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REACCELERATOR UPGRADE, COMMISSIONING AND FIRST EXPERIMENTS AT THE NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY (NSCL) / FACILITY FOR RARE ISOTOPE BEAMS (FRIB)*

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Abstract

The reaccelerator ReA is a state-of-the-art super-conducting linac for reaccelerating rare isotope beams produced via inflight fragmentation or fission and subsequent beam stopping. ReA was subject of an upgrade that increased its final beam energy from 3 MeV/u to 6 MeV/u for ions with charge over mass equal to 1/4. The upgrade included a new room-temperature rebuncher after the first section of acceleration, a new beta = 0.085 QWR cryomodule and two new beamlines in a new experimental vault. During commissioning, beams were accelerated with near 100 percent transport efficiency through the linac and delivered through beam transport lines. Measured beam characteristics match those calculated. Following commissioning, stable and long living rare isotope beams from a Batch Mode Ion Source (BMIS) were accelerated and delivered to experiments. This contribution will briefly describe the upgrade, and results from beam commissioning and beam delivery for experiments.

INTRODUCTION

The reaccelerator (ReA) at NSCL/FRIB [1] is a worldwide unique facility accelerating rare isotope beams, which are initially produced by projectile fragmentation or fusion-fission and stopped in gas cells. ReA has been operated since 2015 accelerating rare or stable isotope beams from 0.3 MeV/u to 3 MeV/u for the mass to charge ratio (Q/A) of 4 and 6 MeV/u for Q/A of 2.

Low-energy beams from the beam stopping facilities are mass separated and injected into a beam-cooler-buncher (BCB). The BCB is a radio-frequency quadrupolar 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) [2]. In the EBIT, the beam is charge breed for achieving charge states compatible with the needs for acceleration and beam purity. After the EBIT, the beam is mass selected in the achromatic Q/A separator and injected at the energy of 12 keV/u in a multi-harmonic buncher, where it is buched to the operation frequency of the Radio Frequency Quadrupole (RFQ) at 80.5 MHz [3]. Following the RFQ, the beam is injected into the first superconducting quarter wave resonator (QWR) with beta = 0.041 acting as a rebuncher. Two superconducting solenoids (SS) with a maximum field of 9 T are installed in this cryomodule. Following the rebuncher, a first accelerating cryomodule has six QWRs with beta = 0.041 and three SS. The third and last cryomodule of ReA3 has eight QWRs with beta = 0.085 and three SS. Following the accelerator, the beam is energy analyzed and sent to an experimental area with three beam lines, one dedicated to the spectrometer SECAR for astrophysics studies, and two others general purpose without permanent experimental setups.

For providing broader opportunities for nuclear physics experiments with higher beam energies, an upgrade of ReA was started in May 2019 with the goal to double the final beam energy and add new experimental stations with equipment adapted to the new scientific areas. The upgrade, which was completed in April 2021, included a new room-temperature rebuncher at 161 MHz after the first section of the accelerator, a new FRIB-style cryomodule [4] with beta = 0.085 quarter wave resonators and two beamlines in a new experimental vault adapted to higher energies.

Simultaneously, a Batch-mode-ion source (BMIS) was completed. BMIS is based on the ISOLDE/VADIS target/ion source [5]. Its purpose is to provide beams of stable of 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.

In this contribution we'll briefly present the new rebuncher as well as the new cryomodule and beam lines, the beam optics calculations and commissioning results. Finally, we'll provide information regarding beams used for experiments after the commissioning of the upgrade.

THE REA6 PROJECT

The low energy and reaccelerator areas as well as the new upgrade of the reaccelerator (called ReA6) is shown in Fig. 1. Labels 1, 2, 3 and 4 indicate the location of the batch mode ion source, the new room-temperature rebuncher, the new cryomodule and the new experimental area. The new cryomodule for ReA6 is identical to the ones

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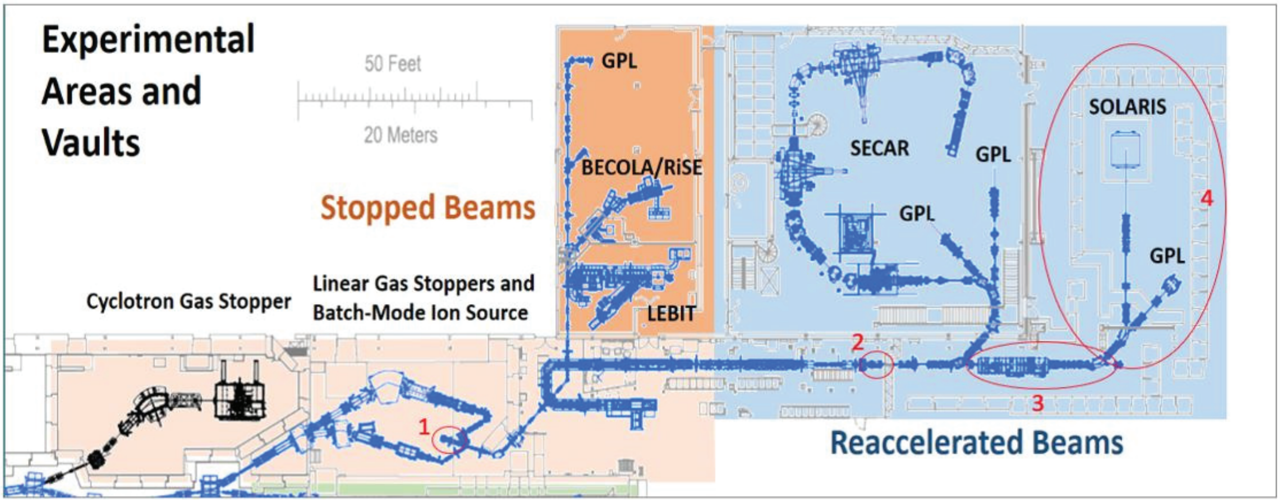

Figure 1: The stopped and reaccelerated beam areas of the NSCL/FRIB facility; the upgrades are indicated as: 1) batch mode ion source; 2) room-temperature rebuncher; 3) new cryomodule and 4) new experiment beamlines.

used in FRIB with eight beta = 0.085 QWR resonators and three superconducting solenoids. The ReA6 cryomodule and the new experimental areas are located in shielded vaults for the purpose of radioprotection against neutrons. The upgrade profited from elements already developed either for the previous ReA3 or for the FRIB linac. The two beam analyzing dipoles after ReA6 and the quadrupoles are the same as ones used in the first section of the FRIB linac. All steerers are the same as those already present in ReA3. Except for minor improvements the diagnostics are the same used in ReA3 and designed to for detecting a wide range of beam intensities. Beam viewers are based on CsI(Tl) crystals and a CCD camera, which are sensitive down to about 1,000 pps. Faraday cups can be reliably used down to about 50 fA with an error of about 10 fA. The response time of Faraday cups can be adjusted to meet beam tuning requirements.

Silicon detectors in the end of the straight section noted as "3" in Fig.1 or in front of the experimental devices are also used as tools to perform phasing of the SC-linac, to measure extremely low beam intensities, or identify contaminants of the beam.

All diagnostics are interceptive and can be remotely positioned in the beamline.

The Room-Temperature Rebuncher

A 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 to reduce the bunching voltage by a factor of two and therefore greatly decrease the RF power consumption making the design possible. The cavity is only 0.6 m high and has an inner tank diameter of 0.3 m. Its $\beta_{opt} = 0.1$ allows us to cover the whole range of ReA3 beam energies above 1.2 MeV/u for any beam species accelerated in the linac. 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 successful RF conditioning. In addition to matching beams to the ReA6 cryomodule, the cavity provides debunching (i.e. minimizing the beam energy spread) for ReA3 experiments. In the $3{\cdot}\beta\lambda/2$-mode the rebuncher can also cover 0.3 – 1.0 MeV/u range.

The Reaccelerator

The cryomodule of ReA6 contains eight beta = 0.085 80.5 MHz quarter waver resonators and three SC solenoids, equivalent to the ReA3 third cryomodule. This cryomodule is the 12th of the QWR085 FRIB series, operating at 4.3K, phase locked at average of 6 MV/m. Phase and amplitude stabilities met the FRIB specifications of ± 1% and ± 1°, like FRIB cryomodules. The calculated beam envelope from the entrance of the new ReA6 to the end of SOLARIS beamline is shown as example in Fig. 2.

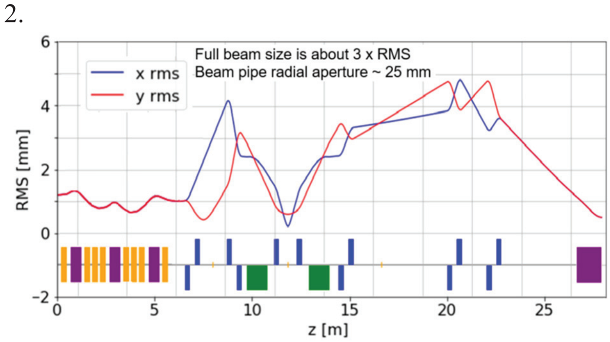

Figure 2: Calculated beam envelope RMS (mm) from the entrance of the ReA6 cryomodule to the end of the SOLARIS beamline; the two dipoles are represented by the green squares, quadrupoles by the blue rectangles (up horizontal focusing and down vertical focusing).

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COMMISSIONING AND FIRST EXPERIMENTS

Commissioning of the whole ReA6 elements was performed using the isotopic 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 was close to 100%. The scaling from ^{14}N(6+) to ^{20}Ne(9+) was fast, performed automatically (Q/A = 0.428 to Q/A = 0.45) and requested a minimum of steering correction after the cryomodule.

The new rebuncher was used to focus longitudinally the beam in the entrance of the new cryomodule. A new micro-channel plate detector placed upstream the cryomodule was used to tune its phase and voltage. The longitudinal beam shape was optimized to have a FWHM of 11.5°.

The beam accelerated by the LINAC was detected by a silicon detector downstream the cryomodule, which was also used to phase the resonators. The energy gain per resonator is shown in Fig. 3 for ^{14}N(6+) beam. The entrance energy of the beam in the cryomodule is 4.9 MeV/u and the energy at exit is 10.2 MeV/u. Each peak corresponds to the energy gain per resonator.

The beam was transported successfully with no losses up to the end of each new beamline. As an example, Fig. 4 shows the image of the beam at a viewer at the end of one of the beamlines. Note that the beam is illuminating the central orifice of the viewer (1 mm diameter) which indicates the center of the beam-line. Up to the time when this contribution was written, ReA6 delivered a total of 17 different beams for commissioning and experiments, including stable pilot beams as well as rare isotope beams from the BMIS. A selected list of the beams accelerated in ReA6 is provided in Table 1.

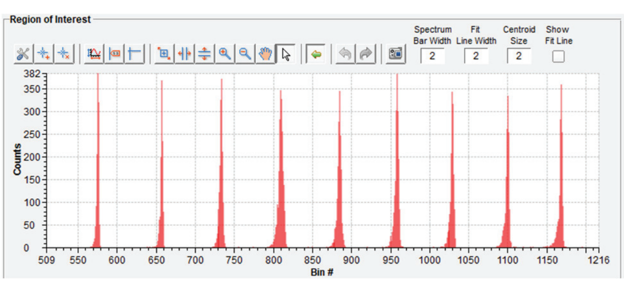

Figure 3: Silicon detector spectrum showing the energy gain per resonator of ReA6; The energy at entrance (first peak) of the cryomodule is 4.9 MeV/u and the energy at exit (last peak) is 10.2 MeV/u.

CONCLUSION

The upgrade of ReA accelerator (ReA6), with 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 properties of ReA6 agree with those expected from calculations. ReA6 was already used for a number of experiments since March 2021 involving stable and rare isotope beams.

Figure 4: ^{14}N(6+) at 10.2 MeV/u image in the SOLARIS viewer, see text for details.

Table 1: Selected beams accelerated by ReA6, the intensity corresponds to that requested and delivered to experiments

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	2.0×10^7	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	3.0×10^7	BMIS
^{112}Sn	3.85	10^6	Colutron
^{116}Sn	3.81	10^6	Colutron
^{120}Sn	3.73	10^6	BMIS

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