The Facility for Rare Isotope Beams (FRIB): Motivation, Status, and Technical Challenges

Thomas Glasmacher
FRIB Laboratory Director

NAPAC2019
North American Particle Accelerator Conference: 1-6 September 2019

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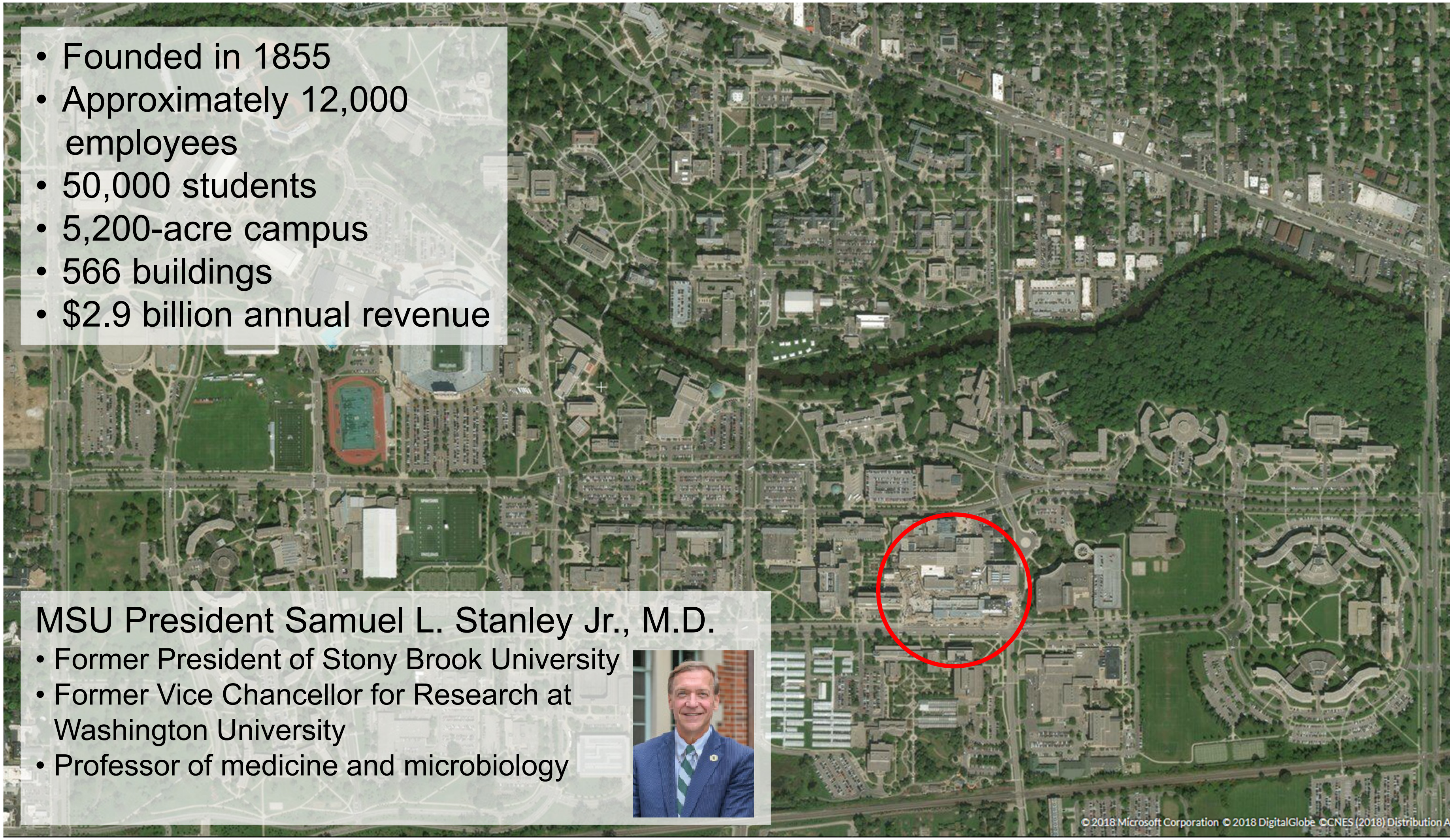
Michigan State University

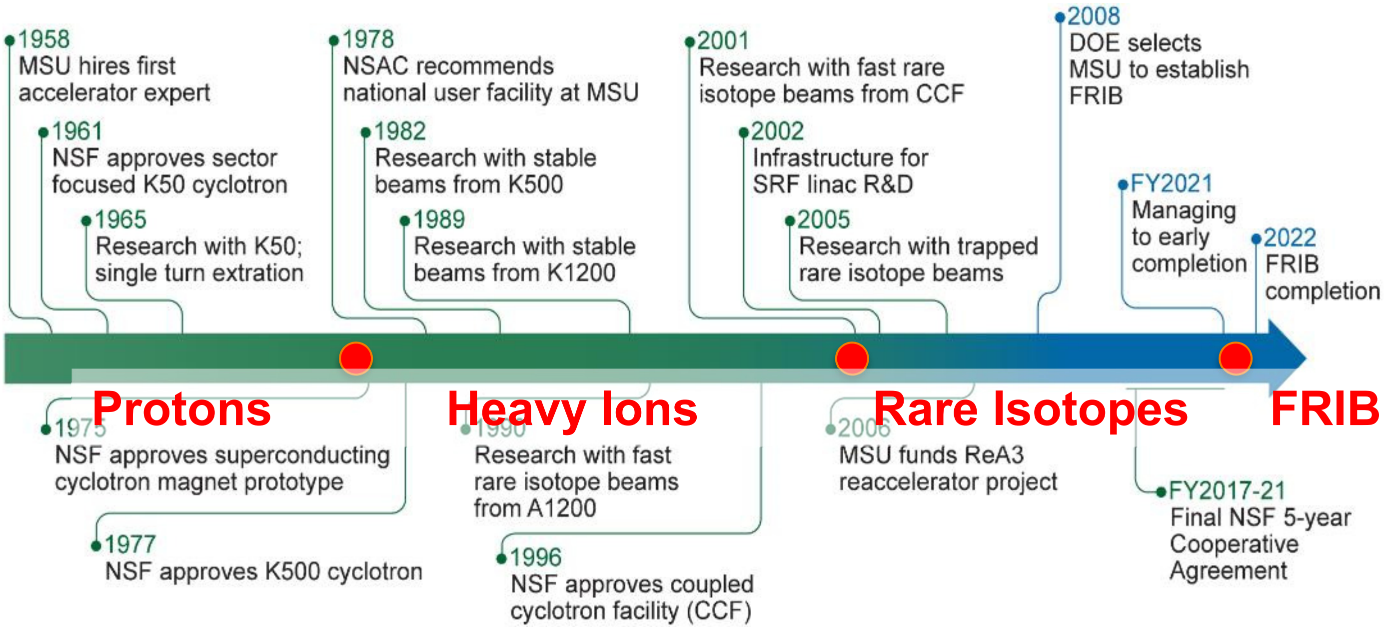


- Founded in 1855
- Approximately 12,000 employees
- 50,000 students
- 5,200-acre campus
- 566 buildings
- $2.9 billion annual revenue

MSU President Samuel L. Stanley Jr., M.D.

- Former President of Stony Brook University
- Former Vice Chancellor for Research at Washington University
- Professor of medicine and microbiology

Accelerator-based Nuclear Science at MSU has a Long History: Three Major Reinventions



#1 ranked nuclear physics graduate program
-U.S. News & World Report

26% of U.S. nuclear physics graduate students receive part of their education at MSU

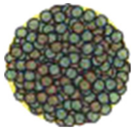
Three disruptive innovations required to survive: Leverage assets to create larger assets. We have to evolve or close the laboratory

MSU awards 10% of nuclear physics PhDs earned annually. 75% domestic students

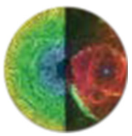
FRIB – the Most Powerful Superconducting Heavy-Ion Linear Accelerator: 92% Complete

- FRIB Project constructs a $730 million national user facility funded by the Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
  - Congressional budget line item, DOE-SC $635.5 million, State of Michigan $94.5 million
- CD-4 date is June 2022, managing to early completion in 2021
- FRIB will be a DOE-SC scientific user facility for world-class rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC. FRIB is being established, owned, and operated by MSU
- FRIB will enable 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

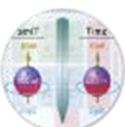
FRIB Enables Scientists to Make Discoveries Science Aligned with National Priorities



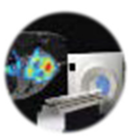
- **Properties of atomic nuclei**
  - Develop a predictive model of nuclei and their interactions
  - Many-body quantum problem: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.



- **Astrophysics: What happens inside stars?**
  - Origin of the elements in the cosmos
  - Explosive environments: novae, supernovae, X-ray bursts …
  - Properties of neutron stars



- **Tests of laws of nature**
  - Effects of symmetry violations are amplified in certain nuclei

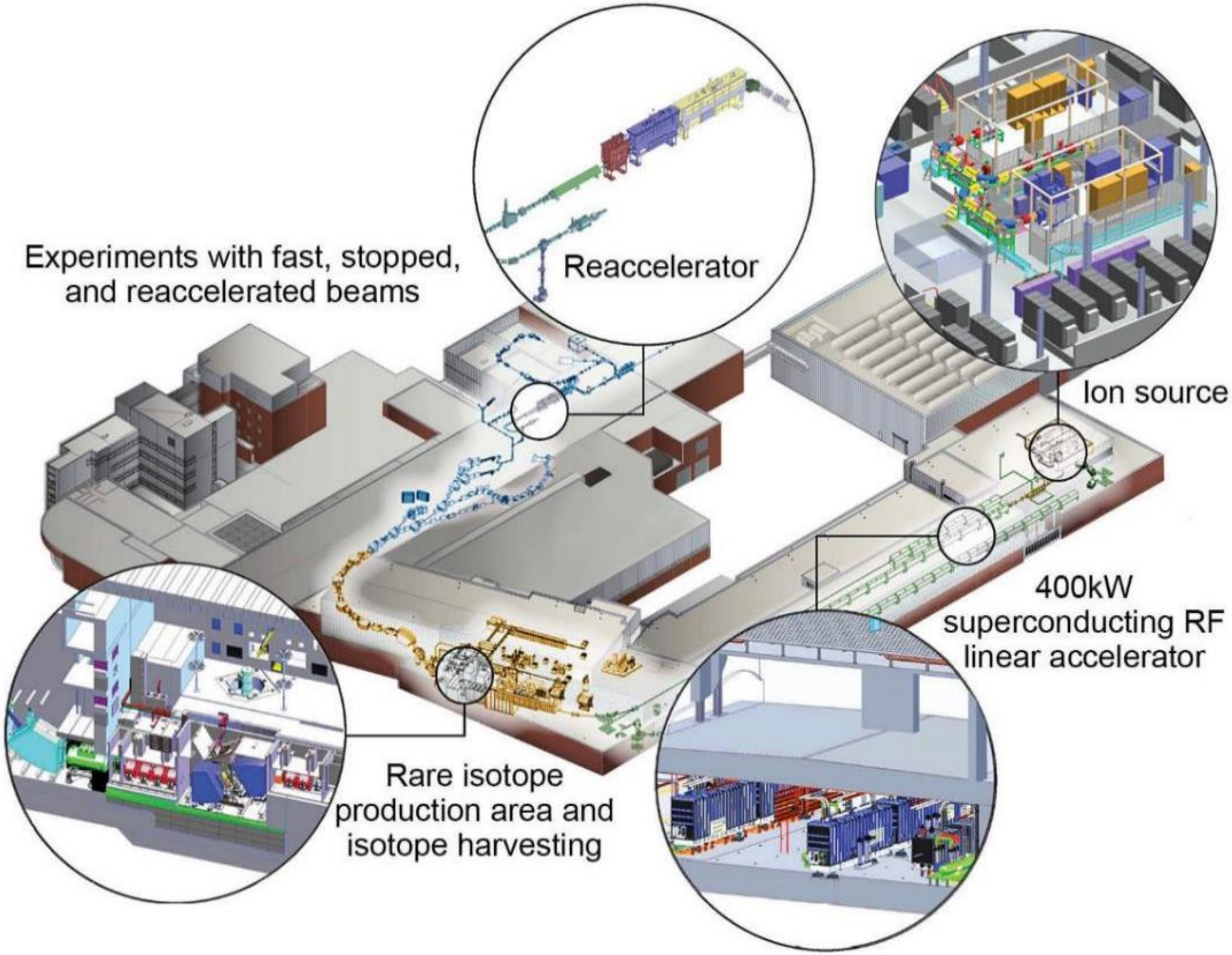


- **Societal applications and benefits**
  - Medicine, energy, material sciences, national security

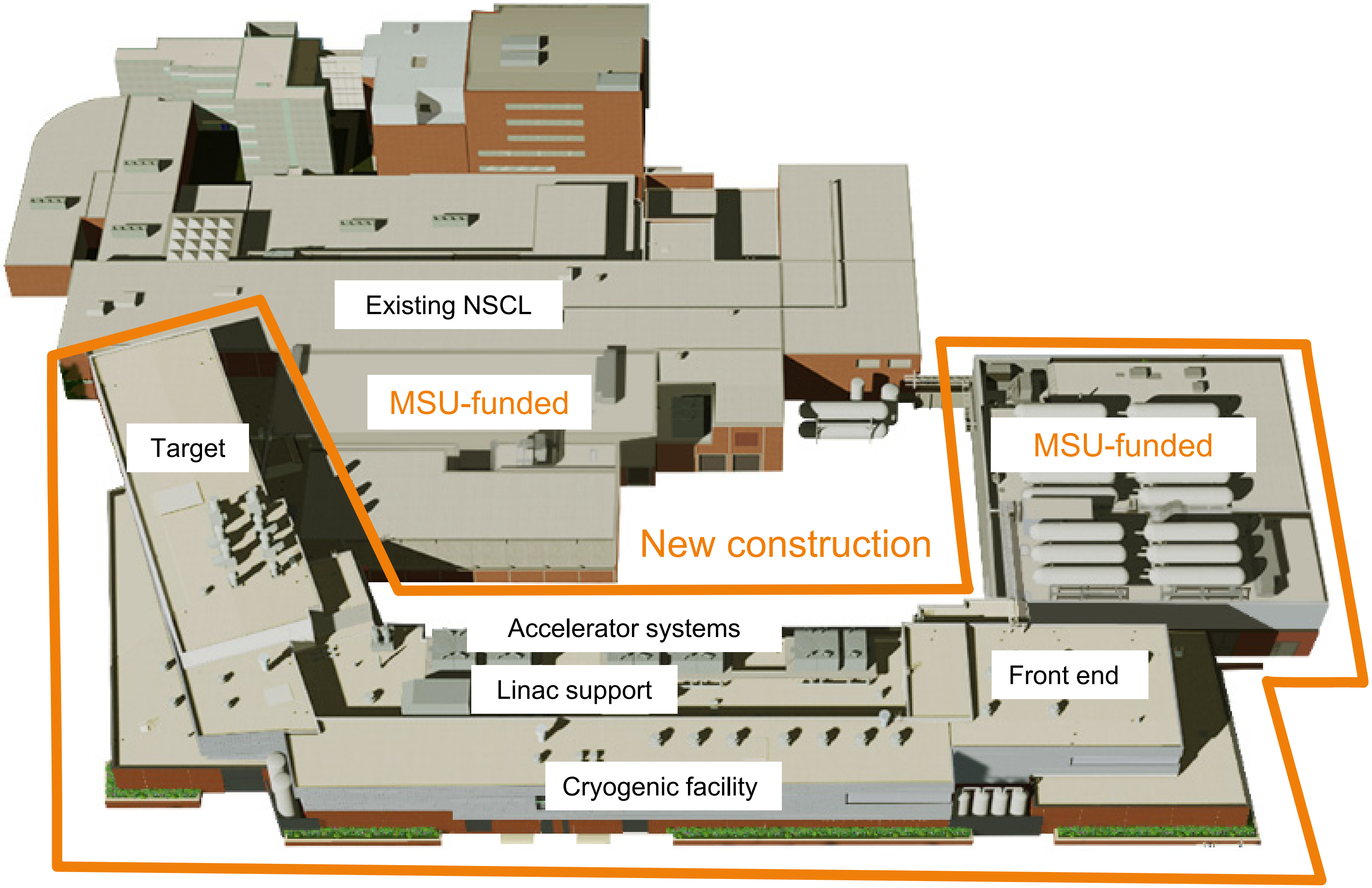
Science is aligned with national priorities articulated by

- Nuclear Science Advisory Committee to DOE and NSF *Long Range Plan for Nuclear Science* (2015)
- National Research Council *Decadal Survey of Nuclear Physics* (2012)
- National Research Council *Rare Isotope Science Assessment* report (2006)

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



FRIB Site Layout Optimized for Science



Civil Construction: March 2014 - March 2017


Groundbreaking – March 2014


March 2015


March 2016


Beneficial Occupancy – 2017

Civil Construction Reached Beneficial Occupancy in March 2017

Web cams at frib.msu.edu

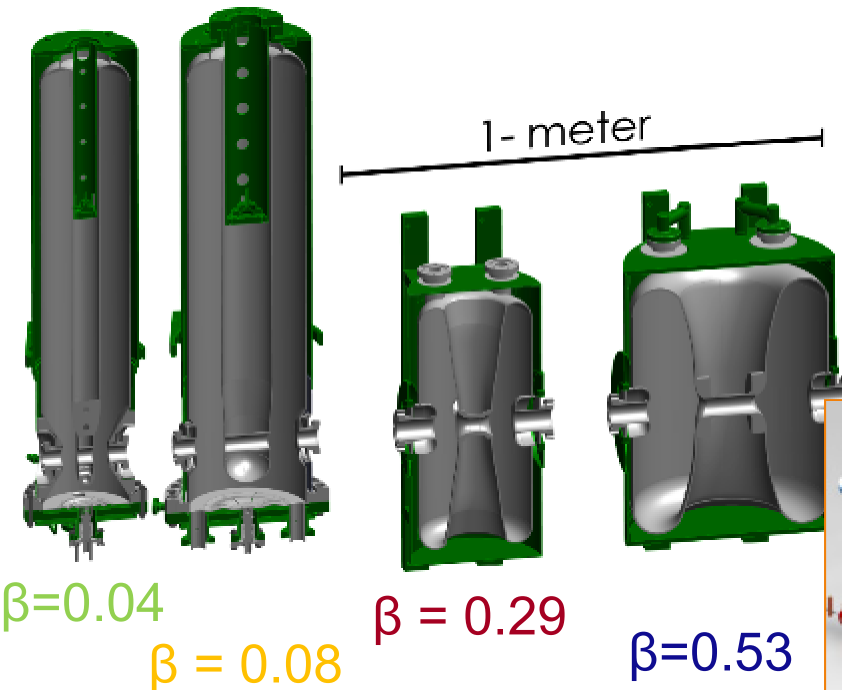
Challenges

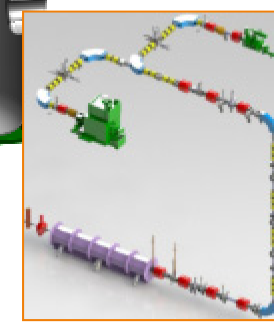
- Interaction of intense heavy-ion beams with materials
  - Charge stripper
    - » 40 kW at 20 MeV/nucleon
    - » Liquid lithium film
  - Rare isotope production target
    - » 400 kW at 200 MeV/nucleon
    - » Rotating carbon discs
  - Beam dump shell
    - » 300 kW at ~150 MeV/nucleon
    - » Rotating titanium shell, water-filled to harvest isotopes and to dissipate power
- Versatile, affordable, energy-efficient helium liquefaction plant (15 kW at 4 K)
  - Versatile: Need to design and order while 4K and 2K loads are not finalized
  - Affordable: Transferring all risk to industry was too costly
    - » FRIB assumed responsibility for the planning, process design, integration, and commissioning of the sub-systems and the over all cryogenic system performance
    - » Side benefit: Design completely integrated across cryoplant, cryogenic distribution, and cryomodules and superconducting magnets

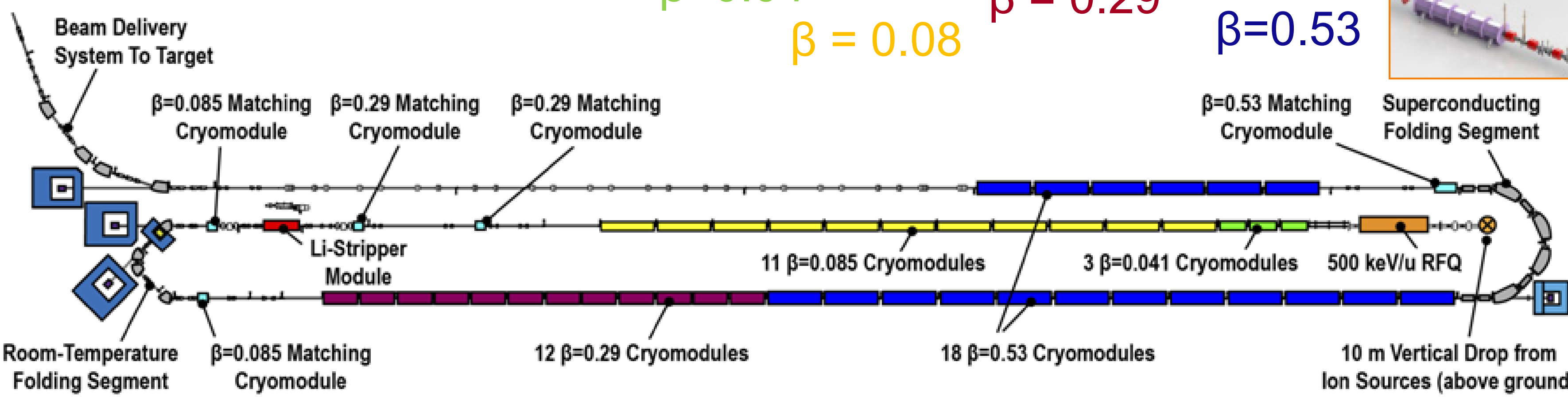
Superconducting Radio-Frequency Linac

J. Wei (head of FRIB Accelerator Division), P. Ostroumov, J. Yamazaki, K. Saito, *et al.*

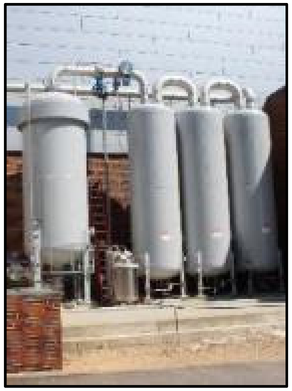
- Accelerate ion species up to ^{238}U with energies of at least 200 MeV/u
- Two frequencies 80.5 MHz and 322 MHz with four cavity types
- Energy upgrade to 400 MeV/u for ^{238}U by filling vacant slots with 12 SRF cryomodules
- Provisions for ISOL upgrade







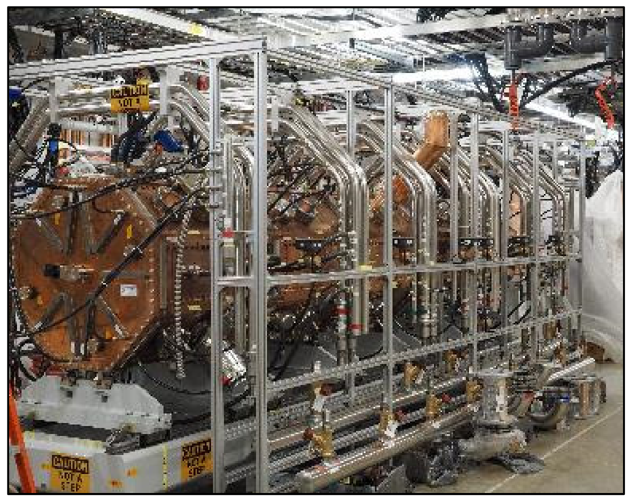
Technical Construction started in October 2014







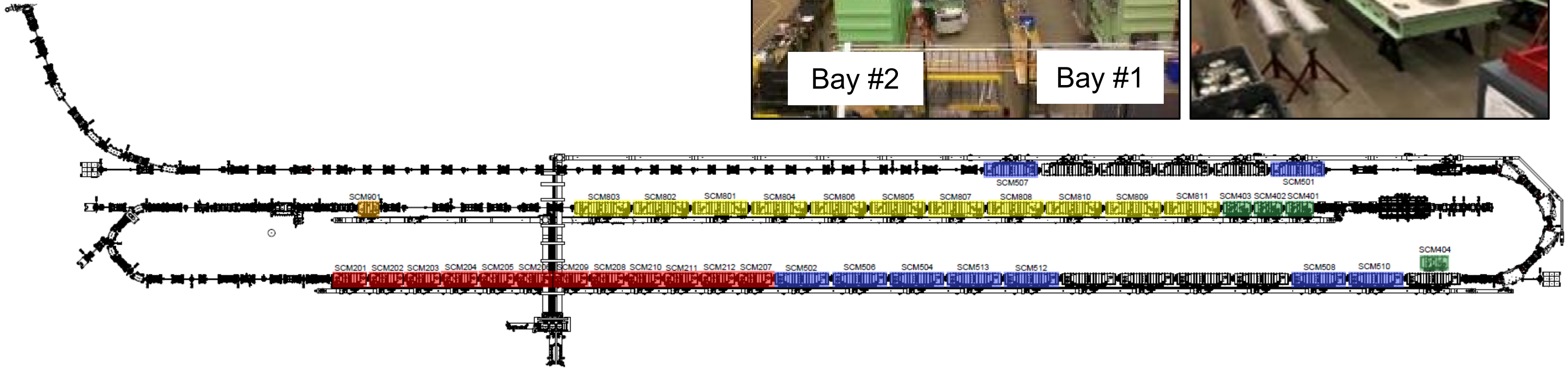




Cryomodule Production Winding Down
Averaged Nine Cryomodules Every Six Months

T. Xu, *et al.*

- FRIB's linear accelerator consists of 46 cryomodules that will accelerate the heavy ion beam to a target where rare isotopes will be produced
  - Produced nine cryomodules in six months at peak production in five bays
  - As of 31 July 2019:
    - 43 (plus one spare) of 46 cryomodules produced
    - 37 (plus one spare) tested
    - 36 (plus one spare) installed in tunnel

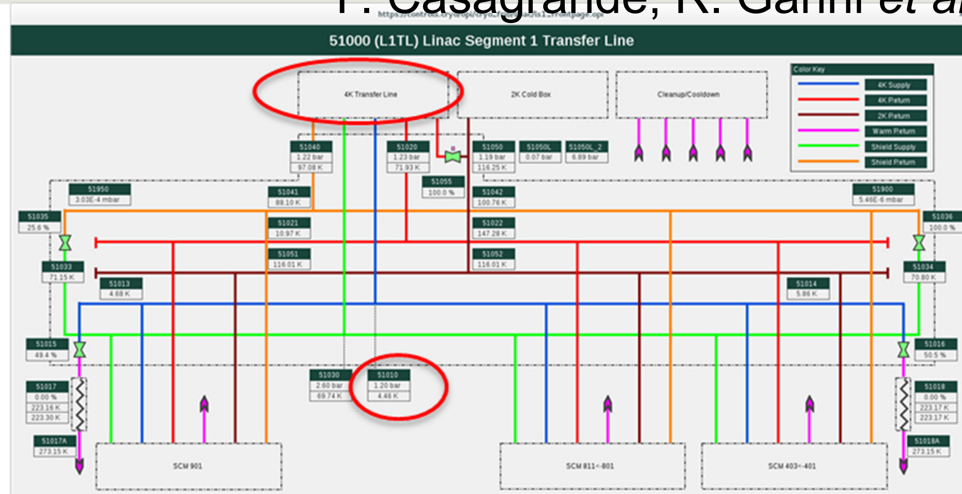


Helium Refrigeration System Operational

Liquid Helium for Superconducting Cavities & Magnets

F. Casagrande, R. Ganni *et al.*

Cryogenic transfer line installed in FRIB tunnel (design assisted by JLab)



May 10, 2018, cryo transfer line LS1 at 4.5 K

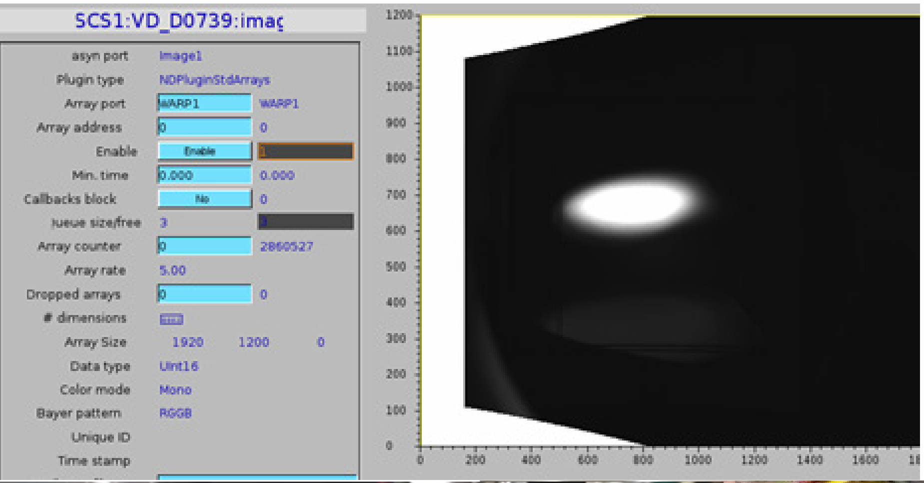
Warm compressor in operation

FRIB Cold Box producing 4 K liquid helium

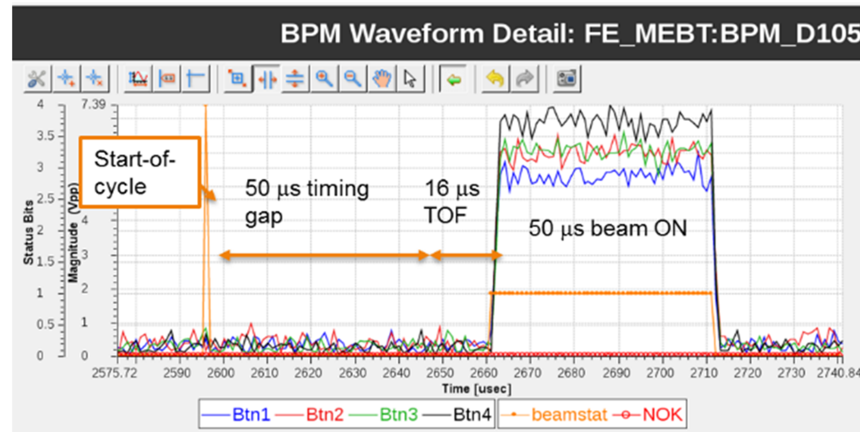
FRIB Front End Beam Commissioned

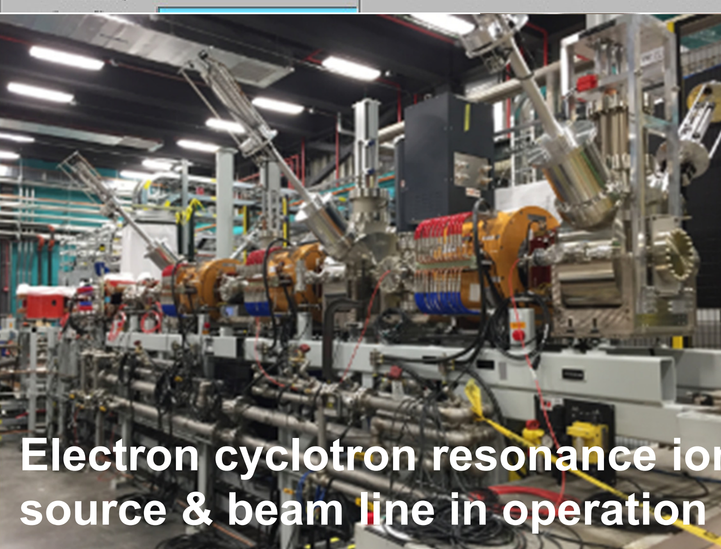
Demonstrated Key Performance Parameters, July 2018

- > 40 μA $^{40}Ar^{9+}$ and > 25 μA $^{86}Kr^{17+}$ beams accelerated through RFQ exceeding key performance parameters (KPP)
- Beam based measurement and radio frequency calibration in agreement within 1%

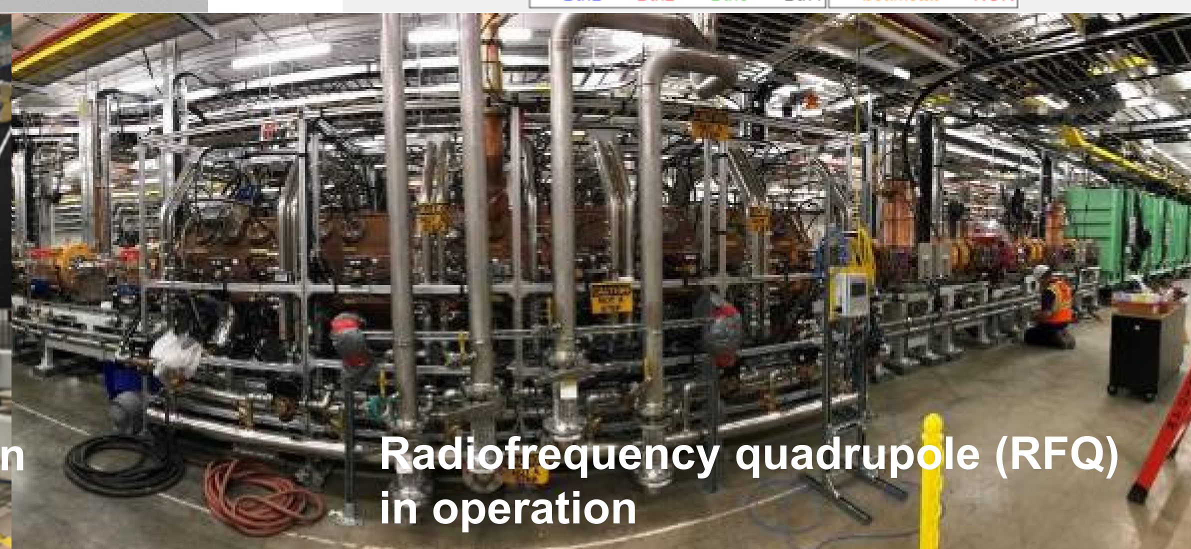


50 μs pulse @ 100 Hz (beam current ~ 3 eμA)





Electron cyclotron resonance ion source & beam line in operation



Radiofrequency quadrupole (RFQ) in operation

Helium Refrigeration System Commissioned at 2 K

All Cryomodules in Linac Segment 1 Cooled Down to 2 K

- August 2018: 2 K cold box installation
- December 2018: 2 K cold box commissioned and operational
- March 2019: All cryomodules in linac segment 1 cooled to 2 K

August 2018: 2 K cold box installation

F. Casagrande, R. Ganni *et al.*

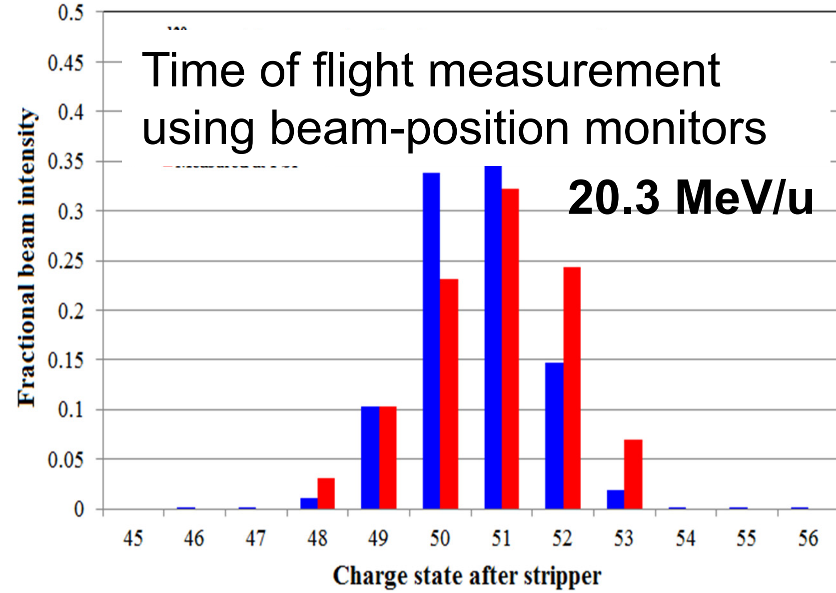
March 2019: Linac segment 2 cooldown

Linac Segment 1 Beam Commissioned

Demonstrated Key Performance Parameters, February 2019

P. Ostroumov, *et al.*

- July 2018: Superconducting radio frequency (SRF) cryomodule 1 – 3 beam commissioned
  - Met KPP in two days upon authorization
  - Accelerated argon and krypton beams to 2 MeV/u, 1 percent of FRIB’s final beam energy
- February 2019: SRF cryomodule 1 – 15 beam commissioned
  - Met KPP in a week upon authorization
  - Accelerated argon and krypton beams above 20 MeV/u, 10 percent of FRIB’s final beam energy



July 2018: Ar^{9+} beam accelerated by cryomodule 1 – 3 to 2 MeV/u

FRIB linac segment 1 containing 16 SRF cryomodules

Liquid-Lithium Charge Stripping Enables High-Power Heavy-Ion Charge Stripping

T. Kim, F. Marti *et al.*

- Collaborated with ANL to establish liquid-lithium film with controllable thickness and uniformity for charge stripping
  - World's most powerful proton source (LANL's 100 mA LEDA ion source) was restored at MSU, used to test lithium charge stripper
  - Feasibility test successfully conducted
    - » Liquid-lithium film sustained ~200% of FRIB maximum power density deposition
- August 2018: Circulated liquid lithium and established lithium film in charge stripper
- September 2019: Lithium charge stripper completed 50 hours of continuous attended operations
  - Round-the-clock monitoring by trained operators
- March 2019: Circulated liquid lithium in it charge stripper for 10 days
  - Remote monitoring

Melted liquid lithium seen from the chamber view port

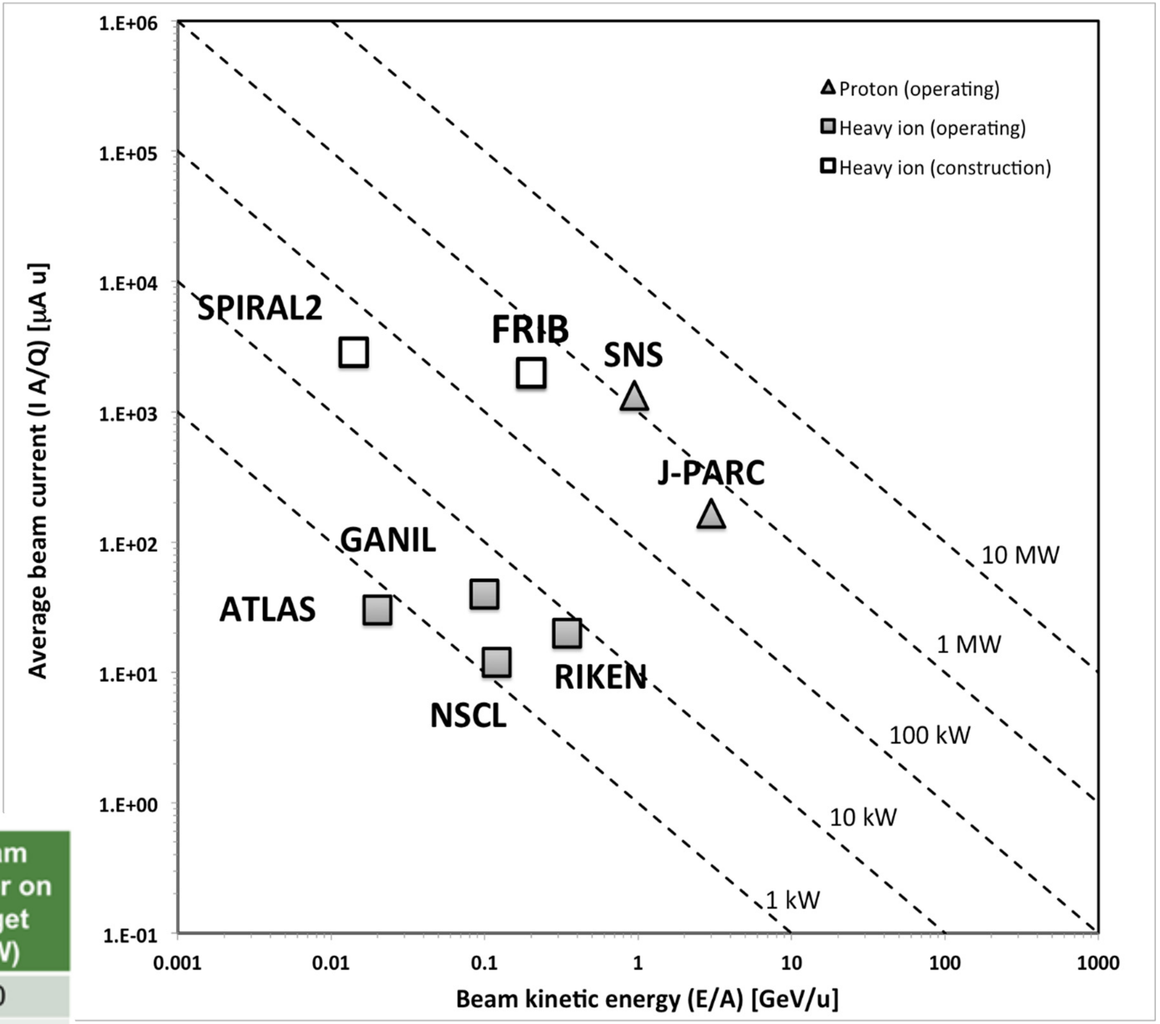
Fragment Separator Progress

G. Bollen, F. Pellemoine, A. Villari, T. Xu *et al.*

- November 2018: Two superconducting warm-ion quadrupole (WIQ) magnets were installed using remote-handling equipment
  - Following two years of magnet design, construction, assembling, and testing
- December 2018: FRIB's thermal-imaging system was successfully tested
  - System will monitor the beam spot on the production target
- June 2019: First of two fragment separator type 2 WIQ magnets cooled to 4 K in testing area and installed
  - All coils ramped to full field

FRIB: High Power Heavy-ion Accelerator
Anticipating Complexity of a High-Power Machine

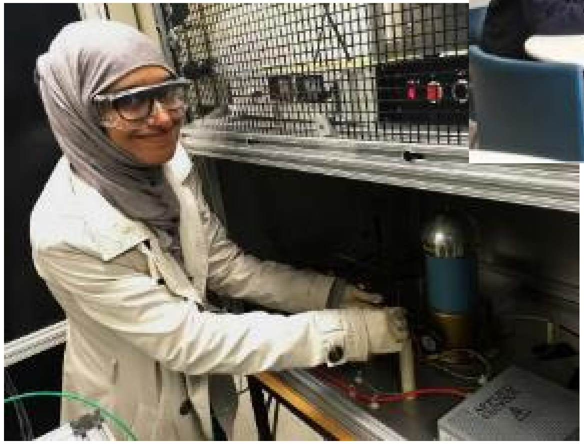
- FRIB will provide more beam power by two-to-three orders of magnitude over existing heavy-ion facilities
- Past experience for proton machines (one ion, one charge state), SNS and J-PARC, indicates steep learning curve
- Successful early operation is key to achieving desired power ramp-up profile (SNS took eight years to reach design power 1.4 GW for protons)
- Beam losses will limit power ramp-up, mitigation takes time and experience needs to be gained

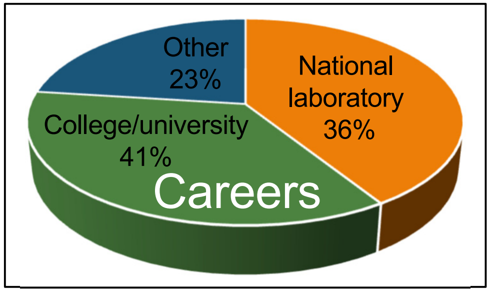


Year after CD-4	Beam power on target (kW)
1	10
2	50
3	100
4	200
5	400

Training the Next Generation of Scientists and Engineers

- MSU nuclear physics graduate program ranked #1 in nation
- 26% of U.S. nuclear physics graduate students receive part of their training at NSCL
- 116 graduate students in Physics, Chemistry, Electrical Engineering, Mechanical Engineering
- 23 new graduate students in 2019 (21 physics, 2 chemistry)
- 120 undergraduate students
- 70 graduate students graduated since 2013
  - 26% female, 74% male
  - 79% United States, 21% international
- Median time to Ph.D. is 5.1 years
  - National median in physics is 6.2 years
- Graduating student careers
  - 41% Universities
  - 36% National laboratories
  - 23% Other
- nscl.msu.edu/grad/ for more information and to apply to graduate school at MSU





all numbers as of August 2019

Leveraging FRIB, MSU Addresses National Workforce Shortage

- Accelerator scientists and engineers needed for DOE-SC programs and facilities
- FRIB, College of Natural Science, College of Engineering launched Accelerator Science and Engineering Traineeship program leveraging FRIB
- Over 20 faculty plus 30 academic staff, focusing on four areas with critical workforce needs:
  - Design and operation of large accelerator facilities,
  - Superconducting RF (SRF) technology
  - RF power engineering,
  - Large-scale cryogenic systems
- Supported by DOE-SC Office of High Energy Physics
- Participants intern at national laboratories
- Working with national advisory council to evaluate program and propose improvements
- https://frib.msu.edu/science/ase/graduate-studies.html

MSU Cryogenic Initiative: Workforce Development Leveraging FRIB

- Prof. Rao Ganni, Director
- FRIB and MSU College of Engineering collaboration
- Addressing a national shortage of cryogenic engineers
- Led by nation's leading cryogenic engineering faculty
- Since 2017 program inception, five students in the program
  - Three graduate students, two undergraduate students (as of spring 2019)
- Increasing enrollment in MSU courses
  - Since 2017, forty-five students enrolled in Cryogenic Engineering classes
- Class held at U.S. Particle Accelerator School (USPAS) MSU 2018 summer session at capacity of 20

- Educate and train future cryogenic engineers and systems innovators
- Develop and maintain a cryogenic system knowledge base of cryogenic technology and skills
- Investigate, propose, and foster efficient cryogenic process designs, and research of advanced cryogenic technologies
- Maintain a knowledge base to operate unsupported equipment

Outreach Efforts Engage Communities Across Michigan

- Over 10,000 contacts per year
- New Impression 5 Science Center exhibit will reach 150,000 per year
- Open house in 2018
  - More than 4,500 tours given
- Programs in public schools and beyond
  - including Michigan school districts, colleges, private schools, homeschooling groups
- Other collaborations
  - Summer program with Gifted and Talented office
  - PAN summer program assessment with College of Education
  - Road shows with Detroit schools
  - MSU Science Festival
  - MSU Grandparents University
  - Isotopolis game with MSU Communication Arts and Sciences
  - Dance of the Isotopes with Wharton Center
  - Virtual tour with MSU Planetarium
  - Art exhibits

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 (formerly OHSAS 18001), since 2007
  - ISO 9001 - Quality, since 2008

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

Best-value Procurement
93.7% of Expenditures and Obligations in US

- FRIB uses a best-value procurement approach and works to establish long-term relationships with qualified suppliers
- $1,147M in procurements and labor spent and obligated since January 2011, $870M (75.8%) in Michigan, $1,039M in United States
(as of 31 July 2019)

FRIB and NSCL Spending and Commitments since 2011

Michigan
$870M (75.8%)

Other States
$205M (17.9%)

Other Countries
$72M (6.3%)

Domestic Manufacturing Key to FRIB Success

Strategic Sourcing Enhances Project Success

- β=0.085 cryomodule cryogenic system (Portage, MI)
- Magnetic shields β=0.085 cavities (Tomahawk, WI)
- 30K He gas storage tanks (Dallas, TX)
- Shielding blocks (Bay City, MI)
- Vacuum vessel transportation (Southfield, MI)
- Target hall workstand table (Fenton, MI)
- Shield glass window (Kent, WA)
- Magnet source wire (Waterbury, CT and Shrewsbury, MA)
- Bridge crane (Shore View, MN)
- Target hall machine lift (Milwaukee, WI)
- Chambers (Yuma, CA)
- Chambers (Williston, FL)
- Temp monitors (Westerville, OH)
- Level monitors (Oak Ridge, TN)
- HWR cryomodule cryogenic manifold assemblies (South Holland, IL)
- FSQ5 magnet thermal shield (South Holland, IL)
- Helium purifier (South Holland, IL)
- β=0.041 cavities (College Point, NY)
- RT magnet power supplier (San Diego, CA)
- β=0.085 cavities magnetic shield (Philadelphia, PA)
- Production β=0.53 cavities (Brownsburg, IN)
- Titanium rings (New Baltimore, MI)
- Vacuum vessel seals (Farmington Hills, MI)
- Beam dump rotation drum (Brownsburg, IN)
- RF directional couplers (Cheshire, CT)
- Master slave manipulator (Red Wing, MN)
- Lead glass window and Insert (Kent, WA)
- Vacuum vessels (Camden, NJ)
- β=0.085 cavities magnetic shield hoods (Bensenville, IL)
- RF rigid transmission lines (Gorham, ME)
- RF directional couplers (Mahwah, NJ)
- RF adapters (Mahwah, NJ)
- Cold beam position monitors (Watervliet, NY)
- Warm beam position monitors (Watervliet, NY)
- High voltage transformer (Palo Alto, Ca)
- Diagnostic vacuum chambers (Williston, FL)
- RT magnet stands (St. Johns, MI)
- RFQ cold model (St. Johns, MI)
- Cold tuner assemblies (Albuquerque, NM)
- Dipole chambers (Elk Grove, CA)
- Male bayonet cryogenic tubes (Brazil, IN)


Vacuum vessel (Camden, NJ)


Warm helium compressor skids (Hilliard, OH)


4.5K cold box (Tulsa, OK)


Cryomodule (Merrill, MI)


Multi-layer insulation (Middlesex, VT)

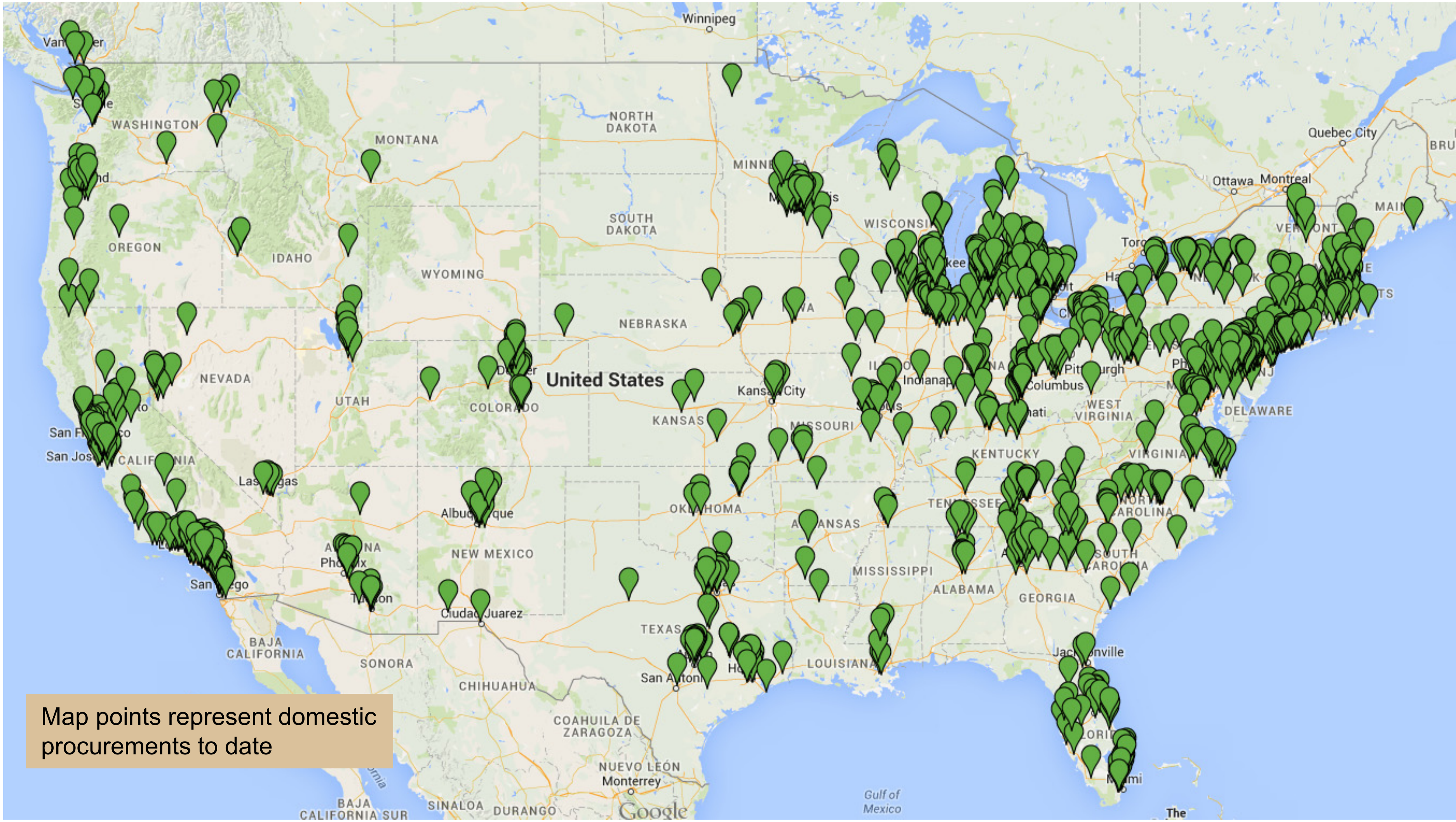

SRF cavity (Brownsburg, IN & Medford, NY)


FSQ5 magnet thermal shield (South Holland, IL)


HWR cryomodule cryogenic manifold assemblies (South Holland, IL)


B=0.085 cryomodule cryogenic system (Portage, MI)

Procurements Span the United States



Map points represent domestic procurements to date

Collaborating with National Laboratories and International Partners

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

- RIKEN
  - Helium gas charge stripper
- TRIUMF
  - Beam dynamics design, physics modeling SRF, QWR etching (DONE)
- INFN
  - SRF technology (DONE)
- KEK
  - SRF technology, SC solenoid prototyping (DONE)
- IMP
  - Magnets (DONE)
- Budker Institute, INR Institute
  - Diagnostics (DONE)
- Tsinghua Univ. & CAS
  - RFQ (DONE)
- ESS
  - Accelerator physics (DONE)
- DTRA
  - RFQ power supply (DONE)
- 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
- U Notre Dame
  - Recoil implantation testing of materials

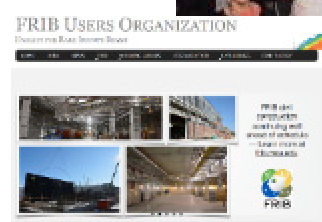
1,400 Users Engaged and Ready for Science

www.fribusers.org

- Users organized as part of independent FRIB Users Organization (FRIBUO)
  - Chartered organization with an elected executive committee
  - 1,400 members (119 U.S. colleges and universities, 13 national laboratories, 52 countries) as of 31 July 2019
  - 19 working groups on instruments

- User needs and high user satisfaction are important to FRIB
  - Users establishing programs and preparing for FRIB science now
  - Very high proposal pressure, 2-year backlog, 40% approval rate
  - Support for major user initiatives, e.g., GRETINA campaign
  - User feedback recorded, tracked, and acted on
  - NSCL research user satisfaction 100% over past 4 years
  - Last NSCL PAC in 2019 (First FRIB PAC in 2020)

- Annual meetings
  - User meeting (three days with 200-300 participants)
    - » Last meeting August 2019 at Duke University
  - FRIB Scientific Advisory Committee
    - » Ensures FRIB project remains aligned with mission
    - » Will evolve into FRIB PAC in 2020



FRIB Project on Budget, Ahead of Schedule

- FRIB project is about 92% complete, on budget, and being managed to early completion in 2021, CD-4 is in June 2022
  - Cryoplant commissioned to 4 K and 2 K in linac segment 1
  - Linac segment 1 commissioned with beam
- Isotope Harvesting capability foreseen in FRIB baseline design
- Users preparing for science
  - 1,400 users engaged in working groups, performing experiments at NSCL, and getting ready for FRIB science – workshop to prepare for first PAC next year
- Leveraging FRIB as training ground for accelerator scientists and engineers
- Lessons learned that support FRIB success
  - Continued support from MSU, DOE Office of Science, and elected officials
  - Strong technical leadership for all systems
  - Phased commissioning
  - Strategic partnerships with key vendors for one-of-a-kind equipment is key
    - » Transfer risk to industry very deliberately (not a procurement decision)
  - A stable, committed team that works well together and is focused on success