Overview of the Rare Isotope Accelerator

This document provides a description of the Rare Isotope Accelerator (RIA) design at the time of the Harrison NSAC Sub-committee (January 2001) charged with evaluating the cost of RIA. In large part this is the same documentation provided to the Harrison Sub-committee prior to their deliberations.

RIA is an innovative concept embodying the best features of both in-flight and ISOL techniques and providing both reaccelerated and fast beams. Owing to its greatly expanded capabilities relative to previous concepts, RIA will be the most powerful facility of its kind in the world. The RIA facility will substantially extend present understanding of nuclei, provide a firm foundation for quantitative descriptions of the processes that fuel the cosmos and create the elements in stars, and provide isotopes for precision tests of weak interaction symmetries at low energies. This document provides a short overview of: 1) the science based specifications of the RIA facility, as documented in numerous white papers by the nuclear community, 2) the technical description of the facility as it evolved from the NSAC ISOL Task Force and interactions with the community and 3) the project cost estimate.

Scientists and engineers of the Physics Division of Argonne National Laboratory and the National Superconducting Cyclotron Facility of Michigan State University jointly prepared this document.

SCIENCE BASED SPECIFICATIONS

The field of nuclear physics with exotic nuclei is both rich and diverse. While there are many critical scientific questions that can be addressed with these beams, it is useful to classify the scientific purview of exotic beam science according to the following three themes:

- **The Nature of Nucleonic Matter**
- **The Origin of the Elements and Energy Generation in Stars**
- **Tests of the Standard Model and of Fundamental Conservation Laws**

There have been a series of White Papers and other documents that have summarized the scientific case for RIA:

- The Isospin Laboratory (1991)
- Concept for an Advanced Exotic Beam Facility (ANL 1995)
- Scientific Opportunities with an Advanced ISOL Facility (Columbus 1997)
- Scientific Opportunities in Nuclear Astrophysics (Notre Dame 1999)
- Scientific Opportunities with Fast Fragmentation Beams from the Rare Isotope Accelerator (MSU 2000)
- RIA Physics White Paper (Durham 2000)

In order to meet the scientific needs envisioned in these documents, RIA must provide a wide range of rare isotopes with the necessary intensities. The concept for RIA is to provide for a variety of production methods, e.g., fragmentation, fission, fusion and spallation that can be optimized for the production of a specific nuclide. This flexible concept will also use innovative ideas in isotope separation to provide beams of all elements with little dependence on half-life or chemistry. The desire to use multiple production mechanisms and have efficient collection and separation of the nuclides produced determines the characteristics of the driver linac. These considerations dictate a primary beam energy of at least 400 MeV/u for all beams including uranium, and beams of nearly all elements from hydrogen to uranium at a beam power of at least 100 kW.

In the following our intent is not to reproduce all the arguments of the various white papers. However, some selected examples are provided in order to indicate the scope of the facility necessary to meet the scientific needs. We will discuss the intensities of secondary beam necessary, the required beam parameters, and the need to push toward as neutron rich nuclei as is possible.

1.) <u>Intensities.</u>

The rare isotope beam intensities expected from RIA have been summarized and are available on the web (see http://www.orau.org/ria for an overview and http://www.phy.anl.gov/ria/ria_yields/yields_home.html for detailed intensity estimates). Because the production mechanisms are relatively well characterized these estimates should be reasonably reliable and indicate that the experiments discussed below are feasible.

The intensities required from RIA for various experiments are determined by a number of aspects. Basic information on a nucleus, such as its stability to particle emission, can be determined with only a few atoms. Half-lives and mass can be measured with 100s to 1000s of atoms. In the range of a few ions/s it is possible to determine some information on the nuclear wave function, size, shape, and excitation spectrum. For more information, intensities greater than 10^4/s of fast fragmentation beams or reaccelerated beams with precisely controlled energies are needed, ~10^9/s for high-resolution precision measurements comparable to what is currently available with stable low-energy (≈ 5-10 MeV/nucleon) beams. The following list is far from a complete overview; in order to illustrate the intensity requirements some examples of experiments are:

- The determination of *single-particle states and effective interactions* near closed shell nuclei. Closed shell nuclei are benchmarks in nuclear physics and RIA will likely nearly double the number of cases for study. Precision information and data comparable to that available with stable, magic nuclei would be of great value. A case where this is possible is ^{132}Sn and the nuclei differing by one or two nucleons from it. Precision measurements with low-energy beams (E/A ≈ 7 – 12 MeV) will require secondary beam intensities of >10^9/s and good beam qualities. Alternatively, for magic nuclei where beams of this intensity are not available, e.g. ^{48,78}Ni and ^{100}Sn, some information on their level structure, resonance properties, single particle levels, and wave functions can be determined with higher energy beams of a few ions/s.

- What are the limits of the combination on neutrons and protons that can make up a nucleus?

    - Currently we only know the answer to this question for elements up to Z=8. The determination of the *neutron drip line* will be realized with RIA to approximately Z=25 and depending on the actual location of the drip line, perhaps to the proton number 40. Intensities as low as 1/day or even a few/week are sufficient for an existence proof and only RIA can provide this capability for nuclei up to Z=40, while the r-process takes place from Z=26. For heavier nuclei, RIA will establish nuclear existence along an isotopic chain 10 to 20 neutrons beyond the heaviest nucleus identified to date. This information, combined with mass measurements, will provide the stringent constraints required for accurate predictions/extrapolations of the location of the neutron drip line. The minimum requirement for a mass measurement is about 1000 ions/day for $1{:}10^6$ mass resolution.

    - RIA will complement the present program of production of *superheavy elements* with stable beams in at least two ways. First, it will help delineate the "island" of super-heavy nuclei through the formation of many new, neutron-rich superheavy nuclei. For example, the fusion of intense beams ($>10^9$/s) of neutron-rich Kr isotopes from RIA at energies close to the Coulomb barrier (~5.5 MeV/A) with ^{208}Pb targets will form isotopes of element 118, predicted to be more stable than less neutron-rich isotopes. RIA will also make a significant contribution to our firm identification of the new superheavy elements created in fusion reactions with stable beams. These elements are identified by their alpha decay chains, which have end points in a region not accessible with stable beams. With neutron-rich beams from RIA it will be possible to create and study many of the nuclei which are part of these decay chains, thus putting the identification of superheavy elements on solid experimental footing. The production of longer-lived neutron rich superheavy elements will also aid in chemical studies of these nuclei.

- What role do nuclei play in the cosmos? For measurements of *astrophysical interest*, it is necessary to produce the nuclei along the nucleosynthetic path, particularly in the hottest environments, where the shortest-lived nuclei play important roles.
    - The *r-process*, thought to occur in supernova explosions and perhaps elsewhere, has a major role in the synthesis of heavy elements. Recent data from the Hubble and Keck telescopes clearly show the fingerprint of the r-process, but interpretation of these astronomical data is not possible with our current knowledge of the properties of nuclei along the synthesis path. The key inputs needed are atomic masses, half-lives, and decay

modes. Some information on structure that can help assess neutron capture reaction rates or the dipole response of these nuclei is also desirable. Most of these measurements can only be done with RIA. Of particular interest is the determination of masses and lifetimes along the isotones with N=82, and N=126 where there are closed shells. There is no information whatever along the relevant part of the N=126 line, and for N=82 it is limited. Some of these studies will require only 1 to 1000 atoms per day.

  - Novae and x-ray bursts are the most common explosive astrophysical events and, thus, have been studied extensively with both ground and space-based telescopes. These events occur in binary systems where one of the objects is a white dwarf or a neutron star. Due to their strong gravitational interactions with their companion star and the deep gravitational potential at their surface, these compact objects accumulate onto their surfaces hydrogen and helium that is ignited once sufficient material has piled up (the rp-process). Again there is a wealth of new observational data, including observations from gamma-ray observatories of nuclides produced in these environments. The beginning of the rp-process and modeling of these environments requires knowledge of reaction rates for proton and helium capture on nuclei from oxygen to tin. Direct measurements of these rates are very difficult and require intensities of up 10^{12} ions/s. Such intensities will only be available with RIA. For many rp-process nuclei, especially those near ^{100}Sn, the intensities are not sufficient to make direct measurements and indirect techniques must be employed. Other relevant nuclear properties such as masses and resonance energies can be measured with beams of much lower intensities.

- Finally fundamental interaction studies will greatly benefit from the highest intensities that will enable measurements with a precision that is limited by systematic (rather than statistical) errors.
  - The best probe of CP or T violation for flavor conserving interactions is the measurement of the permanent electric dipole moment of an atom or the neutron. Indeed, supersymmetric theories predict values for the EDM that are just below the present limits. Rn (Z=86) is one of the best new candidates for discovery of EDMs and measurements should have a precision comparable to or better than the existing most precise EDM limits: ^{129}Xe (Z=54) and ^{199}Hg (Z=80). The higher Z provides greater sensitivity to CP violation, and for isotopes having low-lying octupole vibrational excitations or possessing permanent octupole deformations (e.g., ^{223}Rn), additional enhancement by a factor of 100 or more greatly improves the sensitivity.
  - Parity violation measurements in Fr (Z=87) will provide a more sensitive probe for deviations from the Standard Model than Cs, the best studied case thus far, as electron-nucleus interactions scale approximately as Z^3 . In addition, Fr isotopes can be studied over a very wide range of neutron number. This provides a test of the predicted isotopic dependence of the

spin-independent interaction. Precise measurements of electromagnetic interactions in atoms are now possible with modern atom trapping methods, and initial measurements with Fr atoms have provided tests of the atomic theory of Fr at the level of 1% with production rates of the order of 10^6 atoms per second. With improvements in trapping methods and higher intensities at RIA (more than 10^8 atoms per second for most isotopes between ^{205}Fr and ^{228}Fr, and up to 10^{11} atoms per second for the most intense), standard model tests at the level of 0.1% will be possible.

- The weak interaction mixes the quarks that lie behind the Standard Model and the mixing is described by the "Cabibbo-Kobayashi-Maskawa" (CKM) matrix which must be unitary. At present, experiments on superallowed beta-decay transitions from 0^+ to 0^+ states suggest that the unitarity test of the top row of the CKM matrix deviates from unity by more than two standard deviations. This discrepancy has already led to much speculation, but before invoking "new physics" it must first be confirmed by studying superallowed 0^+ to 0^+ beta-decay transitions in heavier Z=N nuclei, where uncertainties associated with nuclear charge and radiative corrections can be determined. These N=Z nuclei such as ^{62}Ga, ^{66}As, ^{70}Br and ^{74}Rb are good potential cases to study with sufficient intensities (>10^4/s) for the required high-precision mass determinations.

2.) **Energies and beam quality**.

For some classes of measurements stopped beams are best, others require precisely controlled beams of secondary short-lived nuclei with energies up to a few times the Coulomb barrier, yet others require high energies.

- *Stopped beams for fundamental interaction studies and precise mass measurements*. The primary requirement, besides intensity of the beams of exotic ions, is isotopic and isobaric purity. In addition, for most applications good beam quality (low emittance, small energy spread) is also important to facilitate capture in traps or implantation in a tightly defined geometry.

- *Low-energy beams for measurements of astrophysical reaction rates* in the regime that are prevalent in hot stars. They range from the few hundred keV to the few MeV region. The beams must have precisely controlled energy, excellent isobaric purity, and good emittance.

- *Intermediate and high energies for nuclear structure*, where a variety of energies are desirable.

    - Precision beams are needed at energies in the vicinity of the Coulomb barrier (e.g. 5-12 MeV/u) with energy resolution of << 10 keV and good timing properties, suitable for time of flight measurements--generally longitudinal emittances of << 100 keV-ns. Transverse emittances also

  need to be small for good definition of scattering angles and accurate compensation for kinematic shifts, on the order of 1 mm-mrad.
- Higher energies permit clean isotopic identification and tracking of the fragments. At these energies, the luminosity can be greatly enhanced by using thick targets. These energies are also needed to allow the use of certain reaction mechanisms.

3.) <u>Avoidance of chemical limitations.</u>

The standard ISOL techniques with light production beams, protons, secondary neutrons, or light ions, can produce the most intense yields of secondary nuclei. Yet these must be extracted from the production target, and while this is easy for some of the elements (e.g. noble gases, alkalis, etc.) it is almost impossible for refractory elements or ones that are chemically very reactive. Essentially this drives the need for intense beams of heavy ions, using the helium gas stopper technique to catch any fragmentation product in an ionized state and ready for reacceleration. The multiplicity of production techniques with RIA will allow the optimization of yields, even in the completely unknown regime, where the predictions for yields are uncertain.

- For instance, for key nuclei in the r-process path it is particularly important to have the capability of carrying out measurements on waiting-point nuclei over a wide range of species, including neutron-rich isotopes of Fe, Co, Ni, Zr, Pd and Cd. The lack of chemical sensitivity of the fragmentation products is important in enabling these studies.

- Key nuclei for nuclear structure may not be accessible without the fragmentation capability (e.g. S, Ni, Zr,). For example

  - Doubly magic nuclei such as ^{44}S (16 protons and 28 neutrons) or ^{68}Ni (with 28 and 40). In both cases the detailed high-resolution exploration of the level structure will supply important information on the shell structure in weakly bound systems, and neither sulfur nor nickel diffuse readily out of a production target, so that the helium gas stopper technique and in-flight experiments are essential.
  - Nuclei with isospin 0, along the N=Z line. These are of considerable interest and the chemical sensitivity enters in a number of them, for instance, ^{78}Y, ^{80}Zr, ^{82}Nb, or ^{84}Mo. None of these can be reached with normal ISOL techniques. Measurements of transfer reactions will explore single-particle structure and pairing excitations.
  - The study of even light halo nuclei with high resolution techniques would be extremely interesting. At present ^{14}Be is an excellent example, it is extremely loosely bound, and because of the chemistry of beryllium, to produce it as a secondary beam will require the gas catcher technique for some experiments and in-flight techniques for others.

4.) <u>Desirability to go as far as possible in neutron excess.</u>
The greatest area of uncertainty at present in the understanding of nuclei is for very neutron rich systems. This is also the area we know least about, and where there is the greatest potential for new phenomena because of the asymmetry in the Fermi surface. The best way to reach these nuclei is from fission -- where the most promising is the neutron induced fission of uranium (for cases where the ISOL technique and reaccelerated beams are needed and the chemistry is suitable) and the in-flight fission of uranium for cases where the chemistry is not favorable or the high energies are desired. These requirements drive the need for 400 MeV/u intense uranium beams. The intrinsic yields favor ISOL by about two orders of magnitude, but for unfavorable cases, the difficulty of getting many elements to diffuse out of a target more than overcomes this advantage.

- To study the properties of nuclei along the r-process requires the most neutron-rich nuclei that can be obtained. These measurements will be a combination of identifying nuclei, measuring their lifetimes, masses, decay modes, and possibly in some cases obtaining structural information that will help deduce reaction rates. The combination of techniques available at RIA will make it possible to reach a large number of r-process nuclei.

- The properties of nuclei, where the neutron distribution becomes diffuse because of the loose binding of the last 5-10 neutrons is poorly understood. In these there is a diffuse region near the surface where the nuclei consist of almost pure neutron matter, something that is not the case in any well-known nuclei. There are theoretical speculations about the nature of the spin-orbit force, modification to the pairing interaction and other phenomena. To explore these, one needs to get as far out as possible in neutron excess.

With these specifications in intensities, beam energies, beam qualities, and no chemical limitation on beam species, RIA will be a powerful, unique facility world-wide to address our understanding of nuclei in the coming century.

Overview of the Technical Approach to RIA

Figure 1 below is a simplified schematic of the RIA layout. RIA comprises a driver linac to produce the rare isotopes, a variety of targets and ion sources, isotope separators, post accelerators, and experimental areas equipped with a variety of instrumentation for research over a broad range of secondary beam energies. The driver linac, based on superconducting radio-frequency (RF) accelerating structures, will accelerate ions of any mass, from protons (up to 900 MeV) to uranium (up to 400 MeV per nucleon), with beam power up to 400 kW. The driver linac enables the utilization of a wide choice of nuclear physics production mechanisms and experimental methods for the production of rare isotopes. The methods vary from standard ISOL techniques, i.e. the spallation of thick, hot, heavy targets with high-energy, light-ion beams such as protons, deuterons, or ^{3}He, to in-flight fragmentation or fission of heavy ion beams, such as tungsten or uranium, on light targets such as lithium. The in-flight separation mechanism is independent of the chemistry of the product elements. The isotopes can be separated magnetically and either delivered at full energy as secondary beams or stopped as 1+ ions in helium gas for reacceleration to satisfy the specifications in the previous section. The gas-catcher concept is the basis of a new paradigm for exotic beam facilities. The most important figure-of-merit of RIA is the yields of the rare isotopes made available for basic research in nuclear science. Figure 2 shows the predicted yields for the ISOL-quality beams, i.e. the intensities of mass separated beams available for areas 1-3 in Fig. 1. Figure 3 shows the predicted yields for the in-flight-type beams, i.e. the intensities of beams available for delivery to area 4 of Fig. 1. The major components of RIA are briefly described in the following sections.

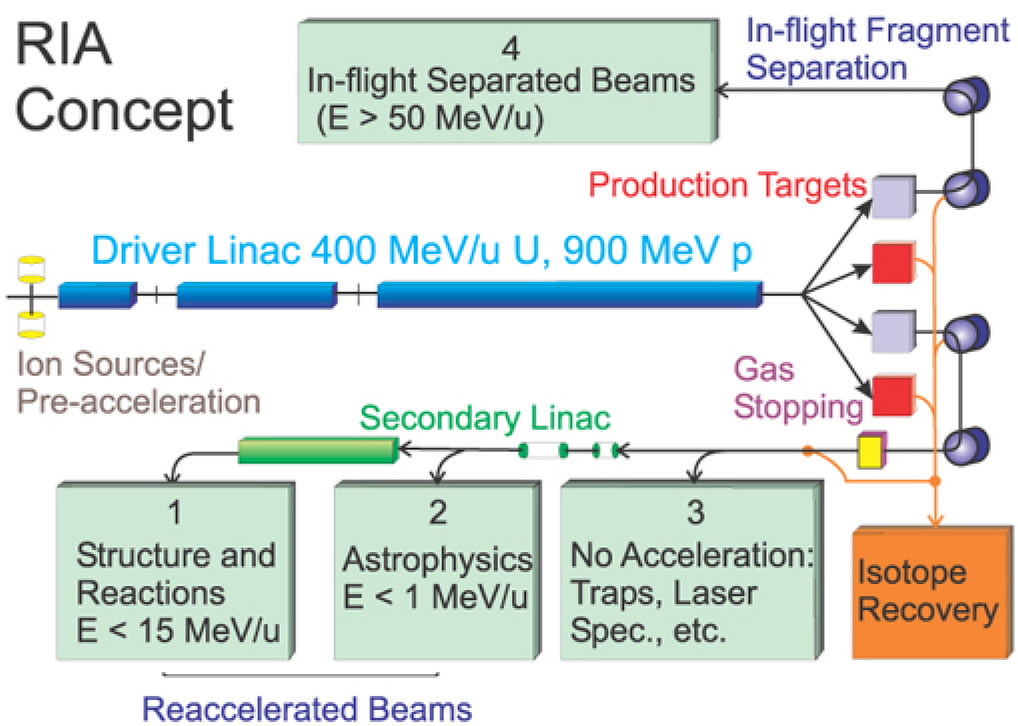

Fig. 1. Simplified schematic layout of the Rare-Isotope Accelerator (RIA) facility.

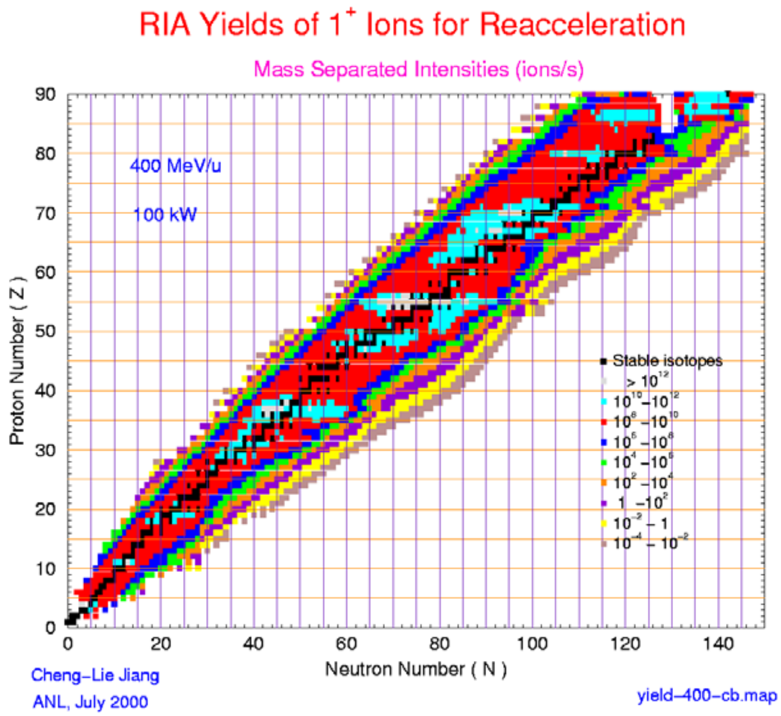

Fig. 2. RIA yields for rare isotopes predicted by a variety of reaction mechanisms. The yields are given in ions/s at the output of the isobar mass separator. These are the yields of rare isotopes available for delivery to the stopped-beam area 3 or to the post-accelerators for delivery to areas 1 or 2.

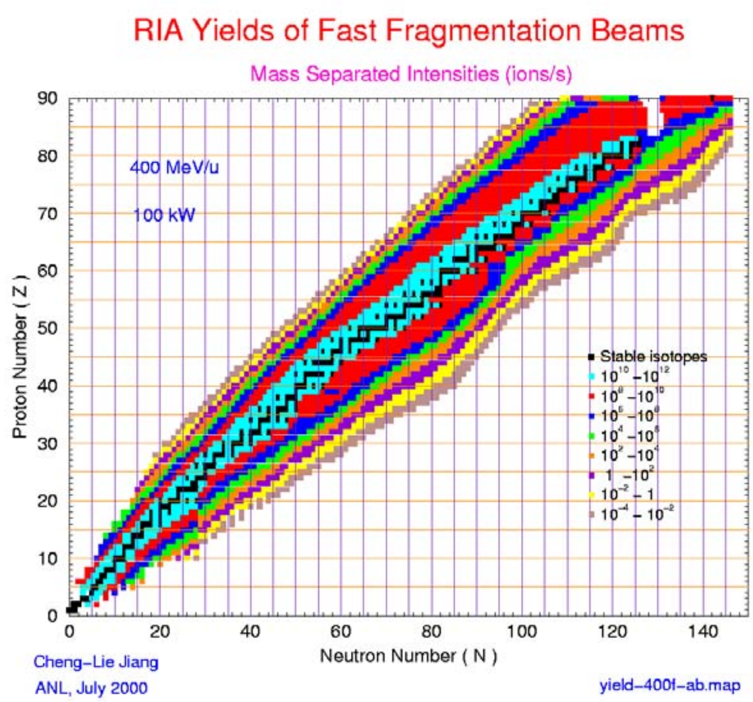

Fig. 3. RIA yields for rare isotopes produced in-flight via fragmentation of heavy ions or in-flight fission of uranium. The yields are given in ions/s at the output of a magnetic fragment separator. These are the yields of rare isotopes available for delivery at full energy, in-flight, for research in area 4.

Driver System Description

The driver accelerator comprises the following major components: an electron-cyclotron-resonance (ECR) ion source, a low energy beam transport (LEBT) and pre-buncher (28.75 MHz) section, a radio-frequency-quadrupole (RFQ) accelerator (57.5 MHz), a section of superconducting linac consisting of 256 niobium drift-tube resonators (57.5 to 345 MHz), and a section consisting of 188 niobium, compressed-elliptical superconducting resonators. These major components of the driver are described briefly below.

The velocity profile of the full superconducting linac is optimized for the uranium beam since it is the most challenging in terms of charge-to-mass ratio. The design parameters were chosen to achieve the required 400 MeV per nucleon uranium beam energy with beam power above 100 kW. Such beam energy and intensity is possible with present-day source technology and with a total linac voltage of only 1.4 GV due to the use of multiple-charge-state acceleration. For the uranium beam, two charge states (28 and 29) are selected from the ion source and accelerated through the first drift-tube section (low-beta section) up to the first stripper. Five charge states are selected and accelerated through the second drift-tube section (medium-beta section) up to the second stripper. The second stripper is located between the medium-beta section and the elliptical-cell (high-beta) section of the linac. Four charge states of uranium are accelerated following the second stripper. A schematic diagram of the elements of the proposed linac is shown in figure 4. Simulations of the driver linac performance for selected beams from protons to uranium yield the output energies and beam powers indicated in Table I.

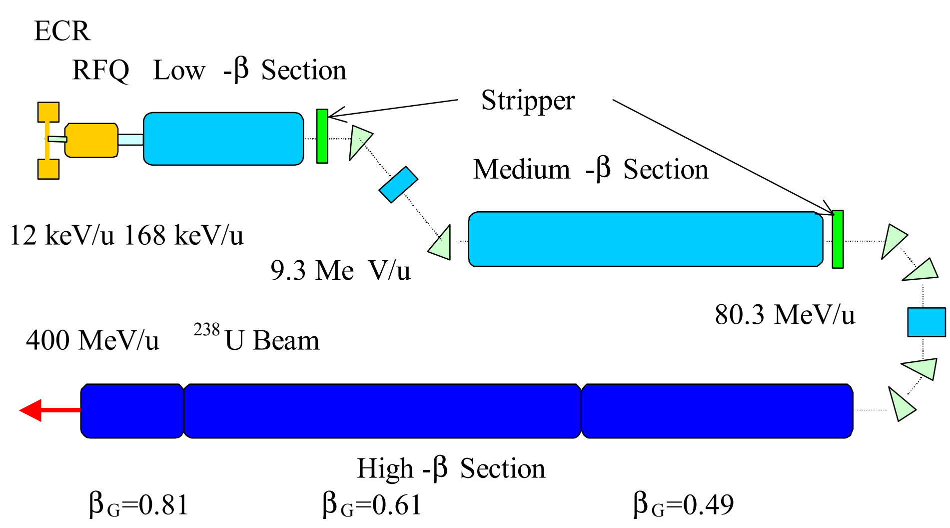

Fig. 4. Elements of the proposed driver linac.

Table I. Summary of the driver linac simulations for selected beams. The assumptions for the ECR ion source charge states and currents are indicated.

A	I source	Qout	I out	Energy out	Beam Power
	pμA		pμA	MeV/u	kW
1	556*	1	445	899	400
3	232*	2	186	717	400
2	416*	1	333	600	400
18	54*	8	40.3	551	400
40	29†	18	18.0	554	400
86	15†	36	8.8	515	390
136	12†	53-54	6.2	476	400
238	3†	87-90	1.6	403	152

* Limited by RF power in linac.
† Limited by ECR source.

Ion sources

The sources must provide beams of any isotope from protons to uranium at currents sufficient for output beam powers of up to 400 kW from the driver. Since the driver operates in continuous-wave (CW) mode, the beam current requirements are modest for the light ions (e.g. less than 600 microamperes DC for protons), but are challenging for the heaviest ions (e.g. about 8 particle microamperes of uranium at the 29+ charge state). [These numbers are also predicated on the acceleration of multiple charge states following the stripping stages in the SC linac sections, as described above.] The present state-of-the-art for uranium at this charge state is about 1.5 particle microamperes. Such performance is possible with the 14-GHz ECR called the AEC-U at the LBNL 88" cyclotron and sources of the same design at other laboratories. By using a front-end design capable of utilizing 2 charge states (28+ and 29+) simultaneously, uranium beam power of about 150 kW is possible. The new source VENUS, currently under construction at LBNL, is expected to achieve higher performance levels. The VENUS source operating at either 18 or 28 GHz is likely to be the source of choice for RIA. For operational flexibility a simpler, existing ECR source is planned as a second RIA ion source for use with the lighter ions that do not push source technology.

Front end

To achieve over 100 kW of uranium beam power with present-day ion source technology, a front-end design has been developed that is capable of simultaneously accelerating two charge states from the ion source. The front-end components are the LEBT with an analysis section and a pre-bunching section, the RFQ, and a medium-energy-beam-transport (MEBT) section with a re-buncher and focusing section for matching into the SC drift-tube linac section. The analysis section is an achromat that first disperses the beam for charge state selection. One or two charge states can be selected and delivered to the pre-buncher. The pre-buncher operates at one-half of the RFQ frequency. The drift and focusing channel that follows the pre-buncher is designed such that the two charge states of uranium arrive at the RFQ entrance to be accepted in two successive RF buckets at the RFQ frequency. A re-buncher just before the RFQ kicks the successive charge states just enough to equalize their velocities at the RFQ entrance. Detailed simulations of the entire system following the ECR analysis section have been carried out. The full six-dimensional phase space has been followed through the MEBT section to match the two-charge-state beam into the drift-tube linac section.

Superconducting drift-tube linac sections

The superconducting drift-tube section comprises the six type of resonators listed in Table I. The first stripper is located between the fourth and fifth resonator types. These niobium resonators will be operated at 4.6 K, and are in the process of being modeled and prototyped. Single-cell prototypes of the spoke-type have been constructed and operated in a test stand at the design gradient. The spoke-type resonator covers an ion velocity range higher than previous drift-tube resonators and lower than any existing elliptical-cell resonators. It is planned to develop a thin, flowing liquid lithium film to be used at this stripping location. The backup, but less desirable, solution is to use a rotating wheel of carbon foils. For uranium beams, two charge states, 28 and 29, are accelerated prior to the stripper and five charge states, 69-73, after the stripper to the end of the drift-tube section. Superconducting solenoids with fields between 7 and 10 tesla are used in this section for transverse focusing.

Table II. Parameters of the six drift-tube resonator types. The peak fields and rf energy are referenced to an accelerating gradient of 1 MV/m.

Beta	Cavity Class	Frequency (MHz)	Active Length (cm)	RF energy (mJ)	E peak (MV/m)	B peak (G)	Q/R	Gradient (MV/m)
0.021	Fork	57.5	18	77	4.1	68	12.6	4
0.030	Fork	57.5	26	120	4.0	91	18.2	4
0.062	QWR	57.5	20	148	3.3	60	19.2	5
0.128	Split-ring	115	36	165	3.9	190	21.9	4
0.190	Lollipop	172.5	36	127	3.5	144	46.5	5
0.380	Spoke	345	38	142	3.2	80	78.1	5

Elliptical-cell linac sections

Three types of elliptical-cell resonators are planned for the velocity regime above the second stripper. Four charge states of uranium, 87-90, are accelerated through this linac section. The frequency of the RIA elliptical-cell resonators was chosen to match that of the SNS resonators, so that two of the three types are in common. The lowest velocity type (beta=0.49) is unique to RIA. Due to the higher frequency of this linac section it will be operated at 2.1 K, similar to the SNS and CEBAF linacs. The total voltage of this linac section is slightly over 1 GV. Superconducting solenoids with fields between 5 and 9 tesla will be used for transverse focusing in this section. Table III lists all nine types of superconducting resonators used in the RIA driver linac.

Table III. The superconducting resonators, type and quantity, used in the RIA driver linac.

Section	Element Type	Beta = v/c	Frequency (MHz)	Temp. (K)	Number of Elements	Section Voltage (MV)
Source	*ECR*	*(Ions from H^{1+} to $^{238}U^{30+}$)*			*2*	0.1
Injector	RFQ	0.00507-0.01892	57.5	293	1	1.2
Low-β section	4-gap cavity	0.01893 - .041	57.5	4.5	7	5.7
Low-β section	2-gap cavity	0.041 –0.091	57.5	4.5	24	28
Low-β section	3-gap cavity	0.091 - 0.14	115	4.5	57	50
1st Stripper	*Stripper*	*(Lithium film)*				
Medium-β section	3-gap cavity	0.14 - 0.3	172.5	4.5	72	112
Medium-β section	3-gap cavity	0.3 - 0.389	345	4.5	96	150
2nd Stripper	*Stripper*	*(carbon wheel)*				
High-β section β_G=0.49	6-cell cavity	0.384 - 0.54	805	2	76	299
High-β section β_G=0.61	6-cell cavity	0.54 - 0.666	805	2	84	507
High-β section β_G=0.81	6-cell cavity	0.666 - 0.714	805	2	28	276

Radio-frequency beam switching for multiple users

To serve more than one experimental area at a time, the RIA driver beams will be switched on a pulse-to-pulse RF time scale to two or more targets. The baseline concept is to serve two targets at a time. Generally the light ion beams will be used with standard ISOL targets and will be switched between two such targets. The heavy-ion beams will be used for fragmentation or in-flight fission and will be switched between two different fragmentation targets, one that serves the fast gas catcher and the other for delivery of high-energy fragments to the in-flight experimental area. The baseline design of RIA now includes two standard ISOL-type targets and two fragment separators, between which the primary beam can be shared as described here. The relative priority for extending this concept to serve 3 or 4 targets simultaneously will be discussed with users during the Conceptual Design phase of RIA.

Target Concepts and Isotope Production Areas for RIA

As discussed above, the RIA facility will use beams from the driver linac to produce rare nuclei via several different reaction mechanisms in a variety of targets. Ion beams will be available with a broad range of masses, as light as protons and as heavy as uranium, and at power levels of 100 kW and higher. To date there are no rare-isotope ISOL (isotope separation on-line) or fragmentation facilities operating at such beam powers. However, engineering concepts exist for high-power targets that are considered viable for both types of exotic beam sources.

In the standard ISOL source, the nuclear reaction products formed by protons, neutrons, or light ions from a primary driver machine are brought to rest in a thick target or solid catcher kept at high temperature and connected to an ion source. The species produced are separated from the target bulk and often from other isobaric reaction products via diffusion, effusion, and chemical processes, which permit their transfer into the rare-species ion source. This method has been successfully used in the last 30 years at several on-line mass separators to produce low-energy radioactive ion beams of many exotic species. The method is tailored to the specific physical and chemical properties of the elements involved. Schemes that work well for short-lived isotopes of ~30% of the elements have been demonstrated. The efficiencies of the extraction and ionization processes can be ~20% to 100% for long-lived species of many elements. However, for short-lived species with half-lives of the order of 10 ms, the efficiency drops typically to 0.1% to 0.01% or even less due to decay during the extraction process. Development of these standard ISOL-type targets is ongoing at facilities such as ISOLDE, ISAC and Oak Ridge. This method can produce the most intense beams by orders of magnitude of mass separated rare isotopes of the elements for which it works well. This is reflected by the most intense "islands" shown in Fig. 2.

Fragmentation sources, by contrast, involve a target in which an incident heavy-ion beam loses roughly 10-30% of its energy in a low-Z target, but produces the rare species of interest as it does so. Following the target is a magnetic fragment separator that removes the residual incident beam as well most other fragments not of interest to the experiment. This method is the basis of several in-flight secondary beam facilities around the world, including the NSCL in the United States, GANIL in France, GSI in Germany, and RIKEN in Japan. At RIA the primary heavy-ion beam energies of at least 400 MeV per nucleon can be used to produce and deliver rare isotopes of any element at energies of 50 to 400 MeV per nucleon for research in area 4 of Fig. 1. To provide an additional stage of purification of the in-flight beams delivered to area 4 of RIA, a Wien filter or possibly an RF separator stage will follow the traditional high-resolution fragment separator.

A new concept for RIA is to use the fragmentation production mechanism combined with a "fast gas catcher" to produce ISOL-type beams of all chemical species in a time comparable to lifetimes of the beta decaying isotopes. The beam out of a large acceptance fragment separator/monochrometer is stopped with high efficiency in helium gas, from which it is extracted and delivered to the stopped beam area or to the post accelerator. The high power target concept for both fragment separators is a recirculating liquid lithium loop as discussed below. Figure 5 is a schematic layout of this new concept showing the magnetic fragment separator, energy-bunching section, and gas catcher.

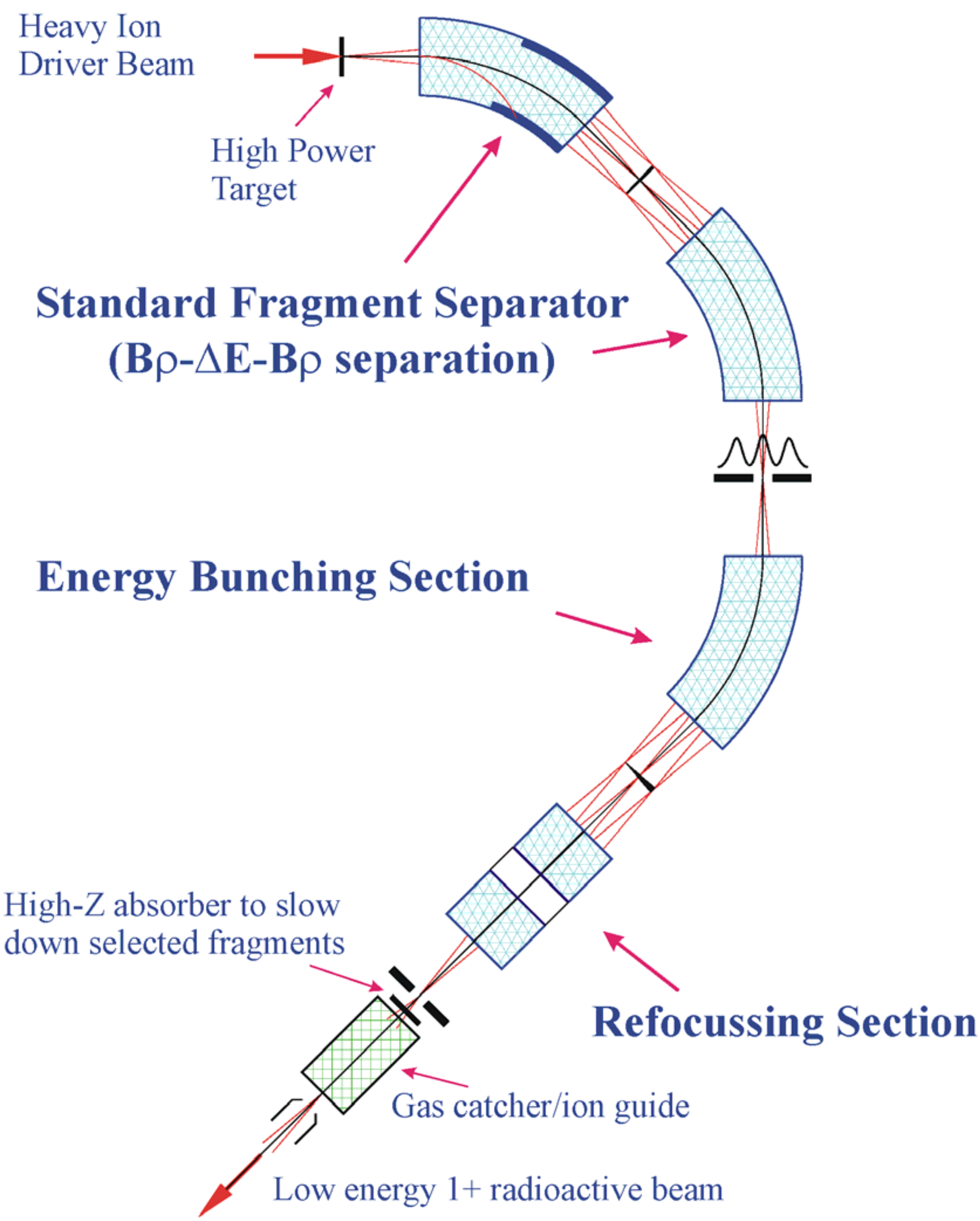

Fig. 5. Schematic layout of a fragment separator to collect heavy-ion fragmentation products and deliver them to the gas catcher/ion guide apparatus.

Below are some of the high power production target concepts being proposed for RIA:

ISOL target: refractory metal foil. Development of one of these concepts has been pursued for the past few years at the Rutherford Appleton Laboratory, ISOLDE, ISAC, and PNPI (Gatchina). This type of target consists of a stack of many thin metal foils such as tantalum with thin spacers to enhance ion effusion. This concept for an ISOL-type target has been tested with internal electron-beam heating to power levels that indicate its viability for use with protons or other light ions in the 500–2000 MeV energy range at beam power-levels of 50–100 kW.

ISOL target: compressed powder. Another ISOL-type target concept has been developed for use with porous refractory materials such as UC_x. These target materials tend to have low thermal conductivities that require special geometries to minimize the target's internal temperature. Such geometries include thin, large-area sheets of the target material tilted at a high angle with respect to the incident beam. The tilt increases the target thickness seen by the beam while minimizing the thickness for conduction of heat from the interior of the target. Such targets are appropriate for spallation of heavy target materials with relatively light driver beams, with $1 \leq A \leq 40$. This concept is a variation of a method used routinely in the production of medical isotopes with high-power beams at relatively low beam energies.

Liquid-lithium-cooled two-step ISOL targets. A concept for a high-power two-step production target has also been developed. The two-step concept separates the high power deposited by the beam from the secondary target in which the radionuclides are produced. High-energy, light-ion beams such as deuterons or ^{3}He irradiate a primary target such as tungsten to produce secondary neutrons with high multiplicity. The neutrons, in turn, irradiate a thermally decoupled secondary target such as UC_x to produce short-lived, neutron-rich fission fragments. The fission target is geometrically close to the primary target in a coaxial geometry to enhance the radionuclide production rates. The driver beam deposits 50 to 100 kW of power in the primary target. The primary target is cooled via liquid lithium that is flowing in a closed loop through a heat exchanger.

Liquid-lithium targets for heavy-ion fragmentation. One of the unique features of RIA is the availability of high-power heavy-ion beams to produce very exotic isotopes via the beam fragmentation mechanism. In this mode the beam is heavy, e.g., xenon or uranium, and the target is light, e.g., lithium, beryllium, or carbon. With primary beam powers of 100 kW and small beam spots appropriate for matching into the fragment separator, the power density in the target exceeds that feasible with traditional thick-foil solid materials. Thermal and hydraulic analysis of flowing-liquid lithium targets indicates that this is a viable solution. Such targets have been built and tested for potential use in fusion materials test facilities. The liquid-lithium target system tested at Hanford, for example, was sized with a mass flow rate adequate for total beam power of up to 10 MW. Such a system scaled down by a factor of 100 in flow rate to match the 100 kW beams of RIA would operate with lithium temperature rises of less than 100 K.

Post-Accelerator

The rare-isotope post-accelerator (RIB linac) will be called upon to deliver a wide variety of beams for various types of experiments. To summarize the demands placed on this element of RIA, it must:

- Provide continuously variable output beam energy.
- Accelerate the full mass range of ions to energies above the Coulomb barrier.
- Provide state-of-the-art beam quality: energy, time resolution and transverse emittance.
- Exhibit high overall efficiency and maximize beam current.
- Accept ions beginning from the 1+ charge state.

Almost all of the post-accelerator is based on current superconducting rf (SRF) technology. Existing superconducting ion linacs consist of arrays of short, independently phased, high-gradient rf cavities closely interspersed with transverse focusing elements and have the properties specified above except for the low-charge-state requirement.

In order to utilize the most efficient ion sources, the injector section presents a special requirement for accommodating low charge states. This problem has been studied, and technical solutions have been developed which accommodate even the most difficult case—singly charged uranium—with high efficiency and without compromising beam quality. The following outlines a configuration which would meet all of the above requirements, sized to provide maximum energies of about 8 MeV/nucleon for ^{132}Sn, increasing to about 15 MeV/nucleon for the lighter ions:

- An injector section mounted on a high-voltage platform, including:
  - A gridded gap, multiple harmonic buncher.
  - 2.2 m of 12 MHz, normal-conducting RFQ providing 1.2 MV of acceleration.
  - A thin helium gas stripper for light ions $A \leq 132$.
  - 4.4 m of 12 MHz, normal-conducting RFQ providing 3.1 MV of acceleration.
- A thin helium gas stripper for heavy ions $A > 132$.
- 4.0 m of 24 MHz, normal-conducting RFQ providing 2.75 MV of acceleration.
- A low-charge-state linac section using technology similar to the existing ATLAS positive ion injector, providing 45.5 MV acceleration.
- An optional foil stripper
- A linac very similar to the existing ATLAS ion linac, providing an additional 57 MV acceleration

This configuration is highly flexible, and can be set up to optimize performance for a variety of beams and users. For example, rare isotopes below mass 60 can be accelerated to the energies required for nuclear astrophysics measurements as 1+ ions without any stripping stages, thereby retaining maximum beam intensity for this important physics area (shown as area 2 in Fig. 1). The elements of the RIB linac are listed in Table IV.

Table IV . Accelerating elements of the RIB linac. The velocity profile is given for lowest charge-to-mass ratio 1/66.

Section	A/q	Beta = v/c	Frequency (MHz)	Temp. (K)	Number of Elements	Section Voltage (MV)
1^+ Ion source and Isobar separator	6≤A/q≤240	***(Ions from $^6He^{1+}$ to $^{240}U^{1+}$)***			***1***	**0.1**
RFQ-1	6≤A/q≤240	0.0021-0.0039	12.125	293	1	1.2
1st Stripper (Light Ions 67≤A≤132)		***Helium Gas***				
RFQ-2	6≤A/q≤240	0.0039-0.0066	12.125	293	1	3.12
1st Stripper (Heavy Ions 133≤A≤240)		***Helium Gas***				
RFQ-3	6≤A/q≤66	0.0066-0.0115	24.25	293	1	2.75
β_G=0.015	6≤A/q≤66	0.0115-0.0176	48.5	4.5	14	7.9
β_G=0.025	6≤A/q≤66	0.0176-0.0284	48.5	4.5	24	22.6
β_G=0.037	6≤A/q≤66	0.0284-0.0360	72.75	4.5	16	15.0
2nd Stripper		***Carbon Foil***				
β_G=0.037	6≤A/q≤240/29	0.036-0.0528	72.75	4.5	8	7.5
β_G=0.06	6≤A/q≤240/29	0.053-0.065	97.0	4.5	12	9.8
β_G=0.105	6≤A/q≤240/29	0.065-0.1206	97.0	4.5	36	40.3

Experimental Equipment

A wide variety of detection equipment is required for RIA to fulfill its scientific potential. These devices must be designed to obtain data from even the rarest beams produced, and hence must be large, high-efficiency detectors. They must also be able to tolerate the high event rates produced by the background radiation environment from a plethora of unstable background beams. This requires the capability for fast timing to perform the complex coincidences that may be required to separate the nuclei or reaction products of interest from those from background beams. Finally, studies of reactions in inverse kinematics will require detectors with high position resolution to allow angular distributions to be measured and to correct for reaction kinematics.

The four energy regimes for nuclear science at RIA are shown as areas 1-4 of Fig. 1. These areas are the stopped-beam area (3), the low energy area (2) for post-accelerated beams, the medium energy area (1) for post-accelerated beams, and the high energy area (4) for in-flight beams. The major equipment items required for RIA to undertake the wide variety of experiments that are planned for it have been discussed by the user community at the Columbus and Durham workshops and are listed below. Here we divide the list into general-purpose equipment, that is likely to move between areas, and equipment specific to the four areas.

General-purpose equipment

- **Gamma-Ray Detectors.** Two types of detectors will be required. One will be used in high-event-rate, low-multiplicity situations, and will consist of small arrays of high-efficiency detectors in close geometry. The other will be used in virtually all studies of high-multiplicity reaction gamma rays, and will consist of large position-sensitive germanium detectors with fine-grained energy-tracking capability.
- **Charged-Particle Detectors.** The required charged-particle detectors include a **large solid-angle array of CsI detectors** and an **array of Si strip detectors**. Heavy-ion detection at low energy will require a variety of **gas detectors**. Neutron detection will utilize neutron walls with either **solid- or liquid-scintillator neutron detectors**.
- **Special targets.** Two classes of general-purpose special targets are currently envisioned for RIA. One, a **windowless gas target**, is likely to be shared between the low- and medium-energy areas. The other is a facility for preparation of **radioactive targets** for a variety of uses.

Stopped-beam area

- A **laser atom trap** will be required for parity violation measurements, and an **ion trap** will be utilized in mass measurements. A **beta-gamma coincidence setup** will be used for spectroscopic studies. **Nuclear orientation and beta-nuclear magnetic resonance facilities** will also be used, possibly in condensed matter experiments. An **electron beam ion trap** will allow study of the heaviest elements.

Low-energy area

- Recoil Separator System. This will be used primarily in nuclear astrophysics experiments, and will be required to have very high background rejection. It is likely to be similar to the Dragon separator system at ISAC.

Medium-energy area

- **Recoil Separator System.** The recoil separator for this area must have high energy and mass resolution, good solid angle and effective background rejection.
- **Gas-filled Magnetic Separator.** This is a large-acceptance device similar to the Berkeley Gas-filled Spectrometer.
- **Magnetic Spectrograph.** This will be a general-purpose magnetic spectrograph with large angular acceptance, broad momentum range, and intermediate energy resolution.

High-energy area

- **Magnetic Spectrograph.** A large magnetic spectrograph similar to the NSCL S800 but useful for ions at energies up to 400 MeV per nucleon is required. It will be designed for an optimal combination of momentum resolution, momentum range, and angular acceptance.
- **Time-projection Chamber.** This device is useful for studies of reactions with very low-intensity, high-energy heavy ions.

Radiation Handling and Facility Classification

Safety and health issues associated with induced radioactivity can be responsibly and economically handled by addressing the engineering requirements from the very start in the RIA facility design. The criteria for safely dealing with induced radiation in a high-power hadron-accelerator environment are well established from years of experience in laboratories such as LAMPF, PSI, and TRIUMF. RIA will require several types of shielded facilities, as well as a remote handling system with hot cells for dealing with the various sources of radiation. The driver accelerator will not need a remote handling system since beam losses in the driver are kept low enough to allow hands-on maintenance of accelerator components. The CERN ISOLDE and the TRIUMF ISAC facilities provide effective solutions to the radiation-handling requirements for ISOL-type targets. The fragmentation target/separator system requires magnets to operate in a high-radiation environment. The secondary beam lines at LAMPF, PSI, and TRIUMF demonstrate that radiation-hardened magnets can be operated and maintained near high-power targets.

At the controlled beam-loss locations (i.e., strippers, targets, and beam dumps) it is convenient to use local stackable shielding that can be easily removed so that the activated components can be accessed by the remote handling system. For example, at ISAC the remote handling system is based on an overhead crane that is operated remotely from within a shielded room. This crane is used to transport components between the hot cell and the target systems. In the regions of high radiation, activated components such as targets, ion sources, diagnostics, and ion-beam optical elements are mounted on the bottom of 2-m-long steel modules that fit inside a large evacuated tank. Services and vacuum O-rings for these modules are located near the top where the radiation fields are low enough to permit hands-on servicing. All of the components inside the module are designed so that they can be removed, installed, and aligned inside a hot cell using manipulators. An overview of this modular concept for the target areas of ISAC is shown in Fig. 6.

Experience at ISOLDE shows that in addition to shielding for the prompt and delayed radiation induced in the structures at a rare-isotope production facility, it is also necessary to contain the vapors of non-ionized radioactive species. These vapors escape from the target and ion-source region and propagate along vacuum chambers, vacuum lines, and beam lines, on which the vapors partly condense. To control the risk of contamination from this very loose radioactivity, both ISOLDE and ISAC have taken the approach of enclosing the target/ion source in a containment vessel. At any time the volatile components from the target region are either condensed inside the containment box on the cool surfaces surrounding the target or pumped into sealed storage vessels. The activity is kept in the storage vessels until the contamination is determined to be sufficiently low to be released through monitored air filters. A conventional nuclear exhaust system is required to prevent the accidental release of radioactivity to the environment. Very little modification is required to this modular approach for the spallation-type target stations. A similar remote handling system is envisioned for the target and beam dump areas of the fragment-separators of RIA.

Preliminary analysis indicates that the target areas of RIA will be classified as a non-reactor nuclear facility class 3. This is the lowest nuclear facility classification. This classification is based on the inventory of radionuclides estimated to be present in the RIA target areas. An engineering design that passively contains the great majority of isotopes will be developed to limit the portion of RIA that has the nuclear facility classification.

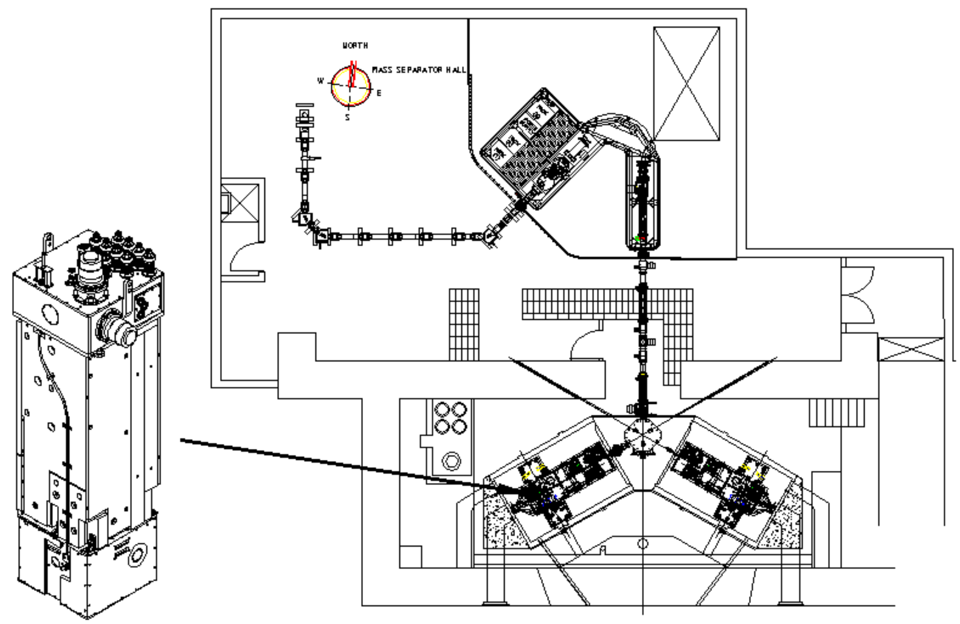

Fig. 6. The items having the highest potential residual activity are located in the heavily shielded vault shown in the lower part of this plan view of the ISAC target area. Inside the target vault, two target vacuum tanks each house five modules. An enlarged schematic of the target/ion source module is shown in the left of the figure. The containment box at the bottom of the target module confines the products from the target and is used to prevent the spread of loose radioactive contamination to the outside of the module. Steel shielding separates the target from the vacuum seals that are all located on the service cap. The modules and the tank housing the modules each have their own separate vacuum system. Each of the modules can be picked up remotely and delivered to a hot cell (not shown).

Project Cost Estimate Overview[1]

The estimate was prepared by a Collaboration of MSU and ANL. The Sub-committee members were Jim Beene ORNL, Mike Harrison (chair) BNL, Christoph Leemann JLAB, Jay Marx LBNL, Thom Mason SNS, and James Symons (ex-officio). Denis Kovar DOE, was present as an observer. The estimate presented was a TEC of $695M, including 32% contingency, which together with other project costs resulted in a TPC of $885M. The Collaboration expects that contributions to the costs from existing facilities or non-federal funds will reduce the TPC by ~$50M. An estimate for the annual operating costs of $65M was presented. All costs were in FY01 dollars. The proposed RIA facility consists of a driver Linac together with both ISOL and fast fragmentation beams and associated experimental facilities. A 6-year construction schedule was assumed.

The Sub-committee believes that the TEC presented is reasonable. The 32% contingency is judged to be appropriate at this point in the development of the estimate. The other Project costs (R&D, Pre-operations, conceptual design and environmental studies) were not estimated as carefully. The pre-operations costs of $150M appear to be somewhat high, whereas the R&D costs of $25M appear to be underestimated. The projected operating budget of $65M per year is found to be minimal for a national user facility of approximately the scale of CEBAF.

[1] From the Executive Summary of the "Report of the NSAC RIA costing-subcommittee" chaired by Harrison (January 2001).