# OFFLINE TESTS WITH THE NSCL CYCLOTRON GAS STOPPER*

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*Abstract*

Rare isotopes are produced at the National Superconducting Cyclotron Laboratory NSCL by projectile fragmentation at energies of ≈100 MeV/u. The NSCL has successfully used linear gas stopping cells for more than a decade to decelerate projectile fragments to the keV range; first for experiments at low-energy and more recently for reacceleration.

A novel reverse-cyclotron has been constructed by the NSCL based on a superconducting sectored-cyclotron magnet and $LN_2$-cooled He gas to confine and slow down the fragments. Efficient stopping is predicted even for light ions that are difficult to thermalize in linear gas cells. The thermalized ions are transported to the center by a radial RF-carpet system, extracted through the yoke with an ion conveyor and accelerated to <60 keV for delivery to users.

Measured field profiles have confirmed field calculations. The cryogenic beam-stopping chamber has been installed inside the magnet. The RF ion-guiding components have been tested successfully offline and are being prepared for low-energy ion-transport tests inside the magnet.

## INTRODUCTION

The NSCL facility uses fast projectile fragmentation to provide rare-isotope beams (RIB) for a broad range of research. The production method is chemically unselective and allows the production of isotopes far from the valley of stability as evidenced by the more than 900 RIBs delivered to users at NSCL so far. While most of the beams have been provided at the production energies on the order of 100 MeV/u, beams are increasingly requested at rest or at energies of a few MeV/u.

Linear gas stopping cells have been used for more than a decade at NSCL to slow down the beam to the keV-energy range. These 'stopped beams' are delivered to NSCL's low-energy experimental area, i.e. the Penning-trap mass spectrometer LEBIT [1] and the laser spectroscopy setup BECOLA [2] as well as the re-accelerator ReA [3].

The linear gas stopping cells use solid degraders to slow down the incoming beam to an energy that can be dissipated in helium gas at a pressure of ≈100 mbar to a bar and over a typical length of a meter. While a higher pressure allows for efficient stopping in more compact cells, recent installations favor larger sizes to reduce ionization per volume and use lower pressure to benefit from efficient RF ion guiding techniques for fast ion extraction [4], [5].

Extreme purity of the stopping gas is required to prevent charge-exchange of stopped ions with contaminants and other reactions, which can lead to loss of ions and/or unwanted molecular ions. In order to provide cleaner beams, the latest generation of gas stopping cells, including a new cell currently under development at NSCL, use cryogenic cooling to freeze out contaminants.

Most of the fragments provided as stopped beams at NSCL so far had masses of ≈40 u and higher, which allowed for efficient stopping in NSCL's currently operational 1.2 m long ≈80 mbar stopping cell [6].

Slowing down energetic *light* ions with solid degraders and low-pressure gas can induce several meters of range straggling and prevent efficient stopping in gas cells of practicable size or with extraction times comparable to nuclear lifetimes. Demand for stopped light-ion beams at NSCL has been on the rise, in particular since reaction studies with RIBs at the reaccelerator ReA have become possible. Even more interest has been voiced as significantly higher beam rates are expected with the primary beam upgrade in the FRIB (Facility for Rare Iostope Beams) era. The cyclotron gas stopper will be one of several complementary stopping options, built to specifically address the demand for light ions: It provides extreme stopping length as the beam is injected into stable orbits of a cyclotron magnet. Following energy degradation to an appropriate magnetic rigidity, the beam continues in an inward-spiraling motion as it slows down in the presence of buffer gas.

The concept of a gas-filled cyclotron-type magnet has been used to slow down and trap exotic light particles at LEAR/CERN [7], it was considered for the slowing-down of light ions such as $Be^+$ [8] and developed for a wider application by our group [9]–[11].

## CYCLOTRON GAS STOPPER CONCEPT

Figure 1 illustrates the concept of the cyclotron stopper. The high-energy beam delivered from NSCL's A1900 fragment separator enters the gas-filled stopping chamber through a penetration in the return yoke of a three-sectored cyclotron-type magnet. After ≈ 1/4 turn and at a radius of about 0.9 m, the beam passes through a solid degrader, which reduces the beam rigidity to 1.6 Tm and puts the beam on a stable orbit. At this point, the beam is nearly fully stripped. The presence of the helium gas causes the beam to lose energy and pick up electrons. In average, the rigidity of the

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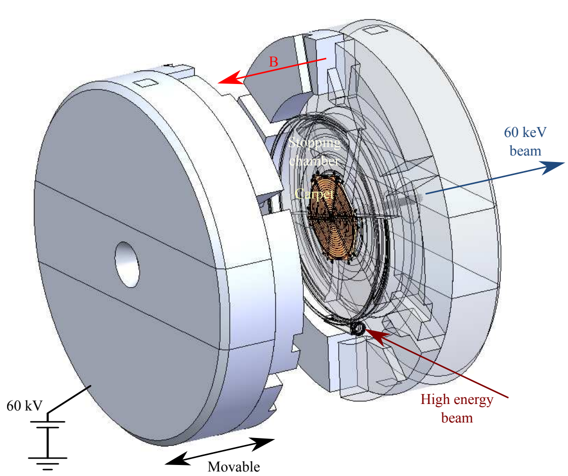


Figure 1: Sketch of the cyclotron stopper.

beam is kept smaller than needed for circular orbits and the beam slows down on an inward spiral to come to rest in a stopping volume with radius of $< 0.5$ m. The sectoring of the magnet is essential to provide axial focusing in the slowing-down process.

Inside the central stopping volume the thermalized ions, now singly or at most doubly-charged, are exposed to an axial electric field that pushes them towards radiofrequency (RF) ion carpets [12], installed vertically on the exit side of the magnet. The ion carpets use electric fields to transport the ions to the axis in a 'surfing'-type ion motion [13]. At this point, aided by gas flow, they enter an extraction region with a pressure of several mbar. Here a 1 m long ion conveyor [14] takes the ions through the axial bore in the return yoke. Outside the bore of the magnet, the ions pass through more pumping stages, before they are electrostatically accelerated to 60 keV energy. For this purpose, most of the cyclotron stopper infrastructure is placed at high voltage (HV).

## THE MAGNET

The cyclotron gas-stopper magnet is a vertical superconducting split solenoid generating a focusing dipole field with maximum field of 2.6 T at a nominal excitation of 180 A. The design is a result of numerous Monte-Carlo type beam stopping simulations using successively refined 3D-magnetic TOSCA field maps [10], [15]. The magnet poles are divided into three hill and three valley regions. Their profiles required special care in order to provide sufficient axial focusing during deceleration and not to lose beam to an excitation of motion in the so-called Walkinshaw resonance. The clearance between the pole pieces was maximized to accept the large-emittance beam from the fragment separator and provide the necessary space for the cryogenic stopping chamber with its RF carpet structure and push-field electrodes. The minimum gap between the hills is 18 cm, leaving an effective stopping volume, 10 cm wide and $\approx 2$ m in diameter.

The 4-meter diameter, 2-meter wide, 165-ton return yoke is split in two at the median plane for access to the interior of the magnet: the half housing the extraction electrode system is fixed to the floor, while the other one rests on a movable support structure that provides 1.5 m clearance when opened; see Fig. 2 for a photograph of the device. For ease of assembly and transport the yokes are made of three major parts: a lower and an upper crescent with a horizontal slab between. Base plates holding the hill-and-valley pole pieces screw into the assembly of the outer three parts. A total of 12 return-yoke inserts near the median plane complete the yoke and provide radial openings for degraders, diagnostics, electric feedthroughs, the three support links for the central stopping chamber and the injection channel. More details about magnet design and construction can be found in [11], [16].

### *The Cryostat*

The two superconducting coils are cooled by a pair of cryostats, which are mounted into the two halves of the yoke. The cryostats use three CryoMech PT415-RM pulse-tube cryorefrigerators each and liquid-nitrogen cooled thermal shields to cool the coils to liquid-helium temperature. With a nominal cooling power of $\approx 1.35$ W per cold head, the system generates and maintains its liquid inventory, a total of $\approx 15$ liters, from gaseous helium. This concept avoids the problematic transfer of liquid helium to the cryostats when operated on HV. HV insulators in the He connections of the cold heads allow the compressors to remain on earth ground.

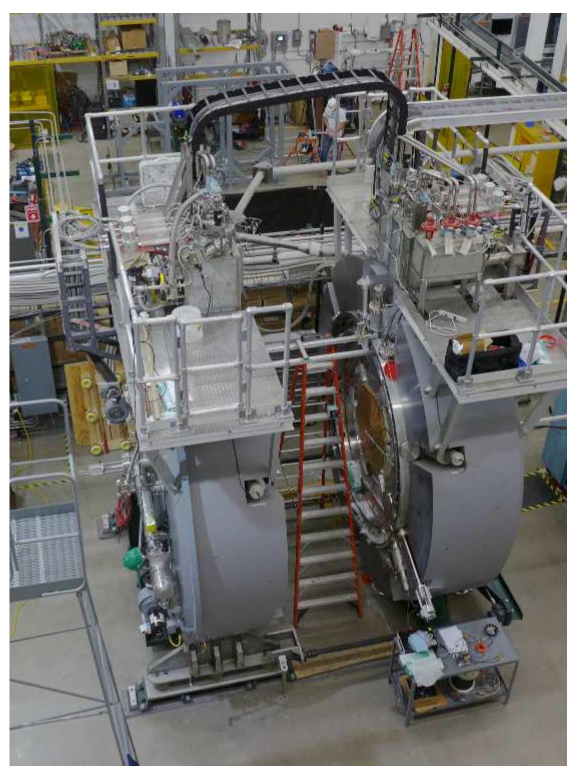

Figure 2: Photo of the cyclotron stopper, opened for installation of the ion carpets.



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A complete cool-down from room temperature requires about two weeks; the liquid He inventory builds up in the last two days. More details on the cryogenic system of the cyclotron stopper can be found in [15], for reports on the performance of the cooling system see [17], [18].

### *Magnet Tests*

After a number of tests and support link adjustments at lower currents, the magnet was brought up to the nominal field at full current in 2015. Field profiles were taken with a movable Hall probe that could slide either radially across a hill or a valley or inside the magnet's axial bore. In all cases, the measurements confirmed the calculated profiles, peaking at 2.6 T [18]. Consequently, the magnetic field index derived from the measured data agrees well with expectations [11], which has been identified as critical for efficient stopping of the injected beam.

As part of the magnet tests, the magnet's quench protection system has been tested as well, leading to valuable information on how quickly the stored energy is removed at various field levels. As an example, when a quench was triggered at the nominal current, the field decayed within 130 s to one percent, in reasonable agreement with thermal calculations [19].

### *The Stopping Chamber*

The central aluminum vacuum chamber, which houses the RF ion carpets described below, is suspended inside the magnet by three radial tension links. Thermal isolation of the liquid-nitrogen cooled stopping chamber is facilitated by a guard vacuum. Because of limited space inside the magnet, the pole pieces of the magnet are part of the axial walls of the guard vacuum, while an extension of the fixed-side cryostat completes the vacuum chamber radially. Due to its large 2.35 m diameter, the lids of the chamber do not tolerate significant pressure differences between the inside and the guard vacuum. A pressure bypass system has been installed to protect the chamber during pumping cycles and operation at 100 mbar room-temperature equivalent pressure.

## EXTRACTION ION GUIDES

While the damping force of the helium gas allows for the stopping of injected ions, it also slows down the process of extracting ions. Currently the most effective technique to transport ions quickly in high-pressure gas, e.g. in linear gas stopping cells or analytical chemistry applications, is a combination of static and inhomogeneous RF electric fields.

### *RF Ion Carpets*

In the cyclotron stopper, a static electric field pushes the stopped ions towards a 'surfing'-type RF ion carpet, see Fig. 3 for a sketch of the arrangement and Fig. 4 for a photograph. The ion carpet is comprised of a large number of concentric electrodes. An RF voltage is applied so every electrode is $180^{\circ}$ out of phase with its neighbor. This results in a net force that counteracts the static field generated

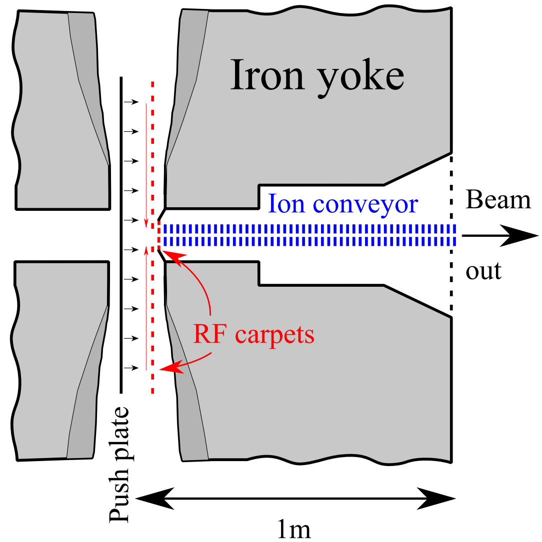


Figure 3: Sketch of the extraction system.

with the push plate and positions the ions at a small distance above the carpet. In order to move the ions across the carpet, a high-frequency (HF) voltage is added with phase shifts of $90^{\circ}$ between neighbor electrodes. Depending on conditions such as pressure, push field and RF/HF parameters, the ions can 'surf' in the troughs of the electric HF wave with transport speeds approaching the wave velocity. For a more detailed description of the concept, see e.g. [13], [14].

Several prototype carpets with different geometries, areas, electrode spacings had been built and tested [12], [20],

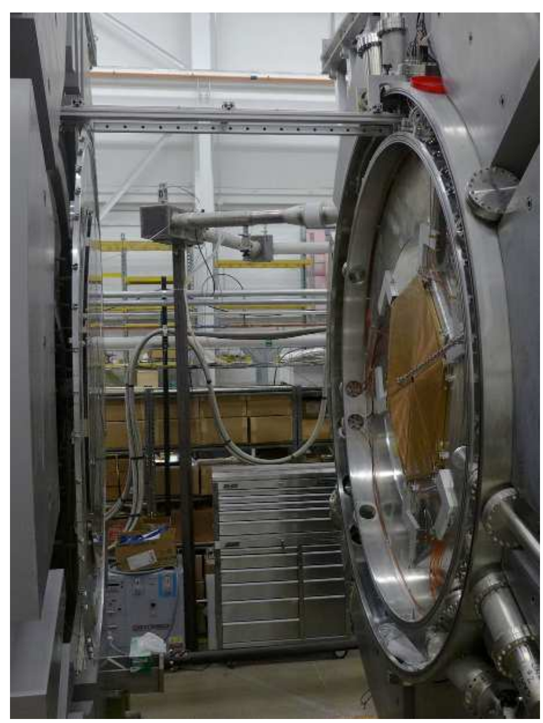

Figure 4: Closeup showing the stopping chamber with the RF ion carpets installed inside the opened cyclotron stopper.

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demonstrating that ions with a wide range of masses can efficiently be transported over the required distance of a few tens of cm. The currently installed ion carpet, printed circuit boards with Kapton backing, cover a diameter of 0.89 m. With an active area of $\approx 0.6\,\mathrm{m}^2$ the 896 electrodes present a capacitive load of several nF to the RF system. Because of this load and for practical reasons, the carpet has been built as six 60-degree sectors with separate resonant RF driver circuits, capable of delivering the required RF amplitudes. To minimize RF losses, the resonant circuits have been placed at the perimeter of the carpets, in pockets added to the vacuum chamber, which use space in the pole valleys.

### *Ion Conveyor*

Once within a radius of ≈25 mm from the axis of the cyclotron stopper, the ions continue on and through a miniature RF ion carpet, installed for differential pumping purposes and enter an ion 'conveyor' for transport through the bore of the magnet. An RF ion conveyor uses a traveling RF wave in a similar fashion as the surfing ion carpets, however it is shaped as a stack of ring-shaped electrodes to move ions along the inside [21]. In the cyclotron stopper, 536 electrodes are set up in groups of eight for 45-degree RF phase shifts; see Fig. 5 for a photograph. Despite its complexity,

Figure 5: The 1 m RF ion conveyor with a 1-1/4" wrench for scale.

this type of ion guide was chosen as it is expected to transport ions rapidly and efficiently even in the presence of the magnetic field, which drops from 2.4 T to a few 100 G along the structure.

The ion conveyor system with its entrance and exit mini-carpets have been tested in NSCL's stopping vault to benefit from existing pumping and diagnostics infrastructure. The expected pressure drops across the mini-carpet pumping barriers have been confirmed. A variable-frequency digital driver circuit has been developed to provide the required eight 45-degree phase-shifted RF signals for the conveyor. Ion transport tests through the 1 m long ion conveyor with Na, K and Rb ions, produced by surface ionization sources, have demonstrated efficiencies exceeding 80 %.

Transit times have been measured by using an electrode upstream the conveyor as a beam gate and recording the time when the resulting ion pulse appeared downstream. As an example, Figure 6 shows measured transit times of K-ions as a function of the RF wave frequency at a conveyor pressure of ≈ 4 mbar. Subtracting the expected flight time from the beam gate to the conveyor, the transit time through the conveyor can be estimated to be below 5 ms for frequencies up to 800 kHz.

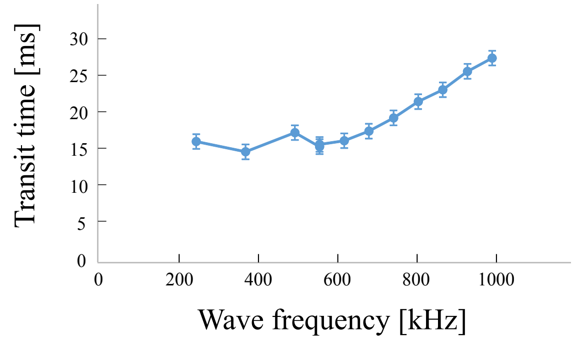


Figure 6: Measured transit times of $K^+$ ions through the conveyor as a function of wave frequency.

## CONCLUSION, STATUS

The cyclotron stopper is currently installed in an assembly area, separated from NSCL's beam lines, in order to allow low-energy beam operation during commissioning activities. Following the recent installation of the large-scale carpets and the ion conveyor in the cyclotron stopper, ion transport tests along the entire extraction system at room temperature are about to start. A test ion source has been installed on a rotatable arm reaching across the main RF carpets. This setup will allow systematic transport tests along these RF carpets in the presence of magnetic field and helium gas. Another test with the source placed at the entrance of the conveyor and reduced gas pressure will test the ion conveyor's performance with a magnetic field gradient. A repeat of these tests with the central chamber cooled by liquid nitrogen and demonstrated operation at high-voltage are important steps before moving the cyclotron stopper from its offline location to a production area.

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