

FACED ISSUES IN REA3 QUARTER-WAVE RESONATORS AND THEIR SUCCESSFUL RESOLUTION*

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Abstract

The 80.5 MHz, $\beta=0.085$ QWR production cavities for the ReA3 project at MSU have initially shown puzzling behaviour and unexpected lack of performance. This was due to a combination of design problems and subtle mechanical effects, which have been pointed out during a brief but intense testing campaign made by the FRIB SRF group. The same cavities could be eventually refurbished and brought to performance well above original specifications. This work will be presented with emphasis to the technical problems encountered, their diagnosis and the adopted solutions.

All ReA3 resonators have been designed and produced before 2011. While the seven lower beta cavities could be installed and operated according to the design specifications since 2011, ten following $\beta=0.085$ ones based on the same design (except for a larger diameter to accommodate the larger beam velocity) showed a puzzling behaviour with very good results for the naked (i.e. without helium vessel) prototype, and rather bad and unpredictable ones for the same resonators after dressing them with helium vessel. This worrisome and unexpected situation triggered an intense effort of simulation, testing and cavities prototyping in order to be overcome [4].

INTRODUCTION

The ReA [1] and FRIB [2] superconducting linac projects at MSU share the same SRF resonators technology [3]. ReA is an operating low- β linac, used for nuclear physics experiments, which is designed to accelerate up to several MeV/u low-current ion beams, both stable and radioactive ones produced by means of the NSCL cyclotron. The FRIB linac will be the driver of the large radioactive beam facility under construction at MSU (in which ReA is the post-accelerator) and will accelerate ion beams with mass up to Uranium to an energy of 200 MeV/u, for a total power of 400 kW on target. Both linacs require quarter-wave resonators (QWRs) with $\beta=0.041$ and $\beta=0.085$, working at 80.5 MHz. Since the ReA construction started first, its QWRs became prototypes for the FRIB ones and for the development of SRF technology at MSU. ReA is now operating with 7, $\beta=0.041$ QWRs (6 plus one buncher). A new cryomodule containing 8, $\beta=0.085$ QWRs is now being installed and will bring the beam energy above 3 MeV/u (ReA-3 stage). A new cryomodule, containing 8 FRIB type $\beta=0.085$ QWRs, is presently under construction and will bring the beam above 6 MeV/u (ReA-6 stage) by 2014, thus making possible at MSU experiments with re-accelerated radioactive beams above the Coulomb barrier. Future upgrades (e.g. ReA-12, for 12 MV/u) are foreseen, especially once FRIB will be completed.

THE EARLY ReA3 QWR DESIGN

The ReA3 QWRs are 80.5 MHz cylindrical coaxial structures, with 30 mm aperture beam ports and cylindrical inner conductors (IC), partially flattened in the beam tube region (Fig. 1). This simple design gives RF parameters R_{sh} , E_p/E_a and B_p/E_a well adequate to the ReA scope.

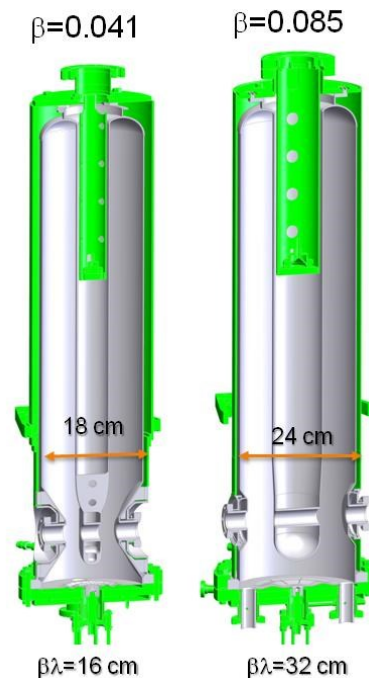


Figure 1: The original ReA QWR design.

The main advantage, however, is mechanical simplicity and compact size which allows reducing the resonator

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cost and risk significantly. The resonators are mostly made of 2 mm, $RRR > 200$ Nb sheets, rolled or deep drawn; the Helium vessel is made of Titanium, which shares with Nb very similar thermal contraction coefficients. In the early design [5] all flanges were made of NbTi which can be welded both to Nb and to Ti.

In the $\beta=0.041$ ReA3 cavities the only apertures are the two beam ports and the bottom flange, made of NbTi and in contact with liquid Helium. The RF coupler and pickup are mounted on RF ports located in the 1.2 mm thick Nb tuning plate, which is provided with radial slots in its centre part to facilitate elastic deformation (Fig. 2). The plate edge overlaps, for a few millimetres, the NbTi bottom flange of the cavity which provides cooling and RF contact. The pressure on the contact – and the vacuum inside the cavity – is kept by a thick, stainless steel (SS) backing plate bolted to the NbTi bottom flange (to its rotatable SS ring). Between the backing plate and the NbTi bottom flange, outside the tuning plate diameter, an Indium wire provides vacuum sealing. This design was validated first in test cryostats with naked cavities and then, after installation of helium vessels, in the ReA linac, where seven such cavities are operating successfully.

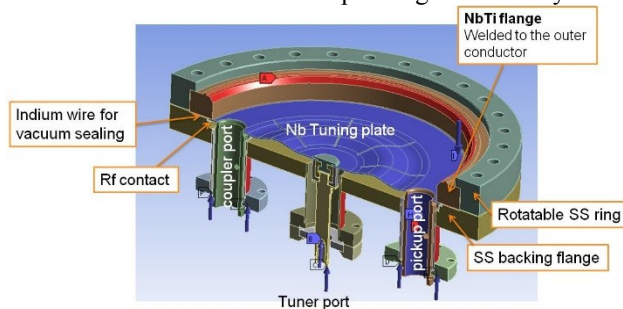


Figure 2: Mechanical details of the original tuning plate.

PUZZLING RESULTS

The same mechanical solutions were used also for the $\beta=0.085$ resonators, which differed from the previous ones essentially in their outer conductor (OC) diameter (24 cm instead of 18 cm). After successful prototyping of one naked cavity [6], which confirmed the good RF results of the $\beta=0.041$ ReA3 ones, 10 more cavities with Helium vessel were produced for the next $\beta=0.085$ cryomodule. Unexpectedly, all tests at 4.2 K gave very disappointing, non-reproducible results, with low Q_0 , strong Q-slope and early cavity quench. Even the good performing prototype started failing after He vessel installation. Several causes have been suspected: Q-disease, unwanted changes in the surface treatment and cavity preparation, construction and welding defects, tuning plate overheating from the RF coupler and normal conducting transition, high residual magnetic field from new components, bad RF contact at the tuning plate.

Q-disease was soon pointed out by 4 K testing at different cooling speed with naked cavities. However, even fast cooling could not solve the problem in dressed resonators, and Q-disease was ruled out as the major responsible for low Q. Construction and welding defects

were excluded because not compatible with the good but irreproducible results of the naked prototype. Surface treatments, based on Chemical Polishing (CP) and High Pressure Rinsing (HPR), were thoroughly checked and all chemicals and procedure steps were analyzed and controlled. They were finally ruled out because they were anyhow giving good results with the FRIB half-wave resonators (HWR).

The possibility of tuning plate overheating by the RF power coupler was confirmed by computer simulations. The different behaviour of the $\beta=0.085$ cavity from the $\beta=0.041$ one could be partially explained by its larger plate diameter and larger RF power requirements. However, even in naked test where the SS backing plate is directly cooled with liquid helium, improving the tuning plate and the RF ports cooling, the results were unsatisfactory. Moreover, overheating and partial transition to normal conducting state should have appeared only at sufficiently high RF power, while low Q was observed even at the lowest gradient.

Residual magnetic field was ruled out by measurements and because the only material added to the dressed prototype, compared to the naked one, was the Titanium vessel with no possibility of magnetization.

The RF contact between tuning plate and outer conductor was checked by mounting the tuning plate assembly with pressure films on the contact surface, and analysing them after plate dismounting. This test showed that the pressure on the RF contact was rather uncertain and not reproducible, even at room temperature. Several types of rings (spring type, Indium, blunt edge ...) have been tried to improve the contact, giving however unpredictable and unsatisfactory SRF results. After this first testing campaign, the knowledge of the design problems was significantly improved, but the RF results were still disappointing and the real culprit was still unknown.

TESTING CAMPAIGN WITH CAVITY MODIFICATIONS

The main questions for us were: why a cavity design, which works well in $\beta=0.041$ cavities, fails when used in $\beta=0.085$ ones? Which fundamental role is played by the different diameter, which is apparently the only difference? Can we still recover these 11 resonators? To find it out, we decided to re-analyse all available old measurements data and to perform new measurements in a more systematic way. This campaign required the small team in place to perform about three months of continuous testing, with one to two cryogenic tests per week, with all related cavity surface treatments and preparation and, in parallel, mechanical modifications of prototypes including EB welding [4].

Role of Tuning Plate-inner Conductor Distance

Analysing old data of the tuner test with the naked prototype (thus completely immersed in liquid Helium) we observed that the high gradient Q was degraded when

tuning to low frequency, thus moving the tuning plate closer to the inner conductor (IC) tip (Fig. 3). This action increases the RF current both on the plate and through the RF joint. Field emission could not be the cause of this effect since no increase in X-rays was observed.

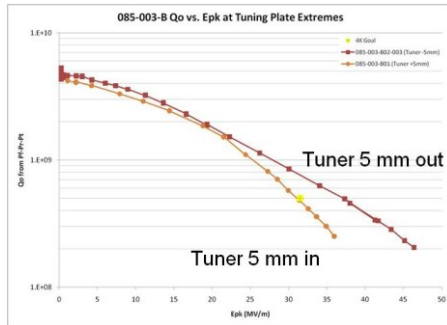


Figure 3: Q reduction after decreasing the tuning plate-inner conductor distance.

We interpreted this behaviour as overheating of the plate and generation of normal conducting spots, presumably near the RF contact. This was not sufficient to explain bad results at low field, but only the loss of performance at high field. Simulations demonstrated that the magnetic field at the RF joint was about 2 mT at the design gradient. To reduce the magnetic field at the RF joint below 1 mT (in our experience a “safe” value at 4.2 K) we decided to elongate the outer conductor (OC) in one cavity. In the following RF test we immediately obtained an order of magnitude higher Q and a factor of 2 higher gradient before quench, demonstrating the critical role of the RF joint. However, the performance was still below specifications and the reason was not yet clear.

Q-disease

To verify the importance of Q-disease in our results, we did various “12 hours, 100 K soaking” tests. Q-disease was clearly present, and could be eliminated by applying high vacuum thermal treatment at 600 °C, performed at J-Lab. The following cryogenic test with 100 K soaking showed that Q-disease was removed and the maximum E_a before quenching had further increased above specifications. However, Q_0 did not improve yet.

RF Joint Modification

We were aware that the RF contact between NbTi flange and Nb plate could be responsible of the dominant RF losses. In case of bad contact, some current might flow beyond the Nb plate over the SS flange, up to the In seal for vacuum. Even a small current on stainless steel would cause large RF losses. We then decided to modify the RF contact by adding a second, inner In seal between Nb plate and NbTi flange. To verify its effectiveness, we measured the change of Q between operation at 4.2 K and 2 K and the expected Q jump at 3.4 K (the superconductive transition temperature of Indium). Surprisingly, this Q-jump did not appear at all, showing that the RF contact was not really where it was expected. We explained it as a result of differential thermal

contraction: the SS end plate contracts 0.5 mm more than the NbTi bottom flange strictly bolted to it, creating in the flange a conical deformation (similarly to a bow bent by its string, see Fig. 4) which opens a gap in the RF contact but not at the In vacuum seal, which is close to the bolts line. (The rotatable SS ring was split in two and did not exert valuable forces). If it was true, removing the SS parts would have eliminated this problem.

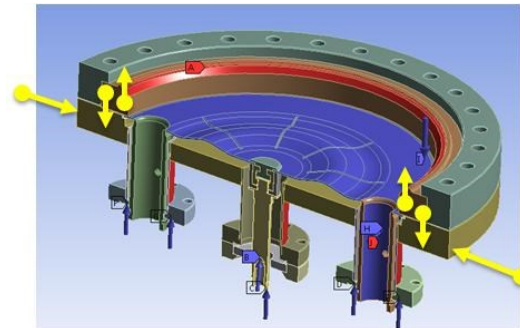


Figure 4: Schematic representation of the forces causing conical deformation of the old NbTi bottom flange.

Test with Thick Nb Tuning Plate

To confirm our hypotheses, we replaced the 1.2 mm standard tuning plate by a 14 mm thick, high RRR Nb end plate, strong enough to hold the He bath pressure. RF coupler and pickup were installed at the beam ports. We could then eliminate the SS end plate and thus any differential thermal contraction issues and conical deformation. This configuration significantly improved the tuning plate cooling, removing any thermal load from RF coupler. Then we used only one In ring to provide both vacuum sealing and RF joint: good vacuum would have guaranteed the presence of a good RF contact.

The test results were at last fully satisfactory, with high Q and high E_a , showing that the problem was finally understood and that the solution was close at hand.

We repeated the single In seal test with thick Nb plate on the “good” prototype, not yet elongated, which still had the standard, rotatable NbTi flange. The SS ring was replaced by a Ti one to eliminate any risk of differential thermal contraction. The results at low field were very good as well, showing again good RF contact. The Q slope, however, started at a much lower field than in the elongated cavity, confirming that a short distance between inner conductor and tuning plate decreased cavity performance.

Test with Realistic Tuning Plate

The thick plate could not represent the final, 1.2 mm thick one required for resonator tuning. So a new, thin Nb tuning plate as wide in diameter as the bottom flange, and a new end plate made of Ti, were built and used for a new test. Again, a single In wire was used for both RF and vacuum sealing on the RF side of the Nb plate (another In vacuum seal was placed between the Nb plate and the Ti backing plate). The results were very good both in Q and E_a , almost reproducing the ones obtained with a thick

plate. The slightly lower Q and Ea suggested however that cooling issues were still present even with the cavity fully immersed in liquid He and could become critical in the normal operation with He vessel where the plate is cooled only through the bottom flange (Fig. 5). This concern was confirmed by a measurement of the cooling time of the plate in a dressed cavity with a NbTi flange.

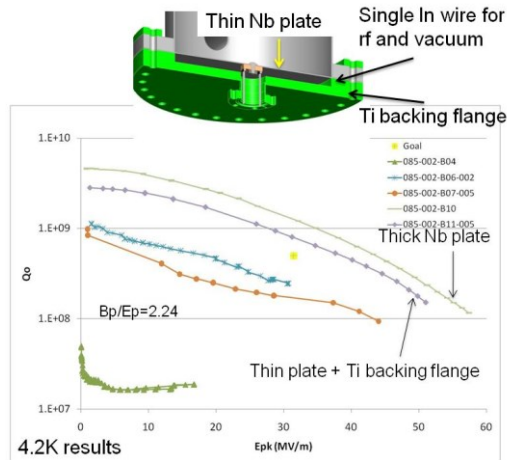


Figure 5: Top: Test setup with the thin Nb plate. Bottom: Evolution of the cavity performance at 4.2 K after subsequent modifications. Green: Initial result; Light blue: after outer conductor elongation; Orange: after H degassing; Light green: with thick Nb plate and single In wire; Grey: with thin Nb plate and Ti backing plate.

Final Diagnosis

The conclusions of this demanding, but fruitful campaign were the following:

1. The bad results of the first lot of $\beta=0.085$ QWRs were caused by a subtle mechanical effect related to differential thermal contraction of Nb, NbTi and SS parts, which caused opening of the RF joint at cryogenic temperature. This effect was not visible in the $\beta=0.041$ cavities because of their smaller diameter and their smaller differential contraction, and because of their lower RF current at the RF joint.
2. The thermal conductivity of NbTi, the material the standard bottom flange is made of, is too low to guarantee reliable cooling of the Nb tuning plate by contact. High RRR Nb, with 100÷1000 times higher thermal conductivity at cryogenic temperatures, is needed.
3. The RF coupler mounted on the tuning plate delivers a thermal load that is difficult to remove through the thin Nb sheet in the $\beta=0.085$ cavity.
4. The small distance between the IC tip and the tuning plate caused RF performance reduction. This distance had to be increased.
5. A single In wire between the bottom flange and the tuning plate could successfully provide at the same time vacuum sealing, thermal contact and RF contact.

6. The existing, low performing cavities built for ReA3 could be brought to full performance by a modification of their end part. This action would have been relatively inexpensive compared to the construction of new cavities.

These findings gave us a clear roadmap for refurbishment of the 10 ReA resonators, and for the design of the FRIB QWRs.

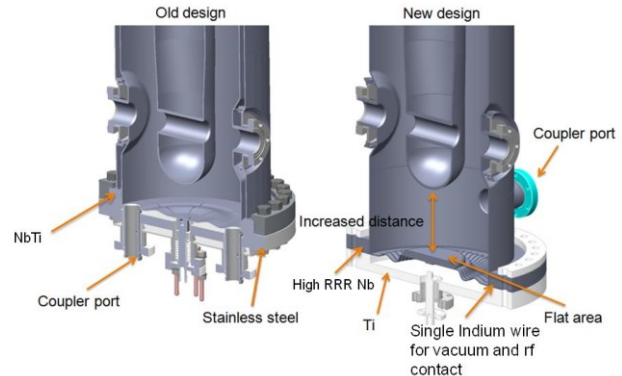


Figure 6: Comparison between the original and the refurbished ReA QWR design.

ReA CAVITIES REFURBISHMENT

The ReA3 resonators design was modified as follows (see Fig. 6):

1. The cavities outer conductor was elongated to match both low magnetic field at the RF joint (0.5 mT) and sufficient sensitivity from the tuning plate (>2 kHz/mm);
2. The NbTi/SS rotatable bottom flange was replaced with a fixed, high RRR Nb one;
3. The old tuning plate with RF ports was replaced by a new one, without RF ports and with longer slots and larger deformation capabilities (± 10 mm) to reach ± 20 KHz tuning range;
4. The SS end flange with RF and tuner ports was replaced by a Ti one with only the tuner port;
5. The RF ports have been moved to the side of the resonator, in a position which was optimized for minimum RF losses in the coupler.

We then tested the refurbished cavity design by modifying our old “good” prototype. The RF tests, first with the naked cavity and then after He vessel installation, gave excellent results. Hydrogen degassing at 600 °C after 150 μ m CP have been added to the production cavity preparation recipe, eliminating Q-disease completely. Further “light” etch of 30 μ m is applied to eliminate possible contamination during furnace treatment, with no Q-disease reappearance. Final baking at 120 °C after HPR have shown to improve high field Q considerably at 4.2 K also in our ReA QWRs, and was included in the standard procedure.

The remaining 9 underperforming resonators, built for the ReA3 cryomodule, have been refurbished accordingly and then tested at 4.2 and 2 K, all showing results largely above specifications (Fig. 7). To reduce the risk of

damaging them with uncontrolled sparks before installation, these cavities were finally tested only up to the administrative limit of $E_p=42$ MV/m (maximum operation specification: $E_p=35$ MV/m), although showing no limitation to higher performance.

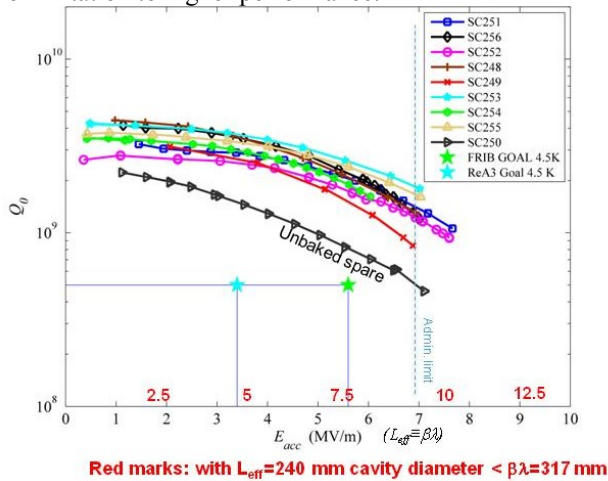


Figure 7: Refurbished QWR performance (tested up to the administrative limit $E_p=42$ MV/m at 4.2 K), before installation. In addition to the one calculated with our standard accelerating length definition $L_{eff}=\beta\lambda$, E_a is shown also for the widely used definition $L_{eff}=D$, where D is real cavity OC diameter (red marks).

FRIB CAVITIES OPTIMIZATION

Once detected the problems and demonstrated the good quality of the solution, we looked for cost reduction, which is critical in a large machine like FRIB.

The design of the FRIB QWRs was kept very similar to the refurbished ReA3 one. The only modification was in the outer conductor diameter of the $\beta=0.085$ cavity, increased from 240 to 270 mm (while keeping the same flange to flange distance along the beam line) in order to increase R_{sh} and reduce E_p/E_a . This allowed us to increase the FRIB operation gradient by 10% in the $\beta=0.085$ QWR section and remove one cryostat from the original linac design. In the $\beta=0.041$ cavities no change was made in the OC diameter, but the refurbished design with side RF ports and cavity elongation was adopted anyhow.

Significant cost reduction was obtained by replacing the well performing, but rather expensive, high RRR Nb bottom flange with a new, low cost one with the same shape but made mostly of Ti. Only a small, 3 mm thick Nb ring was left in the area of the In seal. This ring is electron beam welded to the resonator outer conductor on one side, and on the other side to the new Ti flange, which is provided with channels for liquid helium to allow it to flow directly over the Nb ring. This results in excellent cooling of the Indium and, through it, of the tuning plate. This low cost flange design was tested with remarkable results both in a $\beta=0.085$ (Fig. 8) and in a $\beta=0.041$ ReA3 cavities, and was finally adopted for all FRIB QWRs. The In seal have shown excellent heat transmission and low RF losses both at 4.2 and 2 K,

allowing to reach with refurbished QWRs a residual resistance as low as 1 ± 2 n Ω at 2 K. Studies for further cost reduction by means of new materials and alternate gasket design are ongoing.

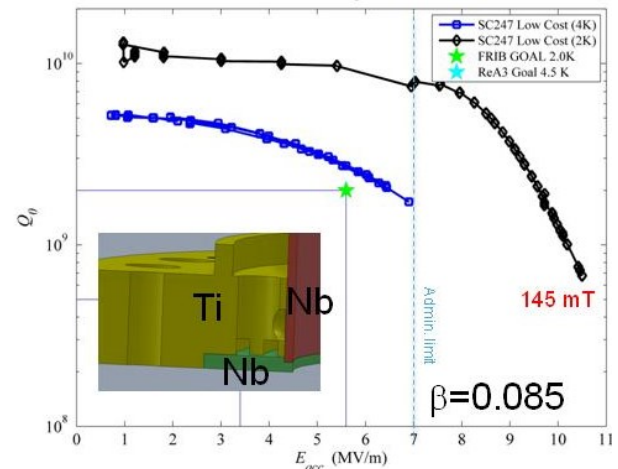


Figure 8: Performance of the refurbished QWR prototype with low-cost bottom flange (see schematic in the box).

CONCLUSIONS

Subtle phenomena can cause sometimes big trouble and large delays. A similar problem appeared in the ReA QWRs after apparently insignificant modifications of a working design, which were expected to preserve performance without drawbacks and without need of systematic testing. Eleven underperforming QWRs of the first ReA3 production lot could be fully recovered by detecting and fixing with hardware modifications the causes of a puzzling behaviour. This work, in addition to bringing resonators to full performance, gave us precious information for the design of the FRIB resonators and for the assessment of their optimum cavity treatment.

ACKNOWLEDGMENTS

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