RESULTS FROM INITIAL TESTS OF THE 1ST PRODUCTION PROTOTYPE BETA=0.29 AND BETA=0.53 HWR CAVITIES FOR FRIB*

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Abstract

The first prototypes of the beta=0.53 and beta=0.29 HWR production design cavities for FRIB fabricated early this year by C.F. Roark Welding and Engineering (Roark) have completed initial acceptance testing at MSU. The extensive evaluation program is intended to validate both mechanical and electromagnetic designs prior to proceeding with a pre-production fabrication run which will consist of 10 cavities of each beta. Results from physical inspections, warm RF measurements, chemical processing, and cryogenic vertical testing are presented.

INTRODUCTION

The driver linac for the Facility for Rare Isotope Beams (FRIB) [1] is comprised of cryomodules that contain superconducting quarter-wave and half-wave accelerating cavities. These cavities span the range in β=v/c from 0.041 to 0.53. The higher β cavities (0.29 and 0.53) are of the half-wave resonator (HWR) style, while the lower β cavities are of the quarter-wave resonator (QWR) style [2]. The linac will consist of 49 cryomodules containing a total of 330 cavities, not counting spares or pre-production prototypes. These cavities will be produced by industrial vendors who will deliver the properly tuned niobium cavities encased in the titanium helium vessels. Prior to delivery, the vendor will remove the damage layer via bulk chemical polish using the vendor's facility.

Full-scale industrial production of over 225 HWRs is required to complete the FRIB linac. As part of the vendor development phase, two bare (without helium vessel) cavities fabricated by C.F. Roark Welding and Engineering (Roark) of each design are to be extensively evaluated at MSU. The cavities are fabricated using niobium supplied by MSU and according to MSU-supplied drawings, procedures, stamping and electron-beam-welding techniques, with further process development by Roark through mutual consent with MSU. Chemical processing capabilities have been established at the vendor to etch weld prep surfaces, though the capability to perform bulk BCP etching remains to be developed during the pre-production run. To date, two cavities, one of each beta, have been supplied to MSU by Roark for evaluation (Fig. 1).

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CAVITY FABRICATION

Both cavity designs built during the vendor development phase consist of six major sub-assemblies, including two short plates, two beam cups, one inner conductor and one outer conductor, which are formed, machined, and e-beam welded to specifications provided in the mechanical drawings. The sub-assemblies are then checked using a coordinate measurement machine (CMM) for compliance with mechanical specifications. Welding of the sub-assemblies follows with the welding of each short plate to the inner and outer conductors and the cavity is completed with the welding of the beam cups to the outer conductor. Frequency tuning is done between these welding steps. Coarse tuning is achieved by trimming the length of the inner and outer conductors (after allowing for appropriate weld shrinkage), and fine tuning is achieved after the short plate welding by final beam port placement.

Figure 1: The first prototype HWRs manufactured by Roark. The β=0.29 is on the left, the β=0.53 is on the right.

Though the mechanical and electromagnetic designs had been previously validated for similar HWR designs which followed an identical fabrication scheme [3, 4], the present design was optimized by incorporating improved mechanical features and reducing the peak surface magnetic fields [5]. The primary objective of this vendor development phase is to validate the electromagnetic design and ensure the fabrication scheme yields a cavity that meets performance requirements and is cost-effective to produce. The secondary objective is to refine the fabrication procedure such that it incorporates sufficient tuning mechanisms to allow the vendor to deliver completed (and jacketed) cavities within a tight frequency range. Data collected during the development phase is being used to generate a statistically valid database such that the tuning mechanisms can be fully established for use by the vendor during the pre-production phase. An outline of the tuning steps is shown in Table 1 along with the corresponding acceptance range for each step.

Table 1: Cavity Fabrication Frequency Acceptance Ranges

Description of frequency measurement	**Acceptance Range (MHz)**
Stack-up, full stock (+0.350in)	Coarse Tune via trim
After IC/OC trim	(-.150, +.150)
Weld Shorts (2)	(-.250, +.250)
Place beam cups (2)	Fine tune with position
Weld beam cups (2)	(+.025, -.025)

ACCEPTANCE INSPECTIONS

Upon delivery, the cavities underwent a series of inspections and measurements which are identified in an Acceptance Criteria Listing (ACL) to ascertain whether the cavity was fabricated to within mechanical specifications. The ACL for the β=0.53 cavity includes the following items:

- verify submittal of vendor test reports
- metrological (CMM) inspection of critical dimensions
- incoming visual inspection including
    - weld inspection
    - borescope inspection of interior
    - inspection of sealing surfaces
- leak checking
- nominal frequency, coupling, and field-flatness measurement

When incoming inspections of the β=0.29 and β=0.53 reveal instances where the cavities do not conform to specifications (i.e., deviations exist), non-conformance reports are generated and delivered to the appropriate staff. Subsequently, corrective actions may be pursued with the vendor if necessary. This is part of an established formal and comprehensive QA program that has been adopted throughout the FRIB project. Through cooperation with the vendor, improved procedures have been developed to ensure future deviations are minimized. Documenting deviations in non-conformance reports has already led to improved drawings, procedures, and tooling. Though a few deviations could not be fully rectified for these prototype cavities, changes are already being implemented prior to beginning the preproduction and full production phases.

TUNING SENSITVITY MEASUREMENTS

In order to validate the mechanical models [5, 6] which are used to develop the dynamic frequency tuning mechanisms for the FRIB HWR cryomodules [7], measurements are used to characterize the tuning sensitivity and stiffness of the prototype HWRs. The results are presented in Table 2. The instrument set-up is shown in Fig. 2. The measurement system consists of a network analyser to measure cavity frequency, a load cell to determine applied force, and a portable CMM arm to measure the displacement of the cavity beam ports. The test fixture, specifically designed for these measurements, allows bi-lateral displacement of the beam ports.

Additional measurements of the tuning coefficients will be performed after the helium vessels are attached. For the bare cavities, the tuning coefficients were insensitive to either bulk BCP processing or hydrogen degassing.

Table 2: Dynamic Tuning Coefficients for Bare 322 MHz HWRs

	β=0.29	**β=0.53**
Sensitivity (kHz/mm)	280	105
Stiffness (kN/mm)	2.9	4.9

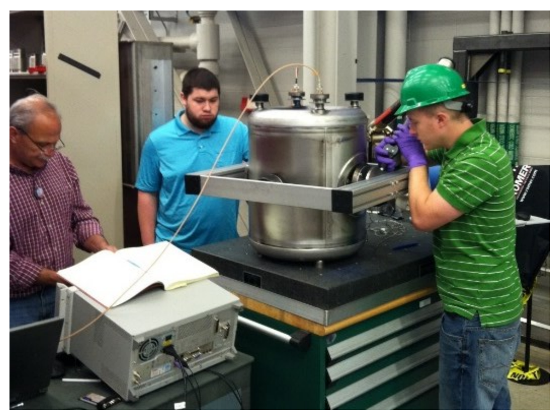

Figure 2: Tuning sensitivity and stiffness measurements being performed on the β=0.53 HWR.

CAVITY PROCESSING

β=0.53 HWR Processing

The β=0.53 cavity was processed in accordance with the standard FRIB cavity processing recipe, which includes

- soak in saltwater (indicates presence of ferrous inclusions)
- DI water rinse
- ultrasonic cleaning/degreasing
- bulk BCP etch (performed in 3 stages for prototype evaluation) : target 130 µm
- rinse, ultrasonic cleaning
- H degassing (600 °C, 10 hours)
- ultrasonic cleaning/degreasing
- light BCP etch : target 20 µm
- high pressure rinse – 3 hrs

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- drying in Class 100 area

In addition to these standard processes, additional measurements were performed during cavity etching. In particular

- ultrasonic thickness measurements of the cavity walls to determine the uniformity of the etch rate,
- measurement of cavity frequency to track changes during cavity chemical processing, and
- borescope inspection of the interior to verify macroscopic integrity of the RF surface

were performed before and after each chemical etching process.

The following additional activities were also carried out on the first β=0.53 prototype :

- vacuum leak checks including cryogenic (77 K) cycling post H degassing
- additional tuning sensitivity measurements post H degassing.

Ultrasonic thickness measurements after each of 3 bulk etch cycles revealed that the cumulative average etch amount was 131 µm, in good agreement with the goal of 130 µm. However, presumably vapor bubbles, formed from the chemical reaction of BCP acid and niobium, collected along the RF ports, resulting in lower than desired removal amounts in these areas (as low as 60 µm in some cases), while other areas experienced significantly higher etch amounts approaching 200 µm. Figure 3 depicts the etch uniformity – green areas correspond to areas with less than 100 µm removal, while red areas represent sections with greater than 150 µm material removal. Results of ultrasonic thickness measurements which provide a metric of total material removal are indicated numerically in the graphic. Modifications are underway to improve etch uniformity in the next cavity, based on etch rate studies [8, 9].

After bulk etching was completed, the cavity underwent a hydrogen degassing treatment to remove hydrogen from the Nb bulk which can lead to so-called "Q-disease". The cavity was heated at 600 °C for 10 hours, followed by ultrasonic cleaning, and then a light etch (goal=20 µm), followed by high-pressure ultra-pure water rinsing for 3hrs. During HPR, a liquid particle counter is used to monitor the rinse water, and the rinse cycle is not terminated until the measured particle counts fall to the baseline value.

β=0.29 HWR Processing

The β=0.29 prototype is undergoing the same processing steps as the earlier-delivered β=0.53 cavity. At present the cavity has received two bulk etches (for a total of 120 µm) and is being prepared for H degassing. Figure 4 presents the cumulative etch uniformity – as before green areas correspond to areas with less than 100 µm removal, while red areas represent sections with greater than 150µm material removal.

147	119	137	142	142	160	145	124	155	152	140	163	INNER CONDUCTOR
150	104	137	155	178	137	122	107	147	160	146	165	
145	112	135	145	147	152	132	114	160	160	173	157	
145	117	145	165	183	163	130	127	173	173	185	157	
152	131	119	168	183	147	160	127	180	193	201	166	RINSE PORT S.P.
157	145	147	188	X	140	155	135	170	180	152	150	
145	150	188	185	157	155	157	150	152	203	165	145	
140	122	175	188	107	157	152	127	152	173	86	150	OUTER CONDUCTOR
145	124	157	160	79	152	165	122	152	147	86	152	
160	170	180	157	64	170	193	185	191	152	122	157	
168	BP1	221	168	122	170	196	BP2	218	163	145	163	
196		185	168	RF2	188	236		180	163	RF1	152	
198		183	170		178	224		175	165		180	
163		211	168	74	168	188		213	168	130	165	
155	160	183	160	61	165	191	178	188	155	94	155	
147	124	163	152	81	150	160	127	160	152	74	152	
147	130	175	183	157	157	160	124	145	173	107	152	
155	150	188	183	168	142	152	152	160	175	163	152	FIDUCIAL SHORT PLATE
151	151	150	157	150	142	140	142	147	152	157	145	
168	114	130	173	173	163	150	145	135	180	183	170	
150	119	145	163	168	147	140	119	165	160	183	168	INNER CONDUCTOR
145	109	127	145	142	157	135	114	145	155	196	160	
142	107	124	137	152	150	127	107	140	152	163	147	
155	122	135	142	150	157	137	117	140	152	150	147	

Figure 3: Graphical representation of etch uniformity in the β=0.53 HWR. Vertical position denotes position along the cavity long axis, horizontal position denotes azimuthal position along the cavity circumference.

119	130	155	127	160	152	142	114	127	86	104	112	SHORT PLATE
180	163	RP1		150	124	140	140	RP2		147	160	
165	157	132	109	114	135	150	142	145	127	140	165	
127	99	89	86	81	168	130	102	91	86	122	165	OUTER CONDUCTOR
124	104	94	81	69	147	130	107	97	81	64	140	
114	104	94	84	71	86	117	104	99	81	74	84	
94	99	99	BP1			91	107	104	BP2			
91	RF1	79				94	RF2	76				
84		89				79		89				
97	91	89				94	91	84				
91	97	107	84	76	89	94	97	107	81	71	86	
86	97	117	124	69	81	89	99	117	122	63	79	
81	91	117	137	109	84	81	94	112	140	112	79	
132	132	142	132	124	114	135	147	140	135	119	122	SHORT PLATE
RP4	114	112	97	109	RP3		102	117	91	140	RP4	
84	99	127	142	130	147	142	114	76	132	140	127	

Figure 4: Graphical representation of etch uniformity in β=0.29 HWR. Vertical position denotes position along the cavity long axis, horizontal position denotes azimuthal position along the cavity circumference.

VERTICAL TESTING

After completion of the chemical processing described above, the β=0.53 cavity was prepared for vertical dunk testing. This included attaching the (fixed) input and field probe couplers to the cavity, blank-off of the rinse ports and unused beam port, and connection via one beam port to the test insert vacuum pumping line, using CF flanges and Cu gaskets. The cavity was then evacuated and leak checked. Figure 5 shows the cavity prepared for testing.

The cavity was then inserted in the Dewar and cooled down to 4 K. At 4 K calibrations were completed and RF measurements were performed. The cavity was then further cooled to 2 K, while additional RF data (Q_0, f, etc.) were taken as a function of temperature (Fig. 6). Frequency shifts during cooldown and RF testing, along with changes during processing steps, are summarized in Table 3. These data, once supplemented with data from jacketed cavity testing, are to be used to better define the required as-fabricated frequencies of production cavities.

Figure 5: β=0.53 HWR mounted on insert in preparation for a "dunk" test. The cavity vacuum space is actively pumped during cooldown and testing.

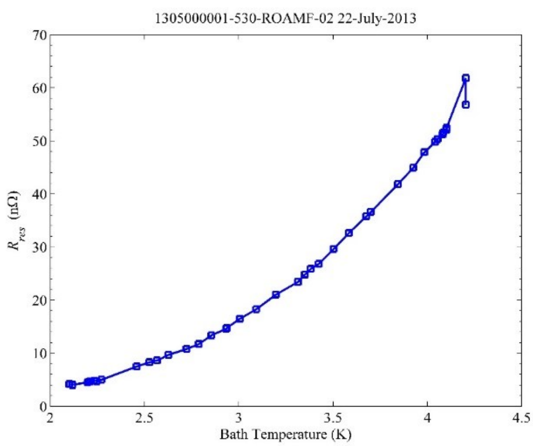

Figure 6: r_s vs T at E_{acc} ~1 MV/m. The residual surface resistance is less than 4 nΩ, well below the requirement of 11 nΩ.

Table 3: Frequency Shifts and Frequency Sensitivities Under Various Conditions

Phenomena	**Frequency Shift (kHz)**	**Sensitivity**
E @ 7.5 MV/m	-0.284	-5.05 Hz/(MV/m)^2
Reduce bath pressure from 800 to 23 Torr	+7.66	-9.85 Hz/Torr
Cool from 300 K to 4.2 K	+507	1.71 kHz/K
Cavity at vacuum	-7.5	-9.85 Hz/Torr
Remove air dielectric	+94	
Light BCP (20)	-16	
Heat Treatment	none	
Bulk BCP (120)	-106	

Table 4 : Performance Parameters of 1st β=0.53 Prototype (s/n 1305000001-530-ROAMF)

Parameter	**Design**	**Measured**
$E_{acc,\ op}$ (MV/m)	7	14.5
B_{pk} (mT)	60	125
Q_0 at 1 MV/m	-- --	3.5×10^{10}
Q_0 at $E_{acc,\ op}$	9.2×10^9	2.5×10^{10}
Q_0 at $E_{acc,\ max}$	-- --	3.4×10^9
r_{s0} (nΩ)	< 11	4
FE onset (MV/m)	> 7	9
X-Ray flux (mR/hr) @ E_{op}	-- --	0
X-Ray flux (mR/hr) @ E_{accmax}	-- --	3000

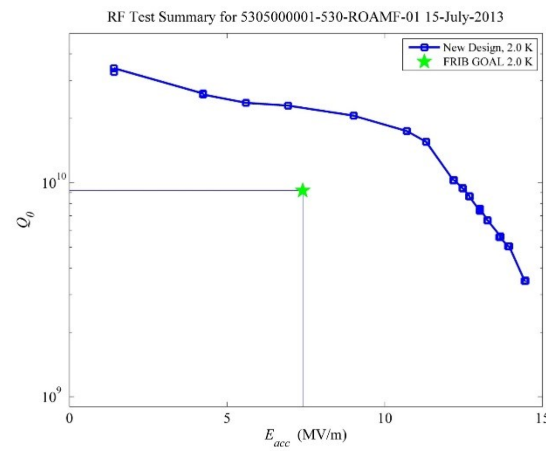

Figure 7: Q_0 vs E for the 1st β=0.53 (bare) HWR from Roark. The FRIB performance specification is given by the green star.

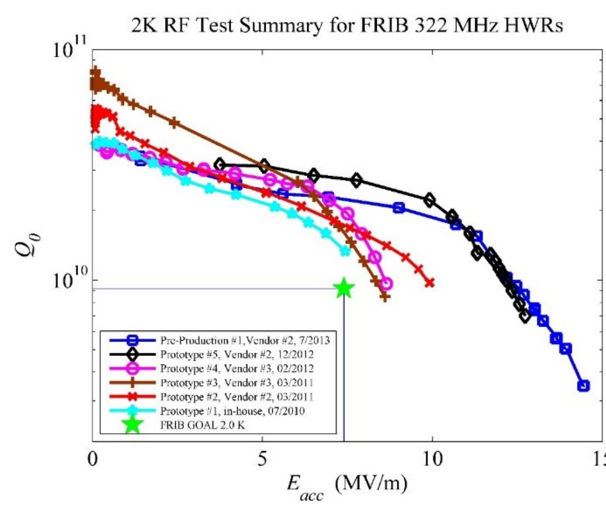

Figure 8: Comparison of present prototype β=0.53 HWR with prototypes fabricated to an earlier design iteration.

Once at 2 K, CW measurements were performed in order to determine the cavity Q_0 were taken as a function of cavity gradient, while logging relevant test parameters. The cavity reached a maximum gradient of 14.5 MV/m ($E_{acc} = V_{acc}/\beta\lambda$), being limited only by available RF power (see Fig. 7). The onset of field emission was observed to

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be about 9 MV/m, significantly above the FRIB operating gradient of 7 MV/m. Cavity Q_0 at this operating gradient was > 2 x 10^{10}, suitably above the operational requirement of 9 x 10^9 . There is an observed high-field Q-drop beginning at about 11 MV/m again suitably above the FRIB operating gradient. This cavity's performance, summarized in Table 4, easily surpassed the FRIB requirements. Indeed, this cavity performed better than all β=0.53 HWRs previously fabricated (either in-house or by vendors) and processed/tested at MSU, all of which required more than one processing cycle to achieve their best performance, and were all limited by quench (see Fig. 8).

FUTURE WORK

The β=0.53 prototype is currently undergoing welding of its helium vessel. During this welding process, the cavity frequency is being consistently monitored, to better understand frequency changes due to weld shrinkage. This information will assist the vendor in refining assembly and fabrication procedures so that the target operating frequency is more easily and consistently achieved in production. Since the presence of a helium vessel on HWR-type cavities typically has a noticeable effect on cavity performance, especially tuning stiffness/sensitivity and thermal environment, an essentially identical set of comprehensive measurements and processes will be performed on the jacketed cavity, namely :

- leak checking with cryogenic cycling
- borescope inspection of interior
- tuning stiffness and sensitivity measurements
- bulk etch : target 30-50 µm
- frequency measurements
- hydrogen de-gassing
- tuning stiffness and sensitivity measurements
- ultrasonic cleaning /degreasing
- light BCP etch : target 30 µm
- high pressure rinse – 3 hrs
- vertical test @ 2K

The β=0.29 prototype is undergoing the final stages of processing (hydrogen degassing, light etch, HPR) and assembly in preparation for its 1st vertical test at 2 K. Subsequent to this, it will also be jacketed and evaluated in the same manner as the prototype β=0.53 cavity.

An additional pair of cavities, one of each β, are expected from the vendor shortly. They will also be evaluated in the same comprehensive manner as these first prototypes.

Following successful evaluation of all 4 prototype cavities, Roark will be given approval to proceed with a pre-production run of 10 jacketed β=0.53 HWRs (to include the bulk etch process), which will then be further processed and tested at MSU. This is a vital step in the development and qualification of the vendor for further mass production of the full production run of the β=0.53 HWR cavities for FRIB.

Likewise, a solicitation for a 10 cavity pre-production run of jacketed and bulk-etched β=0.29 HWRs will be issued to vendors, as a prelude to engaging in the full production run.

SUMMARY

MSU has received two of four industrially produced bare HWR prototypes, one of each β (0.29 & 0.53). The β=0.53 prototype has undergone a thorough incoming inspection and complete chemical processing sequence, culminating in 2 K testing. During vertical testing, it demonstrated excellent performance, easily achieving all of the FRIB performance specifications upon its initial cooldown. Not only does this validate the cavity design and fabrication process, but it also demonstrates the maturity of the cavity surface preparation procedures and tooling, and QA protocols. Further successful processing and testing of the remaining prototypes (and eventually their jacketed versions), incorporating lessons learned in their fabrication, is crucial to proceeding forward with pre-production runs of the FRIB HWRs.

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