Final Report

Developments for a Fast Gas Stopping Scheme for High-Intensity Rare Isotope Beams from Projectile Fragments at RIA

Development of a fast cyclotron gas stopper for intense rare isotope beams from projectile fragmentation: Study of ion extraction with a radiofrequency carpet

DOE Award Number: DE-FG02-06ER41413

Recipient: Michigan State University

Principal Investigator: Georg Bollen; Co-PI: David J. Morrissey

MSU Collaborators:

NSCL Staff: S. Schwarz, F. Marti, Y. Batygin, A. F. Zeller, S. Chouban

Graduate Student: G. Pang

Research Associates (postdocs): C. Campbell, C. Guénaut

External Collaborators:

M. Wada, RIKEN,

C. Scheidenberger, GSI, Darmstadt, Germany

Executive Summary

How does Research add to understanding of area investigated?

The technical effectiveness and economic feasibility of the methods/techniques investigated and demonstrated

Other benefit of the project to the public

Minimum of 1 paragraph

Research and development has been performed in support of the design of a future rare isotope beam facility in the US. An important aspect of plans for earlier RIA (Rare Isotope Accelerator) and a requirement of FRIB (Facility of Rare Isotope Beams) to be built at Michigan State University are the availability of so-called “stopped beams” for research that contributes to answering questions like how elements in the universe are created and to provide better insight into the nature of Fundamental Interactions. In order to create “stopped beams” techniques are required that transform fast rare isotopes beams as they are available directly after addresses questions like the origin of that will allow and High priority is given to the evaluation of intensity limitations and the efficiency of stopping of fast fragment beams in gas cells and to the exploration of options to increase the efficiency and the reduction of space charge effects.

Systematic studies performed at MSU as part of the RIA R&D with a linear gas cell under conditions close to those expected at RIA and related simulations confirm that the efficiency of stopping and extracting ions decreases with increasing beam intensity. Similar results have also been observed at RIKEN in Japan. These results indicate the concepts presently under study will not be able to cover the full range of intensities of fast beams expected at RIA without major losses. The development of a more robust concept is therefore critical to the RIA concept. Recent new beam simulation studies performed at the NSCL show that the stopping of heavy ions in a weakly focusing gas-filled magnetic field can overcome the intensity limitation of present systems while simultaneously providing a much faster ion extraction. We propose to design and build such a cyclotron gas stopper and to test it at the NSCL under conditions as close as possible to those found at RIA.

Comparison of the actual accomplishments with project goals

Summary of project activities and results over period of funding

Products developed (publications, collaborations fostered, technologies)

This is a proposal to continue ongoing R&D work (DE-FG02-06ER41413) related to the development of a cyclotron gas stopper for rare isotope beams. The previous (FY06/07) effort concentrated on simulations of the slowing down of fast ions. The ongoing effort (FY07/08) deals with the development and construction of a test stand for the study of ion extraction from the gas stopper using radiofrequency carpet techniques. Here we request resources to perform systematic tests of various carpet/electrode systems under realistic operational scenarios. The results will be applicable to both a cyclotron gas stopper and linear gas cells.

Status of gas stopping and the cyclotron gas stopper project

Several groups from around the world are presently working on projects to thermalize energetic rare isotope beams from projectile fragmentation processes [Wei05, Wad03, Tak05] and from low energy reactions [Sik03, Sav03]. These studies use linear gas-filled stopping chambers with electrodes for transporting stopped ions to an extraction orifice by means of static (DC) and/or radiofrequency (RF) electric fields. The projectile-fragment gas stopper at the NSCL [Wei04a, Wei04b, Wei04c, Wei05] was the first system in the world used for nuclear physics experiments. Since 2005, precision Penning trap mass measurements [Bol06, Rin07, Sch07] have been performed with the LEBIT facility at the NSCL on short-lived isotopes of Si, P, Ca, S, Fe, Co, Ge, As, Se, Br, produced at energies in the range of 90 - 120 MeV/u. At RIKEN research and development work has been performed [Wad03, Tak05] on stopping very light ion beams (80 MeV/u) and the first successful laser spectroscopy experiment has recently been reported [Nak07]. A large gas catcher built by a collaboration headed by ANL was tested with radioactive sources [Sa03, Tr06] before being used in a single test at GSI with Cr isotopes at about 280 MeV/u. The present high-energy linear gas cell systems operated at MSU and RIKEN for the stopping of fast beams show (1) severe degradation of performance with incident beam rate, (2) long extraction times, and (3) a low stopping efficiency for light ions. While the possibility exists for increasing the beam rate capability of linear gas cells by using RF guiding techniques under certain conditions, the fast extraction and the efficient stopping of light ions is expected to remain difficult.

Concept and design of the cyclotron gas stopper

A cyclotron gas stopper takes advantage of the focusing properties of a cyclotron-type magnet which confines the ions in the radial and axial dimensions during the deceleration process. Similar devices have been successfully used to stop antiprotons, pions and muons [Sim88, Sim93] and have been proposed [Kat98] for stopping light ions. Figure 1 (top) shows the cross section of a schematic cyclotron gas stopper for rare isotope ions. The cyclotron magnet surrounds a helium-filled vacuum chamber. Fast ions are injected tangentially into the system and pass through a solid degrader with a thickness adjusted such that the degraded beam follows an inwards spiraling motion. Once thermalized close to the center of the system the ions are transported to the extraction orifice on the central axis by an RF carpet [Wad03]. An RF quadrupole ion guide on the central axis is used to finally transport the ions through a differential pumping system out of the cyclotron stopper.

The conceptual design work and detailed simulations of ion stopping in a cyclotron gas stopper was supported, in part, by DOE under DE-FG02-06ER41413. Simulation work is continuing with resources provided by MSU. Figure 1 (bottom) shows the latest version of the mechanical and magnet design. The system will use a vertical iron-dominated superconducting sector-field magnet with a maximum field strength of approximately 2.5 Tesla and a near constant field index of $k \approx -0.3$. This magnet concept has resulted from a series of more than 15 magnet designs utilizing the TOSCA code, aimed at maximizing the stopping efficiency for a large range of rare isotope species available from a high-energy fragment separator. The vertical orientation of the magnet was found to provide the best match to the properties of most beams having passed a momentum compression stage needed to reduce the momentum spread of the beam to typically $\Delta p/p < 0.5\%$. The stopping chamber in its present design has a radius of approximately 100 cm and an inner height of approximately 10 cm; the beam injection radius is 95 cm. The chamber will be cryogenically cooled in order to ensure high purity of the stopping gas. A thin beam window will separate the stopping chamber from the evacuated injection channel. An adjustable radial beam degrader will reduce the injected beam rigidity to approximately 1.6 Tm and send the ions onto their initial trajectory in the gas. The chamber will be equipped with electrodes for ionization collection and ion guiding and a central RF carpet and DC electrode system will be used for the extraction of the stopped ions. It is important to note that the central region of the cyclotron gas stopper very much resembles the extraction region of a linear gas cell employing RF-carpet techniques, because once thermalized the effect of the magnetic field on the ion migration is practically zero.

Status of simulations

The initial simulations presented in [Bol05] included the Lorentz force provided by a simple magnetic field and the energy loss in helium from the stopping and range tables from SRIM [Zie03]. The charge states and charge changing cross sections of the ion beam was taken from simple formulas that had been bench-marked with low-energy data (<200 MeV). These early simulations have been followed by a substantial number [31] of more detailed studies going hand-in-hand with the conceptual design of a realistic system funded in part by DOE and continuing using MSU funds. The simulations were performed for a variety of realistic magnetic fields and using a large number of chemical elements each with for a large range of neutron-to-proton ratios. During the course of these studies better descriptions of physical processes involved in the stopping of the ions were found to be necessary and implemented in the simulation codes. Two important processes will be discussed in the following.

Energy loss and straggling, angular scattering: Energy loss and straggling as well as angular scattering in the cyclotron gas stopper will occur in the beam window, the final degrader and in the stopping gas itself. A version [Tor06] of ATIMA [Atim] is used to model the beam interaction in solids. For the energy loss in the gas the Stopping and Range Tables (SRT) calculated with SRIM are used for the different ion species in helium. A semi-empirical approach [Yan91] is used to describe energy loss straggling during the complete stopping process. Angular scattering due to collisions in the gas was not included in the early simulations but was found to be an important process that could lead to losses at the end of the stopping path. Two different approaches to angular straggling have been implemented in our simulations codes, one based on the treatment of small angle multiple scattering as developed by Sigmund et al. [Sig74], the other is based on scattering in single collisions following a suggestion made by Amsel [Ams03].

Charge exchange: Experimental charge exchange cross-sections in helium are only known for a limited number of elements and most of the data available have been obtained at energies of less than one MeV/u. In the early simulations [Bol05] formulas and data from [Bet72] were used for cross section extrapolations and for the determination of the mean charge state $\langle q \rangle$ of the stopping ions. We found that these estimates of the cross sections were too large, leading to very short mean-free paths and relatively smooth trajectories even at gas pressures of a few mbar. Several codes (Charge, Global [Sch98], and Etacha [Roz96]) exist for the prediction of charge state distributions for ions passing through matter, but the number of electrons they can handle is rather restricted and their validity is typically limited to energies well above 10 MeV/u. Empirical scaling laws have been developed for electron loss [DuB05] and capture [Sch83] that satisfactorily describe the existing data. Simple formulas also exist to describe the variation of charge-changing cross section close to the equilibrium charge states [Sch01]. Based on comparisons of the different codes and formulas with each other and with existing data we developed a procedure for the calculation of electron loss and capture cross sections in the energy range up to a few tens of MeV/u. The physics model for electron loss used in the Etacha code was found to provide cross sections that agree well with experimental data down to a few MeV/u. The semi-empirical formula by Schlachter et al. [Sch83] for capture cross sections shows good agreement with experiment for a wide energy range and different ions. These loss and capture cross sections are used at high energies. At low energies the capture and loss cross sections close to $\langle q \rangle$ are calculated with an empirical formula by Franzke [Fra92], using Schlachter's capture cross sections and $\langle q \rangle$ from a formula by Schiwietz [Sch01]. For intermediate energies an interpolation between both approaches is used. This procedure was found to reproduce known cross sections satisfactorily and to lead to average charge states close to those observed in the few experiments available. We are in contact with R. Watson from TAMU and plan to perform a

number of electron capture and loss cross section measurements for a selection of elements in the critical energy regime of a few MeV/u to a few tens of MeV/u. The main impact of the overall change of the lower cross sections was that a higher gas pressure is needed for the efficient stopping of the ions. Compared to pressures ranging from 10-200 mbar in the early simulation, gas pressures of 150-250 mbar will be required.

Expected Properties: The new simulations of the cyclotron stopper are nearing completion and the expected performance with respect to stopping efficiencies and extraction times and rate capability is becoming clear. The stopping efficiency is determined by axial and radial losses inside the cyclotron stopper. Axial losses occur at the pole gaps and are determined by the initial beam emittance and by angular scattering, the latter being dominant at lower pressures. The simulations for realistic secondary beams give stopping efficiencies between 80% and 95% at gas pressures between 150-250 mbar. Figure 2 shows typical stopped ion distributions together with ionization densities. For medium mass and heavier ions a spatial separation of the region of maximum ionization and the region where the ions stop is achieved. The mean stopping radius of the ions with $A < 100$ is typically less than $\langle r \rangle = 40$ cm and as low as $\langle r \rangle = 15$ cm for the lightest ions. An important feature of the cyclotron stopper is the fact that light ions can be stopped with high efficiency close to the extraction point. This behavior is in strong contrast to that of linear gas cells where the efficient stopping of light ions is essentially impossible. The stopping of the ions close to the central extraction orifice leads to short extraction times, typically between 15 and 50 ms, for a realistic electric guiding field of $E = 10$ V/cm towards the center.

The average ionization density per stopped ion in the stopping volume, depending on the ion to be stopped, is typically below 100 to 1000 e-He⁺/cm³/ion. A comparison with linear gas cells for fast fragment beams where ionization rate densities can reach values up to 1000-10000 e-He⁺/cm³/ion in the stopped-ion region, indicate the advantage of the cyclotron stopper concept for handling high beam rates. In order to obtain more detailed and reliable information on the effect of space charge in the region of the RF carpet, particle-in-cell (PIC) simulations are being prepared that will follow the dynamics of the space charge distribution. The results of such calculations will provide important guidance for studying of the transport properties of RF carpets, the main goal of the present proposal. These results will be relevant for both linear gas cells and the cyclotron gas stopper.

Fig. 2: Stopped ion-distributions (white crosses) for different ion species. Also shown (color-coded) is the ionization density due to helium ions created during in the stopping process.

Study of ion extraction with an RF carpet

The remaining problem to be studied for the cyclotron gas stopper is the ion transport and extraction after thermalization in the central region with the help of RF carpet techniques. In order to investigate possible beam rate limitations of gas stoppers using RF carpet or related techniques these studies need to consider the effect of space charge. A dedicated test stand for RF carpet and beam extraction tests is presently being built. The goal of the proposed work is the study and systematic test of RF carpet/electrode systems for a wide range of realistic operational scenarios.

An RF carpet is a planar arrangement of concentric electrodes to which an RF voltage (with a phase shift of 180 degree between neighboring electrodes) is applied to create a net repelling force for ions moving in a buffer gas. The nature of this force is the same as the confining force in a radiofrequency ion trap and in ion guide systems, as well as other alternating-gradient focusing systems. In order to guide the ions above the surface of the RF carpet to a central extraction point an additional electric field is generated parallel to the carpet surface by appropriately biasing individual (or groups of) RF electrodes. The principle of RF carpets is the same as for RF funnels so that many of the results will be applicable to such systems. While RF funnels are often used in low-pressure gas cells [Sik03,Sav03] and in mass spectrometers used for chemical analysis [Tan05], RF carpet systems have only been built and operated at RIKEN in a linear gas stopper [Wad03] for light ions. Challenges in the design and construction of an RF carpet for a cyclotron gas stopper are the large physical size (up to about 1 m diameter if no additional electrostatic ion guiding is used), the large number of the electrodes to which RF and DC voltage signals need to be applied.

A dedicated RF carpet and beam extraction test stand is being built during the present funding period in order to study the properties and operation of RF carpets under conditions that apply to the cyclotron gas stopper. The prototype RF carpets that will be studied are based on flexible printed circuit boards, similar to the concept already in use at RIKEN. The insulating material will be polyimide because of its good electrical and vacuum properties. This printed circuit board concept is expected to have advantages with respect to simplicity and reliability over “classical” designs used, for example for RF funnels or RF walls, in which a large number of individual electrodes need to be mounted, insulated, and supplied with RF and DC voltages.

RF carpet test stand

Figure 3 shows a mechanical drawing of the carpet test stand under development. A large vacuum chamber will provide the environment to install different electrode and RF carpet systems. Electrostatic optics and a Faraday cup will be installed in a central extraction port. A mechanical system will allow an ion source to be moved parallel to the RF carpet. The chamber will be evacuated with a turbo-molecular pump isolated with a gate valve backed by a scroll pump that can also be used to provide gas flow and a differential pressure in the extraction port region. A possible carpet/electrode system is also indicated in the inset. The RF carpet will provide the repelling force and the potential gradient to guide the ions towards the center. A similar potential gradient will be created along the surface of the guiding/pushing electrodes, which have an additional bias to create an electric field component towards

Fig. 3: Schematic of test stand.

Fig. 4: Mechanical design of the RF carpet and beam extraction test stand.

the RF carpet surface.

Substantial progress has been made in the construction of the test stand at this point. The design of the vacuum chamber shown in Fig. 4 is completed. The chamber has an inner diameter of 1.2 meters and will allow carpets and electrodes to be installed with a maximum gap of 20 cm. A vertical arrangement of the chamber was chosen to provide easiest access to carpet and electrode systems to be mounted inside. Flexible mounting fixtures in the main body and the chamber door ease the installation of different electrode and carpet systems. A sufficient number of flanges are provided for feedthroughs for RF and DC voltages, gas inlet, vacuum gauges and viewports. A rotary feedthrough and a gearbox will be used to move the insulated arm with the ion source, which can be biased to match the potential between the RF carpet and the pushing electrode. Commercially available alkali surface ionization pellet ion sources (Heatwave Labs, Inc.) will be mounted in an existing electrode design, modified to allow for pulsed ion extraction. Procurement and construction of the components shown in Fig. 4 have started. Design of the electrode/Faraday cup system in the extraction port is underway and will be followed by the design of the first guiding/pushing electrode and RF carpet systems.

Small prototype tests

The performance of the RF carpets for fast ion transport will depend on the electrode geometry and the RF and DC voltages that can be applied without creating discharges. Before manufacturing full-size RF carpets it is prudent to perform basic tests with small simplified RF carpet prototypes. Figure 5 shows a fixture with a small RF carpet prototype. RF and DC voltage breakdown tests will be performed with such prototypes for different electrode pitch and gap sizes and different gas pressures. The measurements will be performed in a small chamber for high-voltage breakdown tests available from our previous RIA R&D work (DE-FG02-05ER41384) on high-intensity beam cooling. The tests are easy and fast and are expected to be very effective in guiding the design of the larger RF carpet systems to be used in the beam extraction tests.

RF-carpet related calculations and simulations

Work is going on to study of the stability of ion motion for different masses, gas pressures, carpet parameters, and the strength of electric pushing fields perpendicular to the RF carpet surface. Such fields are needed to guide the ions to the carpet surface, but will also be caused by space charge that may be built up in the extraction region due to the ionization of helium atoms. At high beam intensities this space charge field is expected to become a limiting factor for the efficiency of ion transport with RF carpets and similar systems like RF walls and funnels.

Analytical (exact) expressions were developed (to our knowledge for the first time) that describe the electric field created by parallel planar electrodes to which alternating potentials are applied. With these expressions effective pseudo potentials [Deh67]

Fig. 5: Fixture (left) for HV breakdown tests of small simplified RF carpet prototypes (right) based on flexible circuits boards.

Fig. 6: Pseudo potential over one electrode pitch of $a = 1$ mm as a function of the distance y from the carpet surface for $A=40$ ions, $p_{He}=200$ mbar, $U_{RF} = 200V$, $f_{RF} = 10$ MHz. A pushing field $E_y = 2.5$ kV/m was applied. The electrode center is at $x=0.5$ mm and the width is $w=-0.3$ mm.

above the surface can be easily evaluated and optimized. Figure 6 shows an example for an analytically calculated pseudopotential, taking a pushing field perpendicular to the carpet into account.

Proposed Work and Milestones

The design and construction of the RF carpet test stand will be completed in the ongoing period (FY07/FY08). The RF and voltage supply system will be assembled and resonant circuits designed and built. The design of a first carpet system will be based on tests performed with the small prototypes and on simulations. Commissioning of the test system and first ion transport and extraction tests is the goal for the ongoing funding period. The proposed work for the next funding period, for which resources are being requested, will focus on the feasibility test of operating large RF carpets based on flexible printed circuit boards, the development of several RF carpet-based ion extraction systems, and a study of their properties in a wide parameter space. Part of this work will be to optimize the RF-carpet/electrode systems with respect to efficient transport and fast extraction of ions over a large mass range, taking the effect of space charge into account. The experimental tests will be accompanied with detailed simulations for which sophisticated codes (IONCOOL [Sch05], PIC codes, and other beam stopping simulation codes) have been developed at the NSCL. We expect that these tests and the further development of the RF-carpet/electrode system will require an iterative procedure.

Workplan and Milestones:

The ion-repelling properties of carpet systems will be studied for a range of gas pressures and for light and heavy ions. Ions leaving the source will be guided with weak guiding fields towards the central region of the carpet, which will be used as a simple charge-collection electrode. The strength of the pushing field perpendicular to the carpet will be varied and the collected ion current will be recorded. These studies are critical for assessing the ion repelling and transport properties of RF carpets and for benchmarking the codes and analytical expressions that describe the carpet properties. *Milestone: Complete determination and analysis of basic RF carpet properties in experiment and simulations.*

PIC simulations will be performed to determine the electric fields at the carpet surface created by space charge resulting from the ionization of the helium during the stopping process. The simulations will be based on ionization rate densities calculated in realistic stopping simulations for a range of secondary beams and will take into account the possible loss of ions at the carpet surface. The field strength obtained in the PIC simulations will be reproduced in the test chamber by applying corresponding pushing fields and the ion losses will be studied. This procedure is expected to provide key information for the operation of RF guiding techniques relevant to all gas stopper concepts. *Milestone: Obtain detailed picture of the effect of space charge in the extraction region on beam transport with RF carpets.*

Extraction of ions through the extraction orifice and collection by the Faraday cup. The design of the orifice is critical in any gas stopper system using RF carpets. If the diameters of the circular RF electrodes and of the extraction orifice become similar, fields can occur in which ions are trapped. The extraction time of the ions is largely depending on the guiding field strength that can be applied. For extraction-time measurements ion pulses (< 1 ms) will be produced with the ion source and the arrival time at the Faraday cup will be measured for different ion species, source positions, RF carpet parameters and gas pressures. *Milestone: Determine influence of RF carpet parameters on beam extraction times.*

Study the feasibility of building and operating an RF carpet beam extraction system with a radius of up to 50 centimeters. Technical challenges that will have to be met are a minimization of the required RF power to drive the carpets and the development of DC-RF coupling schemes to create the desired drift fields. *Milestone: Realize and operate large RF carpet-based beam extraction electrode system.*

The work will be conducted at the NSCL at MSU. The systematic tests and optimization studies are anticipated to be a one-year effort. The effort benefits from collaboration with M. Wada from RIKEN because of his experience in designing and operating RF carpets.