FRIB PROJECT: MOVING TO PRODUCTION PHASE *

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Abstract

The Facility of Rare Isotope Beams (FRIB) project was presented in SRF2013 [1]. This paper reports the progressed situation of this project since SRF2013. FRIB project is now moving to production phase. FRIB superconducting RF (SRF) linac project and challenges are presented. This paper address the status of the SRF hardware production, SRF infrastructure status and plans for ramping to full production, and also focus on information that can be relevant for future large proton/ion SRF linac projects.

FRIB PROJECT

FRIB is a Department of Energy (DOE) joint project operated at MSU and obtained CD3-B approval in August 2014. Conventional facilities construction began in March 2014. Accelerator system construction also started in October 2014, and will be completed in 2022 (CD4). Early commissioning is schedule in 2017 - 2020 starting with the Front end [2]. SRF is the core technology in this project [3].

Figure 1: FRIB conventional facility contraction status on August 2015.

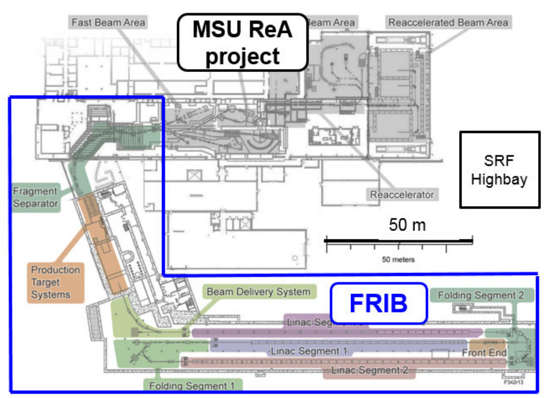

Figure 2: FRIB configuration in MSU campus.

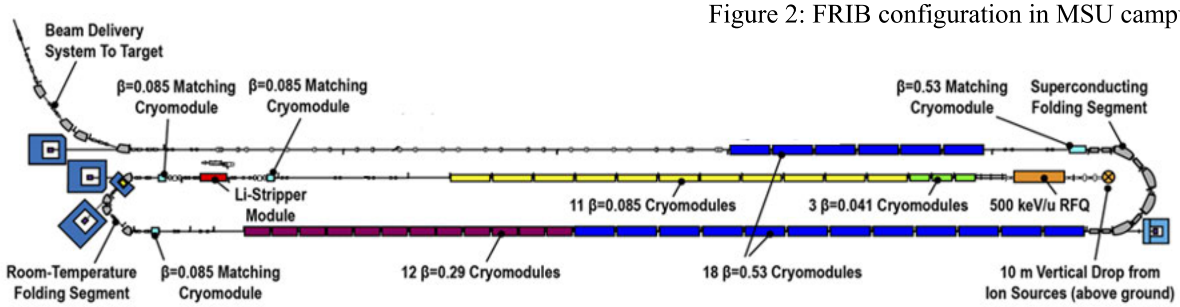

Figure 3: FRIB linac configuration.

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Figure 1 shows the current status of FRIB conventional facility construction on August 2015. FRIB accelerator tunnel has been already completed and the accelerator building on the ground is under construction. FRIB configuration in the MSU campus is shown in Fig. 2. NSCL is leading the nuclear science in the world and strong research activities are ongoing. The ReA project is one of them [4], which is reaccelerating isotope beams up to 3 MeV/u using SRF linac and 12 MeV/u in near future. This is a good bench mark for the future FRIB machine operation. FRIB is a heavy ion driver linac to produce rare isotopes on the target and bring them into the existing ReA experiment area. FRIB linac configuration is shown in Fig. 3. FRIB linac consists of three folded SRF linac segments with a total length about 500 m. Heavy ion is accelerated up to 0.5 MeV/u at Front end and injected to SRF linac. FRIB linac accelerates from Proton to Uranium up to 200 MeV/u, with beam power of 400 kW maximum on the target. FRIB is a high intensity frontier machine for heavy ions, for instance it is designed to accelerate ^{238}U particles of $5 \cdot 10^{13}$ /s, which is 250 times greater than ATLAS.

FRIB SRF LINAC

FRIB SRF Linac

FRIB utilizes SRF linac from very low beta 0.041 to medium beta 0.53, which is the first large scale application over such a wide beta range in the SRF low beta community. FRIB applies four different types of cryomodule (CM): 0.041CM, 0.085CM, 0.285CM, and 0.53CM as seen in Fig.3. Heavy ion beam is injected at 0.5 MeV/u into SRF linac and accelerated up to 16.6 MeV/u by three 0.041CMs and eleven 0.085CMs at Segment 1, then after through a 0.085 matching CM it hits Lithium charge striper and more electrons are striped from the heavy ion pieces in order to accelerate more efficiently by afterword linacs. The heavy ion goes through another 0.085 matching CM and is bend by 180^{O} at the normal conducting bending magnet at the First holding segment and after through another 0.085 matching CM, it comes into Segment 2 consisted of twelve 0.285CMs and twelve 0.53CMs. The ion beam is accelerated up to 148.6 MeV/u at the outlet of Segment 2. The beam is again bent by 180^{O} at Second folding segment and after through a 0.53 matching CM it is

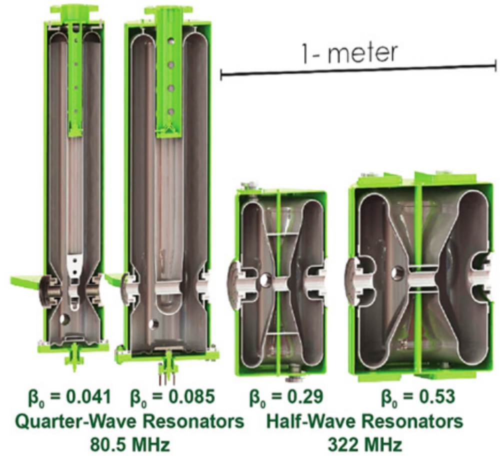

Figure 4: FRIB SRF cavity families with helium jacket.

injected into Segment 3 consisted of six 0.53CMs. The ion beam is accelerated successively up to 202.1 MeV/u. The vacant slot in Segment 3 is for future energy upgrade modules. The heavy ion is derived on the target through the beam delivery system, hits the target at 400 kW maximum, and produces rare isotopes. The Lithium charge striper is a big technical challenge in FRIB but not scope in this paper [5].

FRIB Cavities and Cryomodules

FRIB utilizes the four different type cavities: β = 0.041 quarter wave resonators (QWRs), 0.085 QWRs, 0.285 half wave resonators (HWRs), and 0.53 HWRs. The cavity shapes are illustrated in Fig. 4 [6]. The details about cavities are described later in the section of hardware components.

According to these four different cavities, FRIB needs four different cryomodules [7]. Here two examples are illustrated in Fig. 5 (0.085CM) and Fig. 6 (0.53CM). 0.085CM includes eight 0.085QWRs and three 50 cm superconducting solenoid packages. They are supported on the cold rail mounted on the baseplate of the vacuum chamber (Bottom up supported assembly). 0.041CM has similar structure with 0.085CM but six 0.041QWRs and two 25 cm solenoid packages are installed. Cavities are cooled at 2K and solenoid packages are cooled at 4.5 K.

0.285CM and 0.53CM have also bottom up supported assembly structure. 0.29CM includes six 0.0285HWRs

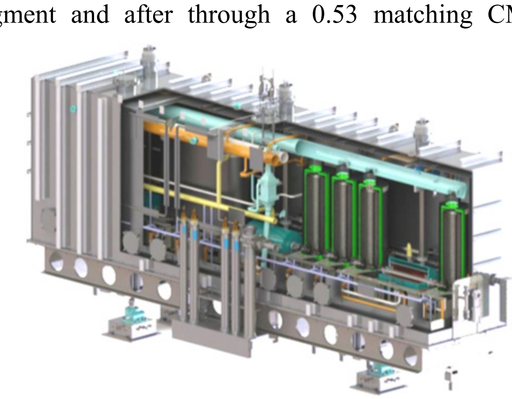

Figure 5: FRIB 0.85QWR cryomodule design.

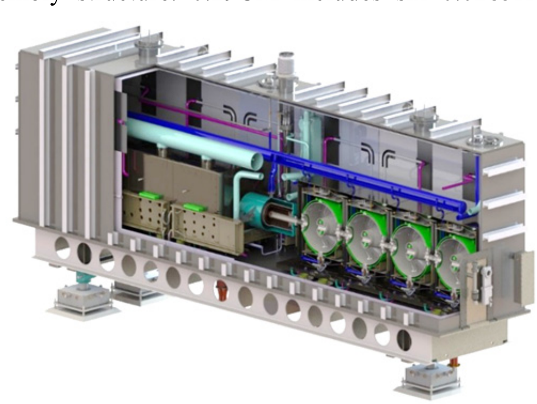

Figure 6: FRIB 0.53HWR cryomodule design.

and one 50 cm solenoid package. 0.53CM includes 8 0.53HWRs and one 50 cm solenoid package.

One technical risk in FRIB SRF is they have to prepare all different type components for each family, which makes the project complicate and needs large human resources. Jlab is designing the 0.041CM and 0.285CM under the work for others (WFO) in order to resolve this risk.

SRF MAIN HARDWARE AND VALIDATION

FRIB SRF main hardwires are explained here but cryomodule detail information is not scope in this paper. The information can be seen in other reference [7, 8].

FRIB Cavity Design

As mentioned above, FRIB SRF linac applies four different cavity families (Fig.4). The low beta families of β = 0.041 and β = 0.085 apply quarter wave resonator (QWR) with two beam acceleration gaps at both 80.5 MHz. FRIB cavity design parameters are summarized in Table 1. Cavity RF design is well optimized to have lower Ep/Eacc and Bp/Eacc ratios for all cavity types [6]. These cavies are CW operated at the gradient Eacc = 5.3 – 7.9 MV/m (Ep = 25.5 - 33.5 MV/m), corresponded to Bp = 54.6 – 63.2 mT at 2 K. The cavity RF designs took place so that Bp does not exceed 70 mT at the FRIB operation gradient. Specification of unloaded Q (Q_O) is 1.4 x 10^9 (0.041 QWR) to 9.2 x 10^9 (0.53HWR) at 2 K. In the electron SRF cavity community these numbers look not so high but it is due to the small geometrical factors by the low beta cavity design feature (see Γ-value in Table 1).

Cavity Fabrications

FRIB cavity fabrication is presented in this conference by C. Compton [9]. Both QWRs dress the helium vessel made of titanium on the outer cavity wall, which is TIG welded. QWRs are fabricated using RRR grade niobium material (RRR > 250) [10]. NbTi material is used for all cavity port flanges. The vacuum seal is used ICF copper gasket for all ports except for bottom cavity flange of QWRs, where indium sealing is used.

The bottom of the QWRs is demountable so that high pressure water rinsing (HPR) can access easily into the cavity inside. A mechanical tuning plate made of niobium is sandwiched by indium seals between the cavity bottom flange made of titanium weld a niobium ring on it and the bottom vacuum flange (titanium). This tuning plate is conductively cooled by liquid helium in the helium vessel through the cavity bottom flange/Indium seal. Special care is needed for the cavity bottom flange design in order to provide a sufficient cooling capability for the mechanical tuning plate. FRIB has developed special cavity flange so called low cost flange [11].

The medium beta structures of β = 0.285 and 0.53 utilize half wave resonator (HWR) with two gas at both frequency 322 MHz. Two HPR rinsing ports are electron beam welded on one cavity short area, totally 4 HPR ports on the cavity. Helium jacket is welded (TIG welding) on cavity wall. Both HWRs are fabricated using the RRR grade (RRR > 250) niobium.

Table 1: FRIB SRF Cavity Parameters

Cavity Type	QWR	QWR	HWR	HWR
β	0.041	0.085	0.285	0.53
f [MHz]	80.5	80.5	322	322
V_a [MV]	0.810	1.80	2.09	3.70
E_{acc} [MV/m]	5.29	5.68	7.89	7.51
E_p/E_{acc}	5.82	5.89	4.22	3.53
B_p/E_{acc} [mT/(MV/m)]	10.3	12.1	7.55	8.41
R/Q [Ω]	402	455	224	230
Γ [Ω]	15.3	22.3	77.9	107
Aperture [m]	0.036	0.036	0.040	0.040
$L_{eff} \equiv \beta\lambda$ [m]	0.153	0.317	0.265	0.493
Lorenz detuning [Hz/(MV/m)^2]	< 4	< 4	< 4	< 4
Specific Q_O @VT	1.4x10^9	2.0x10^9	5.5x10^9	9.2x10^9

Cavity Frequency Control

All FRIB cavies already have been ordered vendors and under fabrication as described later. Cavity frequency control during cavity fabrication is crucial as described in section of technical challenges. Stack up tuning method has been successfully developed to control the cavity frequency within ± 25 kHz [9].

Tuning for frequency increase is very difficult for HWRs by methods developed so far. For instance cavity frequency only decreases by the following chemical etching process. New tuning method so called virtual tuning has been innovated to increase the HWR frequency by shrinking the cavity length with electron beam welding [12]. For QWRs both way is possible by BCP local etching so called differential etching: etching the bottom

Figure 7: Left, BCP for 0.041 QWR at SRF Highbay facility, Right, HPR in the SRF clean room.

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Figure 8: Left, particle count checks are performed on the inside of a beta – 0.085 QWR cavity prior to assembly. Right particle count on the tuning puck.

part of cavity for frequency increase or top part of cavity for frequent decrease, which can control the cavity frequency within 5 kHz [13].

Cavity Processing

FRIB cavities are processed using buffered chemical polishing (BCP) using new chemical etching facility in the SRF highbay after acceptance inspections (Fig. 7 left) [14]. FRIB processing procedure is: after the bulk etching, hydrogen degassed at 600 ^{O}C for 10 hr takes place, then fiducial machining the helium vessel flange, and final etching (20 μm), and after water rinsing, HPR (Fig. 7 right) in the clean room are carried out, and finally assembled for vertical Dewar test.

During the HPR and the cavity assembly, particles are counted in the waste water from HPR and on the flange surface (assembly) as seen Fig. 8 by particle counter as the QA process, which produces almost secondary emission free cavity [15, 16]. After the assembly, the cavity is connected oil-free vacuum evacuation system on the test stand in the class 1000 clean room. 120 ^{O}C low temperature bake does not take in the present baseline procedure. Every cavity family has enough cavity performance against FRIB requirement even without low temperature bake.

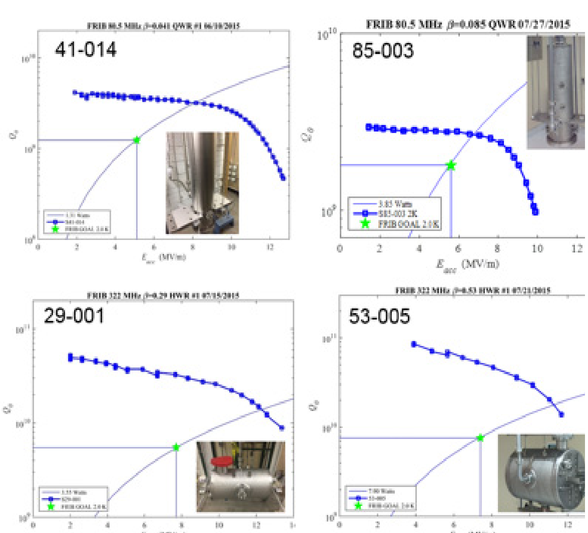

Figure 9: Cavity performance validated at 2 K.

Cavity Performance Validation

FRIB cavities have been tested in the vertical Dewar at 4 K and 2 K in East highbay. Every type cavity has multipacting at very low field Eacc < 1 MV/m, which needs RF processing for more than 4 hr at 4 K. After the RF processed up to several MV/m at 4 K, cavity is cooled at 2K and measure the Qo-Eacc curve. The cavity is measured using fixed input coupler so far. Variable coupler is under development. FRIB successfully certificated all FRIB cavity designs and vendors. Fig. 9 shows the cavity performance validated for all families at 2 K. Q-drop at high field is so called high Q-slope and not field emission. Each type has enough margin against FRIB goal.

Couplers

FRIB requirements for FPCs are summarized Table 2. Both QWR families use coaxial bellows coupler and 90^{O} bend as seen in Fig. 10, which was designed at ANL. The bellows is fixed after coupling adjustment manually. The adjustment range is ½ to 2 times band width. The RF

Table 2: FRIB Coupler Parameters

Cavity Type	QWR	QWR	HWR	HWR
β	0.041	0.085	0.285	0.53
f [MHz]	80.5		322	
Cavity RF Band width [Hz]	40		30	
Installed RF Power [kW]	2.5		5	
Max. Coupler Rating [kW]	4.0		10	
Manual coupling Adjustment				
Total Heat Load to 2 K at Nominal RF Power [W]	0.13		0.6	
Total Heat Load to 4.5 K art Nominal RF Power [W]	1.3		2.7	
Total Heat Load to 38/55 K at Nominal RF Power [W]	7.1		6.2	

Figure 10: QWR ANL-type power coupler.

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handled power is 4 kW maximum with QWR FPCs.

The validation test has been successfully done for QWR FPCs in the integration test: ReA6 cavity/coupler in the vertical Dewar (Fig. 11). The cavity was operated continuously for longer than 48 hr at Eacc = 6.1 MV/m and Eacc = 6.7 MV/m for 6 hr (10% and 20% above nominal FRIB gradient). The endurance test has been successfully done for 27 hr at 2 kW and Eacc = 6 MV/m. No overheating, no multipacting, and no field emission were observed. The heat load was low as simulated. Measured bandwidth was 31 Hz. Other results in ReA3 was 37 – 44 Hz, which gave a confidence in band width control for FRIB cavities. The band width control of 40 Hz for QWR coupler was demonstrated.

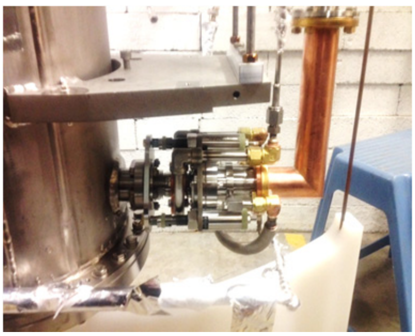

Figure 11: QWR coupler mounted on ReA6 cavity.

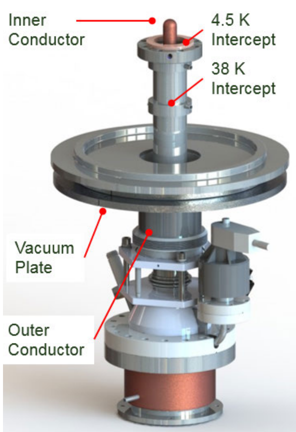

Figure 12: FRIB HWR power coupler, KEK/SNS type.

Figure 13: RF conditioning system for HWR couplers.

Both HWRs uses KEK/SNS type coaxial coupler as shown in Fig. 12. The handing power is 10 kW maximum. This coupler is also manually adjustable coupling in the similar range as QWR coupler. Two couplers were mounted on a bench mark (Fig. 13) and RF conditioned up to 9.25 kW at room temperature. One of these couplers was assembled on a 0.285HWR with the pneumatic tuner (Fig. 15) and cold integration test took place. The cavity was operated continuously at Eacc = 7.7 MV/m for 24 hr without any trouble, thus the validation of HWR power coupler has been completed. More test is scheduled for the integration test with 0.53 HWR.

Tuner

Both QWRs utilize tuning plate for cavity frequency control located at bottom of the cavity (Fig.14). Thin niobium plate 1 mm thick with flexible structure is driven

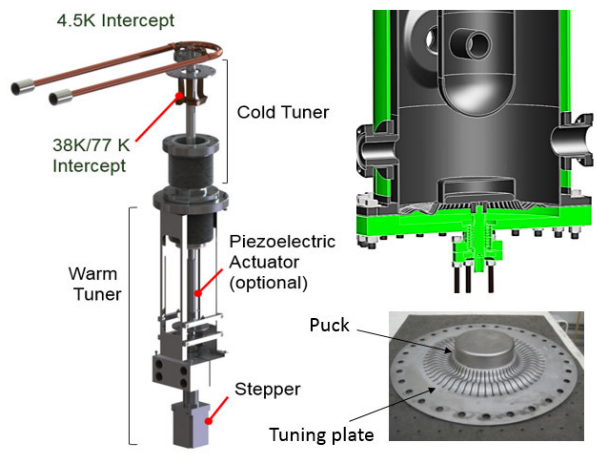

Figure 14: QWR Tuner, tuning plate drived left, tuning on cavity bottom flange(right upper), Tuning plated welded puck (right bottom) .

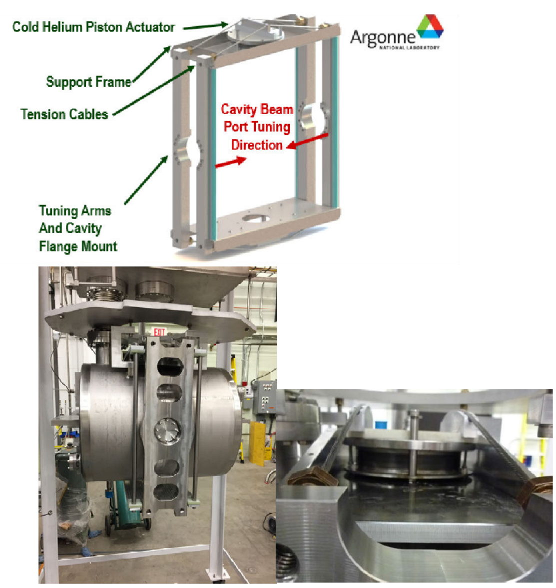

Figure 15: ANL type pneumatic ture, Top shows the tuning principle, bottom left shows the tuner on 0.53HWR at FRIB, bottom right shows soom of the coldhelium piston actuator part.

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Table 3: Requirements for FRIB Tuners

	QWR	HWR
Tuning range [kHz]	30	120
Tuning Resolution [Hz]	0.8	0.6
Maximum Backlash [Hz]	2	1.5
Cavity tuning sensitivity [kHz/mm]	3.2	236.2
Cavity df/dp [Hz/torr]	- 1.4	- 3.43
Cavity Lorentz detuning [Hz/(MV/m)^2]	- 0.7	- 3

by a pulse motor located bottom of cryomodule. Tuner parameter is listed in Table 3. Tuner range is 30 kHz and tuner sensitivity is 3.2 kHz/mm with QWR tuner. Piezo tuner does not need is demonstrated even in ReA3 CM operation environment which is installed on the ReA mezzanine. FRIB tunnel is much quiet on the microphonic noise. Other CM1 and CM2 are also operated in ReA without any microphonics issue for longer than three years. Thus validation with QWR tuner is well established.

ANL type pneumatic tuner is used for both HWRs as shown in Fig. 15 (0.53HWR). In this tuner, a cold piston actuator is located at the top the tuner flame and the bellows operation with helium gas pushes/pulls the cavity through the beam port flanges. As shown in Fig. 15 integration test, this tuner has been successfully cold tested and confirmed to work well with 0.285HWR. The results are: 1) the tuning range is 54 kHz with mean sensitivity of 1.36 kHz/psi, 2) tuning speed is between 250 and 600 Hz/s. Another integration test is ongoing for 0.53HWR.

Table 4: FRIB Superconducting Solenoid Package Parameters

	25 cm solenoid package	**50 cm solenoid package**
Peak solenoid file on beam axis [T]	≧ 8	≧ 8
Bz^2 integrated solenoid field [T^{2}m]	≧ 13.6	≧ 28.2
Fringe field [G]	≦ 240 G at 26cm from solenoid centre in longitudinal	≦270 G at 39 cm from centre of solenoid in longitudinal
Solenoid nominal current [A]	≦ 90.9	≦ 90.9
Deviation of field /mechanical centres [mm]	≦ 0.3	≦ 0.3
Dipole Bx and By integrated field [Tm]	≧ 0.03	≧ 0.06
Dipole Nominal current [A]	≦ 19.0	≦ 19.0
Operation temperature [K]	4.5 ± 0.5	4.5 ± 0.5

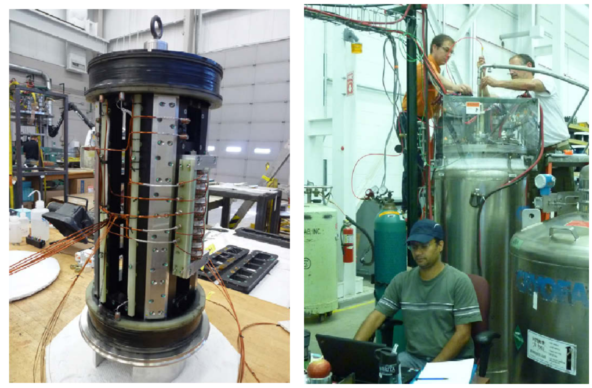

Figure 16: First production superconducting solenoid package test, the left shows the coldmass of the solenoid package before helium vessel welded, the right shows the view of the cold testing.

Superconducting Solenoid Package

FRIB utilizes two types of superconducting solenoid packages: 25 cm package for 0.041CMs and 50 cm package for other CMs, which consist of one main solenoid, a set of bucking coils, and two set of beam steering dipole coils. The FRIB requirements are summarized in Table 4 for these superconducting solenoid packages. Bucking coil is to cancel the fringe field from both the main solenoid and the diploe coils. Bucking coils are connected to the main solenoid in series. Two dipoles are independently operated to kick the beam in transverse directions (X and Y). The fringe field strength in Table 4 is was decided by the optimized solenoid package design [16]. All magnets are made of superconducting NbTi wire. All coils are operated at 4.5 K. The solenoid has to be operated very reliably in the FRIB linac, otherwise when solenoid quenched, the beam might hit cavities and make heavy damages on the cavity performance. The peak solenoid field was 9 T in the original design but decreased to 8 T to allow reliable operation [17].

As mention below, FRIB applies local magnetic shield. The solenoid packages design are well optimized so that the fringe field strength does not exceed the requirements in the Table 4. The first 25 cm package was prototyped and tested at 4.2 K at KEK under the MSU/KEK collaboration [18]. Very excellent performance was demonstrated, which excited 8.9 T without any quench training. The first 50 cm development solenoid package, which was reused from TDCM [19] was validated in the ReA6-1 CM test. The package has been operated stably with cavities in ReA6-1 test [20].

The first 50 cm production solenoid package was completed by in-house and tested in early September 2015 (Fig. 16). The field distribution was measure by Flux gauges and Hall probes. The main solenoid was successfully excited up to 8.26 T (82.6 A) without any quench. The dipoles also energized up to 19 A (0.06 Tm) under the solenoid field (8.26 T) without any quench. The deviation between the magnetic field centre and mechanical centre was within 0.25 mm. The first article met FRIB requirements well.

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Magnetic Shielding

FRIB takes local magnetic shield scheme to enhance the shielding performance while to reduce the material cost of the shield. The magnetic shield is located nearby cavities and cooled around 25 K. So generally saying, cryogenic shield material has to be used. The local magnetic shield has to protect the cavity from the strong fringe field (~ 250 G). The fringe field < 1600 G (H_{C1} of niobium lower critical field at 2 K) has no degradation on SRF cavity performance when the cavity was already in Meissner state before energized solenoid. However, when the cavity quenched under a fringe field penetrated the local magnetic shield, a rather serious Q-drop could happen [17]. The saturation field of shielding ability has be known for local magnetic shield. FIRB has investigated and Fig. 17 is the result at 10 K [21]. Field penetration starts around 250 G with several cryogenic magnetic materials. The fringe field strength has to be lower than this value on the magnetic shield outer surface. This gave a criterial for the solenoid package design. FRIB solenoid package design is very consistent with this criteria as seen Table 4.

FRIB requirement for the remnant field is < 15 mG in the magnetic shield. QWR magnetic shield design of ReA3/ReA6 cryomodule is shown in Fig. 18. This design has been validated the FRIB requirement with cryogenic materials as seen later, however it was not assembly friendly and as the result needs many assembly labour costs. The design was simplified eliminating the all sleeves around holes on the shield [22]. A full modelling included Erath magnetic field (500 G), vacuum chamber of the cryomodule made of carbon steel, magnetic shield, and cavity RF magnetic field distribution concluded that the shield 1 mm thick with μ > 9000 can meet FRIB requirement for QWR magnetic shield [23].

Table 5 shows the FRIB requirement for magnetic shields. Any specific cryogenic material is not assigned. Intensive measurement results at KEK with various magnetic shield materials included conventional μ-

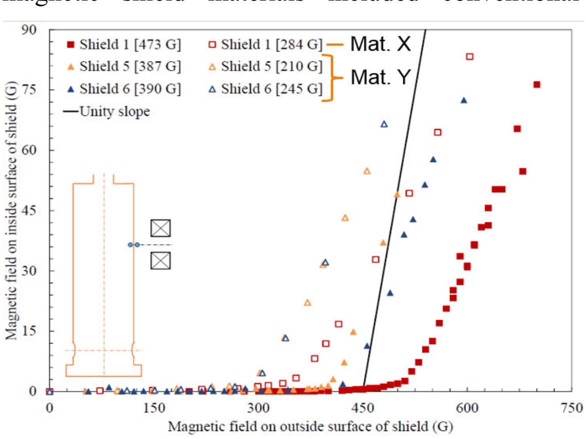

Figure 17: Shielding performance of the magnetic shield at high field. The all solid marks are results at room temperature, the all empty marks are results at 10 K. Shields made of two different cryogenic materials were measured.

Table 5: FRIB Requirement for Magnetic Shield

	QWR Shield	HWR Shield
Permeability m at 500 G @ 25 K	≧ 10000	≧ 10000
Thickness	1.0 mm	TBD

Figure 18: Magnetic shield design of ReA3/ReA6.

material shows that even the μ-metal has μ > 10000 at 4.2 K [24]. Stress during fabrication will degrade μ but the suitable annealing after shield fabrication can recover the performance. So FRIB keeps the possibility of μ-metal application to reduce material cost. FRIB has ordered two types of magnetic shields to a vendor: cryogenic material and μ-metal for the first 0.085QWR production cryomodule and the result will make the final material selection. On the HWR magnetic shield, FRIB has not yet conclusion. HWR's cavity performance is more sensitive against the remnant field because the high RF magnetic field region is closely facing solenoid in the FRIB cryomodule design. The investigation is ongoing.

TECHNICAL CHALLENGES IN FRIB SRF

As described above, FRIB is challenging several innovations to build compact SRF heavy ion linac with high performance. Here, these challenges and the cures are addressed.

First SRF Large Scale Application over Wide Beta Range

As already mention above, FRIB linac utilizes SRF technology from very low β(v/c) = 0.041 to medium β = 0.53 in the SRF linac, which is the first application for such a beta wide range in the low beta SRF community. FRIB needs four family cryomodules according to four betas 0.041, 0.085, 0.285, and 0.53, which makes production very complicate and increases risk. Many US demotic labs are supporting the FRIB to mitigate this issue, for instance Jlab is making the 0.041 QWR and0.285 HWR cryomodule designs, and ANL is supporting QWR coupler design and HWR tuner design.

SC Solenoid in the Cryomodule

FRIB challenges to build a compact SRF linac with high beam quality. For this purpose they apply the CM design installing superconducting solenoid package in the cryomodule, which can focus the beam strongly and quickly, as the result produce high quality heavy ion beam while increases the real estate gradient. Superconducting solenoid package locates nearby SRF cavities. This

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scheme produce two issues: 1) magnetization of components located around the solenoid package and 2) cavity Q-drop at cavity quench due to the cavity/solenoid fringe field interaction. FRIB has developed local magnetic shielding and well optimized solenoid package design to reduce fringe field [16]. FRIB has had a confidence on this challenge by the ReA6-1 test result at least for QWRs, which will described next section.

Tight Alignment Tolerance

If heavy ion hits the SRF cavity surface during the machine operation, a large damage is expected due to the very shallow black peak by the heavy ion, and result in serious cavity performance degradation. Of course various kinds of beam protection system are introduce in FRIB linac to protect cavities, however the alignment should be good enough to handle the high intensity heavy ion beam. The diameter of FRIB cavity beam port is rather small compared to SRF electron linac: 36 – 40 mm for the optimized cavity designs. These factors requires the tighter alignment tolerance. FRIB requests the tolerance less than 1 mm in transverse. Usually the top down assembly has been used in existing SRF low beta linacs which allows a tolerance about 2.0 mm by bending due to weight or thermal contraction. FRIB has innovated the bottom up support cavity assembly method to meet the FRIB requirement. This has been validated in the ReA6-1 test [7].

Narrow Cavity Band Width

RF band width of FRIB operation cavities is 30 - 40 Hz due to the small beam loading, even FRIB is the intensity frontier heavy ion machine the beam current is smaller than 2 mA. This is much different from the electron SRF linacs, which has typically ~100 kHz due to the very heavy beam loading. Microphonics is the serious issue in such a narrow band width. Pressure fluctuation of the helium gas in the 4 K cavity operation enhances the microphonics. FRIB chose 2 K cavity operation, which allows very small pressure fluctuation. Appling high power amplifier is an easy way against the narrow bandwidth but the cost of amplifier and operation electricity power increase remarkably by this way. The tight cavity frequency control is very crucial. The stack up tuning [9], virtual tuning [12], bulk etching control [14], deferential etching [13], puck height adjustment, and mechanical tuners have been developed for the tight cavity frequency control.

High Cavity Performance

FRIB cavities are operated at rather high gradient @ high Q to reduce the number of cryomodules for saving a capital cost. The cavities are operated at 2 K with enhanced cavity performance. The high gradient and high Q performance requires a high quality control. FRIB has developed field emission free cavity/coupler assembly procedure [15].

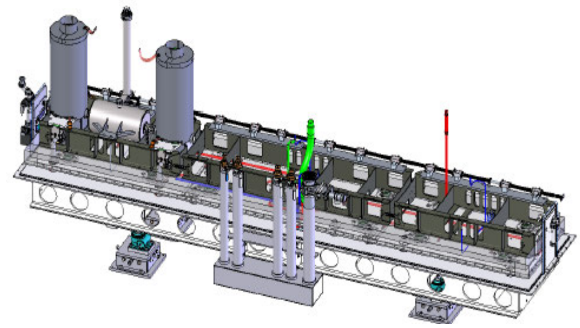

Figure 19: Illustrated picture of ReA6-1 coldmass on the CM baseplate.

CRYOMODULE INTEGRATION TEST

As mentioned above, each SRF hardware in the cryomodule has been successfully validated, however still several items remain to be validated before production, which need to build a prototype cryomodule. FRIB built a FRIB 0.085QWR prototype cryomodule so called ReA6-1, which installs two 0.085QWRs at one end of the module, and one superconducting solenoid package between the cavities as shown Fig. 19. Goals of this cryomodule integration test are:

1) Validate the alignment tolerance by Bottom up supported assembly,
2) Validate local magnetic shield benefits,
3) Demonstrate stable operation of integrated cavity system: cavity, FPCs, tuners, and solenoid package.
4) Validate FRIB liquid helium transfer line (this is not a scope in this paper, the information is seen in [25]).

Figure 20: Completed ReA6 cryomodule located in the East Highbay bunker test area.

Table 6: Summary of the overall measured cryomodule component alignment.

Component	Assembly (mm)	Cool-down(mm)	Overall (mm)
Resonator Transverse	0.237	0.254	0.491
Resonator Vertical	0.505	0.327	0.832
Solenoid Transverse	0.362	0.181	0.543
Solenoid Vertical	0.580	0.102	0.682

Figure 20 shows the completed ReA6 cryomodule located in the East highbay bunker area. FRIB type liquid helium transfer line and ReA6 cryomodule are seen. Wire position monitor was installed on the rail to monitor the rail movement by thermal contraction during cool-down.

Validation of Alignment Tolerance by Bottom up Supported Assembly

The movement of cold rail supporting cavities and solenoid was measured during cool cycles. The cooling down/warming up cycle took place twice to see reproducibility of measurement result. The result is summarized in Table 6. The measurement overall movement of the solenoid, which is the reference of alignment, was 0.543 mm in transvers and 0.682 mm in vertical. Thus FRIB successfully validated that the bottom up supported assembly meets the FRIB alignment tolerance requirement: 1 mm with both transverse and vertical direction of the resonators and solenoids. The detail information can be seen in this conference [7].

Validation of Local Magnetic Shielding Benefits

Remnant magnetic field inside/outside magnetic shield was measured during ReA6-1 test as shown in Fig. 21. The sensors were placed at three locations: ① cavity top side near the high RF magnetic field region of the QWR, ② near the beam port of the cavity on the side facing away from the solenoid, ③ cavity beam port facing solenoid.

The measurement results are summarized in Table 7. The remnant field at the cavity top region after cool down was 2.5 mG (μT), which meets FRIB requirement: ≦15 mG.

During the solenoid package operation at the FRIB spec. the remnant field was 162 mG at the cavity top. From our previous study using HWR, the fringe field > 2.5 G produces a detectable Q-drop at cavity quench is known [19]. The measurement result in the ReA6-1 suggests no detectable Q-drop at cavity quench under the full solenoid package operation, which makes reliable the cryomodule operation in the FRIB machine.

In Table 7, the remnant field inside magnetic shield of 30.7 mG after the solenoid package switched off (the

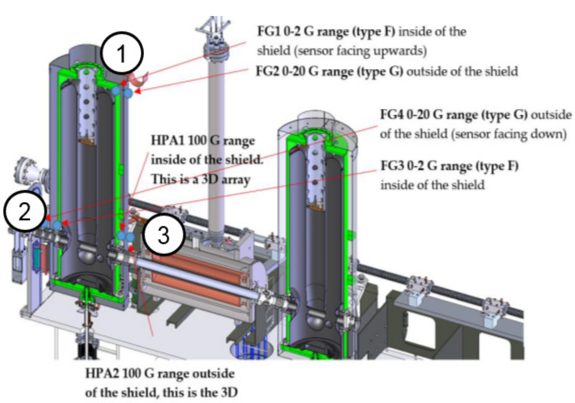

Figure 21: Remnant magnetic field measurement in the ReA6, The sensor location and types.

Table 7: The magnetic fields measured by the fluxgates during the different stages of testing. The values, except 'after cool down' and 'after CM warm-up,' are averaged over three cycles of degaussing.

Process	Magnetic field at fluxgates (μT)			
	Top of cavity		Bottom of cavity	
	In	Out	In	Out
After cool down (shield T=24.5 K)	0.25	0.81	0.30	20.93
During solenoid operation	-16.16 ±0.12	-36.12 ±0.21	165.95 ±2.07	87.20 ±2.02
After solenoid operation	3.07 ±0.06	2.76 ±0.12	1.59 ±0.12	29.09 ±0.03
After full degauss	0.42 ±0.07	0.87 ±0.11	0.05 ±0.17	20.76 ±0.16
After CM warm-up	0 ±0.01	-0.5 ±0.01	0.06 ±0.01	20.50 ±0.01

package temperature was still 4.5 K) seemed to be magnetized. Degaussing took place and the remnant field reduced to 4.2 mG, which looked the demagnetization worked. However this conclusion was wrong. Actually when coils were warmed up to > 9 K without degaussing after the package operation, the remnant field degreased to 4 mG. So the remnant field 30.7 mG after solenoid operation is the effect of the persistent currents circulating in the superconducting solenoid coils. From these experiment facts we can conclude no degaussing procedure is required for FRIB QWR cryomodule operation. The detail report of the remnant field measurement result in ReA6 is seen the reference in this conference [20].

Demonstration of Stable Operation for Long Run

The integrated operation test with cavities/FPCs/ tuners/ superconducting solenoid package took place in the ReA6-1 test. The solenoid package was independently continuously operated at the FRIB target fields for 1 hr very stably, then operated with cavities/FPCs/tuners for 1 hr stably. They confirmed that solenoid package operation is stable and gives no impact on cavity integrated system [26].

The cavity integrated system: cavity/FPCs/tuner was operated at 6.2 MV/m (10% higher gradient of FRIB goal) for 24 hr very stably. No x-ray was observed within measurement sensitivity during this operation. They confirmed the cavity integration system is very reliable. In addition FRIB coldmass assemble procedure is very excellent. Table 8 show measurement result for the control parameters: gradient, detuning, phase, and

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amplitude errors, which meets well FRIB retirement even 4 K operation except for detuning with QWR2, which is close to the goal.

PRODUCTION READINESS STATUS

FRIB is moving to production phase. Here the readiness of the production is described. FRIB has three steps for vendor contract. FRIB orders two articles first and technical transfer and development take place with the vendor and FRIB together for build to print. FRIB will test the article and validate the performance. If the quality is validated, the vender certification completes. As the next step (preproduction), the vendor will produce 10 articles by their own, in which FRIB will evaluate their capability for future mass-production and also some technical feedback will be done to resolve issues appeared in this preproduction phase. Then they will move to mass-production. Fig. 22 summarizes the status for validation (V), vender certification (VC), preproduction, and mass-production. The number in brackets in Fig. 22 means the quantity of the article ordered. The all competes have been completed V and VC except for tuner and solenoid. These have a complicate history and first articles are been produced in-house at FRIB.

Delivery Status

Already many hardware are being delivered MSU. Fig. 23 show some phots of these deliveries. Niobium material has been delivered all for FRIB production cavities. About 50 cavities have been delivered at the date of middle of September 2015. Nineteen all 0.041QWRs have been delivered and production has been completed. The deliveries of ten preproduction 0.085QWRs have been completed and the vendor is moving to mass-production. Six 0.285 HWRs have been delivered by earl September. Twelve 0.53HWRs have been delivered. Tuning plates for QWRs and eight FPCs for 0.085QWRs have been received for first FRIB 0.085CP production.

INFRASTRUCTURE FOR FRIB PRODUCTION

MSU completed the SRF highbay in March 2015 for FRIB SRF production as seen in Fig. 25 [1, 27, and 28]. The purpose of this facility is: 1) Acceptance inspections, 2) Cavity processing, 3) Cavity assembly, 4) Cavity vertical Dewar testing, 5) Coldmass assembly, 6) Cryomodule bunker test.

Figure 24 shows infrastructures already installed or under preparation. Acceptance inspections (Acceptance Control Level: ACL): visual inspection using bore scope, dimensional inspection with CMM, magnetization inspection, cold shock cycling, and vacuum leak test,

Component	Status, V(Validation), VC (Vendor Certification)				Delivery and Needed Date
Nb materials	NbTi flange (done), Nb sheets (done), Seamless pipes (done)				FRIB production Nb material has been done
Cavity with Helium jacket	0.041QWR Vendor A			Production (19) done	All 0.041QWRs has been delivered
	0.085QWR Vendor B/C	Development (2) Done V, VC	Preproduction (10) Delivered 10, done all	Production (102) Started mass-production	Needs 8 by 1st Sep. 2015 (FRIB first 0.085CM)
	0.285HWR Vendor D	Development (2) Done V, VC	Preproduction (10) Delivered 3	Production (72)	Needs by Aug. 2017
	0.53HWR Vendor D	Development (2) Done V, VC	Preproduction(10) Delivered 10	Preproduction (138)	Need by Apr. 2016
Fundamental Power Coupler	QWR parts Vendors	QWR FPC (2) Done V, VC	Preproduction (8) Delivered 8 Aug. 2015	QWR FPC(104)	Needs 8 by 1st Sep. 2015 (FRIB first 0.085CM)
	HWR Vendor E	Development (2) Done V, VC	HWR FPC (2) to be delivered Oct. 2015	HWR (217)	Need by Apr. 2016 (FRIB 1st CM)
Tuner	QWR Vendor F	Development (8) Done V, ReA3	Production(112) Delivered (8), tuning plates		Needs by Sep. 2015
	HWR Tuner	Development (2) Done V by integration test but still finalizing design	Production (217)		Need by Jun. 2016 (FRIB 1st 0.53CM Prototype)
Solenoid	25cm Vendor G	Development (1) Done V		Production (6)	Need by March 2017
	50cm Vendor G/MSU	Development (1) Done V	Preproduction (4) in MSU, completed for preproduction CM Other in vendor G	Production (62)	Need 3 by Sep. 2015 for FRIB first 0.085 CM

Figure 22: Readiness of production.

Figure 23: Some examples of recent deliveries. From top left to right, niobium materials, dampers for QWRs, HWR pneumatic tuner, 50 cm superconducting solenoid package. From middle left to right 0.041QWRs, tuning plate for QWRs. From bottom left to right, 0.041/0.085QWRs and 0.53HWRs, FPCs for 0.085QWRs, magnetic shield on the 0.085QWRs (ReA6-1).

Figure 24: Infrastructures in SRF Highbay: from top left to right CMM measurement (dimensional inspection), large clean room for cavity assembly, BCP system for cavity processing, PR system. From middle left to right, Hydrogen degassing vacuum furnace, Ultrapure water system, coldmass assembly area, test stand area. From bottom left to right, 900W cold box, 2 K helium gas evacuation pump, Low level control area, vertical Dewars for cavity certification test.

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frequency measurement and so on is being conducted in the SRF highbay ACL area.

Cavity processing: BCP, hydrogen degassing (600 ^{O}C x 10 hr), HPR also is taking place in the SRF Highbay [28]. So far FRIB cavities are vertical tested at East highbay after assembled in the SRF highbay clean room. Two vertical Dewars have been installed and the liquid helium transfer line connection is underway in SRF Highbay. We have four vertical test. They have four cold test stands now and increased to six soon for FRIB cavity production.

Coldmass assembly has started for the FRIB first 0.085 cryomodule in the SRF Highbay cleanroom. Low level control system is also under installation (seen in Fig. 24).

900W cold box has been installed in SRF highbay and completed commissioning on September 1, 2015 (Fig. 24). Liquid helium will be ready for 3000L reservoir by end of September. Dewar shielding block installation is scheduled in end of October. The first vertical Dewar test of cavity is scheduled in mid-November 2015. SRF Highbay is scheduled to go into full operation from end of November 2015.

RAMPING TO FRIB FULL PRODUCTION

FRIB SRF Schedule

Figure 26 shows the FRIB master schedule related to SRF. FRIB will start early beam commissioning for Front end from end of 2017, and successively the SRF linac com missioning begins from mid-2018 to mid-2020.

Figure 25: SRF Highbay constructed nearby FRIB tunnel.

FRIB final completion is in 2022. The current first priority in the Cryomodule Department is to complete the FRIB first 0.085QWR production cryomodule by end of this year. The coldmass assembly has started for this cryomodule as mentioned above. After this cryomodule, we will produce first 0.053HWR cryomodule in mid-2016. Cryomodule production already started mid-2015 and finish August 2019.

Cavity Production Capability

To meet this schedule FRIB needs 8 – 9 cavities per month for coldmass assembly at the maximum production stage. So far FRIB received about 50 cavities from vendors. The current vendor average cavity production rate is 7 cavities/month in the past 7 months. Vendor

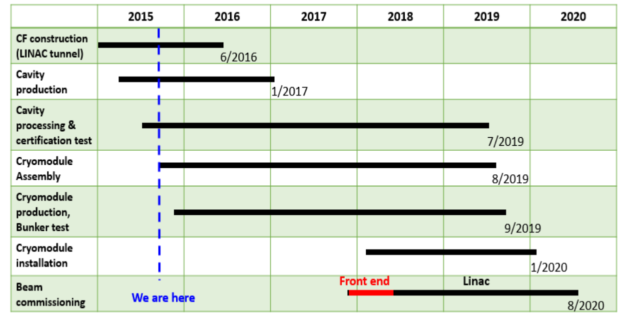

Figure 26: FRIB master schedule related to SRF.

cavity production is speeding up now and will complete all FRIB cavities by early 2017. No problem is expected for FRIB with cavity delivery schedule. FRIB ACL processing is catching up the past delivery schedule. The cavity vertical testing rate has been demonstrated two tests per week with the current existing test facility.

As mentioned above SRF highbay will come into full production from mid-November 2015. The cavity processing and testing capability can increase double. FRIB cavity projected actual work rate expects the cavity production rate of 11-12 cavities per month with 20% downtime and 80% cavity yield., which can manage enough the cavity schedule required by FRIB schedule.

Cryomodule Production

Bunker test of the cryomodules is planned in the SRF highbay. FRIB needs 1.5 cryomodule test per month. MSU has already four cryomodule production experiences: ReA CM1, CM2, CM3, and ReA6-1. They have rather reliable test schedule for bunker test. Fig. 27 shows the FRIB bunker test plan based on the previous experiences. Totally twenty-seven working days is necessary for one test. SRF highbay is preparing two bunker test systems. Two bunker systems can meet the FRIB cryomodule production rate. All cavities in the cryomodule will not be excited simultaneously because the amplifier is prepare only one cavity due to the tight budget.

FOR FUTURE LARGE SCALE PROTON/HEAVY ION SRF LINACS

FRIB is just early production phase but here a relevant information will described for future large scale proton/heavy ion linacs. As emphasized several time above, it is important to build a compact SRF linac with high beam quality. The reliable operationability is also very crucial. For these purpose, the solenoid in cryomodule scheme with local magnetic shielding is very good way. FRIB has validated it to have very benefits for at least for QWR CM. The validation of HWR CM will be done in the first 0.53 production cryomodule.

SUMMARY

FRIB SRF hardware have been all validated. They have been ordered to vendors. The first articles are under delivery. FRIB is coming to production phase. SRF highbay has been completed and some facility is under

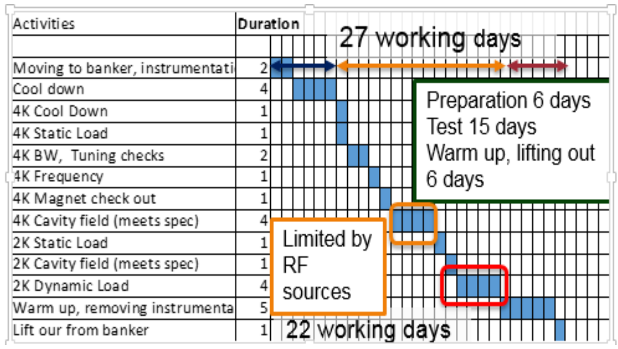

Figure 27: Required working days for cryomodule bunker testing.

operation. SRF highbay will start full operation from mid-November 2015. The production rate will be increased double and will meet the FRIB master schedule. .

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