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UPGRADE OF THE FRIB ReACCELERATOR*

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Abstract

The ReAccelerator facility at FRIB was upgraded to provide new science opportunities. The upgrade included a new ion source to produce stable and long livied rare isotopes in a batch mode, a new room-temperature rebuncher, a new β = .085 quarter-wave-resonator cryomodule to increase the beam energy from 3 MeV/u to 6 MeV/u for ions with a charge-to-mass ratio of 1/4, and a new experimental vault with beamlines.

INTRODUCTION

The ReAccelerator (ReA) at FRIB [1] is a worldwide unique facility accelerating rare isotope beams to energies of 3 MeV/u for ions with a charge-to-mass ratio of 1/4. The rare isotopes are initially produced in-flight by projectile fragmentation or fission, stopped in gas cells and re-injected in ReA for reacceleration. ReA has been operated since 2015.

In order to provide broader opportunities for nuclear experiments with higher beam energies, an upgrade of ReA was started in May 2019 with the goal to double the final beam energy and to add experimental stations. The ReA facility upgrade, which was completed in April 2021, included a new Batch Mode Ion Source (BMIS) to provide beams of longer-lived isotopes, a room-temperature rebuncher at 161 MHz, a new cryomodule with β = 0.085 quarter wave resonators to increase the beam energy from 3 MeV/u to 6 MeV/u for ions with a charge-to-mass ratio of 1/4, and two beamlines in a new experimental vault.

In this contribution we shall present the new Batch-Mode-Ion-Source (BMIS), the rebuncher as well as the new cryomodule and beam lines, the beam optics calculations, and commissioning results. Finally, we shall provide the list of beams used for experiments after the commissioning of the upgrade.

THE ReACCELERATOR

The ReA was originally built to reaccelerate beams of rare isotopes produced and separated in-flight by the Coupled Cyclotron Facility. With the completion of the FRIB facility, ReA will be able to reaccelerate beams produced with primary beams from a superconducting heavy-ion linac and separated by the Advanced Rare Isotope Separator ARIS [2].

After separation, rare isotope beams are injected in one of two beam stopper systems [3], are mass separated and injected into a beam-cooler-buncher (BCB). The BCB is a buffer-gas filled linear radio-frequency quadrupole ion trap with axial and radial confinement of ions in a buffer gas, designed to improve the optical properties by cooling and to convert the incoming continuous beam into bunches for efficient injection and capture in the Electron Beam Ion Trap (EBIT) [4]. In the EBIT, trapped ions are charge-bred for achieving charge states compatible with the needs for acceleration and beam purity. After the EBIT, the beam is mass selected in an achromatic Q/A separator and injected into a multi-harmonic buncher at an energy of 12 keV/u. There it is bunched to match the operation frequency of the Radio Frequency Quadrupole (RFQ) of 80.5 MHz [5].

Following the RFQ, the beam is injected into a sequence of 3 cryomodules with quarter wave resonators (QWR) and superconducting solenoids (SS). A total of seven QWR with β = 0.041, eight QWRs with β = 0.085, and eight SS provide acceleration and focusing for the ensemble initially called ReA3. Following the accelerator, the beam can be energy-analyzed and sent to an experimental area with three beam lines: One is dedicated to the recoil spectrometer SECAR [6] for astrophysics studies, while two others are general purpose beam lines. With the accelerator upgrade the beam can now be rebunched and injected into the new cryomodule, which allows acceleration up to 6 MeV/u for a charge-to-mass ratio of 1/4 and sent to a new experimental area with two beam lines for experiments.

Stable beams and more recently long living rare isotopes can also be accelerated by ReA. Two 1+ ion sources can inject beams directly into the BCB. The BMIS, located in the N4 vault, is based on the ISOLDE/VADIS target/ion source [7] coupled to a front-end. Its initial purpose was to provide beams of stable and long-lived rare isotope beam for reacceleration during the time NSCL's coupled cyclotron facility was shut down in the transition phase of FRIB project completion and start of operation. Following its successful operation, BMIS will also be used for standalone operation of ReA in the FRIB era.

THE ReA PROJECT

The upgrades to the ReAccelerator are shown in Fig. 1. The ReA6 cryomodule and the new experimental areas are located in shielded vaults designed for the purpose of

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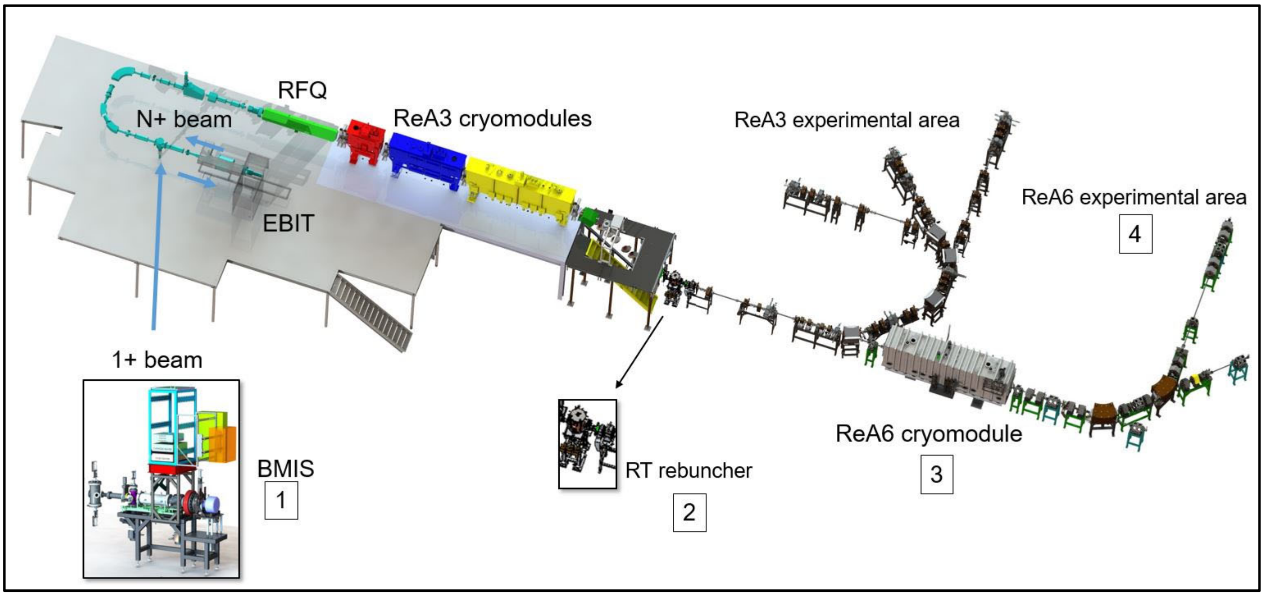

Figure 1: The stopped and reaccelerated beam areas at FRIB; the upgrades are indicated as: 1) batch mode ion source (BMIS); 2) room-temperature (RT) rebuncher; 3) ReA6 cryomodule and 4) new experiment beamlines.

radio-protection against neutrons. The upgrade profited from elements already developed either for the previous ReA3 or for the FRIB linac.

The Batch Mode Ion Source

The Batch Mode Ion Source (BMIS) is located in the shielded vault that also accommodates the beam stopping systems. BMIS has been built following designs and concepts developed and employed at ISOLDE/CERN. BMIS consists of an oven ion-source (OIS) module coupled to a front-end with optics elements for beam transport. The OIS for BMIS is an ISOLDE target module with a VADIS [7] plasma ion source, shown in Fig. 2. The target container serves as an oven holding the material for the desired beam. BMIS can provide beams for stopped and reaccelerated beam experiments.

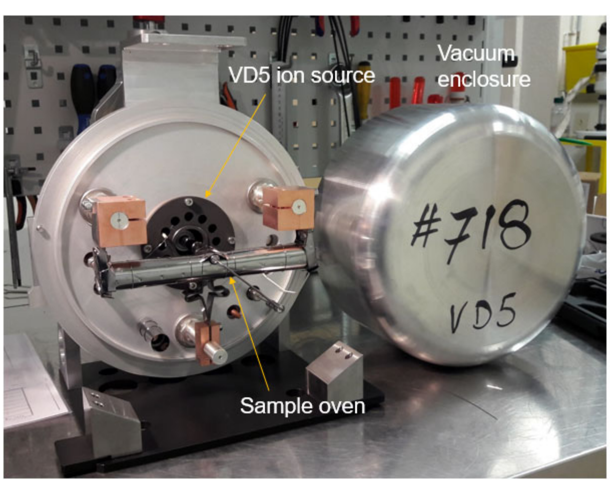

Figure 2: BMIS source.

Several beams were developed since the commissioning of BMIS for stand-alone operations. The first beam developed and used in an experiment was Be-10 for which NF3 was introduced into the oven as a reaction gas to create a fluoride for lower temperature release. Subsequent beam developments included the stable isotopes Na-23, Sr-88, Cr-50, Fe-58, Ni-60, Si-28, and Si-30, as well as the long-lived isotopes Be-7, Al-26, and Si-32.

The Room-Temperature Rebuncher

The new room-temperature rebuncher was built for longitudinal beam matching between the ReA3 linac and the new ReA6. The rebuncher cavity is a double-gap quarter-wave resonator operating at 161 MHz which is a second harmonic of the beam frequency. This lets one reduce the bunching voltage by a factor of two and therefore greatly decrease the RF power consumption allowing for a room-temperature design possible. The cavity is only 0.6-meter-high and has an inner tank diameter of 0.3 m. It has $\beta_{opt} = 0.1$ and allows the entire range of ReA3 beam energies above 1.2 MeV/u to be covered for any beam species, as presented in Fig. 3. In addition to matching beams to the ReA6 module, the cavity provides debunching (i.e. minimizing the beam energy spread) for ReA3 beam users. In the $3{\cdot}\beta\lambda/2$-mode the rebuncher is also capable of covering the 0.3–1.0-MeV/u energy range.

The mechanical design features of the rebuncher cavity are the same as those of the FRIB H-type rebunchers [8]. The stem with the central drift tube, tank body, tuners, and side drift tubes, were machined from copper, and then brazed to stainless steel flanges. The top lid is bimetal, while the bottom one is copper-plated. The drift-tube stem and the top lid were brazed together without any flanges in between, because this joint is exposed to high RF current densities.

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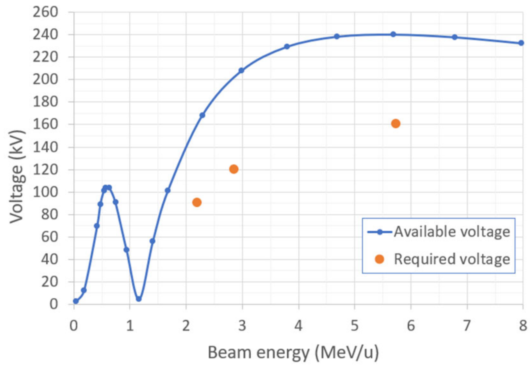

Figure 3: Effective voltage available from the rebuncher with a 6-kW RF power amplifier, and the voltages required for matching to ReA6 cryomodule.

For similar reason, the joint between the tank and the top lid is equipped with a canted-coil spring. The side drift tubes are connected to the tank via the flanges, which allow to easily change them in the future to adjust the geometrical β of the cavity, if needed. The cavity is equipped with two capacitive tuners. One of them is stationary and was used for fine frequency adjustment during the manufacturing, and another one is movable and being used for operation.

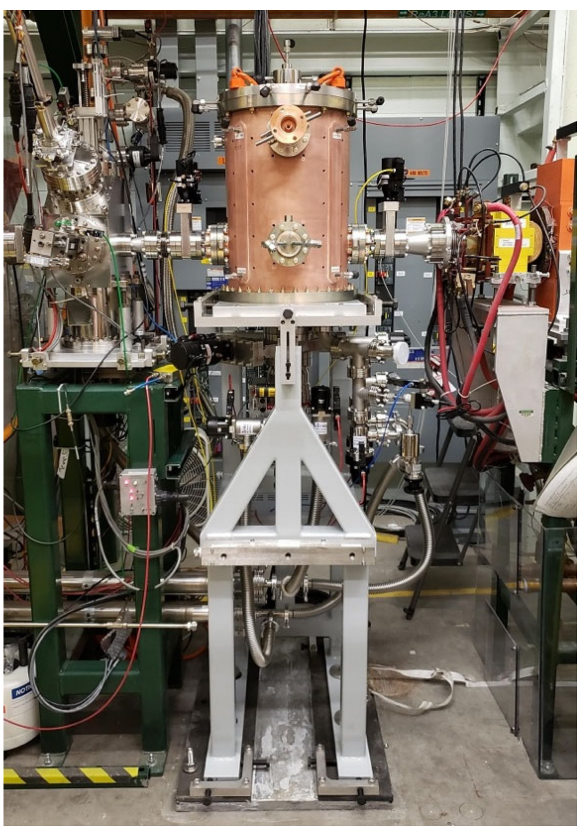
Figure 4: Room temperature rebuncher installed in the beamline.

Following the design of the FRIB H-type bunchers, the ReA rebuncher does not have any water-to-vacuum joints. The assembled rebuncher in the beamline is presented in Fig. 4. The tank body has four cooling channels with water supply and return on the external side wall. The steel part of the top lid has four L-shaped channels with supply and return through the side wall of the flange. The side drift tubes, tuners, and the RF power coupler are also water-cooled. The central stems with a drift tube has a long straight channel with a double-threaded insert supplying the cooling water inside of it directly toward the drift tube, and returning it via double-spiral paths up to the top lid. We believe the double spiral increases the cavity availability (in case of a blockage of one of the channels) unlike the single-spiral channel of the FRIB H-type bunchers. The central drift tube does not have any cooling channels for simple machining and avoiding water-to-vacuum brazed joints.

The cavity was installed and conditioned in early 2021 and followed by the ReA6 beam commissioning in April, 2021. The maximum voltage of 200 kV was achieved at 5 kW of input RF power, and maintaining the peak surface fields at moderate levels of 0.6 Kilpatrick units, which guarantees the breakdown-free operation. Although the pressure gauges show some evidence of multipacting in the cavity, it does not present an issue thanks to the successful RF conditioning. Thanks to the direct supply of water toward the central drift tube, its temperature remains way below the water boiling point. The temperature gradient between the stem and the drift tube is only around 12 K, and does not present any issue because the drift tube and the stem are machined from a single piece of copper. One can see a significant temperature gradient between the stem and the threaded insert. This also does not cause a mechanical stress issue because the inner diameter of the stem channel is slightly larger than the outer diameter of the threaded insert that the stem may freely expand.

The ReA6 Cryomodule

For the accelerating cryomodule of ReA6 Upgrade, we chose to use a FRIB β=0.085 quarter-wave resonator (QWR) cryomodule, the same type as used in the FRIB driver linac [9]. The cryomodule, installed in the beamline is shown in Fig. 5. This is to minimize technical and schedule risks of the ReA6 Upgrade project as FRIB cryomodule production is matured and performance of 11 cryomodules of the same type has already been verified in RF and beam commissioning in the FRIB driver linac [10]. With this approach, we were able to complete cryomodule cooldown and commissioning in a timely fashion: starting ReA6 cryomodule cooldown in March 2021 and delivering beams to users in May 2021. The ReA6 cryomodule contains eight QWRs and three superconducting solenoid packages. Their specifications are shown in Table 1.

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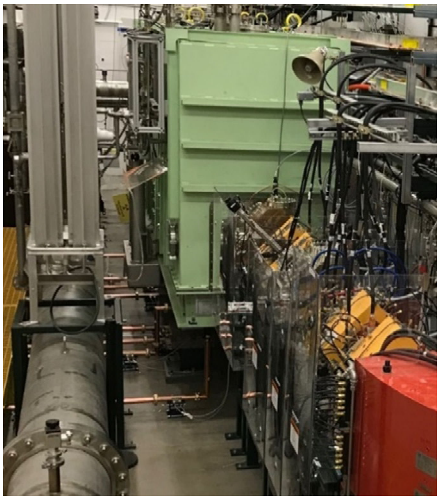

Figure 5: ReA6 cryomodule installed in the beamline.

Table 1: ReA6 Cryomodule SRF Cavity and SC Solenoid Parameters

Parameter	Value
Cavity (8 ea)	
Operating Temperature	4.3 K
Frequency	80.5 MHz
β	0.085
Accelerating gradient E_{acc}	5.6 MV/m
R/Q (shunt impedance)	455 Ohm
Geometric factor $G = Q_0 {*} R_s$	22 Ohm
Peak surface electric field E_{peak}*	33 MV/m
Peak surface magnetic field*	69 mT
Solenoid integrated with XY dipole steering coils	
Bmax	8 T
Operation current	100 A

*At the nominal condition, E_{acc} = 5.6 MV/m

In the commissioning, we achieved the nominal accelerating gradient, 5.6 MV/m for β = 0.085 particles, in all eight cavities. RF field calibration was done by measuring fundamental power coupler (FPC), Q_{ext} (coupling strength of input coupler) and transmission coefficient at resonance using a vector network analyzer, the same method as used for the FRIB driver linac. Errors of this RF calibration were within 3% compared to beam based calibration. Phase and amplitude stabilities met the FRIB requirements, ±1° and ±1% respectively, with ample margins. No issues in long-term stabilities of phase lock were observed in the commissioning and, thereafter, user operation. Alignment of the solenoids and cavities was done in the same way as the FRIB cryomodules [11]. In the beam commissioning, beam trajectories were corrected with minimal currents of the dipole steering coils, which indicates the cold cavities and solenoids are well aligned to the ideal beam axis.

Beam Diagnostics

The diagnostics for the ReA6 accelerator and beamline upgrade are largely based on proven diagnostic designs used in the ReA3 accelerator and the experimental beamlines. These designs were modified slightly to account for improvements and lessons learned during ReA3 commissioning and experimental operation. Twenty nine diagnostic drives were fabricated, assembled, and installed in the eight beamline diagnostic boxes for initial commissioning and experimental operation of ReA6.

Seven new Faraday cups are installed throughout the ReA6 beamline for beam intensity and transport efficiency measurements. These hemispherical shaped cups are fabricated from niobium with an aperture of 40 mm (Fig. 6). An electron repeller ring at the front is supplied voltage from a negative 500 VDC maximum supply with variable voltage output control provided through the control system. A nominal –48 VDC has been shown to be sufficient for secondary electron suppression for most beams.

Figure 6: Faraday cup and scintillator viewer assemblies.

Current is read through a commercial electrometer capable of detecting currents on a ~10 fA level. Electrical noise is reduced by using triaxial cable between the BNC feedthrough on the Faraday cup vacuum flange and the electrometer, with the electrometer being positioned as close as reasonably possible to the feedthrough.

Six scintillator viewers are positioned at key optics locations throughout the beamline for viewing the transverse size, shape, and position of the beam. These consist of a 45-degree wedge-shaped holder supporting a 1.5-mm thick by 19-mm diameter CsI(Tl) crystal. This scintillation material was chosen both due to its low potential for particulate generation, as well as its high light output and radiation hardness exhibited in previous ReA3 tests comparing crystal scintillation materials [12].

Video images taken through viewports on opposing flanges are provided remotely by 1/3" CCD bullet cameras equipped with 25-mm focal length lenses fed into a 16-channel digital video encoder with Ethernet interface.

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A commercial 14.5-mm diameter 2-stage microchannel plate (MCP) with sub-nanosecond rise time is located in the diagnostic box just upstream of the ReA6 accelerating cryomodule. This allows for bunch length measurements of the attenuated impinging beam. The beam's longitudinal bunch structure can then be optimized before acceleration by adjusting the upstream room temperature rebuncher RF cavity amplitude.

A single ion-implanted 0-degree silicon detector with 500-µm depletion depth and 19.5-mm diameter active area is installed in the straight section downstream of the cryomodule. This allows for phasing of the 8-SRF accelerating cavities, as well as ion mass contamination measurements. Readout of the silicon detector is accomplished using a digital signal analyzer, which can create a histogram energy spectrum directly from the detector pre-amplifier signal output.

Beam Optics

The calculated beam envelope from the entrance of the new ReA6 to the end of each new beamline was calculated to define gradients and positions of all beam optics elements. The SOLARIS beamline is shown as example in Fig. 7. Experimental results matched calculations.

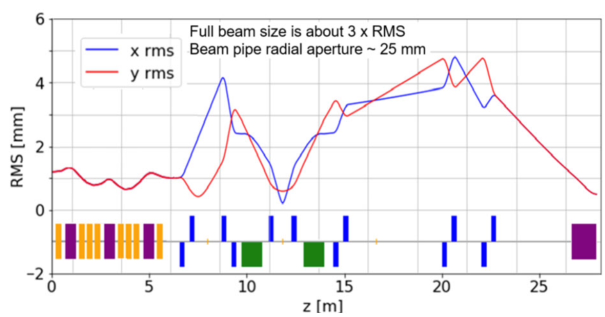

Figure 7: Calculated beam envelope RMS (mm) from the entrance of the ReA6 cryomodule to the end of the SOLARIS beamline; the two dipoles are represented by the green squares, quadrupoles by the blue rectangles (up horizontal focusing and down vertical focusing).

COMMISSIONING AND FIRST EXPERIMENTS

Commissioning of the ReA6 was performed using the beams of $^{14}N(6+)$ and $^{20}Ne(9+)$. For both beams, the design energy of 10.2 MeV/u was achieved. The transmission through the whole SC-linac and both beam lines very close to 100%. The scaling from $^{14}N(6+)$ to $^{20}Ne(9+)$ was performed automatically ($Q/A = 0.428$ to $Q/A = 0.45$) over merely 5 minutes, and required minimal steering correction after the cryomodule. The new rebuncher was used to focus longitudinally the beam in the entrance of the new cryomodule. The longitudinal beam shape was optimized to have a FWHM of 11.5° using the new microchannel plate system.

Table 2: Selected beams accelerated by ReA6. The intensity corresponds to that requested and delivered to experiments. The ion sources are indicated. Colutron is the ion source directly coupled with the BCB.

Isotope	Energy (MeV/u)	Intensity (pps)	Source
^{7}Be	7.4	10^5	BMIS
^{10}Be	9.6	10^6	BMIS
^{14}N	10.2	$2.0x10^7$	EBIT residual
^{16}O	10.2	5000	Colutron
^{20}Ne	10.2	10^6	Colutron
^{32}Si	8.45	10^6	BMIS
^{50}Cr	9.5	10^6	BMIS
^{86}Kr	3.85	$3.0x10^7$	BMIS
^{112}Sn	3.85	10^6	Colutron
^{116}Sn	3.81	10^6	Colutron
^{120}Sn	3.73	10^6	BMIS

Since ReA6 was commissioned, 10 different experiments have received beams in the two ReA6 beam lines. Examples of the experimental setups were the ATTPC and Silicon detectors in SOLARIS [13] and SEGA in barrel and plunger mode [14]. Table 2 lists the beams delivered up to March 2022. Beam purity verification, is performed with a silicon detectors and a thin foil. The energy loss of the beam in the foils allows discrimination between isobars.

CONCLUSION

The upgrade of the ReAccelerator (ReA6), including the new Batch Mode Ion Source, a new room-temperature rebuncher, a new cryomodule with eight SC-resonators and two beamlines in a new experimental vault was successfully completed. The measured beam properties of ReA6 agree with those expected from calculations. ReA6 has already been used for a number of experiments since March 2021 involving stable and long-lived rare isotope beams.

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