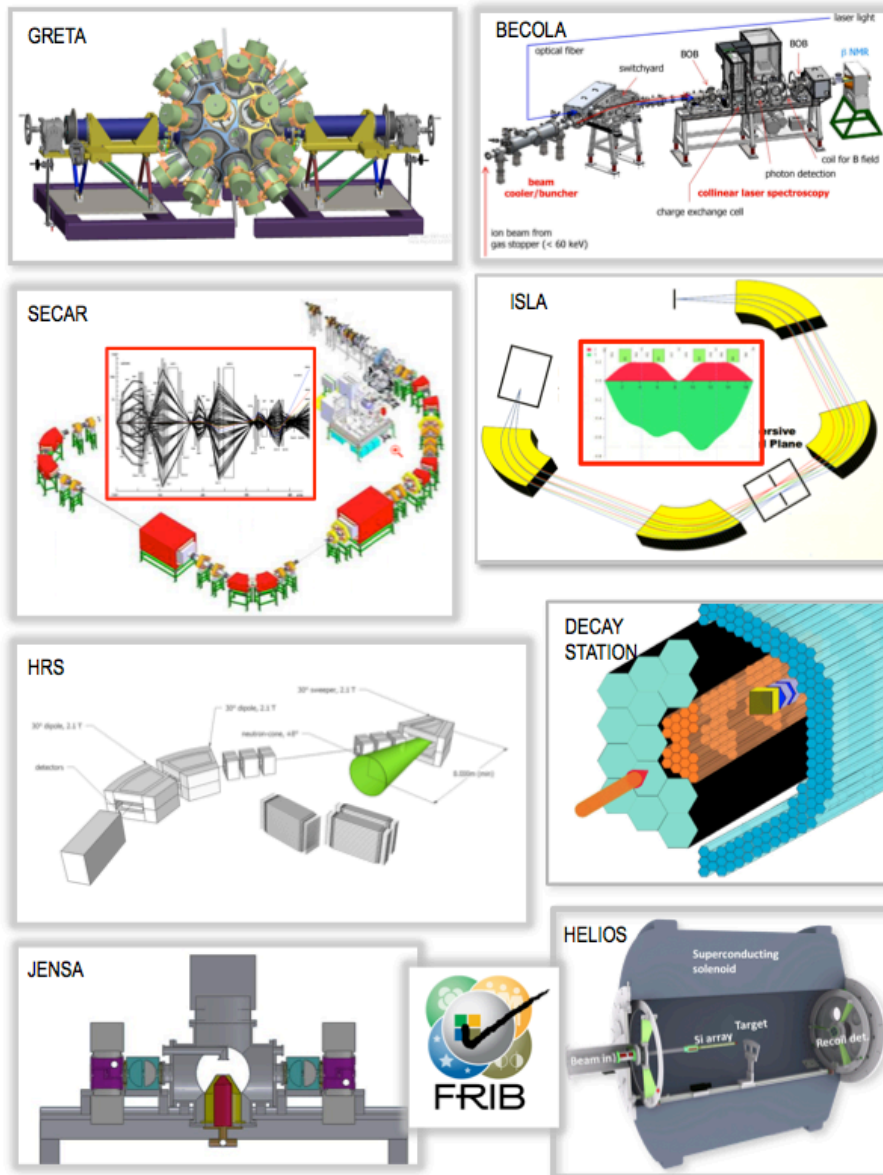


# Experimental Equipment Needs for The Facility for Rare Isotope Beams (FRIB)



Prepared for the APS DNP Low Energy Town Meeting  
February 13, 2015

**Abstract:** This document presents a list of the major experimental systems needed to carry out a robust scientific program at the Facility for Rare Isotope Beams (FRIB). Input for the list was obtained from the Working Groups and Executive Committee of the FRIB User Organization, FRIB management, and other members of the Low Energy Nuclear Science community.

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## 1. Overview

Science at the Facility for Rare Isotope Beams (FRIB) will cover a wide range of topics at the forefront of nuclear science. These include probing the limits of nuclear stability, improving our understanding of the force binding nucleons together into nuclei, measuring the reactions that cause some stars to explode, constraining the properties of dense nuclear matter, exploring the evolution of nuclear shell structure off stability, providing an empirical foundation for advanced nuclear models, discovering new isotopes for medical and security applications, and much more. The beams produced at FRIB for studies of these, and other, fascinating issues in nuclear science will be world leading in terms of intensity and variety of species. The discovery potential of FRIB is significant, since its coverage of 80% of all nuclei predicted to exist with atomic number less than 82 represents a substantial expansion of the nuclear chart available for study. World-class experimental devices are required to realize the discovery potential of the unique exotic beams anticipated from FRIB. There are numerous superb detector systems available at NSCL, and FRIB will make full use of these. However, some key capabilities are missing, and three of the experimental halls (ReA3, ReA12, and the High Energy High Bay) are new and need to be instrumented. This document presents a list of the major new experimental systems needed to capitalize on FRIB beams, as envisioned by Working Groups of the FRIB User Organization. This section describes the facility, the User Organization, a summary list of Major Equipment needs, and the mechanism we used to generate it. Details of the systems are given in Section 2.

### 1.1. Facility for Rare Isotope Beams

The Facility for Rare Isotope Beams (FRIB) will be the premiere low energy nuclear science facility in the world when it becomes operational in 2022. Currently under construction on the campus of Michigan State University, FRIB will utilize two different techniques to produce thousands of exotic nuclei over a wide range of energies. Short-lived, high-energy beams will be produced by a fast fragmentation approach, while a subsequent gas stopping and reacceleration approach will be used to produce low- to medium-energy beams with superlative characteristics. FRIB is the highest priority for new construction in the nuclear science community, and has endorsements from the NSAC Long Range Plan, the RISAC task force, and numerous other review panels and reports.

### 1.2. FRIB User Organization

With over 1350 members, the FRIB User Organization ([fribusers.org](http://fribusers.org)) is the largest organization of researchers in low energy nuclear science. The independent organization has 20 Working Groups covering the range of physics and experimental equipment envisioned for FRIB. The Working Groups met at an FRIB Equipment Workshop in February 2010, and subsequently at the annual Low Energy Community Meetings. Working Groups have, on two occasions, submitted preliminary versions of plans for measurements and equipment to the FRIB Scientific Advisory Committee for review. In Spring 2014, Working Groups were contacted to write up details of their equipment plans for input in the upcoming NSAC Long Range Plan. This report contains brief summaries of these plans. More information can be found in the white papers (with references given in Section 2) that have been written on a number of these projects.

### 1.3. FRIB Experimental Halls

Figure 1.1 shows the experimental halls at FRIB. There are two halls for reaccelerated beams: the ReA3 hall with beams up to 3 MeV/u for Uranium, with somewhat higher energies available for lighter species; and the ReA12 hall with the heaviest beams available up to 12 MeV/u with higher energies available for lighter species. There is a Stopped Beam Hall, and halls for fast fragmentation beams: the Fast Beam Halls from NSCL, and a planned new High Energy High Bay hall. At the present time, the Stopped Beam and ReA3 hall do have some experimental

instrumentation, while the ReA12 hall is empty and the High Energy High Bay is not yet constructed. The Fast Beam halls have served the NSCL facility for many years and include, for example, the S800 spectrometer and Sweeper Magnet. The distribution of the proposed new instruments in these experimental halls is given in the subsection below.

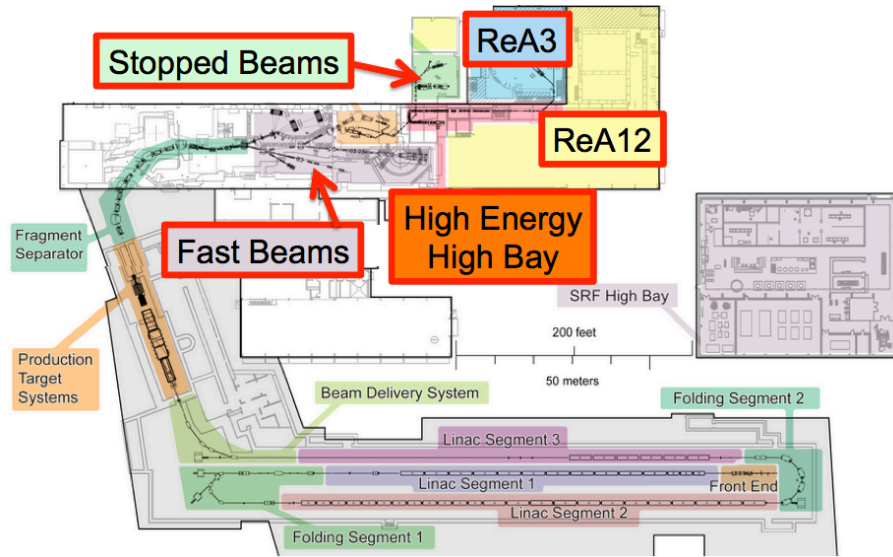


Figure 1.1. Layout of the FRIB facility showing the Stopped Beams, ReA3, ReA12, Fast Beams, and (planned) High Energy High Bay experimental halls.

#### 1.4. Summary of Equipment Needs

The need for new equipment at FRIB is driven by requirements of a scientific program designed to capitalize on the variety and intensities of exotic beams produced at the Facility. Table 1.1 lists the proposed instruments and a one-line statement of their scientific focus. These short statements are solely meant to be representative of how researchers will utilize these proposed instruments and are in no way a comprehensive description of the role they will serve in the FRIB research program. The acronyms of these projects used in this Table and throughout this document are: GRETA – Gamma Ray Energy Tracking Array; HRS – High Rigidity Spectrometer; SECAR – SEparator for astrophysical Capture Reactions; ISLA – Isochronous Separator with Large Acceptance; HELIOS – HELical Orbital Spectrometer; BECOLA – BEam COoling and LASer Spectroscopy; CRIS – Collinear Resonance laser Ionization Spectroscopy; and HRTPC-AT – High Rigidity Time Projection Chamber and Active Target.

| Device           | Science Focus  |
|------------------|--|
| GRETA            | exploration of the structure of new nuclei with max resolving power & acceptance         |
| HRS              | evolution of shell structure, single particle structure of rare isotopes                 |
| Decay Station    | structure of most exotic isotopes, site of the r-process                                 |
| SECAR            | direct measurements of thermonuclear reactions in exploding and exotic stars             |
| ISLA             | reactions & structure of rare isotopes, develop comprehensive model of nuclei            |
| Data Acquisition | critical infrastructure for all experimental halls                                       |
| HELIOS           | single particle & cluster states in rare isotopes, develop comprehensive model of nuclei |
| Scintillators    | portable detectors for all experimental halls  |
| BECOLA / CRIS    | atomic spectroscopy of rare isotopes, delineation of nuclear landscape                   |
| Silicon Array    | portable strip detectors and digital electronics for all experimental halls              |
| HRTPC-AT         | study of nuclear equation of state in n-rich, diffuse, and compressed matter             |
| Gas Jet Target   | critical technology for inverse kinematics reactions                                     |

Table 1.1. Summary of proposed new equipment and their respective science focus at FRIB.



Some of these instruments are fixed in particular experimental halls, such as the large spectrometers and separators, while other detector arrays can be moved between halls as needed for specific experiments. Such rearrangements of these instruments greatly enhances the utilization and science return of these devices and is a unique feature of FRIB among the major nuclear science laboratories in the U.S. These instruments can be categorized as spectrometers/separators, detector arrays, target and other systems, and “essentials” that are needed in all experimental halls. Table 1.2 shows the distribution of the proposed instruments across the categories and their utilization in the different FRIB experimental halls. Below is a short description of the proposed equipment distribution and utilizations in these Halls.

| Device Type   | High Energy High Bay | Experimental Hall |               | Stopped Beams |
|---------------|----------------------|-------------------|---------------|---------------|
|               |                      | ReA12             | ReA3          |               |
| spectrometers | HRS                  | ISLA              | SECAR         |               |
|               |                      | HELIOS            | HELIOS        |               |
| detectors     | GRETA                | GRETA             | GRETA         | BECOLA/CRIS   |
|               | DECAY STATION        | DECAY STATION     | DECAY STATION | DECAY STATION |
|               | HRTPC-AT             |                   |               |               |
| Other         |                      | Gas Target        | Gas Target    |               |
| Essentials    | Scintillators        | Scintillators     | Scintillators | Scintillators |
|               | Silicon Array        | Silicon Array     | Silicon Array | Silicon Array |
|               | DAQ                  | DAQ               | DAQ           | DAQ           |

Table 1.2. Summary of the different categories of proposed new instruments for FRIB and the experimental halls where they will be utilized.

### ***High Energy High Bay***

In the High Energy High Bay, the HRS will serve as the primary spectrometer for fast beams. It will be utilized for a wide variety of measurements with numerous detector systems, covering more than half of the scientific topics identified in the NSAC RIB Task Force in 2007 as crucial for the FRIB science program. The detectors utilized with HRS include GRETA and the Decay Station for structure and reaction studies, and the HRTPC-AT for studies of the nuclear equation of state. The HRS will also be used with existing detector systems such as the MoNA-LISA neutron detector array.

### ***ReA12 Hall***

In the ReA12 Hall, ISLA will serve as the primary spectrometer for reaccelerated beams with energies of up to 12 MeV/u. ISLA will address more than half of the science topics identified by the NSAC RIB Task Force. HELIOS is a smaller solenoid spectrometer for this hall that excels at measurements of transfer reactions. GRETA and the Decay Station will be utilized in connection with ISLA or in a standalone operation, and a gas jet target system will facilitate measurements needed for H, He, or other gaseous targets.

### ***ReA3 Hall***

In the ReA3 Hall, the SECAR separator will serve to enable direct measurements of capture reactions on p-rich unstable nuclei that play a critical role in stellar explosions and exotic astrophysical objects. SECAR will utilize the existing JENSA gas jet target system as a front end, and JENSA itself can be utilized independently of SECAR when coupled to Silicon Detectors and

other arrays for a variety of scattering, transfer, and  $(p,\alpha)$  and  $(\alpha,p)$  measurements. The HELIOS spectrometer will be used for measurements of transfer and other reactions, and will employ the existing large solenoid magnet from the existing AT-TPC instrument. GRETA and the Decay Station will also be utilized in a standalone mode on a beamline in the center of the ReA3 hall.

### ***Stopped Beam Hall***

In the Stopped Beam Hall, the BECOLA and CRIS instruments will be the instruments for atomic spectroscopy of rare isotopes. The Decay Station will also be used on a beamline in this hall for decay measurements of the most exotic nuclei.

The preliminary cost estimates of these proposed new systems are given in Table 1.3. These cost estimates have not been made in a uniform manner, and most of them do not yet have contingency added. The Working Groups are revising their preliminary estimates, and updated version will be posted as they become available. This table also contains an estimate of the start and completion times of a number of the equipment projects. These time frames are tentative at present, and will likely be adjusted in the years to come.

| Device            | Cost (M\$)   | Notes                                | Start | Finish |
|-------------------|--------------|--------------------------------------|-------|--------|
| GRETA             | 45.0         | includes 17% contingency             | FY17  | FY22   |
| HRS               | 29.0         | includes beam line & 27% contingency | FY17  | FY22   |
| Decay Station     | 16.4         |                                      |       |        |
| SECAR             | 11.7         | includes 33% contingency             | FY15  | FY21   |
| ISLA              | 10.0         | includes over 20% contingency        | FY16  | FY20   |
| Data Acquisition  | 8.0          |                                      | FY17  | FY20   |
| HELIOS            | 4.0          |                                      | FY16  | FY20   |
| Scintillators     | 5.0          |                                      |       |        |
| BECOLA / CRIS     | 1.8          |                                      | FY16  | FY19   |
| Silicon Array     | 1.5          |                                      | FY16  | FY20   |
| HRTPC-AT          | 1.4          |                                      |       |        |
| Gas Jet Target    | 1.2          |                                      | FY16  | FY19   |
| <b>Total Cost</b> | <b>135.0</b> |                                      |       |        |

Table 1.3. Summary of the preliminary cost estimates of the proposed new experimental equipment for FRIB and a time window for their completion.

### **1.5. Contributors**

Researchers from the following institutions are currently collaborating on the projects described in this document: Argonne National Laboratory, Augustana College, Bucknell University, University California Berkeley, Central Michigan University, Colorado School of Mines, University of Connecticut, Florida State University, Gettysburg College, Hampton University, Hope College, Indiana University, Kalamazoo College, Lawrence Berkeley National Laboratory, Louisiana State University, Univ. of Massachusetts Lowell, McMaster University, Michigan State University, University of Notre Dame, Oak Ridge National Laboratory, Ohio University, Oregon State University, Pacific Northwest Laboratory, University of Richmond, University of Rochester, Rutgers University, Technical University of Darmstadt, University of Tennessee, Ursinus College, Wabash College, Washington Univ. St. Louis, Western Michigan University, Westmont College, and Yale University.

Contributors to this report include M.S. Smith<sup>1</sup>, A.M. Amthor<sup>2</sup>, D. Bazin<sup>3,4</sup>, M.P. Carpenter<sup>5</sup>, K.A. Chipp<sup>6,1</sup>, P. Chowdhury<sup>7</sup>, J. Cizewski<sup>8</sup>, P. Fallon<sup>9</sup>, A. Gade<sup>3,4</sup>, R. Grzywacz<sup>6,1</sup>, F. Kondev<sup>5</sup>,



## 2. Experimental Equipment Details

### 2.1. Gamma Ray Energy Tracking Array (GRETA)

**Device Name:** Gamma Ray Energy Tracking Array (GRETA)

**Experimental Hall:** Various, including existing areas (S3), ReA Halls, High-Energy Hall

**Working Group:** High-Resolution In-Flight Gamma-Ray Detection

**Conveners:** P. Fallon (LBNL), A. Gade (MSU), M. Carpenter (ANL)

**Cost:** 45 M\$

**Timeline:** Start FY17, Finish FY22 (see Figure 2.1.b)

#### Motivation:

First discussed in the 1996 NSAC Long Range Plan (LRP) and then recommended as a major new initiative in both the 2002 and 2007 LRPs, the gamma ray tracking array GRETA has been identified [1] as a powerful new instrument ideally suited for a broad range of experiments. In 2007, the NSAC Rare Isotope Beam Task force introduced 17 “benchmark experimental programs” to provide a measure of facility performance capabilities for rare-isotope research and to characterize the physics that can be pursued at FRIB. A majority of these topics, and hence the FRIB program, will rely on high-resolution, high-efficiency, in-flight  $\gamma$ -ray detection. GRETA will provide this necessary capability. It will play a central role in the FRIB science program and allow us to fully utilize and maximize the physics opportunities using both fast-fragmentation and reaccelerated beams. GRETA will also be an important instrument at existing facilities, such as ATLAS (ANL), extending the science reach and adding new capabilities.

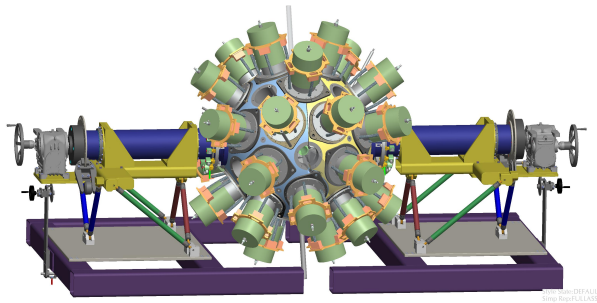


Figure 2.1.a. The  $4\pi$  GRETA  $\gamma$ -ray spectrometer

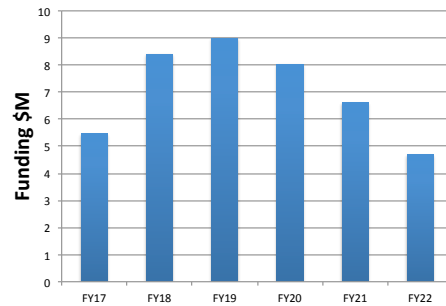


Figure 2.1.b. Proposed GRETA cost profile

#### Description:

GRETA (Figure 2.1.a) is a high-resolution, high-efficiency  $4\pi$   $\gamma$ -ray spectrometer consisting of highly segmented germanium detectors grouped in 30 quad-crystal modules. It uses advanced signal processing to reconstruct the individual interaction positions of incident  $\gamma$ -rays. When combined with tracking algorithms, this provides a large increase in sensitivity and resolving power over existing arrays.

#### Status:

The GRETA project builds upon GRETINA [2] and involves the addition of 18 detector modules together with the associated electronics, computing, and mechanical support. GRETINA (with  $1\pi$  coverage) has successfully demonstrated the technology and scientific impact of a gamma ray tracking array. Over 200 users from over 20 institutions worldwide used the system for 24 experiments and 3300 hours of beam time in the first GRETINA “fast-beam” science campaign carried at NSCL (summer 2012-summer 2013). The experiments included complementary studies

of shell evolution (single-particle and collective degrees of freedom, the role of 3N forces), the determination of excitation energies and spectroscopic factors of astrophysical relevance, and benchmarking the treatment of weak interactions in modern shell-model Hamiltonians. These measurements address several of the FRIB benchmarks mentioned above, and the high demand for GRETINA beam time in the first NSCL campaign illustrates the key position that a gamma ray tracking array can hold at a rare isotope beam facility. A list of the physics publications so far from this NSCL campaign is given below [3-9]. GRETINA is currently operating at ATLAS/ANL and first experiments using reaccelerated radioactive ions from CARIBU have begun.

The build-up towards GRETA will enable forefront experiments at existing accelerator facilities with its potential reach increasing significantly as more detectors are added beyond GRETINA. This will help maintain US leadership by increasing the science opportunities at existing facilities prior to FRIB. A plan based on current technology has been developed to complete GRETA for early “day one” experiments at FRIB, and the goal is to receive CD0 for GRETA in 2015. The proposed cost profile is shown in Figure 2.1.b.

### References

- [1] NSAC LRP 2007 (pages: cover, 9,65,73,74,100,110,157); NSAC LRP 2002 (pages: 132,133); NSAC LRP 1996 (pages: 12,16,64)
- [2] S. Paschalis *et al.*, “The performance of the Gamma-Ray Energy Tracking In-beam Nuclear Array GRETINA”, Nucl. Instrum. Methods A **709** (2013) 44.
- [3] F. Recchia, C. J. Chiara *et al.*, "Configuration mixing and relative transition rates between low-spin states in  $^{68}\text{Ni}$ ", Phys. Rev. C **88** (2013) 041302(R).
- [4] A. Gade, R. V. F. Janssens *et al.*, "Nuclear Structure Towards N=40  $^{60}\text{Ca}$ : In-Beam  $\gamma$ -Ray Spectroscopy of  $^{58,60}\text{Ti}$ ", Phys. Rev. Lett. **112** (2014) 112503.
- [5] H. Iwasaki, A. Lemasson *et al.*, "Evolution of Collectivity in  $^{72}\text{Kr}$ : Evidence for Rapid Shape Transition", Phys. Rev. Lett. **112** (2014) 142502.
- [6] C. Langer, F. Montes *et al.*, "Determining the rp-process flow through  $^{56}\text{Ni}$ : Resonances in  $^{57}\text{Cu}(p,\gamma)^{58}\text{Zn}$  identified with GRETINA", Phys. Rev. Lett. **113** (2014) 032502.
- [7] S. Noji, R. G. T. Zegers *et al.*, "Beta+ Gamow-Teller transition strengths from  $^{46}\text{Ti}$  and stellar electron-capture rates", Phys. Rev. Lett. **112** (2014) 252501.
- [8] L. A. Riley, M. L. Agiorgousis, *et al.*, “Inverse-kinematics proton scattering on  $^{50}\text{Ca}$ : Determining effective charges using complementary probes”, Phys. Rev. C **90**, (2014) 011305(R).
- [9] S. R. Stroberg, A. Gade *et al.*, “Single-particle structure of silicon isotopes approaching  $^{42}\text{Si}$ ”, Phys. Rev. C **90** (2014) 034301.

## 2.2. High Rigidity Spectrometer (HRS)

**Device Name:** High Rigidity Spectrometer (HRS)

**Experimental Hall:** High Energy High Bay

**Working Group:** HRS

**Conveners:** R. Zegers (NSCL/MSU; contact person), D. Bazin (NSCL), J. Brown (Wabash C.), P. Fallon (LBNL), A. Gade (NSCL/MSU), M. Thoennessen (NSCL/MSU), I. Wiedenhoever (FSU).

**Cost:** 29 M\$ (excluding new experimental hall)

**Timeline:** Start FY17, Finish ~FY22

### **Motivation:**

FRIB will produce beams of rare isotopes at unprecedented rates by in-flight fragmentation. The High Rigidity Spectrometer (HRS) will be the centerpiece experimental tool to achieve the scientific goals of the FRIB fast-beam program. It will allow for experiments with the most exotic and short-lived isotopes at the highest yields produced at FRIB and provide a tremendous discovery potential in nuclear physics and astrophysics, with important implications for applications, for example in stockpile stewardship. The High Rigidity Spectrometer will present a flexible and efficient environment for users to perform state-of-the-art experiments and maximize the output from other high-priority and very significant investments by DOE and NSF, such as GRET(IN)A and MoNA-LISA.

The HRS will allow for a wide variety of experiments and cutting-edge auxiliary detection systems can be used in combination with the HRS, thereby even further enhancing the scientific reach. Reaction types that can be studied with the HRS include, but are not restricted to:

- Total reaction/interaction measurements
- Projectile fragmentation and in-flight fission
- Invariant-mass spectroscopy
- Time-of-flight mass measurements
- Charge-exchange reactions
- Life-time studies
- Knockout reactions
- Quasifree scattering
- Electromagnetic excitations
- Elastic scattering
- Inelastic scattering
- Heavy-ion multifragmentation reactions

The scientific opportunities enabled by the HRS are detailed in a whitepaper [HRS].

### **Description:**

Several pre-conceptual layout designs with first-order ion-optical calculations have been made for the High-Rigidity Spectrometer. Figure 2.2.a shows the current base design, which has also been used for estimating the system cost. The first element of the HRS is a “sweeper” dipole magnet, which deflects charged particles into the “spectrometer” section, which consists of two large-acceptance quadrupole triplets and two dipoles.

The main parameters of the HRS are: [1] Maximum magnetic rigidity  $B\rho$  of 8.0 Tm; [2] Angular acceptance of 10 msr; [3] Momentum acceptance of 10 %; [4] Momentum resolution of 1/5000; [5] Ion optical image after sweeper stage for removing beam; [6] Dispersion of 7 cm / % ; [7] Sweeper bending angle of 30°, maximum field of 2.1 T, gap of 60 cm; [8] Dipoles x2 bending angle of 30° each, maximum field of 2.1 T, gap of 12 cm; and [9] Quadrupoles based on FSQ7/8 design for FRIB separator with a ~50 cm maximum bore.



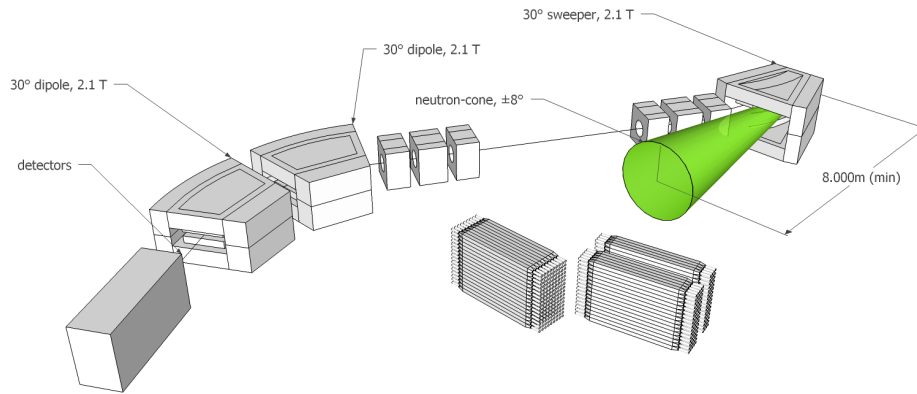


Figure 2.2.a. Schematic layout of the pre-conceptual base design for the High Rigidity Spectrometer. The green cone indicates the maximum angle for which neutrons can emerge from the sweeper dipole towards the MoNA-LISA neutron detector array.

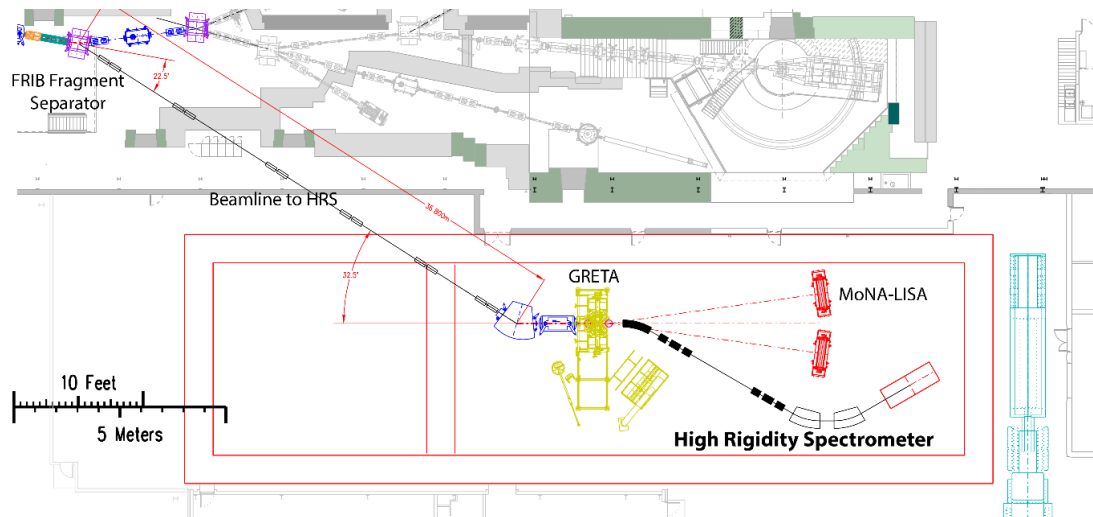


Figure 2.2.b. Schematic Layout of the HRS at FRIB.

A specially designed large-acceptance beam line (Figure 2.2.b) will transport rare isotopes produced by in-flight fragmentation with minimal losses from the FRIB fragment separator to the target station in front of the HRS. The bending capability of the beam line and the HRS matches to the rigidity for which the rare isotopes are produced at the highest intensity in the FRIB fragment separator. The beam line includes a switching magnet, six doublets, a dipole and one quadrupole triplet. Figure 2.2.b shows the placement of the neutron-array MoNA-LISA and gamma-ray tracking array GRETA at the HRS.

**Status:**

Table 2.2 shows the cost estimates for the HRS and for the beam line from the FRIB fragment separator to the HRS. Labor estimates for design, manufacturing, installation and project management are included. A 30% contingency is assumed for magnets with the technical scope well established – a 50% contingency is assumed for the HRS sweeper and 2 spectrometer dipole

magnets for which the uncertainties are larger at present. A separate cost is the construction for the high bay for the spectrometer. It was estimated at \$10M (+\$1M contingency), including the necessary utility infrastructure, radiation shielding/interlocks and overhead crane. A part of these expenses will add to the project cost. The design of the HRS is envisioned to start by 2017, and the completion of the spectrometer is envisioned for early operation of FRIB, thereby immediately and maximally enhancing the discovery potential of FRIB.

Table 2.2. Cost estimate for the HRS and associated beamline

|   | Equipment | Labor   | Total   | w/contingency | Note |
|---|-----------|---------|---------|---------------|------|
| Beam line   | \$3.9M    | \$4.8M  | \$8.7M  | \$11.4M       | 1    |
| HRS   | \$4.1M    | \$8.3M  | \$12.4M | \$17.8M       | 2    |
| Total   | \$8.0M    | \$13.1M | \$21.1M | \$29.1M       |      |
| 1 - Includes switching dipole, 6 doublets, beam line dipole and quadrupole triplet, and associated infrastructure       |           |         |         |               |      |
| 2 - Includes sweeper dipole, 2 quadrupole triplets, 2 spectrometer dipoles, and associated infrastructure and detectors |           |         |         |               |      |

The most recent workshop on the High Rigidity Spectrometer was held on July 11, 2014 at NSCL [HRS-workshop]. The workshop focused on the pre-conceptual design studies, as well as the scientific motivations for the construction. 61 participants, including 10 online participants, attended the workshop. The discussions and materials presented served as input for the writing of the whitepaper, which was underwritten by 74 scientists from over 20 institutions. In the resolutions of the 2014 Low-Energy Nuclear Science Community Meeting, timely construction of the HRS as a state-of-the-art instrument for FRIB was recommended. In the resolutions of the 2014 Nuclear Astrophysics Town Meeting, the HRS was listed as a critical piece of equipment, and the development and implementation was recommended.

[HRS] Whitepaper on “A High Rigidity Spectrometer for FRIB”.

[http://people.nsl.mscl.msu.edu/~zegers/HRS\\_draft.pdf](http://people.nsl.mscl.msu.edu/~zegers/HRS_draft.pdf)

[HRS-workshop] <https://people.nsl.mscl.msu.edu/~zegers/hrs.html>

### 2.3. Decay Station

**Device Name:** Decay Station

**Experimental Hall:** various

**Working Group:** Decay Station

**Conveners:** S. Liddick (MSU / NSCL), R. Grzywacz (UT / ORNL), D. Seweryniak (ANL)

**Cost:** 16.4 M\$

**Motivation:**

FRIB will produce a wide range of isotopes, many with production rates as low as one particle per second or less. For these cases, decay spectroscopy is an ideal experimental approach. The initial information to be measured is typically the half-life, providing one a first point of comparison with nuclear models. Even though the half-life is an integral measurement of the beta-decay strength function, it provides a critical anchor point needed to extrapolate into unknown regions of the nuclear chart. More detailed studies of the decay strength above and below the neutron separation energy, and investigation of discrete levels, requires the implementation of a modular suite of particle, gamma-ray, and neutron detectors which can be combined in various configurations depending on experimental requirements.

**Description:**

We are planning a system composed of detectors for heavy ion implantation, charged particles,

gamma rays, and neutrons (Figure 2.3). The systems are modular and component purchases can be staged over multiple years. In addition, some of the detector arrays can serve other experimental programs.

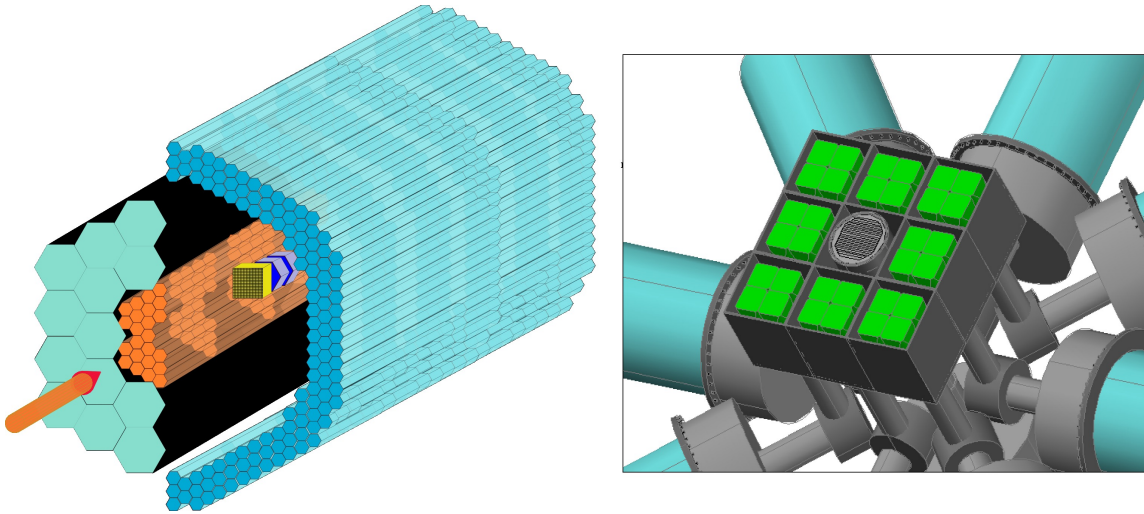


Figure 2.3. Schematic diagram of the Decay Station systems.

*Implantation Station:* Decay spectroscopy experiments require a position sensitive, high efficiency, good energy resolution, low detection threshold, large dynamic range detector to correlate the radioactive ion and its subsequent decay on an event-by-event basis. At low implantation rates, a thick Ge double-sided strip detector would be ideal and have the additional benefit of being sensitive to gamma rays. A prototype exists at NSCL, and the cost of modifying the detector for FRIB is approximately 1 M\$. At high implantation rates, a system comprised of ten 100x100-strip double-sided Si strip detectors is required, with a cost of 0.7 M\$.

*Gamma-ray detector arrays:* Detecting photons emitted following beta-decay to study excited states of exotic nuclear systems is a well-developed method to study nuclear structure and its evolution as a function of neutron and proton numbers. Three complementary arrays are possible. (1) A high resolution HPGe array with cryostats designed to enable close packing with an efficiency of ~50% at 100 keV and ~20% at 2 MeV. The FRIB array would become a workhorse for the decay spectroscopy community and would be flexible enough to serve other experimental programs. Total cost would be approximately 10 M\$. The decay array is complementary to GRETA and constructed specifically for decay spectroscopy to accomplish a high gamma-ray efficiency with a small amount of Ge, while allowing for the flexible inclusion of other detector arrays ( $^3\text{He}$ , neutron scintillators,  $\text{LaBr}_3$ , implantation stations, and others). Close packing of existing detectors is limited based on cryostat designs. High position sensitivity is not necessarily required since the gamma rays are emitted from rest. Both the decay array and GRETA could also be combined for high efficiency recoil decay tagging experiments. (2) The high-resolution studies can be complemented by calorimetry studies, which is a domain of total absorption gamma-ray spectroscopy. Based on the existing Modular Total Absorption Spectrometer (MTAS) design and experience, a new device could be constructed for 0.7 M\$. (3) A compact array of  $\text{LaBr}_3$  crystals would offer high efficiency, good energy resolution and excellent timing for life time measurements at a cost of 1 M\$.

*Neutron detector arrays:* Beta-delayed neutron emission is predicted to be the dominant decay mode of many neutron-rich nuclei. The neutron separation energy of the decay daughter may fall in the hundreds of keV range and the majority of states populated in the decay will be neutron

unbound. A neutron detector based on TOF techniques with high efficiency (>50%), wide dynamic range, and low threshold and neutron-gamma discrimination can be constructed based on the evolved VANDLE design for approximately 2.5 M\$. Precision measurement of the neutron emission branching ratios with  $^3\text{He}$  proportional counters with 90% efficiency would require modifications to existing detectors at a cost of 0.5 M\$.

**Status:**

The total package for the decay spectroscopy detector arrays is 16.4 M\$. Detailed plans for the interconnection of the subsystems described above, within a 10-foot cube volume, are currently being made.

## 2.4. Separator for astrophysical CAPture Reactions (SECAR)

**Device Name:** SEparator for astrophysical CAPture Reactions (SECAR)

**Experimental Hall:** ReA3

**Working Group:** Astrophysics

**Conveners:** H. Schatz (MSU / NSCL / JINA), M.S. Smith (ORNL)

**Cost:** 11.7 M\$ includes 33% contingency

**Timeline:** Start FY15, Finish FY21

**Motivation:**

Many of the thermonuclear capture rates on unstable nuclei needed to address the open questions in studies of novae, X-ray bursts, supernovae, and other stellar explosions or extreme stellar environments have never been measured. There is a strong overlap of the beam species anticipated at ReA3/FRIB with the unstable nuclei which have thermonuclear capture reactions driving the element creation and energy generation in these explosions. For this reason, the direct measurement of such capture reactions will be a critical component of the science program planned at FRIB. The importance of these measurements was explicitly described in the last NSAC Long Range Plan. These are challenging measurements which must be made in inverse kinematics wherein an unstable heavy-ion beam bombards an H or He target, and a recoil separator placed immediately downstream of the target serves to direct the low-intensity recoils to a detector system for identification and counting. The separator must simultaneously eliminate the background from unreacted beam particles that can be  $10^{14}$  -  $10^{18}$  times more intense. Recoil counting enables an absolute cross section determination of the capture reaction, which is the empirical basis for the subsequently calculated thermonuclear capture reaction rate. Because of the extremely low signal-background ratio, and because the beam times needed to measure these low ( $\sim \mu\text{b}$ ) reaction cross sections can be long, a dedicated and optimized device is needed for these experiments.

**Description:**

SECAR (Figure 2.4) will be the experimental endstation at ReA3 and FRIB optimized for the direct detection of the recoils produced by proton- and alpha-capture reactions on proton-rich unstable nuclei. The SECAR collaboration has determined a set of Science, Technical, and Design Requirements for the system on the basis of representative reactions spanning the mass and energy range of interest for stellar explosion studies. For Science Requirements, SECAR must be able to measure  $(p,\gamma)$  and  $(\alpha,\gamma)$  capture reactions over a beam mass range of 15 – 65, and must be sensitive to resonances with center of mass energies of 0.5 – 3 MeV and strengths of 100 meV to 1  $\mu\text{eV}$ . To meet these Science Requirements, we have defined the following ultimate technical performance parameters: a  $10^{-17}$  rejection of beam projectiles by the separator combined





FRIB equipment priority for the nuclear astrophysics community, and has received positive evaluations by expert committees, including FRIB Science Advisory Committee. The SECAR collaboration has prepared a pre-Conceptual Design Report, a Preliminary Project Execution plan, and other project documentation. The proposal, including science case, technical solution, cost, and management has been very favorably reviewed in a FRIB Director's review in Summer 2014, chaired by I-Yang Lee from Berkeley, and in a DOE/NSF Technical Cost Schedule and Management (TCSM) review in October 2014. Funding is anticipated to begin in FY15, and we anticipate a project completion in FY21.

## 2.5. Isochronous Separator with Large Acceptance (ISLA)

**Device Name:** Isochronous Separator with Large Acceptance (ISLA)

**Experimental Hall:** ReA12

**Working Group:** ReA12 Separator

**Conveners:** A. M. Amthor (Bucknell), W. Mittig (MSU/NSCL), J. Nolen (ANL)

**Cost:** 10 M\$ includes 20% contingency

**Timeline:** Start FY16, Finish FY20

### **Motivation:**

The FRIB and NSCL user communities have strongly endorsed the early implementation of reaccelerated beams with energy of all species up to 12 MeV/u at FRIB. This capability would provide a world-unique set of beams from in-flight separation and gas stopping at energies compatible with many of the experimental and theoretical tools necessary for the FRIB scientific program. A recoil spectrometer coupled to ReA12 is needed to address large parts of the nuclear physics mission of FRIB—for aspects from nuclear structure and nuclear astrophysics to applications—including a majority of the Benchmarks from the 2007 NSAC RIB Taskforce report.

FRIB will provide unprecedented rare isotope beam intensities and variety of species, as discussed in Section 1. ReA12 will reaccelerate stopped FRIB beams, providing high quality beams of rare isotopes at a range of energies ideal for transfer reactions, multiple Coulomb excitation, massive transfer in deep inelastic scattering and fusion reactions. A ReA12 recoil spectrometer will have the important ability to extend the reach of FRIB to study isotopes that cannot be reached by fragmentation but that can be produced by multi-nucleon transfer in deep inelastic scattering, or by transfer or fusion using incoming beams from FRIB. This includes studies of any elements beyond  $Z=92$ , in addition to particular isotopes of many other elements.

In the energy domain of ReA12 rare isotopes will have many charge states after a reaction. The identification of nuclei without ambiguity in this mass region and at low to medium energy will be a necessary and challenging task. Only a spectrometer specifically designed for this task can meet these needs. Without a spectrometer, lack of precise identification will render most reaccelerated beam experiments either impossible or impractical due to the orders of magnitude higher statistics that would be necessary to disentangle different contributions.

### **Description:**

The spectrometer is needed to reject unreacted beam and to fully characterize and identify the reaction products from sub-barrier fusion to transfer reactions up to the maximum energy available in the ReA12 hall. In many experiments, the spectrometer will be used in coincidence with detector arrays around the target to detect prompt radiation from nuclear excited states.



Focal plane detection will facilitate decay studies and decay-delayed spectroscopy studies of the reaction products in addition to providing unambiguous identification of nuclei associated with prompt radiation detected at the target.

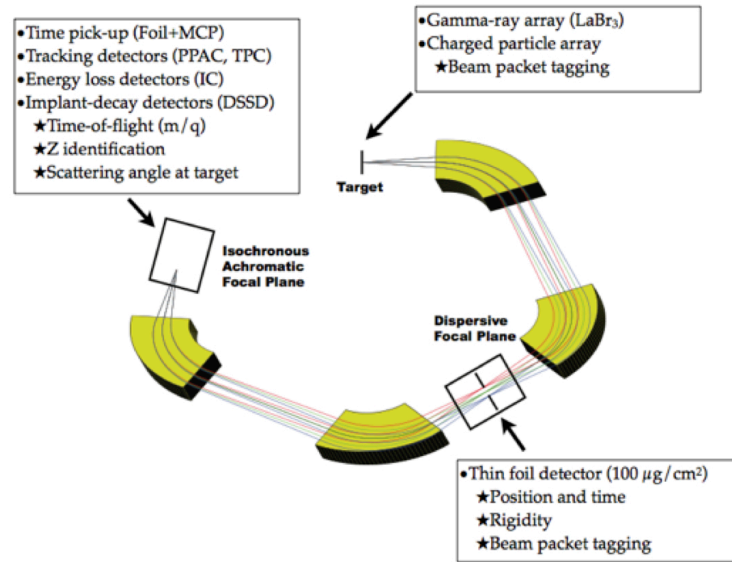


Figure 2.5. ReA12 Separator design based on the concept of the TOFI spectrometer. M/Q resolving power is provided by the time-of-flight between the target and an isochronous final focal plane. Unreacted beam within the momentum acceptance may be blocked by fingers at the intermediate dispersive focal plane.

Consideration of the needs of multiple physics cases—outlined in detail in the working group whitepaper of August 2014—led to the following essential properties of the spectrometer:

- Large solid angle acceptance
- Large momentum and charge state acceptance
- M/Q resolving power > 400
- Magnetic rigidity  $B\rho_{\text{max}} = 2.6 \text{ Tm}$  and high or unlimited electric rigidity
- Atomic number resolution up to Uranium
- Variable incoming beam angle
- Space around the target to accommodate large detector arrays (e.g. GRETA/Gretina)

**Status:**

Following extensive work and discussion within the prospective community of users, including preliminary design studies of three initially proposed concepts, a single spectrometer with these characteristics has emerged. The ISLA (Isochronous Separator with Large Acceptance) device (Figure 2.5) has the above characteristics and will be world unique with its high M/Q resolving power of up to 10000. The cost of ISLA has been estimated on the basis of actual cost estimates from prior NSCL projects to be about \$10.0M with a 20% contingency included. In order for the spectrometer to be available already at FRIB start-up in 2020 to 2022, and to make the most of early research opportunities and to develop expertise to operate the spectrometer and its detectors efficiently (which is possible before FRIB startup using stable beams from ReA12), funding should become available for an official start of the project before the end of FY16.

## 2.6. Data Acquisition

**System Name:** Data Acquisition for FRIB

**Experimental Hall:** All Experimental Halls

**Working Group:** Data Acquisition

**Conveners:** R.L. Varner (ORNL), R. Fox (NSCL), J. Tompkins (NSCL), K. Teh (ANL), J. Anderson (ANL), M. Cromaz (LBNL)

**Cost:** 8.0 M\$ - \$3.0 M hardware, \$5M in software development

**Timeline:** Start FY17, Finish FY20

### **Motivation:**

FRIB will begin operation in ~8 years, a long time in the fast-changing world of networks, processors, storage, and electronics. Data acquisition is a common resource among the experiments at FRIB, but it is not budgeted in the facility construction. The FRIB Data Acquisition Working Group proposes to develop a data acquisition architecture that will take advantage of the recent developments in nuclear physics data acquisition, as well as advances and projected advances in computing, networking, and storage.

More and more, nuclear physics data acquisition is based on deeply buffered waveform digitizers that capture the detector signal, either for analysis in firmware with FPGAs or for software analysis on general-purpose processors. First level hardware triggers in such a system are usually simple to maximize the speed of moving data. More complex “triggers”, such as coincidence requirements and threshold cuts, are applied to the highly buffered data that await event building. These are applied using FPGAs in some systems, but in other systems these second level triggers are applied using software during event building. FRIB experiments will add more complexity: the high value of the exotic beams will instigate groups to employ multiple detector systems to fully characterize reactions and reaction products. The data acquisition system must easily enable experimenters to combine detector systems, with widely varying level of buffering and internal trigger capabilities, in order to handle more powerful and complete measurements. FRIB data acquisition must take advantage of recent developments in commodity computer hardware that lead to increasing processor throughput, storage speed and density, and network speed. These changes are driven by applications outside of nuclear physics, such as gaming, high frequency trading, high performance computing, and delivery of high-resolution video. Our intention is for the acquisition system development to take advantage of rapidly evolving commodity computer systems, rather than be trapped by this evolution in obsolete systems.

### **Description:**

The data acquisition system properties that we anticipate are:

- A synchronized timestamp generation and distribution system, critical for building events from buffered data and diverse detector systems
- The ability to build events from fragments contributed by the multiple, diverse detector systems
- A flexible, easily configured triggering system
- A coherent run state control system (single button start)
- The ability to quickly couple and decouple detector systems as experiments transition from shakedown to production running

We must also provide the foundation on which this will operate:

- Components from which detector data acquisition systems can be built and run in standalone mode

- Sufficient flexibility to support coupling detectors whose data acquisition systems are *not* built around the FRIB components above

The development of these ideas and the required components will take time and manpower. As a reasonable guess, we presume two FTEs working from now until FRIB is online may accomplish the task. The software components include protocols for buffer management, trigger management, event building, timestamp management, run control, and performance monitoring.

These protocols need to be implemented in a reference design for front ends as individual detector or detector system readouts. The trigger management and event building system need to be implemented so that detector systems can easily be joined to an experiment, and provide suitable tools for physicists to construct triggers. All of this will depend on obtaining the lowest latency out of the network interconnection. We estimate the cost of this software system development to be 5 M\$.

There is a need for development hardware, to assemble tests of the concepts for building this model of the DAQ. We expect that hardware to cost 50 k\$.

Equipping the facility will require hardware. First, there will be a need for a high performance network infrastructure to interconnect detectors with trigger processors, event builders, and event storage throughout the experimental halls. Second, there will be a need to provide a timestamp synchronization infrastructure. Finally, there will be a need for data acquisition hardware, trigger processors, event building hardware, and event storage. Our initial estimate of this cost is 3 M\$ on hardware, firmware, and interface electronics to have a working DAQ system for FRIB when it begins operation.

**Status:**

The FRIB DAQ working group is producing a conceptual design of the data acquisition system and evaluating mechanisms to receive input from the FRIB community about its needs. The SBIR process may be useful to get industrial partners interested in supporting our needs. In the next year, we will complete the overall specifications and begin investigating the technology required to implement the conceptual design.

## 2.7. Scintillator Arrays

**Device Name:** Scintillator Arrays

**Experimental Hall:** ReA12

**Working Group:** Scintillator Arrays

**Conveners:** P. Chowdhury (Univ. Massachusetts Lowell), F. Kondev (ANL), W. Reviol (Washington Univ. St. Louis), V. Werner (TU Darmstadt)

**Cost:** 5 M\$

**Motivation:**

There is a need for arrays of scintillators for a wide variety of measurements to be carried out at FRIB. The principal applications and physics goals are:  $\gamma$ -ray spectroscopic measurements (especially fast-timing lifetime measurements), total-absorption  $\gamma$ -ray spectrometry, and improved ability for neutron- $\gamma$  discrimination and fast-neutron spectroscopy.

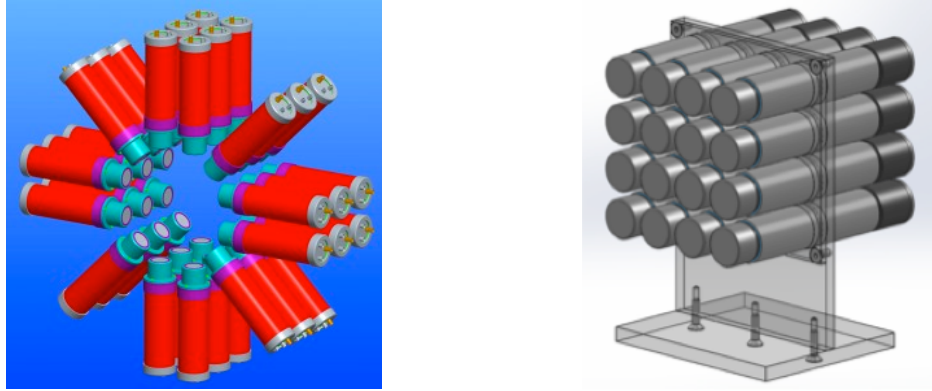


Figure 2.7. Proposed fast-timing array of  $\text{LaBr}_3\text{:Ce}$  crystals for GSI by the DESPEC Collaboration (left) and a 16-element CLYC array with enriched  $^7\text{Li}$  currently in operation at UMass Lowell (right).

**Description:**

The favored detector materials are  $\text{LaBr}_3\text{:Ce}$  for the  $\gamma$ -ray and CLYC for dual neutron/ $\gamma$  neutron measurements, respectively. Three basic scenarios for scintillator arrays have been identified: (1) a  $4\pi$  target array, perhaps of a geodesic shape, consisting of  $\text{LaBr}_3\text{:Ce}$  detectors; (2) same as (1) but consisting of CLYC detectors; and (3) a focal-plane/decay-station array, perhaps of a cubic shape, consisting of  $\text{LaBr}_3\text{:Ce}$  detectors for  $\gamma$ -rays or CLYC for beta-delayed neutrons. The focal-plane array could be a hybrid array, in combination with Si detectors, for  $\gamma$ -rays, neutrons and charged particles.

The favored system consists of a  $\text{LaBr}_3$  array for fast timing, to be used in-beam or at a decay station, coupled to HPGe as well as charged particle or neutron detectors. Large volume  $\text{LaBr}_3$  detectors of at least 3-inch diameter by 3-inch length are a second item under consideration, to be used for high-efficiency detection of high-energy gamma rays – specifically, high-energy resonances accessible through light-ion scattering. This system could also be used both in-beam or at decay stations. The configuration could resemble the fast-timing  $\text{LaBr}_3\text{:Ce}$  array (Figure 2.7) proposed by the DESPEC collaboration for measurements at GSI. Neutron detection plans include consideration of emerging scintillators such as CLYC (Figure 2.7), where large-volume crystal growth is still under development. Cost estimates for the FRIB system lie in the \$1M to \$5M range depending on array size, granularity, and scope. Given that scintillator arrays probably do not need a great deal of lead time, final decisions on these arrays could wait till concrete needs and plans are finalized by the community.

**Status:**

We are currently matching detector requirements to physics experiments in preparation to begin a design effort for the arrays.

## 2.8. Solenoid Spectrometer (HELIOS)

**Device Name:** Solenoid Spectrometer (HELIOS)

**Experimental Hall:** ReA3 Hall, ReA12 Hall

**Working Group:** Solenoid Spectrometers

**Conveners:** B. Back (ANL), A. H. Wuosmaa (UConn)

**Cost:** 4 M\$

**Timeline:** Start FY16, Finish FY18

### **Motivation:**

Information provided from single- and few-nucleon transfer reactions has been invaluable in building up the nuclear shell model. These reactions are especially valuable for nuclei far from stability, where questions of the modification of shell structure and single-particle and exotic excitations have been a major focus of investigation at facilities providing rare-isotope beams. One technical approach proven effective for inverse kinematics transfer reaction measurements utilizes a high-field magnetic solenoid to transport light-reaction products to an array of position-sensitive detectors located on the solenoid axis. An embodiment of this approach is found in the HELIOS (HELical Orbit Spectrometer) device in operation at Argonne National Laboratory. Since 2008, HELIOS has been used to study a wide variety of nuclear reactions in inverse kinematics, including  $(d,p)$ ,  $(d,t)$ ,  $(d,^3\text{He})$ ,  $(d,^4\text{He})$ ,  $(^6\text{Li},d)$ ,  $(^3\text{He},d)$ , and  $(t,p)$ . These measurements have provided information about single-particle states, pairing and cluster excitations, nucleon correlations, and the structure of nuclei of astrophysical importance.

### **Description:**

HELIOS utilizes the uniform magnetic field produced by a large superconducting solenoid to transport light ions (e.g.,  $p$ ,  $d$ ,  $t$ ,  $^3\text{He}$ ,  $^4\text{He}$ ) from a reaction target located on the solenoid axis, to an array of position-sensitive detectors also aligned with the solenoid axis. Light targets including solid  $\text{CD}_2$ ,  $\text{CH}_2$ , and  $^3\text{H}$ -implanted Ti have been used, and a cryogenic gas target for reactions with  $^3\text{He}$  and  $^4\text{He}$  has been developed and tested. The recoiling heavy beam-like partner travels through the solenoid and can be detected with a number of different heavy-ion detectors such as silicon-detector telescopes for light nuclei and ionization counters for heavy nuclei. This transport mode simplifies the kinematical analysis of the reaction, and enables the excitation energy of the nucleus of interest to be measured with very good resolution. The detection and identification of the heavy partner permits the suppression of backgrounds and can be used to provide a precise determination of different decay modes of excited states. A schematic diagram of HELIOS appears in Figure 2.8.



Figure 2.8. Illustration of the HELIOS device.

**Status:**

The first implementation of this technique has been in operation at the ATLAS facility at Argonne National Laboratory since 2008. The technical approach and operational characteristics are well understood, and the existing design can be taken over directly for a device to be used at FRIB, or before with reaccelerated radioactive beams at the NSCL. We foresee a two-phase implementation of a solenoid spectrometer for FRIB. The first step involves constructing a device that can be used to measure  $(d,p)$  (and other) reactions with the low-energy beams from ReA3 that are already being developed. For  $(d,p)$ , the large solenoid magnet that is already present in the ReA3 experimental hall for the ATTPC (Active Target Time Projection Chamber) will work well for our spectrometer, and the silicon-array mechanical design can permit simple installation and removal of the detector so that the magnet can be shared with the ATTPC. For higher-energy beams, a new, high-field magnet would be installed in the ReA12 experimental hall. The detector mechanics from the low-field version would be moved, and the only additional construction would be in the installation of the new magnet and adapting the detector to the new solenoid. From experience with HELIOS, the Phase I costs are expected to be 0.8 – 1.0 M\$, and the most significant expenditure for the Phase II implementation is in the procurement of a new solenoid magnet. Depending on size and field strength, the new magnet cost is expected to be between 2M\$ to 3M\$. Implementation of Phase I could begin immediately, with expansion into Phase II awaiting the development of higher-energy reaccelerated beams. The full implementation of a solenoid detector could be in place at the time FRIB operations begin.

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## 2.9. BECOLA and CRIS

**Device Name:** BECOLA and CRIS

**Experimental Hall:** Stopped Beam

**Working Group:** Laser Spectroscopy

**Conveners:** K. Minamisono (MSU)

**Cost:** 1.8 M\$

**Timeline:** Start FY16, Finish FY19

### **Motivation:**

A laser spectroscopy station will be used at FRIB to determine nuclear magnetic and quadrupole moments, and charge radii in ground/isomeric state of exotic nuclei, through hyperfine structure and isotope shift measurements. BECOLA facility is fully functional and operational. Upgrade of BECOLA and new development of CRIS are proposed here for high sensitive detection of low yield beams.

### **Description:**

The BEam COoling and LAsEr spectroscopy (BECOLA) facility (Figure 2.9) is an experimental station for the laser spectroscopy of exotic nuclei at NSCL. The development and offline commissioning tests [Klo112, Min13, Klo13] were completed and BECOLA has been fully operational. Successful online commissioning tests were carried out in summer 2013 using radioactive K beams, where resonant fluorescence was detected in coincidence with the beam bunches to determine the hyperfine structure [Ros14a]. The coincidence technique increases the detection sensitivity [Nie02, Cam02] and is essential in low ion-rate measurements. Sensitivities of approximately  $10^3$  ions/second beam rate were achieved and rates potentially as low as  $10^2$  ions/second can be expected. A nuclear polarization was produced using the optical pumping technique as part of the online commissioning test in summer 2014. Charge radius of  $^{36}\text{K}$  was determined for the first time using a beta-decay asymmetry detection with a few  $10^2$  atoms/second rate of the  $^{36}\text{K}$  beam. The first-row transition elements will be targeted next and we have one approved experiment (#14006 [Ros14b]) by the NSCL PAC 38 for charge radii of neutron-deficient Fe isotopes.

The proposed extension of this facility by the BECOLA Collaboration (NSCL/MSU, TU Darmstadt, TRIUMF, ORNL) for use with FRIB beams includes the development of an ion mass analysis line for the offline Penning Ionization Gauge (PIG) ion source, and the addition of a frequency comb system. The mass analysis line will be installed between the PIG source and the cooler/buncher in order to remove the support-gas-originating beam component in the extracted ion beam as well as to have mass resolution. The frequency comb system will be used to determine the absolute frequency of laser light and will provide an accurate calibration of the laser frequency. The signal from the comb can be distributed and used to calibrate any laser system requiring precise determination of laser frequencies.

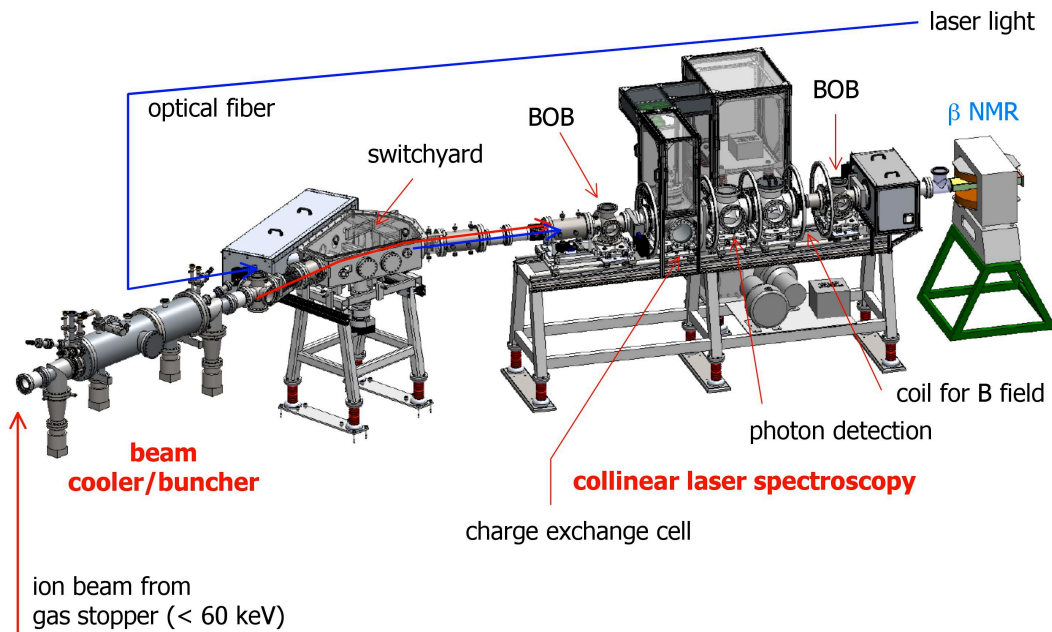


Figure 2.9. BEam COoling and LAsER spectroscopy (BECOLA) facility at MSU NSCL

The Collinear Resonance laser Ionization Spectroscopy (CRIS) facility is a new development to access very exotic nuclides near the drip lines, such as  $^{78}\text{Ni}$  and  $^{100}\text{Sn}$ , whose production rates will be very low ( $< 10$  ions/second). A CRIS system exists at the ISOLDE facility at CERN. At FRIB, the ion beam from the gas stopper will be neutralized through charge-exchange reactions with an alkali-metal vapor in a charge exchange cell. The neutral atoms will interact with laser light and be selectively ionized through two- or three-step laser excitations. The subsequent detection of ions will be an indication of a resonance [Kud82, Fed12]. The detection sensitivity (background rate) is ultimately determined by the vacuum conditions of the interaction region. The CRIS technique can be potentially applied to ion rates of a few Hz, owing to two factors: the high elemental selectivity of the multiple laser excitations; and the highly-sensitive ion detection method which does not suffer from the background associated with conventional fluorescence detection and stray laser light.

#### Status:

A preliminary conceptual design of the CRIS system has been made and discussions of the preferred pulsed laser system are underway. Major components of the CRIS station include a laser system (850 K\$), room air conditioning (200 K\$), an ultra-high vacuum system (350 K\$), a beam line (100 K\$), and a detection system (50 K\$). The cost of the BECOLA extension includes an ion mass analysis line (40 K\$) and a frequency comb (250 K\$). Both BECOLA and CRIS can be used at pre-FRIB NSCL and FRIB without any modification.

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## 2.10. Instrumented Silicon Arrays (ISA)

**Device Name:** Instrumented Silicon Arrays (ISA)

**Experimental Hall:** All

**Working Group:** Silicon Array

**Conveners:** Jolie Cizewski (Rutgers), Romualdo De Souza (Indiana), Kate Jones (Univ. Tennessee), Steve Pain (ORNL), Lolly Pollacco (CEA Saclay), Grisha Rogachev (TAMU), Darek Seweryniak (ANL)

**Cost:** 1.5 M\$

**Timeline:** Start FY16, Finish FY20

### **Motivation:**

Arrays of highly segmented silicon detectors form the backbone of charged-particle detection, and are critical to numerous types of experiments, ranging from the measurement of products from direct reactions with slow and fast beams to implantation/decay experiments. Silicon arrays are usually highly configurable and are often coupled to other experimental devices such as gamma-ray arrays and recoil separators. This results in various experiment-specific setups optimized for various types of measurement, including transfer reactions, charge exchange reactions, elastic and inelastic scattering, Coulomb excitation, lifetime measurements, and knockout reactions. Recent developments in digital instrumentation suggest that a single suite of detectors and digital data acquisition system could be developed to cover most experimental requirements at FRIB while minimizing duplication of equipment and effort.

### **Description:**

ISA is a suite of silicon detectors instrumented with a suite of digitizers optimized for signals from ohmic- and resistive-contact silicon detectors. It is anticipated that digitizers with a ~250MHz sampling rate and a minimum 12-bit resolution will be required. This standardized instrumentation for silicon detectors will facilitate straightforward coupling to other major devices including GRETA, ISLA, HRS, JENSA Gas Target, SECAR, and others. We will outfit a base suite of approximately 100 silicon detectors with a customizable configuration enabling optimization in different experiment geometries. The detectors will be accompanied with ~1000 channels of preamplifiers and digitizers. Figure 2.10 shows an example of a modern silicon detector array, SuperORRUBA [1].

### **Status:**

The digitizer requirements for instrumenting various types of silicon detectors and preamplifiers are currently being investigated. The total cost of the system will be 1.5 M\$, including 1000 digitized channels at 1k\$ per channel, 0.4 M\$ for large area silicon detectors at 5 k\$ per channel, and 100 k\$ for preamplifiers.

### **References:**

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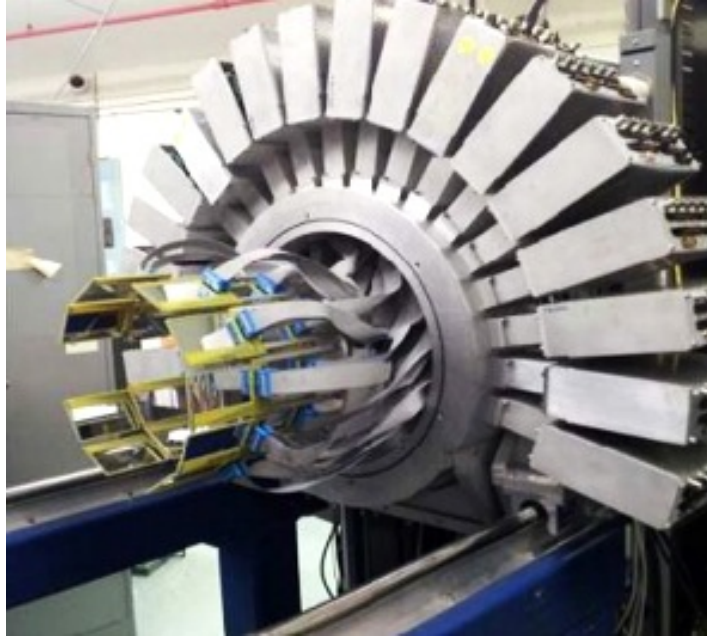


Figure 2.10. The SuperORRUBA system is an example of a modern array of silicon strip detectors [1].

## 2.11. HRTPC-AT

**Device Name:** High Rigidity Time Projection Chamber – Active Target (HRTPC-AT)

**Experimental Hall:** High Energy High Bay

**Working Group:** Equation of State Physics

**Conveners:** W. Lynch (MSU)

**Cost:** 1.4 M\$

### **Motivation:**

Installing a Time Projection Chamber (HRTPC-AT) on a high-rigidity beam line at FRIB can enable significant constraints on the density dependence of the symmetry energy. The HRTPC-AT would allow two operating modes: 1) a conventional TPC with an internal fixed target and 2) an active target. The design of this TPC would be optimized for coincidence studies between charged particles detected in the TPC and heavy ions detected in a high resolution spectrometer and neutrons and charged particles detected in external detection arrays.

In internal target mode, the HRTCP-AT would enable comparisons of  $\pi^-$  and  $\pi^+$  spectra and flows in collisions with the most neutron-rich and neutron-deficient systems such as  $^{136}\text{Sn}+^{124}\text{Sn}$  and  $^{106}\text{Sn}+^{112}\text{Sn}$ . Calculations predict that this would provide constraints on the symmetry energy at  $1.5\rho_0$ . This mode would also enable comparisons of  $t$  and  $^3\text{He}$  spectra and flows in collisions with the same systems. This allows constraints to be placed on the momentum dependence of the symmetry energy, and on the difference between the neutron and proton effective masses. Finally, this mode would enable experimental probes of the neutrino-sphere Equation of State. This would involve using the HRTPC-AT as a centrality trigger and charged particle detector, in combination with external charged particle and neutron detectors and an external high-resolution recoil separator such as the HRS. This approach provides high-resolution measurements of neutron-rich matter at neutrino-sphere densities under laboratory-controlled conditions.

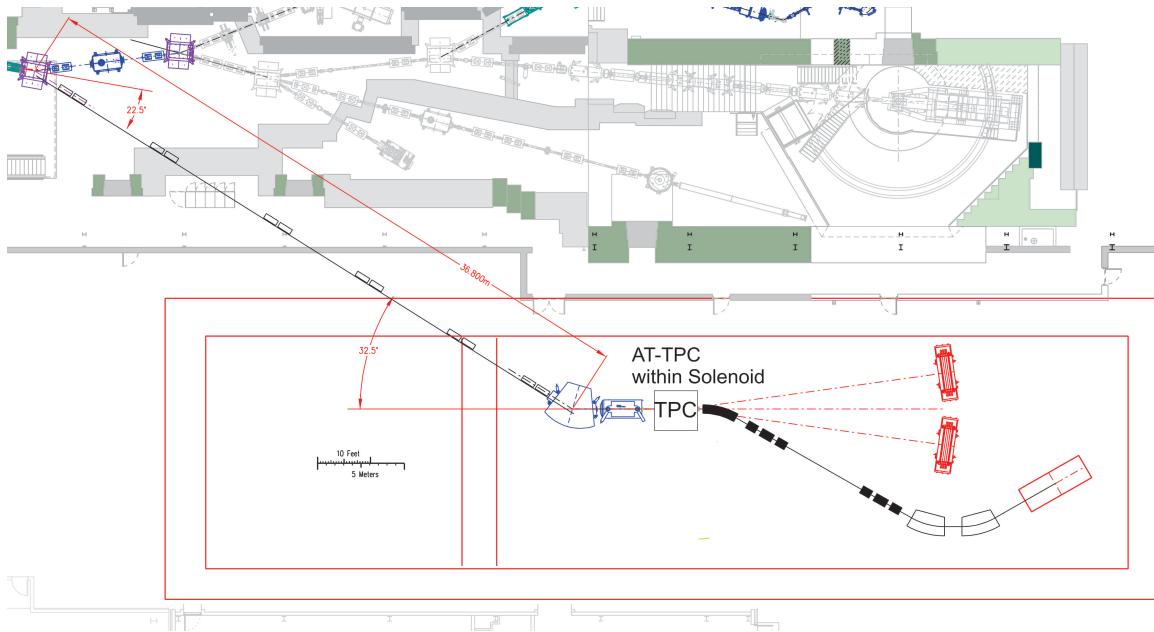


Figure 2.11.a. HRTPC-AT at HRS target position

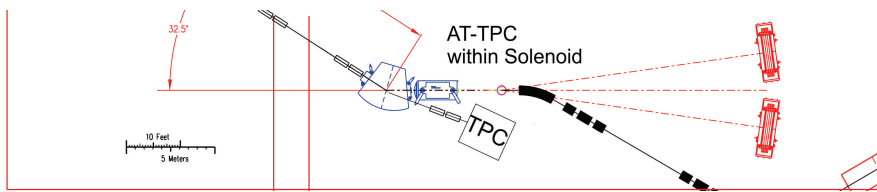


Figure 2.11.b. HRTPC-AT on a standalone beamline

In active target mode, the HRTCP-AT would enable measurements of the Isoscaler Giant Monopole Resonance (GMR) in exotic rare isotope beam nuclei. This has, for example, been measured for  $^{56}\text{Ni}$  using deuterium target gas in the MAYA active target. Measurements of the GMR in  $^{104}\text{Sn}$ - $^{134}\text{Sn}$  nuclei could be performed with the HRTPC-AT at FRIB when used in conjunction with the HRS. Such measurements would provide significant constraints on  $K_2$ , which is governed by the first and second derivatives (as a function of density) of the symmetry energy at sub-saturation densities. The active target mode would also enable measurements of ( $d, ^2\text{He}$ ) excitations of Gamow-Teller and Spin Dipole resonances in exotic nuclei. Such measurements can be made by putting deuterium gas in the HRTCP-AT and would require use of the HRS. The spin-dipole resonance is predicted to be an interesting probe of the neutron skins in exotic neutron-rich nuclei.

**Description:**

The measurement programs described above require placing the HRTPC-AT on a high rigidity beam line and, as indicated above, use of the HRS. Figures 2.11.a and 2.11.b show two options for implementing the HRTPC-AT at FRIB, mounted on the target position of the HRS or on a standalone beam line in the HRS vault. The cost of the system is 1.4 M\$, and details are given below in Table 2.11.

| Item                 | Cost M\$ |
|----------------------|----------|
| Solenoid Magnet      | 0.2      |
| Cryogenic System     | 0.15     |
| Mechanics            | 0.12     |
| Quadrupole triplet   | 0.4      |
| Beam Lines and pumps | 0.15     |
| TPC                  | 0.38     |
| Total                | 1.4      |

Table 2.11. HRTPC-AT Cost Estimate

**Status:**

Additional details are being investigated, to be followed by a pre-conceptual design with an updated cost estimate.

## 2.12. JENSA Gas Jet Target System

**Device Name:** JENSA Gas Jet Target System

**Experimental Hall:** ReA3, ReA12

**Working Group:** Jet Target

**Conveners:** K. Chipps (Univ. Tennessee / ORNL)

**Cost:** 1.2 M\$

**Timeline:** Start FY16, Finish FY17 (0.2M\$); Start FY17, Finish FY19 (1.0 M\$)

**Motivation:**

Measurements of scattering and transfer reactions using radioactive beams on hydrogen and helium targets will be an integral part of the FRIB science program. These measurements are crucial to addressing important open questions in nuclear structure, reactions, and astrophysics. A localized gas target is needed at FRIB to take full advantage of the tremendous increase in available radioactive beam species for scattering, transfer and capture reaction measurements. The Jet Experiments in Nuclear Structure and Astrophysics (JENSA) Collaboration have constructed a windowless, differentially-pumped, recirculating gas jet target system, which is an ideal target for both capture reaction measurements with SECAR and stand-alone transfer and scattering reaction measurements.

**Description:**

JENSA (Figure 2.12.a) employs an industrial-strength gas compressor to force gas through a specialized convergent-divergent Laval nozzle to create a downward-oriented supersonic jet. Two concentric cone-shaped receivers located beneath the jet nozzle efficiently collect the expanding gas where it is pumped by a series of 13 high-throughput roots blowers and multi-stage roots pumps. The pump exhaust is fed back into the compressor to form a recirculating system. The beam enters the system through four differential pumping chambers upstream of the jet, and interacts with the target gas in the region between the nozzle and receiver. When used as the target system for SECAR, capture reaction products exit the system through four downstream differential pumping chambers and enter SECAR. The differential pumping apertures on the downstream side are necessarily larger than those upstream to accommodate the opening angle of the capture reaction products. When used in stand-alone mode, a larger central chamber is used that can accommodate arrays of Silicon strip detectors, and the downstream differential pumping chambers are not employed.



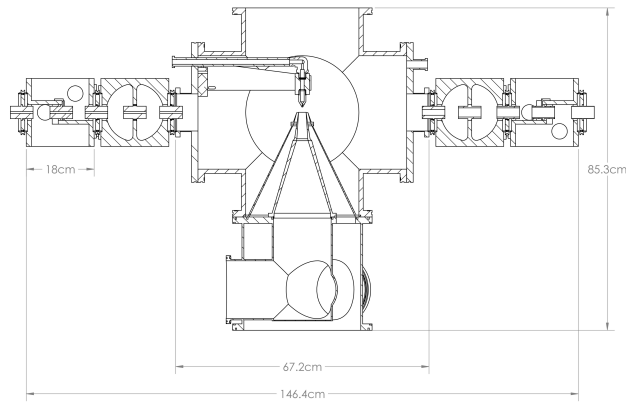


Figure 2.12.a. CAD drawing of JENSA beamline components configured to run as the target system for the SECAR system.

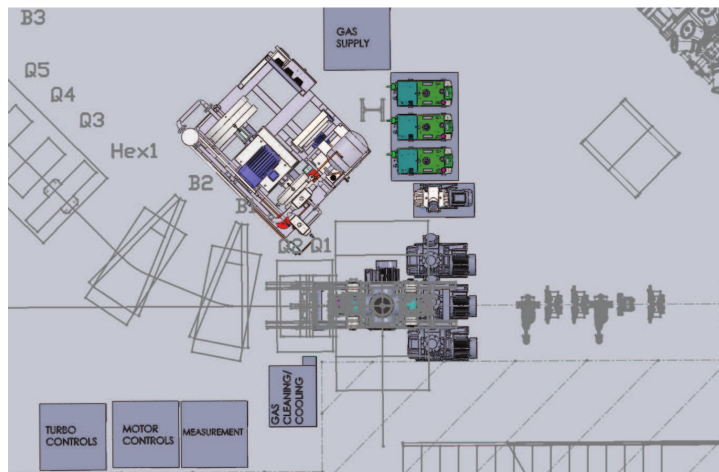


Figure 2.12.b. The JENSA gas jet target system shown in the ReA3 hall. Some of the upstream-most components of the SECAR Mass separator are also indicated.

**Status:**

JENSA was constructed and commissioned at ORNL. It achieved areal densities approaching that of a solid target ( $\sim 10^{19}$  at/cm<sup>2</sup>), an extremely narrow jet diameter ( $\sim 4$  mm), a rapid drop in pressure (by  $10^3$ ) outside the jet, a high purity ( $> 99\%$ ), and very good stability (less than 2% pressure variation per hour). The localization of the target material in the jet effectively produces a point source of reaction products, ideal both for angular distribution measurements with Silicon strip detectors placed in the chamber and for capture measurements using SECAR. The system was moved to the ReA3 hall and installed (Figure 2.12.b), and initial commissioning work has begun.

While the JENSA target in the ReA3 hall is effectively complete, there are ongoing upgrades and additions that are necessary to facilitate experiments in the FRIB era. The addition of a pre-compression stage, on the order of 0.1 M\$, would increase the density of the gas jet by up to a factor of two. Cryogenically cooling the target, with a high-throughput chiller (also on the order of 0.1 M\$), would also contribute roughly a factor of two to three in density. This work can begin in mid FY15 to FY16.

In the longer future, a gas jet target based on the JENSA design (either an exact replica or a similar system, as it is not feasible to move the existing JENSA target out of the ReA3 hall) may be desired in the ReA12 hall for use in transfer, Coulex, fusion evaporation, and other reactions requiring a higher beam energy. This would require 1 M\$ to design, fabricate, construct, and test. This work can begin in FY17 and be completed in FY20.

### 3. Summary

The systems described above represent the major experimental instruments necessary to make full utilization of the world-leading radioactive beams anticipated at FRIB for studies in nuclear structure, nuclear astrophysics, fundamental symmetries, and societal applications. These systems are in various stages: some are on the floor and require upgrades to be FRIB-ready; some have detailed cost estimates, management plans, and large collaborations; and others have concepts and are working towards developing detailed plans. By implementing this package of experimental devices, we can ensure that FRIB can reach its full scientific potential.