COMMISSIONING AND FIRST ACCELERATED BEAMS IN THE REACCELERATOR (REA3) OF THE NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY, MSU*

A. C. C. Villari†, D. Alt, G. Bollen, D.B. Crisp, M. Ikegami, S.W. Krause, A. Lapierre, S.M. Lidia, D.J. Morrissey, S. Nash, R.J. Rencsok, R. Ringle, S. Schwarz, R. Shane, C. Sumithrarachchi, S.J. Williams†† and Qiang Zhao,
Facility for Rare Isotope Beams, National Superconducting Cyclotron Laboratory,
Michigan State University, East Lansing, MI 48824-1321, USA

Abstract

The ReAccelerator ReA3 is a worldwide unique, state-of-the-art reaccelerator for rare isotope beams. Beams of rare isotopes are produced and separated in-flight at the NSCL Coupled Cyclotron Facility 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 gas in the EBIT. ReA3 was commissioned recently with stable ^{14}N, ^{40}Ar, ^{39}K and ^{78}Kr as well as with the rare isotope beams of ^{46}Ar,^{46}K and ^{37}K. This contribution focuses on the properties and techniques used to accelerate and transport the rare isotope beam ^{37}K and will show results obtained during the preparation of the first experiment with this beam in the ReA facility.

INTRODUCTION

The National Supeconducting Cyclotron Laboratory NSCL is a facility dedicated to the production of rare isotope beams via projectile fragmentation [1]. In-flight technique for production of rare isotope 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 good quality beams of virtually any isotope, including those that are very short living.

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 [4,5] 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 commissioning phase and the preparation of selected experiments using the ReA3 facility. In particular, results of the production of ^{37}K beam at 4.46 MeV/u are used as an example.

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 (0.6 mm diameter) via a supersonic jet. The gas stopper is placed at high voltage (around 30 kV to 60 kV) respective to ground. Therefore, ions extracted from it are accelerated to these energies. For maximizing

* Based on work supported by NSF under grant PHY-11-02511 and the Michigan State University. † email address: villari@frib.msu.edu
†† Present address: Diamond Light Source Ltd., Didcot, UK.

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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 [6], which consists in having 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 [3] was built by the Argonne National Laboratory; it is 1.2 m long and is operated at at a pressure of about 100 mbar. One of the recent experiments performed with the full ReA3 facility involved the stopping and reacceleration of ^{37}K ($T_{1/2}$ = 1.227 s). Figure 1 shows the stopping signature of these ions in the gas-stopper cell. The solid curve represents the current created by the electrons from the ionization of the helium gas by the incoming ion beam as a function of the total thickness of the degraders and wedge. It's a measurement of the stopping power of the ions in He and corresponds to the Bragg curve. The dashed curve corresponds to the beta activity detected just after the cell and corresponds to the extraction of ^{37}K. The thickness variation is obtained by changing the angle of a degrader in front of the gas cell, allowing fine tuning of the path of ions in the cell and maximizing the stopping efficiency. After extraction, the beam is selected by a mass separator (resolution of the order of 1500) and directed to a cooler buncher.

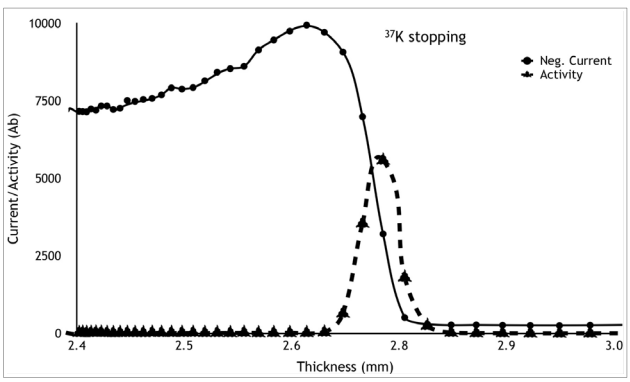

Figure 1: Negative current in the front window of the gas cell (solid curve) and beta activity detected after the gas cell (dashed curve) as a function of the total degrader thickness. See text for details.

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) [7]. The beam extracted from the gas stopper is continuous, whilst the injection into the EBIT should be pulsed, for reaching maximum ions breeding performance.

In the EBIT, the beam is charge bred fto achieve charge states compatible with the needs for acceleration. In the case of ^{37}K, the chosen charge state was 17+, which was compatible with the requested final energy of the beam (4.46 MeV/u), 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 such 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. Figure 2 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.

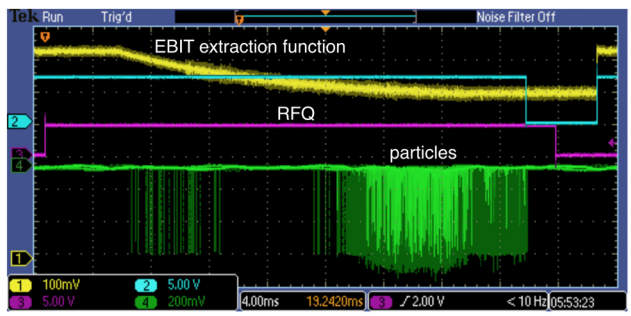

Figure 2: Particle distribution (^{78}Kr) extracted from the EBIT and detected in the experiment.

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 [8], where it is buched 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 [9] 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 Continuos 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 high profile 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 ions. The temperature of the vanes are controlled to the level of +/- 0.2° C with this method.

Following the RFQ, the beam is injected in the first superconducting quarter wave resonator (QWR) with β_{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 β_{opt} = 0.041 and three SS. The third and last cryomodule of ReA3 has eight QWR with β_{opt} = 0.085 and three SS. See [10] 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 1000. Following the separator, three beam lines can selectively 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 scale 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 planned 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 for Q/M as far as 20% of the final beam.

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 needed energy and the amount of contaminants in 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+.

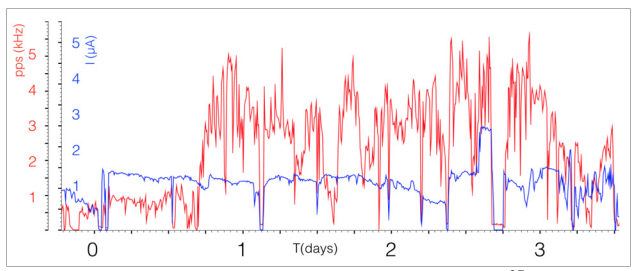

Figure 3: Beam intensity of rare isotope ^{37}K in the experimental set-up (red curve) together with the primary beam intensity of ^{40}Ca beam (blue curve) provided by the Coupled Cyclotrons of NSCL .

The final beam intensity delivered to an experiment has instabilities as we can see in Figure 3. Presently, the main contribution to it is located in the extraction of the EBIT and coupling between BCB and EBIT. By adjusting steerer settings in this portion of the accelerator could recover the intensity. Studies are being done to understand this behaviour and improve stability.

The final ReA3 beam quality is compatible to the expected, i.e. energy spread of 0.5% and normalized emittance of 0.1 π mm mrad FWHM. An image of the beam in the target viewer is shown in Figure 4. The beam is on purpose off-centred.

Figure 4: ^{37}K measured beam spot in the target of the experiment. The beam intensity is 1000 pps and timing macro-structure of 2Hz. The size of the spot is 2mm.

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System efficiencies vary mainly with the lifetime and primary beam intensity. For the particular case of ^{37}K, the table below shows measured experimental efficiencies for the various parts of the accelerator.

Table 1: Efficiencies in selected sections of ReA3 for ^{37}K. Please, note that efficiencies are strongly dependent on the charge state, lifetime and particular conditions required by the experiments.

Equipment	Efficiency (%)
Gas cell	10
BCB	53
BCB-EBIT coupling	65
EBIT (17+)	7.4
RFQ-LINAC	50
Transport to experiment	75

CONCLUSION

The NSCL ReA3 accelerator was recently commissioned and 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 the expected ones. 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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