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INSTALLATION PROGRESS ON FRIB β = 0.041 CRYOMODULES TOWARD BEAM COMMISSIONING*

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Abstract

The driver linac for the Facility for Rare Isotope Beams (FRIB) is to accelerate all stable ion beams from proton to uranium beyond 200 MeV/u with beam powers up to 400 kW. After the first Accelerator Readiness Review (ARR01) in July 2017, beam commissioning of the radio-frequency quadrupole began, and then the beams of $^{40}Ar^{9+}$ and $^{86}Kr^{17+}$ were successfully accelerated to 0.5 MeV/u. ARR02 will be held prior to beam commissioning of the first three superconducting quarter-wave resonator cryomodules (β = 0.041) and the diagnostic station. The next commissioning step is to accelerate $^{40}Ar^{9+}$ and $^{86}Kr^{17+}$ through the cryomodules to 1.46 MeV/u. All beam line devices and support systems are installed, and we are preparing to cool down the cryomodules. We are planning for ARR02 in May 2018 and cryomodule beam commissioning in July 2018.

INTRODUCTION

FRIB is a new joint project for a nuclear science facility funded by the DOE Office of Science, Michigan State University, and the State of Michigan [1]. The FRIB driver linac will accelerate stable ion beams (from protons to uranium) to energies > 200 MeV/u, and at continuous wave beam power up to 400 kW, requiring full utilization of four types of superconducting radio-frequency (SRF) cavities after the RFQ [2].

The room temperature electron cyclotron resonance ion source (RT ECR IS) was first operated in October 2016. ARR01 was held in July 2017 to assess the readiness to commission the Front End (FE). Beams commissioning of the RFQ began in September 2017. After that, beams of $^{40}Ar^{9+}$ at 40 eμA and $^{86}Kr^{17+}$ at 26 eμA were accelerated to 0.5 MeV/u, exceeding the key performance parameters [3].

As shown Fig. 1, ARR02 beam commissioning includes the three β = 0.041 cryomodules (CMs) and the diagnostic station (D-station) in Linac Segment 1 (LS1). The three CMs accelerate $^{40}Ar^{9+}$ and $^{86}Kr^{17+}$ to 1.46 MeV/u. This will be the first beam accelerated by FRIB cryomodules and also the first integrated operation of cryomodules with the FRIB cryogenic system and support systems.

This paper describes the installation progress of the β = 0.041 CMs, including support systems, and plans for ARR02.

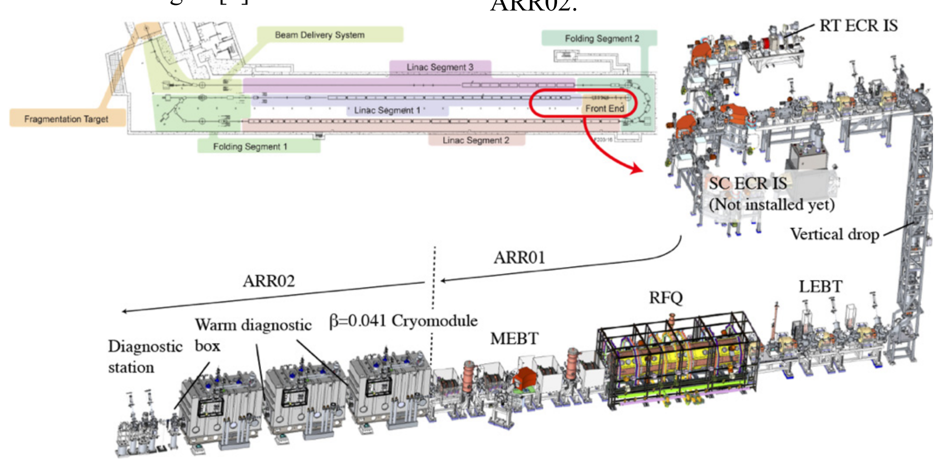

Figure 1: Scope of ARR02 beam commissioning, including the Front End (ion source to Medium Energy Beam Transport, MEBT), β = 0.041 cryomodules, and diagnostic station.

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INSTALLATION PROGRESS

Cryomodules and Beam Line Devices

Each β = 0.041 CM includes four quarter wave resonators (QWRs, 80.5 MHz), two superconducting solenoids (8 T, 25 cm), and two cold beam position monitors (BPMs). All of the CMs were cooled down to 2 K, and the performance of the cavities and solenoids was verified before installation. The beam commissioning is planned to be done at 4 K.

During CM assembly, we surveyed and aligned the cavities, solenoids and BPMs, using a laser tracker. We also measured relative positions between the beam line and external fiducials on the CMs. In the tunnel, CMs were aligned using the external fiducials (see Fig. 2). Maximum misalignments relative to the beam line (in mm) were Δx = 0.39, Δy = 0.42, Δz = 0.73 for the cavities and Δx = 0.20, Δy = 0.05, Δz = 0.36 for the solenoids. These were within the requirement of $\pm\sigma$=0.5, where σ is the standard deviation.

Figure 2: β = 0.041 cryomodules installed on beam line.

Each warm diagnostic box includes one BPM and one halo monitor ring (HMR). The chamber and monitors were assembled and leak checked in a Class 100 clean room, and then installed into the beam line in a temporary clean room (see Fig. 3). The pressures in all three warm boxes met the requirement (< 5E-9 Torr); the D-station pressure is in the mid E-8 Torr and is gradually decreasing.

Figure 3: Left: Installation of a warm diagnostic box between cryomodules. Right: D-station.

As shown in Fig. 4 and described in Table 1, the D-station includes two BPMs, two beam current monitors (BCMs), a profile monitor (PM), a halo monitor ring (HMR), a silicon detector (SiD), and a Faraday cup (FC). D-station will be used for ARR02 commissioning only and will then be replaced with a β = 0.085 CM prior to commissioning of the downstream portion of LS1.

All beam-line-vacuum devices were cleaned, assembled and installed with the same clean-room procedures as the warm diagnostic boxes between the CMs.

The PMs were originally designed for warm sections and hence are not fully compatible with the particulate cleanliness requirements of the SRF linac. Since excessive particle counts were still found after several mitigation efforts, we did particle transport tests to evaluate the risk to the CMs. We decided to install the PMs with stringent pumping and venting procedures to minimize particle migration.

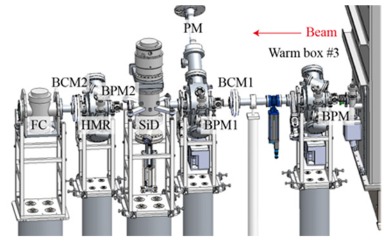

Figure 4: Layout of the D-station.

Table 1: Beam Measurement Plan and Diagnostics (RMS ε = Root-Mean-Squared Beam Emittance)

Measurement	Required diagnostics
Phase scan of 3rd CM QWRs	Two aligned and timing-calibrated BPMs
Transverse RMS ε	Profile monitor (PM)
Longitudinal RMS ε	Silicon detector (SiD)
Transverse beam halo	Halo monitor ring (HMR)
Differential beam current	BCM1 and BCM2
Contaminant fraction	Silicon detector (SiD)

We used a SiD for energy measurements in ReA3 [4]. The SiD includes a ^{228}Th alpha source for energy calibration and provides an energy resolution of approximately 20 keV (FWHM) and a time resolution of approximately 200 ps (FWHM, at vendor).

Cryogenics

The cryogenic plant made its first liquid helium at 4.5 K in November 2017 and 4.5 K refrigerator commissioning was completed in December 2017 [5]. The three cryogenic transfer lines (TL) for LS1, 2, and 3 are independent of one another. The TL for LS1, shown in Fig. 5, feeds the β = 0.041 CMs and downstream CMs. It was installed and successfully pressure-tested. The first cool-down with cold nitrogen was completed; we are preparing for the cool-down with cold helium.

Figure 5: LS1 cryogenic transfer line (viewing the cryomodules from the side opposite that of Fig. 2).

Support Systems

Support systems, including DC power supplies, RF, vacuum, controls, and diagnostics, were installed at the ground

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level (see Fig. 6). All of the hardware is installed, and all of the cables are routed and terminated. Some cables are to be connected to the CMs after cool-down.

Figure 6: Racks for the β = 0.041 cryomodules. Each row of racks corresponds to one cryomodule.

The RF amplifiers were energized and tested up to the design power of 2 kW into the RF transmission lines with a short termination in the tunnel [6]. The control system has been deployed and tested. Control screens were originally developed for the pre-installation cool-down test, and they have been updated for commissioning. Interlocks and alarms have been defined and are partially tested. The full system will be validated through integrated testing after the cool-down.

Global Systems

Global systems, which consists of the Global Timing System (GTS), Machine Protection System (MPS), and Run Permit System (RPS), will be needed for beam commissioning. The GTS was tested during the FE beam commissioning, including chopper operation and beam pulse measurements with a BCM and FC. The MPS and RPS provide a beam-inhibit interlock for the CMs and the D-station by turning off the electrostatic bend, chopper, and ion source extraction high-voltage (see Fig. 7). The MPS will provide an interlock for Programmable Logic Controller (PLC)/ Low-Level RF (LLRF) events at ARR02. Interlocks from the chopper monitor, BCM, and FC will be activated after verification with a low-power beam during commissioning. Until the MPS is tested and fully activated, the beam power will be limited to < 2 W with an attenuator.

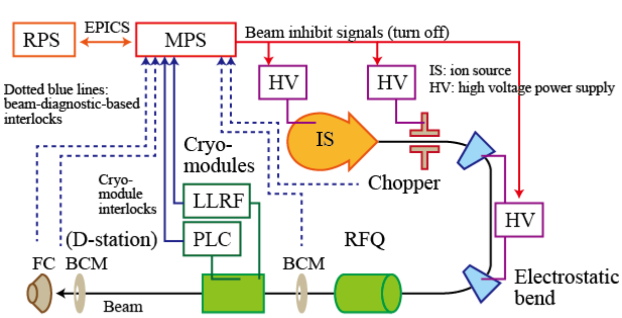

Figure 7: MPS for ARR02.

Personnel Protection System

ARR02 beam commissioning requires two personnel protection systems, as shown in Fig. 8: an oxygen deficiency hazard control system (ODHCS) and an access control system (ACS). The ODHCS mitigates oxygen deficiency hazards due to potential cryogen leaks, and the ACS mitigates radiation hazards due to X-rays from the SRF cavities and neutrons from the beam interaction.

The ODHCS monitors the oxygen concentration in the linac tunnel and alarms to evacuate personnel if it detects a low oxygen level. The system hardware was deployed and validated in March 2018.

The ACS provides RF-inhibit (for the CMs) and beam-inhibit interlocks when the tunnel is unsecured and in the event of an access violation when the tunnel is secured. The system components are installed. The PLC programming and system validation are to be completed shortly.

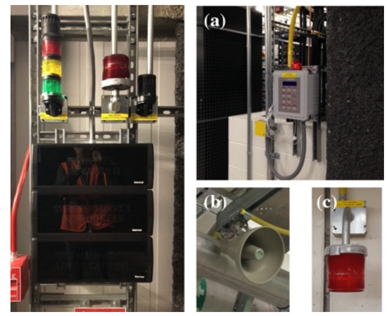

Figure 8: Left: ACS status display. Right: ODHCS (a) oxygen monitor, (b) public address system, (c) warning light.

SUMMARY

We have reported on the installation progress for the FRIB β = 0.041 cryomodules and support systems. These first three cryomodules in the FRIB linac are in the transition from installation to initial beam commissioning. Cooling down the cryomodules in the tunnel and accelerating beam to the downstream diagnostic station will be a significant technical milestone and an opportunity for a realistic test of the integration of the technologies needed for the FRIB driver linac. Preparations for cryomodule cool-down are on track for a readiness review in May 2018 and beam commissioning in July 2018.

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