ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAL039

COMMISSIONING OF THE FRIB RFQ*

H. Ren†, E. Pozdeyev, D. Morris, S. Zhao, P. Morrison, R. Walker, N. Bultman, M. Konrad, X. Rao, J. Brandon, H. Maniar
FRIB, Michigan State University, East Lansing, MI, USA

Abstract

The radio-frequency quadrupole (RFQ) at the Facility for Rare Isotope Beams (FRIB) is a 4-vane type cavity designed to accelerate heavy ion beams with charge states Q/A between 1/7 and 1/3 from 12 keV/u to 0.5 MeV/u. The RFQ was assembled in the FRIB tunnel in November 2016. Bead-pull measurements and tuning were performed with low RF power. The RFQ has been conditioned to 59 kW in August 2017, which is sufficient to accelerate the Key Performance Parameter (KPP) beams, Argon and Krypton. The RFQ has been successfully commissioned with KPP beams in CW regime in October 2017. $^{40}Ar^{9+}$ and $^{86}Kr^{17+}$ beams were accelerated by the FRIB RFQ in the CW regime to the designed energy of 0.5 MeV/u. With the multi-harmonic buncher operational, the FRIB RFQ commissioning has been completed with bunched beam in February 2018. The beam transmission efficiency through the RFQ was in good agreement with PARMTEQ simulation results. The detailed results from the FRIB RFQ tuning, high power conditioning and beam commissioning will be presented in this paper.

INTRODUCTION

The FRIB at MSU will be a scientific user facility for nuclear physics research with rare isotope beams [1]. The FRIB linac consists of a room-temperature front end and a SRF linac providing stable ion beams to achieve 400 kW beam power on the fragmentation target. The FRIB front end includes two ECR ion sources, two charge selection system, Low Energy Beam Transport (LEBT), RFQ, and Medium Energy Beam Transport (MEBT). The front end layout is shown in Figure 1.

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 [2]. The RFQ beam physics design is optimized to minimize the longitudinal emittance of the accelerated beam as described in [3, 4]. With proper sizing of the vane undercuts, a linear accelerating voltage ramp is implemented on the FRIB RFQ to increase the output energy. The design details of the RFQ are described in [5].

DC beam produced by the ECR ion sources is bunched and matched to the RFQ acceptance by an external multi-harmonic buncher (MHB). The MHB is located in the LEBT upstream of the RFQ, which includes three harmonics operating at 40.25, 80.5, 120.75 MHz, respectively.

To measure the beam current and transmission efficiency, Faraday cups are used in the front end upstream and downstream of the RFQ. A 45 degree bending magnet and a viewer are located in the MEBT to check the accelerated beam energy.

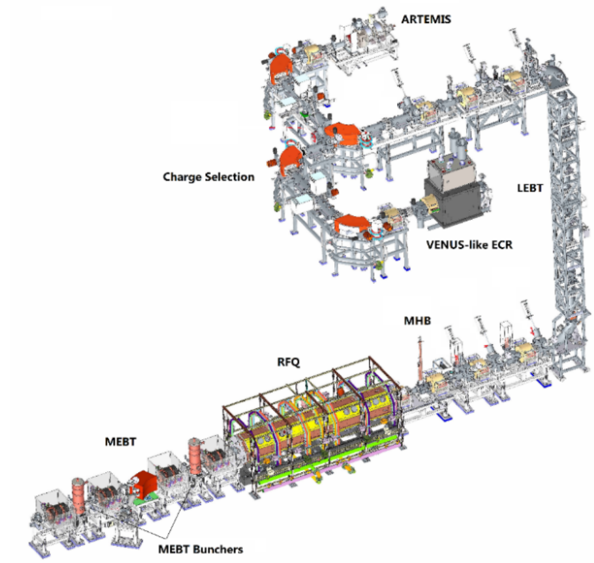

Figure 1: FRIB Front End layout. Two ECR ion sources (ARTMIS and VENUS-like ECR) are located at the ground level. The MHB, RFQ and MEBT are located in the linac tunnel 10 m below grade.

Table 1: FRIB RFQ Principle 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 – 120
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

CAVITY ASSEMBLY AND TUNING

The FRIB RFQ consists of 5 longitudinal segments, around 1 meter per segment. The RF power is fed into the RFQ through a single coaxial loop coupler. 27 fixed slug tuners are distributed along the length of the cavity to fine-tune the field profile for 4 quadrants and the cavity resonance frequency. The RFQ was installed and assembled in the FRIB tunnel on a precision adjustable support system in November 2016. The whole RFQ was assembled with alignment for all 5 segments.

* This work is supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661 #wei@frib.msu.edu
† ren@frib.msu.edu.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAL039

A bead-pull system, including pulleys, stepper motor, Arduino UNO [6] and aluminium supporting end-plates, has been developed at FRIB for the RFQ tuning with a low RF power. The tuning algorithm was developed utilizing the superposition of the perturbations caused by the slug tuners to minimize the field profile difference as well as the frequency deviation compared to the designed value. These perturbations were obtained through CST Microwave Studio simulations for the quadrupole mode and dipole mode, respectively.

The bead-pull system and tuning algorithm has been successfully tested on a RFQ cold model which is aluminium cavity with quarter size of the FRIB RFQ. The cold model is electrically nearly identical to the FRIB RFQ.

The tuning was first performed with 28 aluminium tuners which are adjustable in length. Then the coupler was installed instead of one of these tuners in the 3^{rd} segment, and the other three tuners at the same longitudinal positon were readjusted to compensate for the perturbation caused by the coupler. After the accelerating field and resonance frequency had been tuned to the required value with the coupler and aluminium tuners, the copper tuners were cut at MSU according to the aluminium tuner length.

Figure 2 and Table 2 show the final bead-pull and tuning results. The field difference between 4 quadrants was less than 0.5%. The resonance frequency under vacuum was 80.503 MHz (target value 80.5 MHz). The bead-pull was performed with the RFQ filled by dry nitrogen. A frequency correction for the effect of the vacuum was implemented based on the CST Microwave Studio calculation.

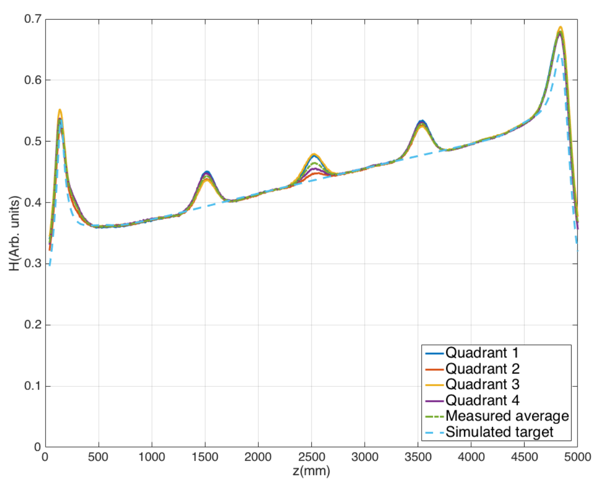

Figure 2: Final RFQ bead-pull measurement showing the magnetic field profiles of the four quadrants.

The peak dipole field is less than 0.5% of the quadrupole field and frequency with N2 at 19.5°C is 80.498 MHz. The humps in the field profile are caused by the tuners. The tuners perturb the magnetic field locally. The field between the humps was used for the correction algorithm.

The input coupler was rotated to achieve the coupling beta=1.2 corresponding to the measured S11of -18.3 dB. A tube amplifier with a amximum power of 150 kW in the CW regime was connected to the RFQ after tuning.

Four 550 l/s turbo pumps were installed on the first segment of cavity and one 56 l/s turbo on the coupler. The background vacuum of RFQ reached ~1e-8 Torr.

Table 2: RFQ Final Tuning Results

Parameter	Measured Value
Q_0	14700
F_accel (MHz)	80.503 (under vacuum)
F_dipole (MHz)	77.797/82.888
F_dipole_rod (MHz)	83.207/76.325
Coupling β	1.2

Cooling water temperature adjustment is the sole mean of controlling the RFQ resonance frequency after the slug tuners have been cut and fixed. Two closed-loop water skids were designed to allow separate control of the wall and vane water temperature. Two operation modes can be selected for each skid, temperature control and frequency control. The temperature control means holding the RFQ water inlet temperatue constant. The frequency control is achieved by tuning the RFQ water inlet temperatue to minimize the resoncane frequency offset. Figure 3 shows the RFQ was ready for RF conditioning in June 2017.

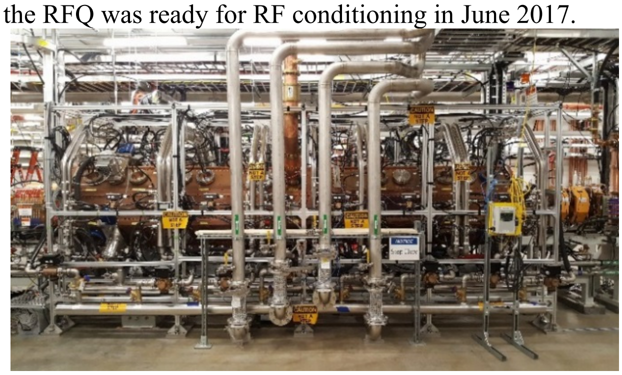

Figure 3: FRIB RFQ installed in beamline with support stand, water cooling manifold, vacuum pump and RF waveguide connected to the input coupler.

RF CONDITIONING

The RF conditioning started with a low duty, pulsed mode. Then the pulse length was gradually increased towards the CW regime. The RFQ has been conditioned to 59 kW without beam in August 2017, which is sufficient to accelerate the Key Performance Parameter (KPP) beams, $^{40}Ar^{9+}$ and $^{86}Kr^{17+}$.

Three out of six anode power supplies of the tube amplifier were locked out to limit the output power to 59 kW. No elevated radiation dose rate was observed around RFQ at 59 kW, corresponding to ~86 kV max. vane voltage.

Multipacting was observed in RFQ at a low power level. One barrier has been found in the cavity, likely between the vanes, at around 100 – 300 W, which can be jumped over or conditioned out in a couple of hours. The other mutipacting barrier was in the coupler between 3 kW and 15 kW, which is predicted well by the CST simulation. It can be passed through or jumped over without problem.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAL039

It takes about 4-5 hours and 100-200 sparks to reach CW for a new power level with 10 kW increments. The RFQ vacuum pressure can reach 3e-7 Torr during the conditioning with a trip limit of 5e-6 Torr. After conditioned to 40 and 50 kW, the RFQ operates reliably in CW regime for hours without sparks and the vacuum is around 2~3e-8Torr.

The RFQ vane voltage was calibrated with an X-ray detector. Measured X-ray energy shows good agreement with the calculation and LLRF measured power (Fig. 4).

Both vane and wall skids operated on the temperature control mode during the RF conditioning. The process water flow in both vane and wall skids was adjusted to minimize the frequency detuning as RF power applied. After the water flow was adjusted, the frequency deviation reduced to ~ 0.3 kHz which is way smaller than previous value of 4 kHz.

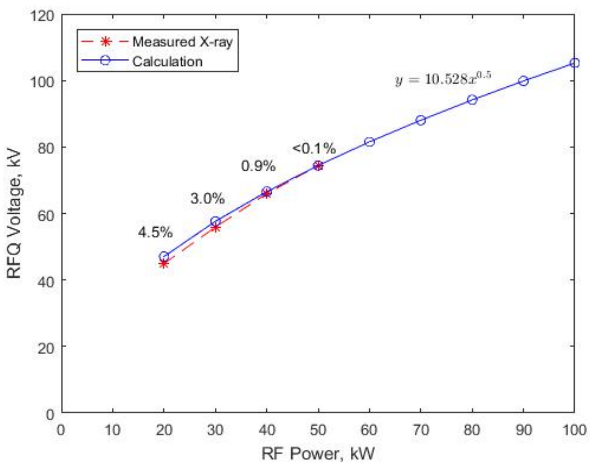

Figure 4: RFQ vane voltage calibration results.

BEAM COMMISSIONING

Without MHB

The RFQ beam commissioning without MHB (DC beam) was carried out in October 2017. The measured transmission efficiency through RFQ was ~31% as predicted by PARMTEQ simulations. Figure 5 demonstrates very good agreement between the measured transmission and that calculated by PARMTEQ [7].

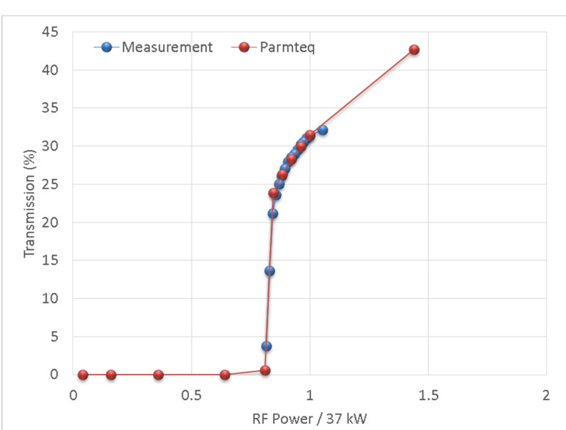

Figure 5: Comparison between measured and calculated RFQ transmission for $^{40}Ar^{9+}$. Power normalized on 37 kW.

The beam energy and energy spread after the RFQ have been measured using a viewer after the MEBT 45 degree dipole magnet. The $^{40}Ar^{9+}$ and $^{86}Kr^{17+}$ beams has been accelerated to energy of 500 keV/u. The measured energy spread is approximately 1%.

With MHB

With MHB operational, the MHB was tuned with beam and the RFQ transmission was measured for both $^{40}Ar^{9+}$ and $^{86}Kr^{17+}$ in February 2018.

Figure 6 illustrates the measured RFQ transmission efficiency with MHB for $^{40}Ar^{9+}$ beam (40 eμA through MEBT). It is above 85% compared to 83% simulated by PARMTEQ. Over 26 eμA of $^{86}Kr^{17+}$ was measured on the Faraday cup in MEBT with similar transmission efficiency through RFQ. The accelerated beam energy of 500 keV/u has been verified with MEBT dipole magnet.

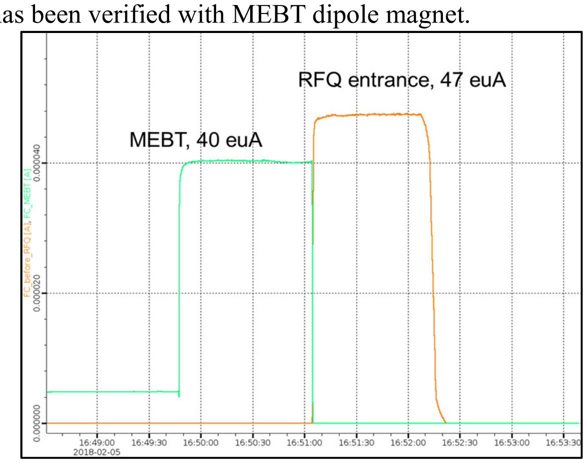

Figure 6: Transmission of $^{40}Ar^{9+}$ beams through RFQ with MHB.

During the beam commissioning with MHB, the vane skid was operated in temperature control model, while the wall skid in frequency control to stabilize the resonance frequency of the RFQ. The frequency is stable with offset around +/- 500 Hz.

CONCLUSIONS

The FRIB RFQ has been successfully commissioned and accelerated beams to the energy as expected, satisfying the commissioning requirements.

ACKNOWLEDGEMENTS

The authors would like to thank Q. Xing of Tsinghua University, J. Bernardin of LANL for their input to this work.

REFERENCES

[1] J. Wei *et al.*, in *Proc. LINAC'12*, Tel-Aviv, Israel, Sept. 2012, paper TU1A04.

[2] E. Pozdeyev *et al.*, in *Proc. PAC'13*, Pasadena, CA, USA, paper WEOAB1.

[3] P. Ostroumov *et al.*, Phys. Rev. ST Accel. Beams 5, 060101, 2002.

[4] Q. Zhao *et al.*, in *Proc. LINAC'04*, pp. 599.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAL039

[5] N. Bultman *et al.*, in *Proc. IPAC'13*, paper WEPFI075.

[6] Arduino: https://www.arduino.cc

[7] K. R. Crandall and T. P. Wangler, in *Proc. AIP 177*, 1988, pp. 22.