# SUPERCONDUCTING RESONATORS DEVELOPMENT FOR THE FRIB AND ReA LINACS AT MSU: RECENT ACHIEVEMENTS AND FUTURE GOALS*

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*Abstract*

The superconducting driver and post-accelerator linacs of the FRIB project, the large scale radioactive beam facility under construction at MSU, require the construction of about 400 low-β Quarter-wave (QWR) and Half-wave resonators (HWR) with four different optimum velocities. 1st and 2nd generation prototypes of $\beta_0$=0.041 and 0.085 QWRs, and of $\beta_0$=0.53 HWRs have been built and tested, and have more than fulfilled the FRIB and ReA design gradients. The present cavity surface preparation at MSU allowed production of low-β cavities nearly free from field emission. The first two cryostats of $\beta_0$=0.041 QWRs are now in operation in the ReA3 linac. A 3rd generation design of the FRIB resonators allowed to further improve the cavity parameters, reducing the peak magnetic field in operation and increasing the possible operation gradient, with consequent reduction of the number of required resonators. The construction of the cavities for FRIB, which includes three phases for each cavity type (development, pre-production and production runs) has started.

## INTRODUCTION

The driver accelerator of the FRIB project is the largest superconducting low-β heavy ion linac under construction worldwide, able to accelerate ions of any mass and in multiple charge state, with a final beam power of above 400 kW on target [1]. These remarkable characteristics are obtained by means of 330, independently phased 2-gap resonators of the quarter-wave and half-wave type, working at high gradient. Differently from previous superconducting low-β linacs, the large size of the machine has required optimization of the resonator design not only for maximum performance but also for low cost in the view of a large production [2]. This requirement guided the choice of the resonators geometries, materials and mechanical solutions, avoiding complicated shapes, minimizing the amount of electron beam welds, eliminating bellows, optimizing construction and surface treatment procedures. This development could be done in parallel with the construction of the ReA3 re-accelerator linac for radioactive beams at MSU, in operation since 2011, which shares with FRIB the superconducting QWRs design and which can be seen also as an "operation test bench" for the FRIB cryomodules. Differently from ReA, working at 4.5K, FRIB will work with superfluid helium at 2K. The increase in cavity Q more than compensates the loss of efficiency of a 2K cryogenic system, both in terms of installation and operation cost. This is an innovative choice in a low-β linac, which will allow operation of cavities in very stable pressure conditions and with high safety margin on the maximum surface fields.

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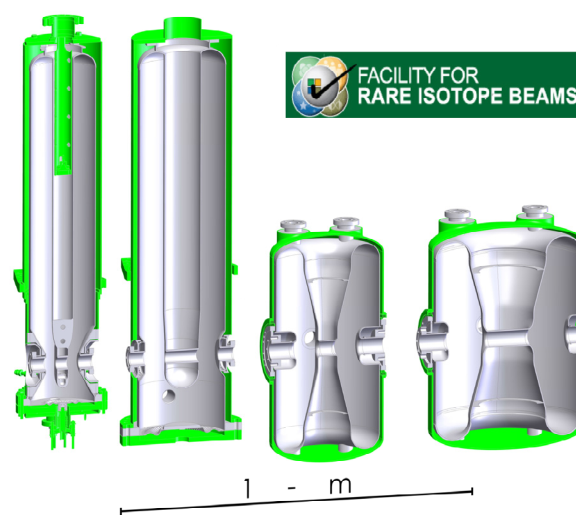


Figure 1: FRIB resonators. From left: $\beta_0$=0.041 and 0.085 QWRs, $\beta_0$=0.29 and 0.53 HWRs.

## THE FRIB AND ReA3 RESONATORS

### *Resonators Development*

The FRIB resonators design has been finalized after a long prototyping phase. The 2nd generation QWR prototypes are now the ReA3 linac resonators (7 with $\beta_0$=0.041, in operation [3], and 8 with $\beta_0$=0.085, under installation). This last cavity type underwent important modifications which include the displacement of the rf coupler from the bottom plate to the resonator side and an


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increased distance between the tuning plate and the inner conductor tip, in order to remove a critical thermal problem in the 2nd generation design [4]. The new tuning plate includes slots and undulations to increase its maximum elastic displacement and thus its tuning range, and a "puck" whose length can be adjusted for cavity tuning before final welding. Concerning the $\beta_0$=0.53 HWR prototype, conceived also as a model for the rather similar $\beta_0$=0.29 cavity, 4 units of the 2nd generation have been built by 2 different vendors and one in house. After positive test results, the $\beta_0$=0.085 QWR and the HWRs designs have been further refined in a 3rd generation, upgraded design with increased diameter that takes maximum advantage of the space available in FRIB cryomodules (Figure 1 and Table 1).

### *Surface Treatments*

Test results and cost considerations for a large production led us to the choice of BCP (buffered chemical polishing) as surface treatment for the FRIB resonators. The effort was concentrated in the development of a reliable procedure [5] able to produce field emission free, high gradient cavities. The treatment includes the following BCP steps: 1) bulk etch (~150µm removal), 2) differential etching in QWRs for final cavity tuning if required, 3) light etch (~30 µm removal). Thermal treatment in high vacuum at 600 °C is applied before step 3) for Hydrogen removal to prevent Q disease. High pressure water rinsing (HPR) is applied before cavity final installation. To guarantee maximum surface cleanliness, dust particle count is performed on resonator surfaces during cavity assembly in the clean room and the water purity is continuously monitored during HPR. During BCP both the resonator and the acid temperatures are stabilized to control removal rate and to avoid excess of hydrogen absorption in Nb. The acid flow path in the $\beta_0$=0.53 HWR was studied by means of simulations and experiments to obtain homogeneous removal over the entire inner resonator surface. Final thermal treatment at 120 °C was also implemented, showing significant reduction of the Q-slope at 4.2K (Fig. 2), but negligible improvement at 2K. This prompted us to include this step in the ReA3 cavities preparation, but not in the FRIB ones.

### *Test Results in Prototypes*

The prototypes have been tested at 4.2 and 2K [6].

**$\beta_0$=0.041 QWR -** In "vertical" test without He vessel ("naked"), the prototype reached very high gradient both at 4.2 and 2K. The dressed resonators in operation in ReA3 at 4.2 K reached the specified fields for that linac without problems. However, at the much higher fields planned for FRIB, overheating of the tuning plates associated with Q-drops were observed. To remove this problem we decided to replace, in the FRIB resonators, the NbTi bottom ring material with high RRR Nb, increasing heath conductance to the tuning plate by more than two orders of magnitude (the same modification could solve a much more critical problem in the $\beta_0$=0.085 cavities).

**$\beta_0$=0.085 QWR –** Two prototypes of ReA3 resonators, obtained by refurbishing two cavities of an underperforming lot of 10 affected by critical tuning plate overheating, were tested several times to optimize the cavity treatment and to validate the new design with side coupler and slotted tuning plate. Both refurbished prototypes largely exceeded the FRIB design goals at 4.2K and 2K, reaching or exceeding surface fields of about 50 MV/m and 110 mT (See Fig. 2 and 3). The Q at 2K was flat up to about 90 mT, allowing for a 10% increase of the FRIB specified gradient in the $\beta_0$=0.085 section. Similar results have been obtained in cavities before and after assembly of the helium vessel. All of the cavities from the underperforming lot were completely refurbished with the new design and will be installed in the first $\beta_0$=0.085 ReA3 cryomodule, presently under assembly, which will be put in operation this year.

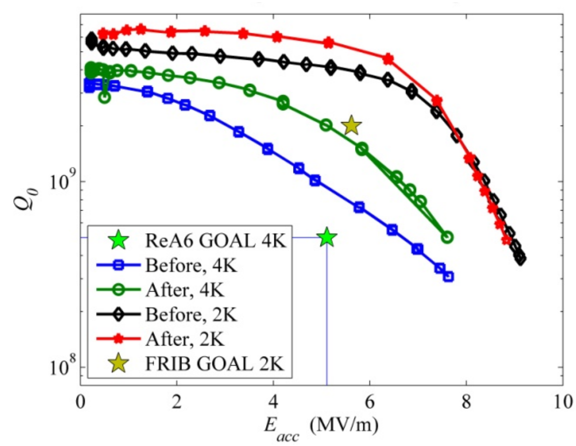


Figure 2: ReA3, $\beta_0$=0.085 QWR prototype Q vs. $E_a$ at 2K and 4.2K, before and after 120°C baking.

**$\beta_0$=0.53 HWR –** The first prototype, built in house, reached the specified Q but quenched just below the design gradient. Among the following four prototypes built by vendors, three have been tested without He vessel, exceeding the design gradient (Fig. 3). All of them quenched at, or above, 90 mT with a hot spot in the high B region, showing that the performance limit was set by the high $B_p/E_a$ design value of the 1st generation prototype. The last tests were characterized by rather low x-rays counting rate, showing the good quality of the surface treatment. Two cavities were dressed with a Ti He vessel and installed in the TDCM (Technology Demonstration CryoModule) together with a FRIB type superconducting solenoid, where testing in realistic linac conditions is ongoing. Vacuum problems were caused by the Ti bellows joining the vessel to the beam ports, but modifications of the He vessel design allowed removal of all bellows in the production cavities, with increased reliability and cost reduction. One naked cavity was sent to JLAB, underwent a new surface and thermal treatment and was tested at 2K. The results previously obtained at MSU were reproduced and exceeded (Fig. 3, red line).

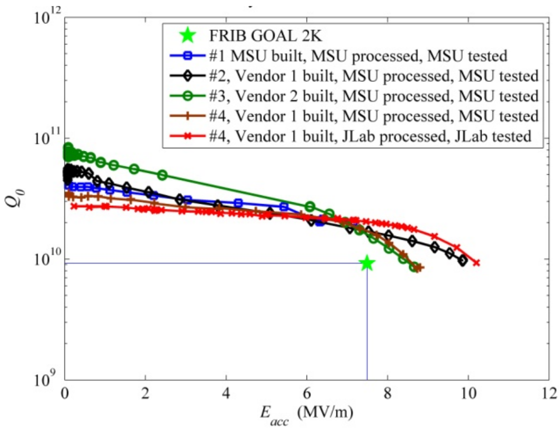


Figure 3: Performance of the $\beta_0$=0.53 HWR prototypes processed and tested at MSU and JLAB.

**Residual resistance –** The residual resistance measured in the three prototype families was below 5 nΩ up to about 100 mT in QWRs, and about 80 mT in HWRs. Considering that the FRIB specified limits are 11 nΩ and 70 mT, a large safety margin exists for future upgrades.

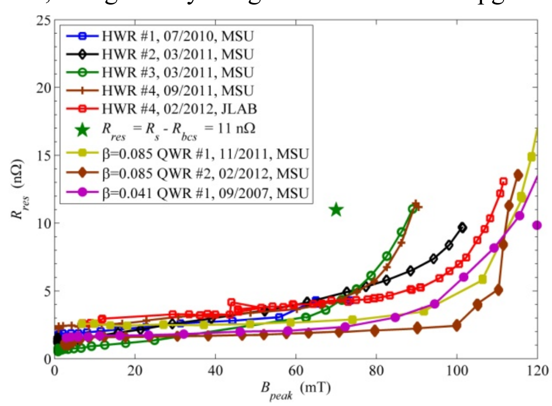


Figure 4: Residual surface resistance at 2K of $\beta_0$=0.041 QWR, $\beta_0$=0.085 QWR and $\beta_0$=0.53 HWR prototypes.

## DESIGN UPGRADE

The new resonators design optimization resulted in significant improvement of peak fields $E_p/E_a$, $B_p/E_a$ and of shunt impedance $R_{sh}$, with consequent reduction of the overall linac cost and operational risk. $E_p$ and $B_p$ in operation could be moved below the safe values of 35 MV/m and 70 mT in all cavities. At the same time, the specified operation design gradient of the $\beta_0$=0.085 QWR and $\beta_0$=0.29 HWR could be raised by 10% without increasing the total cryogenic load, allowing the reduction of the number of required cryomodules by two units. The aperture of all QWRs was enlarged from 30 to 34 mm, and their bottom rings have been modified to reduce material cost while cooling the tuning plate efficiently.

The HWRs design was optimized to facilitate the mechanical construction and tuning procedure. In all resonators, the helium vessel is made of titanium in order to avoid brazed Nb-SS interface and problems of differential thermal contraction with the Nb cavity. The higher Ti cost, compared to stainless steel, was more than compensated by the elimination of bellows.

Table 1: Upgraded FRIB Resonators Parameters

| Resonator | QWR1 | QWR2 | HWR1 | HWR2 |
|---|---|---|---|---|
| $\beta_0$ | 0.041 | 0.085 | 0.29 | 0.53 |
| $f$ (MHz) | 80.5 | 80.5 | 322 | 322 |
| $V_a$ (MV) | 0.81 | 1.8 | 2.1 | 3.7 |
| $E_p$ (MV/m) | 31 | 33 | 33 | 26 |
| $B_p$ (mT) | 55 | 70 | 60 | 63 |
| R/Q (Ω) | 402 | 452 | 224 | 230 |
| G (Ω) | 15 | 22 | 78 | 107 |
| Aperture (mm) | 34 | 34 | 40 | 40 |
| $L_{eff} \equiv \beta\lambda$ (mm) | 160 | 320 | 270 | 503 |
| n. of cavities | 12 | 94 | 76 | 148 |

## RESONATORS PRODUCTION

The construction of the ReA3 linac cryomodules will continue in 2013 with the installation of one $\beta_0$=0.085 cryomodule with eight FRIB-type QWRs. The FRIB resonators procurement has started in 2012 [7] and will be performed in three steps: development run and pre-production run, with 2 and 10 cavities per type, respectively, and finally production run with all cavities produced plus 10% spare. This staged procurement will allow refining the production quality before the large production, which is planned to be completed by 2017.

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