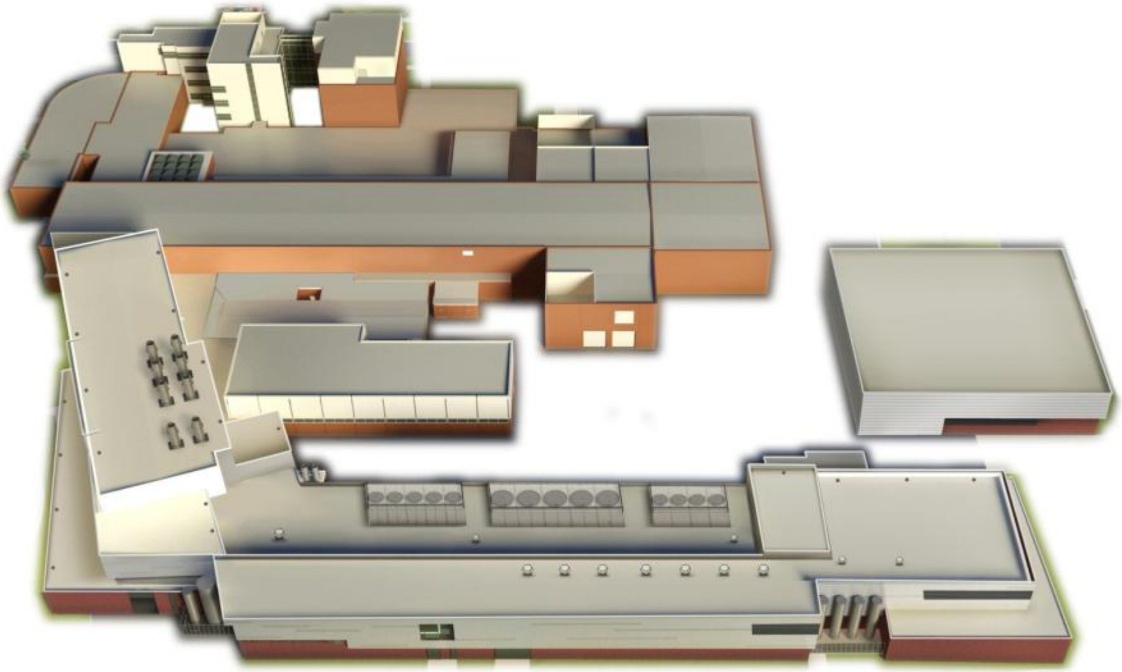


Facility for Rare Isotope Beams – Science and Status

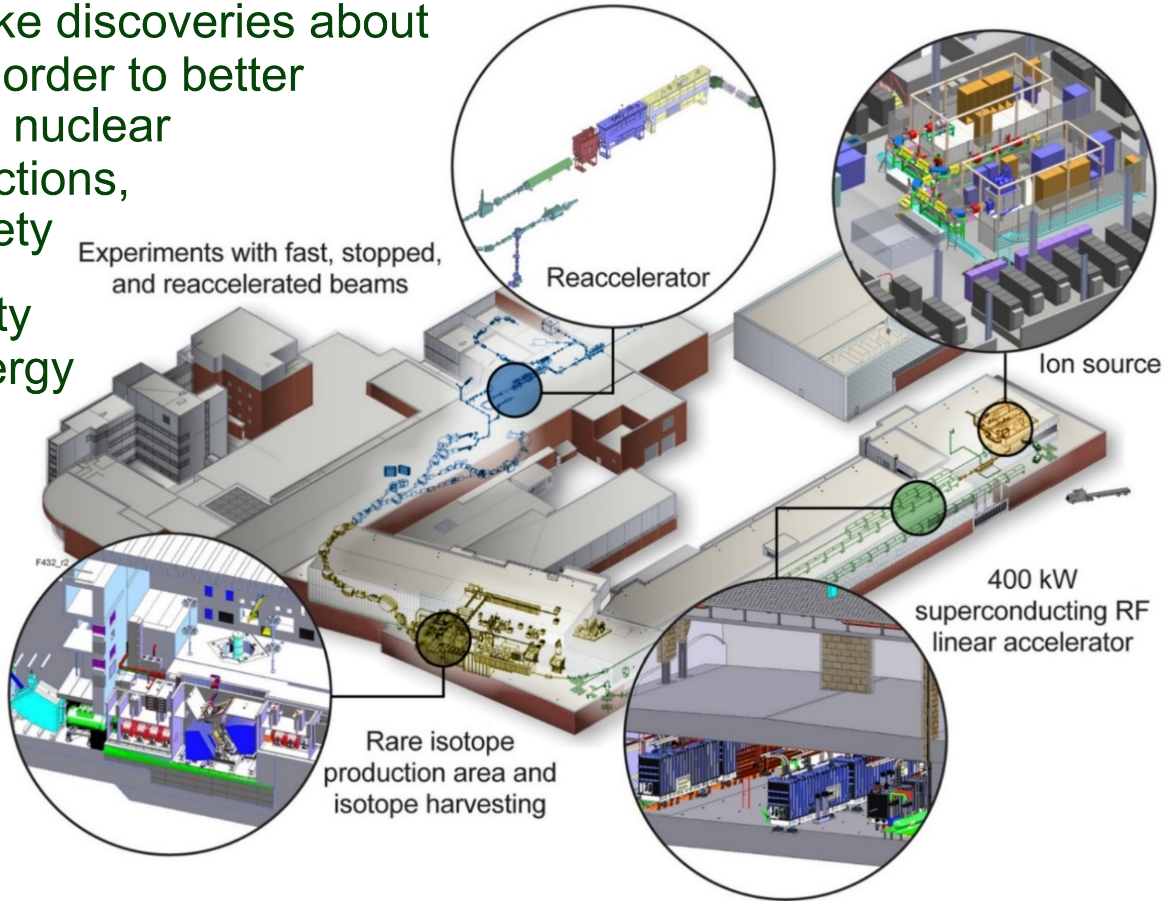
Georg Bollen
Michigan State University

MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

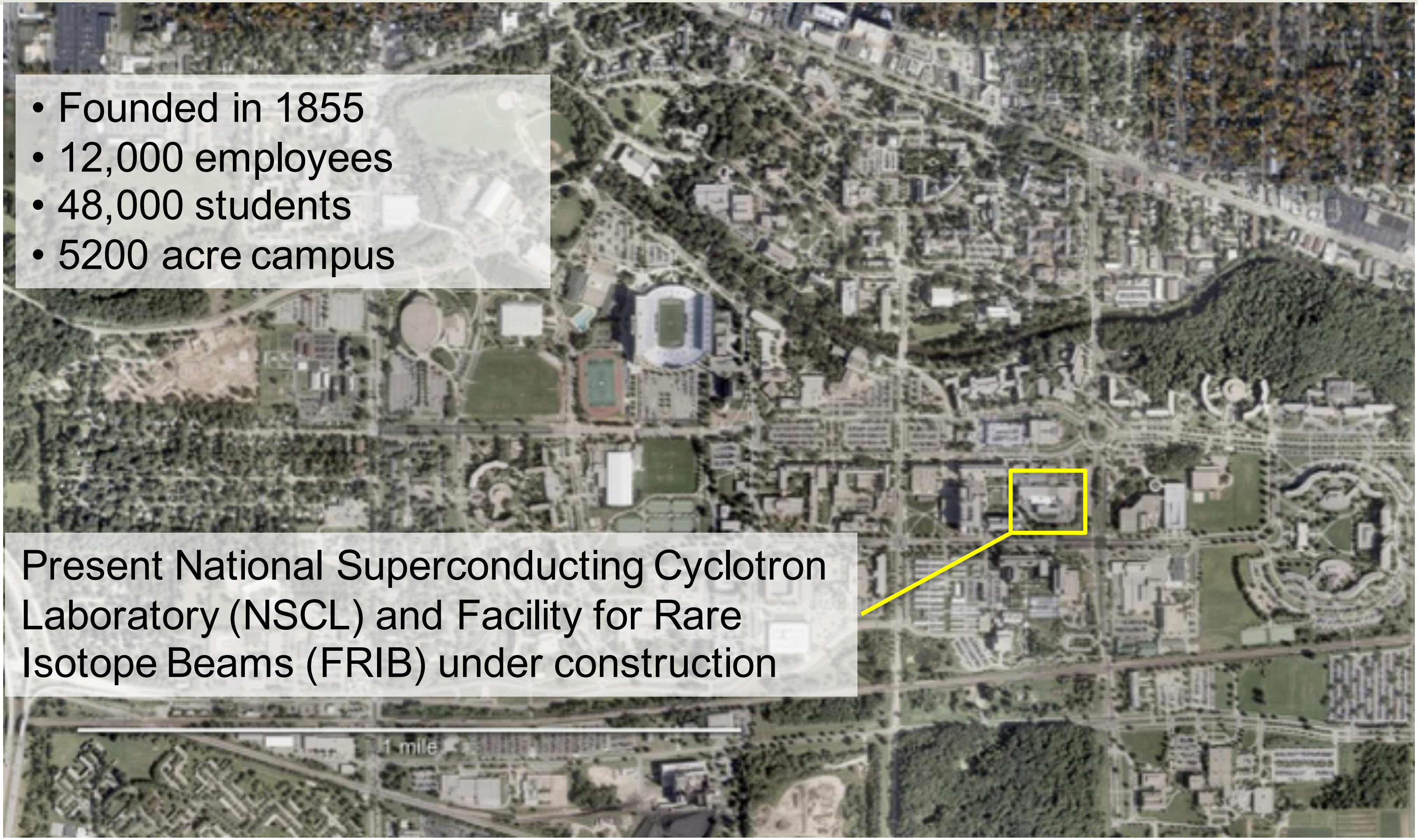
Facility for Rare Isotope Beams

- FRIB will enable scientists to make discoveries about the properties of rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and support applications for society
- FRIB will be a national user facility funded by the Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- FRIB Project completion date is June 2022, managed to an early completion in FY2021



Michigan State University, East Lansing
Home of Future FRIB

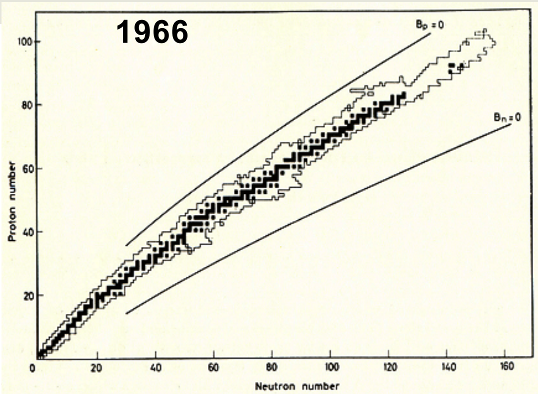
- Founded in 1855
- 12,000 employees
- 48,000 students
- 5200 acre campus



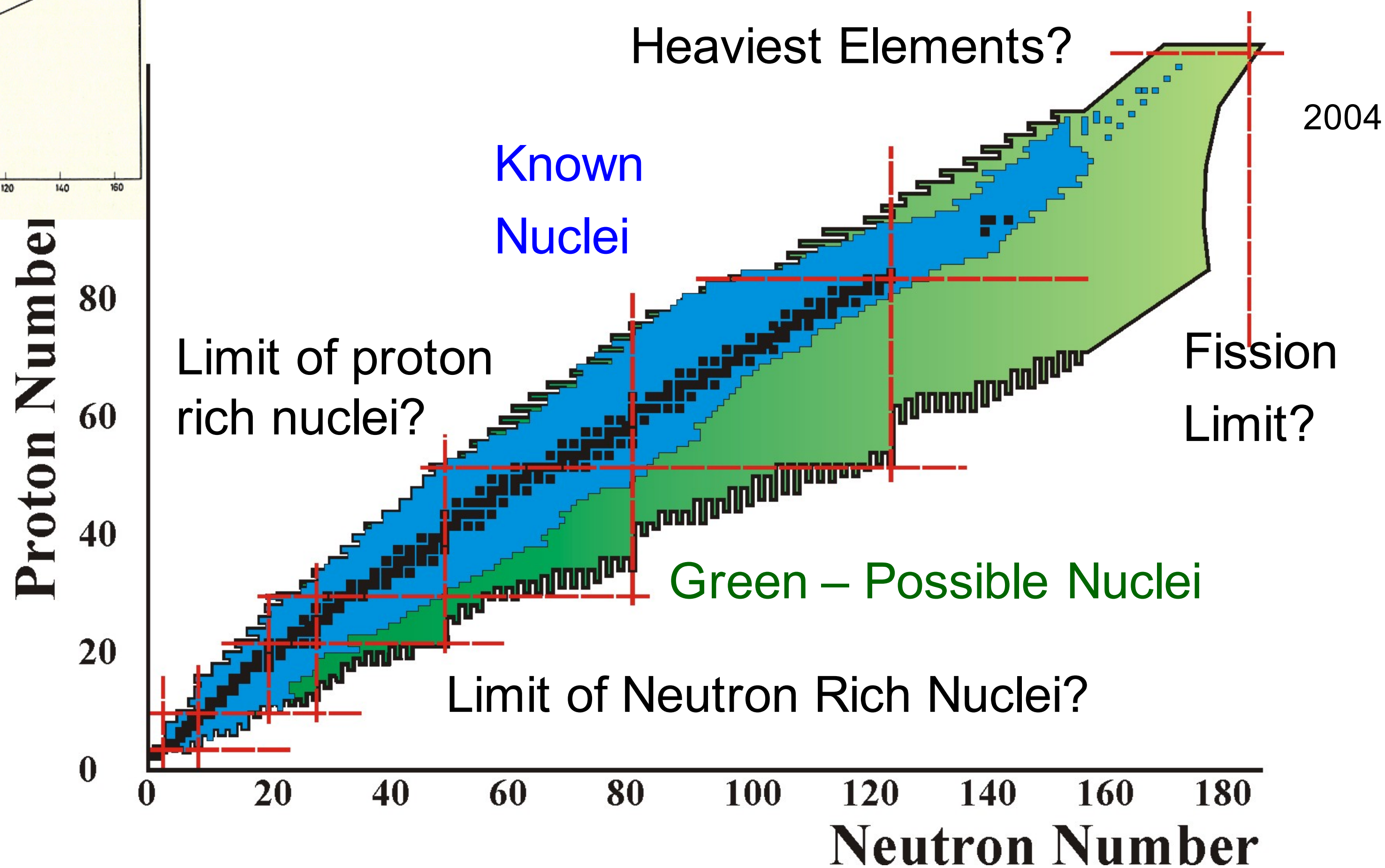
Present National Superconducting Cyclotron Laboratory (NSCL) and Facility for Rare Isotope Beams (FRIB) under construction

Facility for Rare Isotope Beams

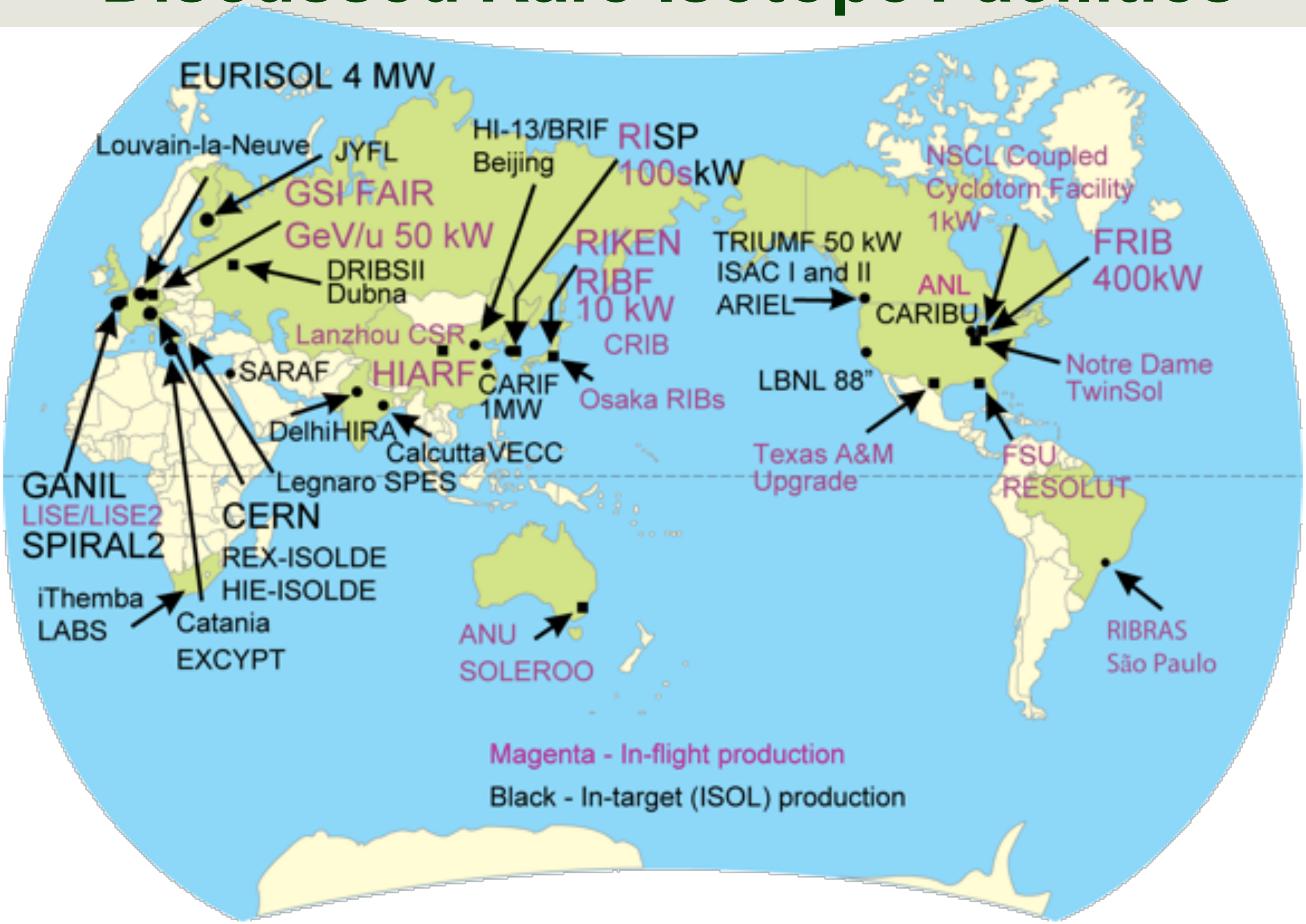
Rare Isotopes
Which do We Know? Which May Exist?



1966 Lysekil Symposium on "Why and How should we investigate nuclides far off the stability line?"

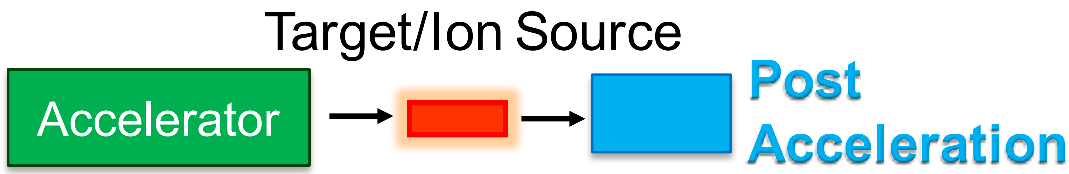


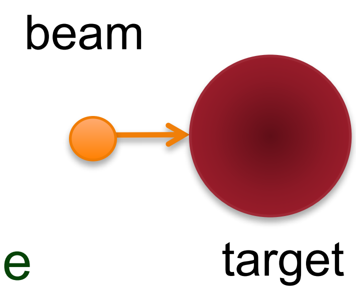
World View of Existing + Planned + Discussed Rare Isotope Facilities



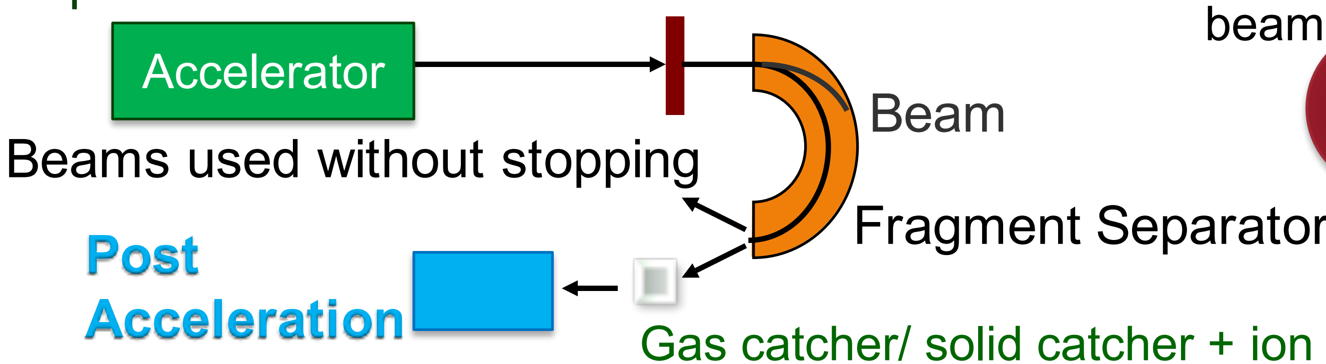
Rare Isotope Production Techniques

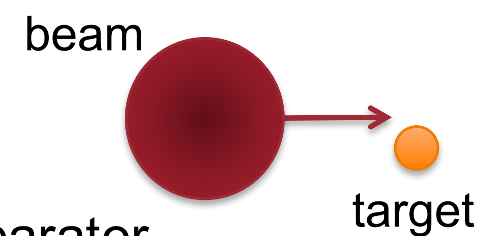
- Extraction from a heated target following target spallation, fragmentation, and/or fission by light ions (ISOL – Isotope separation on line) – CERN ISOLDE, TRIUMF ISAC are examples





- In-flight separation following nucleon transfer, fusion, projectile fragmentation/fission (Fragmentation) – GSI/FRS, RIKEN/RIBF, NSCL/CCF are examples



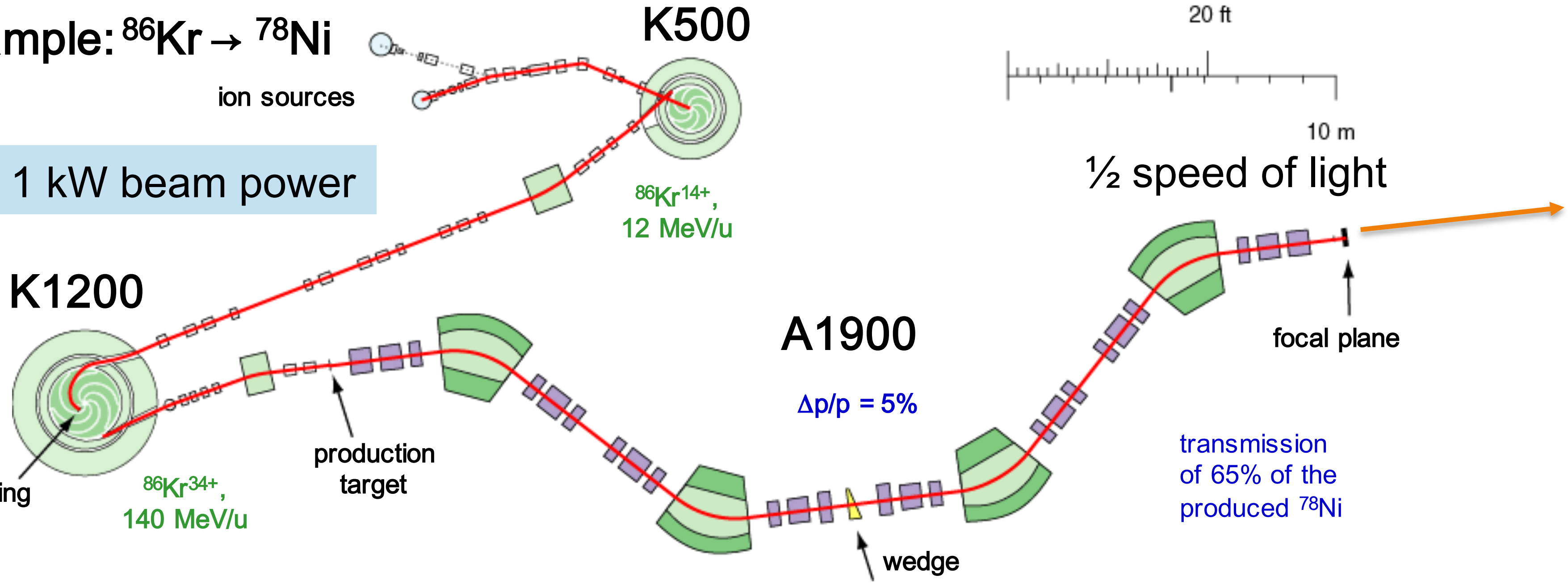


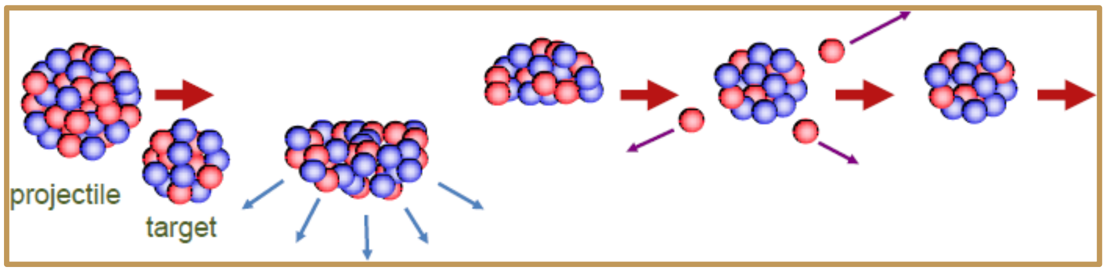
In-Flight Production of Rare Isotopes

Example: National Superconducting Cyclotron Laboratory (NSCL) at MSU

Example: $^{86}Kr \rightarrow {}^{78}Ni$

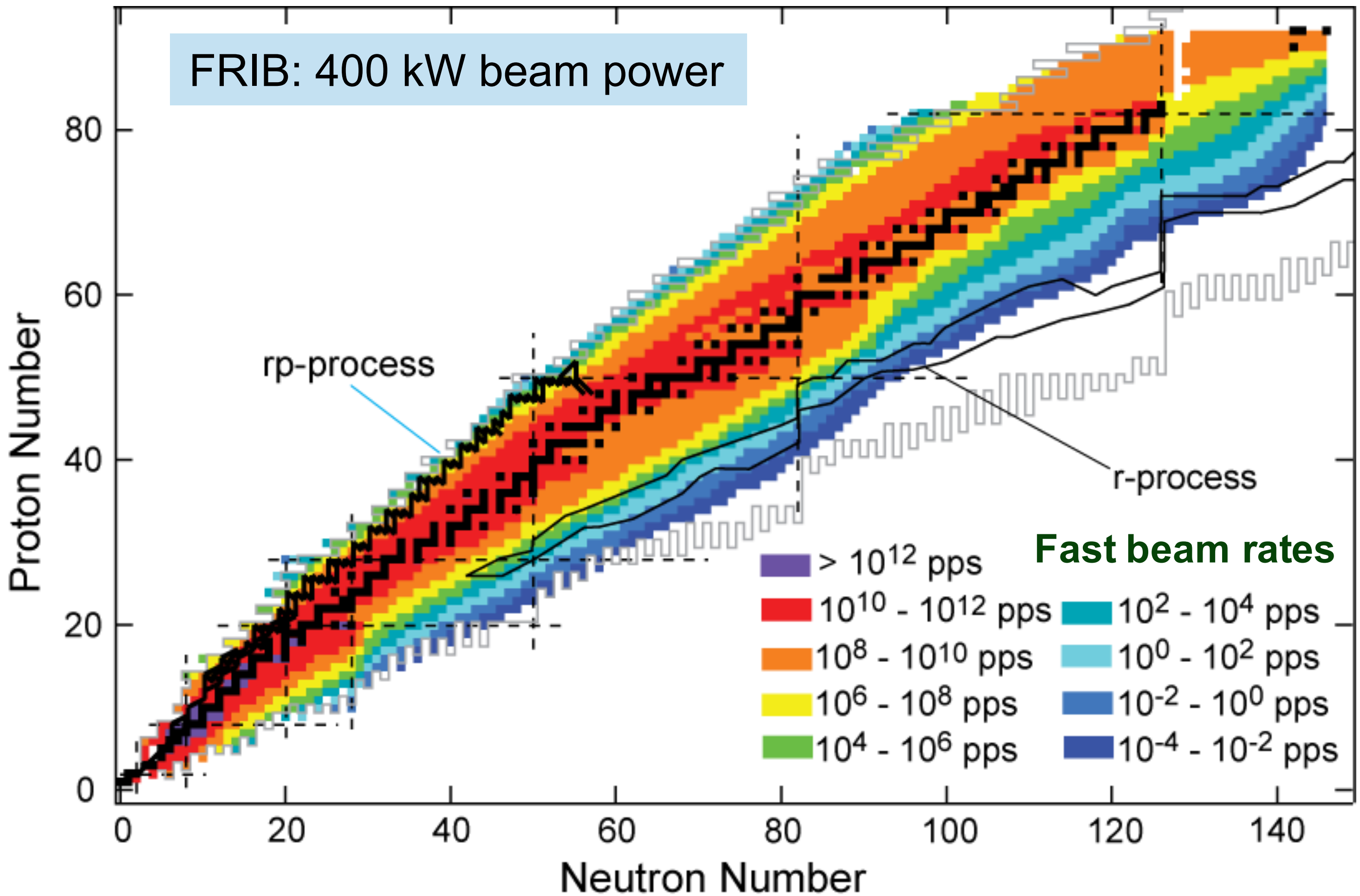
1 kW beam power





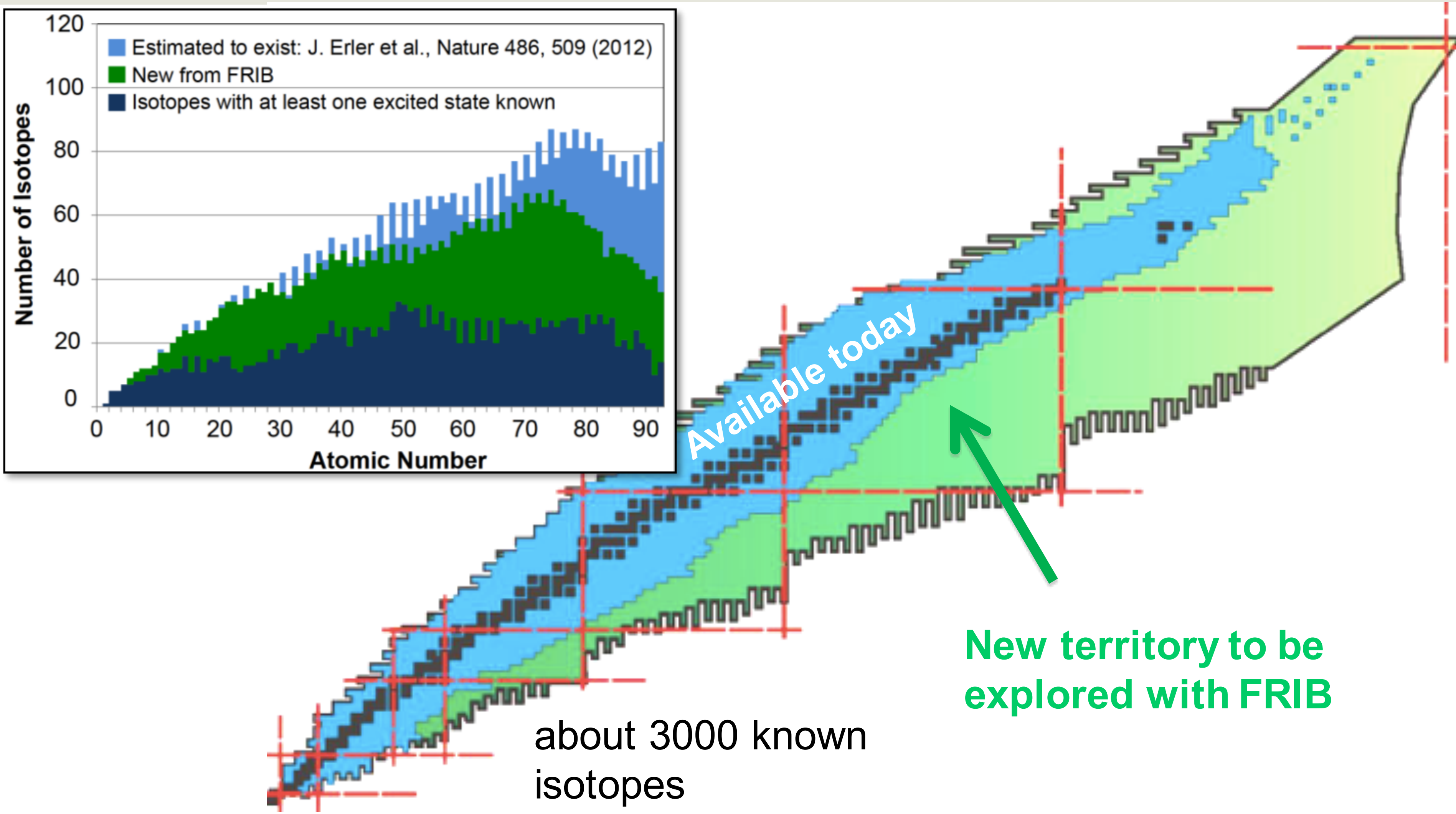
No chemistry involved, fast, universal production

FRIB Rare Isotope Beams
High Beam Rates to Maximize Science Reach



Rates are available at http://groups.nscl.msu.edu/frib/rates/

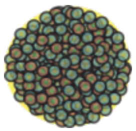
FRIB Isotopes Will Enable New Discoveries



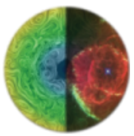
New territory to be explored with FRIB

about 3000 known isotopes

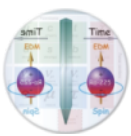
FRIB – Four Science Themes



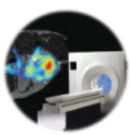
Properties of nuclei
- Develop a predictive model of nuclei and their interactions
- Many-body quantum problem: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.



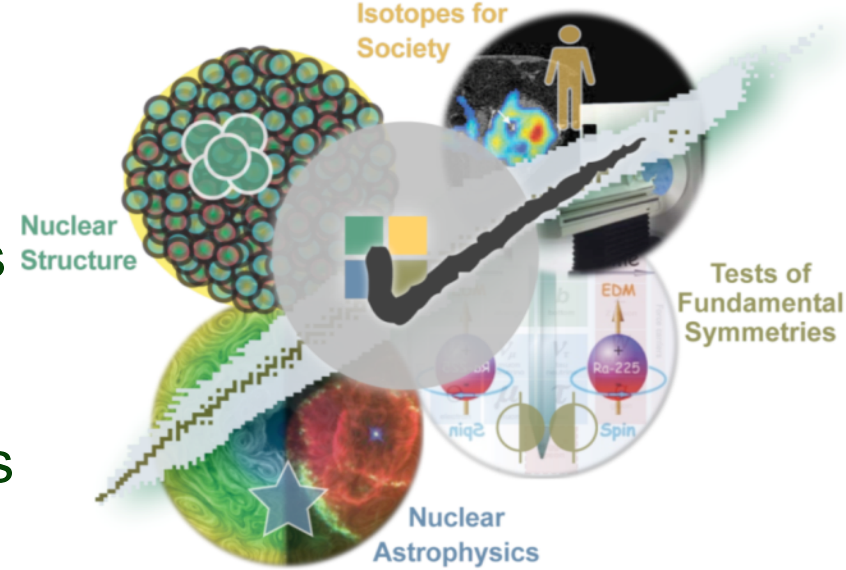
Astrophysical processes
- Origin of the elements in the cosmos
- Explosive environments: novae, supernovae, X-ray bursts …
- Properties of neutron stars



Tests of fundamental symmetries
- Effects of symmetry violations are amplified in certain nuclei

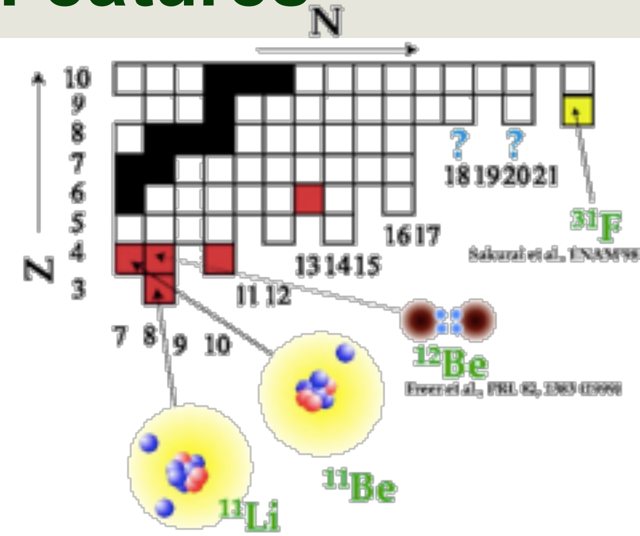


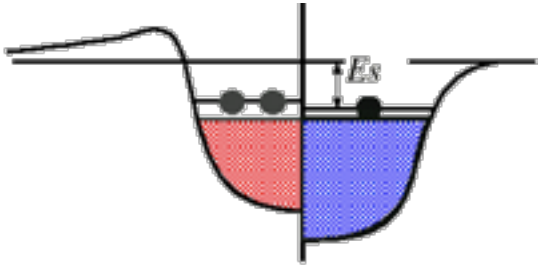
Societal applications and benefits
- Bio-medicine, energy, material sciences, national security

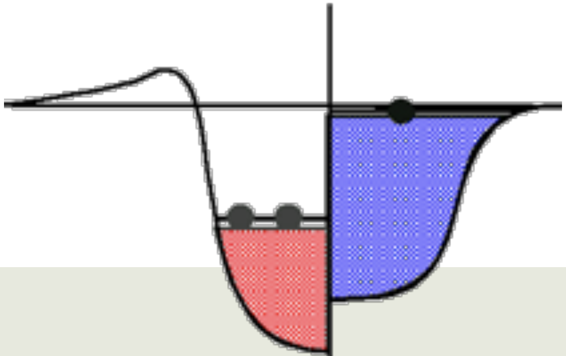


Properties of Nucleonic Matter
Rare Isotopes Reveal New Features

- Studies of rare isotopes are crucial for developing reliable models of nuclei and their reactions
  - Link to mesoscopic science – deriving the properties of complex systems from their simple building blocks
- Stable nuclei: N/Z ≈ 1 - 1.5, $S_p \approx S_n \approx 6 - 8$ MeV
  - Homogeneous admixture of protons and neutrons
  - Good mean-field description & "single-particle" picture
  - Large gaps between major shells (magic numbers)
  - Empirical shell-model interactions
- Very neutron-rich nuclei: N/Z ≈ 2 - 2.5, S_n << 1 MeV
  - Extended neutron distributions – neutron skins & halos
  - Proximity of the Fermi surface – coupling to the continuum
  - Redefinition of magic numbers
  - Unknown shell-model interactions

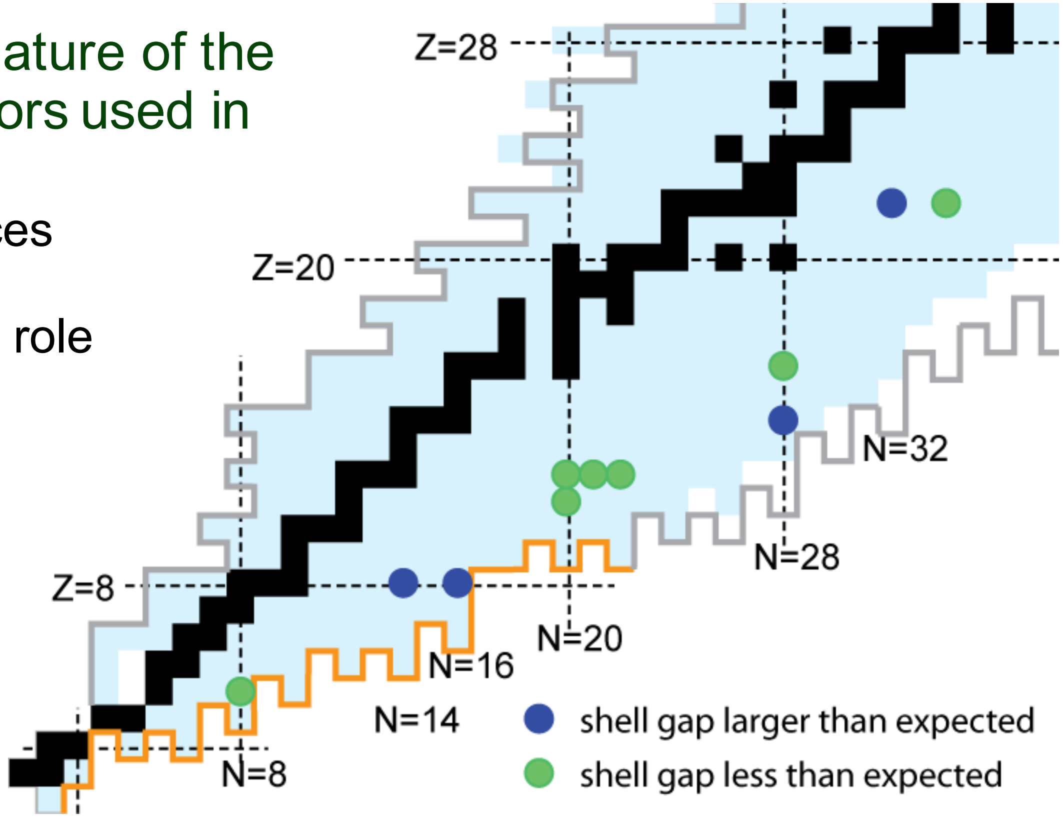






Properties of Nucleonic Matter
Example: Evolution of Shell Structure

- How magic are magic numbers?
- Improved understanding of the nature of the effective interactions and operators used in nuclear structure models
  - Insight into tensor and 3-body forces in nuclei
  - The continuum plays an important role in weakly bound nuclei
- Needed: excitation energies, B(E2) gamma decay strength, spectroscopic factors, nuclear moments, masses, …
- Further surprises are to be expected

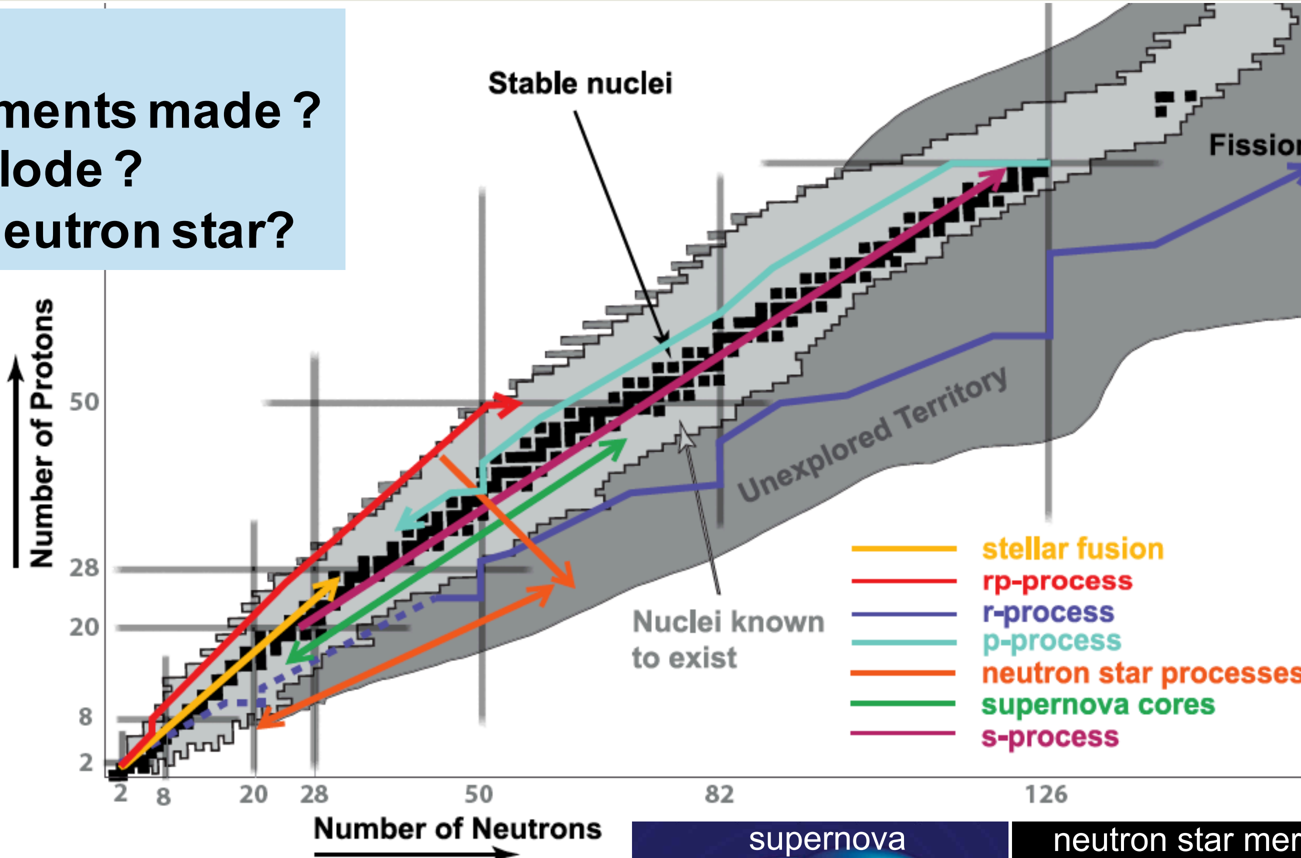


Search for new nuclear "magic" numbers

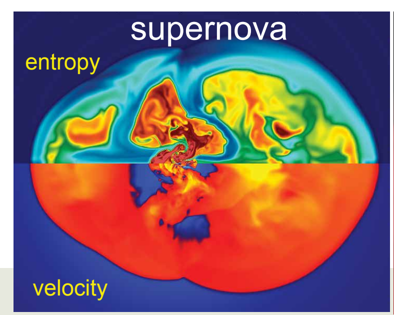
Rare Isotopes are Key for Astrophysics

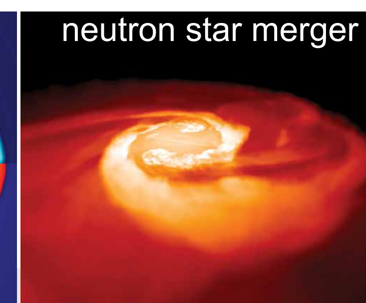
FRIB will reach most of the relevant isotopes

Science questions:
- How were the elements made ?
- How do stars explode ?
- What is inside a neutron star?



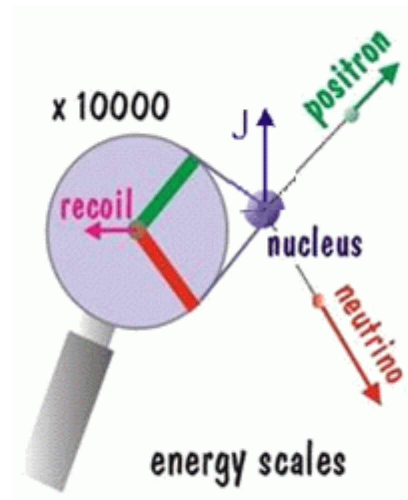
- Needed
  - Nuclear experimental data (masses, half-lives) plus improved nuclear theory
  - Precision observations of abundance patterns produced by the r-process in nature

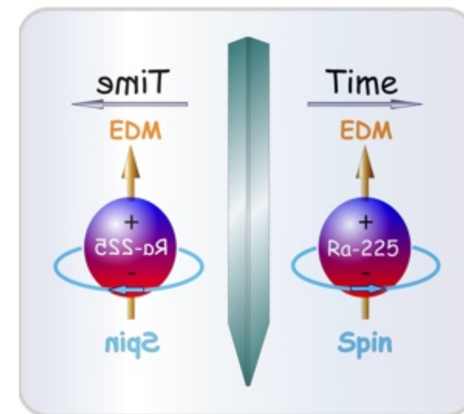




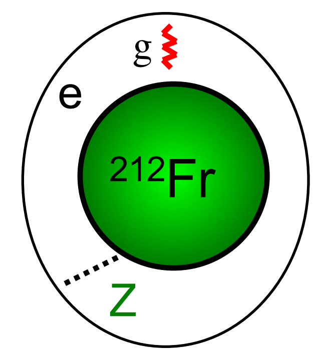
Tests of Fundamental Symmetries
Why is here more matter than antimatter in the universe?

- Angular correlations in β-decay and search for scalar currents
  - Mass scale for new particle comparable with LHC
- Electric Dipole Moments
  - ^{225}Ra, ^{223}Rn, ^{229}Pa
- Parity Non-Conservation in atoms
  - Weak charge in the nucleus (francium isotopes)
- Unitarity of CKM matrix
  - V_{ud} by superallowed Fermi decay
  - Probe the validity of nuclear corrections





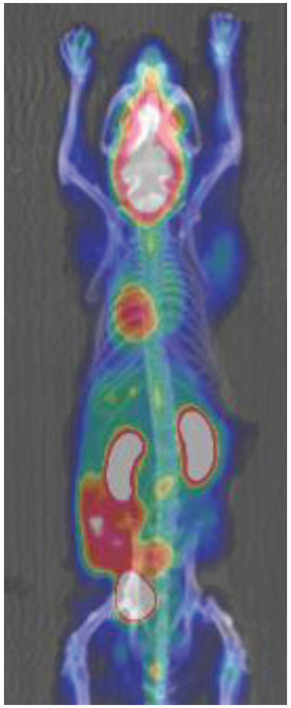
$$\begin{vmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix}$$



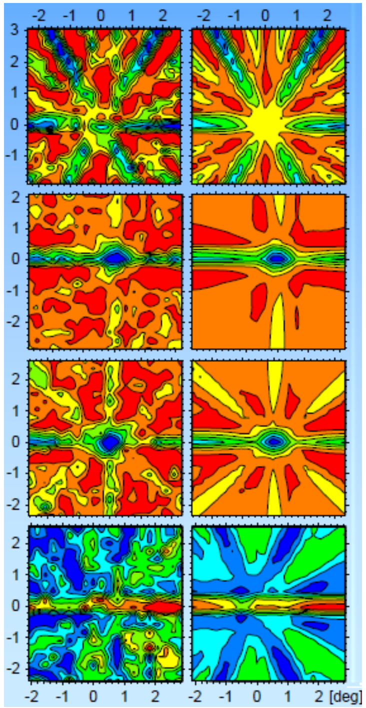
Applications of Rare Isotopes

FRIB will Provide Research Quantities of New Isotopes

- Isotopes for medical research
  - Targeted cancer imaging and therapy, quantities sufficient for preclinical studies and early clinical trials, (^{67}Cu, ^{225}Ac, …)
- Isotopes for national security
  - Study of important nuclear reactions needed for national security missions of stockpile stewardship and nuclear forensics
- Isotopes to support new research in ecology and biochemistry
  - Study of rates and specific sites of enzyme activity within microbe and plant cells
- Isotopes of importance for the energy industry
  - Measurable quantities of nuclear-power relevant actinides and their fission products
- Isotopes for nanoscience, material science, and engineering
  - Rare isotopes provide low-density, very-high-signal-to-noise in situ probe of local atomic environments



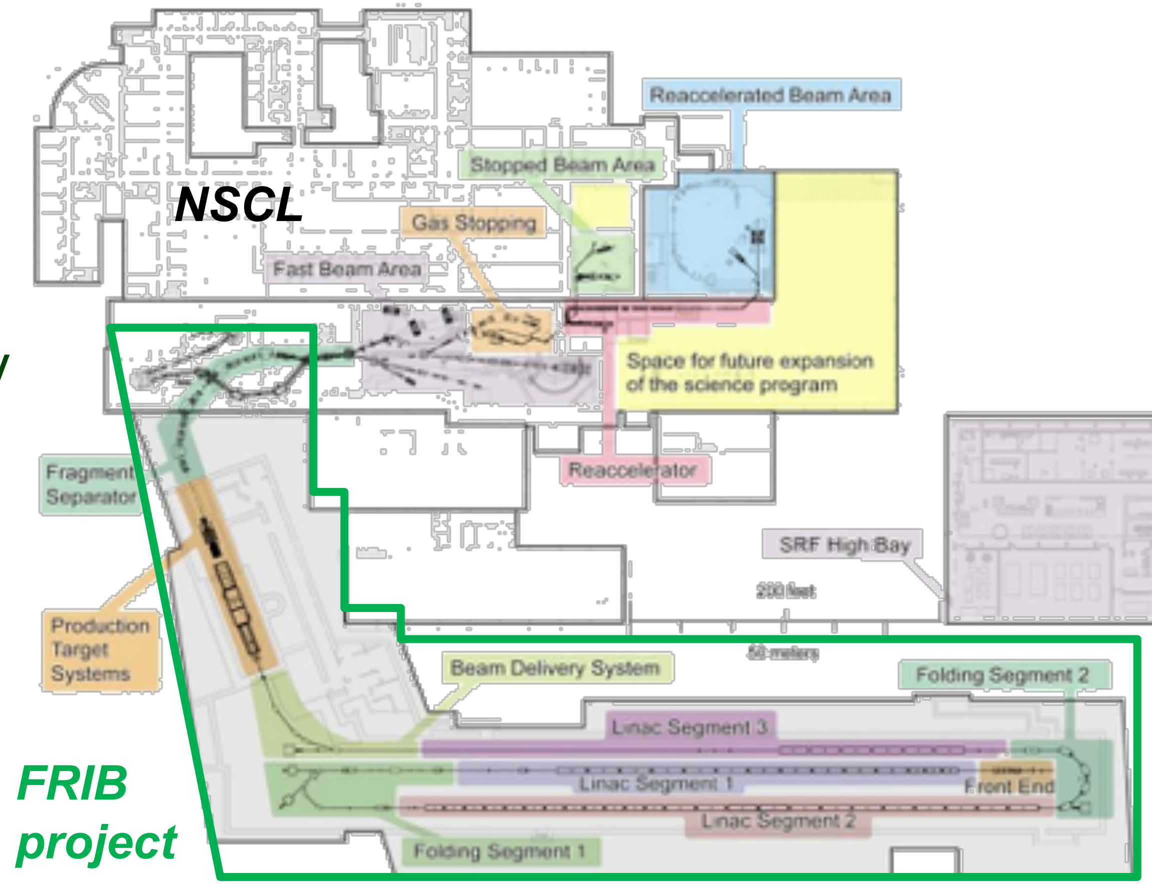
Preclinical research: PET-CT image



β^- emission channeling at ISOLDE/CERN: ^{24}Na site changes in ZnO semiconductor

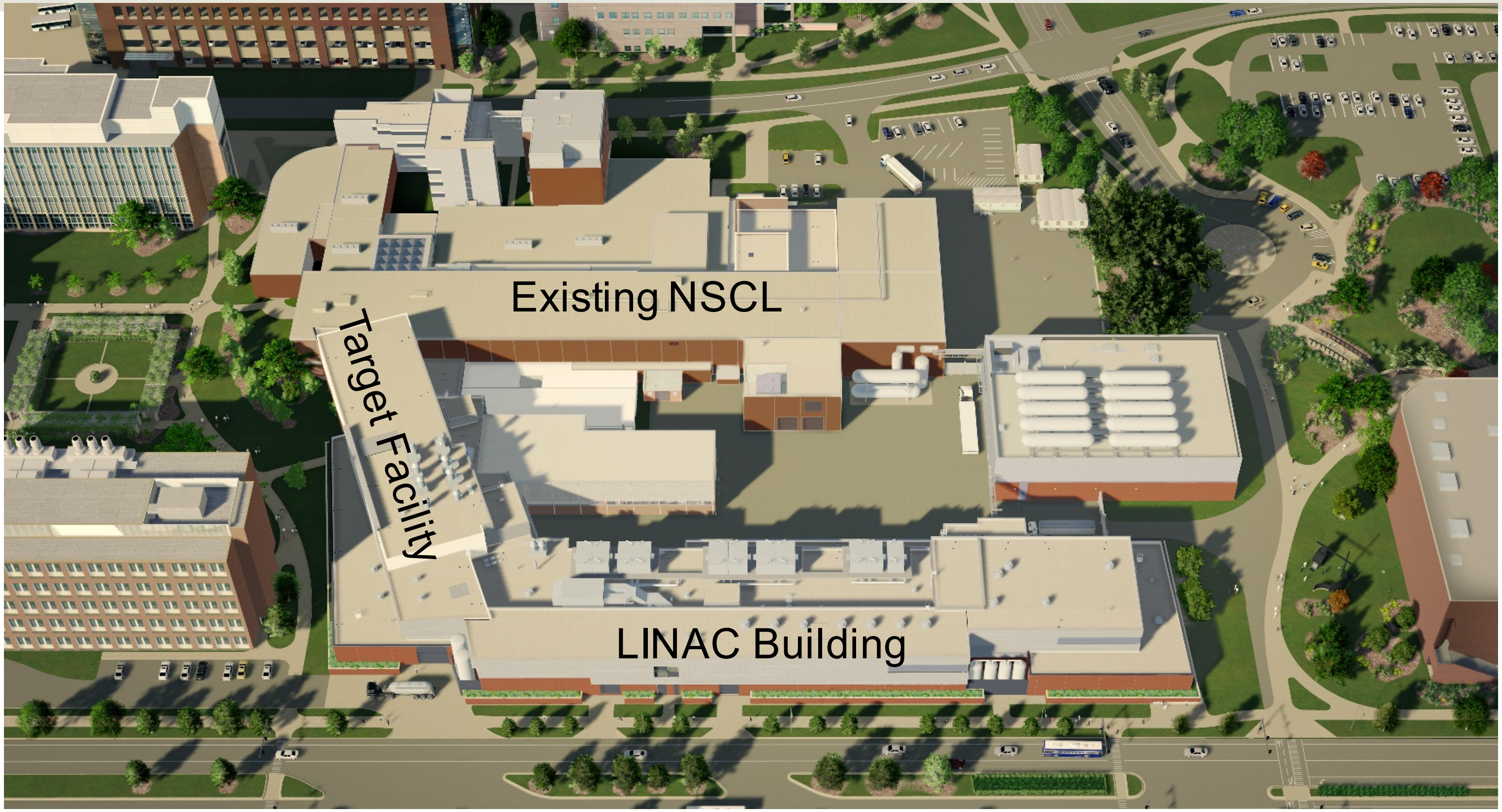
FRIB - Facility for Rare Isotope Beams
NSCL enables pre-FRIB science

- Rare isotope production via in-flight technique with primary beams up to 400 kW, 200 MeV/u uranium
- Fast, stopped, and re-accelerated beam capability
- NSCL provides pre-FRIB science opportunities
  - Facilities will be integrated into FRIB
- FRIB has upgrade options
  - Provisions for 400 MeV/u
  - Provisions for ISOL production



Total project cost $730 million

FRIB Construction Underway



FRIB Civil Construction on Track

Started March 2014, 10 weeks ahead of Schedule

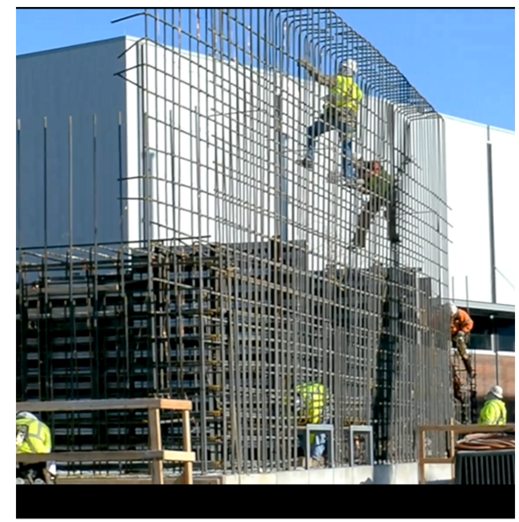
- FRIB construction site on 23 January 2016 - web camera at www.frib.msu.edu – 22nd month

FRIB Civil Construction Progress
Linac Tunnel and Target Facility

High voltage platforms for ion sources

Target facility hot-cell remote handling

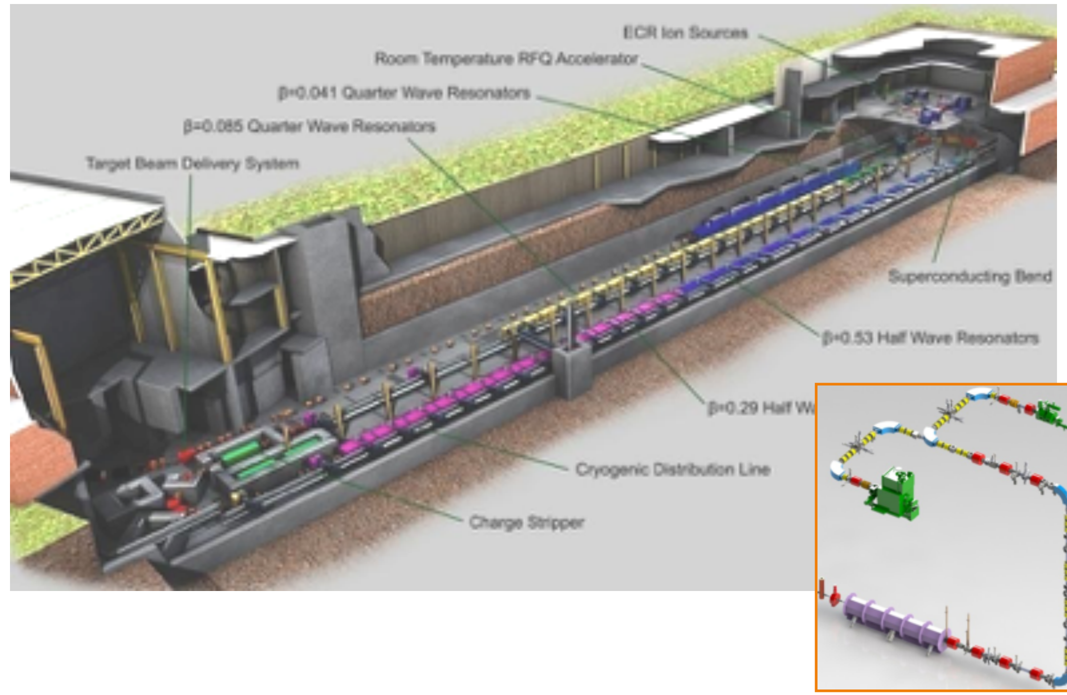
Non-conventional utilities

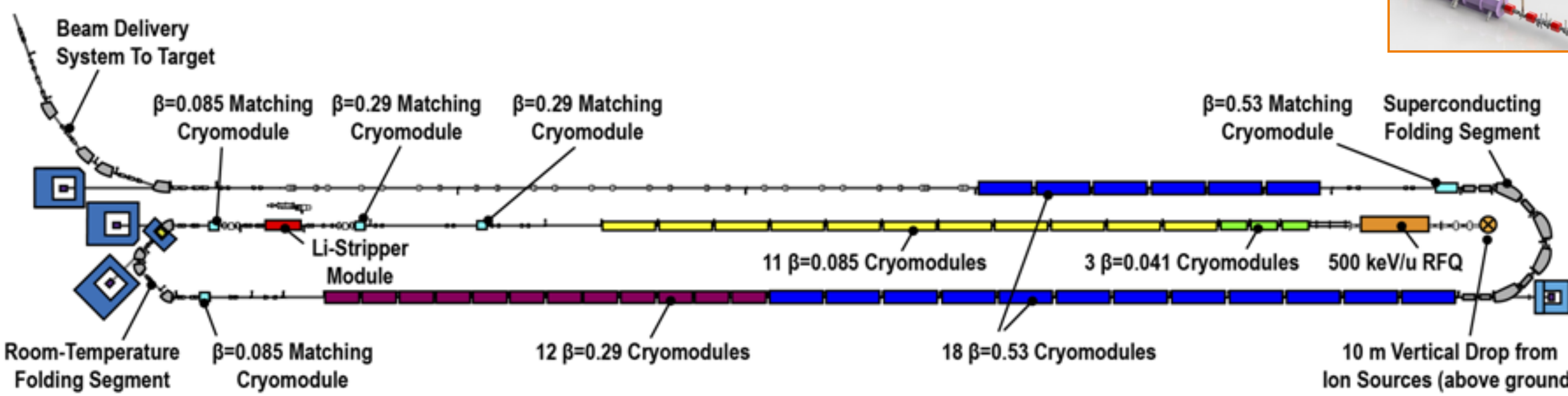


Target hot-cell wall forming

FRIB Accelerator Systems
Superconducting RF Driver Linac

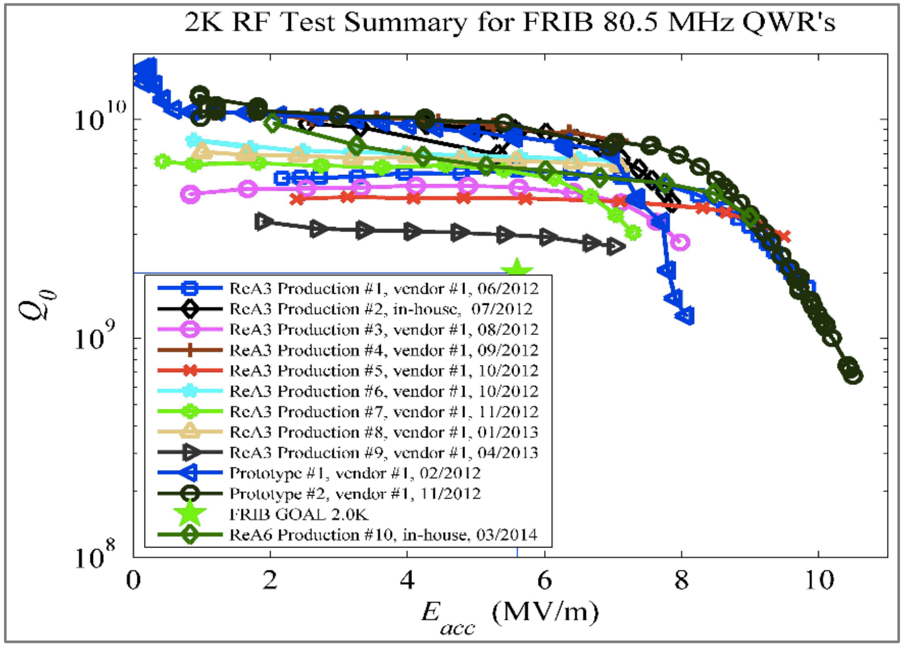
- Accelerate ion species up to ^{238}U with energies of no less than 200 MeV/u
- Provide beam power up to 400kW
- Energy upgrade to 400 MeV/u for ^{238}U by filling vacant slots with 12 SRF cryomodules

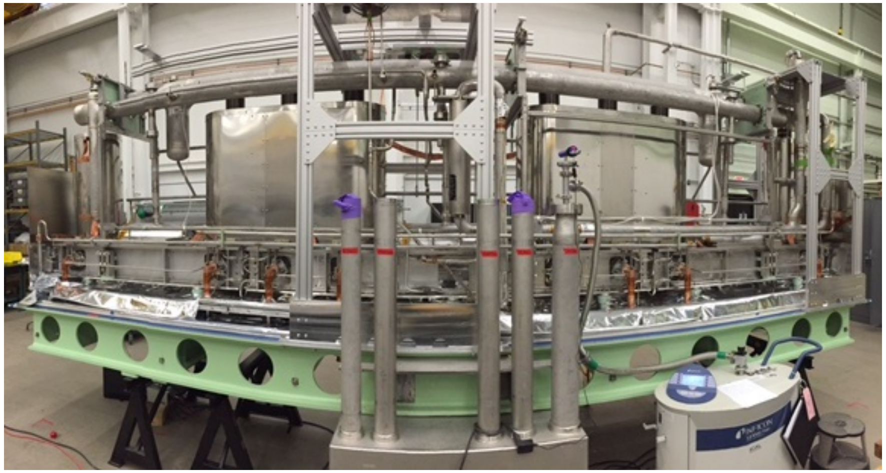




FRIB Accelerator Systems
Production underway

- Cavity and cryomodule production underway
  - Cavities exceed FRIB performance goals

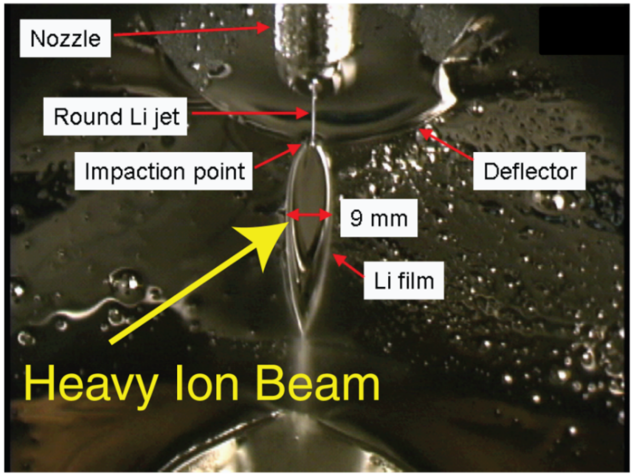


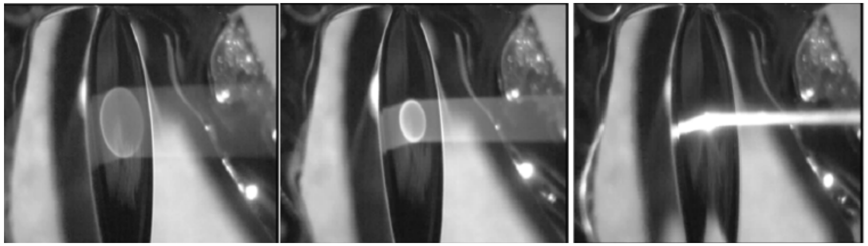


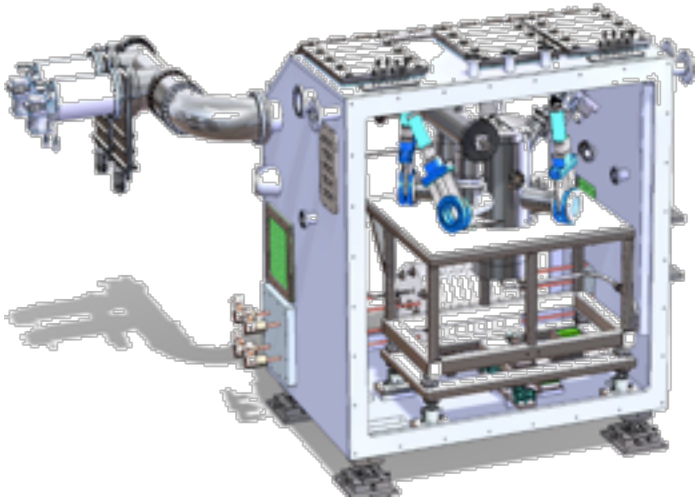
Accelerator Technical Challenges Being Met

Example: Charge Stripping of Intense Heavy Ion Beams

- High specific power loss of heavy ions in matter
  - Solid stripper not an option (10 MW/cm^3 power density)
  - Fast liquid metal film, plasma stripper are options
- Liquid Lithium Film Charge Stripper
  - Liquid lithium film (10 μm thick), ~50 m/s
  - Uniformity to ~10% within beam spot area
  - Beam power tests at ANL on liquid lithium film successful

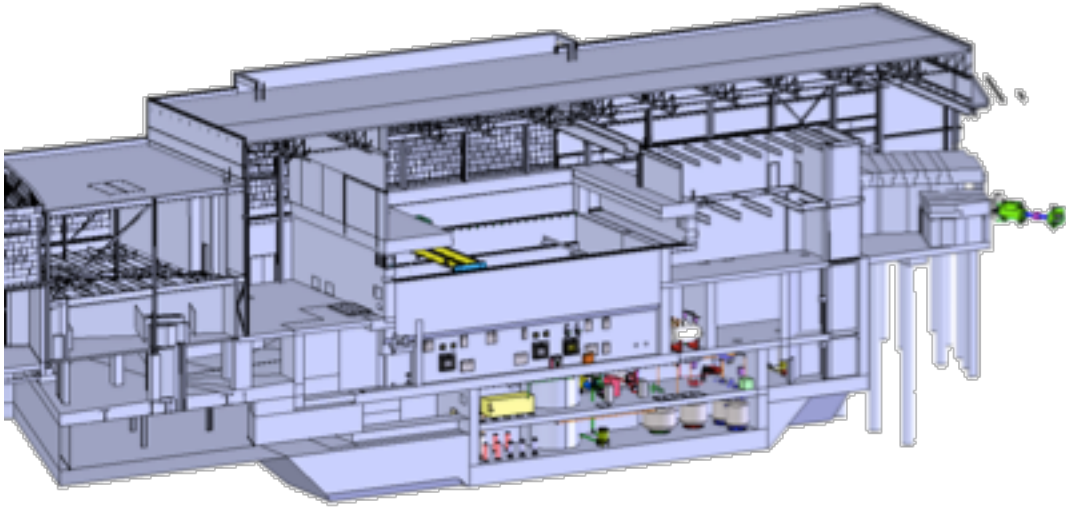


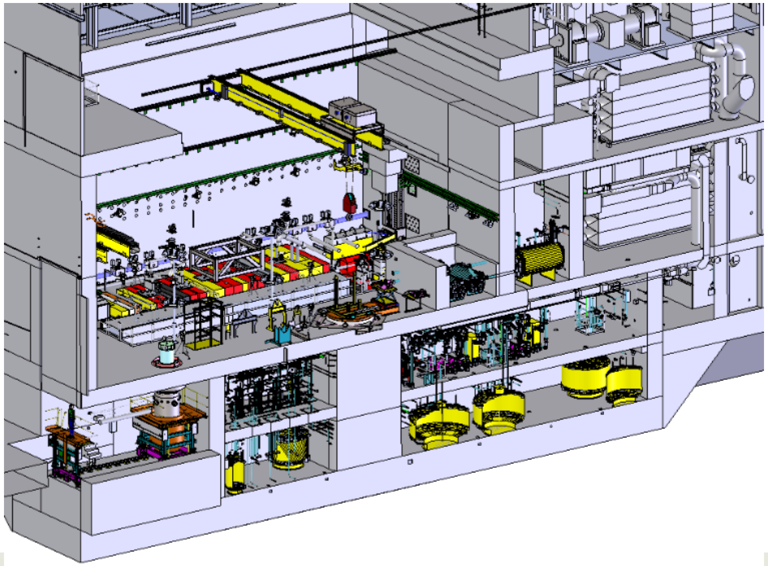


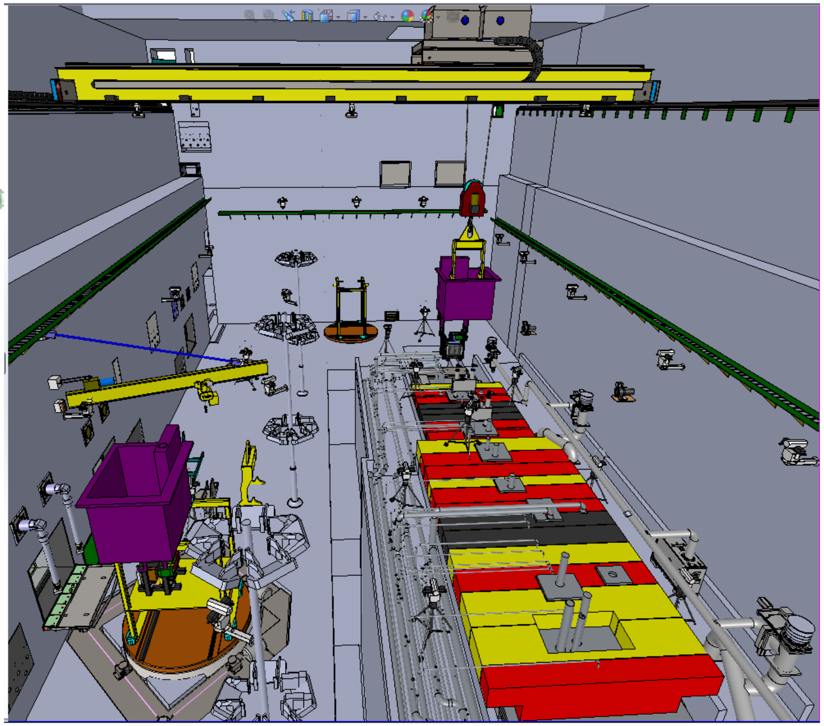


Argonne NATIONAL LABORATORY

FRIB Rare Isotope Production Facility
Designed for 400 kW Operation





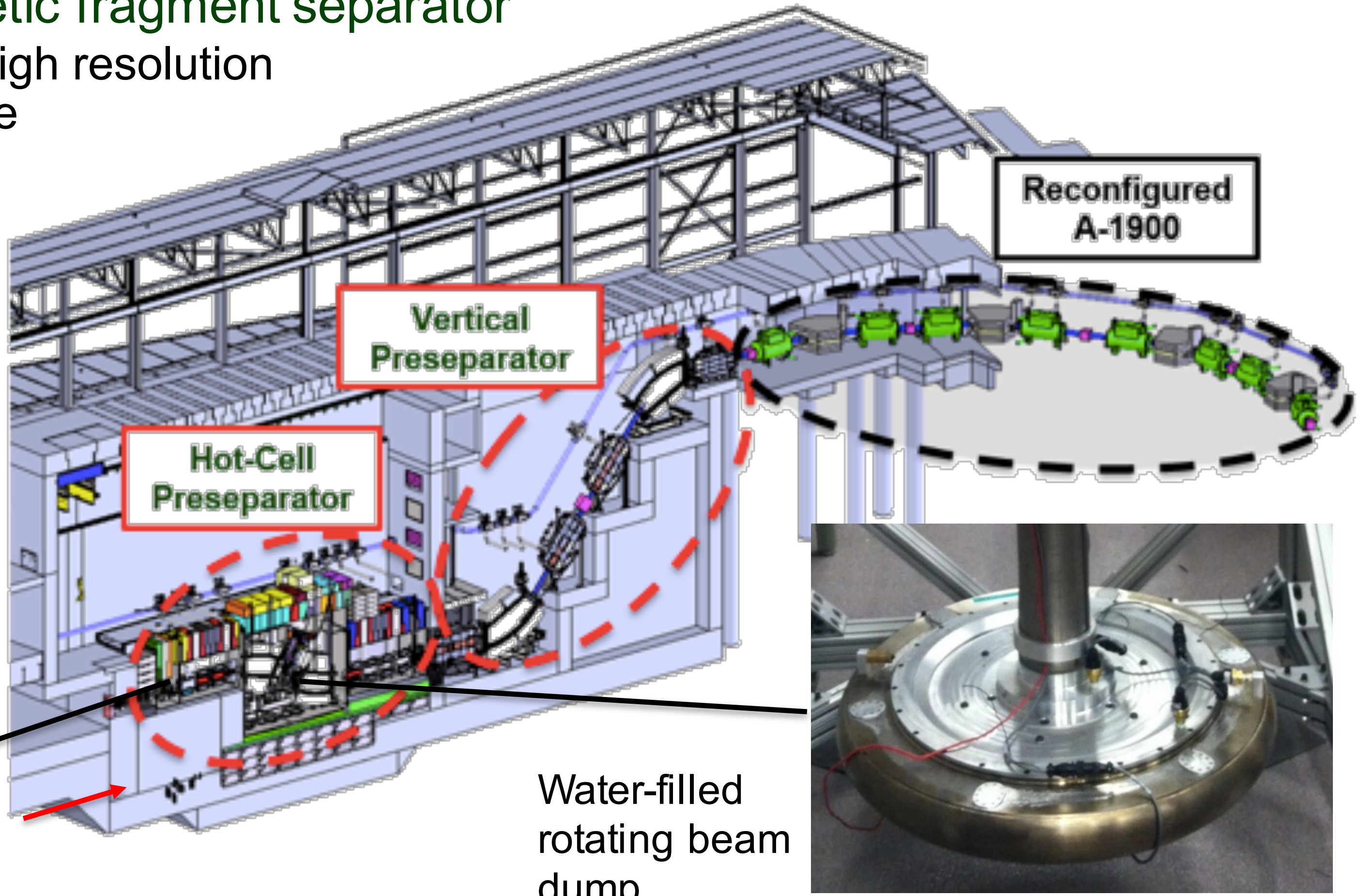


- Accommodates first part of fragment separator with target and beam dump
- Remote-handling of activated components (target change within 24 h)
- Non-conventional utilities

Oak Ridge National Laboratory

FRIB Fragment Separator
Producing and Selecting Rare Isotope

- Three stage magnetic fragment separator
  - High acceptance, high resolution to maximize science
- Challenges due to 400 kW heavy ion beams
  - High radiation
  - High power densities

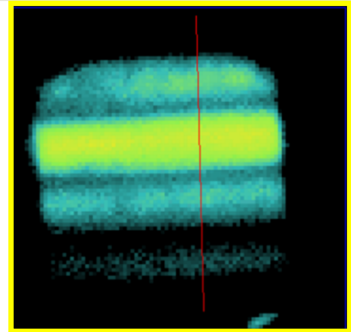


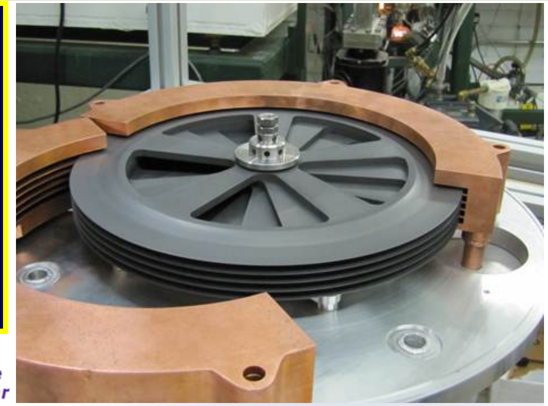
Multi-slice rotating graphite target

Water-filled rotating beam dump

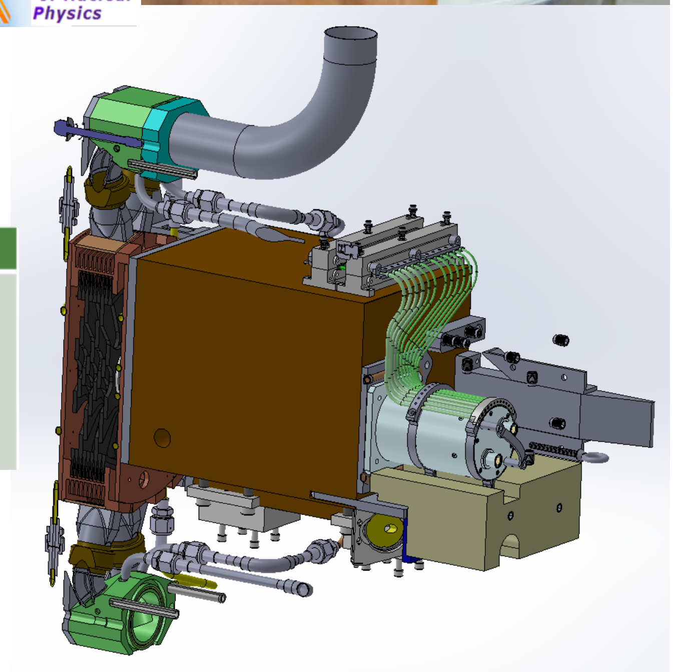
High-power Production Target
High Power Density Challenge Being Met

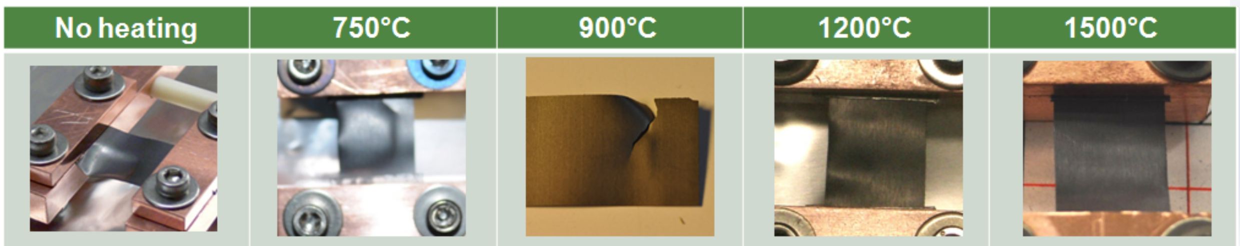
- Production Target
  - 100 kW beam power loss
  - 1 mm beam spot → 60 MW/cm^3 for ^{238}U
- Multi-slice rotating graphite target
  - 5000 rpm, 30 cm diameter
  - T_{max} =1900 C, P_{max}/slice=10 kW
- Target concept validated
  - High power electron beam tests
  - Graphite heavy ion irradiation studies





Budker Institute of Nuclear Physics





Confirmed with additional material tests

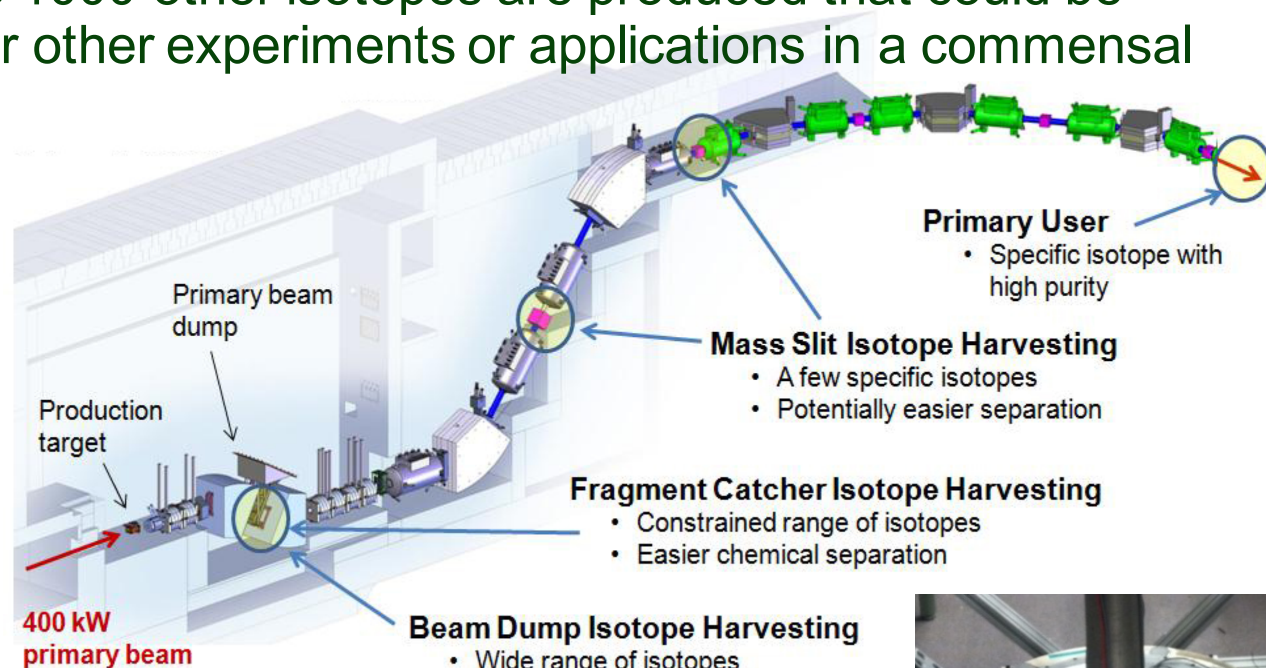
Isotope Harvesting Opportunity at FRIB
Make Best Use of Rare Isotopes Produced

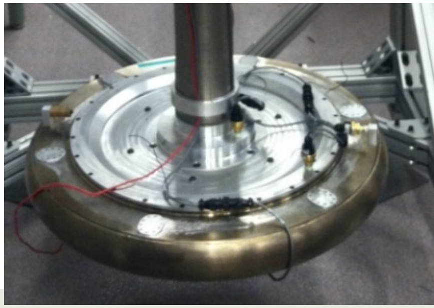
- Produce a rare isotope beam for a primary user, for example ^{200}W from a ^{238}U primary beam
- At the same time up to 1000 other isotopes are produced that could be harvested and used for other experiments or applications in a commensal mode of operation

1st workshop on "Isotope Harvesting at FRIB", Santa Fe, 2010

2nd workshop on "Isotope Harvesting at FRIB", East Lansing, 2012

3rd workshop on "Isotope Harvesting at FRIB", St Louis, 2014



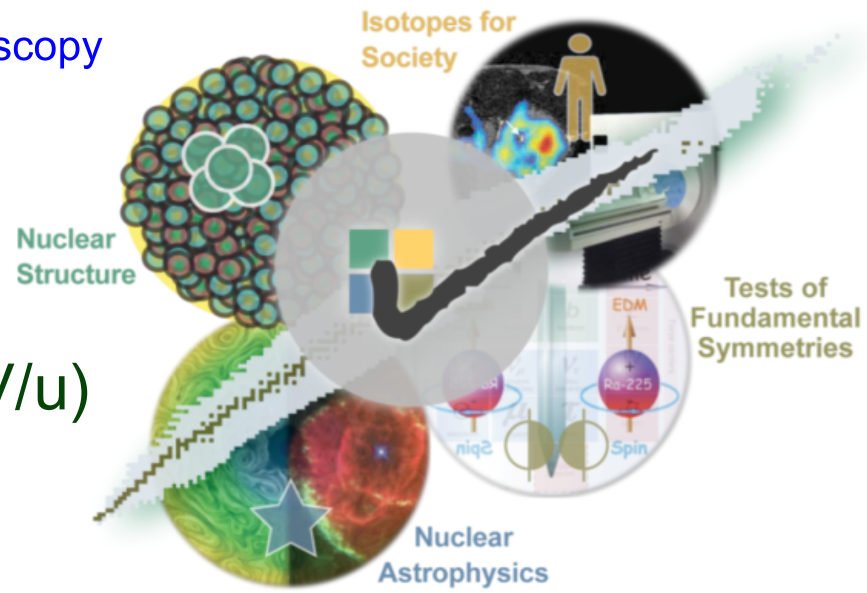


FRIB has provisions for isotope harvesting incorporated in the design

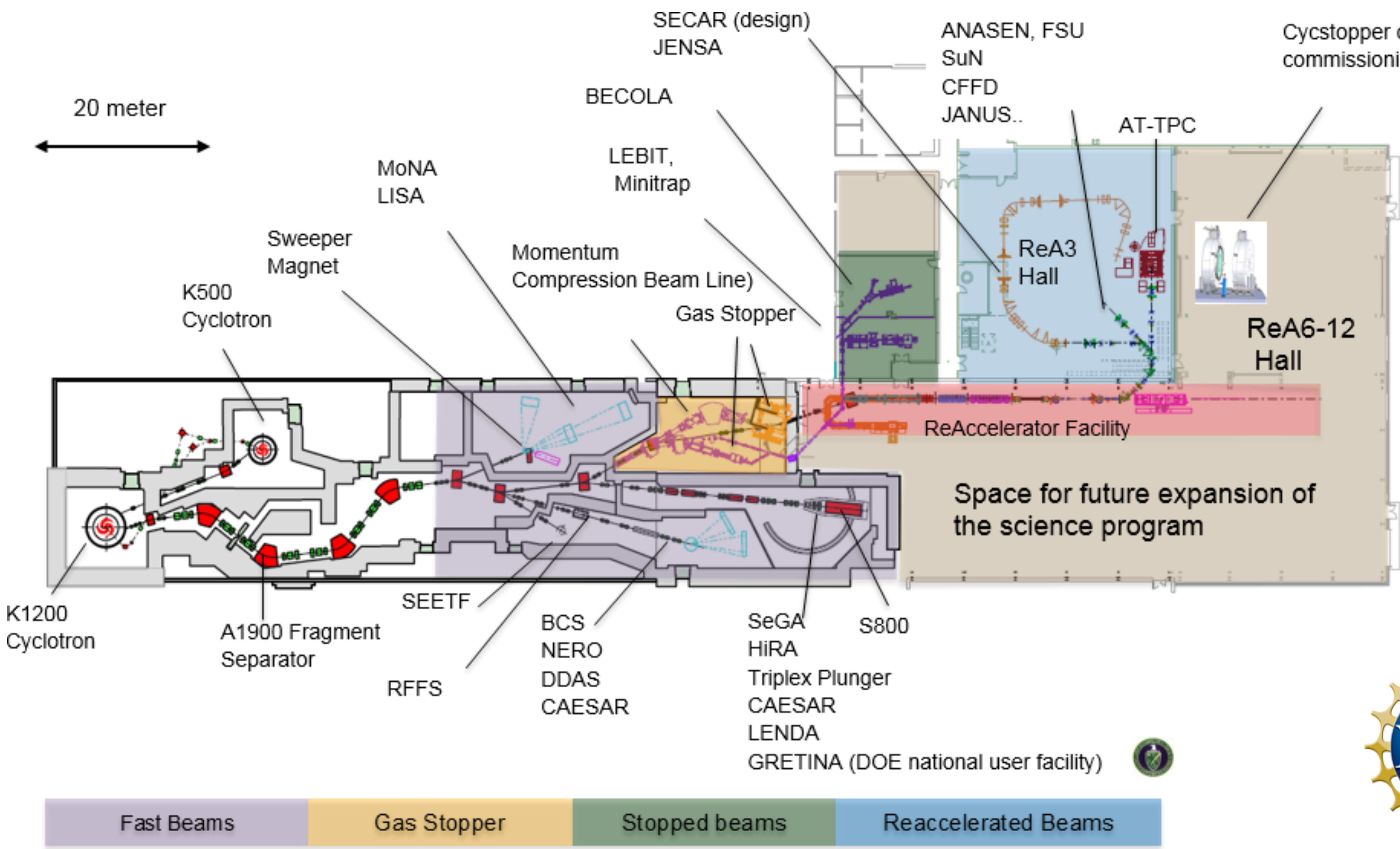
FRIB Rare Isotope Science

Fast, Stopped, and Reaccelerated Beams are Needed

- Fast beams (>100 MeV/u)
  - Farthest reach from stability, nuclear structure, limits of existence, EOS of nuclear matter
    - » Nuclear reactions, particle and gamma spectroscopy
- Stopped beams (0-100 keV)
  - Precision experiments – masses, moments, symmetries
    - » Ion traps, laser spectroscopy
- Reaccelerated beams (0.2-20 MeV/u)
  - Detailed nuclear structure studies, high-spin studies
    - » Gamma detector arrays
  - Astrophysical reaction rates
    - » Gas targets, recoil separators



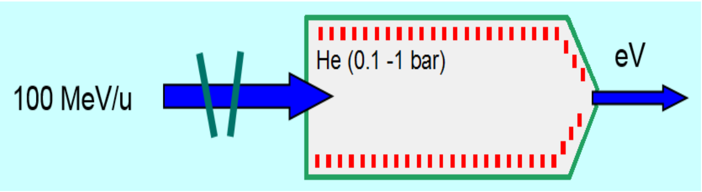
NSCL Provides Early Science Opportunities with Fast, Stopped, Reaccelerated Beams



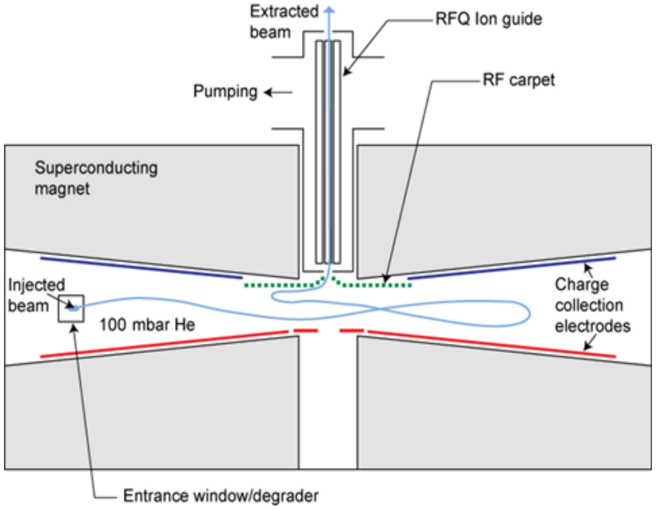
NSCL is a NSF funded national user facility for rare isotope science

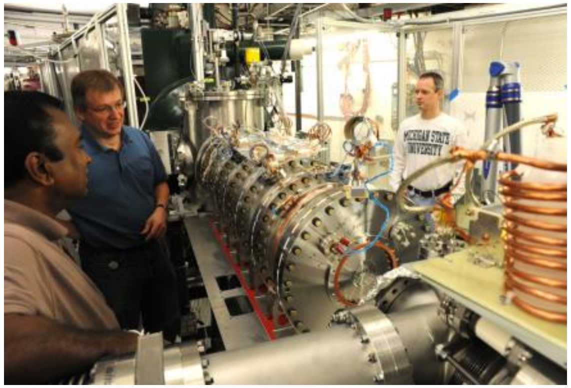
Stopped Beams at NSCL and FRIB
For Precision Experiments and Reacceleration

- Linear gas stopper (heavier ion beams)

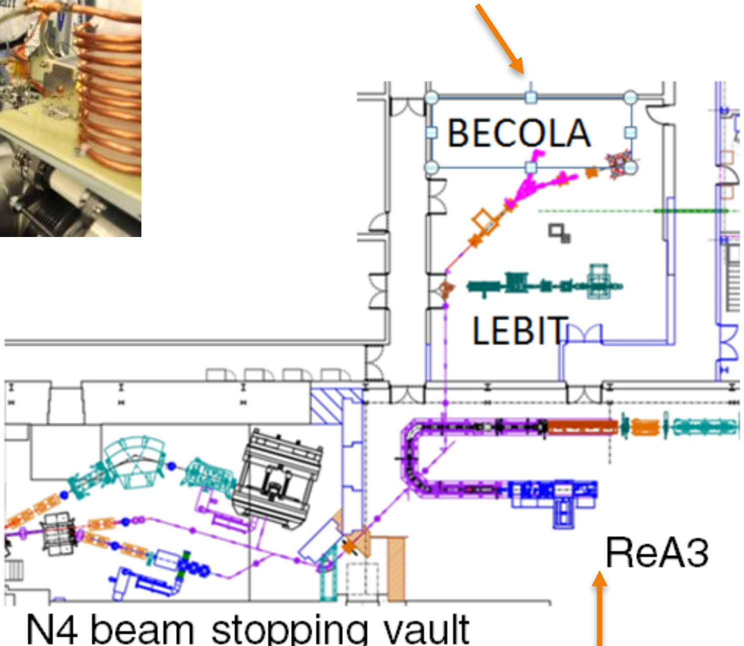


- Cyclotron gas stopper (lighter ion beams)





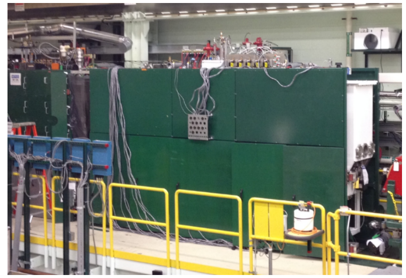
Penning trap mass measurements + Laser spectroscopy

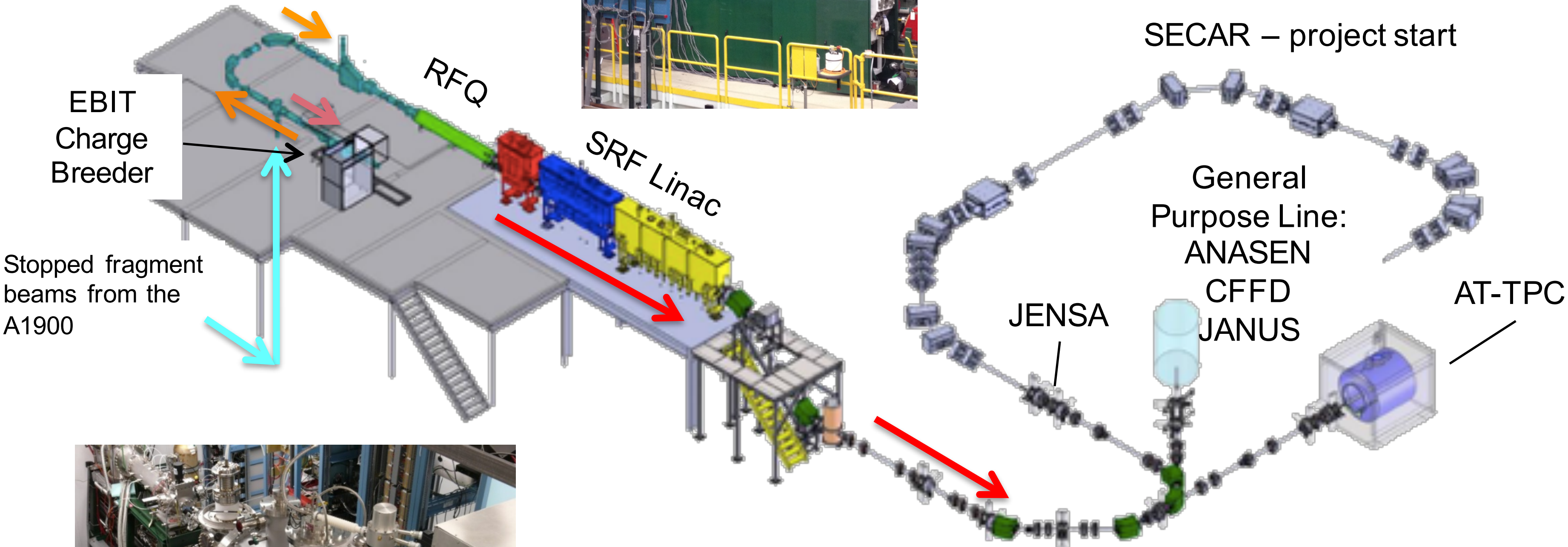


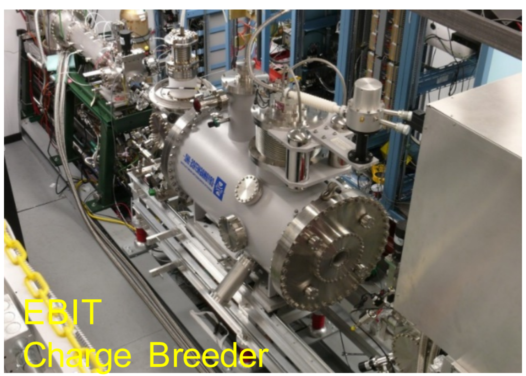
Re-acceleration

Reaccelerator Beams at NSCL and FRIB

Unique reaccelerated beams from projectile fragmentation



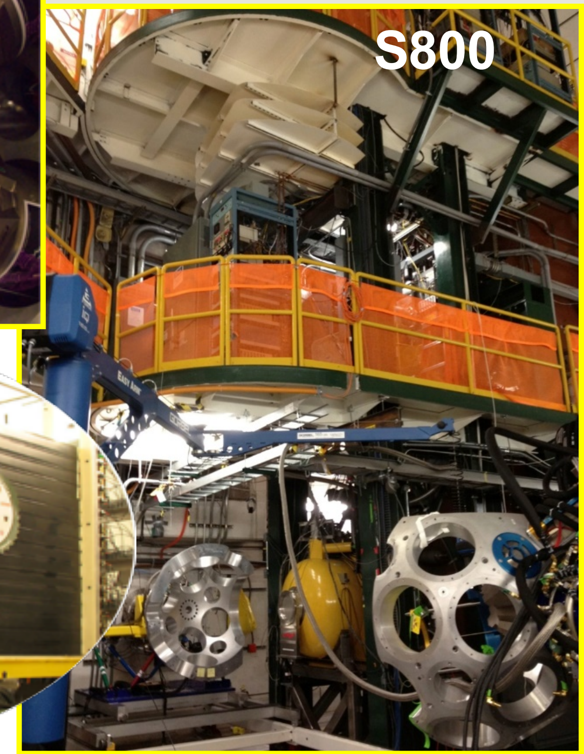


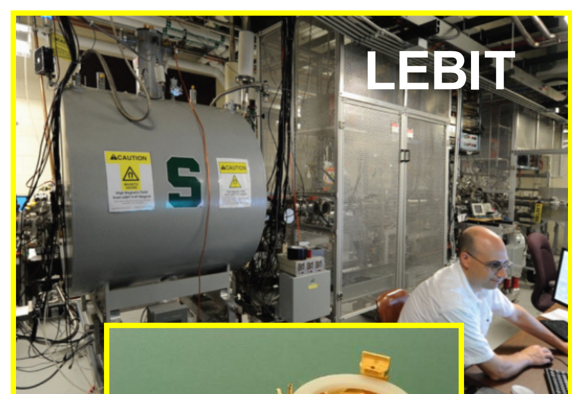


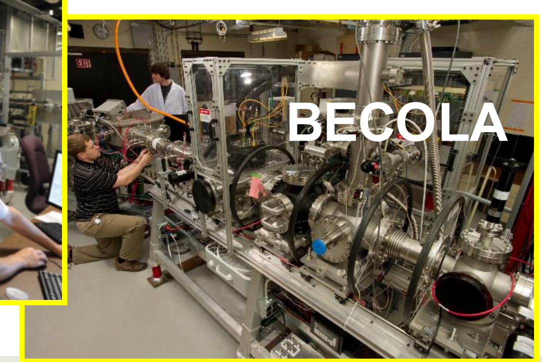
First experiments completed September 2015 – nine approved experiments

FRIB Experimental Equipment

- Equipment at NSCL (existing or under development):
  - S800, SeGA, MoNA, MoNA-LISA, LENDA, NSCL-BCS, LEBIT, BECOLA, AT-TPC, CAESAR, SUN, ...
- Equipment available in the community and movable (existing, under development, or planned):
  - GRETINA, ANASEN, CHICO, Nanoball, ORRUBA, JANUS, …
- Science-driven new equipment developed by FRIB user community:
  - SECAR, GRETA, HRS, ISLA, …







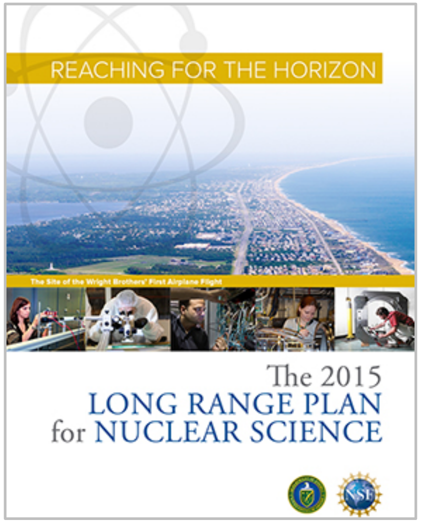
Over 1300 Users Engaged and Ready for Science

FRIB Users Organization
FACILITY FOR RARE ISOTOPE BEAMS

- Users are organized as part of the independent FRIB Users Organization (FRIBUO)
  - 1350 members (92 U.S. colleges and universities, 10 national laboratories, 55 countries)

www.fribusers.org

- FRIBUO has 19 working groups on experimental equipment
- Low Energy Nuclear Physics Town Meeting and Nuclear Astro-physics Town Meeting, 21-23 August 2014, Texas A&M University
  - *“The highest priority In low-energy nuclear physics and nuclear astrophysics is the timely completion of the Facility for Rare Isotope Beams and the initiation of its full science program”*
- Nuclear Science Advisory Committee : The 2015 Long Range Plan for Nuclear Science
  - *“Expeditiously completing the Facility for Rare Isotope Beams (FRIB) construction is essential. Initiating its scientific program will revolutionize our understanding of nuclei and their role in the cosmos.”*



Summary

- FRIB on track to become a world-leading next-generation facility for rare isotope science
  - Highest-power heavy ion linac worldwide
  - Fast, stopped, and reaccelerated beams
  - Provisions for isotope harvesting
- FRIB project makes excellent progress
  - Civil construction ahead of schedule and technical construction underway
- NSCL enables pre-FRIB science
  - Well tested and optimized experimental equipment when FRIB starts
- Strong, growing, and committed FRIB user group in place