# FRIB FRONT END DESIGN STATUS*

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*Abstract*

The Facility for Rare Isotope Beams (FRIB) will provide a wide range of primary ion beams for nuclear physics research with rare isotope beams. The FRIB SRF linac will be capable of accelerating medium and heavy ion beams to energies beyond 200 MeV/u with a power of 400 kW on the fragmentation target. This paper presents the status of the FRIB Front End designed to produce uranium and other medium and heavy mass ion beams at world-record intensities. The paper describes the FRIB high performance superconducting ECR ion source, the beam transport designed to transport two-charge state ion beams and prepare them for the injection in to the SRF linac, and the design of a 4-vane 80.5 MHz RFQ. The paper also describes the integration of the front end with other accelerator and experimental systems.

## FRONT END LAYOUT AND PARAMETERS

The FRIB Front End is designed to provide stable ion beams up to uranium with intensity sufficient to achieve 400 kW beam power on the FRIB target [1]. The FRIB Front End includes two ECR ion sources, two charge selection systems, LEBT, RFQ, and MEBT. To enhance availability and maintainability, the ECR sources and their charge selection systems are placed at the ground level in the support building about 10 m above the linac tunnel floor. Table 1 shows principle parameters of the Front End. The Front End layout is shown in Figure 1.

Table 1: FRIB Front End principle parameters

| LEBT (before RFQ) | |
|---|---|
| Energy (keV/u) | 12 |
| Nominal beam current (eμA, typ.) | 400 |
| Emittance (πμm, 99.5%, norm.) | 0.9 |
| **MEBT (after RFQ)** | |
| Energy (keV/u) | 500 |
| Nominal current (eμA, typ.) | 330 |
| Emittance (πμm, 99.5%, norm.) | 1.1 |
| Long. Emittance (πkeV/u·ns, 99.5%) | 1.5 |
| Bunch repetition rate (MHz) | 40.25, 80.5 |
| Beam pulse length (μs) | 0.6 – CW |

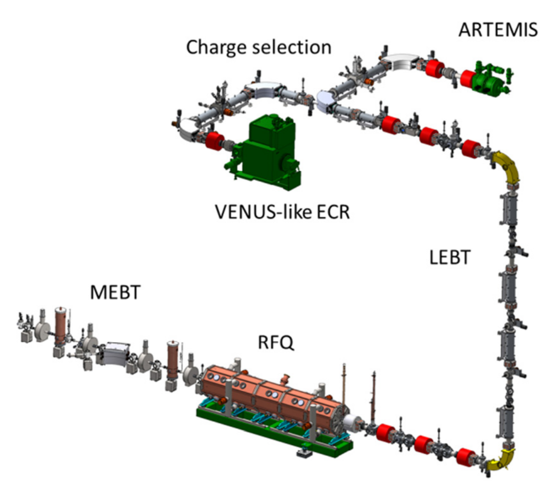


Figure 1: FRIB Front End Layout. Two ECR sources are located at the ground level. The RFQ and MEBT are located in the linac tunnel 10 m below grade.

## FRONT END SYSTEMS

### *Ion Sources*

FRIB Front End includes two ion sources: a superconducting high-power source based on the VENUS ECRIS developed at LBNL [2] and, primarily for commissioning, a room-temperature ECR ARTEMIS. The sources are placed on high voltage platforms to match the RFQ injection energy for all beams.

The ARTEMIS ECR source, built at MSU and based on the AECR-U ECR developed at LBNL, operates at 14.5 GHz with room temperature coils. Minimal re-configuration of the source is required to make the source compatible with operation on a high voltage platform.

The superconducting high-performance source will be based on the design of VENUS ECR ion source operating at a maximum frequency of 28 GHz. In 2007, VENUS demonstrated intensity required for FRIB for a 238U beam with the two charges states, 33+ and 34+, combined. Based on this result, FRIB was designed to accelerate two charge states from an ion source to double intensity. Recent beam tests demonstrated that better

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performance from VENUS can be obtained by better tuning and coupling of microwave power to the ion source. A new intensity record of 450 eA of U was demonstrated by VENUS at LBNL with a direct participation of the NSCL ECR group. The measured emittance for this charge state showed that 95% of the beam was within the FRIB acceptance. This test demonstrated that VENUS can satisfy the FRIB intensity requirement in a single charge state that can significantly simplify linac tuning. FRIB modifications to the original design of the VENUS cryostat include the cooling capacity at 4.2K been extended from 6 W to 12 W to include the dynamic heat load generated by the plasma Bremsstrahlung electrons.

### *Beam transport*

Beams extracted from the sources are filtered in the charge selection systems. The systems are achromatic, designed to select and transport two charge states simultaneously for beams heavier than xenon.

The LEBT design is achromatic allowing transporting two charge states simultaneously. To facilitate transport of two-charge state beams through LEBT electrostatic quadrupoles and two 90° deflectors are used in the vertical transport line. To reduce losses in the superconducting linac, the beam is collimated by several apertures in the LEBT. To satisfy experimental system requirements and facilitate linac tuning the Front End is able to vary intensity of accelerated beams by several orders of magnitude. A chopper is used to vary the duty cycle controlling the pulse length from several hundreds of ns to CW and the pulse frequency from 0 to 30 kHz. Several mesh screens allow reduction of the beam intensity by several orders of magnitude while keeping the nominal bunch frequency. The two 90° electrostatic deflectors in the vertical transport line are incorporated into the machine protection system. The voltage on the deflector electrodes is controlled by fast switches that receive the inhibit signal from the MPS with shut-off time below 1 μs. Additional details on the beam dynamics in the LEBT can be found in [3].

Downstream of the RFQ, MEBT includes two room-temperature QWR bunchers, four SC solenoids, an energy analyzing dipole, and diagnostics. MEBT matches the beam to the SC linac and removes un-accelerated beam from the RFQ.

### *Multi-harmonic buncher and velocity equalizer*

The CW beam is bunched before injection into the RFQ by a multi-harmonic buncher (MHB) operating at 40.25, 80.5, and 120.75 MHz. The design of the buncher is described in [4]. A second RF cavity conceptually similar to MHB but operating at 40.25 MHz is required upstream of the RFQ for two-charge-state beam injection, acting as a velocity equalizer (VE). The construction and assembly of MHB have been completed (Figure 2). The buncher currently undergoes tuning and testing.

### *MEBT Bunchers*

Two identical FRIB MEBT bunchers are used in MEBT to longitudinally match the beam to the SRF linac. The bunchers are room temperature quarter wave resonators similar in design and dimensions to the PIAVE bunchers developed at Legnaro [5]. Table 2 shows a summary of main parameters of the MEBT bunchers. The RF design of the buncher, including the coupler loop, has been completed. The thermal management analysis and development of mechanical drawings and details are in progress.

Table 2: **M**ain parameters of FRIB MEBT bunchers

| | |
|---|---|
| Frequency (MHz) | 80.5 |
| Voltage (Typical, uranium, kV) | 120 |
| Transit time factor | 0.82 |
| Power (kW) | 1.3 |

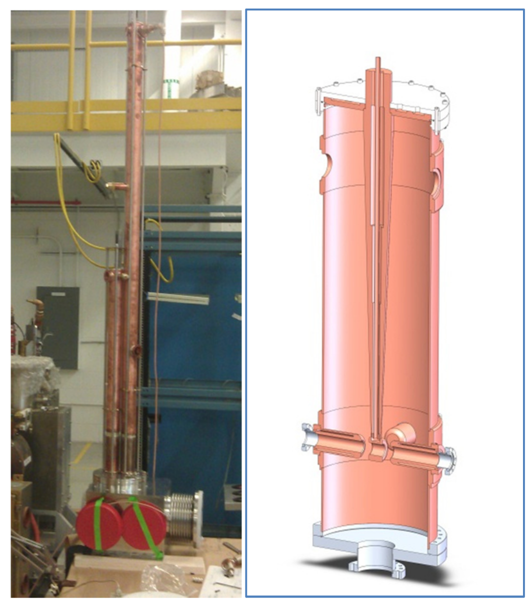

Figure 2: FRIB Front End bunchers. Left: multiharmonic LEBT buncher completed assembly. Right: MEBT 80.5 MHz QWR buncher assembly drawing.

### *RFQ*

The FRIB RFQ utilizes a 4-vane structure to accelerate single and two-charge state beams from 12 to 500 keV/u with estimated transmission efficiency above 80%. Table 3 shows main RFQ parameters, while Figure 3 shows evolution of structure parameters along the RFQ length.

The RFQ beam physics design is optimized to minimize the longitudinal emittance of the accelerated beam as described in [6][7]. To increase the RFQ output energy a linear accelerating voltage ramp is implemented. The linear voltage ramp is accomplished through proper sizing of the vane undercuts. Dipole mode suppression rods attached to the structure endplates are utilized to move dipole mode frequencies away from the accelerating mode frequency. The quadrupole and dipole



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mode local perturbations are fine-tuned during construction using 27 fixed mechanical slug tuners distributed along the length of the machine. A full 3D model of the RFQ, including undercuts, stabling rods, and the slug tuners, was implemented in the CST Microwave Studio (MWS) [8] to accurately select required parameters and simulate fields and surface losses. Figure 4 shows the design voltage profile used in PARMTEQ and the voltage profile simulated by CST MWS. The difference between the design and simulated voltage profiles is less than 1%.

Mechanical construction of the RFQ will be performed as a brazed structure with dual-circuit cooling water resonance control. Mechanical fabrication is performed in 5 longitudinal sections to optimize machining and handling. Although thermal management of CW RFQs is challenging, given the modest drive power, no significant cooling issue is expected. All components are made of high-conductivity copper and actively water cooled. Additional care is taken in the vane-undercut regions where the local RF heating is increased due to magnetic-field compression in these zones. The power is fed using a single magnetic-field loop-coupler drive.

Table 3: FRIB Front End RFQ design parameters. RF parameters obtained in CST Microwave Studio simulations.

| | |
|---|---|
| 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 |

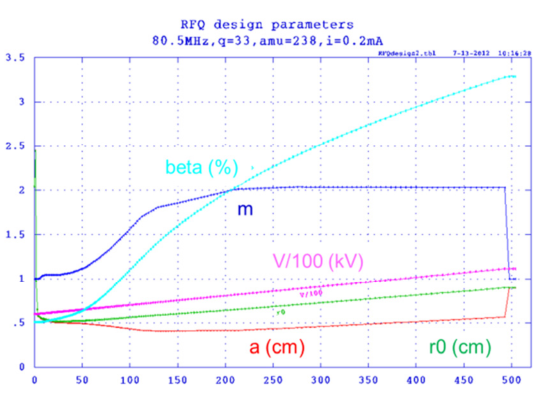


Figure 3: RFQ structure parameters as a function of the longitudinal coordinate (PARMTEQ notations).

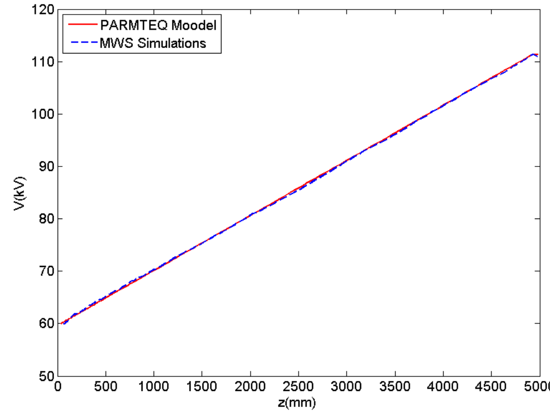


Figure 4: RFQ design voltage profile (red solid line) and the voltage profile simulated by CST MWS.

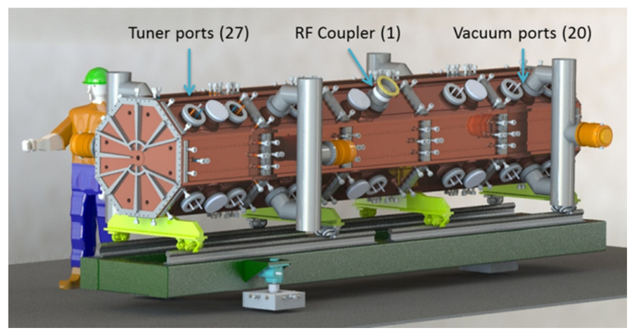


Figure 5: RFQ assembly drawing.

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