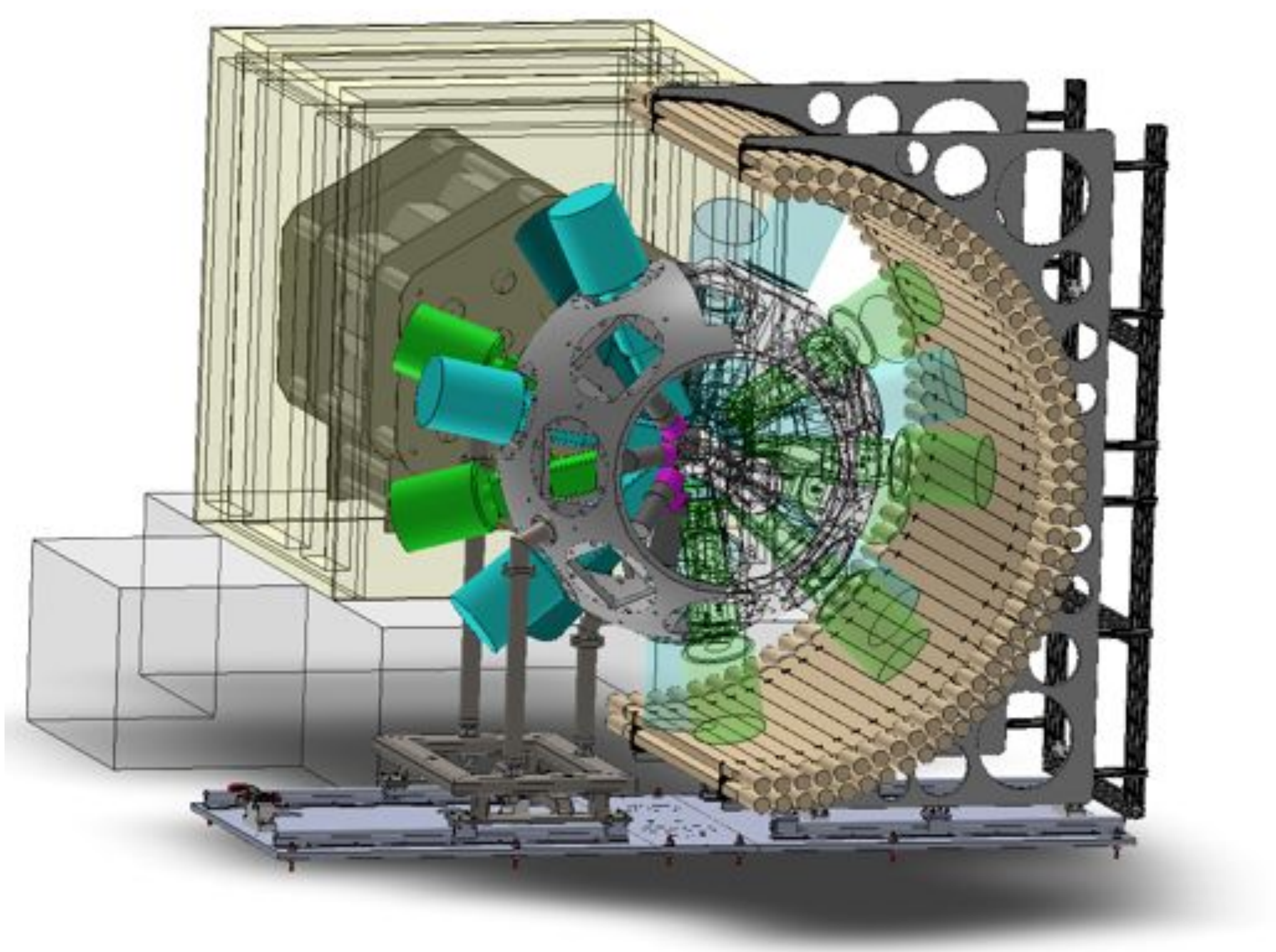
FRIB **D**ecay **S**tation **i**nitiator



Proposal
May 2020

Executive Summary

The Facility for Rare Isotope Beams (FRIB) will provide unprecedented access to exotic nuclei; approximately 80% of the isotopes predicted to exist up to uranium (Z = 92) will be produced. The FRIB Decay Station (FDS) — an efficient, granular, and modular multi-detector system designed under a common infrastructure — will be uniquely positioned for discovery experiments at the extremes of the accessible regions due to the high sensitivity and relatively low beam-rate requirements of decay spectroscopy techniques. In addition, for nuclei produced at higher rates, the FDS will be able to conduct high-precision measurements for thorough characterization of emergent phenomena, which can be used to benchmark and differentiate between leading models. The FDS will have a transformative impact on our understanding of nuclear structure, nuclear astrophysics, fundamental symmetries, and isotopes of importance to applications. The scientific program enabled by the FDS is well aligned with the overarching science goals that have been formulated by the broader nuclear science community, most recently outlined in the 2015 NSAC Long Range Plan. The FDS will contribute to the majority of the seventeen benchmark programs specified in the 2007 NSAC report "FRIB: Opening New Frontiers in Nuclear Science".

The FRIB Decay Station Initiator (FDSi), led by the FDSi Coordination Committee and supported by the FDSi Group, is the initial stage of the FRIB Decay Station (FDS), https://fds.phy.ornl.gov. *The FDSi is primarily an assembly of the best detectors currently available in the community within an integrated infrastructure for Day One FRIB decay studies*, ultimately providing a means for FRIB users to conduct world-class decay spectroscopy experiments with the best equipment possible and to transition to the FDS without interruption to the user program. *The FDSi infrastructure will remain intact at FRIB, ready to receive community detectors that will nominally travel.*

The majority of the underlying components of the FDSi exist within the community. Comprehensive integration of community resources within a common infrastructure and an investment in additional electronics and detectors, particularly aimed towards a hybrid Si DSSD and fast scintillator implant detector, XSiSi, will enable the FDSi to reach its full discovery potential by extending the scientific reach further towards the limits of nuclear existence. *The new XSiSi implant detector is required to enable high-rate, proton-rich, and Z > 50 (multi-charge state) studies, which the community has expressed strong interest in pursuing. XSiSi will also expand the number of measured nuclei per experiment, thereby maximizing the results and overall value.*

The scientific reach accessible through decay spectroscopy of isotopes produced at FRIB will be realized with the FDSi, which will bring multiple complementary detection modes together in a framework capable of performing spectroscopy with multiple radiation types (e.g., gamma rays, charged particles, and neutrons) over a range of beam production rates spanning ten orders of magnitude. The performance of the FDSi hardware and its reach for scientific output depends on the combined efficiency and sensitivity of the instrumentation and the rapid reconfigurability permitted by the infrastructure.

The FDSi mechanical infrastructure approach will enable execution of multiple measurements in quick succession when particular detector systems cannot be combined, by placing two systems along the beam trajectory and using removable implantation detectors to choose the stopping point at the first (discrete spectroscopy) or second (total absorption / neutron-counting spectroscopy) location together with manipulating the focal length of the last stage of the fragment separator beamline. Such a combination of instrumentation and measurements will provide a unique and powerful opportunity for consistent and thorough decay measurements.

In order to reconfigure the discrete array between proton- and neutron-rich investigations, particularly within a single campaign, the FDSi infrastructure will necessitate a switchyard or cart system for exchanging hemispheres. A new platform system on rails for the second focal point provides similar strategic advantages. *These reconfiguration capabilities of the infrastructure will minimize downtime, maximize FDSi opportunities, and, therefore, the FDSi scientific productivity.* This rapid reconfiguration capability of the infrastructure is also important in year 1 due to it being positioned immediately behind the separator where there will be limited access. *The FDSi will be capable of nominal proton- and neutron-rich workhorse configurations on Day 1 FRIB with tandem discrete and total-absorption spectroscopy capabilities.*

The total cost estimate to implement the FDSi is $1283k, which is spread over three years and based on a combination of budgetary quotes and actual costs from prior projects. The cost estimate includes mechanical infrastructure, electronics, Si detectors, and 10% contingency. Tax, overhead, and engineering costs were not included but an FDSi Project Engineer from FRIB is also requested to assist with the remaining (low risk) mechanical designs and implementation at FRIB. Otherwise, the FDSi Group will need to provide this additional in-kind contribution. *No new technological developments are necessary for implementing the FDSi.* Facility requirements and community contributions can be found in the appendices.

Table: Cost estimate for three stages of the FDSi, which do not include tax, overhead, or engineer time. The 2nd and 3rd year of funding will enable additional opportunities in-line with FRIB beam development.

	Y1 ($k)	**Y2 ($k)**	**Y3 ($k)**	**Comments**
Mechanical	290	145	100	$535k mechanical needs (#1 priority)
Electronic	162	253	35	$450k electronic needs
Detector	108	10	43	$161k of new detector needs
Other	0	20	0	$20k of other needs
Contingency	**56**	**43**	**18**	10% contingency
Total	**616**	**471**	**196**	Grand total of $1283k over 3 years

Table of Contents

1. Introduction

The Facility for Rare Isotope Beams (FRIB) will provide unprecedented access to exotic nuclei; approximately 80% of the isotopes predicted to exist up to uranium (Z = 92) will be produced [Erl12, Afa13]. *The FRIB Decay Station*, *which will be used to study the decay properties and structure of these isotopes, will have a transformative impact on our understanding of nuclear structure, nuclear astrophysics, fundamental symmetries, and isotopes of importance to applications*.

The FRIB Decay Station Initiator (FDSi), led by the FDSi Coordination Committee and supported by the FDSi Group, is the initial stage of the FRIB Decay Station (FDS), https://fds.phy.ornl.gov. *The FDSi is primarily an assembly of the best detectors currently available in the community within an integrated infrastructure for Day One FRIB decay studies*, ultimately providing a means for FRIB users to conduct world-class decay spectroscopy experiments with the best equipment possible and to transition to the FDS without interruption to the user program. *The FDSi infrastructure will remain intact at FRIB, ready to receive community detectors that will nominally travel.*

The majority of the underlying components of the FDSi exist within the community. Comprehensive integration of community resources within a common infrastructure and an investment in additional electronics and detectors, particularly aimed towards a hybrid Si DSSD and fast scintillator implant detector, XSiSi, would enable the FDSi to reach its full discovery potential by extending the scientific reach further towards the limits of nuclear existence. *The new XSiSi implant detector is required to enable high-rate, proton-rich, and Z > 50 (multi-charge state) studies, which the community has expressed strong interest in pursuing. XSiSi will also expand the number of measured nuclei per experiment, thereby maximizing the results and overall value.*

The scientific program enabled by the FDSi and eventual FDS is well aligned with the overarching science goals that have been formulated by the broader nuclear science community, see Table 1 [NSAC02, NRC13, NSAC RIB07, NSAC07, NSAC15]. These principal areas of investigation in nuclear science have been reaffirmed multiple times, most recently in the 2015 NSAC Long Range Plan [NSAC15]. A total of seventeen specific benchmark programs were specified in the NSAC report "FRIB: Opening New Frontiers in Nuclear Science" [NSAC RIB07] that are matched to the broad scientific questions in Table 1. *The FDSi will contribute to the majority of the seventeen benchmark programs.*

The FDSi is uniquely positioned to make crucial contributions towards discovery experiments at the extremes of the accessible regions, see FRIB beam rates in Figure 1. The high sensitivity and relatively low beam-rate requirements of the various decay spectroscopy techniques, which are outlined in Figure 2, enable decay measurements at the very limits of the production capabilities at FRIB. In addition, for nuclei produced at higher rates, the FDSi will enable high-precision measurements for thorough characterization of emergent phenomena, which can be used to benchmark and differentiate between leading models.

Table 1: The seventeen benchmark programs determined by the NSAC Rare-Isotope Beam Task Force [NSAC RIB07] are organized under the four priority questions in nuclear physics identified by the Nuclear Science Advisory Committee [NSAC15] and the National Academy of Sciences [NRC13]; The FRIB Decay Station will contribute to the majority of the benchmark programs (listed in bold).

Nuclear Structure	**Nuclear Astrophysics**	**Fundamental Symmetries**	**Applications of Isotopes**
How does subatomic matter organize itself and what phenomena emerge?	*How did visible matter come into being and how does it evolve?*	*Are the fundamental interactions that are basic to structure of matter fully understood?*	*How can the knowledge and technical progress provided by nuclear physics best be used to benefit society?*
1. Shell structure	**1. Shell structure**	**12. Atomic EDM**	**10. Medical**
2. Superheavies	6. Equation of state	**15. Mass surface**	**11. Stewardship**
3. Skins	**7. r-Process**	**17. Weak interactions**	
4. Pairing	**8. ^{15}O(α,γ)**		
5. Symmetries	**9. ^{59}Fe s-process**		
6. Equation of state	**13. Limits of stability**		
13. Limits of stability	**15. Mass surface**		
14. Weakly bound nuclei	**16. rp-process**		
15. Mass surface	**17. Weak interactions**		

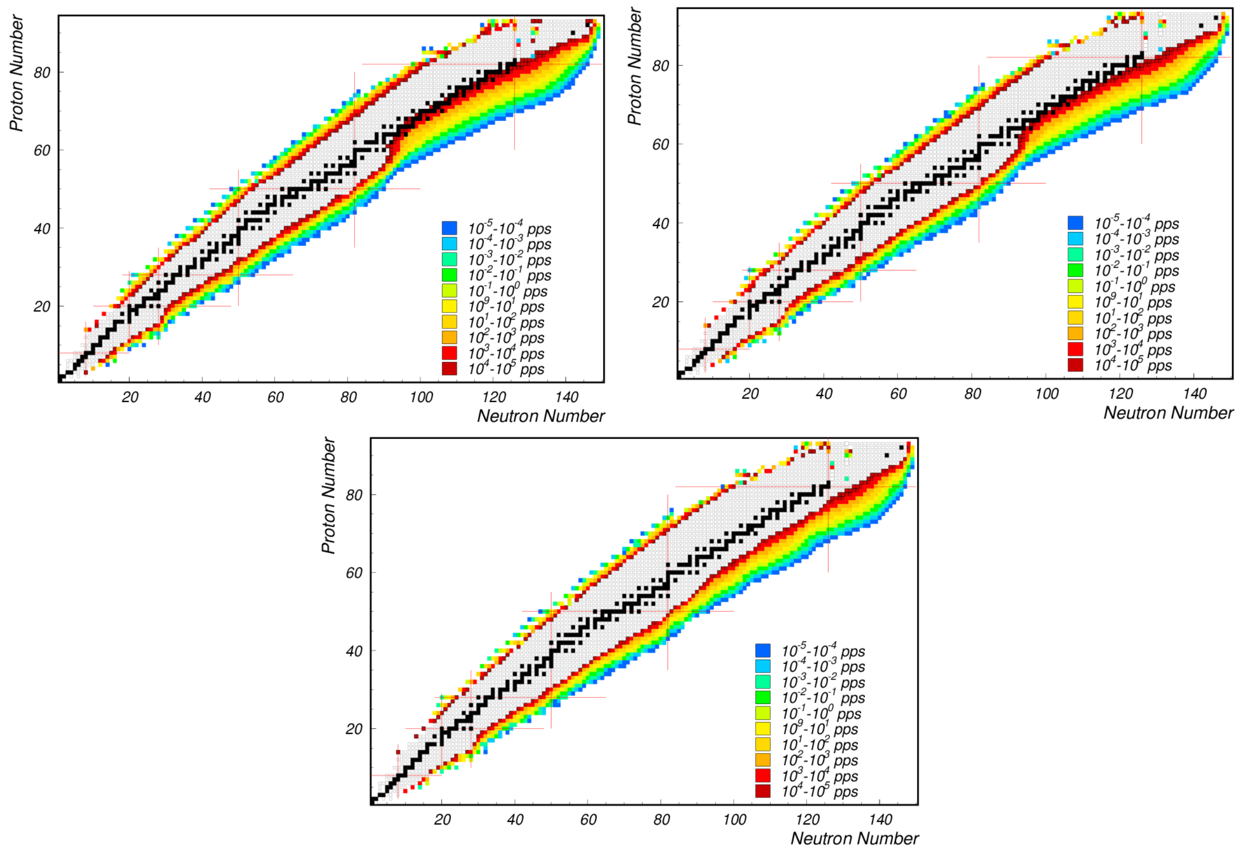


Figure 1: FRIB fast-beam rates between 10^{-4} and 10^{5} pps, [FRIB]. Rates > 10^{5} pps not shown. (Top Left) Year one 10 kW, (Top Right) Year two (50 kW), (Bottom) Full FRIB (400 kW)

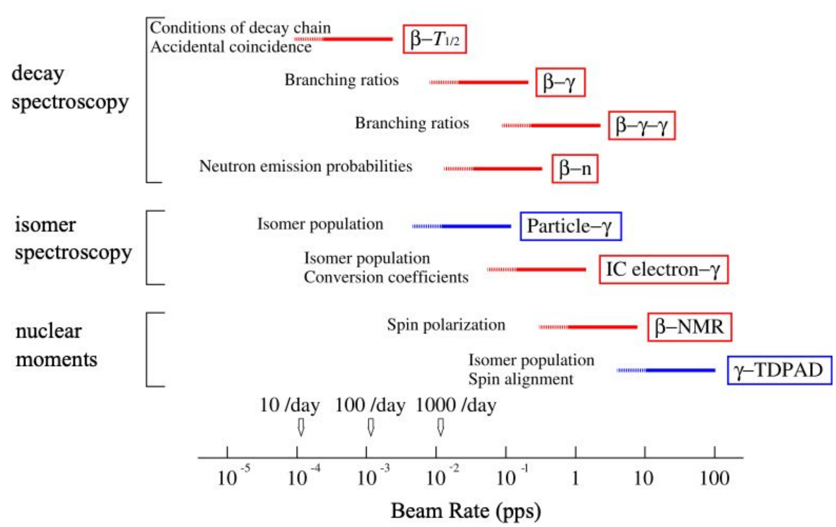


Figure 2: Rate requirements for various decay-spectroscopy techniques [Nak17], assuming efficiencies of 50% for β particles, 10% for γ rays, and 20% for neutrons, which is comparable to the FDSi. The FDS will reduce these rate requirements by increasing both individual and combined efficiencies.

The scientific reach accessible through decay spectroscopy of isotopes produced at FRIB will be realized with the FDSi, which will bring multiple complementary detection modes together in a framework capable of performing spectroscopy with multiple radiation types (e.g., gamma rays, charged particles, and neutrons) over a range of beam production rates spanning ten orders of magnitude. The performance of the FDSi hardware and its reach for scientific output depends on the combined efficiency and sensitivity of the instrumentation and the rapid reconfigurability permitted by the infrastructure. *The FDSi will be capable of nominal proton- and neutron-rich workhorse configurations on Day 1 FRIB with tandem discrete and total-absorption spectroscopy capabilities.*

The physics opportunities in strategic regions will be outlined in Section 2. Technical details of the FDSi are outlined in Section 3. Section 4 summarizes the organizations involved. Finally, the cost and scheduling are given in Section 5. Facility requirements and community contributions can be found in the appendices.

2. Towards the Limits of Nuclear Existence with the FDSi

The breadth of science and discovery potential enabled by the FDS, and similarly for the FDSi, was outlined in the FDS Whitepaper, https://fds.phy.ornl.gov/FDS-WP.pdf. Here we provide a summary of strategic regions for Day 1 and the early years of FRIB, see Figure 3, and make the connection in Table 2 to (1) the primary beam, (2) the science opportunity, and (3) the required detector configurations. These regions encompass the contributed interests of the community that were expressed in preparation for the FDS Whitepaper and the FRIB First Experiments: Proposal Preparation Workshop, https://indico.frib.msu.edu/event/20/.

In addition, specific examples of FDSi science opportunities within these strategic regions for Day 1 FRIB were outlined by the community at the FRIB Day 1 Science Workshop at the 2017 LECM, see the program and talks at https://fribusers.org/gatherings/fribday1-2017.html. The following examples were highlighted:

- Shell survival near ^{60}Ca, ^{100}Sn, and ^{226}Pb
- Island of inversion and np-mh structure: ^{33}Mg, ^{30}Ne, and ^{29}Ne
- Sub-shells near ^{54}Ca, ^{55}Sc, ^{53}K, ^{51}Ca, ^{53}Ca, and ^{55}Ca
- Portal to the 5th island of inversion, deformation, and r-process waiting point: ^{77}Ni and ^{78}Ni
- Bottlenecks for modeling type I X-ray burst light curves: ^{20}Mg decay
- Nucleosynthesis constraints from decay data in the open-shell regions: ^{124}Nb

These community examples require the diverse set of detector configurations provided in Table 2.

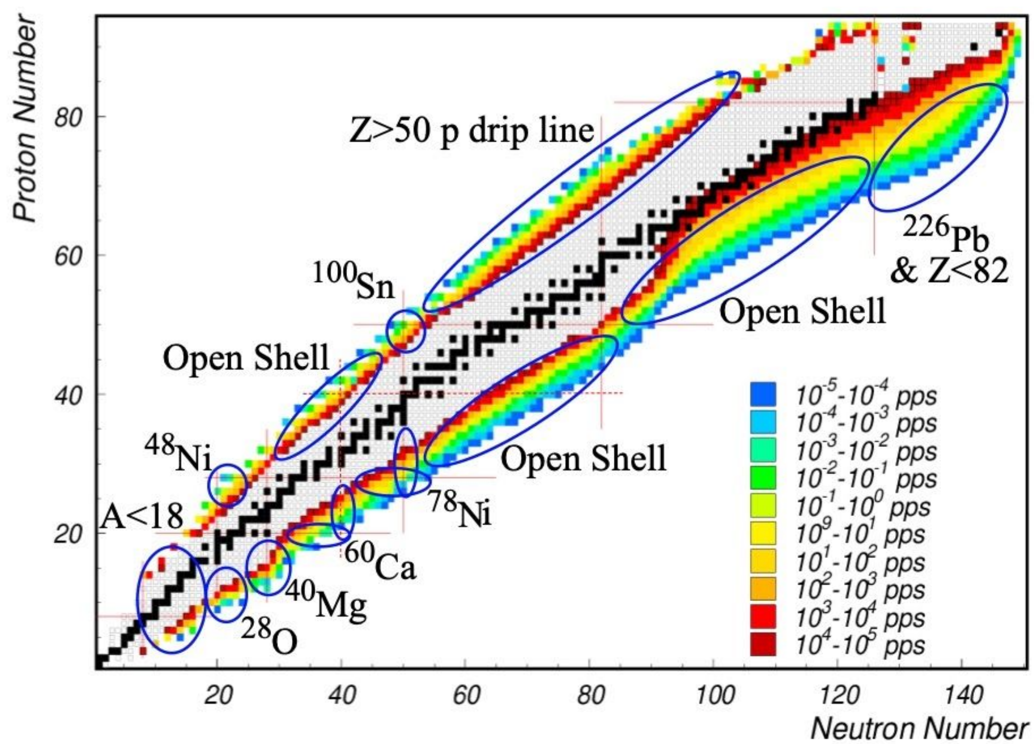


Figure 3: Strategic regions for Day 1 and the early years of FRIB: approaching the extremes.

Table 2: Regions of interest and physics opportunities listed by primary beam and required detector configuration. Primary beams for each region were taken from the FRIB Day 1 calculator

Primary Beam	Region	Physics Opportunities	Detector Configuration
^{18}O	**A<18**	Ab-initio theory benchmarks, neutron-drip line	XSiSi-NEXTi-DEGAi 3HeNi
^{36}Ar**	**N>Z<20**	Ab-initio theory benchmarks, neutron-dripline	XSiSi-NEXTi-DEGAi, MTAS, 3HeNi
^{48}Ca*	**^{28}O**	Deformation and islands of inversion	XSiSi-NEXTi-DEGAi, MTAS, 3HeNi
	^{40}Mg	Deformation and islands of inversion	XSiSi-NEXTi-DEGAi, MTAS, 3HeNi
^{78}Kr	**^{48}Ni**	Exotic pn correlations and 2p-emission	XSiSi/GADGET-DEGAi
	Open Shell 20<N=Z<38	Exotic pn correlations and deformation	XSiSi/GADGET-DEGAi
^{82}Se*	**^{60}Ca**	Weak binding effects and 3N forces	XSiSi-NEXTi-DEGAi, MTAS, 3HeNi
	N-rich Open Shell Z=20-28	Deformation, 3N forces, and benchmark of state-of-the-art theory	XSiSi-NEXTi-DEGAi, MTAS, 3HeNi
^{86}Kr**	**^{78}Ni**	Portal to the 5th island of inversion? R-process, antineutrino, decay heat	XSiSi-NEXTi-DEGAi, MTAS, 3HeNi
^{124}Xe	**^{100}Sn**	Exotic pn correlations and decay modes, superallowed alpha	XSiSi/GADGET-DEGAi, MTAS
	Open Shell N=Z>36	Exotic pn correlations and deformation	XSiSi/GADGET-DEGAi, MTAS
^{238}U	**N-rich Open Shell Z>28**	Search for asymmetric shapes and new classifications of collectivity; r-process ; decay heat; antineutrino	XSiSi-NEXTi-DEGAi, MTAS, 3HeNi
	Z>50 p drip line	Mapping the drip-line and xp-emission	XSiSi/GADGET-DEGAi, MTAS
	^{226}Pb and Z<82	Seniority at the extreme, r-process	XSiSi-NEXTi-DEGAi, MTAS, 3HeNi

*unique to FRIB

**Guaranteed beams (CD-4)

3. The FRIB Decay Station Initiator (FDSi)

The FRIB Decay Station Initiator (FDSi), led by the FDSi Coordination Committee and supported by the FDSi Group, is the initial stage of the FRIB Decay Station (FDS), https://fds.phy.ornl.gov. The construction of the FDSi will enable access to the physics opportunities outlined in the previous section of this proposal. *The FDSi is primarily an assembly of the best detectors currently available in the community within an integrated infrastructure for Day One FRIB decay studies*, ultimately providing a means for FRIB users to conduct world-class decay spectroscopy experiments with the best equipment possible and to transition to the FDS without interruption to the user program. *The FDSi infrastructure will remain intact at FRIB, ready to receive community detectors that will nominally travel;* campaigns are anticipated in the early years of FRIB.

The majority of the underlying components of the FDSi exist within the community. Comprehensive integration of community resources within a common infrastructure and an investment in additional electronics and detectors, particularly aimed towards a hybrid Si DSSD and fast scintillator implant detector, XSiSi, would enable the FDSi to reach its full discovery potential by extending the scientific reach further towards the limits of nuclear existence. *The new XSiSi implant detector is required to enable high-rate, proton-rich, and Z > 50 (multi-charge state) studies, which the community has expressed strong interest in pursuing. XSiSi will also expand the number of measured nuclei per experiment, thereby maximizing the results and overall value.*

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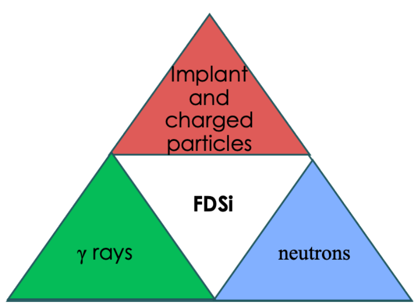


Figure 4: Decay modes and core FDSi components

The FDSi will require an infrastructure composed of modular multi-detector systems with the ability to measure nuclear decays and the resulting delayed emissions, which include charged particles, photons, and neutrons, see Figure 4. At the core of the FDSi is a system to stop the incoming exotic ions and detect subsequent charged-particle decay emissions (XSiSi). Additional detector arrays will surround this system to measure emitted photons (DEGAi), neutrons (NEXTi), or both. The exact configuration of the charged-particle, photon, and neutron detection arrays will be dependent on the specific science goals of each experiment, and it will be adaptable to optimize tradeoffs between energy resolution, time resolution, efficiency, and background. Behind the discrete array at a second focal point, there will be a segmented total absorption spectrometer, MTAS, which is the largest and most efficient total absorption gamma-ray spectrometer in the world.

The FDSi infrastructure approach will enable execution of multiple measurements in quick succession (and possibly simultaneously) when particular detector systems cannot be combined, by placing two such systems along the beam trajectory and using removable implantation detectors to choose the stopping point at the first (discrete spectroscopy) or second (total absorption / neutron-counting spectroscopy) location together with manipulating the focal length of the last stage of the fragment separator beamline. Such a combination of instrumentation and measurements will provide a unique and powerful opportunity for consistent and thorough decay measurements. The FDSi with a two-focal point solution can be seen in Figure 5.

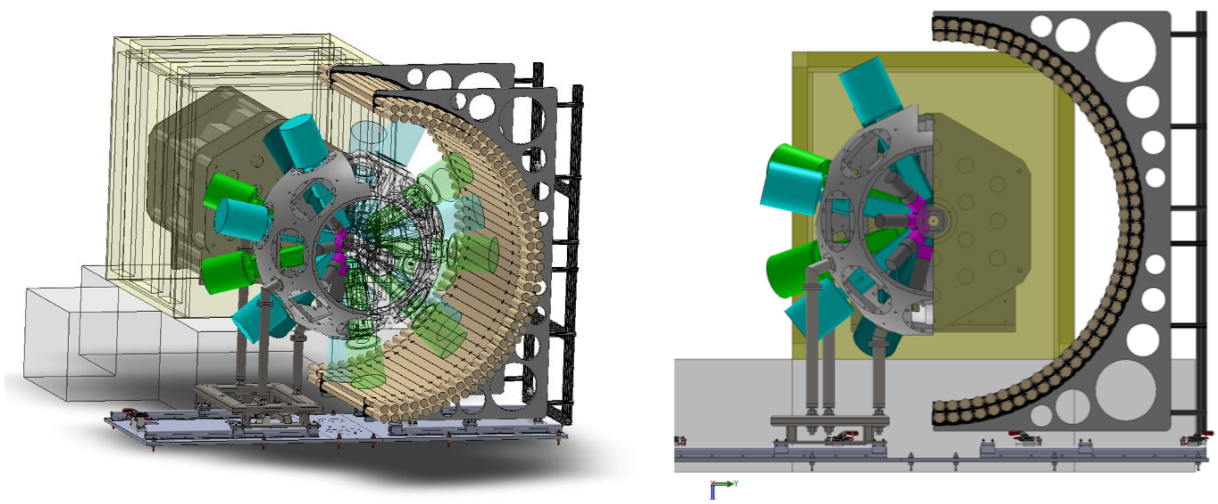


Figure 5: Two-focal point solution of the FDSi mechanical infrastructure from two perspectives.

In order to reconfigure between proton- and neutron-rich investigations, particularly within a single campaign, the FDSi infrastructure will necessitate a switchyard or cart system for exchanging hemispheres. A new platform system on rails for the second focal point provides similar strategic advantages. *These reconfiguration capabilities of the infrastructure will minimize downtime, maximize FDSi opportunities, and, therefore, the FDSi scientific productivity.* This rapid reconfiguration capability of the infrastructure is also important in year 1 due to it being positioned immediately behind the separator where there will be limited access. *The FDSi will be capable of nominal proton- and neutron-rich workhorse configurations on Day 1 FRIB with tandem discrete and total-absorption spectroscopy capabilities.*

3.1 Detector Subsystems

3.1.1 DEGAi - Discrete Gamma Rays

General description of the instrument

Discrete gamma-ray spectroscopy is essential for nearly all experiments on both the proton- and neutron-rich side of stability (see Table 2 in Section 2). The DEcay Germanium Array initiator (DEGAi) will provide a hybrid of 2π and 4π solid-state and scintillator-based solutions with variable balancing of energy resolution, time resolution, and efficiency. DEGAi will use roughly $4.7M dollars worth of existing discrete gamma-ray detectors integrated through the existing CLARION1 hemispheres, which are worth nearly $0.5M. New port adapters, sleighs, posts, platforms, and rails are required for integration into the DEGAi-FDSi framework.

Technical description

Within the FDSi Group, there are 11 CLARION (ORNL) and 8 CloverShare (ANL) HPGe clover detectors at a value of nearly $3M; there are additional clover detectors within the community that could be used with the FDSi on occasion, e.g., FSU. HPGe provides the pinnacle of energy resolution (FWHM~2-3 keV at 1.3 MeV) and good photopeak efficiency. A clover schematic is shown in Figure 6.

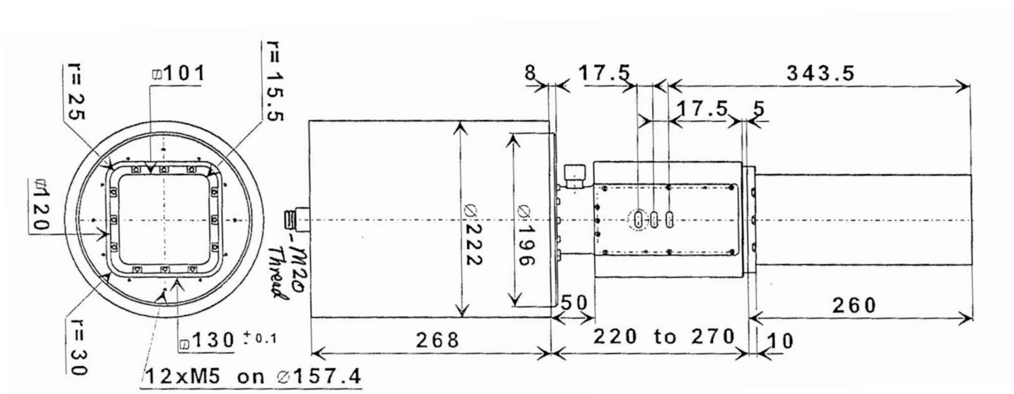


Figure 6: EURISYS clover design common to CLARION, CLOVERSHARE, and others within the USA community, which have four 5 cm x 8 cm (pre-cut) HPGe crystals per cryostat. However, the neck length (i.e., from preamp housing slots to dewar flange) can vary between serial numbers. Yet, the distance from the front face of the detector to the preamp slots are uniform among all the EURISYS clovers of this type.

In addition to HPGe clover detectors, there are 10 3” x 3” and 20 2” x 2” $LaBr_3$ detectors from the HAGRID array at UTK; 4 3” x 3” $CeBr_3$ and 10 3” x 3” $LaBr_3$ detectors from Miss. SU; 16 1.5” x 1.5” $LaBr_3$ detectors from MSU; and 12 2" x 2" $CeBr_3$ detectors (special low background) from the clover array at TUNL, which total to a value of nearly $1.7M. These scintillator-based detectors provide fast timing capabilities, high efficiency, and relatively good energy resolution (3% at 1.3 MeV).

It is imperative that the discrete gamma-ray array be able to support both 2π and 4π configurations and that reconfiguration between the two is rapid and seamless, e.g., reconfigurating between

DEGAi(2π)-NEXTi(2π)-XSiSi and DEGAi(4π)-XSiSi. The CLARION1 hemispheres are an existing resource that can accommodate this requirement along with the demand of port and detector combination options, supporting both neutron- and proton-rich physics opportunities. Three views of the 4π DEGAi configuration, which are fully loaded with 24 HPGe clover detectors, are shown in Figure 7. With 24 clovers, the expected efficiency at 1 MeV is 13.1(26)%. With 16 clovers, the expected efficiency at 1 MeV is 10.4(21)%. 2π DEGAi configurations, which will typically couple to NEXTi, are shown in Figure 8. The $LaBr_3$/$CeBr_3$ efficiency at 1 MeV for nominal 2π and 4π configurations with clovers installed are 2.1(4)% and 4.2(8)%, respectively, but these can be made higher at the expense of HPGe efficiency.

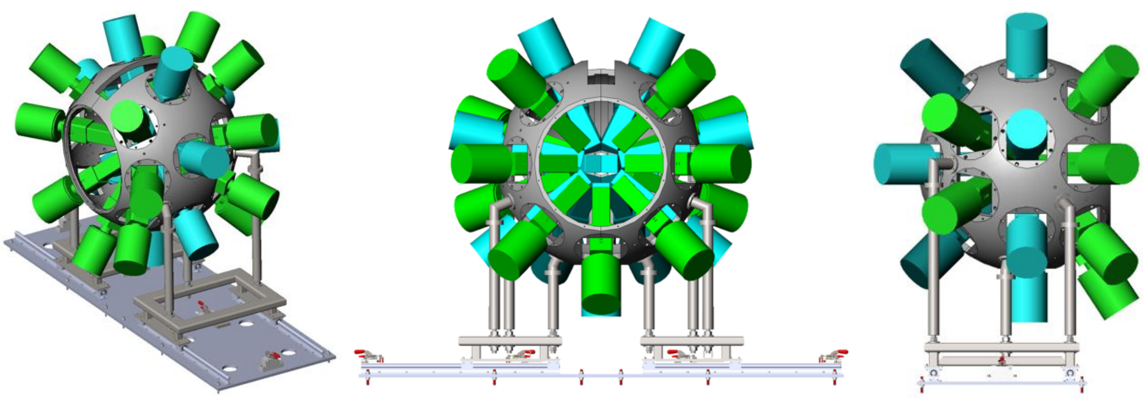


Figure 7: CLARION1 reconfigured for a 4' beam height. Blue clovers = nominal clovers at small radii for primary efficiency. Green clovers = spare ports for additional clovers at larger radii, $LaBr_3$, etc.. The HPGe photopeak Efficiency(1 MeV) = 13.1(26)% with all 24 ports populated with clovers and 10.4(21)% with 16 ports populated with clovers.

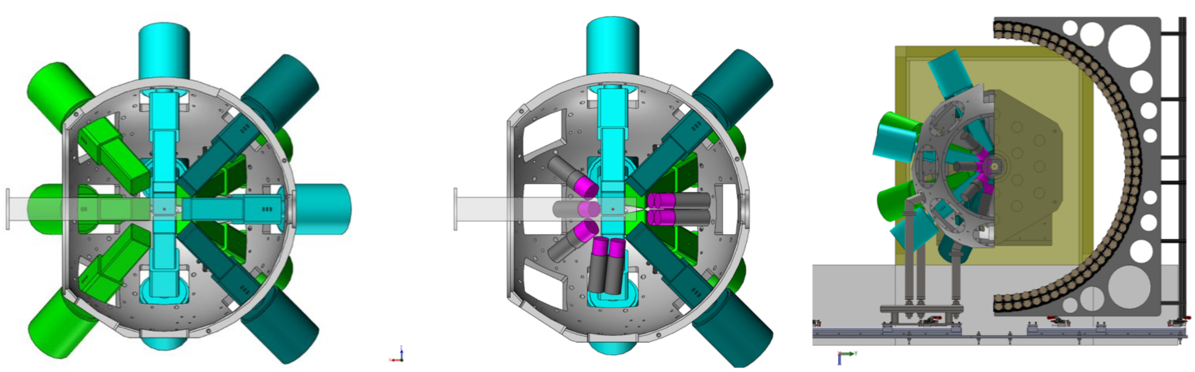


Figure 8: 2π CLARION1 HPGe Efficiency(1 MeV) = 6.0(12)% for the left configuration and 4.1(8)% for the middle and right configurations. $LaBr_3$/$CeBr_3$ Efficiency(1 MeV) = 2.1(4)% for the middle and right configurations. These configurations do not intrude into the other 2π of solid angle.

The port ids, pad distances, pad angles, nominal clover radii, and expected clover efficiencies are provided in Table 3. The nominal orientation positions the large opening side of the hemispheres upstream, which can be used to support implant housing, support, and preamp infrastructure. However, the hemispheres can be rotated by 180 degrees to place the large opening side downstream if necessary but at the expense of having to remove or pull clovers from ports C11 and C12 to larger radii.

Table 3: Port geometry (24 total) of CLARION1 hemispheres and nominal clover radii. X = up and Z = beam direction. Eff = Eff(sim) * 0.8 +/- Eff(sim) * 0.2

Port id	Pad r (inches)	Theta	Phi	Clover r (cm)	Eff (1 MeV)%
c1	22.2	90.0	308.6	10.67	0.82
c2	22.2	90.0	257.1	10.67	0.82
c3	22.2	90.0	205.7	10.67	0.82
c4	22.2	90.0	154.3	10.67	0.82
c5	22.2	90.0	102.9	10.67	0.82
c6	22.2	90.0	51.4	10.67	0.82
c7	22.2	48.0	334.0	14.48	0.50
c8	22.2	48.0	206.0	14.48	0.50
c9	22.2	48.0	154.0	14.48	0.50
c10	22.2	48.0	26.0	14.48	0.50
c11	22.2	25.0	270.0	10.67	0.82
c12	22.2	25.0	90.0	10.67	0.82
h1	22.2	123.0	0.0	18.8	0.34
h2	22.2	60.0	290.0	18.8	0.34
h3	22.2	60.0	250.0	18.8	0.34
h4	22.2	60.0	110.0	18.8	0.34
h5	22.2	60.0	70.0	18.8	0.34
p1	22.2	123.0	315.0	18.8	0.34
p2	22.2	123.0	270.0	18.8	0.34
p3	22.2	123.0	225.0	18.8	0.34
p4	22.2	123.0	135.0	18.8	0.34
p5	22.2	123.0	90.0	18.8	0.34
p6	22.2	123.0	45.0	18.8	0.34
EP1	22.2	90.0	0.0	10.67	0.82
TOTAL					13.1(26)%

*These positions have undergone two rotations of 180 degrees with respect to the original orientation of CLARION when the hemispheres were hanging and the large opening side was downstream.

Present status of GEANT4 simulations

The simulated efficiencies of 4π and 2π DEGAi are compared to other arrays in Figure 9. DEGAi provides a clear improvement over betaSeGA at NSCL. The gains of the GRIFFIN array at TRIUMF in Vancouver, Canada, a possible box configuration of 5 GRETINA detectors, and DEGA, as outlined in the FDS Whitepaper, over DEGAi exemplify the need for DEGA-FDS. Nevertheless, DEGAi provides a critical first step towards DEGA and our reach for the extreme limits of nuclear existence. At present, two parallel / independent simulations of DEGAi have been developed, showing consistent results.

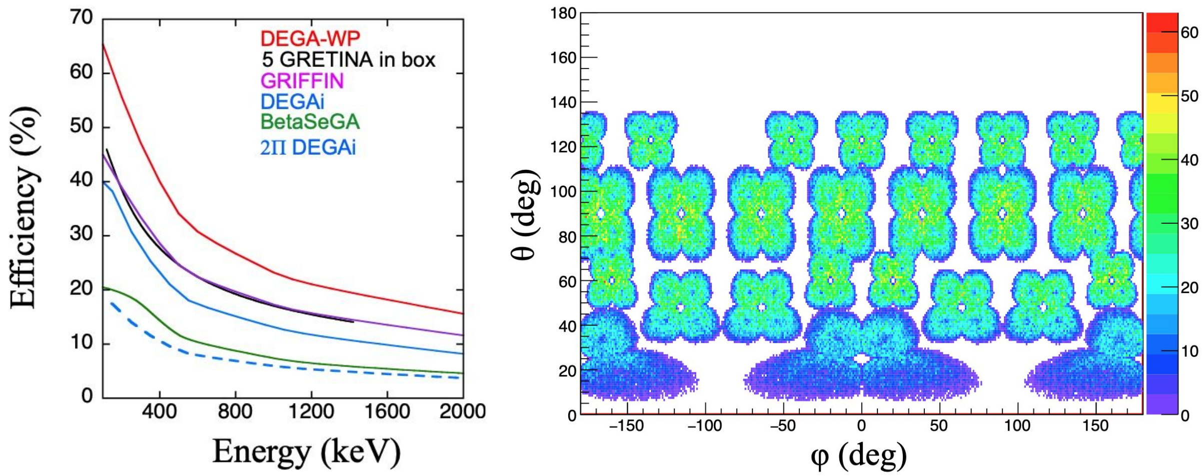


Figure 9: (left) HPGe efficiencies for the future DEGA-WP (WhitePaper), a box configuration of 5 GRETINA detectors, GRIFFIN, DEGAi (present proposal), BetaSeGA, and 2π DEGAi (present proposal); the 2π configuration of DEGAi is slightly less than half of the 4π efficiency due to removal of detectors on the split of the hemispheres; this is to remove all shadowing with NEXTi (VANDLE). (right) Simulated theta-phi map of DEGAi clovers showing minimal shadowing of clovers.

Present status of the instrument

Reconfiguration of a CLARION hemisphere from the original hanging design at HRIBF-ORNL to a floor supported design was recently implemented in the move from room C-116 to C-110 at ORNL, see Figure 10, and the array was subsequently tested through decay studies of neutron-activated ^{237}Np. The new support structure to place the CLARION hemispheres at the required 4' beam height at FRIB is based on this tested design.

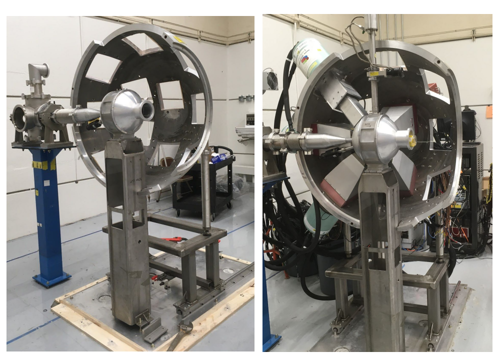


Figure 10: A CLARION hemisphere unpopulated and partially populated in the new floor-supported design. 12% of 4π opens on the right hand side of the image, which will normally be used as the upstream side of the FDSi.

Description of electronics and integration methods

The channel density of DEGAi will be fairly modest in that no more than 96 are ever anticipated. For the clovers, there are several existing Pixie16 (14-bit 100 MHz) waveform digitizer systems, including the CLARION2 Pixie16 (REV F) digital system, that can be used and integrated with the others. The $LaBr_3/CeBr_3$ detectors will require Pixie16 (14-bit 250 MHz or better) digitizers from the UTK, Miss. SU, or FRIB pool. No new costs are expected for DEGAi data acquisition. However, a new integrated HV-LN2 system to operate the large variety of detectors and to monitor and protect the contributed community resources is necessary.

Plan for development and required budget

New port adapters, sleighs, posts, platforms, and rails are required for integration of the CLARION hemispheres, clovers, and $LaBr_3/CeBr_3$ detectors into the DEGAi-FDSi framework. This is estimated to cost \$100k (\$25k per hemisphere and \$50k for the adapters). Additional funds on the order of \$75k will be required for the FDSi to implement a switchyard or cart system to exchange 2π DEGAi and NEXTi arrays for proton- and neutron-rich studies, see Section 3.3.1 for additional details. This reconfiguration capability of the infrastructure will minimize downtime, maximize FDSi opportunities, and, therefore, the FDSi scientific productivity; this rapid reconfiguration capability of the infrastructure is also important in year 1 due to it being positioned immediately behind the separator where there will be limited access. Costs are based on commercial parts and machining; machining some parts at UTK, FSU, TUNL, or MSU shops could save money.

The CLARION and CLOVERSHARE HPGe clovers and their preamps are generally maintained by ORNL and ANL, respectively. Preamps are one of the largest costs in routine maintenance of the clover detectors; crystals with new preamps tend to show the best resolution. Further, the latest preamp design supports a motherboard and socket design, permitting rapid preamp replacement without the need to solder or change wires and headers. As the older clover preamps fail or show signs of degraded energy resolution, they will be replaced with the new preamp design. However, preamp failures do occur at random and upon improper usage. Therefore, it is imperative to maintain a supply of spare preamps as well. In order to help support the maintenance of community clovers, \$35k is requested to provide 4 clovers worth of spare preamps. Maintenance of the CLARION clovers will remain with ORNL as an in-kind contribution.

In order to benefit from the large variety of HPGe (up to 96 crystals) and $LaBr_3/CeBr_3$ (up to 72 PMTs) detectors within the community, a single integrated LN2 and HV system is needed for DEGAi to not only operate the devices but also to monitor and protect the resources entrusted upon us. The aging CLARION HV mainframe system could be used if necessary but it is no longer reliable for routine transport and it is anticipated to be occupied elsewhere, as is its LN2 system. A duplication of the ORNL GRETINA and CLARION LN2 systems, which are familiar to local FRIB staff and are maintained by a FDSi Group member, can be produced for \$30k, which would include: two 13-port supply manifolds; two 13-port exhaust manifolds; 28 solenoids; rtds; cables; nalgene hoses, insulation, and fittings; and a computer with adcs and relays. Further, a LN2 buffer tank from FRIB will be required or a new one will need to be purchased for \$15k. The LN2 system will also control a single HV mainframe with 48 3.5-kV / 3.5-mA channels and 96 8-kV / 20-μA channels, which will cost \$102k. This system will have mixed polarity capability and it will be able to power more recent small-anode HPGe detectors, which often require > 5kV. The DEGAi HV-LN2 system will also fulfill all future DEGA-FDS requirements, permitting a seamless transition.

Two months of Engineer time will be required for adapter designs and integrating DEGAi into the FDSi framework of versatile reconfigurations. In addition, engineer time will be required to oversee the machining and implementation of DEGAi-FDSi on the floor.

		Cost ($k) **(Y1) (Y2) (Y3)** **(in-kind 1) (2) (3)**	**Comments**
DEGAi (γ)	Mechanical	(100) (30) (0) (0) (0) (0)	Hemi sleighs on rails + adapters, LN2 system (with an existing FRIB buffer tank, +$15k otherwise).
	Electronic	(0) (102) (35) (0) (0) (20)	HV mainframe + modules, spare preamps Preamp, FET, and misc. repairs
	Detector	(0) (0) (0) (0) (0) (0)	
	Other	(0) (0) (20) (0) (0) (6)	Signal cables Transport
		(100) (132) (55) **(0) (0) (26)**	

Implementation in the Day0 floor space

The DEGAi system will require a minimum floor space of 2.7 m x 1.2 m for rails and platforms but additional space will be required for reconfiguration with NEXTi (VANDLE), as outlined in Section 3.3 and 3.4.

3.1.2 NEXTi - Discrete Neutrons

VANDLE neutron array

General description of the instrument

The main component of NEXTi will be an upgraded VANDLE array [Pau14, Pet16], which is a hybrid neutron time-of-flight (TOF) detector that consists of straight plastic bars placed about 1 m from the source. It was designed and optimized for discrete energy measurements of beta-delayed neutrons between 100 keV and 5 MeV, see Figure 11. It uses digital electronics with a custom-developed triggering algorithm which enables the detection of low-energy neutrons. In the current implementation, it is not able to perform pulseshape neutron-gamma discrimination; new detectors will provide this capability in the future.

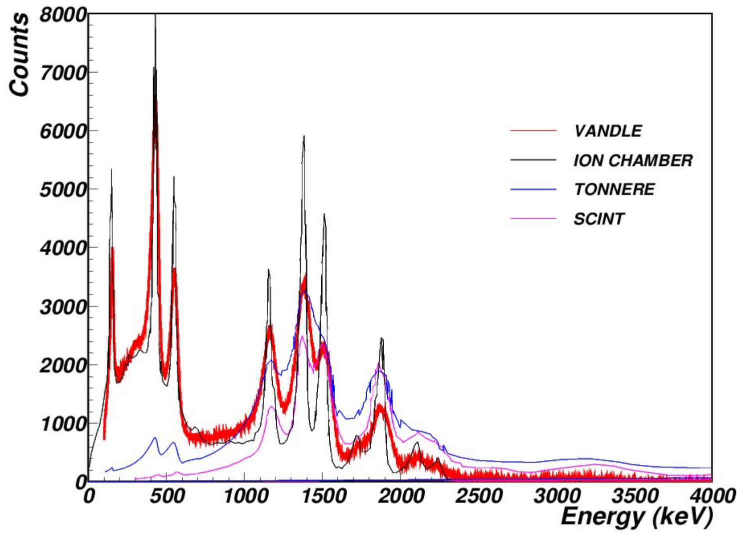


Figure 11: Example neutron spectrum from the VANDLE array taken with ^{49}K, showing the low-energy sensitivity compared to other neutron-detector systems.

Few typical experiments

VANDLE has conducted multiple experiments, see Figure 12, on beta-delayed neutron emitters at ISOL and fragmentation type facilities; it is well tested. The experimental program with the FDSi will focus on studies of beta-delayed neutron emitters near the neutron drip lines and r-process nuclei. The results will be used in part to validate beta-decay models of weakly bound nuclei and to search for multi-neutron emission in cases where P_{2n} exceeds 10%.

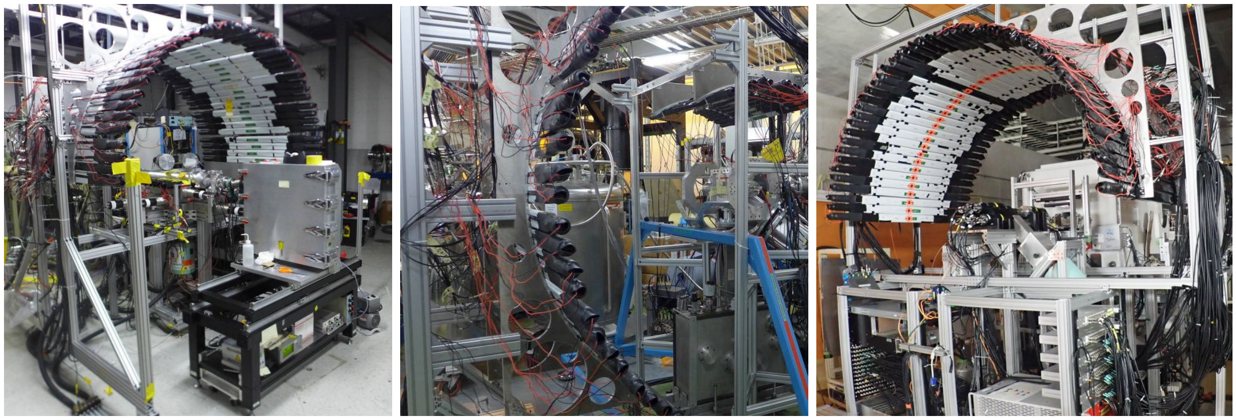


Figure 12: VANDLE detector at ORNL, CERN and RIKEN.

Experiments for Z < 55 can be performed with the existing YSO-based implantation array. However, for heavier nuclei, XSiSi (a hybrid fast scintillator and Si DSSD array) has to be implemented to provide identification for ions with multiple charge states.

Technical description

NEXTi (VANDLE) will include 92 scintillator bars in two vertical arches with 46 detectors per arch, see Figure 13. The detectors will be double stacked to maximize detection efficiency. The scintillator bars are 120x3x6 cm^3 and they are tapered on both ends where two photomultipliers with integrated voltage dividers and high amplification (Hamamatsu model R580) are attached using optical cement. Each bar is wrapped in aluminized mylar and black tape. They will be arranged in a double arch with two parallel modules mounted to an aluminum frame, which will be connected to a rail system. Each detector is connected via 18-ft long cables to a high-voltage power supply rack and digital data acquisition system. The HV system consists of a CAEN mainframe and eight 24-channel modules, which can power 92 bars; the typical operating voltage is 1200 V.

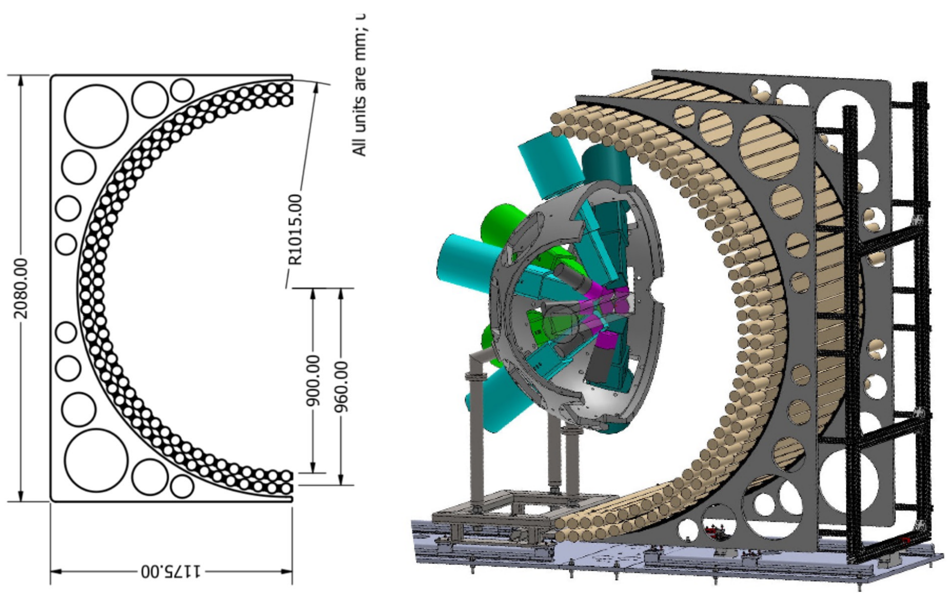


Figure 13: General layout of the VANDLE array and associated gamma-ray array.

The key element of VANDLE is a TOF start trigger with a fast, sub-nanosecond response; this will be provided by a family of fast, segmented scintillator detectors made of YSO [Yok19a] within XSiSi. The readout of these detectors is done using a 8 x 8 segmented, flat-panel photomultiplier (Hamamatsu H12700B). The interaction position is encoded using Anger logic and digital electronics, where only four position signals and one common dynode signal are required.

Present status of the instrument

Presently there are 50 VANDLE modules available. They have been tested and proven to work in previous experiments. The frame for a single-layer configuration exists and can be reused. The existing digital electronics is sufficient to instrument 92 VANDLE modules, a fast scintillator-based implantation array, and associated gamma-ray detectors. The triggering modes have already been implemented and tested in fragmentation type experiments.

The 90 PMTs necessary to construct 45 more detectors already exist. The frame and holders for the FDSi can be designed, machined, or 3D printed at UTK. The fast implantation array needed for VANDLE, which will be integrated into XSiSi, consists of various YSO-based arrays. There are two 5-mm thick implantation arrays with 2”x2” and 3”x3” form factors; a 12-mm thick, 2”x2” array is under construction.

Description of electronics and integration methods

VANDLE uses a fully digital system. Currently, it is instrumented with Pixie16 RevF modules with 12-bit ADCs and 250-MHz sampling frequency. The trigger scheme is described in Ref. [Pau14]. It uses a combination of pairwise coincidences within a single bar and validation by the TOF-start trigger detector, effectively a triple coincidence. This enables a very low-energy detection threshold, placing VANDLE among the most efficient neutron detectors at low energies. The event readout is done using the standard National Instruments PXI interface, which can maintain a stable 70-MB/s data throughput. The data stream consists of time-stamped energies and 300-500-ns long traces for each triple coincidence event. The online analysis code supports high-resolution timing and charge integration. The code is written in C++ and supports root export. Data synchronization can be done using the front panel TTL interface, which can accept an external clock and clear signal. Each event will have a second time-stamp provided by an external clock in addition to the internal time-stamp. This enables easy data synchronization with other systems and it has been tested in experiments at RIKEN and NSCL. The data streams are merged in post processing using root libraries.

Present status of GEANT4 simulations

A VANDLE simulation model has been developed and it has already undergone multiple revisions. Presently, GEANT4 is capable of modeling neutron interactions in the detector and frame materials. It is also capable of photon tracking which is required for complete modeling of the response function. The simulation is capable of modeling the detection efficiency for a given detector configuration and the TOF response. Simulations for a single-arch and double-arch version of VANDLE is given in Figure 14.

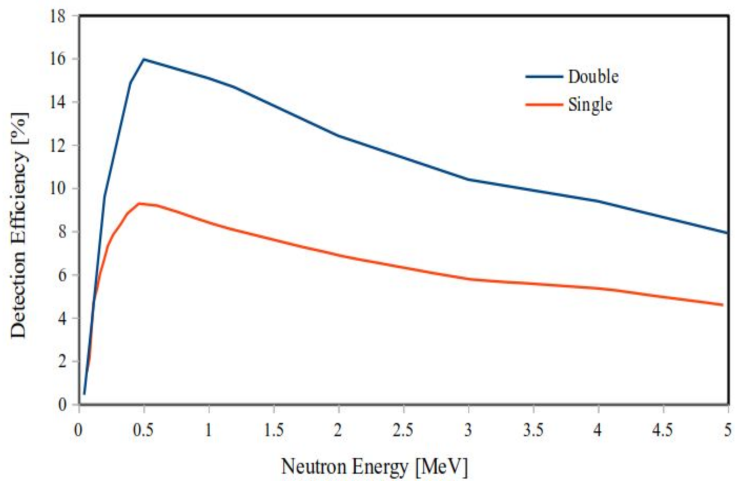


Figure 14: Single and double-layer detection efficiency for 48 detectors at a 1-m TOF distance.

Plan for development and timeline

In order to implement VANDLE as NEXTi at FRIB, a new frame and construction of about 40 new modules are required. The construction of 30 detector modules is foreseen in 2020, and the remaining 10 modules can be constructed in 2021, depending on the available funding. The frame and holders for a single-layer implementation are mostly available and were implemented previously at NSCL and RIKEN. The frame for a double-layer implementation has been designed. The material for the aluminum arch has already been acquired, and the 8020 extruded aluminum will be purchased in 2020. The final construction will be achieved at the UTK machine shop, and the new holders for the double-layered modules will be 3D printed at UTK.

Required budget

The VANDLE research program is supported by a NNSA DOE grant, which ends on the 31st of May 2022. The intent to use VANDLE in the early years of FRIB was explicitly articulated in the proposal request, and the construction of new 40 detectors can be achieved within this budget.

The mechanical support tailored for FDSi is estimated to cost about $25k. The total value of VANDLE within the XSiSi implementation is approximated to be about $500k, including readout electronics and power supplies. However, only $25k total is requested to supplement the UTK in-kind contribution.

Implementation in the Day0 floor space

VANDLE requires a footprint of about 150x150 cm^2.

		Cost ($k) (Y1) (Y2) (Y3) (in-kind 1) (2) (3)	Comments
NEXTi (n)	Mechanical	(25) (0) (0) (0) (0) (0)	Arch sleigh on rails
	Electronic	(0) (0) (0) (0) (0) (0)	
	Detector	(0) (0) (0) (80) (0) (0)	40 new VANDLE bars for 2nd arch
	Other	(0) (0) (0) (0) (0) (6)	Transport
		(25) (0) (0) **(80) (0) (6)**	

3.1.3 XSiSi - Charged-Particle and Implantation

Silicon double-sided strip detectors (SiDSSDs) have traditionally been the workhorse for experiments with fragmentation beams because of their good energy resolution for charged particles (20-50 keV FWHM), adequate timing characteristics, mm spatial resolution, and compatibility with most γ-ray detector arrays [Pri03] (i.e., size and minimal attenuation of low-energy γ rays). *SiDSSDs will be particularly well suited for (1) experiments targeting isotopes on the proton-rich side of stability because the β-delayed charged particles can be studied with the same detectors, and (2) Z > 50 experiments where good total-kinetic-energy resolution is needed for resolving ions with multiple charge states.* The stopping power of silicon is low, necessitating several mm-thick layers to stop the heavy ions of interest and the electrical segmentation pitch must be at a minimum of 2 mm to handle the implantation rates and subsequent decays. In addition, a large dynamic range is required to handle both high-energy implants and low-energy decays with good energy resolution and low detection thresholds. *However, for the neutron-rich side of stability, a fast position-sensitive inorganic scintillator is also required for neutron TOF measurements with NEXTi (double-bar VANDLE).* These fast detectors also enable decay measurements for the shortest-lived nuclei with sub-ms lifetimes due to their fast recovery from large implantation signals.

The implantation detector configuration must vary from experiment-to-experiment to match the specific range of isotopes provided by the FRIB ARIS separator. The stopping range of isotopes in Si- and YSO-based material is dictated by their energy and atomic number, see Figure 15. For fully stripped isotopes (typically Z < 50), there is no need to measure the total kinetic energy of the ion because its identification can be achieved conventionally by the measurement of the time of flight and residual energy loss. Passive energy degraders are used in these cases, meaning only a few SiDSSD detectors are needed to cover the range of implanted species. However, for lower-Z nuclei, e.g., fluorine or magnesium isotopes, the cumulative thickness of many silicon detectors may be needed, e.g., 10 mm, to capture all of the species produced. Therefore, *increased Si thickness (i.e., number of SiDSSD detectors) expands the number of nuclei that can be measured in a single experiment, maximizing the scientific output and value of each experiment.*

Nuclei with Z > 50 will not be fully stripped so the charge states of the ions passing through the spectrometer will complicate the identification process. *For charge-state identification in Z > 50 experiments, a high-resolution total-kinetic-energy measurement of the ion is required (a passive stopper is no longer tolerable). This requires a larger number of active Si detectors to cover the entire stopping range of all the isotopes.* Fortunately, the high-Z fragments at FRIB will have a very small spread in range, necessitating only 1-3 of the Si detectors to be highly pixelated.

A hybrid SiDSSD and fast-scintillator implant detector, XSiSi, is required to match FRIB capability and fulfill the FDSi scientific program. A conceptual drawing of the XScint-SiDSSD hybrid array (XSiSi), which is relatively compact in size, is shown in the center of DEGAi in Figure 16. New Si-DSSD detectors, a chamber, and amplifiers are needed to complete XSiSi and expand the coverage and scientific reach of the FDSi. SiDSSDs are the only new detectors requested in this proposal as they are critical to supporting broad coverage of Z and physics opportunities.

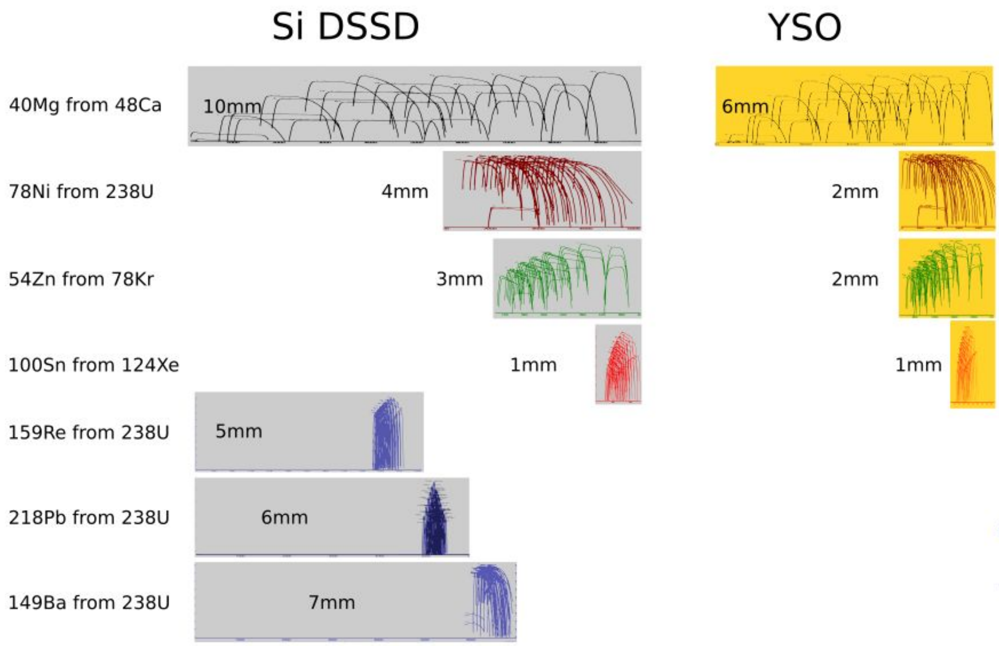


Figure 15: Implant range and spread examples for various fragments at FRIB. On the left-hand side, example simulations for Si detector arrays are shown. The top four panels show the situations where a passive degrader is used to control the range of ions. In the bottom three panels, the total energy of the implanted ion has to be measured but the ions are stopped in a very narrow range. The right-hand side shows simulations for the inorganic scintillator YSO, which has relatively high stopping power. However, YSO does not have the required energy resolution for multi-charge-state identification.

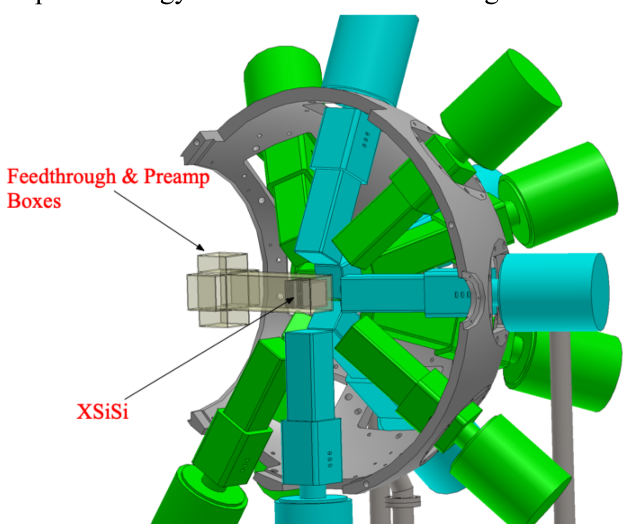


Figure 16: Schematic drawing of the implantation station, XSiSi, inside of DEGAi.

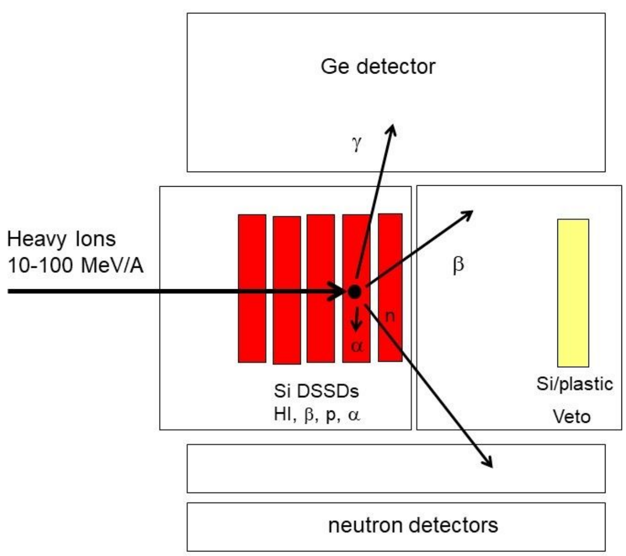
- Si implantation array for XSiSi-FDSi

Introduction

In decay spectroscopy experiments, products of fragmentation reactions selected by a mass separator are stopped in an implantation detector where they subsequently decay. Typically, implantation detectors are segmented to facilitate temporal and spatial correlations between implants and their subsequent decays. Several types of implantation detectors exist depending on experimental needs. Implantation detectors based on double-sided Si strip detectors (DSSD) are characterized by high granularity, good energy resolution, and minimal attenuation of low-energy gamma rays. They are particularly useful for studies of decays involving emission of charged particles such as beta particles, protons, and alphas. Implantation stations are used in connection with gamma-ray arrays and neutron detectors. DSSD implantation arrays have been extensively used at fragmentation facilities worldwide and are considered essential in decay spectroscopy studies.

Detectors

As part of XSiSi, we propose to construct a dedicated implantation array of Si DSSDs. Compared to existing implant stations, it will have a large active area, minimal dead area, and high granularity. It will consist of up to 5 Si DSSDs. Currently, two varieties of Si DSSDs are considered for the implantation array: 5 BB7 Micron detectors (32x32 strip, 64x64 mm^2, 2-mm pitch, 1.5-mm thickness) and 3 relatively large surface-area TTT Micron detectors (128x128 strip, 97x97 mm^2, 0.75-mm pitch, 1.5-mm thickness), where the latter are nominally for the proton-rich side of stability or high-rate experiments, which require more granularity and surface area. The two varieties can also be operated together. A schematic of XSiSi is provided in Figure 17, where the red detectors represent the Si DSSDs and the yellow detector represents a light-ion veto and/or fast scintillator detector for NEXTi.



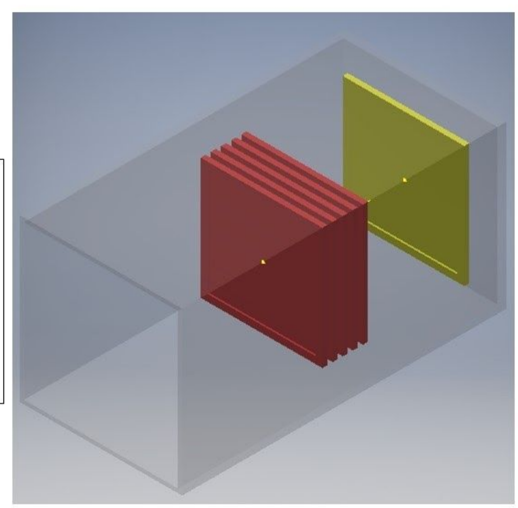


Figure 17: Schematic drawing of the XSiSi implantation station and a 3D rendition.

Electronics

Large dynamic range and good energy resolution is required for both the implants (to determine the charge state and particle identification) and subsequent decays; implanted heavy ions will deposit up to 3 GeV in a detector, whereas the energy loss of beta particles can be 100 keV or lower. In order to fulfill the large dynamic-range requirement, strips on the front side of each DSSD will be connected to large-gain, linear-logarithmic preamplifiers while the back side will be connected to low-gain linear preamplifiers, see Figure 18. The latter signals will be split and digitized but one copy will be sent to a shaping amplifier in advance to facilitate low-threshold triggering of beta particles. This combined preamp and shaping amp solution will be implemented using MESYTEC electronics. A similar solution will be used for the MTAS SiDSSD array. When instrumenting TTT detectors, shaping amplifiers nominally for the MTAS SiDSSD array will be shared with XSiSi due to the large channel density. XSiSi will be independent from MTAS electronics when instrumenting BB7 detectors.

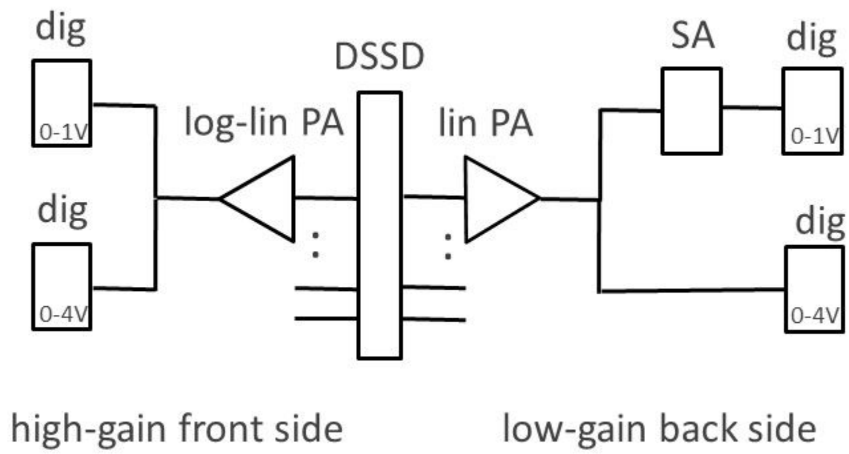


Figure 18: DSSD signal processing electronics.

The signals will be processed using existing waveform digitizers (12-14 bit, 100 MHz) from the FRIB pool or new Pixie64 modules (see Section 3.2.3). For an array of 3 fully instrumented BB7 detectors (32 x 32 strips), a minimum of 3 * (2*32 + 2*32) = 384 electronic channels will be required. For an array of 3 fully instrumented TTT detectors (128 x 128 strips bused to 64 x 64 strips), a minimum of 3 * (2*64 + 2*64) = 768 electronic channels will be required. When 5 detectors are required, 2 can be partially instrumented (i.e., re-bussed or without shaping amplifiers on the low-gain linear side).

Detector chamber

The stack of DSSDs will be housed in a rectangular chamber, which will be placed inside a 4π HPGe and $LaBr_3/CeBr_3$ detector array, DEGAi. The implantation array can be used in connection with other detectors such as active degraders upstream, a fast segmented scintillator downstream, and/or a veto detector downstream. Downstream detectors can be placed in a detachable section of the chamber, which can be easily replaced without disturbing the implantation array. In order to optimize the performance of the whole system, the position of the chamber along the beam line will be adjustable. Furthermore, the chamber will be able to move vertically to pass beams downstream at the second focal point, where total absorption / neutron-counting spectroscopy will be performed in quick succession.

Cost and effort

New DSSDs need to be purchased from Micron Semiconductor LTD (5 BB7s and 3 TTTs for ~$88k). The chamber needs to be designed, manufactured, and assembled (~$25k). Preamplifiers (3 lin-log, 64-ch mesytec units and 3 linear, 64-ch mesytec units for ~$47k) and shaping amplifiers (6 16-ch mesytec units for ~$42k) need to be procured. Digitizers from the FRIB pool or new Pixie64 modules (see Section 3.2.3) will be used for signal processing. Existing power supplies will be used. The total cost of the whole system will be about $202k. Also, two months of mechanical and engineering support will be required to complete the project. *No new technological developments are required for XSiSi; all detectors and electronics are "off-the-shelf".*

		Cost ($k) **(Y1) (Y2) (Y3)** **(in-kind 1) (2) (3)**	**Comments**
XSiSi (q^+/q^-) - Si DSSD	Mechanical	(25) (0) (0) (0) (0) (0)	Detector and preamp housing and support
	Electronic	(89) (0) (0) (0) (0) (0)	Dual gain amp solution
	Detector	(88) (0) (0) (0) (0) (0)	3 micron TTT and 5 micron BB7
	Other	(0) (0) (0) (0) (0) (0)	
		(202) (0) (0) **(0) (0) (0)**	

- Fast scintillator arrays for XSiSi-FDSi

General description of the instrument

This is a relatively new technology which was recently implemented for implantation-decay correlation experiments [Yok19a, Yok19b, Xia19] and it is required for NEXTi-XSiSi n-TOF operation. The detector consists of a segmented scintillator connected to a segmented photomultiplier through a light diffuser or segmented light guide, see Figure 19. The scintillation light generated from an implantation or decay event is guided through a narrow scintillator segment and dispersed in the diffuser over multiple segments of the photomultiplier. The center-of-mass of the collected light is calculated from the segmented photomultiplier response using a resistive network (Anger logic), which provides the position of the interaction with the resolution given by the segmentation of the scintillator detector. The scintillator materials used are: plastic, para-terphenyl, and inorganic scintillators such as YSO, LYSO, and YAP. The thickness of the detectors varies from 100 um to 15 mm. These detectors have already been implemented in several experiments using projectile fragmentation. The key advantage of this technology is the very fast response time, enabling fast-pileup [Xia19] and n-TOF measurements. They have very high detection efficiency for charged particles, particularly when high-Z inorganic scintillators are used. The readout simplicity and compactness also enables them to be used in applications with limited space.

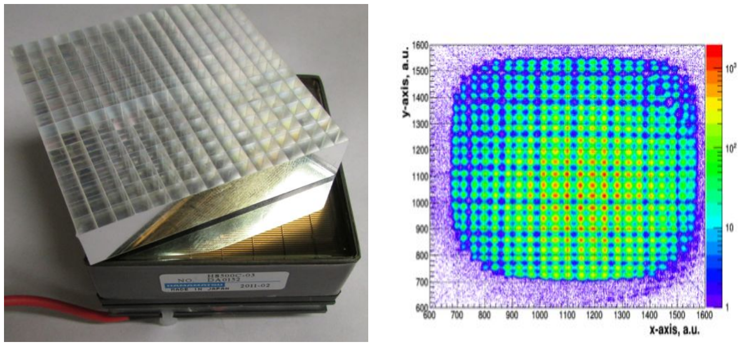


Figure 19: (left) A detector module consisting of a segmented scintillator coupled to a segmented photomultiplier and (right) an example hit-map image for implanted ions.

Few typical experiments

These scintillator implant detectors, which can be operated in tandem with a Si DSSD stack, can be used for very efficient and fast triggers for (1) isotopes and isomers with lifetimes in the sub-ms range, where silicon detectors are more limited from saturation effects, (2) fast-timing experiments with $LaBr_3$/$CeBr_3$, and (3) all neutron time-of-flight experiments. Due to the energy resolution of 10%, they have limited use in charged-particle emission spectroscopy and multi charge-state determination. Furthermore, due to relatively high-Z of the scintillator, the gamma-ray absorption below 200 keV has to be taken into account. For these reasons, a hybrid Si-DSSD and fast-scintillator array is required.

Technical description

The detector typically consists of 1 to 10-mm thick segmented scintillator material (YSO, $CeBr_3$, Ej200 plastic), connected to a segmented photomultiplier (e.g. 8x8 segment H12700 or 16x16 segment H13700 by Hamamatsu) through a 1 to 3-mm thick diffuser. The individual signals from each anode can be read out either individually [Als15, Cri16] or using a resistive network ([Yok19a, Xia19]), which greatly simplifies the readout, as only four signals are recorded. Strong light quenching for a heavy-ion implant enables the measurement of both implantation and decay events, where the electronics chain is capable of a 1:50 dynamic range. The big advantage of using the Hamamatsu family of photomultipliers is the provided common dynode signal, which is used for fast timing.

Present status of the instrument

A variety of implant detectors were developed at the University of Tennessee in collaboration with Proteus/Agile and Vertilon. The examples are: 2”x2”-segmented YSO with a 5-mm thickness and

1x1-mm^2 segment pitch; 3”x3”-segmented YSO with a 5-mm thickness and 2x2-mm^2 segment pitch; 2”x2” segmeneted plastic scintillator with a 1-cm thickness and 3x3-mm^2 segment pitch; and 2”x2” segmented YSO with a 12-mm thickness and 2x2-mm^2 segment pitch. They can be connected to various models of the Hamamatsu H12700 segmented photomultiplier. Multiple versions of Anger-logic boards have been implemented. Detectors with different scintillator thicknesses permit tailoring the setup to a selected range of isotopes and energies. The 3”x3” array uses a segmented light guide to map the larger area scintillator onto a smaller 2”x2” surface of the photomultiplier. Furthermore, Mississippi State University has developed a variant of this detector using $CeBr_3$.

Description of electronics and integration methods

The UTK based detectors use Anger logic readout which is fed directly into the digital system. In fast timing and pile-up experiments, 500-MHz, 14-bit Pixie16 (RevF) digitizers are used. In n-TOF experiments, 250-MHz, 12-bit Pixie16 (RevF) digitizers are used. The Mississippi State University detector uses individual readout and Pixie16 electronics.

Implementation in the Day0 floor space

These detectors can be very compact and lightweight. A detector box can be made as small as 2.5”x2.5”x4”, employed in various detector configurations, and coupled to the Si DSSD array.

		Cost ($k) **(Y1) (Y2) (Y3)** **(in-kind 1) (2) (3)**	**Comments**
XSiSi (q^+/q^-) - Scintillator	Mechanical	(5) (0) (0) (0) (0) (0)	Integration with Si DSSD housing
	Electronic	(0) (0) (0) (0) (0) (0)	
	Detector	(0) (0) (0) (0) (0) (0)	
	Other	(0) (0) (0) (0) (0) (0)	
		(5) (0) (0) **(0) (0) (0)**	

3.1.4 TAS - Total Absorption Spectrometers

- Modular Total Absorption Spectrometer MTAS

General description of the instrument

MTAS is currently the largest and most efficient total absorption gamma-ray spectrometer in the world with a value of nearly \$1.5M. It is a large segmented array of 19 modules consisting of nearly one ton of sodium iodide, see Figure 20. At FRIB the radioactive ions will be implanted into a double-sided silicon strip detector (DSSD) and/or segmented scintillator array located in the center of the 2.5-inch diameter opening in the central module of the array. MTAS has a heavy shielding structure, mostly lead layers and blankets, around the array itself. MTAS will be used at the second focal point along the beam axis of the FDSi, downstream from the discrete array, where measurements will be made in quick succession. A recent upgrade of MTAS includes an optically segmented central module to improve its low-energy gamma-ray counting and identification capabilities; it also allows for a higher beam rate. This new central module has been procured and is currently being commissioned at the University of Warsaw. It is expected to be installed into MTAS by its manufacturer St. Gobain (OH) in FY 2021.

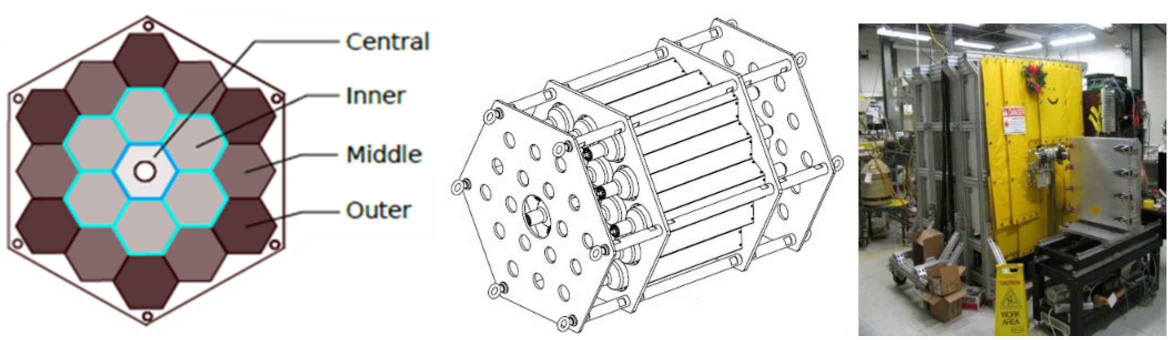


Figure 20: The cross section of MTAS (left), NaI(Tl) segments inside the supporting frame and MTAS array with shielding on-line to the mass separator at the HRIBF Tandem.

Few typical experiments

MTAS has been used in multiple experiments on beta-decaying isotopes at ISOL facilities, i.e., HRIBF-ORNL and CARIBU-ANL. It was used to determine beta-decay strength distributions, which included beta-delayed neutron emissions and ground-state to ground-state feedings. The MTAS experimental results address reactor decay-heat and antineutrino physics [Ras16, Fij17, Ras17]. MTAS is capable of measuring gamma rays and electrons, as well as beta-delayed neutron branches and the corresponding neutron energy spectra with an energy resolution of FWHM~250-keV, all determined by the NaI(Tl) response [Ras17]. It is anticipated that MTAS will be employed in the majority of beta-decay experiments to provide complementary data to those obtained using high-resolution gamma-ray and neutron spectroscopy with the discrete array at the first focal point. The FRIB experiments will address fundamental questions of nuclear structure and astrophysical processes as well as the anti-neutrino emission from exotic nuclei with high decay energies. The data will also be used to generate level densities and calculate (n, γ) cross sections through the beta-Oslo technique, developed by NSCL's SUN and Oslo (Norway) groups. MTAS has a very high photopeak efficiency, see Figure 21, which makes it ideal to search for basic decay properties of new exotic isotopes at the border lines of known nuclei produced at low rates.

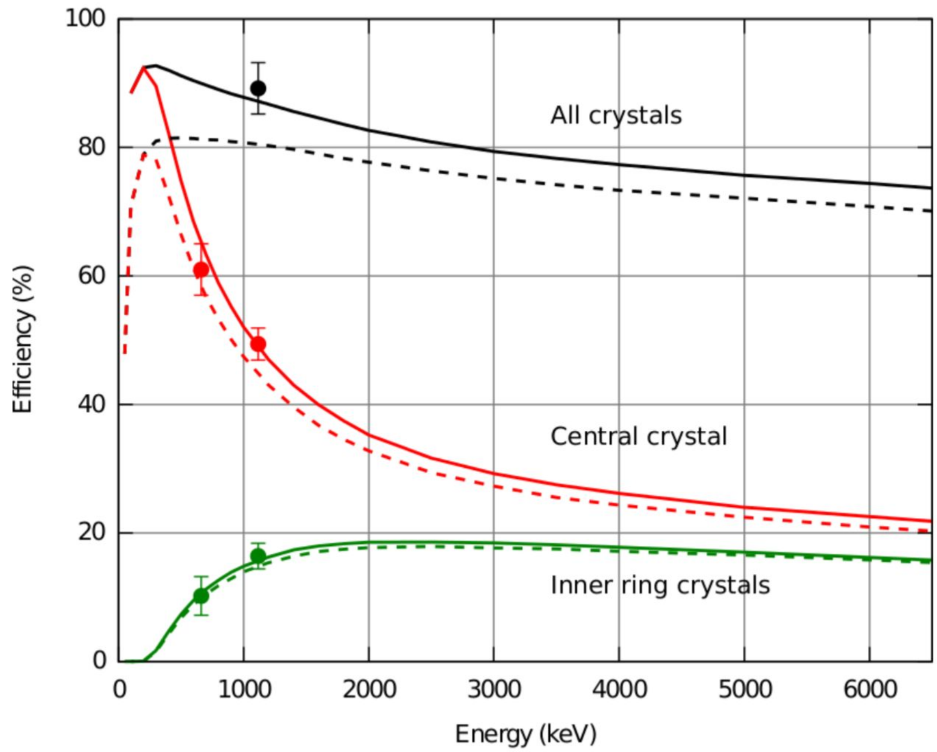


Figure 21: MTAS photopeak efficiency for detecting a single gamma ray (black). Dashed curves include auxiliary detectors and the solid curves do not.

Technical description

MTAS was manufactured at St. Gobain (OH) and consists of 19 hexagonal NaI(Tl) detectors that are 21" long and 8" in diameter. The total mass of NaI(Tl) from the 19 modules is 990 kg (~1 ton). The current MTAS shielding consists of about 6 tons of lead mounted in 3 movable segments surrounding the array, see Figure 20 and Ref. [Kar16].

The background rate in the full MTAS array was ~2400 Hz at HRIBF-ORNL and 2000 Hz at CARIBU-ANL, i.e., 2.4 Hz and 2.0 Hz per 1 kg of NaI(Tl). Radioactive nuclei arrive at the middle of MTAS through a 2.5" hole in the central module by a tape transport at a ISOL facility or by direct beam into an implant array at a fragmentation facility. The gamma-ray energy resolution at 662 keV is FWHM~8.5% for the current central module and 6% for the other modules.

Present status of the instrument

MTAS is currently installed at the CARIBU-ANL facility where it was used to study beams of ^{252}Cf fission fragments up to March 2020. MTAS was implemented at the HRIBF-ORNL ISOL facility between 2012 and 2016, and later during the studies of longer-lived radioactivities. MTAS uses a digital data acquisition system and software suite similar to VANDLE. In order to improve the rate and low-energy gamma-ray detection capabilities, a new MTAS center module that is optically segmented into 6 parts was acquired from St. Gobain (OH). It is currently being commissioned at the University of Warsaw. Before MTAS is brought to FRIB, the array will be shipped to the St. Gobain factory in Ohio for the installation of the new 6-fold segmented central module. Two custom-designed 1.5-mm thick DSSD counters with 32x32 strips and a pixel size of 1.1-mm have been acquired from Micron (UK) using ORNL base funding. These custom detectors fit into the 2.5" opening of MTAS and have little inactive area. Two additional DSSD counters, preamplifiers, and shaping amplifiers still need to be procured to finish the custom MTAS implant array, which is similar to XSiSi but necessarily smaller. A custom designed, segmented YSO array with SiPM readout for the MTAS implant array will be developed at the University of Tennessee.

Description of electronics and integration methods

MTAS uses a digital Pixie16 (RevD) system with 12-bit ADCs and 100-MHz sampling. The data stream consists of timestamped energies for each detector channel. The analysis code is written in C++ and supports root export. Data synchronization can be done using the front panel TTL interface, which can accept an external clock and clear signal. Each event will have a second time-stamp provided by an external clock in addition to the internal time-stamp.

Present status of GEANT4 simulations

The MTAS response functions for gamma rays, neutrons, and beta particles have been developed and extensively validated [Ras16, Fij17, Ras17], see Figure 22. The GEANT4 model contains multiple critical elements required for high-fidelity spectrum deconvolution. Simulation models for the DSSD and YSO detectors of the custom MTAS implant detector exist but have not yet been validated inside of MTAS.

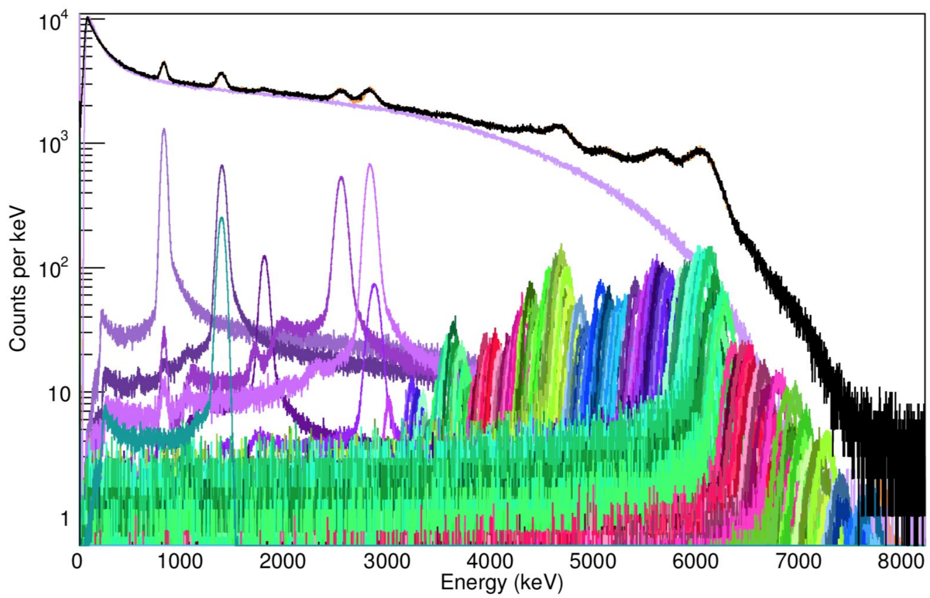


Figure 22: Deconvolution of ^{92}Rb decay from Ref. [Ras16], cf. the dominating β component (violet) of the total energy spectrum.

Plan for development and timeline

The commissioning and installation of the new central module, see Figure 23, and construction of the new custom implantation array, see Figure 24, need to be completed. In addition, heavy shielding is necessary to operate this detector, which requires a significant logistical effort to install. The DSSD and YSO implantation detectors of the custom MTAS implant array will need to be tested and included in the GEANT4 model and analysis software. These efforts will largely be carried out by the MTAS ORNL-UTK-Warsaw-LSU collaboration.

A new segmented scintillator implantation detector for MTAS needs to be developed. The small size of the MTAS opening precludes implementation of the 2”x2” H12700 photomultiplier. We will develop a system based on SiPM technology which will use small clusters of 2x2, 6x6 mm^2 arrays; this detector was proposed to be developed within the UTK DOE grant. The cost of a single YSO-based scintillator array varies between \$6k and \$10k. The cost of the photomultiplier with Anger logic is about \$3.5k.

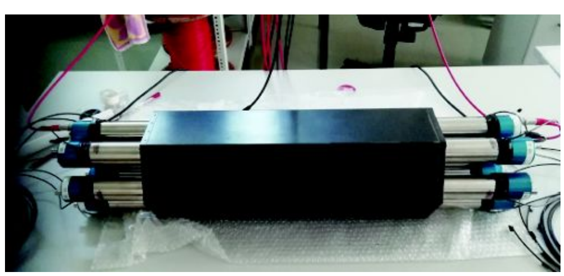


Figure 23: The new MTAS central module, optically segmented into 6 sectors, being commissioned at the University of Warsaw.

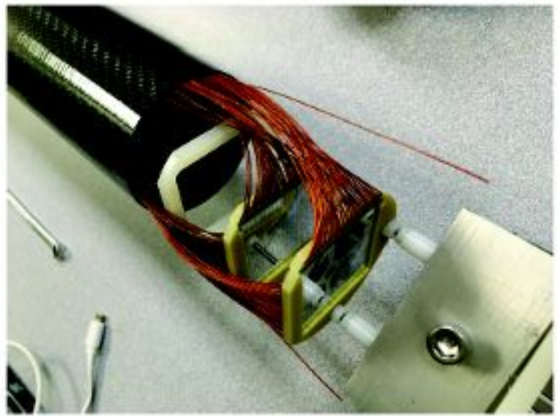


Figure 24: Two DSSD counters mounted on two supporting rods, designed to fit in a 2.5” inner diameter carbon-fiber tube.

Required budget

The installation of the new central module at St. Gobain will cost approximately \$50k and will be an ORNL in-kind contribution. In order for MTAS to be used with high-Z fragmentation beams, a full stack of four 1.5-mm thick DSSD detectors are required. Two detectors have already been purchased but \$20k is requested to purchase two additional DSSD detectors. The electronics envisioned to instrument the MTAS DSSD array will be similar to XSISi. In this solution the custom MTAS silicon stack will need preamplifiers (2 lin-log, 64-ch mesytec units and 2 linear, 64-ch mesytec units for ~\$31k) and shaping amplifiers (6 16-ch mesytec units for ~\$42k). For experiments requiring more preamps or shaping amps, electronics from XSiSi will be shared with the MTAS DSSD array. Existing power supplies will be used.

For experiments with lighter nuclei, which require a large stopping power that goes beyond four DSSD detectors, segmented YSO scintillator detectors will be used. The cost of a new scintillator array with SiPMs is estimated to be about \$20k. This funding will be through the UTK DOE grant in 2020. However, \$5k is requested for modifications to the Si DSSD housing.

While MTAS has a dedicated acquisition system, additional digitizers from the FRIB pool or new Pixie64 modules (see Section 3.2.3) will be required to instrument the custom MTAS DSSD implant array.

In total, \$98k is requested to supplement ORNL and UTK funding for the purpose of mechanical integration and instrumenting the custom MTAS DSSD implant array.

Implementation in the Day0 floor space

MTAS and its existing shield is a heavy 7-ton instrument, challenging to move and reposition. MTAS will be positioned at a second focal point behind the discrete array and it is anticipated to be used in tandem with the discrete array for most experiments, providing relatively complete measurements. The MTAS array is nominally mounted on a heavy-duty cart and the shielding is divided into three parts on wheels, making the fine adjustment of its position and eventual dismounting possible. While MTAS and its shielding can be placed on the floor in its current form without additional mechanical infrastructure, a new platform system on rails for MTAS and its shielding will (1) reduce the footprint caused by the shielding outriggers, (2) enable relatively simple reconfiguration of the second focal point for other devices such as SUN and 3HeNi, while maintaining MTAS readiness, and (3) permit temporary distancing of the array from NEXTi (VANDLE) for the purpose of reducing the neutron-scattering background during "discrete array" measurements. This heavy-duty platform system is expected to cost up to $75k, which is further discussed and budgeted in Section 3.3.1 as part of the more general FDSi mechanical infrastructure.

		Cost ($k) **(Y1) (Y2) (Y3)** **(in-kind 1) (2) (3)**	**Comments**
MTAS	Mechanical	(5) (0) (0) (0) (0) (0)	Si-DSSD and YSO integration
	Electronic	(73) (0) (0) (0) (0) (0)	Dual gain preamp solution
	Detector	(20) (0) (0) (15) (0) (0)	2 additional Si-DSSDs YSO-based scintillator for custom implant detector
	Other	(0) (0) (0) (58) (0) (8)	Central module installation @ St. Gobain and transport
		(98) (0) (0) **(73) (0) (8)**	

- SuN

General description of the instrument

SuN (Summing NaI detector) is a total absorption spectrometer developed to perform decay and reaction studies of astrophysical relevance [Sim13]. It was the first detector of this kind used at a fragmentation facility for these types of experiments. SuN is a segmented array of eight NaI(Tl) crystals read out by 24 photomultipliers. It can be used with a DSSD detector for fast beam experiments, and a tape system for low-energy beam decay measurements, see Figure 25. It has no significant shielding from the environmental background radiation and, therefore, relies on electron-coincidence measurements to isolate the decay of interest.

Figure 25: (Left) SuN consists of eight NaI(Tl) segments. SuN was implemented at fast (middle) and slow (right) beam lines at NSCL.

Few typical experiments

SuN can be used for decay experiments using fast and slow beams. It was mainly used for measurements using the beta-Oslo method [Spy14], and it is intended to be implemented in a similar way at FRIB. It is smaller than MTAS and, therefore, easier to move and it requires a smaller footprint, but it is not as efficient at higher energies.

Technical description

SuN is a cylindrical detector, which consists of eight optically segments of NaI(Tl) manufactured by Scionix. Each of the sections is read out by three photomultiplier tubes. The dimension of the active volume of NaI(Tl) is 16” x 16” (diameter x length). The diameter of the borehole is 1.8”. SuN also includes a power supply (WIENER MPOD) and uses 100-MSPS, 16-channel Pixie16 digitizer modules from XIA LLC for energy and timing signals with an embedded DAQ computer. Some auxiliary detectors used with SuN require faster digitizer modules (e.g. the plastic fiber detector used with the tape system).

It can achieve 6.1% energy resolution and 85(2)% detection efficiency at 662 keV (without auxiliary detectors installed), see Figure 26.

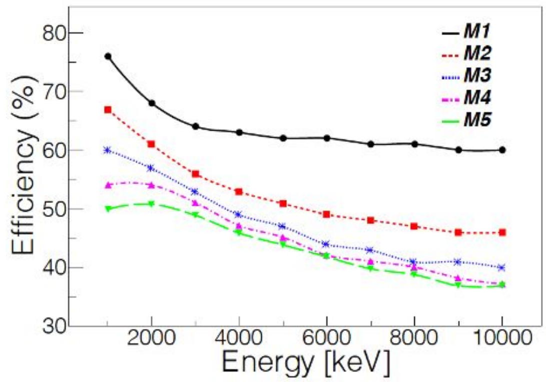


Figure 26: SuN's summing efficiency for a typical fast beam setup. The different curves represent the efficiency dependence on the number emitted γ rays in a cascade. The horizontal axis corresponds to the full available energy (independent of individual γ-ray distribution).

The silicon DSSD detectors used in fast-beam experiments are 1-mm thick with 16 x 16 strips (1.2-mm pitch), see Figure 27. They were custom developed for SuN by Micron. They are coupled to a set of dual-gain preamplifiers; the low-gain setting can detect the implanted ions in the energy range of a few GeV and the high-gain setting is focused on the detection of decay electrons up to about 10 MeV. Downstream from the DSSD, a Si surface barrier detector is used to “veto” the light ions that do not get implanted in the DSSD.

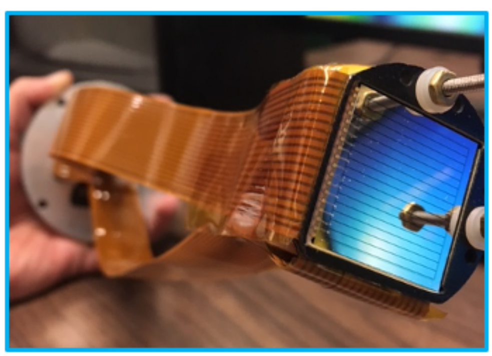


Figure 27: The DSSD detector implemented at SuN in fast beam fragmentation experiments.

Present status of the instrument

SuN is fully operational and is currently placed at the ATLAS facility, at Argonne National Laboratory. It is expected to return to MSU in the fall of 2020.

Description of electronics and integration methods

Currently, SuN is instrumented with Pixie16 (RevF) modules with 12-bit ADCs and a 100-MHz sampling frequency. It can use similar data synchronization methods as other Pixie-based electronics systems. Analysis software exists for fast- and slow-beam experiments and for Total Absorption Spectroscopy and the β-Oslo method. The software is not publicly available (except the Oslo method packages which were developed by the University of Oslo and are available on GitHub).

Present status of GEANT4 simulations

Simulations of the SuN detector exist for each configuration. Experiments can vary and, therefore, each experiment has a dedicated simulation that is optimized for the particular setup.

Plan for development and timeline

The SuN detector and accompanying systems are ready for use.

Required budget

No funding is needed for the SuN setup.

Implementation in the Day0 floor space

SuN, which has a relatively small footprint, can be easily positioned at the second focal point, particularly if MTAS and its shielding is placed on a platform with rails, see Section 3.3.1, enabling it to be easily moved out of position. Otherwise, MTAS and its shielding will have to be removed from the second focal point; it may be possible to place SUN in the middle of the fully opened discrete array at the first focal point. Depending on the scientific priorities, it can also be installed at the stopped beam location, where it has been previously implemented.

		Cost ($k) **(Y1) (Y2) (Y3)** **(in-kind 1) (2) (3)**	**Comments**
SUN	Mechanical	(0) (0) (0) (0) (0) (0)	
	Electronic	(0) (0) (0) (0) (0) (0)	
	Detector	(0) (0) (0) (0) (0) (0)	
	Other	(0) (0) (0) (0) (0) (0)	
		(0) (0) (0) **(0) (0) (0)**	

3.1.5 Neutron Counter

General description of the instrument

A ^{3}He-based neutron counter that is large and highly segmented will allow users to count implanted radioactive ions and the subsequent beta, neutron, and gamma radiation. Neutrons detected through the $^3\mathrm{He} + n \rightarrow p + t$ reaction are emitted directly from neutron-unbound states after beta decay of exotic nuclei. The detection of neutrons will be made with very high efficiency through an optimized combination of ^{3}He-gas ionization chambers and a high-density polyethylene (HDPE) moderator. Neutron counting can be done without a beta trigger, which is one of the important advantages of this detector. The FDSi neutron counter called 3HeNi can be assembled using ^{3}He detectors and electronics from the ORNL 3Hen array and ^{3}He and BF_3 detectors from the NSCL Nero detector, totaling to nearly \$5M in value.

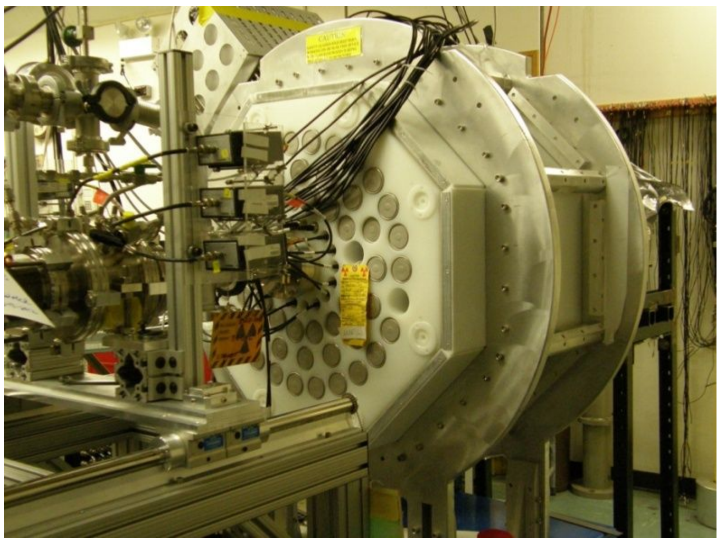


Figure 28: 3Hen detector in compact geometry.

Few typical experiments

After necessary modifications of 3Hen, see Figure 28, for use with fragmentation beams, 3HeNi will be ideally suited for discovery experiments on new nuclei and characterization of their basic decay properties, including neutron radioactivity and βxn emission; 3HeNi is well suited for detection of 2n emission. This will provide beta-delayed branching ratios necessary for r-process analysis. A future Super-3HeN array is foreseen to be implemented for the FDS with about 180 ^{3}He tubes and directional sensitivity for the inner rings.

Technical description

Thermal neutrons are detected within a ^{3}He-filled gas detector with very high efficiency. A typical ^{3}He-based neutron counter uses a large volume moderator with multiple ^{3}He filled proportional counters working with gas compressed to 10 atm. Elements of the detector constructed at ORNL, called 3Hen, will be used to implement 3HeNi at the FDSi. This detector uses 2” and 1” diameter tubes, which are 2’ long, placed in a HDPE hexagonal-shaped matrix. There are two configurations for 3Hen that have been implemented in the past, 3Hen-Compact and 3Hen-Hybrid [Grz14], see Figure 29. The 3Hen-Compact configuration maximized the neutron-detection efficiency and used 58 x 2” and 16 x 1” tubes. The 3Hen-Hybrid configuration used only 48 x 2” ^{3}He tubes and had space for two HPGe clover detectors. These arrays reached neutron-detection efficiencies of 77% and 34% at 1MeV, see Figure 30. At FRIB, a ^{3}He based detector will require a compact implantation array and neutron shielding. With the number of ^{3}He detectors already available, an HDPE matrix compatible with the future Super-3Hen array can be manufactured using LSU or UTK machine shops. The 3HeNi HDPE moderator will have a 2.5” diameter opening which is the same at MTAS; 3HeNi will use the MTAS implant detector array.

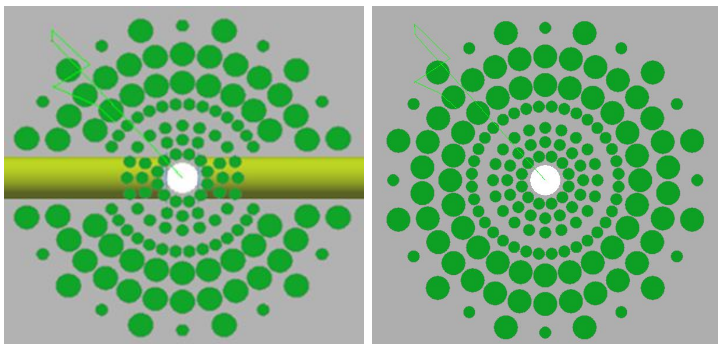


Figure 29: (left) 3HeNi-Hybrid configuration and (right) 3HeNi-Compact configuration. The HDPE moderator size is about 28” x 28”.

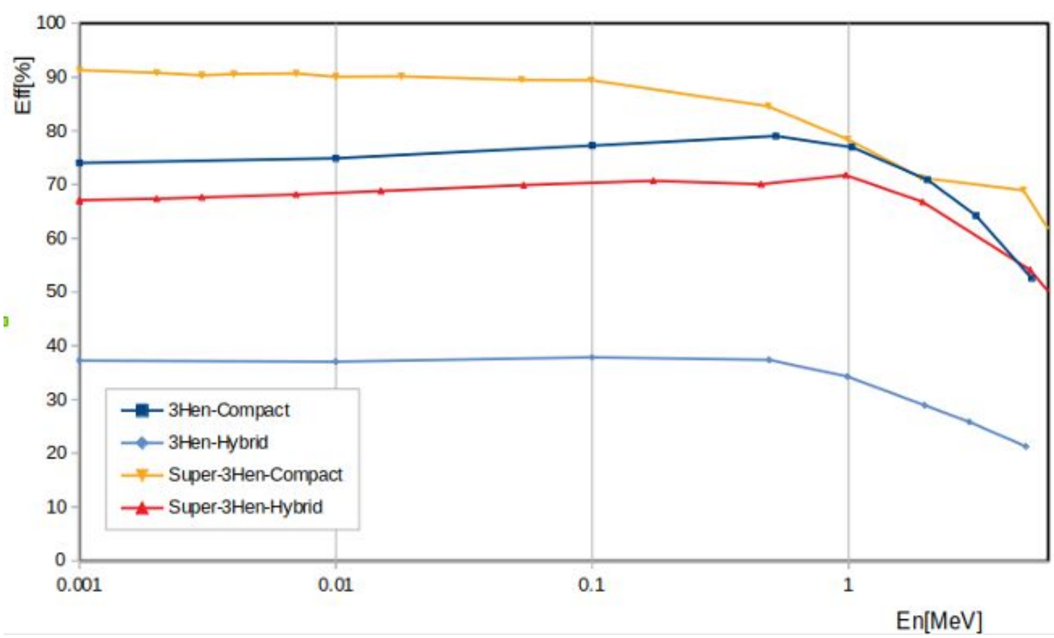


Figure 30: Summary of detection efficiencies for existing and future ^{3}He-based neutron counters.

Present status of the instrument

ORNL can provide 900 liters of ^{3}He for 3HeNi. There are 67 2-inch diameter, 2-foot long, 10-atm pressure tubes and 17 1-inch, 2-foot, 10-atm tubes available at ORNL. There are also several neutron detectors which can be provided by the JINA collaboration. These are 1-inch diameter detectors previously used in NERO detectors with the following parameters: 12 x 1-inch diameter, 36-cm long, 4.0-atm tubes and 6 x 1-inch diameter, 25-cm long, 5.7-atm tubes. Additional 2-inch diameter NERO detectors, 44 x 51-cm long BF_3, can be added to the system. These tubes can be arranged in the concentric rings close to the central opening. The larger diameter 2-inch tubes will serve the outer rings. A Hybrid design requires shorter tubes that are 1-inch diameter and 1-foot long to cover the neutron detection solid angle around two clovers. There are 27 such tubes already owned by ORNL. Presently, the majority of 3Hen is located at RIBF RIKEN as a part of the BRIKEN array [Tar17]. This includes preamplifiers owned by ORNL and UTK and HV power supply systems (ORNL). The BRIKEN scientific program is defined until 2022.

Description of electronics and integration methods

3Hen uses 16-channel integrated amplifiers manufactured by Mesytec. Currently, UTK and ORNL own 9 units, which amounts to a total of 144 channels. This is sufficient to instrument all of the seventeen 1-inch long tubes with position-sensitive readout (2 channels per tube) and 110 other single-ended detectors. 3Hen uses a fully digital system. At HRIBF it was used with Pixie16 (RevF) modules with 12-bit ADCs and a 250-MHz sampling frequency. The VANDLE electronics or FRIB Pixie16 pool can be used for 3HeNi experiments. The standard firmware can efficiently trigger the slow-rise time signals from a ^{3}He ionization chamber. The data stream consists of time-stamped energies for each detector channel. The online analysis code supports onboard timing. The analysis code is written in C++ and supports root export. Data synchronization can be done using the front panel TTL interface, which can accept an external clock and clear signal. Each event will have a second time-stamp provided by an external clock in addition to the internal time-stamp.

Present status of GEANT4 simulations

A ^{3}He-based neutron-counter model has been developed at ORNL and it has undergone multiple revisions. It is thoroughly tested and vetted. The JINA collaboration also developed such capability based on their NERO detector experience.

Plan for development and timeline

An updated version of 3HeNi array, called Super-3Hen, will have about 80% single-neutron counting efficiency in the broad energy range of 1 keV up to several MeV neutron energy. Its full capability for the FDS can be reached with over 1000 liters of ^{3}He compressed gas (900 liters already available at ORNL) and a new High-Density Polyethylene (HDPE) moderator matrix. For the FDSi, a new 3HeNi moderator will be constructed and populated with existing ^{3}He and BF_3 detectors, which will approach the Super 3Hen-Hybrid equivalent detection efficiency. Future funding will be required for additional ^{3}He. A new moderator can be machined within one month from the delivery of the HDPE to LSU or UTK machine shops. HDPE sheets that are 4-inches thick with various dimensions are commonly stocked, e.g., by McMaster-Carr.

Required budget

A new HDPE moderator for 3HeNi is about $10k, an additional SHV board is $7k, and a new support structure will be $20k. The 3HeNi-Hybrid configuration will require an additional 20 short tubes in year 2 for $43k. The MTAS implant detector will be used for 3HeNi. A total of $80k is requested to implement and integrate this device into the FDSi.

Implementation in the Day0 floor space

The relatively heavy 3HeNi array can be easily positioned at the second focal point, particularly if MTAS and its shielding is placed on a platform with rails, see Section 3.3.1, enabling it to be easily moved out of position. Otherwise, MTAS and its shielding will have to be removed from the second focal point; it may be possible to place 3HeNi in the middle of the fully opened discrete array at the first focal point provided that it opens by more than 48".

The actual implementation for Day0 will depend on the availability of the ^{3}He tubes, which is currently implemented at RIBF as part of BRIKEN array but there are no major technical reasons excluding its early implementation.

		Cost ($k) **(Y1) (Y2) (Y3)** **(in-kind 1) (2) (3)**	**Comments**
3HeNi	Mechanical	(0) (20) (0) (0) (0) (0)	New support structure
	Electronic	(0) (7) (0) (0) (0) (0)	SHV board
	Detector	(0) (10) (43) (0) (0) (0)	New HDPE matrix, 21 short 1" tubes
	Other	(0) (0) (0) (0) (0) (0)	
		(0) (37) (43) **(0) (0) (0)**	

3.1.6 Auxiliary Detectors

- *GADGET* - Time Projection Chamber (TPC) for correlated charged-particle decays

General description of the instrument

Gas implantation detectors can be used to directly image the charged-particle decay tracks. They stop the ion in the gas, where the subsequent decay is observed. Beta particles are not observed in the gas, enabling clear identification of direct and β-delayed (multi-) proton and α emission. This is achieved by using a TPC with high segmentation for high count-rate applications or an optical light scintillation TPC for the most exotic decays. The GADGET TPC was originally designed to fit inside the SeGA array at NSCL but it can be adapted to fit inside DEGAi-FDSi, see Figure 31.

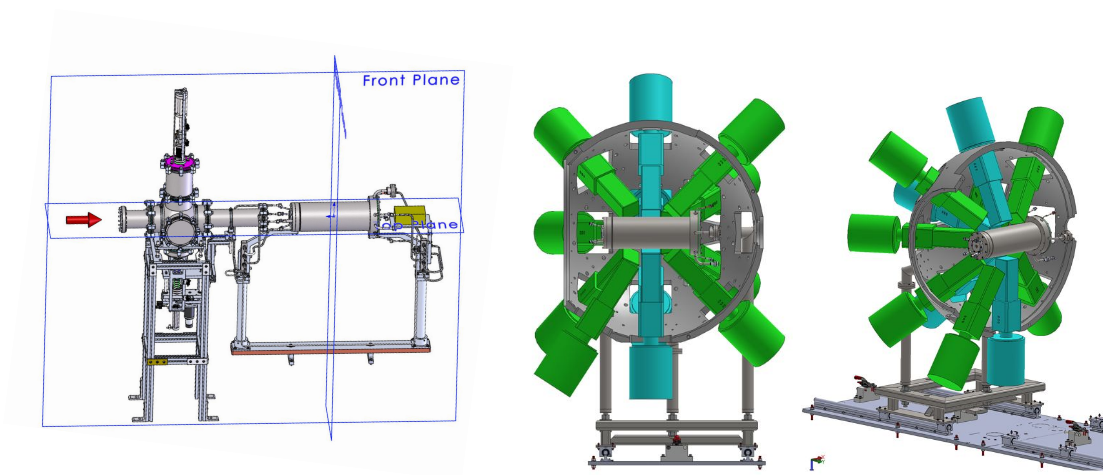


Figure 31: (left) current design of GADGET with SeGA removed [Fri19] and (middle, right) insertion into DEGAi.

Few typical experiments

The top priority of the GADGET collaboration is to constrain the most important nuclear reaction rate uncertainty in the modeling of Type I X-ray bursts, i.e., $^{15}O(\alpha,\gamma)^{19}Ne$. This can be done by using $^{20}Mg(\beta p\alpha)$ decay to measure the α-particle branching ratio of the key 4.03-MeV ^{19}Ne resonance.

The GADGET collaboration is interested in searching for the β^--delayed proton decay of ^{11}Be, motivated by the need for exotic nuclear structure (and possibly even exotic fundamental physics) to explain recent controversial observations. GADGET I data acquired at NSCL on ^{11}Be decay in 2019 will be very sensitive to a narrow proton peak, but the particle identification provided by the GADGET II TPC will provide additional sensitivity to a broad proton peak.

Technical description

The Gaseous Detector with Germanium Tagging (GADGET) is a detection system consisting of a cylindrical gas-filled detector incorporating a Micromegas (MM) for amplification, surrounded by SeGA. In Phase I, the gaseous Proton Detector has 13 MM pads and acts as a proton calorimeter. In Phase II, the granularity of the MM is increased to include over 1000 pads, so that it can function as a TPC enabling particle identification. The GADGET system also includes a beam-energy degrader and beam diagnostics.

Present status of the instrument

The GADGET I system is fully operational at NSCL using SeGA. The GADGET II system design using SeGA is essentially complete. Purchasing of the GET electronics for GADGET II is nearly complete. Fabrication of the Micromegas for GADGET II awaits the re-opening of the CERN detector lab.

Description of electronics and integration methods

The GADGET I system uses XIA Pixie16 digitizers equivalent to the NSCL Digital Data Acquisition System (DDAS). The GADGET II system uses the General Electronics for Time Projection Chambers (GET) system for the TPC and DDAS for SeGA. The DDAS and GET data streams need to be merged (equivalently, the GET data stream needs to be merged with the DEGAi-FDSi Pixie16 data stream).

Present status of GEANT4 simulations

A GEANT4 simulation exists for GADGET I in its SeGA configuration. This simulation must be modified to include the unique pad plane geometry of the GADGET II TPC and to replace SeGA with DEGAi-FDSi.

Plan for development and timeline

In 2020, we will complete the mechanical design of GADGET integrated with DEGAi-FDSi and fabricate the necessary components. In 2021, we will work on integrating the GET electronics of the GADGET II TPC with DEGAi-FDSi electronics. GADGET II is scheduled to be fully operational by the time FRIB begins delivering secondary beams to experiments.

Required budget

The GADGET TPC is normally supported mechanically using SeGA's mechanical support infrastructure. Design and fabrication efforts will be needed to support the TPC inside DEGAi-FDSi, and to potentially modify the rigid gas lines, an electronic feedthrough flange, and preamp stand. We estimate that 250 hours of design time and $25k for materials and fabrication will be needed. The GADGET collaboration has no funds to contribute to the integration with DEGAi-FDSi (only research personnel).

		Cost ($k) **(Y1) (Y2) (Y3)** **(in-kind 1) (2) (3)**	**Comments**
GADGET	Mechanical	(25) (0) (0) (0) (0) (0)	GADGET (TPC) integration: modification and support structures
	Electronic	(0) (0) (0) (0) (0) (0)	
	Detector	(0) (0) (0) (0) (0) (0)	
	Other	(0) (0) (0) (0) (0) (0)	
		(25) (0) (0) **(0) (0) (0)**	

- *PXCT* – Extension of the Particle X-ray Coincidence Technique

General description of the instrument

Following EC decay of an isotope of proton number *Z*, an atom fills its vacant inner shell and emits a characteristic X-ray. If the nuclear daughter state is unbound, charged particle (proton or α) emission may compete with γ-ray emission. The timescales for X-ray and charged-particle emission are similar. If the X-ray is emitted first, then the X-ray energy corresponds to *Z*-1. If the proton or α is emitted first, then the X-ray energy corresponds to *Z*-2 and Z-3, respectively. The ratios of the X-ray peak intensities yield the lifetime of the state: this is the established PXCT. Extending PXCT to include a measurement of the ratios of proton, α, and γ-ray intensities yields their branching ratios. Together, these are all of the quantities needed to construct thermonuclear reaction rates associated with the unbound state, or a statistical ensemble of states. Development of such an extended PXCT setup for use with stopped beams at FRIB has been funded by NSF. Coupling this setup with DEGAi-FDSi would improve the γ-ray detection efficiency and granularity substantially.

Few typical experiments

Competition between the ^{59}Cu(p,γ)^{60}Zn and ^{59}Cu(p,α)^{56}Ni reactions currently makes them 2nd and 3rd most important reaction-rate uncertainties to constrain for the modeling of Type I X-ray bursts. They can both be constrained by a single measurement of the EC decay of ^{60}Ga to ^{60}Zn using PXCT.

Moreover, highly uncertain rates of photodisintegration reactions influence the astrophysical γ-process that may be responsible for the production of dozens of rare p nuclides in nature. All of the ingredients needed to determine the thermonuclear rates of these reactions can be provided by PXCT. A campaign of measurements will constrain the most important reactions.

Technical description

The stand-alone setup includes a solid-state X-ray detector, a charged-particle telescope, a high-volume HPGe γ-ray detector, and the necessary infrastructure and electronics, see Figure 32.

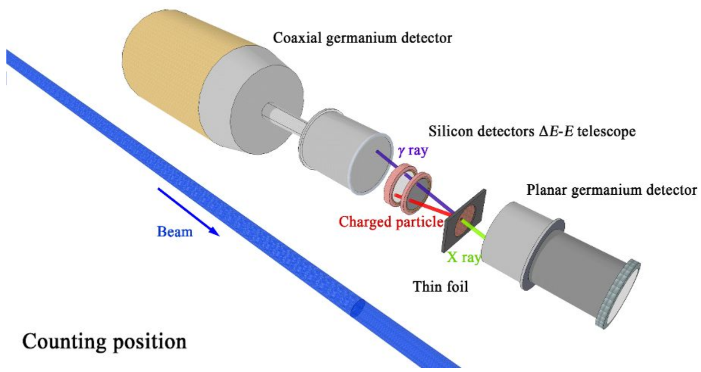


Figure 32: Conceptual design of the PXCT setup in stand-alone mode. The thin foil is periodically moved in and out of the beam to collect a radioactive sample.

Present status of the instrument

Conceptual design.

Description of electronics and integration methods

XIA Pixie16 digitizers will be employed (already consistent with DEGAi-FDSi).

Present status of GEANT4 simulations

GEANT4 simulations have not yet been completed.

Plan for development and timeline

Mechanical design begins in August, 2020, at NSCL. Purchasing and fabrication begins in August 2021. Commissioning experiments are planned in 2022, followed by first science.

Required budget

Since the mechanical design of PXCT has not been initiated, the design could begin with DEGAi-FDSi integration in mind from the beginning. The design will have to be compatible with stand-alone mode, as well, to facilitate bench-top tests and independent experiments. Designing for both operating modes will be more expensive than for the stand-alone mode, but doing both in parallel should provide some cost savings. We estimate that $20K of additional funds (on top of the NSF-funded stand-alone portion) will be needed to enable the mechanical integration of the two systems. An additional 200 hours of mechanical design time will be required, on top of the NSF-funded portion needed for the stand-alone system.

		Cost ($k) (Y1) (Y2) (Y3) **(in-kind 1) (2) (3)**	Comments
PXCT	Mechanical	(0) (20) (0) (0) (0) (0)	PXCT integration with DEGAi-FDSi and support structures
	Electronic	(0) (0) (0) (0) (0) (0)	
	Detector	(0) (0) (0) (0) (0) (0)	
	Other	(0) (0) (0) (0) (0) (0)	
		(0) (20) (0) **(0) (0) (0)**	

- GeDSSD

General description of the instrument

In decay spectroscopy experiments, products of fragmentation reactions selected by a mass separator are stopped in an implantation detector where they subsequently decay. Typically, implantation detectors are segmented to facilitate temporal and spatial correlations between implants and their subsequent decays. Implantation detectors based on double-sided Ge strip detectors (GeDSSD) are characterized by high granularity and good energy resolution. They are particularly useful for studies of decays involving emission of delayed low-energy electrons and photons and it can be used in combination with gamma-ray and neutron detector arrays. GeDSSD implantation detectors have been previously used at fragmentation facilities worldwide

Few typical experiments

If the rare isotope beam is deposited in the middle of the detector, a large volume of germanium surrounds the decaying nucleus leading to nearly complete detection efficiency for low-energy photons and electrons. The detector is uniquely suited to characterize isomeric transitions of highly electron-converted states.

Technical description

The planar GeDSSD is a 1-cm thick, 9-cm wide cylindrical HPGe detector, see Figure 33. The GeDSSD is segmented on the front and back into 16 5-mm strips.

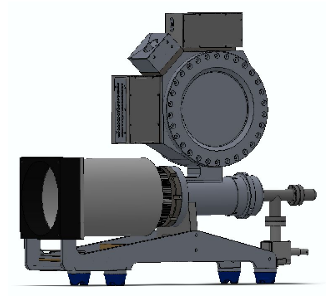


Figure 33: Drawing of the existing GeDSSD.

Present status of the instrument
The GeDSSD is fully operational at NSCL and has been used in prior experimental campaigns.

Description of electronics and integration methods
The GeDSSD uses the XIA digital electronics incorporated into the NSCL Digital Data Acquisition System (DDAS).

Present status of GEANT4 simulations
A simplified GEANT4 simulation exists for the planar GeDSSD

Plan for development and timeline
The planar GeDSSD is ready to be used at any time.

Required budget
Minor modifications to the support structure of the planar GeDSSD may be necessary to integrate it into DEGAi-FDSi, see Figure 34. Roughly $5k is anticipated for these modifications.

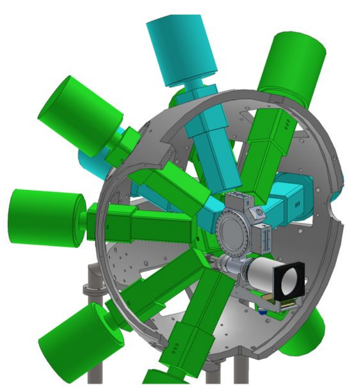


Figure 34: GeDSSD inserted into DEGAi. A new vertical support stand can be implemented through the vertical port EP1.

		Cost ($k) (Y1) (Y2) (Y3) (in-kind 1) (2) (3)	Comments
GeDSSD	Mechanical	(5) (0) (0) (0) (0) (0)	GeDSSD integration with DEGAi-FDSi and support structures
	Electronic	(0) (0) (0) (0) (0) (0)	
	Detector	(0) (0) (0) (0) (0) (0)	
	Other	(0) (0) (0) (0) (0) (0)	
		(5) (0) (0) **(0) (0) (0)**	

3.1.7 Stopped Beam Capabilities

The FDSi enables very comprehensive measurements of nuclear decays. While most of this document is focussed on experiments with “fast” beams directly from the fragment separator, the available instrumentation will be sufficient to instrument an equally powerful detection setup with stopped beams. Therefore, in this section, we will not discuss the technical details of the individual systems. The FDSi instrumentation also provides flexibility and redundancy, which will enable us to schedule experiments with fast and stopped beams within weeks (or less) from each other.

The slow beam setup requires the tape transport system and must be operated in a vacuum. The class of experiments performed at the stopped beamline will complement those at the fast beamline. The critical factor is the loss of beam rate due to the process of slowing and extracting the beam. However, the isotopic purity will be superior to the fast beams, and the 50-keV beam can be stopped in a thin layer of material. This enables experiments that cannot be performed with fast beams. The advantages of the stopped beamline are particularly apparent in high-Z nuclei, where there are challenges from in-flight separation and relatively long lifetimes that preclude implant-beta correlations.

One particular experimental method that is very difficult to implement with the fast beams is conversion-electron spectroscopy, which is a particularly useful tool to study multipolarities, E0 strengths, and decays of high-Z nuclei that can often exhibit several converted transitions (e.g., first excited states Z^3 dependence of the conversion process). This will be particularly important for searches and characterization of octupole deformation in connection to EDM candidates, amongst other physics inquiries, e.g., shape coexistence.

The majority of the FDSi contributed arrays have been used and operated with stopped beams at other facilities, including NSCL, which do not require special modifications. VANDLE, MTAS, and 3Hen operated at ORNL with a tape system developed at LSU. SuN uses its own tape system based on the LSU design. Figures 11, 20, and 25 demonstrate prior use of tape systems with VANDLE, MTAS, and SuN, respectively. Several electron and beta-trigger detectors exist, which include Si(Li) and fast-plastic-SiPM technology.

There are two distinct possibilities for operating on the stopped beam line: (1) move the entire FDSi infrasture and arrays for campaigns, or (2) duplicate some of the infrastructure between the two locations but use alternative, existing frames. For instance, the high-resolution gamma-ray spectroscopy system may utilize one of the existing frames: CLARION2, CAGRA, or NSCL-Rhombi, see Figure 35. All three frames nominally support 16 HPGe clovers, which can be transferred from the DEGAi frame on the fast beam line to the stopped beam line. While the CLARION1 frame can remain relatively static with the DEGAi-FDSi infrastructure, CLARION2 and CAGRA frames are likely to travel at times to fulfill other missions, particularly CLARION2. Therefore, access to all three frames for the stopped beamline is beneficial to the FDSi.

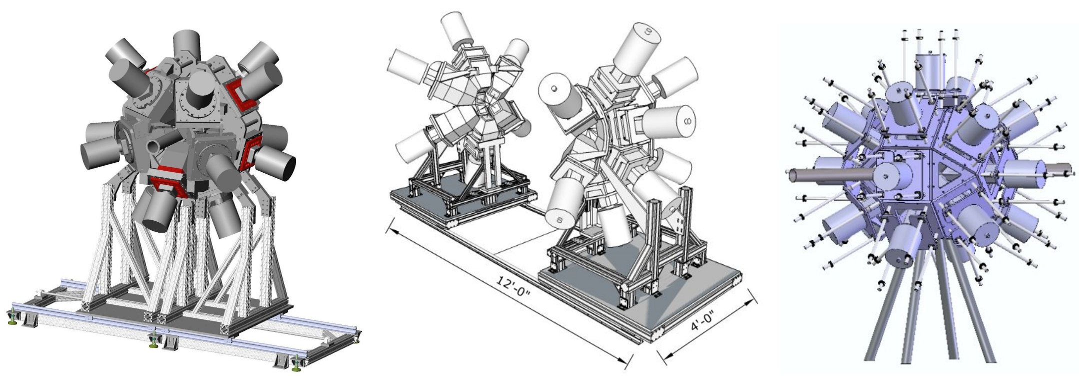


Figure 35: Existing clover frames which can be implemented in the stopped beam location: (left) CLARION2, (middle) CAGRA and (right) NSCL-Rhombi.

The CLARION2 frame, including rails and platforms, exists and it is currently being commissioned at FSU. The 80/20 support legs make it easy to adjust for 48- to 80-inch beam heights. It is designed to accommodate both CLARION and CLOVERSHARE BGO shields which have different sizes and flanges but it can also be used without shields. Furthermore, when the array is Compton-suppressed, coincident 511-keV gamma rays are also suppressed due to the lack of back-to-back detectors. CLARION2 has a dedicated Pixie16-based acquisition system and integrated LN2-HV system. No significant funding is anticipated to operate CLARION2 on the stopped beamline at FRIB.

The CAGRA frame is anticipated to be readily available for FRIB experiments on the stopped beam line and it supports the CLOVERSHARE BGO shields. The support structure is modular and modifications to the detector holders is possible to house other Compton Shields such as those for Clarion or to hold bare

Clover or other configuration detectors as has been routinely done for the CAGRA campaigns at RCNP. In addition, the utilization of 80/20 T-slot Aluminum profiles allows the height of the structure to be easily matched to the height of the FRIB beamline. Other infrastructure available includes ISEG HV modules for both Ge detectors and BGO shields as well as a 16 detector LN manifold and auto fill system. It has a dedicated GRETINA digitizer system for data acquisition with 200 channels.

The NSCL-Rhmobi frame will be available at FRIB. However, the frame in its current form does not split open or support BGO shields. This system would use the FRIB pool of Pixie16 digitizers.

Infrastructure and coordination of the existing equipment is the key factor in managing the FDSi activities at the fast and stopped beamline locations. We envision to prioritize the fast beam setup in the first year of FRIB operations. But ultimately, the scheduling will be determined by the decisions made by the PAC and FRIB operational capabilities. Stopped-beam decay studies are traditional within the community and several resources exist that are more-or-less ready to deploy. However, we anticipate that $100k in funding will be required to cover additional mechanical integration needs between community resources.

		Cost ($k) **(Y1) (Y2) (Y3)** **(in-kind 1) (2) (3)**	**Comments**
Stopped Beams	Mechanical	(0) (0) (100) (0) (0) (0)	
	Electronic	(0) (0) (0) (0) (0) (0)	
	Detector	(0) (0) (0) (0) (0) (0)	
	Other	(0) (0) (0) (0) (0) (0)	
		(0) (0) (100) **(0) (0) (0)**	

3.2 Data Acquisition

3.2.1 Digitizers

Figure 36: Pixie16 digitizers in a Wiener PXI crate; common to most FDSi Group members

The majority of FSDi subsystems use Pixie16 digitizers by XIA, see Figure 36, which were originally developed for the HRIBF decay spectroscopy program and later adopted by multiple laboratories, including NSCL. Some of the detector systems already have their own digital data acquisition systems and can be used without additional cost. The existing 16-channel Pixie16 modules are available in various combinations of bit depth (12 to 16 bit) and sample frequency (100 to 500 MSPS). They use a custom chassis manufactured by Wiener, which in the most recent implementation holds up to 13 modules or 208 channels. Larger multi-chassis systems can be constructed using XIA provided back-plane synchronization modules. Pixie16 features a reliable external-clock synchronization scheme. The system uses the PCI-PXI standard, featuring stable data-transfer speeds of 70 MB/s per crate (peak transfer is theoretically 133 MB/s). These digitizers are used by most of the FDSi Group members and they have been used extensively with various custom firmware solutions. The following devices have dedicated electronics:

- **VANDLE -** Pixie16 modules, 12 bit, 250 MSPS, and uses 194 channels (13 modules).
- **DEGAi ($LaBr_3$/$CeBr_3$) -** Pixie16 modules, 14 bit, 250 MSPS, and uses up to 44 channels (3 modules); available as part of HAGRID array pool.
- **MTAS (not including implant) -** Pixie16 ReVD modules, 12 bit, 100 MSPS, and uses 48 channels (3 modules).
- **GADGET -** Pixie16 modules, 16 bit, 250 MSPS, and uses 32 channels (2 modules).

The following devices do not have dedicated electronics or are not fully instrumented:

- **GeDSSD -** Pixie16 modules, 12-14 bit, 100-250 MSPS, and uses 64 channels (4 modules).
- **SuN -** Pixie16 modules, 12 bit, 100 MSPS, and uses 24-112 channels (2-7 modules).

- **DEGAi (HPGe) -** 24 clovers x 4 crystals = 96 channels; options include 6 modules (Pixie16, 14 bit, 100 MSPS) from the FRIB pool, 6 modules (Pixie16, 12 bit, 100 MSPS) from UTK/ORNL, or 6 modules (Pixie16, 14 bit, 100 MSPS) from CLARION2.
- **3HeNi -** 144 channels; options include 9 modules from UTK/ORNL, shared with $LaBr_3$/XSiSi scintillator arrays, or 9 modules from the FRIB pool.
- **MTAS / 3Hen (Implant SiDSSD) -** 3 detectors of 32+32 DSSDs at two ranges = 384 channels (24 modules, 2 crates); options include the FRIB Pixie16 pool or new 64-channel digitizers.
- **XSiSi (SiDSSD) -** 3 detectors of 32+32 DSSDs at two ranges = 384 channels (24 modules, 2 crates); 3 detectors of 64+64 DSSDs at two ranges = 768 channels (48 modules, 4 crates); options include the FRIB Pixie16 pool or new 64-channel digitizers.

The arrays without dedicated electronics will require up to 864 additional channels (54 modules or 5 crates) at a single point in time. The FRIB pool of digitizers include:

- 1 x Pixie16, 12 bit, 500 MSPS
- 12 x Pixie16, 14 bit, 500 MSPS
- 14 x Pixie16, 16 bit, 250 MSPS
- 6 x Pixie16, 14 bit, 250 MSPS
- 34 x Pixie16, 12 bit, 100 MSPS

If 81% of the FRIB pool of Pixie16 digitizers (54 of 67 modules) can be committed to the FDSi during scheduled operations, no new digital electronics are required. However, we anticipate that this will be a strain on local resources and other groups, potentially causing scheduling difficulties and last-minute debugging. In addition, the large number of required modules and crates increases the complexity of the acquisition system. A prudent option, particularly for the high-density SiDSSD implant array XSiSi, which will compete with SEGA-JANUS and other devices for the 34 12-bit, 100-MSPS Pixie16 modules, is to advance the FRIB pool with 9 new 64-channel, 14-bit, 100-MSPS Pixie64 digitizers that will be made available in early 2021 from XIA LLC. With this addition, only 18 of the existing 67 FRIB modules (27%) will be required. These new high-density digitizers are estimated to cost $16k per module ($250 per channel, 1/4th the price per channel compared to Pixie16) and they will have the same form factor as the Pixie16 digitizers, providing compatibility with the existing Pixie16 chassis (i.e., it is a drop in solution). They will also enable new sophisticated triggering solutions for the front and back strips of the implant Si-DSSDs.

		Cost ($k) **(Y1) (Y2) (Y3)** **(in-kind 1) (2) (3)**	**Comments**
Pixie64	Electronic	(0) (144) (0) (0) (0) (0)	9 Pixie64 modules (576 channels, 14 bit, 100 MSPS)
		(0) (144) (0) **(0) (0) (0)**	

3.2.2 Software

Much of the required software exists, particularly for the Pixie16 acquisition systems, but additional software for online and offline analysis will need to be developed. This will happen through the DAQ and Analysis Software Working Groups of the FDSi Group. No additional costs are required.

3.2.3 Network and Storage

The FDSi will have its own local network for acquisition systems, control, and immediate storage. However, access to MSU resources for on/off-line analysis and long-term data storage is requested.

3.3 Mechanical Systems, Integration, and Footprint

The mechanical infrastructure of the FDSi is the backbone of the system and it is by far the most important aspect of this proposal. Its aim is to: (1) combine the best detectors from the community for the maximum scientific reach, (2) permit rapid reconfiguration to maximize readiness and scientific opportunities, and (3) protect and monitor the resources entrusted upon us.

3.3.1 Integration of Support Structures for Rapid Reconfiguration

The FDSi mechanical infrastructure approach will enable execution of multiple measurements in quick succession when particular detector systems cannot be combined, by placing two systems along the beam trajectory and using removable implantation detectors to choose the stopping point at the first (discrete spectroscopy) or second (total absorption / neutron-counting spectroscopy) location together with manipulating the focal length of the last stage of the fragment separator beamline. Such a combination of instrumentation and measurements will provide a unique and powerful opportunity for consistent and thorough decay measurements. *The FDSi will be capable of nominal proton- and neutron-rich workhorse configurations on Day 1 FRIB with tandem discrete and total-absorption spectroscopy capabilities.*

In order to reconfigure the discrete array between proton-and neutron-rich investigations at the first focal point, particularly within a single campaign, the FDSi infrastructure will necessitate a combination of rails, platforms, and a switchyard or cart system for exchanging 2π hemispheres of DEGAi and NEXTi. For the second focal point, a new platform system on rails for MTAS and its shielding, which weighs 7 tons, would (1) reduce the footprint caused by the shielding outriggers, (2) enable relatively simple reconfiguration of the second focal point for other devices such as SUN and 3HeNi, while maintaining MTAS readiness, and (3) permit temporary distancing of the array from NEXTi (VANDLE) for the purpose of reducing the neutron-scattering background during "discrete array" measurements. It would also provide additional space for exchanging 2π hemispheres of DEGAi and NEXTi. *These reconfiguration capabilities of the infrastructure will minimize downtime, maximize FDSi opportunities, and, therefore, the FDSi scientific productivity.* This reconfiguration capability of the infrastructure is also important in year 1 due to it being positioned immediately behind the separator where there will be limited access. Locations will be discussed in Section 3.4.

The footprint required by the FDSi is outlined in Figure 37. A minimum space of 6 m x 5 m is required to enable a two-focal point solution with shielding (see Section 3.3.3) and reconfiguration capabilities. The double-ended arrows within the figure represent the motion necessary for rapid reconfiguration.

As outlined in the detector sections, the cost to implement DEGAi and NEXTi on a rail and platform system totals to \$75k (\$25k per hemisphere); this level of funding is sufficient for static setups. A switchyard or cart system for exchanging 2π hemispheres of DEGAi and NEXTi will require an additional \$75k. A heavy-duty platform on rails for the second focal point will require yet another \$75k. Roughly two months of engineer time will be required to detail the designs. Temporary occupancy outside of the 6 m x 5 m box may be required in the final design. Additional mechanical needs for each detector subsystem are detailed in Section 3.1.

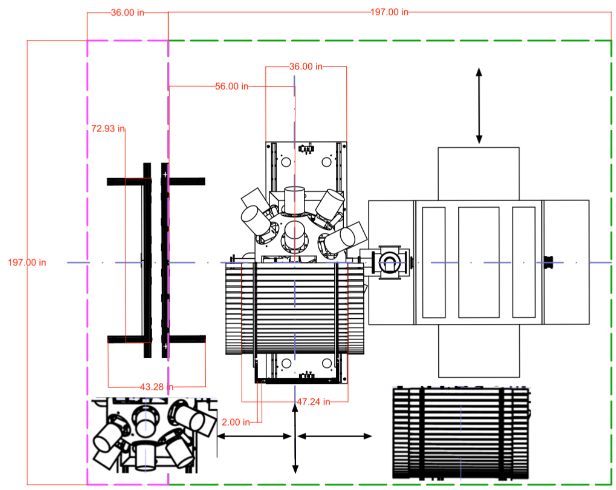


Figure 37: Minimum FDSi footprint (6 m x 5 m) required for a two-focal point solution with shielding and rapid reconfiguration capabilities. The green dashed box is 5 m x 5 m and the purple dashed box extends the space to 6 m x 5 m. The beam direction is from left to right.

		Cost (\$k) **(Y1) (Y2) (Y3)** **(in-kind 1) (2) (3)**	**Comments**
FDSi Reconfig	Mechanical	(75) (75) (0) (0) (0) (0)	Switchyard or cart system (\$75k) and heavy-duty platform on rails (\$75k)
		(75) (75) (0) **(0) (0) (0)**	

3.3.2 Liquid Nitrogen Distribution and Monitoring

In order to benefit from the large variety of HPGe (up to 96 crystals) detectors on loan from the community, a single integrated LN2 and HV system is needed for DEGAi to not only operate the devices but also to monitor and protect the resources entrusted upon us. A duplication of the ORNL GRETINA and CLARION LN2 systems, which are familiar to local FRIB staff and are maintained by a FDSi Group member, can be produced for \$30k, which would include: two 13-port supply manifolds; two 13-port exhaust manifolds; 28 solenoids; rtds; cables; nalgene hoses, insulation, and fittings; and a computer with adcs and relays. Further, a LN2 buffer tank from FRIB will be required or a new one will need to be purchased for \$15k. The DEGAi HV-LN2 system will also fulfill all future DEGA-FDS requirements, permitting a seamless transition. This expense is budgeted within DEGAi and is only shown here for completeness.

LN2	Y1 (\$k)	Y2 (\$k)	Y3 (\$k)	Comments
Mechanical	30	0	0	LN2 system (with an existing FRIB buffer tank, \$45k total otherwise).

3.3.3 Shield Wall and Energy Degrader

General description of the instrument

Fragmentation experiments at FRIB will require a remotely controlled energy degrader to adjust the beam position within the implantation array. The energy degrader will consist of a two-wheel system with attached beam-intersecting degraders. The combination of two degraders will permit both coarse and fine adjustments. In order to protect the FDSi detectors from stray particles and gamma-rays generated in the separator and energy degrader, a shielding system is required. A large shield wall in front of the FDSi is envisioned to fulfill this role, see Figure 38. This wall will also provide structural support for the energy degrader and, possibly, a chamber with a modest silicon array for ΔE identification, particularly useful for online particle identification and diagnostics.

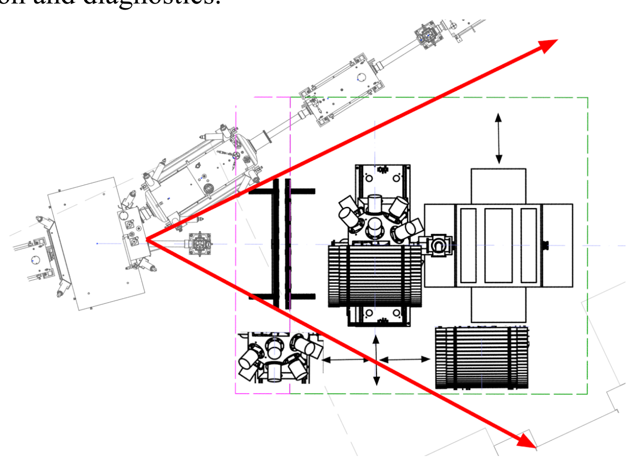


Figure 38: A shield wall will protect the FDSi from unwanted stray particles and gamma rays generated by secondary radiation. Additional shielding may be required after an empirical survey.

Technical description

The energy degrader will consist of two wheels with eight positions for beam-intersecting degraders, see Figure 39. One position is required for a beam stopper. Furthermore, each wheel will have a single empty slot to permit the passing of non-degraded beams. Thus, 7 x 6 = 42 thickness combinations are possible. Each wheel will be operated by a remotely controlled step motor. The degraders will have the dimension of 4” x 4” to match the size of the largest possible beam dimension and implantation detector. The combination of two degraders will enable fine and coarse adjustments to the effective thickness.

Figure 39: The energy degrader will consist of two wheels with foils to provide variable thicknesses with coarse and fine adjustments. The wheels will be driven by remotely controlled step motors.

The shield wall will be constructed from HDPE and lead sheets supported by an 8020 structure, see Figure 40. The dimension of the wall will be 86” x 96”. The HDPE will be 4-inches thick and the lead wall will be 1-inch thick; this will block 120-MeV protons. It will also absorb gamma rays up to 4 MeV (half-thickness) and reduce the energy of fast neutrons. For additional shielding, lead-wool blankets can be added, similar to those used with MTAS.

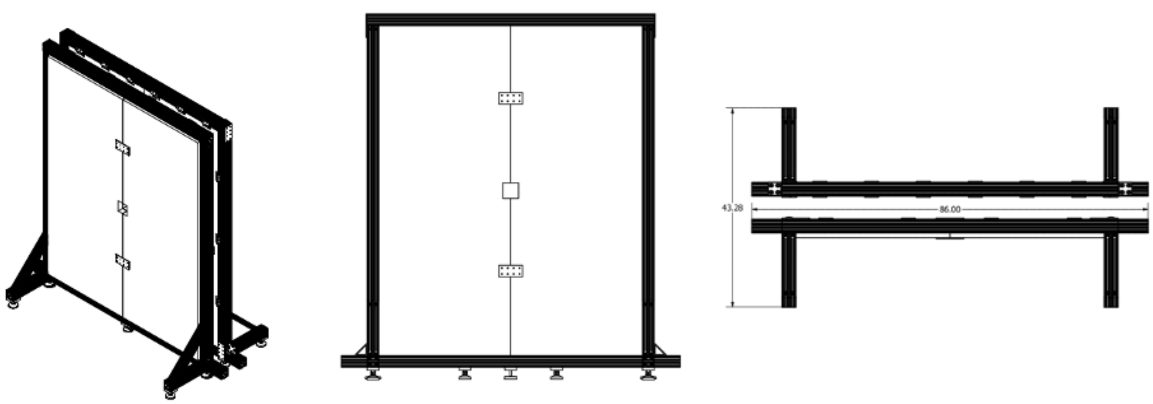


Figure 40: A shield wall consisting of 4-inch thick HDPE and 1-inch thick Pb.

Present status of simulations

Only elementary simulations have been performed thus far.

Plan for development and timeline

The wall can be constructed relatively easily from commercially available materials and can be designed, constructed, and acquired within 2-3 months.

Required budget

HDPE and lead are relatively inexpensive materials. The 8020 design has to be sturdy to support this massive structure. We anticipate a budget of about $15k for the shield wall and $10k for the energy degrader.

		Cost ($k) **(Y1) (Y2) (Y3)** **(in-kind 1) (2) (3)**	**Comments**
Wall and Degrader	Mechanical	(25) (0) (0) (0) (0) (0)	Wall and degrader
		(25) (0) (0) **(0) (0) (0)**	

3.4 Locations at FRIB

Locations for the FDSi are highlighted in Figure 41. The footprint of the FDSi, which was outlined in Section 3.3.1, is superimposed on the latest building design. Temporary occupancy outside of specific regions of the 6 m x 5 m box may be required in the final design of the switchyard / cart transfer system at the first focal point and it will be required to move MTAS in and out of the shielding at the second focal point. Furthermore, large doors and/or crane access must be provided to get equipment in and out of the room. Space is also required to store unused detector arrays. Because the building designs have not been finalized, we request that our provided drawings be a guide for finalizing the FDSi spaces while adhering to the FDSi requirements.

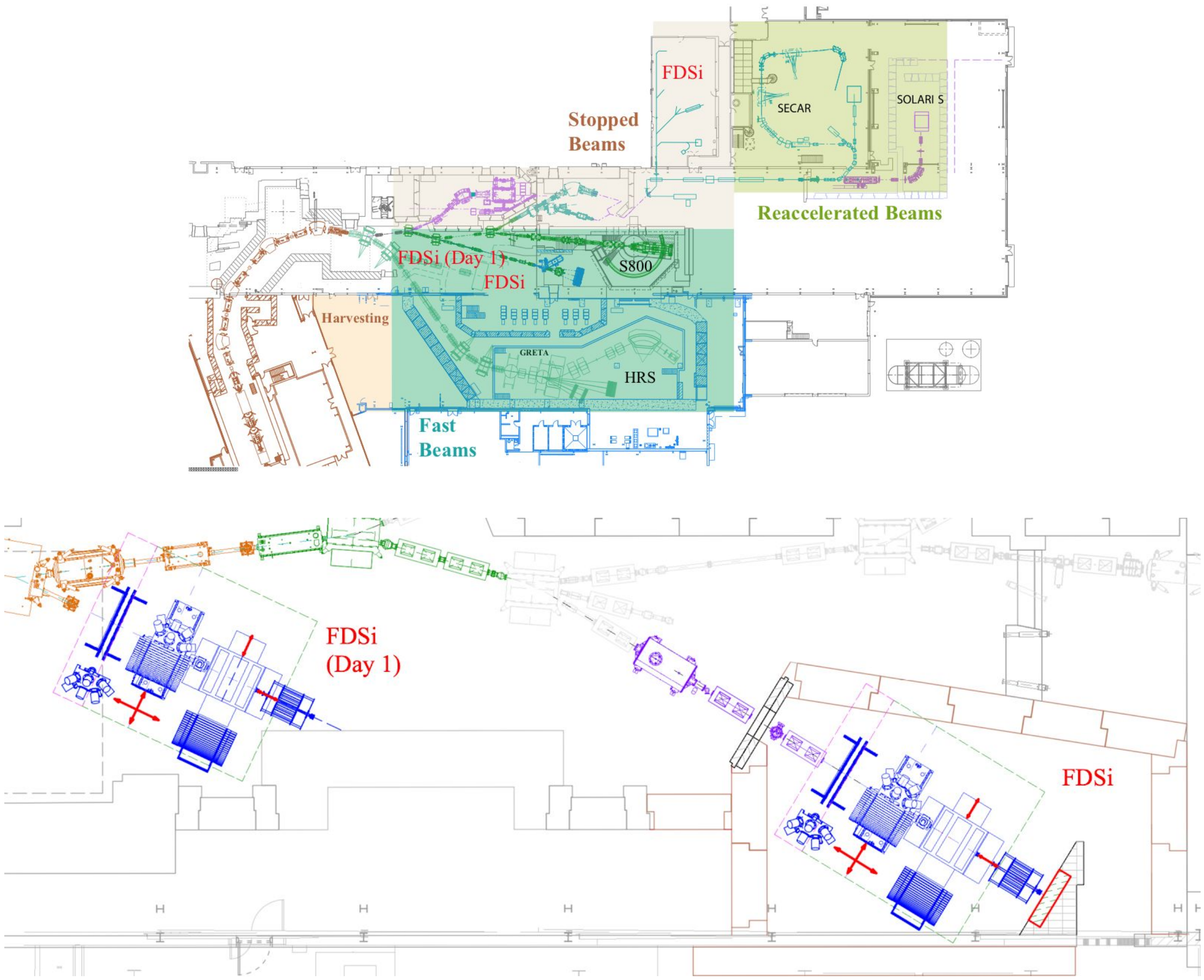


Figure 41: (top) Locations for the FDSi in the temporary position behind the separator for Day 1, the permanent FDSi vault for Year 2 and beyond, and the stopped beam area. (bottom) Overlay of current building design and FDSi footprint for the fast-beam locations.

4. Organizations

4.1 General

FDS Spokesperson - R. Grzywacz (ORNL/UTK)
FRIB Management: Thomas Glasmacher, Brad Sherrill, Georg Bollen

4.2 FDSi Coordination Committee

R. Grzywacz (ORNL/UTK)
J. M. Allmond (ORNL)
D. Seweryniak (ANL)
S.N. Liddick (FRIB)

4.3 FDSi Engineering

Proposal Engineer: Darryl Dowling (ORNL)
Proposal Drawing Assistance: Toby King (UTK)

Project Engineer: *to be negotiated and determined (Kent Leslie, Craig Snow, and/or Don Lawton)*

4.4 FDSi Group

ORNL
R. Grzywacz
J. M. Allmond
K. Rykaczewski
C. Rasco

ANL
D. Seweryniak
M.P. Carpenter

FRIB
S.N. Liddick
A. Spyrou
C. Wrede
H. Schatz

UTK
R. Grzywacz

K.L. Jones
M. Madurga

FSU
V. Tripathi

MSU (Mississippi)
B. Crider

LBNL
A. Macchiavelli

URSinus
L. Riley

UNC
R.V.F. Janssens

UML
A. Rogers

4.5 FDS Users Group

FDS UEC
C. Rasco (ORNL)
A. Spyrou (FRIB)
V. Tripathi (FSU)
B. Crider (MSU)
K. Kolos (LLNL)

4.6 FDS and FDSi Documents

FDS Users Group Charter

1. Definition and Purpose:

The FRIB Decay Station (FDS) Users Group is an organization of scientists interested in supporting the construction and use of the FDS at FRIB. The goal of the FDS is to produce scientific discoveries in nuclear structure and astrophysics, as well as in fundamental symmetries and applied physics. The Group will also seek to incorporate and use equipment provided by collaborators, from the US and abroad, to improve the capabilities of the FDS.

The purposes of this association are:

(a) To provide a formal channel for the exchange of information and advice between the scientists who use the device and those that support the device.

(b) To encourage and support further developments of the capabilities of the FDS.

(c) To provide a means for the exchange of information and advice among the users and to facilitate collaboration of interested users in experiments, aspects of data analysis, technical developments or the operation of the device.

(e) To promote the FDS as a research tool within the Nuclear Physics community at large and with the funding agencies.

(f) To establish FDS proposal, usage, data, and publication rules.

2. Membership:

The membership of the FDS Users Group is open to all scientists interested in the research and/or technical programs associated with the device. The list of the membership is held by the Chair of the Users Executive Committee of the Users Group.

3. Users Executive Committee:

A Users Executive Committee will conduct the day-to-day business of the FDS Users Group. This committee consists of five voting members, selected from the Users Group membership. The members of the Executive Committee must be active or expected users of the device, and no two voting members can be from the same institution. The FDS Spokesperson and Project Director (or equivalent position prior to the commencement of the FDS project), will be non-voting ex-officio members of the Users Executive Committee. New member(s) of the Users Executive Committee will be elected annually by members of the Users Group by written ballot and shall take office on August 1. The normal term of office is two years. The first UEC was established on August 9, 2019. For the first UEC, all members but the acting UEC Chair and Secretary will be up for re-election after two years.

The Users Executive Committee will propose a slate of at least three candidates for the open elected position(s) on the Users Executive Committee. Written nominations signed by at least seven members of the Users Group from a minimum of three different institutions shall also be accepted. Members may only serve up to two consecutive terms. The Users Executive Committee will select one of its members to serve as Chair and another to serve as Secretary. Neither the Chair nor the Secretary will be associated with FRIB. The term of the Chair is one year. If a vacancy arises on the Users Executive Committee, the remaining Committee members will select a member of the Users Group to serve out the unexpired term. The unexpired term counts as one term for the selected member. In the event that the Chair's or the Secretary's position becomes vacant, the members of the Committee shall first select a new member as described above, and then proceed with an election to the vacated position. The newly selected Committee member may not be a candidate to the Chair's or Secretary's position.

3. FDS Proposals, Usage, Data, and Publication Rules:

The FDS is available to all members of the user group. The UEC will coordinate with detector owners or stewards and provide to the community the available detectors, conditions of use, and configurations for a given proposal cycle. The UEC will facilitate the development of FDS proposals and define appropriate data sharing and publication rules.

4. Procedures:

(a): The Users Executive Committee will meet at a regular basis. The minimal quorum for all meetings of the Users Executive Committee is three members.

(b): The Users Group shall meet at least once a year at a time and place designated by the Users Executive Committee. In addition, the Users Executive Committee shall organize, or help organize FDS related workshops.

(c): The elections to the Users Executive Committee will be organized by the Secretary of the Users Executive Committee.

5. Amendments:

Amendments to this Charter will be accomplished by a two-thirds majority vote of ballots cast by the membership at large. Proposed changes may be submitted by majority vote at a meeting or workshop, or by petition to the Users Executive Committee from a minimum of 10 members of the Users Group from a minimum of three different institutions.

The FDS Initiator (FDS$_i$)

The FRIB Decay Station (FDS) — an efficient, granular, and modular multi-detector system designed under a common infrastructure — will be staged, beginning with equipment from existing arrays and subsequently upgraded, increasing the energy resolution, granularity, and combined efficiencies along the way; this will increase the scientific output and extend the scientific reach towards the drip lines.

The FDS Initiator (FDS$_i$) is the initial stage of the FDS that will be ready for Day One FRIB, and the FDS Initiator Group is the body of contributors responsible for establishing the FDS$_i$, which will occur before official FDS funding, in accord with the vision outlined in the FDS White Paper. The FDS Initiator Group will work towards the FDS$_i$ in coordination with the FDS Users Executive Committee (FDS UEC) and FRIB, ultimately providing a means for FRIB users to conduct world-class decay spectroscopy experiments with the best equipment possible. This document represents a joint agreement between the

FDS Initiator Group and the FDS UEC, which represents the wider community, and it outlines the opportunities, procedures, and conditions for using the FDS_i. The terms within this document may be renegotiated only once per year with suggestions for possible changes presented at the one of the annual nuclear physics community meetings (e.g., LECM or APS DNP).

- Prior to each PAC cycle, the FDS UEC, in coordination with the FDS Initiator Group, will provide a list of available detector systems for decay spectroscopy studies, points-of-contact for each detector system, and nominal array configurations to FRIB and the user community. Users interested in other configurations or additions should communicate their needs with the FDS UEC prior to a PAC cycle.
- Anyone can submit a FDS_i proposal, regardless of country or affiliation. However, PIs should coordinate their proposals with the detector points-of-contact for technical review.
- Primary authorship and data sharing are to be negotiated and resolved amongst the proposal PIs and detector points-of-contact. All FDS Initiator Group contributors are permitted to participate in all FDS_i experiments if they desire. All people who contribute to a proposal, detector setup, experiment, analysis, or manuscript are to be included as authors. FRIB data management and authorship policies must be strictly followed for continued use of the FDS_i. The experimental PI is ultimately responsible in fulfilling any FRIB defined pre-experiment procedures but the FDSi Group will make the best effort to assist in this process.
- PIs are encouraged to submit a short abstract (one-page limit) to the UEC that communicates the aim of their intended proposal 30 days before a proposal deadline. The UEC and FDS Initiator Group will use this information to recommend possible bundling of proposals that can be achieved simultaneously. In such situations, the UEC, in coordination with the FDS Initiator Group, will contact the involved parties and broker an agreement on the nominal detector configuration and data sharing.
- All issues surrounding duplicate or overlapping proposals should be resolved amongst the proposal PIs and detector points-of-contact if possible before final submission.
- When contributors within the FDS Initiator Group submit proposals surrounding their own hardware, they must follow the rules set in this document and those of the FDS Users Group Charter if they rely on FDS_i resources that do not belong to their institution, or, if they use the FDS_i branding.

5. Cost and Schedule

5.1 Remaining Development

Engineer designs for DEGAi detector-port adapters, XSiSi housing, a switchyard or cart system for rapid reconfigurations, a heavy-duty platform on rails for the second focal point, a shield wall, and miscellaneous detector support structures are required to complete the FDSi. These developments are considered low risk but they require a FDSi Engineer and coordination with FRIB building engineers. The other developments rely on off-the-shelf electronics and detectors. *No new technological developments are required to implement the FDSi.*

5.2 Work Breakdown Structure (WBS) and Working Groups

1. FDSi
    - 1.0 Coordination: ORNL-UTK, ANL, FRIB
    - 1.1 Detector Subsystems
        - 1.1.1 DEGAi
        - 1.1.2 NEXTi
        - 1.1.3 XSiSi
        - 1.1.4 TAS
        - 1.1.5 3HeNi
        - 1.1.6 Auxiliary
        - 1.1.7 Stopped Beams
    - 1.2 DAQ
    - 1.3 Analysis Software
    - 1.4 Simulations
    - 1.5 Site Utilities and Preparation
    - 1.6 Mechanical Integration
    - 1.7 Shield Wall and Energy Degrader

5.3 Cost Estimate

The total cost estimate to implement the FDSi is $1283k, which is spread over three years and based on a combination of budgetary quotes and actual costs from prior projects, plus an additional $193K worth of new expenses from expected in-kind contributions. The cost estimate includes mechanical infrastructure, electronics, Si detectors, and 10% contingency. Tax, overhead, and engineering costs were not included but an FDSi Project Engineer from FRIB is also requested to assist with the remaining (low risk) mechanical designs and implementation at FRIB. Otherwise, the FDSi Group will need to provide this additional in-kind contribution. *No new technological developments are necessary for implementing the FDSi.* Facility requirements and community contributions can be found in the appendices.

Table 4: Cost estimate for three stages of the FDSi, which do not include tax, overhead, or engineer time. The second and third year of funding will enable additional opportunities in-line with FRIB beam development. "In Kind" contributions of FDSi Group members represent future expenses.

	Y1 ($k) **(in kind)**	**Y2 ($k)** **(in kind)**	**Y3 ($k)** **(in kind)**	**Comments**
Mechanical	290	145	100	$535k mechanical needs (#1 priority)
Electronic	162	253	35	$450k electronic needs
Detector	108	10	43	$161k of new detector needs
Other	0	20	0	$20k of other needs
Contingency	**56**	**43**	**18**	10% contingency
Total	**616** **(153)**	**471** **(0)**	**196** **(40)**	Grand total of $1283k over 3 years

Table 5: Cost estimate to implement the FDSi per subsystem. "In Kind" contributions of FDSi Group members represent future expenses but do not include personnel or engineer time.

		Cost ($k) **(Y1) (Y2) (Y3)** **(in-kind 1) (2) (3)**	**Comments**
DEGAi (γ)	Mechanical	(100) (30) (0) (0) (0) (0)	Hemi sleighs on rails + adapters, LN2 system (with an existing FRIB buffer tank, +$15k otherwise).

	Electronic	(0) (102) (35) (0) (0) (20)	HV mainframe + modules, spare preamps Preamp, FET, and misc. repairs
	Detector	(0) (0) (0) (0) (0) (0)	
	Other	(0) (20) (0) (0) (0) (6)	Signal cables Transport
		(100) (152) (35) **(0) (0) (26)**	
NEXTi (n)	Mechanical	(25) (0) (0) (0) (0) (0)	Arch sleigh on rails
	Electronic	(0) (0) (0) (0) (0) (0)	
	Detector	(0) (0) (0) (80) (0) (0)	40 new VANDLE bars for 2nd arch
	Other	(0) (0) (0) (0) (0) (6)	Transport
		(25) (0) (0) **(80) (0) (6)**	
XSiSi (q^+/q^-) - Si DSSD	Mechanical	(25) (0) (0) (0) (0) (0)	Detector and preamp housing and support
	Electronic	(89) (0) (0) (0) (0) (0)	Dual gain amp solution
	Detector	(88) (0) (0) (0) (0) (0)	3 micron TTT and 5 micron BB7
	Other	(0) (0) (0) (0) (0) (0)	
		(202) (0) (0) **(0) (0) (0)**	
XSiSi (q^+/q^-) - Scintillator	Mechanical	(5) (0) (0) (0) (0) (0)	Integration with Si DSSD housing
	Electronic	(0) (0) (0)	

		(0) (0) (0)	
	Detector	(0) (0) (0) (0) (0) (0)	
	Other	(0) (0) (0) (0) (0) (0)	
		(5) (0) (0) **(0) (0) (0)**	
MTAS	Mechanical	(5) (0) (0) (0) (0) (0)	Si-DSSD and YSO integration
	Electronic	(73) (0) (0) (0) (0) (0)	Dual gain preamp solution
	Detector	(20) (0) (0) (15) (0) (0)	2 additional Si-DSSDs YSO-based scintillator
	Other	(0) (0) (0) (58) (0) (8)	Central module installation @ St. Gobain and transport
		(98) (0) (0) **(73) (0) (8)**	
3HeNi	Mechanical	(0) (20) (0) (0) (0) (0)	New support structure
	Electronic	(0) (7) (0) (0) (0) (0)	SHV board
	Detector	(0) (10) (43) (0) (0) (0)	New HDPE matrix, 21 short 1” tubes
	Other	(0) (0) (0) (0) (0) (0)	
		(0) (37) (43) **(0) (0) (0)**	
Aux	Mechanical	(30) (20) (0) (0) (0) (0)	GADGET, PXCT, GeDSSD integration: modification and support structures
	Electronic	(0) (0) (0) (0) (0) (0)	

	Detector	(0) (0) (0) (0) (0) (0)	
	Other	(0) (0) (0) (0) (0) (0)	
		(30) (20) (0) **(0) (0) (0)**	
Stopped Beams	Mechanical	(0) (0) (100) (0) (0) (0)	
	Electronic	(0) (0) (0) (0) (0) (0)	
	Detector	(0) (0) (0) (0) (0) (0)	
	Other	(0) (0) (0) (0) (0) (0)	
		(0) (0) (100) **(0) (0) (0)**	
Pixie64	Electronic	(0) (144) (0) (0) (0) (0)	9 Pixie64 modules (576 channels)
		(0) (144) (0) **(0) (0) (0)**	
FDSi Reconfig	Mechanical	(75) (75) (0) (0) (0) (0)	Switchyard or cart system ($75k) and heavy-duty platform on rails ($75k)
		(75) (75) (0) **(0) (0) (0)**	
Wall and Degrader	Mechanical	(25) (0) (0) (0) (0) (0)	Wall and degrader
		(25) (0) (0) **(0) (0) (0)**	
TOTAL		**(560) (428) (178)** **(153) (0) (40)**	

5.4 Schedule

Legend for Primary Task Lead		FRIB CALL	FRIB SUB	FRIB PAC		FDSi INST		FRIB CD4				
ORNL												
UTK			2021				2022				2023	
ANL	Jul	Oct	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct	Jan	Apr
MSU / FRIB	Y1				Y2				Y3			
FDSi Group / FRIB	1	2	3	4	1	2	3	4	1	2	3	4
1.1 Detector Subsystems												
1.1.1 DEGAi												
Install at FRIB						Craft						
Design Frame Support (platform/rails)	Engineer											
Design Detector Adapters	Engineer											
Procure Materials and Machine Parts		100										
Procure LN2 components					30							
Procure HV mainframe and modules					102							
Procure Cables					20							
Procure spare preamps									35			
1.1.2 NEXTi												
Install at FRIB						Craft						
Design Frame	Engineer											
Construct Frame		in-kind										
Assemble Second Layor Detectors		in-kind										
Design Frame Support (platform/rails)	Engineer											
Procure Materials and Machine Parts		25										
1.1.3 XSiSi												
Install at FRIB						Craft						
Procure 5 BB7 and 3 TTT Si DSSDs		88										
Procure Mesytec PAs + SAs (Dual Gain)		89										
Design Detector Frame and Housing	Engineer											
Procure Materials and Machine Parts		25	5									
Acceptance Testing of Si												
Acceptance Testing of YSO												
1.1.4 TAS												
Install at FRIB						Craft						
Procure 2 Custom Si DSSDs		20										
Procure Mesytec PAs + SAs (Dual Gain)		73										
Install Central Module at St. Gobain				in-kind								
Acceptance Testing of bare MTAS												
Design Si-YSO Housing Integration		Engineer										
Procure Si-YSO Integration Parts			5									
Assemble YSO		In-kind										
Acceptance Testing of MTAS Si-YSO												
Relocate Sun												
1.1.5 3HeNi												
Install at FRIB										Craft		
Design HDPE matrix and Support Structure				Engineer								
Procure Materials and Machine Parts						30						
Procure Additional SHV board						7						
Procure 20 short 3He tubes									43			

1.1.6 Auxiliary												
Design GADGET Support Structure	Engineer											
Procure Materials and Machine Parts		25										
Design PXCT Support Structure	Engineer											
Procure Materials and Machine Parts						20						
Design GeDSSD Support Structure	Engineer											
Procure Materials and Machine Parts		5										
1.1.7 Stopped Beams												
Design Misc. Support Parts and Adapters								Engineer				
Procure Materials and Machine Parts										100		
1.2 DAQ												
Procure 9 Pixie64 modules					144							
Update Acquisition Software for Pixie64												
1.3 Analysis Software												
1.4 Simulations												
1.5 Site Utilities and Preparation												
Install Utlities in Temporary Location	Craft											
Install Utlities in Permanent Vault								Craft				
1.6 Mechanical Integration												
Install at Temporary Location				Craft								
Install at Permanent Vault								Craft				
Design Switchyard / Cart System	Engineer											
Procure Materials and Machine Parts		75										
Design 2nd Focal Point Platform on Rails	Engineer											
Procure Materials and Machine Parts					75							
1.7 Shield Wall and Degrader												
Install at Temporary Location				Craft								
Install at Permanent Vault								Craft				
Design Wall and Degrader	Engineer											
Procure Materials and Machine Parts		25										

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APPENDIX A: Utility and Facility Requirements

<u>Behind Separator (Year 1):</u>

Power:

The power requirements of the FDSi in the temporary location are provided in the summary table below. The “Max Watts” represents the upper limit of possible power use, which is smaller than the “Max Outlet Watts” = V * Amp * Outlets; most outlets will be underutilized.

	V	Amp	Outlets		Max "Outlet" Watts	Max Watts	%
Clean (single phase)	120	20	10		24000	17625	74
Clean (single phase)	240	30	2		14400	5760	40
				Total Clean:	38400	23385	61
Dirty (single phase)	120	20	8		19200	14400	75
Dirty (single phase)	240	30	1		7200	2200	31
Dirty (triple phase)	208	30	1		6240	5000	81
				Total Dirty:	32640	21600	67
						Max Amps	
					480V line Clean Pwr	49	
					480V line Dirty Pwr	45	

Water:

The FDSi may require one water supply and return line for cooling (e.g., detectors, some turbo pumps, cryopump compressor, etc …). A recirculated water unit would be sufficient.

Compressed Air:

The FDSi will need compressed air to operate gate valves, air motors and tools, and other incidentals (e.g., LN2 buffer-tank pressure and static-free cleaning). Up to three drop points are expected.

Internet:

The FDSi will need one wifi unit with public internet access for guests so that laptops and cellphones work in the cave, which will be useful when installing, configuring, and testing the FDSi.

The FDSi will likely have its own private 10Gb network with well-defined static IPs and its own gateway. However, the FDSi will need two cat5 cables run into the temporary room for wired public internet and private 10Gb services. The MSU (public) network would connect to the FDSi gateway and give access to the outside world. There would also be a non-public 10Gb MSU network line that bypasses the FDSi gateway and connects directly to a second NIC within a FDSi control / event-builder computer (i.e., a computer that sends commands to all the acquisition systems, receives and merges all the data, sends data for backup and offline analysis to some MSU resource, etc..).

Liquid Nitrogen:
The FDSi will require a building supply of LN2 brought into the room via a vacuum jacketed line and a buffer tank that is 240 liters or more. The FDSi will have its own autofill system and manifolds. The HPGe clover dewars are nominally 3 liters with a 24-hour hold time. A fully loaded 4π DEGAi configuration has 24 clovers with a total boil-off rate of 3 liters per hour. While cooling down the manifolds and filling the detectors, which occurs every 8 hours, 72-96 liters worth of LN2 could be released into the room within a 20-40 minute window. Therefore, the acute boil-off rates can be as large as 3.6-4.8 liters per minute. The FDSi will consume up to 216-288 liters of LN2 a day. The exact numbers will be contingent upon the cool-down times of the manifolds, supply lines, and exhaust lines.

Oxygen Alarm:
The FDSi will have its own alarm system but FRIB policy may require a local / building alarm as well. The acute boil-off rate of the FDSi could be as large as 4.8 liters per minute.

LED Lighting:
The FDSi will require >= 50 Foot-candles of lighting.

Fire Sprinklers:
As FRIB building policy requires.

HVAC:
The FDSi requires temperature stability of < 5 degrees F for the operation of the detectors and electronics.

Phone:
The FDSi will require one analog phone line for the analog phone text dialer, which is part of the LN2 monitoring system. This protects the FDSi against potential problems associated with power outages and computer lockups / freezes / crashes.

<u>FDS Vault (Year 2+):</u>

The FDSi utility requirements in the FDS Vault are identical to those behind the separator. However, we anticipate that the FDS may have up to twice the clean power needs in the FDS Vault.

APPENDIX B: Contributed Resources

ORNL: 11 Clovers, MTAS, 3Hen, CLARION1 (fast beam) and CLARION2 (slow beam) frames

UTK: VANDLE, segmented scintillator-based implant detectors, 30 $LaBr_3$ detectors

ANL: 8 clovers, CAGRA (slow beam) frame

FRIB: SUN, GADGET, PXCT, GeDSSD, 16 $LaBr_3$ detectors, Pixie16 pool (67 modules), Vacuum pumps and gauges

FSU: 3 clovers**

MSU (Mississippi): 4 $CeBr_3$ and 10 $LaBr_3$ detectors, segmented $CeBr_3$-based implant detector

URSinus: Simulation support

UNC: 12 $CeBr_3$ detectors

LBNL: 2 clovers**

**On limited occasions and contingent on schedule due to local program / facility needs.

The FRIB Decay Station Initiator