FRIB Construction Status and Day 1 Physics

Presentation to the June 2, 2017, Nuclear Science Advisory Committee

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U.S. DEPARTMENT OF ENERGY | Office of Science

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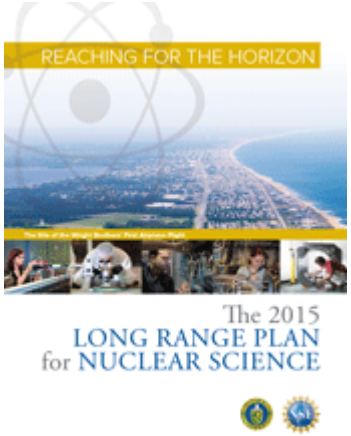
NSAC Long Range Plan Recommendations Regarding FRIB



"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."

The 2015 Long Range Plan for Nuclear Science

"We recommend construction of the Facility for Rare Isotope Beams (FRIB), a world-leading facility for the study of nuclear structure, reactions, and astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, provide an understanding of matter in the crust of neutron stars, and establish the scientific foundation for innovative applications of nuclear science to society.

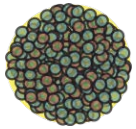
The Frontiers of Nuclear Science: A Long Range Plan (2007)

FRIB started in June 2009 and is on Budget and Ahead of Schedule

- FRIB is about 76% complete, on budget, and being managed to early completion in 2021, CD-4 is in June 2022
- Civil construction is 97% complete and turned over to technical staff
- Technical construction is 71% complete
  - Frontend will be complete in July 2017 (10 months ahead of baseline schedule), beams for key performance parameters will be demonstrated in FY2017 – accelerated argon and krypton beams
  - Eight of 49 cryomodules tested and in tunnel, and planning for beam accelerated in cryomodules in 2018
  - 4K cryoplant tracking towards liquid helium in 2017 (6 months ahead)
- FRIB ready for early operations in FY2018 to enhance mission success (power ramp with many primary beams) after project success
- Transition from NSF-funded NSCL user facility to DOE-funded FRIB user facility on track and planned for 2021
- 1,400 users engaged in working groups, performing successful experiments at NSCL, and getting ready for FRIB science

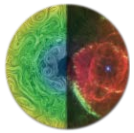
FRIB Science Is Important for the Nation

Four areas of science articulated by National Research Council RISAC Report (2006), NSAC LRP (2007), NRC Decadal Survey of Nuclear Physics (2012)



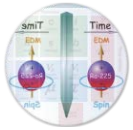
Properties of nuclei

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



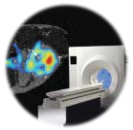
Astrophysical processes

- 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

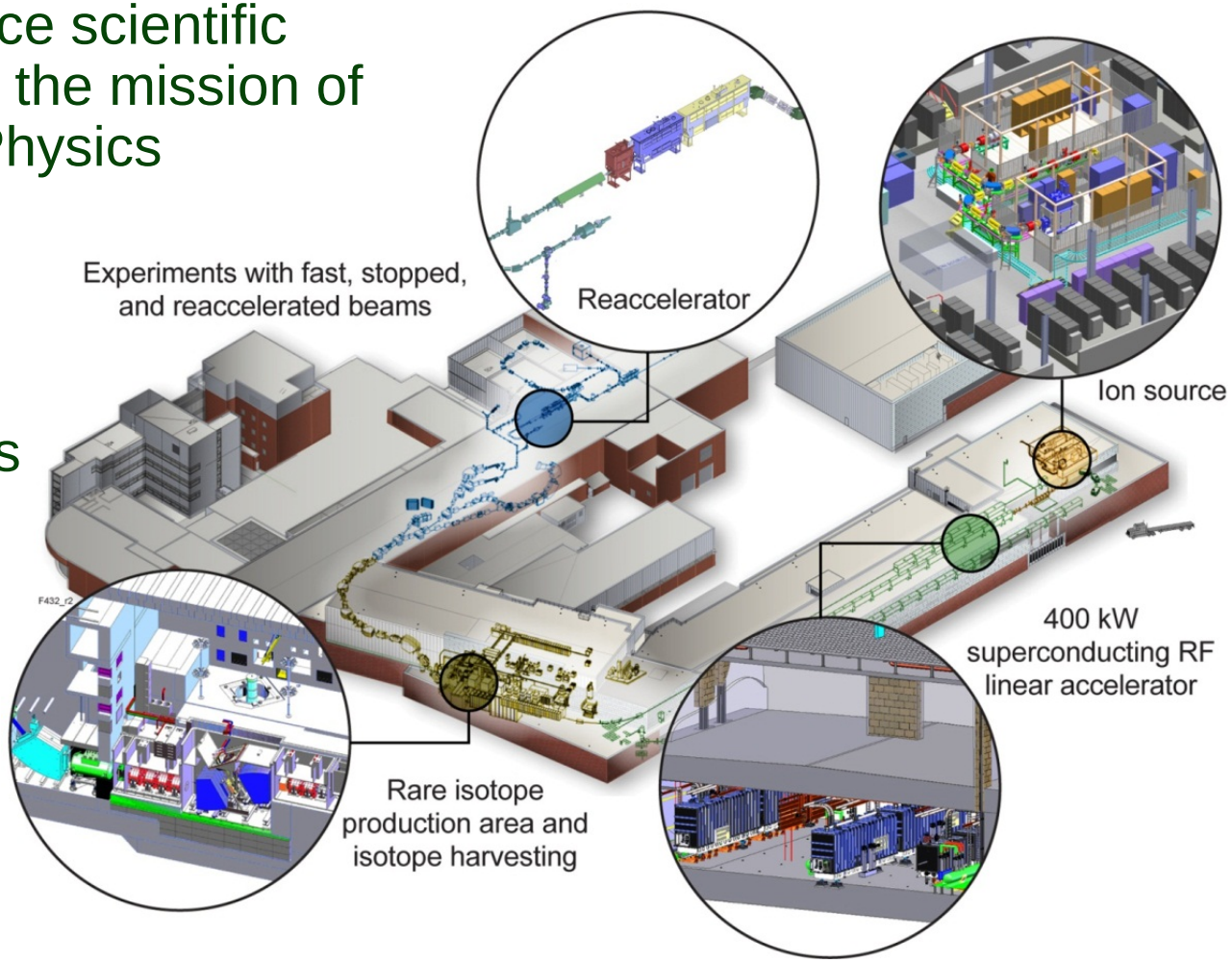
- Bio-medicine, energy, material sciences
- National security

"Data to date on exotic nuclei are already beginning to revolutionize our understanding of the structure of atomic nuclei. FRIB will enable experiments in uncharted territory at the limits of nuclear stability. FRIB will provide new isotopes for research related to societal applications, address long-standing questions about the astrophysical origin of the elements and the fundamental symmetries of nature."

2012 NRC Decadal Study

FRIB is Poised to Enable Major Discoveries in the Four Science Areas on Day One

- A DOE Office of Science scientific user facility supporting the mission of the Office of Nuclear Physics
- Serving user group with 1,400 members
- Key feature is 400 kW beam power for all ions (e.g. $5x10^{13}$ $^{238}U/s$)
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - All elements and short half-lives
  - Fast, stopped, and reaccelerated beams



Civil Construction Substantially Complete
Beneficial Occupancy in March 2017

Web cameras at www.frib.msu.edu

March 2016
12 Months Prior to Beneficial Occupancy

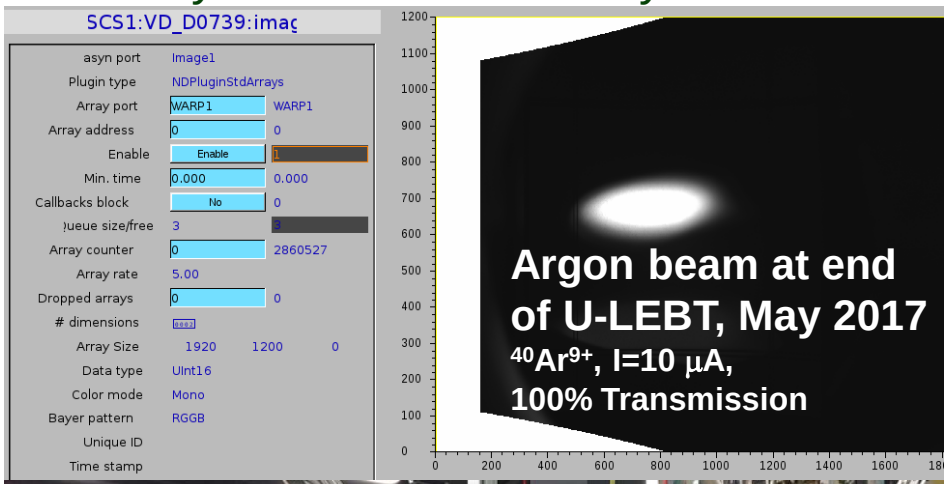
May 2015
22 Months Prior to Beneficial Occupancy

May 2014
34 Months Prior to Beneficial Occupancy

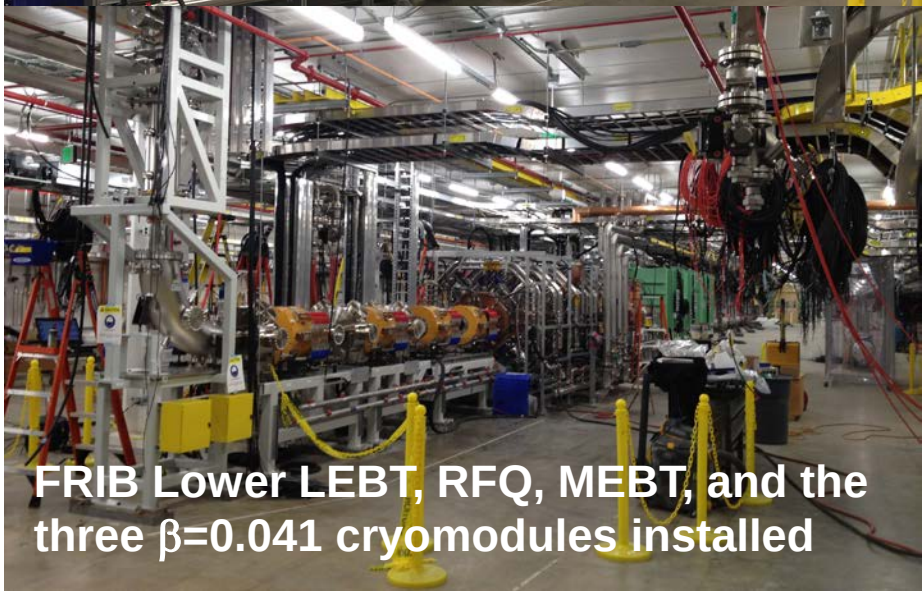
Ground Breaking in March 2014
36 Months Prior to Beneficial Occupancy

Transported Beam Through U-LEBT
Reached Key Performance Parameter Intensity for Ar

- Transported argon beam through Upper part of Low Energy Beam Transport (U-LEBT) at Key Performance Parameter intensity with 100% efficiency



- Lower LEBT, Radio Frequency Quadrupople (RFQ) and Medium Energy Beam Transport ready for Accelerator Readiness Review in July 2017



Cryomodule Production, Testing, and Installation Underway

Chemical processing of cavities

Coldmass assembly in clean room

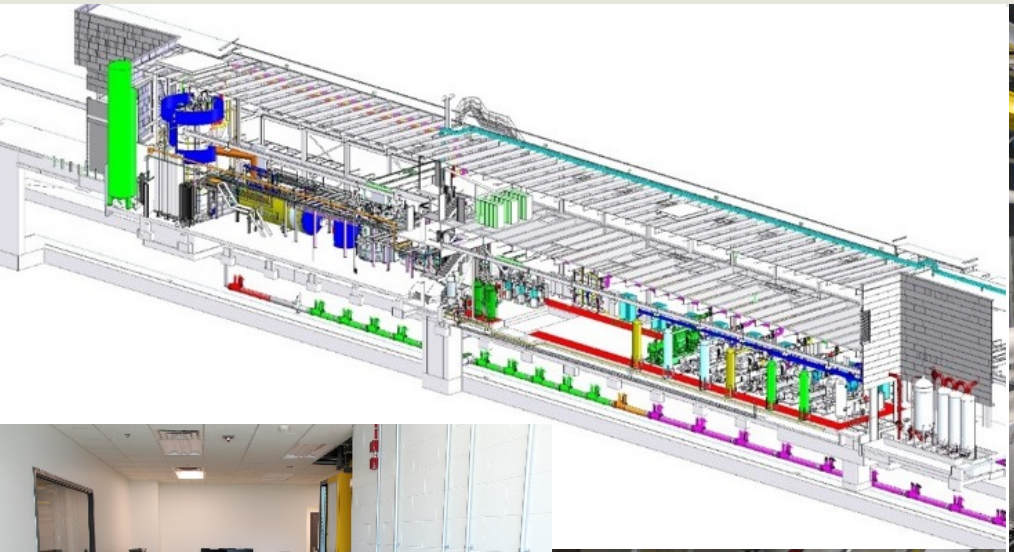
Cryomodule assembly (four of five bays)

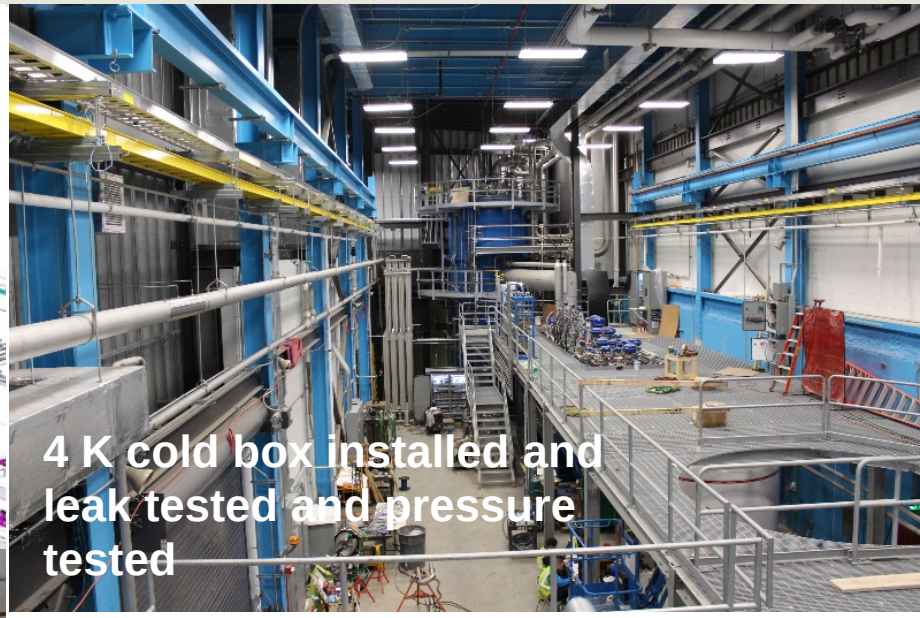
The three β=0.041 cryomodules installed and being cabled up in the FRIB tunnel

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

Cryoplant on Track for 4K Liquid in 2017

50% larger than SNS Cryogenic Plant





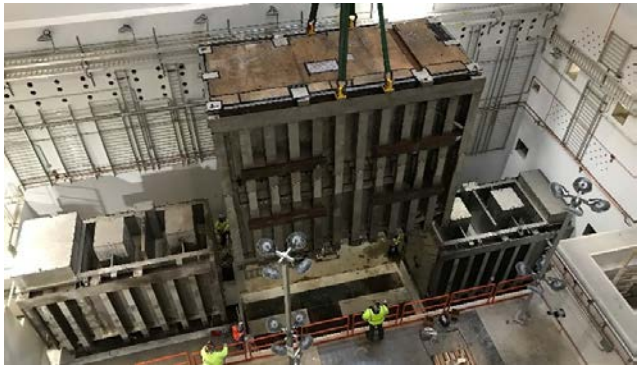
4 K cold box installed and leak tested and pressure tested

Cryogenic control room in preparation

Transfer lines to tunnel and distribution in tunnel installed

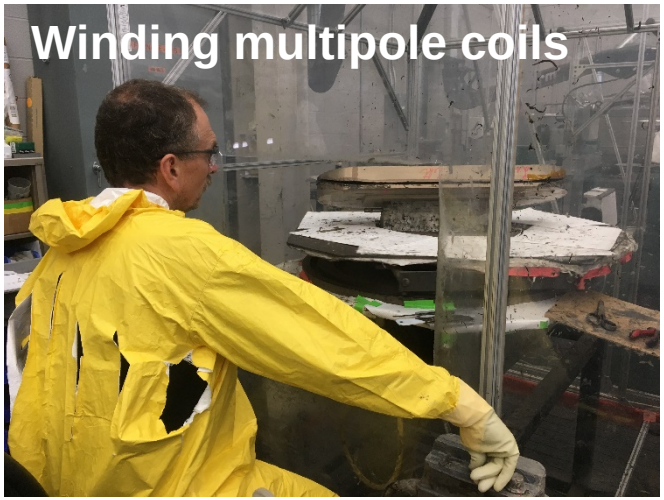
Warm compressor installed and energized

Vessels for Rare Isotope Production Fabricated, Installed and Leak Checked



Target Hall Cranes Operational and Equipment Lift Installed

Superconducting Magnets Being Fabricated



Collaborating with National Laboratories and International Partners

- ANL
  - Liquid lithium stripper**
  - Beam dynamics verification; β=0.29 HWR processing and test; SRF tuner validation; beam dump
- 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**
- LANL
  - Proton ion source
- LBNL
  - ECR coldmass; beam dynamics**
- ORNL
  - Remote Handling, diagnostics; large-vessel acuum, cryoplant controls
- SLAC**
  - Cryogenics**, SRF multipacting**, physics modeling**

- RIKEN
  - Helium gas charge stripper
- TRIUMF
  - Beam dynamics design, physics modeling **
  - SRF, QWR etching**
- INFN
  - SRF technology
- KEK
  - SRF technology, SC solenoid prototyping
- IMP
  - Magnets
- Budker Institute, INR Institute
  - Diagnostics
- Tsinghua Univ. & CAS
  - RFQ
- ESS
  - Accelerator Physics*
- DTRA
  - RFQ power supply**

* Under discussion or in preparation

** Completed

Red: Active/actively planned WFO contract

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 (from 113 U.S. colleges and universities, 12 national laboratories, 51 countries) as of March 2017
  - 19 working groups on instruments
    - » Astrophysics and SECAR
    - » Nuclear Data
    - » Data Acquisition
    - » Detectors for Equation of State Physics
    - » Gas Jets
    - » High Resolution In-beam Gamma Spectroscopy
    - » HRS: High Rigidity Spectrometer
    - » Ion Traps
    - » ISLA: ReA12 Recoil Separator
    - » Isotopes and Applications
    - » Laser Spectroscopy and Neutral Atom Traps
    - » Neutron Detection
    - » Radioactive Decay Station
    - » ReA Energy Upgrade
    - » Scintillator Arrays
    - » Silicon Arrays
    - » Solenoid Detectors
    - » Target Laboratory
    - » Time Projection Chambers

- Annual low-energy nuclear science community meetings (since 2011)
- FRIB Day 1 Science Workshop August 2, 2017, at Argonne National Laboratory

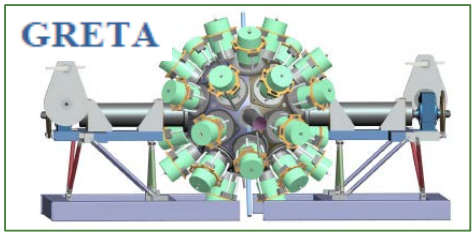
FRIB Provides Capabilities to Address Benchmark Programs Defined by NSAC

- Representative list of scientific capabilities
- Based on RISAC and NSAC Symon's committees
- Used by FRIB project
  - to check the facility capabilities
  - to develop the preliminary beam priority development list

No	Program	RI Beams	Capability
1	Study of Shell Structure	^{60}Ca, ^{48}Ni, ^{100}Sn	Fast and 12 MeV/u
2	Superheavy Elements	^{16,17,18}C, ^{90}Kr	10^{10}/s 6 MeV/u
3	Neutron Skins	^{48}Ni, ^{84}Ni	Fast beams > 0.01/s
4	Pairing	N=Z to ^{100}Sn, ^{138}Sn	N=Z, n-rich reaccelerated 12 MeV/u
5	Nuclear Symmetries	^{96}Kr, ^{134}Sm, ^{156}Ba	Fast 100/s, Reacc >10^4/x
6	Equation of State	^{102}Sn, ^{138}Sn	Fast, > 200 MeV/u+
7	r-process	^{194}Er, ^{195}Tm, ^{196}Yb	Fast, masses, (d,p) at 10 MeV/u
8	^{15}O(α,γ)	^{15}O	Low-E, Mass Separator
9	^{59}Fe s-process	^{59}Fe	Harvesting
10	Medical Isotopes	^{149}Tb	Harvesting
11	Stewardship	^{88,89}Zr, ^{78}Br	Harvesting, 12 MeV/u
12	Atomic EDM	^{225}Ra, ^{229}Pa	Harvesting, High Z
13	Limits of Stability	^{76}Cr, ^{88}Ni, ^{122}Zr	3-stage separator
14	Halo Nuclei	^{76}Cr	Drip-line nuclei
15	Mass Surface	^{79}Ni, ^{195}Ta	Penning Trap, TOF
16	rp-process	^{64}Ge, ^{65}As, ^{70}Kr	Mass separator
17	Weak Interactions	^{82}Ge, ^{102}Zr	Near 200 MeV/u

Users Develop Plans for Detectors and Day One Science Programs

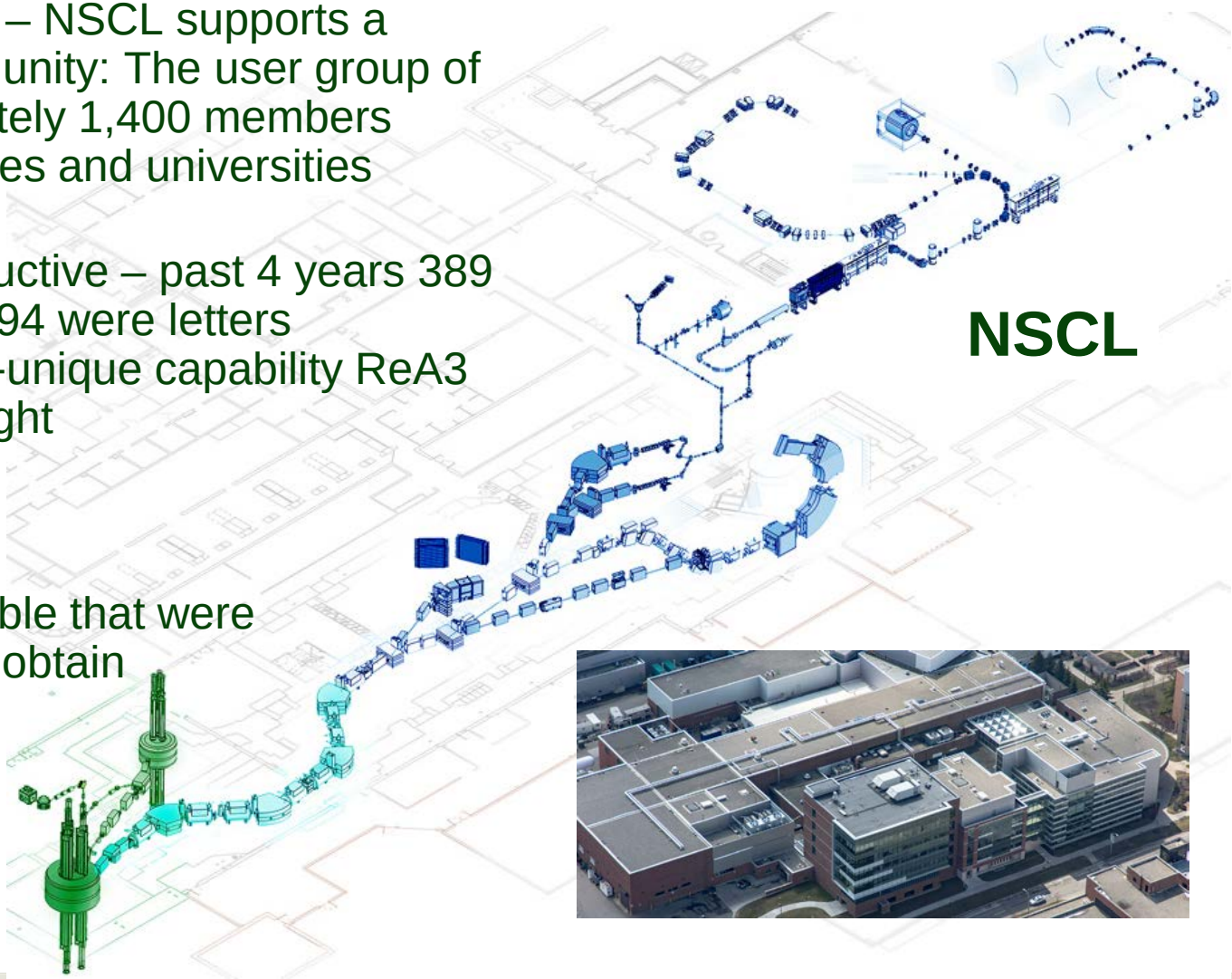
- FRIB Science Advisory Committee reviews user plans, detector initiatives, advises Laboratory and gives feedback
- FRIB Science Advisory will transition into Program Advisory Committee in FY2020
- Large Detector Initiatives from 2015 LRP
  - SECAR – Separator for Capture Reactions (started at MSU, supported by DOE and NSF)
  - GRETA – Gamma Ray Energy Tracking Array (started at LBNL)
  - HRS – High Rigidity Spectrometer (not started)
  - Beta-decay endstation (not started)



SECAR
Separator for Astrophysical Capture Reactions

Operation of NSF-funded NSCL Enables Outstanding Science Now and Educates us on FRIB

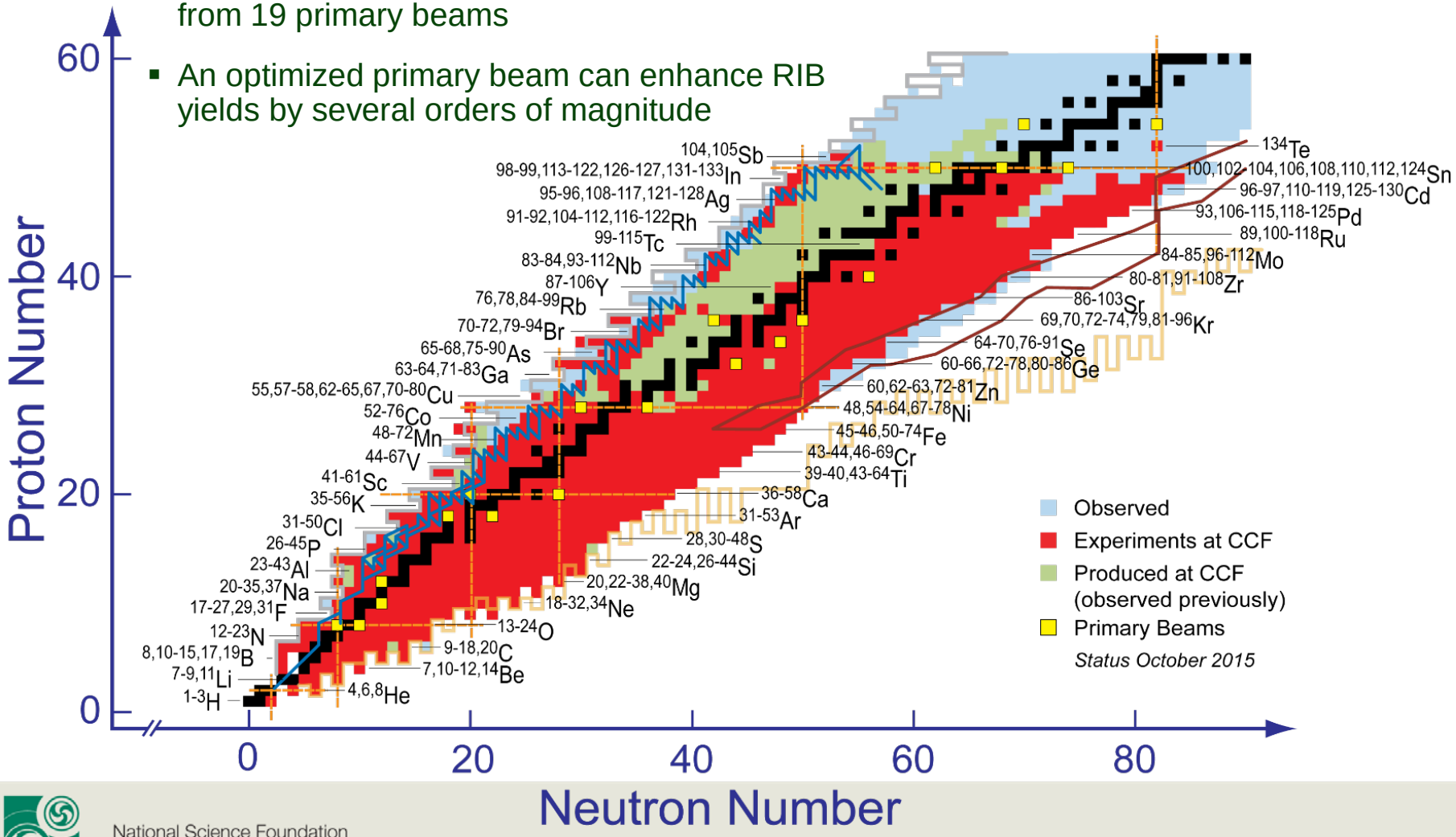
- National User Facility – NSCL supports a broad scientific community: The user group of NSCL has approximately 1,400 members (nearly 100 US colleges and universities involved)
- NSCL users are productive – past 4 years 389 publications of which 94 were letters
- New in FY2016 world-unique capability ReA3
  - First system for in-flight separation and reacceleration of rare isotopes
  - Makes beams available that were previously difficult to obtain



Operation of NSCL user facility is supported by NSF Physics Division

NSCL's Experience with Rare Isotope Beams
NSF-funded National User Facility

- From 2001-2017 more than 1,000 RIBs have been made, more than 950 RIBs have been used in experiments from 19 primary beams
- An optimized primary beam can enhance RIB yields by several orders of magnitude



Primary Beams for FRIB Day-One Science Program Established

Year 1 Beams	Notional Weeks/Year	Abundance (%)	Benchmark Programs
^{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
^{82}Se	5.25	9.4	1,3,4,5,6, 13,14,15
^{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
Total	23.8		

Year 2 Beams	Notional Weeks/Year	Abundance (%)	Benchmark Programs
^{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		

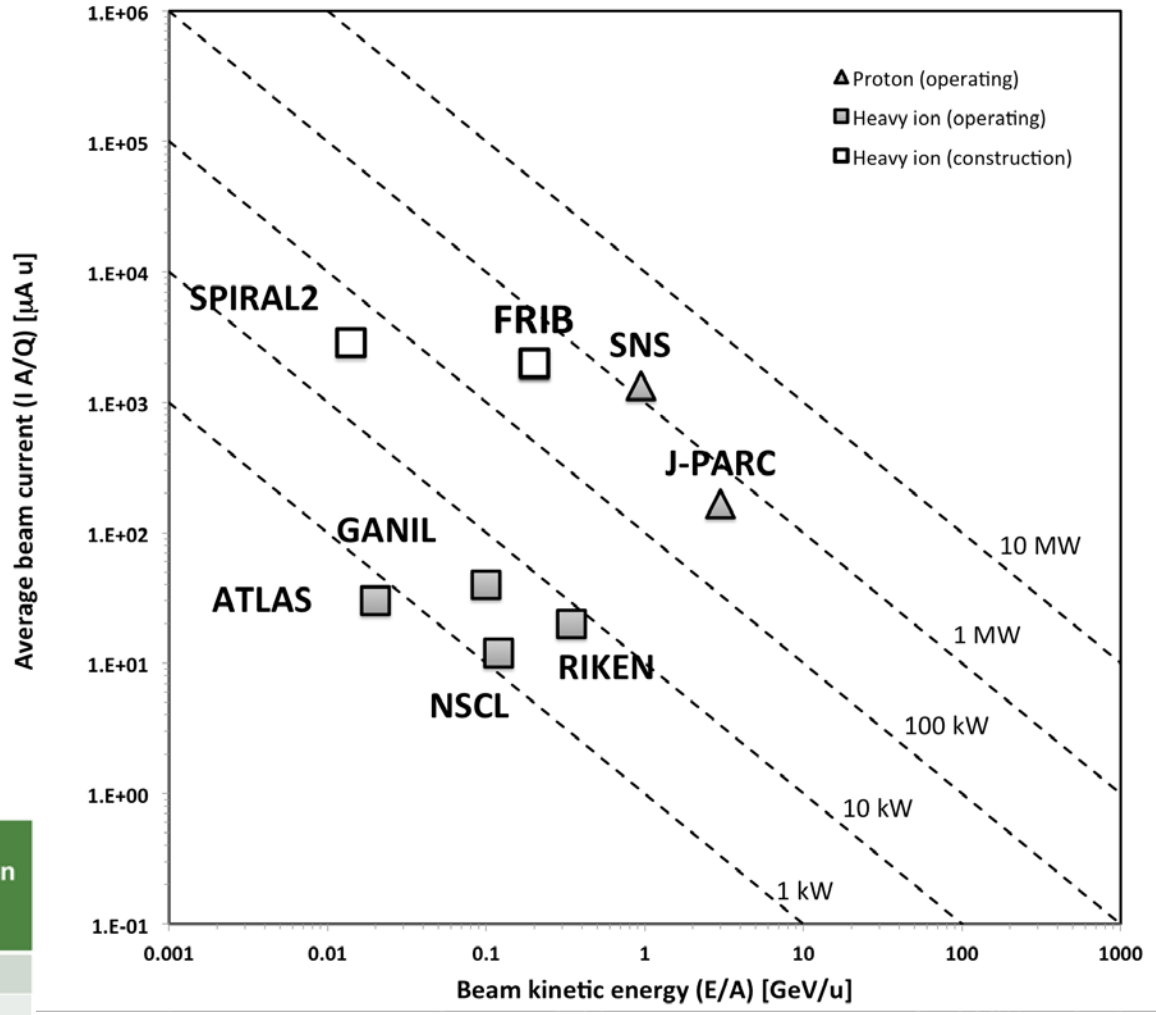
^{86}Kr and ^{36}Ar demonstrate FRIB Project's Key Performance Parameters

- FRIB user program demands frequent primary beam changes
  - Similar to NSCL operations but with high power
  - RHIC experience can provide a reference (but many fewer beam changes and fewer beams)
- Added complexity: Primary beam tune impacts selection and tuning of secondary beam isotope after the production target
- Accelerating multiple charge states of heavy ions to increase the beam intensity, requires a careful and complex tuning of the beam to control losses.
- ^{36}Ar and ^{86}Kr will be developed as part of FRIB Project, primary beams beyond ^{36}Ar and ^{86}Kr will be developed during early operations and operations

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

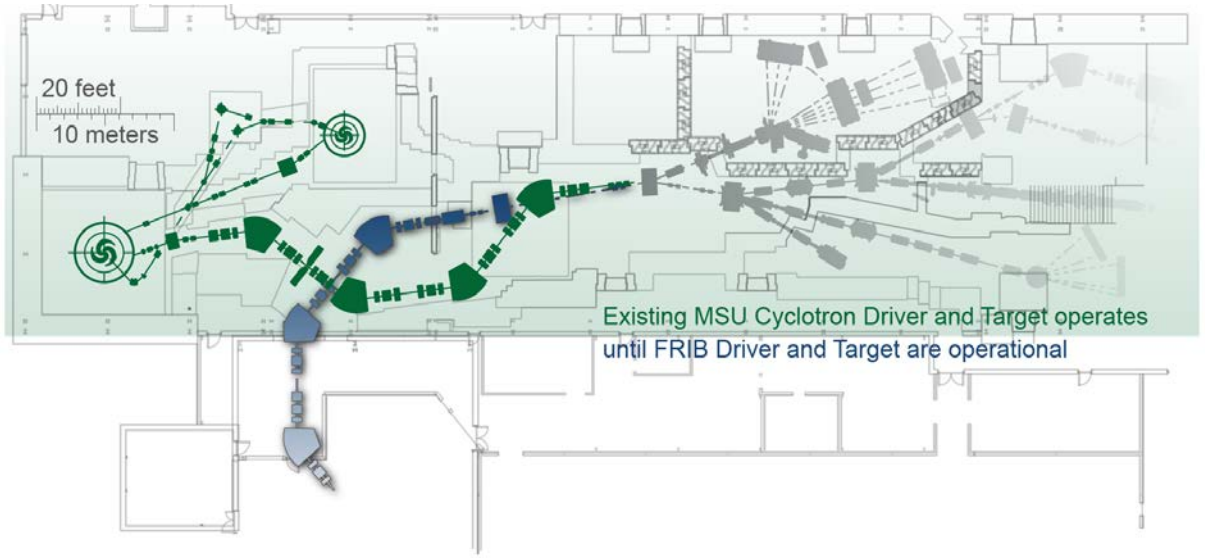
- FRIB will provide more beam power by two-to-three orders of magnitude over existing facilities
- Past experience for less-complex proton machines (one ion, one charge state), SNS and J-PARC, indicates steep learning curve
- Successful early operation is key to achieving desired power ramp-up profile (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

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



Transition Planned From NSF-funded NSCL to FRIB as Scientific User Facility

- Guiding Principle: Retain nation's leadership in rare isotope science and minimize impact on scientific discovery
- DOE-SC and NSF coordinate through Joint Oversight Committee
  - MOU between NSF and DOE-SC
- NSCL operated as NSF-funded national user facility through FY2021
- FRIB Project manages to completion with high likelihood of success in 2021
- FRIB accelerator and target commissioned when NSCL stops user operation
  - Then: open pre-made hole in wall, re-arrange transfer hall magnets, start FRIB user program
- NSCL and FRIB Users and Science Advisory Committee support and plan for FRIB science program



FRIB Theory Alliance Constituted and Active

Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

First cycle: June 1st 2015 – May 31st 2017

- Modest start (support 2 FRIB theory fellows at 50%)
- Inaugural meeting: March 31-April1 2016 (Charter approved)
- Two fellows hired (Lonardoni at LANL, Potel at MSU)
- Developed framework for applications for FRIB-TA bridge program
- Call for proposals for bridge program: Spring 2017

Second cycle: June 2017 through May 2020

- Recommended for funding by the Office of Nuclear Physics
- Expand fellow program to total 4 fellows (3 National, 1 MSU)
- Initiate the bridge program (planning 2 faculty/staff bridge by 2020)

Many great things to come so stay tuned at fribtheoryalliance.org

FRIB Project on Budget, Ahead of Schedule Looking Towards Enhancing Mission Success

- FRIB Project is about 76% complete, on budget, and being managed to early completion in 2021, CD-4 is in June 2022.
- FRIB Project success is likely
- 1,400 users engaged in working groups, performing successful experiments at NSCL, and getting ready for FRIB science
- Transition from NSF-funded NSCL user facility to DOE-funded FRIB user facility planned for 2021
- FRIB increases heavy-ion beam power by 2-3 orders of magnitude over existing heavy-ion machines
  - Proton machines (SNS and J-PARC) taught us that such an increase is hard and achieving mission success takes time
- FRIB is ready to start early operations in FY2018 to enhance likelihood of mission success