ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLH06

COMMISSIONING STATUS OF THE FRIB FRONT END*

H.T. Ren†, J. Brandon, N.K. Bultman, K.D. Davidson, E. Daykin, T. Elkin, B. Galecka,
P.E. Gibson, L. Hodges, K. Holland, D.D. Jager, M.G. Konrad, B.R. Kortum, S.M. Lidia,
G. Machicoane, I.M. Malloch, H. Maniar, T. Maruta, G. Morgan, D.G. Morris, P. Morrison,
A.C. Morton, P.N. Ostroumov, A.S. Plastun, E. Pozdeyev, X. Rao, S. Renteria, T. Russo,
J.W. Stetson, R. Walker, J. Wei, Y. Yamazaki, T. Yoshimoto, Q. Zhao, S. Zhao,
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

The FRIB Front End was successfully commissioned in 2017 with commissioning goals achieved and Key Performance Parameters (KPP) demonstrated for both ^{40}Ar^{9+} and ^{86}Kr^{17+} beams. Two more ion species, ^{20}Ne^{6+} and ^{129}Xe^{26+}, have been commissioned on the Front End and delivered to the superconducting linac during the beam commissioning of Linac Segment 1 (LS1) in March 2019. In August 2019, Radio Frequency Quadrupole (RFQ) conditioning reached the full design power of 100 kW continuous wave (CW) that is required to accelerate Uranium beams. Start-up/shutdown procedures and operational screens were developed for the Front End subsystems for trained operators, and auto-start and RF fast recovery functions have been implemented for the Front End RFQ and bunchers. In this paper, we will present the current commissioning status of the Front End, and performance of the main technical systems, such as the ECR ion source and RFQ.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is a scientific user facility for nuclear physics research [1] being built on the campus of Michigan State University (MSU). The FRIB linac consists of a room-temperature front end and a SRF linac providing stable ion beams to the fragmentation target. The FRIB driver accelerator will accelerate ions with a mass up to Uranium to energies higher than 200 MeV/u and beam power on target up to 400 kW. The FRIB front end includes two Electron Cyclotron Resonance (ECR) ion sources, Lower Energy Beam Transport (LEBT), RFQ, and Medium Energy Beam Transport (MEBT). The front end layout is shown in Fig. 1.

One of the Front End ion sources is a room-temperature ECR ARTEMIS existing in the lab, primarily for commissioning of the FRIB. ARTEMIS is a 14 GHz ECR ion source built at MSU and based on the AECR-U (LBNL). This approach presents a low-risk, low-cost solution for linac commissioning. The other ion source is a 28 GHz superconducting high-power ECR to satisfy ultimate performance requirements for heavy ions. This source is based on the design of VENUS ECRIS developed at LBNL [2]. Source assembly and installation is ongoing in 2019 and conditioning is planned in 2020.

The FRIB RFQ is a 4-vane structure cavity designed to accelerate single and two-charge state ion beams from 12 keV/u to 0.5 MeV/u with estimated transmission efficiency above 80%. Table 1 shows the main RFQ parameters [3]. The RFQ beam physics design is optimized to minimize the longitudinal emittance of the accelerated beam as described in [4,5]. With proper sizing of the vane undercuts, a linear accelerating voltage ramp is implemented on the FRIB RFQ to increase the output energy.

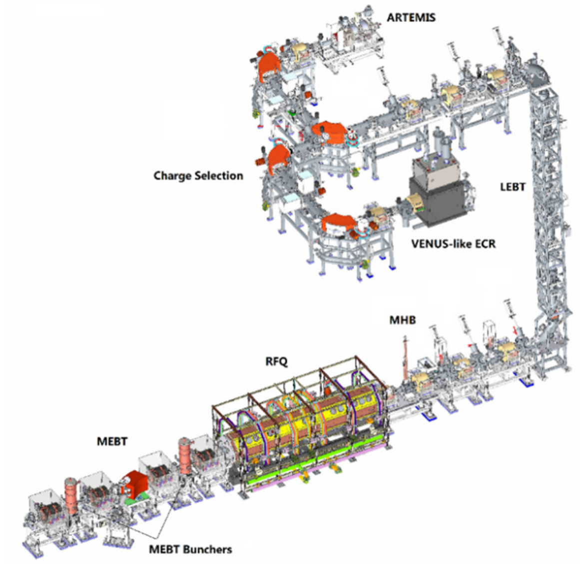

Figure 1: FRIB Front End layout. Two ECR ion sources are located at the ground level. The MHB, RFQ and MEBT are located in the linac tunnel 10 m below grade.

Table 1: FRIB RFQ Principal Parameters

Frequency (MHz)	80.5
Injection/Output energy (keV/u)	12 / 500
Design charge-to-mass ratio	1/7 - 1/3
Accelerating voltage ramp (U, kV)	60 - 112
Surface electric field (Kilpatrick)	1.6
Quality factor	16500
Operational RF power (kW, O-U)	15 - 100
Dipole modes (closest, MHz)	78.3 / 83.2
Length (m)	5.04

DC beam produced by the ECR ion sources is bunched and matched to the RFQ acceptance by an external multi-harmonic buncher (MHB). The accelerated beam from the

---

* This work is supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661.

† ren@frib.msu.edu

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLH06

RFQ is re-bunched by two MEBT bunchers before entering the superconducting linac.

The FRIB commissioning and operational requirements are translated to the requirements for the front end shown in Table 2.

Table 2: Front End Performance Goals and Key Performance Parameters

Parameter	Commissioning	Operation
Ion Species	Ar, Kr	O - U
Beam Intensity (eμA, typ.)	5 - 25	350
Beam Energy (keV/u, MEBT)	500	500
Beam Power (W, MEBT)	50	1500
RFQ Power (kW, CW)	50	100

RFQ HIGH POWER CONDITIONING

The RFQ was conditioned to 59 kW without beam in August 2017 [6]. This is sufficient to accelerate the Key Performance Parameter (KPP) beams, $^{40}Ar^{9+}$ and $^{86}Kr^{17+}$. High power conditioning is to condition the cavity up to 100 kW from 59 kW to meet the requirement for $^{238}U^{33+}$ (Q/A =7) acceleration. The power was increased in 10 kW increments to 70 kW, 80 kW, 90 kW, and then 100 kW. Conditioning was started in a low duty factor (10 - 20%), pulsed mode to prevent high spark rates. The pulse length was then gradually increased towards the CW regime. As the new power level achieved in pulsed mode, we switch to CW mode for condition at all power levels.

In August 2019, the FRIB RFQ successfully exceed the full design power of 100 kW CW that is required to accelerate Uranium beams. This took approximately 150 hours of conditioning and over 700 sparks were observed before reaching the final power of 102 kW CW. The cavity power can be increased to 102 kW from 0 kW (in CW mode) in 3 minutes with a reflected power of 3 - 5% and maximum frequency deviation of ~ 18 kHz with the LLRF in self excited loop (SEL). Figure 2 shows 6 hours of high power conditioning in CW mode.

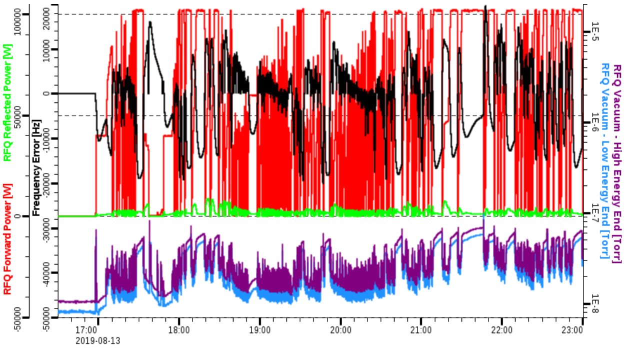

Figure 2: RFQ high power conditioning in CW mode.

The measured cavity loss vs cavity voltage was in good agreement with the expected power vs voltage law, as shown in Fig. 3. The equivalent shunt impedance did not change much for the RF power increasing to 100 kW.

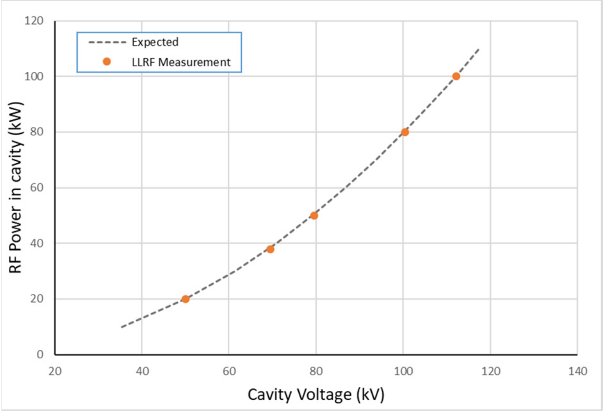

Figure 3: Expected and measured cavity power vs voltage laws.

The RFQ vacuum pressure reached 1e-7 Torr during the high power conditioning with an interlock limit of 5e-6 Torr. After conditioning to 102 kW CW, the RFQ pressure remains around 7e-8 Torr as shown in Fig. 2.

No multipacting was observed during the high power conditioning for RF power over 20 kW. Multipacting barriers were only observed at a few hundred watts, likely between the vanes, and at 3 – 15 kW in the coupler which can be passed through or jumped over without problems.

There are surface RTDs installed on RFQ segments (1-5), end walls, tuners, and the coupler. At 102 kW CW, the measured maximum temperature rise was ~10 °C on the tuner surface in segment 5 due to the highest magnetic field there. The RFQ main return water temperature increased ~ 1.5 °C with a total water flow of 280 gpm. The maximum temperature rise on the surface RTD of the RFQ coupler was ~5 °C and the return water temperature increased ~3 °C at 102 kW, as shown in Fig. 4.

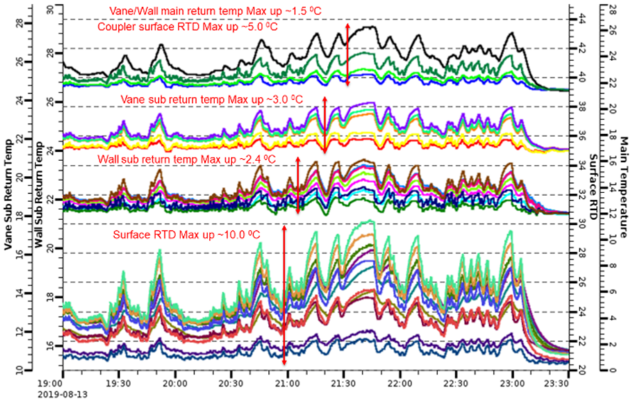

Figure 4: Measured temperatures on RFQ cavity during high power conditioning.

FRONT END COMMISSIONING

Beam Commissioning

The ARTEMIS ion source commissioning was complete in September of 2016 and the beam intensity is being improved with conditioning efforts. The source can produce ~250 eμA of 40Ar9+ beam and ~35 eμA of 86Kr17+ beam at 12 keV/u, meeting the intensity requirements for commissioning and the first years of operation.

LEBT was successfully commissioned with Argon beam in spring and summer of 2017. The beam transmission was nearly 100% (~31 m) practically instantaneously indicating a good agreement between the machine and the design model, and good alignment of beam line components.

In September of 2017, Argon beam was accelerated through the RFQ without the MHB (DC beam) [7]. The MHB in front of the RFQ was not operational then. The measured transmission efficiency was ~31% as predicted by PARMTEQ simulations. The accelerated beam energy measured by the 45-degree dipole magnet was 500 keV/u with an energy spread less than 1%. In several days, a Krypton beam was accelerated producing results nearly identical to those of the Argon beam with scaling of beamline electromagnetic fields for different Q/A.

The RFQ 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 increased to 80 - 86% for both Argon and Krypton. The beam energy was 500 keV/u.

During LS1 beam commissioning in March 2019, the front end delivered two more ion species, ^{20}Ne^{6+} and ^{129}Xe^{26+}, to the superconducting linac. In total, four ion species of ^{40}Ar^{9+}, ^{86}Kr^{17+}, ^{20}Ne^{6+} and ^{129}Xe^{26+} were all accelerated up to 20.3 MeV/u by scaling electromagnetic fields. The RFQ transmission was above 95% including un-accelerated beams. The LS1 acceleration efficiency was nearly 100%. Figure 5 shows measured beam current monitor (BCM) results for ^{40}Ar^{9+} transmission from RFQ through LS1.

Auto-Start Development for RFQ/FE Bunchers

Operator Interfaces (OPI) have been developed for the front end RFQ and bunchers. The OPIs include all necessary information for operating the cavities. Startup and shutdown procedures were developed based on the OPIs. FRIB operators have been trained to operate the RFQ and front end bunchers without supervision.

An auto-start function was implemented for both the RFQ and bunchers. The RF power can be turned on and ramped up automatically to the expected setpoint with one button. The auto-start process includes the following steps: 1) Start with a low RF power of 1 kW CW (100% duty cycle); 2) Go directly to 20 kW with 20% duty cycle to jump over the multipacting barrier in the coupler; 3) Gradually ramp up the pulse height to the final setpoint (e.g. 38 kW) with 20% duty factor; 4) Gradually increase the duty factor up to 100% and then start tuning the cavity frequency error by adjusting the water temperature (as the water skid works in frequency control mode); 5) Switch to phase close loop as the frequency error runs to the range of ± 1 kHz.

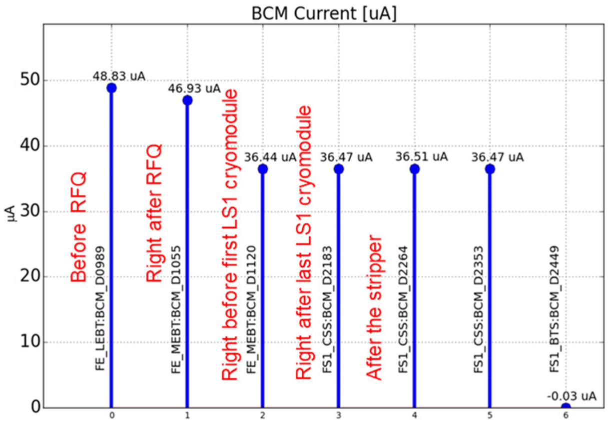

Figure 5: BCM current of ^{40}Ar^{9+} from RFQ through LS1.

During the power ramp up, the vacuum and reflected power are monitored to avoid drastic increases. Figure 6 shows an example of auto-start process for FRIB RFQ. The entire process takes about 20 minutes to reach 38 kW and the full time depends on the final power setpoint.

An RF power fast recovery function was also developed and implemented for the RFQ and bunchers. For S11 or reflected power trips, the RF power can be fast recovered automatically within 3 seconds.

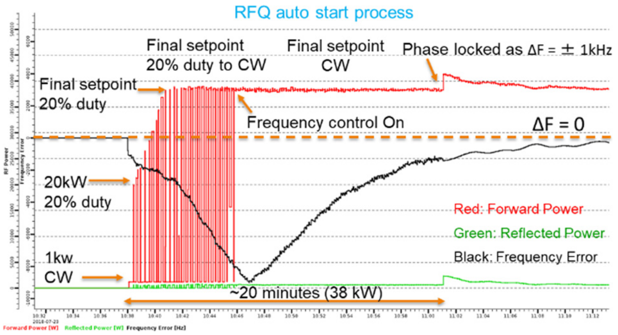

Figure 6: RFQ auto-start process for 38 kW.

CONCLUSIONS

The FRIB Front End has been successfully commissioned and has accelerated two more ion species beyond the KPP beams to 500 keV/u as expected, satisfying the commissioning requirements. The FRIB RFQ was recently conditioned to 100 kW CW, achieving the full design power.

ACKNOWLEDGEMENTS

We would like to thank colleagues for their contributions to the project and useful discussions: A. Aleksandrov, G. Ambrosio, J. Bernardin, M. Champion, A. Hodgkinson, A. Facco, J. Fuerst, R. Laxdal, D. Leitner, C. Luongo, R. Pardo, A. Pisent, J. Steimel, R. Vondrasek, and D. Xie. We like to separately acknowledge L. Young and J. Stoval's contribution to the design of the FRIB RFQ.

REFERENCES

[1] J. Wei *et al.*, “FRIB Accelerator Status and Challenges”, in *Proc. LINAC'12*, Tel Aviv, Israel, Sep. 2012, paper TU1A04, pp. 417-421.

[2] D. Leitner *et al.*, “High intensity production of high and medium charge state uranium and other heavy ion beams with VENUS,” *Rev. Sci. Instrum.*, vol. 79, no. 2, p. 02C710, Feb. 2008. `doi:10.1063/1.2816790`

[3] E. Pozdeyev, N. K. Bultman, G. Machicoane, G. Morgan, X. Rao, and Q. Zhao, “Status of the FRIB Front End”, in *Proc. NAPAC'13*, Pasadena, CA, USA, Sep.-Oct. 2013, paper WEOAB1, pp. 734-736.

[4] P. Ostroumov *et al.*, “Design of 57.5 MHz cw RFQ for medium energy heavy ion superconducting linac,” *Phys. Rev. ST Accel. Beams*, vol. 5, p. 060101, Jun. 2002.

[5] Q. Zhao *et al.*, “DESIGN IMPROVEMENT OF THE RIA 80.5 MHZ RFQ”, in *Proc. LINAC'04*, Lübeck, Germany, Aug. 2004, paper THP03, pp. 599-601.

[6] H. T. Ren *et al.*, “Commissioning of the FRIB RFQ”, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 1090-1093. `doi:10.18429/JACoW-IPAC2018-TUPAL039`

[7] G. Pozdeyev, “FRIB Front End Construction and Commissioning”, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 58-62.
`doi:10.18429/JACoW-IPAC2018-MOZGBF1`