SUPERCONDUCTING COAXIAL RESONATOR DEVELOPMENT FOR ION LINACS AT MICHIGAN STATE UNIVERSITY*

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Abstract

Niobium quarter-wave resonators (QWRs) and half-wave resonators (HWRs) are being developed at Michigan State University (MSU) for two projects: a 3 MeV per nucleon (MeV/u) superconducting linac for re-acceleration of exotic ions (ReA3, under construction, requiring 15 resonators), and a 200 MeV/u driver linac for the Facility for Rare Isotope Beams (FRIB, under design, requiring 344 resonators). The QWRs (80.5 MHz, optimum $\beta = v/c = 0.041$ and 0.085) are required for both ReA3 and FRIB. Both QWRs include stiffening elements and frictional dampers. Nine $\beta = 0.041$ QWRs have been fabricated; seven of them have been Dewar tested successfully with a helium vessel for use in ReA3. Production and testing of ten $\beta = 0.085$ QWRs is in progress. The HWRs (322 MHz, optimum $\beta = 0.29$ and 0.53) are required for FRIB, but not ReA3. Both HWRs are designed for mechanical stiffness and low peak surface magnetic field. A prototype $\beta = 0.53$ HWR has been fabricated and tested, and a prototype $\beta = 0.29$ HWR is planned.

INTRODUCTION

MSU is building a new accelerator facility for nuclear physics research, FRIB [1, 2], funded by the US Department of Energy. A key element of the project is the 200 MeV/u superconducting driver linac. In addition, a 3 MeV/u re-accelerator for exotic ion beams, ReA3 [3], is being built with funding from MSU. Initially, ReA3 will use beams from MSU's National Superconducting Cyclotron Laboratory (NSCL). After the FRIB driver linac is commissioned, ReA3 will use FRIB beams to provide higher production rates for rare isotopes.

The FRIB superconducting linac will consist of QWRs optimised for $\beta = 0.041$ [4] and $\beta = 0.085$ [5, 6], as well as HWRs optimised for $\beta = 0.29$ [7], and $\beta = 0.53$ [8]. ReA3 requires the same QWR types.

This paper covers the resonator development effort for ReA3 and FRIB, including Dewar test results. A separate paper covers resonator and cryomodule production for ReA3, along with plans for resonator and cryomodule acquisition for FRIB [9].

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RESONATOR DESIGN

Selected resonator parameters for FRIB are shown in Table 1. The accelerating voltage per cavity (V_a) is set by the requirement that the peak surface electric field (E_p) be ≤ 31.5 MV/m. The corresponding peak surface magnetic field (B_p) is ≤ 77 mT for all cases. The resonator design is the same for ReA3, but the required accelerating voltages are lower, corresponding to $E_p = 16.5$ or 20 MV/m.

Drawings of the resonators are shown in a companion paper [9]. The QWR designs are based on resonators developed by Legnaro for ALPI and PIAVE [10]. Some design modifications were implemented, including a larger beam aperture, separation of cavity and insulation vacua for improved resonator cleanliness, and bottom-mounted probe couplers instead of side-mounted loop couplers.

Simple "first-generation" designs and more advanced "second-generation" designs have been developed. Second-generation QWR tuning plates are slotted to reduce the tuning force [11]. The new tuning plate design is similar to designs for TRIUMF [12] and the ALPI upgrade [13]. Nb sleeves are used to ensure RF contact on the outer conductor for the input and pick-up couplers.

The HWR designs are similar to the QWR designs. Probe couplers are used with RF ports 90° from the beam ports; tuning is done by deforming the cavity at the beam ports. In the second-generation versions, the shorting plate is formed from sheet Nb instead of being machined from plate Nb. Second-generation HWRs have tapered inner conductors formed as 2 halves and welded together, in

Table 1: FRIB resonator parameters: β_m is the optimum β; f is the resonant frequency; R_a is the shunt impedance (linac definition), Q_0 is the intrinsic quality factor; G is the geometry factor; T is the operating temperature.

Type	QWR	QWR	HWR	HWR
β_m	0.041	0.085	0.29	0.53
f (MHz)	80.5	80.5	322.0	322.0
V_a (MV)	0.81	1.62	1.90	3.70
E_p (MV/m)	30.0	31.5	31.5	31.5
B_p (mT)	53	71	75	77
R_a/Q_0 (Ω)	433	408	202	219
G (Ω)	15	18	59	101
Design Q_0	$5 \cdot 10^8$	$5 \cdot 10^8$	$6.1 \cdot 10^9$	$1 \cdot 10^{10}$
Aperture (mm)	30	30	30	40
T (K)	4.5	4.5	2.0	2.0

contrast to the first-generation cylindrical inner conductor. Rinse ports and a more mechanically rigid beam port region are part of the second-generation design.

The QWR resonator and helium vessel designs use stiffening elements to reduce the frequency shift due to fluctuations in bath pressure and Lorentz detuning [14]. For the HWRs, the cylindrical outer conductor, tapered inner conductor, and redesigned beam port region improve the mechanical stiffness relative to the first-generation design.

For the ReA3 $\beta_m = 0.041$ QWR, the helium vessel is made of titanium; the ReA3 $\beta_m = 0.085$ QWR has a Nb vessel. Both QWR vessel designs include a Legnaro-type frictional damper [10] inside the inner conductor to mitigate microphonic frequency disturbances.

RESONATOR FABRICATION AND PREPARATION

The $\beta_m = 0.041$ QWRs for ReA3 and the prototype $\beta_m = 0.53$ HWR were fabricated by MSU, along with the first-generation prototype $\beta_m = 0.085$ QWR. Forming was done at MSU and in the local area, while electron beam welding was done with industry.

The production $\beta_m = 0.085$ QWRs for ReA3 are being fabricated with an industrial partner: MSU provided the Nb material to the vendor; the vendor fabricated and welded the parts, and delivered sub-assemblies to MSU. The final trimming and welding of the sub-assemblies is being done under the supervision of MSU.

Cleaning, etching, high-pressure water rinsing, and assembly of resonators for Dewar testing are done at MSU [9]. Figure 1 shows resonators in some of the final preparation steps prior to Dewar testing.

DEWAR TESTS

All of the production $\beta_m = 0.041$ QWRs have been Dewar tested with their helium vessel; a reservoir feeds helium into the vessel with the Dewar under vacuum to simulate the conditions in the cryomodule (Figure 1a). The $\beta_m = 0.53$ HWR has been only "dunk" tested (with the cavity fully immersed in liquid) so far, since it does not yet have a helium vessel (Figure 1c). For the $\beta_m = 0.085$ QWRs, some testing has been dunk testing (Figure 1b); the rest has been with liquid just in the QWR's helium vessel.

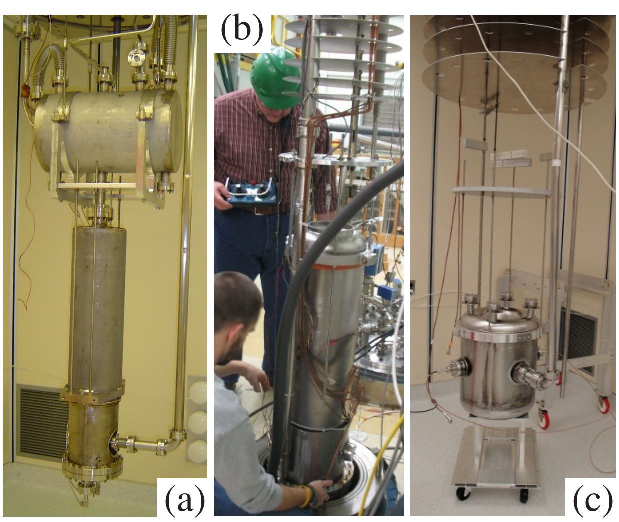

Figure 1: Resonator photographs: (a) $\beta_m = 0.041$ QWR with helium vessel in clean room; (b) $\beta_m = 0.085$ QWR without full helium vessel being lowered in to the Dewar; (c) $\beta_m = 0.53$ HWR in the clean room.

Figure 2 shows Dewar test results for the seven production $\beta_m = 0.041$ QWRs; the purple stars indicate the design goals. Some cavities had marginal performance initially, with either a low quality factor or a downward jump in Q_0 with increasing field. It was observed that the problems were more likely when the tuning plate was retracted. It was hypothesised that the performance decrease was due to overheating of the tuning plate, which was originally cooled only by conduction to the outer conductor and the helium bath surrounding the outer conductor. The stainless steel bottom flange was redesigned to allow for a liquid helium reservoir. Three of the QWRs have marginal performance without bottom flange cooling (Figure 2a), but they meet the design goals when the bottom flange is cooled

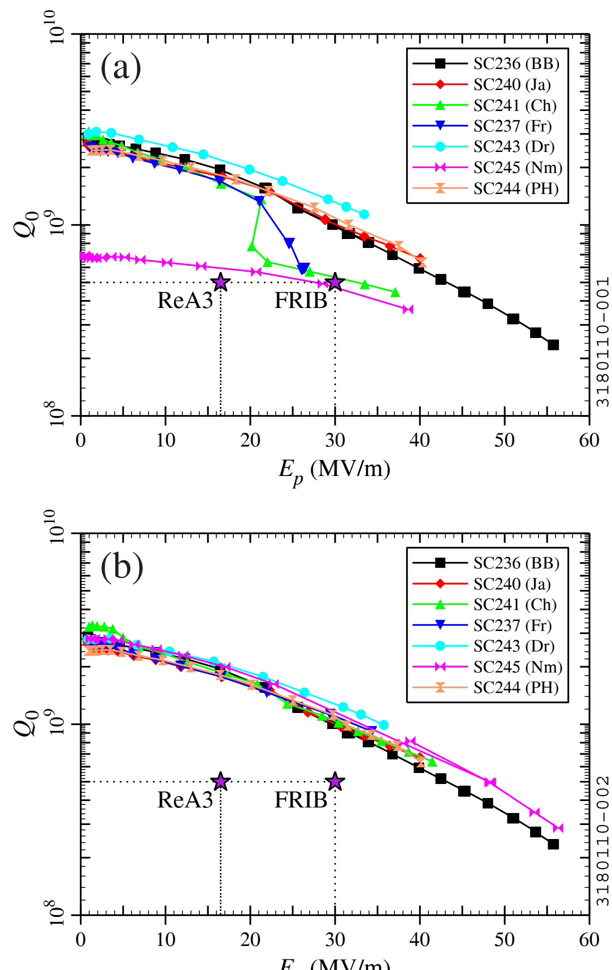

Figure 2: Dewar test results at $T = 4.3$ K for $\beta_m = 0.041$ QWRs: (a) measurements with no cooling of the bottom flange; (b) measurements with cooling of the bottom flange for all resonators except the first one.

(Figure 2b). Note that the first production cavity (SC236) was not tested with a reservoir flange. For the rest of the resonators, measurements were done in the same Dewar test, before and after opening the valve which supplies liquid helium to the reservoir flange. For most tests, an administrative limit of $E_p = 40$ MV/m was imposed, as high field deconditioning was seen in some of the early testing.

Figure 3 shows Dewar test results for two $\beta_m = 0.085$ QWRs, one first-generation QWR and one second-generation QWR. In both cases, the resonator was dunk tested with the helium vessel not yet present. The first-generation QWR meets the design goal, but has no performance margin; the second-generation QWR, encouragingly, has some margin for both Q_0 and field.

A total of 5 second-generation $\beta_m = 0.085$ QWRs have been fabricated and tested. The other 4 resonators do not yet meet the design goals. Additional testing is in progress to investigate the performance spread between resonators.

Figure 4 shows Dewar test results for the first prototype $\beta_m = 0.53$ HWR. The resonator was tested with and without plungers in the rinse ports. In both cases, the field was limited to $E_p \approx 30$ MV/m due to quench. The quality factor is slightly higher with the plungers absent. The maximum field is a bit below the design goal of $E_p = 31.5$ MV/m.

Multipacting simulations for the $\beta_m = 0.53$ HWR were done by the SLAC National Accelerator Laboratory [15]. The simulations indicated that there is a risk of hard multipacting barriers associated with the plungers in the rinse ports. For the Dewar test, a plunger penetration of +3 mm was used; the simulations suggested that this penetration would be less problematic than having the plungers flush with the resonator wall. Encouragingly, no multipacting barriers were observed in the Dewar tests (with or without plungers). The case of plungers flush with the wall has not yet been tested.

CONCLUSION

Superconducting resonator development is in progress at MSU for a 200 MeV/u stable ion linac and a 3 MeV/u exotic ion linac. Seven $\beta_m = 0.041$ resonators have been produced for the re-accelerator, with an additional ten $\beta_m = 0.085$ resonators under fabrication and testing. One prototype $\beta_m = 0.53$ resonator has been tested. Fabrication of four additional $\beta_m = 0.53$ resonators is underway.

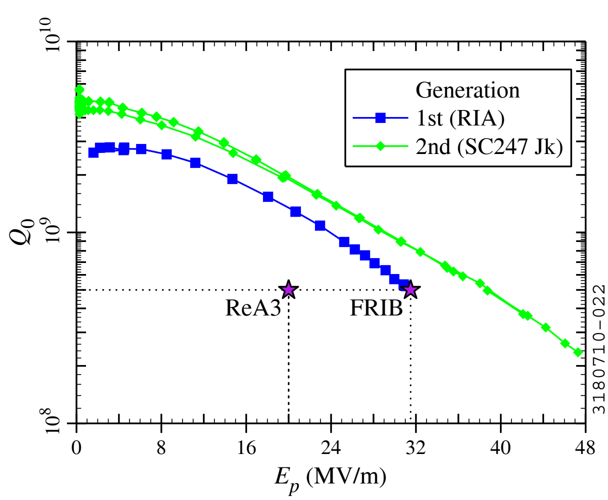

Figure 3: Dewar test results at $T = 4.3$ K for first-generation and second-generation $\beta_m = 0.085$ QWRs.

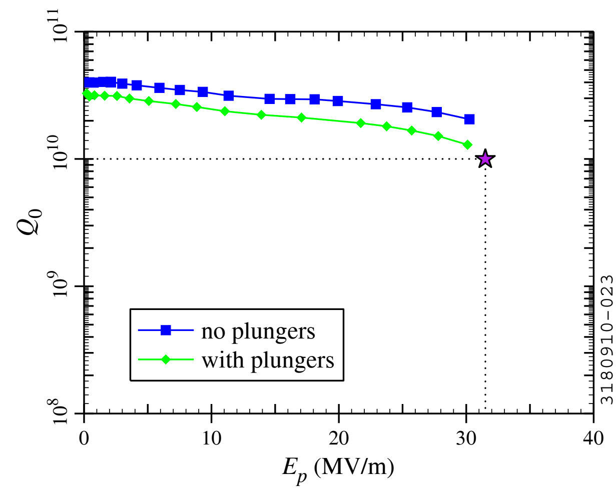

Figure 4: Dewar test results at $T = 2$ K for the first prototype $\beta_m = 0.53$ HWR.

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