NOVEL TECHNIQUES FOR ISOTOPE HARVESTING AT FRIB*

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Abstract

Exotic isotopes have applications in medicine, industry, and national security. Historically, the U.S. has relied on foreign sources for these isotopes [1]. FRIB will be a domestic source of these isotopes. While FRIB is mainly focused on producing exotic isotopes for basic nuclear physics experiments, it also offers an opportunity to harvest unused isotopes for other applications. It is critical that isotope harvesting take place in a synergistic manner that does not adversely affect experiments that will be simultaneously taking place at the facility. Beam optics schemes will be calculated to determine the best locations and methods of separation. These calculations will use COSY Monte Carlo and G4beamline in conjunction with other state of the art ion optical codes that simulate isotope dynamics in magnetic fields and in matter. The results of these simulations will be used to determine the best beam-target combinations to produce the isotopes that are most in-demand and calculate purities of these isotopes in multiple locations in the fragment separators.

INTRODUCTION

The Facility for Rare Isotope Beams, FRIB, is a world-leading facility for the study of nuclear structure, reactions and astrophysics. Experiments with the new isotopes produced at FRIB are needed for a comprehensive description of nuclei to elucidate the origin of the elements in the cosmos, (e.g., understanding of matter in the crust of neutron stars). The standard mode of operation at FRIB will be to produce a rare isotope beam for a primary user, for example ^{60}Ca from a ^{82}Se beam. At the same time, the fragmentation or fission of the production beam will produce up to 1000 other isotopes that could be collected (harvested) and used for other experiments or applications. The potential applications of these harvested isotopes range from the determination of neutron cross-sections for homeland security to use of alpha-emitters for the treatment of metastatic cancer. Longer-lived samples of the unused isotopes could be collected and used in an ion source for accelerated beam experiments at ReA3, ReA12 or accelerator facilities outside FRIB.

Given these possibilities, there are two general areas that can expand the potential of the FRIB program:

- The potential uses of rare isotopes at FRIB that fall outside of basic research in nuclear physics, astrophysics, and particle physics
- The collection of selected isotopes that could be used to prepare radioactive targets or samples for experiments, and allow a degree of multi-user capability at FRIB.

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ISOTOPE ISOLATION

Next-generation rare isotope facilities such as FRIB will use in-flight fragmentation and fission to produce secondary beams of rare isotopes of interest to nuclear physics. Fragment separators, composed of magnets, selection slits, and energy degraders separate isotopes according to nuclear mass and nuclear charge with high precision [2]. A conceptual design of the FRIB fragment separators is shown in Fig. 1. There are multiple locations where isotope harvesting may be possible. In particular, harvesting stations could be located at the achromatic images between fragment separator segments without affecting ongoing experiments. Specialized apertures may be used in such a case. Another option is to exploit the primary beam dump area. The highest rates of most isotopes will be in the beam dump area, however, the purity will be low. A trapping scheme that allows for additional purification in this region would be desirable. In any case, harvesting stations will need to be designed to fit into the existing layout of the fragment separators.

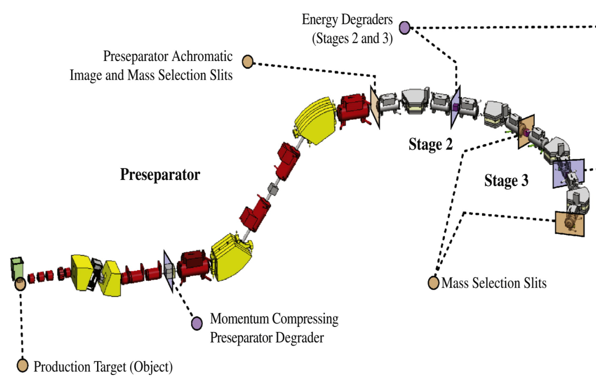

Figure 1. Conceptual design of FRIB fragment separator. A vertical momentum compressing pre-separator is followed by two horizontal separator stages. The beam enters from the left. Figure 1: Layout of papers.

Because the most interesting isotopes are often the most rare, isotope separators must capture a large fraction of the angular and energy range of the selected fragment produced. This is only possible if the selected fragment is focused back to a small area, which requires two dispersive sections, where the second stage counteracts the dispersion of the first stage. This is the basic principle of the achromatic separator. However, the magnetic separator cannot separate different isotopes with the same A/Z ratio. To achieve this, a degrader has to be used. A degrader is just a piece of matter that the beam has to pass. Because the atomic slowing down of the ions is roughly proportional to Z^2/v^2, different isotopes with different Z will have different velocities after passing through the degrader. This change in velocity causes the isotopes with the same A/Z ratio to be separated in the second dispersive stage. These concepts are illustrated in Fig. 2 [3].

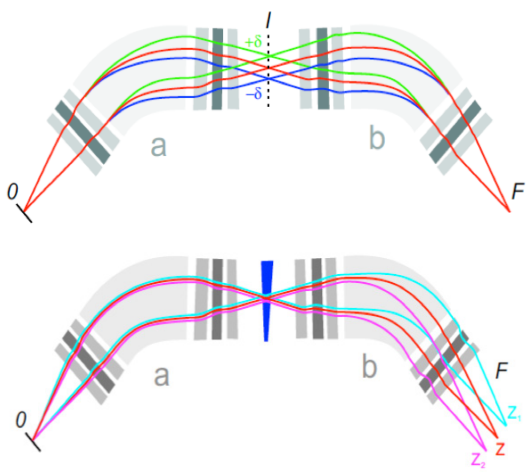

Figure 2: (top) Ion optics of an achromatic magnetic separator. (bottom) Three different isotopes with the same m/q ratio and the same velocity pass through the first spectrometer stage. A degrader at the intermediate plane slows the beam particles down depending on their nuclear charge. The velocity difference separates the isotopes in the second stage.

The problem of optimizing isotope separation will involve iterations on these principles in simulations of particle trajectories in complex magnetic fields, and, at various points through matter. We are also considering the use of RF to magnify the physical separation of the isotopes.

Muons, Inc. has tackled problems of similar complexity involving particle tracking in our muon collider cooling channel designs. As with some of the rare nuclear isotopes, muons are short-lived, and designs of muons colliders have required new capture and cooling technology. Our signature innovation in six-dimensional muon cooling, the Helical Cooling Channels (HCC) [4] required the ability to iterate over the parameter space of a combination of magnet fields, RF acceleration and absorber material (for ionization cooling). In particular, a variant of these 6D cooling techniques, Parametric-resonance Ionization Cooling (PIC) [5] has required innovative and technically challenging magnetic channel designs, particularly in manipulating and exploiting dispersion relations to achieve levels of cooling beyond the limits of simple ionization to achieve very low-emittance, bright muon beams. Figs. 3 and 4 illustrate this technique. These advanced cooling schemes involved iteration over many possible configurations for cooling optimization using the GEANT4 interface tool G4beamline [6]. In addition, the ability to calculate the aberrations that arise with complex magnetic channels was needed. This latter was achieved using COSY INFINITY [7]. We intend to use our experience in developing very complex cooling channels, and in particular, the exploitation of dispersion relations to manipulate phase space, to improve and innovate on isotope harvesting techniques. We will use an approach toward optimizing isotope harvesting that is similar to previous muon "super-cooling" projects, using these complementary software tools.

SOFTWARE TOOLS

G4beamline

Muons, Inc. is actively developing the simulation tool, G4beamline. G4beamline uses an ASCII file to specify all aspects of the simulation, so that physicists have the power of the GEANT4 code without having to deal with the considerable software and library management overhead normally associated with C++ programming. A series of commands controls the simulation, defines elements to be used in the simulation, places elements into the simulated world, and directs the generation of results. The complexity of the input file is comparable to the complexity of the system to be simulated (compared to system-specific simulation programs which are much more complex than the system itself). G4beamline has an extensive repertoire of common elements used in particle accelerators and detectors, such as bending magnets, quadrupole magnets, RF cavities, etc. In particular, G4beamline can simulate the magnetic fields of detector spectrometers. "Beamlines" can be defined within the simulation, with the ability to vary the relative amounts of different particles for different studies. For purposes of design, G4Beamline is ideal since it allows for quick simulation of simple problems.

COSY Monte Carlo

An integrated beam optics-nuclear processes framework is essential for accurate simulation of fragment separator beam dynamics. The code COSY INFINITY provides powerful differential algebraic methods for modeling and beam dynamics simulations in the absence of beam-material interactions. However, these interactions are key for accurately simulating the dynamics of heavy ion fragmentation and fission. COSY Monte Carlo is an extended version of the code COSY Infinity that includes these interactions, and a set of new tools that allows efficient and accurate particle transport in materials. The code tracks the fragmentation and fission of the beam in target and absorber material while computing energy loss, energy

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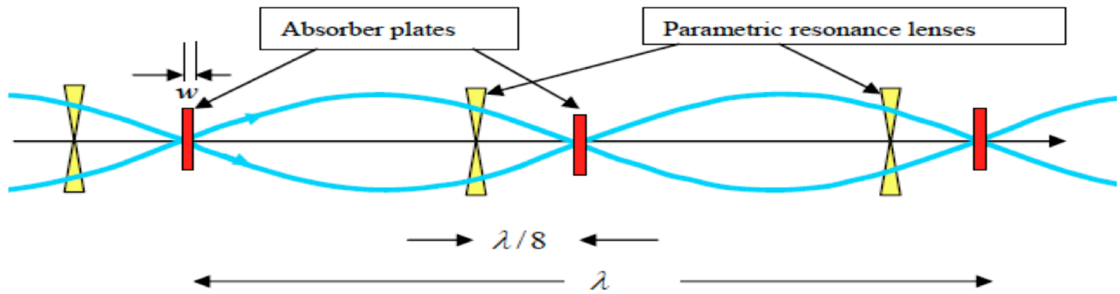

Figure. 3: Trajectories (blue) indicate the betatron motion of particles that define the beam envelope in a PIC lattice. Disperion is low at the absorber wedges (to minimize energy straggling) but not zero (to enable emittance exchange)

Figure 4: A G4beamline (described below) simulation display of particle trajectories described by the schematic pictured in Figure 3. The absorbers are blue, the horizontal and vertical parametric resonance elements are green and yellow, respectively. The focal points in both transverse planes are at the absorbers.

and angular straggling, as well as charge state evolution. The extensions to the code have made it possible to simultaneously compute high order optics and beam-material interactions in one cohesive framework. We have demonstrated the consistency between G4beamline and COSY Monte Carlo in Fig. 5.

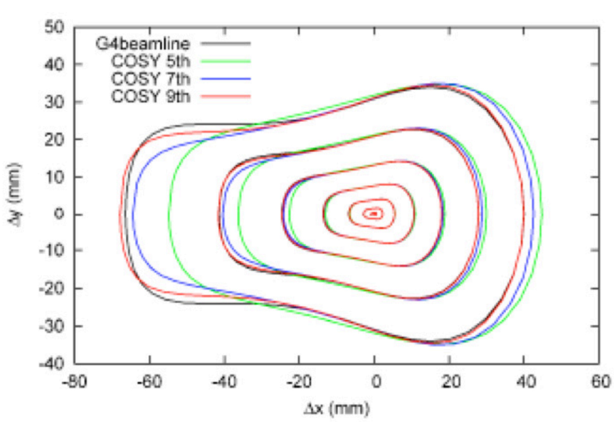

Figure 5: G4beamline simulation is compared to various-order COSY Infinity calculations. Here, beam smear due to spherical aberrations after 2 periods of an epicyclic PIC channel [5].

FUTURE PLANS

One of the primary tasks will be to simulate an optical tune of the FRIB fragment separators that allows for parasitic harvest isotopes during a typical nuclear physics experiment at FRIB. To that end we intend to use established computer codes to calculate rates of isotopes at potential harvest sites such as the beam dump area and at achromatic images of the fragment separators. We will then need to calculate an optical mode of the fragment separators that will allow for harvesting to take place during a typical nuclear physics experiment. This mode should not interfere with ongoing experiments. Furthermore, we will need to investigate isotope trapping and extraction schemes with an emphasis on matching the trapping technique to the beam characteristics at a particular location in a given fragment separator.

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