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NUCLEAR SCIENCE DIVISION

The Gamma-Ray Energy Tracking Array (GRETA)

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Zakopane Conference on Nuclear Physics Extremes of the Nuclear Landscape
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ZAKOPANE CONFERENCE on Nuclear Physics 2026 Extremes of the Nuclear Landscape

U.S. DEPARTMENT OF ENERGY

Outline

- Introduction
  why GRETA, how it works, what it is
- GRETA Project
- GRETA Status

GRETA - A key γ-ray detector for FRIB

The Facility for Rare Isotope Beams (FRIB) is a world leading accelerator facility to understand the properties of exotic nuclei and how the elements are synthesized.

GRETA is a key instrument for FRIB capable of reconstructing the energy and three-dimensional position of γ-ray interactions.

Its design provides the unprecedented performance needed to carry out a large fraction of the nuclear science programs at FRIB.

FRIB at Michigan State University

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
Intellectual challenges from NRC Decadal Study 2013			
How does subatomic matter organize itself and what phenomena emerge?	How did visible matter come into being and how does it evolve?	Are fundamental interactions that are basic to the structure of matter fully understood?	How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?
1. Shell structure ✓ 2. Superheavies ✓ 3. Skins ✓ 4. Pairing 5. Symmetries ✓ 6. Equation of state 13. Limits of stability ✓ 14. Weakly bound nuclei ✓ 15. Mass surface ✓	1. Shell structure ✓ 6. Equation of state 7. r-Process ✓ 8. $^{15}O(\alpha,\gamma)$ 9. ^{59}Fe s-process 13. Limits of stability ✓ 15. Mass surface 16. rp-Process 17. Weak interactions ✓	12. Atomic electric dipole moment ✓ 15. Mass surface 17. Weak interactions	10. Medical 11. Stewardship ✓

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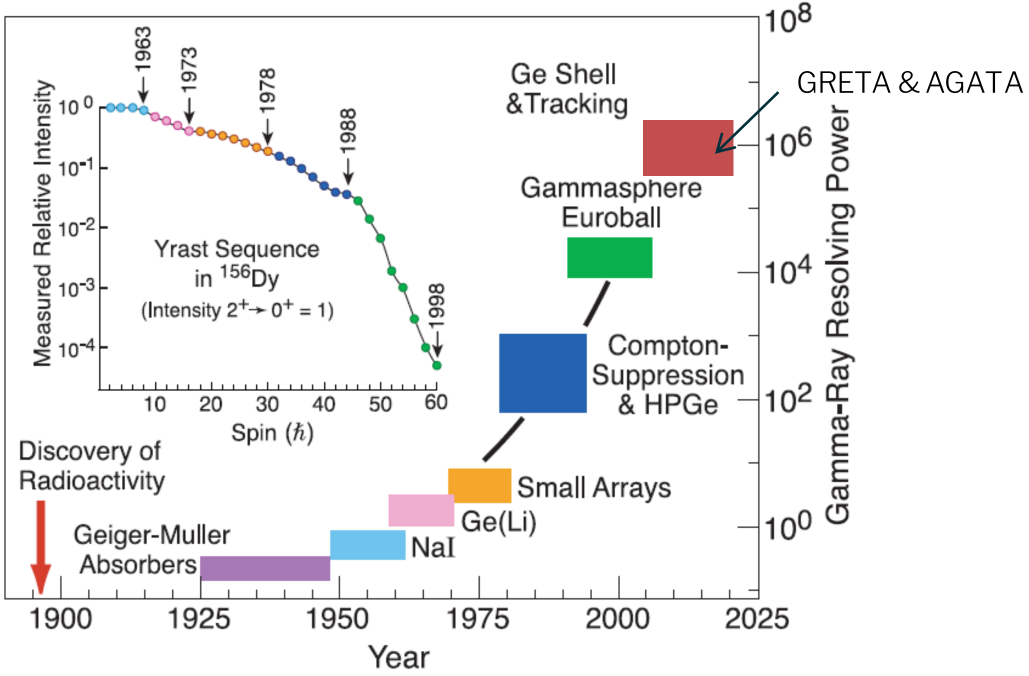
γ-Ray Detection Plays a Central Role

- Of the many experimental tools and techniques developed to study nuclei, high-resolution γ-ray spectroscopy has proven to be among the most powerful

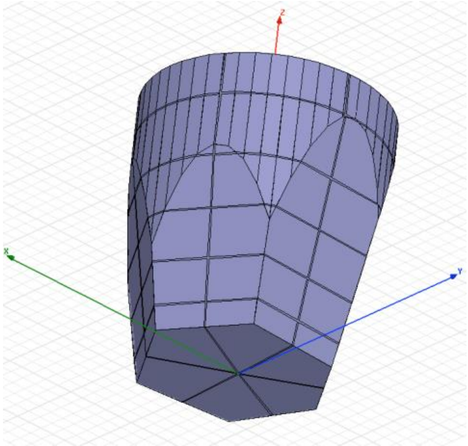
- Advances in detector technology extend science reach
- GRETA achieves large gains because it provides a detector technology to create a "Ge-shell"
- Maximizes and optimizes:
  - Efficiency,
  - Energy Resolution,
  - Peak-to-Total

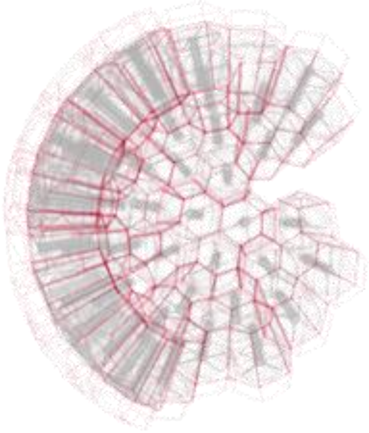


Gamma-Ray Energy Tracking Array

GRETA concept for a shell of close packed Ge crystals

- Combines (120) highly segmented, hyper-pure germanium crystals with advanced digital signal processing techniques





I-Yang Lee, 2016 Tom. W Bonner Prize

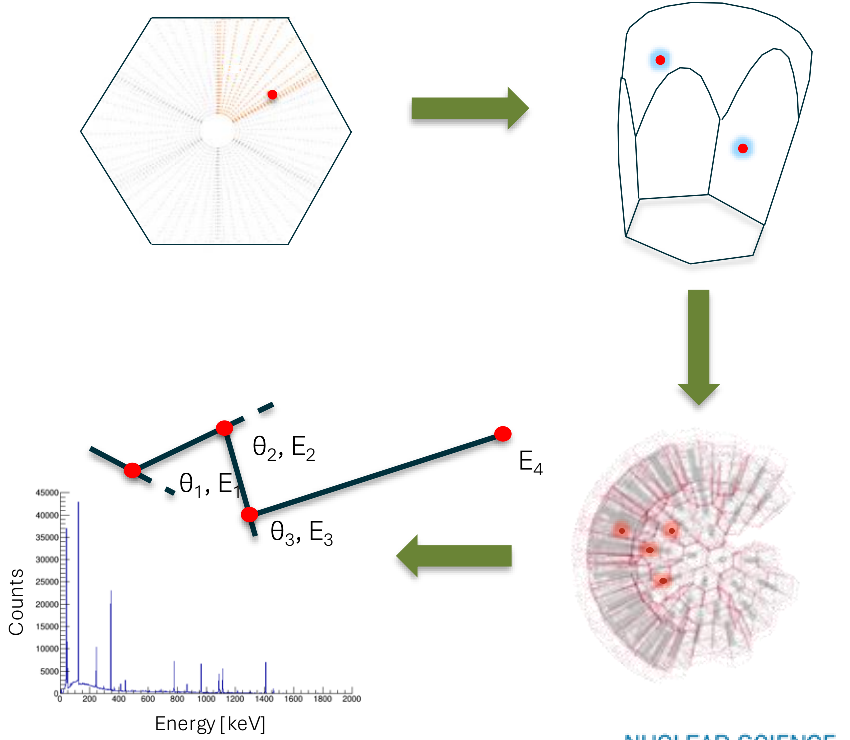
Gamma-Ray Energy Tracking Array

GRETA concept for a shell of close packed Ge crystals

- Combines (120) highly segmented, hyper-pure germanium crystals with advanced digital signal processing techniques
- Identify the position and energy of γ-ray interaction points within a compact “shell” of detectors
- Track γ-ray path both within and between detector elements, using the angle-energy relation of the Compton scattering process

Maximizes and Optimizes

- Efficiency, Energy Resolution, Peak-to-Total



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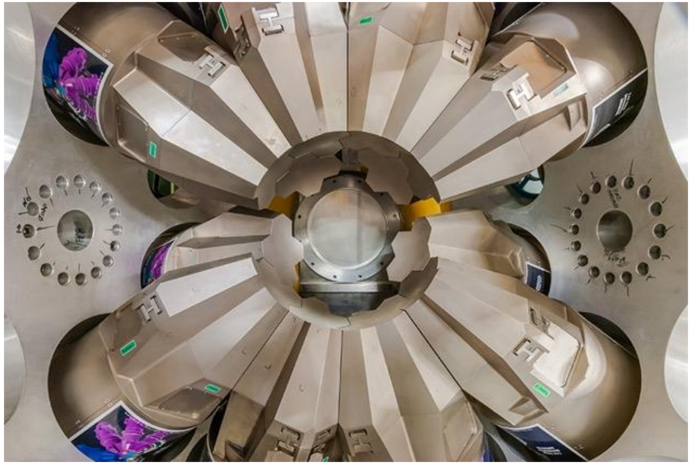
GRETINA – First Stage to GRETA

Gamma-Ray Energy Tracking In-beam Nuclear Array

Between 2003 and 2011, the US low-energy nuclear physics community constructed GRETINA, a 1π tracking detector employing the same segmented detector and signal decomposition technology as GRETA.

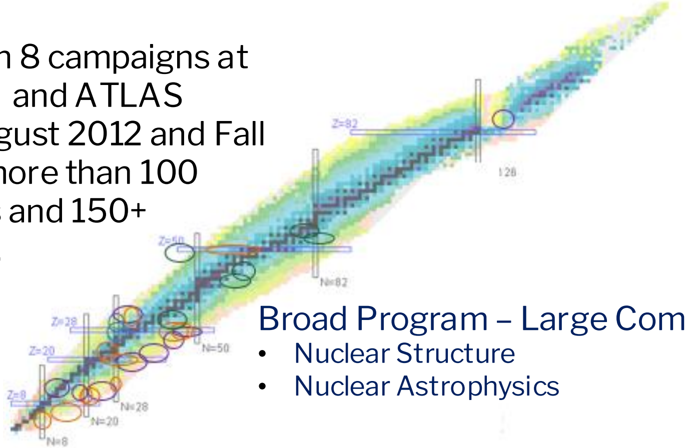
Covered ~¼ of a sphere with 7 Quad Detector Modules

Added Quad Detector Modules – total of 12 (+ 1 spare)



12 Quad Detector Modules of GRETINA at NSCL

GRETINA ran 8 campaigns at NSCL / FRIB and ATLAS between August 2012 and Fall 2025, with more than 100 experiments and 150+ publications.



Broad Program – Large Community

- Nuclear Structure
- Nuclear Astrophysics

GRETINA successfully demonstrated the science reach and impact of a γ-ray tracking array

The GRETA Project

The overall objective of the GRETA project is to deliver all necessary subsystems required to expand the existing GRETINA array to subtend the full 4π coverage of γ-ray tracking detectors.

- 18 (+1) Quad modules, to be combined with existing GRETINA modules for a total of 30 in the array
- Full mechanical structure for a 30 module, close-packed array, covering 80% of solid angle
  - Removable forward and rear detector rings
  - Rotation and translation capabilities
- Electronics to instrument all 30 Quad modules
  - Detector-mounted digitizer modules with continuous streaming of waveforms to FPGA-based signal filter boards
  - New trigger, timing and controls systems
- Computing cluster to support full array
  - Real-time signal decomposition up to total through-put of 480k decompositions/s
  - High-speed local network
  - Large local RAID storage

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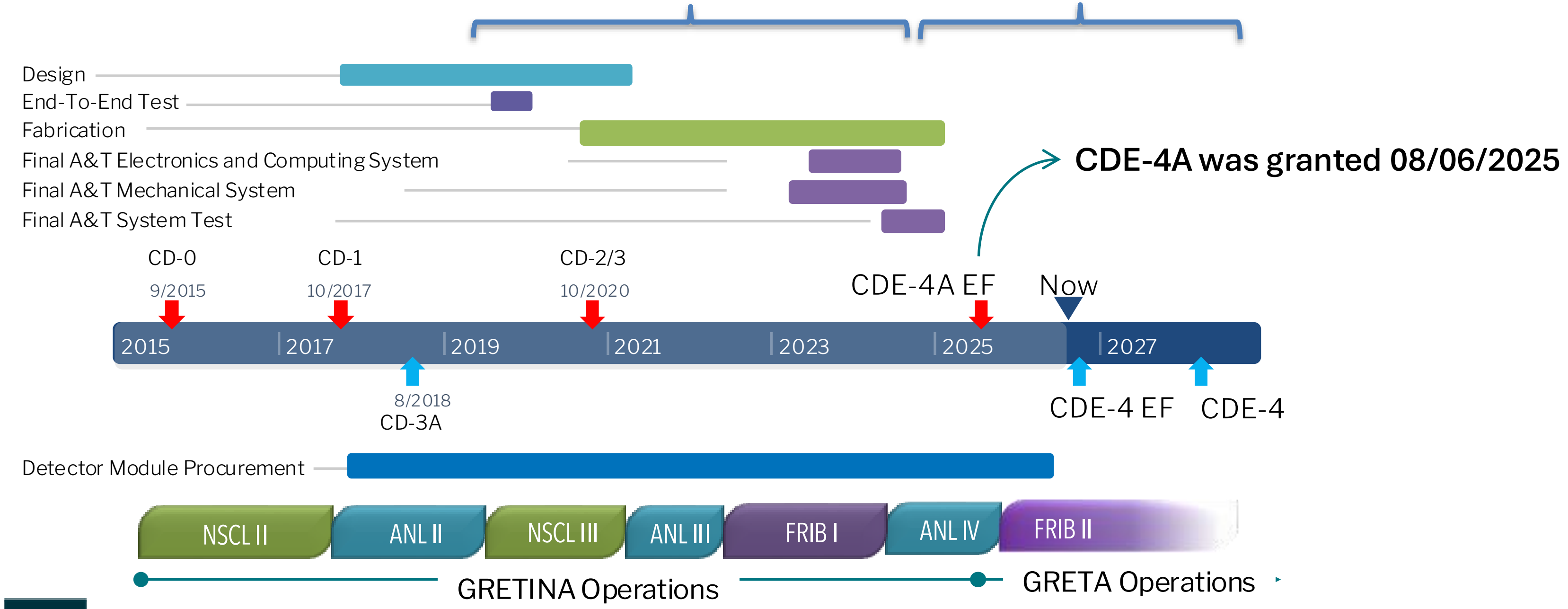
GRETA Timeline

CD-4A Scope ✓

- Electronics, Computing and Mechanical systems for 30 Quad Detector Modules
- Subset of Detector Modules (14, Q14-Q27)

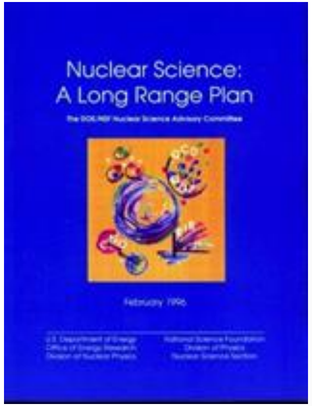
CD-4 Scope ✓

Accept the remaining Quad Detector Modules (For a total of 19)



The Path to GRETA

1996



GRETA first discussed in the 1996 NSAC LRP

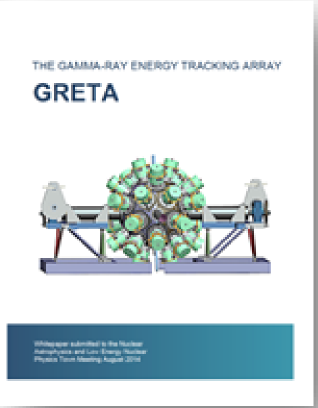
2002

2002 NSAC LRP
"The detection of γ-rays .. plays a vital and ubiquitous role in nuclear science .."

2007 NSAC LRP
"Construction of GRETA should begin immediately upon successful completion of the GRETINA array"

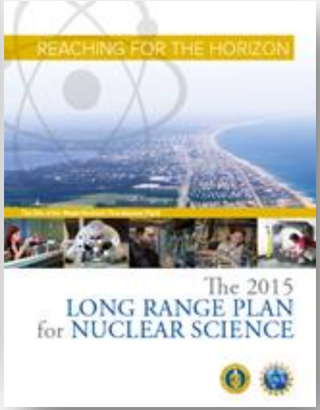
2007

2014



Concept endorsed – GRETA identified as a key instrument for FRIB

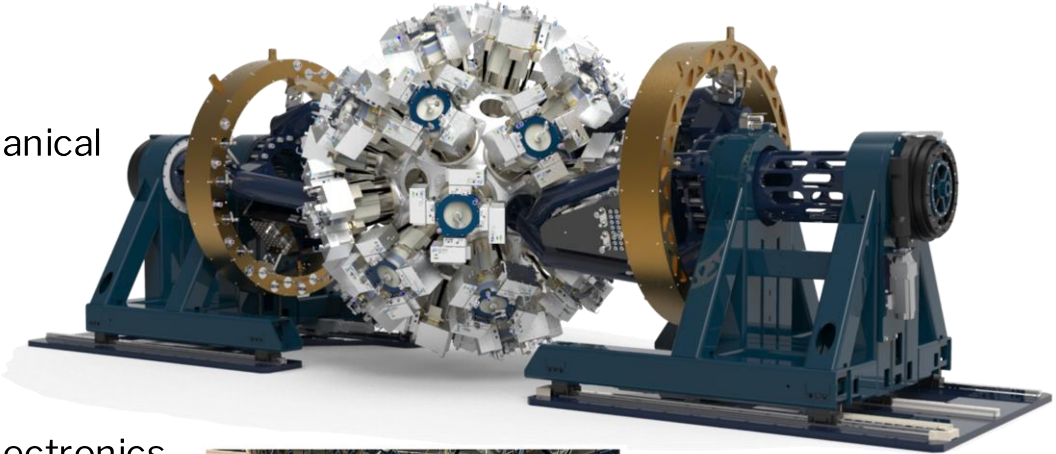
2015



GRETA Subsystems

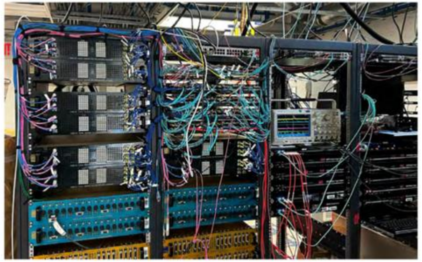
Detectors

Mechanical



Computing

Electronics

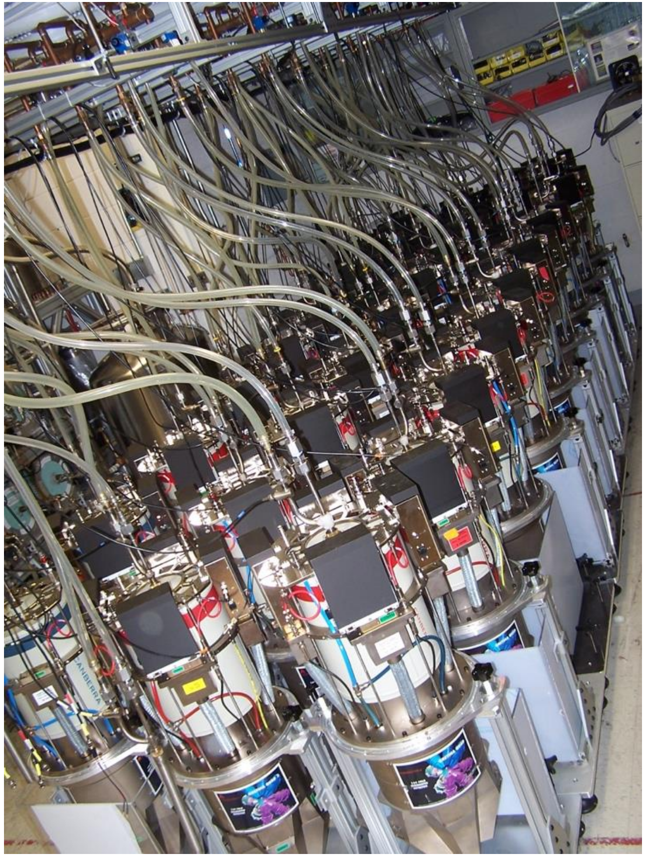


GRETA Quad Detector Modules

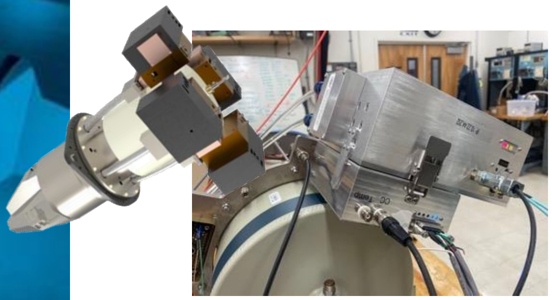
23 Quads at FRIB – Photo by Shumpei Noji (FRIB)

- The GRETA Quad detectors are identical to the modules used in GRETINA (operating since 2011)
- Quads were developed in collaboration with Canberra/MIRION in the early 2000s
- Demonstrated performance and serviceability; experts within the GRETA project at FRIB and LBNL
- GRETA includes 18 (+1 spare) Quads – 18 have been delivered (last 1 in June/July)

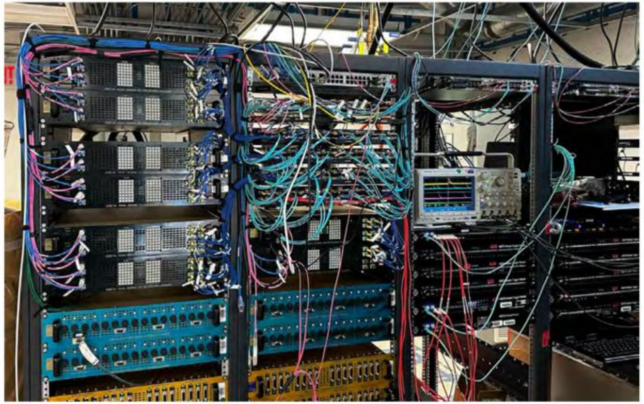
GRETA Quad Detector Modules - *30+ Quads in Gamma Lab at FRIB !*



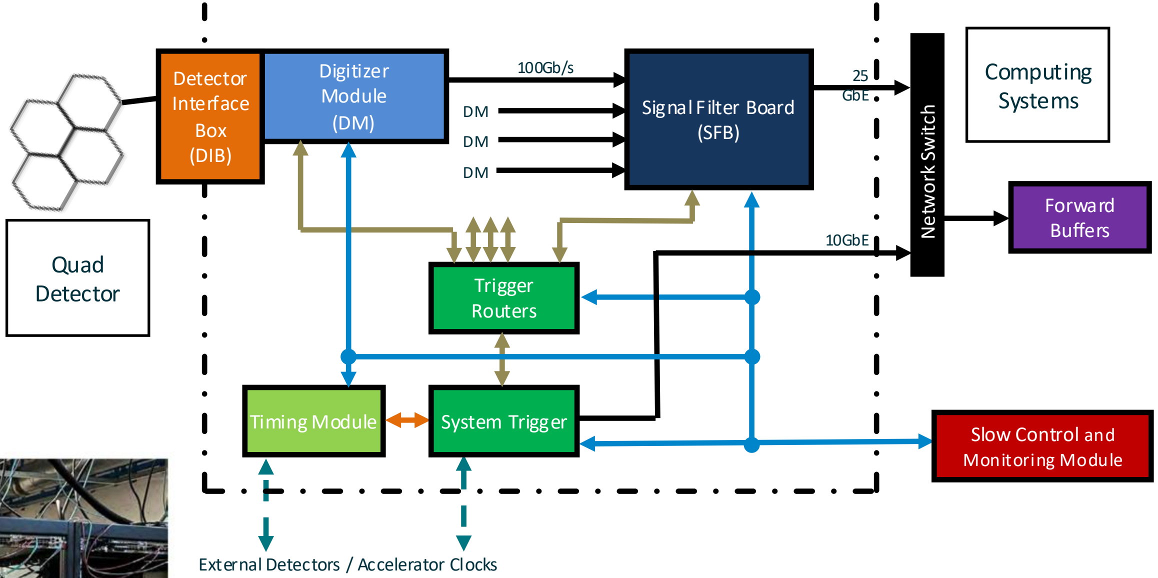
Electronics Systems



Electronics (ADC) are on the Detectors, Digitized signals sent to Signal Filter Boards



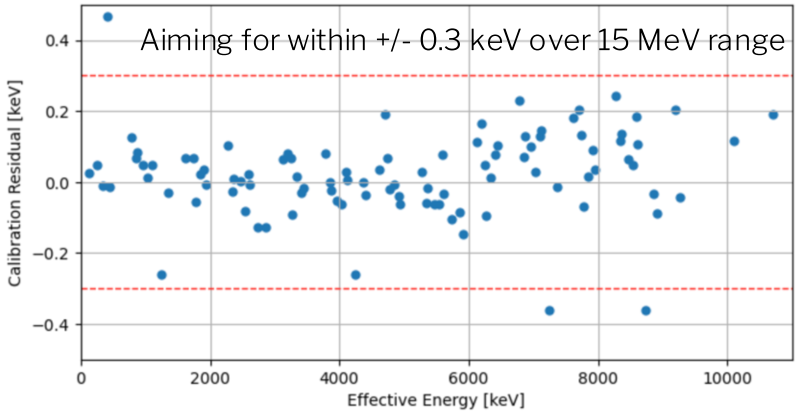
Digitize at the detector, fiber-based network carries data and controls

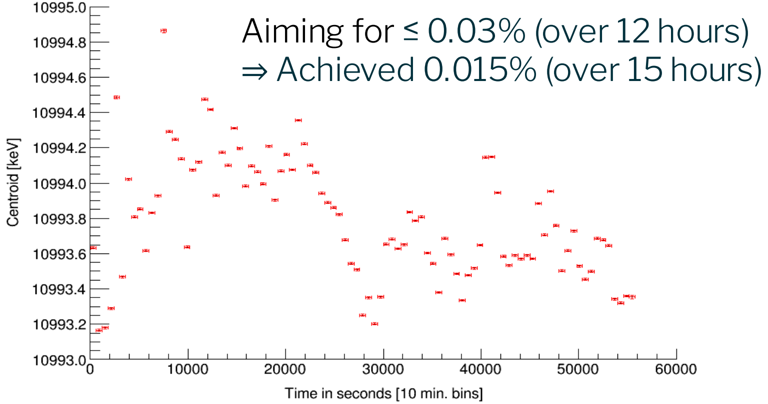


4800 Channels

- 120 Detector Interface Boxes and Digitizer Modules (DM)
- 16 Signal filter boards, 11 Trigger and Timing modules
- Ancillary systems (8 DM power supplies, 8 cable-break-out chassis, and associated signal and power cables/fibers)
- FPGA firmware

Electronics Performance – Linearity and Gain Stability





- The electronics performance was verified with testing across the duration of the project
- The digitizer is an extremely performant module, and detector mounted
- All power delivery met and exceeded the noise requirements
- The GRETA production systems delivery performance at the same level as fully optimized bench testing

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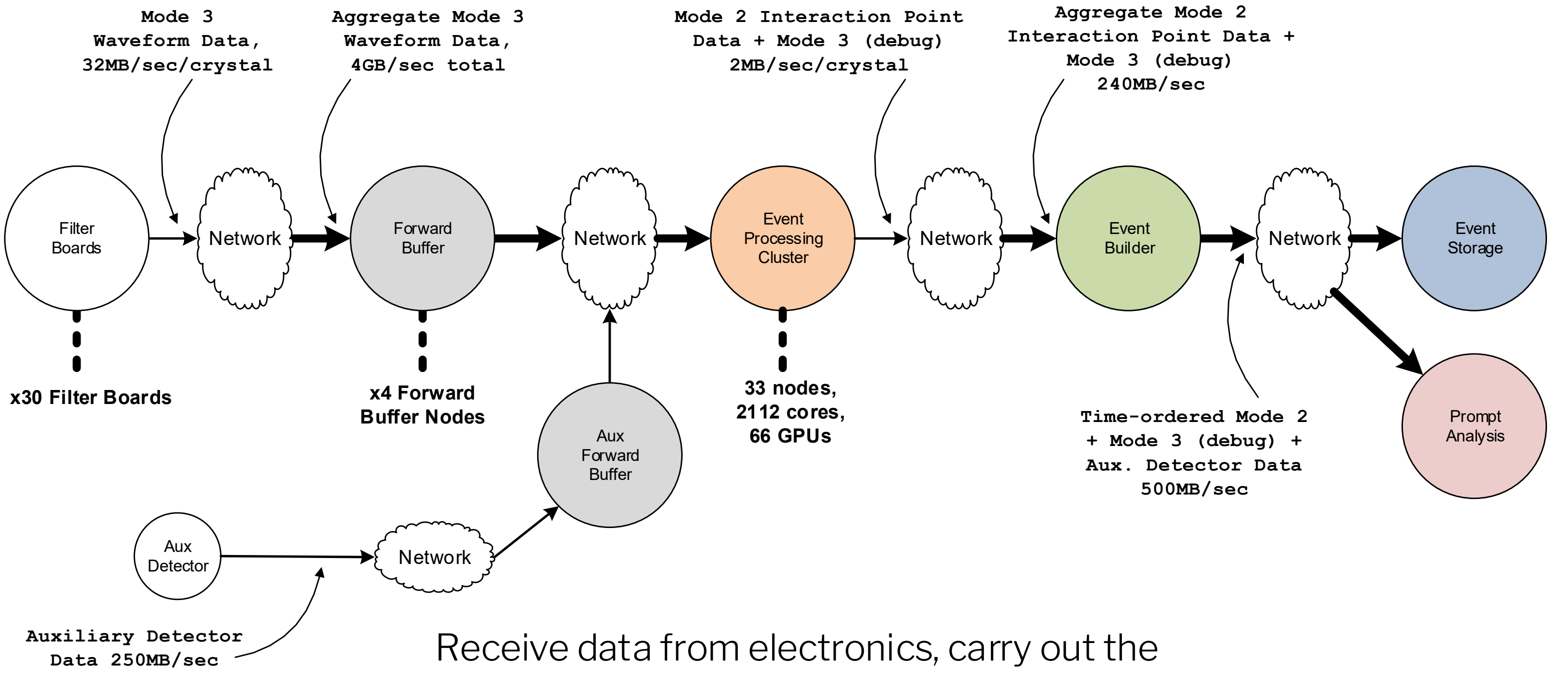
Computing Systems

Pipeline-Based Network Architecture Enables Cutting-Edge Performance



Receive data from electronics, carry out the signal decomposition calculations, and build events to store

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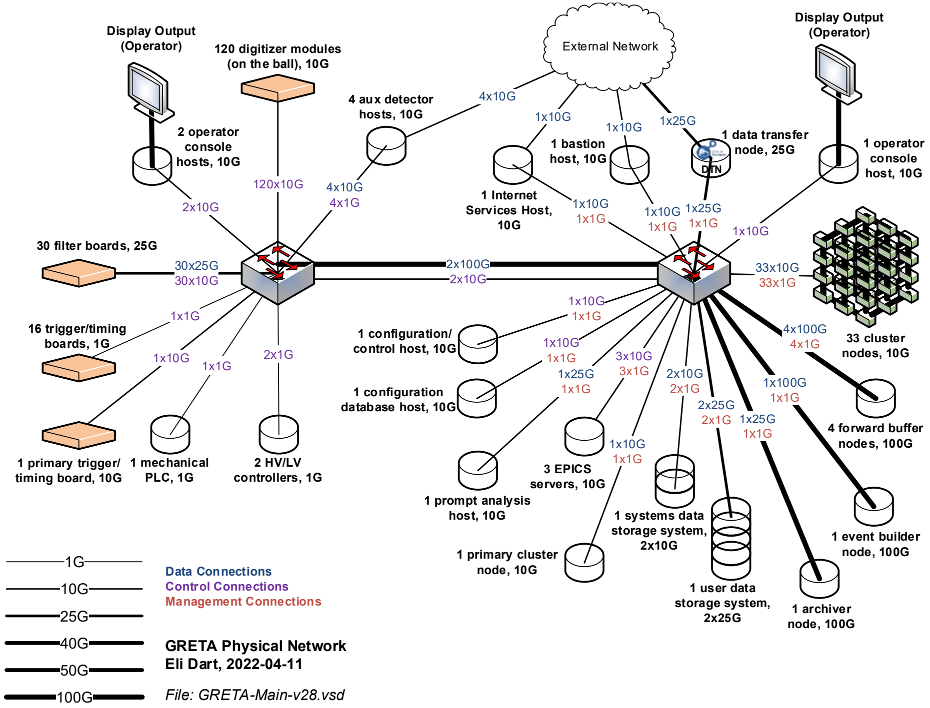
Computing Systems



- With strong collaboration from ESnet, the GRETA computing team developed a novel pipeline-based network architecture to enable cutting edge performance
- High-performance computing cluster enables in-line compression and supports > 500k signal decomposition calculations per second
- 500TB full SSD storage improves ability to sort online, and move data quickly off the cache to the DTN

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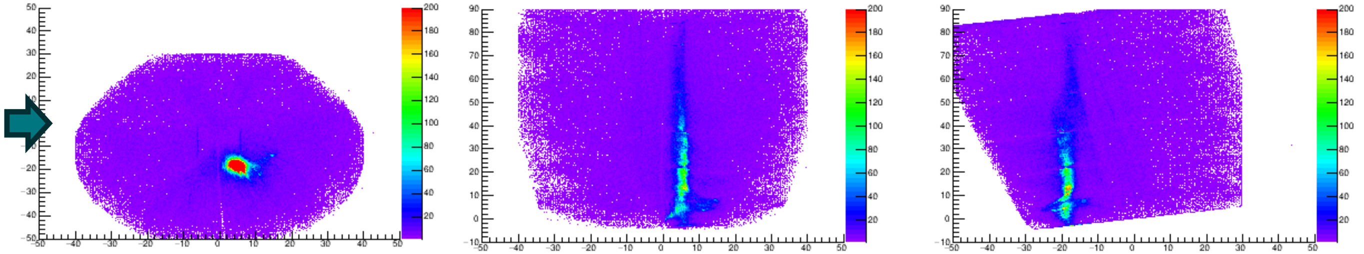
Computing Systems Performance

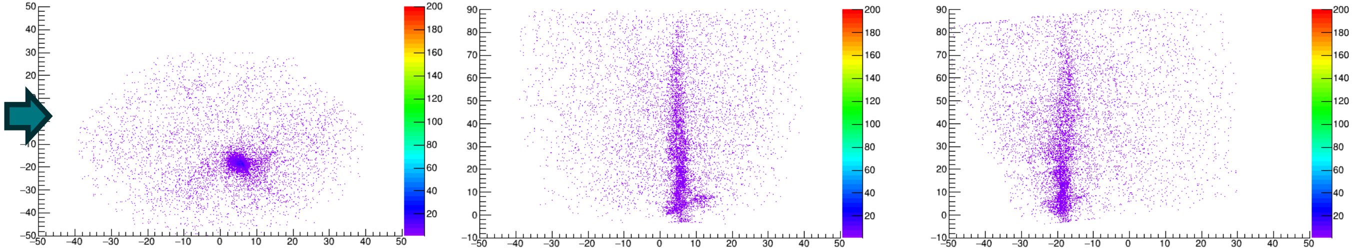
Throughput of > 500k signal decomposition calculations / s

- The computing throughput test was conducted entirely within the GRETA computing systems, using pre-recorded pencil beam data taken at FRIB following Q14 acceptance testing
- Four unique data sets with four different calibrations and bases were used, and sent at rate from filter-board-simulation tools in the computing cluster to the forward buffers
- From the forward buffers, the computing ran identically as if data were coming from Quad Modules
- Sustained for more than 1 hour, throughput of **511k** signal decompositions/s was demonstrated

Full “GRETINA” decomp-ed pencil beam from Q14P1



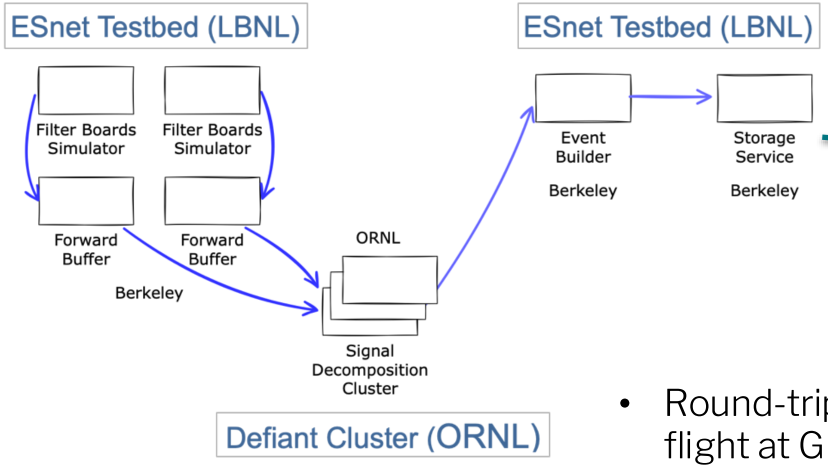
10k events for GRETA pencil beam from Q14P1

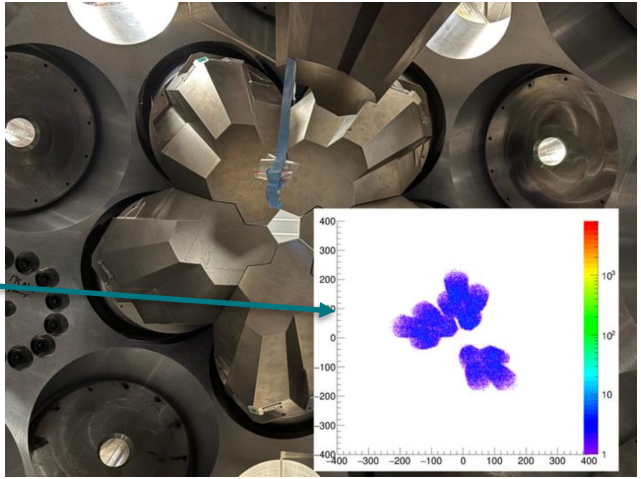


Deleria (next generation streaming)

Distributed Event-Level Experimental Readout and Integrated Analysis

- GRETA DAQ Pipelines Work Over Wide-Area Networks
- Real-time source data from 3 Quad detectors sent to ORNL, analyzed on “Defiant Cluster” (IRI testbed) and results sent back to LBNL





- Round-trip-time = 110 ms ~50k events in-flight at GRETA design rate

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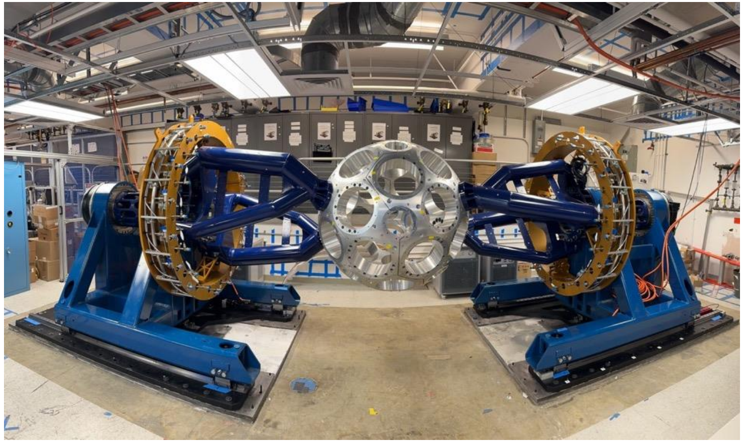
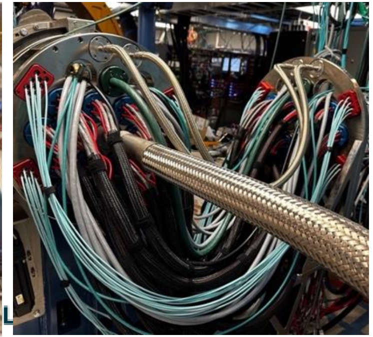
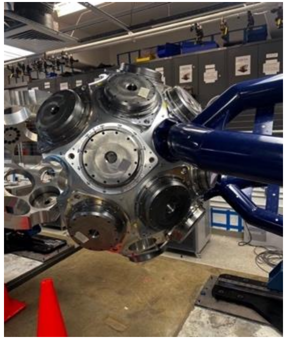
Mechanical Systems



- 2 hemispheres each with 15 ports to locate a total of 30 Quad Modules (QDM)
- Achieved a position of QDM ≤ ±0.40 mm (x, y, z) as required
- Linear translation of 500 mm and rotation of +180 and -172 degrees meets the requirement to install all detectors from either side

Gap between adjacent QDM end-caps mounted in the array was measured to be 0.89 mm – 1.09 mm (1 mm nominal gap).





Hemispheres Fabrication Steps

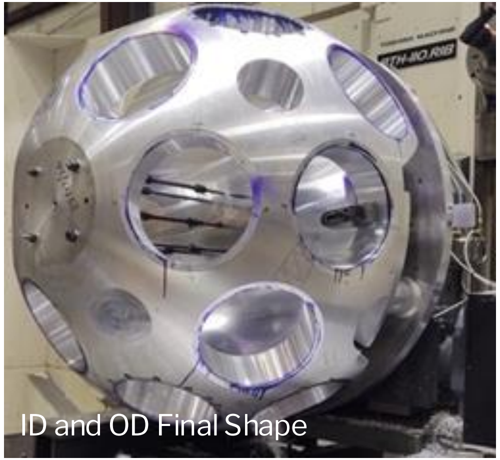

Raw Material

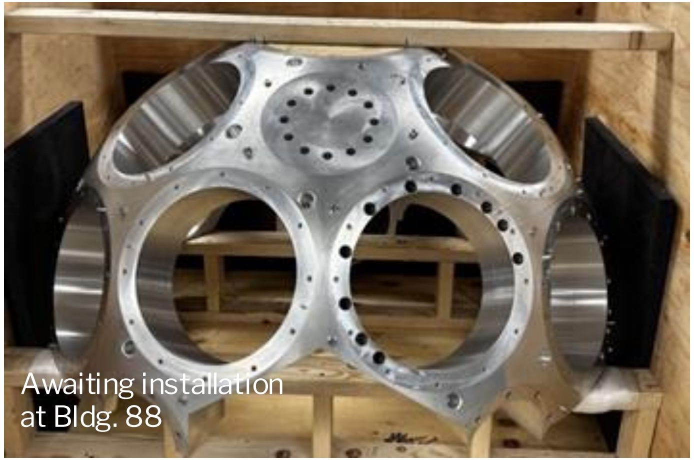

First Inner Machining Step


First Rough Hemisphere

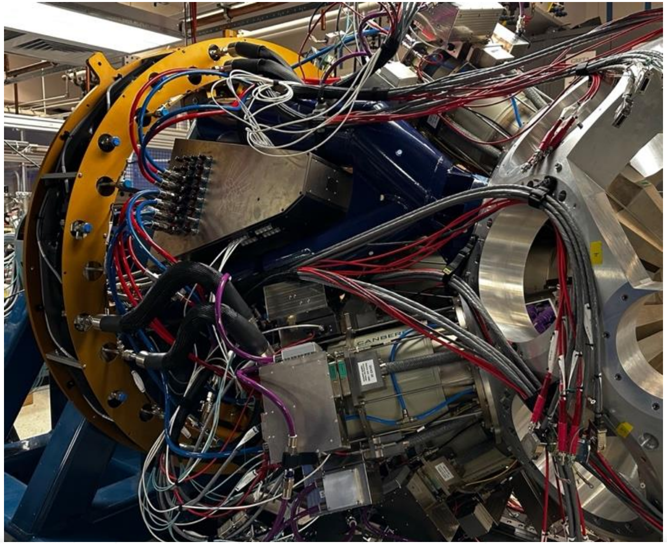

Ready for Last Machining Step


Ports Added to Hemisphere

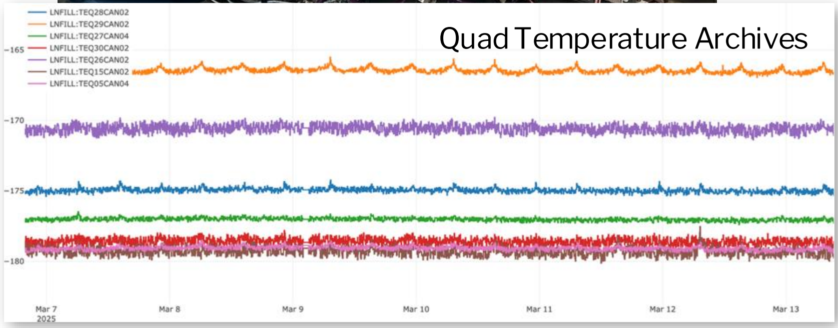

ID and OD Final Shape

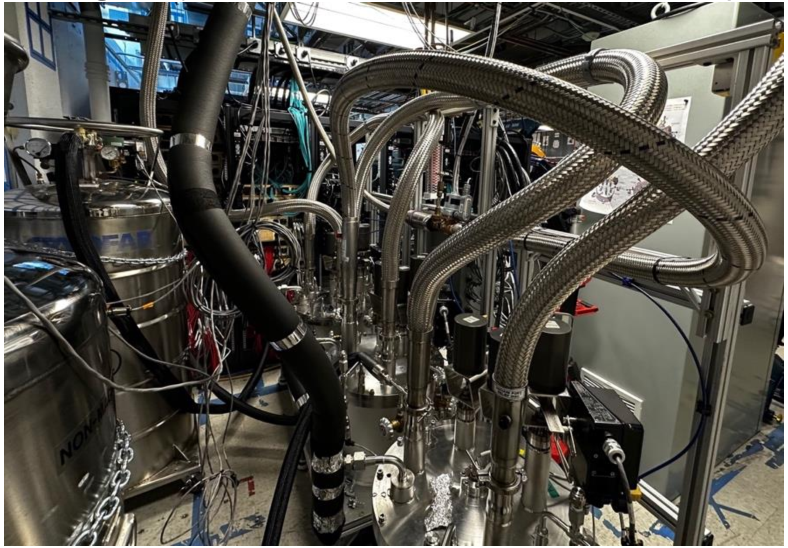

Awaiting installation at Bldg. 88

LN and Closed Loop Cooling Systems

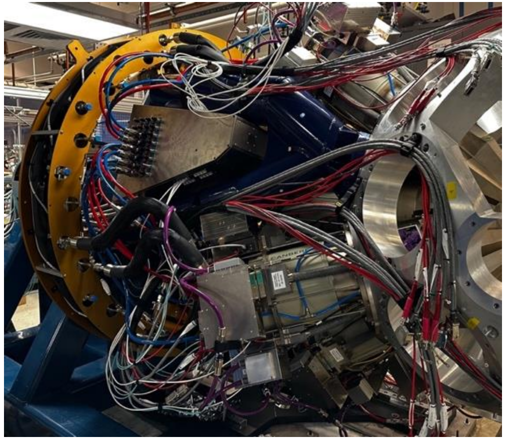


- The LN PLC filling system was integrated and used with the first (and subsequent) installations of Quad Detector Modules
- The system is running in an automated mode with scheduled Quad Module and tank fills
- The two closed-loop glycol circuits flow coolant through the manifolds on the arms and to the Quad Detectors, maintaining temperatures with better than 2℃ stability





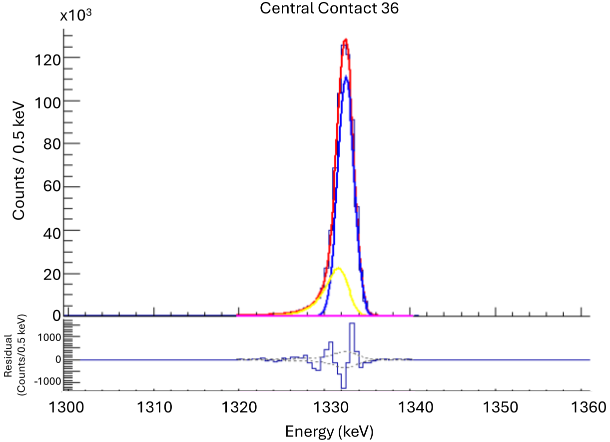
Integrated Testing with 6 Quad Modules



- Testing over 6 months (December 2024 – June 2025) demonstrated full system performance across three different geometry configurations
- Benchmarked performance compared to acceptance tests of Quad modules

Low-Rate Resolution

Core Contact	FWHM @ 1.33 MeV
36 (20 MeV)	2.38 keV
37 (8 MeV)	2.35 keV
38 (4 MeV)	2.33 keV
39 (60 MeV)	2.65 keV



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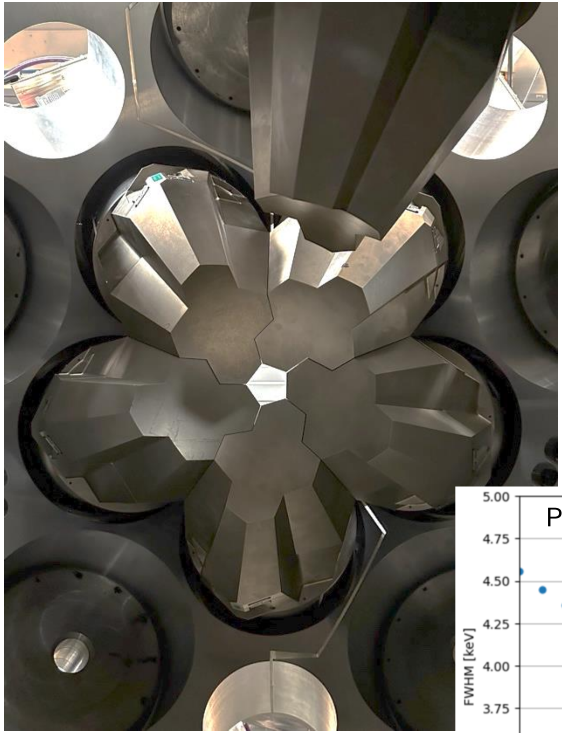
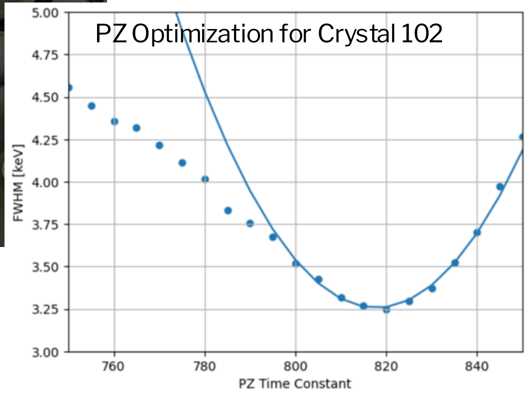
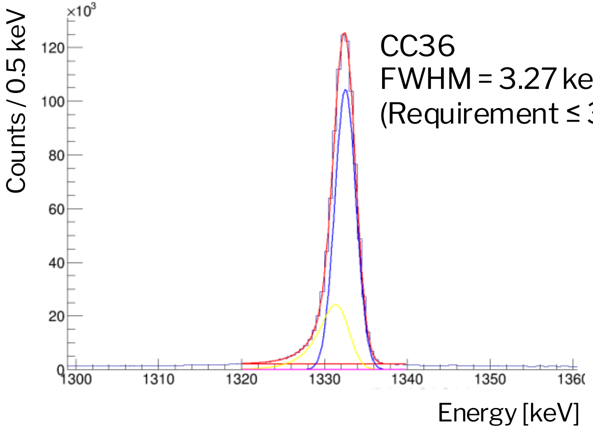
High-Rate Performance



- The third installation of Quad Detector Modules was installed in late February, populating positions surrounding the beam entrance pentagon hole
- High-rate resolution was been specifically explored
- High rate ^{60}Co (65 kcps average rate, from 56 kcps to 96 kcps) was explored, first optimizing filter parameters (pole zero, baseline restoration and integration time) per crystal





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Shipment of the GRETA Systems to FRIB

- Dedicated shipping platforms for the GRETA structures were key to shipping as integrated assemblies - enabling fast and ‘simple’ installation
- Internal LBNL review leveraged experience from past projects (e.g. DESI shipment)
- Conventional crating was employed for remainder of GRETA equipment - shipped in 7 dedicated trucks over 2 months

Shipment of the GRETA Systems to FRIB

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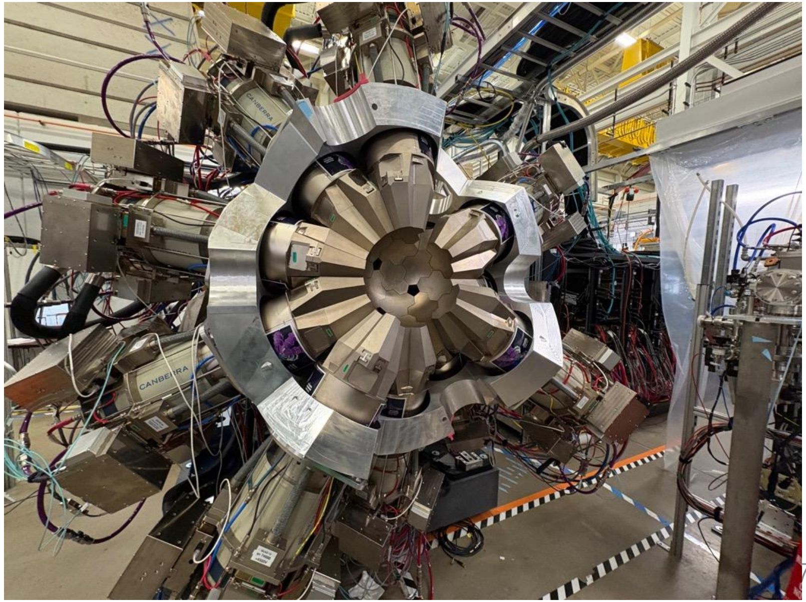
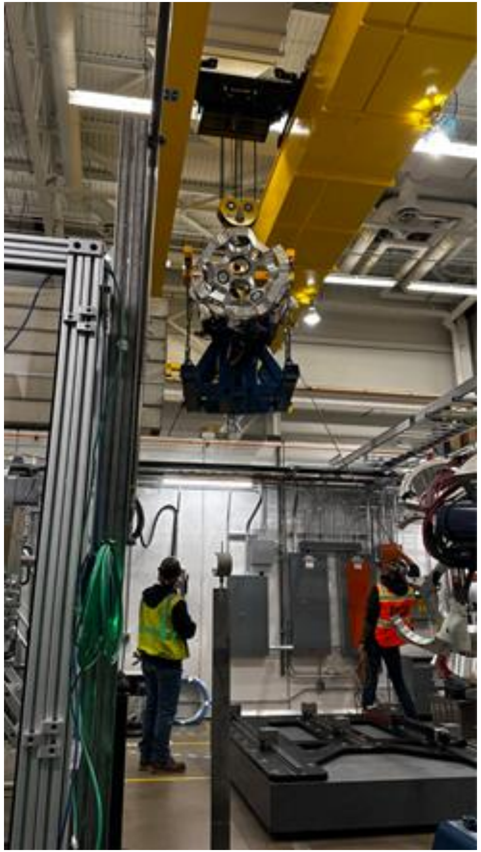
Installation at FRIB

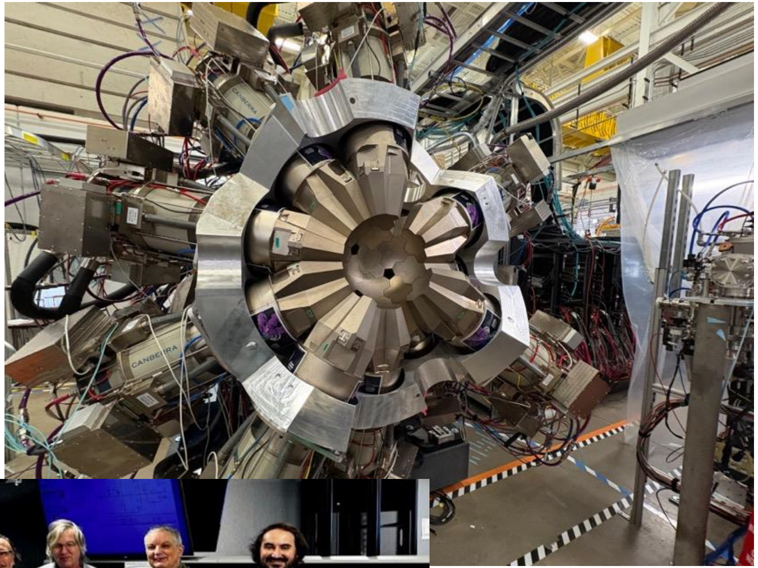
- Installation at FRIB of the support frame, electronics and computing hardware was completed last Fall; the full complement of Quad modules was installed in the array over the last several months





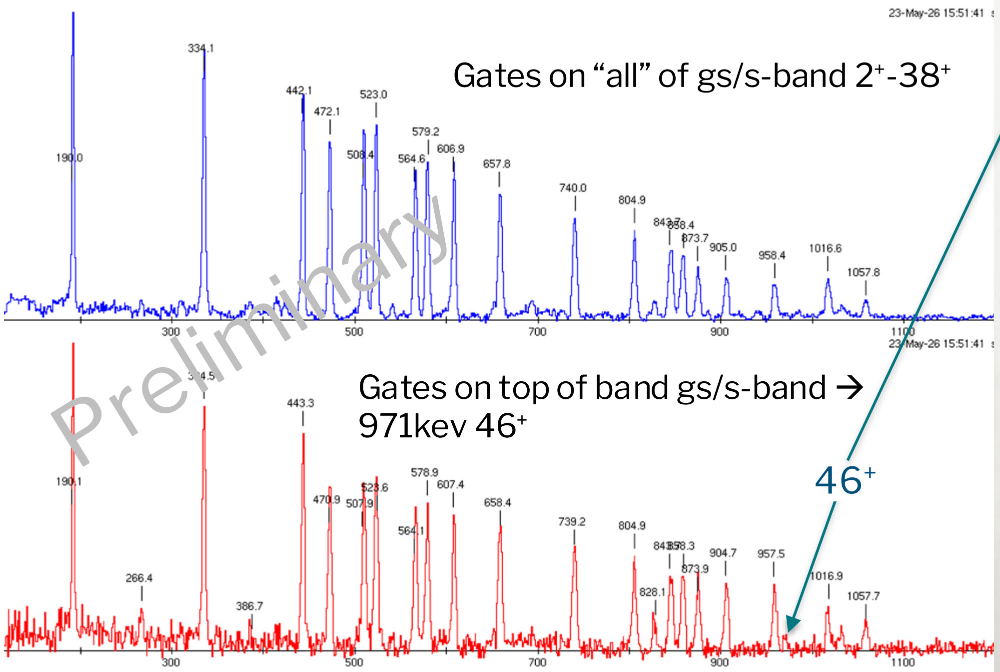
GRETA - high gamma multiplicity

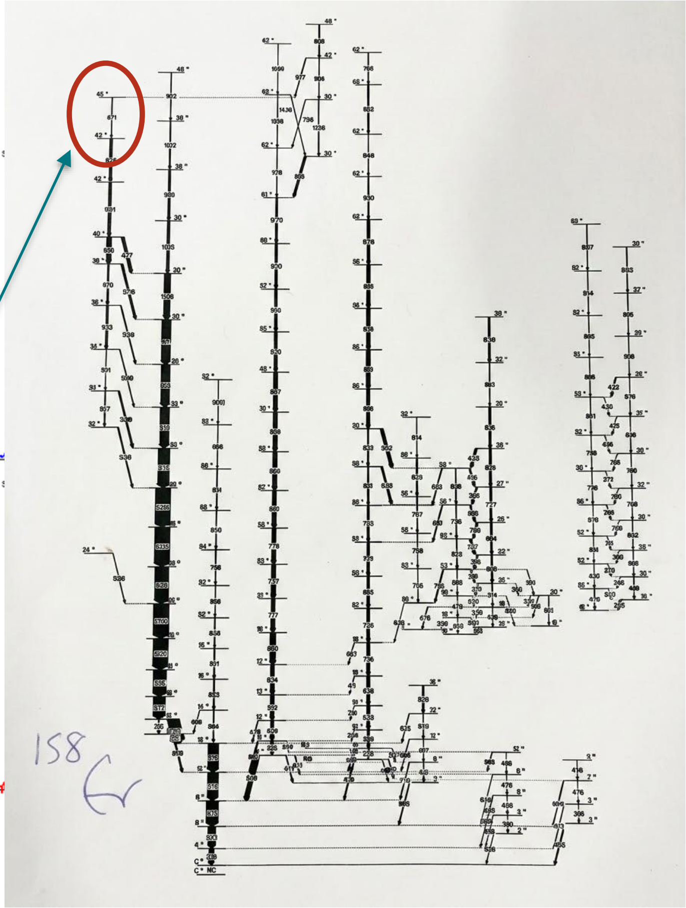
- First time a “full 4pi” HPGe setup on the ReA beam line.
- Provided a unique/timely opportunity
- Discretionary in-beam commissioning took place last month (May 18-25) at ReA6 - ^{40}Ar beam on ^{122}Sn and ^{96}Zr to benchmark high gamma-ray multiplicity performance



^{158}Er GRETA@ReA6

178 MeV ^{40}Ar + ^{122}Sn (0.5mg) ~5*10^{8} pps (~33hrs data);
Fold 7 gated matrix - 'online' data, not tracked





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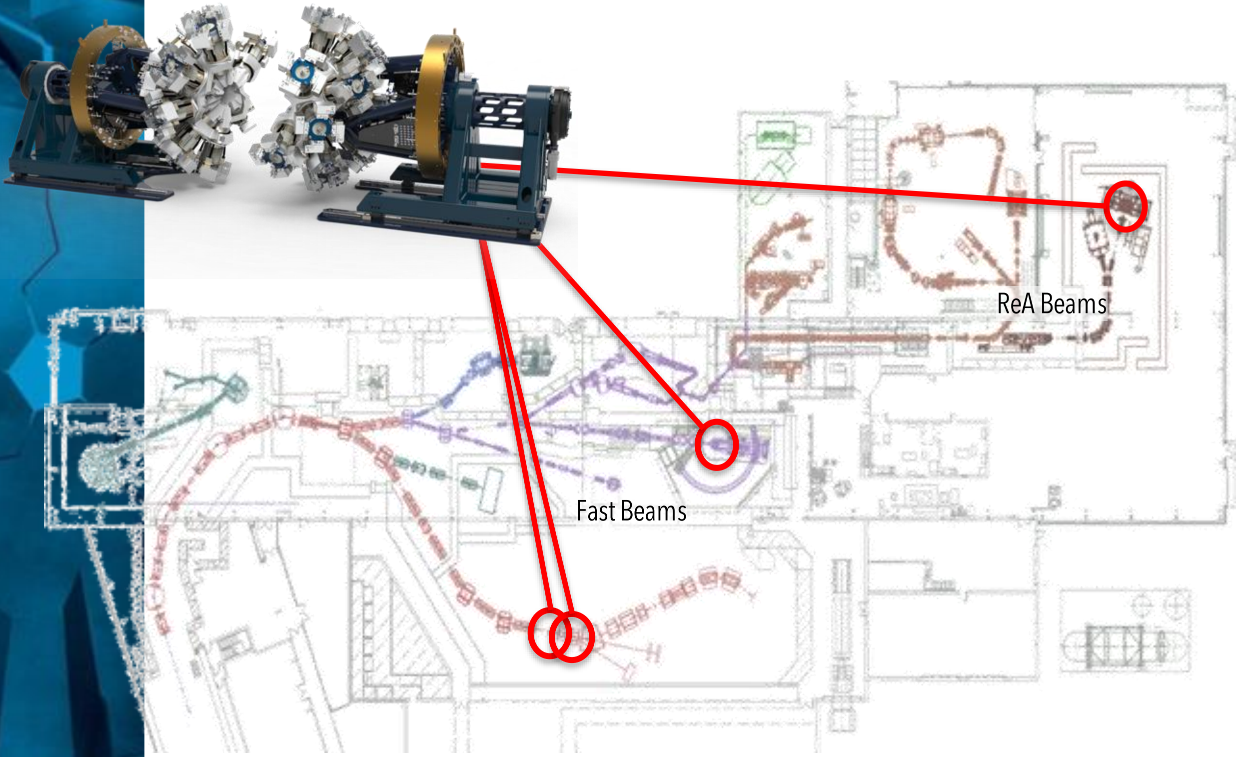
GRETA Science

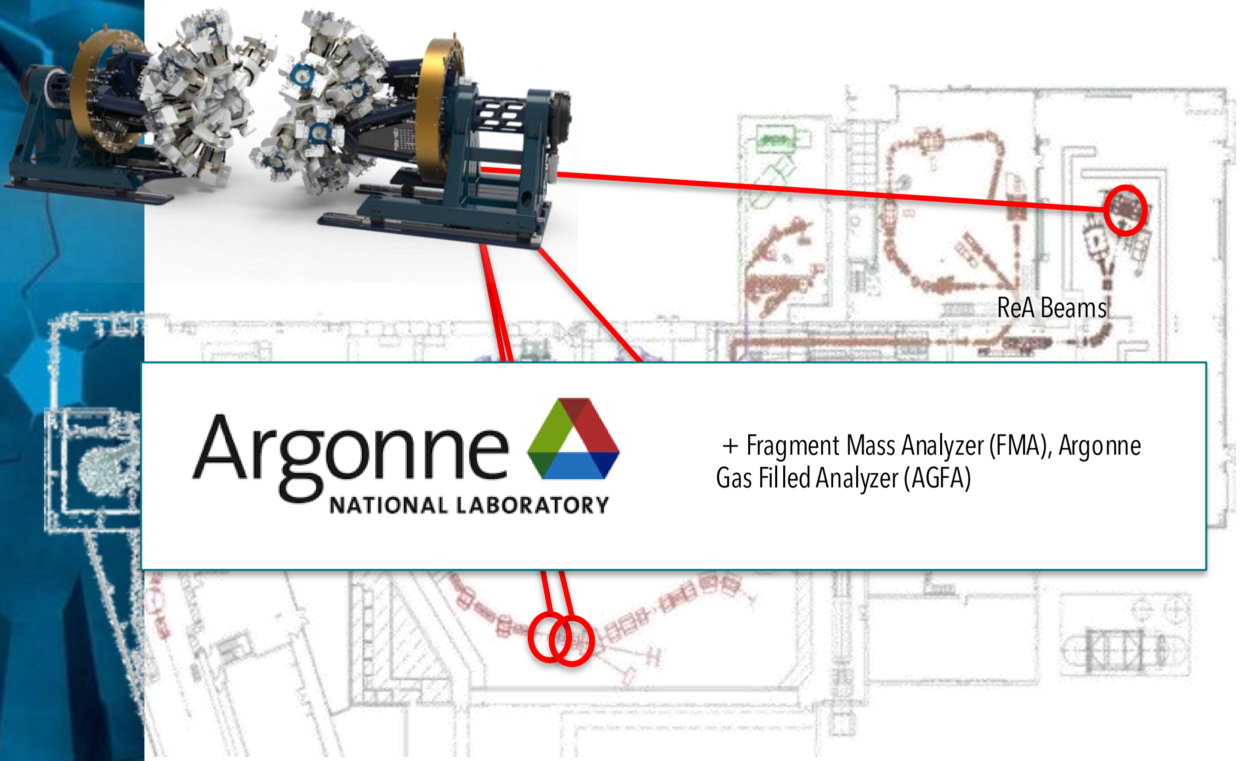


Broad Program
- Nuclear Structure
- Nuclear Astrophysics

Requires measurements with Fast/Reaccelerated Beams

GRETINA Demonstrated

GRETA Science



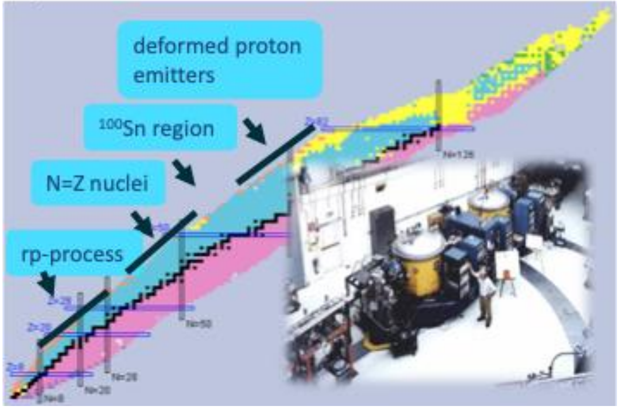
Broad Program

- Nuclear Structure
- Nuclear Astrophysics

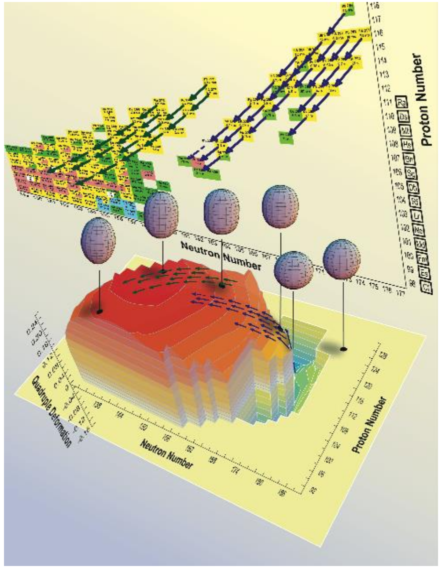
Requires measurements with Fast/Reaccelerated Beams and **high(er) intensity (stable) beams**

Science Opportunities: High Intensity Beams, High γ Multiplicities

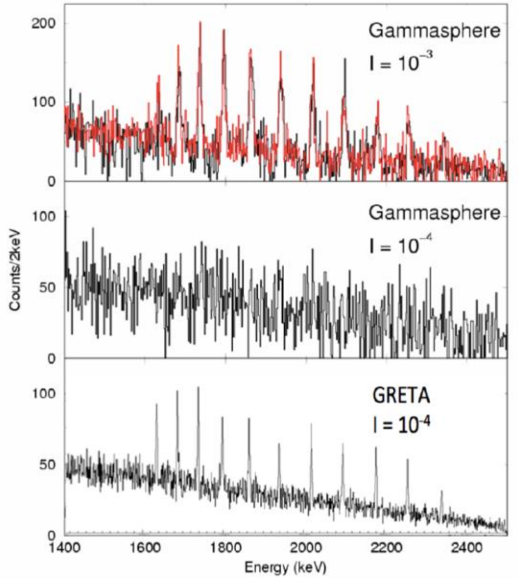
Studies of exotic proton-rich nuclei



Heavy Nuclei



Shapes and Symmetries



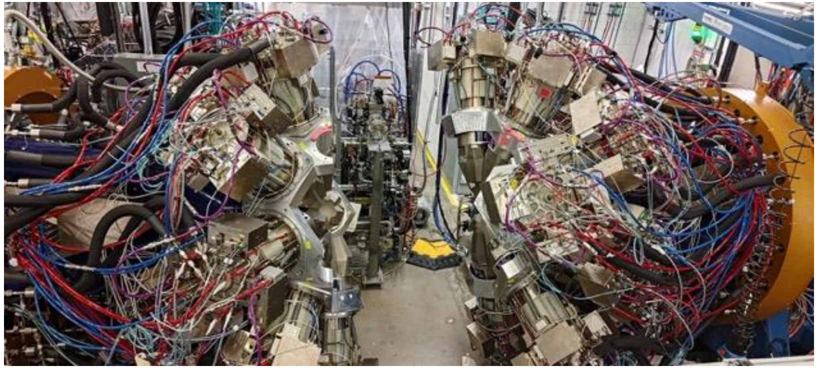
GRETA Present Status

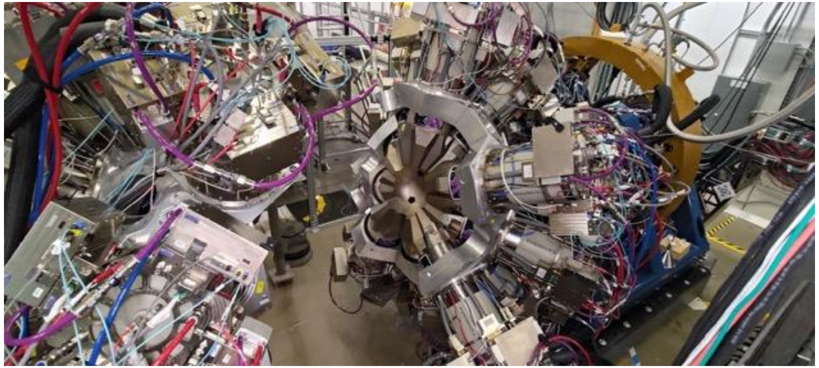
Project

- All technical scope complete, all detectors delivered and accepted
- Preparing for project closeout
- CD4 review scheduled for October

Operations

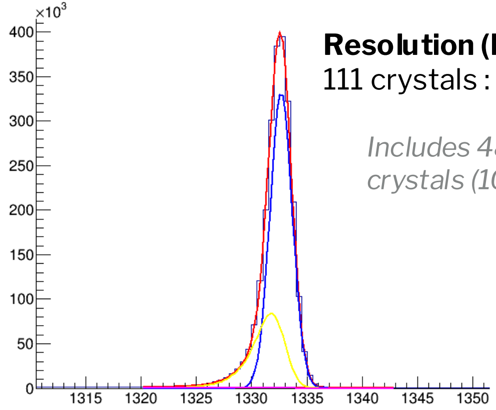
- Source testing (UPP)
- Discretionary in-beam run at ReA6 (May 18-25)
  - ^{40}Ar beam on ^{122}Sn and ^{96}Zr to benchmark high gamma-ray multiplicity performance
- Coulex ^{68}Ge (PAC3, Surrey) - ran end June
- FRIB PAC call was just released and includes with GRETA fast and reaccelerated beams
  - Experiments with GRETA at FRIB in 2027
  - Future campaign at ANL





GRETA Ultimate Performance Parameters (underway)

Array Parameter	UPP
Full Energy Efficiency (Add-back)	$\geq$ 30% at 1.33 MeV
Peak-to-Total	$\geq$ 50% at 1.33 MeV
Ge Energy Resolution	$\leq$ 2.8 keV at 1.33 MeV
Average Position Resolution[(b)]	$\leq$ 2 mm $\sigma_{x,y,z}$
Count Rate (per crystal)	$\geq$ 50,000 / second



Resolution (FWHM) for sum of 111 crystals : **2.55 keV**

Includes 48 GRETINA crystals (10+ years in service)

Preliminary

Efficiency at 1.33 MeV for 111 crystals

Calorimeter – 29%
Single Crystals – 18%

Average Position Resolution

- GRETINA Quads were validated in-beam
- GRETA Quads were all scanned and pencil beams to confirm position resolution for each crystal (underway)

*D. Weisshaar et al., NIM A **847**, 187 (2017)*

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GRETA Ready for Science

Many years and much work in the making .. Now looking forward to the exciting future and new opportunities

BERKELEY LAB

FRIB

Argonne NATIONAL LABORATORY

OAK RIDGE National Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science


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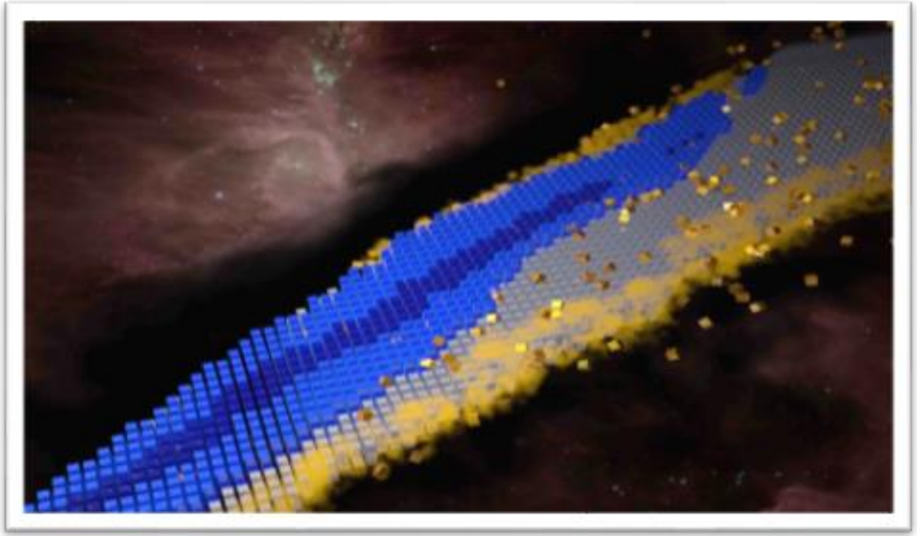
Thank you

The Science: The Big Questions

- How did visible matter come into being and how does it evolve?
- How does subatomic matter organize itself and what phenomena emerge?
- Are the fundamental interactions that are basic to the structure of matter fully understood?
- How can knowledge and technological progress provided by nuclear physics best be used to benefit society?



Nuclear Science is a broad, diverse subject, connecting the very earliest times after the Big Bang to the creation of protons, neutrons, and the elements around us.