Status of the Facility for Rare Isotope Beams (FRIB) at Michigan State University

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MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

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FRIB Opens Doors to Discovery with Ribbon-Cutting Ceremony in May 2022

- U.S. Secretary of Energy Jennifer M. Granholm and MSU President Samuel L. Stanley Jr., M.D., cut the ribbon to officially mark the start of FRIB's scientific mission on 2 May 2022
- About 900 guests attended the ribbon-cutting to celebrate FRIB officially opening for scientific research
- First user experiments started one week later

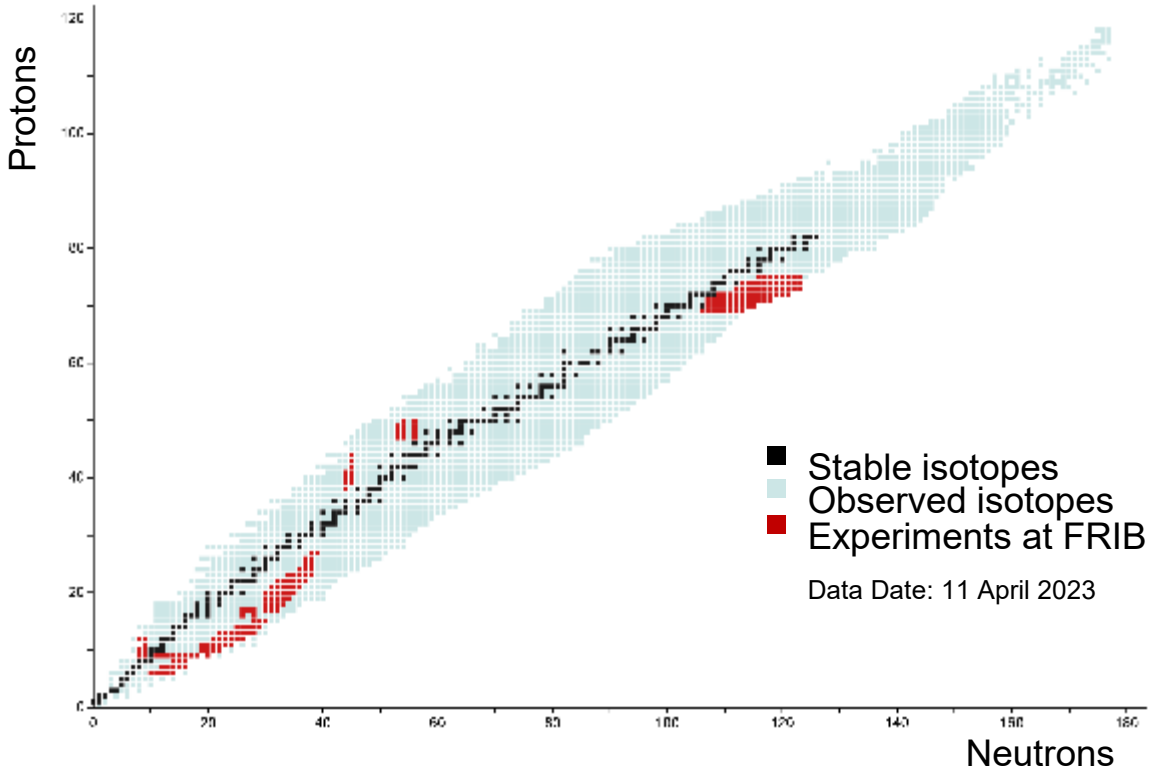
First FRIB Science in the News

- FRIB-related news in media and trade publications October 2022 to February 2023
  - Coverage about first FRIB publication
    - » It may be possible to cram more neutrons into atomic nuclei than previously thought, 26 October 2022, Science
    - » Powerful linear accelerator begins smashing atoms – two scientists on the team explain how it could reveal rare forms of matter, November-January, Yahoo News, Salon/MSN News, Fast Company online
    - » Half-lives of rare isotopes revealed, 25 November 2022, Chemical & Engineering News
    - » How long can exotic nuclei survive at the edge of stability?, 14 November 2022, ScienceDaily

- *Cision media monitoring service estimates that potentially 1,144 million people saw news about the first FRIB publication between October 2022 and February 2023*

More than 200 Rare Isotope Beams Delivered and 354 Experimenters Supported

- Since the start of user operation in May 2022, FRIB has:
  - Delivered more than 200 rare isotope beams to experiments
  - Supported 354 participants across 27 experiments from 89 institutions and companies, including:
    - » Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, Lawrence Livermore National Laboratory, Mississippi State University, University of Tennessee Knoxville, Florida State University, Rutgers University, Ursinus College, universities in the UK, Italy, France, Spain, and others.
- In 2023, FRIB will:
  - Offer a broad scientific program
  - Serve more than 400 scientific users from about 70 institutions
  - Continue technical developments to further enhance user discovery opportunities



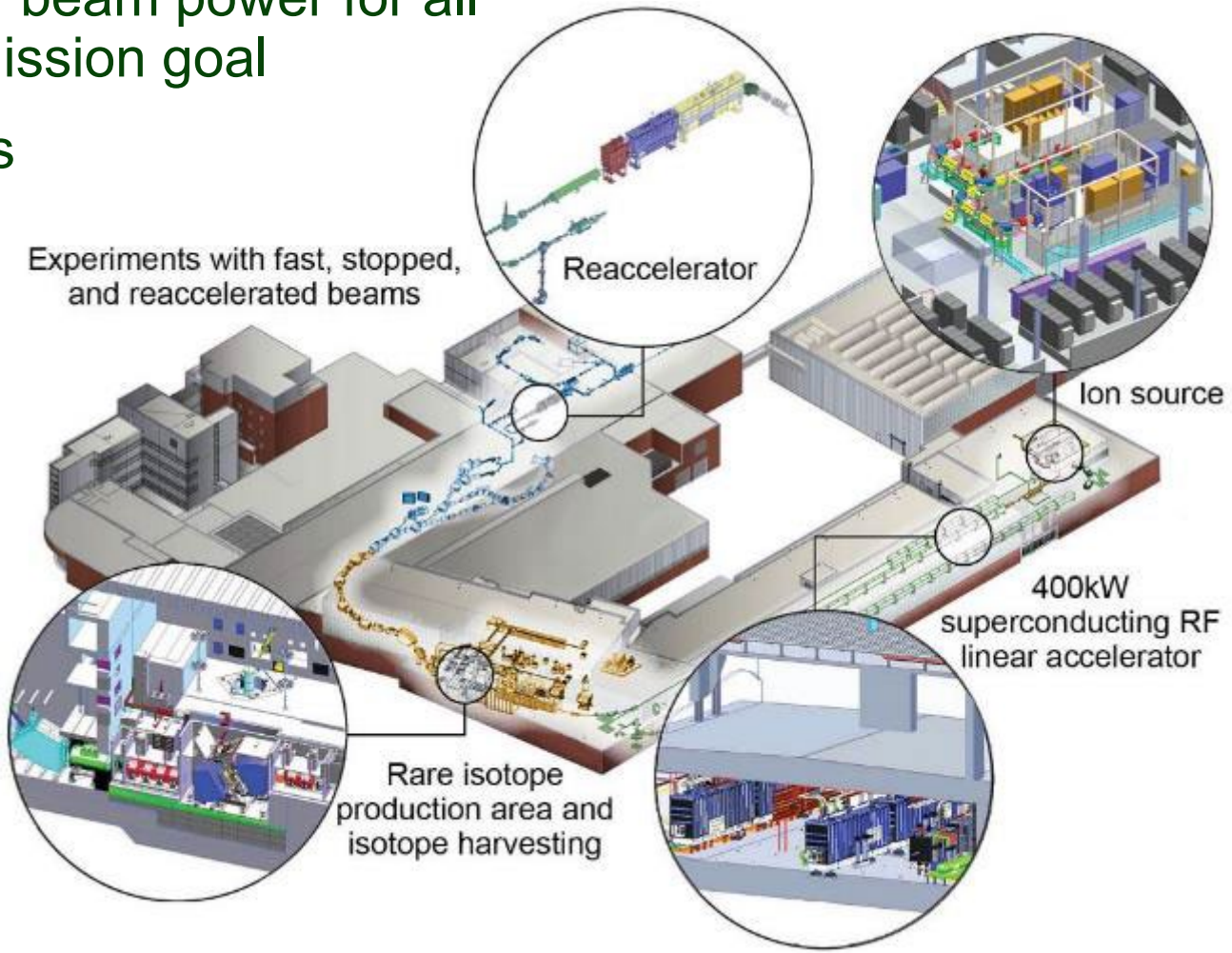
BERKELEY LAB
Lawrence Livermore National Laboratory
OAK RIDGE National Laboratory
THE UNIVERSITY OF TENNESSEE KNOXVILLE
RUTGERS
FSU
STATE

Facility for Rare Isotope Beams is Operating as a DOE-SC User Facility

- FRIB is a $730 million scientific user facility funded by the U.S. Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- FRIB Project started in 2008, concluded on budget and ahead of schedule in January 2022, ribbon cutting and first experiments started in May 2022
- FRIB is a DOE-SC user facility for world-unique rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC
- Rare isotopes are combinations of protons and neutrons that do not naturally exist on earth – they are made in stars and FRIB can make them until they decay
- FRIB enables scientists to make discoveries about the properties of these rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society

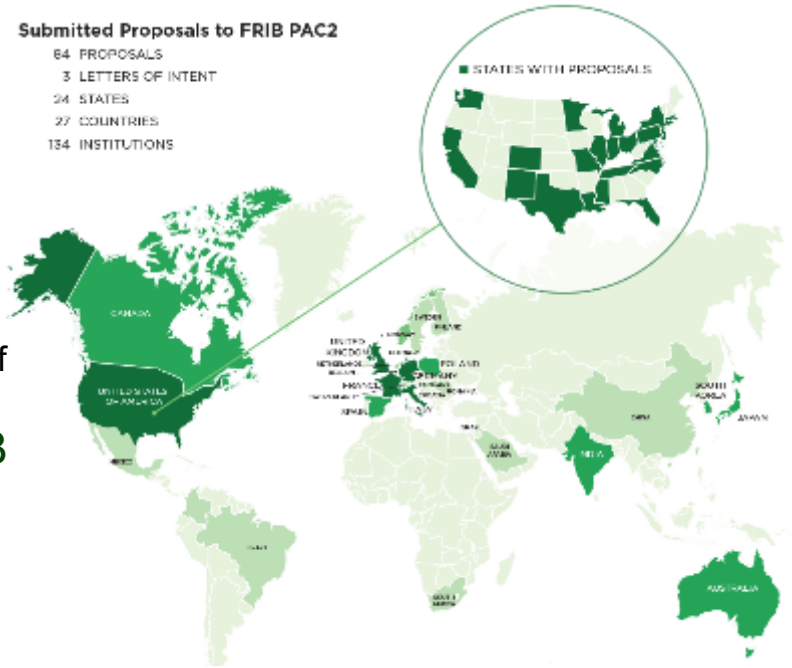
FRIB Optimized for Science
with Fast, Stopped and Reaccelerated Rare Isotope Beams

- Key feature is 400 kW beam power for all ions (5×10^{13} ^{238}U/s) mission goal
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - Beams of all elements and short half-lives
  - Fast, stopped, and reaccelerated beams
- Isotope harvesting capability from beam dump water (where 75% of beam particles fragment)



High Demand for Science at FRIB
Science Program Serves Global Users, Spans FRIB Capabilities

- FRIB is in high demand: 3:1 oversubscribed
  - About 35% of requested beam time in the Second Program Advisory Committee (PAC2) in March 2023 was recommended
  - PAC-recommended experiments represent:
    - » 38 out of 84 experiments proposed
    - » 454 out of 611 scientists
    - » 4,127 hours out of 11,859 facility-use hours
    - » 23 out of 27 countries
    - » 111 institutions
- FRIB science is of high merit
  - International world-leading scientists comprise PAC; proposals reviewed based on scientific merit, consistent with Department of Energy Office of Science (DOE-SC) user facility policy
- Approved science program covers spectrum of FRIB science themes
  - Properties of rare isotopes; nuclear astrophysics; fundamental interactions; and applications for society, including in homeland security
- Additionally, PAC-recommended experiments:
  - align with national science priorities
  - utilize full spectrum of FRIB's capabilities: fast, stopped, and reaccelerated rare-isotope beams
  - use all FRIB experimental areas, as well as all major FRIB instruments



1,800 Users Engaged and Ready for Science
fribusers.org

- Users organized as part of independent FRIB Users Organization (FRIBUO)
  - Chartered organization with an elected executive committee
  - 1,800 members (123 U.S. colleges and universities, 12 national laboratories, 51 countries) as of 30 April 2023
  - 21 working groups on instruments
- First experiments have begun
  - February 2021: 82 proposals received representing 597 scientists
  - August 2021: FRIB Program Advisory Committee (PAC1)
  - May 2022: First user experiments
  - January 2023: 84 proposals received representing 611 scientists
  - March 2023: FRIB Program Advisory Committee (PAC2)
- User needs and high user satisfaction are important to FRIB
  - ISO 9001 quality systems to assess user satisfaction
- Annual meetings
  - User meeting (three days with 200-300 participants)
    - » August 2022: User meeting hosted by ANL
    - » 9-11 August 2023: User meeting hosted by FRIB

We Built What we Planned

230,000 sqft new construction
Tunnel 570 ft long, 70 ft wide, 32 ft underground

Site plan
2012

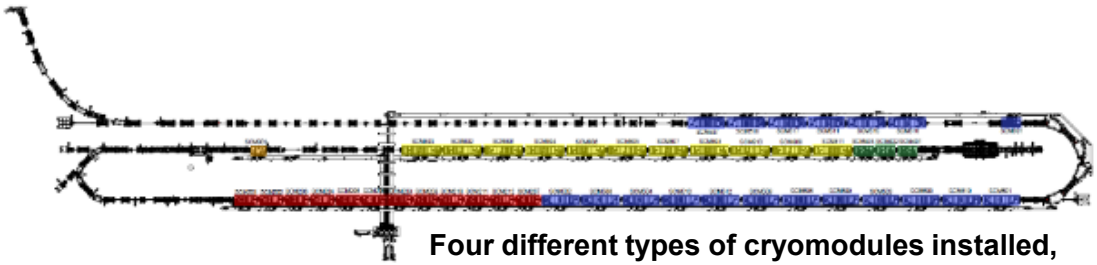
Actual site 2018

Designed, Built and Operating Very Efficient Helium Liquefaction Plant – out of Necessity

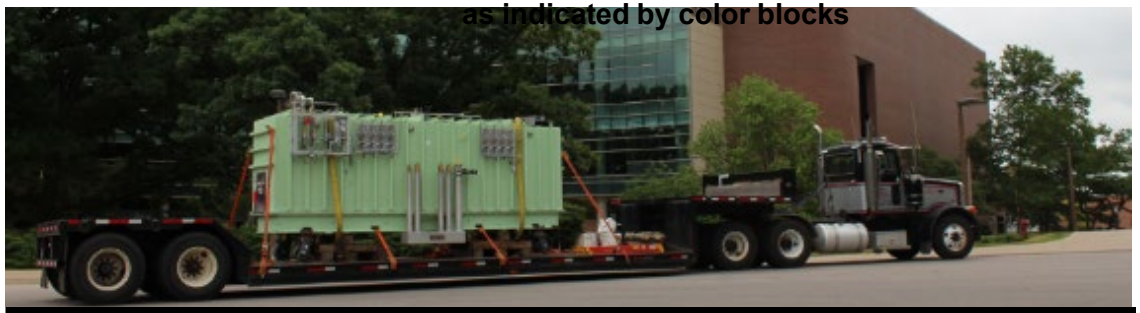
- FRIB's first large procurement failed: Cost twice as much as planned – too much risk for market to assume at reasonable cost
- Had to build team to design and build cryoplant, 15 kW at 4K, operating at at 4 K for s.c. magnets and at 2 K for SRF linac.
- Integrated design of the cryogenic refrigeration, distribution, and cryomodule systems
- Energy efficiency: Can stably regulate its capacity down to 30 percent of its maximum capacity

Largest, Fastest US Construction of SRF Cryomodules With High Quality at MSU

- Linear accelerator consists of 46 cryomodules of six different types
- Cryomodules accelerate the heavy-ion beam to a target where rare isotopes are produced
- At peak, FRIB staff delivered nine cryomodules every six months, utilizing five assembly bays and on-site testing



Four different types of cryomodules installed, as indicated by color blocks



Forty-sixth and final baseline cryomodule (eighteenth beta=0.53 cryomodule) being transported to the tunnel

All three β=0.041 cryomodules installed

Chemical processing of cavities

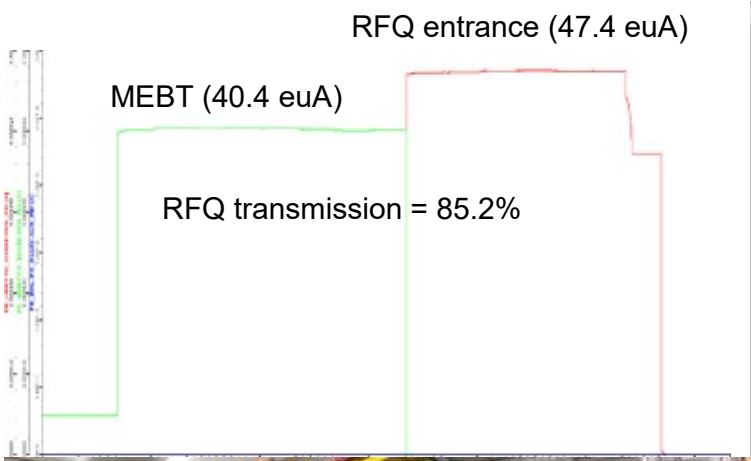
Cryomodule assembly (four of five bays)

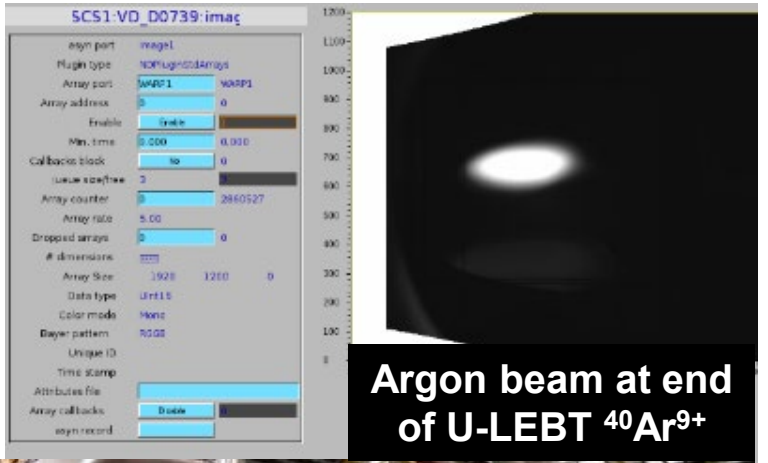
Cold mass assembly in clean room

2017: Front End Beam Commissioned

Radio Frequency Quadrupole is large, precision-brazed copper structure, took 3 years to design and build

- Frontend was completed in May 2017, 16 months ahead of schedule
- Beam-based measurement and radio frequency calibration in agreement within 1%
- Radio Frequency Quadrupole built by Tsinghua University





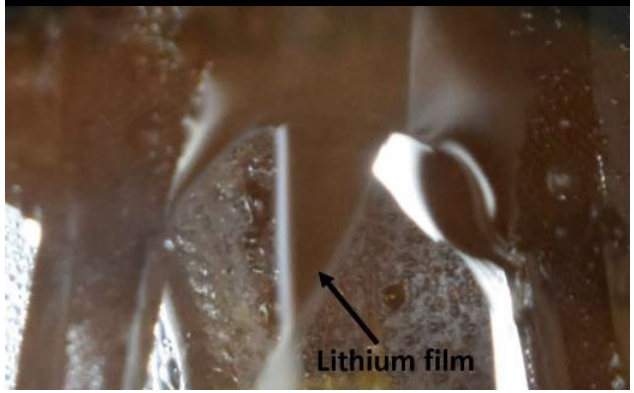
Argon beam at end of U-LEBT $^{40}Ar^{9+}$

FRIB Lower LEBT, RFQ, MEBT, and the three β=0.041 cryomodules installed

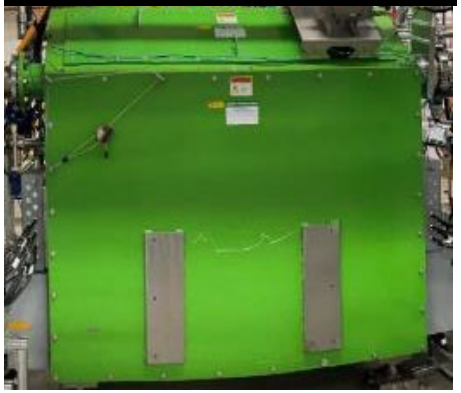
FRIB Developed World's First Liquid Lithium Charge Stripper for Operating Facility

- Need to charge-strip heavy ions at ~0.1 c to make 400 kW of beam
- Power density on charge stripper is about 56 MW/cm^3
  - Need a self-healing (liquid), heat-conducting (metal) material, that does not get too radioactive (low-*Z*)
- Liquid Lithium stripper developed, commissioned, and now operating. Original idea from Jerry Nolen at ANL.

Melted liquid lithium film as seen from a view port in the charge stripper



Liquid lithium charge stripper installed in FRIB tunnel



2021: Fragment Separator Magnets Built at MSU and Being Installed

T. Xu, *et al*.

- Two 120-ton and two 180-ton dipole large-gap iron-dominated superconducting dipoles and three quadrupole triplets being installed for fragment pre-separator

SCD3 magnet (left) and SCD4 magnet (right) installed in vertical preseparator

Instruments for Initial Science

Road Map in Place, Community Engaged, Instruments Being Built

- Four large instruments identified in 2015 Nuclear Physics Long Range Plan (NP-LRP)
  - High Rigidity Spectrometer (CD-1)
    - » Evolution of shell structure, single particle structure of rare isotopes, limits of stability
    - » Extended scientific reach to neutron-rich isotopes by a combined production-rate luminosity increase of up to a factor of more than 100
  - GRETA gamma detector array (CD-2/3), Berkeley Lab
    - » Exploration of the structure of new nuclei with maximum resolving power and acceptance
  - SECAR recoil separator (in operation since 2021)
    - » Direct measurement of thermonuclear reactions in exploding and exotic stars
  - FRIB Decay station (pre-conceptual design), UT Knoxville
    - » Structure of most exotic isotopes, site of the r-process
- Additional instruments being installed and upgrades underway – first experiments performed
  - SOLARIS spectrometer (FSU, ANL)
    - » Nuclear reaction studies with reaccelerated beams
  - FDSi – FRIB Decay Station initiator (UTK, ORNL)
  - RiSE (MIT)
    - » high sensitivity laser spectroscopy via collinear resonance ionization (MIT)
  - SALER (Colorado School of Mines)
    - » Test of Standard Model via detection of sub-keV nuclear recoils
  - EOS Active Target Time Projection Chamber (TAMU)
    - » Equation of state of neutron matter, reactions of exotic beams with low rates

BERKELEY LAB

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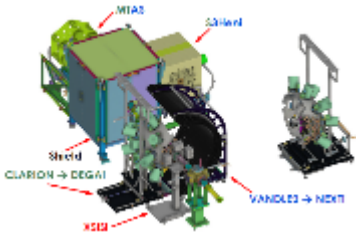
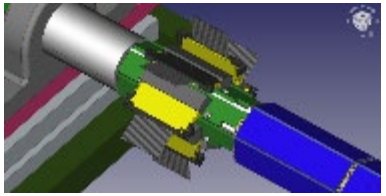


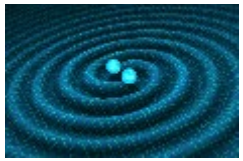
SECAR

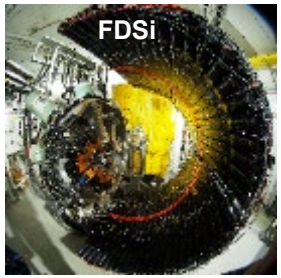
SOLARIS

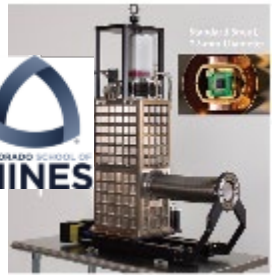
OAK RIDGE National Laboratory



Argonne NATIONAL LABORATORY

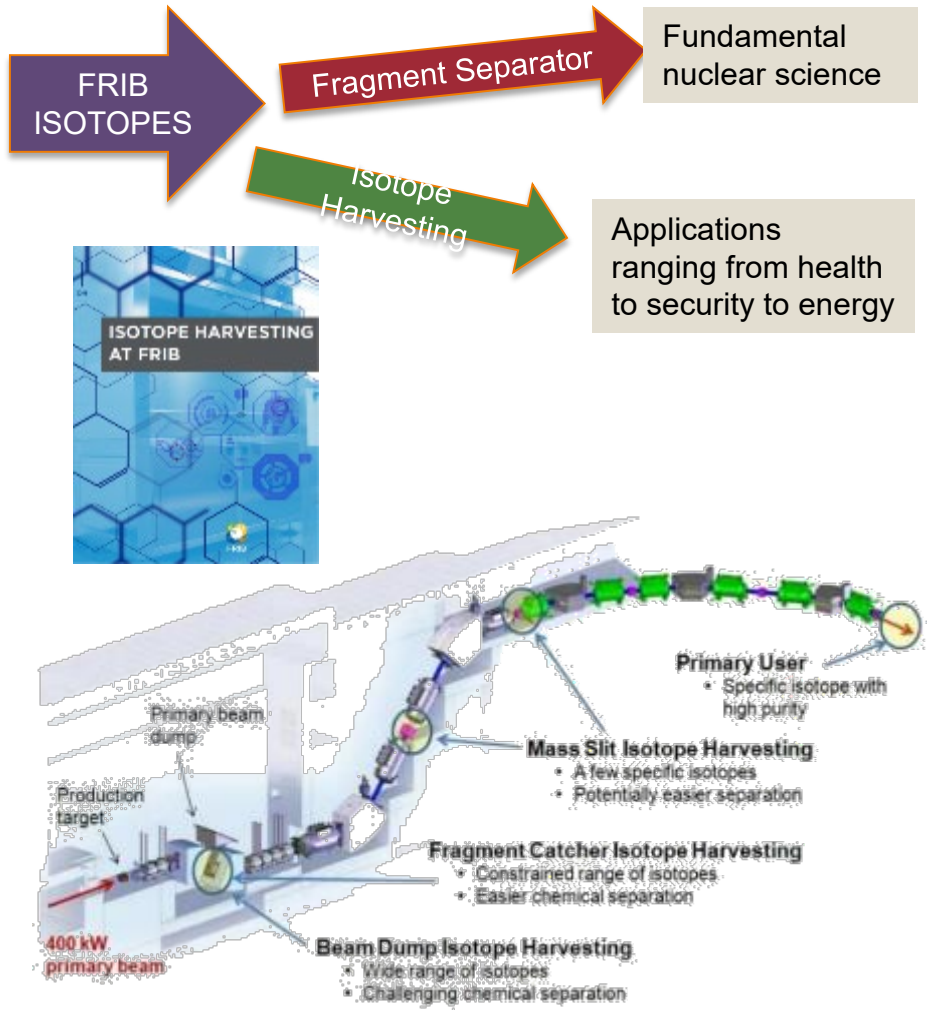






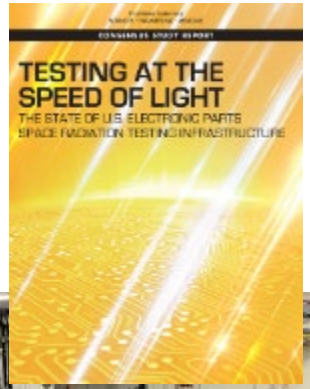
Opening a New Frontier with Isotope Harvesting at FRIB

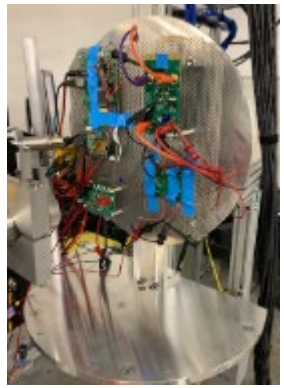
- Many rare isotopes are produced but only one isotope delivered to single user
  - Often 1000 other isotopes are produced that could be harvested and used for experiments or applications
- Isotope harvesting done during routine operation fro FRIB's nuclear physics mission—without interfering with FRIB's primary users
- 2015 Long Range Plan (LPR) for DOE-NP Isotope Program recommends investment in infrastructure for isotope harvesting at FRIB
- Isotope harvesting whitepaper published
  - J. Phys. G: Nucl. Part. Phys. 46(2019) 100501
- FRIB had provisions for isotope harvesting incorporated in the design
  - Hot cells ordered with support from DOE Isotope Program and laboratory being prepared in MSU-provided building
  - Implementing commensal isotope harvesting capabilities from FRIB beam dump water
  - Operational in 2024

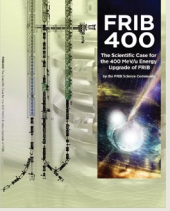


FRIB Single Event Effects Beamline Serves the National Need for Analysis Facilities

- FRIB Single Event Effects (FSEE) facility established, user operations began in 2022
  - New beamline is attached to existing FRIB folding segment 1
- Part of radiation-testing infrastructure for electronic systems
  - Includes component reliability and qualifying for space missions
  - National need established in NAS report
- User community spans multiple sectors
  - Gov't agencies and contractors
  - Commercial spaceflight
  - Semiconductor manufacturers
  - Sixth-generation internet, autonomous vehicles all require
- Existing facilities are oversubscribed
  - Need for additional 3,000-5,000 hours per year now, additional 7,000-10,000 hours by 2030
- FSEE facility will provide up to 2,000 hours per year to users
- Funding established from Defense Threat Reduction Agency, $2.9M







Community Excited About FRIB Energy Upgrade
400 MeV/nucleon for U

FRIB400 will:

- Enable significant gains in isotope yields will be realized, **nearly doubling the reach of FRIB along the neutron dripline and bringing into reach more nuclei relevant for the r process and neutron-star crust processes**
- Create dense nuclear matter of up to twice saturation density, critical for multi-messenger astrophysics
- Provide **up to two-orders-of-magnitude increase in luminosity** for spectroscopy in key regions of the nuclear chart
- Expand the scientific impact of harvested isotopes by **increasing the available yield of many isotopes by factor of 10**

FRIB400 Opportunity:

- Can be implemented in a phased approach, with gains at every stage
- Retain team to build SRF accelerator

FRIB400 endorsed by our field at Low energy community meetings since 2019

2019: *"The science case for an energy upgrade of FRIB to 400 MeV/u is extremely compelling and would significantly expand the science opportunities at FRIB, as outlined in the FRIB400 whitepaper."*

2020: *"The science case for an energy upgrade of FRIB to 400 MeV/u is extremely compelling and would significantly expand the science opportunities at FRIB."*

2021: *"The science case for an energy upgrade of FRIB to 400MeV/u is extremely compelling and will significantly expand the FRIB program."*

2022: *"FRIB and its key FRIB400 upgrade will provide access to the extreme isotopes required to build a more complete picture of nuclear matter."* and *"FRIB and its key FRIB400 upgrade will provide access to the extreme isotopes required to build a more complete picture of nuclear matter."*

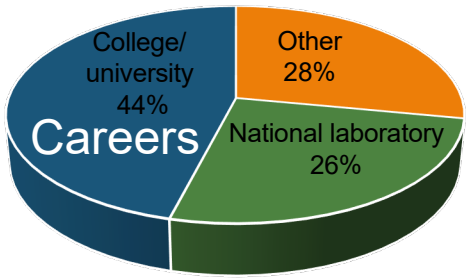
FRIB400 features in **Resolution 2** of the 2022 DNP **Long Range Plan Town Hall Meeting**

*"The science case for an energy upgrade of FRIB to 400 MeV/u is compelling. **FRIB400** greatly expands the opportunities in the field. We strongly endorse starting the upgrade during the upcoming Long Range Plan period to harness its significant discovery potential.*

FRIB400 Whitepaper (2023 update) linked from: frib.msu.edu/frib400

Training the Next Generation of Scientists and Engineers

- 26% of U.S. nuclear physics graduate students receive part of their training at NSCL
- 120 graduate students in Physics, Chemistry, Electrical Engineering, Mechanical Engineering
- 20 new graduate students in 2021
  (15 physics, 2 chemistry, 1 mechanical engineering)
- 90 undergraduate students
- Median time to PhD is 5.3 years
  - National median in physics is 6.2 years
- Graduating student careers (2010 – 2021)
  - 44% Universities
  - 26% National laboratories
  - 28% Other



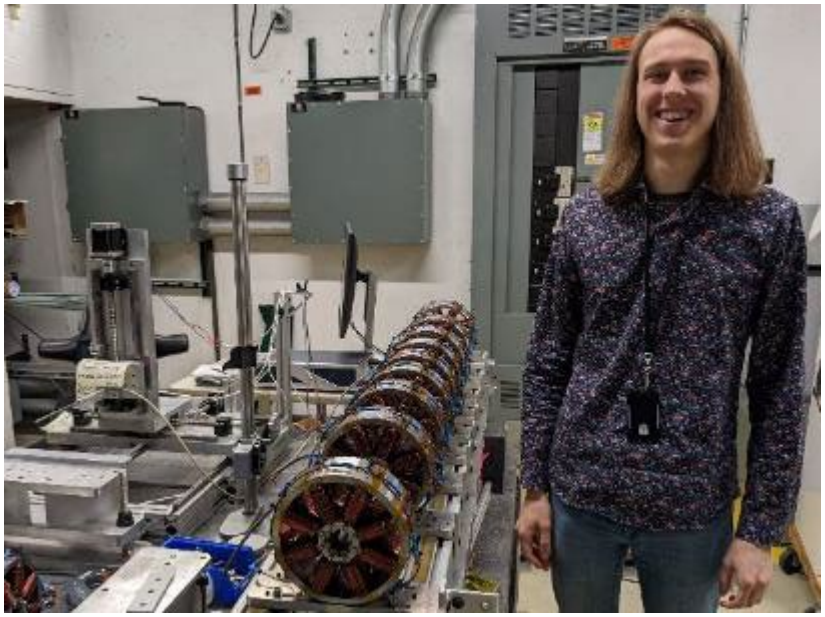
all numbers as of January 2022

Outreach Programs Engage the Public and Draw Youth to STEM Fields at FRIB

- 11,000 contacts in 2022
  - 141 tours, with 4,800 tour visitors
  - 59 talks, with 3,200 attendees
  - 19 outreach programs, with 3,000 attendees
- "Isotopolis" digital game with MSU Communication Arts and Sciences
  - Over 43,000 unique users, update released in 2021
  - Sequel "Isotopolis Racer" game in development
- Of Equal Place: Isotopes in Motion
  - 2022 event expressed FRIB research through dance
  - Workshops, activities, and tours following performances hosted 1,000 visitors (video)
- Programs for schools and the public
  - Reaching public and private schools, homeschoolers, colleges, community groups, businesses
  - Summer programs successfully transitioned to a virtual platform for high school students and science educators—both increased attendance by 50 percent or more (video)
- Other collaborations
  - Short courses offered through Gifted and Talented office, Grandparents University, 4-H, and MSU Extension
  - 1500-square-foot exhibit at Impression 5 Science Center
  - Road shows with Detroit schools
  - MSU Science Festival
  - MSU Gifted University for Parents and Precocious Youth (GUPPY)
  - "Rare Connections" film

Leveraging FRIB to Address Workforce Shortage

- Accelerator Science and Engineering Training (ASET) program
  - Trains accelerator scientists and engineers needed for DOE-SC programs and facilities, in four areas with critical workforce needs
    - » Design and operation of large accelerator facilities,
    - » Superconducting RF (SRF) technology
    - » RF power engineering,
    - » Large-scale cryogenic systems
  - Partnership between FRIB, MSU College of Natural Science, College of Engineering
  - Supported by DOE-SC Office of High Energy Physics
  - 26 students currently enrolled in program
- MSU Cryogenic Initiative
  - FRIB and MSU College of Engineering collaboration
  - Addressing a national shortage of cryogenic engineers
  - Led by nation's leading cryogenic engineering faculty
  - Educates and trains future cryogenic engineers and system innovators
  - Four graduate students, three undergraduate students in program



FRIB Approach to Environment, Safety, Health & Quality

- FRIB operates under well-defined regulatory framework
  - U.S. Nuclear Regulatory Commission
  - FBI for export control
  - Michigan Department of Licensing and Regulatory Affairs
  - State of Michigan OSHA
  - Michigan Department of Environmental Quality
  - MSU Environmental, Health and Safety
- FRIB ESHQ management systems are registered to
  - ISO 14001 - Environment, since 2006
  - ISO 45001 - Safety, since 2007 (was OHSAS 18001)
  - ISO 9001 - Quality, since 2008

  by NSF International Strategic Registrations
- Achieved ISO 27001 Information Security Management Systems registration in 2018
- Metrics include internal and external audits
- External ESH Advisory Committee with experts from national laboratories

Collaborating with National Laboratories and International Partners

- ANL
  - Liquid lithium charge stripper
  - Beam dynamics verification; β=0.29 HWR processing and testing; SRF tuner validation; beam dump
  - SRF components development; RF couplers for multi-gap buncher
  - β=0.65 upgrade cavity R&D
  - SOLARIS
- BNL
  - Plasma window & charge stripper, physics modeling, magnets
- FNAL
  - Diagnostics, SRF processing
- JLab
  - Cryoplant; cryodistribution design & prototyping
  - Cavity hydrogen degassing; e-traveler
  - HWR processing & certification
  - QWR and HWR cryomodule design and engineering support for production
- LANL
  - Proton ion source
- LBNL
  - ECR coldmass, beam dynamics; Nb_3Sn ECR coldmass
- MIT
  - CRIS
- ORNL
  - Remote handling, diagnostics; large-vessel vacuum, cryoplant controls
  - FDSi
- SLAC
  - Cryogenics, SRF multipacting, physics modeling

- RIKEN
  - Helium gas charge stripper
  - Rare isotope physics, fragment separators;
- TRIUMF
  - Beam dynamics design, physics modeling SRF, QWR etching
- INFN
  - SRF technology
- KEK
  - SRF technology, SC solenoid prototyping
- IMP
  - Magnets; spare magnets
- Budker Institute, INR Institute
  - Diagnostics
- Tsinghua Univ. & CAS
  - RFQ; 2nd RFQ
- ESS
  - Accelerator physics
- DTRA
  - RFQ power supply
- CSNSM-JaNNUS
  - Nuclear recoil damage to materials
- RaDIATE
  - Nuclear recoil damage to materials
- GANIL
  - Rare isotope physics, target development
- GSI
  - Rare isotope physics, fragment separators
  - Nuclear recoil damage to materials
- U Notre Dame
  - Recoil implantation testing of materials

Summary

- FRIB is operational and has delivered 300 rare isotope beams to users
- FRIB Project started in 2008, concluded on budget and ahead of schedule in January 2022, ribbon cutting and first experiments started in May 2022
- Enabling scientific discoveries aligned with national priorities for an international community of 1,800 scientific users
- Isotope harvesting capabilities built into FRIB for medical applications and intellectual property development
  - Research quantities, hot cells being installed this year
- Advancing state of the art through technological advancement
- FRIB 400 upgrade increases luminosity by up to two orders of magnitude and can be implemented incrementally with science gains at each stage
- Addressing needs in workforce development: Next generation of nuclear scientists (physicists and chemists), accelerator scientists and engineers
- Public outreach is a priority to engage public and draw youth to STEM careers
- Nuclear Science underway, users engaged