The NP Low-Energy User Facilities

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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Overview

Have heard overview talks on RHIC and TJNAF;
I will discuss *low-energy* user facilities

- The physics
- The NP LE accelerator user facilities
  - ATLAS (ANL)
  - The future FRIB (MSU)
- Examples of experimental equipment
  - The GammaSphere and GRETINA gamma-detector arrays

The Physics: Intellectual Drivers

- How did the matter that makes up the visible universe come into being, and how does it evolve?
  - Nature of building blocks (quarks+gluons, hadrons, nuclei, atoms,…)
  - Cosmic evolution of visible matter
- How do the building blocks of subatomic matter organize themselves, and what phenomena emerge as they do so?
  - Nature of composite structures and phases
  - Origin of simple patterns in complex systems
- How have hidden forces shaped the properties of matter?
  - In search of the New Standard Model
  - The nucleus as a laboratory for testing fundamental symmetries
- How can we best use the unique properties of nuclei and technologies developed in nuclear physics to benefit society?
  - Unique opportunities for applications

Examples of techniques & measurements

Nuclear Structure and Reactions

- Coulomb excitation in regions of magic and doubly magic nuclei
- In-beam gamma-ray spectroscopy
- Decay spectroscopy (many kinds)
- Identification and detailed study of crucial single-particle states
- Systematics: The evolution of single-particle states and nuclear shells
- Synthesis and study of heavy elements

Nuclear Astrophysics

- Masses, decay properties, and reactions for r-process nuclei
- Direct reactions on rp-process nuclei
- Structure studies of specific states that affect reaction rates

Societal applications and benefits

- Surrogate reactions for astrophysics, energy, and stockpile stewardship
- Isotope production for medicine and industry
- Detection techniques for medicine, homeland security
- Accelerator Mass Spectrometry

What we need for a typical experiment

- An accelerator facility to provide a beam of ions
  - Beam may be composed of unstable (radioactive) ions
  - Beam energy can be low (~100 keV) or high (~ 3 to 100 MeV per nucleon)
- A target (for higher-energy beams)
  - A small fraction of the beam ions react with target nuclei to make something of interest
- Detectors and associated electronics to study that "something"
  - Gamma-rays, light charged particle, fragments, heavy residuals, …
    - HPGe detectors
    - Double-sided strip detectors (Si or Ge)
    - Scintillators, with either PMTs or photodiodes
    - Magnetic spectrometers
    - Gas counters
    - Ion traps
    - Many more
- Digitizers, computers, data storage, and software

The Facilities

User Facilities

- Encourage and support experiments proposed by and/or involving outside users (labs, universities, international)
- Beam time is allocated based on proposals judged on scientific merit

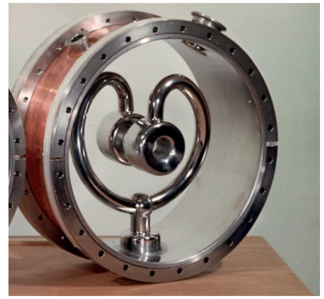
- The Argonne Tandem-Linear Accelerator System (ATLAS)
  at Argonne National Laboratory

- The Facility for Rare Isotope Beams (FRIB)
  to be constructed at Michigan State University

- The Holifield Radioactive Ion Beam Facility (HRIBF)
  at Oak Ridge National Laboratory

ATLAS: The world's first SC ion accelerator

Dedicated in 1985



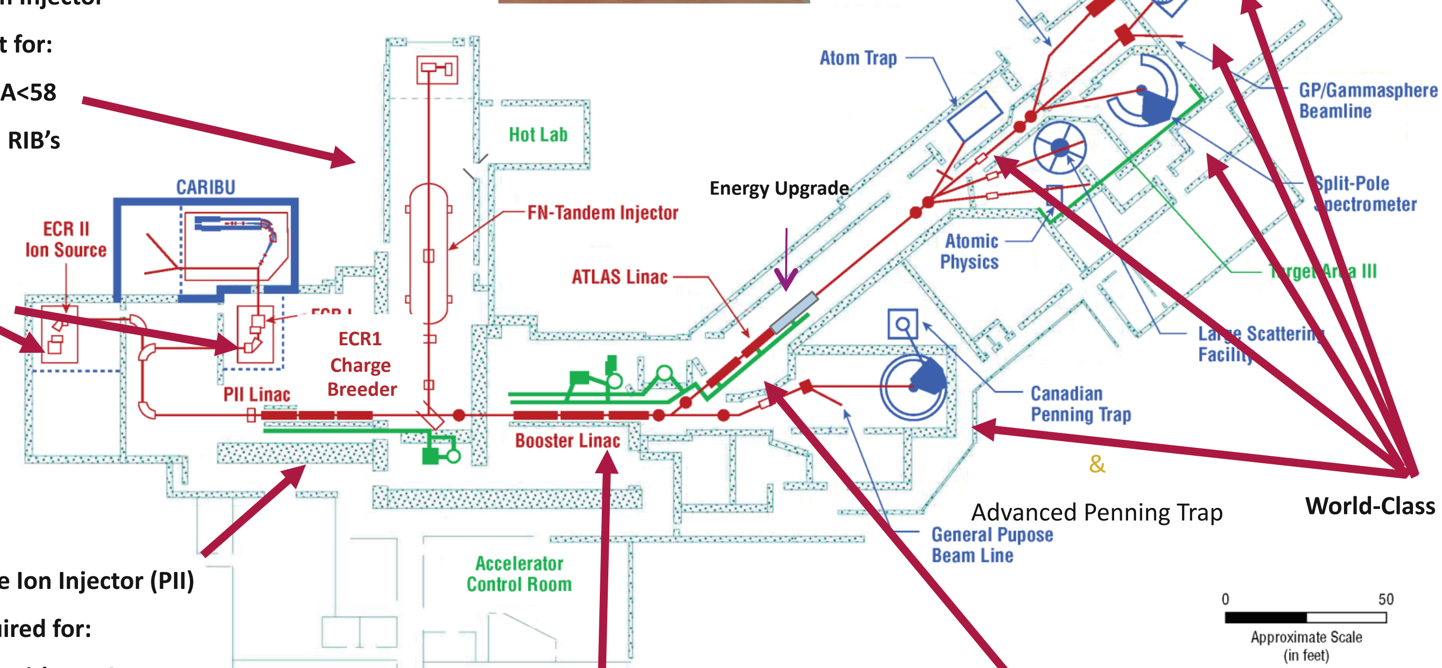
8.5-MV Tandem Injector

Important for:

Beams of A<58

Long-lived RIB's

2 ECR Ion Sources
on HV platform



World-Class Equipment

12-MV Positive Ion Injector (PII)

Required for:

Beams with A>58

Noble gases

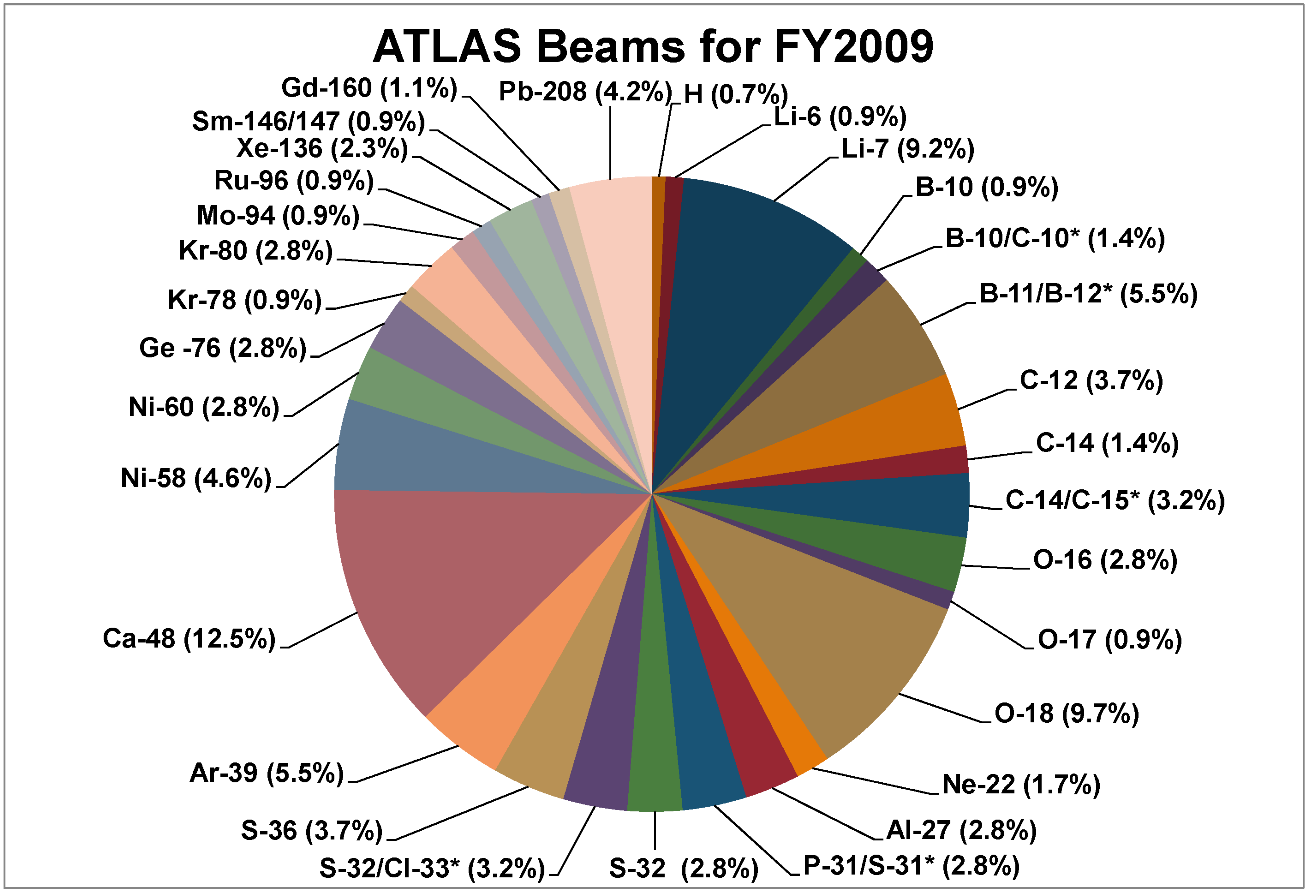
High current

18 Quarter-wave SC resonators

24-Resonator Booster

19-Resonator ATLAS

ATLAS Beams



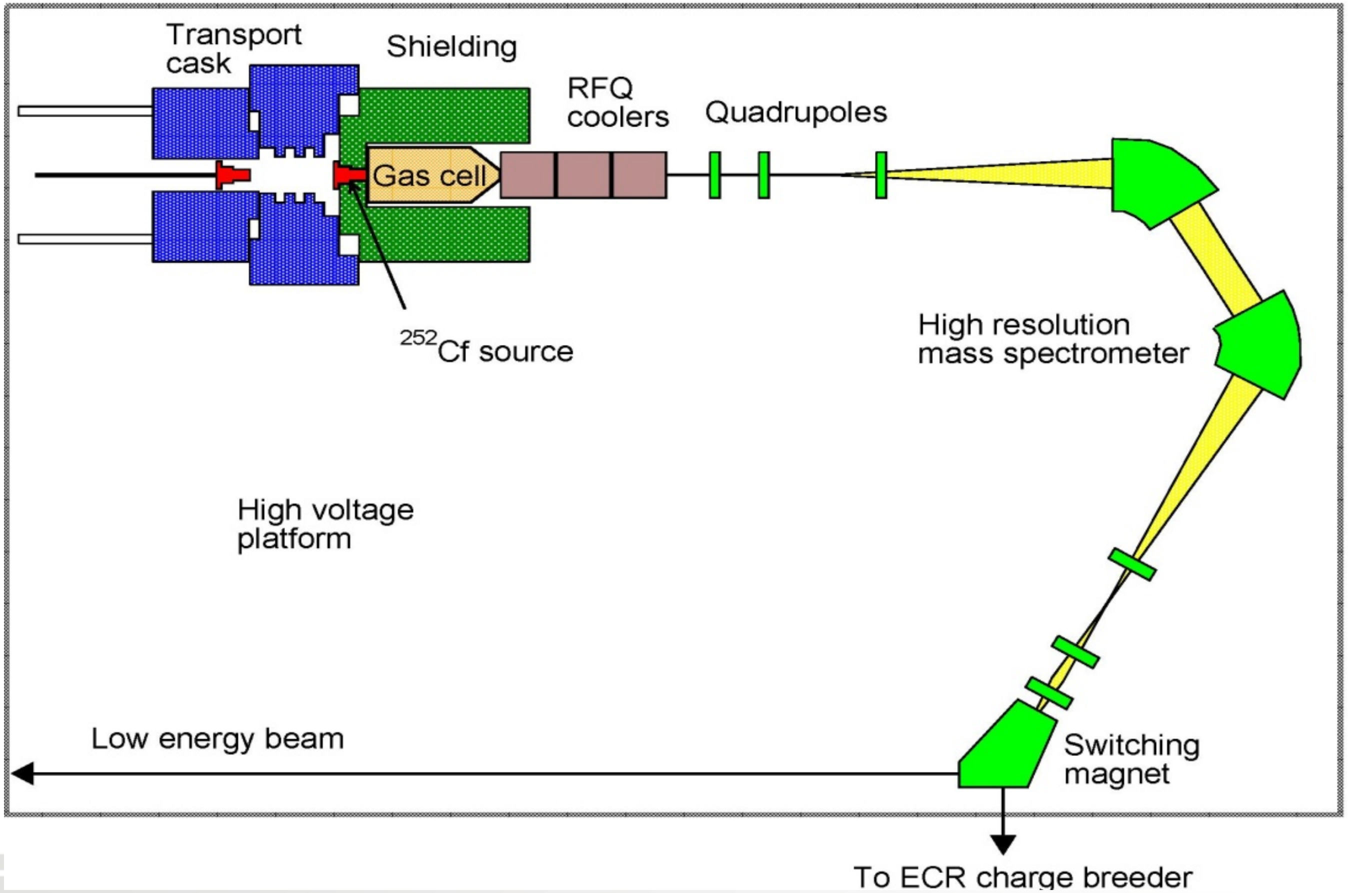
31 Different Isotopes

~ 18% beam time for Radioactive Beams

ATLAS: The CARIBU project

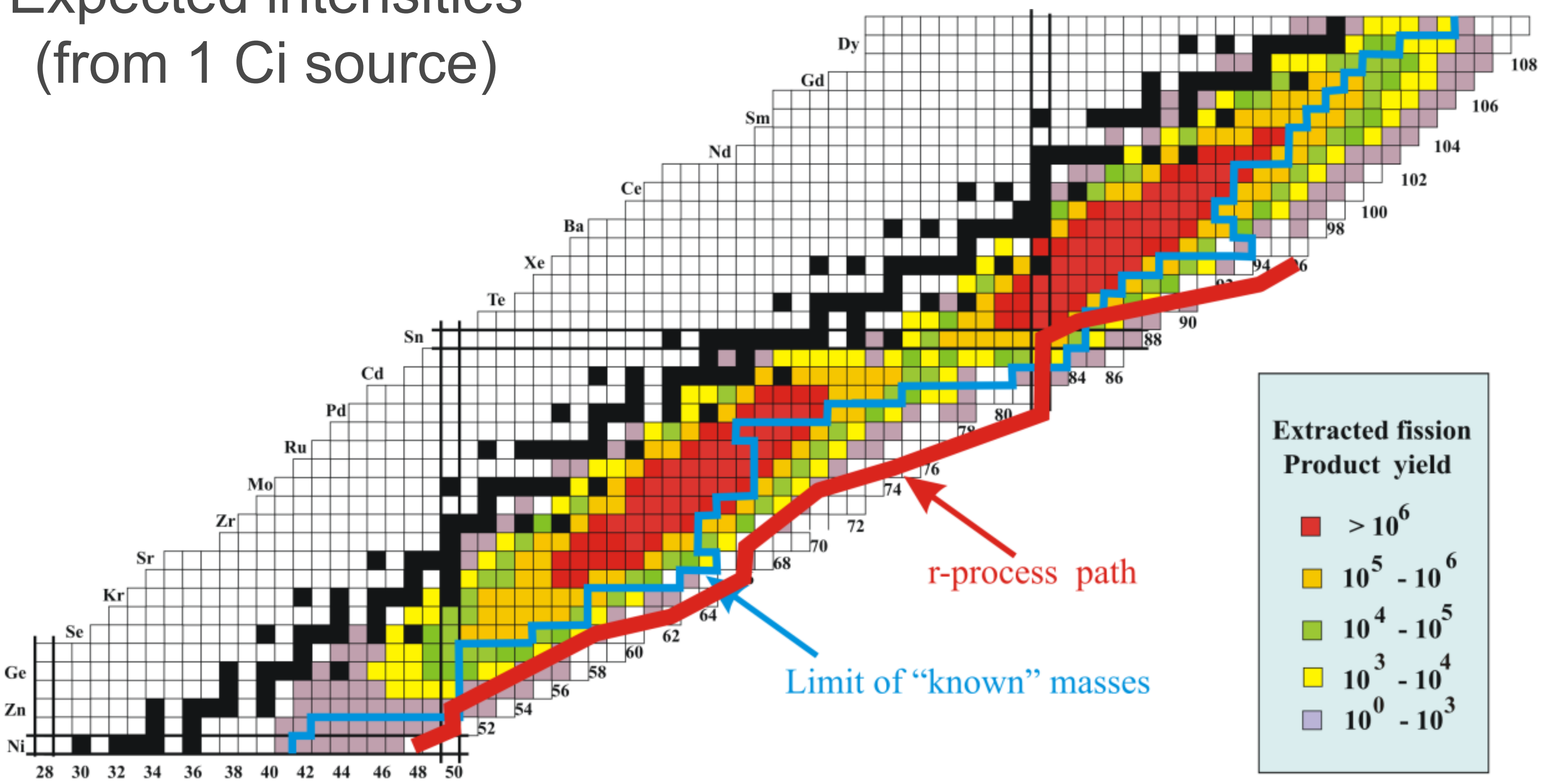
Californium Rare Ion Breeder Upgrade

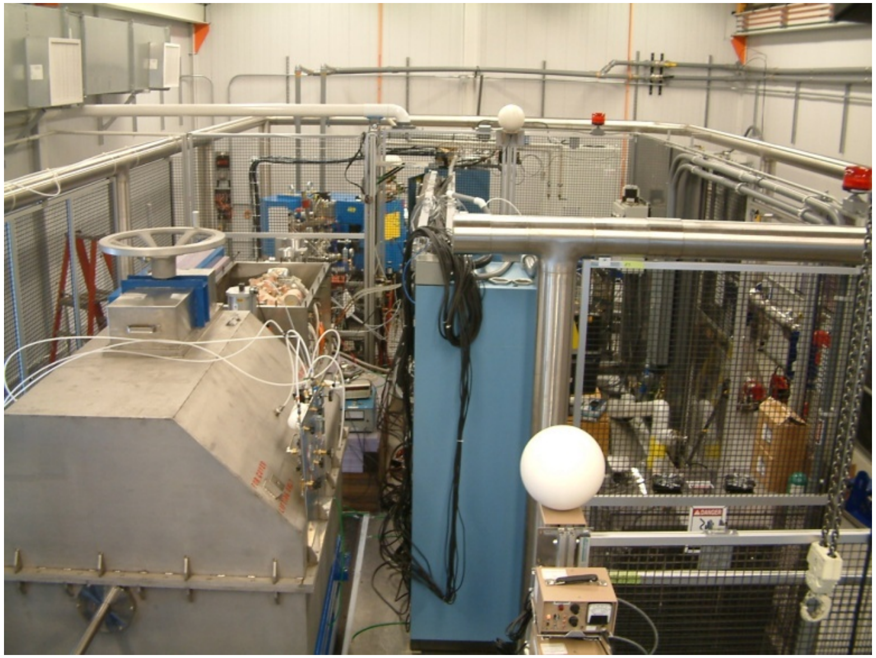
- Will provide beams of neutron-rich radioactive ions from ^{252}Cf spontaneous fission
- $T_{1/2}$ = 2.6 years 3.1% fission branch



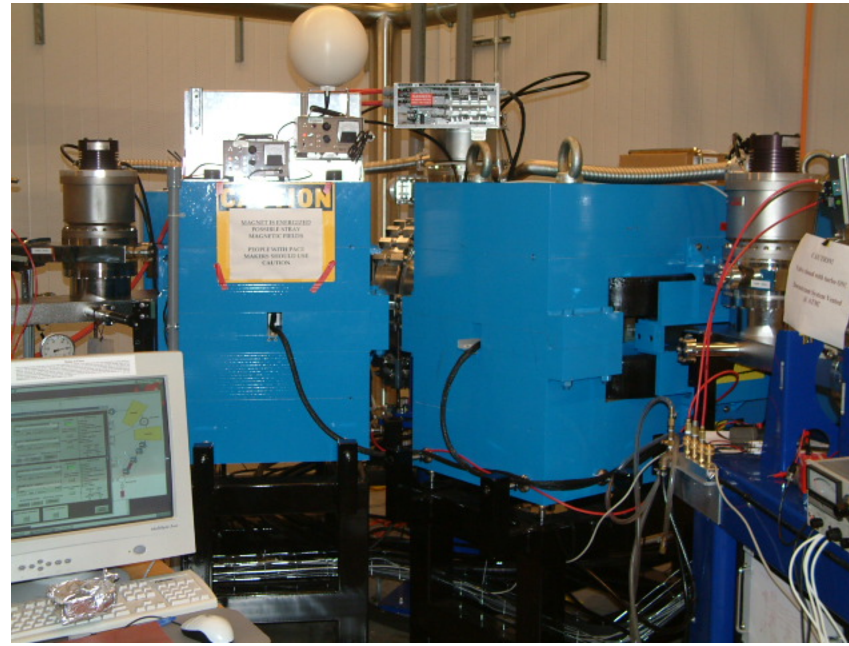
CARIBU:
A Californium Fission Source for ATLAS

Expected intensities
(from 1 Ci source)





CARIBU Platform



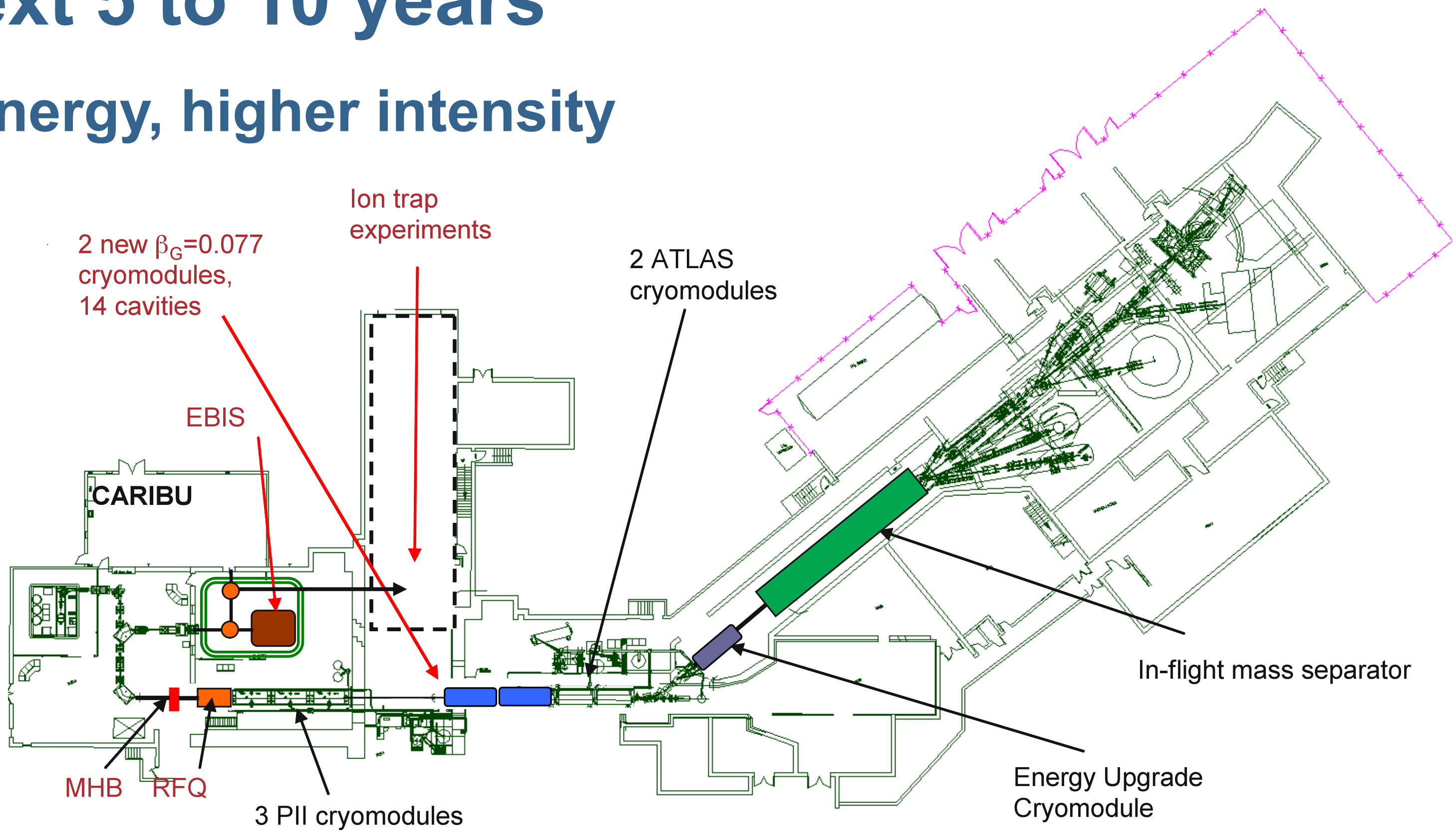
Isobar Separator

CARIBU Status:

- Hardware complete & installed
- Subsystem commissioning complete
- 100 mCi ^{252}Cf source installed in March 2011
- Mass measurements with CPT (Penning trap) have begun
- Ongoing: Beam tests through isobar separator, charge breeding of radioactive beam

Planned Upgrades to ATLAS
for the next 5 to 10 years

⇒ Higher energy, higher intensity



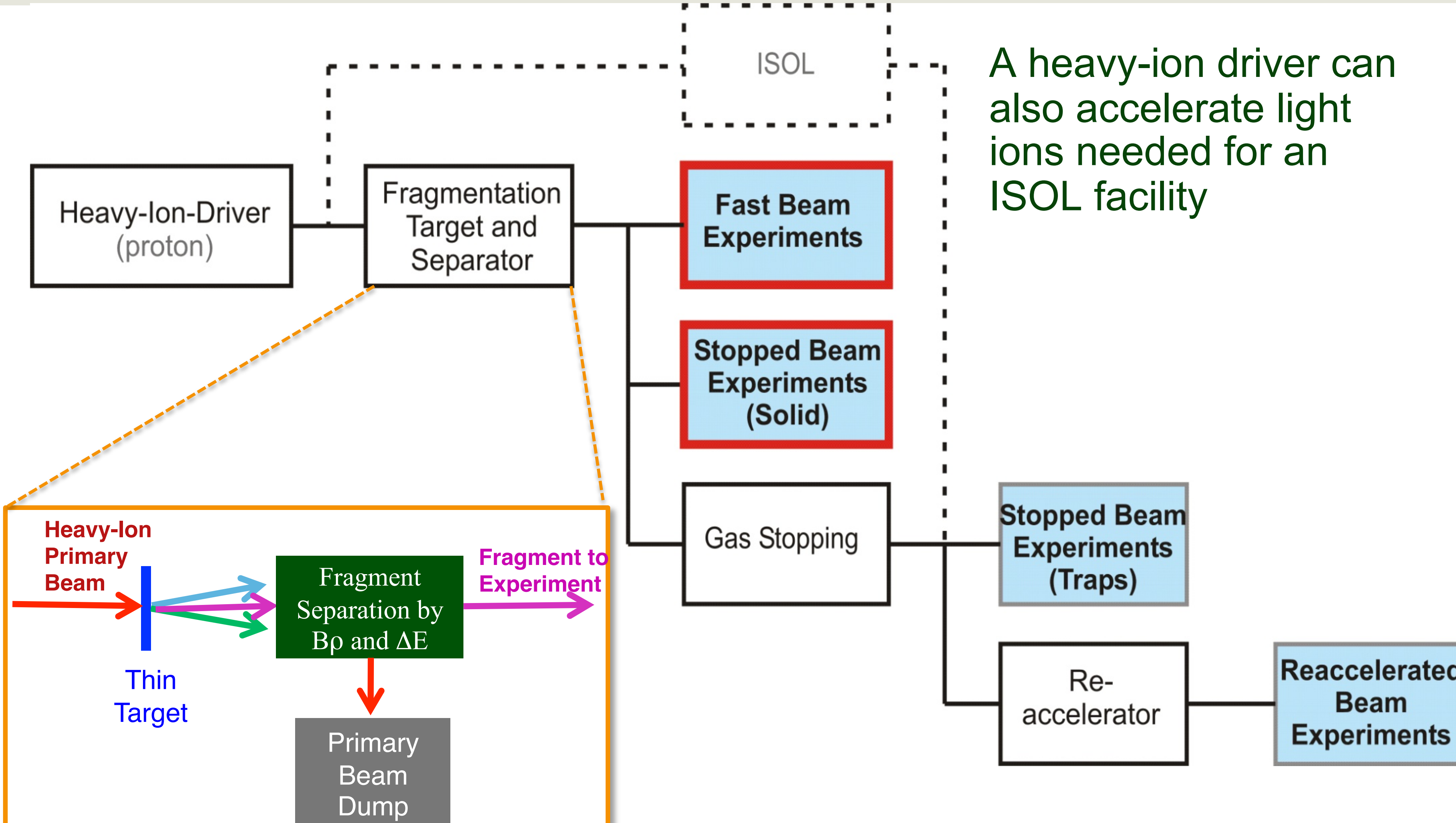
- New RFQ (250 keV/u, q/A ≥1/7)
- New quarter-wave SC resonators
- Upgrade liquid helium system
- Replace CARIBU ECR by EBIS
- Remove Tandem accelerator

- New cryomodules
- Reconfiguration of ATLAS
- New stable-beam ECR source
- Recoil separator for in-flight RIBS

Facility for Rare Isotope Beams (FRIB)

- A DOE-SC National User Facility to be built at MSU
- Scheduled for construction starting in 2012,
  completion in 2018-2020
- Rare isotope production via projectile fragmentation and in-flight fission
- Driver accelerator: Heavy-ion linac
  - E/A ≥ 200 MeV for all ions
  - Beam power = 400 kW
  - Use of existing NSCL; enables pre-term science, fast start of FRIB science
- Fast, stopped, and reaccelerated beams

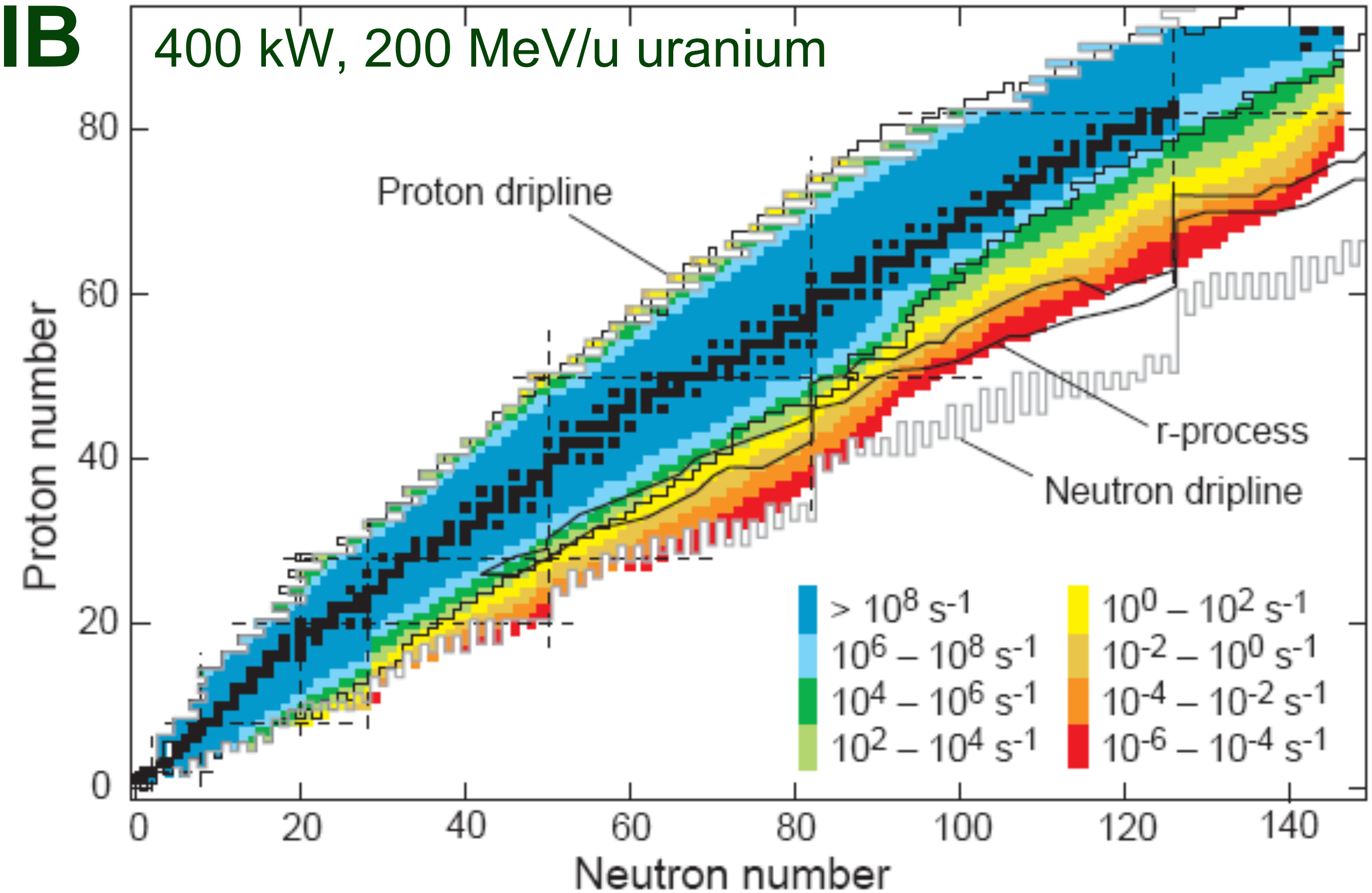
FRIB concept



A heavy-ion driver can also accelerate light ions needed for an ISOL facility

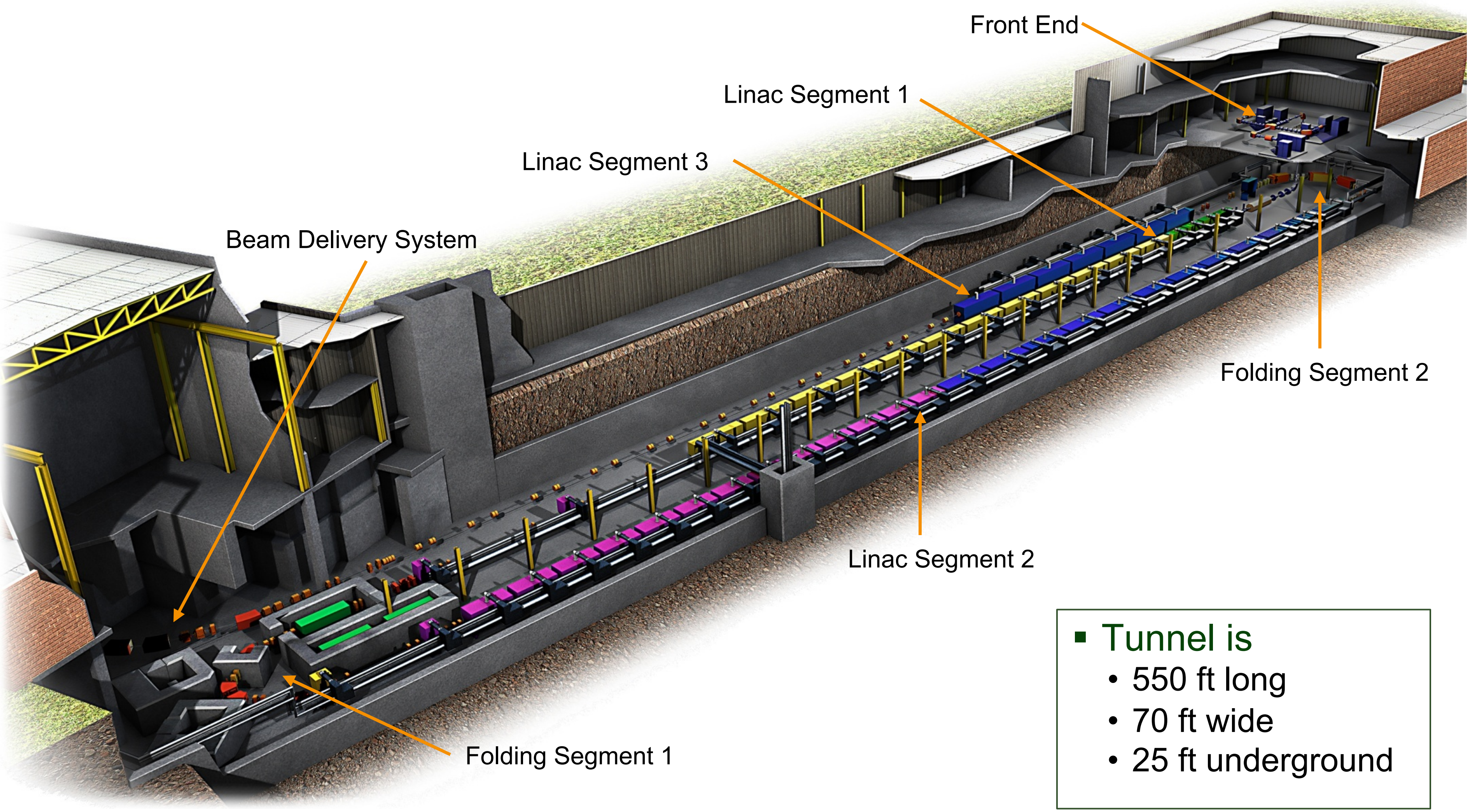
FRIB Beams

FRIB



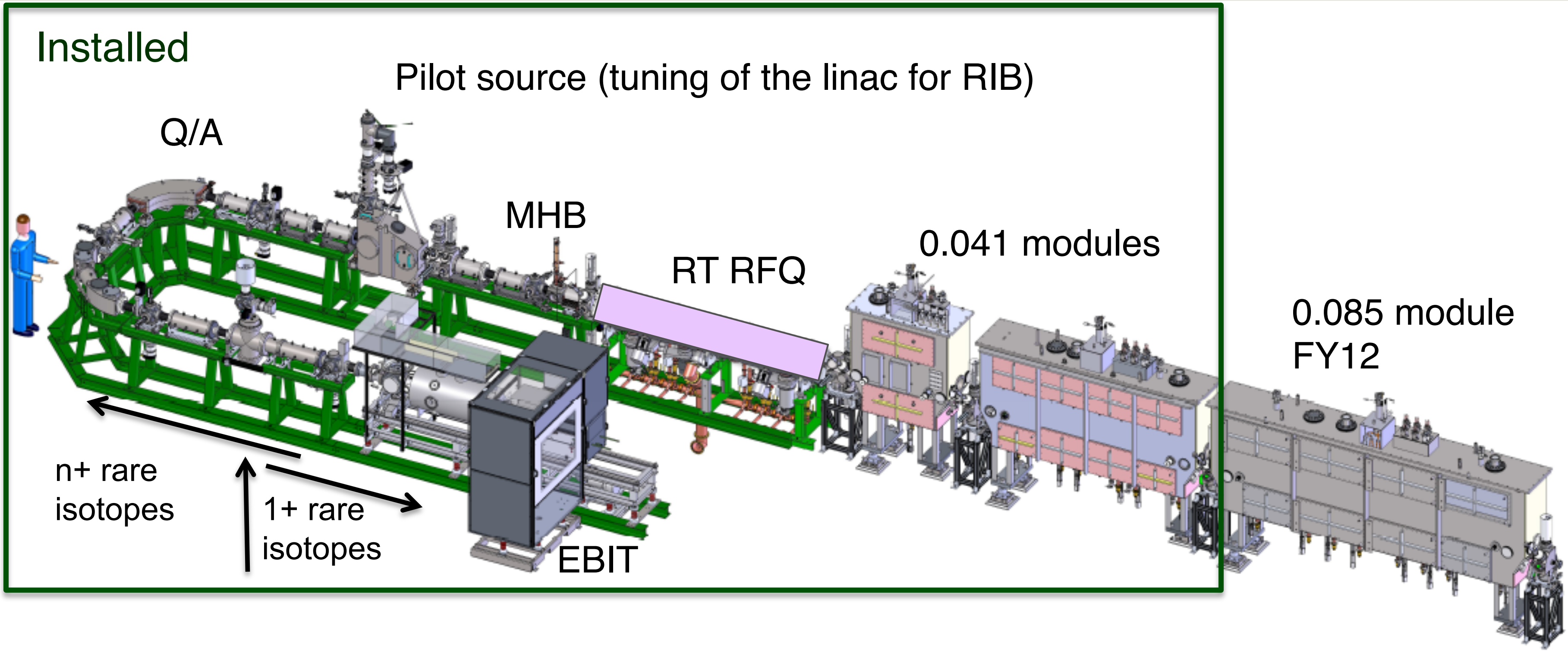
Gain factors of 10-10000 over operational facilities

Driver Linear Accelerator



- Tunnel is
  - 550 ft long
  - 70 ft wide
  - 25 ft underground

Reaccelerated Beams at FRIB

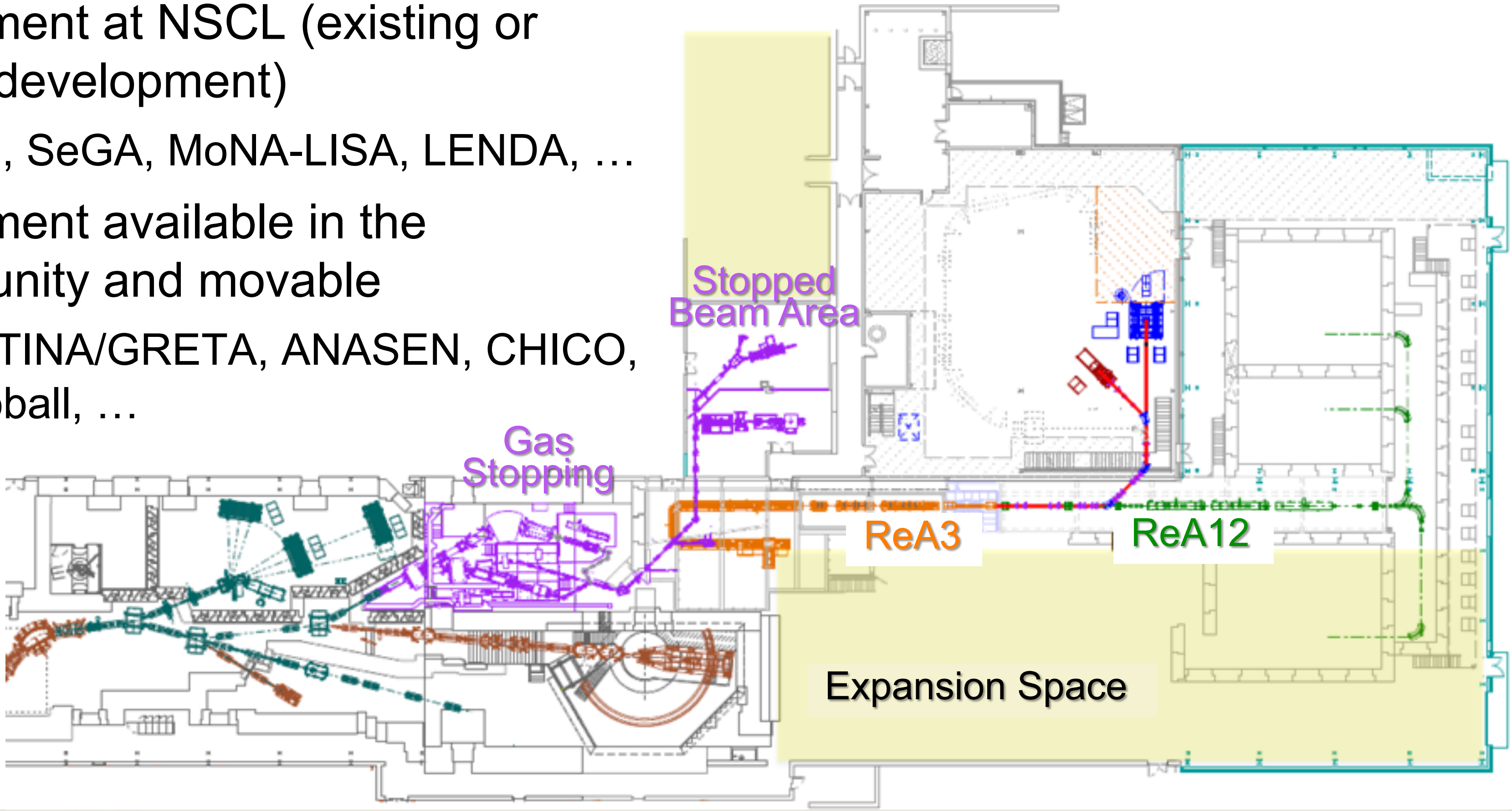


ReA3 in operation by 2013

- 0.3-3.2 MeV/u for uranium
- 0.6-6.2 MeV/u for ^{48}Cr
- Option to upgrade to 12 MeV/u for uranium, >20 MeV/u for light ions

Experimental Areas and Equipment

- Experimental Equipment
  - None in FRIB scope
  - Equipment at NSCL (existing or under development)
    - » S800, SeGA, MoNA-LISA, LENDA, …
  - Equipment available in the community and movable
    - » GRETINA/GRETA, ANASEN, CHICO, Nanoball, …



FRIB is On Track, Nearing Construction

▪ Conceptual design	completed 9/2010 (CD-1)
▪ Preliminary design	2010-2012
• CD-2/3A (civil) review in April 2012	
▪ Civil construction begins	2012
▪ Final design	2012-2013
• CD-3B (technical) review in 2013	
▪ Technical construction begins	2013
▪ Integration/commissioning	2016-2018
▪ Early project completion	2018
▪ Project completion	2020

Examples of Experimental Equipment

Gamma detectors

- Usually *arrays* of HPGe detectors or scintillators
- *In-beam* or *out-of-beam*

Recoil and light-ion detectors

- Magnetic spectrometers and separators
- Gas counters
- Si detectors (usually DSSD or position-sensitive)
- Scintillators

Electronics

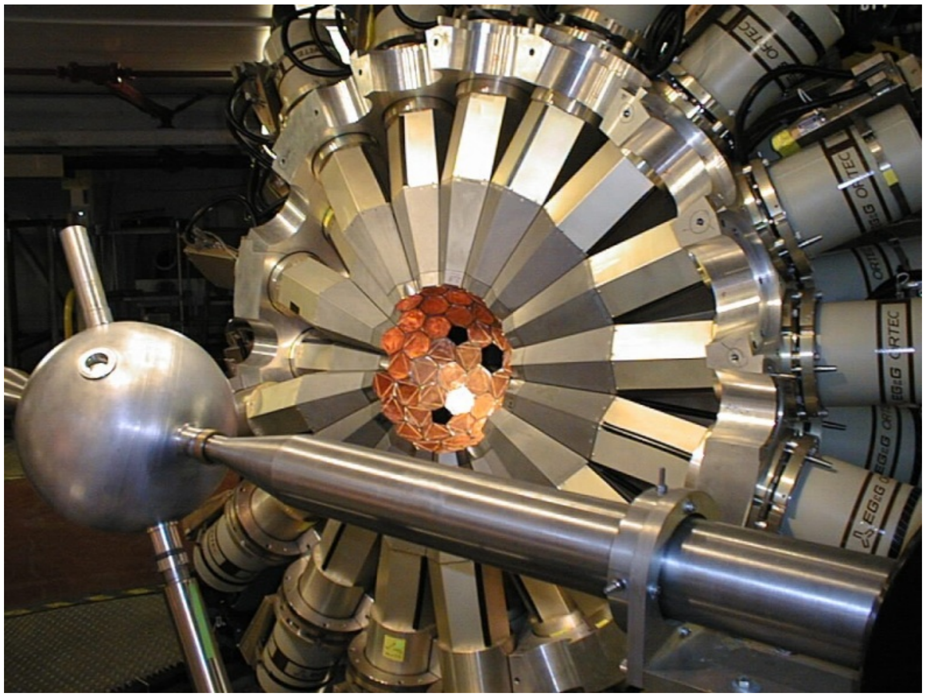
- Waveform digitizers, ASICs, preamps
- Digital pulse processing

All of these have benefitted greatly from DOE-SC SBIR/STTR program. Improvements in instrumentation greatly extend the physics reach of the facilities.

The Gammasphere Array

108 Compton suppressed HPGe spectrometers

Dedicated Dec 1995

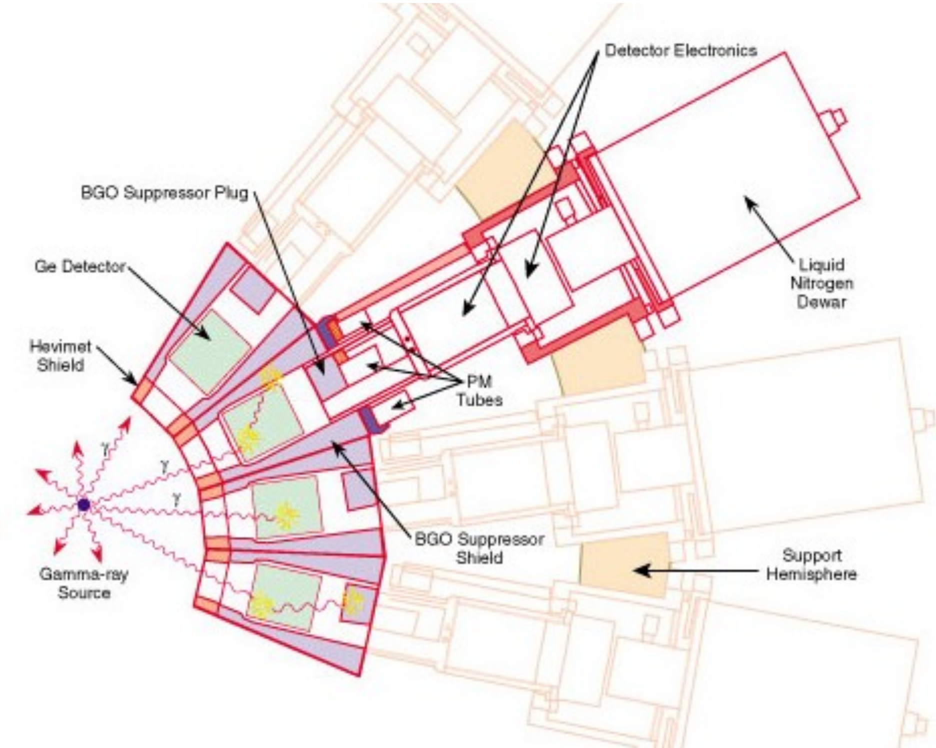


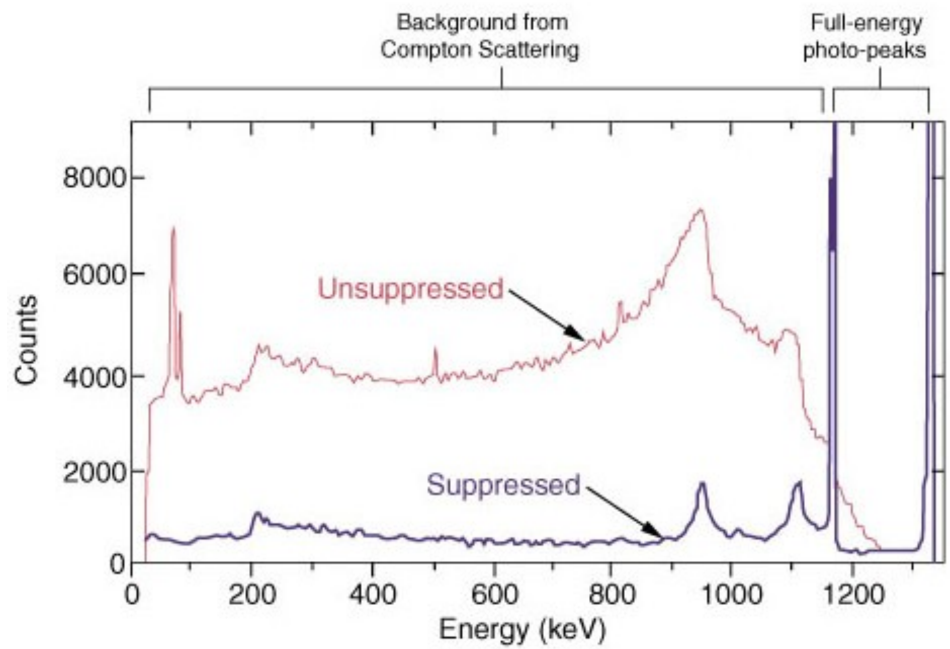
Absolute photopeak efficiency ~ 0.09 at 1.33 MeV

Peak-to-total ratio ~ 0.55

Compton Suppression

– Improves the peak-to-background ratio (P/T ~ 0.2 ➔ 0.55)





But Compton suppression also leads to losses in efficiency

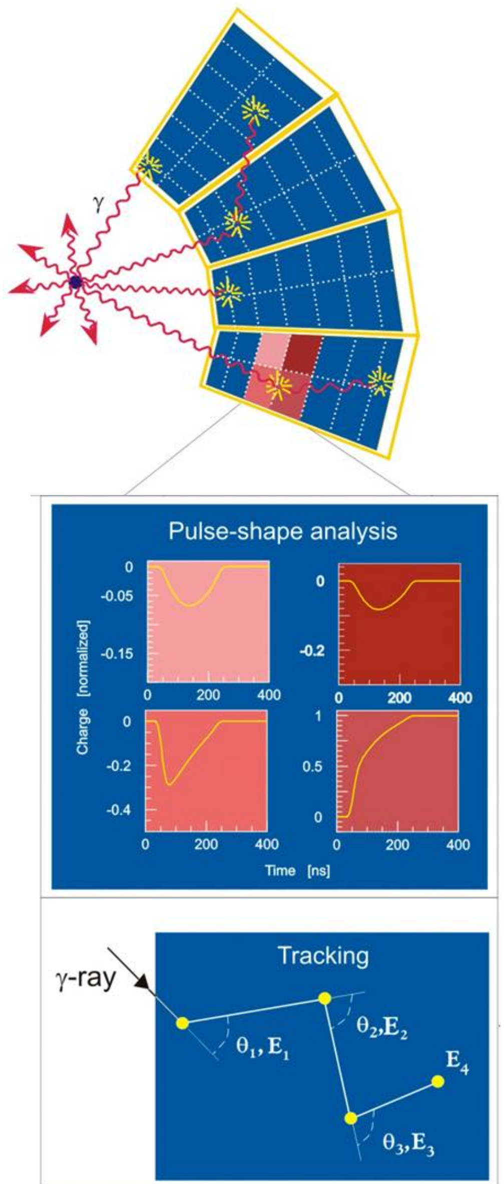
- In Gammasphere, only 50% of the solid angle is covered by Ge
- Compton-vetoed events are thrown away; it would be better to precisely determine the energy and use those events

Gamma-ray Tracking

3D position sensitive Ge detector

Resolve position and energy of all interaction points

Determine scattering sequence



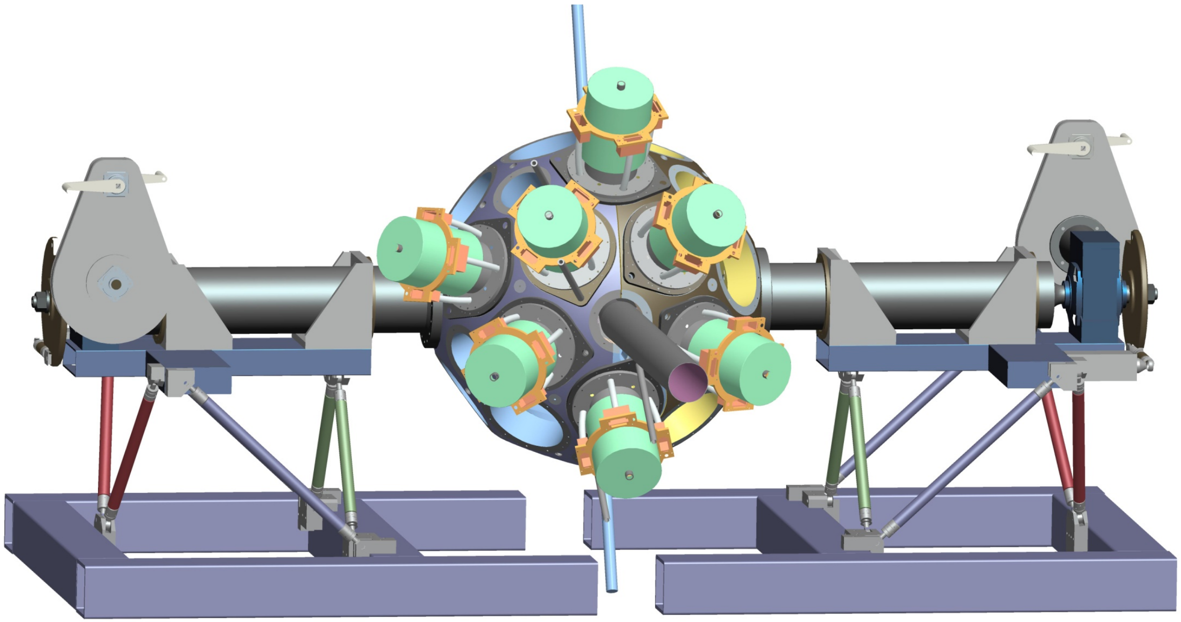
- Large n-type HPGe detectors
- Outside surface electrically segmented into 36 contacts

- Digital pulse processing to get sub-segment position resolution
- Process all signals (hit segment and neighbours)
- Need a sophisticated *signal decomposition algorithm*

- Group interactions;\ determine scattering sequence from Compton formula
- Reject incomplete-energy events on basis of chi-square

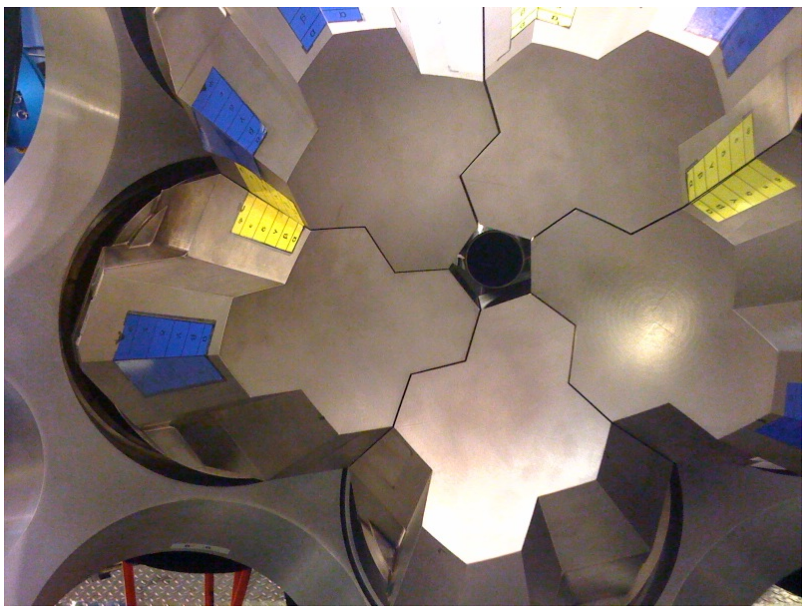
GRETINA: Gamma-ray tracking detector array

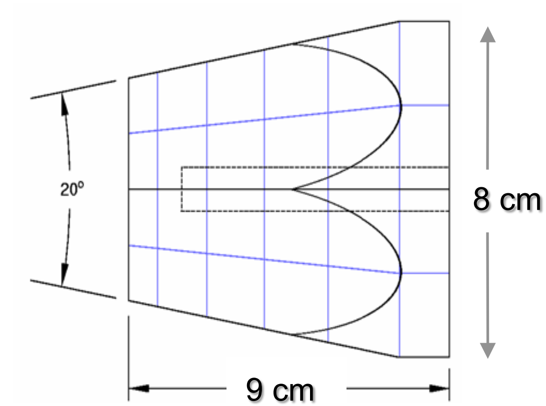
- 28 highly segmented Ge detectors
- All associated electronics and software
- Construction completed March 2011
- Currently running commissioning experiments at LBNL
- One-fourth of the full sphere (GRETA)

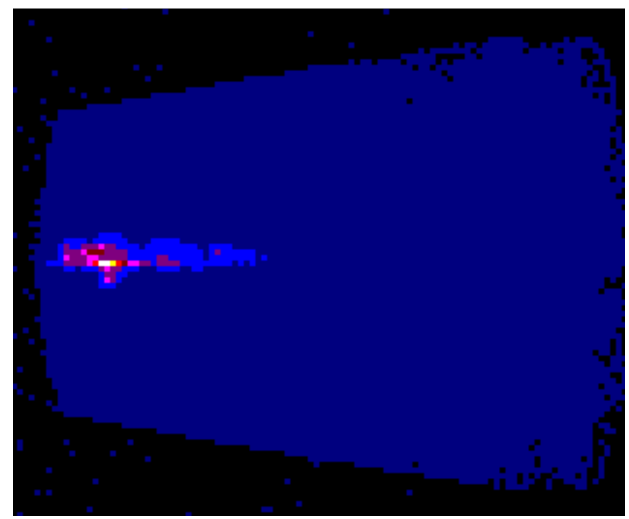


GRETINA detector crystals

- 28 highly segmented Ge detectors, in seven groups of four
  - 36-fold segmentation (6 azimuthal, 6 longitudinal)
  - Tapered irregular hexagons
  - 2mm (RMS) position resolution
- Total coverage ~1π steradians



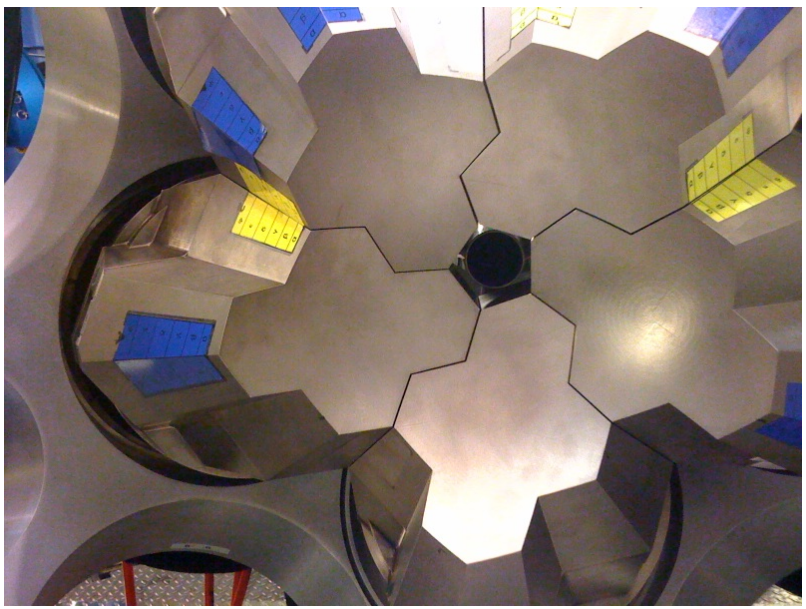


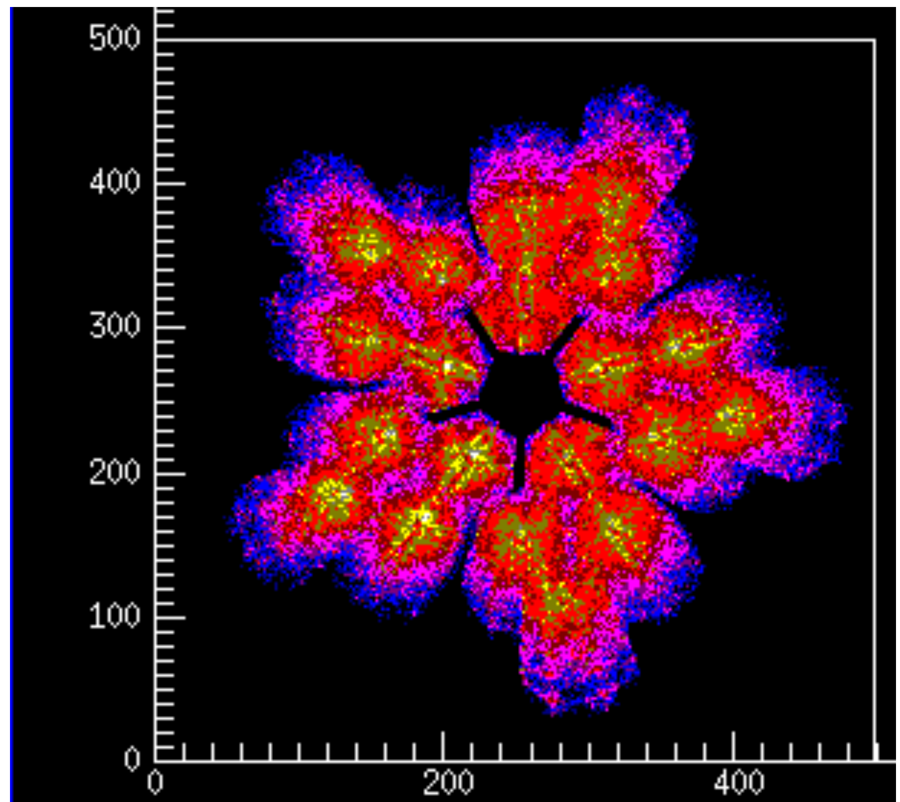


Oak Ridge National Laboratory

Signal decomposition

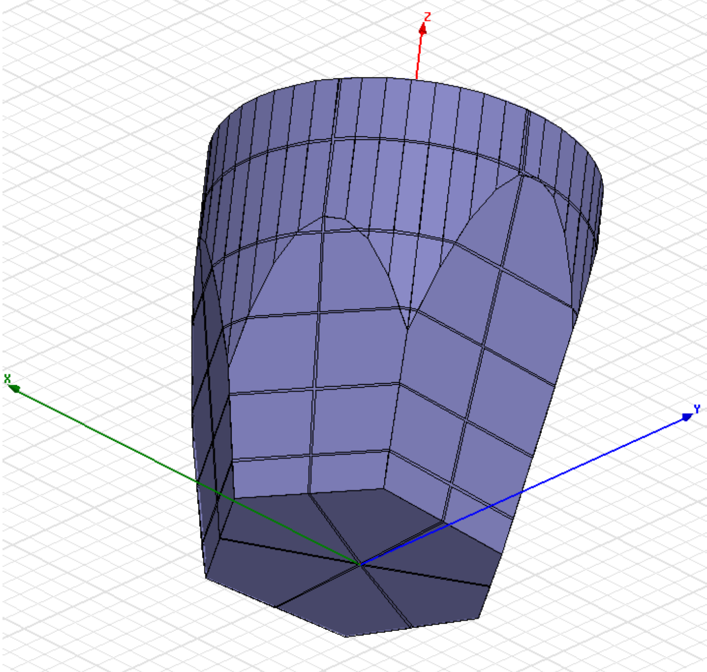
Position of interaction points determined by signal decomposition

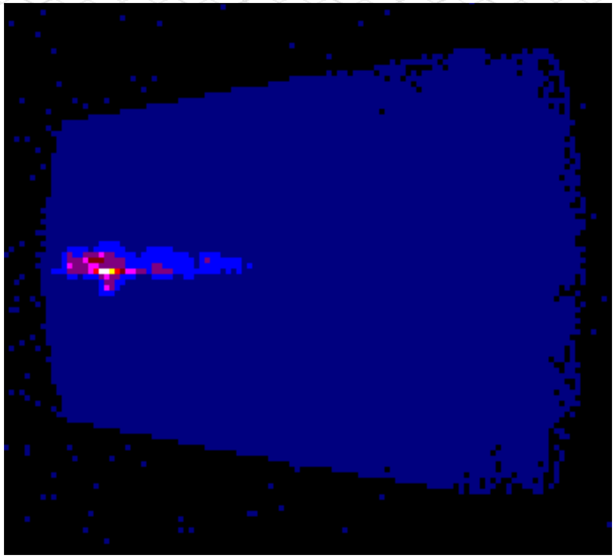




Signal decomposition

- Determine, in near-real-time, the *number, positions,* and *energies* of gamma interactions in the crystal
- Required as input for gamma tracking
- Uses a set of pre-calculated basis pulse shapes
- *Position resolution* is crucial; dominates energy resolution, efficiency, and peak-to-total ratio
- *Speed* is also crucial; determines triggered count-rate capability of array
- Met GRETINA requirements of σ < 2mm, and processing of at least 20,000 γ/s





SBIR/STTR Program

Some of the many crucial contributions of the SBIR/STTR program to low-energy user facilities are illustrated by talks at this meeting:

- Instrumentation, Detection Systems and Techniques
  - Adelphi, RMD, PHDs*, Tech-X*
- Electronics Design and Fabrication
  - XIA, Blue Sky
- Software and Data Management
  - Tech-X
- Accelerator Technology
  - Alameda Appl. Sciences, FM Technologies, Saxet

* Collaborations on Majorana & GRETINA

Acknowledgements

Material or slides were provided by

- Michael Carpenter, Richard Pardo (ANL)
- Georg Bollen, Thomas Glasmacher, Brad Sherill (MSU)

Backup Slides….

The Physics

Nuclear Structure: Properties of nucleonic matter

- Many-body quantum problem (mesoscopic quantum science)
- Structure far from stability (neutron-rich, proton-rich, or super-heavy)
- Structure at high excitation energy and/or high angular momentum
- Competition and interplay between collective & single-particle behaviors
- Exotic nuclear shapes

Nuclear Astrophysics: Nuclear processes in the universe

- Energy generation in stars
- Nucleosynthesis in stars, novae, and supernovae
- Properties of neutron stars; EOS of asymmetric nuclear matter

Tests of fundamental symmetries

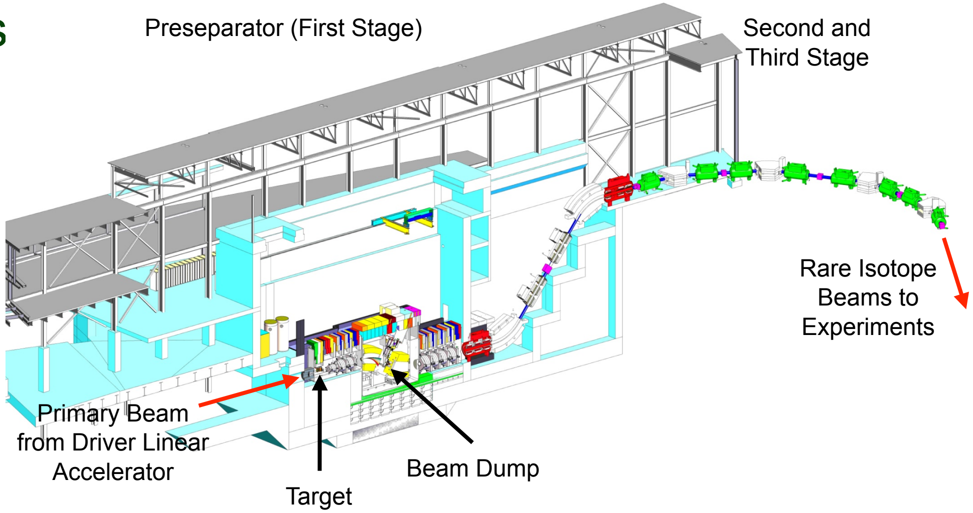
- Effects of symmetry violations are amplified in certain nuclei

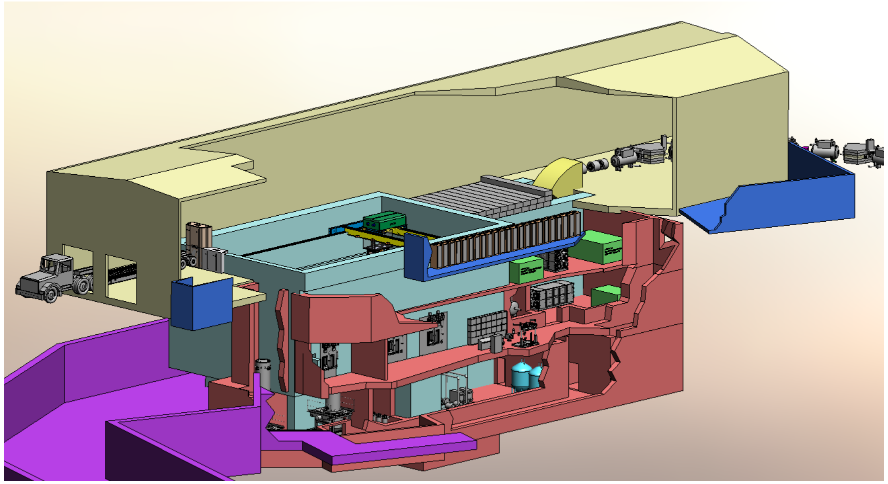
Societal applications and benefits

- Bio-medicine, energy, material sciences, national security

Production Target Facility and Fragment Separator

- High radiation and high power densities pose technical challenges
- Self-contained target building to keep most-activated and contaminated components in one spot
  - Remote handling to maximize efficiency
- High-power targets for light and heavy primary beams
  - R&D on multi slice graphite target promising approach
- Fragment separator to separate primary beam and select rare isotope beam
  - R&D on radiation resistant magnets
- High-power beam dump to intercept unreacted primary beam
  - R&D on rotating water-filled drum concept and alternatives

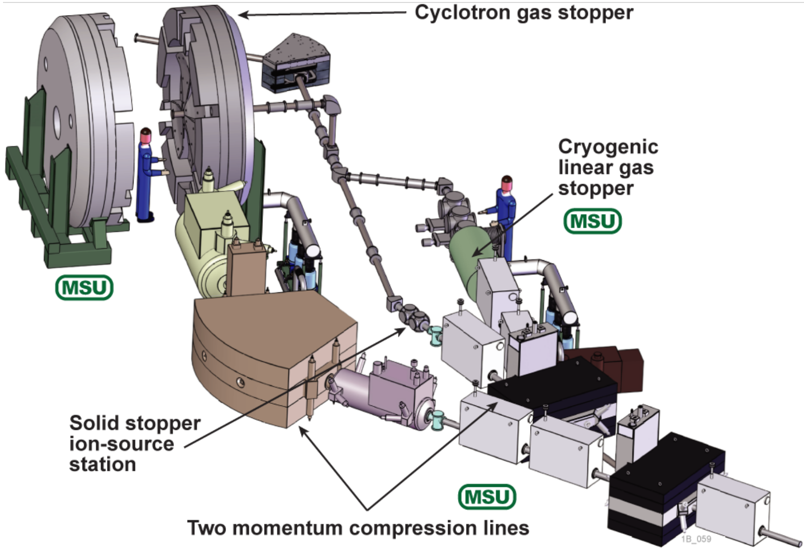


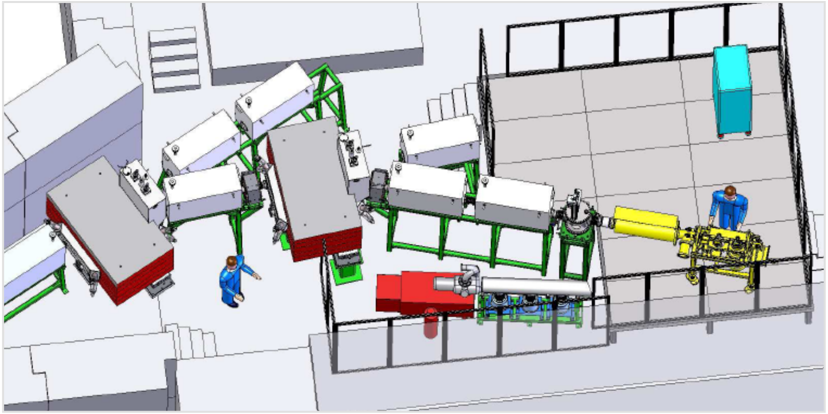


Stopped Beams at FRIB

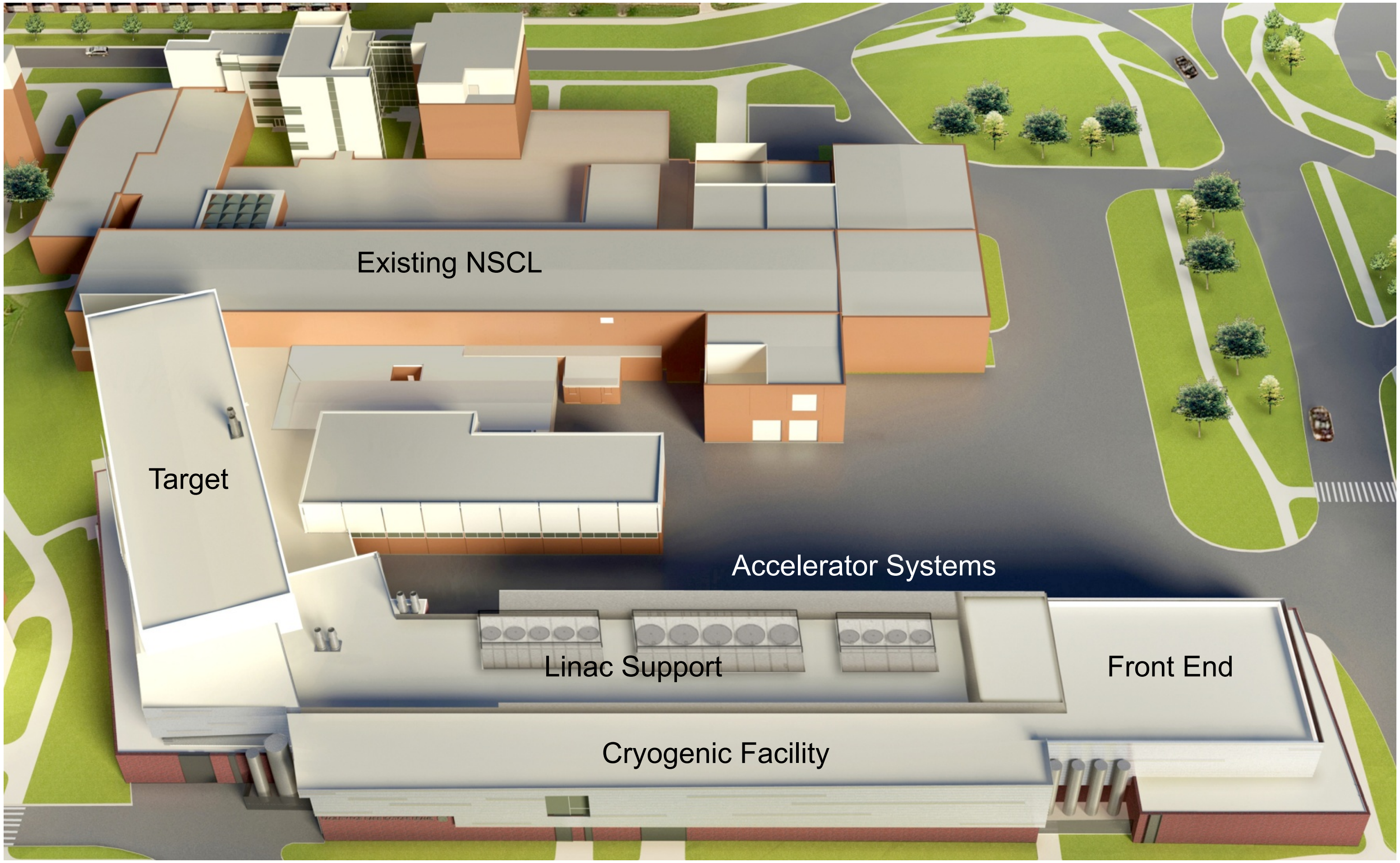
Beams for precision low-energy experiments, and for reacceleration

- Linear gas stopper
- Cyclotron gas stopper
- Solid stopper
- Phase 1 (by 2011), two momentum compression lines
  - MSU linear cryogenic gas cell and **ANL gas catcher**
- Phase 2 (after 2012):
  - One linear gas stopper
  - Cyclotron stopper (funded as NSF-MRI)
  - Solid-stopper/reionizer

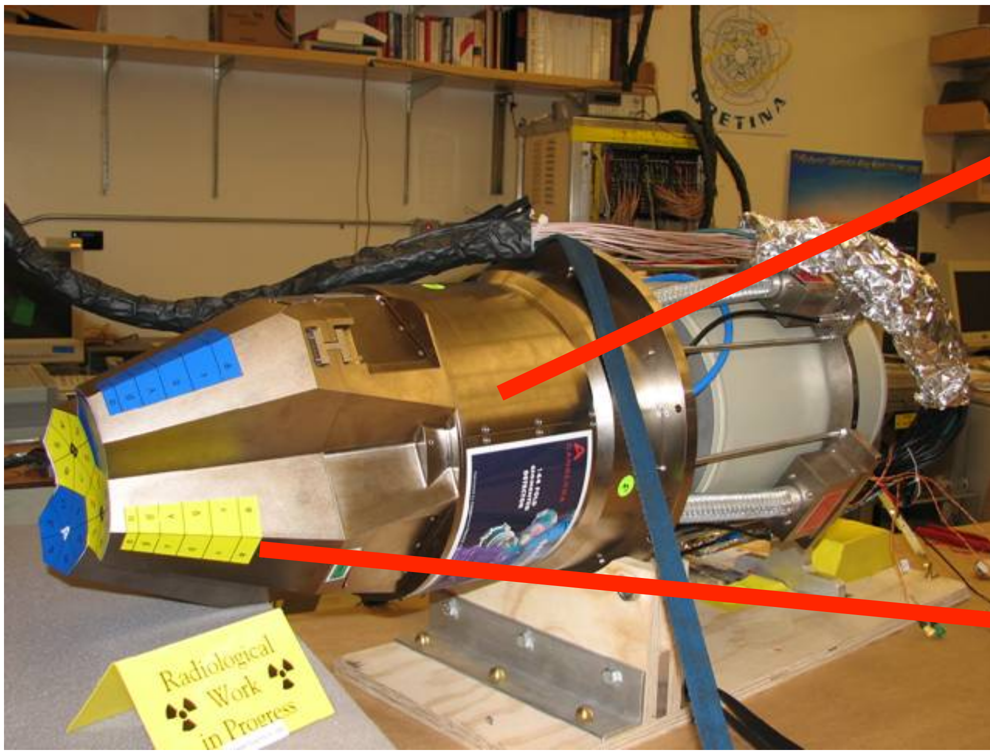


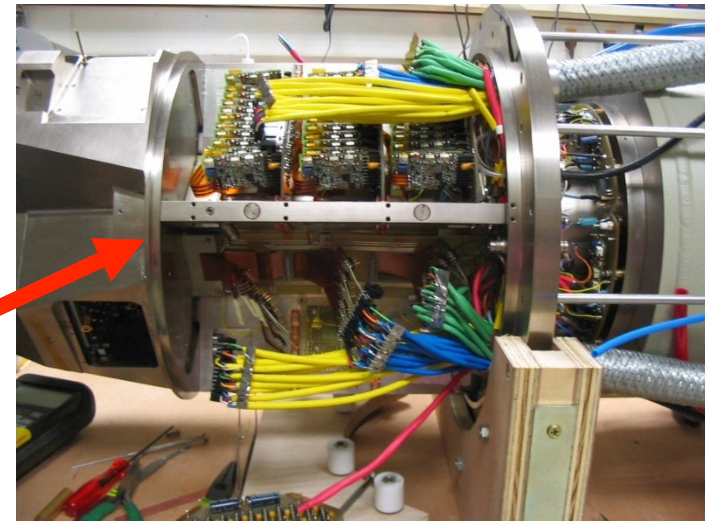


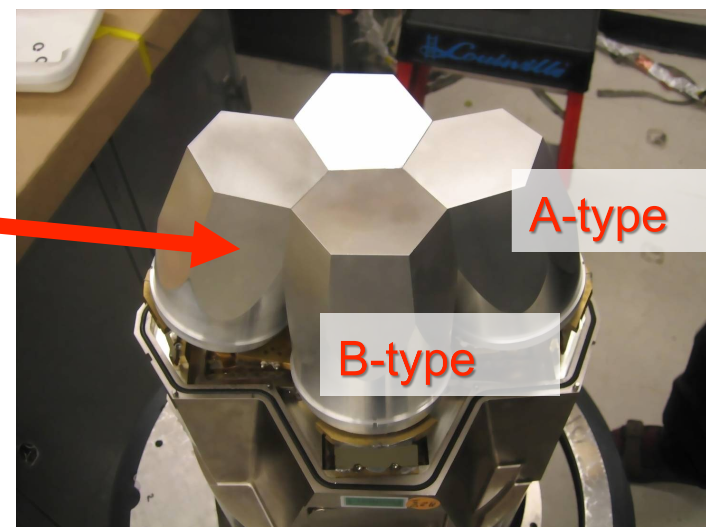
Preliminary Civil Design Complete & Integrated with Technical Systems; Final Design Started



Quadruple-Crystal Clusters







Signal Decomposition Algorithm

Hybrid Algorithm

- *Adaptive Grid Search with Linear Least-Squares (for energies)*
- *Non-linear Least-Squares (a.k.a. SQP)*

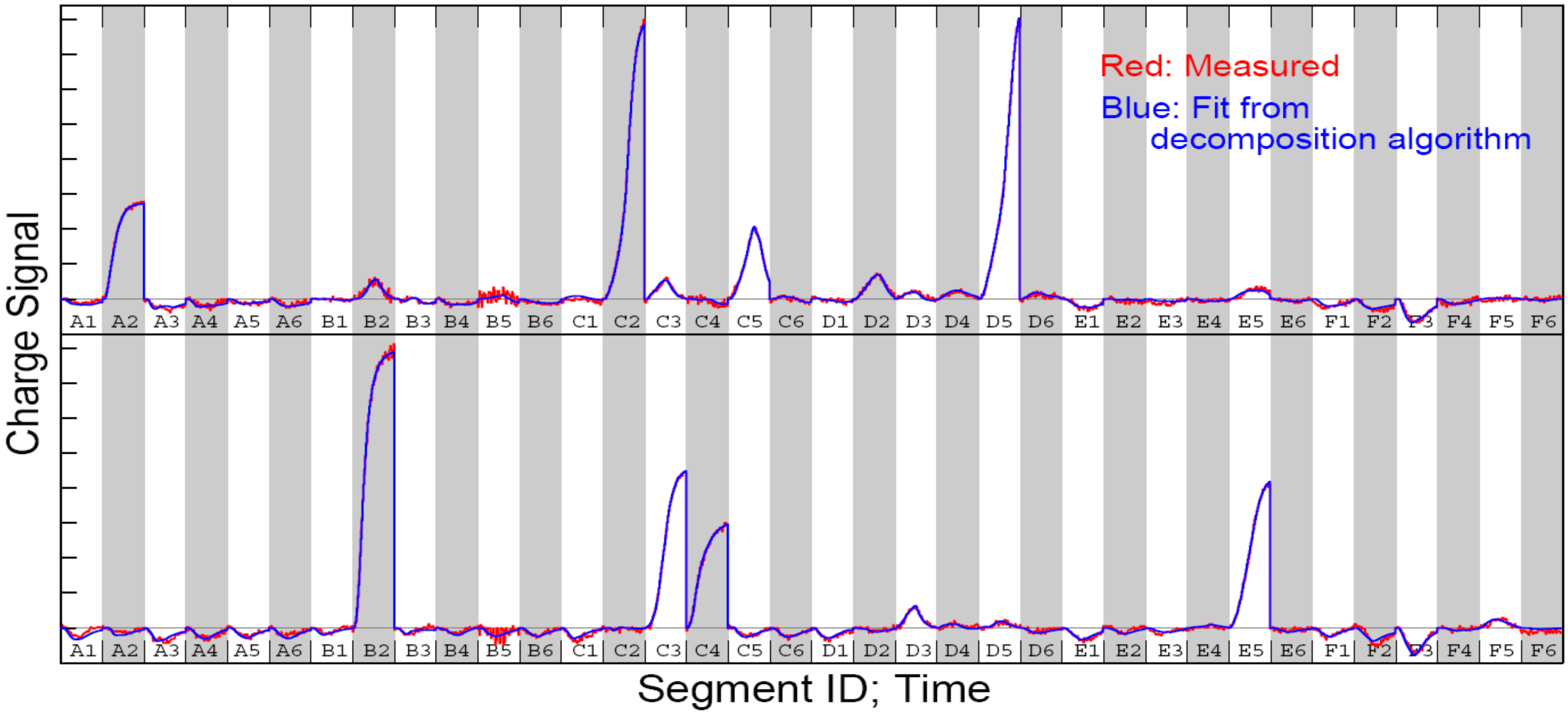
Status:

- ✓ Can handle *any number* of hit detector segments, each with *one or two interactions* (*three interactions* for single hit segment in the crystal)
- ✓ Uses optimized, irregular grid for the basis signals
- ✓ Incorporates fitting of signal start time t_0
- ✓ Calculated signals are accurately corrected for preamplifier response and for two types of cross talk
- ✓ CPU time meets requirements for processing 20,000 gammas/s

Decomposition Algorithm: Fits

- Red: Two typical multi-segment events measured in prototype triplet cluster
  - concatenated signals from 36 segments, 500ns time range
- Blue: Fits from decomposition algorithm (linear combination of basis signals)
  - includes differential cross talk from capacitive coupling between channels

Requires excellent fidelity in basis signals!

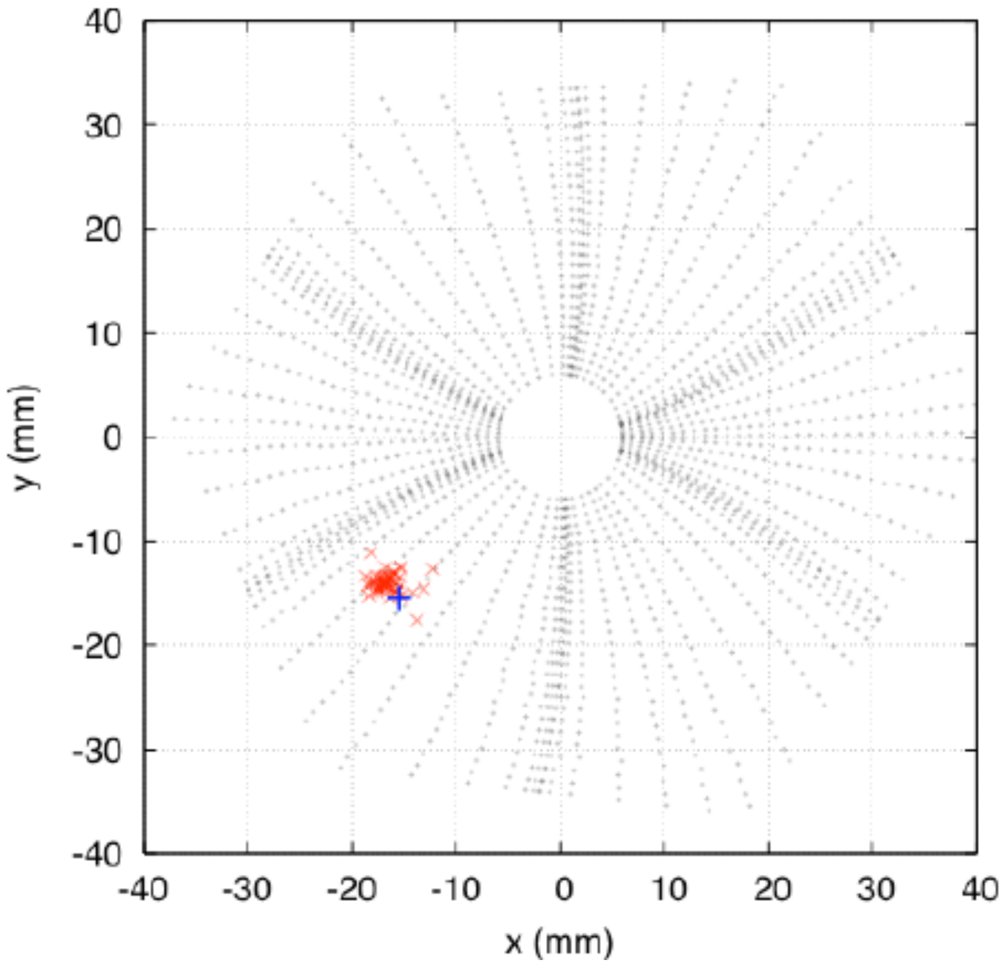


Scanning-table coincidence-data test

Evaluated positions (red)
Collimator position (blue)

66 events

Position resolution:
σ_x = 1.2 mm; σ_y = 0.9 mm



Auxiliary Detectors for GRETINA

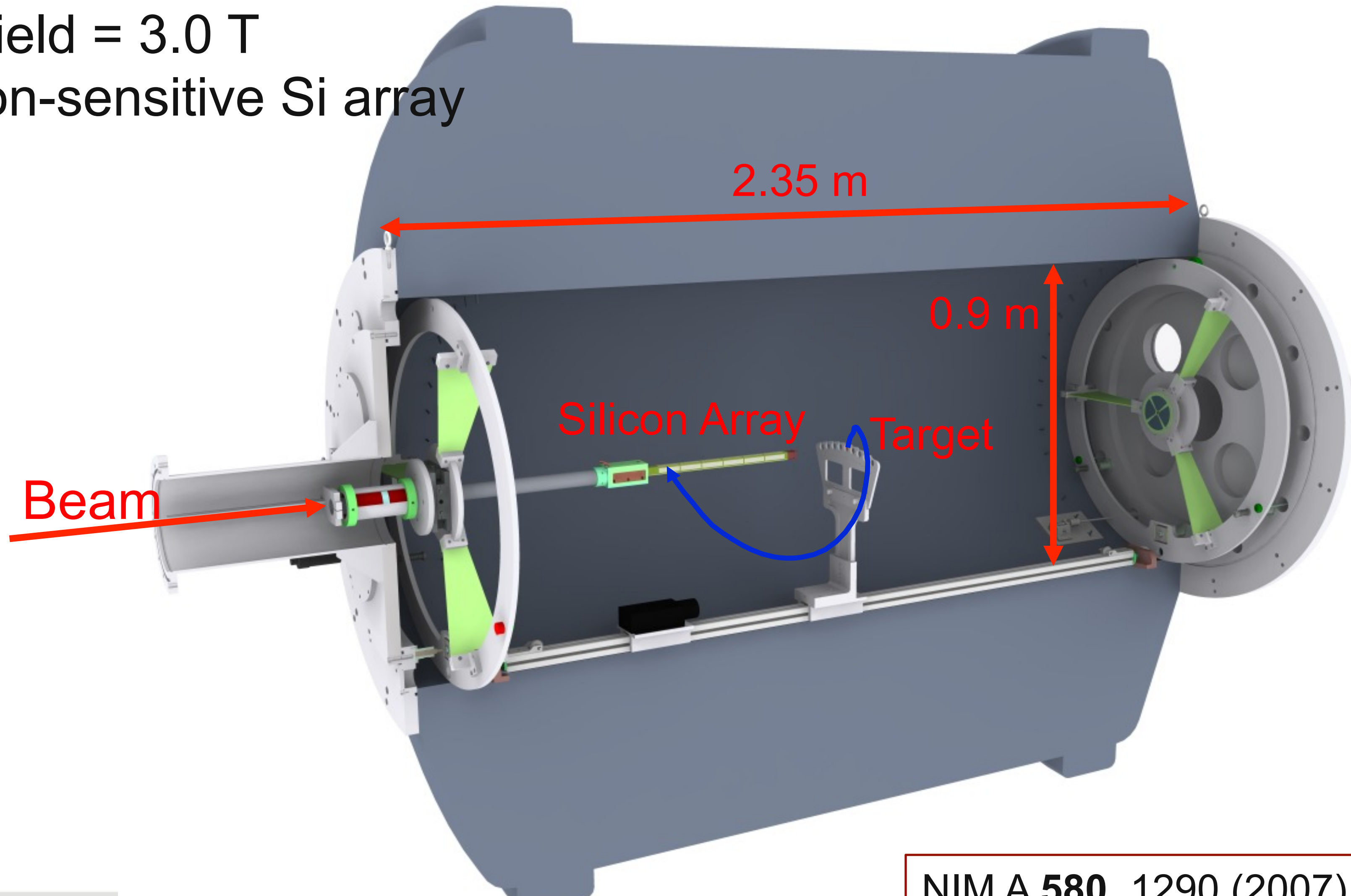
For in-beam studies, gammas are emitted by fast-moving nuclei. The excellent position resolution improves the Doppler-shift correction, thereby giving much better energy resolution.

But to take full advantage of GRETINA at HRIBF and ATLAS requires new auxiliary detectors for charged particles and/or recoils; e.g.

- Forward-angle CsI array with high granularity
- CHICO-II for recoiling heavy ions (large-area gas avalanche counter)
- Recoil-distance (“plunger”) apparatus that interfaces properly with GRETINA and with auxiliary particle detectors

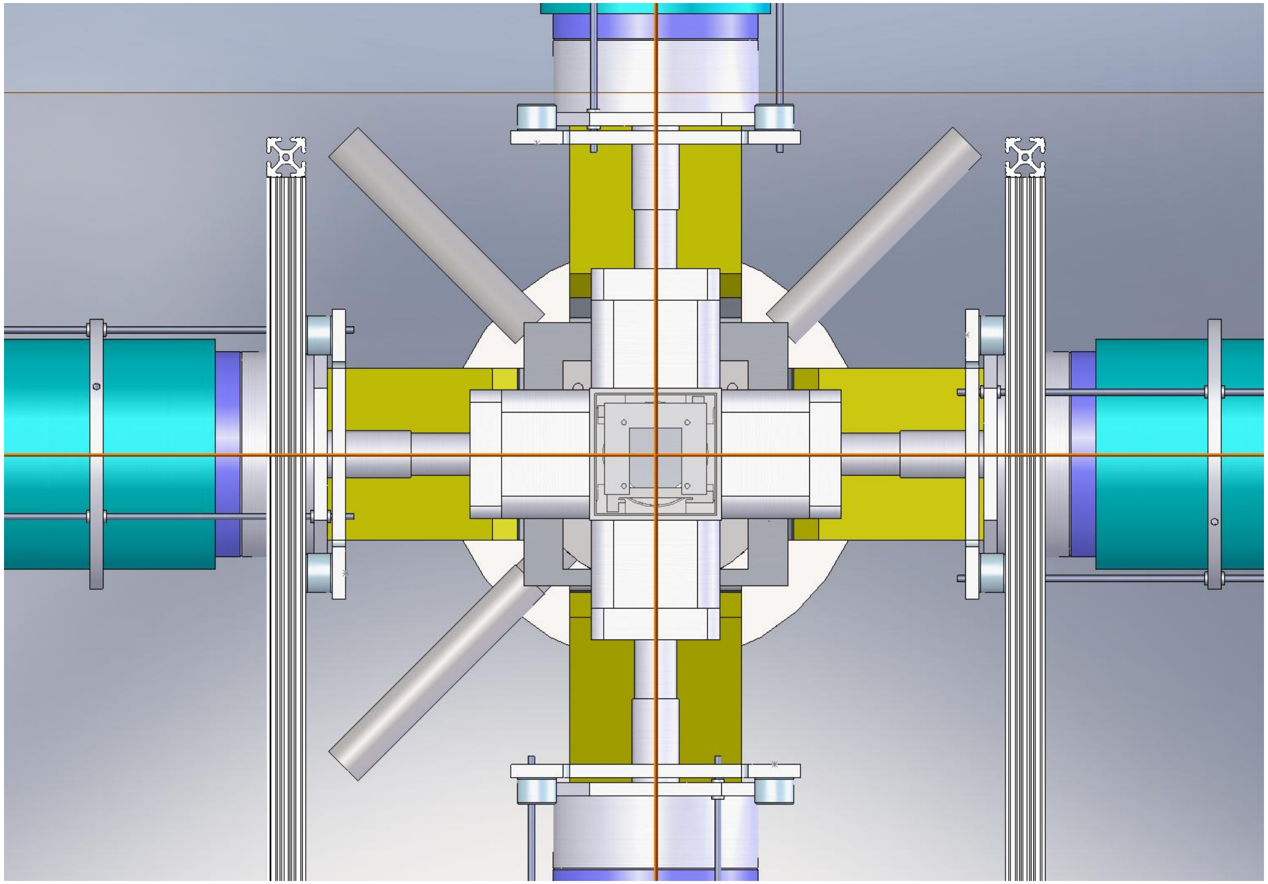
The HELIOS spectrometer for light-ion reactions

Novel spectrometer design, recently completed at ANL
Superconducting solenoid with on-axis Si detectors
Max. field = 3.0 T
Position-sensitive Si array



NIM A **580**, 1290 (2007)

The X-array



- 5 clover detectors in a box geometry
- 64x64 mm, 160x160 DSSD