

ON THE ACCELERATION OF RARE ISOTOPE BEAMS IN THE REACCELERATOR (REA3) AT THE NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY AT MSU*

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Abstract

The ReAccelerator ReA3 has run continuously for one year delivering rare isotopes and stable beams for experiments at the National Superconducting Cyclotron Laboratory (NSCL) at the Michigan State University (MSU). Beams of rare isotopes are produced and separated in-flight at the NSCL Coupled Cyclotron Facility (CCF) and subsequently stopped in a gas cell. The rare isotopes are then continuously extracted as 1+ (or 2+) ions and transported into a beam cooler and buncher, followed by a charge breeder based on an Electron Beam Ion Trap (EBIT). In the charge breeder, the ions are ionized to a charge state suitable for acceleration in the superconducting radiofrequency (SRF) linac, extracted in a pulsed mode and mass analyzed. The extracted beam is bunched to 80.5 MHz and then accelerated to energies ranging from 300 keV/u up to 6 MeV/u, depending on their charge-to-mass ratio. Alternatively, ions of stable isotope can be accelerated by injecting stable ions from an external ion source in the EBIT. ReA3 has provided stable ^{14}N , ^{40}Ar , ^{39}K and ^{78}Kr as well as the rare isotope beams of $^{34,46}\text{Ar}$, $^{37,46}\text{K}$ and ^{75}Ga for a total of 11 experiments since August 2015. This contribution focuses on the properties and techniques used to accelerate and transport the rare-isotope beams and will show average results obtained during the preparation of these experiments in the ReA facility.

INTRODUCTION

The National Superconducting Cyclotron Laboratory NSCL [1] is a facility dedicated to the production of rare isotope beams via projectile fragmentation. The In-flight technique for production of rare isotopes provides excellent production performance for fast medium-to-high-energy beams. Optimal beam properties and intensities are obtained when the primary beam is in the range of several hundreds of MeV per nucleon, where the reaction probability for projectile fragmentation and/or fission are high, whilst the kinematics provides fragments

with high longitudinal and low transversal momentums with low dispersion. The fragments, therefore, maintain the primary beam momentum and have, consequently, high energy.

Another important characteristic of the in-flight technique is that the rare isotope production is independent of the chemical property of the fragments. As they are produced in-flight, the fragments leave the production target without any chemical interaction, which is different from Isotope On-Line Separator (ISOL) approach [2]. Lower-energy beams can be produced using degraders. However, this approach has limitations due to energy and angle straggling after the degraders, generating poor beam characteristics, i.e. large emittance with poor energy resolution.

Gas-stoppers [3] followed by a reaccelerator combine the advantages of the in-flight technique, fast and no chemical dependence, with the delivery of high quality beams as available from the ISOL technique. This combination allows the generation of high-quality beams of virtually any isotope, including those that have very short half lives.

Rare isotope ions produced by projectile fragmentation are energy degraded and stopped in a gas-stopper cell with helium, re-extracted and re-accelerated. The combination of a gas-stopper cell and the new reaccelerator ReA3 [4] of the NSCL is unique worldwide and provides energies ranging from 300 keV/u to up to 6 MeV/u, depending on their charge-to-mass ratio of the ions. This contribution focuses on the properties and techniques used to stop, reaccelerate and transport rare isotope beams and shows results obtained during the first year of the ReA3 facility.

GAS-STOPPER TECHNIQUE

In order to convert the fast, rare-isotope beam into a low-energy, high-quality beam, the fast ions are sent through a momentum compression beam line consisting of a set of solid degraders, a dipole magnet and subsequently stopped in a gas stopper filled with helium gas. The ions are transported inside the gas stopper via electric and radio-frequency fields and extracted through a small orifice (1.3 mm diameter) via a supersonic jet. The gas

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stopper is placed at high voltage (from 30 kV to 60 kV). Therefore, ions extracted from it are accelerated to these energies. For maximizing the scientific reach, high efficiency in stopping the fast, rare-isotope beam and converting it into a low-energy beam is important. As mentioned before, degrading the energy results in energy straggling. As the effective gas-stopper thickness at low gas pressure – which is mandatory for achieving relatively high transport efficiency inside the cell – is small, it is of paramount importance to minimize the momentum dispersion of the beam. This is achieved using the so called “range focusing” technique [5], which is achieved by creating a momentum dispersion at the position of a second wedged-shaped degrader with a thickness profile designed to achieve a reduced momentum spread of the beam after passing through this degrader. This procedure compresses the momentum spread and reduces the width of the range distribution of the stopped ions in the gas.

The present gas-stopping cell of NSCL was built by the Argonne National Laboratory; it is 1.2 m long and is operated at a pressure of about 100 mbar. After extraction, the beam is selected by a mass separator (resolution of the order of 1,500) and directed to a cooler buncher.

INJECTOR

After separation, the beam is injected in a beam-cooler-buncher (BCB), which is a radio-frequency quadrupolar trap with axial and radial confinement of ions in gas, designed to improve the optical properties as well as to adapt the timing macro-structure of the beam prior to injection in the Electron Beam Ion Trap (EBIT) [6]. The beam extracted from the gas stopper is continuous, whilst the injection into the EBIT should be pulsed, for reaching maximum ion-breeding performance.

In the EBIT, the beam is charge bred to achieve charge states compatible with the needs for acceleration. For each case, the choice of the charge state produced in the EBIT is a trade-off between achieving the requested final energy of the beam, whilst reducing the contamination rate to acceptable levels. It should be noted that contamination by radioactive as well as stable ions with similar Q/M, is a major issue for experiments. Therefore, the choice of the charge state to be accelerated is fundamental for managing both energy and purity of the rare-isotope beam.

The EBIT can produce ions with high charge states, which is the main reason why ReA3 can reach high energies with few resonators. However, the macro-structure timing of the extracted beam can constitute a problem for experiments if the beam would not be reasonably spread in time. For this reason, in the ReA3 EBIT the beam is extracted using a slowly varying function, which generates a longer beam distribution in time, compatible with the RFQ duty cycle. Fig. 1 shows the EBIT extraction function as well as the RFQ duty cycle, and the particle time distribution detected at the

experiment. One can note that particles are spread over about 15 ms in this case. Presently, we can reach up to 100 ms time distribution without efficiency losses.

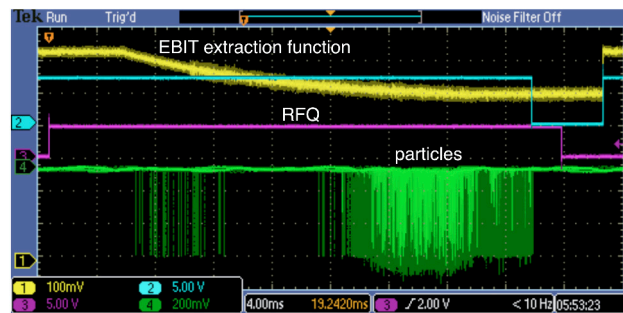


Figure 1: Particle distribution (⁸Kr) extracted from the EBIT and detected in the experiment.

After the EBIT, the beam is mass selected in the achromatic Q/A separator and injected at the energy of 12 keV/u into a multi-harmonic buncher, where it is bunched to the operation frequency of the Radio Frequency Quadrupole (RFQ) accelerator and Superconducting Radio-Frequency linac (SRF) of 80.5 MHz.

ACCELERATOR

The ReA3 4-rod room temperature RFQ [7] accelerates the beam from 12 keV/u to the energy of 600 keV/u for ions with Q/A from 0.25 to 0.5. The RFQ, built in a collaboration with the University of Frankfurt, has a cell design compatible with the pre-bunching, i.e. a synchronous phase of -20° and an initial modulation of 1.15, which evolves to 2.6 all along the length of the accelerator. An inter-vane voltage of 70.0 kV is required to accelerate ions with Q/M = 0.25 which corresponds to about 80 kW RF power. However, the RFQ is not used in Continuous Wave (CW) mode. This is firstly due to the fact that the system becomes unstable and abnormally hot for an integrated power higher than 40 kW. Secondly, a pulsed timing macro-structure of the beam is more adapted to the EBIT operation as discussed in the previous section. Finally, the ReA3 RFQ is not placed in a zone of the facility with good ambient temperature control, which could turn out to be a serious issue for the RF tuning. The solution is to run the RFQ in pulsed mode with a power profile having an acceleration portion giving the correct acceleration voltage and a second (CW component), used exclusively to compensate external temperature variations of the system. The vane temperature is monitored continuously and the CW component is corrected to obtain the correct tuning of the accelerator. This has given excellent stability to the system and was fundamental to successfully accelerate rare-isotope ions. The temperature of the vanes are controlled to the level of $\pm 0.2^\circ$ C with this method.

Following the RFQ, the beam is injected in the first superconducting quarter wave resonator (QWR) with $\beta_{opt} = 0.041$ acting as a rebuncher. Two superconducting solenoids (SS) with maximum field of 9 T are installed in

this cryomodule. Following the rebuncher, a first accelerating cryomodule has six QWR with $\beta_{\text{opt}} = 0.041$ and three SS. The third and last cryomodule of ReA3 has eight QWR with $\beta_{\text{opt}} = 0.085$ and three SS. See [8] for details.

The HEBT consists of two sections, one vertical and a second horizontal with maximum magnetic rigidity of 1.4 Tm. The second section can act as a spectrometer for beam selection with resolution of the order of 400. A modification of this beam line will bring this resolution to approximately 1500. It's important to note that the Q/A separator (just after the EBIT) provides also a separation of the order of 1,000. Following the separator, three beam lines can receive the ReA3 beam. The full accelerator was commissioned in September 2015 and is presently providing beam for science.

Various diagnostics are installed all along the accelerator, as faraday-cups, beam timing detectors as well as beam profilers and silicon detectors. Specific diagnostics for radioactive beams are installed, as decay counters (for beta radiation) as well as a gamma detector in the low energy branch.

TUNING METHODS AND RESULTS

For tuning of the accelerator for rare-isotope-beam acceleration, one uses an alternative stable isotope with similar Q/M as pilot of the rare-isotope-beam and scales the whole accelerator to the final Q/M. All elements, including resonators, solenoids and other magnetic elements are scaled. For example, for the case of ^{37}K (17+), provided to the experiment with energy of 4.464 MeV/u, with $q/M = 0.459$, the chosen pilot beam was ^{40}Ar (18+) with $q/M = 0.450$. This technique has been successfully used with differences in Q/M as large as 20 % from that of the rare-isotope.

An important aspect of acceleration of rare-isotope beams, which are always associated with very-low intensities, is the amount of contamination. As mentioned previously, the choice of the correct charge state to be accelerated is a compromise between the required energy and the amount of contaminants at a particular Q/M. Moreover, there are contaminants which cannot be easily suppressed, like isobars coming from radioactive decay in the gas cell and/or other beam-line components where the beam is stopped (BCB and EBIT). The best choice for the suppression of isobars is always to choose the highest possible charge state; this is particularly useful in case of neutron deficient nuclei, where daughters have atomic numbers of $Z - 1$, $Z - 2$, etc. As an example, the choice of 17+ for potassium ion makes its daughters (argon and chlorine) harder to produce in the EBIT in the same charge state. Evidently the choice of the charge state in this case was also driven by the intensity. ^{37}K at the charge state 17+ provided yields 5 times higher than the 18+ and more than 10 times the charge state 19+.

The final ReA3 beam quality is compatible to the expected, i.e. energy spread of 0.5 % and normalized emittance of $0.1 \pi \text{ mm mrad}$ FWHM. An image of the beam in the target viewer is shown in Fig. 2. The two images refer to the pilot beam (^{39}K) and the final rare isotope beam (^{46}K) in the same location and after having scaled the whole LINAC as well as the beam lines.

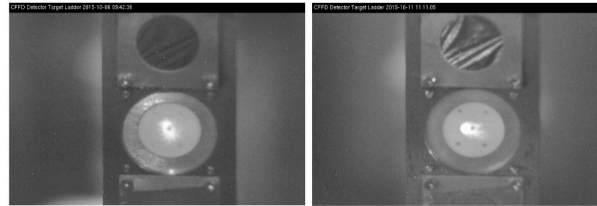


Figure 2: Left- ^{39}K pilot beam spot in the phosphorous screen of the experimental target. Right- ^{46}K rare isotope beam spot in the same location after scaling the LINAC and beam lines. The beam intensity is 15,000 pps and its timing macro-structure is 2 Hz. The size of the spot is 3 mm.

The overall system efficiency varies mainly with the lifetime and primary beam intensity. The overall efficiency of the whole system, from the entrance of the gas cell to the experiment and for a beam of about one second lifetime is of about 1 %.

CONCLUSION

The NSCL ReA3 accelerator has run continuously since August 2015 and has been used successfully in a series of experiments involving rare-isotope as well as stable-isotope beams. Special methods for tuning and controlling those very-low-intensity beams were developed and were shown to work satisfactorily. The beam properties of both rare isotopes as well as stable ion beams are compatible with expectations. Future developments aim to stabilize the system and to improve its reliability as well as its overall efficiency for the acceleration of rare isotope beams.

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