NEW DEVELOPMENTS AND CAPABILITIES AT THE COUPLED CYCLOTRON FACILITY AT MICHIGAN STATE UNIVERSITY*

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Abstract

This brief overview of the Coupled Cyclotron Facility will focus on the newly commissioned gas stopping area and reaccelerated radioactive ion beam capabilities. First commissioning results and operations experience of the combined system of Coupled Cyclotron Facility, A1900 fragment separator, gas stopper, EBIT charge-breeder and ReA linac will be presented.

INTRODUCTION

The Coupled Cyclotron Facility (CCF) at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University consists of two coupled cyclotrons, which accelerate stable ion beams to energies of up 170 MeV/u. Rare isotope beams are produced by projectile fragmentation and separated in-flight in the A1900 fragment separator. For experiments with high-quality rare isotope beams at an energy of a few MeV/u, the high-energy rare isotope beams are transported to a He gas cell for thermalization, and then sent to the ReA post-accelerator for reacceleration (Fig. 1). Rare isotope beams in this energy range allow nuclear physics experiments such as low-energy Coulomb excitation and transfer reaction studies as well as for the precise study of astrophysical reactions. In August 2013, the first commissioning experiment using a reaccelerated ^{37}K beam was completed.

COUPLED CYCLOTRON FACILITY

Two coupled superconducting cyclotrons, the K500 and K1200 [1], are used to accelerate stable ion beams produced by ECR ion sources. Two ECR ion sources are available for axial injection into the K500 cyclotron. ARTEMIS is a modified version of the AECR at LBNL operating a frequency of 14.5 GHz. SuSI is a third generation superconducting ECR designed at NSCL, presently operating at 18 GHz [2].

Beams in the range of 8 – 14 MeV/u extracted from the K500 are injected mid-plane into the K1200 through a stripper foil located within one of the dees. Amorphous carbon foils with thicknesses of 300 – 800 μg/cm^2 are used to achieve the required charge ratio of 2.5 between injected and stripped beam. Beams from oxygen to uranium can be accelerated to final energies between 45 – 170 MeV/u. Net beam transmission measured from just before the K500 to extracted beam from the K1200 is often about 30%, resulting in an extracted beam power of about 1 kW for most medium-heavy beams [3].

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Table 1 list a subset of primary beams available from the Coupled Cyclotron facility. Beam intensities in the published beam list are generally not the all-time peak intensities but are the typical intensities that can be used for experiment planning purposes and are considered maintainable for extended time periods.

Table 1: Partial NSCL Primary Beam List (the full list is published on the NSCL website) [4]

Isotope	Energy [MeV/u]	Intensity [pnA]	Isotope	Energy [MeV/u]	Intensity [pnA]
^{16}O	150	175	^{82}Se	140	35
^{18}O	120	150	^{78}Kr	150	25
^{20}Ne	170	80	^{86}Kr	140	25
^{22}Ne	150	100	^{112}Sn	120	4
^{24}Mg	170	60	^{118}Sn	120	1.5
^{36}Ar	150	75	^{124}Sn	120	1.5
^{40}Ar	140	75	^{124}Xe	140	10
^{40}Ca	140	50	^{136}Xe	120	2
^{48}Ca	160	80	^{208}Pb	85	1.5
^{58}Ni	160	20	^{209}Bi	80	1
^{76}Ge	130	25	^{238}U	80	0.2

A1900 FRAGMENT SEPARATOR

The A1900 fragment separator is a high-acceptance magnetic fragment separator consisting of four superconducting iron-dominated dipole magnets and 24 superconducting large-bore quadrupole magnets arranged in triplets [5]. Sixteen of the quadrupoles include a coaxial set of hexapole and octupole coils for aberration correction. Rare isotope beams are produced by projectile fragmentation of the primary beams on a transmission target at the object position of the A1900 fragment separator. Several production targets, usually consisting of beryllium foils with thicknesses between 100 – 2000 mg/cm^2, can be installed on a water-cooled target ladder. The mixture of unreacted primary beam and reaction products is filtered to obtain a single magnetic rigidity in the dispersive first half of the fragment separator. Isotopic selection can be achieved by passing the selected ions through a wedge-shaped energy degrader from which ions with different atomic numbers emerge with different momenta. The second dispersive half of the separator then provides isotopic separation.

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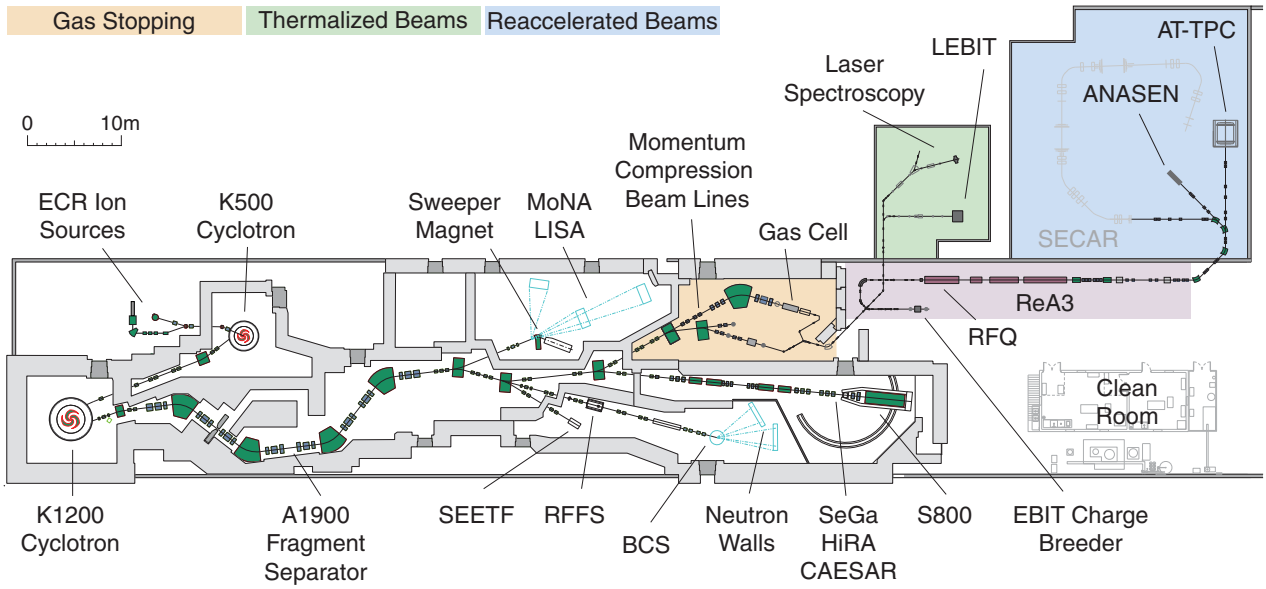

Figure 1: Facility layout of the National Superconducting Cyclotron Laboratory with the Coupled Cyclotron Facility and the newly commissioned gas stopping area and reaccelerated radioactive ion beam capabilities.

Detector stations installed at the mid-plane and at the final focal plane allow the unambiguous identification of single isotopes passing through the separator by measurement of time-of-flight, energy loss, and residual energy. The choice of primary beam, target and degrader material and thickness, and apertures in the fragment separator are parameters that are adjusted to control the intensity and purity of the rare isotope beam [6].

Fast projectile fragmentation does not depend on the chemical properties of the isotope, thus providing a wide range of rare isotope beams with minimum development time and even very short-lived isotopes are accessible. Fragment production rates depend on the number of nucleons removed from the primary projectile and can vary over many orders of magnitude (from 10^7 particles per second to less than 1 particle per day at a primary beam intensity of 1 pnA). Simulation codes are available to reliably predict the production rates and transport efficiencies through the separator [e.g., 7].

Since the inauguration of the CCF in 2001, more than 1000 rare isotope beams have been produced and almost 900 have been delivered to experimenters (see Fig. 2). The resulting rare isotope beam energy is generally close to the primary beam energy. While the beam energy can be degraded to some extent by passing through solid degraders, a different approach is needed to provide low-energy high quality rare isotope beams.

GAS STOPPING

For experiments at lower energies, rare isotope are transported to a linear He gas cell, where they are slowed down and thermalized to less than one eV. Thermalization in the gas stopper allows producing beams with small transverse and longitudinal emittances [8]. The singly charged ions are extracted and accelerated from the gas cell at a few tens of keV and are transported using electrostatic elements with a magnetic mass-analyser to low-energy experimental stations or to a post-accelerator for reacceleration to energies of a few MeV/u.

A 1.2 m long linear gas cell from ANL [9] was installed at NSCL and has been commissioned with several rare isotope beams. Ion beams with intensities of up to 10^5 particles per second have been thermalized and total extraction efficiencies of up to ~10% have been achieved. The gas cell is mounted on a high-voltage platform with variable potential of up to 60 kV. The extraction efficiency of a single mass-analyzed fraction of medium-heavy ions transported into the reaccelerator ranged from ~3% to ~10% due to chemical reactions with impurities in the gas cell.

A cyclotron gas stopper, that will thermalize ions in a gas-filled cyclotron magnet, is under construction at NSCL and will be installed in the gas beam thermalization vault next year.

REA EBIT CHARGE BREEDER

While it would be technically possible to directly accelerate the 1+ and 2+ ions emerging from the gas cell, the use of a charge booster to convert the thermal ions to highly charged ions prior to injection into a linear accelerator allows the implementation of a compact and cost efficient reacceleration scheme.

A charge breeder based on a high-current electron beam ion trap (EBIT) with an 80 cm long cryogenic trap structure and a flexible magnetic field configuration (<6 T) has been installed as the first acceleration element of ReA [10]. The EBIT and gas cell are mounted on a high-voltage platform with an adjustable potential to match the velocity requirement of the RFQ. Singly-charged rare isotopes from the gas cell are transported to the EBIT platform by a electrostatic beam line. A kicker-bender deflects the ions into the EBIT, where they are

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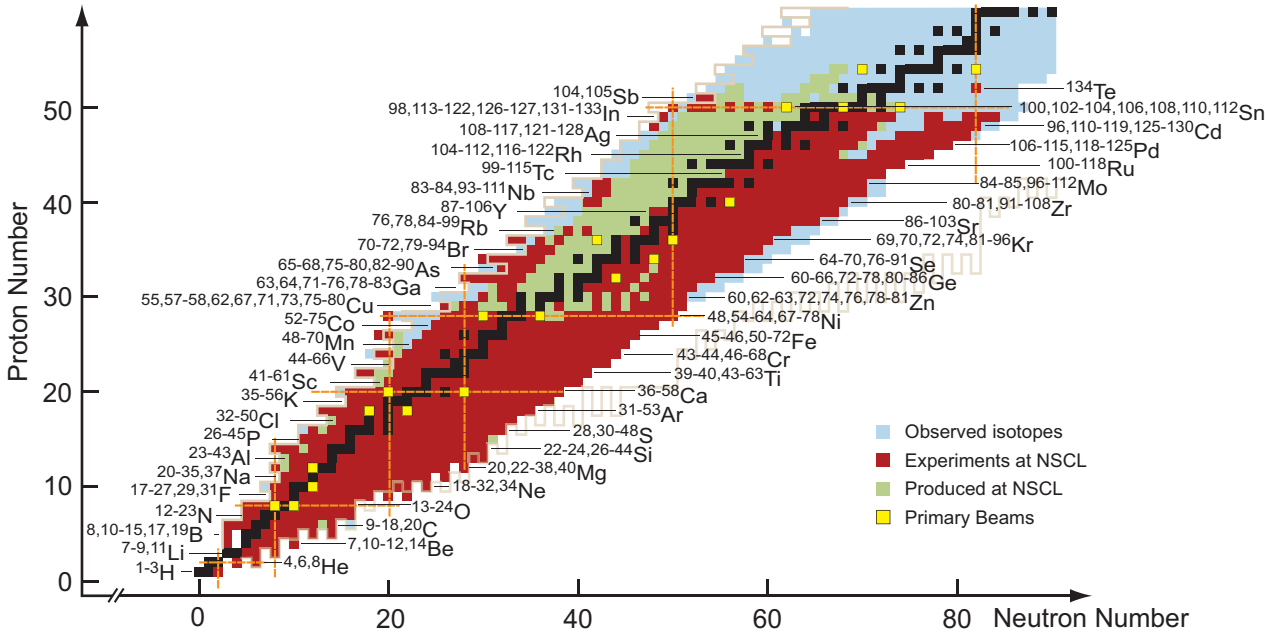

Figure 2: Nuclear chart of rare isotope beams produced (green) and delivered to experiment (red) at NSCL. Only rare isotopes produced from primary beams up to xenon are shown.

continuously captured and charge-bred by electron impact ionization to the desired charge state. Charge breeding times of less than 10 ms, comparable to the extraction time of the gas cell, allow reducing losses by nuclear decay of short-lived isotopes.

A charge breeding efficiency of 5% for $^{39}K^{15+}$ was obtained during first commissioning tests with an EBIT electron-beam current of 750 mA and an accumulation-breeding time of 100 ms. The total capture efficiency over all charge states of about 30% is in good agreement with theoretical expectations at an electron-beam current density of about 400 A/cm^2 [11].

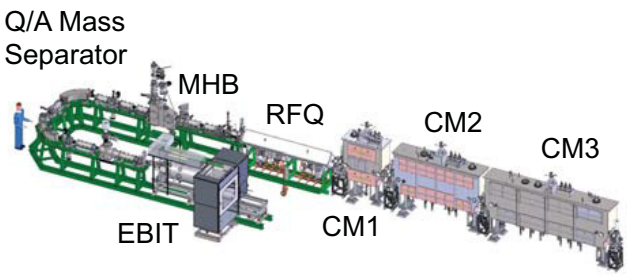

Figure 3: Overview of the ReA reaccelerator facility with EBIT charge breeder, Q/A mass separator, multi harmonic buncher (MHB), RFQ, beta=0.041 cryomodules (CM1 and CM2), and beta=0.085 cryomodule (CM3).

REA POST-ACCELERATOR

After exiting the EBIT charge breeder (Fig. 3) the highly-charged ions are mass separated in an achromatic Q/A separator consisting of a 90-degree electrostatic bender and a 90-degree dipole magnet. Several diagnostic stations are available to measure the ion beam properties before injection into the post-accelerator [12]. Then an external multi-harmonic buncher (MHB) [13] is used to achieve the required beam properties for nuclear physics experiments of an energy spread of 1 keV/u and a bunch length of ~1 ns.

The ReA accelerator consists of a room temperature RFQ and a superconducting linac utilizing quarter wave resonators (QWR). The 3.3 m long 4-rod RFQ accelerates all ion beams from 12 keV/u to 600 keV/u. Together with the MHB, the RFQ (running at 80.5 MHz) was designed to achieve high accelerating efficiency while maintaining a small longitudinal emittance. The measured transmission through the RFQ is ~82% which matches the theoretical design value [14].

The ReA3 superconducting linac uses two types of 80.5 MHz QWR cavities inside three different cryomodules. The first cryomodule, providing beam matching from the RFQ, contains a single beta=0.041 cavity and two 9 T superconducting solenoids. The second cryomodule, with six beta=0.041 cavities and three solenoids, provides beam acceleration to nominally 1.5 MeV/u and 3 MeV/u for Q/A=0.25 and Q/A=0.5, respectively, or deceleration to 300 keV/u. The accelerating cryomodule has been fully commissioned to an acceleration voltage of 0.8 MV/cavity (ReA3 specification value is 0.46 MV/cavity) [15].

The third cryomodule will contain three solenoids and eight beta=0.085 cavities and will provide acceleration to the final desired energy (up to 3 MeV/u for Q/A=0.25 and up to 6 MeV/u for Q/A=0.5 ions). A temporary beam pipe is installed at present for beam transport in place of the third cryomodule.

An achromatic beam transport and distribution line delivers the reaccelerated rare isotope beams from the

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ReA3 platform to multiple experimental end stations in the new ReA experimental hall [16].

FIRST COMMISSIONING RESULTS

Recently, the first rare isotope beams have been charge bred, reaccelerated and used in an experiment, achieving an important milestone of commissioning of the new facility. In preparation for commissioning with thermalized beams, singly charged ^{87}Rb isotope beams from a surface ion source installed in the gas cell area were charge bred to $^{87}Rb^{28+}$ and then reaccelerated. Residual gas ions from the EBIT with an A/Q ratio close to that of the rare isotope beam are used as pilot beams for scaling the EBIT platform acceleration voltage, transport beam lines and the linac to different rigidities. Figure 4 shows an energy spectrum of three different accelerated isotopes (stable $^{16}O^{5+}$ and $^{40}Ar^{13+}$ and long-lived $^{87}Rb^{28+}$) measured by scattering from a foil into a silicon detector [11].

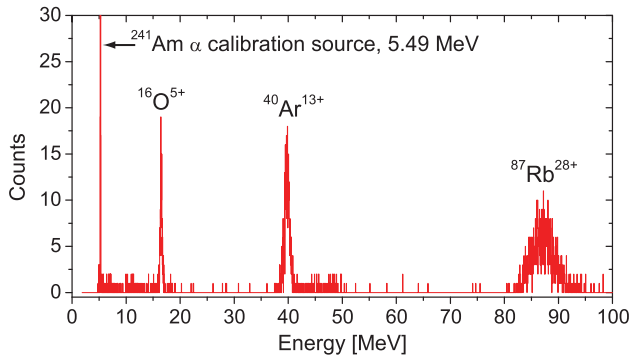

Figure 4: Measured energy spectrum of reaccelerated stable and long-lived isotopic beams.

This pilot beam technique was critical to the reacceleration of the first rare isotope beam. ^{76}Ga ions ($T_{1/2}$ = 33 s) was produced from of a stable 130 MeV/u ^{76}Ge primary beam, separated in the A1900 fragment separator, and then thermalized in the linear gas cell. Activity extracted from the gas cell was mainly distributed between three masses: ^{76}Ga and ^{76}Ga with one and two water molecules attached. Ions with the highest mass yield, $^{76}Ga(H_2O)^+$, were injected into the EBIT and charge bred for an accumulation/breeding time of approximately 100 ms. $^{76}Ga^{24+}$ and $^{76}Ga^{25+}$ were extracted from the EBIT at 12 keV/u and then reaccelerated to 1 MeV/u using the RFQ and two superconducting cavities. The presence of ^{76}Ga was confirmed by detecting the beta-decay activity at the end of the linear accelerator with a decay counter.

The first experiment using a reaccelerated rare isotope beam at the NSCL was performed in August 2013. A fully stripped ^{37}K beam ($T_{1/2}$ = 1.2 s) with an energy of 76.7 MeV/u was produced by fragmentation of a 140 MeV/u ^{40}Ca primary beam. A production rate of ~$9{\cdot}10^6$ particles per second at a primary beam intensity of 70 pnA was measured at the final focal plane of the A1900 fragment separator. After thermalization in the linear gas cell and subsequent charge breeding in the EBIT, a $^{37}K^{16+}$ beam was reaccelerated in the ReA accelerator and delivered to the ANASEN detector installed in the ReA3 experimental hall. Sustained reaccelerated rare isotope beam intensities in excess of 500 particles per second were achieved at the experiment location.

CONCLUSION

Substantial progress has been made with the commissioning of the reaccelerator facility at NSCL with achieving the important milestone of delivery of a thermalized and subsequently reaccelerated rare isotope beam to an user experiment. Commissioning will continue over the next year with an emphasis on reaching higher gas cell extraction and charge breeding efficiencies. The installation of the third cryomodule scheduled in mid-2014 will allow achieving the full energy of the ReA3 accelerator.

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