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The Holifield Radioactive Ion Beam Facility at the Oak Ridge National Laboratory: Present Status and Future Plans

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Abstract

The Holifield Radioactive Ion Beam Facility (HRIBF) is a first generation national user facility for nuclear physics and nuclear astrophysics research with radioactive ion beams (RIBs). The reconfiguration, construction, and equipment-commissioning phases have been completed and the beam development program is in progress. In this article, descriptions of the facility and newly implemented experimental equipment for use in the nuclear and astrophysics programs will be given and an outline of the initial experimental program will be presented. Special target/ion source related problems, endemic to the production of specific short-lived RIBs will be discussed. In addition, plans, which involve either a 200 MeV or a 1 GeV proton-linac driver for a second-generation ISOL facility, will be presented.

Introduction

Many of the reactions fundamentally important in nuclear physics and astrophysics can only be studied with high-energy radioactive ion beams (RIBs). Therefore, the availability of radioactive ion beams offers unique opportunities to further our knowledge about the structure of the nucleus, the stellar processes which power the universe, and the processes of nucleosynthesis responsible for heavy element formation. As a consequence of a worldwide interest in RIBs, several facilities have been built, funded for construction, or proposed for construction throughout the world, including the Holifield Radioactive Ion Beam Facility (HRIBF) at the Oak Ridge National Laboratory (ORNL). These facilities either rely on projectile fragmentation to form short-lived

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species by break-up of energetic beams of heavy-ions as they pass through a thin production target or on the isotope separator on-line (ISOL) technique. In an ISOL facility, of which HRIBF is an example, radioactive nuclei are produced essentially at rest in a thick target by bombardment with particles from a driver accelerator. These radioactive species must be diffused from the target material and effusively transported to an ion source, ionized, extracted, and accelerated to energies suitable for experiments in a time commensurate with the lifetime of the species of interest. The diffusive and effusive delay times limit the speed at which the species can be delivered to the research station and thus determine the species that can be successfully accelerated. These limiting processes are governed by the chemical and metallurgical reactions which take place between the species of interest and the target material during diffusion release and between the species of interest and the surfaces of the vapor transport system during transport from the target to the ion source. The RIB generation process is faced with difficult technological challenges related to targets and their design including: their physical (refractory) properties, particulate size or laminar thickness, geometry, design, operational temperatures, and means for removal of beam deposited heat. Nevertheless, a broad array of targets must be developed since, in order to have a viable research program, the facility must produce beams of a variety of radioactive species of particular scientific interest, at an intensity sufficient to produce statistically significant results. While some experiments will obtain useful results with very low beam intensities, many will require minimum intensities in the range $10^7 - 10^{10}$ particles per second.

In this presentation, details of the present status of the HRIBF, including newly implemented experimental equipment for use in the astrophysics and nuclear physics research programs will be discussed, and an outline of the initial experimental program will be given. In addition, plans for a second-generation ISOL facility will be briefly outlined.

Present Status of the HRIBF

The HRIBF, illustrated schematically in Fig. 1, was begun in 1993 and completed in 1996. The facility is based on the use of the original Holifield Heavy Ion Research Facility (HHIRF) accelerator systems augmented by additional equipment to enable the production, generation, and post-acceleration of short-lived radioactive ion beams (RIBs) by the ISOL technique. Conversion of the HHIRF facility into the HRIBF entailed the following major modifications: (1) construction of a high-voltage platform onto which is mounted the target/ion source system, the first-stage mass separator system, provisions for charge exchange, and beam-transport lenses, etc.; (2) design, fabrication, and installation of an isobar separator system; (3) the design and implementation of a radioactive materials handling system, complete with a robotic handler for removal/insertion of contaminated ion sources and targets; (4) the design and development of several new concept ion

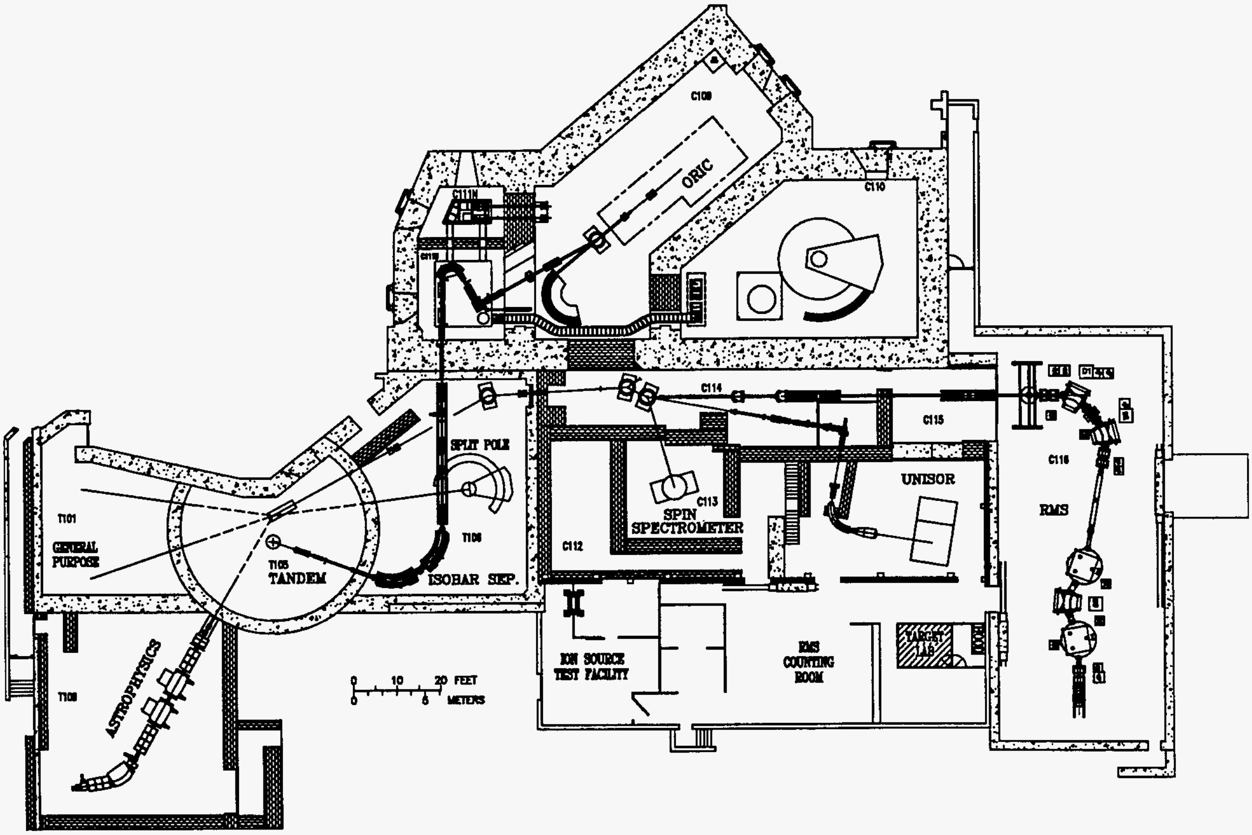

Fig. 1. Schematic layout of the Holifield Radioactive Ion Beam Facility (HRIBF) showing the principal components of the facility.

sources for use in generating RIBs for the facility; (5) acquisition, installation, and commissioning of the Daresbury Recoil Separator (DRS) for use in the nuclear astrophysics research program; and (6) design, fabrication, and commissioning of the Oak Ridge Recoil Mass Spectrometer (RMS) for use in the nuclear structure research program. In addition, an aggressive on-line beam development program has been effected to characterize new high-release-efficiency targets. Since the 25-MV tandem accelerator is used as the RIB accelerator, negative-ion beams must provided.

The Oak Ridge Isochronous Cyclotron. The Oak Ridge Isochronous Cyclotron (ORIC) is a $k = 100$ cyclotron capable of providing ~ 65 MeV proton, 50 MeV deuteron, 133 MeV $^3He^{++}$, or 100 MeV $^4He^{++}$ beams for the production of radioactive species. Beam-on-target intensities on the order of 50 µA should eventually be achieved, but present intensity limits are in the 10 to 20 µA range. A new PIG source has been designed and installed, and the central field geometry of the extraction system is being revised to provide better beam centering, orbit definition, focusing, and consequently, improved extraction efficiency.

The RIB injector. The major development required to convert the HHIRF into the HRIBF was the addition of a high-voltage platform that serves as the injector for the 25 MV tandem accelerator. The injector, shown schematically in Fig. 2, is segmented in two sections, (1) a shielded instrumentation platform that houses all power supplies and (2) a hardware platform that houses the target/ion source, beam transport lenses, the first-stage mass separation system, and the charge-exchange cell. The injector is powered by a –300 kV, 1-mA supply. The injector typically operates between –200 kV and –300 kV relative to ground potential to ensure high efficiency transport of negative-ion beams to the tandem accelerator. The instrumentation platform is separated from the hardware platform by a shielding wall. This segmentation is necessary to shield

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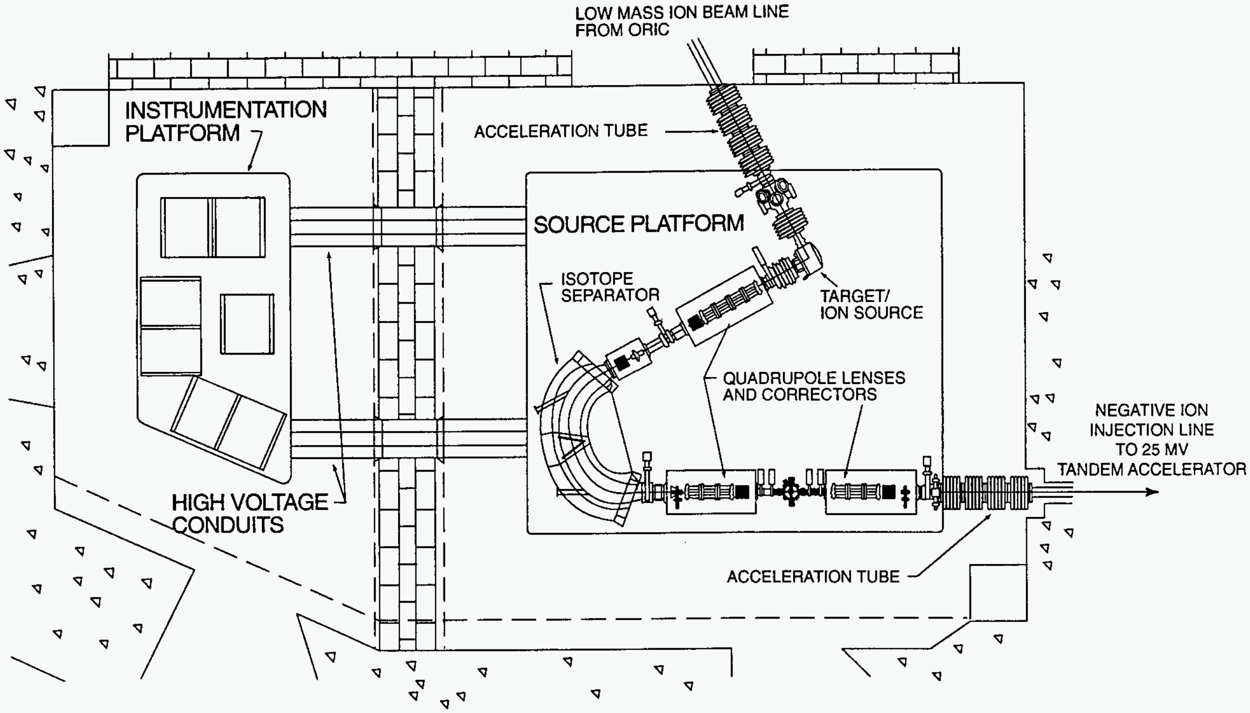


Fig. 2. Schematic drawing of the high voltage injector for the HRIBF 25-MV tandem electrostatic accelerator.

power supplies from the high neutron fluxes in the immediate proximity of the target/ion source (~ 1 × 10^{15} n/cm^2 after 2000 hours of operation with a medium mass target material) and, thus, prevent radiation damage to solid state components. Power is supplied from the instrumentation platform to components mounted on the hardware platform (e.g., the isotope separator magnet, electrostatic lenses, the target ion source, etc.) through two electrically isolated conduits maintained at either platform potential or platform-plus-ion-source potential. Power is supplied to components at platform or platform-plus-ion-source potential by two 40-kVA motor generator sets. Beams from the ORIC are directed through a linearly-graded acceleration tube onto a high-temperature target to produce radioactive species. The radioactive species must then be diffused from the target material where a fraction of the species is ionized and extracted. Following extraction, circularly symmetric beams are transformed into thin vertical beams and focused onto vertical object slits by the action of two sets of electrostatic doublets to facilitate optimum mass analysis with a 152-degree split-dipole magnet with edge angle focusing at entrance, center, and exit of the magnet.

Following mass analysis, a single RIB species is selected for transport through the system and the line-image beam is transformed into circular symmetry and focused through a charge-exchange cell by the action of an electrostatic quadrupole triplet. Charge exchange is used to efficiently convert positive-ion beams into negative-ion beams for injection into the 25-MV tandem accelerator. Following charge exchange, the beam is focused at the entrance to a linearly graded acceleration tube by the action of an electrostatic triplet which accelerates the beam up to tandem injection energies (200 keV to 300 keV, typically).

Target and ion sources for initial use at the HRIBF. Ion sources for RIB generation must ideally exhibit the following properties: high efficiency, low energy spreads, chemical selectivity, operation at controllable temperatures, flexibility for adaptation to other ranges of temperature and modes of operation, reliability, long lifetime, and stable electrical and mechanical properties. Of paramount importance, the source must be mechanically designed for safe and expedient installation/removal from the ISOL facility to permit interchange of sources and target materials and repair of failed components. A side view of the modular ion source assembly, used to house sources for initial use at the HRIBF, is shown is Fig. 3. A number of ion sources have been developed for initial use in the HRIBF research programs including CERN-type electron impact ionization sources, positive- and negative-surface ionization sources, kinetic-ejection negative-ion sources, and Cs-sputter negative-ion sources. For more details on ion-source developments for initial use at the HRIBF, attention is called to Refs. 3–5. Each of the targets and ion sources is designed to fit into a modular vacuum chamber that is remotely removable from the remainder of the source at the interface of the shutters. Future plans call for the use of new generation ECR ion sources that can simultaneously dissociate molecules and efficiently ionize their atomic constituents.

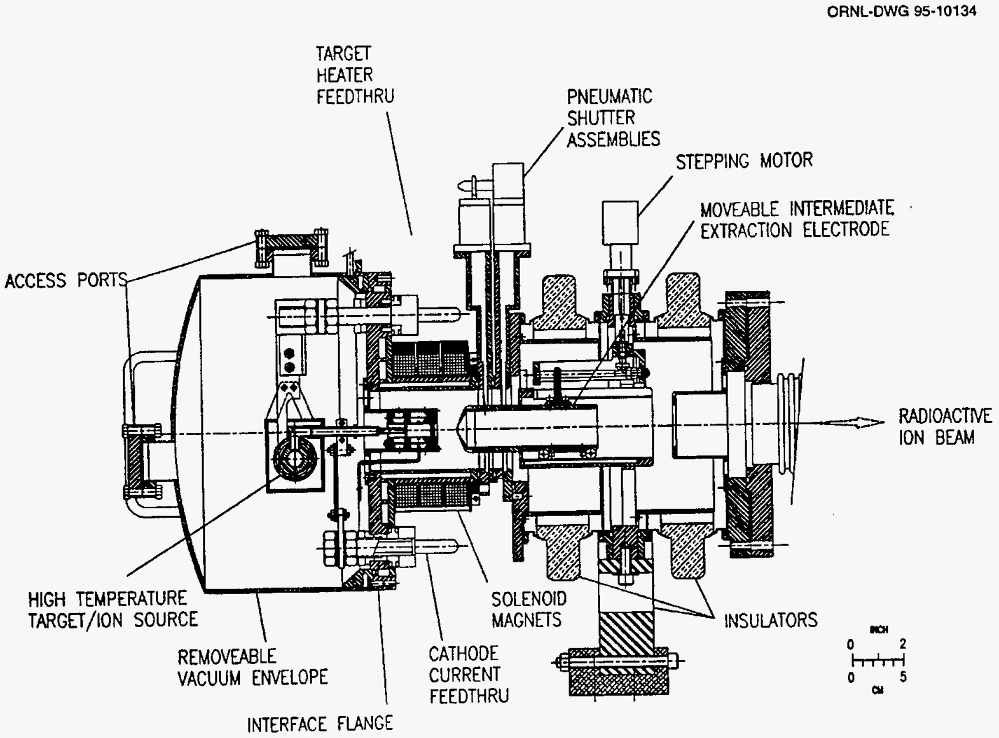


Fig. 3. Side view of the modular ion source assembly used to house sources for initial use at the HRIBF. The rear vacuum canister portion of the assembly is designed for disconnection/connection at the interface of the two shutters and removal/installation by a remotely-controlled pneumatic/robotic system.

The degree of success of any ISOL facility will rely heavily on solutions to target related problems. For example, provisions must be made to remove, as efficiently as possible, heat deposited in the target by the beam during passage through the target matrix, so that high beam intensity on target can be utilized to maximize radioactive species production while permitting control of the target temperature. Targets must be designed to effect fast and efficient release by diffusion of the species produced within the bulk of the target material. This implies that the targets be highly permeable and have thickness chosen so that the species of interest can be diffused from the target within its half-life. Progress has been made in developing targets with these characteristics for initial use at the HRIBF for the generation of RIBs of ^{17,18}F, ^{58}Cu, ^{56}Ni, ^{69}As, etc. More details of the target development program at the HRIBF are described in Refs. 6–8.

The radiation handling system. To safely operate a RIB facility, provision must be made for remotely handling high-level, radioactively contaminated targets and ion sources, as well as other equipment. A robust, remotely controllable, integrated radioactive material handling system has been implemented at the HRIBF for removing/installing targets/ion sources for repair, storage or disposal. This system is illustrated schematically in Fig. 4. Target/ion sources are designed so that the target/ionization chamber of the source, which contains essentially all high-level residual radioactivity, can be remotely disconnected from the extraction electrode assembly by means of a pneumatic-valve/pneumatic-actuator system. The electrode assembly remains on the platform while the modular target/ion source assembly can be remotely removed from or installed on the high voltage platform by means of a robotic arm with six degrees of freedom. Sources and other equipment that are removed from the high-voltage platform are lowered onto a conveyor belt system and placed in a light-weight storage container for transport to an end-station where a robotic gantry crane is located. The robotic gantry crane is programmed to remotely place contaminated

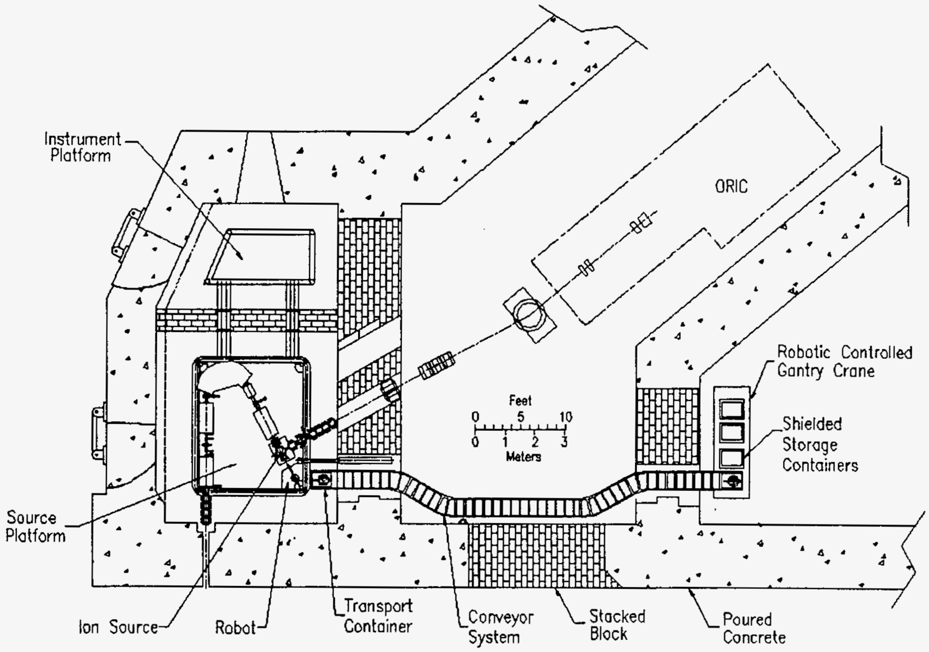


Fig. 4. Schematic representation of the RIB injector for the 25-MV tandem accelerator and the radiation handling system for installation/removal/storage/disposal of radioactively contaminated targets and ion sources.

equipment in shielded containers for transport to a hot-cell for repair, to storage, or disposal. The procedure is reversed for installation of new or replacement target/ion source assemblies.

The isobar separation system. A schematic drawing of the beam-transport line from the high-voltage injector to the tandem accelerator is shown in Fig. 5. Beams from the RIB injector can be focused onto a removable radionuclide identification system by the action of a set of electrostatic quadrupole lenses. The radionuclide identification unit is comprised of a tape system, a gamma-ray detector and a low-intensity beam diagnostics detection unit. Following species identification, the beam is focused into a thin, vertical line which serves as the object for a high resolution magnetic isobar separation system. Isobaric contaminants are removed by passing the beam through two 55-degree magnets with bending radii of 2.8 m, which in combination, have a mass resolution $\Delta M/M = 1/20000$. RIB beams are then transformed back into circular symmetry

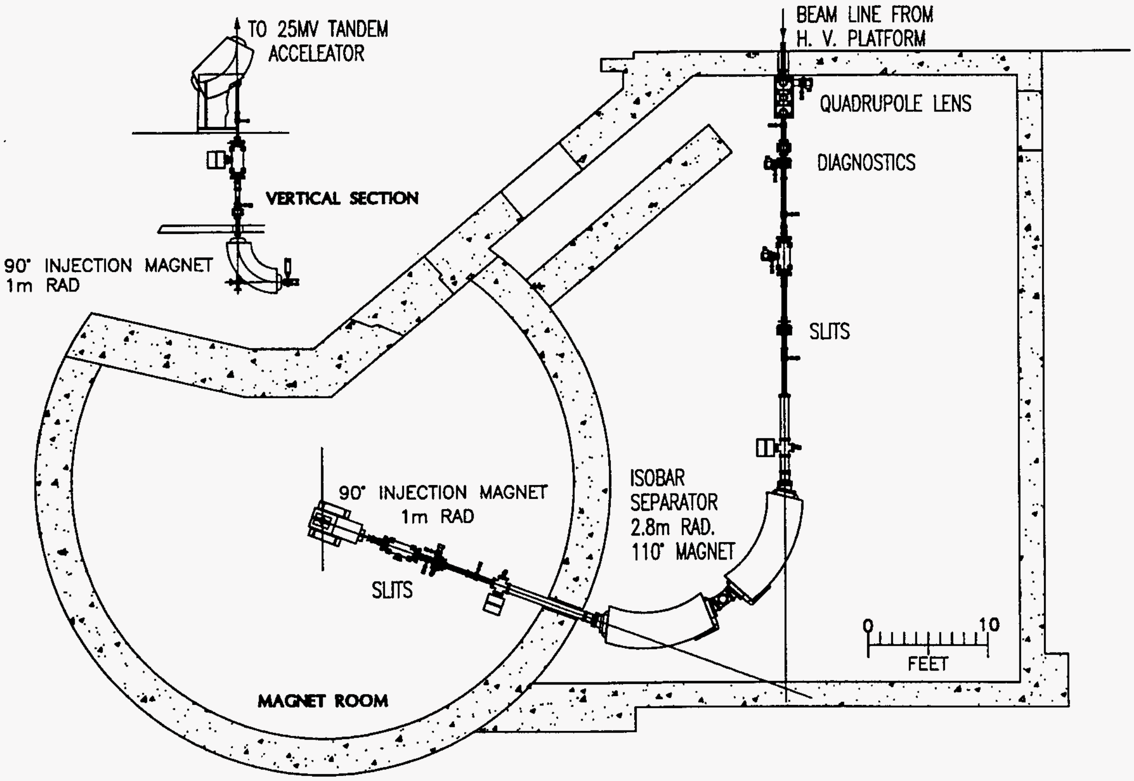


Fig. 5. Schematic representation of the injection line between the high voltage injector and 25-MV tandem electrostatic accelerator showing the magnetic isobar separation system.

with another set of electrostatic quadrupole lenses and injected into the 25-MV tandem for acceleration to final research energies.

The 25-MV tandem accelerator. The Model 25 URC electrostatic accelerator, shown schematically in Fig. 6, is a product of the National Electrostatics Corporation, Madison, WI. The machine was inaugurated for use at the HHIRF in 1982 and used continuously in the stable projectile research program until 1993. It is highly reliable, folded-geometry device with excellent beam quality ($\Delta E/E = 1 \times 10^{-4}$). Figure 7 displays E(MeV)/u versus mass for the tandem at a terminal voltage of 25 MV for both gas and foil strippers. As noted, the tandem can accelerate beams above the Coulomb barrier (5 MeV/amu) up to mass 52 at transmission efficiencies of over 20% when a gas stripper is used and up to mass 80 with transmission efficiencies of ~ 8% when a foil stripper is used. Since many of the nuclear astrophysics experiments require on-target beam energies of a few MeV, it is important that the tandem accelerator be able to operate at low terminal voltages without suffering catastrophic

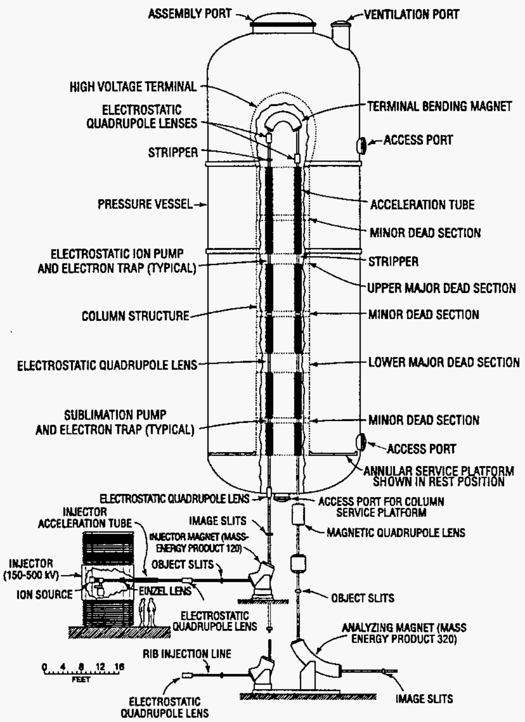


Fig. 6. Side view of the 25-MV tandem electrostatic accelerator showing the principal components of the machine and RIB injection line.

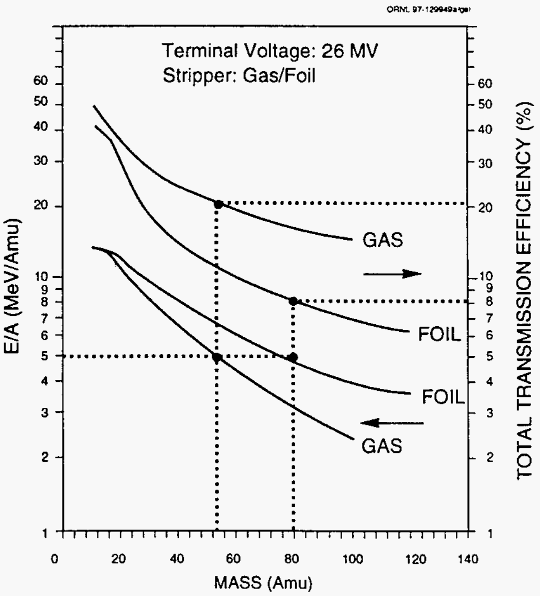


Fig. 7. Energy (MeV/amu) and total transmission efficiency versus mass (amu) for the 25-MV tandem electrostatic accelerator when operated with either a gas or foil stripper.

transmission losses. The original corona-based grading system has been replaced with a resistor voltage grading system that provides better voltage stability at low terminal voltages. The tandem accelerator has been operated with beam at terminal voltages as low as 1 MV without shorting sections of the machine, changing the SF_6 insulating gas pressure, or suffering catastrophic transmission losses. Experiments with ^{16}O indicate that the transmission losses at 1 MV are only factors of two lower than those for 25-MV terminal operation. Further improvements in transmission efficiency can probably be realized by shorting optimally-chosen sections of the machine.

The Nuclear Astrophysics Research Program

Energy is released and heavy elements are synthesized in nuclear reactions which take place in a variety of cosmological environments. Under conditions of sufficiently high temperatures and densities, such as those reached in certain catastrophic stellar explosions, these reactions can occur on such a rapid time scale that unstable (radioactive) nuclei produced in one reaction can participate in subsequent reactions before decaying. Accelerator-based experiments with radioactive ion beams (RIBs) offer unique and direct means for quantitative study of such reactions [9,10]. Cross sections, derived from such measurements, provide essential input to the development of a better understanding of astrophysical phenomena. The nuclear astrophysics research at the HRIBF centers about the use of the Daresbury Recoil Separator (DRS).

The Daresbury Recoil Separator (DRS). The Daresbury Recoil Separator (DRS), shown in Fig. 8, has been installed for use in the nuclear astrophysics program. This instrument is well suited for studying inverse (p, γ) reactions which occur in stellar explosions. The DRS separates recoiling reaction products from the incident beam with two 2-meter-long, ExB velocity filters and a 50-degree dipole magnet. Three sets of quadrupole triplet lenses are used for focusing reaction product beams and two sets of septupole lenses are used to correct higher order aberrations. The DRS is a large acceptance (6.5 mstr, ±2.5% in velocity), high mass resolution ($\Delta M/M = 1/300$) device originally designed to detect weak signals in fusion-evaporation reactions where there is a large difference between the velocities of the projectiles and recoil particles. However, in inverse proton capture reactions, there is little difference in the momenta of the projectiles and recoils, a difference in velocity of only a few percent, and a difference in mass of only one amu. A suppression factor of scattered projectiles on the order of 10^{-11} to 10^{-12} is required and, therefore, because of the typically low reaction cross sections, the optics of the DRS have been redesigned to enhance suppression of the primary ion beam. A compact gamma-ray array will be used to measure (p, γ) reactions and charged-particle (p, p), (p, α) reactions will be measured with the LEDA silicon detector system. These detector systems will be used interchangeably at the target position. The DRS focal plane detector system consists of a ΔE-E gas ionization counter and two carbon-foil micro-channel plate detectors. The ΔE-E detector can resolve masses up to 20. Future plans call for implementation of a time-of-flight system for identifying masses greater than 20.

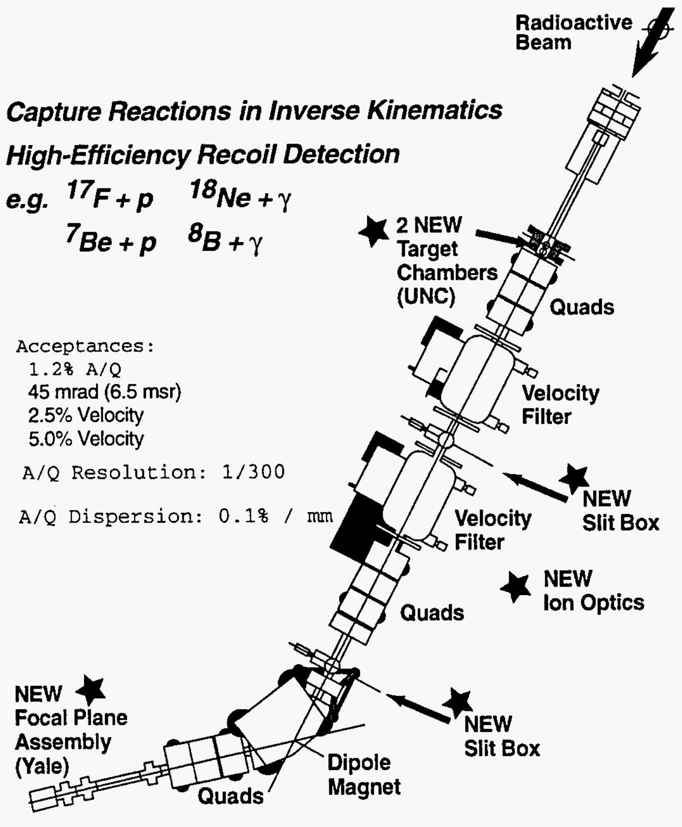
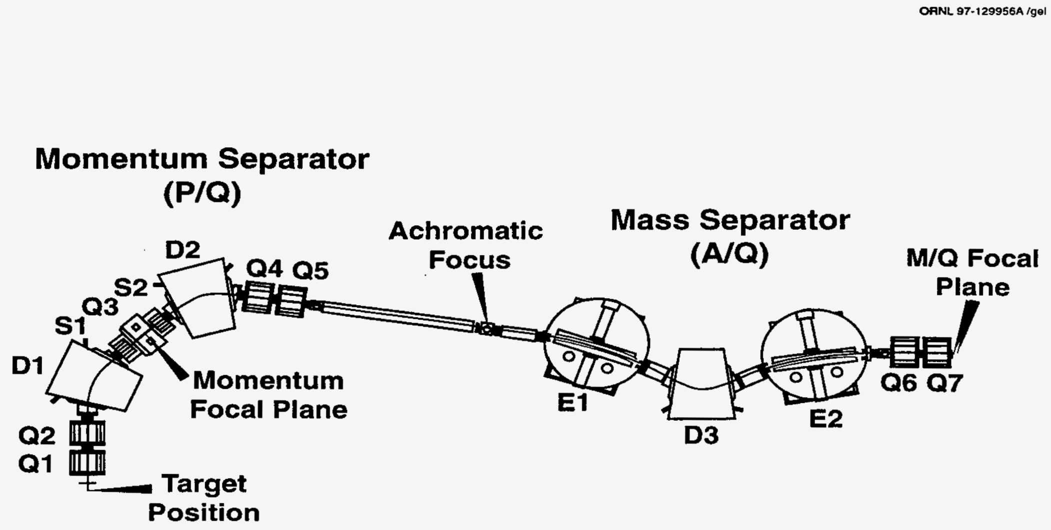


Fig. 8. Schematic drawing of the Daresbury Recoil Separator (DRS) as modified for nuclear astrophysics research at the HRIBF.

The Nuclear Structure Physics Research Program

In the early stages of operation of the HRIBF, studies will be made of the structure of unstable nuclei near the proton drip line. Because of the small cross sections for production and the low intensities of the RIBs, these studies will require experimental hardware equipped with ultra-sensitive detector systems. Because of the ability to select masses of recoiling nuclei, the Recoil Mass Spectrometer will be used primarily for these studies. Two complex detector systems are used in conjunction with the RMS to carry out nuclear structure research. One detector system located at the target position, is optimized for detection of in-beam reaction products including light-charged particles, neutrons, and γ-rays. The second detector system is positioned at the RMS focal plane, and is responsible for detection and Z-identification of heavy recoils and for detection and spectroscopic study of delayed activity.

The Oak Ridge Recoil Mass Spectrometer. The nuclear structure physics research program will center around the use of the Recoil Mass Spectrometer (RMS), shown schematically in Fig. 9. The device is designed to detect rare events following heavy-ion inverse kinematic reactions. The RMS is a large-acceptance (13 msr) zero-degree spectrometer with a mass resolution of $\Delta M/M = 1/450$. The RMS consists of two distinctly different optical systems, a momentum separation or p/Q stage and a mass separation or M/Q stage. At the target end, the reaction products and primary ion beam are separated in momentum inside Q3. Seven vertical rods called fingers can be independently positioned within Q3 to block sharply focused charge states of the primary beam. The RMS is capable of suppressing the primary beam by a factor of $\sim 1 \times 10^{-12}$. The momentum separator refocuses the beams of chosen momenta at the achromat which serves as the object point of the M/Q separator section of the RMS. The M/Q stage consists of two cylindrical-sector electrostatic-energy analyzers (E1 and E2) separated by a dipole magnet (D3) that, in combination, can be used to separate nuclei as a function of M/Q independent of their energy. The RMS has large energy (±10%) and large M/Q (±5%) acceptances that permit transmission of multiply-charged beams of the same mass M, resulting in high-detection efficiency



Inverse reactions
High rigidity beams (K=100)
Excellent beam rejection (>10^{12})
Excellent mass separation (M/ΔM=450)
Large energy acceptance
Large solid angle
Large A/Q acceptance

Fig. 9. Schematic drawing of the Recoil Mass Spectrometer (RMS) showing the principal components used to separate recoils from the primary ion beams.

and, consequently, greater accuracy in cross-section measurements. The detector systems used at the focal plane of the RMS include: a position-sensitive avalanche counter (PSAC) system, double-sided silicon-strip (DSSS) detectors, and a pair of segmented-clover germanium detectors, for gamma-ray spectroscopy. For light to medium mass nuclei, atomic number information is derived from the ionization chamber located at the focal plane of the RMS. A target-position array has been designed for in-beam spectroscopy tagged by evaporation residues detected in the RMS. The array is based on a high resolution Compton-suppressed γ-ray detector system based on 11 new segmented-clover Ge detectors and 12 smaller Ge detectors recycled from the HHIRF Ge array. A near 4π low-mass, hybrid charged-particle array (HYBALL) is positioned around the target to aid in Z-identification of heavy residues. Eventually, a neutron detector array will be added in the forward direction.

Future Plans for an Advanced ISOL Facility

Of the major nuclear physics facilities under consideration for funding in the USA, the U.S. Department of Energy places top priority for new construction on a second-generation ISOL facility as recommended by the Nuclear Science Advisory Committee. Funding is expected to begin following commissioning of the Relativistic Heavy Ion Collider (RHIC) now nearing completion at the Brookhaven National Laboratory. This facility will be competitively selected from proposals submitted by interested national laboratories including the Oak Ridge National Laboratory. The second-generation ISOL facility will produce RIB intensities that far exceed those of the present HRIBF.

At the HRIBF, we are initially concentrating on beams of proton-rich radioactive species produced with fusion-evaporation reactions. In the near future, we will begin development of beams of neutron-rich species produced by proton induced fission of actinide nuclei. Since many fusion-evaporation reactions have cross sections strongly peaked near the Coulomb barrier, the proton, deuteron, and helium beam energies available at HRIBF are well suited for production of proton-rich species. However, the total proton-induced fission cross section on, for example, ^{238}U, is almost independent of energy for bombarding energies from ~20 MeV to > 1 GeV. Higher energy beams therefore have an obvious advantage for neutron-rich species production because of the increasing range (and, hence, target thickness) which can be used with higher beam energy.

Two options have been suggested for the ORNL-based second-generation ISOL facility. The first option would be to upgrade the existing HRIBF facility by replacing the ORIC with a linear accelerator that can deliver 200 μA beams of either 50 MeV, q/A =1/2, or 200 MeV protons to either of two vertically oriented targets. A schematic of this option is shown in Fig. 10.

As a preferred option, the ISOL facility would be constructed in close proximity to the Spallation Neutron Source (SNS) that has strong support for construction at the Oak Ridge National Laboratory and has been budgeted for design during this fiscal year. The first phase of the SNS

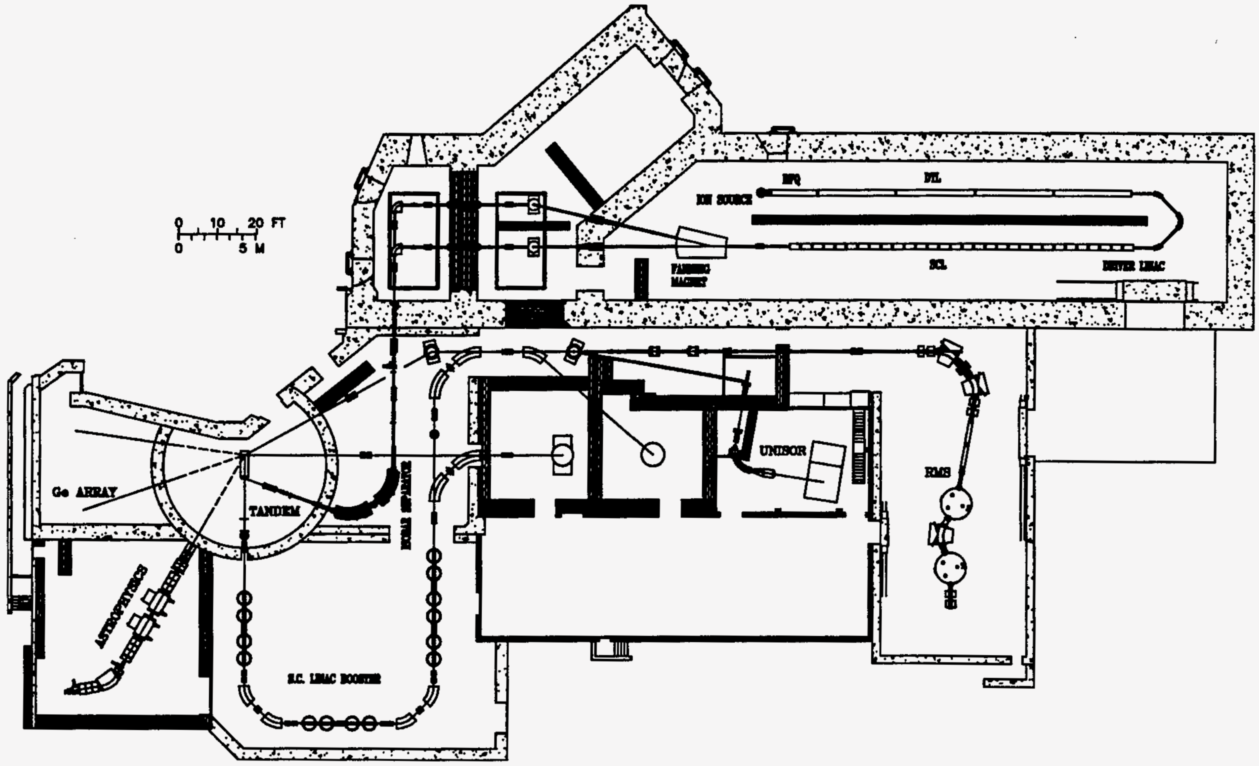


Fig. 10. Proposed scenario for a second generation HRIBF with a linear accelerator with capabilities of accelerating particles with Q/A = 1/2 up to 50 MeV and Q/A = 1 up to 200 MeV with respective intensities of 200 μA on target. The targets are assumed to be vertically oriented.

will produce neutrons by spallation reactions induced by a 1-mA proton beam from a 1-GeV linear accelerator in a liquid Hg target. The ISOL facility would rely on pulsed manipulation of a 1-mA H^- ion beam to divert 100 μA for use with the ISOL facility. We believe that this manipulation can be effected without disturbing operation of the SNS; however, alternative techniques such as the magnetic stripping of a fraction of the H^- ion beam are being considered.

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