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FIRST ACCELERATION AT FRIB*

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Abstract

FRIB is now moving to commissioning interleaved with installation. The ECR, low energy transport and RFQ have been commissioned with beam. By the time of the conference the 4K cryogenic system and first three beta 0.041 QWR cryomodules will be commissioned with beam. The talk will focus on hardware and beam performance.

INTRODUCTION

The Facility for Rare Isotope Beams [1] is the premiere DOE-SC national user facility for nuclear physics research built on the campus of Michigan State University. The FRIB driver accelerator will accelerate ions with the mass up to Uranium to energies higher than 200 MeV and beam power on target higher than 400 kW. The main focus of the experimental program is rare isotope beams by fragmentation, gas stopping, and reacceleration.

Project commissioning performance requirements are defined by Key Performance Parameters (KPP) for CD-4:

1. Accelerate Argon beam with the energy larger than 200 Me/u and a beam current larger than 20 pnA
2. Detect 84Se in FRIB separator focal plane. The last KPP requirement for the experimental systems can be translated to the following requirement for the accelerator: accelerate 86Kr beam to produce 84Se by fragmentation.

Phased Beam Commissioning

FRIB has adopted a “paper-clip” design shown in Fig. 1. The FRIB Front End and RFQ are located on the east side of the project site (marked in red). The beam is accelerated in Linac Segment 1 (LS1) through three beta 0.041 (blue) and eleven 0.085 (yellow) 80.5 MHz QWR cryomodules to the energy of approximately 20 MeV/u. A lithium stripper will be installed at the end of LS1. The stripped beam is collimated in first folding segment (FS1) and accelerated by HWRs operating at 325 MHz in linac segments 2 (LS2, green) and 3 (LS3, grey) and sent towards experimental facilities through BDS. Another folding segment FS2 is used between LS2 and LS3 to reduce the footprint of the facility.

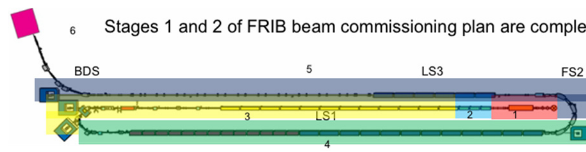

Figure 1: Paper-clip design of the FRIB accelerator. Colors and numbers mark commissioning stages: red - Front End, blue – three beta 0.041 cryomodules, yellow – eleven 0.085 cryomodules and part of FS1, green – LS2, and grey – FS2 and LS3.

FRIB beam commissioning is interleaved with installation and is approached in stages as show in Fig. 1. Commissioning follows installation of linac systems along the beam path starting from the Front End. In this article, we describe commissioning of the Front End, completed earlier in 2018, and the first beam acceleration in the first three beta 0.041 QWR cryomodules demonstrated in July 2018.

HIGHLIGHTS OF TECHNICAL SYSTEMS

Figure 2 shows the layout of the FRIB Front End [2] with the first three beta 0.041 QWR cryomodules and a temporary diagnostics station (D-Station). The front end is located on two levels to allow for maintaining one ion source while the other source is used for the program.

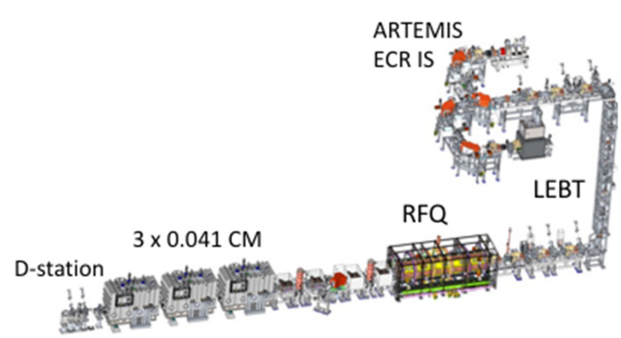

Figure 2: FRIB Front End with the first three 0.041 cryomodules and the temporary diagnostics station.

The front end includes

1. Two ECR sources on High Voltage (HV) platforms. 1) ARTEMIS is a 14 GHz ECR ion source. The source has been installed and commissioned in 2016. 2) The second source is a 28 GHz superconducting (SC) source based on VENUS (LBNL). The superconducting source is under construction, with planned delivery in 2019.

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2. LEBT. The beam energy is 12 keV/u. LEBT includes a chopper, electrostatic quads, and solenoids.
3. 4-vane RFQ accelerating ion beams from 12 keV/u to 500 keV/u
4. MEBT, Beam energy is 500 keV. MEBT includes two RF bunchers and quadrupole magnets.
5. Instrumentation and diagnostics
6. Subsystems powering and otherwise enabling front end components: RF, PS, Vacuum, etc.

The commissioned portion of the SRF linac includes

1. Three beta 0.041 cryomodules separated by warm boxes with diagnostics. The design beam energy after the cryomodules is 1.5 m/eV/u.
2. A temporary diagnostic station (D-Station) to characterize the beam accelerated by SRF cavities. D-Station was installed in place of the first beta 0.085 cryomodule, which temporarily was set aside in the tunnel.

Room Temperature Ion Source ARTEMIS B

ARTEMIS B ECR Ion Source is used for FRIB commissioning. ARTEMIS B is a 14 GHz room-temperature ECR ion source built in 2005 as a development source and a spare for Cyclotron operations. The source is based on the design of AECR-U (LBNL) and is easy to operate and maintain. This approach presents a low-risk, low-cost solution for the linac commissioning.

The source performance easily meets intensity requirements for commissioning. The source demonstrated more than 150 eμA of 40Ar9+ beam, corresponding to a beam power of 150 kW on the production target.

RFQ [3]

The FRIB RFQ is a four-vane brazed structure with a variable cross section and voltage profile. Table 1 shows main RFQ parameters while Fig. 3 shows the fully assembled RFQ in the FRIB tunnel. The RFQ engineering design has been developed at FRIB with important contributions from L. Young and J. Stovall. Detailed thermal analysis was performed by the Tsinghua University under a contract from FRIB. An order to procure the RFQ was placed with an industrial vendor. The RFQ 150 kW tube-based amplifier was developed at MSU.

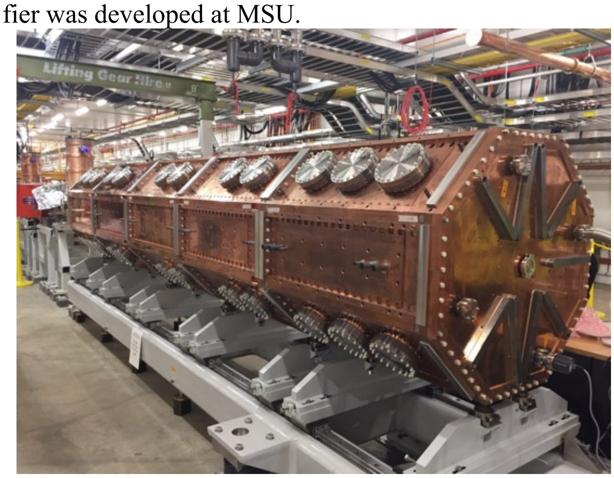

Figure 3: FRIB RFQ in the FRIB tunnel.

Table 1: FRIB RFQ Parameters

Parameter	Value
Frequency, MHz	80.5
Beam energy (Inj/Ext, keV/u)	12/500
Q/A	1/3 – 1/7
Accelerating efficiency	> 80%
CW RF Power (kW, Uranium)	100
Length	5

FRIB RFQ was installed and tuned in the FRIB tunnel in October-November of 2016. Slug tuners were cut to match the required frequency and the voltage profile. The deviation between the measured RFQ field and the target field did not exceed 0.5% after tuning. The frequency correction for the effect of vacuum was implemented, resulting in a frequency error under vacuum of only a few kHz.

The RFQ has been conditioned to 60 kW, sufficient to accelerate KPP beams. At this power, no measurable X-ray radiation above the background level has been detected. The RF amplifier power was limited to 60 kW to allow RFQ operations with personnel present in the tunnel.

Front End Beam Line and Instrumentation

The installation of the beam line was completed in July of 2017. Figure 4 shows LEBT, RFQ, MEBT, and 0.041 cryomodules in the FRIB tunnel.

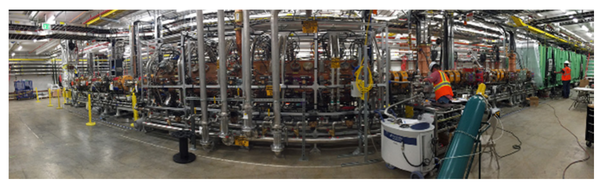

Figure 4: LEBT (left), RFQ (centre), MEBT (right), and 0.041 cryomodules (far right) in the FRIB tunnel.

The front end includes an extensive suite of instrumentation systems, Fig. 5. To start the commissioning, however, only a small subset, consisting of the charge-selection slits, viewers, and Faraday Cups, was used. A 45-degree dipole magnet in MEBT has been used to measure the beam energy of the beam accelerated by the RFQ.

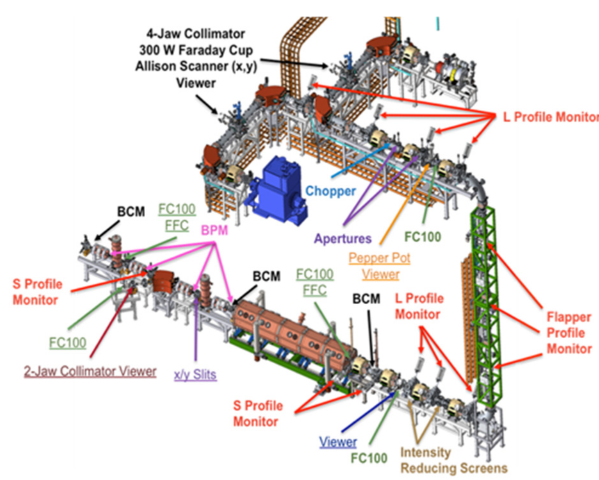

Figure 5: Front End diagnostics.

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Three Beta 0.041 QWR Cryomodules [4, 5]

Linac Segment 1 (LS1) includes three beta 0.041 QWR cryomodules, shown in Fig. 6, and eleven beta 0.085 QWR cryomodules. The 0.041 cryomodules were installed and connected earlier this year. The 0.085 cryomodules with the rest of LS1 will be commissioned in 2019.

Each 0.041 cryomodule includes four QWRs operating at 80.5 MHz and two superconducting solenoids with dipole correctors. The 0.041 resonators were operated in the CW regime at 4K. Eventually, the cavities will be operated at 2K following the staged commissioning of the cryoplant. More details about cryomodule design can be found in [4].

The cryo distribution lines were cooled down in April of 2018 and the cryomodules were cooled down to 4K in the middle of May 2018. All the cavities were conditioned to the nominal field of 5.1 MV/m within a week.

Figure 6: Thee beta 0.041 cryomodules with the D-Station.

D-Station

A temporary diagnostics station (Fig. 7) was installed in place of the first beta 0.085 QWR cryomodule with a goal to fully characterise the beam parameters after the 0.041 cryomodules and before commissioning the rest of the linac. D-Station included the following diagnostics:

- Two BPMs
- Two ACCTs
- Faraday cup
- Profile monitor
- Silicon detector
- Halo monitor Rings with current readout

The components installed in D-Station were temporarily repurposed from other accelerator areas.

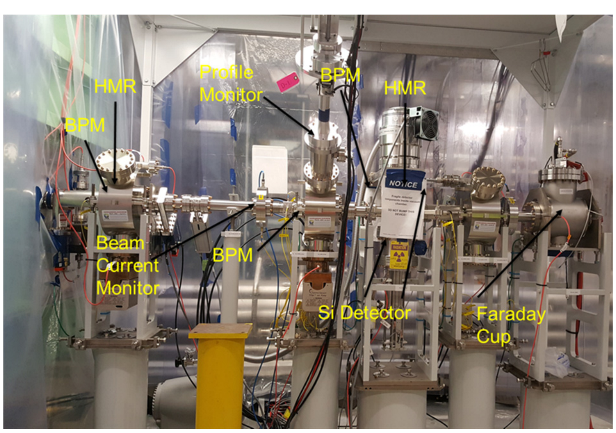

Figure 7: D-Station with its subsystems.

ACCELERATOR READINESS REVIEW PROCESS

FRIB conducts Device Readiness Reviews to assess hardware readiness and authorize a start of integrated testing. The reviews are typically internal unless external expertise is required.

Accelerator Readiness Reviews (ARR) assess readiness of accelerator for beam commissioning. ARRs review system and documentation readiness, people readiness, hardware readiness (see Table 2).

Table 3: ARR Scope, Dates, and Status

Review/ Stage	Scope	Date	Status
ARR1	Front End	7/2017	Complete
ARR2	0.041 CM	5/2018	Complete
ARR3	0.085 CM, LS1	2/2019	Planned
ARR4	FS1, LS2	4/2020	Planned
ARR5	FS2, LS3	9/2020	Planned

COMMISSIONING RESULTS

Front End Commissioning [2]

LEBT was commissioned with the beam in Spring and Summer of 2017 as new sections of LEBT were added. The beam was transported with nearly 100% requiring little tuning. This indicated a good agreement between the machine and its model and good alignment of beam line components.

The beam emittance and Twiss parameters were measured after the ion source using Alison scanners. The measured r.m.s. emittance of the Argon beam was 0.056 mm*mrad and 0.5 mm*mrad in horizontal and vertical planes respectively. This result was in a good agreement with simulations.

The measured Twiss parameters were used to improve beam matching to LEBT. After these adjustments, the measured beam transport agreed well with simulations. Figure 8 shows the beam profile measured by viewers along LEBT (upper row) compared to simulated profile at same locations (lower row). The measured and simulated profiles are in good qualitative and quantitative agreement.

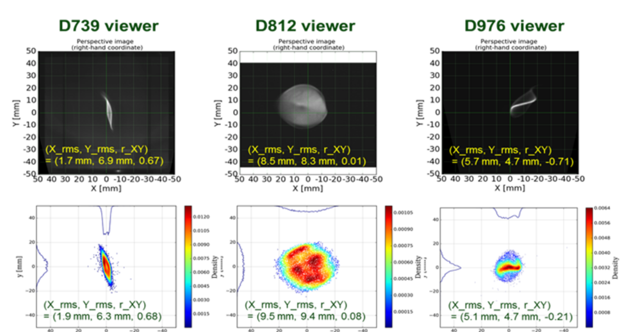

Figure 8: Measured (upper row) and simulated (lower row) beam profiles at LEBT viewers show a good agreement.

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In September of 2017, after ARR01, Argon beam was accelerated through RFQ. Initially, the multi-harmonic buncher in front of the RFQ was kept off. The measured acceleration efficiency was 31%. The accelerated current readings measured by the Faraday cup in the straight section and the Faraday cup after the 45-deg. bend were same, confirming that only the accelerated current was measured. The beam energy measured by the dipole magnet was 500 keV/u. The energy spread did not exceed 1%. In several days, the beam line and the RFQ were retuned and Krypton beam was accelerated producing results nearly identical to those with the Argon beam. Figure 9 shows images of the beam spot on the viewer after the MEBT dipole.

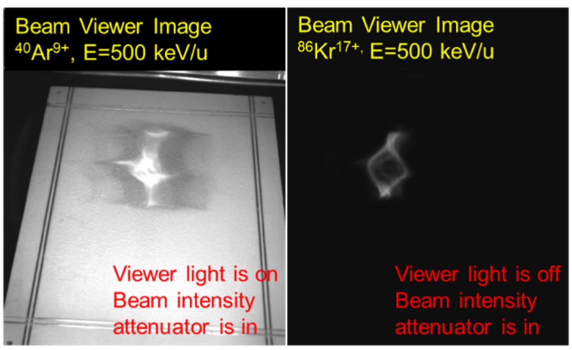

Figure 9: Argon and Krypton beam spots on the viewer situated after the 45-degree bend in MEBT. Beam energy after RFQ is 500 keV/u.

The RFQ acceleration efficiency was measured as a function of the RFQ RF power. Figure 10 shows the measured efficiency and the efficiency simulated by PARMTEQ for 40Ar9+. The two curves nearly overlap. The full transmission efficiency, including non-accelerated current, was measured by two AC current transformers situated on both sides of the RFQ. The measured transmission can reach 100% for good matching. Some degradation of the total transmission efficiency for mismatched beam can be used for beam matching and alignment at the entrance of RFQ.

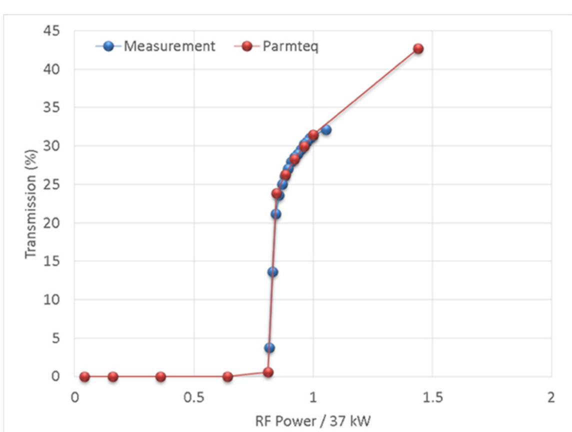

Figure 10: RFQ acceleration efficiency as a function of the RFQ forward power (normalized to 37 kW)

The beam transmission increased to the design value, >80%, with MHB operational. Figure 11 shows the accelerated Ar beam current measured by the FC at the end of MEBT. Krypton beam exhibited very similar behaviour.

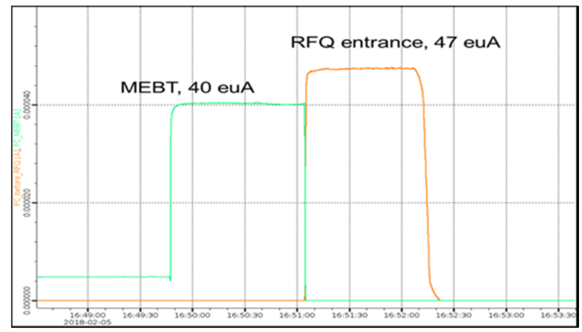

Figure 11: Argon beam current reading from Faraday cups at the entrance of the RFQ and after the RFQ. The transmission efficiency is 86%.

Commissioning of Beta 0.041 Cryomodules

First, the beta 0.041 cryomodules were commissioned with 40Ar9+ beam. Figure 12 shows the measured beam energy as a function of the number of powered cavities. Initially, Cavity 8 exhibited excessive microphonics and was kept off. In this setup, the beam energy reached 2 MeV/u. After the acceleration of Argon, accelerator settings were scaled to accelerate 86Kr17+ beam. The Krypton beam was accelerated to 2 MeV/u with nearly 100% efficiency. After minimal orbit and settings adjustments, the transmission reached 100%. Figure 13 show the beam current measured by ACCTs before the RFQ in LEBT, after RFQ in MEBT, at the exit of MEBT, and in D-Station after the cryomodules. The beam is transported through the RFQ with 100% efficiency but only 80% of the beam is accelerated. The beam accelerated by the RFQ is accelerated further by the cryomodules without losses. Halo monitor rings installed in cryomodules and D-station and sensitive to losses below a nanoamp did not show detectable losses. The lossless transport with minimal tuning and small orbit deviations clearly indicated good alignment of accelerator components and good agreement of between the actual machine and its model.

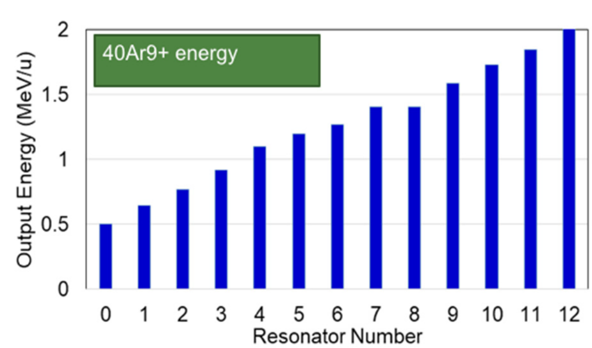

Figure 12: Beam energy after vs the number of energized 0.041 resonators.

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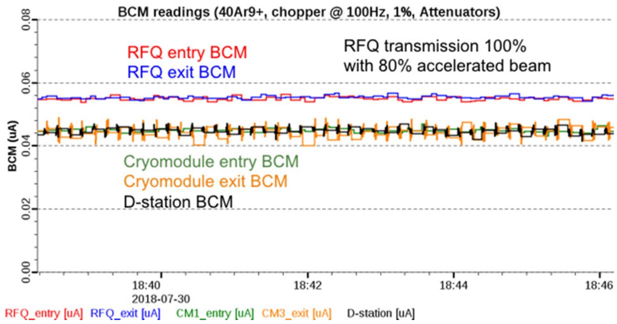

Figure 13: Beam current measured along the accelerator.

The beam emittance was measured in MEBT using the quad scan method and a profile monitor. A similar technique was applied to measure the beam emittance in D-Station but the strength of the last SC solenoid was changed. Both measurements gave very similar number for the beam emittance, showing beam quality preservation (Fig. 14).

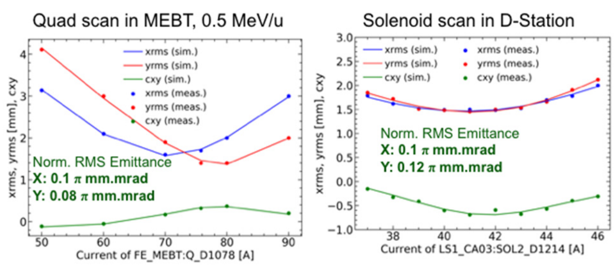

Figure 14: Results of emittance measurements in MEBT and D-Station show beam quality preservation.

The silicon detector installed in D-station was used to measure the absolute energy of the beam, the energy spread, and the longitudinal bunch profile.

The longitudinal emittance in D-Station was measured by scanning the field of the last SRF cavity. Figure 15 shows the bunch length measured by the Si-Detector as a function of the accelerating field in the last cavity. The measurements were done for two settings of the multi-harmonic buncher. The longitudinal emittance can be reduced by changing MHB stings although it is achieved at some loss of beam intensity. The measured emittance numbers were consistent with the expected r.m.s. value of the longitudinal emittance.

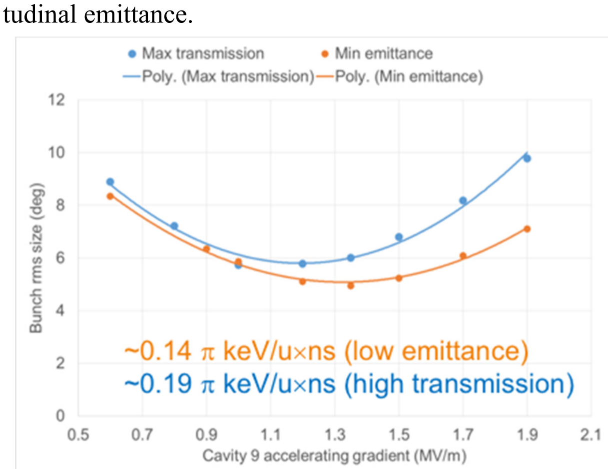

Figure 15: Results of longitudinal emittance measurement.

The maximum energy demonstrated with Argon beam was 2.3 MeV/u. Although even a higher energy was possible, the energy was limited to below 2.4 MeV/u to avoid neutron production at this stage of commissioning.

To test system behaviour under a higher beam power, an attempt to run 35 μA CW beam was made. Unfortunately, extensive outgassing of the D-Station faraday caused us to terminate the test at the duty factor of 30%, corresponding to an average power of ~80W. Other accelerator systems performed reliably and did not exhibit unusual behaviour.

CONCLUSION

FRIB Front End and the three beta 0.041 cryomodules have been successfully commissioned with Argon and Krypton beams. Measured beam properties are consistent with simulations. All commissioned accelerator components operate reliably and as expected. Preparation for commissioning of the rest of LS1 linac systems on track for successful completion.

FRIB commissioning proceeds according to the established plan and schedule.

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