Nuclear astrophysics at FRIB: Present status and future opportunities

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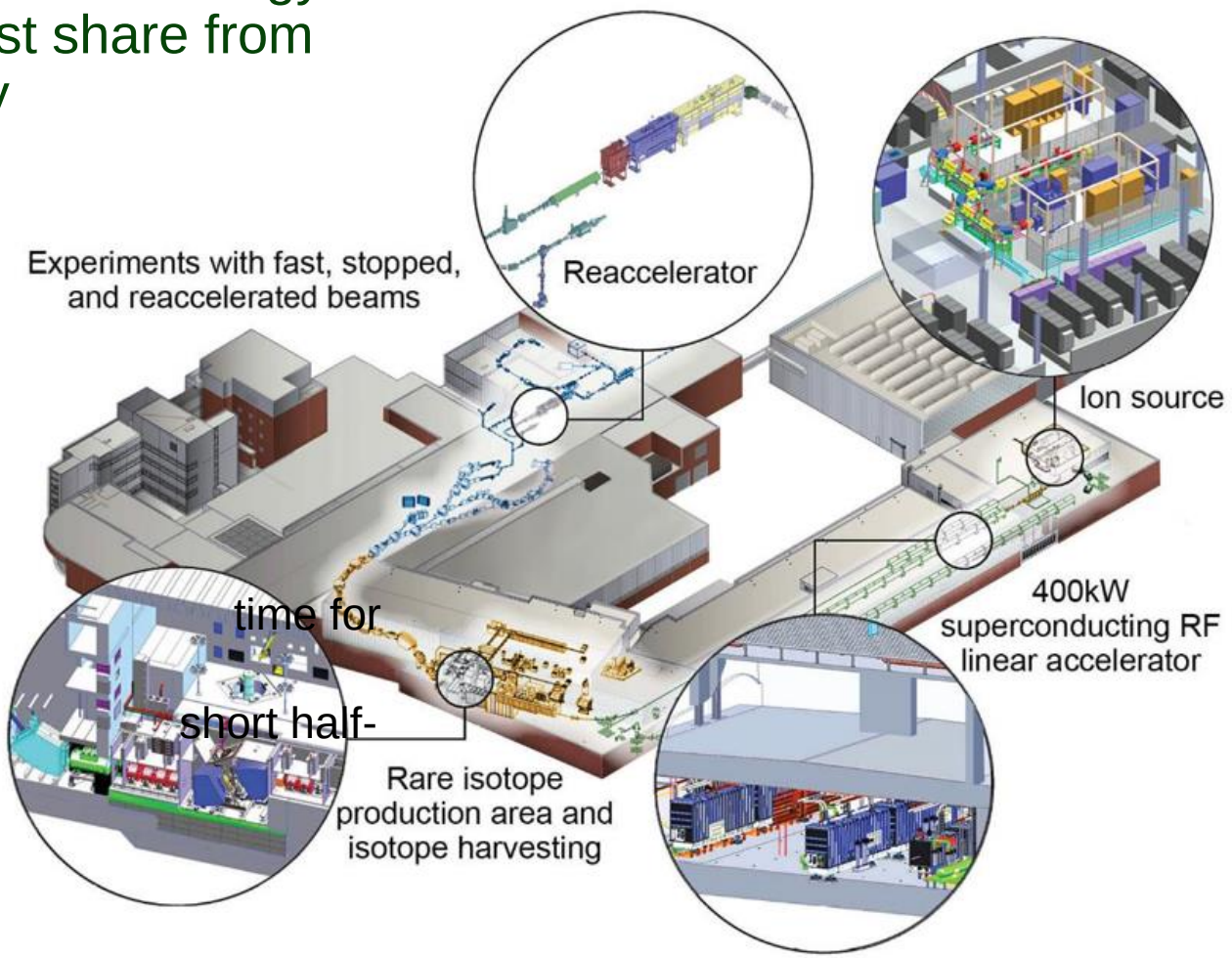
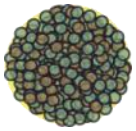
MICHIGAN STATE UNIVERSITY

Facility for Rare Isotope Beams
A Future User Facility at Michigan State University

- Funded by U.S. Department of Energy with contributions and cost share from Michigan State University
- Serving over 1,400 users
- Key feature is 400 kW beam power for all ions (e.g. 5×10^{13} ^{238}U/s)
- Separation of isotopes in-flight provides
  - Rapid development of any isotope
  - All elements and half lives
  - Fast, stopped, and reaccelerated beams

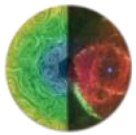


Isotopes from FRIB Will Enable Scientists to Make Discoveries



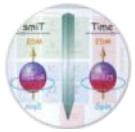
Properties of nuclei

- Develop a predictive model of nuclei and their interactions
- Many-body quantum problem: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.



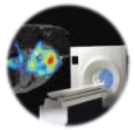
Astrophysical processes

- **Origin and evolution of the elements**
- **Explosive environments: novae, supernovae, X-ray bursts, …**
- **Properties of neutron stars**



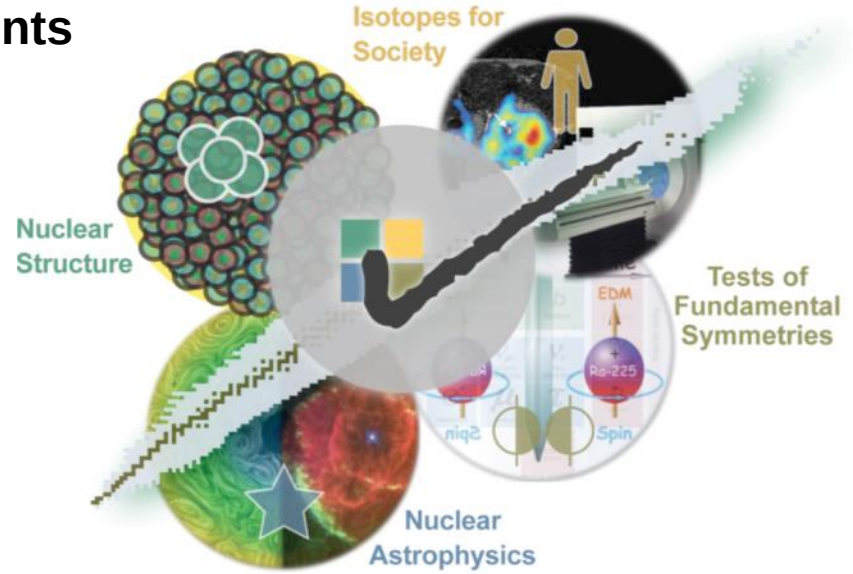
Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei

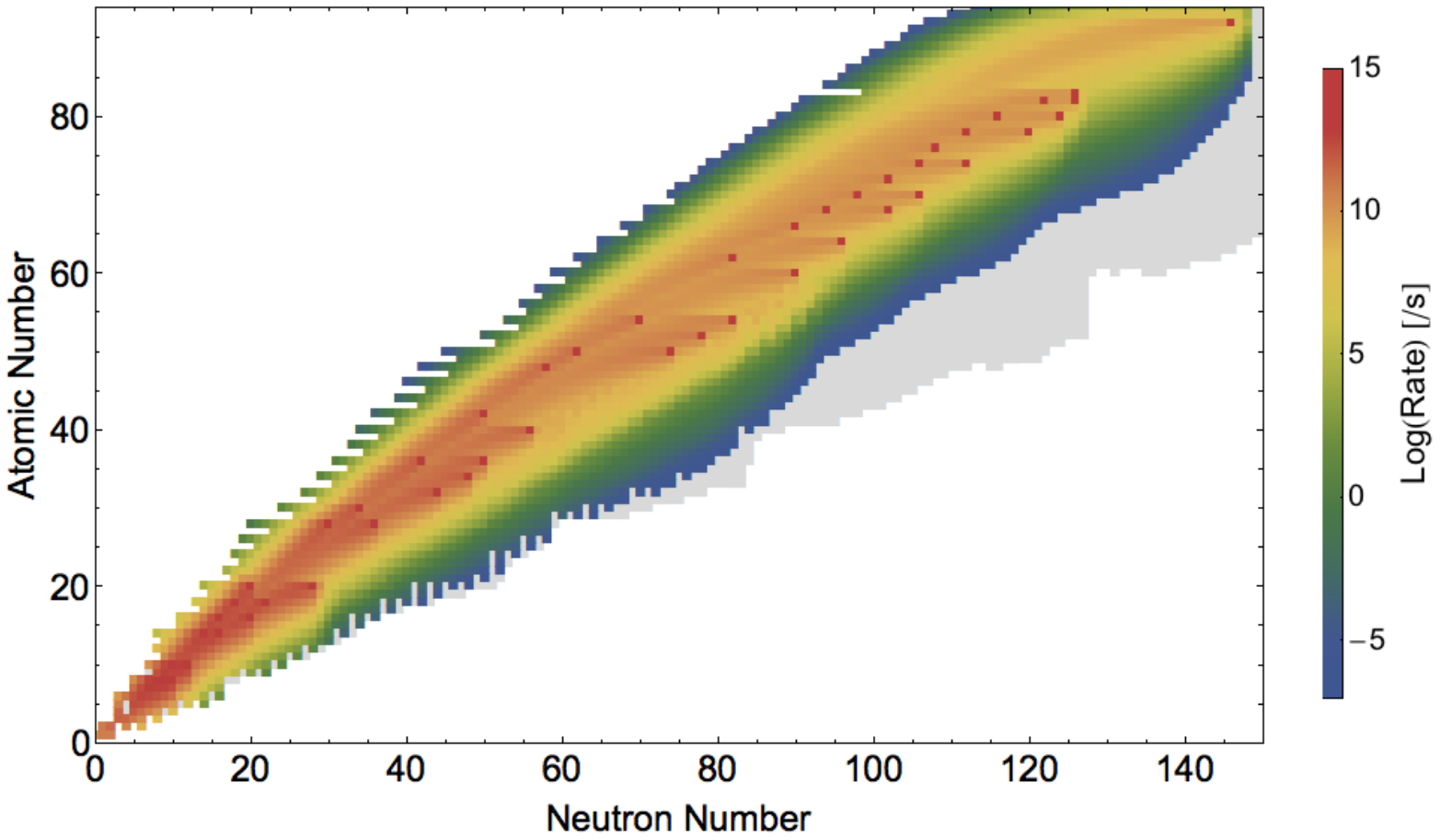


Societal applications and benefits

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



FRIB Fast Rare Isotope Beam Rates
High Beam Rates to Maximize Science Reach



Projected rates are available at
https://groups.nscl.msu.edu/frib/rates/fribrates.html

Rates will ramp up with primary beam power:

2022: 10 kW
2023: 50 kW
2024: 400 kW

Aerial View of Civil Construction Progress

Winter 2015

Groundbreaking for civil construction was held 17 March 2014

Spring 2017

Beneficial occupancy of the FRIB building was achieved 24 March 2017

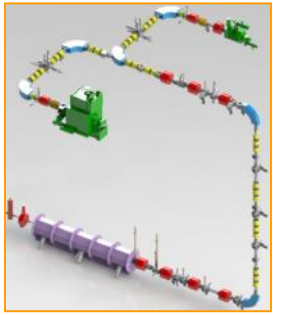
FRIB Accelerator Systems
Superconducting RF Driver Linac

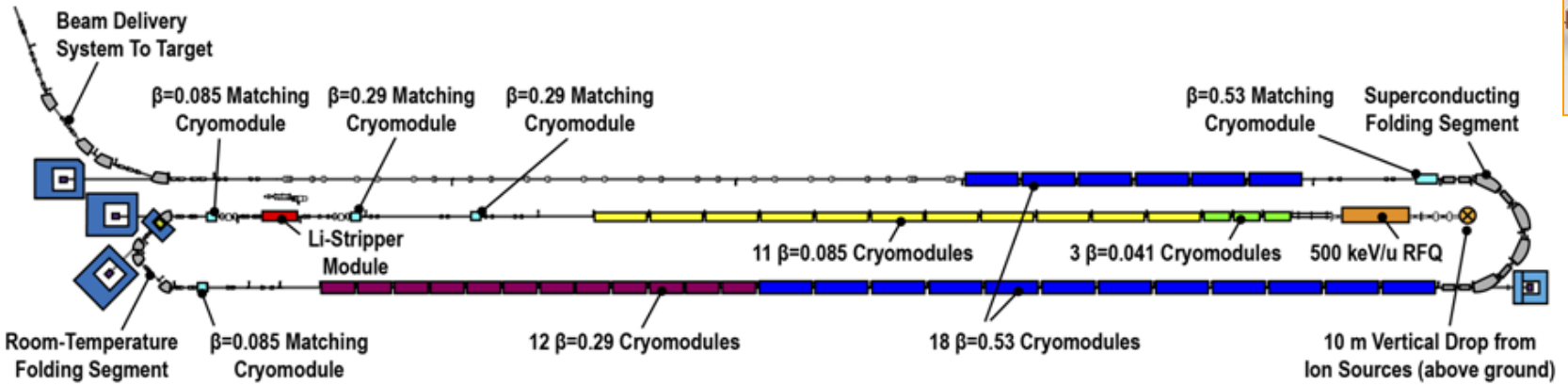
- Accelerate ion species up to ^{238}U with energies of no less than 200 MeV/u
- Provide beam power up to 400kW on production target
- Energy upgrade to 400 MeV/u for ^{238}U by filling vacant slots with 12 SRF cryomodules
- Provisions for ISOL upgrade

Panoramic view of linear accelerator cryomodules

- Technical construction and commissioning interleaved: completed up to first folding segment; rest by 12/2020

ECR ion sources





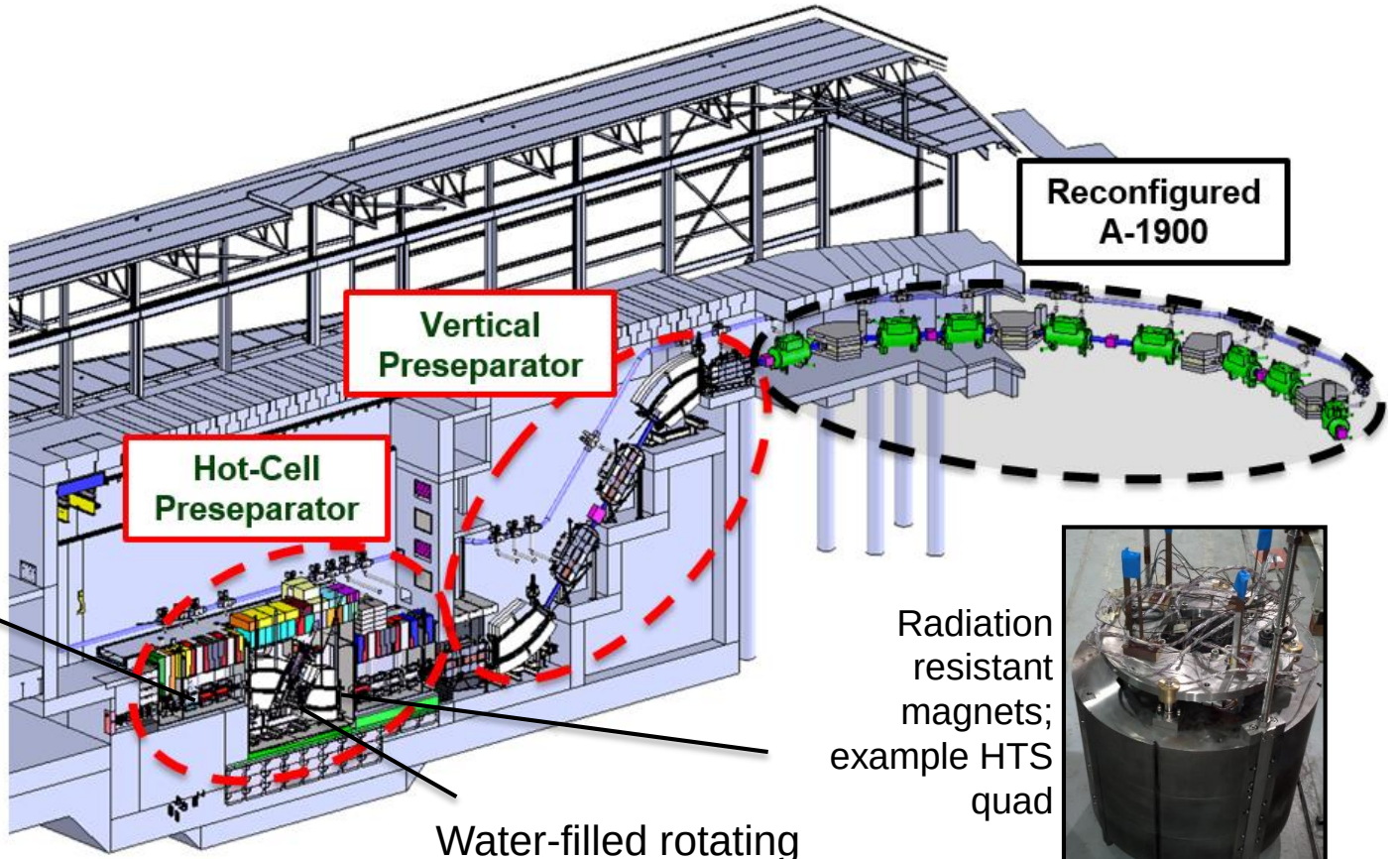
Linear accelerator

FRIB Production Target & Fragment Separator

- Three stage magnetic fragment separator
  - High acceptance, high resolution to maximize science
  - Isotope harvesting incorporated in the design
- Challenges
  - High power densities
  - High radiation

- Under construction: to be completed by 12/2021

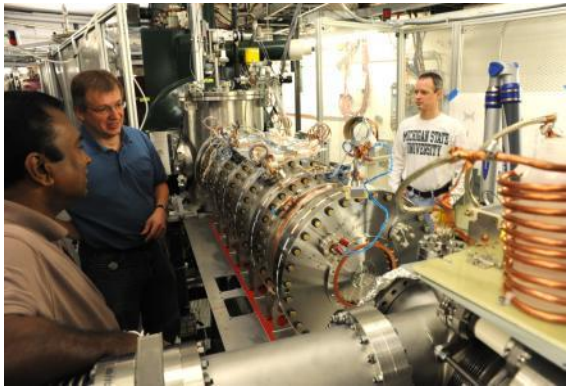
Multi-slice rotating graphite target

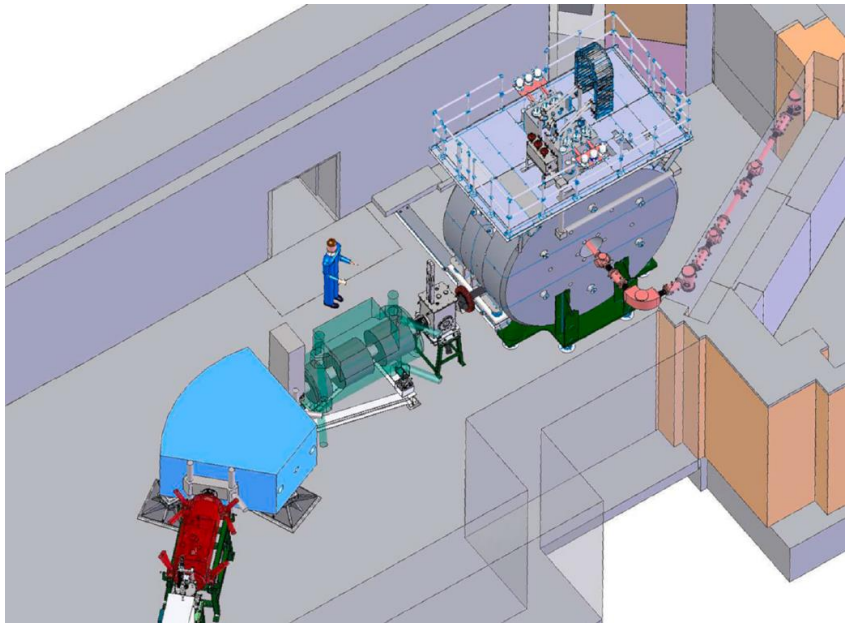


Radiation resistant magnets; example HTS quad

Stopped Beams

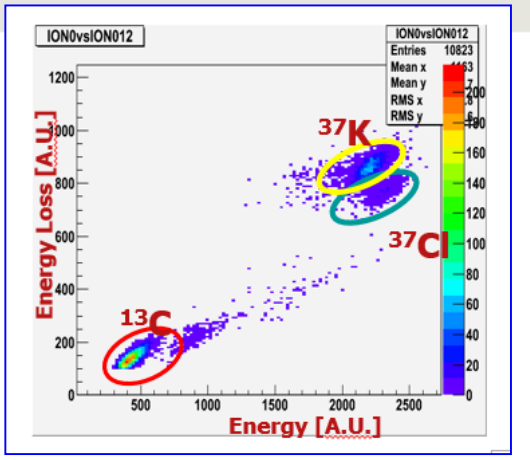
- Multifaceted approach
  - Linear gas stopper (heavier ion beams)
  - Cyclotron gas stopper (lighter ion beams)
  - Solid stopper (certain elements, highest intensity)
- Beam Stopping developments
  - Linear gas catcher (ANL) operational
  - Advanced Cryogenic Gas Stopper operational
  - Cyclotron gas stopper installed and RIB commissioning imminent

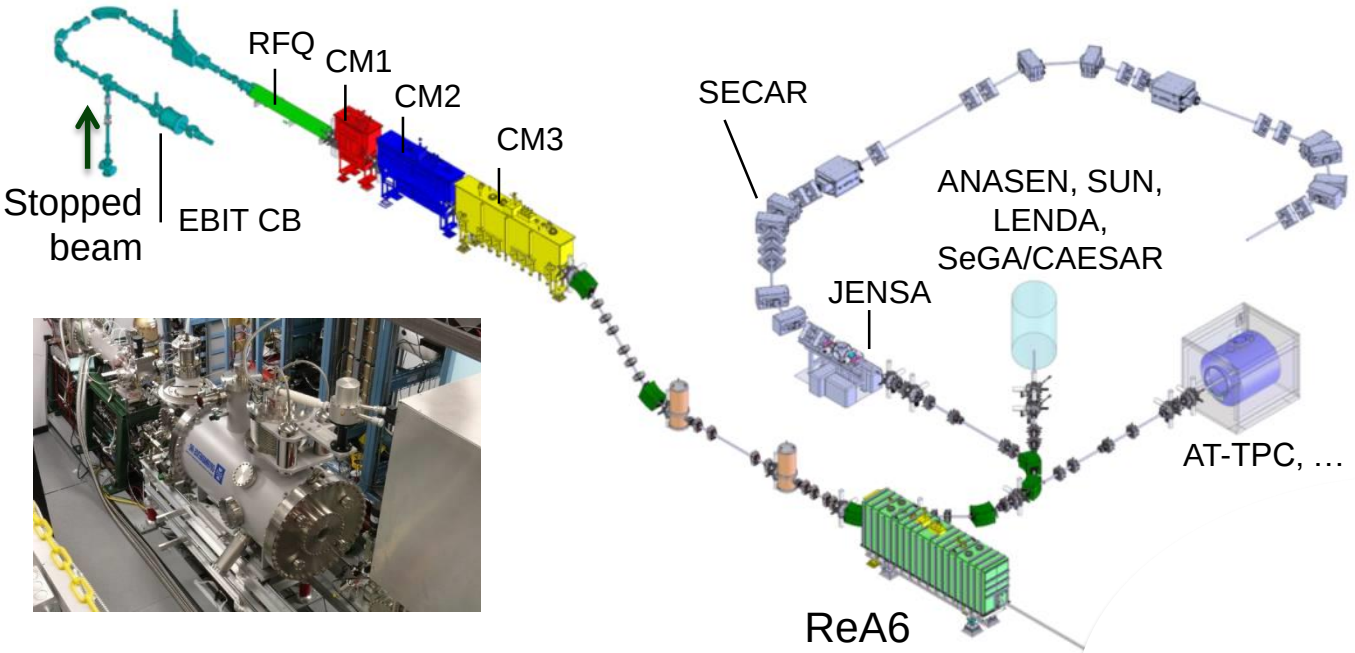


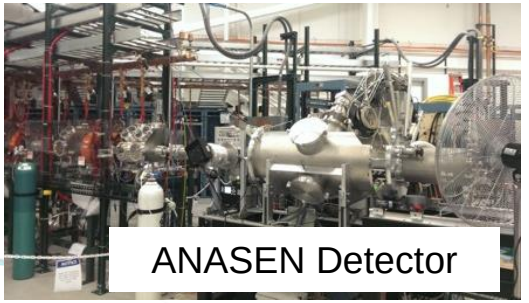


Reaccelerated beams (ReA)

Delivering beam to NSCL users since 2013







EBIT charge breeder

SRF linac

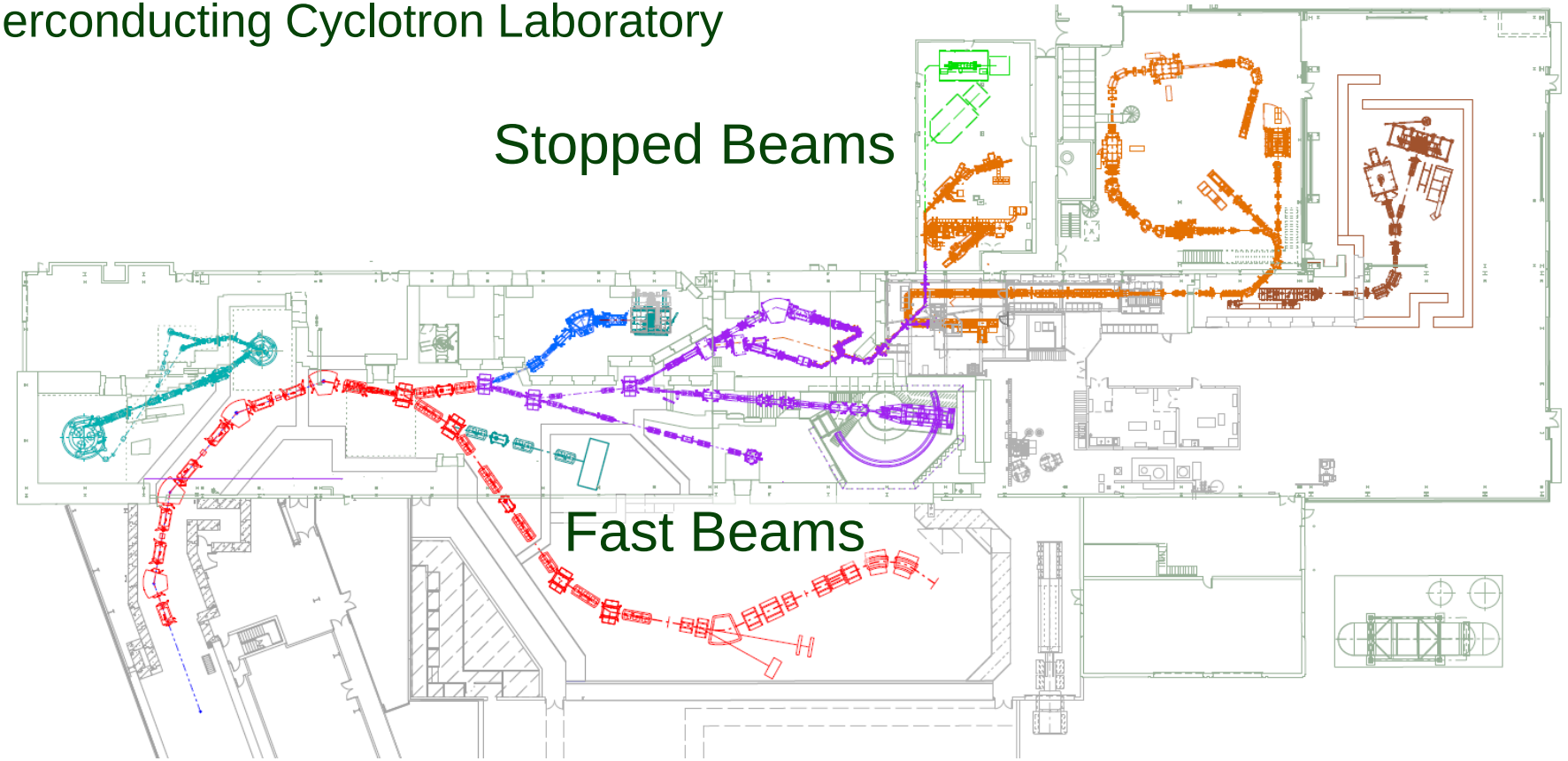
ReA3 – 3 MeV/u for ^{238}U

Expandable to >12 MeV/u for ^{238}U

ReA6 / ReA12 experimental areas (future)

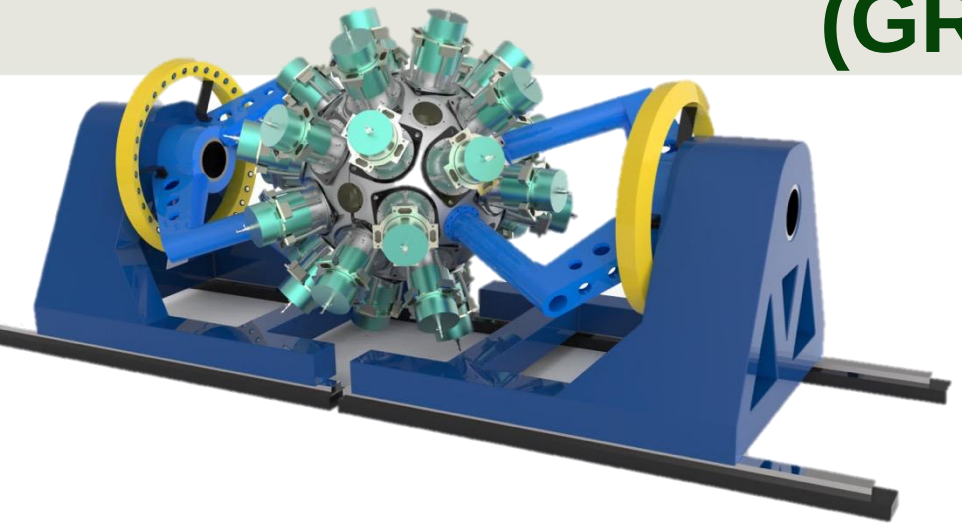
FRIB experimental areas

- FRIB subsumes and expands experimental areas of currently operational National Superconducting Cyclotron Laboratory



Isotope Harvesting

The Gamma-Ray Energy Tracking Array (GRETA)



GRETA is a 4π tracking detector for in-beam γ-ray spectroscopy capable of reconstructing energy and 3D position

Provides an unprecedented combination of

- *full solid angle coverage and high efficiency*
- *excellent energy and position resolution*
- *good background rejection (peak-to-total)*

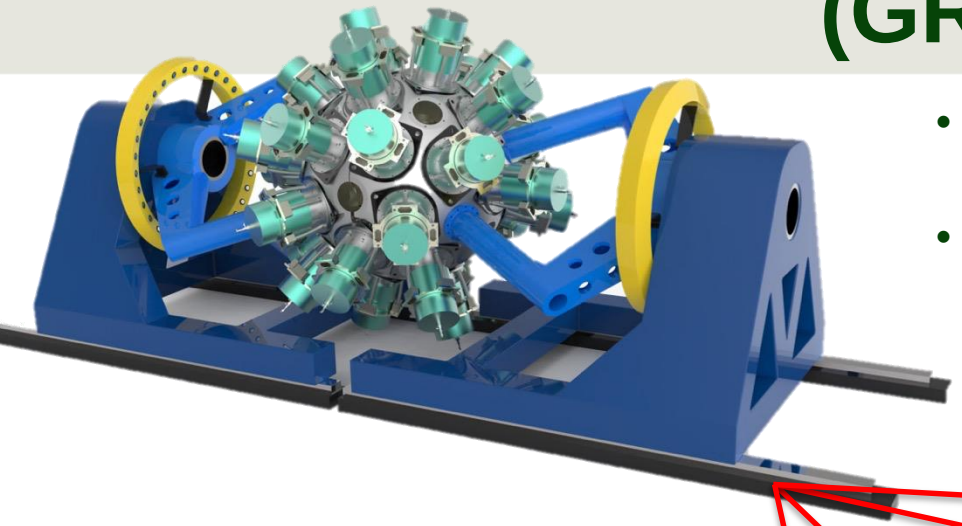
LBNL-led project funded by U.S. Department of Energy and in collaboration with ANL, NSCL, and ORNL

GRETA builds directly off of the success of GRETINA, which has been operating since 2012, with 4 physics campaigns completed

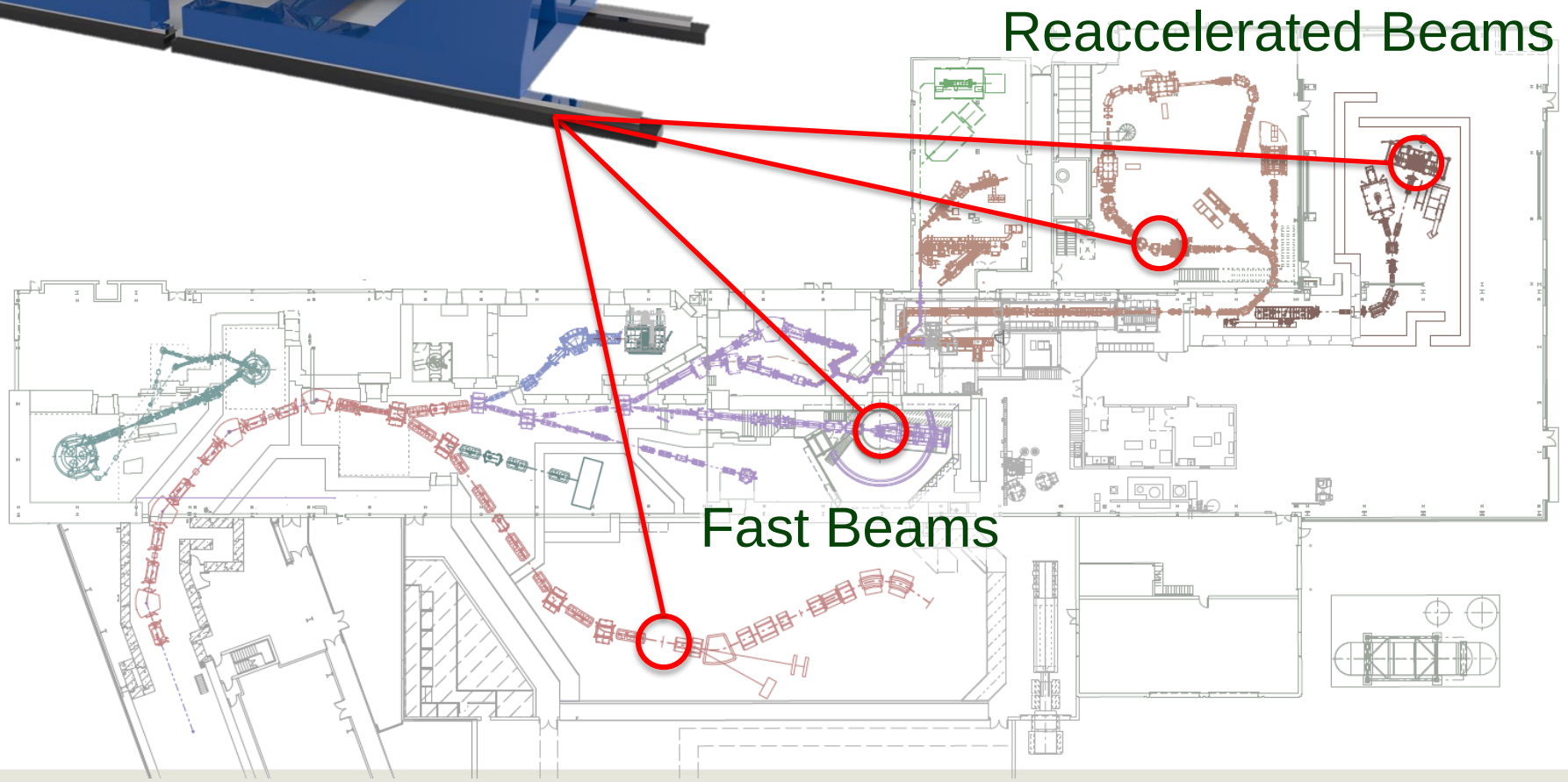
Selected nuclear astrophysics:

- (d,nγ) and (d,pγ) reactions for (p,γ) and (n,γ) reactions in *rp* and *r* processes
- Charge-exchange reactions for weak interactions in supernovae

The Gamma-Ray Energy Tracking Array (GRETA)

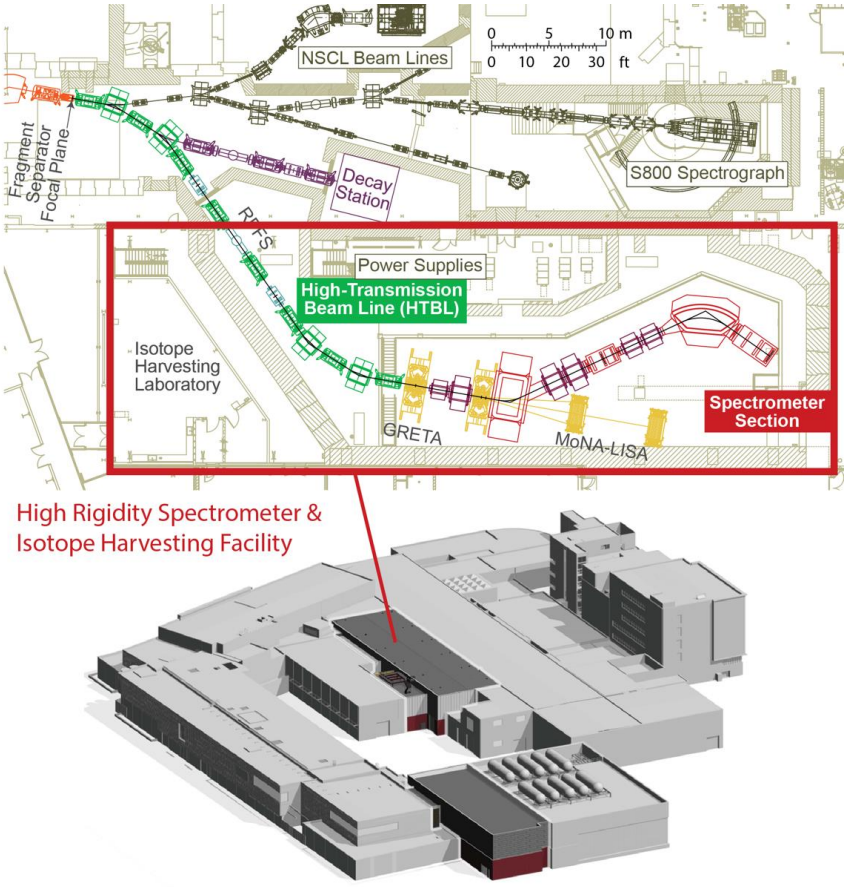


- Preliminary design complete: accommodates operation in several locations
- Project staged to optimize physics with early delivery to FRIB before 2025



High-Rigidity Spectrometer (HRS)

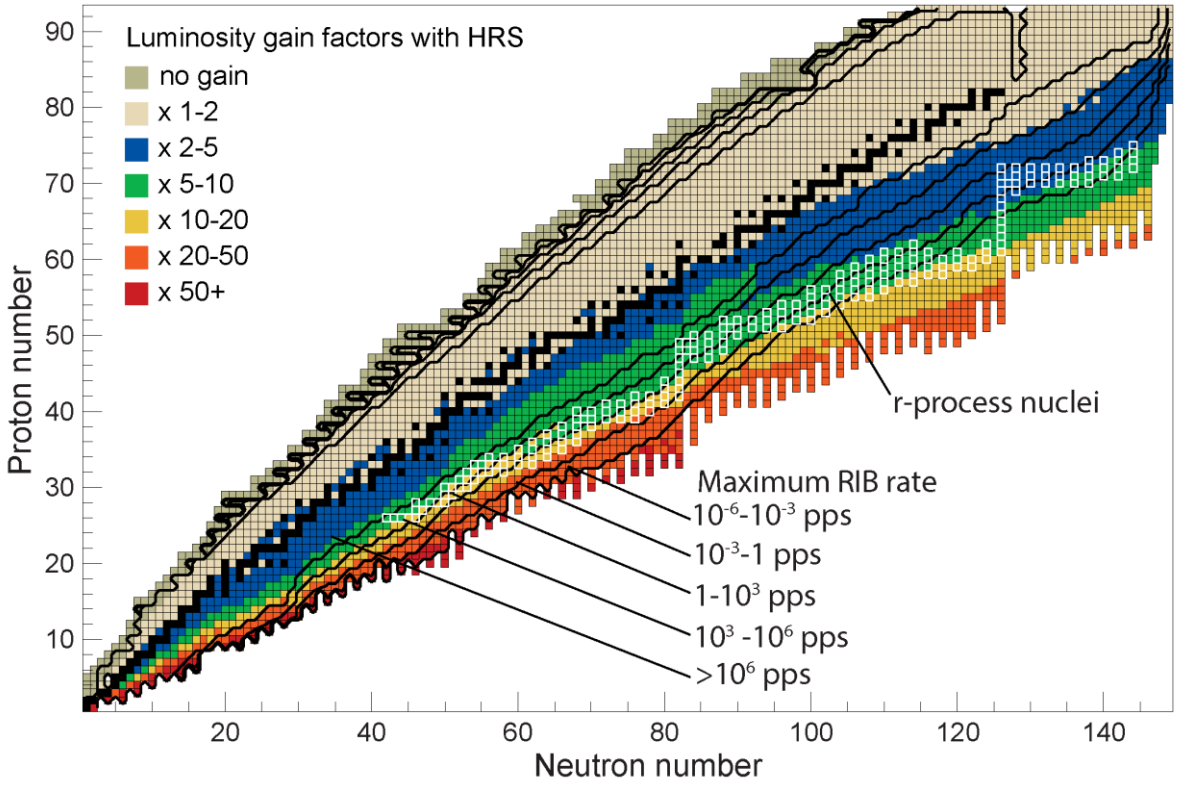
- Similar to NSCL's S800, but optimized for FRIB fast beams
- High Transmission Beam Line and Spectrometer Section enable experiments at magnetic rigidities of up to 8 Tm



- High priority for U.S. community
- Conceptual Design Report complete
- MSU funded 31000 sq. ft. experimental area: to be completed by end of CY 2019

Increased luminosity with the HRS

- HRS increases the scientific reach of FRIB through increased luminosity
  - Gain: Use rare-isotope beam at the rigidity that optimizes production
  - Gain: Use thicker reaction targets at high rigidity to maximize yield

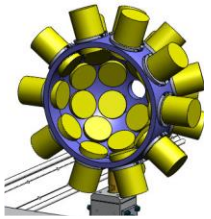


- For over 90% of neutron-rich isotopes gain factors of 2-100 are achieved
- For nuclei in the path of the astrophysical *r* process gain factors are 5-20

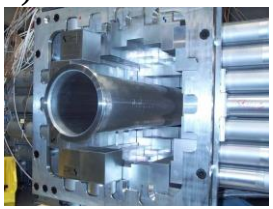
HRS Ancillary Detectors

a) GRETA

b) LANL-Apollo

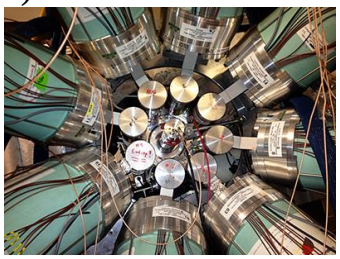


c) CAESAR

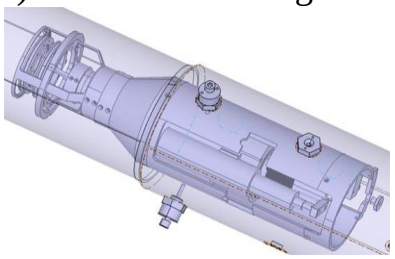


d) HiRA

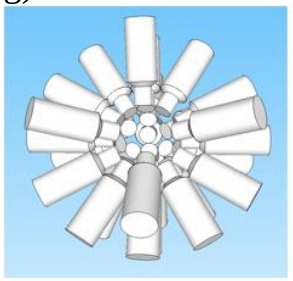
e) SeGA



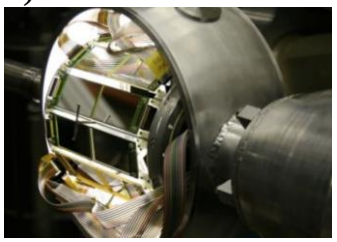
f) NSCL-Köln Plunger



g) HaGRID

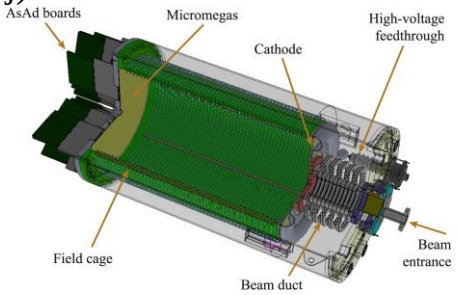


h) ORRUBA

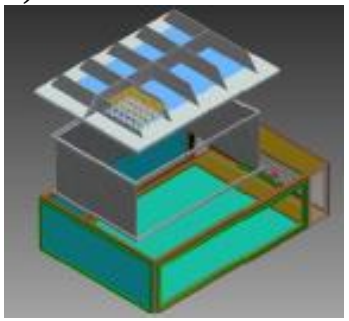


i) LENDA & VANDLE

j) AT-TPC



k) SπRIT-TPC



Selected nuclear astrophysics:

- Heavy-ion collisions for nuclear equation of state
- Bρ-ToF mass measurements for *r* process

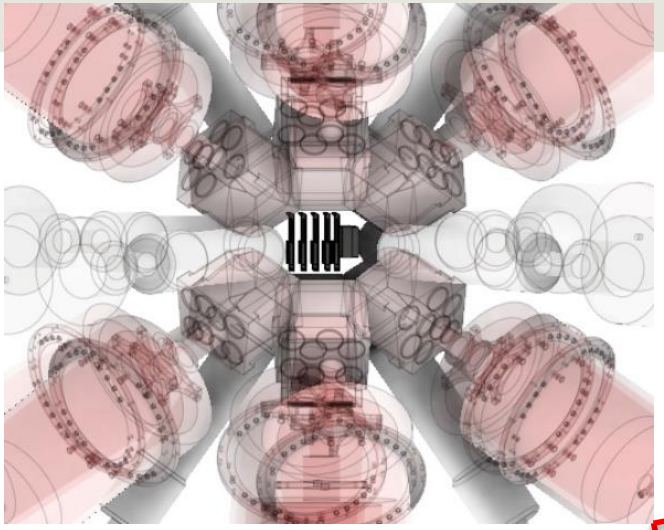
+GRETA science mentioned previously

FRIB Decay Station (FDS)

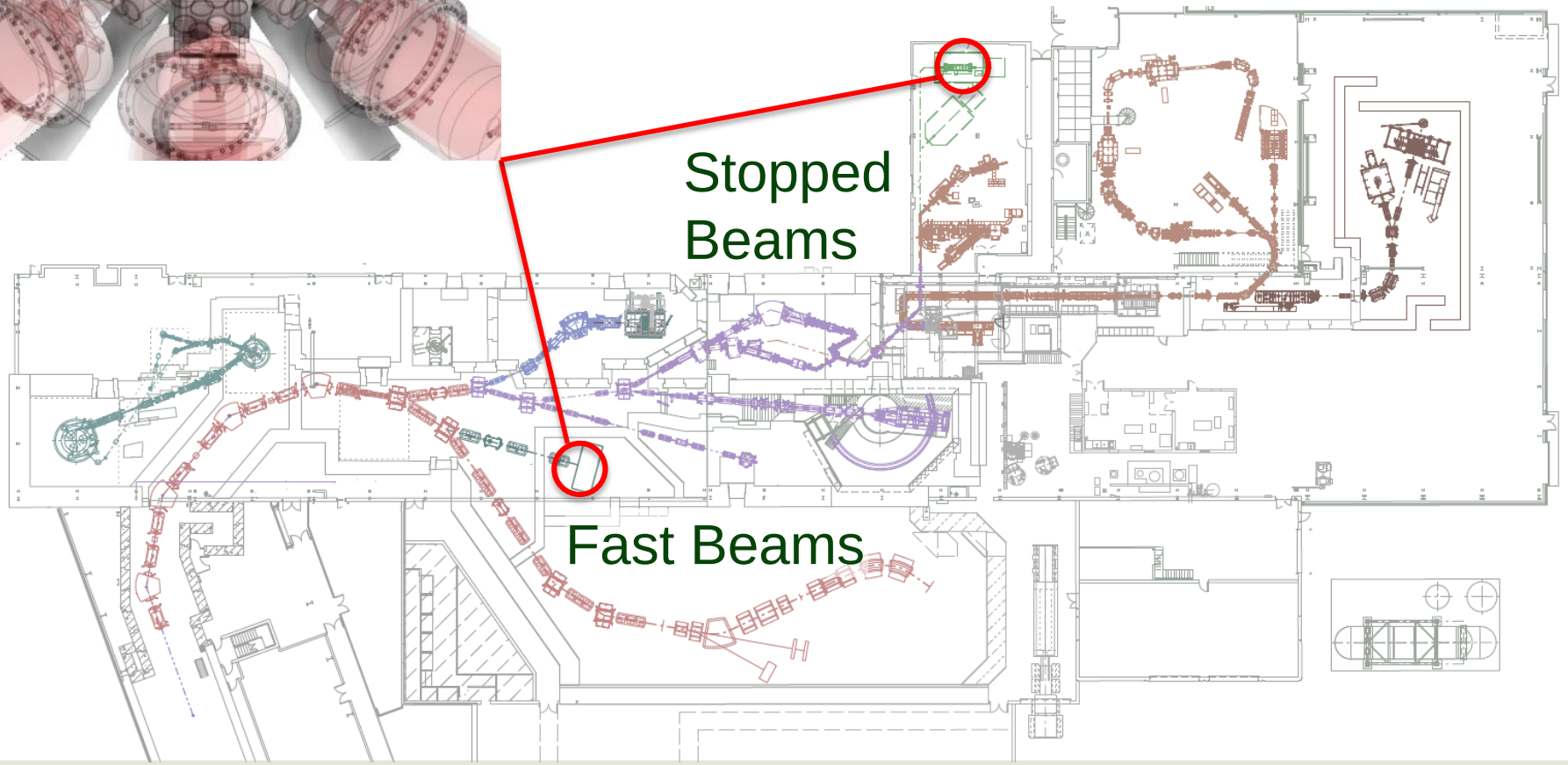
- Modular system for detection of all decay radiations

Subsystems	Detection type	Path	Comment
SiDSSD - XSiS	**implant & charged particles**	**new**	Good resolution for proton and α spectroscopy
XScint - XSiS	**implant & charged particles**	**new**	Fast segmented scintillator
GeDSSD	**implant & charged particles**	**exists**	High resolution detection of X-rays and conversion electrons.
TPC	**implant & charged particles**	**exists**	Correlated charged-particle detection
HPGe Clovers - DEGA	**γ rays**	**new**	High-resolution, large-volume (4 crystals x 7 cm x 8 cm), and tapered
BGO Shields - DEGA	**γ rays**	**new**	Recessed Compton-suppression coverage for high efficiency configuration
HPGe PCs - DEGA	**γ rays**	**new**	Large-face and very high resolution at low and medium energies
$LaBr_3$	**γ rays**	**upgrade**	Fast timing and good resolution
NaI(Tl) – MTAS / SUN	**γ rays / neutrons**	**upgrade**	Segmented total absorption
^{3}Hen	**neutrons**	**upgrade**	Highly segmented and efficient neutron counter
n TOF - NEXT	**neutrons**	**new**	Good resolution, large solid-angle and efficiency, granular, discrete neutron spectrometer (pairs with XScint for TOF)

FRIB Decay Station (FDS)



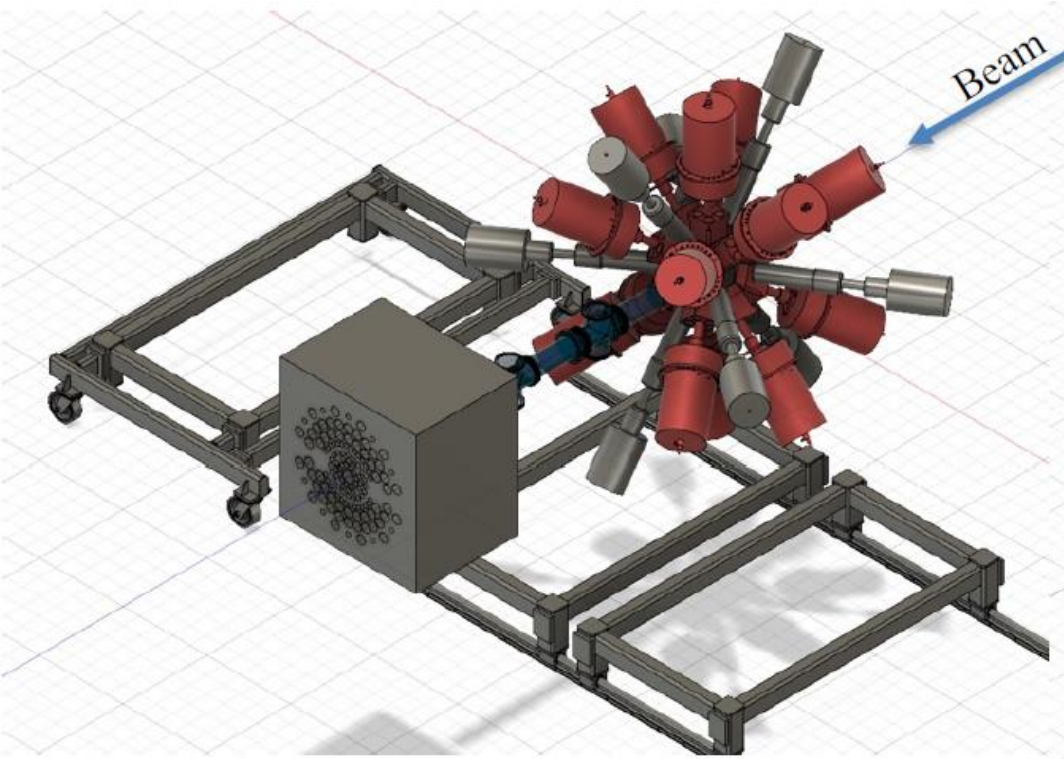
- Two locations: fast and stopped beam areas



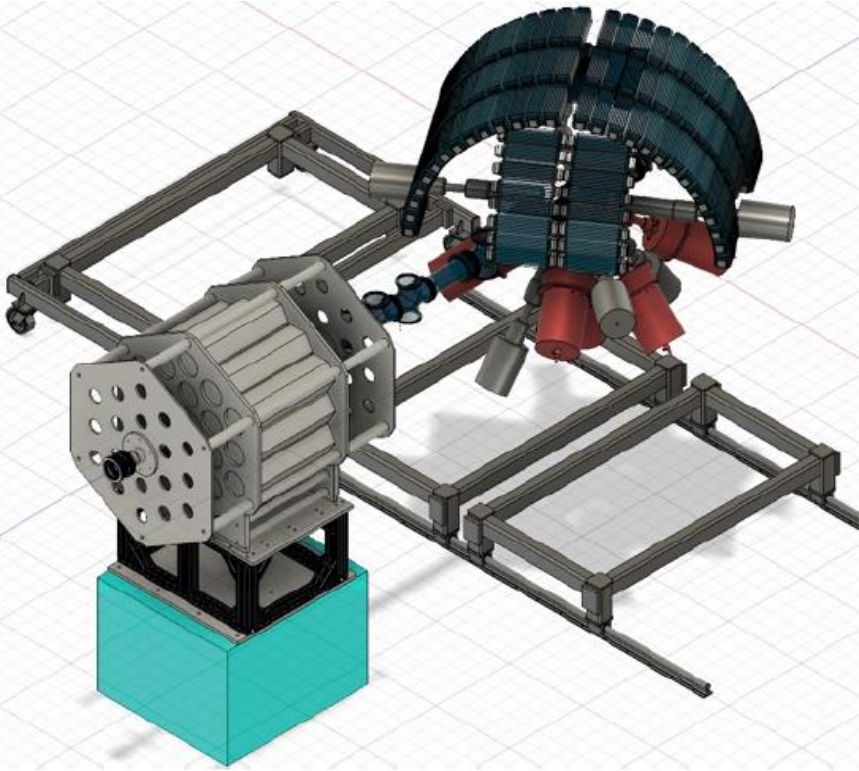
FRIB Decay Station (FDS)

Selected nuclear astrophysics:

- Lifetimes, branching ratios, β-decay strength functions, resonance properties, and statistical properties for *rp* and *r* process

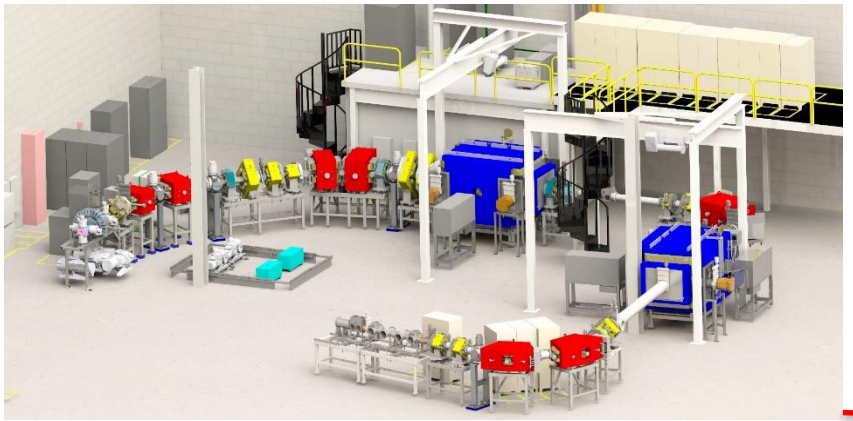


DEGA-^{3}Hen configuration



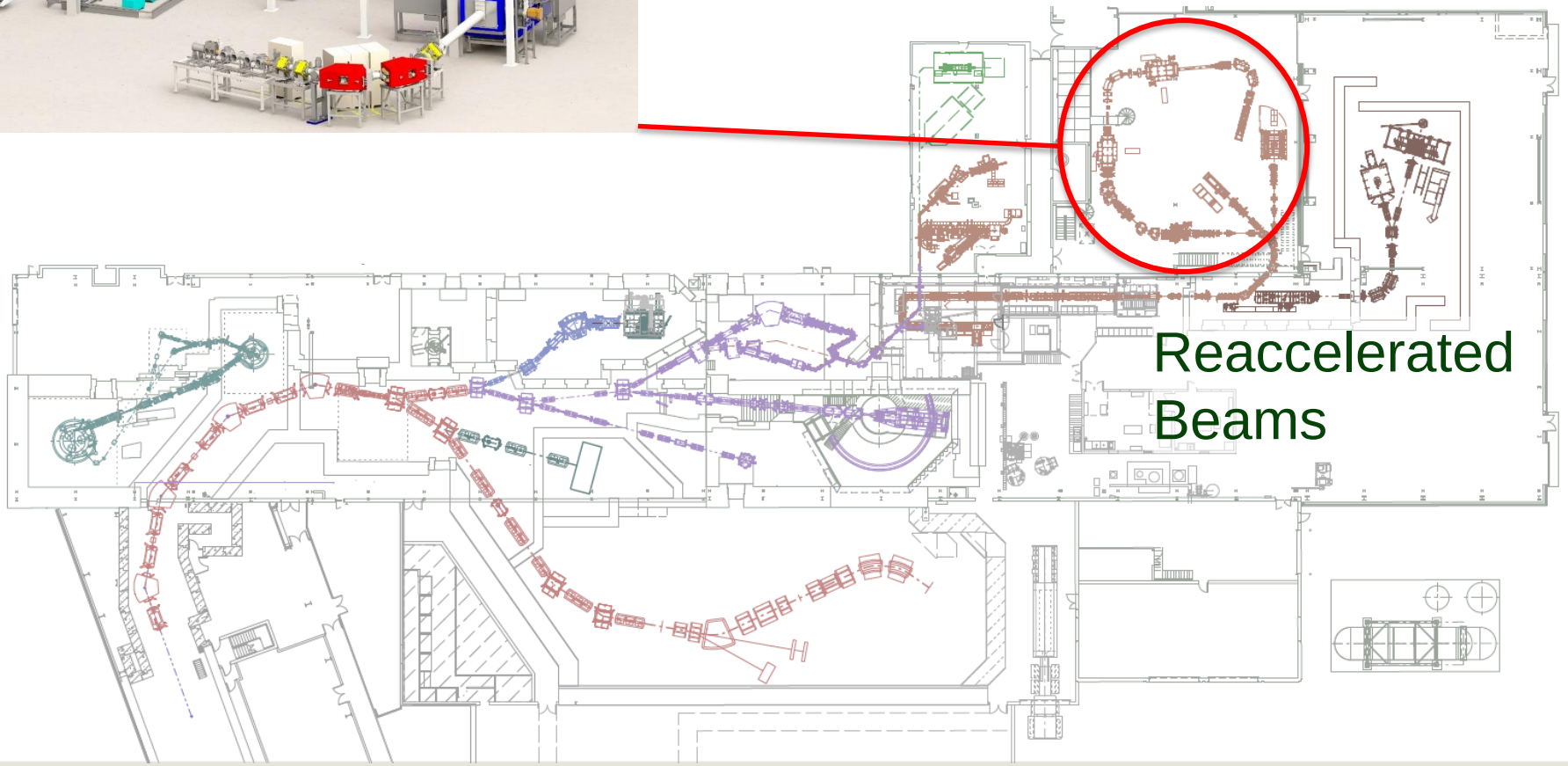
NEXT-DEGA-MTAS configuration

SECAR Recoil Separator

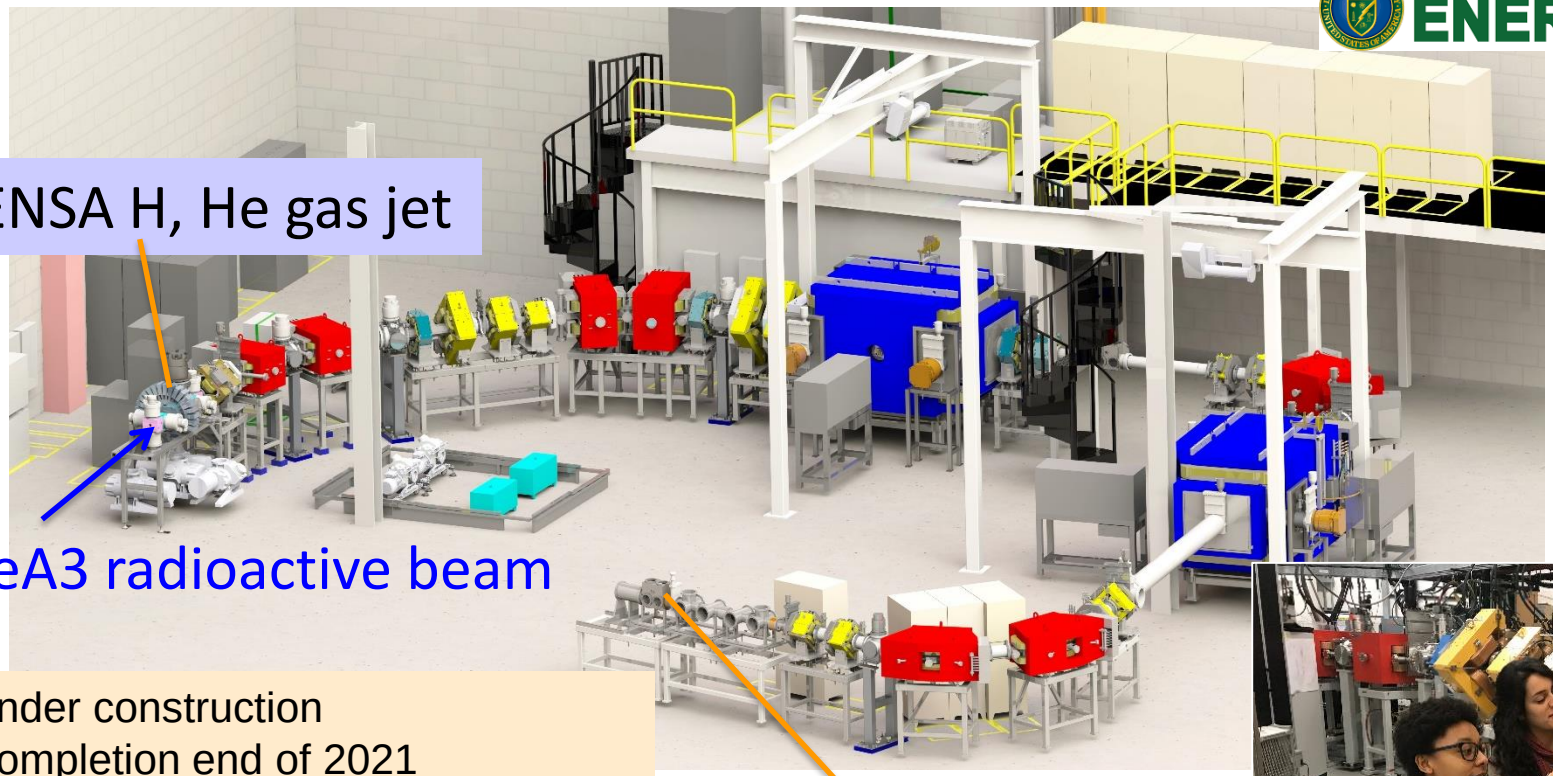


Nuclear astrophysics:

- Specialized to directly measure radiative proton and α-particle capture reactions on unstable nuclides at astrophysical energies: *rp* process



SECAR Recoil Separator



JENSA H, He gas jet

ReA3 radioactive beam

Focal plane recoil detection

Under construction
Completion end of 2021
Design: M. Couder, G. Berg Notre Dame
H. Schatz, F. Montes MSU
J. Blackmon LSU
K. Chipps, M. Smith ORNL
U. Greife CSM
+ many other institutions

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

FRIB Users Engaged and Ready for Science
www.fribusers.org

- Users are organized as part of the independent FRIB Users Organization (FRIBUO)
  - Chartered organization with an elected executive committee
  - Approximately 1,402 members (118 U.S. colleges and universities, 13 national laboratories, 52 countries) as of 12 February 2019
  - 19 working groups on instruments
  - Next community meeting at TUNL in August 2019

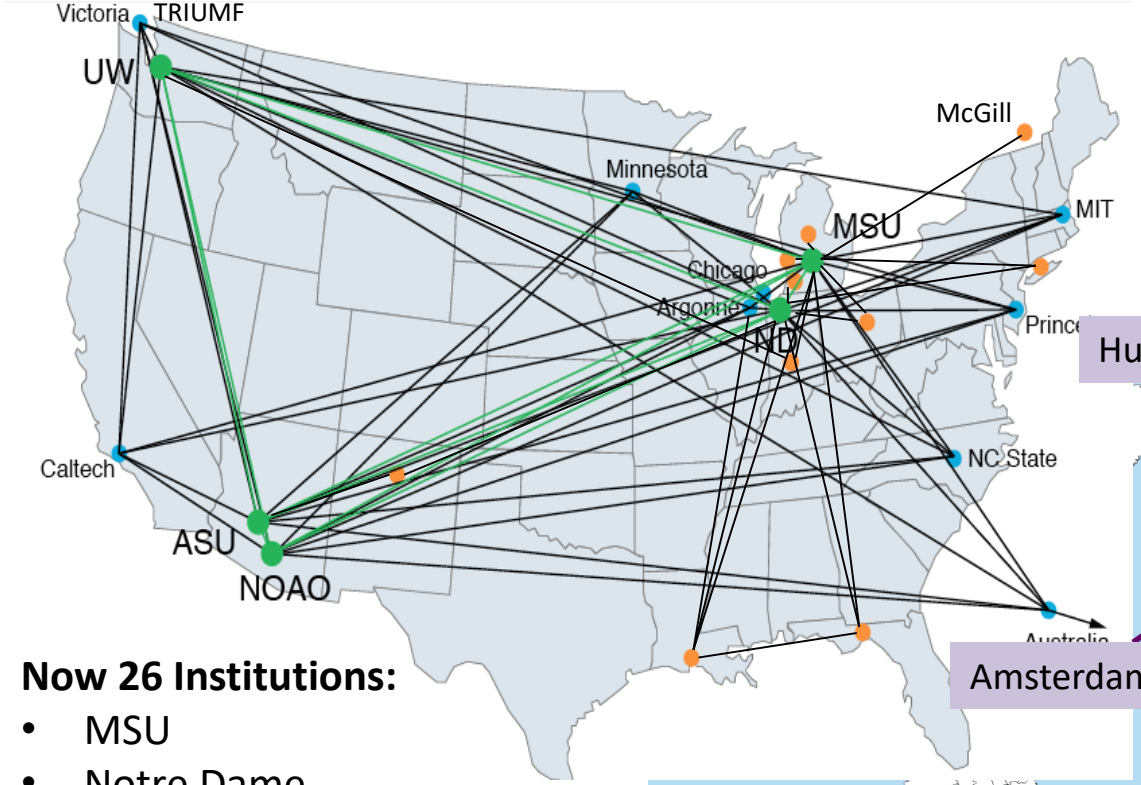
Your participation and creative ideas are welcome!

Nearly 260 users participated in the most recent community meeting (August 2018) held at FRIB

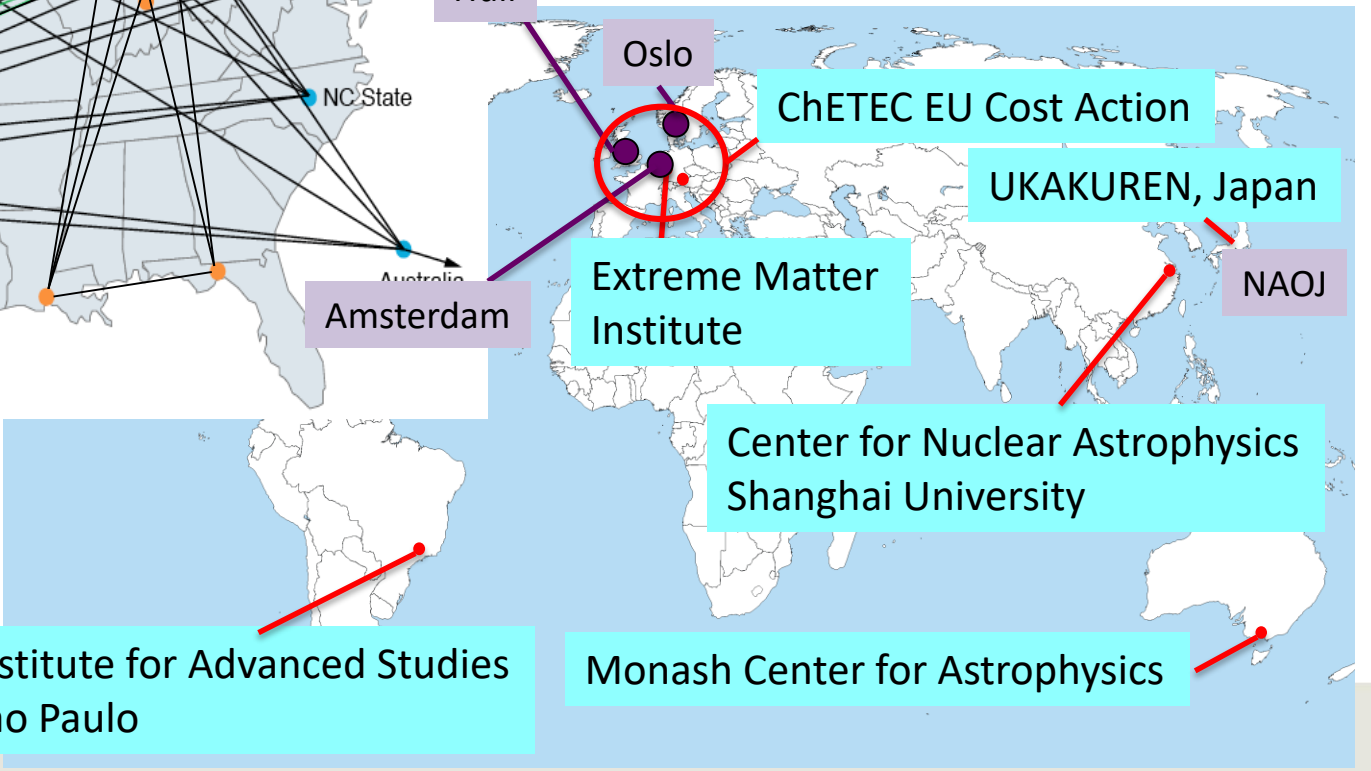
JINA-CEE NSF Physics Frontiers Center

Developed Large Open Network Approach to Nuclear Astrophysics

Joint Institute for Nuclear Astrophysics – Center for the Evolution of the Elements



- Nuclear Experimenters
- Nuclear Theorists
- Astrophysics Theorists
- Astronomers
- Computational Physicists



Now 26 Institutions:

- MSU
- Notre Dame
- ASU
- University of Washington/INT

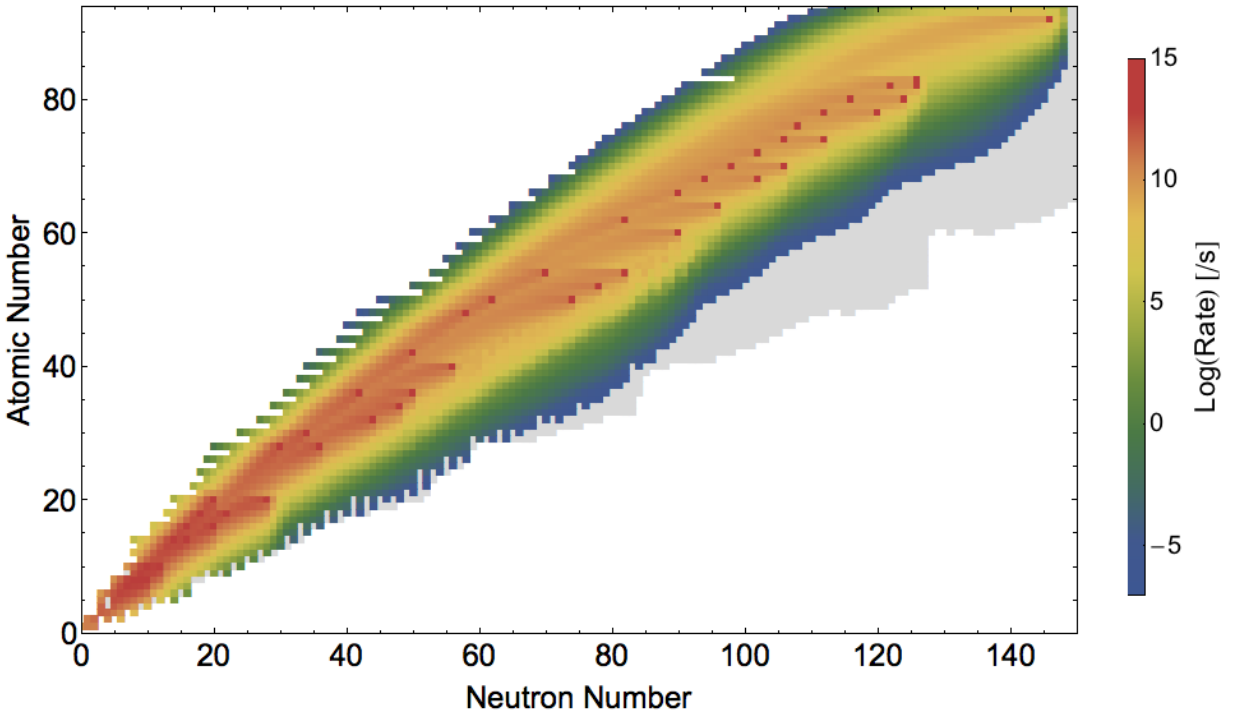
+ 24 associated institutions

Jinaweb.org

National Science Foundation
Michigan State University
NSCL

Acknowledgements

- Material provided by: Heather Crawford, Robert Grzywacz, Paul Mantica, Hendrik Schatz, Remco Zegers, and others



FRIB rates are available at
https://groups.nscl.msu.edu/frib/rates/fribrates.html

Thank you for your attention!