RARE ISOTOPE ACCELERATOR (RIA) PROJECT*

R.C. York#, Michigan State University, East Lansing, MI 48824 U.S.A.

Abstract

The proposed **R**are **I**sotope **A**ccelerator (RIA) Project will provide world-class intensities of radioactive beams created by any of the known production mechanisms. A driver linac will be used to accelerate any stable isotope from protons through uranium to energies of ≥400 MeV/u and intensities of ≥100 kW. Lighter elements will be used to produce radioactive ion beams by the **I**sotope **S**eparation **O**n **L**ine (ISOL) method. Typically heavier elements will be used to produce radioactive ion beams by the **P**article **F**ragmentation (PF) method. A hybrid method of stopping radioactive ion beams produced by the PF method in a gas cell will also be employed. The RIA project has strong support from the Nuclear Science community as evidenced by RIA being the highest priority for major new construction in the most recent Nuclear Science Advisory Committee (NSAC) Long Range Plan [1]. In addition, RIA is tied for third position for the near term priorities of the Department of Energy (DoE) 20-year plan [2]. The status of the RIA design is presented.

INTRODUCTION

The broad range of RIA's scientific benefits provide compelling arguments for its support. The research capabilities of RIA will produce important benefits for both basic as well as applied science. RIA's performance will allow the study of a large number of isotopes that heretofore have only existed in the cosmos. These research programs will, for example, provide quantitative information necessary for theories of stellar evolution and the formation of elements in the cosmos. Synergistically, RIA research will support space-based astronomical observations by providing quantitative comparisons with theoretical predictions of stellar evolution. Of course, nuclear science theories for predicting the properties of nuclei with unusual neutron-to-proton ratios will be advanced and refined. In addition, the broad range and quantity of radioisotopes produced will provide fertile venues in, for example, radio-medical research and materials science.

DESIGN

The schematic layout of RIA, utilizing all the tools developed for rare isotope research worldwide, is given in Figure 1. The acceleration of any stable isotope to energies greater than 400 MeV/u with beam power of at least 100 kW is achieved by a cw superconducting linac. The linac design further calls for a beam power capability of 400 kW if the ion source current production is sufficient. The baseline design has two ISOL targets shown in red feeding a low energy experimental area for research programs utilizing beams at post-production energies up to about 15 MeV/u. Two PF targets shown in gray are coupled to two fragment separators, the output of which will be used either for experiments at velocity (E > 50 MeV/u) or stopped in a gas cell and used in the low energy area.

Alternative Layouts

At least two groups have been actively pursuing a RIA design. One group is based at Michigan State University (MSU) and the other is at Argonne National Laboratory (ANL). Both designs realize the requirements shown in Figure 1. Both designs have a driver linac with initial acceleration provided by normal conducting technology,

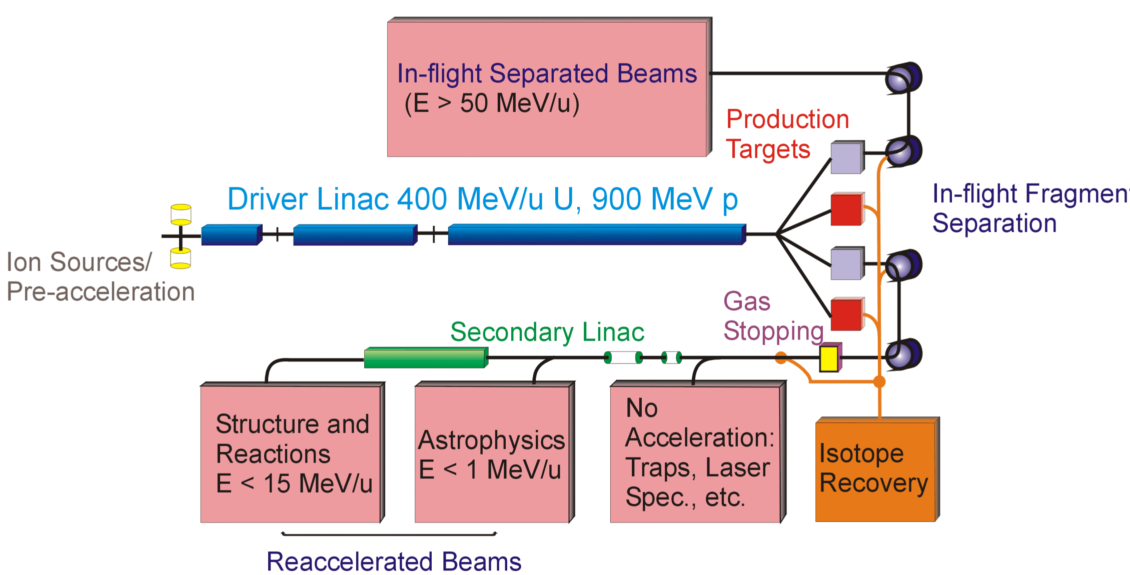

Figure 1. Conceptual layout of the Rare Isotope Accelerator (RIA) facility.

*Work supported by DOE and Michigan State
#york@nscl.msu.edu

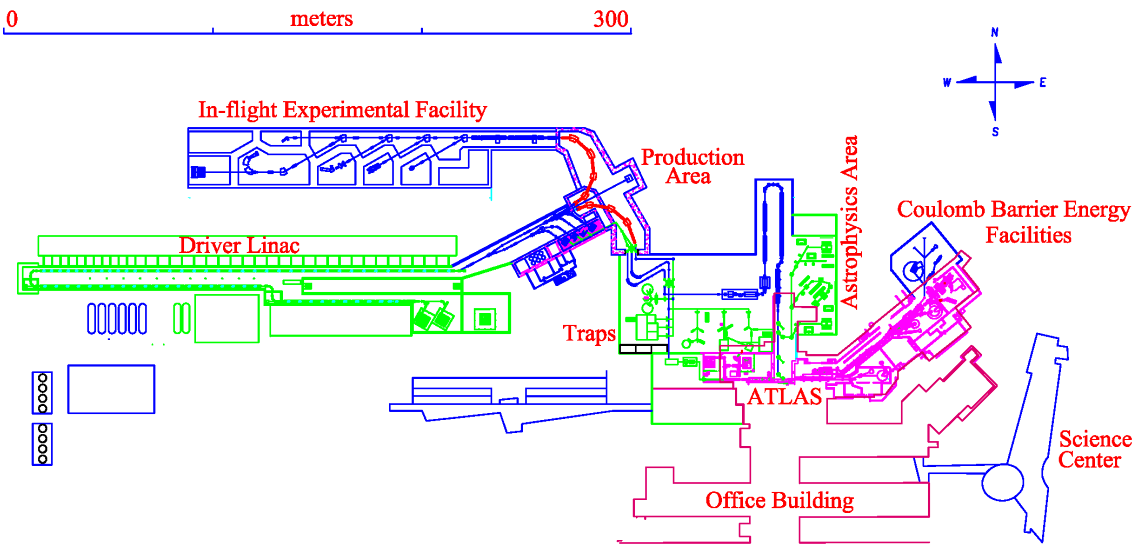

Figure 2. RIA layout proposed by Argonne National Laboratory (ANL).

utilize two charge stripping stations to increase acceleration efficiency, and have superconducting solenoidal focusing in the first two linac segments.

Figure 2 shows the RIA layout proposed by ANL. The six cavity types to be utilized for their driver linac are shown in Figure 3. All ANL prototypes have operated at >9 MV/m at 4.2K [3,4].

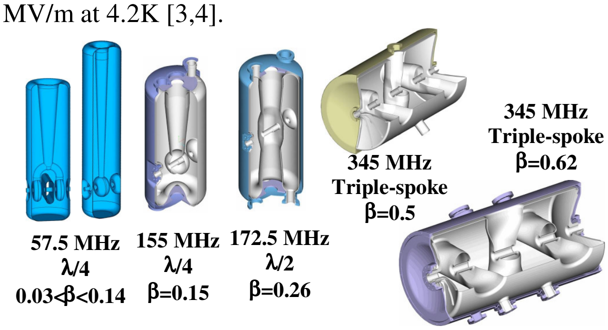

Figure 3. Six cavity types for the ANL RIA driver linac.

Figure 4 shows the RIA layout proposed by MSU. All cavity types necessary for the MSU driver linac are shown in Figure 5. All structures have been prototyped and have achieved design specifications [5,6,7].

Driver Linac

There have been substantial efforts focused on the driver linac. As a consequence, the linac designs have advanced to the point of detailed analyses and optimization strategies.

The front end is based upon room temperature technology, and will have at least two Electron Cyclotron Resonance (ECR) ion sources and a Low Energy Beam Transport (LEBT) system capable of appropriately injecting up to two charge states of a single isotope into a Radio Frequency Quadrupole (RFQ). The RFQ will be at the base frequency of the linac acceleration lattice and there will be a Medium Energy Beam Transport (MEBT) to match the beam into the superconducting linac at about 0.3 MeV/u [8,9].

Alternative accelerating lattice designs have been developed by ANL and MSU [10,11]. Both require the same number of cavity types as shown in Figures 3 and 5, and both have been prototyped. The 57.5 MHz base frequency for the ANL design is lower than the 80.5 MHz used for the MSU design. The lower frequency requires fewer accelerator structures but is more susceptible to microphonic issues [5,12]. Up to particle velocities (v/c) of β~0.3, both designs use quarter and half-wave geometries. The ANL design continues the half-wave geometry to the higher velocities (β>0.3) using a four-gap configuration called the triple-spoke. The MSU lattice uses a six-cell elliptical geometry for the higher velocities (β>0.4). The lower triple-spoke frequency (345 MHz) compared to that of the elliptical cavities (805 MHz) means fewer structures and larger longitudinal acceptance. On the other hand, the elliptical structures are mechanically less complex and have a larger transverse acceptance when compared to the triple-spokes.

The driver linac consists of three accelerating segments separated by two stripping stations. The superconducting linac has a longitudinal acceptance sufficient to simultaneously accelerate several charge states of the same isotope. This allows the use of several charge states from the ECR and the retention of several charge states after each stripping station. The efficiency afforded by the retention of multiple charge states is particularly necessary for the heaviest ions to meet the goal of a minimum beam power of 100 kW.

The linac configuration is driven by the design criteria of uranium at 400 MeV/u, with all lighter ions achieving significantly higher energies. For example, the driver linac will provide about 1 GeV/u protons and 0.55 GeV/u oxygen.

Two charge states of uranium, 28+ and 29+, will be injected into the first linac segment at about 0.3 MeV/u, accelerated to about 12 MeV/u, and then stripped to higher charges states (73±2). These charge states will

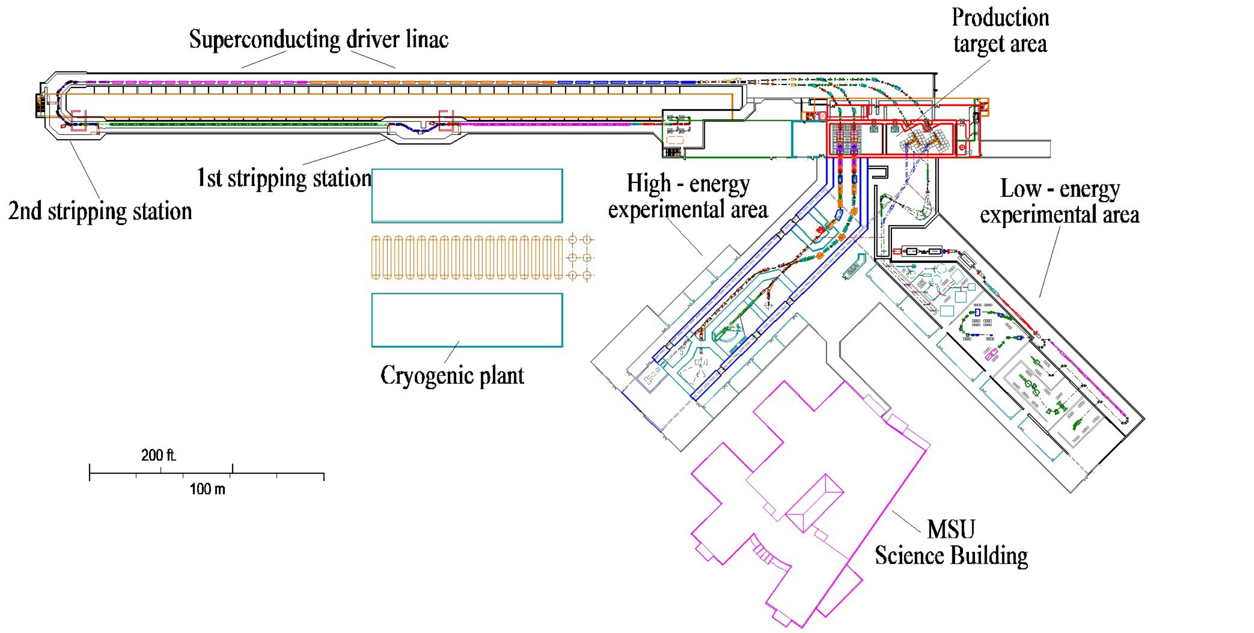

Figure 4. RIA layout proposed by Michigan State University.

then be accelerated in the second linac segment to about 90 MeV/u and stripped to higher charge states (88±1) before finally being accelerated to 400 MeV/u.

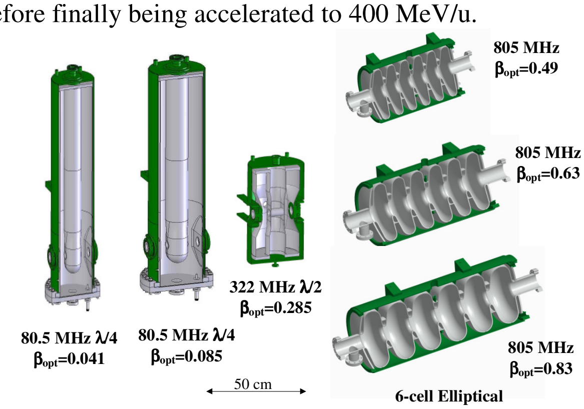

Figure 5. Six cavity types for the MSU RIA driver linac.

The first and second linac segments will utilize cryomodules similar to that shown in Figure 6 where the insulating and beam vacuum chambers are isolated, as is typical for β=1 systems [13]. The inherent inefficiency of returning to room temperature to implement focusing elements and the desire to obtain the strongest focusing possible led to a design using superconducting solenoids in close proximity with high performance SRF accelerating structures. A significant challenge lies in shielding the high field (9 T) of the solenoids from the accelerating structures whose high performance require <25μT or a reduction of $>10^5$, but this has been experimentally demonstrated at MSU [13]. To provide misalignment correction, dipole windings on the solenoids are planned.

For the ANL design, superconducting solenoids will also be used in the third and last linac segment to provide focusing appropriate for the triple-spoke aperture. The larger aperture of elliptical design allows for the weaker focusing of room temperature quadrupoles and dipole correction elements in the warm region between cryostats.

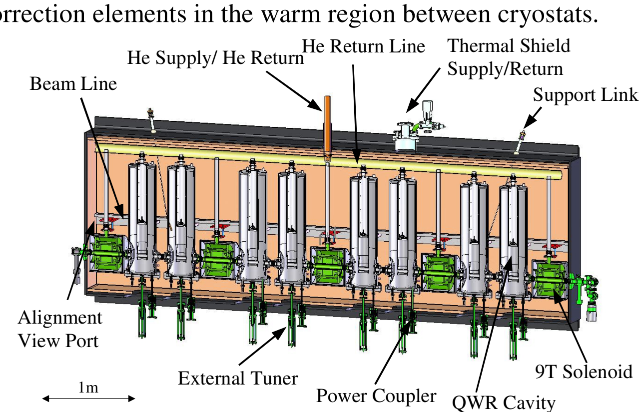

Figure 6. RIA cryomodule concept for λ/4 and λ/2 cavity geometries.

Driver Linac end-to-end simulations

End-to-end simulations of the linac performance including errors such as misalignments and rf system phase and voltage variation and a charge stripping foil model, including elastic and inelastic scattering, energy loss, and straggling, have been done by both ANL and MSU [8,14,15]. These simulations focused on the most challenging uranium acceleration. The initial beam phase space was chosen to be compatible with experimental results from the Lawrence Berkeley ECR ion source constructed as a prototype of a RIA ECR [16].

As an example, the results of an end-to-end simulation are shown in Figures 7 and 8 for the longitudinal and transverse phase space, respectively. The focusing elements for the first two segments were superconducting solenoids with mechanical misalignments based on a Gaussian distribution with a 2σ cutoff and a σ value of 0.5 mm. The focusing elements for the third segment were room temperature quadrupole doublets with a misalignment σ value of 1 mm. A misalignment σ value of 1 mm was used for all SRF accelerating structures. The rf phase and amplitude errors assumed a uniform distribution with a range of ±0.5° in phase and ±0.5 % in amplitude. In addition, the stripping foils were assumed to have a ±5% thickness variation. Plotted in Figures 7 and 8 are the phase space of the unperturbed beam (red) and the worst case of 100 seeds at each longitudinal position (blue). Even with errors the beam requires less than 20% of longitudinal acceptance and less than 65% of the radial aperture with the possible margin for error increasing as the beam goes further down the linac [17].

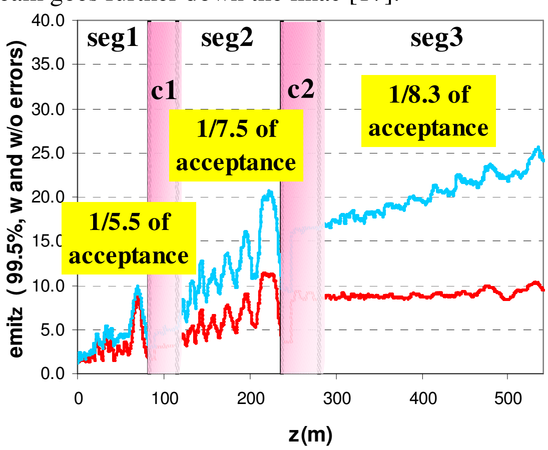

Figure 7. End-to-end simulation of the RIA driver linac for the longitudinal phase space. The first, second, and third linac segments are labeled seg1, seg2 and seg3, while the two charge-stripping regions are labeled c1 and c2. The results for the case of no errors are shown in red. The worst result for any of 100 seeds at each longitudinal position is plotted in blue.

Driver Beam Transport

The baseline design provides two beams of the same isotope to be delivered to two targets simultaneously. This will be accomplished by using an rf separator operating at 1.5 times the fundamental linac frequency providing an equal and opposite horizontal deflection for every other microbunch as illustrated in Figure 9. Since the ISOL targets will require the lightest and the Fragmentation targets will require the heaviest isotopes, generally both beams will go to either the two Fragmentation or the two ISOL targets. This concept can be expanded to provide more than two beams. Further, the relative proportion of beam supplied to each target can be adjusted by implementing a system to differentially load every other microbunch in the Medium Energy Beam Transport area preceding the linac.

Production Target Area

A possible configuration for the production target area is shown in Figure 10. Because of the high beam power, the production target area will provide challenging though not insurmountable engineering problems. A significant issue is the high dE/dx of heavy ion beams and the concomitant high energy densities. The high radiation environment will require remote handling and radiation resistant elements. A particularly challenging aspect will be the development of high performance, radiation resistant superconducting magnets for use just after the PF targets.

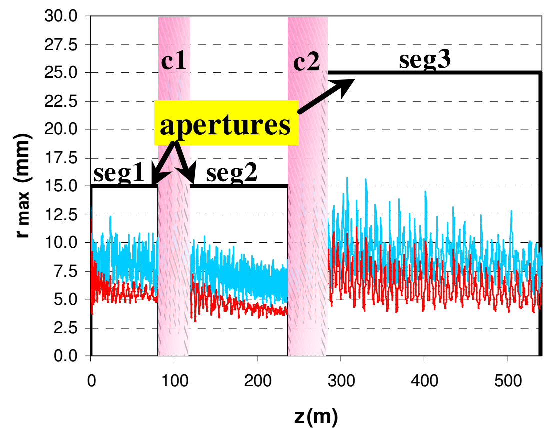

Figure 8. End-to-end simulation of the RIA driver linac for the transverse phase space. The results for the case of no errors are shown in red. The worst result for any of 100 seeds at each longitudinal position is plotted in blue.

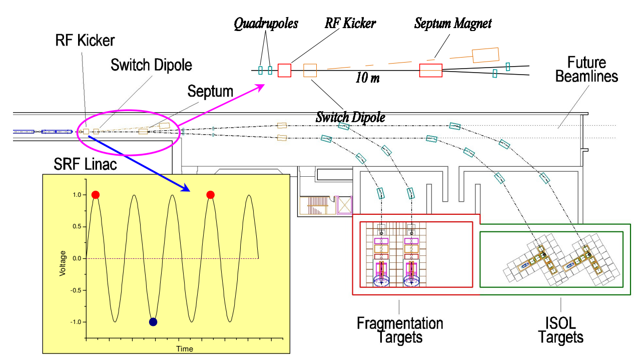

Figure 9. Schematic layout for distribution of stable isotopes accelerated in the driver linac to the radioactive beam production targets.

Experimental Areas

Generally, there will be two experimental areas. The higher energy area is labeled the In-Flight facility in Figure 2 and the High-energy area in Figure 4. A lower energy experimental area is shown as the Traps area and down stream in Figure 2 and labeled the Low-energy experimental area in Figure 4.

The higher energy area will utilize radioactive ion beams produced by the PF technique providing beam energies greater than about 50 MeV/u.

The lower energy area will utilize beam produced by the ISOL technique as well as PF-produced beam that is stopped in a gas cell. The lower energy experimental areas are characterized by the amount of reacceleration applied and range from trap applications to astrophysics appropriate measurements to experiments near the coulomb barrier.

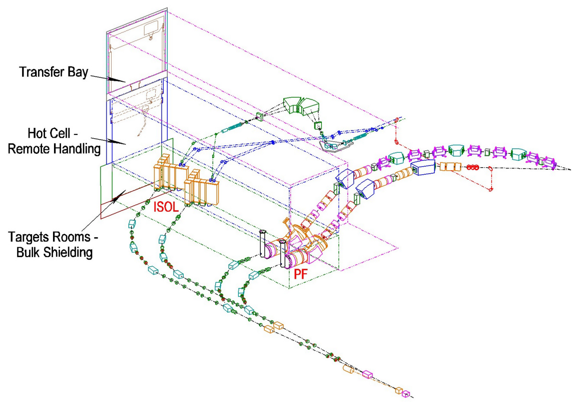

Figure 10. Schematic layout of the RIA radioactive beam production target area.

The final detailed equipment and facility layout will be accomplished through participation of the nuclear science community RIA will serve.

SUMMARY

The design of the Rare Isotope Accelerator has been developed over approximately the last five years. There are no technical "show stoppers", but significant engineering challenges remain, particularly in the production target areas.

The superconducting driver linac has from the beginning been the focus of significant efforts by several groups. As a consequence, there are now well developed designs that have received significant analyses and research and design efforts.

The production target and experimental areas have received relatively less attention, but much more emphasis has been placed on these aspects in recent years. Naturally, significant challenges have been identified, primarily because of the high power densities and high radiation environments. However, research and development paths are actively being pursued, and will not be a rate-determining scheduling issue.

In summary, a sound solution set for the RIA facility design has been developed, is being continuously refined, and stands ready for implementation.

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