

THE MSU/NSCL RE-ACCELERATOR ReA3*

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Abstract

The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) is currently constructing its new reaccelerated beam facility: ReA3. ReA3 will provide unique low-energy rare isotope beams by stopping fast rare isotopes in gas stopping systems and reaccelerating them in a compact linac. The main components, which will be explained in this paper, are a linear cryogenic gas cell to stop the fast beams produced by projectile fragmentation, an Electron Beam Ion Trap (EBIT) charge state booster, a room temperature Radio Frequency Quadrupole (RFQ) and a linac utilizing superconducting quarter wave resonators. An achromatic beam transport and distribution line towards the new experimental area will complete ReA3. Beams from ReA3 will range in energy from 0.3 to 6 MeV/u: the maximum energy is 3 MeV/u for heavy nuclei such as uranium, and 6 MeV/u for ions with $A < 50$, as the charge state of the ions can be adjusted by the EBIT. ReA3 will provide pioneering beams for nuclear physics research, initially using beams from the Coupled Cyclotron Facility at NSCL and later providing reacceleration capability for the next-generation rare isotope facility FRIB that will be hosted at MSU. The ReA3 concept and status of ReA3 are presented, with particular emphasis on the superconducting linac.

INTRODUCTION

Experiments with reaccelerated beams of rare isotopes are at the foremost frontier of nuclear physics research [1]. Reaccelerated beams of rare isotopes in the energy range of 0.3–12 MeV/u allow for a rich experimental program ranging from low-energy Coulomb excitation experiments and transfer reaction studies to the study of astrophysical reactions. Isotope Separation On-line (ISOL) and Projectile Fragmentation (PF) are the two methods used to produce high quality radioactive ions beams (RIBs) for the nuclear science experiments. The NSCL has been using the PF method since 1989 to produce fast RIBs for nuclear structure and nuclear reaction experiments, especially after the completion of the coupled cyclotron facility (CCF) and the A1900 Fragment Separator in 2001. With the development of gas stopping, low energy beams of rare isotopes are available from fragmentation facilities [2]. The connection of a reacceleration scheme to a gas stopper at NSCL/MSU in the framework of the reaccelerator project (ReA3) [3] is of

particular importance, since it will provide high quality beams of nuclei not available in this energy regime at any other facility. The reacceleration scheme implemented in ReA3 is 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 reacceleration of rare isotopes at present and future facilities. Charge breeding eliminates the large losses in efficiency associated with conventional electron stripping; it allows for a much simpler accelerator structure; it makes the accelerator more compact and therefore more cost effective [4].

THE REACCELERATION CONCEPT

Figure 1 illustrates the n^+ reacceleration concept chosen for ReA3 and Figure 2 shows the layout of the components. Rare isotope beams 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 from the gas stopper will be mass analyzed and sent to a high charge state ion source, which is operated as a charge state breeder. Afterwards the ions are extracted from the breeder and guided towards a mass separator. The n^+ ions will pass through an achromatic charge state (Q/A) separator to select the desired charge state and suppress unwanted background ions before the beam enters the accelerator. 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. Numerical simulations and measurements for the REX-ISOLDE RFQ have shown that the longitudinal beam emittance can be reduced by a factor of four by using external bunching, at the expense of lower transmission.

The linac of the reaccelerator consists of a room temperature RFQ and a superconducting (SC) linac. The main parameters are summarized in Table 1. 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. It can accelerate or decelerate beams from the RFQ output energy of 600 keV/u to the desired final energies ranging from 0.3 to 3 MeV/u for uranium.

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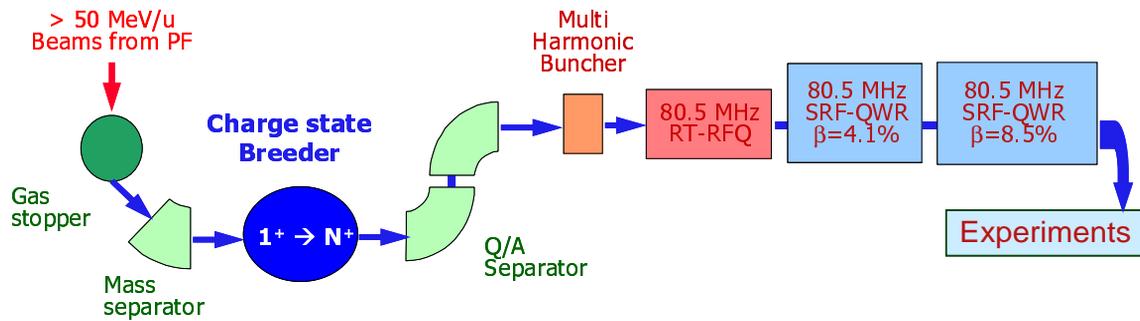


Figure 1: Reacceleration concept for ReA3.

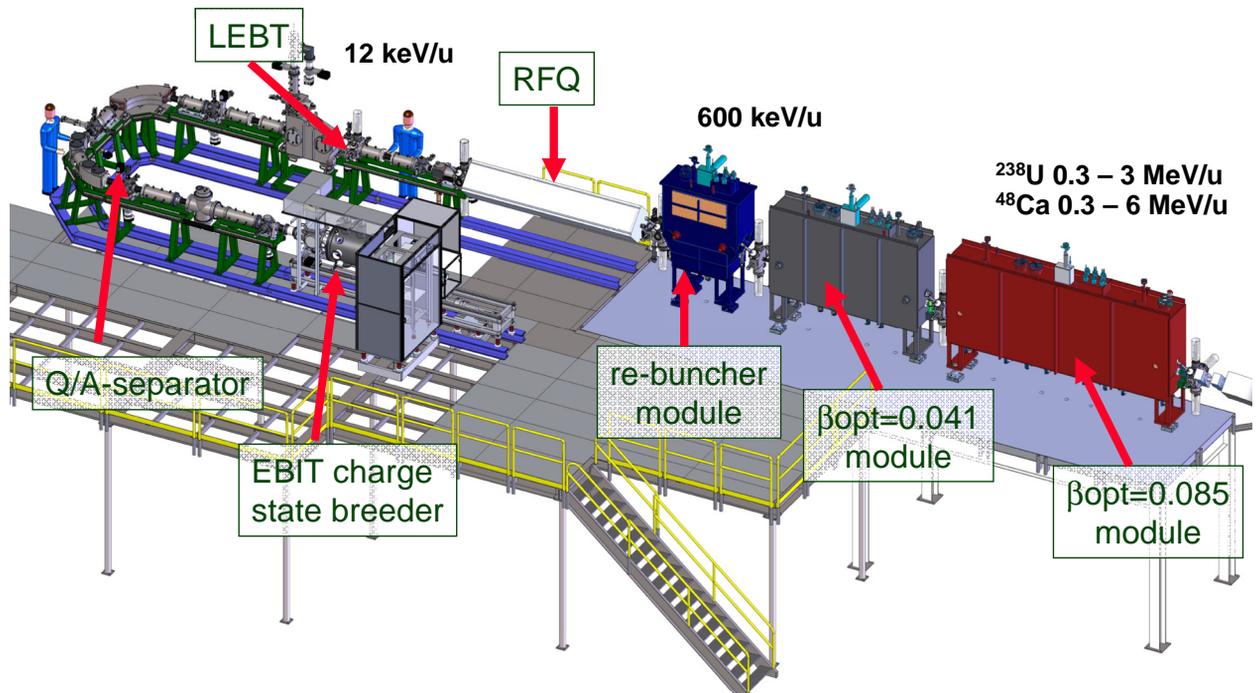


Figure 2: Isometric view of the ReA3 deck.

The basic components of the cryomodules are the SC quarter wave resonators (QWR), optimized for $\beta=0.041$ and $\beta=0.085$, and solenoid lenses for transverse focusing. The accelerated beams will finally be guided via a beam line with magnetic elements to the ReA3 experimental area.

STATUS OF THE LOW BEAM ENERGY SECTION

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 compression 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 lines minimize the risk of

single-point failure by being able to switch from one gas stopper to another. The two dedicated beam lines will be beneficial to develop, test, compare, and optimize the different gas stopper concepts effectively. A novel cyclotron gas stopper and a next-generation cryogenic linear gas stopper are planned to be installed. A third line without momentum compression will accommodate a solid stopper/reionizer system. As an intermediate scenario until the cyclotron gas stopper is realized two linear gas stoppers will be installed at the momentum compression lines.

After the gas stopping region the singly charged ions are guided to the ReA3 platform with electrostatic elements. A mass separator is integrated into this transfer line to separate the rare isotopes from rest gas ions created in the gas cell. The beam optics design of the complete beam line is finished along with the design of the separator magnet. Mechanical design of the beam line assembly is ongoing.

On top of the ReA3 deck, which is shown in Figure 3, electrostatic beam optics elements guide the beam

towards the electron beam ion trap (EBIT) where they are injected into the intense electron beam [5]. Inside the electron beam the rare isotopes are confined for a few ms, while they undergo electron impact ionization. The electron beam ion source/trap (EBIS/T) charge state breeder has been identified as the most promising breeder type with respect to efficiency, breeding time, beam quality and purity. The EBIS/T type charge state breeder has superior performance in comparison to electron cyclotron resonance ion source (ECRIS) based breeder system except for the maximum beam intensity available with an EBIS/T system. The EBIT will deliver 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. With a second EBIT charge breeder, a quasi continuous duty cycle could be established, and this is foreseen as a future upgrade option. Presently the electron beam system of the EBIT is under investigation on a test setup. Up to 400 mA of electron beam has been produced. The superconducting magnet and the drift tube structure of the EBIT are under construction.

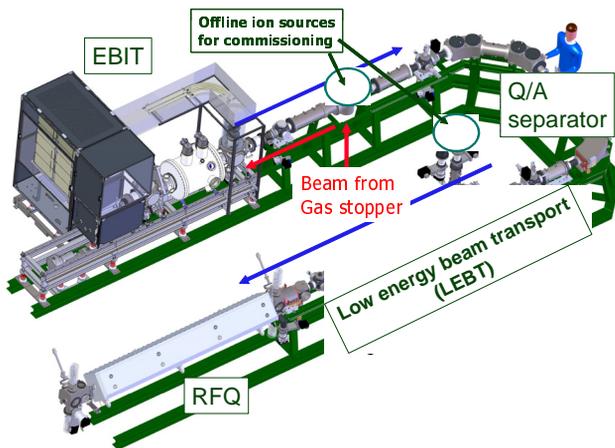


Figure 3: Low beam energy area of the ReA3 deck, including the charge breeder, Q/A -separator and LEBT.

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 emittances of up to 120 mm mrad, which is much 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 [6]. Therefore the Q/A -separator follows a Nier-type design. A temporary ion source on a high voltage platform has been installed for first beam commissioning of the Q/A -separator, which is underway.

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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 triple bender is implemented in the LEBT in order to allow a stable ion source to deliver $^4\text{He}^{1+}$ beam into the RFQ for SC linac tuning and calibration of the beam diagnostics. The bender can also deliver beams from the EBIT to the stopped beam area and can accept beams from a possible 2nd EBIT in a future upgrade.

The nuclear physics experiments require a beam on target with an energy spread of ~ 1 keV/u and a bunch length of ~ 1 ns simultaneously. Therefore, a longitudinal beam emittance of less than 0.3 ns \cdot keV/u from ReA3 is needed. For comparison, the longitudinal beam emittance of the REX-ISOLDE linac is 1.6 keV/u \cdot ns. Since the intensities from the rare-isotope beams will be low, the scheme of external bunching upstream of the RFQ can be used. Hence a multi harmonic buncher (MHB) [7] has been integrated into the LEBT. 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 recently. The LEBT assembly is complete so that commissioning of this section can start.

STATUS OF THE LINAC

The first accelerating structure is a normal conducting 4-rod RFQ structure. 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. These values are a compromise to achieve a reasonable ratio between the longitudinal acceptance and emittance. An intervane voltage of 86.2 kV is required to accelerate ions with $Q/A=0.2$, which generate an electric peak field of 1.6 times the Kilpatrick limit. The transverse phase advance is larger than the longitudinal one to avoid parametric resonances. Together with the external MHB in the LEBT, the ReA3 RFQ should achieve an 82% beam transmission.

Table 1: Linac specifications

Parameter	ReA3 value
Resonance frequency	80.5 MHz
Injection energy	12 keV/u ($\beta = 0.005$)
final energy for $Q/A=0.25$	3 MeV/u ($\beta = 0.08$)
Max. A/Q	5
duty cycle	cw
acceptance	0.6 mm mrad (normalized)

The RFQ parameters require a mini-vane structure of 6 mm tip radius, mid-cell aperture of 7.3 mm and a length of 3.3 m. The RFQ tank has an outer length of 3.5 m. The

tank has a square cross section and is made of aluminum. The resonant electrode structure is made of copper. Extensive cooling of the stems, mini-vanes, tuning plates and tank is foreseen in order to remove the rf power of 160 kW dissipated in operation at highest rod voltage. The 4-rod structure is currently under construction at Frankfurt University and being prepared for tuning measurements.

The reaccelerator has been designed to deliver beams with variable energies depending on the Q/A -ratio of the ion species. The charge-to-mass ratio of the ions, which can be accelerated with the ReA3 linac ranges from 0.2 to 0.5. The nominal energy range according to design is 0.3 to 3 MeV/u for ions with Q/A of 0.25, and 0.3 to 5.8 MeV/u for ions with Q/A of 0.5, assuming a moderate electric peak field in the QWRs. The design operating peak 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. The load to the cryogenic plant may limit the operating fields, so high quality factors are needed for the resonators. Minimization of frequency fluctuations is also needed to ensure amplitude and phase stability. The sensitivity of the cavity frequencies to bath pressure fluctuations has been reduced by stiffening as verified with both numerical simulations and measurements [8].

The reaccelerator SC linac consists of a total of fifteen 80.5 MHz QWR cavities and eight superconducting solenoid magnets inside the cryomodules. Each solenoid will have two dipole coils to provide alignment error corrections. The magnets are NbTi solenoids with a 40mm aperture. The first cryomodule, which is shown in Figure 4, houses two solenoids and one $\beta_{\text{opt}}=0.041$ cavity. The module is used to re-bunch the beam as it travels from the RFQ to the second cryomodule. 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. Eight $\beta_{\text{opt}}=0.041$ QWRs have been fabricated; welding of the helium vessels and RF testing is in progress.

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. A defining aperture or collimator at the entrance of the SC linac limits the beam size before it enters the second cryo module. Alignment of the beam at the exit of a cryo module can be checked by scanning the beam position in two diagnostic stations downstream. For tuning purposes, energy measurements via scattering of particles in a thin Au-foil and bunch length measurements, using secondary electrons produced by ions hitting a wire, are mandatory in finding the right

amplitude and phase settings. The beam energy measurement can be done independently by time of flight measurements as the ions drift between two diagnostic stations.

The first cryomodule has been manufactured, and was installed on the ReA3 balcony in the middle of 2009. More detailed information on cavity and cryomodule production is provided in ref. [9]. The first module has been connected to the NSCL cryogenic plant and controls wiring and testing have been completed. This re-buncher module 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 second cryomodule have been fabricated and assembly is ongoing. The cold mass of the second module is in preparation in the NSCL clean room. For the third cryomodule of ReA3 the mechanical design has been completed and material is being ordered. Subassemblies of the $\beta_{\text{opt}}=0.085$ cavities are in production by Niowave, Inc.

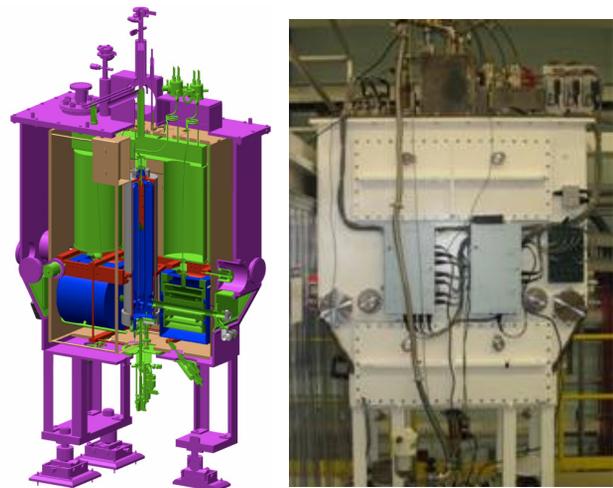


Figure 4: First cryomodule installed on the ReA3 deck containing two solenoid lenses and one $\beta_{\text{opt}}=0.041$ cavity.

The ReA3 HEBT will deliver the radioactive beams from the SC linac to the new experimental area. The beam line, consisting of room temperature beam optics elements, will be capable of transmitting the highest beam energies expected up to a maximum magnetic rigidity of 1.4 Tm. The beam is transported down from the ReA3 deck to the ReA3 experimental facility using two achromatic bending segments and three straight sections. The first bending segment provides the 90° turn from the SC linac towards the new experimental hall and the second bending segment in an S-shape to guide the beam down to the ground level in the experimental area. A cryomodule consisting of a SC solenoid and a QWR with $\beta_{\text{opt}}=0.041$ will be used to rotate the longitudinal phase space of the beam in order to achieve an energy spread of ~ 1 keV/u at all energies.

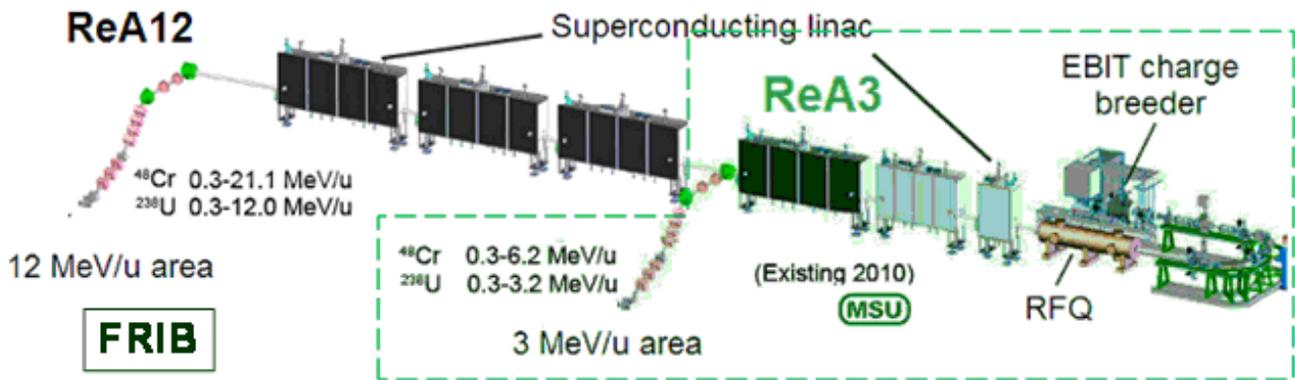


Figure 5: Overview of the ReA12 upgrade to the reaccelerator.

OUTLOOK: ReA12

A second stage for the reaccelerator is planned as an extension of the ReA3 linac to a maximum energy of 12 MeV/u for uranium and up to about 20 MeV/u for lighter nuclei, called ReA12. This upgrade is an essential part of the FRIB project [10]. The ReA12 upgrade will be funded through FRIB, whereas ReA3 funding is provided by MSU.

In contrast to a fixed velocity profile acceleration in a drift-tube linac, every cavity of the NSCL reaccelerator is powered by a single rf-amplifier and can therefore be independently phased. As a result, the energy gain is fully tuneable and any energy in the range stated above can be delivered to the experiment. The ReA12 section will significantly broaden the scientific program with reaccelerated beams, because the Coulomb barrier can be reached in nuclear physics experiments even with all isotopes that become available through FRIB.

As shown in Figure 5, the ReA12 upgrade 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 a temperature of 4.5 K as in the ReA3 case, but with peak surface electric field of 30 MV/m, which is the FRIB specification for the cavities. As the beam transport line to the experimental area requires a bending magnet downstream of the third ReA3 cryomodule a re-buncher module for matching of the longitudinal phase space of the beam to the following cryomodule will be required. This module is a copy of the module foreseen for the ReA3 beam transport line to the experiments. The transport system to the experimental area of ReA12 will provide transverse and longitudinal focusing to control precisely the transverse beam size, the bunch length and the energy spread delivered to the experiment. The layout follows the ReA3 transport and beam distribution system, taking into account the higher rigidity of the beam.

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