FRIB Day-One Science Facility Capabilities

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U.S. DEPARTMENT OF ENERGY | Office of Science

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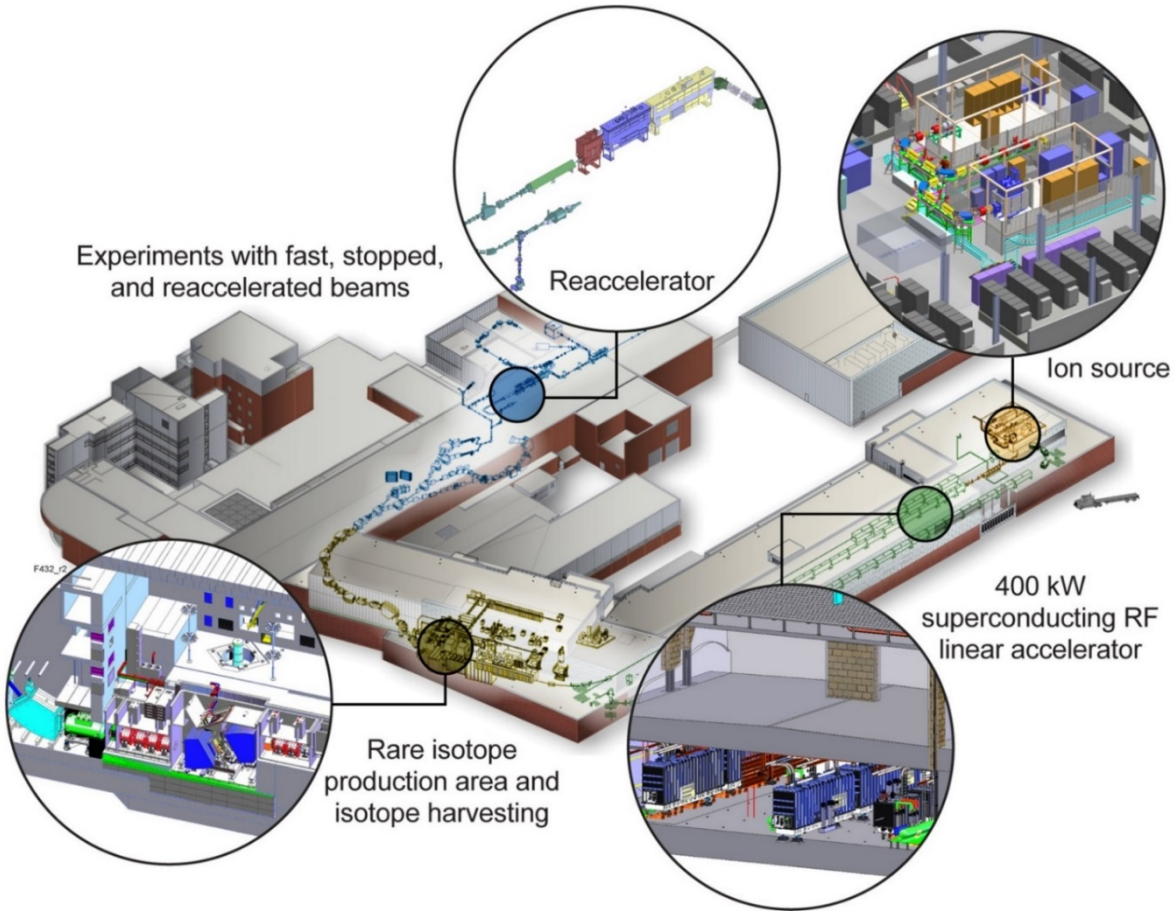
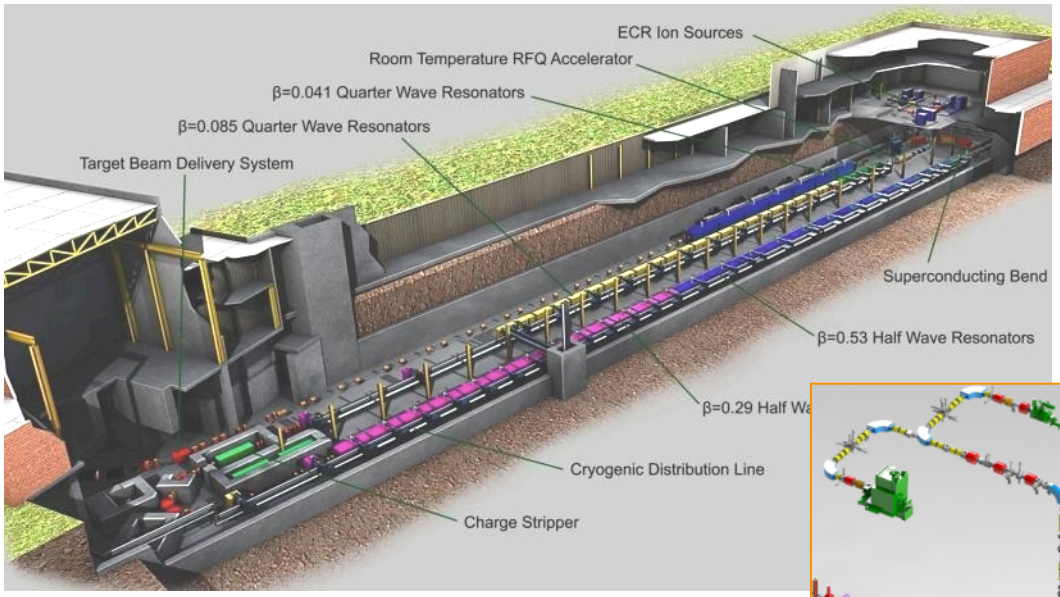
Outline

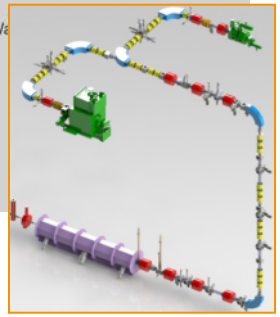
- FRIB rare isotope beams for science discoveries on Day 1
- FRIB fast, stopped, and reaccelerated beam capabilities for science
- Prepared for harvesting and commensal beams
- Broad set of experimental instrumentation for Day 1 experiments available

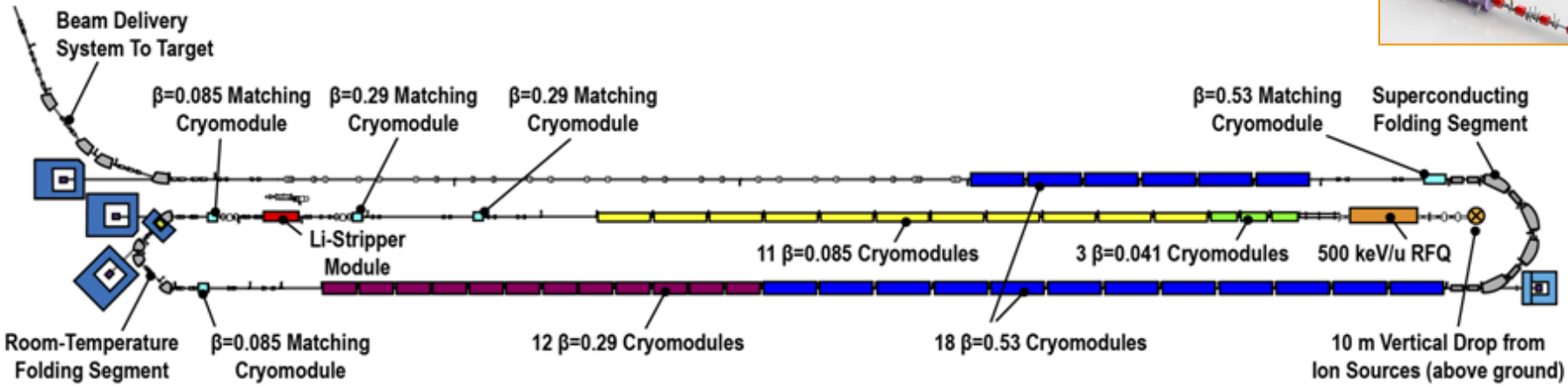


FRIB Accelerator Systems
Providing Broad Set of Primary Beams

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

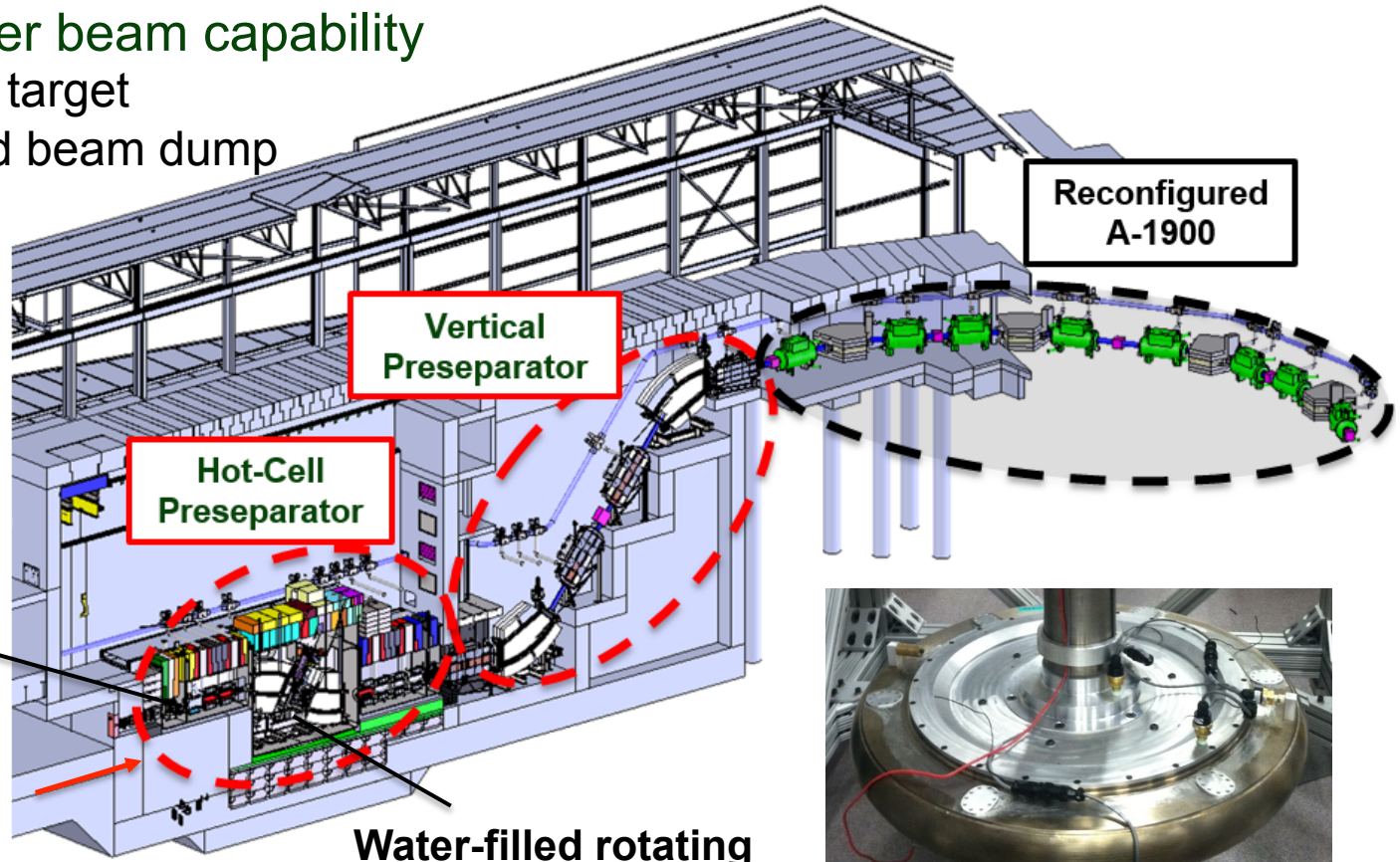




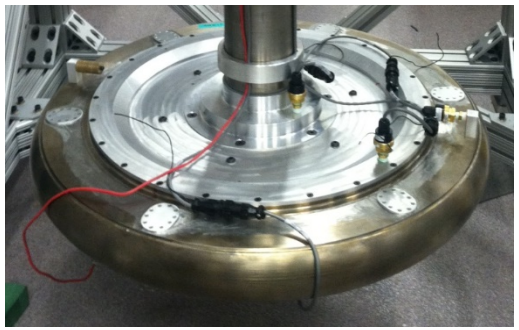


FRIB Rare Isotope Production Facilities and Fragment Separator

- Three stage magnetic fragment separator
  - High acceptance, high resolution to maximize science
- 400 kW beam power beam capability
  - Rotating multi-slice target
  - Rotating water-filled beam dump

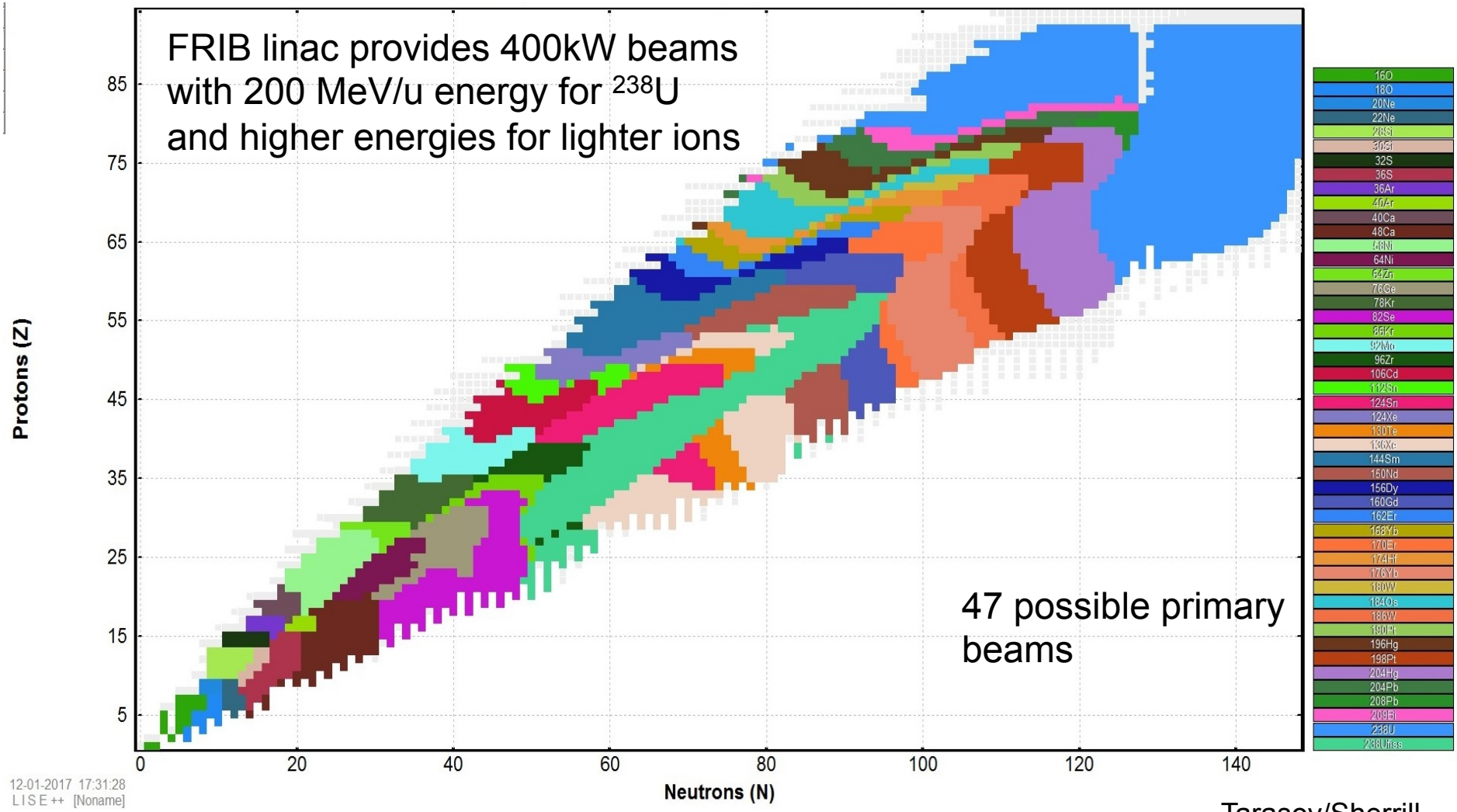


Multi-slice rotating graphite target



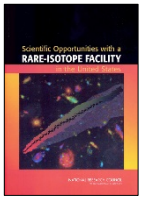
Water-filled rotating beam dump

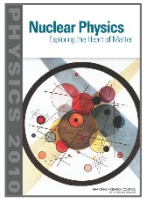
Best Primary Beams for Each Fragment to Meet FRIB Science Goals

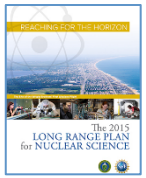


Tarasov/Sherrill

National Research Council's (NRC) RISAC Benchmarks for FRIB Science







Science drivers (thrusts) from NRC RISAC 2007

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?

Overarching questions from NSAC Long Range Plan 2015

How are nuclei made and organized? What is the nature of dense nuclear matter?	Where do nuclei and elements come from? What combinations of neutrons and protons can form a bound atomic nucleus? How do neutrinos affect element synthesis?	Are neutrinos their own antiparticles? Why is there more matter than antimatter in the present universe?	What are practical and scientific uses of nuclei?

Overarching questions are answered by rare isotope research

17 Benchmarks from NSAC RIB TF measure capability to perform rare-isotope research 2007

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

NRC benchmarks are used by FRIB to check facility capabilities and develop beam priorities

Primary Beam Priorities for FRIB Year 1 and 2 Program

- Early beam priorities to support world-leading science program
  - First-year beams and power will enable new discoveries
- 5-year power ramp-up to achieve full FRIB capability
  - Year 1: 10 kW
  - Year 2: 50 kW
  - Year 3: 100 kW
  - Year 4: 200 kW
  - Year 5: 400 kW

Year one

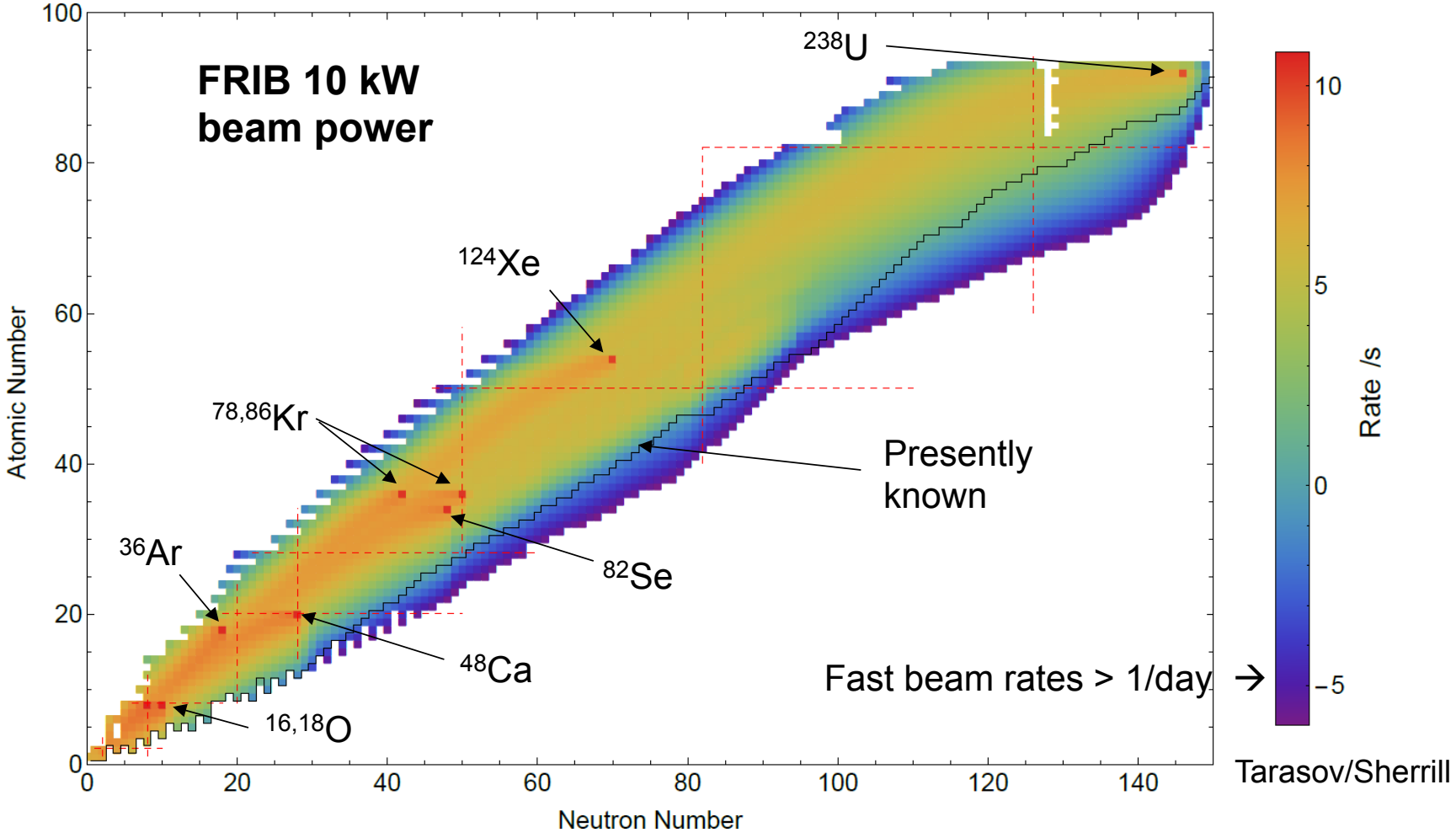
Beam	Notional Weeks/Year	Abundance (%)	Bench-marks
^{238}U	12	99.27	7,10,12,15
^{48}Ca	6.34	0.19	2,14
^{78}Kr	2.21	0.35	3,8,9,16,17
^{124}Xe	1.3	0.1	1,11,17
^{18}O	0.86	0.2	2,8
^{86}Kr	0.63	17.3	1,3,4,6,14,15
^{16}O	0.44	99.76	2,8
^{36}Ar	-	0.33	8
^{82}Se	5.25	9.4	1,3,4,5,6, 13,14,15
Total	23.8		

FRIB commissioning beams

Year two

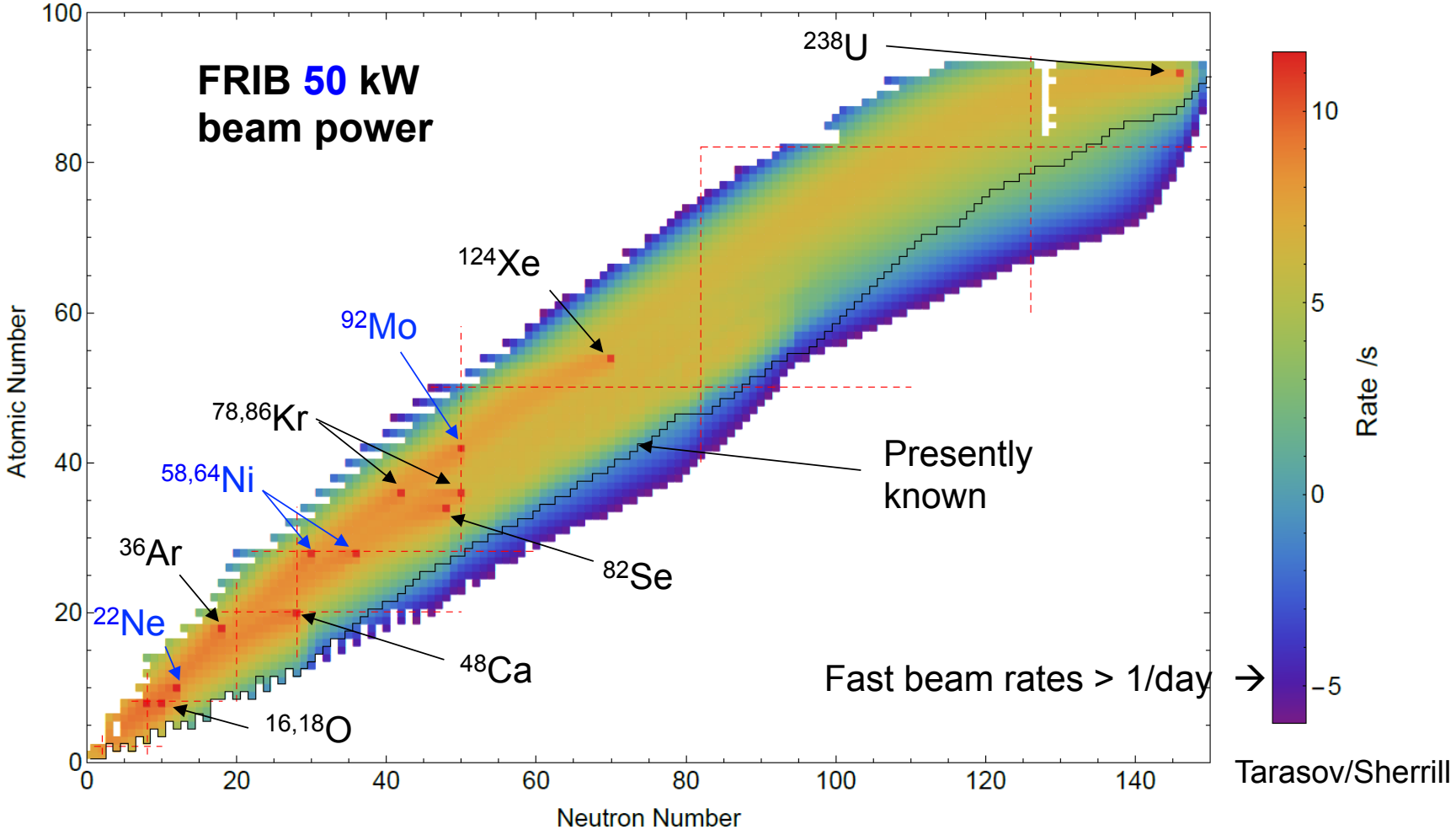
Beam	Notional Weeks/Year	Abundance (%)	Bench-marks
^{92}Mo	2.45	14.84	1,3,9,11, 16,17
^{58}Ni	1.64	68.27	1,3
^{22}Ne	0.54	9.2	2
^{64}Ni	0.5	0.91	1,13,14
Total	10.4		

Year-1 Possible Rare Isotope Beams Enable Discoveries



Year-1 FRIB rates exceed rates at other facilities in many areas

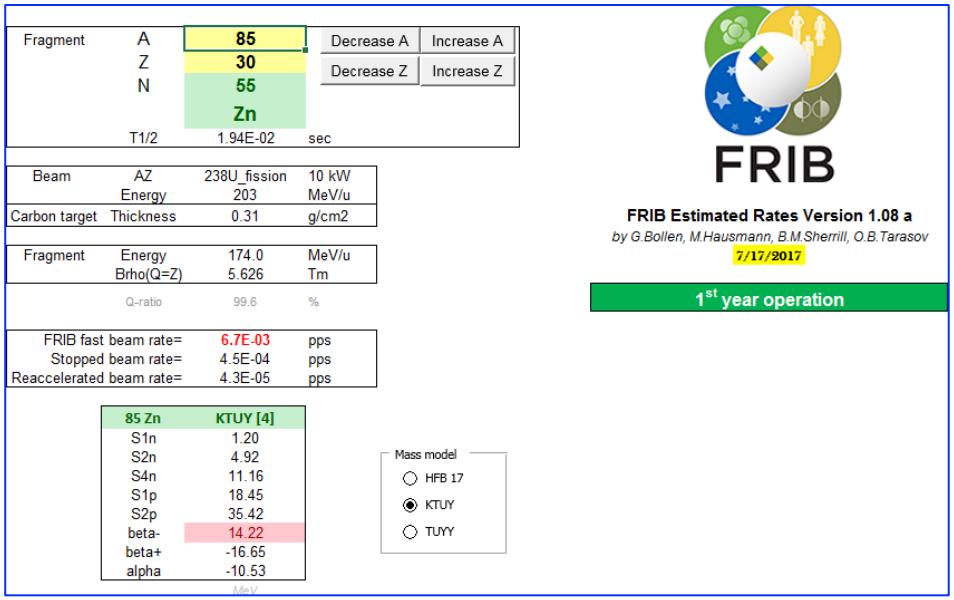
Year-2 Possible Rare Isotope Beams Enable More Discoveries



Year-2 FRIB provides access to ~600 more isotopes with rates > 1/day

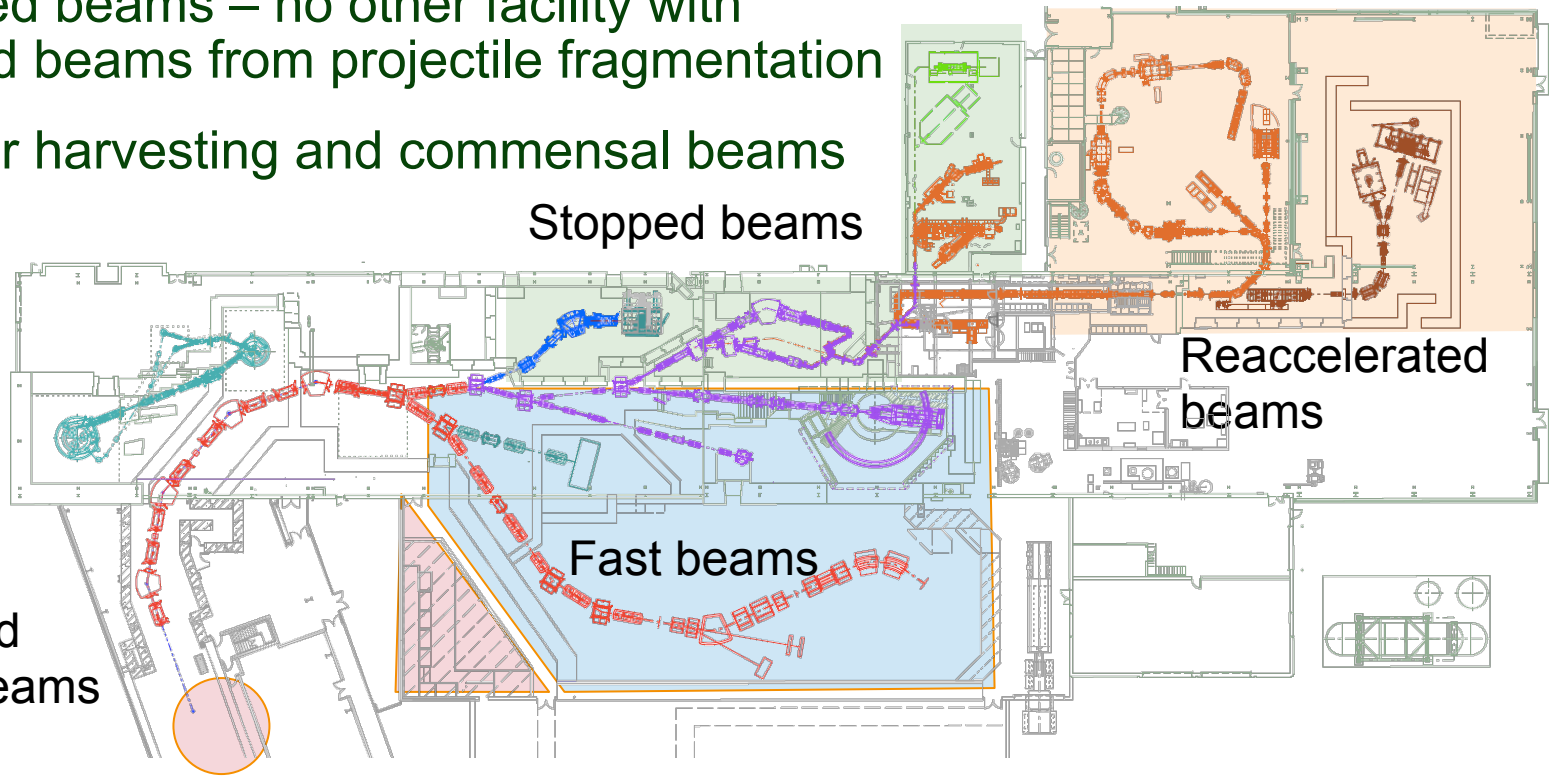
Information on FRIB Rates for Fast, Stopped, and Reaccelerated Beams

- FRIB rate estimates are available on-line
  - Year 1 (10 kW, 9 primary beams)
    - » https://groups.nscl.msu.edu/frib/rates/2017/FRIBrates_v1_08a.xlsx
  - Year 2: (50 kW, 13 primary beams)
    - » https://groups.nscl.msu.edu/frib/rates/2017/FRIBrates_v1_08b.xlsx
  - Full operation (400 kW, all primary beams)
    - » https://groups.nscl.msu.edu/frib/rates/2017/FRIBrates_v1_08.xlsx
- Important to understand that
  - Estimated fast beam rates far from stability have considerable uncertainty
  - Reaccelerated and stopped beam rates >10^9/s are very uncertain



FRIB Day-1 Capabilities are Unique
No other Facility has Similar Breadth

- Fast beams – competitive or higher rates than other facilities
- Stopped beams – multi-facetted approach to provide best beams
- Reaccelerated beams – no other facility with reaccelerated beams from projectile fragmentation
- Provisions for harvesting and commensal beams



NSCL developments aligned with FRIB needs D. Morrissey

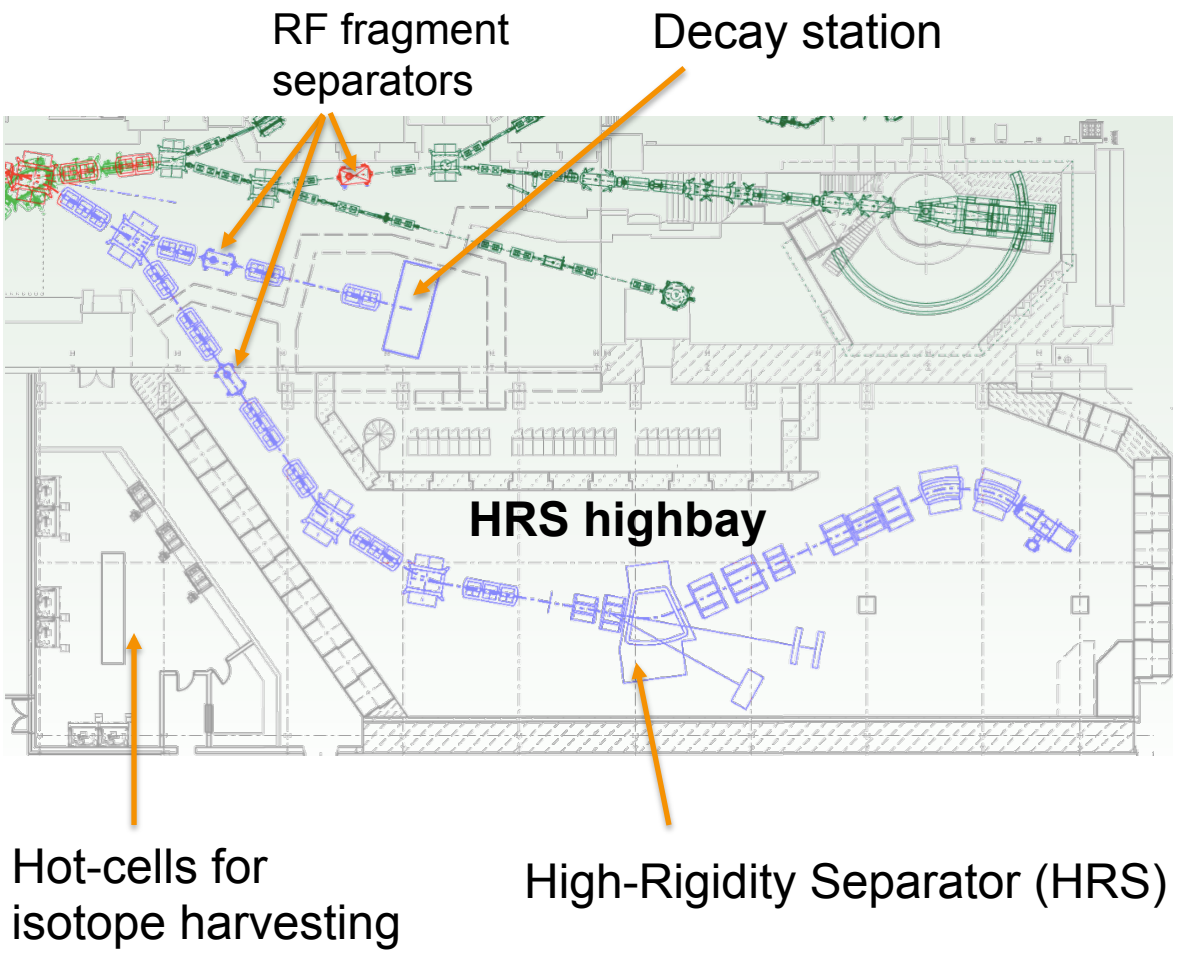
FRIB Capabilities will Grow
Continued Development Maximizes Science Opportunities

	Impact	Status	Year 1
Fast beam capabilities			
High Rigidity Separator (HRS) building	Needed for HRS, home for harvesting hotcells	Design study complete	Priority for Year 1
HRS	Make use of FRIB's high rigidity beam capability	Designs studies under way	Design complete, construction started
RF separator	Cleaner beams (proton-rich isotopes)	Space foreseen in beam line layout	Desirable
Beam line for decay station	Dedicated high-acceptance line with short flight time	line foreseen in optics layout	Very desirable
Stopped beam capabilities (*)			
Advanced Cryogenic Gas Stopper (ACGS)	Clean beams - medium to heavier masses	Construction nears completeion	Operational in N4
Cyclotron stopper	Clean beams - higher rates for low masses	Testing underway	Operational in N2
Solid stopper	Highest intensities for special beams (^{15}O)	R&D underway	Desirable – space foreseen in N4
Isobar separation	Avoid interferences with rare isotopes of interest	Under consideration	Desirable
Reaccelerated beam capabilities (*)			
2nd EBIT	Intensity upgrade - meet FRIB rates	Design considerations ongoing	Operational(?)
ReA6	Energy upgrade	Underway	Operational(?)
Stable intense beam source	Beam commissioning for experiments	Design considerations ongoing	Very desirable
Harvesting Capabilities (*)			
Water harvesting from dump/catcher	Supports DOE-IP program – Research quantities of isotopes for applications and science	R&D ongoing - Develop harvesting scenarios early at NSCL	Desirable
Commensal beam capability (*)			
	Provides multiuser capability	He-jet system under construction, Proof of principle	Operational

(*) continued development will maximize FRIB science reach

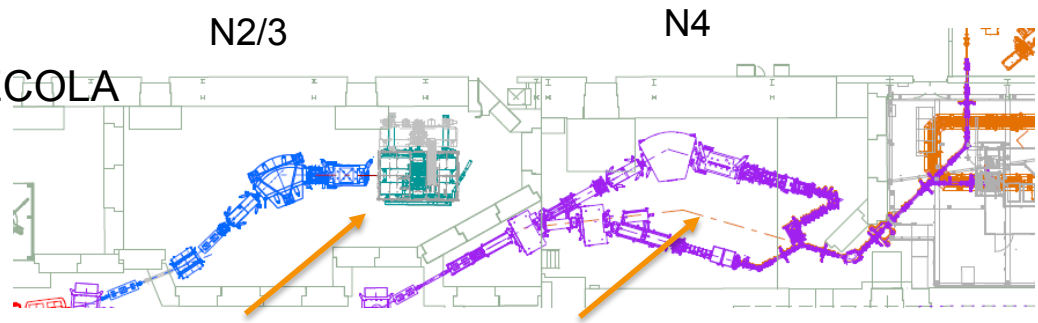
Fast Beam Capabilities
Preparing for High-Rigidity FRIB Beams

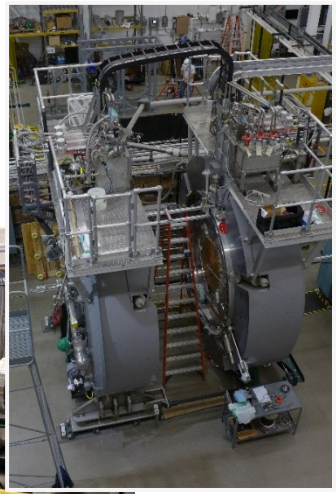
- Successful in operation at NSCL for > 20 years
- Developments underway
  - High rigidity separator (HRS) design study underway
    - » HRS critical for fully leveraging FRIB fast beam capability (Bρ = 8 Tm)
  - HRS highbay design study complete
    - » Decision to move forward expected this fall
  - Dedicated beam line for decay station foreseen in beam line layout
  - Space for RF separators in high energy beam-lines



Stopped Beam Capabilities
Multi-facetted Approach to Maximize Beam Rates

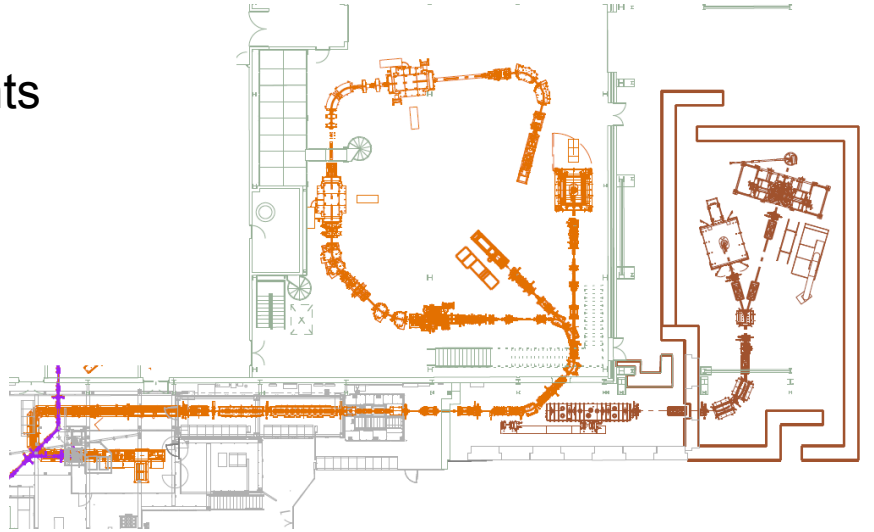
- Successful in operation since 2005
  - Strong LEBIT mass measurement and BECOLA laser spectroscopy programs
- Developments continue
  - Increase beam rate capability
    - » Cyclotron stopper for light beams under construction (<10^8/s)
    - » Advanced Cryogenic Gas Stopper (ACGS) for medium-mass and heavy beams under construction (10^6-10^7/s)
    - » Solid stopper for special beams (R&D at ORNL)
  - Improve beam purity and extraction times
    - » Cyclotron stopper and ACGS cryogenically cooled, fast ion transport
- 2 vaults for beam stopping
  - Provide flexibility for R&D and improvements without interrupting stopped and reaccelerated beam program
    - » Installation of cyclotron stopper in N2/3 with beam lines, final test
    - » Commissioned and in operation prior to start of FRIB



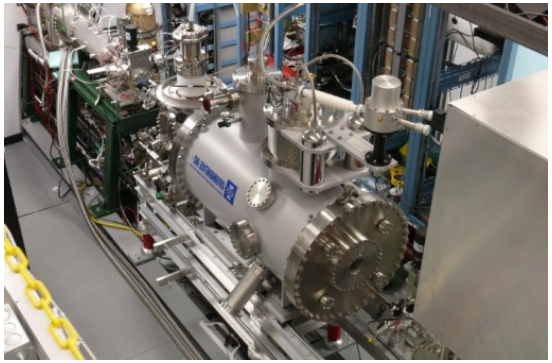


Reaccelerated Beam Capability
ReA Provides Beams for Science

- Successful in operation since 2015
  - 8 experiments performed, 7 more experiments approved
- Developments continue
  - Increase of beam rate capability planned
    - » 2nd EBIT – next generation charge breeder: high intensity, high density
  - Tailoring time structure to experiment needs
    - » Slow extraction, bunch spacing



- Energy upgrades
  - Preparing a ReA6 plan for NSF to consider. NSF recognizes ReA6 is a priority
  - ReA12 eventually needed

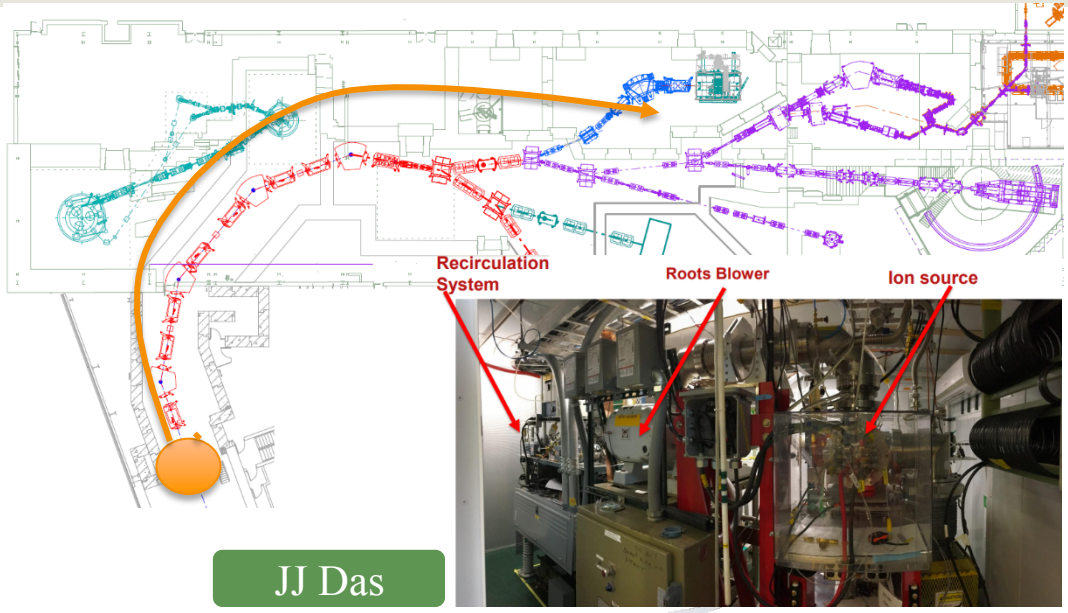


ReA Energy Upgrade Working Group

Commensal Beams and Isotope Harvesting

- Commensal beams
  - He-jet system (NSF-MRI) construction underway – will provide proof of principle and first multiuser experiments at NSCL
  - Gas-stopper and/or solid stopper combined with laser ionization – R&D underway
  - Low-energy beam transport will require integration into facility layout, reconfiguration
- Isotope harvesting
  - R&D underway – whitepaper being developed
  - FRIB facility design has provisions for harvesting

G. Severin



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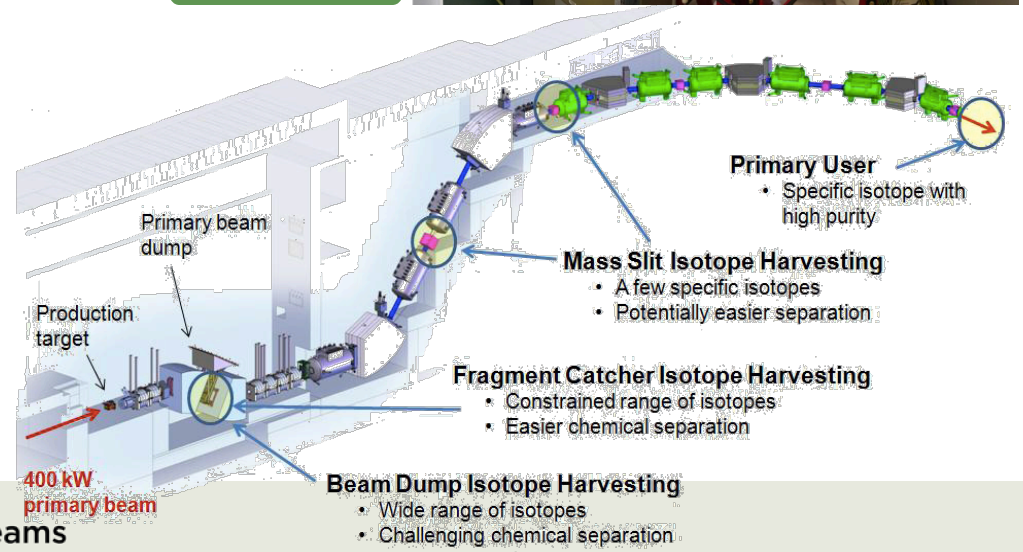
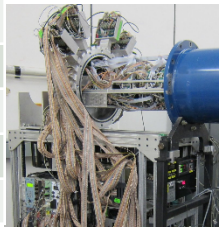


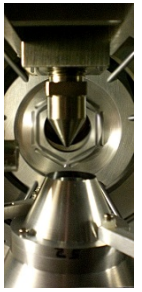
Experimental Equipment For Initial Science

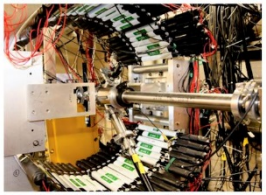
Day-one Instruments Have Already Been Commissioned and Are Ready

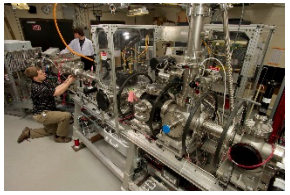
Device	NRC Science Benchmarks			
	Nuclear Structure	Nucl. Astro-physics	Fund. Sym.	Appl.
SeGA	1,4,5,14	7,17		
Beta-NMR	1,2,14			
BCS	1,5	7,16	12	
HiRA/LASSA	1,2,4,5,6		12	10
LEBIT	15	7		
MoNA-LISA	1,14	17		
Neutron Walls	6			
NERO/3HeN	1	7		
S800	1,3-5,13-15	16,17		
Sweeper Magnet	1,14	17		
RFFS	1,4,5,6,13	16		
TriPLEX	1,4,5,14			
92-inch Chamber	1,2,6	16		
Diamond Detectors	1,3-6, 13-15	7,16		
BECOLA	1.3		12	
LENDA/VANDLE	3	17		

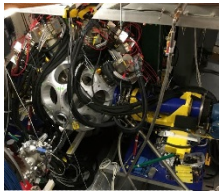
Device	NRC Science Benchmarks			
	Nuclear Structure	Nucl. Astro-Physics	Fund. Sym.	Appl.
DDAS	1,4,5,14	7,16		
CAESAR	1,4,5,14			
AT-TPC	1,3,4,6	16		
SuN/MTAS	1	7,17		10
Liquid H-Target	1,3	17		
CFFD	2			
JANUS	1,5		12	
JENSA		16		
ANASEN	1,2,4	8,16		
GAMMASPHERE	1,4,5,12			
GRETINA	1,2,3,4,5	16,17	12	11
He-Jet		9	12	10
superORRUBA	1,4	7,16		
superCHICO	1,4,5		12	
ORISS	15	7		

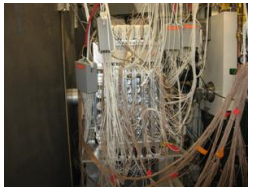












FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

Experimental Equipment For Initial Science
Road-map for New Major Equipment in Place

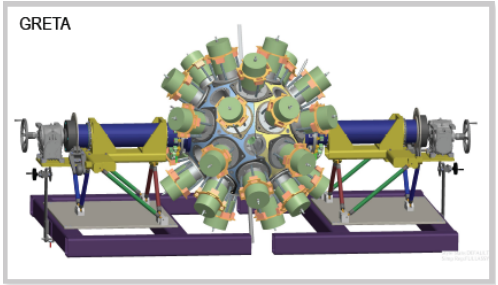
- Four large detector systems identified in 2015 Nuclear Physics Long Range Plan
  - GRETA gamma detector array (CD0), LBNL
    - » Exploration of the structure of new nuclei with maximum resolving power and acceptance
  - SECAR recoil separator (project on track), MSU
    - » Direct measurement of thermonuclear reactions in exploding and exotic stars
  - High Rigidity Separator (pre-conceptual design), MSU
    - » Evolution of shell structure, single particle structure of rare isotopes, limits of stability
  - Decay station (pre-conceptual design), UT Knoxville
    - » Structure of most exotic isotopes, site of the r-process

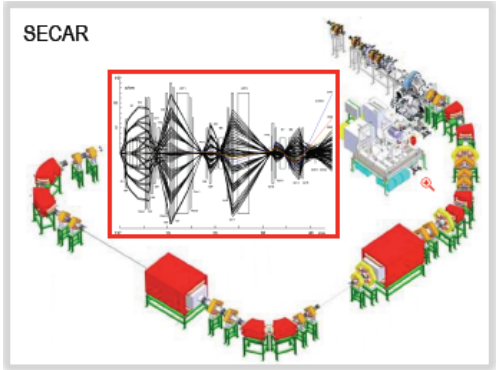
GRETA Workshop

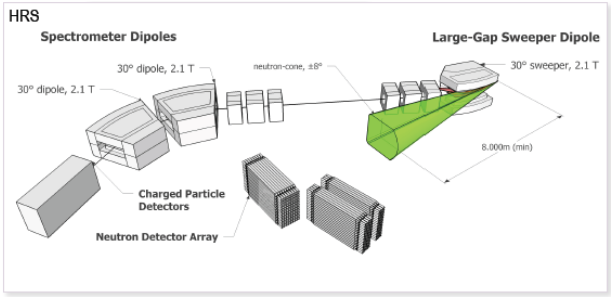
HRS Workshop

SECAR/JENSA Collaboration Mtg

Decay Station Working Group

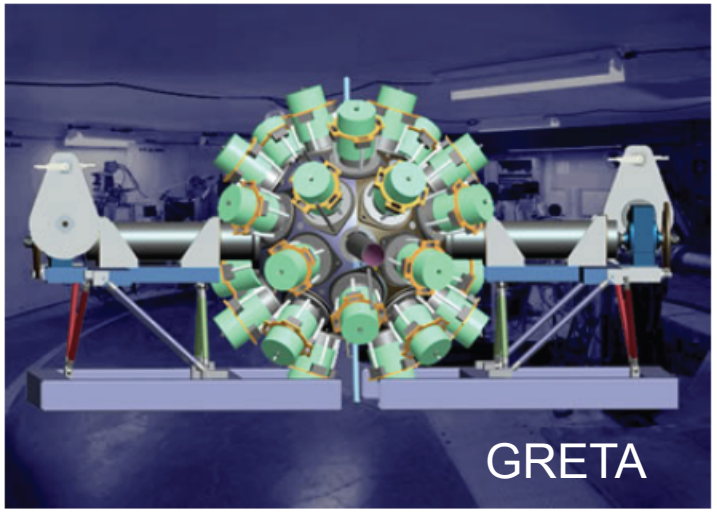






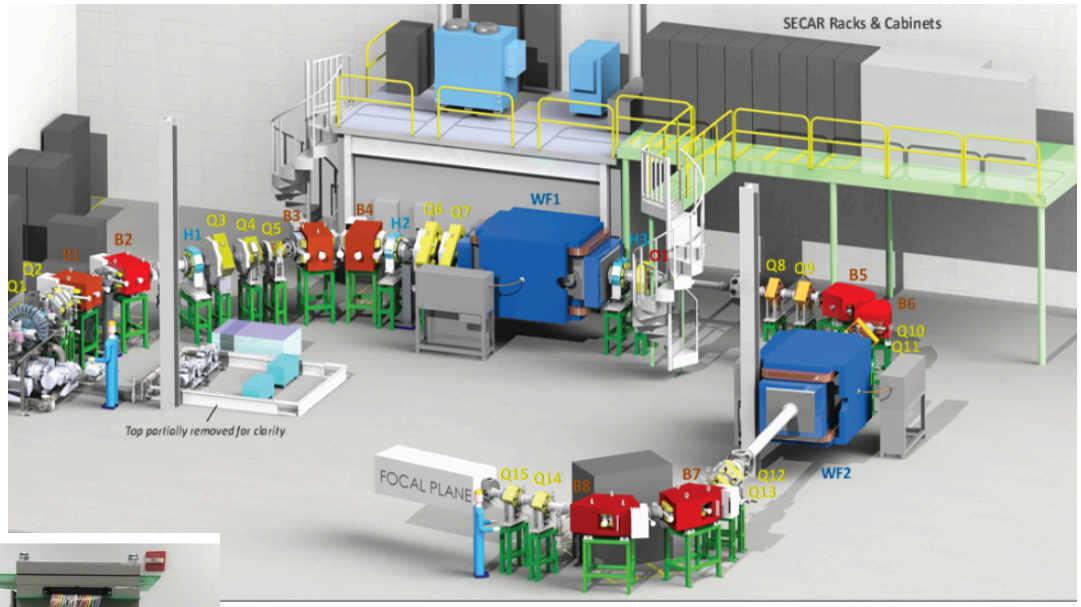
New Major Equipment: Examples GRETINA and GRETA

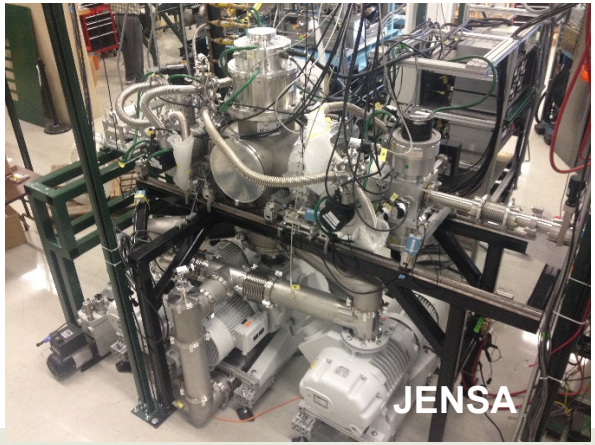
- **GRETINA** is one of the most advanced gamma-ray detector array for nuclear science uses highly segmented detectors to track and reconstruct gamma-rays
  - Science campaigns successful
  - GRETINA is the first phase of the larger Gamma Ray Energy Tracking Array (GRETA).
- **GRETA** has received CD-0 in 2015
  - Conceptual Design Report in 2017
- GRETA will benefit from High Rigidity Spectrometer (HRS) at FRIB
  - Design study funded by DOE-NP underway
- Multi-institutional collaboration (LBNL+8 institutions)

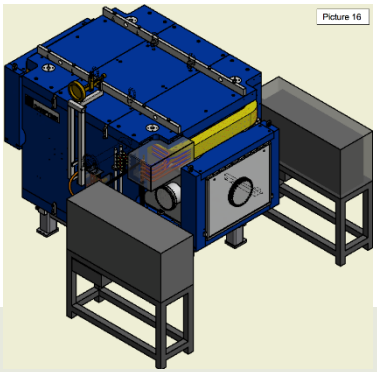


New Major Equipment: Example SECAR

- **SECAR** will enable use of FRIB's unique low energy RIB production capabilities to directly measure astrophysical reaction rates
  - Nova
  - Accreting compact objects
  - Supernovae
  - Extreme stars
- DOE-SC/NSF project to establish SECAR underway and on track
- Multi-institutional collaboration (MSU+12 institutions)

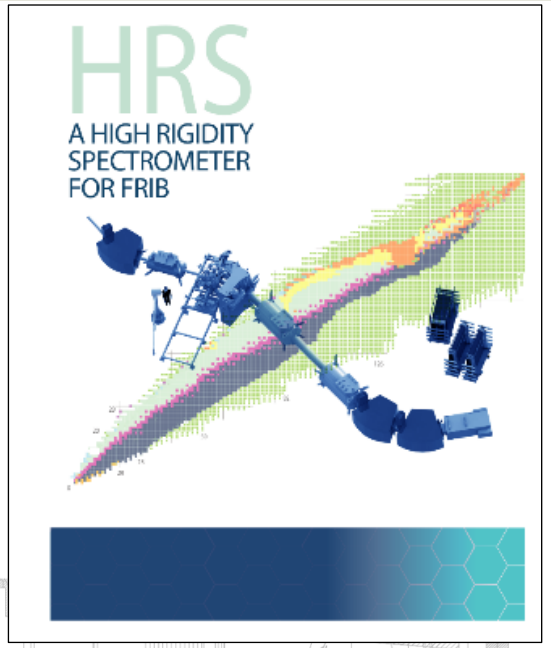


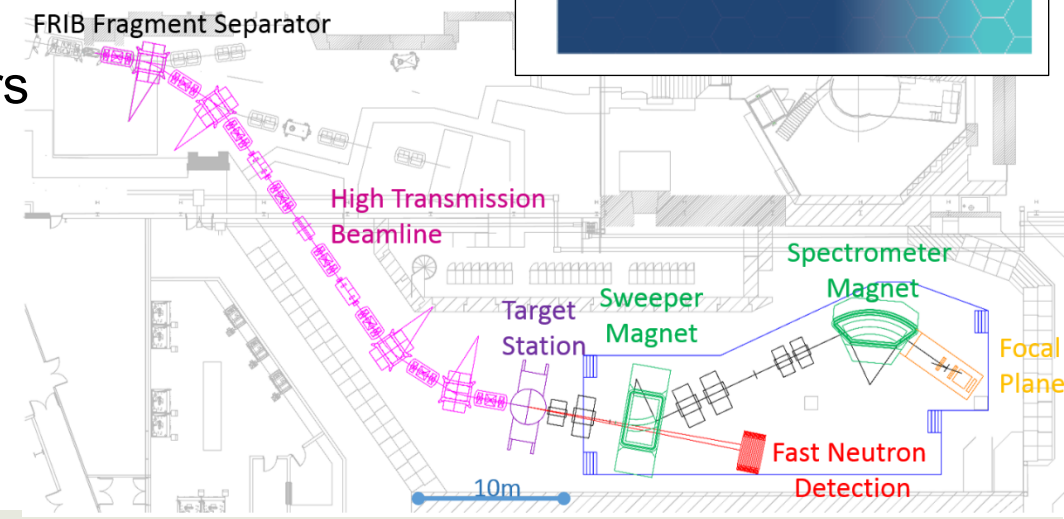




New Major Equipment: High Rigidity Separator (HRS)

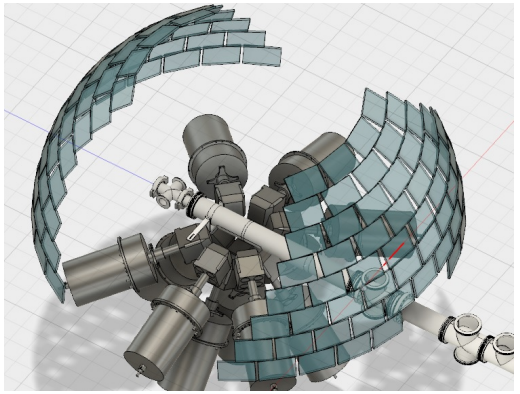
- **HRS** will enable best use of FRIB's high-rigidity rare isotope beams for in-flight reaction experiments
  - In-beam γ-ray spectroscopy near the dripline
  - Invariant-mass spectroscopy with neutrons
  - Knock-out experiments in inverse kinematics
  - ToF mass measurements far from stability
  - In-flight fission measurements
- Multiple ion-optical scenarios for different experiments
- Accommodates different detectors
- Design study (DOE-NP funded) underway
- Multi-institutional collaboration (MSU+20 institutions)



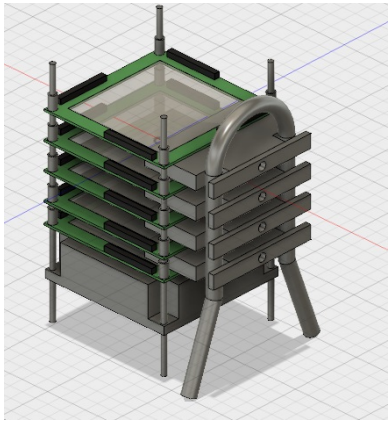


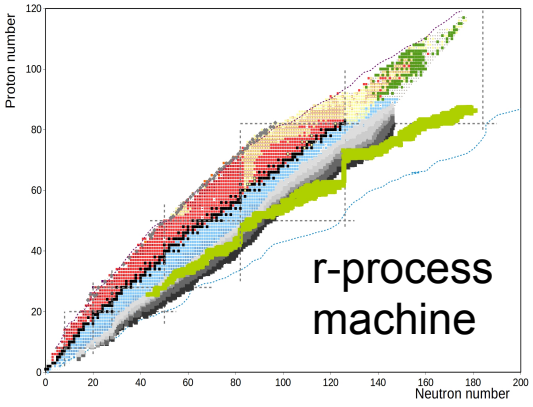
New Major Equipment: Decay Station

- State-of-the-art **Decay Station** will increases discovery potential of FRIB in strategic areas
  - Access the most exotic nuclei
  - Study decays of short lived $T_{1/2}$>100 ns isotopes
  - Measure several nuclei simultaneously with relatively short runtimes

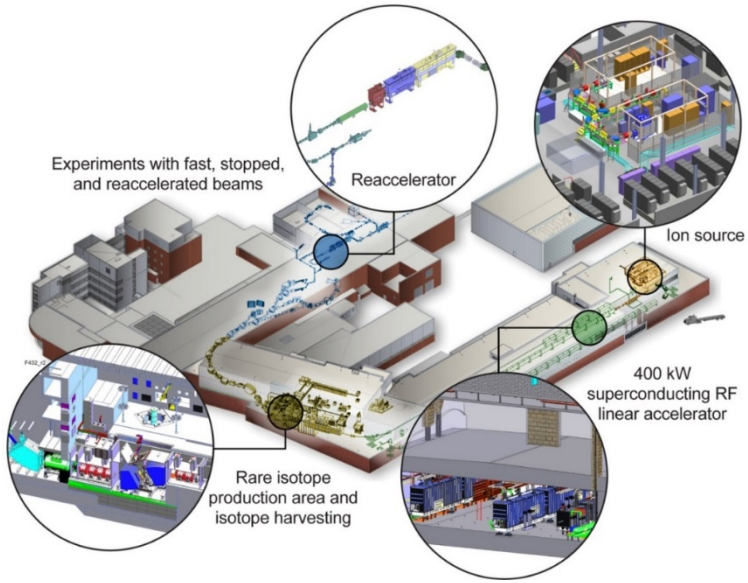


- Required capabilities:
  - Detect every possible type of emitted radiation
  - Measure and resolve all decay paths in the same experiment
  - Maximize detection efficiency and energy resolution
  - Work with high and low rate
  - Work with fast and low-energy beam





- Multi-institutional effort (UT + 15 institutions)
- Pre-conceptional design underway
  - Existing detector arrays can be adopted for Day-1 science program

Summary

- FRIB will have unique Day-1 capabilities that enable fore-front science
  - Beam rates higher than available at other facilities
  - Only facility with fast, stopped and reaccelerated beams
  - Broad set of experimental instruments available – path for major new instruments in place
- Continued developments are underway to be well prepared for FRIB Day-1 science
  - HRS highbay for high-rigidity experiments
  - Continue to improve beam stopping
  - Continue to improve charge breeding
  - Increase of ReA beam energy
  - Prepare for isotope harvesting and commensal beams
- FRIB on track to start Day-1 science in 2021