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FRIB FRONT END CONSTRUCTION AND COMMISSIONING*

E. Pozdeyev†, J. Brandon, N. Bultman, K. Davidson, P. Gibson, L. Hodges, K. Holland, M. Konrad, S. Lidia, G. Machicoane, H. Maniar, T. Maruta, D. Morris, P. Morrison, C. Morton, P. Ostroumov, A. Plastun, H. Ren, T. Russo, J. Wei, Y. Yamazaki, T. Yashimoto, Q. Zhao, S. Zhao
FRIB, MSU, MI 48824 East Lansing, USA
S. Prestemon, D. Arbelaez, Lawrence Berkeley National Laboratory, CA 94720 Berkeley, USA
Q.Z.Xing, Tsinghua University, Beijing 100084, China

Abstract

The Facility for Rare Isotope Beams (FRIB) is based upon the CW, SC driver linac to accelerate all the stable isotopes up to more than 200 MeV/u with a beam power of 400 kW. The front end (FE) commissioning shall start in 2017. This invited talk presents the FRIB front end design, and current status of FRIB front end commissioning, including beam properties and energy, and their relationship to FRIB operational requirements.

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. Figure 1 maps world hadron facilities on a diagram with the horizontal axis showing the beam energy per nucleon and the vertical axis showing the nucleonic current. The diagonal dashed lines are constant power levels corresponding the power increase by an order of magnitude. FRIB increases the power for heavy ion machines by more than two orders of magnitude.

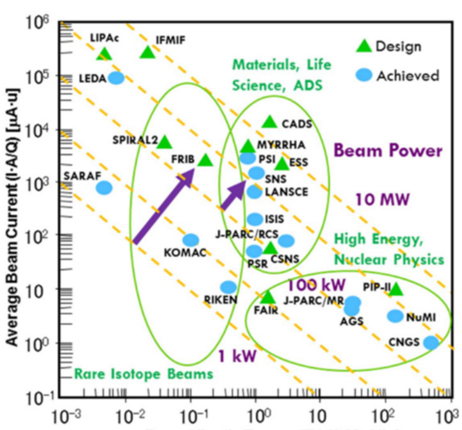

Figure 1: Performance of world hadron facilities. The horizontal axis is the beam energy in GeV/u. The vertical axis is the nucleonic current.

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† pozdeyev@frib.msu.edu.

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.

Figure 2 shows the layout of the FRIB Front End. The front end is located on two levels to allow for maintaining one ion source while the other source is used for the program.

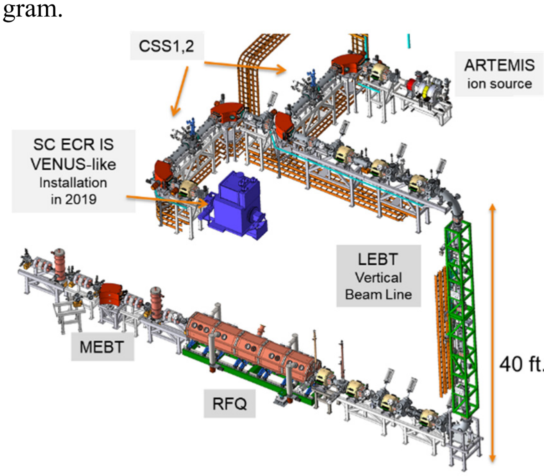

Figure 2: Layouf of FRIB Front End CSS stands for the Charge Selection System.

The front end consists of

1. Two ECR sources on High Voltage (HV) platforms
2. ARTEMIS – 14 GHz ECR ion source
3. 28 GHz superconducting (SC) source based on VENUS (LBNL). Installation planned in 2019
4. LEBT
5. Beam energy – 12 keV/u
6. Chopper
7. Electrostatic quads and solenoids
8. RFQ
9. Injection energy is 12 keV/u
10. Extraction energy is 500 keV/u
11. MEBT
12. Beam energy is 500 keV
13. Two RF bunchers,
14. Quadrupole magnets
15. Instrumentation

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16. Subsystems enabling front end hardware: RF, PS, Vacuum, etc.

The project commissioning and operational requirements are translated to the requirements for the front end shown in Table 1.

Table 1: Front End Performance Goals and Key Performance Parameters

Parameter	Commissioning	Operations
Ion Species	Ar, Kr	O - U
Beam Intensity (eμA, typ.)	5 - 25	350
Beam Energy (keV/u, MEBT)	500	500
Beam power (W, MEBT,25 eμA)	50	1500

High priority beams for first two years of operations defined:

1. FY22 - 238U, 48Ca,78Kr, 124Xe, 18O, 86Kr, 16O, 36Ar, 82Se – 24 weeks
2. FY23 – (in addition to FY22) 92MO, 58Ni, 22Ne, 64Ni.

HIGHLIGHTS OF TECHNICAL SYSTEMS

RFQ

The FRIB RFQ [2] is a four-vane brazed structure with a variable cross section and voltage profile. Table 2 show main RFQ parameters while Fig. 3 shows the fully assembled RFQ at the vendor site. The RFQ engineering design has been developed at the 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.

Table 2: 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

RFQ has been installed in the FRIB tunnel in October-November of 2016. RFQ was tuned with low power in November 2016. The slug tuners were cut at FRIB to match the required frequency and the voltage profile. The frequency correction for the effect of vacuum was implemented. Table 3 shows RF parameters of the RFQ cavity after tuning.

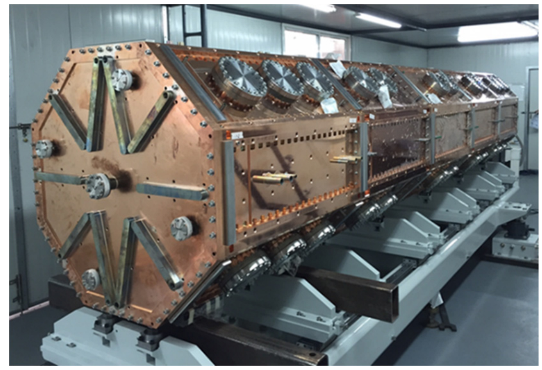

Figure 3: Fully assembled RFQ.

Figure 4 shows the measured magnetic field in the four RFQ quadrants. The simulated field is shown by a light blue dashed line and is the target for field tuning. The local humps in the measured field profiles are caused by tuners. The simulated and measured fields nearly overlap in the areas between the tuners. The deviation between the measured field and the target field do not exceed 0.5%.

Table 3: Parameters of the RFQ Cavity after Tuning

Parameter	Measured Value
Q	14700
F_{accel} (MHz), under vacuum	80.503
F_{dipole} (MHz)	77.797 / 82.888
F_{dipole_rod} (MHz)	83.207 / 76.325
Coupling β	1.2

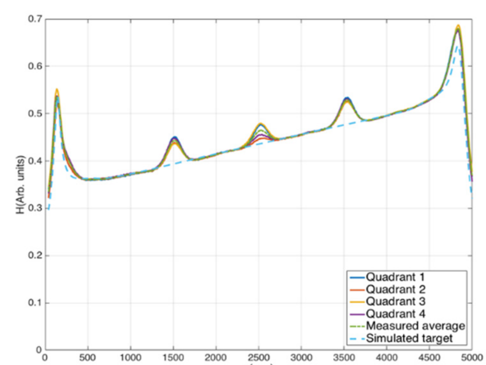

Figure 4: Simulated and measured magnetic fields in the FRIB RFQ after tuning.

The RFQ has been conditioned to 60 kW, sufficient to accelerate KPP beams (Ar, Kr). At this power, no measurable X-ray dose rate above the background level has been detected. The RF amplifier power was limited to allow RFQ operations at daytime with personnel present in the tunnel by locking out three amplifier anode power supplies.

The thermal behaviour of the RFQ structure was as predicted. Table 4 shows the simulated and measured frequency response to the temperature of the cooling water.

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Table 4: Simulated and Measured Dependencies of the RFQ Frequency on the Cooling Water Temperature. V Denotes “Vanes”. W Denotes “Walls”

Parameter	CST	ANSYS	Measured
(dF/dT)_v	-8.7	-9.5	-8.2
(dF/dT)_w	6.9	7.0	7.0
(dF/dT)_v&w	1.85	-2.5	1.39

The vane voltage calibrated by measuring X-ray spectra penetrating through a port in the RFQ walls. The measured vane voltage was in a good agreement with RF measurements. The typical vacuum pressure without RF power was just under 1e-8 Torr. The operational vacuum pressure was ~2-3e-8 Torr.

Room Temperature Ion Source

One of the existing ARTEMIS ECR Ion Sources existing in the lab was repurposed for the commissioning of FRIB. ARTEMIS is a 14 GHz room-temperature ECR ion source. The source design is based on AECR-U (LBNL). This approach presents a low-risk, low-cost solution for the linac commissioning. The source performance meets intensity requirement for commissioning and the 1st year of operation. The source possibly has a longer reach for light and medium mass ions. The source demonstrated ~150 eμA of 40Ar10+ beam and ~35 eμA of 86Kr17+ beam.

Superconducting High Performance Ion source

To satisfy ultimate performance requirements for heavy ions FRIB develops a 28 GHz Superconducting ECR Ion Source, shown in Fig. 5, in collaboration with Berkeley National Laboratory. Source magnet parameters are similar to those of the VENUS ECR [3] but the mechanical design is significantly different to allow for swapping sextupole coils. The design employs water-inflated bladder and shim keys to preload the magnet. This approach was developed at Berkeley for high field accelerator magnets.

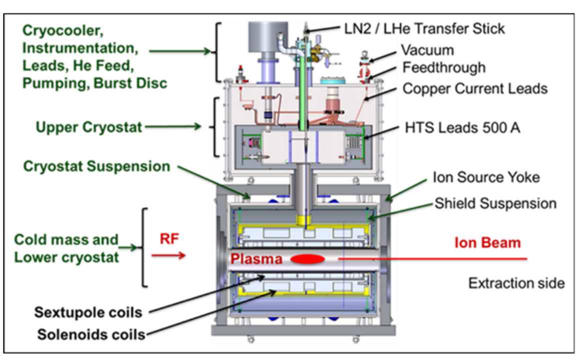

Figure 5: Cross section of the FRIB High Pefromance SC ECR Ion Source.

The construction and testing of the superconducting magnet was completed at Berkeley. Solenoid coils experienced a few training quenches and performed reliably after that. One of the sextupole coils has exhibited an excessive number of quenches during testing and was swapped. After a new coil was installed, the sexupole magnet reached the required field level in five training quenches. The magnet satisfied field requirements for both solenoid and sextupole fields. The magnet, shown in Fig. 6, was delivered to MSU in January of 2018. Figure 7 shows the training history of the sextupole magnet. The cryostat for the source is under procurement at MSU. The source installation and test at FRIB are planned for the end of 2019.

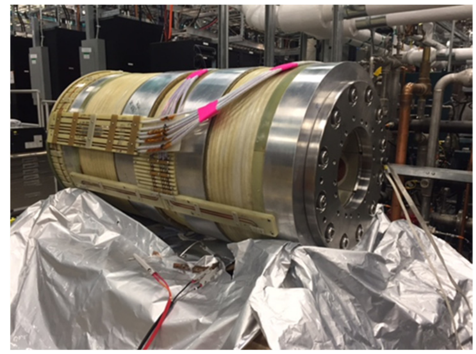

Figure 6: The magnet of the FRIB SC ECR Ion Source at FRIB.

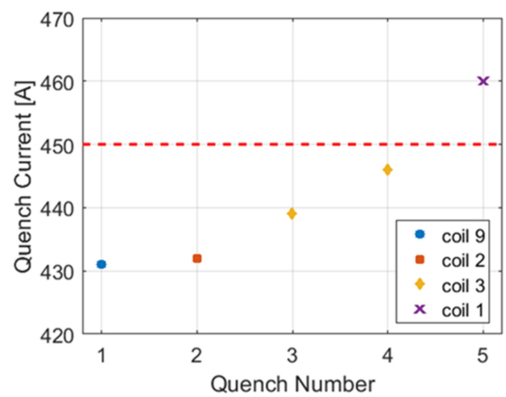

Figure 7: History of training quenches for the sextupole magnet of the FRIB SC ECR Ion Source.

Beam Line

The installation of the beam line was completed in July of 2017. The beam line components, controls, interlocks, and instrumentation were tested on the component level prior to energization. Figure 8 shows LEBT, RFQ, MEBT, and 0.041 cryomodules in the FRIB tunnel.

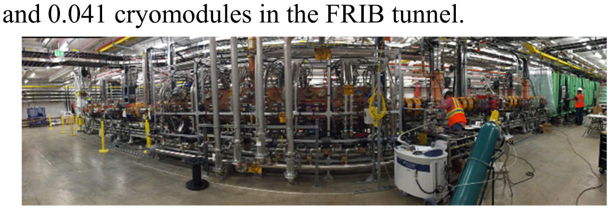

Figure 8: LEBT (left), RFQ (centre), MEBT (right), and 0.041 cryomodules (far right) in the FRIB tunnel.

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ACCELERATOR STARTUP AUTHORIZATION PROCESS

Device readiness reviews assess hardware readiness, authorizes start of integrated testing of reviewed scope. The reviews are typically internal unless external expertise is required. A Division Director makes a request to start integrated power up/test. The FRIB Laboratory Director grants approval upon recommendation from the chief engineer.

Accelerator Readiness Reviews assess readiness of accelerator for beam commissioning. ARRs assess system and documentation readiness, people readiness, hardware readiness. FRIB Laboratory Director makes a request for area beam commissioning. MSU President grants approval upon recommendation from ESH Director.

Table 5 shows Front End DRR and ARR dates and scope.

Table 5: Front End DRR and ARR Dates and Scope

Review	Date	Scope
DRR01-01	21 Sep 2016	ARTEMIS ECR IS
DRR01-02	30 Mar 2017	LEBT Ground Level
DRR01-03	5 Jun 2017	RFQ, LEBT, MEBT
ARR01	22 Jul 2017	Whole Front End

COMMISSIONING

The front end includes an extensive suite of instrumentation systems required to prepare and characterize the beam. To start the commissioning, however, only a small subset of the diagnostics, consisting of the charge-selection slits, viewers, and Faraday Cups, shown in Fig. 9 has been used. A dipole magnet in MEBT has been used to measure the beam energy of the beam accelerated by the RFQ.

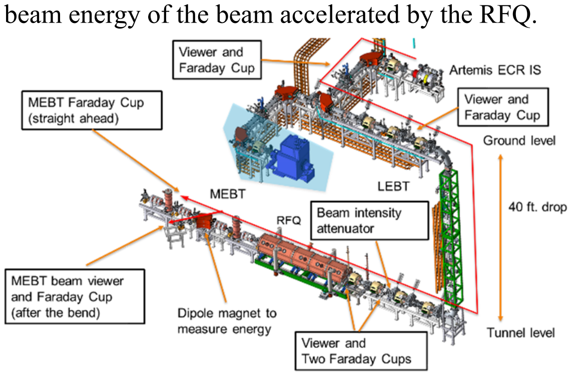

Figure 9: Layout of FRIB Front End with primary diagnostics used for initial FE commissioning.

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% efficiency practically instantaneously indicating a good agreement between the machine and the design model and good alignment of beam line components.

In September of 2017, after ARR01, Argon beam was accelerated through the RFQ. The multi-harmonic buncher in front of the RFQ was not operational. The measured transmission 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 10 shows images of the beam spot on the viewer after the MEBT dipole.

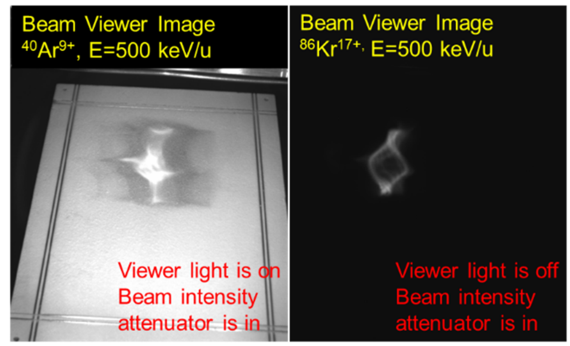

Figure 10: Argon and Krypton beam spots on the viewer situated after the 45-degree bend in MEBT. Beam energy after RFQ is 500 keV/u.

The RFQ acceleration efficiency was measured as a function of the RFQ RF power. Figure 11 shows the measured transmission and the transmission simulated by PARMTEQ for 40Ar10+ as a function of the cavity power (forward power less transmitted power). The two curves nearly overlap. For the nominal power of 37 kW, the simulated transmission is 31.5%. 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 is close to 90% which is similar to the simulated number as well.

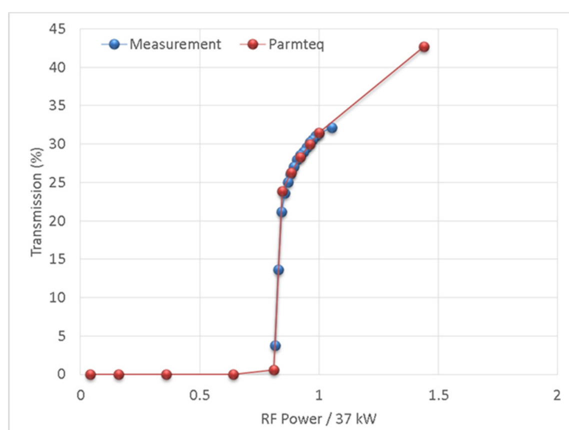

Figure 11: Measured and simulated RFQ transmission efficiency of Argon beam as a function of the cavity RF power. There is a good agreement between the simulated and measured curves. The RF power has been normalized to 37 kW, which is the nominal design power required to accelerate Argon beam.

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The beam transmission increased to the design value with MHB operational. After the voltage and the phase of each MHB harmonic was set according to simulations, the acceleration efficiency has increased to 80% - 86% for both Argon and Krypton. The beam energy was 500 keV/u. Figures 12 and 13 show the accelerated Ar and Kr beam current respectively measured by the FC at the end of MEBT. Note that we were authorized to run this current only for short period of time under a tight administrative control because the MPS system has not been fully commissioned yet. An inserted beam intensity attenuator is used otherwise, reducing the beam intensity by a factor of at least 10.

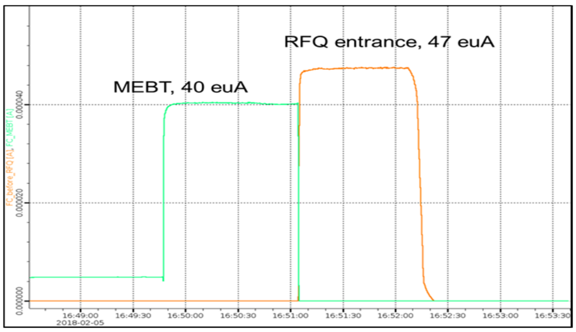

Figure 12: Argon beam current reading from Faraday cups at the entrance of the RFQ and after the RFQ. The transmission efficiency is 86%.

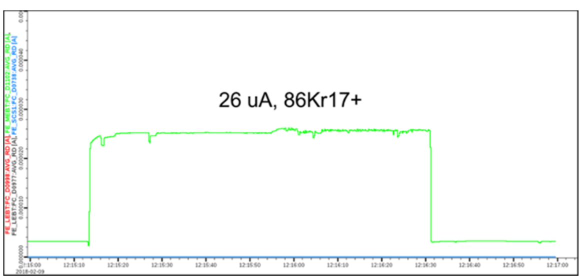

Figure 13: Krypton beam current reading from a Faraday cup in MEBT after the RFQ. The accelerated Krypton current is 26 μA.

All Front End RF system were operated simultaneously synchronized from a reference clock. All the RF systems easily met amplitude and phase stability requirements with a margin of factor of 3 to 20.

FRONT END COMMISSIONING COMPLETE

All the commissioning goals for the FRIB Front End, shown in Table 6, have been met. Operation of all the Front End systems at a level required for the FRIB commissioning have been demonstrated with the only exception of the superconducting ECR ion source which is not required to start the commissioning and will be completed by the end of 2019 according to project baseline schedule.

Table 6: Front End Commissioning Goals and their Status

Commissioning Goal	Status
Detect Ar beam with current of 25 μA in LEBT	Complete 150μA $^{40}Ar^{10+}$
Detect Kr beam with current of 25 μA in LEBT	Complete 38μA $^{86}Kr^{17+}$
Demonstrate chopper operations	Complete
Accelerate Ar beam with current of 25 μA in MEBT	Complete 40μA $^{40}Ar^{10+}$
Accelerate Kr beam with current of 25 μA in MEBT	Complete 26μA $^{86}Kr^{17+}$

FE has been operated for four months, showing stable performance of main systems. RFQ has been operated for the last four month with a power of 40 kW (Ar) and 50 kW (Kr), frequently demonstrating uninterrupted (no-spark) operations over a shift (~7 hours). The Accelerator Physics group works on improving understanding of beam parameters and transport, developing and testing high-level software and algorithms. Front End is used to commission diagnostics, instrumentation, and machine protection system in a combined and focused effort by Beam Instrument & Measurement and Accelerator Physics. This also provides an opportunity to test and improve operational procedures

CONCLUSION

FRIB Front End has been successfully commissioned. Commissioning goals have been achieved, KPP parameters demonstrated. Front End has been operated for four months, providing valuable experience and serving as a testbed for equipment, software, and operational procedures.

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REFERENCES

[1] H. Wei *et al.*, "The FRIB Superconducting Linac: Status and Plans", in *Proc. LINAC 2016 Conf.*, East Lansing, MI, USA, Sep. 2016, pp.1.

[2] H. Ren *et al.*, "Commissioning of the FRIB RFQ", presented at IPAC'18, Vancouver, Canada, Apr.-May 2018, paper MOZGBF1, this conference.

[3] C. Taylor, S. Caspi, M. Leitner, S. Umdgren, C. Lyneis, D. Wutte, S. T. Wang and J. Y. Chen, "Magnet system for an ECR ion source", in *Proc. IEEE Trans on Applied Superconductivity.,* vol. la, No. 1 , Mar. 2000, pp. 224-227.