 80.5 MHz are required for the third cryomodule, which will complete the first stage of the reaccelerator linac. Approximately 100 additional $\beta = 0.085$ QWRs of similar design will be required for the Facility for Rare Isotope Beams (FRIB). This paper covers Dewar testing of the QWRs, performance issues observed in the tests, and design improvements to mitigate these issues.

INTRODUCTION

The National Superconducting Cyclotron Laboratory (NSCL) is building a reaccelerator for exotic ion beams [1]. At present, stable ions are produced and accelerated in the NSCL coupled cyclotron facility; in the future, stable beams will be provided by the FRIB superconducting driver linac [2]. In both cases, the primary beam produces a secondary beam of exotic ions by particle fragmentation.

The reaccelerator will consist of a gas stopper to slow down the secondary ion beam, a charge breeder to increase the charge of the ions by removing electrons, a multi-harmonic buncher and radio frequency quadrupole for initial acceleration and focussing, and a superconducting linac to accelerate the beam to a final energy of 3 MeV per nucleon. Two additional cryomodules can be added to increase the energy to 12 MeV per nucleon (ReA12).

The superconducting linac consists of niobium QWRs optimised for $\beta = v/c = 0.041$ [3] and $\beta = 0.085$ [4]. The cavities are housed in rectangular box cryomodules. The first two cryomodules, containing a total of seven QWRs optimised for $\beta = 0.041$, have been installed and thoroughly tested [5]. This paper covers the prototyping work on the $\beta = 0.085$ QWRs which will be used in the third cryomodule for ReA3.

CAVITY DESIGN GOALS

Though the ReA3 and FRIB cavities will share a similar electromagnetic design, the FRIB cavities are required to provide a higher accelerating voltage than the ReA3 cavities. In addition to QWRs, FRIB requires 322 MHz half-wave resonators operating at 2 K. While the ReA3 cavities will operate at 4.5 K, the FRIB QWRs will operate at 2 K, which will increase the safety margin for their accelerating voltage without increasing the overall plant power requirements. With 2 K operation, the intrinsic quality factor (Q_0) for the QWRs will be approximately four times higher than the ReA3 (and previous FRIB) goal for 4.5 K, and frequency detuning due to pressure fluctuations and helium boiling will be reduced. The cavity figures of merit and operating requirements are shown in Table 1.

Table 1: Cavity figures of merit and operating parameters; R_a is the shunt impedance (linac definition), V_{acc} is the accelerating voltage, and E_{peak} and B_{peak} are the peak surface electric and magnetic fields at the specified operating gradient, respectively. The accelerating field (E_{acc}) is defined via the effective length: $E_{acc} = V_{acc}/ L_{eff}$.

Parameter	ReA3	FRIB
RF frequency	80.5 MHz	
β_{opt}	0.085	
$L_{eff} = \beta_{opt}\lambda$	317 mm	
R_a/Q_0	408 Ω	
E_{peak}/E_{acc}	6.16	
B_{peak}/E_{acc}	13.9 mT/(MV/m)	
V_{acc}	1.03 MV	1.62 MV
E_{acc}	3.24 MV/m	5.11 MV/m
E_{peak}	20 MV/m	31.5 MV/m
B_{peak}	45 mT	71 mT
Operating temperature	4.5 K	2.0 K
Q_0	5×10^8	2×10^9

DESIGN EVOLUTION

The ReA3 QWR design is based on earlier prototyping efforts for the Rare Isotope Accelerator (RIA). The first 80.5 MHz $\beta = 0.085$ QWR [6] was designed for lower voltage, but Dewar and test cryomodule results showed that higher voltages could be achieved [7]. The design evolution is illustrated in Figure 1, where the third-generation design (Figure 1c) is being finalized. All of the designs include a frictional damper for the center conductor [8], although it is not shown in Figure 1c.

The first-generation design (Figure 1a) has a titanium helium vessel which is welded to niobium-titanium transitions on the cavity using tungsten inert gas (TIG) welding. The weld transitions serve multiple purposes.

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The beam port area has weld skirts and 2.75″ Conflat® style vacuum flanges made of NbTi. The NbTi ring at the bottom of the outer conductor is a weld transition and is the backing flange for the RF and vacuum seals. The bottom flange assembly consists of a flat 1.25 mm thick niobium sheet with holes for the RF couplers and a stainless steel bottom flange with ports for the couplers and the tuner actuator. The RF seal is made by a pressure contact between the Nb tuning plate and the Nb outer conductor; the vacuum seal is an indium wire between the NbTi ring and the stainless steel bottom flange.

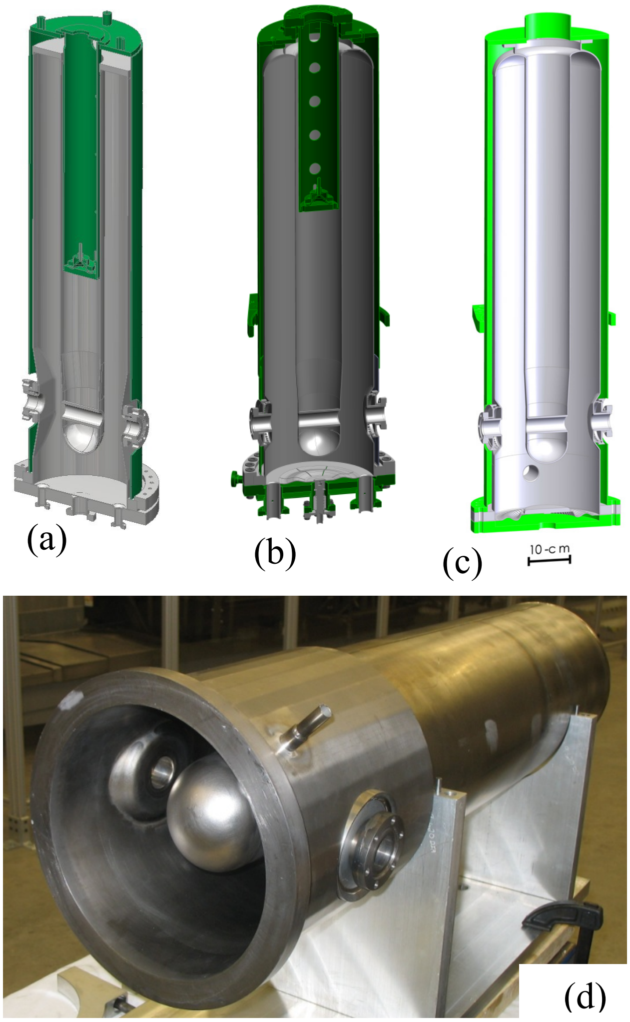

Figure 1: Design evolution of the ReA3 QWR: (a) original RIA QWR prototype; (b) ReA3 production QWR; (c) planned refurbishments for ReA3 (under development); (d) photograph of ReA3 production QWR.

The second-generation design for ReA3 (Figure 1b) improved on the first-generation RIA prototype with cost optimizations and an increased tuning sensitivity. A formed short plate ("cake pan") at the top of the QWR replaced the thick flat niobium plate to reduce production costs. The helium vessel material was changed from Ti to Nb to provide an additional layer of shielding in the case of a cavity quench while the nearby solenoids are energized. The pressure RF contact and In vacuum seal were retained for the second-generation bottom flange assembly, but the larger RF ports were thermally and electrically anchored to the stainless steel bottom flange to obtain better RF grounding. The tuning plate assembly was moved closer to the center conductor, producing a significantly higher tuning range than the previous design. To reduce the frequency sensitivity to pressure fluctuations, a Nb ring was added to connect the cavity top to the helium vessel, along with additional stiffening elements in the beam port region. Based on experience with $\beta = 0.041$ QWRs [9], a liquid helium reservoir was added to the $\beta = 0.085$ stainless steel bottom flange (the bottom flange design is such that there is no direct contact between the Nb plate and the liquid helium).

The reliability of the second-generation design came into question during RF testing, as discussed in the next section. This prompted us to develop a third-generation design (Figure 1c). Because second-generation sub-assemblies were already procured for ReA3, the third-generation design was oriented toward making use of second-generation parts as much as possible.

RELIABILITY CONCERNS FOR THE SECOND-GENERATION CAVITIES

After initial production for the ReA3 $\beta = 0.085$ QWRs had begun, RF testing revealed that the desired performance goals could not be consistently achieved. In initial tests, only 1 cavity out of 5 met the performance goals [9]. A rigorous R&D program was undertaken to systematically identify the design features leading to inconsistent performance.

Initial RF Results

Tests conducted on QWRs prior to completion of the helium vessel had mixed results. Initial Dewar tests on the first production QWR without a helium vessel (SC246) showed very poor performance. A poor RF cable connection to the cavity was suspected, and a helium vessel was later attached to the cavity. Further testing of this cavity revealed the same problems, even after thoroughly debugging the RF circuit.

While the niobium helium vessel was being added to the first cavity, an immersion test was performed on the next cavity (SC247). This cavity met the desired performance goals for ReA3 (see Table 1). However, with the tuning plate in its maximum location, in which the plate is closest to the center electrode tip, the field emission onset was at a lower field (E_{peak} = 17 MV/m) than with the tuning plate retracted (E_{peak} = 33 MV/m). The associated drop in Q_0 due to field emission is shown in Figure 2. Several hours of pulsed RF conditioning did not result in improvement in Q_0, and the 4.5 K FRIB goal could not be achieved. Subsequent tests on the cavity did not reproduce this "good" performance after adding and later removing a helium vessel. The desired performance goals were not achieved again until after the bottom flange assembly had been modified, as will be discussed below.

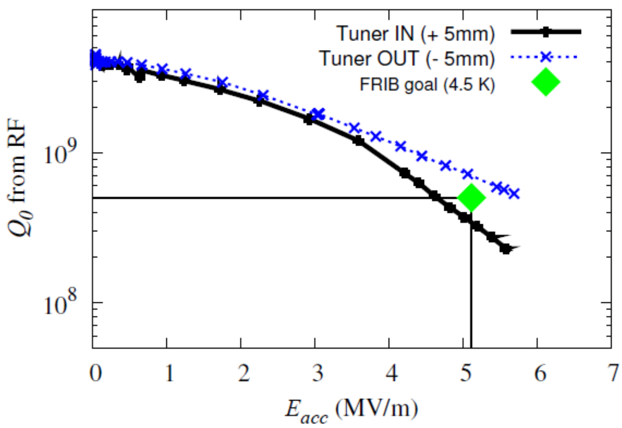

Figure 2: Initial test results at 4.3 K for the second production QWR (SC247) prior to helium vessel welding.

Helium Vessel Issues

In the second-generation design, TIG welding was used for the attachment of the (Nb) helium vessels, as had been done previously for the first-generation (Ti) helium vessels. The Nb vessels developed cold leaks on two of the first three production cavities (i.e. the leaks were only discovered after cooling in a test cryostat). This led to additional studies on the embrittlement of TIG welds. The Nb vessels were ultimately removed, and are now being replaced with Ti vessels. Electron beam welding of Nb vessels is still considered as a viable option, should the additional magnetic shielding be necessary.

TESTING AND REFURBISHMENT

The systematic R&D program included conducting over 40 complete cold tests of five QWRs, additional thermal and electromagnetic calculations, and quality checks of the material and dimensional tolerances. The testing evaluated a long list of potential problems, some of which are summarized in Table 2; most of them have been ruled out as not being responsible for the poor reliability. These tests have led to design changes that will be incorporated in a refurbishment of the QWRs that are being produced for ReA3. The design changes address the potential problems with the RF contact and tuning plate heating from the RF couplers.

The testing program eliminated the majority of the possibilities presented in Table 2, through tests on five second-generation ReA3 QWRs. The majority of the testing was done on the first two cavities, SC246 and SC247. SC246 never reached the performance goals until design modifications were made (detailed below); results on SC247 were not repeatable after the initial tests summarized in Figure 2.

Early tests with additional etching (BCP) treatments ruled out doubts about the damage layer being completely removed, but led to concerns that too many treatments might inhibit the RF performance. These and other concerns about the cavity fabrication steps were alleviated by the promising test results that were achieved after modifications were made to the bottom plate assembly, which includes the tuning plate, tuning plate mounting flange, the RF power coupler ports, and the tuner port.

A number of RF measurements are summarized in Figure 3, which shows the progression of one cavity (SC246) as it moves through several steps in both production and R&D. The RF measurements in Figure 3 were all performed with the cavity immersed in a 4.3 K helium bath.

The black curve (a) suggested that there was a significant problem with the performance of the cavity; with fixed coupling, a poor RF match to the cavity lead to a suspicion that the RF circuit did not properly function. However, even with more careful scrutiny during the installation of the couplers and RF cables for the next tests, the performance remained unchanged.

The blue curve (b) shows the RF results achieved by adding an extension to the cavity without changing the bottom plate assembly. The elongation increased the distance between the tuning plate and the center electrode (CE) tip in the cavity by 50 mm. With the elongation, the resonant frequency of the cavity increased by about 250 kHz, and the tuning sensitivity was reduced from 12 kHz per mm to about 3 kHz per mm. More importantly, the increased distance lowered the magnetic fields at the RF joint from 1.5 mT to 0.5 mT and reduced the surface electric field on the tuning plate from 20 MV/m to 5 MV/m. As a result of the elongation, the cavity immediately reached a much larger accelerating field, although with Q_0 still below the design goals.

Table 2: Potential issues for the $\beta = 0.085$ QWRs.

Issue	Comment	Status
RF contact on tuning plate not reliable	Pressure film tests show poor RF seals, modified RF joints perform better in Dewar tests	design changed
Tuning plate temperature > 9.2 K	Immersion testing does not recover the performance, but thermal anchoring is questionable	design changed
Tuning plate too close to CE tip	Field emission onset changes with plate position	design changed
Damage layer not removed with BCP	Additional BCP did not recover performance	ruled out
Too many etching treatments	Performance recovered after up to 12 etching/rinsing cycles	ruled out
Q disease	Degassing step not sufficient to recover performance	ruled out
Sub-assemblies / material questionable	Additional cavity fabricated by MSU	ruled out
Weld spatter from cake pan weld	Weld spatter cavities perform well with refurbishments	ruled out

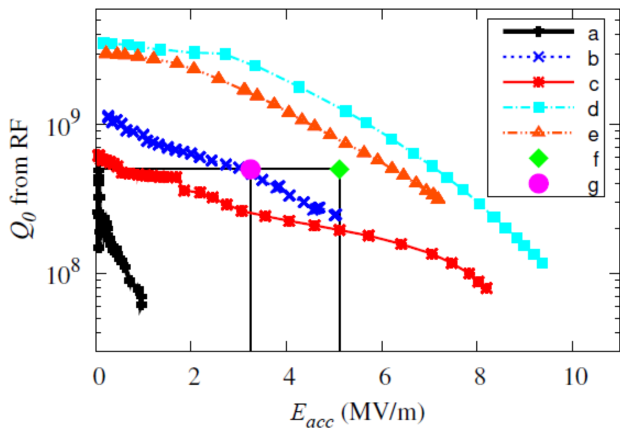

Figure 3: RF performance at 4.3 K of a single cavity (SC246) as it progresses through the R&D leading to the refurbishment. The green diamond (f) indicates the original 4.5 K FRIB goal. The purple circle (g) indicates the 4.5 K ReA3 goal. The curves (a-e) are explained in the text.

The ReA3 performance was only marginally achieved with the blue curve. A degassing step (heat treatment at 600 C in a vacuum furnace) was performed to eliminate any concerns about hydrogen contamination in the bulk material causing Q disease. The red curve (c) shows the performance after degassing. The maximum accelerating field increased significantly, but the desired performance was not yet achieved after degassing. A "Q disease soak" at 100 K and retest were done to check the effect of degassing, as shown in Figure 4. The results indicate that the cavity originally had some susceptibility to Q disease, and that this was removed by the degas treatment. However, as indicated above, the RF performance problems are still present after the degas treatment.

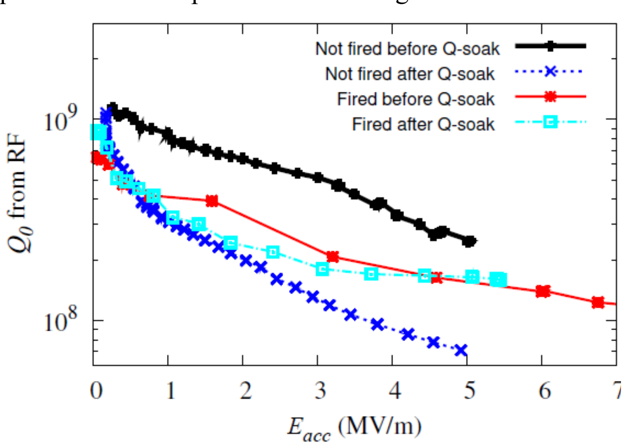

Figure 4: RF measurements before and after a 10 hour "Q disease soak" at 100 K. The RF measurements were performed with immersion in a 4.3 K helium bath.

After the degassing tests, a test with improved RF contact was done. The bottom flange assembly was replaced by a 14 mm niobium sheet; an indium wire provided both the vacuum seal and the RF seal, with direct cooling of the Nb plate by liquid helium. The RF couplers were installed on the beam port flanges. The very promising results with this set up are shown in the cyan curve (d) in Figure 3. This result suggests that the cavities can achieve good performance with a modified the bottom flange design.

After the thick niobium plate showed that the cavity could achieve the design goals, a more realistic test was performed with a thin niobium plate (1.25 mm thick) mocking up a tuning plate and a titanium flange replacing the stainless steel bottom flange (Figure 1c). In this configuration, the liquid helium does not come into direct contact with the entire plate, but there is direct contact along the outer edge. A Ti flange was chosen in order to mitigate the large difference in thermal contraction (about 0.5 mm) between the cavity NbTi backing flange and the stainless steel bottom flange, which we suspected to be the source of unreliable RF contact at low temperature. The orange curve (e) shows the results for this configuration.

During the test with the Ti bottom flange (Figure 3, orange curve), a temperature sensor and heater were installed in the center of the Nb tuning plate to measure the quality factor as a function of input heat at a constant field ($E_{acc} \approx 1$ MV/m). The heater and temperature sensor were epoxied to a copper block. The Cu block was attached mechanically to the tuning plate. As can be seen in Figure 5, the Cu block was able to absorb several watts of heater power without a cavity quench and with very little degradation in Q_0. The Cu block cooled very quickly after the power in the heater was turned off, indicating that the thermal conduction of the tuning plate to the bath is adequate.

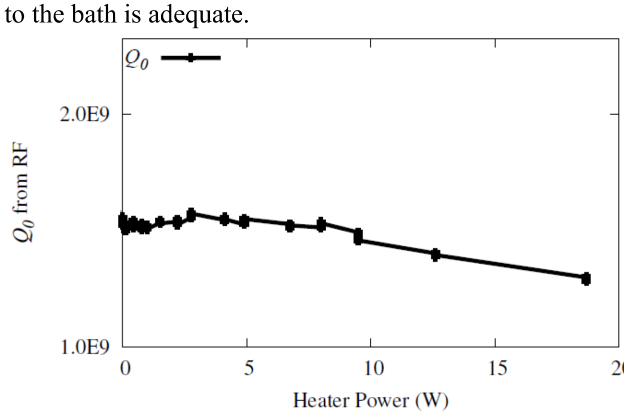

Figure 5: RF measurements with a heater on the tuning plate, with the cavity immersed in a 4.3 K helium bath.

Additional immersion tests were performed on the second cavity (SC247) after refurbishment, with similar performance.

In most cases, the multipacting (MP) barriers in the second-generation QWRs were very simple to "jump over" and proceed to higher field in the RF tests. The very low field (V_{acc}< 10 kV) MP barriers for the second-generation design are being studied in detail with the advanced modelling [10]. The computational results produce good agreement with the RF measurements. In the two tests of SC247 after the side ports were added, MP was more prevalent, requiring several hours of RF conditioning.

PERFORMANCE AT 2 K

Testing of refurbished cavities at 2 K was done to evaluate their potential to achieve the design goals for FRIB. Results of 2 K immersion tests performed on SC246 and SC247 after refurbishing are shown in Figure 6. For SC246, the RF coupling was through the beam ports; for SC247, the coupling was done through new side ports in the outer conductor as planned for the final third-generation cavities (Figure 1c). The quality factor largely exceeded the FRIB 2 K design goal for both cavities, which reached E_{peak} > 50 MV/m and B_{peak} > 120 mT, corresponding to V_{acc} ≈ 3 MV. Thus, the third-generation design can reach the FRIB design goals with significant margin. There is some time to implement additional design improvements for FRIB, which may include increasing the outer conductor diameter.

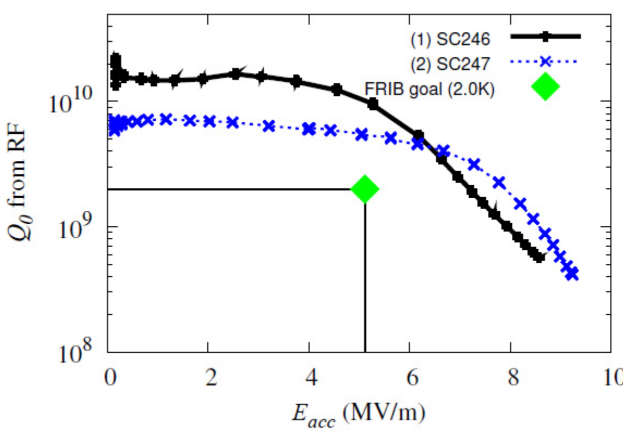

Figure 6: RF tests at 2 K on two refurbished QWRs immersed in a helium bath. The green diamond indicates the FRIB 2 K design goal. Note that E_{peak}/E_{acc} = 6.16, and B_{peak}/E_{acc} = 13.9 mT/(MV/m).

CONCLUSION AND OUTLOOK

The test results for both refurbished β = 0.085 ReA3 quarter-wave resonators are very promising, indicating that it should be possible to reach the ReA3 performance goals through refurbishment. Additional tests are needed to confirm this, most notably a full test of a cavity and vessel with a liquid helium cooling circuit similar to that of the cryomodule. Once a final confirmation is made that the RF performance can be achieved, additional rework will likely be required to achieve a final frequency within the tuning range. The tuning plate is being modified to allow for more travel, which with mitigate the reduced tuning range due to the tuning plate being farther away. This redesign is expected to allow for a 40 kHz tuning range over a 20 mm travel. Adjustments will also be made to the RF input coupler design and cryostat design to allow for the coupling from the side.

The β = 0.085 QWRs will all be certified in a test cryostat which has thermal conditions similar to the cryomodule, as was done for the ReA3 β = 0.041 QWRs. Tests will also be performed at 2 K to build statistics and provide insight for design optimizations for 2 K performance of QWRs for the FRIB project.

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