SRF DEVELOPMENT AND CRYOMODULE PRODUCTION FOR THE FRIB LINAC*

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Abstract

The Facility for Rare Isotope Beams' heavy ion continuous-wave (CW) linac extends superconducting RF to low beam energy of 500 keV/u. 332 low-beta cavities are housed in 48 cryomodules. Technical development of high performance subsystems including resonator, coupler, tuner, mechanical damper, solenoid and magnetic shielding is necessary. In 2015, the first innovatively designed FRIB bottom-up prototype cryomodule was tested meeting all FRIB specifications. In 2016, the first full production cryomodule is constructed and tested. The preproduction and production cryomodule procurements and in-house assembly are progressing according to the project plan.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) driver linac consist of 332 low-beta superconducting RF cavities is designed to accelerate all ions up to 200 MeV/u or higher and will be the largest low-beta superconducting linac in the world [1]. Work on the first superconducting cyclotron at MSU began in 1982. Since then, MSU has been at the frontier of superconducting technology for accelerator applications and associated R&D, as shown in Fig 1. In 2000, the National Superconducting Cyclotron Laboratory (NSCL) at MSU started SRF development work in collaboration with Jefferson Lab and INFN-Legnaro for the Rare Isotope Accelerator (RIA) [2, 3]. Early work was focused on elliptical cavities for medium β, coaxial resonators (QWRs and HWRs) for low β, and prototype cryomodules [4, 5]. In 2006, an ion re-accelerator (ReA3) was funded by MSU as an NSCL experimental facility and test bed for a future driver linac [6]. In 2014, the third ReA3 cryomodule was commissioned [7]. The first ReA3 experiment with a rare isotope beam was conducted in 2015. At the end of 2015, the first FRIB β=0.085 QWR production cryomodule was completed, and cryomodule mass production began. In 2014, a state-of-the-art SRF facility was built to support FRIB cryomodule production [8]. Two linacs, a total of 51 SRF cryomodules, and over 300 superconducting magnets will be in service at MSU when the FRIB is completed in 2022.

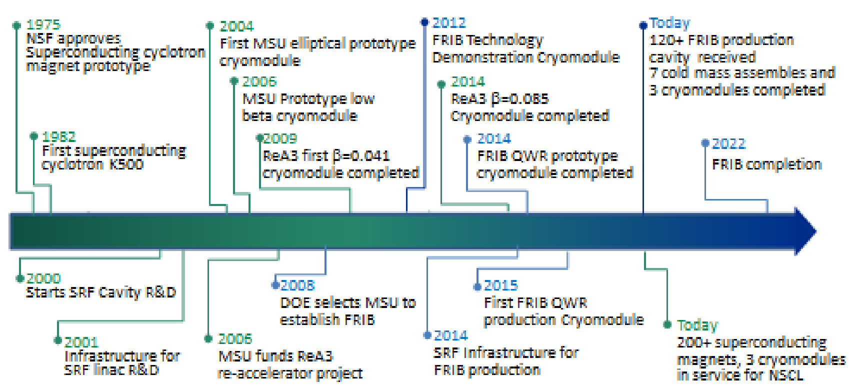

Figure 1: Time line of superconducting and accelerator technology development at MSU.

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The RF parameters of FRIB cavities are summarized in Table 2. The HWR operating gradient is Eacc ≈ 7.5 MV/m with an intrinsic quality factor of Q of up to 9 x 10^9 in CW. The HWRs' peak surface electric and magnetic fields are E_p ≈ 30 MV/m and B_p ≈ 60 mT, which is comparable to E_{acc} ≈ 15 MV/m for multicell elliptical cavities of the type developed for the International Linear Collider. The FRIB operating goals are rather high compared to existing heavy ion SRF linacs [9, 10], hence the cavity performance is a challenge for the FRIB project. An optimized cavity RF design with low B_p/E_{acc}, E_p/E_{acc}, and an operating temperature of 2 K will help to achieve the performance goals.

FRIB cavities are all fabricated from high RRR Nb sheet of thickness 2 to 4 mm. The cavities are formed by deep drawing and assembled by electron beam welding (EBW). The cavity flanges are machined from NbTi. The helium vessels are made from 5 mm thick titanium, welded by tungsten inert gas (TIG). After delivery from the vendor, an acceptance inspection is done by FRIB, followed by machining of the alignment surfaces, which are attached to the helium vessel. All four cavity types have been prototyped with helium vessels and their performance has been validated with Dewar tests and supplementary integrated tests with the define FPC and tuner included.

Table 1: RF Parameters for FRIB Cavities. The Intrinsic Q is the Requirement for the Acceptance Dewar Test

Cavity Type	QWR	QWR	HWR	HWR
β	0.043	0.086	0.29	0.54
f [MHz]	80.5	80.5	322	322
V_a [MV]	0.81	1.78	2.09	3.70
E_{acc} [MV/m]	5.1	5.6	7.7	7.4
E_p/E_{acc}	6.1	6.0	4.3	3.6
B_p/E_{acc} [mT/(MV/m)]	10.8	12.4	7.7	8.6
R/Q [Ω]	401	455.4	224.4	229.5
G [Ω]	15.3	22.3	77.9	107.4
Aperture [m]	0.036	0.036	0.040	0.040
T [K]	2.0	2.0	2.0	2.0
Intrinsic Q [10^9]	1.4	2.0	6.7	9.2

FRIB SRF has many challenges. Here they are summarized for better understanding R&Ds described in following sections. The notable FRIB SRF challenges are:

1) High gradient and high Q performance with cavities
2) High field (8T) beam focussing solenoid configuration nearby cavities
   · Optimization of solenoid design against cavity/fringe field interaction
3) Local magnetic shielding for cost-effective and reliable magnetic shielding Bottom-up assembly for easy module assembly and better alignment
4) 2 K operation for high yields, higher cavity performance and more stable operation against microphonics
5) Mitigation of multipacting in the fundamental coupler.

These technical challenges have been all verified in the FRIB development or early FRIB production stage.

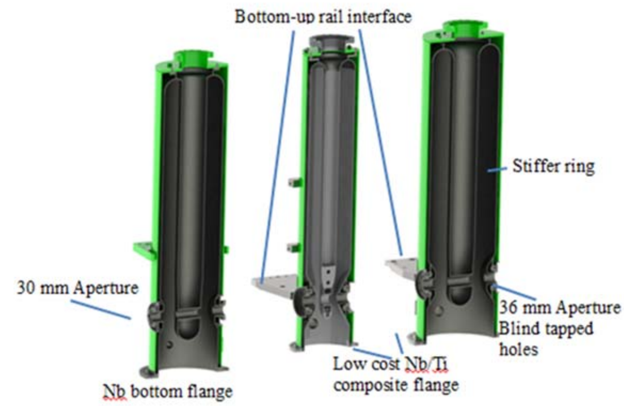

Figure 2: 3D view of FRIB QWRs. Left: Refurbished ReA β=0.085 QWR, Middle FRIB β=0.041 QWR, Right FRIB β=0.085 QWR.

FRIB SRF DEVELOPMENT

QWR Development

FRIB benefits from the design and operation of low-β cavities for NSCL's ReA (Re-Accelerator) project [6]; the ReA linac will ultimately serve as a post-accelerator for FRIB. The design of the FRIB QWRs is very similar to the refurbished ReA3 QWRs as shown in Fig 2. One difference is in the outer conductor diameter of the β = 0.085 QWR, which was increased from 240 to 270 mm (while keeping the same flange-to-flange distance along the beam line). The larger diameter increases the shunt impedance (R_{sh}) and reduces E_p/E_a. This allowed us to increase the operating gradient by 10% in the β = 0.085 portion of the FRIB linac and reduce the cryomodule count by 1 from the original linac layout. Both β = 0.041 and β = 0.085 QWR bottom flanges are changed from solid Nb to Nb and Ti composite to save material cost [11]. Another difference is that the aperture is larger, 36mm, while it is 30 mm for ReA QWRs. During production stage, a stiffer ring is added to outer conductor of β = 0.085 QWR to increase mechanical stability against buckle failure to allow consistent pressure relief scheme across the whole linac.

The FRIB QWR design was validated by two in-house fabricated prototype β = 0.085 QWRs. Up to now, more than 30 industrial vendor produced cavities have been processed and tested at MSU. Over all, the cavity performance meets FRIB specification as shown in Fig 3. However the intrinsic Q shows a wide spread and lower than the MSU prototypes. In-house technical investigation is on-going and so far no conclusion.

HWR Development

FRIB HWR development began after MSU was awarded the FRIB project in 2008. HWR prototyping was done primarily with β = 0.53 cavities; validation of the design was done with the FRIB Technology Demonstration Cryomodule (TDCM) in 2012 [12]. Figure 4 shows models of the FRIB HWR prototype and production β=0.53 cavity.

After prototyping, several design iterations were done to achieve the following goals:

1) Improve cavity performance (RF and mechanical)
2) Apply lessons learned from manufacturing and processing prototype cavities
3) Cost reduction
4) Adapt to pneumatic tuner and bottom-up cryomodule design

Cavity geometry has been optimized by enlarging the outer conductor, inner conductor shape, short plate height and shape, drift tube length and beam port cup radius. The detail optimization analysis can be found in reference [13]. As a result, production 0.53HWR's Ep/Ea lowered from 4.3 to 3.6 and Bp/Ea changed from 10.4 to 8.5 respectively. The beam flange design had to change to use blind tapped holes for Conflat® connection to accommodate larger size cavity while keeping beam port flange to flange size same. A conical inner conductor, with a near elliptical cross-section, is implemented for manufacturing convenience where previously a three dimensional spline profile was used. Moreover, the design of the beam port cup includes a flat surface instead of two tangential arcs in the previous generation design, which allows frequency tuning by means of beam port deformation without exceeding plastic limits. To minimize material costs, the inner and outer conductor wall thickness is set to 3 mm while short plate thickness is 4mm. A stiffening disk is added to inner conductor wall to reduce the df/dp and Lorenz force detuning. Two rinse ports are relocated to

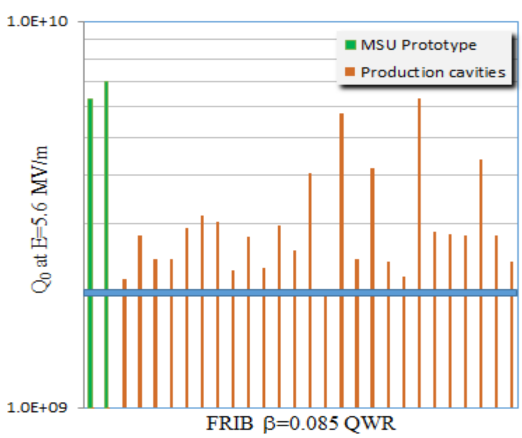

Figure 3: FRIB β = 0.085 QWR VTA test results. Blue line is the intrinsic *Q* specification.

the other side to make the cavity more symmetric. After TDCM test, a design choice of HWR tuner has been made to switch from scissor tuner (actuated by a stepper motor and piezo actuator in series) to pneumatic tuner using helium gas [14]. In order to accommodate pneumatic tuner, RF port on top of the cavity is removed and mechanical linkage remain by replace it with a stud welded to both cavity and helium vessel. Interface to alignment rail also has been redesign to fit the new bottom up cryomodule design described in later section. All these design changes applied to both 0.29HWR and 0.53HWR. After the design was finalized, 10 pre-production cavities were built by industrial vendor. The first pre-production HWR was delivered in January 2015. The last of the 10 pre-production cavities was delivered about 1 year later. 9 of 10 pre-production cavities tested successfully and have comfortable margin against FRIB specification.

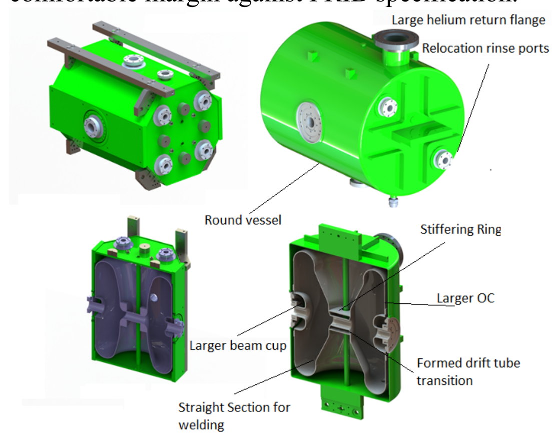

Figure 4: 3D view of the b = 0.53 HWR. Left: prototype HWR. Right: final production HWR.

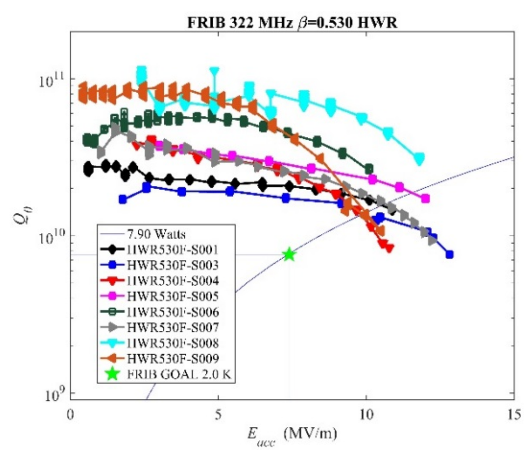

Figure 5: FRIB preproduction β=0.53 HWR VTA test results.

FPC Development

FRIB uses two different fundamental power couplers (FPC) for QWRs and HWRs. FRIB coupler design parameters are summarized in Table 2.

FRIB QWR FPC was developed by Argonne National Laboratory (ANL) under the collaboration with MSU [15]. The design was based on ANL 4kW, 72 MHz coupler for ATLAS [16]. In order to allow slide mount and interface with bottom of vacuum vessel, a 90 degree elbow was added to the original design. The coupler was designed to be adjsutable after cold mass assembled as ReA3 FPC. The coupler consists of 5 components: a variable bellow, a cold rf window with antanna, a 90 degree elbow, a warm transition and a room temperature rf window. Nominal design power is 4 kW. The final design has a coupling adjustment range of 5

(Q_{extmax}/Q_{extmin}). The Coupler has an integrated cooling channel with cold RF windowsTwo prototype couplers were built by ANL and tested at MSU using one of the FRIB prototype 0.085QWRs. More than 48 hours reliable operation at 3 kW at 6.6 MV/m has been demonstated during the test. These two couplers were installed to FRIB prototype cryomodule and integrated tested with FRIB prototype cavties in cryomodule environment. Figure 6 shows the model of the production version which has a few minor changes based on experience of prototype coupler testing.

Table 2: FRIB Coupler Design Parameters

	QWR FPC	HWR FPC
Interface with cavity	2.75 CF	3.375 CF
Frequency (MHz)	80.5	322
Cold RF window	EIA 1-5/8	No
Warm RF window	EIA 1-5/8	custom to EIA 3-1/8
Nominal power required/design (kW)	2.5/4	5/10
Q_{extmax}/Q_{extmin}	5	5
Thermal intercept	38-55K	4K, 38-55K
Static Heat load (W)	0.43@2K	0.16@2K
Dynamic Heat load (W)	0.07@2K	0.2@2K
Instrumentation equipped	Temp sensor at cold window	Spark detector, CCG, Temp sensor, e-probe

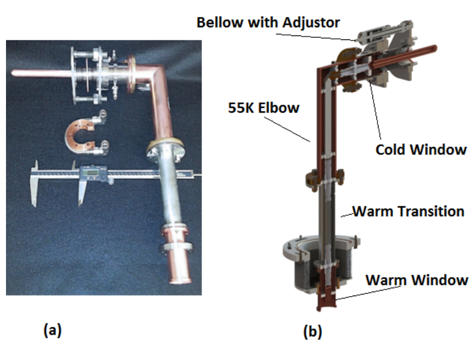

Figure 6: FRIB QWR FPC, (a) Prototype built by ANL, (b) Production design model.

FRIB HWR coupler development began in 2011. The RF window design of FRIB FPC takes advantage of existing technology, which has proven record of reliable operation from KEKB and SNS [17, 18]. Two design iterations have been done on HWR FPC. Side by Side comparison is shown in figure 7. The design use single rf window at room temperature. Coupling can be adjusted outside the cryomodule and has a range of 5 (Q_{extmax}/Q_{extmin}). Two cooling channels are brazed on the outer conductor to thermal intercept at 4K and 55K as show in figure 7. Both designs include spark detector, e-probe, and cold cathode gauge as diagnose and interlock instruments. The current design of FRIB requires maximum 5 kW CW operation for 0.53 cavities. However considering power upgrade in future, more than 10 kW CW operation is considered in the design.

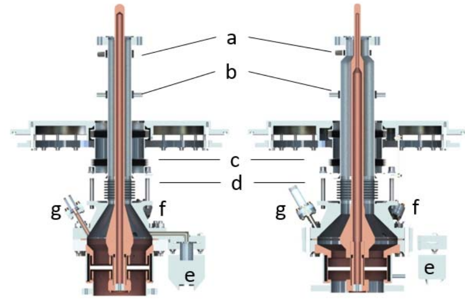

Figure 7: FRIB HWR FPC design: baseline design (left) and multipacting free (MPF) design (right). (a) 4K cooling line, (b) 55K cooling line, (c) vessel interface, (d)coupling adjustor, (e) cold cathode gauge, (f) spark detector and (g) e-probe.

FRIB launched effort to optimize HWR FPC design after TDCM test because of multipacting issues. A multipacting free (MPF) design was developed as shown in figure 7 (right) to be an alternative option for HWR FPC. The design kept the same interface to the cavity and vacuum vessel so that no changes needed for cryomodule design. The detail optimization is described in reference [19]. Outer conductor was enlarged and inner conductor was reduced to raise the multipacting onset power to more than 15 kW, which is beyond FRIB operation envelope. The choke feature around rf window was removed to simplify the design. The geometry is designed such that beam is blinded to rf window to minimize the risk of sparking. The VSWR is about 1.02 and well optimized around 332 MHz.

Ten baseline FPCs and two MPF FPCs were procured to support first preproduction 0.53 HWR cryomodule and validate MPF design in early 2015. All 12 couplers were received in November 2015. A new copper plated conditioning box was designed and fabricated to allow high power conditioning up to 20 kW in traveling wave mode [20]. Multipacting barrier at 9-10 kW was observed on 8 out of 10 baseline FPCs. In worse case, the outer conductor was heated up to 120°C [20]. The results indicate that the severity of multipacting highly depends on surface condition. The average conditioning time of baseline FPC is more than 30 hours. On the other side, MPF took about half time to condition and no evidence of heating during the conditioning. Redo conditioning test after coupler exposed to air in class 100 clean room for 10 days only took 9 hours demonstrated that RF condition effect is memorized. One MPF FPC was integrated tested with 0.53HWR in the same condition successfully. FRIB has selected MPF FPC for the mass production.

Tuner Development

The tuning mechanism of FRIB QWR is similar to Legnaro and TRIUMF design [21]. Tuning is done by using a thin niobium plate mounted at the base of the cavity. The cavity frequency is tuned by mechanically adjusting the distance between the bottom plate and the tip of the inner conductor. A puck is welded to top of the tuning plate to increase tuning sensitivity. Concentric convolutions are stamped into the plate and radial slots are added to reduce the stiffness of the tuning plate to increase the tuning range with the same maximum force. The tuning plate is mechanical connected to tuner assembly shown in figure 8. A high resolution linear actuator (890 N max thrust) is used to drive the tuner without piezo.

FRIB HWR production pneumatic tuner design was done by the collaboration of ANL and MSU. The design parameters are listed in Table 3. The design allows the tuner assembly to be installed after cold mass out of clean room. An aluminium beam port flange adapter has been designed to allow side mount tuner arms to resolve assembling tuner in very tight space. The bellow will not require any sliding guides; this eliminates the risk of sliding joint binding and also future maintenance needed to service them. The tuner design was validated in 0.53HWR integrated test [14].

Table 3: Pneumatic Tuner Design Parameters

	0.29HWR	0.53HWR
df/dx (kHz/mm)	248	101
df/dF (Hz/N)	9.6	6.52
Tuning range design (kHz)	120	120
Flange to flange Disp (mm)	0.48	1.2
Force (kN)	12.5	18.4

CRYOMODULE PRODUCTION

All six types FRIB cryomodule design uses the same bottom-up concept [22]. Four of six designs have been completed so far. Design of β=0.29 accelerating module and β=0.53 matching module is expected to be done by March 2017 with Jefferson Lab collaborated on design of β=0.041 and β=0.29.

All SRF related major procurements are in place and in production phase. 40% of 332 cavities have been received and more than half of received cavities have been cold test and certified in house [22,23]. QWR FPCs components have been all delivered while HWR FPCs production delivery started. SC magnets are expected to be done by end of 2016. QWR cryomodule major components are contracted and most delivered.

A new building (the SRF highbay) with SRF infrastructure has been fully commissioned and in operation to support FRIB cold mass and cryomodule assembly work [8]. The infrastructure is designed for delivery of 1.5 cold masses and 1.5 cryomodules per month at the peak of FRIB production. The production of cryomodule started at the end of 2015 and is ramping up.

Total 7 cold masses (3 β=0.041, 3 β=0.085 and 1 β=0.53) have been assembled in cleanroom. Three cryomodules (1 β=0.085 QWR and 2 β=0.085 QWR) have been completed.

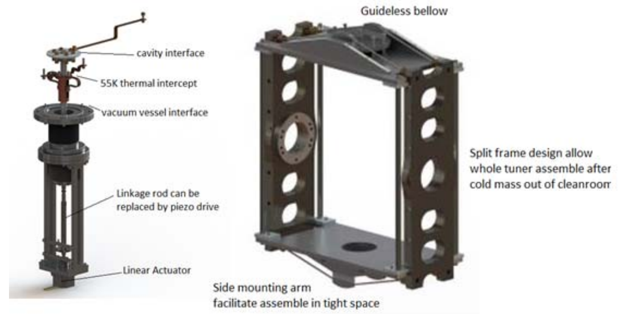

Figure 8: FRIB tuner design. Left, QWR tuner. Right, HWR tuner.

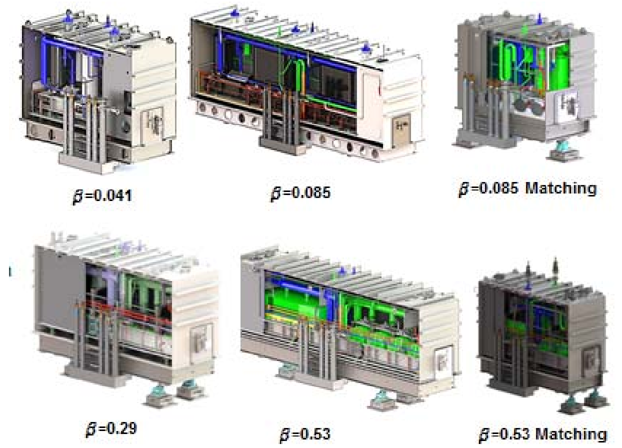

Figure 9: 3D view of FRIB bottom-up cryomodules.

Two 0.085QWR cryomodules have been cold tested and certified. Figure 9 shows the assembled FRIB β=0.53 preproduction cryomodule. This is the first bottom-up full size HWR cryomodule. After final inspection, the cryomodule will be moved and installed to test bunker in SRF highbay. Success of this test will mark the completion of FRIB cryomodule technical validation program. Lesson learned in the assembly process and test will be feedback to production components fabrication and β=0.29 module design.

Figure 10: FRIB β=0.53 preproduction cryomodule assembled in NSCL east highbay.

Figure 11: First FRIB β=0.085 cryomodule moved into linac tunnel for final installation.

CONCLUSION

Over a decade SRF development at MSU provide solid ground for construct FRIB project. Cryomodule scope has finished transition to production phase and progresses well.

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