Holifield Radioactive Ion Beam Facility
Cyclotron Driver White Paper

prepared in response
to a recommendation from the

Annual Science and Technology Review
of the
Holifield Radioactive Ion Beam Facility
(June 2-3, 2008)

Please note that this document has not been updated for this Workshop. It was written at an early stage of development of the project. It should be of some value as a qualitative or semi-quantitative conceptual description of an HRIBF upgrade based on a new commercial cyclotron (specifically the IBA C70) driver. The quantitative details of both project cost and facility performance have changed as planning and design work has progressed. One of the original purposes of the White Paper was a comparison of the performance of a C70 based facility to a facility based on photofission with a high-power electron accelerator as the driver. Consequently performance is often compared to that of the electron driver concept. If we were re-writing the document now, most of these references would not be relevant.

1.0 Introduction

This white paper provides preliminary details of a proposed hadron driver accelerator upgrade (HDU) to the Holifield Radioactive Ion Beam Facility (HRIBF), a national user facility for research with radioactive ion beams (RIBs) located at Oak Ridge National Laboratory (ORNL) and operated by the ORNL Physics Division.

HRIBF produces RIBs by the isotope separator on-line (ISOL) method. Light ion beams from the Oak Ridge Isochronous Cyclotron (ORIC) are used to bombard target material located in a combined target and ion source (TIS) assembly. Radioactive atoms diffuse from the target and effuse into an ion source. The radioactive ions are extracted from the ion source at nominal energies of 40-60 keV, mass separated, injected into the 25 MV tandem electrostatic post accelerator, and then transported to an experimental end station where research in such areas as nuclear structure, reactions, and nuclear astrophysics takes place. HRIBF is in the process of implementing a long-range facility upgrade plan. Initial phases of the plan have focused on the most crucial aspect of a RIB facility: the production system. These efforts have included developments in target, ion source, and beam purification and production techniques. They have also resulted in a second RIB production system known as the Injector for Radioactive Ion Species 2 (IRIS2) which, when completed in FY 2009, will provide much-needed redundancy leading to more efficient facility operation.

The next phase of the HRIBF long range plan addresses the need for driver accelerator improvements including increased capability leading to new science, improved operational efficiency, higher reliability, and lower operating cost. This document describes one very attractive method for achieving these goals. Although extensive ORIC refurbishments are possible, they lead to little new science making it difficult for HRIBF to maintain competitiveness with current and planned international initiatives. There are several options for either replacing ORIC in its entirety, or reducing its role by adding an additional accelerator with capabilities that may be drastically different from ORIC. Although a collaborative effort with other national laboratories or universities may be a possible means of developing an accelerator to meet the needs of HRIBF, it is not our preferred option due to the small staff and limited resources of HRIBF. Outsourcing of effort is a key aspect of any major upgrade at this facility, and thus procurement of a commercial accelerator is appealing.

In the recent past we have explored the concept of adding an electron accelerator to HRIBF that would produce RIBs by photofission of actinide targets. This option is referred to as the electron driver upgrade (EDU) throughout the text of this document. However, because some of the characteristics of an electron-driven facility are so different from the present HRIBF, substantial infrastructure additions are required including a major building addition to house the accelerator system. Consequently, civil construction amounts to more than 20% of the approximately $40M TPC. A white paper related to the electron driver option was written in December 2006, and a preliminary proposal was submitted to DOE-NP in June 2008.

This white paper provides a detailed discussion of what is now our preferred upgrade solution: the addition of a new high-current commercial cyclotron to replace the 48-year-old ORIC. This upgrade would increase the scientific reach of HRIBF on the neutron-rich side of stability to a level compares favorably to that of the EDU, while preserving and extending the existing proton-rich program as well. In addition the upgrade we describe here would enhance the output of the facility, increase reliability and operational efficiency, and result in substantially lower operating cost, while making much better use of existing HRIBF infrastructure than the EDU concept. Included in the white paper is a discussion of the scientific goals and benefits of the project, a description of required technical equipment and facility modifications, and preliminary cost, schedule, and effort information. It was developed to comply with a recommendation made in the panel report of the Annual Science and Technology Review of the Holifield Radioactive Ion Beam Facility held in June 2008.

2.0 Project Overview

HRIBF presently employs a single driver accelerator, ORIC, which was commissioned in the early 1960s. Although many aspects of ORIC have been upgraded over the last decade, reliability concerns remain and maintenance is often quite difficult. Operating costs including electrical power, materials and supplies, and personnel exceed those of a comparable modern, commercial accelerator. ORIC also has limitations that preclude it from being an ideal driver for RIB production. Beam intensities are limited to approximately 30uA for protons, 15uA for deuterons, and 5uA for alpha particles, largely due to the use of an internal Penning ion source, and to the complex rf and magnet systems. Proton energy is also limited by the rf system to around 54 MeV.

Until recently, commercial cyclotrons have been either single beam machines (proton-only) and/or have extracted beam energies that are too low to be useful in RIB production. However, Ion Beam Applications (IBA) Molecular Division has recently introduced a new product that not only fully replaces the functionality of ORIC, but also provides higher proton energy and order of magnitude greater beam intensity. The first of these cyclotrons, model Cyclone 70 (C70), is presently being installed and commissioned (Fall 2008) at the new ARRONAX (Accelerator for Research in Radiochemistry and Oncology at Nantes Atlantic) facility in Nantes, France on the campus of the René et Guillaume Laënnec university hospital and as part of the René Gauducheau cancer center. One of the primary purposes for which ARRONAX is being developed is the production of radioisotopes for innovative research in nuclear medicine. Although the C70 is a new product, IBA has decades of experience in the design and manufacturing of high quality turnkey cyclotrons for Single Photon Emission

Computed Tomography (SPECT) and Positron Emission Tomography (PET) systems, as well as proton cancer therapy.

HRIBF would use essentially all of the capabilities of the C70 for RIB production. The higher, and easily adjustable, proton energy coupled with higher beam current would increase the yield of neutron-rich fission fragment beams by at least a factor of 8 (potentially much more), and broaden our capability to develop proton-rich beams by opening more (p,X) channels. The variable energy deuteron beam would enable us to continue to employ (d,n) reactions at low energy for proton-rich beam production. The 70 MeV alpha beam capability, together with the 8° angle of incidence at IRIS2 would allow us to employ α-induced reactions already developed for proton-rich species much more efficiently than is possible with ORIC, and to develop new thin target systems for new proton-rich species by (α, X) reactions. The dual port extraction capability will allow us to extract two beams of deuterons or protons at different energies. One beam would be used for normal RIB production at IRIS1 or IRIS2 while the other could be used for isotope production. Our own isotope needs would be filled by generating long-lived species used to produce "batch mode" beams for research at HRIBF (see p18, sect. 4.2 for more discussion of this mode of operation), and the potential exists to produce isotopes for research in other fields such as nuclear medicine. The very large intensities available from the C70 could not be used directly on ISOL targets currently available, but could be employed to produce secondary neutron beams by (d,n) or (p,n) reactions. These neutrons would then be used to induce fission and produce neutron-rich RIBs. These RIBs from "cold fission" would lead to gains in intensity that grow dramatically as the neutron number increases toward the limits of stability, as we have discussed extensively in documents related to our EDU proposal. With the C70 and secondary neutron fission, we would expect to reach ~25% of the baseline EDU neutron-rich beam production performance with only modest upgrades to existing IRIS2 infrastructure. With further infrastructure improvements, performance on the order of 75% of the EDU baseline could be reached. The various means of utilizing the C70's capabilities to extend our scientific reach are discussed in more detail in Section 4.

Replacement of ORIC will be instrumental to HRIBF maintaining an international leadership position in the RIB science community, and will lead to the production of radioactive ion beam intensities that are competitive, for neutron-rich beams, with $100M-scale facilities. With the electron driver approach, the accelerator systems are designed to produce desired scientific goals. In the case of the new cyclotron driver approach, the science goals are largely driven by the capabilities of the available commercial accelerator, the C70. Therefore, the remainder of this document begins with an overview of the capabilities of the C70 and a technical description of the major components of the project. This is followed by a discussion of how the C70's capabilities would enhance the RIB production capability of HRIBF, an overall description of HRIBF scientific goals, and concludes with a discussion of project costs, schedule and effort.

In summary, the proposed project would provide the following enhancements and capabilities to HRIBF:

- **Scientific Benefits**
    - Immediate >8x gain in neutron-rich beams from (p,f)
    - Employ (n,f) with n from (p,n) or (d,n) for bigger gains
    - Sample n-rich yields relative to present HRIBF (~23% of EDU)
        - ^{132}Sn x 50, ^{134}Sn x 1100; ^{136}Sn x 1900; ^{133}Sn x 8000
        - ^{82}Ge x 460; ^{84}Ge x 1790; ^{86}Ge x 4300; ^{88}Ge x 7300
    - Above yields attainable with only minor upgrades to existing infrastructure
    - Up to 3x more with infrastructure upgrades
    - Maintains and extends existing proton-rich capability
    - Produce long lived isotopes for batch mode operations very economically using dual port proton or deuteron beams
- **Facility/Operational Benefits**
    - Fully replaces ORIC and expands on capabilities
    - Commercial accelerator sold for isotope production
    - Batch mode sample or isotope production while producing RIB
    - Much improved reliability (effect on both n- and p-rich)
    - Much reduced power cost (~15% of ORIC)
    - Use existing target rooms – no major civil construction
- **Machine Specifications**
    - Multiple beam capability, variable E
    - 750 µA proton, variable up to 70 MeV
    - >50 µA deuteron, variable up to 35 MeV
    - ~50 µA alpha, fixed at 70 MeV

3.0 Technical Scope and Hardware Deliverables

A primary advantage of this upgrade project is that all of the proposed equipment can be accommodated within the existing HRIBF facility, with the possible exception of a suitable isotope production environment. Existing RIB production systems, IRIS1 and IRIS2, can accept beams from the new driver, and no modifications are required to the exiting 25 MV tandem post accelerator. The proposed upgraded facility will consist of the following primary deliverables:

- IBA Cyclone 70 (C70) turnkey cyclotron accelerator system.
- Light ion transport beamline from the C70 to the existing ORIC beamlines.
- Facility modifications within the existing HRIBF building to accommodate the C70
- Optional building addition to house isotope production facilities.

3.1 IBA Cyclone 70 (C70) Cyclotron Accelerator

Ion Beam Applications (IBA) is the only company that presently manufactures a turnkey commercial cyclotron operating in the energy range required for RIB production at HRIBF. Almost all commercial cyclotrons are designed for medical applications that utilize 10-30 MeV proton beams. The C70 (Figure 3.1) not only meets the baseline beam specifications, but also has many advantages in terms of implementation and long term operation. The C70 would be purchased as part of a turnkey system that includes design, manufacturing, installation, commissioning, training, and all pumps, power supplies, and controls. HRIBF would be responsible for providing the facility to house the IBA systems, and also ensure the availability of utilities (such as electrical power, air, water, etc.) to which the system will connect.

Figure 3.1: C70 under construction at the ARRONAX facility in Nantes, France (photo courtesy of IBA)

The C70 is a fixed magnetic field and fixed frequency machine that accelerates ions with a charge to mass ratio q/m=1 on harmonic mode h=2, as well as ions with q/m=1/2 on harmonic mode h=4. Correction coils on each of the magnet poles are used to isochronize the beam. Specifically, the C70 is capable of providing four beams as shown in Table 3.1, three of which are of use to the HRIBF RIB production process: protons, deuterons, and alpha particles.

ion	extraction	E_{min}	E_{max}	I_{max}
		MeV	MeV	μA
H^-	stripping	30	70	750
D^-	stripping	15	35	50
H_2^+	ESD	-	35	50
α	ESD	-	70	50

Table 3.1: C70 Beam Specifications (courtesy of IBA)

Proton and deuteron beams are produced from foil stripping extraction of H- and D- beams originating from a multi-cusp ion source and accelerated to the energies shown in Table 3.1. Foil stripped beams have the advantage of extremely high extraction efficiencies, and beams can be concurrently extracted from dual ports on opposite sides of the machine. This added benefit could be useful for isotope production without interruption of RIB production. Alpha beams originate from an Electron Cyclotron Resonance (ECR) ion source and are circulated as positive ions, then extracted by means of an electrostatic deflector (ESD). Both ion sources are permanently mounted on top of the machine so that beam is injected axially and bent onto the median plane with a spiral inflector (see Figure 3.2).

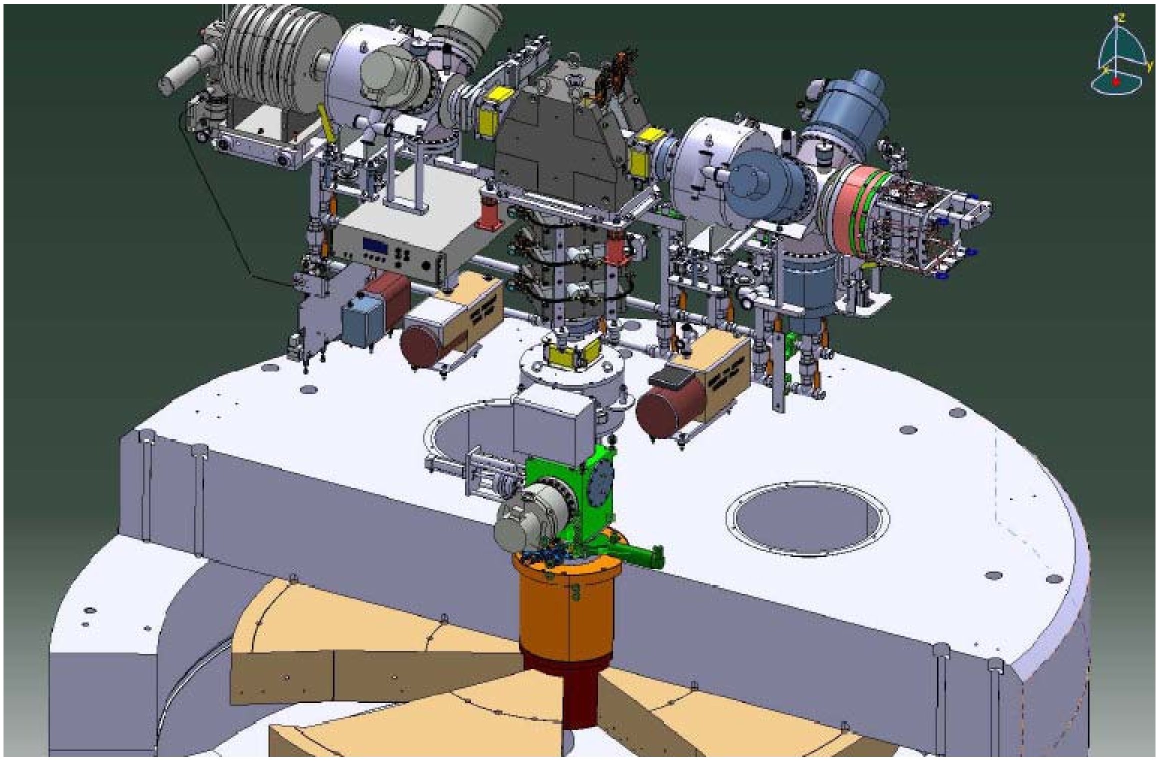

Figure 3.2: Axial injection system with ECR ion source (upper left) and multi-cusp ion source (upper right). (courtesy of IBA)

Overall, the C70 is much simpler to operate than ORIC, employing an rf system having a fixed frequency of 30MHz and a 100kW final stage amplifier. Main magnet coils for the machine's four pole magnet system require 80kW of power to produce a 1.5 Tesla field at the poles and 0.2 Tesla field in the valleys. Correction coils are utilized to isochronize the beam. This accelerator utilizes far fewer power supplies, drive mechanisms, and vacuum seals than ORIC which should lead to a much more reliable machine that is easier to maintain.

3.2 Implementation

The C70 accelerator would be designed, fabricated and assembled at IBA in Belgium. It would then be delivered to ORNL/HRIBF and installed in Building 6000 in an existing heavily shielded vault, room C110, which is adjacent to the ORIC vault, room C109 (see Figure 3.3). Room C110 has approximately 1,700 square feet of floor space, a ceiling height of almost 20 feet, and was originally configured as a target hall for up to three experimental end stations including the Broad Range Spectrograph (BRS). All walls and the ceiling are 7 feet thick, and are constructed from poured standard density concrete.

The BRS was decommissioned when HRIBF was formed from the Holifield Heavy Ion Research Facility (HHIRF) in the early 1990s, but the magnet structure remains and will need to be removed. In recent years, C110 has been utilized for handling and storage of activated target ion source assemblies associated with the IRIS1 (Injector for Radioactive Ion Species 1) production system. Room C110 has a slightly irregular shape, but is well-suited to accommodate the Cyclone 70 with limited modifications. A twelve foot diameter, three-foot deep pit associated with the BRS is situated near the middle of the room and can be partially utilized with the C70. Power supplies and control hardware would be located in a portion of the existing high bay outside of C110.

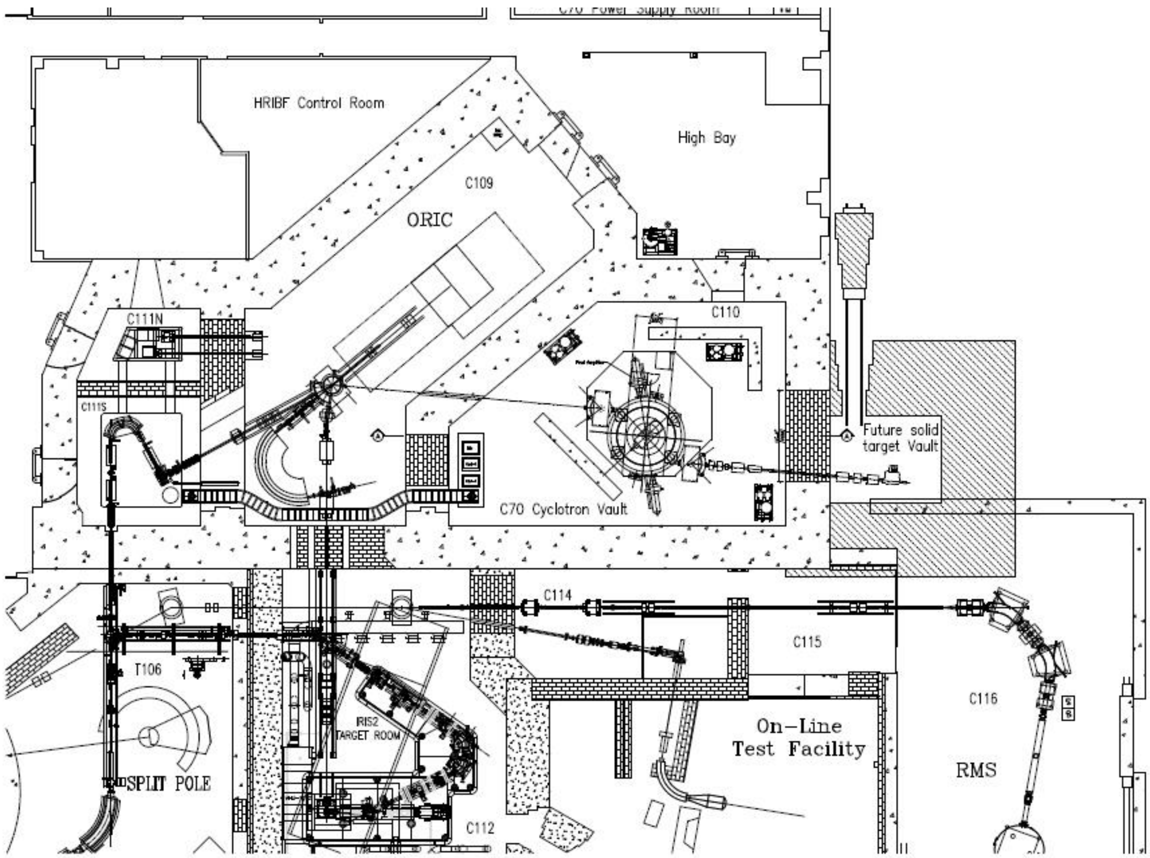

Figure 3.3: Conceptual plan view of C70 installation at HRIBF

Having an existing shielded vault to house the new accelerator is obviously extremely beneficial, but also presents some challenges. First, there is a single access to the room though a 5 foot wide by 7 foot high doorway that accommodates a shielding door. Thus the accelerator must be separable into components that are small enough to be brought into the room through this doorway, or else a temporary access must be cut through the existing 7 foot thick concrete shield wall, then re-poured after machine installation. At present, it is not known whether the existing doorway will be adequate. Secondly, cabling and utilities must be routed from the high bay into C110, normally accomplished within a deep (7 foot high by 6 foot wide pit) under the machine as shown in Figure 3.4. Creation of such a pit is clearly more difficult in an existing floor slab and under an existing shield wall.

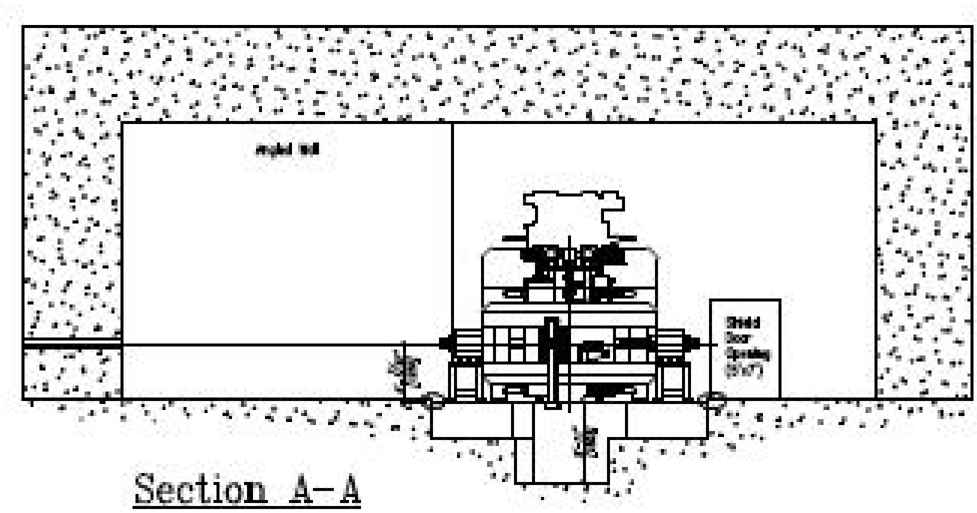

Figure 3.4: Elevation view of C70 installation

With some minor modifications to the shield wall between C110 and C109, the IRIS1 conveyor system, and the ORIC radiation safety system, it will be possible to install the C70 in room C110 while ORIC is operating, thus minimizing the impact of the project to facility operations and the RIB research program.

3.3 Light Ion Beam Transport Line

A light ion beam transport line approximately 50 feet in length will be required to transport beams from the C70 in room C110 to the existing ORIC beamlines in adjacent room C109. This beamline will be very conventional with non-superconducting beam optics components, standard vacuum components, and controls. Water-cooled beam stops or Faraday cups will be required to accommodate the high power beams. HRIBF technical staff members possess the experience to design this system, and it will be assembled by ORNL crafts. For the highest beam intensities, some localized shielding around the beam line will be required. The new beam line will intersect the existing ORIC beam lines at switching magnet BSM_1_1, located beneath the ORIC rf resonator.

For as long as it is feasible, we would maintain ORIC in an operable state so that it could serve as a backup driver.

3.4 HRIBF facility modifications to accommodate the C70

One of the most attractive aspects of this project is that no addition to the existing HRIBF building is required. As mentioned in section 3.2, a large, relatively unused, concrete-shielded vault is available adjacent to the one in which ORIC is located. The present use of the vault is for handling and storage of activated target/ion source assemblies, and for general waste storage prior to processing. Handling systems can remain in the room after the C70 becomes operational. This vault has approximately 1700 square feet of floor space, and a ceiling height of almost 20 feet, making it an ideal size to accommodate the C70. All walls and the ceiling consist of a seven foot thickness of standard density concrete. The general area floor slab is nine inches thick, and a 30" deep pit, approximately 20 feet in diameter, is located in the middle of the room. Beneath the pit is a 36" slab of concrete that was originally used to support the weight of the BRS magnet. A high density concrete, 5-foot-thick shield door provides a single 5-foot- wide by 7-foot- high access to the room. The high bay area adjacent to which the door opens appears to be adequate to accommodate the power supply and controls equipment required for the C70.

However, this does not mean that no facility modifications are needed. Based on an initial evaluation of the existing facility and discussions with IBA, several modifications have been identified. First, the existing BRS magnet must be disassembled and removed. Second, the doorway may not be large enough to facilitate installation of the accelerator. IBA documentation provided early in our discussions indicated that the C70 could be moved into the room in pieces through the existing doorway and assembled in situ. Presently, however, IBA prefers to assemble the machine outside of the facility and then move the entire unit into the vault through a larger opening, 15 feet wide by 11 feet high. The only way to accommodate this requirement would be to cut the required opening through the 7-foot-thick exterior wall at the east end of the vault. Rolling the 140-ton assembled C70 into the room is probably not possible due to the 9" slab thickness. Further, it appears that a new pit will need to be excavated and constructed within the room. This pit needs to be approximately 7 feet deep by 6 feet wide to contain utilities and provide access space for accelerator maintenance. Thus it is likely that the vault floor will need to be entirely replaced, involving excavation within the building. A 7-ton ceiling-mounted bridge crane will also be needed to accommodate installation and long-term maintenance. Finally, a few modifications will be required in the high bay. These include some trenching in the floor slab for utilities routing, extension of electrical power from existing switchgear, extension of compressed air piping, and delivery of both demineralized and process water to the area.
In addition, some modest upgrades of existing beam transport systems will be required. In particular, incremental shielding additions will be necessary to attain maximum performance, and high power beam diagnostics and beam dumps will be added.

3.5 Optional building addition to house isotope production facilities.

Although some isotope production may be possible within room C110, full utilization of the very large proton beam currents for isotope production would require the construction of an additional, small but heavily shielded vault similar to that shown in Figure 3.5. This additional civil construction is not part of this project.

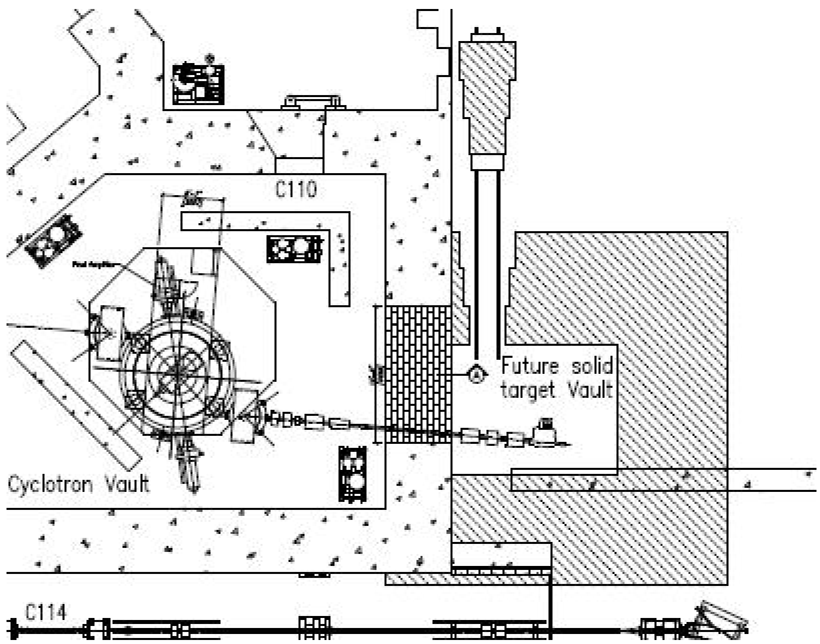

Figure 3.5: Optional isotope production vault at HRIBF

4.0 The C70 Cyclotron and RIB Production at HRIBF

This section explores how specific capabilities of the C70 can be utilized at HRIBF to produce RIBs. It is important to note that the C70 can make good use of the entire ISOL RIB production infrastructure developed at HRIBF over the last decade, particularly the new IRIS2 facility. HRIBF is at present the only facility in the world capable of providing beams of neutron-rich fission fragments post-accelerated to energies above the Coulomb barrier. The scientific program we foresee for HRIBF over the next decade (discussed in section 5) depends strongly on neutron-rich beams, and consequently improved neutron-rich beams are critical to any viable HRIBF upgrade plans. However, proton-rich beams are also important for studies relevant to nucleosynthesis in nova explosions and X-ray bursts, and for key nuclear structure measurements on nuclei with N~Z.

While the C70 may not be the optimum RIB driver accelerator, essentially all its basic features would enhance operations at HRIBF. These include very low operating and maintenance cost, capability for accelerating protons, deuterons and alpha particle (multispecies capability), higher proton energy than ORIC, capability for extracting two beams at different energies when accelerating protons or deuterons (multi-beam capability), very large proton beam currents (750 μA) and substantial deuteron beam currents. Later in this section we see how the high proton (and deuteron) beam current may be applied to produce neutron-rich species at intensities approaching the baseline performance of our electron driver upgrade, how the multispecies capability can maintain and enhance our ability to deliver proton-rich species, and how the multi-beam capability offers an extremely cost effective method for producing long lived species for later post-acceleration (batch mode beam production), for a variety of applications and science programs. This same multi-beam capability can be applied to production of isotopes for research and medical applications. Some aspects of this multifaceted capability will be treated in some detail.

4.1 Neutron-Rich Beams

The importance of neutron rich beams to the scientific goals of the nuclear physics program over the next decade is widely acknowledged. This led us to develop a concept for a facility based on a 25 MeV 100kW scale electron accelerator that was capable of delivering a baseline rate of 10^{13} photofissions per second, but had no proton-rich capability. This fission rate consists entirely of low-excitation energy "cold fission" and consequently, of low neutron emission multiplicity from the compound nucleus and the fission fragments. The yield of very neutron-rich fragments from photofission is strongly enhanced compared to proton induced fission. We will use this EDU performance baseline along with the performance of the present HRIBF facility to calibrate the neutron-rich potential of a C70-based HRIBF.

HRIBF currently produces neutron-rich beams with approximately 12 μA of 50 MeV protons directly incident on a uranium carbide target of density approximately 2 g/cm^3. The corresponding fission rate is ~8 x 10^{11} fs $^{-1}$ (fissions per second). The C70 is capable of delivering proton beams with energies up to 70 MeV and intensities up to 750 μA (52.5 kW). Development of a target capable of withstanding a 50kW beam of 70 MeV protons would be a major undertaking and a major achievement, however preliminary uranium carbide target designs have already been developed that should allow direct proton beam irradiation at currents in the range 30 to 50 μA. At 70 MeV and 50 μA (3.5 kW beam power, 2.5 kW deposited in target), the increase in total fission rate, and hence in RIB intensities, compared to our present rate with ORIC will be a factor of 8.3 or about 7 x 10^{12} f s $^{-1}$ (neglecting secondary reactions – see discussion in next paragraph). This is over half the baseline fission rate for our electron driver upgrade. ISOL targets capable of operating effectively with over 10 kW deposited in the target have been demonstrated. A power deposition of 10 kW in a well-designed uranium-based target for proton-induced fission at 70 MeV bombarding energy would correspond to a proton current of 200 μA (14 kW beam power). This beam current would result in a (p,f) fission rate of ~ 3 x 10^{13} fs^{-1}. A target capable of operating with 200μA of 70 MeV protons is beyond the present state of the art—but certainly not out of the question. In principle an additional 550 μA (total of 750 μA) of proton beam is available if target performance, shielding and beam transport could be upgraded sufficiently to take advantage of it. With minor modifications the current IRIS2 shielding is adequate for 200μA of 70 MeV protons.

These numbers might be interpreted to show that direct proton bombardment of uranium carbide with 70 MeV protons at such currents produces a facility superior to the 10^{13} f s^{-1} baseline of the electron driver upgrade. This is not the case. At equal fission rates a "cold fission" production method such as photofission would have higher yields for the most neutron rich species by factors much more than 100 compared to direct proton induced fission. However, the high-current capabilities offered by the C70 offer an alternative method of implementing a "cold fission" based production of neutron-rich species that compares favorably with the photofission driven facility. This involves secondary neutron induced fission as discussed below.

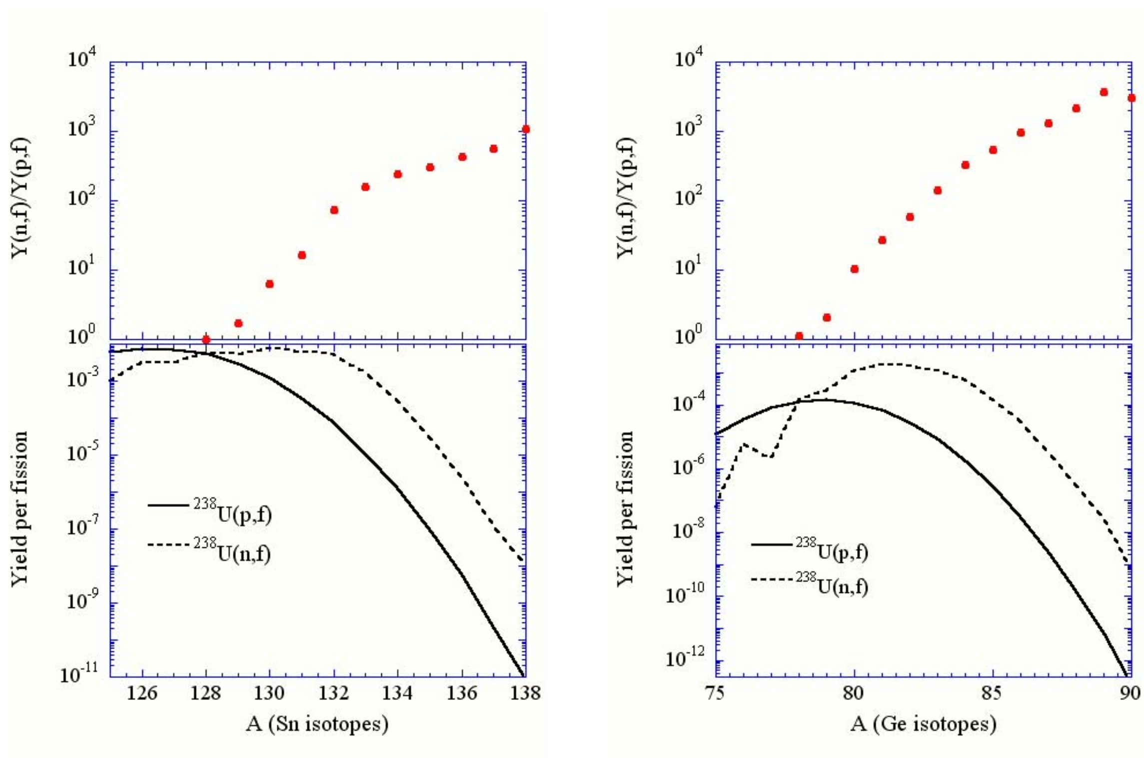

Figure 4.1 Comparison of yields of proton induced fission for 70 MeV protons (solid), and neutron induced fission for ~15 MeV neutrons (dashed) for Ge and Sn isotopes. The upper plots give the yield ratios. The rapid relative increase with increasing neutron excess is characteristic of the "cold" (n,f) fission process.

This is illustrated in figure 4.1 which shows the production rates of neutron rich Sn, and Ge nuclei per fission for proton induced fission at 70 MeV and secondary neutron induced fission for a neutron energy of about 15 MeV. Even with the impressive fission direct proton rates achieved with 50 μA of 70 MeV protons—or even the more speculative 200 μA rate, a secondary neutron (two-step) fission capability could offer advantages, since neutron production targets that can withstand the maximum beam power of the C70 are already available.

Both protons and deuterons can be used to produce secondary neutrons. Systematic information has been developed for targets of Li, Be and C [1, 2, 3, 4]. Heavier targets produce lower forward yields. In this work these systematic data are supplemented with Monte Carlo calculations using MCNPX [5]. Generally, deuteron beams have been chosen for neutron beam production; there are certainly advantages of this choice, but the large proton currents available with the C70 suggest that proton induced production be considered. The systematics of Lone et al. [1] allows us to estimate the relative zero degree yield per incident particle (n sr^{-1} s^{-1}) for p and d incident on Be with E_p = 70 MeV and E_d = 35 MeV. The result is Y_{dn} (0°)/Y_{pn} (0°) = 1.34. This modest advantage for the deuteron reaction would strongly favor proton induced production at a C70 based facility due to the much larger proton current. The biggest disadvantage of proton-based neutron beam production lies in the target. The deuteron breakup reaction behaves in a similar way on all light targets; the yield from d+C is only ~40% lower than that on d+Be, and has the advantage of using a much simpler target to deal with. Forward peaked neutron yield from protons is, however, much more target dependent. The total neutron yield in the angle range 0 – 15° is about equal for Li and Be targets, but is almost 4 times smaller for C targets. Needless to say Li and Be targets are much more difficult to deal with for safety and health reasons. We would consider production with both d+C and p+Be. It is not clear why there is such a large asymmetry between the maximum beam currents for protons and deuterons (factor of 15). We have been told to expect deuteron currents of at least 100 μA once a C70 actually commissioned.

Figures 4.2 and 4.3 show yields of the Ge and Sn isotopes, respectively, for the present HRIBF (12 μA 50 MeV protons), for a baseline C70 based direct proton fission facility (50 μA 70 MeV p), and rates for a secondary neutron induced fission produced by 100 μA of 35 MeV deuterons on C and 250 μA of 70 MeV protons on Be. The results presented here, particularly for neutron induced reactions, depend on the uranium carbide target geometry and density. If conditions are favorable there can be effects of additional fission induced by secondary neutrons produced in the target itself. This is especially true in proton-induced fission for which neutron multiplicities are large. (The total neutron multiplicity from ^{238}U(p,f) at 70 MeV is ν_n~10). The calculated ^{238}U(p,f) yields presented here are based on systematics of fission product cross sections compiled at ORNL by K. Tsukada and collaborators. These systematics are derived from thin target measurements and do not include the effect of secondary particles. Reactions due to secondary particles are best treated in Monte Carlo simulations so that details of target geometry can be included explicitly. For the 50 MeV p+U case, such calculations were made for targets similar to those now used at HRIBF (uranium carbide density 2 g/cm^3, diameter 1.7 cm, length 2 cm). The secondary contribution for this case is rather small and has not been included in the figure. For the 70 MeV 50 μA case targets were assumed to be made of 6 g/cm^3 uranium carbide, 4 cm in diameter and 1.2 cm long (7 g/cm^2). The light dashed curve shows the yield from direct p+U only. The heavy dashed curve includes additional yield at large neutron excess from in-target secondary neutron induced fission for the 50 μA 70 MeV p case. The 4 cm target diameter target is motivated by issues of power handling as well as secondary production. A large diameter target coupled with beam-rastering techniques would be critical design features of targets able to withstand 50μA proton beams, and eventually even higher beam currents.

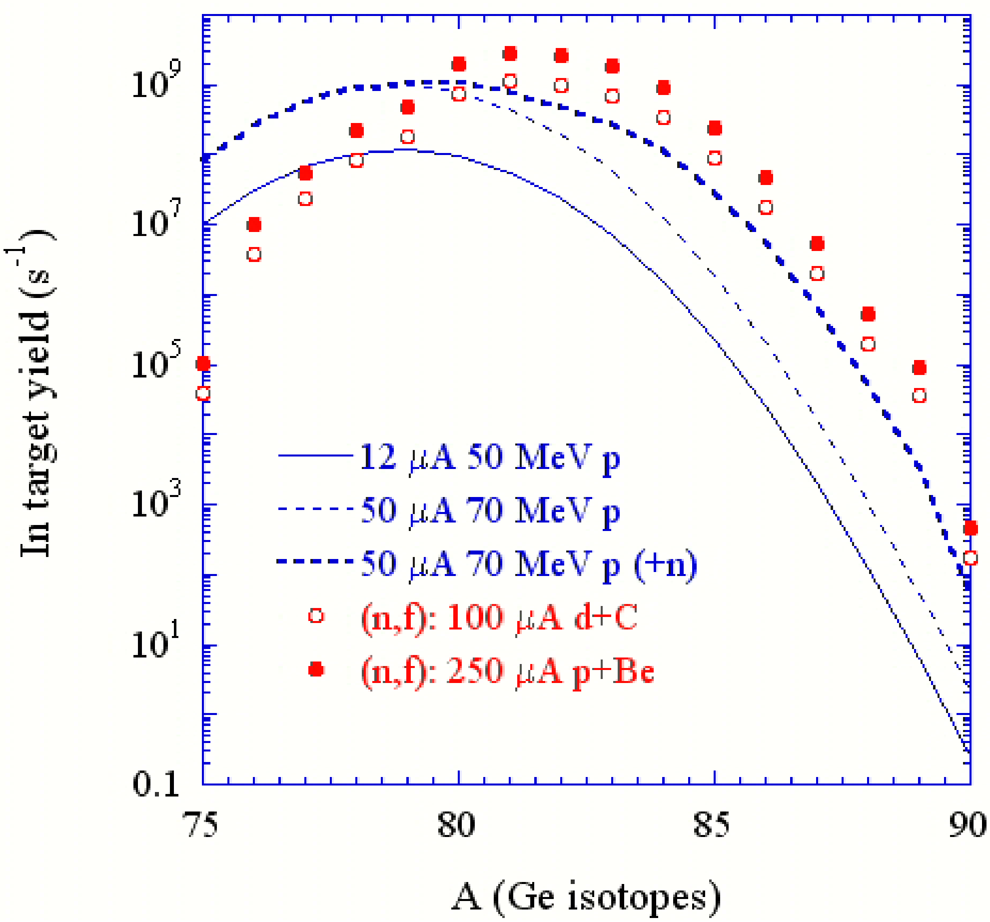

Figure 4.2 In-target yield of Ge fission fragments for several production methods. Two lines are shown for 70 MeV (p,f). The lighter dashed lines includes only the direct (p,f) process. The heavier line includes secondary fission induced by fission neutrons emitted following (p,f); the contribution of secondary fission is substantial because a large (4 cm X 1.2 cm), dense (6g/cm^3) target is used in the simulation. This effect is ignored for (p,f) at 50 MeV, where a 1.4 cm X 2 cm target made of 2 g/cm^3 uranium carbide is used.

The targets for secondary neutron induced fission from d+C and p+Be were also 6 g/cm^3 uranium carbide, with cylindrical geometry 4 cm in diameter and 6 cm long. The center of the neutron production target was assumed to be 3 cm from the front face of the uranium carbide target. (C thickness 2.0 cm, Be thickness 2.7 cm). Significantly larger fission yields can be achieved with larger or higher density uranium targets. SPIRAL2 plans to employ a 8 cm x 8 cm full density (11 g/cm^3) uranium carbide target. Such a large, dense target would produce a substantially larger in-target fission rate; however, we have chosen to limit our simulations to a more conservative format. Our investigation of full-density UC targets showed very poor release. However, we have demonstrated very favorable release characteristics of the 6 g/cm^3 pressed powder material, and the 4 cm x 6 cm size is not radically different from what has already been demonstrated to perform well. The total fission rates achieved with the 100 μA d + C secondary neutrons is 6 x 10^{11} fs^{-1} and 2.3 x 10^{12} fs^{-1} for 250 μA p + Be, or 6% and 23% of the electron driver upgrade cold fission rate baseline, respectively.

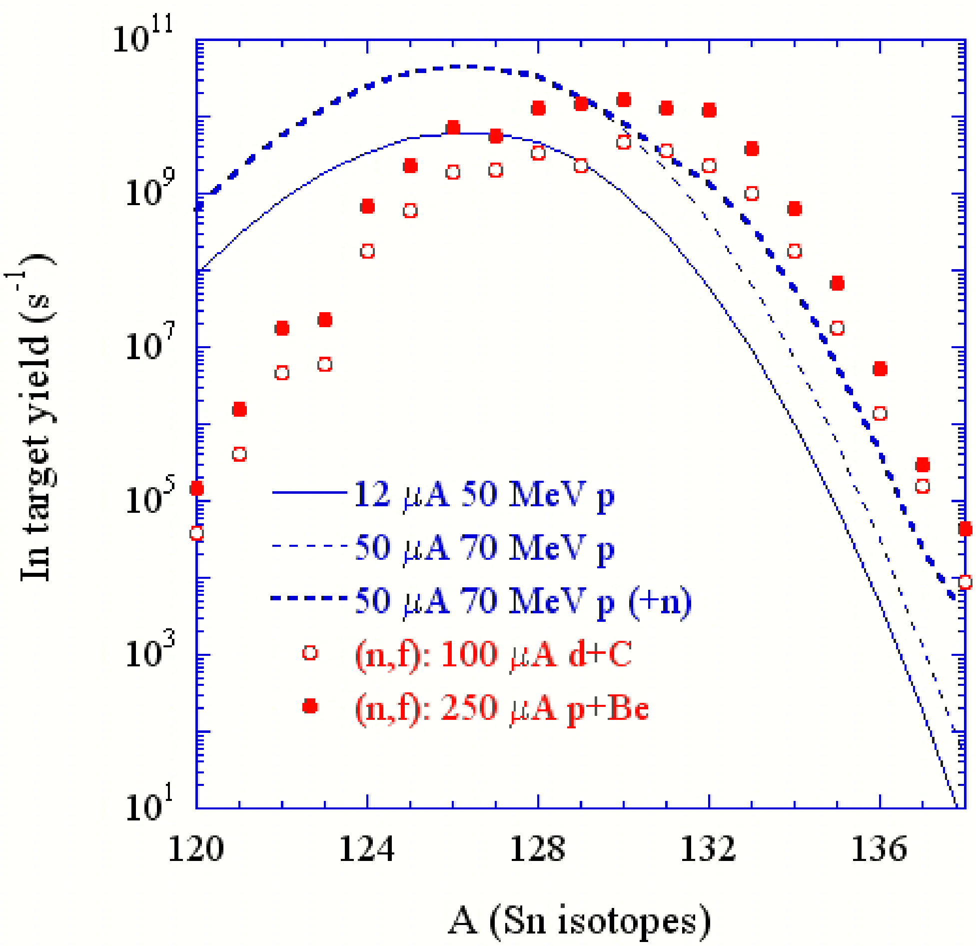

Figure 4.3 As for figure 4.2, but for Sn fission fragments.

The neutron production targets have not yet been developed, but such targets with much more ambitious power handling capabilities have been proposed (e.g. 200 kW deuterons on carbon at SPIRAL2). Operation of HDU would probably begin with direct proton-induced fission for neutron-rich beam production.
We should emphasize that the p + Be scenario discussed here employs only one third of the proton current capability of the C70. In principle, cold fission rates near the EDU baseline can be achieved with the C70. A total power of 52 kW (725 μA) on an aggressively cooled neutron production target would not be especially challenging, compared, for example, to plans for SPIRAL2. However, this could not be achieved without upgrades to HRIBF shielding and beam transport infrastructure.

The shielding at IRIS2 was designed to deal with proton currents in excess of 100 μA on uranium targets. With the additional movable "local shielding" that has already been added around the target ion source, plus additional shielding in the vicinity of the neutron production target, proton beam current in excess of 250 μA on Be or Li targets would be well within the limits of the ORNL shielding policy. Possible limitations on beam current imposed by beam transport from the cyclotron is discussed elsewhere. The performance achieved with 250 μA beams is already impressive; gradual upgrade of the secondary neutron facility to higher beam currents should be expected.

The beam currents that could be employed on IRIS1 are more limited. This would force an asymmetry in how the two beam production vaults can be used. The main limits of the older IRIS1 vault shielding compared to IRIS2 is the relatively thin wall between the bombardment room (C111S) and the instrument room (C111N). Shielding for areas occupied by staff is comparable. Consequently some care in scheduling would be required to limit integrated dose to instrumentation.

4.2 Batch-Mode and Proton-Rich Beams

The C70 was conceived and developed as a tool for efficient and cost effective production of radioisotopes for potential new applications in nuclear medicine. As such, it is immediately adaptable to the production of batch-mode beams for research in nuclear physics or other applications. For species with half-lives longer than a day or two, particularly if they can only be produced with small cross sections, traditional ISOL techniques are usually not the best solution. Instead, such species can be produced in cooled, high-density target materials using high-current production beams. They are then removed from the production environment, sometimes chemically purified, and mounted in an ion source for subsequent acceleration. This multi-step process is referred to at HRIBF as "batch mode" operation. Beams of ^{7}Be have been produced in this way for several experiments at HRIBF, but there is strong interest in several other appropriate nuclides. All the batch mode species we have used, or have near-term plans to use at HRIBF, were produced by accelerators elsewhere. ORIC is simply too expensive to be competitive as a batch-mode production tool, and it is in demand for ISOL RIB production. A C70 driver implementation is almost ideal for batch mode work. Since two beams at different energies can be extracted from the C70, batch mode production could continue simultaneously with ISOL RIB experiments. Furthermore, the very low power usage of the C70 means that in addition to the obvious convenience and delivery time advantages, local production would compare favorably in power cost to any commercial or research accelerator facility. Species likely to be of interest include ^{7}Be, ^{10}Be, ^{26}Al, ^{44}Ti, ^{56}Ni, and perhaps ^{59}Fe, plus others yet to be identified. Production pathways suitable for the C70 have already been identified for some of these, but others remain to be developed.

Science with proton-rich beams remains an important part of the research program at HRIBF. Some of our most important results have come from astrophysical studies relevant to nucleosynthesis in Novae and x-ray bursts with proton rich beams. However, it is important to realize that as a general rule ISOL facilities based on drivers with proton or ^{3}He beams with energies of at least several hundred MeV have a substantial advantage in production of proton-rich RIBs. This is because development of optimized ISOL target system is a time consuming process. Facilities with beam energies high enough to produce broad spallation yields from a target can produce many isotopes of interest from a single target system. At the ORIC-based HRIBF, we can produce no more than two or three interesting species from each target system. We must choose individual targets of opportunity and develop innovative technical solutions to be competitive on the proton-rich side of stability. The capabilities of the C70 will match very well with capabilities we have already built in to the IRIS2 production station, and it will enhance our efforts on proton-rich species in several ways. While the increase in maximum available proton energy in going from ORIC to the C70 is modest, it is large enough to open several more exit channels in (p,X) reactions, thereby expanding the reach of targets. The easy variability of proton and deuteron beams energies will also enhance performance by allowing optimization of reactions. The availability of deuteron beams is important. The large cross section (d,n) reaction can often be used for RIB production in cases where the (p,n) reaction is unfavorable. When the target nuclei and the beam species of interest have the same mass number, isobaric beam purity is generally a serious problem; use of the (d,n) reaction offers a good way to circumvent this. Finally the availability of reasonably high energy alpha particle beams is important. ORIC can produce alpha beams, but at low beam current (few μA). Also the ORIC ion source operates at relatively low duty factor when helium beams are produced, requiring an eight-hour pause for cathode replacement roughly every 40 hours. The availability of alphas broadens the number of reaction channels available to produce proton-rich species of particular interest, and increases the likelihood that an appropriate target material is available. IRIS2 was designed such that the driver beam can intersect a horizontally mounted target at an 8° angle. Such an angle of incidence aids the distribution of beam power over a large area of the target. It also facilitates the use of thin solid or liquid target layers. This feature of IRIS2 is potentially useful for all the C70 beams, but it is especially suited to alpha particle beams.

We expect the focus of our activities over the next decade to be primarily on the neutron-rich side of stability, since we believe that we can be competitive with the best facilities in the world in science with neutron-rich beams until the next generation U. S. facility is commissioned. However, HRIBF has also developed unique capabilities on the proton-rich side of stability. The C70 will allow us to continue to exploit these developments with higher yield and efficiency. It will also allow us continue our innovative development efforts on proton-rich beams, particularly those of interest to the astrophysics program, and nuclear structure studies for nuclei near N=Z. The exploration of C70 capabilities at IRIS2 and an enhanced IRIS1 will ensure that we continue to make important contributions to science with proton-rich beams.

4.3 Comparison with Other Facilities

A full and fair comparison of the eventual capabilities of facilities that are not yet completed is beyond the scope of this White Paper. We intend to add more comparative information later. For now we will offer comparison of the yields that will be available from the HDU at HRIBF compared to that of other ISOL facilities, with additional comments relevant to fragmentation-based facilities.

The ISAC facility at TRIUMF in Canada is the most powerful currently operating ISOL facility in the world. ISAC has not yet begun operation with actinide targets, so they do not yet have a heavy, neutron-rich (i.e. fission fragment) beam capability. However, ISAC has enormous potential for production of beams of proton-rich species. The ISAC driver beam (100 μA, 500 MeV protons) has an energy high enough to produce a wide range of spallation products from a relatively small set of target systems optimized for power handling. HRIBF, even with the HDU, cannot compete with ISAC in terms of the number of proton-rich species available. However, the C70 cyclotron provides enough beam current and flexibility that we expect to be able to broaden our suite of proton-rich beams considerably, and provide high quality beams of a limited number of species of particular importance to our research programs. ISAC has the potential to develop a formidable neutron-rich capability as well, however the HDU can compete very well with the expected TRIUMF capability, as illustrated in Figure 4.4. It should be noted that TRIUMF has recently submitted a proposal for a high-power electron-beam driven photofission facility to add additional neutron-rich capability.

When the SPIRAL2 facility at GANIL in France reaches its full design goals (it is expected to begin operation ~2014) it will be the world's most powerful ISOL facility for neutron-rich (fission fragment) beam production. The driver beam for fission fragment production at SPIRAL2 will be a linac capable of delivering 5 mA of 40 MeV deuterons to a carbon neutron-production target. The present goal is about $5x10^{13}$ fissions per second induced by ~20MeV neutrons. The distribution of fragments from these "cold" fissions will be essentially identical to those shown in figures 4.2 and 4.3 above. The ultimate capability of the C70-based, upgraded HRIBF could be within an order of magnitude of the ultimate SPIRAL2. At this level we would be able to mount a competitive program based on unique capabilities developed at HRIBF.

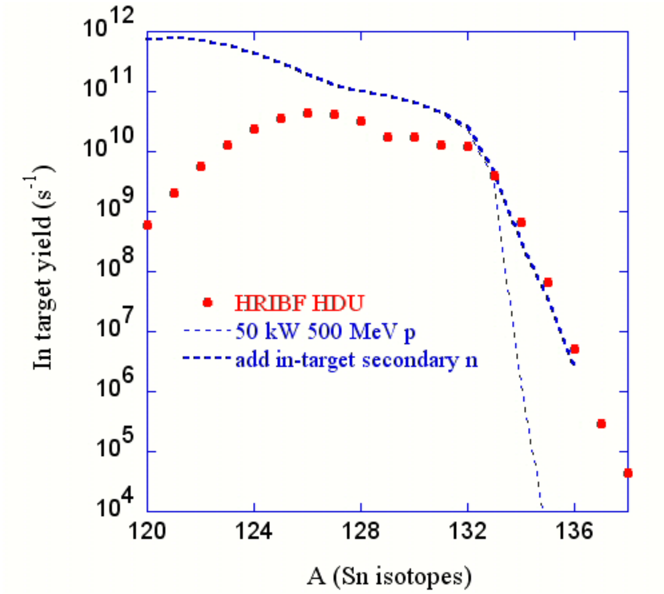

Figure 4.4 A comparison of Sn isotope yields from 500 MeV proton induced fission and the best yield from HRIBF upgrade from figure 4.3 (50 μA 70 MeV p or (n,f) with neutrons from 250 μA p+Be). The light dashed line corresponds to 500 MeV (p,f) with no secondary neutron effects. The heavy dashed line includes additional fission induced by fission neutrons in the UC target, assuming a 4 cm diameter target. The HDU at HRIBF is seen to be competitive with the 500 MeV p case (ISAC-II).

The ISOLDE facility at CERN has operated for many years and pioneered many of the techniques for ISOL beam production. The proposed HIE upgrade will provide more intense proton driver beams and a much improved post-acceleration capability. ISOLDE is based on a 1 GeV proton driver. Part of the HIE upgrade will extend the beam power available to ~10 kW. The facility will have a scientific reach on both sides of stability similar to that of ISAC II.

Comparison with fragmentation facilities is not straightforward. The complementarity between ISOL and fragmentation facilities is often stressed. As is well known, ISOL beam intensities have a strong element dependence. If we consider fission fragment beams from uranium fission, there are radioactive species of about 40 elements produced with appreciable yield. Of these, about 16 elements produce excellent ISOL beams (target/ion source efficiencies down for halflives down to ~50 ms), about 18 more elements can be classified as good ISOL beams (halflives of ~1s or more). Four of the 40 elements (Nb, Mo, Tc, Ru) have never been produced as ISOL beams and five others have been limited to species with halflives on the minute scale. Thus ISOL facilities are capable of delivering intense beams of a large fraction of the fission fragment species, including many in the vicinity of the ^{78}Ni and ^{132}Sn double shell closures. However for very short-lived species of species other than the best 18, fragmentation offers significant advantages. FRIB will provide reaccelerated beams of fragmentation products with halflives as short as ~10 ms.

References for Section 4.

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2. M.A. Lone et al., NIM 143(1977)331.
3. P. Grand and A.N. Goland, NIM 145(1977)49

4. S. Menard et al., Phys. Rev. ST Accel. Beams, 2 033501(1999).
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5.0 Science Case

The science case motivating the hadron driver upgrade at HRIBF (HDU) has been identified by the RISAC report on *"The Scientific Opportunities with a Rare-Isotope Facility in the US"* and by the 2007 NSAC Long-Range Plan "*The Frontiers of Nuclear Science."* Both documents put strong emphasis on the neutron-rich side of stability. The HDU at HRIBF has great potential for production of fission-fragment (neutron-rich) beams. By directly producing fission by proton bombardment of uranium, the HDU can potentially achieve yields well in excess of 10^{13} fission per second. However, better yields of very neutron-rich species are achieved (see figure 4.1) if the primary HDU beams are used to produce comparatively low energy neutrons, which are then used to induce "cold fission". These cold fission yields should approach 10^{13} fissions/second. The HDU described in this white paper, coupled with the existing ISOL infrastructure at HRIBF, will produce world-competitive n-rich beams of fission fragments that will be used for research in nuclear structure, nuclear astrophysics, and applications. The HDU at HRIBF will also have substantial capability for producing proton-rich and batch mode beams. These would be niche beams, directed at addressing issues of particular interest at the time.

Figure 5.1 schematically indicates some benchmark examples of science enabled by HDU. The major research thrusts of the proposed facility on the neutron-rich side of stability are outlined in the following. Mention of some of the general areas that may be addressed with proton-rich beams is also included.

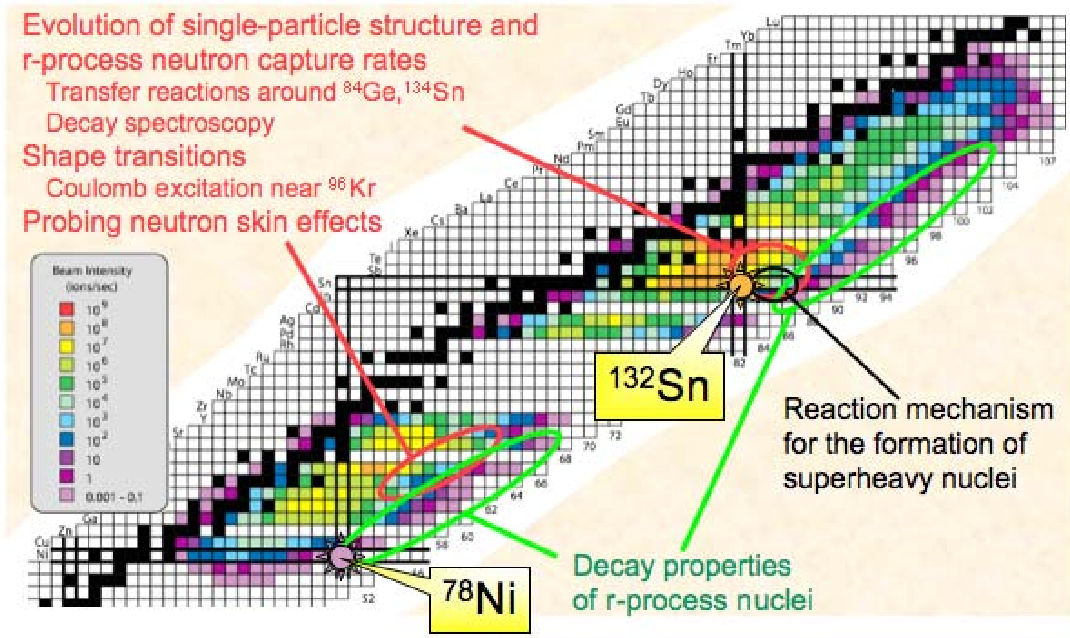

Figure 5.1: Part of the chart of the nuclides indicating beam intensities and science programs at HRIBF with HDU.

5.1 Exploring the limits of nuclear existence and identifying new phenomena, with the possibility that a more broadly applicable theory of nuclei will emerge

One important goal of HDU is to study and explain *the shell structure of new neutron-rich doubly magic nuclei*. Such nuclei are particularly simple probes of the effective inter-nucleon interaction used in the configuration interaction approaches and the energy density functionals of the nuclear density functional theory. In this context, particularly interesting are the short-lived doubly magic neutron-rich nuclei in the vicinity of ^{78}Ni and ^{132}Sn. With beams from the upgraded facility, studies of their single-particle structure will be carried out through nucleon transfer reactions. The lifetime measurements of single-particle states will be carried out using the plunger (RDM) technique by combining a plunger with the heavy-ion transfer (particularly effective for high-*j* states) and in decay spectroscopy employing an array of fast scintillators. Shell structure will also be probed by studies of magnetic moments, by extending the currently employed transient field method and a new β-NMR setup. With the latter technique, magnetic moments of very neutron rich nuclei, such as ^{87}Ge and ^{135}Sn, will be measured.

Through Coulomb excitation measurements and other techniques, HRIBF with the HDU will study and explain *the evolution of collective motion in complex neutron-rich nuclei*. Here, the key question that will be addressed is the consequence of the neutron excess on isovector and isoscalar collective modes, and on static deformations. Of particular interest are modifications of pairing in neutron rich nuclei, which are expected to produce deviations from systematics, and shape coexistence phenomena and the associated shape-transitional behavior, especially in regions of spherical-to-deformed shape transitions around ^{96}Kr and ^{112}Zr. The HDU will allow Coulomb excitation studies out to an extra 4-6 neutrons beyond the current reach of HRIBF, especially if GRETINA is available, opening up not only the *B(E2)* measurements but also the magnetic moments of collective nuclear states.

5.2 Investigating new forms of nuclear matter such as the large neutron excesses occurring in nuclei near the neutron drip line, thus offering the only laboratory access to matter made essentially of pure neutrons

Nuclei with large neutron excesses are known to exhibit distinctive properties, such as the extended neutron densities. For neutron-rich nuclei, such as ^{132}Sn, neutron skin, defined in terms of a difference between radii of neutron and proton distributions, can be around 0.3 fm. One expects to find new collective modes that are a consequence of neutron skin. One of these, a low-energy isovector vibrational mode, could alter neutron capture cross sections important to r-process nucleosynthesis. The information about *E1* polarizability, directly correlated with the neutron skin, can be obtained from studies of electromagnetic strength as a function of energy. After the upgrade, HRIBF will have capabilities to reach very neutron rich nuclei above ^{78}Ni, where the presence of the neutron $3s_{1/2}$ orbital can create unique conditions to study an extended neutron halo in excited states of heavy nuclei.

5.3 Synthesis of the super-heavy elements that are expected to exhibit unusual stability in spite of huge electrostatic repulsion

The mechanisms by which super-heavy nuclei can be produced in the laboratory have not been thoroughly explored. Intense beams of neutron-rich nuclei will complement studies of the heaviest nuclei with stable beams. In fusion reactions studies with the C70 driver at HRIBF, high-intensity high-quality beams of ^{132}Sn (~10^9 ions/s) and ^{134}Sn (~10^6 ions/s) will be used to learn about the reaction mechanism. The applicability of using medium-mass, neutron-rich ions, such as ^{92,94}Sr (~ 10^{6-7} ions/sec) will also be investigated.

5.4 Offering new glimpses into the origin of the elements, which are mostly produced in processes very far from nuclear stability

Neutron-rich nuclei play an important role in the astrophysical rapid neutron-capture process (r-process). At HRIBF, a program of (d,p) transfer reactions on nuclei in and near the r-process path near the N=50 and N=82 closed shells has given the first glimpse of the evolution of single particle strength of low-lying levels as a function of neutron number. Beam intensity, however, limits our ability to measure these strengths systematically. HDU at HRIBF will increase the available intensity of many of these nuclei by factors of 100 to 10000, enabling us to push our measurements from four to six isotopes farther from stability. Furthermore, it will enable the measurement of (d,pγ) coincidence measurements on some of these nuclei. This will be invaluable in probing levels of higher excitation energy closer to the neutron threshold - which have lower energy protons that, in singles mode, are extremely difficult to differentiate from detector noise. Such coincidence measurements will significantly constrain models of the structure of these nuclei.

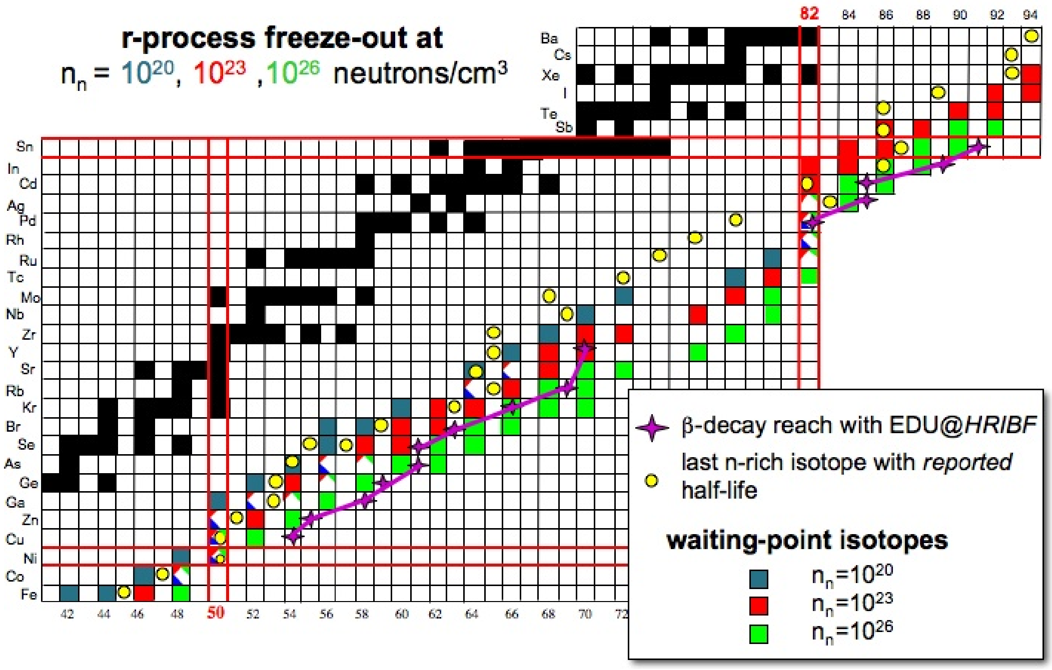

Figure 5.2: Studies of astrophysical r-process at HRIBF after HDU. The beta decay reach refers to an ion rate of about 0.1 pps at the detector station after mass separation. The last neutron-rich isotopes with reported half-lives (as of May 2008) are marked. The r-process network calculations were taken from *Phys. Rev. C67, 055802 (2003) (courtesy of K.L-Kratz).*

The intense beams of neutron-rich nuclei available at HRIBF after the HDU is implemented will also enable decay spectroscopy studies of nuclei in and near the r-process path. The program of measurements includes half-lives, important branchings for β-delayed neutron emission, and energies of excited states fed in the beta decay. Such experiments at HRIBF's Low-energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS), will have a potential to discover and study several new neutron-rich isotopes in the regions critical for the understanding of the r-process at low and high neutron fluxes (see Fig. 2). Collectively, these studies will greatly improve the nuclear physics foundation of astrophysical models of the synthesis of heavy nuclei via the r-process nuclei in supernovae.

Another area of emphasis will be nova explosions and X-ray bursts. Reactions on proton-rich unstable nuclei (the Hot CNO cycle and the rp-process) ignite and power these energetic stellar outbursts, which are the focus of space-based observatories such as INTEGRAL (gamma rays from novae) and CHANDRA (X-rays from X-ray bursts). Nova explosions, occurring on the surface of white dwarf stars, are responsible for the production of nuclei such as ^{13}C, ^{15}N, and ^{17}O that may be difficult to produce in other astrophysical environments. Current nova models have difficulty explaining the amount of ejected material (to within a factor of 10), as well as the composition of the ejecta and the peak luminosity. X-ray bursts, occurring on the surface of neutron stars, which light up the sky in X-rays, may be responsible for the production of the light p-nuclides (^{92}Mo, ^{96}Ru). The ashes of the explosion also alter the structure and evolution of the underlying neutron star. There are also long duration (~hour) explosions called superbursts that are very sensitive to the composition of the ashes of previous bursts. Milestones for these studies include measurements of properties of and reactions on selected proton-rich nuclei in the rp-process to determine radionuclide production in novae and the light outpu in X-ray bursts; and reduction if uncertainties of other reactions (e.g., MgAl cycle)**.**

The HDU at HRIBF will produce beams of proton-rich unstable nuclei with intensities suitable, in some cases, for direct measurement of the astrophysical reaction of interest, and in many more cases suitable for indirect determinations of nova and X-ray burst reaction rates. The nuclear astrophysics group at HRIBF has a distinguished history of important measurements using ^{17,18}F beams to study the ^{14}O(α,*p*)^{17}F, ^{17}F(*p*,γ)^{18}Ne, and ^{18}F(*p*,α)^{15}O. Reactions. A well optimized suite of experimental tools for these studies is available, under development, or in various planning stages. The HDU at HRIBF will facilitate development of new proton-rich beams that can be employed in these studies, including ^{33,34}Cl, ^{25,26}Al, ^{30}P and others.

5.5 Applications of rare isotopes

> Applications from stockpile stewardship, materials science, medical research, and nuclear reactors have long relied on a wide variety of radioisotopes. In the case of stockpile stewardship, the complex nuclear reaction networks needed for understanding device performance would be greatly clarified. (RISAC report)

In general, the cross sections needed for stockpile stewardship issues involve processes such as (n,γ), (n,n'), and (n,2n) on the ground, excited and isomeric states of stable and radioactive isotopes. With the HDU at HRIBF, we will continue a program of neutron transfer measurements (with surrogate reactions) for neutron-rich nuclei relevant to the science-based stockpile stewardship. The *Q*-value resolution of (d,p) reactions in inverse kinematics, studied at HRIBF, is limited by the kinematic conditions. However, it is possible to measure the excitation levels of excited states populated in the reaction, as well as others in the subsequent cascade, using the emitted gamma rays. Gamma-ray cascades also give information on the spin-parities of the states, thus yielding important nuclear structure information. Tagging on the gamma rays can help to clarify the proton spectra and reduce background. We envision a program of (d, pγ) studies at HRIBF, as tested by a recent ^{2}H(^{75}As,pγ) experiment.

The HDU at HRIBF will provide reliable and accurate data on the decay properties of nuclei created during the operation of nuclear reactors, including the isotopes occurring in a new generation of power reactors and nuclear fuels. The energy released during the neutron-induced fission of nuclear fuels is used for energy production in power reactors. The process of β-delayed neutron emission from fission products contributes to the total number of neutrons inducing fission in nuclear fuel. The uncertainties in beta-delayed neutron data may result in undesirable (i.e. expensive) conservatism in the design and operation of nuclear reactor control systems. Therefore, reliable and accurate data on the individual βn-precursors produced in nuclear fuels are needed. In particular, new trends in reactor technologies (Advanced Fuel Cycle, Hybrid Accelerator-Reactor systems) are requiring verification of the available data as well as new measurements. Among other important parameters for modeling the processes inside the reactors are β half-lives of fission products and their daughter activities and the total decay heat released.

Post-accelerated beams of relatively long-lived species (batch-mode beams) have found several applications in industry. An obvious example is the use of ^{7}Be in wear studies. An important specific application, already being pursued at HRIBF, is wear in artificial joints. The HDU at HRIBF has characteristics that make it particularly valuable for facilitating such studies, and for adapting rapidly to new or perceived needs. The same unique characteristics of the C70 cyclotron on which the HDU is based make it particularly well suited for targeted production of radioisotopes for medical applications, or acting as a source for new radioisotopes being evaluated for possible use. This is discussed further in a separate section.

5.6 Summary

The scientific program with the proposed hadron driver upgrade at HRIBF will be fully aligned with the science envisioned in the RISAC report, the community vision expressed in the NSAC Long Range plan report, and the RIA/FRIB documents. The program of systematic measurements with intense neutron-rich beams allowed by the HDU will support the DOE performance measure milestones in nuclear structure and nuclear astrophysics. Also, as shown in Fig. 5.3, the neutron-rich capability of HRIBF with a HDU will contribute to 7 of 12 benchmark science examples taken from the RIA Brochure and to 9 of 17 examples from the Report to NSAC of the Rare-Isotope Beam Task Force. **The proposed facility, employing intense neutron-rich beams of fission fragments, would be competitive world-wide for neutron-rich beams until FRIB-scale facilities are available.** The facility would also have significant proton-rich capability, though this would be less general and more niche-oriented than the neutron-rich capability. The enhanced proton-rich capability would allow us to contribute to at least two additional elements (4. and 16.) of the list in figure 5.3.

	Example:	200 MeV +ISOL	200 MeV	150 MeV	100 MeV
✓	1. Shell Structure	X	X	X	X
✓	2. Superheavies	X	X	X	X
✓	3. Skins	X	X	X	X
	4. Pairing	X	X	X	
✓	5. Symmetries	X	X		
	6. EOS	X	X	X	
✓	7. r-process	X	X		
	8. $^{15}O(\alpha,\gamma)$	X	X	X	X
	9. ^{59}Fe	X	X	X	
✓	10. Medical	X	X	X	
✓	11. Stewardship	X	X	X	
	12. Dipole Moment	X			
	13. Limits of Stability	X	X	X	
✓	14. Weakly bound	X	X	X	
✓	15. Mass Surface	X	X	X	
	16. rp-process	X	X	X	X
	17. Weak interactions	X	X		

Figure 5.3: Examples of various experimental programs at FRIB (from the RIA Brochure and the Report to NSAC of the Rare-Isotope Beam Task Force (2007). HRIBF with the proposed hadron driver upgrade will contribute primarily to the checked areas.

6.0 Potential for Radioisotope Production

The principle application that motivated the development of the C70 cyclotron is isotope production. It is specifically designed with the high electrical efficiency, reliability, simplicity, and ease of maintenance that are critical for this implementation. But it is also designed to provide higher energy beams than most medical isotope production cyclotrons which are used almost exclusively for ^{18} F production. The C70 is intended for a much broader application to isotope production. The first implementation of a C70 will be at the ARRONAX facility in Nantes, France where its isotope production capabilities will be directed at production of “new” diagnostic and treatment isotopes which are currently of great interest to the medical research community. The initial set of isotopes that will be provided by ARRONAX include both a set of isotopes for potential PET imaging applications and isotopes for radionuclide therapy. The potential PET isotopes include ^{124}I, ^{64}Cu, ^{82}Rb, and ^{68}Ga. ^{82}Rb ($T_{1/2}$=75 s) and ^{68}Ga ($T_{1/2}$=68 m) are produced in a generator. The parent isotopes are the relatively long lived ^{68}Ge and ^{82}Sr. The isotopes which will be supplied for radionuclide therapy by the C70 at ARRONAX include ^{67}Cu and ^{211}At.

A C70 installed at HRIBF would have the primary mission to provide radioactive beams for nuclear research. As we have discussed in section 4, production of long-lived isotopes for batch-mode operation at HRIBF is made especially attractive and efficient by the dual port extraction capability of the C70. Batch-mode isotope production is essentially identical operationally to production of isotopes for applications other than post acceleration. Obviously, production of isotopes for medical or other applied research areas could be a part of the mission of the HDU at HRIBF and could be accommodated in an almost completely parasitic mode provided a new heavily shielded production vault with facilities appropriate for isotope production were added to the facility. The cost of this additional vault is not included in the cost estimates given in Section 7.

The possible application of the HDU to isotope production is a very broad subject which would distort the purpose of this White Paper if we attempted to do it justice here. As a final comment, it will be noted that the C70 is a device extremely well suited to production of isotopes that will be in demand over the next decades. It could be used in this way in a parasitic mode while the HRIBF is operating as a RIB facility, and it could remain useful as a full-time isotope production facility after HRIBF has ceased RIB operation.

7.0 Cost, Schedule, and Effort

7.1 Project Cost

Procurement of the C70 turnkey system is overwhelmingly the largest component of the Total Project Cost (TPC). At this stage, IBA has provided a "ballpark" cost estimate of 12M Euro for a system that includes a C70 with proton, deuteron, and alpha capability. Based on initial discussion with IBA, there is some reason to believe that the final cost may be lower, but more detailed discussion is required. Although IBA will be able to provide a very firm quotation in Euro, the cost in U.S. dollars depends on the currency exchange rate at the time of award of the contract. The exchange rate multiplier is 1.35 in the project cost table below (Table 7.1), but it has been as high as 1.59 in recent months. Thus a 30% contingency is shown to account for a significant potential increase in exchange rate. If the contract can be awarded at the current rate or lower, the TPC could be reduced by some $5M. Cost of the light ion transport beamline is based on recent experience with construction of similar beamlines for both the HPTL and IRIS2 projects, and is approximately $20k per linear foot including installation. Structural and utilities effort is estimated based on initial requirements presented by IBA, but a more detailed engineering study is required. Overall project contingency is around 26%. With the exception of the exchange rate, other costs are reasonably well understood based on recent prior experience. Some redirect of facility base capital and AIP may be possible to help to reduce the amount of new funds required for this $31M project.

Table 7.1: Project Cost

Component	Cost w/ tax/OH	Contingency%	Total
Cyclone 70 Turnkey System (IBA quote)	$17,538,000	30	$22,799,400
Light Ion Transport Beamline (50 ft)	$1,096,000	20	$1,315,200
Bridge Crane	$22,800	20	$27,360
Structural modifications	$1,800,000	25	$2,250,000
Utilities reconfiguration	$500,000	25	$625,000
Construction Subtotal	**$20,956,800**		**$27,016,960**
CDR (3%)	$629,000	12	$704,480
PED	$750,000	12	$840,000
Project Manager (Mgmt B) (5yrs @$318k/yr x 50% effort)	$795,000	12	$890,400
Engineering (S&T C) (2ea x 3yrs @$332k/yr x 50% effort)	$996,000	12	$1,115,520
Technician (Tech) (1ea x 3 yrs @ $218k/yr x 50% effort)	$327,000	12	$366,240
PreOps	$300,000	12	$336,000
TPC	$24,753,800		$31,269,600
Contingency			26.32%
exchange rate 1.35 at time of estimate			

7.2 Project Schedule

An approximate project schedule is shown below:

Year 1: Development of Conceptual Design Report (CDR)
Year 2: Preliminary Engineering Design (PED)
Year 3: Construction including C70 procurement/fabrication and facility modifications
Year 4: Construction including C70 fabrication and ORIC beam line construction
Year 5: Construction including C70 fabrication, installation, and commissioning
Year 6: Preops

IBA quotes 24 months from receipt of order to delivery at ORNL, followed by 6 months for installation and commissioning. It is expected that installation and commissioning activities can largely be completed in parallel with ORIC operation. To accomplish this, shield wall openings that currently exist between room C110 and room C109 will need to be temporarily filled with shielding material and the room disconnected from the ORIC Radiation Safety System.

7.3 Project Effort

One of the key attributes of this project is the relatively minimal impact on HRIBF staff due to outsourcing of the accelerator. IBA would be responsible for all aspects of design, fabrication, shipping, installation at ORNL, and commissioning though a single procurement of this turnkey system. ORNL will hire a professional project manager from outside the Physics Division to handle budget, schedule and reporting issues. Physics Division development staff would be responsible for the design of the transport beamline, and installation of the beamline would be accomplished with ORNL crafts. Physics Division staff effort for implementation of this project would be comparable to that required for the recent HPTL and IRIS2 projects including part-time mechanical and electrical engineer services amounting to 3 FTE years, and a technician half time for 3 years to support installation activities. Facility modifications necessary to accommodate the C70, described in section 3.4, would be completed by a combination of ORNL crafts and subcontractors. Examples of facility modifications include the addition of localized radiation shielding, relocation of utilities, penetrations for utilities and machine installation, and configuration of the power supply/controls area.

This project is extremely well-suited to the HRIBF staff that has more than a decade of experience operating and developing a RIB facility. Multiple staff members also have decades of expertise in operation and development of cyclotrons and design of associated beam lines.

7.4 Incremental Operating Cost and Effort

Long-term operation and maintenance of the C70 will differ greatly from that of ORIC. Whereas ORIC requires extensive local craft support, ORNL would contract with IBA for maintenance services for the C70 on an annual basis for around $200k per year. Response time is typically 24 to 48 hours. Routine tasks now handled by HRIBF operations staff such as ion source maintenance would be significantly reduced because of the external ion sources with axial injection. Machine startup and complexity of beam tuning will also be greatly reduced due to the C70 being more modern and much simpler than ORIC, in particular there are fewer magnet coils and a fixed frequency rf system. Archive and restoration of machine settings will greatly facilitate rapid startup. IBA indicates that machine startup time from standby is approximately 30 minutes which is considerably more efficient than ORIC which typically has a startup time ranging from 4-8 hours.

IBA recommends maintaining a local spare parts inventory of crucial and long lead-time items totaling $200k-$300k. These components would be procured over time from operating funds. In addition, IBA maintains an inventory of many spare parts which would be obtainable on an as-needed basis, but with a few days or weeks delay for delivery from Belgium. The C70 utilizes far fewer parts and power supplies than ORIC which has a minimum spare parts inventory of around $500k.

Power requirements for the C70 are approximately 350kW for a 70MeV, 500uA proton beam as compared to 2MW for a 50MeV, 50uA proton beam from ORIC. Projections are for ORIC operation to operate 4000 hours per year with two RIB production systems (IRIS1 and IRIS2) and 7-day operation. Power costs are presently $120/MW-hr. Thus in the 4000 hour mode, the power cost of operating the C70 is $168k compared to $960k for ORIC, resulting in an annual savings of $792k.

No staffing increase will be required beyond current projections due to the addition of the C70. The same number of operators and technicians will be required for the facility, and IBA maintenance contract will result in the reduction of craft effort by approximately 1.5 FTE per year, or $245k.

In summary, we expect an annual operating cost reduction of around $850k for 4000 hours of operation of the C70 as compared to ORIC. The comparatively low operating costs result from simplicity, electrical efficiency, and the turnkey commercial nature of the machine.