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FRIB DRIVER LINAC INTEGRATION TO BE READY FOR PHASED BEAM COMMISSIONING*

H. Ao†, S. Beher, N.K. Bultman, F. Casagrande, C. Compton, J. Curtin, K.D. Davidson, K. Elliott, V. Ganni, A. Ganshyn, P.E. Gibson, I. Grender, W. Hartung, L. Hodges, K. Holland, A. Hussain, M. Ikegami, S. Jones, P. Knudsen, S.M. Lidia, G. Machicoane, S.J. Miller, D.G. Morris, P. N. Ostroumov, J.T. Popielarski, L. Popielarski, J. Priller, T. Russo, K. Saito, S. Stanley, D.R. Victory, X. Wang, J. Wei, M. Xu, T. Xu, Y. Yamazaki, S. Zhao
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA
A. Facco, INFN - Laboratori Nazionali di Legnaro, Legnaro, Italy
R.E. Laxdal, TRIUMF, Vancouver B.C., Canada

Abstract

The driver linac for the Facility for Rare Isotope Beams (FRIB) will accelerate all stable ion beams from proton to uranium beyond 200 MeV/u with beam powers up to 400 kW. The linac currently consists of 104 superconducting quarter-wave resonators (QWR), which is the world largest number of low-beta superconducting radio-frequency (SRF) cavities operating at an accelerator facility. The first 3 QWR cryomodules (CM) (β = 0.041) were successfully integrated with cryogenics and other support systems for the second Accelerator Readiness Review (ARR) in May 2018. The third ARR (ARR3) devices that includes 11 QWR CM (β=0.085) and 1 QWR matching CM (β=0.085) was commissioned on schedule by January 2019. We examine key factors to the successful commissioning, such as component testing prior to system integration, assessment steps of system and device readiness, and phased commissioning. This paper also reports on the current progress on β=0.29 and 0.53 CMs in preparation for the upcoming ARR4 beam commissioning.

INTRODUCTION

Facility for Rare Isotope Beams (FRIB) is a new joint project for a nuclear science facility funded by the Department of Energy (DOE) Office of Science, Michigan State University, and the State of Michigan. The FRIB driver linac will accelerate all stable ion beams from proton to uranium beyond 200 MeV/u with beam powers up to 400 kW. The linac currently consists of 104 superconducting quarter-wave resonators (QWR), which is the largest number of low-beta SRF cavities operating at an accelerator facility in the world [1]. Ion beams (Ne, Ar, Kr, and Xe) were accelerated by cryomodule (CM) 1-14 up to 20.3 MeV/u [2].

FRIB implemented a phased Accelerator Readiness Review (ARR) process to support commissioning (see Table 1). Each commissioning step was preceded by an ARR [3]. Three of seven planned ARRs have been conducted so far. ARR2 was the first SRF commissioning with three β = 0.041 QWR CMs. The systems and devices of ARR3 scope that includes 11 QWR CM (β=0.085) and 1 QWR matching CM (β=0.085) were successfully installed and commissioned on schedule by January 2019 to support ARR3 beam commissioning (see Fig. 1).

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†ao@frib.msu.edu.

Table 1: Phased Beam Commissioning of the FRIB Accelerator

Phase	Area with beam	Energy MeV/u	Date
ARR1	Front end	0.5	7/2017
ARR2	+ LS1 β=0.041 CM	2	5/2018
ARR3	+ LS1 β=0.085 CM	20	2/2019
ARR4	+ LS2 β=0.29, 0.53CM	200	3/2020
ARR5	+ LS3 β=0.53 CM	>200	12/2020
ARR6	+ target and beam dump	-	9/2021
Final	Integration with pre-existing facility	-	6/2022

This paper describes our approach to the phased commissioning from a hardware installation standpoint especially for the SRF system. We examine key factors to the successful system integration to support the beam commissioning including review processes. Finally, we will show our installation progress toward next ARR4 beam commissioning.

INTEGRATE SYSTEMS TO MEET PROJECT MILESTONES

Prototype, Testing, and Validation

Prototype, testing, and validation - these three steps are fundamental engineering approach to develop new systems and devices. Accelerators are highly complex system. Typically, many groups develop each device, e.g. cryomodules, cryogenics, RF, power supplies, diagnostics, controls, vacuum etc., in parallel. To realize prototype, testing, and validation for an integrated accelerator system in early stage is essential to the success of the project especially for large-scale accelerators.

Completed FRIB CMs undergo full system testing in bunkers before being accepted and delivered to the tunnel. There are two test bunkers: one is located in the ReA6 high bay and other is in the SRF high bay (see Fig. 2).

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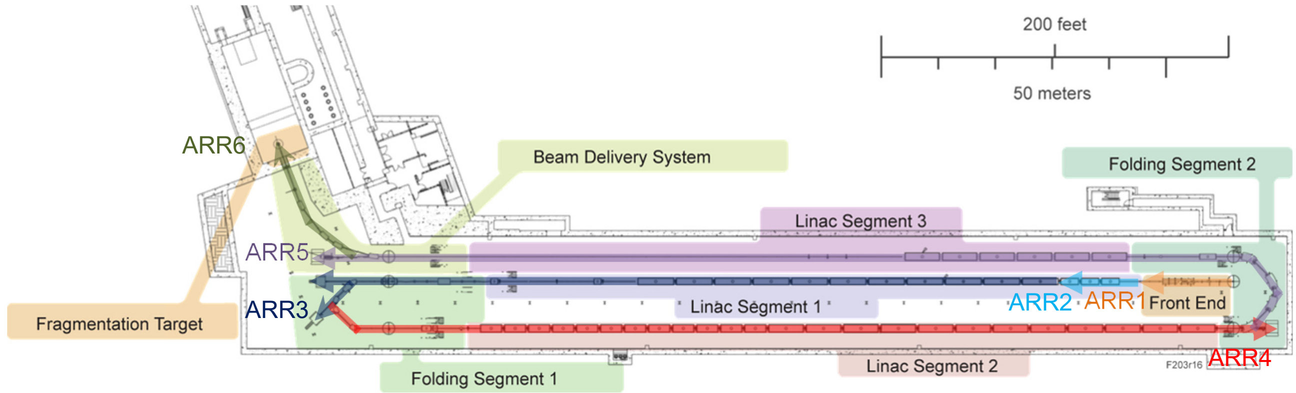

Figure 1: Schematic layout of the FRIB driver linac. Ion beams go through from Front End, Linac Segment 1 (LS1), Folding Segment 1 (FS1), LS2, FS2, LS3, and Beam Delivery system (BDS) to Fragmentation Target. From Front End to LS1 and a part of FS1. Ion beams have so far been accelerated and transported to the beam dumps in FS1 (ARR3 area). The next focus will be on LS2 to accelerate and deliver the beam to the beam dump in FS2 (ARR4 area).

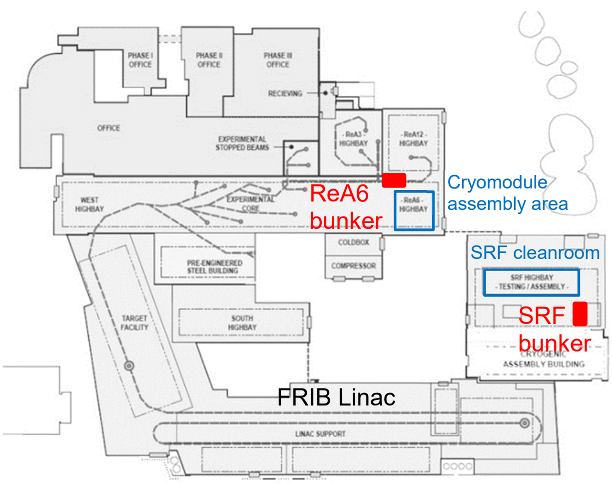

Figure 2: Cryomodule test bunkers in the FRIB site. Completed CMs are fully tested before installation in the FRIB tunnel.

The ReA6 bunker that was set up first to validate a FRIB prototype CM gave us a good opportunity to realize a prototype of the integrated FRIB accelerator system. The bunker is equipped with support systems (RF, magnet power supplies, and controls) that are identical with FRIB ones, so that it could demonstrate CM operation in the FRIB tunnel as the minimum integrated system. The cryogenic transfer line in the ReA6 bunker was built as a prototype of the FRIB, which has the same mechanical interface between the CM and the cryogenics in the FRIB tunnel. Installation and placement of the CM was also checked during the installation into the bunker simulating the FRIB tunnel condition [4].

The support systems of the ReA6 bunker and the first prototype CM were successfully tested in 2015 before starting CM production and system installation in the FRIB building [5]. The results provided confidence in the system and device designs and early feedback for improvements.

The bunker testing is also useful as a test bench to improve and optimize the test and operating procedures for cavities and solenoids. Any farmware update of the LLRF system will only be deployed to the FRIB LLRF systems after being validated in the bunker. The FRIB alarms and interlocks are designed based on the latest configuration of the bunker.

Scaling up: Small to Larger System

It is also important to start from small rather than large for developing a new system. The FRIB SRF system has been scaled up according to the phased commissioning plan.

Table 2 shows the number of cavities and solenoids required to each commissioning phase. ARR2 was the first SRF commissioning in the tunnel with 3 β=0.041 CMs (1-3) [6, 7]. The goal of the system installation at ARR2 was to duplicate the bunker system in the FRIB building and tunnel. ARR3 introduced additional 11 β=0.085 CM (4-14) and 1 β=0.085 matching CM (15). The goal at ARR3 was to expand the SRF system to 12 more CMs.

Table 2: Commissioning Phase vs. Total Number of Cryomodules, Cavities, and Superconducting Solenoids

Phase	Cryomodules	Cavity (in FRIB total)	Solenoid
ARR2	β=0.041 (1-3)	12	6
ARR3	+ β=0.085 (4-15)	104	39
ARR4	+ β=0.29, 0.53 (16-39)	272	63
ARR5	+ β=0.53 (40-47)	324	69

Previous experience installing and commissioning the SRF system is beneficial to determine the schedule and forecast for the next commissioning step. Cavity locking issues occurred in β=0.041 QWRs were resolved by optimizing valve controls logic and reducing helium supply pressure during ARR2 commissioning. At ARR3 β=0.085 QWRs commissioning proceeded at a rate of approximately 1 CM per day. Finally, all β=0.041 and 0.085 cavities were turned on and ready for beam in less than 30 minutes [8].

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ARR4 requires 12 β=0.29 CM (16-27) and 12 β=0.53 CM (28-39) additionally. By leveraging accumulated knowledge and experiences, we are moving forward to meet the requirement.

Assessment Steps of System/Device Readiness

Each ARR is preceded by a device readiness review (DRR) of subsystems (see Fig. 3). The DRR consists of two parts: the Device Hazard Review (DHR) and the Device Operational Review (DOR). The DHRs are conducted before major integrated testing (e.g. CM cool down and high-power RF testing) and used to assure that hazards have been identified and mitigated. The DORs are conducted before ARRs and used to assure that procedures and trained personnel are in place to support the beam commissioning. A set of several DHRs and a DOR functions as a DRR. The Laboratory Director grants approval for each review upon recommendation from the chief engineer.

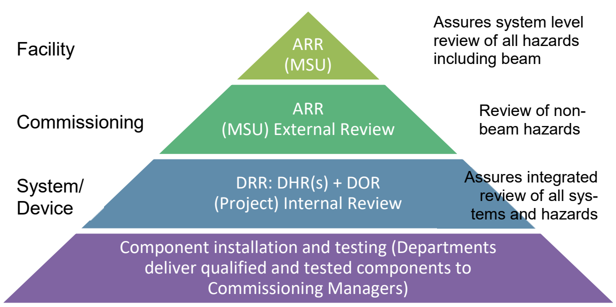

Figure 3: Assessment steps of system/device readiness. ARRs build on previous reviews and component testing with ESH approach.

The date of DHR/DOR serves as a due date for the component installation and testing. All devices and systems in a specified beam line area must be ready for the integrated testing and meet the DHR criteria before the DHR, which practically expedites installation tasks and component testing area by area.

The internal reviews must be meaningful to move forward with device installation and integrated testing. The DHR/DOR criteria defined at the laboratory level need to be updated and optimized flexibly through discussion.

TOWARD ARR4 COMMISSIONING

Figure 4 shows the current state of the FRIB beam line from FS1 to LS2 where the beam goes through during ARR4 beam commissioning. All FS1 magnets and beam line vacuum chambers are installed. The magnet power supplies and the controls are also installed in the rack room at ground level, so that the next step is to connect DC cables to the magnets, and then interlock testing, and final alignment survey.

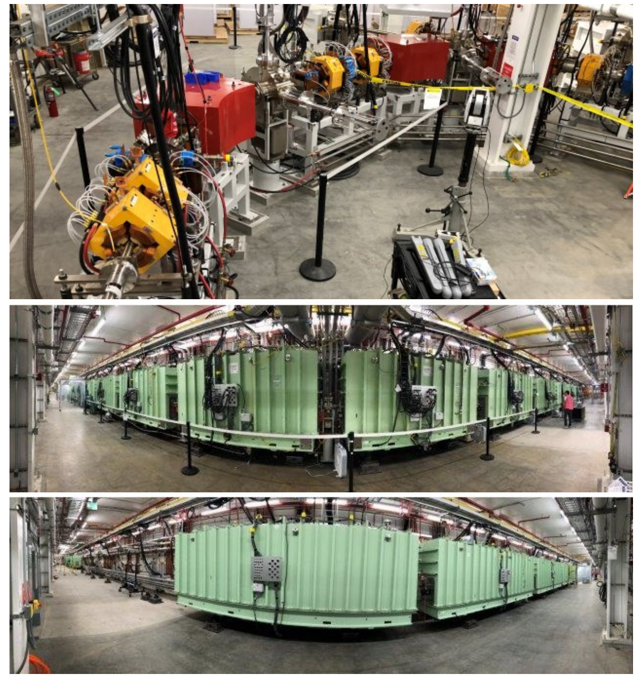

Figure 4: Installation progress in the tunnel. (Top) FS1 bending section, (Middle) LS2 12 β=0.29 CMs cooled down and being ready for RF testing, (Bottom) LS2 1 β=0.53 CM is cold and 6 are under preparation for cool down.

The LS2 CM installation and cool down are progressing. Currently, 21 of 24 CMs are installed on the beam line, and 13 of 24 CMs are at 4K. The LS2 SRF half-wave resonators (HWR), β=0.29 and 0.53, will operate at a frequency of 322 MHz and a temperature at 2K. RF coaxial lines are being installed in the tunnel to be ready for energizing cavities. Controls installation is continuing in the rack room for remaining CMs, six β=0.53 CMs are under preparation for the next cool down.

All LS2 CMs (24 in total) will be placed on the beam line by the end of October 2019. The final cool down is scheduled in November 2019. The SRF cavity commissioning will start from January 2020.

SUMMARY

To verify systems and devices in early stage is essential to the success of the project. We began from the bunker test to validate the prototype CM as well as the minimum integrated system. The phased commissioning plan allows us to start with small system and scale up to larger in the FRIB tunnel. Internal/external reviews make installation and testing process more formalized and expedited.

The accelerator construction is on track according to the phased commissioning plan. Should the installation and integrated testing proceed on schedule, the beam line would be ready for ARR4 beam commissioning in March 2020.

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