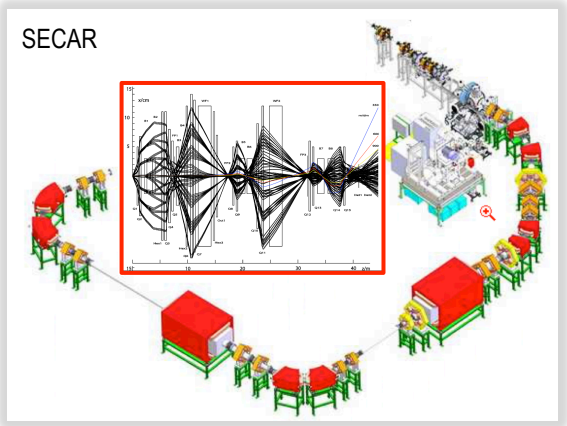
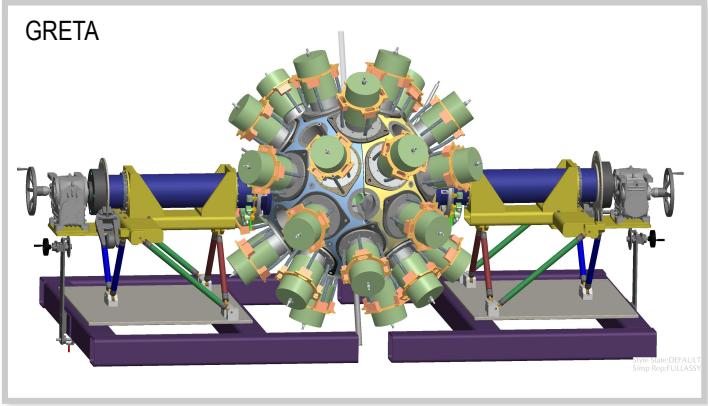
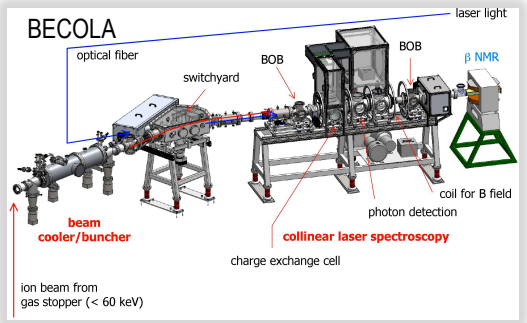
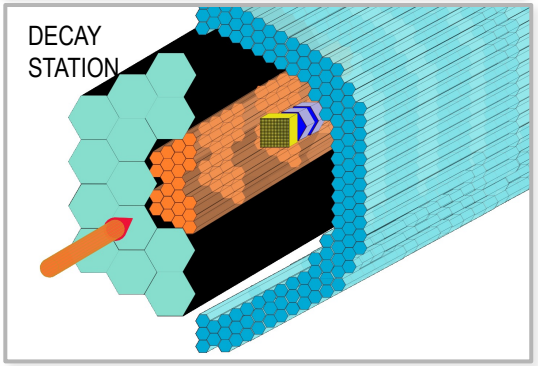
New Equipment Needs for FRIB

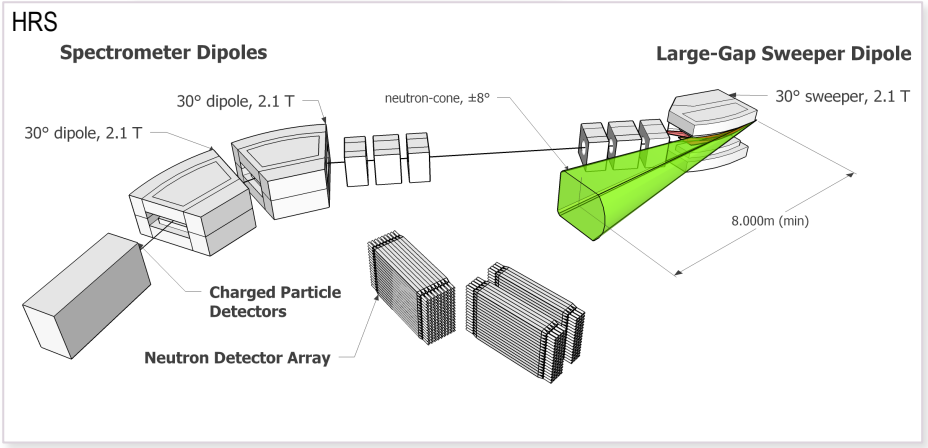
Michael Smith
FRIB Users Organization
ORNL Physics Division



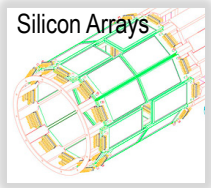


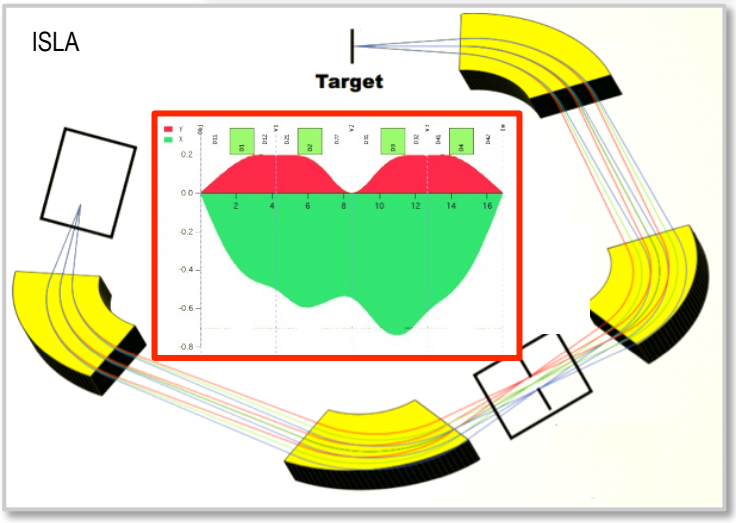




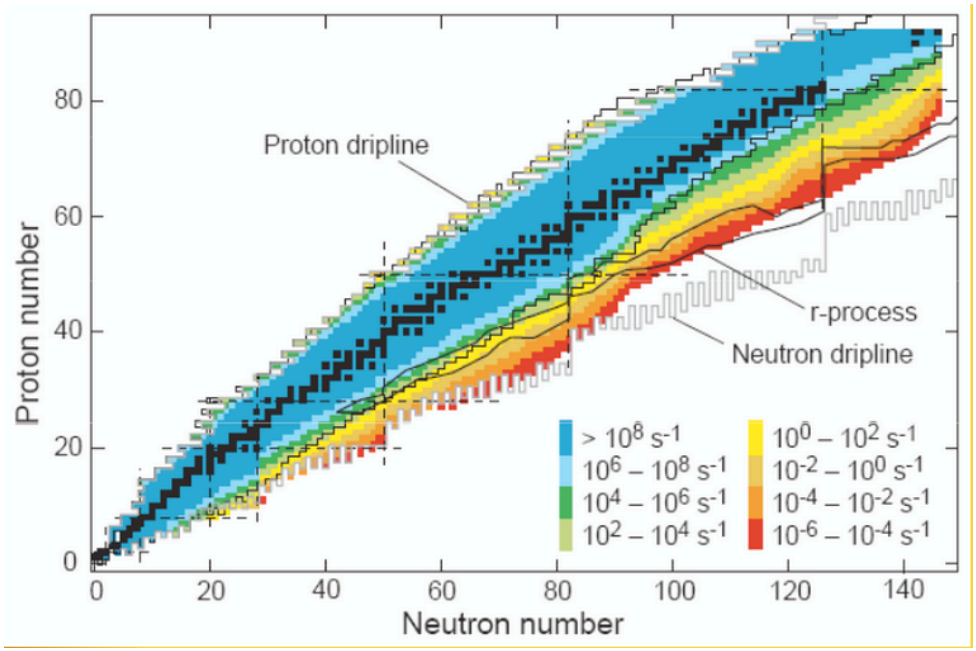


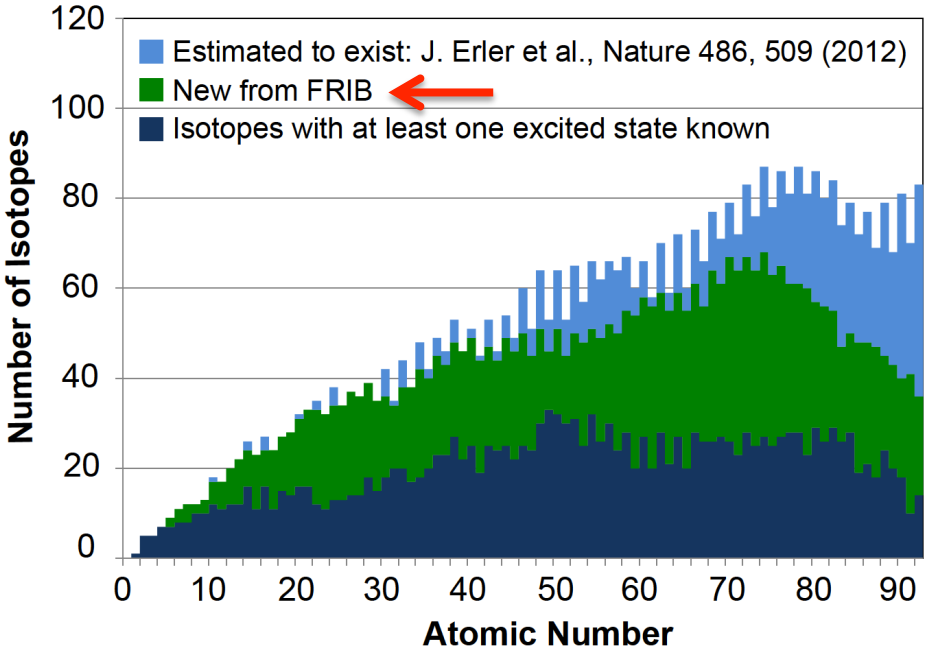
FRIB





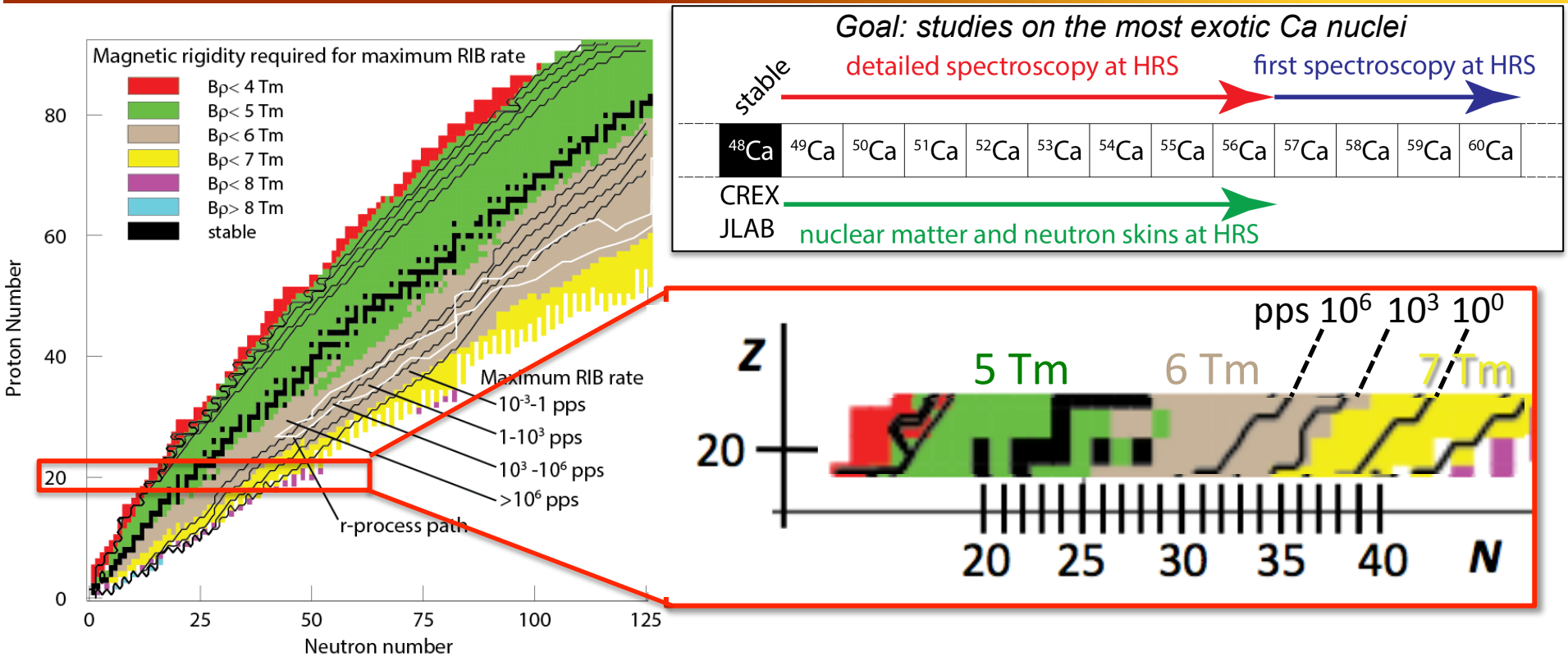
FRIB Beams have Tremendous Discovery Potential





- FRIB beams will be world leading in variety & intensities
- Tremendous discovery potential: 80% coverage Z < 82
- Many examples of fascinating science at FRIB ...
  that **require new equipment**
- Science drives the need for, & requirements of, the devices

Structure of Exotic Calcium Isotopes

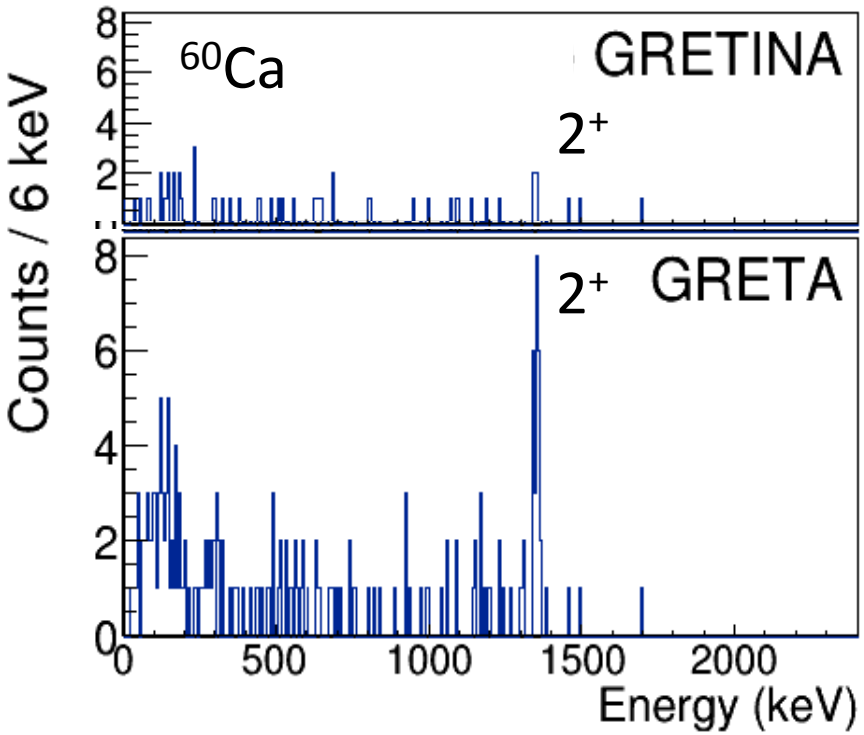


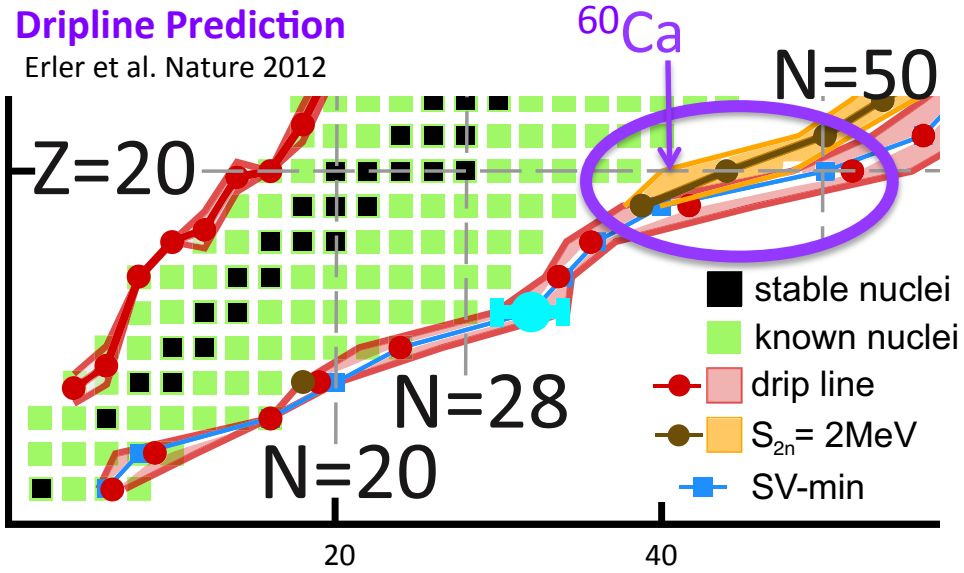
- Structure models can be constrained by **more detailed spectroscopy** of exotic Ca isotopes to *A* = 56, and **first spectroscopy** out to A = 60
- Probing **neutron skins** to A ~ 56 will help understand nuclear matter properties
- To produce fast beams of these exotic Ca isotopes of sufficient intensity, need energies corresponding to $B\rho$ of 5 – 7 Tm → **TOO RIGID FOR CURRENT DEVICES**

High Rigidity Spectrometer HRS can handle

Neutron Drip Line at Calcium ?

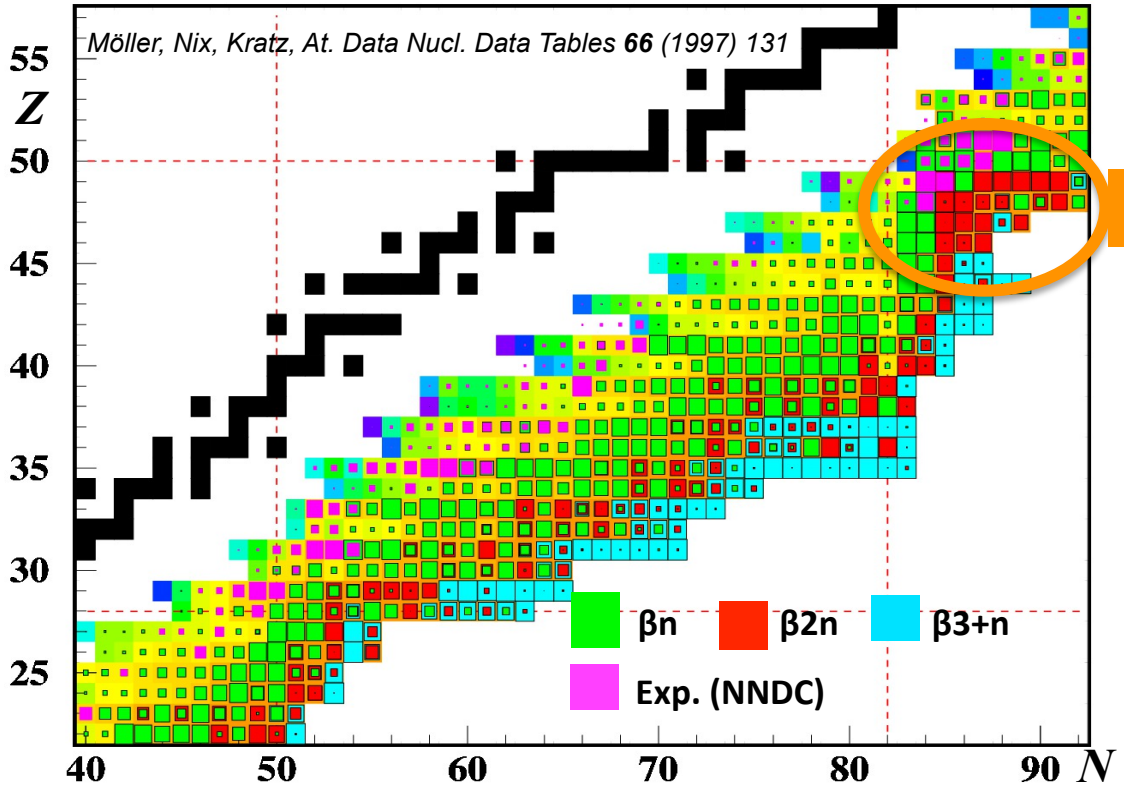
Simulated spectrum of ^{60}Ca populated in one-proton removal from ^{61}Sc





- Where is the **neutron dripline** at *Z* = 20 ? Need to measure structure near ^{60}Ca
- Structures of Ca chain nuclei are test bed for modern nuclear model interactions
- Spectroscopy of ^{60}Ca possible with fast-beam knockouts ^{9}Be(^{61}Sc,^{60}Ca+γ)X
- **Such studies require GRETA w/ much higher γ-ray efficiencies than GRETINA**

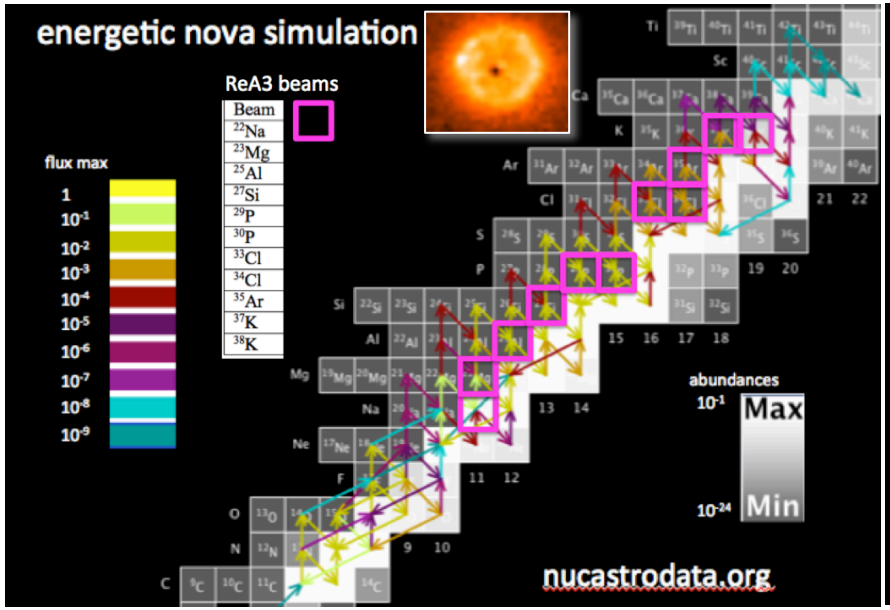
Beta-delayed Neutron spectroscopy on Exotic Nuclei

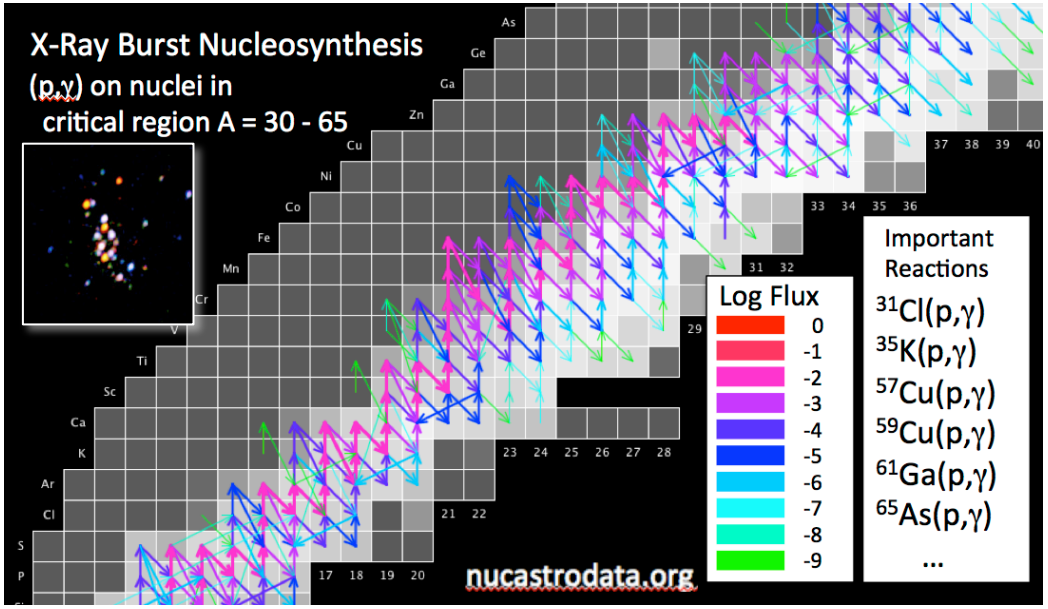


Strong β2n branch predicted

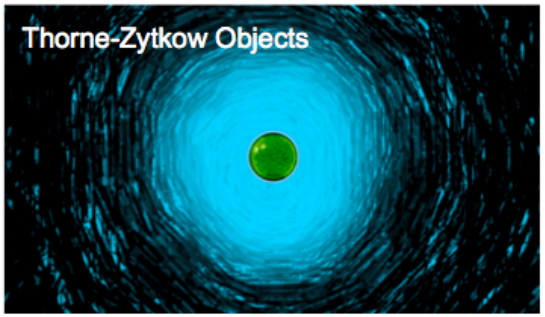
- Is beta-delayed *multi-neutron* emission prevalent near double shell closures (^{78}Ni) ?
- Measurements needed to test models
- Need neutron yields / multiplicities / correlations / γ coincidences
- Also need neutron energies / angles → neutron spectroscopy
- Resulting information impacts r-process simulations
- **Requires optimized combination of implantation detector, high-granulation low threshold neutron array, high efficiency γ array … DECAY STATION**

Thermonuclear Burning on Exotic Nuclei

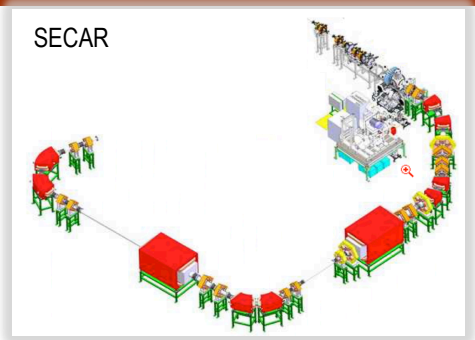


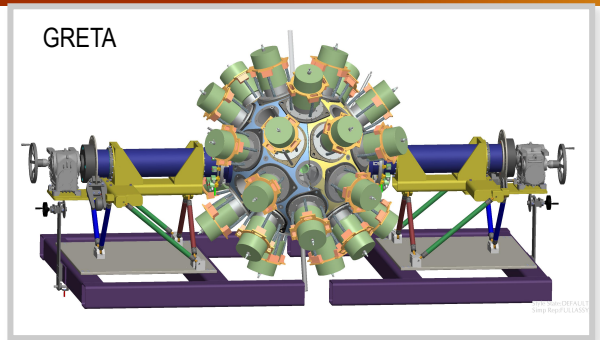


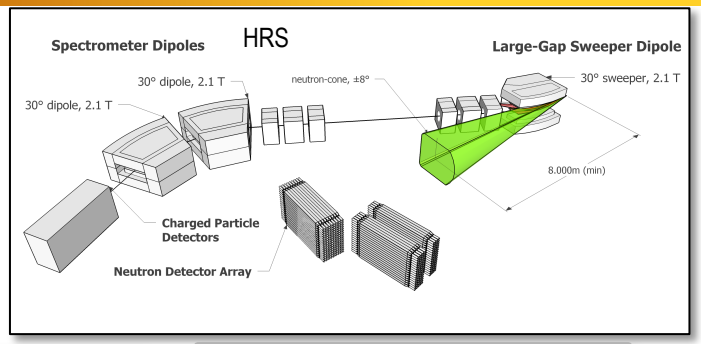
- Many key capture reactions in **nova explosions** have never been measured & have large uncertainties
- Capture reactions on p-rich nuclei from mass 30 – 65 in **X-ray Bursts** shown crucial for energy generation and nuclear flow – but have never been measured
- Burning on exotic nuclei also occurs in **Supernovae**, **Hypernovae**, **Supermassive Stars**, **Thorne-Zytkow Objects** … but **specialized detection system needed – SECAR**

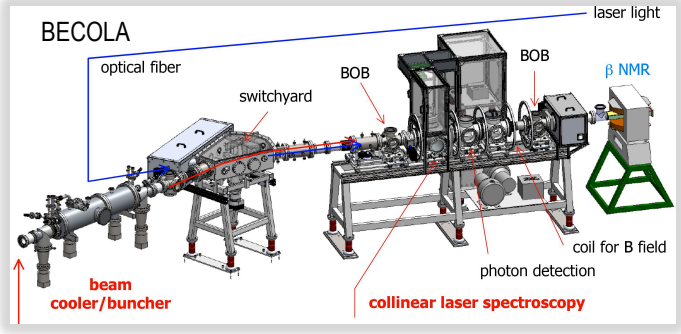


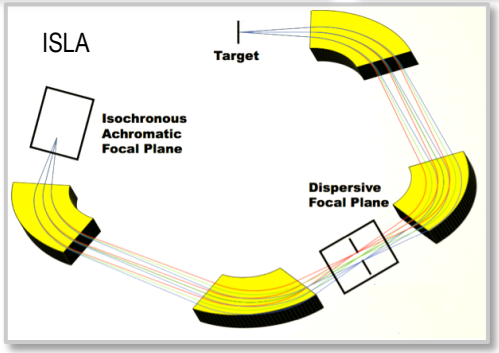
World-Class Equipment Needed for FRIB Science

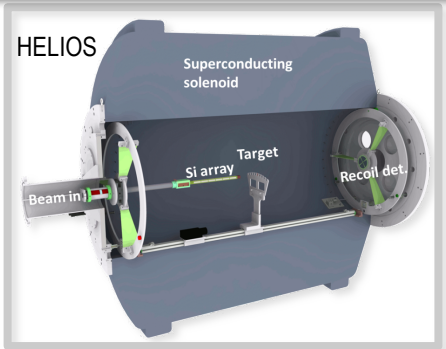








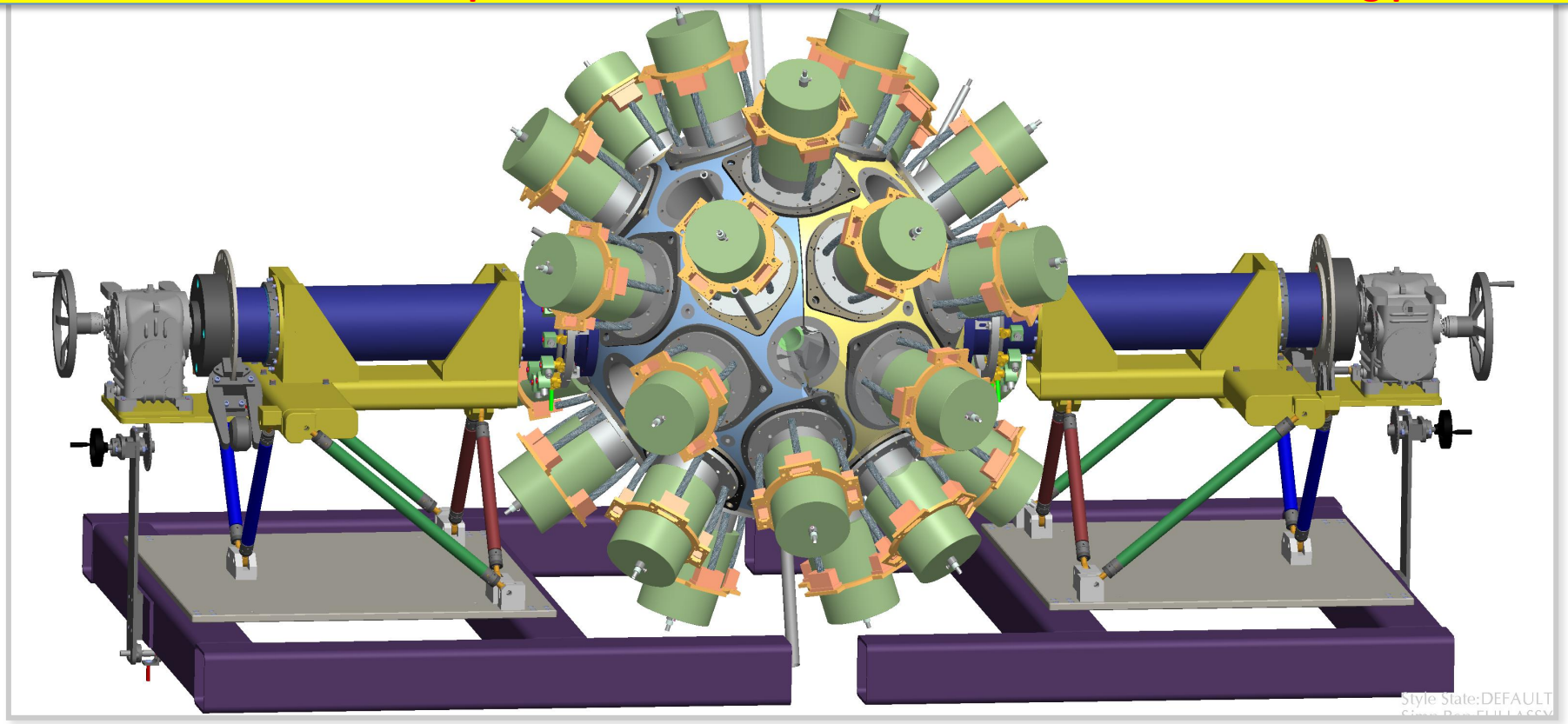




- **Working Groups** of the **FRIB Users Organization** have identified major experimental instruments needed for their measurements
- Instruments **enable important new measurements** in *all* FRIB science areas, beam energies and species, experimental halls …
- Demand driven by FRIB Users, strong contribution by researchers at **many Universities** and **National Labs** in these projects
- Estimated cost ~ **135M$**

GRETA for ReA3 / ReA12 / Fast beams

GRETA Science includes exploration of structure of new nuclei w/max resolving power



- Gamma Ray Energy Tracking Array **GRETA**
- γ-ray tracking array with unmatched position resolution for precise Doppler reconstruction of γ-rays emitted in flight
- High efficiency allows furthest scientific reach
- 4π coverage for angular distribution and polarization measurements

GRETA for ReA3 / ReA12 / Fast beams

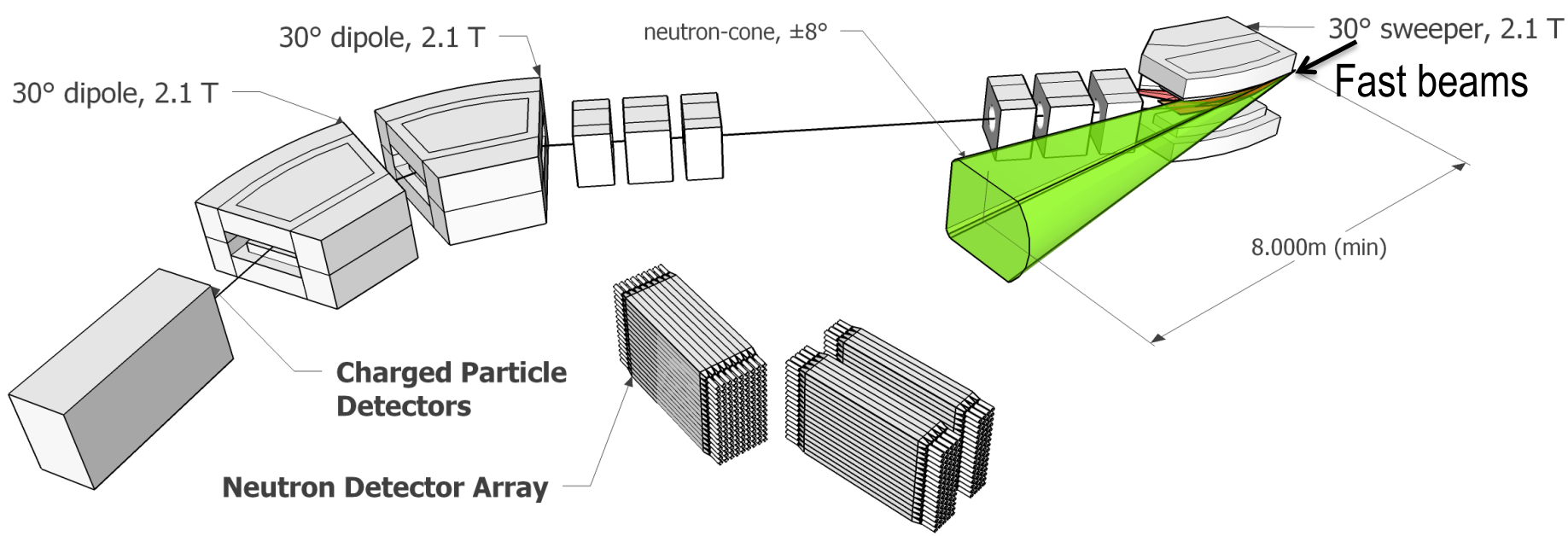
Science drivers (thrusts) from NRC RISAC — Addressed by GRETA ✓

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
Overarching questions are answered by rare isotope research 2007			
17 Benchmarks from NSAC RIB TF measure capability to perform rare-isotope research			
1. Shell structure ✓ 2. Superheavies ✓ 3. Skins ✓ 4. Pairing ✓ 5. Symmetries ✓ 13. Limits of stability ✓ 14. Weakly bound nuclei ✓ 15. Mass surface	6. Equation of State (EOS) ✓ 7. r-Process ✓ 8. $^{15}O(\alpha,\gamma)$ 9. ^{59}Fe s-process 15. Mass surface ✓ 16. rp-Process ✓ 17. Weak interactions ✓	12. Atomic electric dipole moment ✓ 15. Mass surface 17. Weak interactions ✓	10. Medical 11. Stewardship ✓

- **GRETA** enables science in all 4 areas from the NRC RISAC Report
- Concept proven with highly successful GRETINA campaigns at NSCL & ANL
- Community endorsed (NSAC 2002, 2007 LRPs, FRIB SAC)

HRS for Fast beams

HRS Science includes evolution of shell structure, single particle structure of rare isotopes…

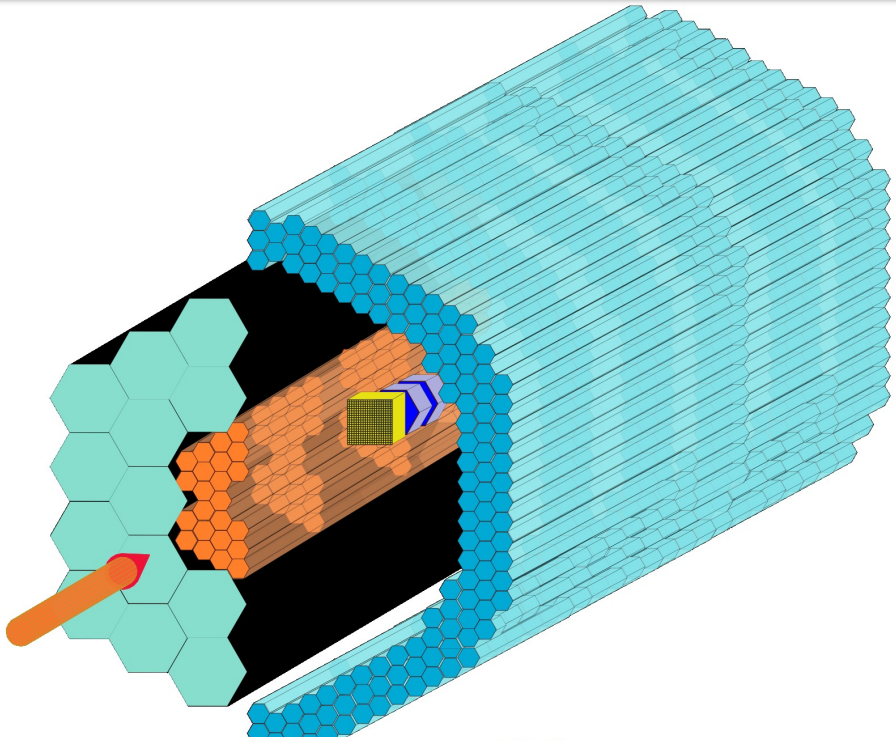


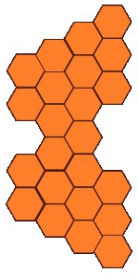
High Rigidity Spectrometer Pre-conceptual design

- Primary spectrometer for fast beams; used along with GRETA, MoNA-LISA …
- Max rigidity ~8 Tm … existing spectrograph and sweeper are ≤ 4 Tm
- Scientific program covers ~ **HALF** of NSAC RIB Taskforce benchmarks
- Whitepaper written with contributions from 19 Universities and Labs

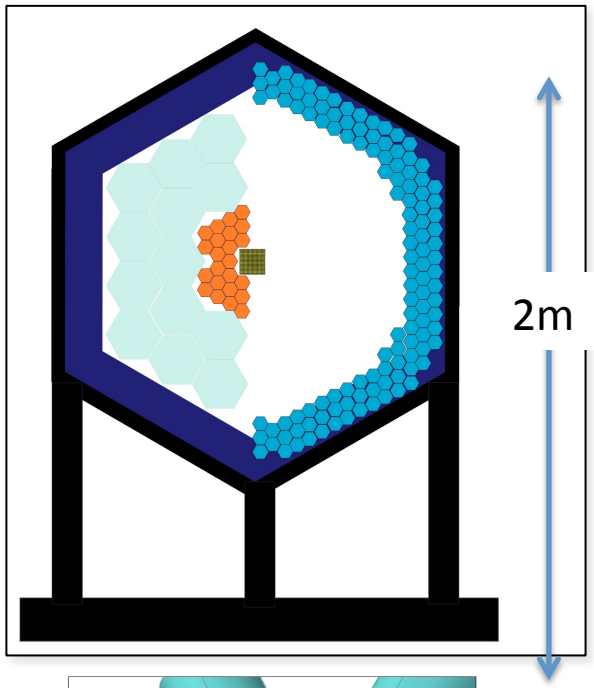
Decay Station for All Experimental Halls

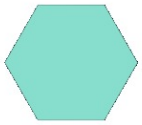
DECAY STATION Science includes structure of most exotic isotopes, site of r-process …



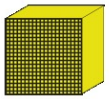


Gammas
+neutrons
(LaBr3,CLYC)

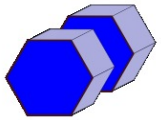




GAMMAS
NaI

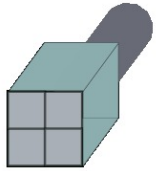


Fast
segmented
implantation

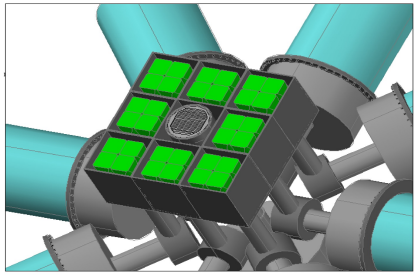


GeDSSD

netruons
TOF



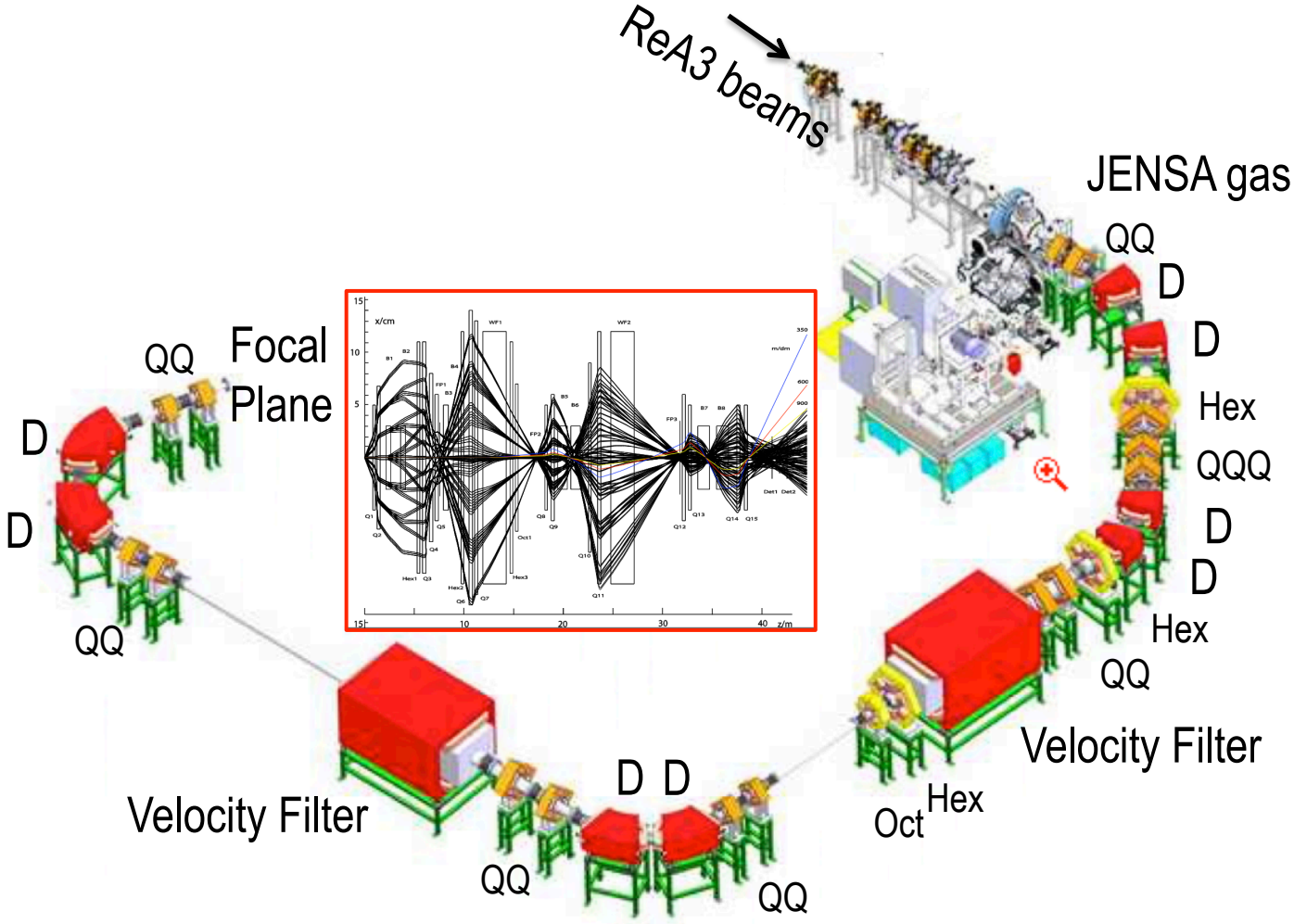
HPGe
Clover



- Combination of implantation (thick Ge DSSD), gamma-ray detectors (HpGe array / $LaBr_3$ / calorimeter), neutrons (VANDLE) & others for decay studies

SECAR for ReA3 beams

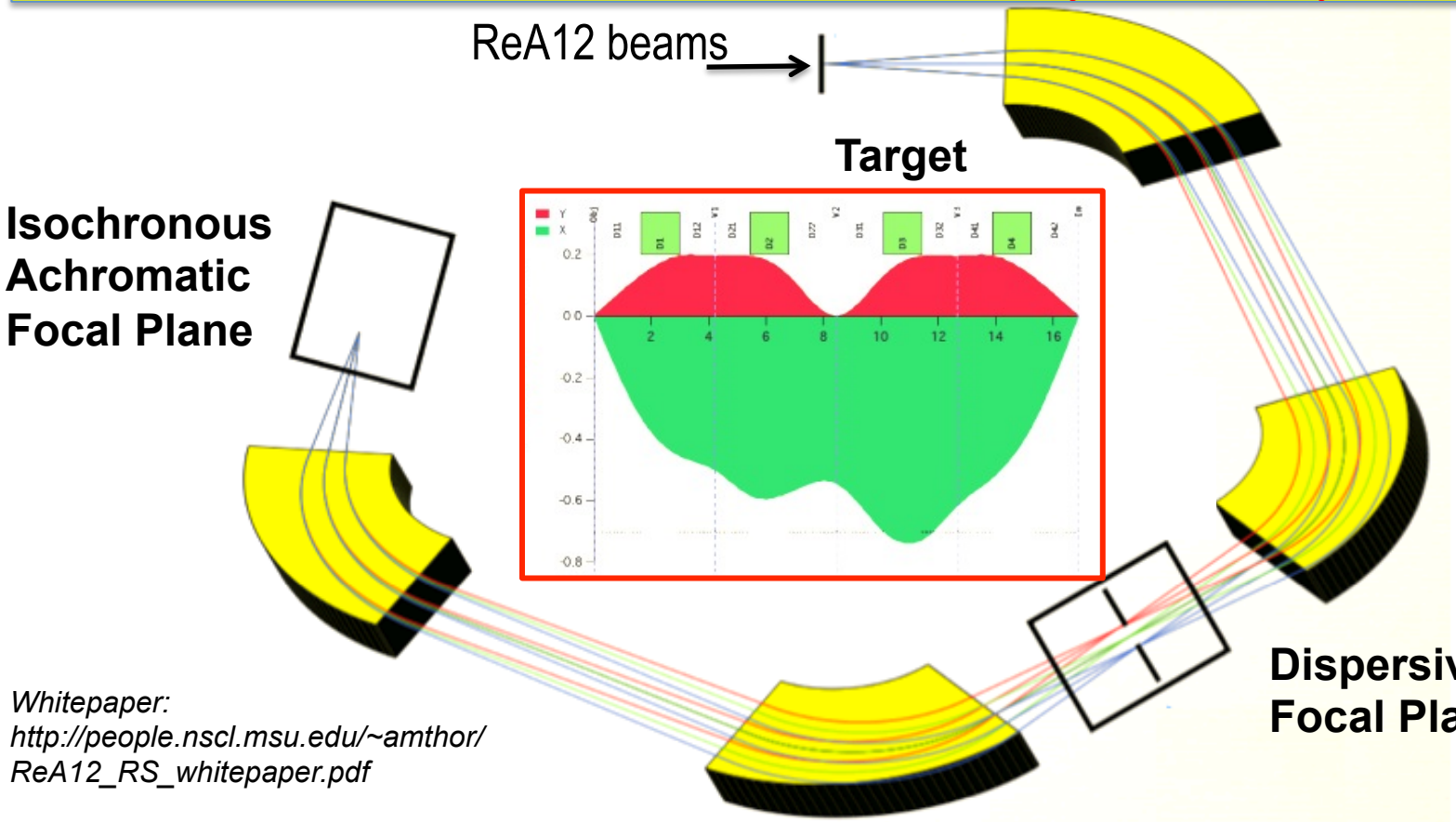
SECAR Science includes direct measurements of reactions that cause novae & X-ray Bursts



- SEparator for astrophysical CApture Reactions SECAR
- Direct inverse kinematics measurements of low-energy (p,γ) and (α,γ) reactions

ISLA for ReA12 beams

ISLA Science includes reactions & structure of rare isotopes to develop nuclear models

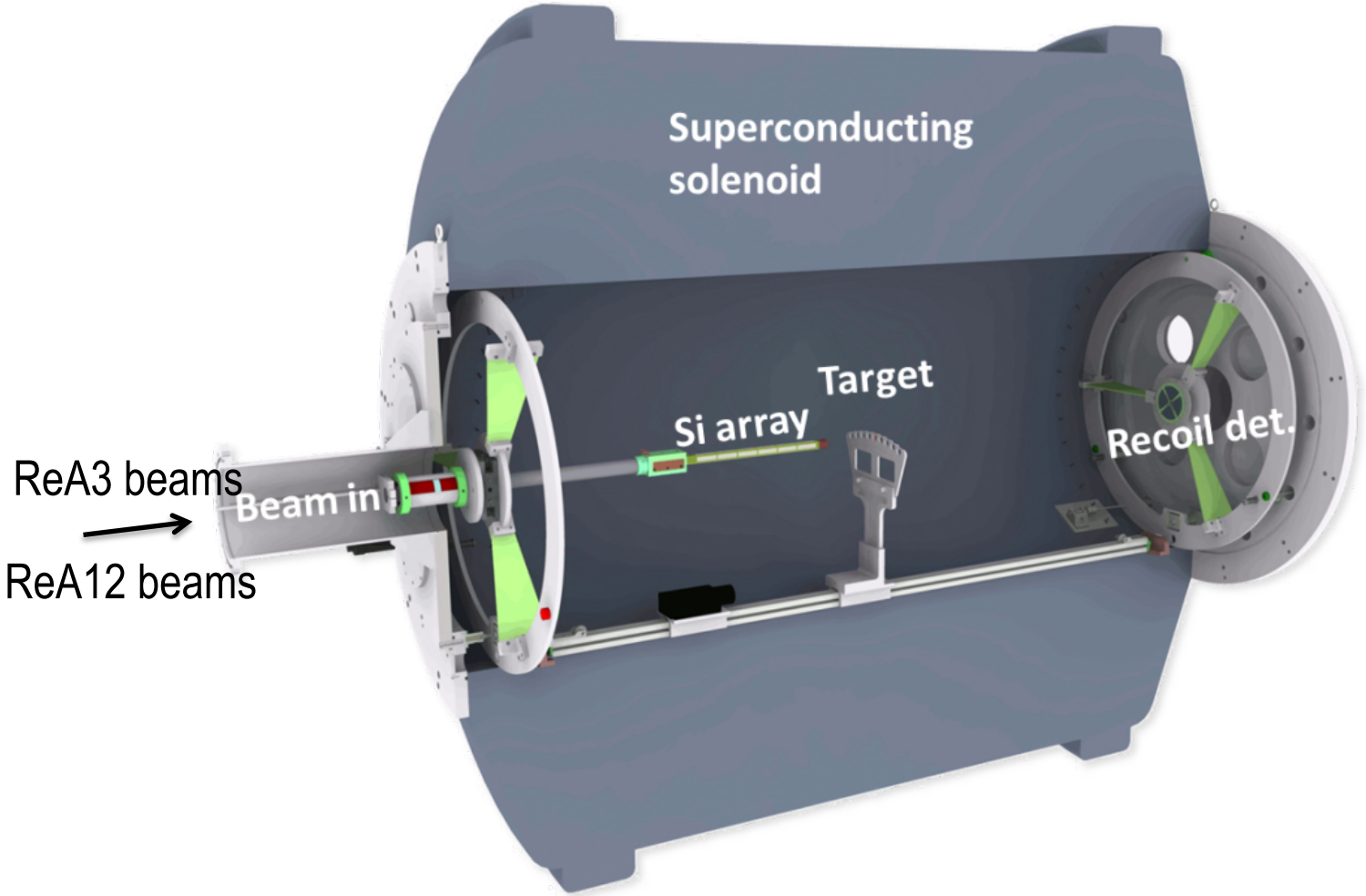


Whitepaper:
http://people.nscl.msu.edu/~amthor/
ReA12_RS_whitepaper.pdf

- Isochronous Spectrometer with Large Acceptance ISLA
- Primary spectrometer for higher-energy reaccelerated beams
- Scientific program covers > half of NSAC RIB TF benchmarks
- Extends FRIB reach through fusion evaporation and multi-nucleon transfer

HELIOS for ReA3 / ReA12 beams

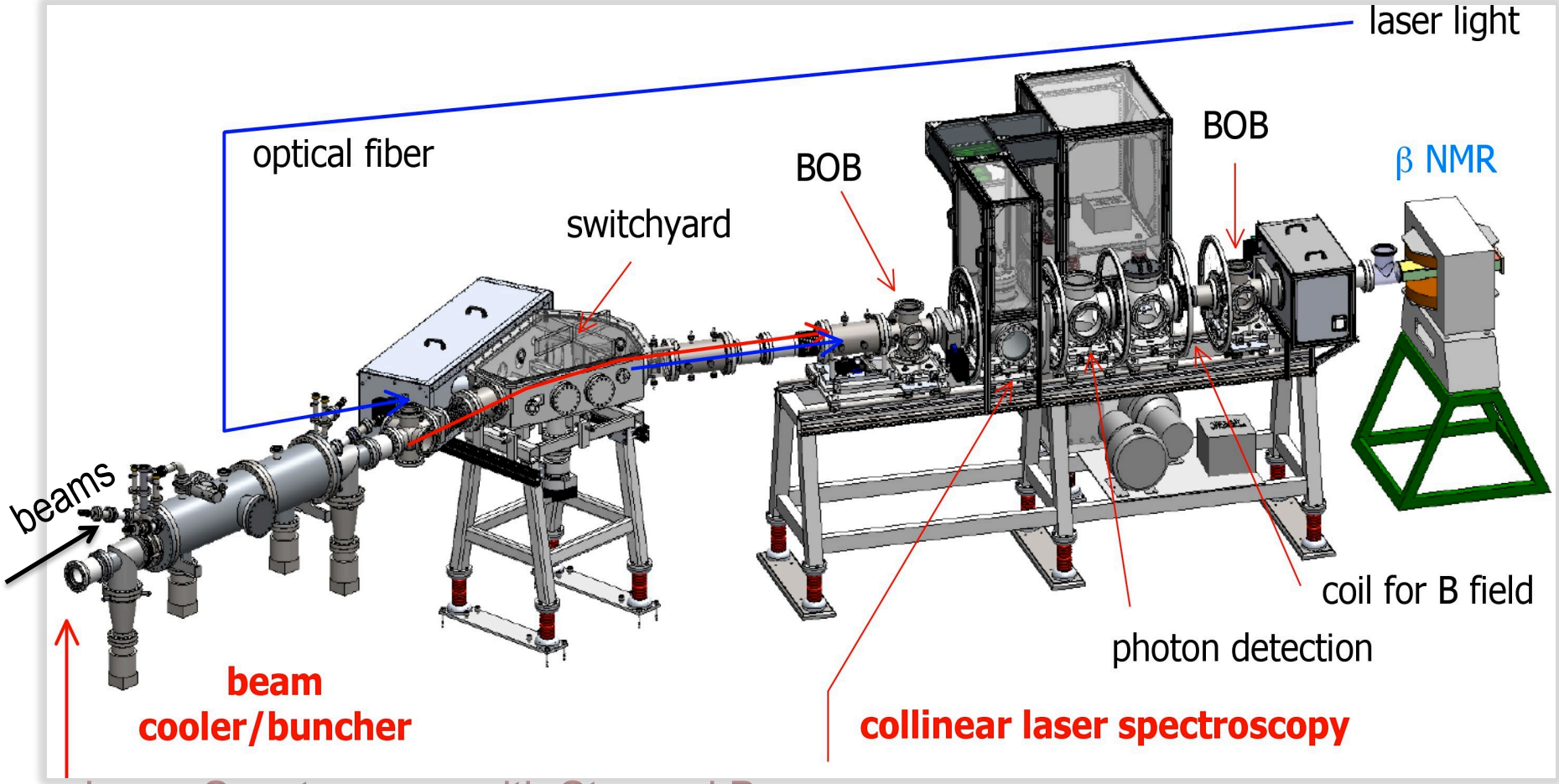
HELIOS Science includes single particle & cluster states in rare isotopes via transfer reactions



- Helical Orbit Spectrometer HELIOS
- Measurement of transfer reactions & others with low- & medium-energy RIBs

BECOLA and CRIS for Stopped Beams

BECOLA Science includes atomic spectroscopy of rare isotopes & finding the driplines

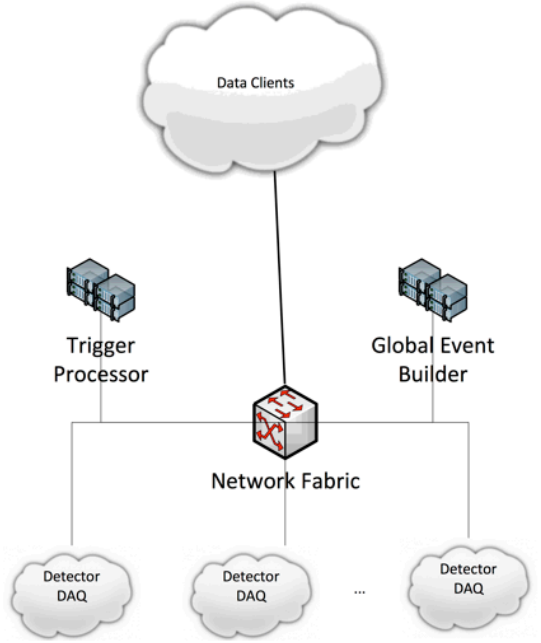


- Laser Spectroscopy with Stopped Beams
- BEam COoling and LAser spectroscopy BECOLA
- Collinear Resonance laser Ionization Spectroscopy CRIS

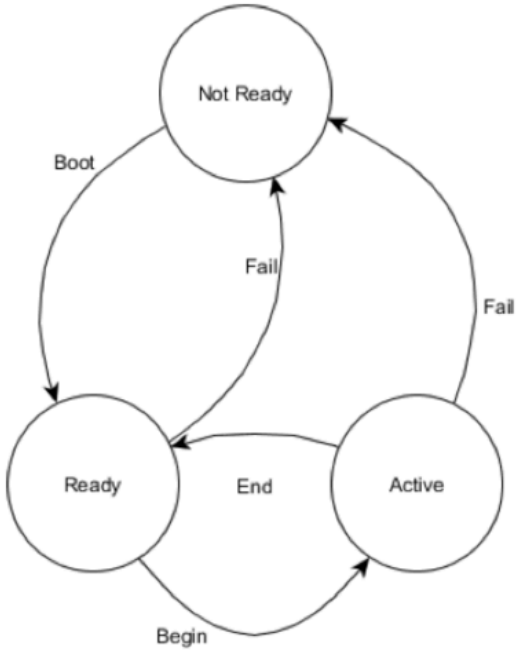
Data Acquisition Systems

Updated DAQ systems needed throughout the facility to enable world-leading science

Network Architecture



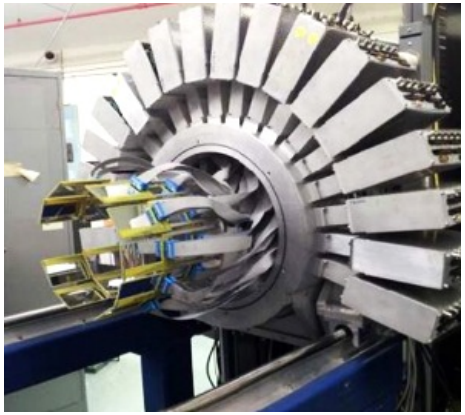
Unified Run Control

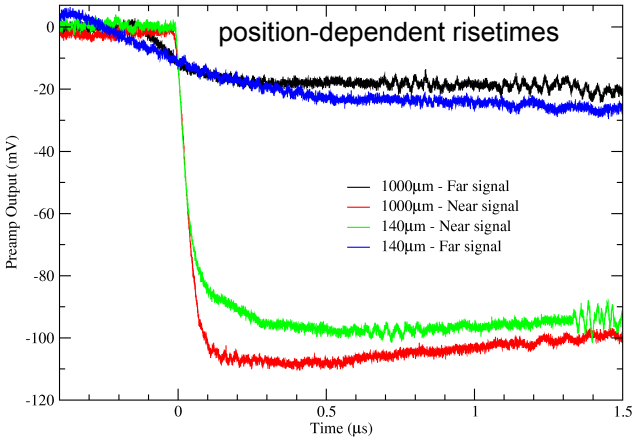


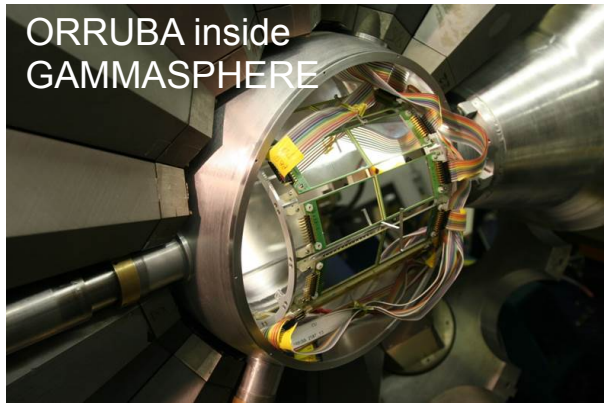
- Advanced features will include:
  - synchronized timestamp generation & distribution system to build events from many detectors
  - build events from fragments contributed by multiple diverse detector systems
  - flexible, easily configured triggering system
  - Unified Run Control
  - quickly reconfigure detectors in experimental setups
  - ability to accommodate detectors with existing, different DAQs

Instrumented Silicon Arrays

Arrays of silicon strip detectors needed for many studies including transfer, scattering, decay



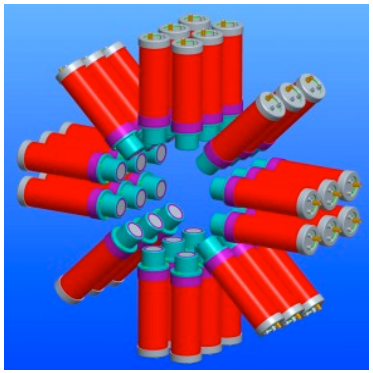




- Silicon arrays are **critical** for measurements of transfer, charge exchange, elastic / inelastic scattering, Coulex, decay, knockout, and other reactions
- **Couple** silicon arrays to many large flagship FRIB devices – GRETA, ISLA, HRS, JENSA, SECAR … – to cover this wide physics scope
- Concept: a **flexible** detector suite that can easily be reconfigured to mate with endstations
- This will **maximize physics** coverage while **minimizing duplication**
- Note: **compact** setups inside 4π gamma arrays may require **position-sensitive detectors**
- A standardized DAQ system (using minimum 250MHz 12-bit **digitizing sampling**) has many advantages – extract the most physics from **pulse shapes**, instrumenting **position-sensitive detectors** in compact setups …

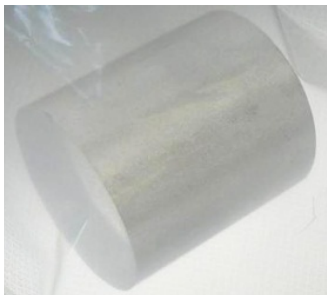
Scintillator Detectors

Advanced scintillators can enable high precision γ-ray and neutron spectroscopy

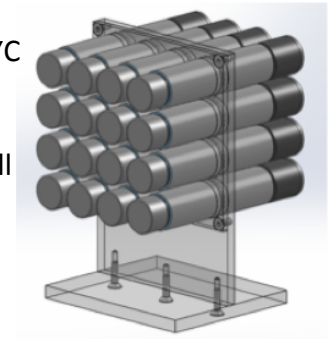


Proposed fast-timing array of LaBr3:Ce crystals for GSI by the DESPEC Collaboration

$LaBr_3$:Ce



16-element CLYC array with enriched 7Li at UMass Lowell



CLYC

Principal Applications (materials on short list, present and emerging)

- γ-ray spectroscopy – fast timing with good energy resolution ($LaBr_3$, $CeBr_3$)
- Total absorption γ-ray spectrometry ($LaBr_3$, $CeBr_3$)
- Dual gamma and fast-neutron spectroscopy (CLYC)

Scenarios for scintillator arrays

- 4π array at target position, possible geodesic geometry ($LaBr_3$ and/or CLYC)
- Focal-plane/decay-station array (possible cubic geometry coupled with Si array)

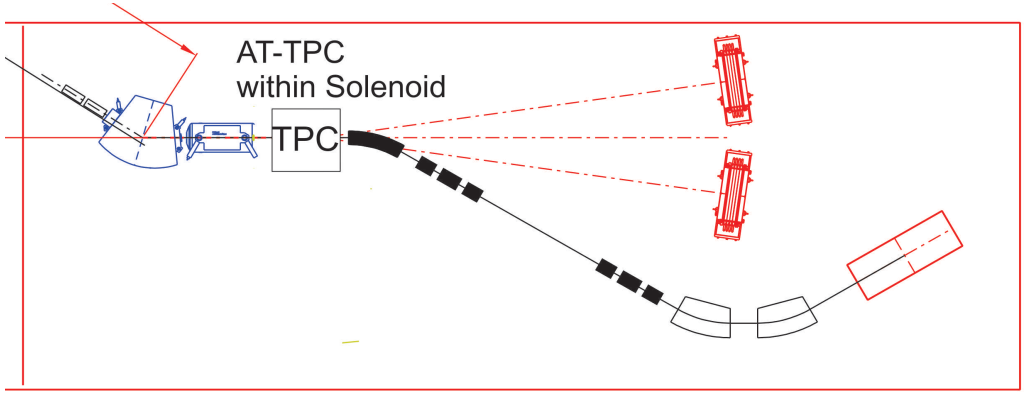
Status

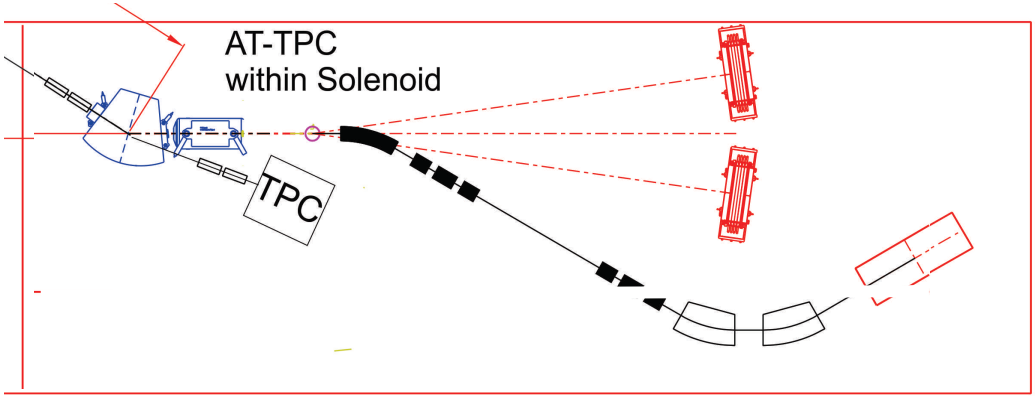
- Lead time for construction significantly shorter than other auxiliary systems
- Late decision allows maturing of emerging technologies like CLYC & $CeBr_3$
- Presently evaluating detector capabilities to physics aspirations
- In-depth design studies to follow consensus on critical capabilities required

P. Chowdhury, F. Kondev, W. Reviol, V. Werner

HRTPC-AT

Constraints on symmetry energy with fast beams facilitated with a TPC

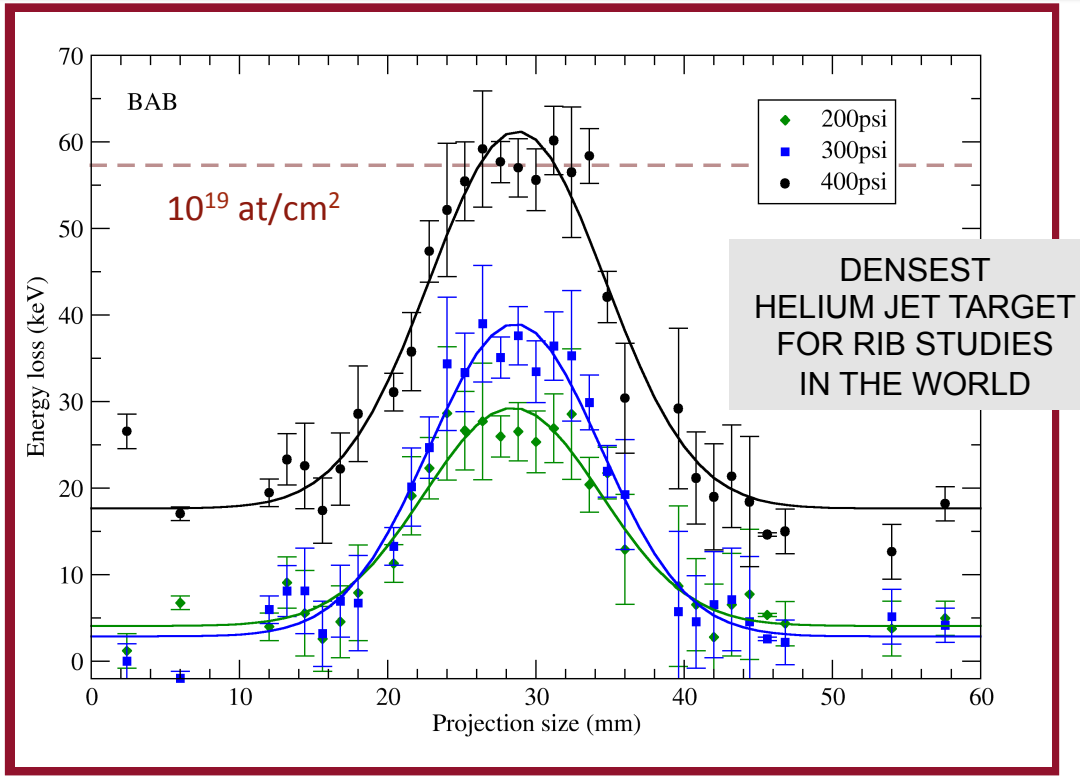




- Place significant constraints on density and momentum dependence of symmetry energy via coincidence measurements of charged particles in a TPC with neutrons and charged particles in HRS spectrometer
- Two operational modes – within the HRS and as a standalone system

Gas Jet Target Systems

Hydrogen- and Helium-induced reaction studies require a gas jet target



DENSEST HELIUM JET TARGET FOR RIB STUDIES IN THE WORLD

- Highly localized, dense, pure target of light gases w/ variable density ~10^{18}-10^{19} atoms/cm^2
- ^{4}He operations proven; H_2,D_2 operations soon; prepping for ^{3}He operations
- Large central chamber for charged particle arrays (SuperORRUBA, SIDAR, others); NaI and soon BGO detectors available for coincident gamma detection
- One system exists in ReA3 hall, a second recommended for ReA6/ReA12 hall
- Built / operated by JENSA Collaboration including ORNL, CSM, UTK, NSCL/MSU, LSU, ND

World-Class Equipment Needed for FRIB Science

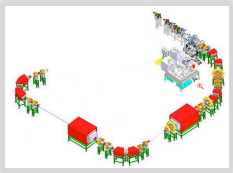
Device	Science Focus
GRETA	exploration of the structure of new nuclei with max resolving power & acceptance
HRS	evolution of shell structure, single particle structure of rare isotopes
Decay Station	structure of most exotic isotopes, site of the r-process
SECAR	direct measurements of thermonuclear reactions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

New Instruments needed in every FRIB Hall

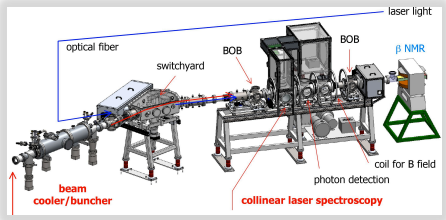
		Experimental Hall		
Device Type	High Energy High Bay	ReA12	ReA3	Stopped Beams
spectrometers	HRS	ISLA	SECAR	
		HELIOS	HELIOS	
detectors	GRETA	GRETA	GRETA	BECOLA/CRIS
	DECAY STATION	DECAY STATION	DECAY STATION	DECAY STATION
	HRTPC-AT			
Other		Gas Target	Gas Target	
Essentials	Scintillators	Scintillators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

New Instruments needed in every FRIB Hall

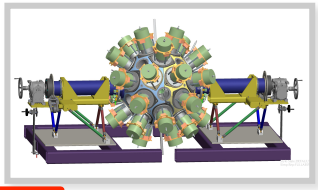
Silicon Array
Scintillators
BECOLA
CRIS
DAQ
SECAR
GAS TARGET



GRETA
Silicon Array
DECAY
DAQ
Scintillators

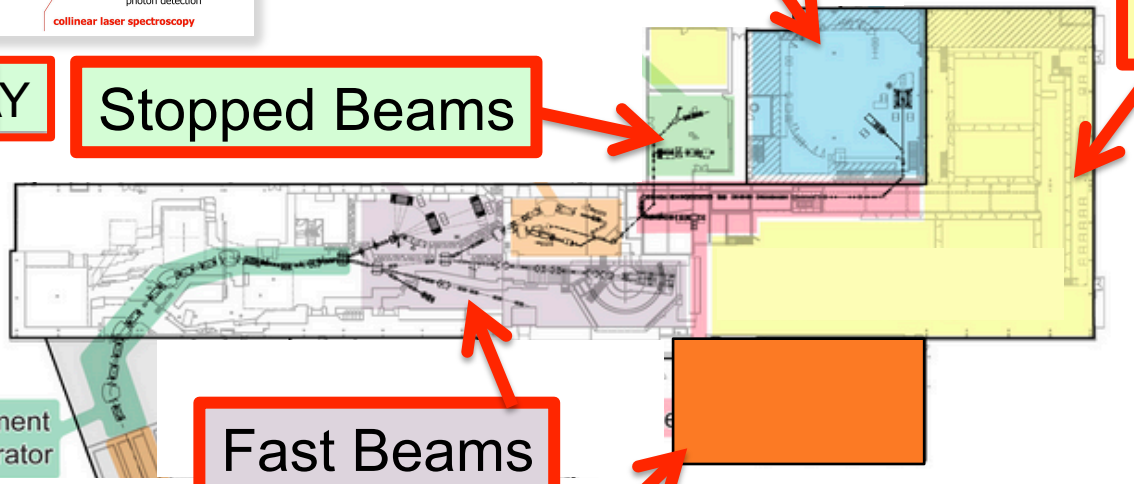


ReA3
HELIOS



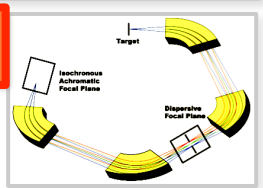
ReA12

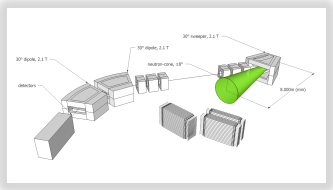
DECAY
Stopped Beams



Fast Beams

GRETA
ISLA
HELIOS
DECAY
GAS TARGET





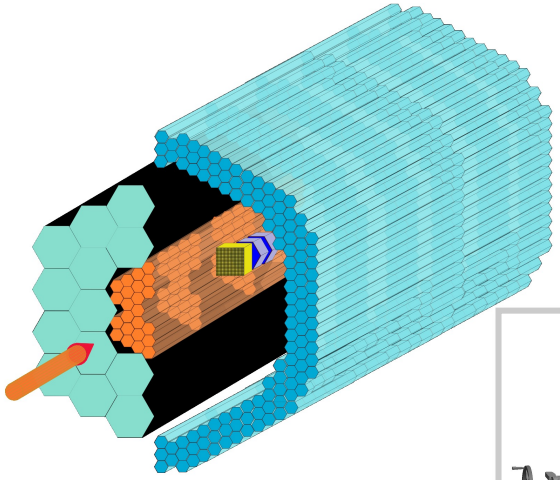
High Energy High Bay
HRS
GRETA
DECAY
HRTPC-AT
Silicon Array
Scintillators
DAQ

Total Cost of Instruments is ~135 M$

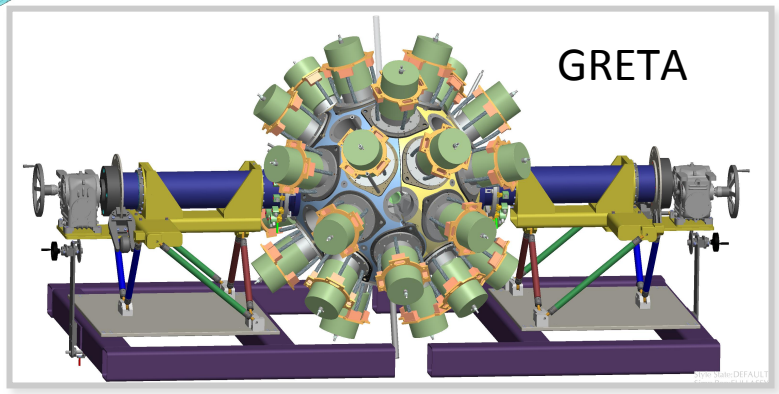
Device	Cost (M$)	Notes	Start	Finish
GRETA	45.0	includes 17% contingency	FY17	FY22
HRS	29.0	includes beam line & 27% contingency	FY17	FY22
Decay Station	16.4			
SECAR	11.7	includes 33% contingency	FY15	FY21
ISLA	10.0	includes over 20% contingency	FY16	FY20
Data Acquisition	8.0		FY17	FY20
HELIOS	4.0		FY16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

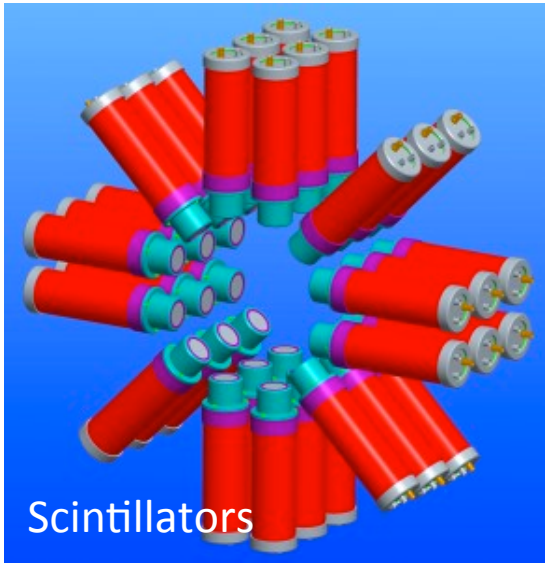
- All costs are preliminary
- Cost estimates were not produced in a uniform manner…
- Start / Finish dates and timelines are those advocated by Working Groups, not those from a funding agency

Synergies to explore



Decay station

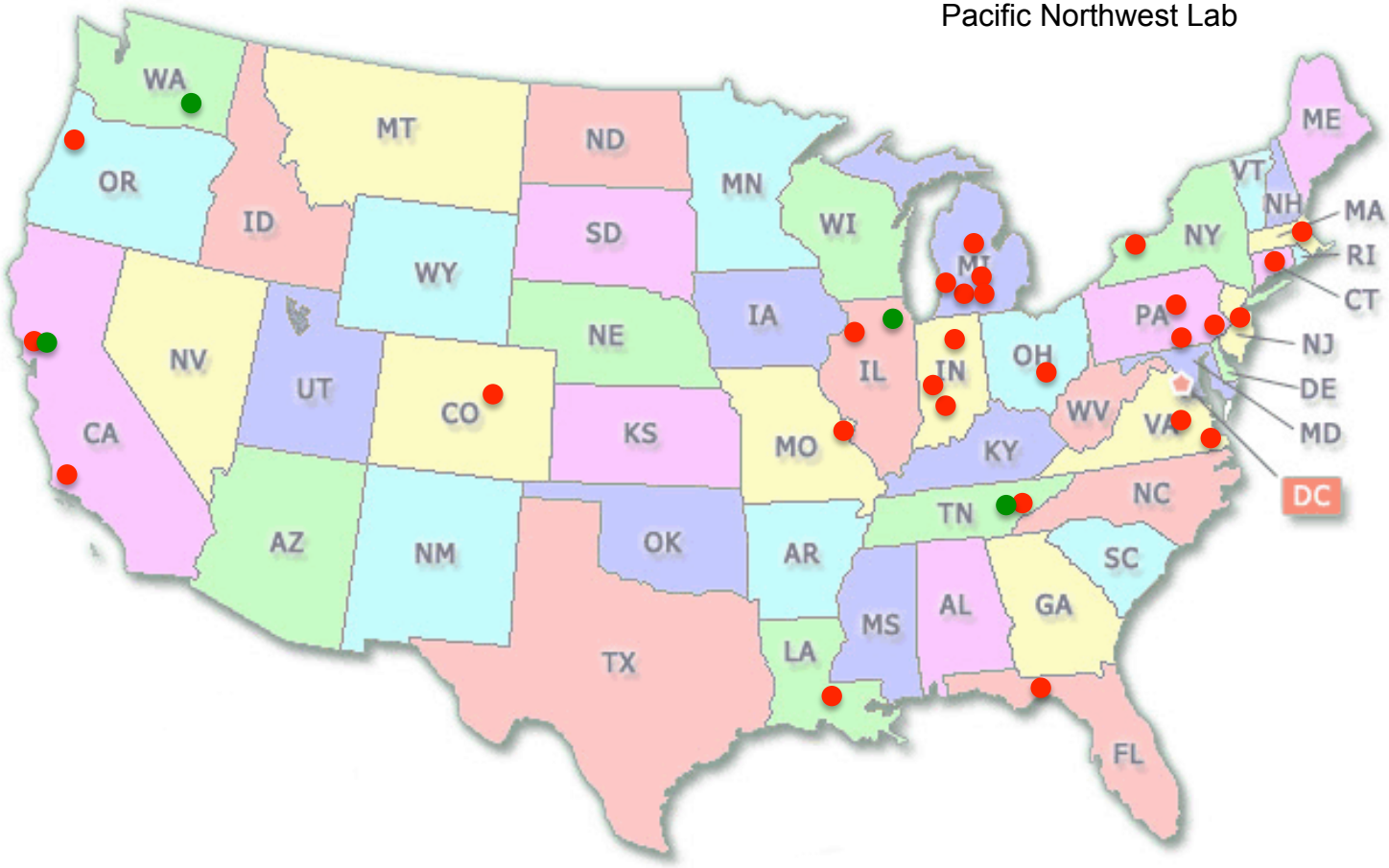




- Commonalities between devices may reduce cost … but would require significant design changes & inter-group coordination
- Examples include:
  - Decay station – GRETA – scintillators
  - DAQ and all major devices [GRETA, HRS, ISLA, SECAR …]
  - Solenoid magnets [HELIOS, ATTPC, HRTPC-AT …]

Projects Driven by FRIB User Community

- Strong involvement by Universities & National Labs



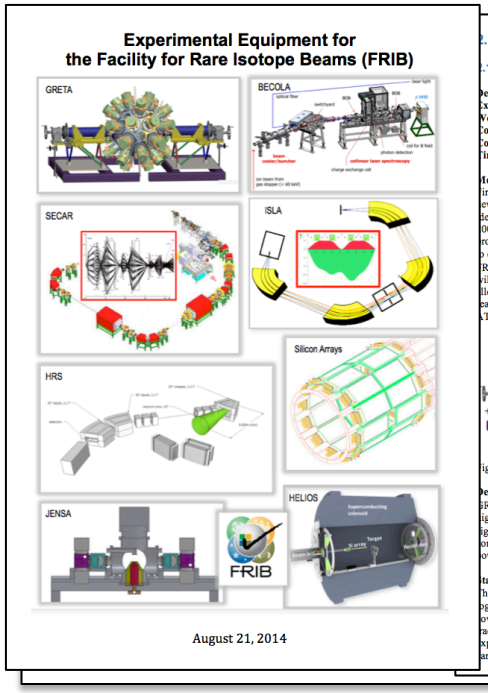
National Labs

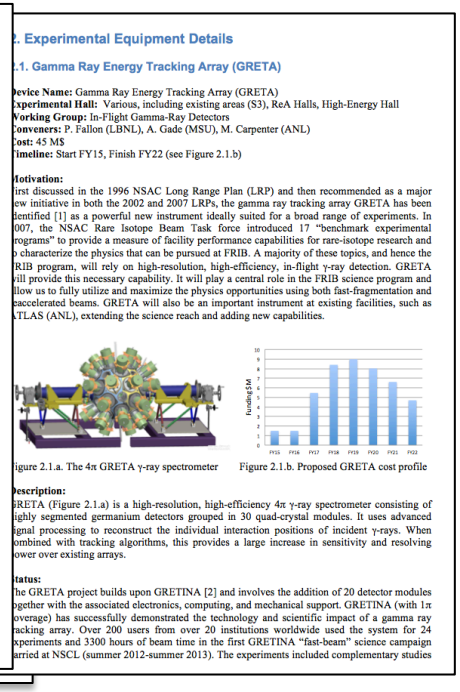
Argonne National Lab
Lawrence Berkeley National Lab
Oak Ridge National Lab
Pacific Northwest Lab

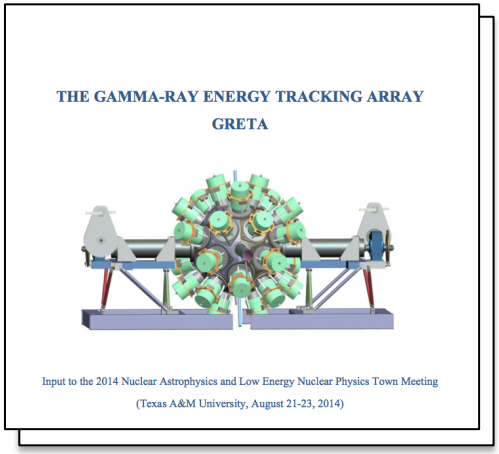
Colleges / Universities

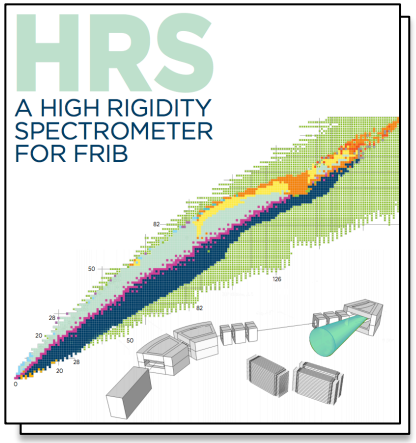
Augustana College
Bucknell University
University California Berkeley
Central Michigan University
Colorado School of Mines
University of Connecticut
Florida State University
Gettysburg College
Hampton University
Hope College
Indiana University
Kalamazoo College
Louisiana State University
Univ. of Massachusetts Lowell
McMaster University
Michigan State University
University of Notre Dame
Ohio University
Oregon State University
University of Richmond
University of Rochester
Rutgers University
University of Tennessee
Ursinus College
Wabash College
Washington Univ. St. Louis
Western Michigan University
Westmont College
also TU Darmstadt

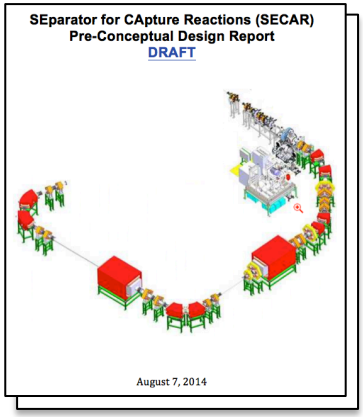
More Information is Available





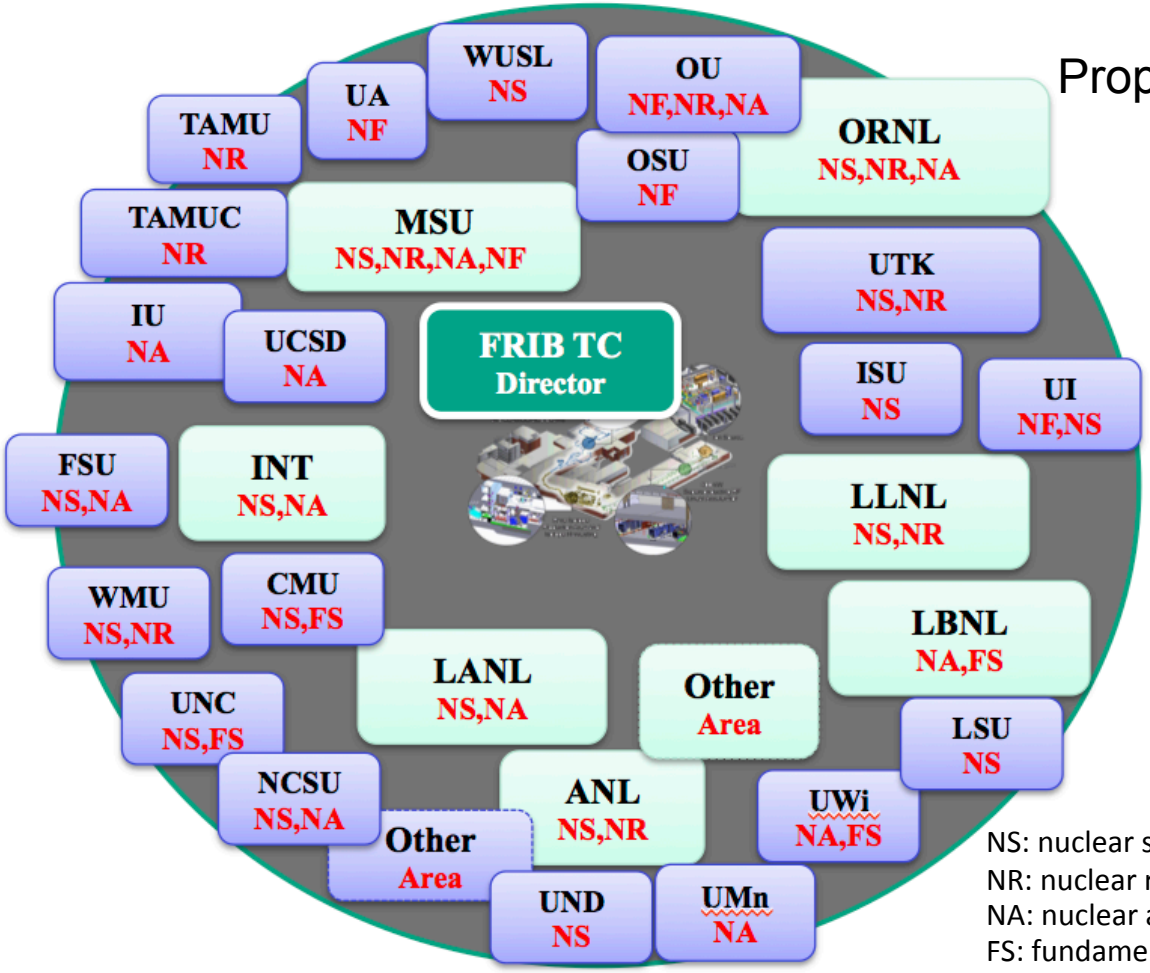






- White papers of GRETA, HRS, SECAR, ISLA …
- FRIB Experimental Equipment White paper
- Town meeting website http://www.lecmeeting.org/whitepapers.html
- Websites: **fribusers.org**, www.physics.fsu.edu/GRETINA.org, www.nscl.msu.edu/~zegers/hrs.html, www.nscl.msu.edu/~amthor/RecSepReA12_2014workshop.html, fribastro.org…

FRIB Theory Users Group



Proposed FRIB Theory Center

Steering Committee:

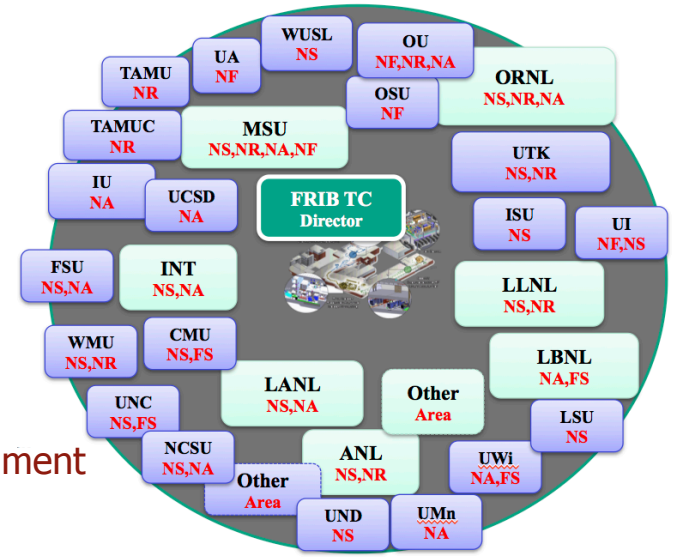
Baha Balantekin (U. Wisconsin)
Joseph Carlson (LANL)
David Dean (ORNL)
George Fuller (U. California San Diego)
Richard Furnstahl (OSU)
Morten Hjorth-Jensen (NSCL, MSU)
Robert Janssens (ANL)
Bao-An Li (U. of Texas Commerce)
Witek Nazarewicz (MSU)
Filomena Nunes (**Chair**) (NSCL, MSU)
Erich Ormand (LLNL)
Sanjay Reddy (INT, U. Washington)
Brad Sherrill (FRIB, MSU)

NS: nuclear structure
NR: nuclear reactions
NA: nuclear astrophysics
FS: fundamental symmetries

- FRIB Theory Users Group is proposing an FRIB Theory Center
- Distributed across many institutions, covering all science fields at FRIB
- White paper drafted as input for NSAC LRP

FRIB Theory Center Vision

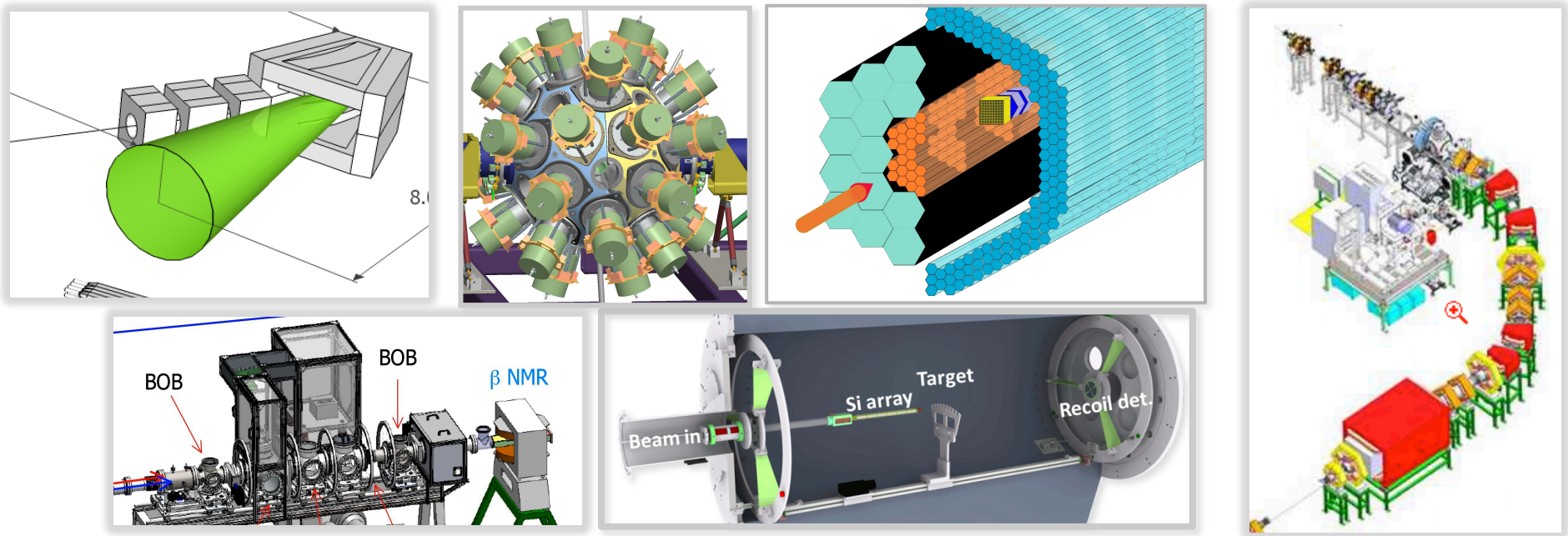
- FRIB Theory Center will
  - connect broadly across fields
  - bring focus to relevant activities
  - identify and nurture the best talent
  - take advantage of high performance computing



- The Center will serve as
  - a home for training in advanced nuclear theory
  - a focal point for stimulating continuous interactions with experiment
  - a home for initiatives such as CUSTIPEN and FUSTIPEN
  - a partner for larger international collaborations

- The Center will:
  - foster interdisciplinary collaborations
  - enable a **prestigious national fellow program** for enhanced visibility of the field and attract the brightest young people
  - emphasize the importance of low-energy nuclear theory
  - enhance the opportunity to create **permanent positions in nuclear theory (bridge positions)**
  - coordinate an educational program in advanced nuclear theory (TALENT)
  - bring multiple opportunities to leverage efforts and funding

Exciting New Science from World-Class Equipment



- **World-class equipment** needed to realize FRIB discovery potential
- new major experimental instruments are planned by **FRIB User Organization Working Groups** at an estimated cost ~ **135M$**
- Instruments **enable important new measurements** in *all* FRIB science areas, beam energies and species, experimental halls …
- Demand driven by FRIB Users, strong contribution by researchers at **many Universities** and **National Labs** in these projects