STATUS OF THE FRIB FRONT END*

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Abstract

The FRIB Front End will provide beams of stable ions with a mass up to uranium at a beam energy of 500 keV/u and intensity required to achieve a power of 400 kW on the fragmentation target. In this paper, we describe progress with the design and construction of the Front End and its systems.

DESIGN AND PERFORMANCE REQUIREMENTS

FRIB will be a premier multiuser nuclear physics facility providing stable ion beams accelerated to energies above 200 MeV/u and with a beam power on the target up to 400 kW [1]. These project requirements are translated into stringent requirements on the front end design and performance. The FRIB front end will provide stable ion beams up to uranium with an energy of 500 keV/u. The required intensity of uranium beam is 13.5 pμA and the charge state is 33+. This intensity is at the edge of performance demonstrated by modern ECR ion sources. To decrease technical risks and reduce operational stress on the sources, the front end is designed to transport two charge states simultaneously for all ions heavier than xenon with a charge state of 25 and higher. To control losses in the linac and meet experimental requirements the front end includes a collimation system to limit the transverse beam phase space. The longitudinal phase space is controlled by means of limiting the longitudinal acceptance of the RFQ. In addition, the front end will provide required variability of the bunch intensity by up to nine orders of magnitude to meet experimental needs. Beyond controlling the bunch intensity, it is also required to control the beam pulse length and the pulse repetition rate to simplify linac tuning and safely ramp up the beam power on the target.

High availability, maintainability, reliability, and tunability are required for the front end to operate FRIB as a national scientific user facility. These requirements, as well as project budget and schedule limitations require using proven, reliable technical solution as much as possible. However, those solutions frequently have to be taken to new levels with evolutionary changes and upgrades to demonstrate world-breaking performance required by the project.

Finally, to meet possible future programmatic demands the front end has to be upgradable and includes required provisions for future enhancements.

FRONT END LAYOUT

The FRIB front end includes two ECR sources, one of which is a room temperature 14 GHz source based on the ARTEMIS source developed at NSCL, and the other is a superconducting 28 GHz source based on VENUS design [2]. The beam extracted from the sources is transported through LEBT to the tunnel, where it is accelerated by an RFQ and injected into the SRF driver linac. The sources are placed on high voltage platforms that can be biased up to 100 kV to match the RFQ injection energy for all beams. Table 1 shows principle parameters of the Front End. The Front End layout is shown in Figure 1.

Table 1: 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

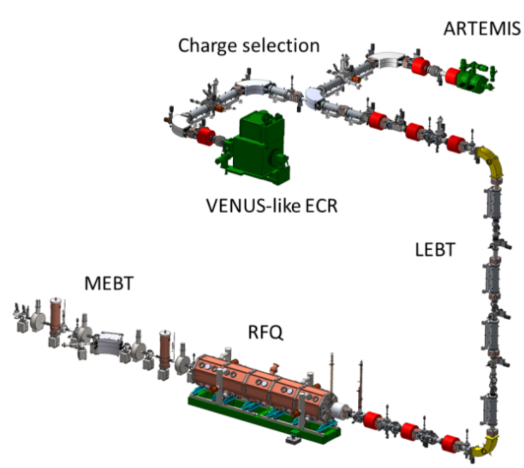

Figure 1: FRIB Front End layout.

FRONT END SYSTEMS

Ion Sources

The ARTEMIS ECR source, built at MSU and based on the AECR-U ECR developed at LBNL, operates at

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14.5 GHz with room temperature coils. The source will be used for commissioning FRIB and during some first years of operations for production of light and medium mass ions. Minimal re-configuration of the source is required to make the source compatible with operation on a high voltage platform and to boost its performance. The source currently produces 70 µA of Ar and Kr beams and will be able to generate up to 100 µA after upgrade.

The superconducting high-performance source will be based on the design of VENUS ECR ion source operating at a maximum frequency of 28 GHz. A world intensity record of 450 µA of U^{33+} was demonstrated by VENUS at LBNL in 2011. Figure 2 shows the M/Q scan with the source world-breaking record performance. The measured emittance for this charge state showed that 95% of the beam was within the FRIB acceptance.

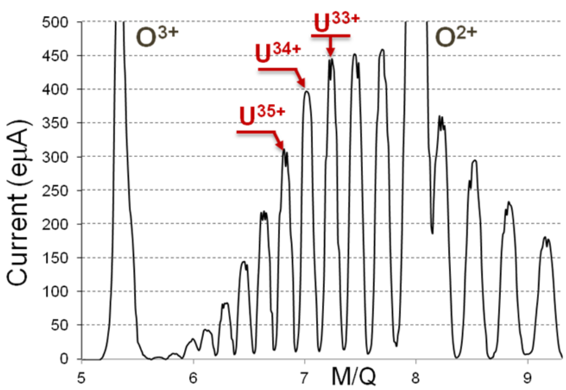

Figure 2: VENUS M/Q intensity scan for a uranium beam, demonstrating world record intensity of charge states 33+ and 34+.

The original VENUS cold mass design employs azimuthal bladders inflatable with liquid Indalloy to provide pre-stress. Once the metal is solid, the magnet could be disassembled only if the whole cold mass is warmed up above the metal's melting temperature, which has never been demonstrated. This design feature of the source was identified as a technical risk. To address the risk, a novel clamping scheme is pursued for the FRIB source. The scheme employs radial keys and water bladders to define the pre-stress state. This approach was developed by SUPERCON/LBNL for LARP high field magnets and allows for disassembling the magnet, changing components, and a fine control of the pre-stress state. A Collaboration between FRIB and LBNL was established to develop a design of the cold mass with radial keys.

In addition to the cold mass modifications, the cryostat will be modified comparatively to the original VENUS to include two GM-JT cryo-coolers to boost the cooling capacity from 6 W to 10 W to account for a higher dynamic heat load generated by the plasma Bremsstrahlung electrons and two Al-330 cryocoolers to cool the heat shield of the cryostat.

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 2 shows main RFQ parameters.

Table 2: 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 – 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

The RFQ beam physics design is optimized to minimize the longitudinal emittance of the accelerated beam as described in [3][4]. 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 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) [5] to accurately select required parameters and simulate fields and surface losses.

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. All components are made of high-conductivity copper and actively water cooled. The power is fed using a single magnetic-field loop-coupler drive. More information on the RFQ design can be found in [6].

Beam Transport and Other Systems

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, the FRIB front end was designed achromatic, able to accelerate two charge states from an ion source to double intensity. Although recent tests demonstrated that significantly better performance from VENUS can be achieved, a decision was made to leave the front end design unchanged. To facilitate transport of two-charge state beams through the LEBT electrostatic quadrupoles and two 90° deflectors are used in the vertical transport line.

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The electrostatic quadrupoles were designed by Kurt Stiebing, manufactured by Roentdek Handles GMBH, and delivered to FRIB in August of 2013. The quadrupole assemblies were made of precision-stamped formed metal to reduce cost and weight of the assemblies. The measured manufacturing errors of the quadrupole assemblies are typically less than 200 µm that satisfies FRIB requirements. Figure 3 shows a photograph of a triplet assembly.

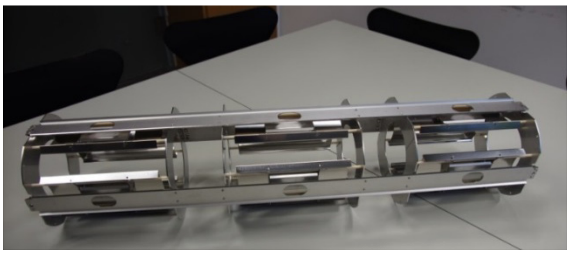

Figure 3: Electrostatic LEBT quadrupole triplet assembly. The length of the assembly is 91 cm.

Upstream of the RFQ, LEBT includes a multiharmonic buncher and a velocity equalizer, both are room-temperature low-power quarter wave resonator cavities. The former is used to bunch the DC beam and the latter is required to eliminate the energy spread of two charge state beams before injecting beams into the RFQ.

To reduce losses in the superconducting linac, the beam is collimated by several apertures in the LEBT. The front end includes a chopper to vary the duty cycle. The buncher will control the pulse length from several hundreds of ns to CW and the pulse frequency from 0 to 30 kHz. Several mesh screens installed in LEBT allow for reducing the beam intensity by up to nine orders of magnitude while keeping the nominal bunch frequency unchanged. 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.

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.

SUMMARY OF PROGRESS

The design of front end systems and early procurement of high priority items are ongoing. The low energy multi-harmonic buncher and electrostatic quads were manufactured and delivered. The commissioning source ARTMEIS is undergoing minor modifications to make it compatible with operations on a high voltage platform. The physics design and the preliminary engineering design of the RFQ have been completed. A design-build contract for the final design and manufacturing of the RFQ was awarded to industry. The final engineering design of the RFQ is in progress. Delivery of the RFQ and its high power test are expected in the summer of 2015. The design of the MEBT quarter wave resonators is in its final stage. Their procurement is expected to begin by the end of 2013. The design of the cold mass of the high performance source is being developed in collaboration with LBNL. It is important to emphasize that the high performance source is not required to start commissioning of the front end and will be brought online approximately a year after the start of commissioning but before the end of the project.

The front end design was integrated with civil facilities to allow for starting civil construction. Also, the front end was integrated with other accelerator and experimental systems. The design was value engineered. One example is the increase of the RFQ energy from the originally planned 300 keV/u to 500 keV/u by implementing voltage ramping that allowed eliminating one cryomodule. Commissioning of the front end with the room temperature source is expected to start in the fall of 2017.

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