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PROGRESS OF FRIB SRF PRODUCTION*

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Abstract

The Facility for Rare Isotope Beams (FRIB), under construction at Michigan State University, will utilize a driver linac to accelerate stable ion beams from protons to uranium up to energies of > 200 MeV per nucleon with a beam power of up to 400 kW. The FRIB linac consists of 46 cryomodules containing a total of 324 superconducting radiofrequency (SRF) resonators and 69 superconducting solenoids. The design of all six types of cryomodules has been completed. The critical SRF components have been tested as subsystems and validated in production cryomodules. The mass production of SRF cryomodules is underway. Here we report on the progress of the technical construction of the FRIB superconducting linac.

INTRODUCTION

FRIB is a new facility for cutting-edge nuclear physics research with rare isotopes. It is being constructed at Michigan State University (MSU), sponsored by the US Department of Energy (DOE). The FRIB driver linac will accelerate stable ion species to energies of no less than 200 MeV/u, providing up to 400 kW on the target to produce rare isotopes [1]. FRIB conventional construction started in March 2014, and the accelerator system construction began in October 2014. The FRIB accelerator building was completed in 2016 (Figure 1, right). Installation of the liquid helium distribution lines in the tunnel is nearly complete; cryomodule installation started in 2017 (Figure 1, right). Considerable progress has been made since the last SRF conference report two years ago [2]. Linac commissioning will be staged, starting with the Front End in Fall 2017. FRIB project completion will be in 2022 and nearly 1,400 users are anticipated.

FRIB DRIVER LINAC

As described in Table 1, the FRIB driver linac has four families of SRF cavities: 2 types of quarter wave resonators (QWRs) at 80.5 MHz, and 2 types of half wave resonators

Table 1: FRIB Cavities and Cryomodules.

Quarter Wave Cryomodule				
β	Type	*Component Counts (baseline + spares)*		
		Cryomodules	*Cavities*	*Solenoids*
0.041	accelerating	3 + 1	12 + 4	6 + 2
0.085	accelerating	11 + 1	88 + 8	33 + 3
	matching	1 + 1	4 + 4	-
Half Wave Cryomodule				
0.29	accelerating	12	72	12
0.53	accelerating	18	144	18
	matching	1	4	-
TOTALS		**46 + 3**	**324 + 16**	**69 + 5**

Figure 1: Left: aerial view of the FRIB accelerator building. Right: cryogenic distribution lines and cryomodules.

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(HWRs) at 322 MHz. A total of 324 cavities are required. Figure 2 shows the 4 cavity designs.

As seen in Table 1, six types of cryomodule (CM) are required, including two matching CM designs. In addition, three spare CMs needed, for a total of 46 CMs. Figure 3 shows the cryomodule configuration in the FRIB tunnel.

The cryomodules contain superconducting solenoid packages, in addition to the SRF cavities. The solenoid package consists of an 8 T solenoid (beam focussing) and two pairs of dipole coils (beam steering), with a helium jacket. The β = 0.041 CMs have solenoid packages of length 25 cm; the other CMs have solenoid packages of length 50 cm. A total of 69 solenoid packages are needed.

Figure 3 shows the linac configuration in the FRIB tunnel. The "front end" includes the beam injection section from the ion source to the 500 keV/u radio-frequency quadrupole (RFQ). Linac Segment 1 (LS1) consists of three β = 0.041 CMs and eleven β = 0.085 CMs. The ion beam is bent by 180° after the β = 0.085 matching CM and the liquid lithium stripper. Linac Segment 2 (LS2) contains β = 0.29 and β = 0.53 CMs. After another 180° bend, the beam travels through Linac Segment 3 (L3), which includes a matching β = 0.53 CM and six β = 0.53 accelerating CMs, and is then transported to the target.

CRYOMODULE PROCUREMENT AND PRODUCTION STATUS

Figure 4 shows the status of major cryomodule procurements as of early July 2017. Nearly all components have been received for LS1 cryomodules. HWR cryomodule components were released for mass production after the first bunker test of the first β = 0.53 cryomodule (SCM501). The β=0.53 matching CM procurement packages are ready to be let. All cavities will be delivered by the second quarter of 2018. QWR fundamental power couplers (FPCs) have all been received. HWR FPCs will be received by the first quarter of 2018. All solenoid packages have been received.

Figure 5 shows the cryomodule production schedule for the FRIB baseline plan. LS1 is to be ready for beam in October 2018, while LS2 is to be commissioned in October 2019. At present, the highest priority is to complete all of the β = 0.085 CMs by the end of 2017, and production is

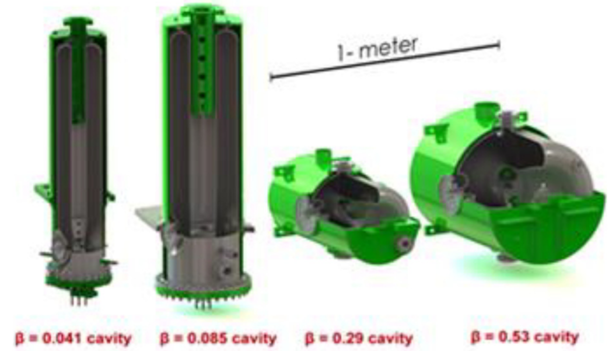

Figure 2: FRIB cavities.

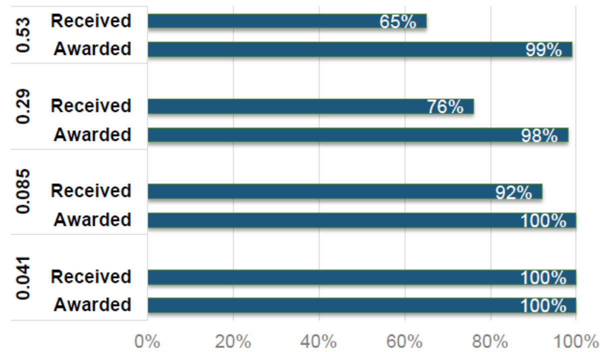

Figure 4: Status of major cryomodule procurements.

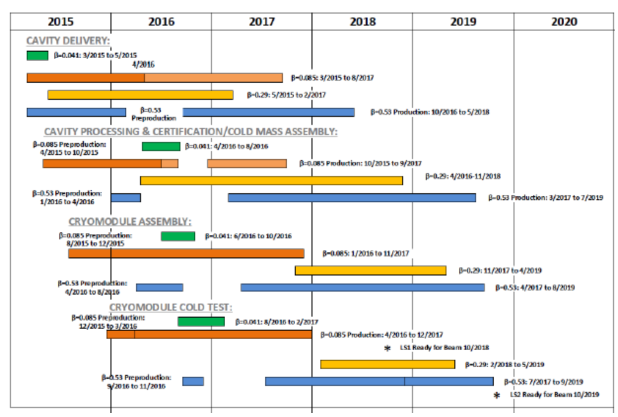

Figure 5: FRIB cryomodule production schedule.

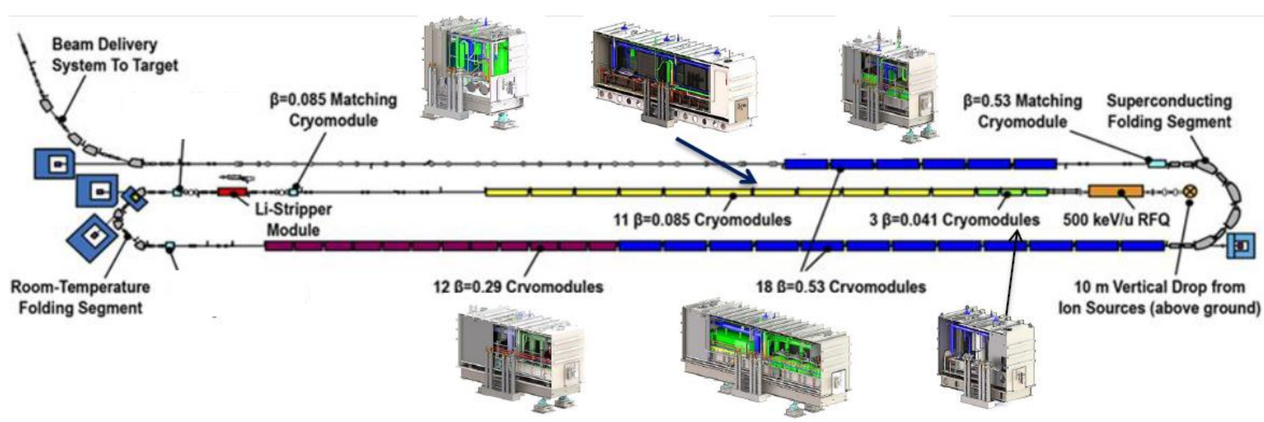

Figure 3: FRIB driver linac configuration and cryomodule distribution.

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on track to meet this goal. Table 2 shows the cryomodule production status as of early July 2017. The three β = 0.041 CMs have already been aligned in the tunnel, as seen in Figure 6. Cryomodules are moved into the tunnel after they are tested in the bunker; four β = 0.085 CMs are presently in the tunnel. HWR CM production started after the validation bunker test of the first β = 0.53 CM. All CMs are on track for completion by the end of 2019, which meets the FRIB baseline schedule.

FRIB CAVITY PRODUCTION FACILITY

FRIB has a dedicated cavity production facility called "SRF Highbay" by MSU fund (Figure 7) [3]. In this facility, all process from SRF component inspection to bunker testing except cryomodule assembly is carried out. This facility is operated since October 2016. The floor area is about 2,164m^2 (23,400ft^2), which installs many equipment for FRIB cavity production: CMM measurement system for dimensional check of delivered articles, BCP facility for FRIB cavity processing, ultrapure water system, ultrasound degreasing bath, cold shock system to check welding or dissimilar material welding part (Ti/Stainless), magnetization measurement/demagnetization system, vacuum leak check system, vacuum furnace for cavity hydrogen degassing, robotic high pressure water rinsing (HPR) system, large cleanroom, class 10 cleanroom for cavity assembly/coldmass assembly, cavity vertical test system (three Dewars), 900W liquid helium refrigerator, 5000L liquid helium storage Dewar, HWR coupler RF condition system, and one bunker test system. Figure 8 shows several photos of these equipment. FRIB unique equipment will be the robotic HPR system, which is full automatized system for high pressure water rinsing and can reduce labour a lot. The refrigerator takes care both vertical cavity test (VTA) and cryomodule bunker test, which gives us very convenience. The VTA is done 4 times per week [4].

Table 2: FRIB Cryomodule Production Status

Type	Coldmass completed	Cryomodule assembled	Cryomodule bunker tested	Cryomodule placed in tunnel	Cryomodule Scope (T + P)
β = 0.041	4	4	3	3	3+1
β = 0.085	7	5	4	4	11+1
β = 0.085 Matching	1	1	1		1+1
β = 0.29	2	1			12
β = 0.53	2	1	1	1	18
β = 0.53 Maching	0				1
Total	16	12	9	8	46+3

Figure 6: β = 0.041 CMs after installation and alignment in the FRIB tunnel.

Figure 7: SRF Highbay for FRIB cavity production.

Figure 8: Many cavity production equipment in the SRF Highbay. A: CMM machine to dimensional inspection, B: Vacuum furnace for hydrogen degas-sing, C: BCP facility, D: Robotic HPR system, E: Large cleanroom, F: Class 10 cavity assembly clean-room, G: Cavity vertical test system, H: Dedicated 900W liquid helium refrigerator and 5000L storage Dewar.

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CAVITY PROCESS AND TEST STATUS

Cavity Processing

FRIB has received and accepted over 240 cavities as of early July 2017.208 cavities of them have been certified and the rest are in the work flow. Figure 9 shows a view of the cavity processing with the BCP facility in the SRF highbay, in which a 0.041QWR is under processing. FRIB cavities are bulk etched by minimum 120 μm using the acid consisted of HF: HNO_3: H_3PO_4 = 1: 1: 2 in volume ratio (BCP) after the degreasing with MICRO90 2%, and then hydrogen degassed at 700^{O}C for 10 hr (Jab recipe) [5]. According to the cavity frequency, the amount of light etching is decided. After the light etching, the cavity is HPR rinsed with ultrapure water for 2.5 - 3 hours. After drying the cavity in class 10 cleanroom, it is assembled for VTA. FRIB QA for particle contamination is to measure the particle count at the cavity flange [6], which well works as the QA control.

Vertical Cavity Test

All FRIB cavities will be certified by VTA cavity test. VTA cavity test information is reported in this conference [4]. After the cavity assembly and vacuum leak check, it is vacuum evacuated ~ 10^{-8} Torr by an oil-free turbo molecular pump and oil-free scroll pump (no baking). The cavity is moved to the VTA mezzanine and prepared VTA testing: attaching temperature sensors, connection to the cavity jacket to liquid helium header, MIL wrapping, and so on. Liquid helium is put into the space between cavity and the jacket through the top header. Figure 10 shows various FRIB cavities hanged in the VTA mezzanine. During cold testing, cavity is vacuum evacuated. The vacuum level is several x 10^{-9} Torr typically. The test is performed both at 4 K and 2 K. Every cavity has two multipacting barriers at very low field (acceleration gap area) and at several MV/m depending cavity shape (two-point MP), typically 2.5 - 3.5 MV/m for HWRs. Usually it takes 1 – 4 hours to process out the MP barriers at 4 K processing. After the MP processing, high field measurement takes place at 4 K, and then pumped down to 2 K. When MP appeared at 2 K, MP condition is performed again. Figure 11 (in next page) shows FRIB cavity performance. Field emission (FE) is not a major issue at least up to the FRIB operation gradient 5~

Figure 9: View of BCP processing in the chemi room in SRF highbay.

Figure 10: Various FRIB cavities hanged in the VTA mezzanine.

8 MV/m. However, the high field Q-slope (w/o X-ray) appears at > 8 MV/m, which is observed commonly in BCP'ed cavities.

Figure 12 shows the current status of FRIB cavity work. So far FRIB completed certification for all 0.041QWRs. 70 for 0.085QWRs (88 required in FRIB) were tested and 69 were certified and only one is unusable. 88% of 0.085QWR cavity work has been done. 72 0. 29HWRs are needed for FRIB. 69 cavities were tested and 68 were certified. Only one cavity is unusable. The overall in-house rework rate is less than 20% for those three families. The rework rate is a little bit high with 0.53HWRs but expected to increase to the planned rate (80%) as processing issues was resolved as described below.

0.53HWR Rework Issue

0.53HWR was processed by the same recipe as the 0.53HWR preproduction cavities, however the rework is frequently required due to FE or unacceptable cavity frequency. The FE issue was in the robotic HPR program in which water jet did not fully hit all SRF surface. The rinsing program was improved and the issue was almost mitigated.

The cavity frequency control issue is in our narrow frequency control rang of ±10 kHz. Frequency shift in each

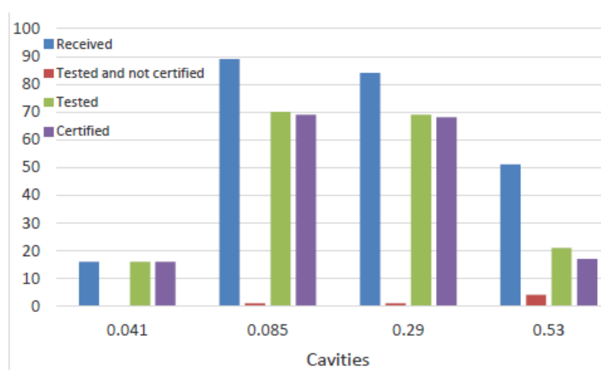

Figure 12: Status of FRIB cavity works.

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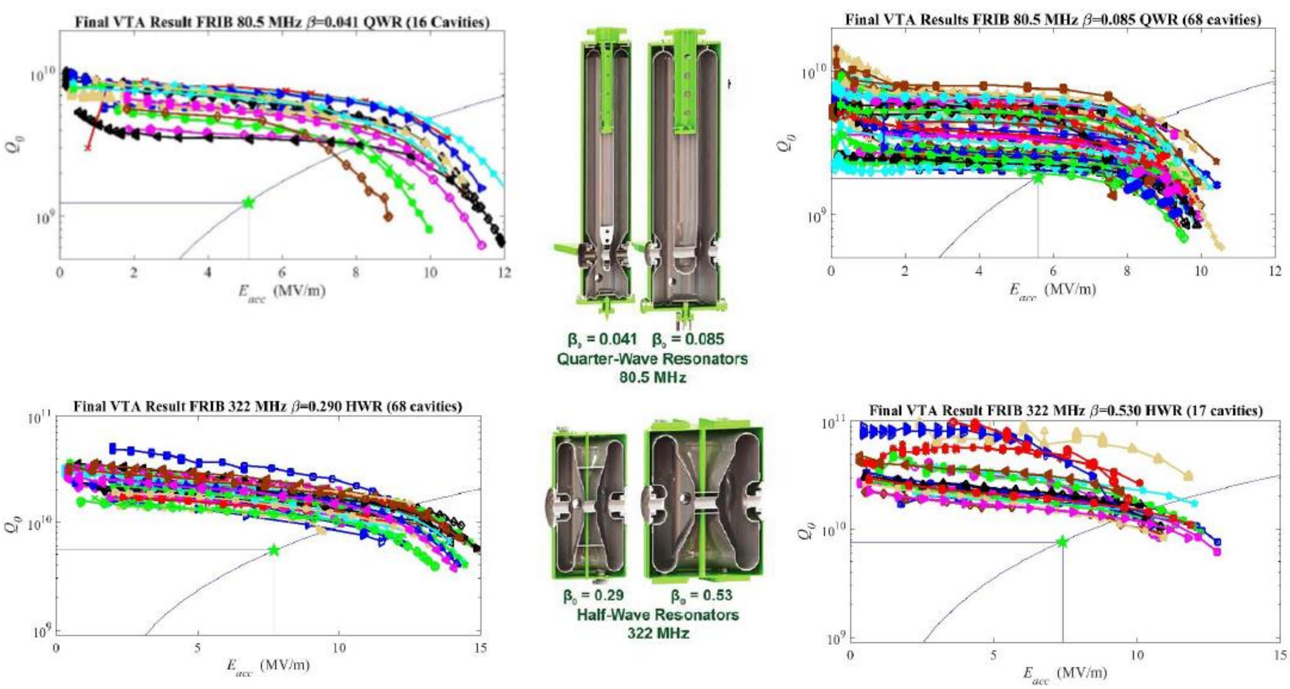

Figure 11: FRIB VTA cavity performance at 2K.

process is collected the statistics and will feedback more precisely.

Low Q Issue with 0.085QWRs

As seen in Figure 11, 0.085QWR production cavities scattered widely in Q_O and the margin is tight for FRIB goal in several cavities. All cavity families were prototyped and validated the performance prior to the mass production. In this prototyping, the 0.085QWRs showed the high Q and high gradient performance. This low Q issue was developed in the production cavities. FRIB investigated and finally resolved this issue by re-torqueing the cavity bottom flange screws prior to VTA [4].

Certified Cavity Storage Procedure Verified

Many 0.29HWRs have certified in advance coldmass assembly. These cavities are bagged in the cleanroom venting particle-free clean nitrogen gas, and then stored in wooden crates on the shelf in SRF highbay. 3 cavities of them stored for > 1 month were retested to verify the storage method. Some case showed a little lower FE onset as seen in Figure 13, however the performance was very similar before/after the storage. FRIB decided to coldmass assemble the stored cavities without any processing, for instance HPR.

HWR COUPLER

MPF Coupler

FRIB has designed multipacting free coupler (MPF coupler) for HWR cavities [7]. FRIB has finally selected this design by the prototypin6and successful integration test with cavity.

FRIB has challenged “assembly ready delivery” on MPF coupler procurement, which means the vendor fabricates

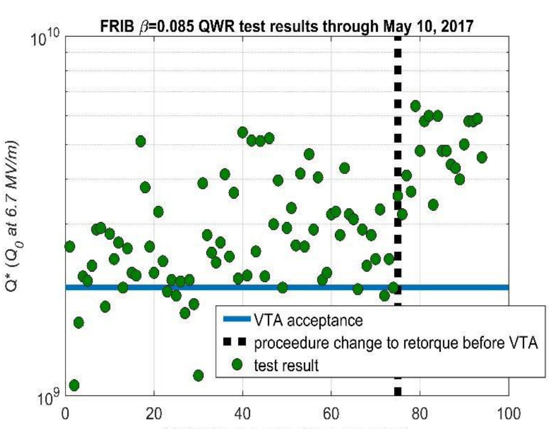

Figure 12: Reliable high Q performance after re-torqueing started.

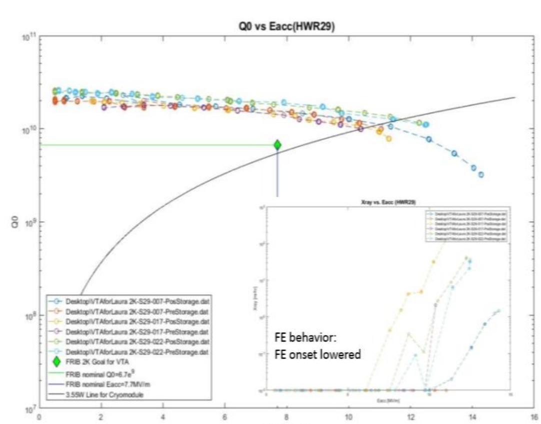

Figure 13: Verification of the storage method.

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couplers and makes RF conditioning at vendor site and delivers to FRIB, FRIB mounts the coupler directly to cavity

Table 3: Cryomodule Alignment Survey Results

Module	Resonator		Solenoid	
	Horizontal RMS/Max Error (mm)	Vertical RMS/Max Error (mm)	Horizontal RMS/Max Error (mm)	Vertical RMS/Max Error (mm)
β=0.041 (4)	0.12/0.26	0.19/0.52	0.12/0.26	0.05/0.13
β=0.085 (6)	0.23/0.53	0.25/0.72	0.16/0.37	0.15/0.43
β=0.29 (1)	0.10/0.17	0.09/0.16	0.19/0.19	0.05/0.05
β=0.53 (1)	0.27/0.81	0.32/0.71	0.18/0.18	0.26/0.26
M β=0.085 (1)	0.07/0.15	0.07/0.13	-	-

* Cool down error is projected to be <0.33 mm

on the coldmass without any processing. If this approach is successful, FRIB can make a reliable schedule and save labour. FRIB send RF conditioning system to the vendor for this approach. FRIB validation program for this procurement strategy was: vendor performs high power RF conditioning (20 kW at 20 % duty cycle), FRIB reconditions FPCs after received to verify shipping method, total reprocessing time should be less than 30 hours (defined by ramping speeds of RF power and duty cycle).

However a contamination issue was discovered by the shipping cap (Figure 14), which needs to hermetic seal the vented nitrogen gas inside coupler. FRIB collaborated with the vendor to improving shipping fixture and decontaminate the couplers. Total 16 FPCs with various contamination and cleaning/transportation histories were reconditioned successfully at FRIB. So far the vendor completed 138 couplers and FRIB received 134. The procurement strategy will be verified by end of 2017.

HWR Cryomodule Test

The first MPF coupler delivery could not meet FRIB cryomodule production schedule. The preproduction coupler with original baseline design were mounted on the first 0.53HWR cryomodule (SCM501) cavities. Actually the MPF couplers begun to mount on the next HWR cryomodules (SCM201), which is under testing.

The preproduction couplers showed a heating (80 ~120 ^{O}C) on the outer conductor due to strong multipacting at the RF conditioning on the benchmark at FRIB [8]. Eight

Figure 14: MPF coupler on left, shipping cap in middle, and contamination on the ICF flange by HDPE on right.

preproduction FPCs were mounted on the SCM501 cavities. In the bunker test of the SCM501, FPCs encountered strong multipacting at wide power range. Multipacting RF conditioning took a long time (several days). Finally bias voltage (-1 kV) was applied to FPC inner conductor to suppress MP, which was very successful.

FRIB CRYOMODULE

FRIB Cryomodule Design

FRIB completed the all six cryomodule designs. The design information is in the reference [9]. FRIB linac requires a tight alignment tolerance < 1 mm vertically. The FRIB cryomodule design feature is in the bottom up assembly concept. This design provides several benefits not only alignment but also easy cryomodule assembly:

1) Rigid baseplate provides stable and reliable platform for the coldmass.
2) Alignment of clod string is achieved by control stack tolerance of coldmass and baseplate.
3) Average time spent on alignment will be within 3 days.
4) Using solenoid adjustment feature to reduce the alignment error to < 0.5 mm max.

Figure 15 shows the coldmass design for all FRIB six cryomodule families. Figure 16 shows the coldmass supports, which can slid during cooling down according to the thermal shrinkage of the coldmass alignment rail. Table 3 shows the measured CM alignment survey results. Cool down error is expected to be torolated less tan 0.33 mm.

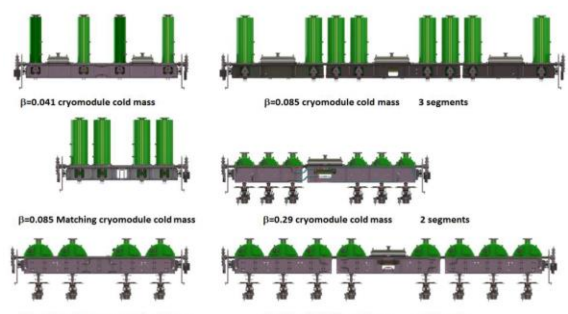

Figure 15: coldmass designs for FRIB cryomodule.

Coldmass Assembly

Coldmasses are assmbled in the cleanroom in the SRF higbay. Cavities are vented with particle-free pure nitrogen

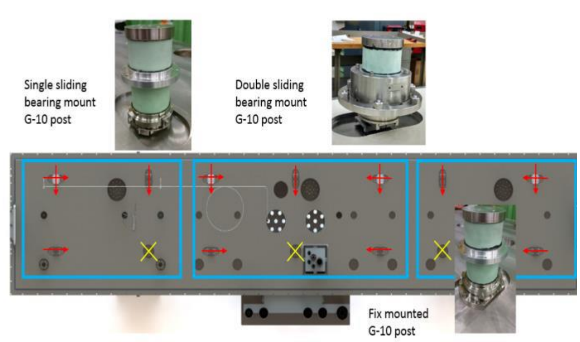

Figure 16: Coldmass support design.

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gas after VTA test. The particle contamination QA control is made by the particle count on the flanges prior to the connection [6]. The cavity degradation is not seen between the VTA result and bunker test as dicrived later. The high Q performance is conserved after the coldmass assembly. Field emission is not major problem in the bunker test.

Cryomodule Assembly

FRIB makes full in-house cryomodule assembly in MSU campus [10]. Five cryomodule assembly bays are secured in NSCL East/North Highbay building. Figure 17 shows the four bays secured in the East highbay. The 5th bay is located at the North high bay just nearby the East Highbay. Figure 18 shows a view of CM assembly. The detail FRIB

Figure 17: FRIB cryomodule assembly bays secured in NSCL East highbay.

Figure 18: Cryomodule assembly view.

cryomodule assembly is reported in this conference [10]. The module production rate is one CM/month. So far 12 cryomodules have been built.

BUNKER TEST

FRIB has two bunker test systems: ReA6 bunker and SRF highbay (Figure 19). ReA6 bunker became operational since May 2016 and SRF highbay bunker since October 2016. Figure 20 shows our bunker test procedure. The streamline production cryomodule testing rate is one module per one month including installation and removal on the latest couple test. So far we have completed bunker test 9 cryomodules of 46 total. All meet FRIB requirements. The detailed bunker test result is reported in this conference [4].

Figure 19: FRIB cryomodule bunker test systems. Left ReA6 bunker, right SRF Highbay bunker.

Figure 21 shows an example of 4 K high power test with SCM501. FRIB operation gradient goal 7.4 MV/m could reach within the acceptable RF power level (4 kW without beam). The cavity RF locking test was successful at 4K for > 1 hr: cavity bandwidth (30Hz), phase and amplitude stability (< 20 for phase, < 2% peak to peak for amplitude). The 2 K dynamic load of the 8 cavities at 2 K is 33W and has a 30 W margin against FRIB spec. Cavity performance has no degradation from the VTA performance. After degaussing of solenoid package and thermal cycle, the high performance has still not changed.

8 T solenoid packages vendor produces are very robust for full field operation (4 K). Solenoid package/cavities integrated operation is very successful for > 1 hr. The static heat load was 6.0W (spec. 6.3W) for 2 K cavity header and 12.3 W (spec. 16.1W) for 4 K solenoid header. Both were within FRIB specification.

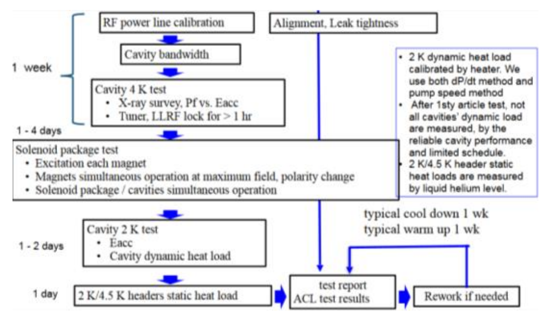

Figure 20: Bunker test procedure.

SUMMARY

FRIB all cryomodule design have been completed and validated. SRF infrastructure established and fully operational to support cavity processing and cold mass assembly. FRIB LS1 cryomodule production is on track to be completed in 2017. FRIB HWR cryomodule production is ramping up. Cryomodule tunnel installation started.

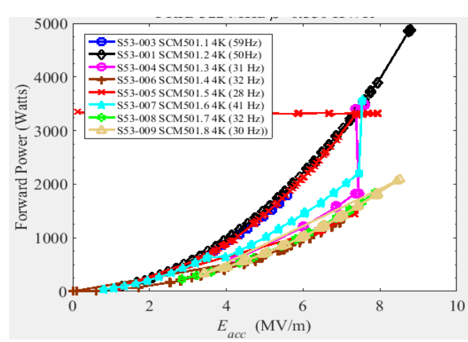

Figure 21: High power test result with SCM501, 0.53HWR cavities.

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