THE CYCLOTRON GAS STOPPER PROJECT AT THE NSCL

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Abstract

Gas stopping is becoming the method of choice for converting beams of rare isotopes produced via projectile fragmentation and in-flight separation into low-energy beams. These beams allow ISOL-type experiments to be conducted on projectile fragmentation products, such as precision mass measurements with traps or laser spectroscopy. Current gas stopping systems for high-energy beams employ a linear gas cell design filled with 0.1-1 bar of helium. While linear gas cells have found success in a variety of experiments, this success is limited due to the space charge effects induced by the ionization of the helium atoms during the stopping process. These space charge effects pose a limit on the maximum incoming beam rate. Furthermore, the extraction time of stopped ions from these devices can exceed 100 ms causing substantial decay losses for very short-lived isotopes. To avoid these limitations, a new type of gas stopper is being developed at the NSCL/MSU. The new system is based on a sector-focused cyclotron magnet with a stopping chamber filled with Helium buffer gas at low pressure. RF-guiding techniques are used to extract the ions. The space charge effects are reduced by the large volume and due to the separation between the region of stopped ions and the region of highest ionization.

INTRODUCTION

Rare isotope production via relativistic projectile fragmentation and in-flight separation produces short-lived nuclides without limitations due to element selectivity. Several fragmentation facilities worldwide are developing systems to slow down and stop fast rare isotope beams. The goal is to produce low-energy beams that can then be used for ISOL-type experiments, *i.e.* experiments using low-energy radioactive beams with small phase space volumes, such as mass measurements with traps, laser spectroscopy, or post-acceleration for low-energy reaction studies. LEBIT, installed at the NSCL at MSU, was the first to demonstrate the slowing down and stopping of fast (100 MeV/u) rare isotope beams for precision experiments. A number of high-precision mass measurements have already been performed, for example on ^{37,38}Ca [1, 2], ^{66}As, ^{64}Ge, ^{69}Se [3], and ^{40,42}S. At GSI, a stopping test with a large linear gas cell [4] was successfully carried out. A laser spectroscopy experiment at RIKEN, using trapped radioactive Be ions obtained via gas stopping of fast fragments, has also been performed recently [5].

Present gas stopping schemes are based on the slowing down and stopping fast fragments using a combination of solid degraders and a chamber filled with helium gas at pressures up to 1 bar. Due to the high ionization potential of the He buffer gas, the ions remain singly or doubly-charged, and are guided out of the gas using electric fields and gas flow and then prepared into a low-emittance, low-energy ion-beam by means of radio-frequency (RF) ion guiding techniques. Different methods are applied for the ion extraction. In the case of low-pressure gas cells (< 300 mbar He) a combination of electrostatic and RF potentials is often employed. The gas cell [6] at the NSCL is operated at high pressure (1 bar He). Static electric fields guide the ions to an extraction nozzle where the the gas flow transports them out of the gas cell.

It has been observed that for high incident beam rates ($> 10^5$ pps), linear gas stoppers exhibit a decreasing extraction efficiency [7, 8, 9]. Extraction efficiencies of existing linear gas cells decrease precipitously with the ionization rate density (rate of generation of ion pairs (IP) per volume) inside the gas cell. The decrease in efficiency has been attributed to space-charge effects, which drive the ions towards the walls of the gas cell. The desired beam rates of next generation facilities will be on the order of 10^9/s, requiring the efficient handling of ionization rate densities of about 10^{11}IP/cm^3/s. This is not feasible with existing gas cells without a significant loss in efficiency.

For the stopping of rare isotope beams with energies of $\approx$ 100 MeV/u, linear gas cells need to be operated with a pressure-length product of typically $p \cdot L$=0.5 bar·m. Limited by the maximum applicable electric field for ion transport and extraction inside the gas cell the average extraction time is about 100 ms. Such long extraction times result in decay losses of rare isotopes and do not match the advantage of fast-beam production.

In order to maximize the benefit of the gas stopping approach, the following requirements have to be fulfilled: 1) Short extraction times. In order to minimize decay losses the extraction time should be comparable or shorter than the shortest half-life of the ions to be studied. Extraction times well below 100 ms are desirable. 2) Efficient stopping and extraction at high beam intensities. Next-generation facilities will provide rare isotope beam intensities of up to 10^9/s, many orders of magnitude higher than available beam intensities at present fragmentation facilities. 3) Applicability to all fragment beams. In order to be universal, a gas stopping station needs to be able to handle beams of isotopes with a large range of atomic numbers and neutron-to-proton ratios.

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The cyclotron gas stopper [10], a new concept currently being developed at the NSCL seeks to fulfill these requirements and overcome the limitations of linear gas stoppers. Such a system, employs a sector-focused cyclotron magnet with a gas-filled stopping chamber with radio-frequency (RF) ion guiding techniques for ion extraction.

CONCEPT

The cyclotron stopper concept has been used for the production of antiprotonic, pionic and muonic atoms [11] and has also been discussed for the stopping of light ions [12]. The use of this concept for the stopping of intense rare isotope beams was first shown in simulations performed at the NSCL/MSU [10].

Figure 1 presents the main components of the cyclotron gas stopper. Ions injected into the system will first pass through a solid degrader and then be slowed down in helium gas at low pressure. The device uses a sectored magnetic field to radially and axially confine the ions and cause the ions to spiral towards the center as they lose kinetic energy through collisions with the gas. The ions are finally extracted by means of static electric fields, an RF carpet [7] and radio-frequency ion guides.

A long stopping path allows for low pressure to be used inside the cyclotron gas stopper. This low pressure will allow for a fast drift inside the magnet and a fast extraction, which will match the advantages of fast-beam production. The larger stopping volume along with the separation of the ionization density from the region of stopped ions reduces the losses incurred by the space-charge effects in linear gas stoppers.

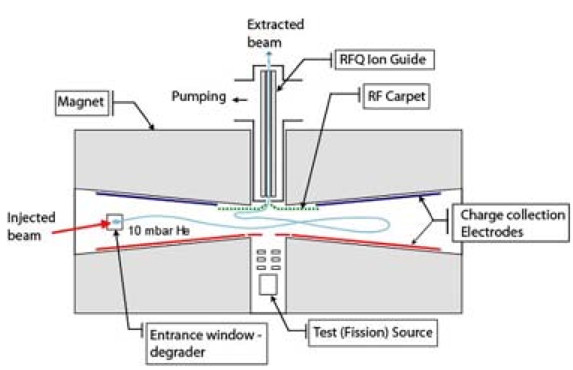

Figure 1: Schematic view of the cyclotron gas stopper showing the main components of the system. A cyclotron-type focusing magnet contains a vacuum chamber filled with helium at low pressure, a beam degrader, charge collection electrodes, and an RF carpet for ion extraction.

An RF carpet has already been used successfully [7] in a linear gas cell. Because of its low pressure (≈ 100 mbar) the cyclotron gas stopper provides a better environment for the operation of RF carpets than high-pressure linear gas stoppers. The modest damping of the ion motion, as compared to high-pressure linear gas cells, allows carpets to be used with a relatively large pitch and low voltages, while still providing a strong repelling force. Static potentials will be used to guide the ions onto the carpet surface and to the extraction orifice.

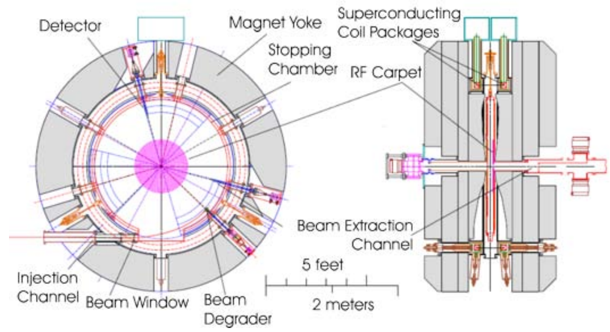

Figure 2: Design concept of the vertical superconducting magnet under consideration.

MECHANICAL DESIGN

The mechanical design of the cyclotron gas stopper is ongoing and will be based on detailed simulations discussed below. At the present stage of design a vertically oriented magnet system is favored. Superferric magnets have been designed that would produce peak magnetic fields between 1.6 and 3 T. The current magnet design has a peak magnetic field of 2.7 T. Two separated coil packages will facilitate access to the inner part of the system for maintenance and development. Figure 2 presents a conceptual design of one of the systems under consideration. The vertical arrangement has practical advantages for the extraction and transport of the low-energy beams out of the fringe field. The sector-focused cyclotron magnet system will house a cryogenically cooled vacuum chamber filled with helium gas. The beam degrader and beam monitors are inserted radially. The current system under investigation has a diameter of 3.8 m and an injection radius of 0.95 m.

BEAM STOPPING SIMULATIONS

Various detailed numerical simulations of the ion motion based on realistic magnetic fields are being carried out to optimize and characterize the system. The simulations currently implement the Lorentz force, energy loss, charge-exchange collisions, small-angle multiple-scattering [13], energy straggling, and the option of using multiple degraders. The simulations are being performed for light and heavy isotopes of key nuclides with different A/Z. Bromine isotopes ^{70,79,94}Br and Iron isotope ^{56}Fe were chosen to represent the central region of the nuclear chart. Iodine isotopes ^{108,127,144}I for heavier isotopes and ^{13,24}O for the lighter mass region. The choice of these nuclides along with their large area of coverage of the chart of the nuclides was also based on the availability of data for low-energy charge-exchange cross sections with helium [14, 15].

Different magnet sizes and field shapes have been investigated. A sector-field was found to be advantageous with regards to injection and transverse focusing. The magnetic field from an early magnet design and a more recent sectored field are shown in Figure 3.

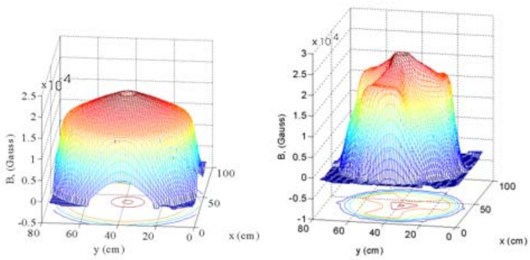

Figure 3: Magnetic fields obtained in a weakly focusing magnet (left) and a sector-field magnet (right), calculated with the TOSCA code.

As examples, beam simulations were for example performed for ^{79}Br ions with energies of 62 MeV/u before the degrader in a sector-field magnet with $B_{max} = 2.7$ T. A helium gas pressure of 180 mbar was used to stop and separate the stopped positions of the ^{79}Br ions from the region of high ionization. The higher pressures as compared to the initial simulations found in [10] is required because of the use of lower, more realistic charge changing cross sections in the recent calculation. Figure 4 shows typical results. On the left the trajectory of a single ^{79}Br ion inside the cyclotron stopper is presented. The figure on the right shows stopped ion distributions of ^{79}Br ions (crosses) together with energy loss (ionization) densities (colored/greyscale areas) inside the gas. An advantage of the cyclotron gas stopper is that there is a separation between the region of highest ionization and the region where the ions stop. Compared to linear stoppers this leads to a reduction in space charge effects.

Stopping efficiencies of approximately 90 % have been achieved for the bromine beams investigated so far with the new charge exchange cross sections and at the higher pressures. The systematic exploration of the stopping characteristics for other rare isotope beams is ongoing.

SUMMARY

The cyclotron stopper concept has the potential to overcome limitations in high beam intensity and long extraction times. Recent calculations have shown a high stopping efficiency and good separation between the position of stopped ions and the region of high ionization density. Additional simulations with various ions and magnetic fields are ongoing. Work supported by DOE under contract DE-FG02-06ER41413

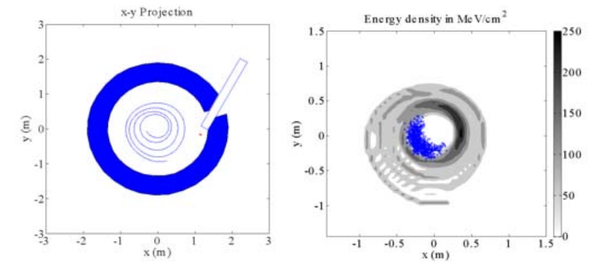

Figure 4: Trajectory of a single ^{79}Br ion with an energy of 23 MeV/u after the degrader inside a sector-focused magnet filled with 180 mbar He (left). Energy deposition and stopped ion distribution (crosses) for a sector-focused magnet (right).

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