

ReA3 – THE RARE ISOTOPE REACCELERATOR AT MSU*

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Abstract

Rare isotope beam (RIB) accelerator facilities provide rich research opportunities in nuclear physics in particular for nuclear structure physics, nuclear astrophysics and applied physics. The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) is constructing a RIB facility, called 'ReA3'. The facility will provide unique low-energy rare isotope beams by stopping RIBs produced in-flight and reaccelerating them in a compact linac. ReA3 comprises gas stopper systems, an Electron Beam Ion Trap (EBIT) charge state booster, a room temperature radio frequency quadrupole (RFQ), a linac using superconducting quarter wave resonators (QWRs) and an achromatic beam transport and distribution line to the new experimental area. Beams from ReA3 will range from 3 MeV/u for heavy ions to about 6 MeV/u for light ions, as the charge state of the ions can be adjusted by the EBIT. ReA3 will initially use beams from NSCL's Coupled Cyclotron Facility (CCF). Later ReA3 will provide reacceleration capability for the Facility for Rare Isotope Beams (FRIB), a new national user facility funded by the Department of Energy (DOE) that will be hosted at MSU. The ReA3 concept and status of ReA3 will be presented, with emphasis on the commissioning of the facility, which is underway.

INTRODUCTION

The nuclear science community will require reaccelerated beams in a range of kinetic energies from thermal to near 20 MeV/u. The scientific potential with reaccelerated beams comprises a rich experimental program ranging from low-energy Coulomb excitation experiments and transfer reaction studies to the study of astrophysical reactions. The combination of a re-accelerator to a gas stopper is of particular importance, since it will provide high quality beams of nuclei not available in this energy regime at any other facility. MSU is presently constructing a re-accelerator [1], called ReA3, that will be capable of accelerating ions with a charge-to-mass ratio $q/m=0.25$ to 3 MeV/u and 6 MeV/u for $q/m=0.5$. ReA3 funding is provided by MSU, whereas commissioning and operation is supported by NSF.

Any re-acceleration concept must provide a high

efficiency of more 20% for ions of all elements available at the facility. Furthermore, beam rate capabilities greater than $10^8/s$ are required which exceed that of the linear gas stoppers and matches the secondary beam rates at FRIB. Finally, a high beam purity to minimize background at the experimental setups and a variable time structure to satisfy the user needs are mandatory. The re-acceleration scheme implemented in ReA3 was optimized with respect to these requirements. It is based on the acceleration of highly charged ($n+$) ions instead of a scheme based on the acceleration of singly-charged ($1+$) ions and stripping. The $n+$ reacceleration scheme has been recognized as the most promising option for the re-acceleration of rare isotopes at present and future facilities for rare isotope research. Charge breeding eliminates conventional electron stripping and its significant losses in efficiency and it allows for a much simpler accelerator structure and makes the accelerator shorter and less expensive [2].

OVERVIEW OF ReA3

Figure 1 illustrates the $n+$ reacceleration concept chosen for ReA3. Rare isotope beams produced by projectile fragmentation and with typical energies above 50 MeV/u will be injected into a gas stopping system, either a linear gas cell or a cyclotron gas stopper. The beam transport of the 60 keV singly charged ions from the gas stopper systems towards the ReA3 platform is provided by electrostatic elements. The cooled beam from the gas stopper will be mass analyzed before it is guided to the electron beam ion trap (EBIT) on the platform that is operated as a charge state breeder. The elements on the ReA3 platform are shown in more detail in Fig. 2, because the main fraction of the hardware on the deck is already installed.

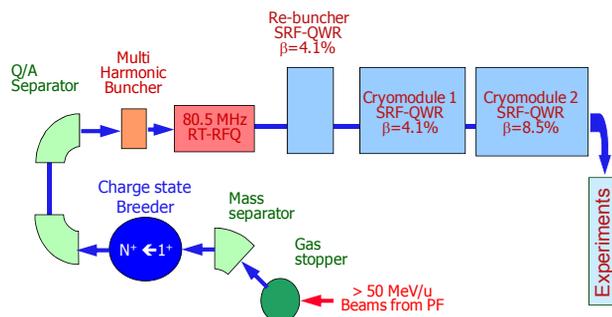


Figure 1: Reacceleration concept for ReA3.

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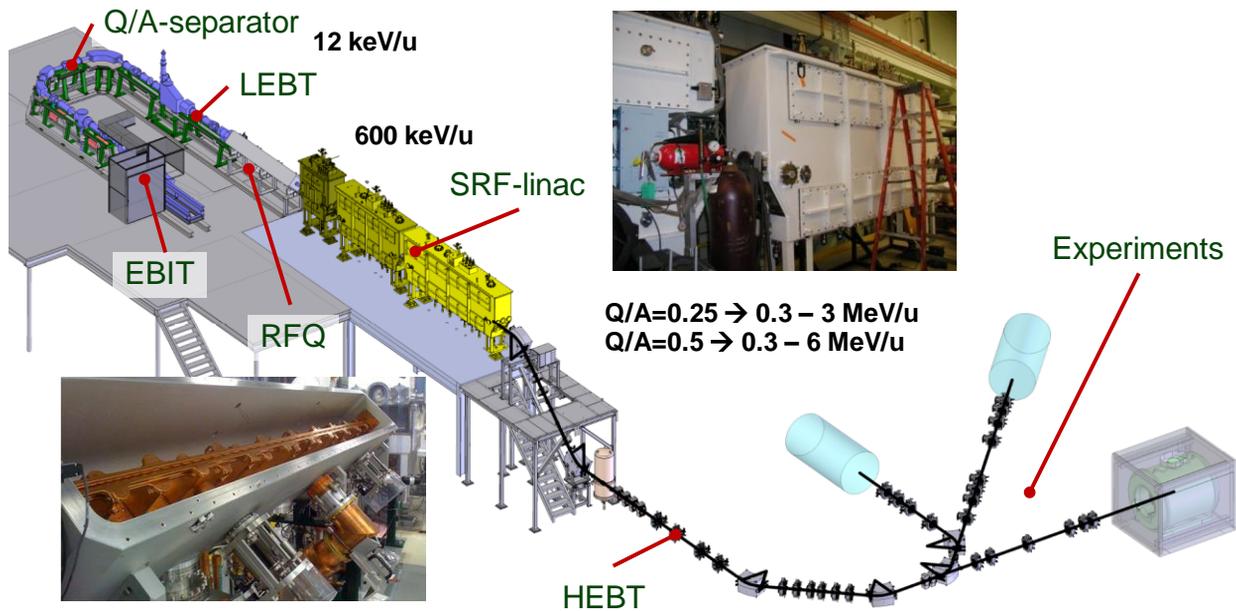


Figure 2: Overview ReA3 linac on the platform and the HEBT area.

Subsequently after the charge breeding process the n^+ ions are extracted from the breeder and guided towards an achromatic charge state (Q/A) separator at an energy of 12 keV/u. The separator selects the desired charge state and suppresses unwanted background ions before the beam enters the accelerator section. The ReA3 LEBT will transport, bunch and match beams from the Q/A -separator into the acceptance of the 4-rod RFQ. To achieve a small longitudinal emittance, an external Multi-Harmonic Buncher (MHB) is used in the LEBT.

The linac of the reaccelerator consists of a room temperature RFQ and a superconducting (SC) linac. The ReA3 4-rod RFQ will accelerate beams from 12 keV/u to 600 keV/u with a Q/A ratio between 0.2 and 0.5. The beam from the RFQ will be injected into the SC linac, which consists of three cryomodules, and which provides the bulk of the acceleration. The accelerated beams will finally be guided via a beam line with magnetic elements to the ReA3 experimental area. The basic components of the cryomodules are the SC quarter wave resonators (QWR), optimized for $\beta=0.041$ and $\beta=0.085$. The transverse focusing is done by solenoid lenses, which can reach up to 9T magnetic field strength. Each solenoid has two dipole coils to provide alignment error corrections. The reaccelerator linac lattice comprises fifteen 80.5 MHz QWR and eight solenoids within the three cryomodules. The first cryomodule houses two solenoids and one $\beta_{\text{opt}}=0.041$ cavity, which is used to re-bunch the beam from the RFQ and for the transverse matching of the beam to the entrance of the second module. The second cryomodule incorporates six $\beta_{\text{opt}}=0.041$ cavities and three solenoids and the third cryomodule contains eight $\beta_{\text{opt}}=0.085$ cavities and three solenoids. Four beam diagnostics stations located in the warm region between cryomodules will be used for linac beam tuning.

The ReA3 beam distribution beam line (HEBT) will deliver the radioactive beams from the SC linac to the new experimental area. The beam lines will be capable of transmitting the highest beam energies expected up to a maximum magnetic rigidity of 1.4 Tm. The ReA3 HEBT will consist of two sections. The first section is the ReA3 Deck Extension, shown in Fig. 2, which is currently being constructed. In an S-bend, the beam line will bring the beams from the ReA3 platform to a height of nominally 60" above the East High Bay concrete floor. The accelerated stable and rare isotope beams from the ReA3 will pass through two dipoles and six quadrupoles so the transverse and longitudinal emittances are preserved. The beam properties will be measured by the three permanent diagnostic stations. The ReA3 Deck Extension will first be used to measure the stable beam properties and demonstrate ReA3 accelerator system meets performance specifications. It will also provide important experience to establish the ReA3 SC linac beam tuning procedures. The second section covers the rest of the beamline to the experimental area on the main floor level, which will be completed in 2011.

THE LOW BEAM ENERGY SECTION

In this section we describe the ReA3 systems that handle the low beam energy ions using electrostatic beam optic elements. This section is the key to a reaccelerator facility for rare isotopes that are produced by projectile fragmentation.

Gas Stopper and the 60 keV Beam Transport Line

The stopping of energetic ions in gaseous helium with prompt extraction and cooling via collisions with helium atoms is a key element of the rare isotope reacceleration. The large momentum spread of the secondary beams

produced in the fragmentation process needs to be drastically reduced prior to stopping of the fragments. The momentum compression [3] is critical in order to keep the effective gas thickness in the gas stopper low and to keep the extraction times for the exotic isotopes short. Momentum compression before the gas stopper is accomplished with a solid degrader that reduces the energy of the projectile fragments, followed by momentum dispersion by means of a dipole magnet and a final wedge degrader shaped to match the dispersion. Two momentum-compression beam lines will be available and connected to the A1900 fragment separator. An advanced linear gas cell will be connected to one momentum compression beam line and a revolutionary cryogenic cyclotron gas stopper [4] will be connected to the other.

The extracted thermal beams from the gas stopper systems will be merged into an electrostatic beam line to transport the secondary fragments to the thermal-beam experimental area and to the reaccelerator. Each stopping device will be on an independent high-voltage platform (~60 kV) to accelerate the thermalized ions into an electrostatic beam line with mass analysis for transport to the thermal beam experimental area and the reaccelerator. The bending and focusing elements will consist almost exclusively of electrostatic devices, with the exception of a magnetic dipole used for mass separation. The dipole bends the beam by 61 degrees over a 681 mm radius. The beam optics calculations used for modelling the transport have shown that the beam can be focused with less than 5 kV at all quadrupoles. The maximum magnetic rigidity is assumed to be ~0.54 Tm for ions with A/Q=238. This requires the separator's magnet to reach a field of ~0.8T. Within the 50 mm vertical gap, a field uniformity of 1 part in 3000 is obtained within a transverse region of 100 mm. This is important for obtaining resolving powers above ~1000 for a beam spot focused to 1 mm or less at the object point. This should be attainable with transmissions >95% for beams of less than 14 -mm-mrad emittance a tune that yields a momentum dispersion of about 15 mm/%. Mechanical design of the beam line assembly is completed.

The EBIT Charge State Breeder

The EBIT charge breeder is another key component of the re-accelerator and is located on top of the ReA3 deck, shown in Fig. 2. An electrostatic kicker bender and electrostatic beam optics elements guide the beam towards the device where they are injected into the intense electron beam. Details about the charge breeder can be found in [5]. Inside the electron beam the rare isotopes are confined for a few ms, while they undergo electron impact ionization. The EBIT will deliver ion beams with a Q/A in the range between 0.2 and 0.5. An offline source is foreseen for beam development and breeding tests, which can be done in parallel with the linac commissioning. The EBIT operates at ultra-high vacuum conditions, which results in a very small background current. While the EBIT accumulates the rare isotopes, no ions can be extracted and hence be delivered

to the experiment. This mode requires the ionization into the 2^+ charge state in the roundtrip time of the injected ions. First commissioning tests have been performed with a 6.35-mm Ba-dispenser cathode. Those tests were carried out with an electron beam energy of 16.5 keV. By properly tuning the gun and collector coils so far an electron beam current of 906 mA could be achieved. The ability to reach higher currents is presently limited by current losses and secondary-electron currents on the anode in the amount of about 0.2%.

The superconducting magnet has been delivered to MSU and acceptance tests were successfully performed. The trap drift-tube electrodes have been constructed and are being assembled. The high-voltage platform of the gun and collector is installed along with the power supplies necessary for operation. The control system is being finalized and the ion optics elements for injection and extraction are presently installed in the beam line. A detailed investigation of ion injection and extraction by numerical simulations is ongoing.

The Q/A Separator and the LEBT

For charge state selection of the highly charged ions from the EBIT, a charge state selector is required with a mass resolving power of about $R \sim 100$ for beams with an emittance of maximum 120 mm mrad [6]. This emittance is about 5 times larger than typical EBIT emittances at 12 keV/u. A large emphasis has been given to obtain achromatic mass separation since the electron impact processes in EBIT type breeders tend to create beams of non-negligible energy spreads. Commissioning of the separator with beams from a temporary ion source on a high voltage platform has been completed. The measurements confirmed the energy dispersion of the electrostatic bender and the mass dispersion of the 90 degree magnet. The mass resolution corresponds to $R=100$ and the separator is achromatic within a range of $\pm 1.5\%$ of the nominal beam energy.

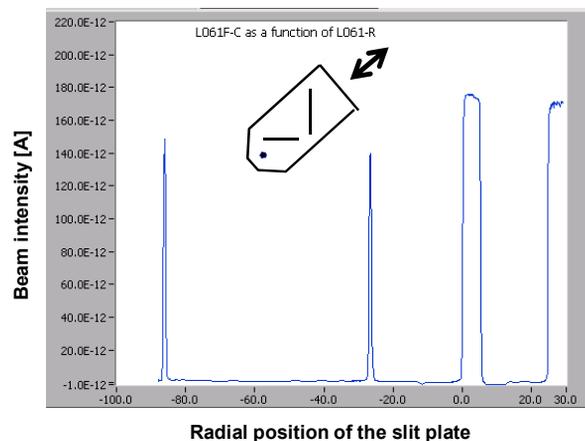


Figure 3: Scan of the beam in front of the RFQ using the slit plate for a symmetric beam tune in front of the RFQ.

For the transport of the highly charged ions and transverse matching from the separator to the linac, four electrostatic quadrupole doublets and a solenoid lens are

used. An electrostatic bender is implemented in the LEBT in order to allow a stable ion source to deliver ${}^4\text{He}^{1+}$ beam for commissioning of the linac. A beam tune with settings according to the optics calculations has been developed, for optimum injection into the RFQ. Figure 3 shows a scan of the beam in front of the RFQ. A slit plate shown in Fig. 3 is moved under a 45 degree angle into the beam. The plate has a 5 mm hole, a horizontal and a vertical slit. The corresponding scan reveals that the size of the beam is about 2 mm and the beam is symmetric in x- and y-direction, which is mandatory for the injection into the linac. The MHB is integrated in the beam line, which performs bunching of the beam prior to injection into the RFQ. The MHB uses three harmonics of the base frequency of 80.5 MHz and consists of two coaxial resonators with a single gridded gap and 50 mm drift tube diameter.

The triple harmonic buncher has been tested and commissioned at the NSCL ARTEMIS B beam line and recently in its final position in the ReA3 LEBT. Figure 4 represents the first bunch measurements using a timing wire detector [7]. The bunch width measured under the different conditions matches beam simulation results extremely well.

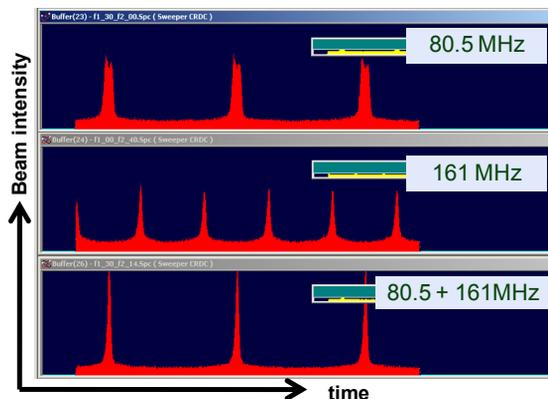


Figure 4: Timing wire detector signals of buncher from the ReA3 MHB. Bunches for the different harmonics and the two harmonics combined are shown.

THE LINAC AND BEAM TRANSPORT

The reaccelerator has been designed to deliver beams with variable energies depending on the Q/A -ratio of the ion species and on the gradients of the SRF cavities. Results of beam dynamics simulation with the IMPACT code are summarized in table 1.

Table 1: Final Energy in MeV/u of the ReA3 Linac for Different Gradients and Q/A Values Derived from Beam Simulations

Q/A	$E_{\text{peak}}=16.5/20 \text{ MV/m}$	$E_{\text{peak}}=30/30 \text{ MV/m}$
0.2	2.4	4
0.25	3	5
0.5	6	9

The Room Temperature RFQ

The ReA3 4-rod RFQ structure has been built at University of Frankfurt. Details of the structure are shown in [10]. Since the beam is already bunched at the entrance, the RFQ cell design uses a synchronous phase of -20° and an initial modulation factor of 1.15, which increases to 2.6 along the length of the RFQ rods. An intervane voltage of 86.2 kV is required to accelerate ions with $Q/A=0.2$ which corresponds to 120 kW rf power according to the shunt impedance of 210 $\text{k}\Omega\text{m}$ derived from low level rf-tuning measurements. Tuning of the rod voltage distribution along the axis resulted in a good flatness of $\pm 1.5\%$.

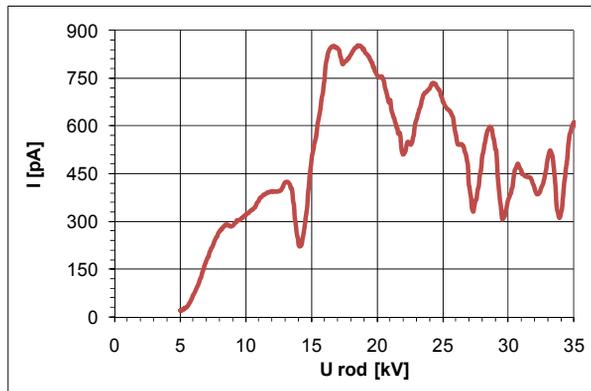


Figure 5: He^+ ions transported by the RFQ at low rod voltage using the RFQ as a focusing channel.

The RFQ tank has been installed in the beam line and after extensive tuning measurements and fixing of leaks the structure could be conditioned up to 55 kW cw. To reduce the heat load and perform HV conditioning, the amplifier has been pulsed for higher power level. Presently the structure is conditioned up to 85 kW peak power. In order to check the injection of beam into the RFQ, He^+ ions have been transported at low power levels, using the RFQ as an rf-quadrupole focusing channel. Figure 5 demonstrates the transmission of current for different rod voltage settings. Maximum transmission of 80% could be reached for 16.5 kV and the optimized transverse beam optics of the LEBT. Only minor steering is required to inject the He-beam from the offline source beam into the ReA3 RFQ.

The SRF Linac

The first two cryomodules of ReA3 have been manufactured and installed on the ReA3 balcony. More detailed information on cavity and cryomodule production is provided in [9]. The re-buncher module has been investigated in details and operational experience with the cavity and the solenoids could be gathered. The second cryomodule is presently under investigations including studies of the heat load to the cryogenic plant, rf-properties, low level rf-controls, and radiation safety. The vacuum vessel, the liquid nitrogen shield and the cryogenic header of the third cryomodule have been fabricated and assembly is ongoing. The cold mass of the

second module has a delay due to issues with the performance of the $\beta_{\text{opt}}=0.085$ cavities [10]. The surface electric field for the two types of SRF cavities used in ReA3, $\beta_{\text{opt}}=0.041$ and $\beta_{\text{opt}}=0.085$, are 16.5 and 20.0 MV/m, respectively. Higher operating fields (30 MV/m) are planned for the FRIB driver linac. If the ReA3 cavities can be operated above their design voltages, higher final beam energies may be possible for ReA3 (see table 1). The load to the cryogenic plant may limit the operating fields, so high quality factors are needed for the resonators.

Four beam diagnostics stations located in the warm region between cryomodules will be used for beam and SC linac tuning. The diagnostics stations in the linac section include Faraday cups to check transmission of pilot beams, timing wire detectors for bunch length determination, movable slits for beam scanning purposes and foil- and silicon detectors for beam energy measurements. Alignment of the beam at the exit of a cryo module will be checked by scanning the beam position in two diagnostic stations downstream. As soon as the RFQ will be operational at full power beam tests with the two installed cryomodules are planned. An application for an automatic phase and amplitude determination of the cavities has been developed. For tuning purposes, energy and bunch length measurements will be mandatory in finding the right amplitude and phase settings

The HEBT Redistribution Line

The HEBT will be capable of transmitting beams with a maximum magnetic rigidity of 1.4 Tm. The ReA3 HEBT will consist of two sections. The first section is the ReA3 deck extension, which is currently being constructed at the NSCL. The beam line comprises an achromatic S-shaped bending section guiding the beam transport the mezzanine to the ground floor level while limiting the beam emittance growth. The ReA3 deck extension will first be used to measure the stable beam properties and demonstrate ReA3 accelerator system meets performance specifications. The second section consists of an FODO transport section with 8 quads and a 90° achromatic bend into the ReA3 experimental area. The transverse focusing is applied by magnetic quadrupoles. The longitudinal phase space will be controlled by a rebuncher. In The ReA3 area three beam lines will guide the beam to corresponding target stations.

OUTLOOK: ReA12

A second stage for the reaccelerator is the planned as an extension of the ReA3 linac to a maximum energy of 12 MeV/u for ions with $Q/A=0.25$ and up to 20 MeV/u for lighter nuclei with $Q/A=0.5$. The resulting machine, called ReA12, will be unique. In contrast to a fixed velocity profile acceleration in a drift-tube linac, the SRF linac of the MSU re-accelerator is very flexible concerning the ion beta as every cavity is powered by a single rf-amplifier and can therefore be independently phased.

As shown in Fig. 6, ReA12 will require three additional cryomodules with $\beta_{\text{opt}}=0.085$ cavities identical to the third cryomodule of ReA3. The cavities will be operated at the same temperature as in the ReA3 case, but with peak surface electric field of 30 MV/m, which is the FRIB specification for the cavities. One of the additional large cryomodules will extend the ReA3 linac section on the main floor and will deliver beams at energies up to 6 MeV/u for $Q/A=0.25$ into the ReA3 experimental hall.

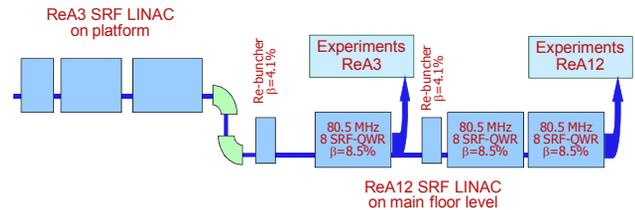


Figure 6: Schematic overview of the ReA12 upgrade to the reaccelerator.

Two more large cryomodules that will be able to deliver energies up to 12 MeV/u to the new ReA12 experimental hall. In addition to these cryomodules, three small cryomodules will be constructed to house rebuncher QWRs for longitudinal matching of the beam.

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