System Integration and Technical Readiness for FRIB Accelerator Commissioning

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On Behalf of FRIB Accelerator Team & Collaboration

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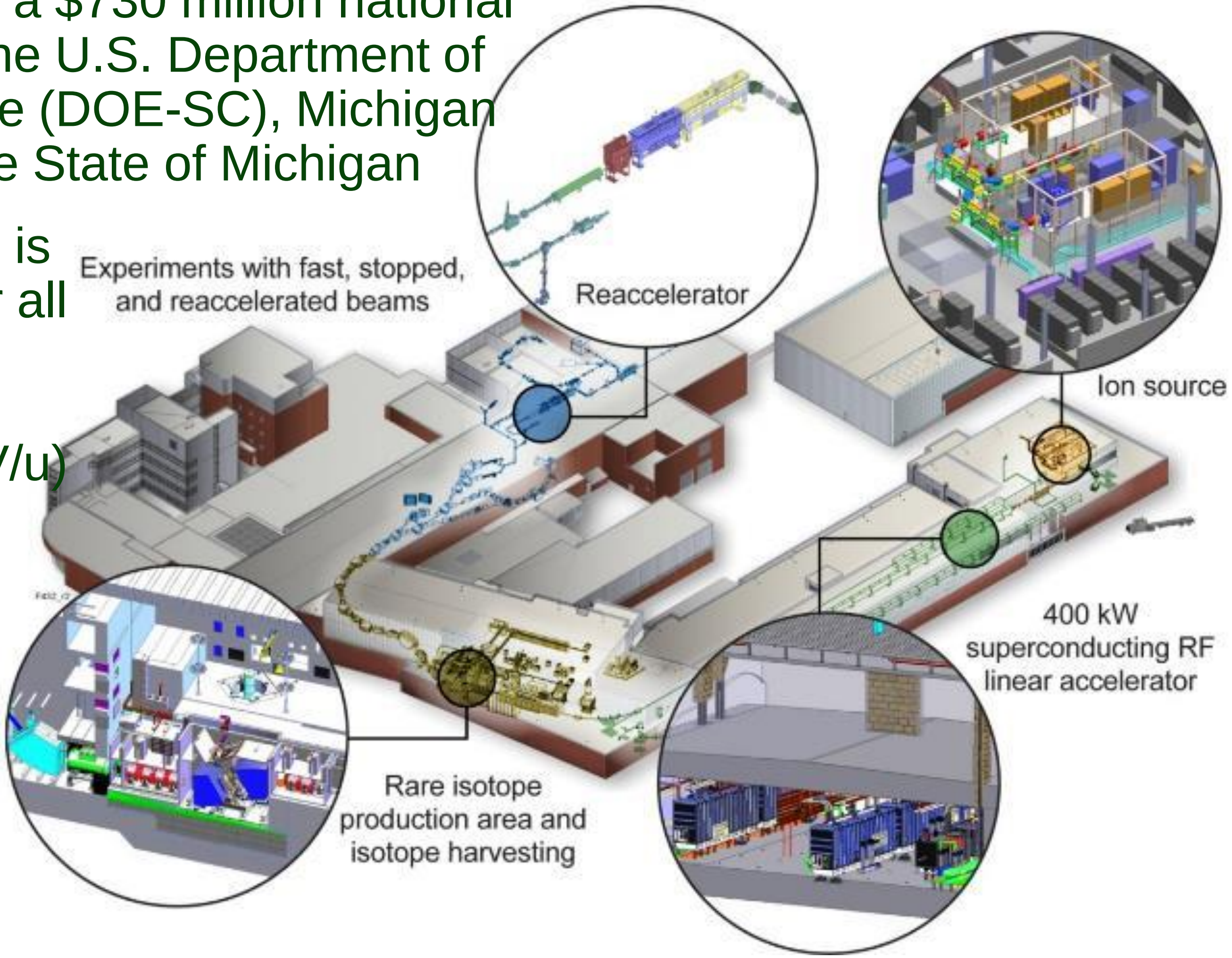
Outline

- Introduction
- Phased installation and commissioning
- Lessons learned
- Summary

Facility for Rare Isotope Beams Completed 14-year Project in 2022

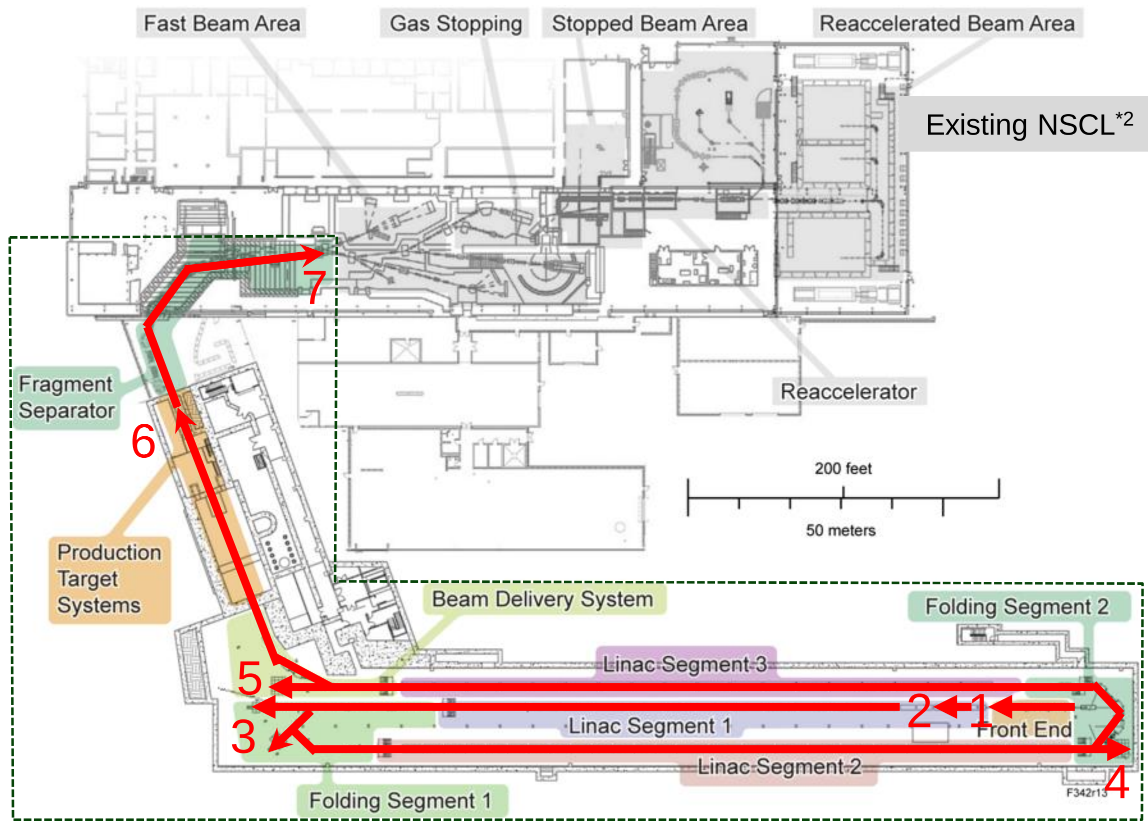
- FRIB Project constructs a $730 million national user facility funded by the U.S. Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- Driver Linac key feature is 400 kW beam power for all ions (8 pμA or 5x10^{13} ^{238}U/s) > 200 MeV/u (upgradable to 400 MeV/u)
- 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



System Integration and Phased Installation/Commissioning

- Pursed phased approach to install and commission in parallel (ARR1 – 7)
- Three steps of accelerator system integration
  1. Installation of beamline components
  2. Device Readiness Review (DRR)
     » Integrated system testing – e.g. Cool down, RF commissioning
  3. Accelerator Readiness Review (ARR[*1])
     » Beam commissioning

*1 Must be held per DOE O 420.2C



Key Performance Parameters (KPP) at CD-4

- ^{36}Ar beam with energy larger than 200 MeV/u and a beam current larger than 20 pnA
- ^{86}Kr beam to produce ^{84}Se by fragmentation. Detect and identify ^{84}Se in fragment separator

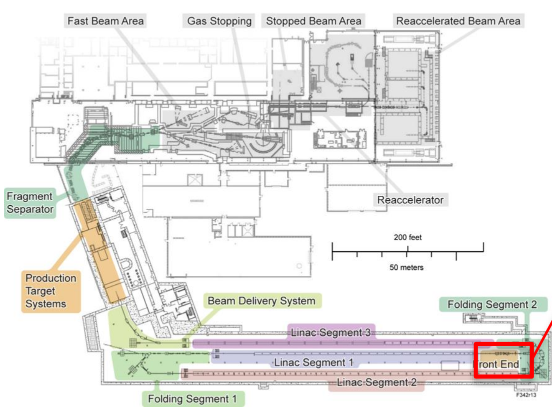
*2 National Superconducting Cyclotron Laboratory

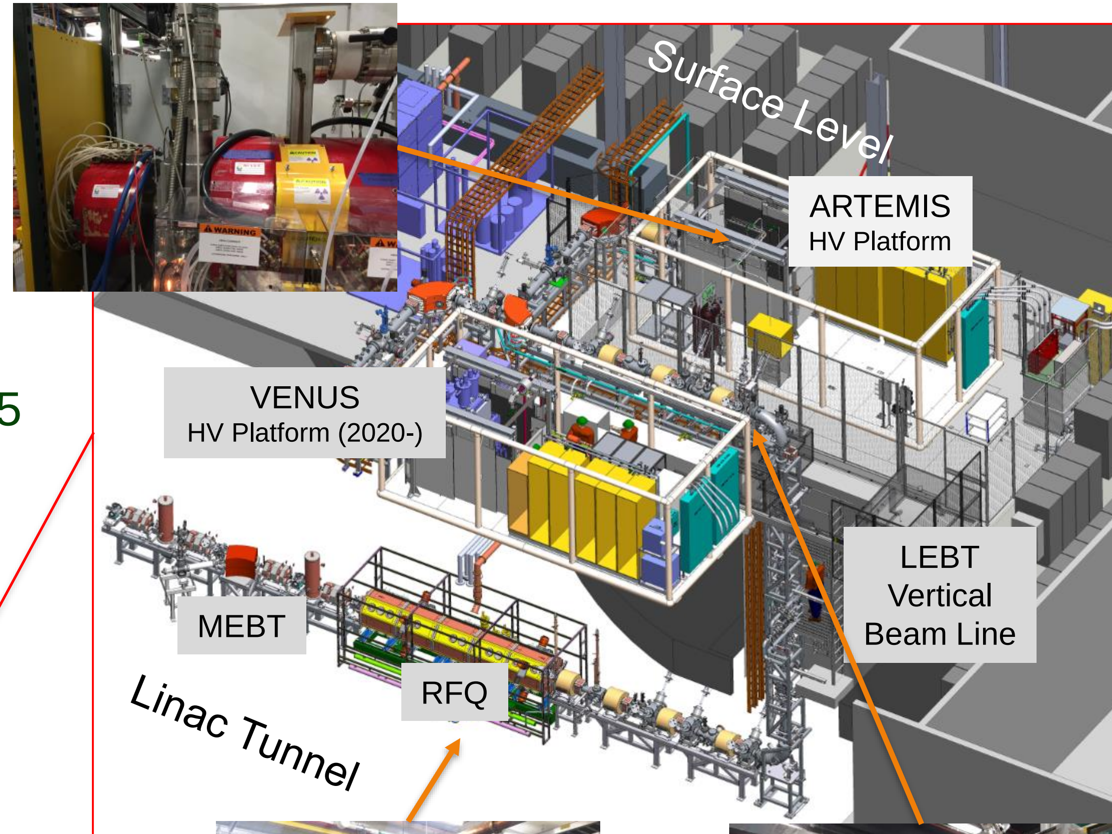
Front End

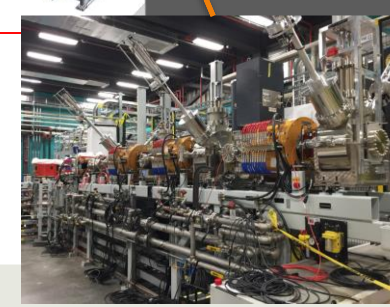
Installation 2015-, Beam Commissioning 2017-

- ARTEMIS*1 14 GHz Electron Cyclotron Resonance (ECR) ion source
  - Used to commisson FRIB
- VENUS*2 high power 28 GHz SC ECR (LBNL)
- 80.5 MHz RFQ – beam energy 0.5 MeV/u

*1 Advanced Room TEMperature Ion Source
*2 Versatile Ecr ion source for NUclear Science

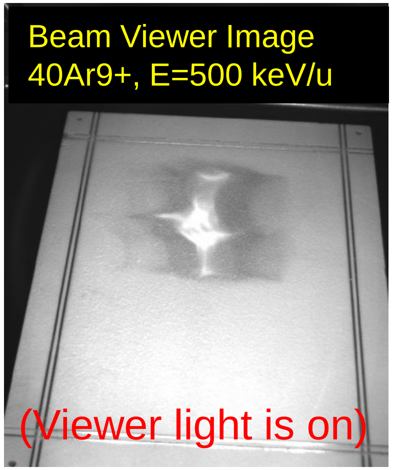


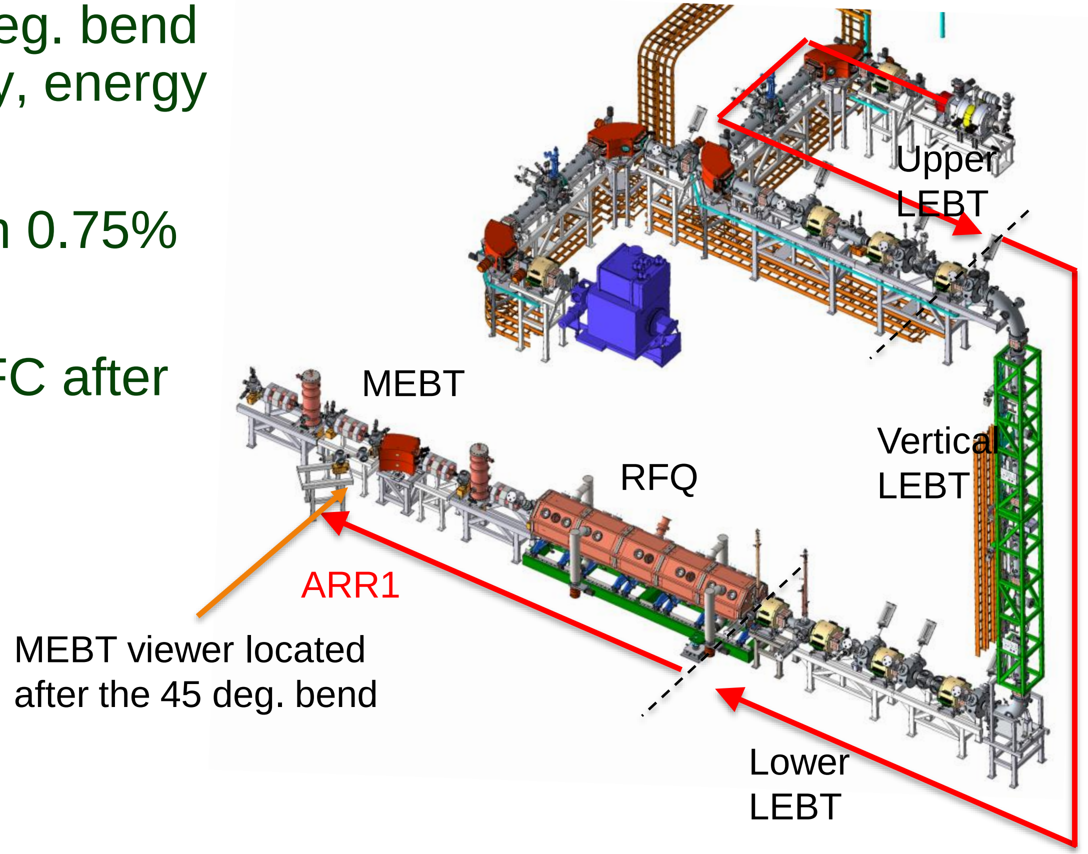




Beam Commissioning – ARR1

- The viewer after the MEBT 45 deg. bend is used to measure beam energy, energy spread, and beam profile
- Bending magnet current is within 0.75% of predicted value
- The straight ahead FC and the FC after bend read same current



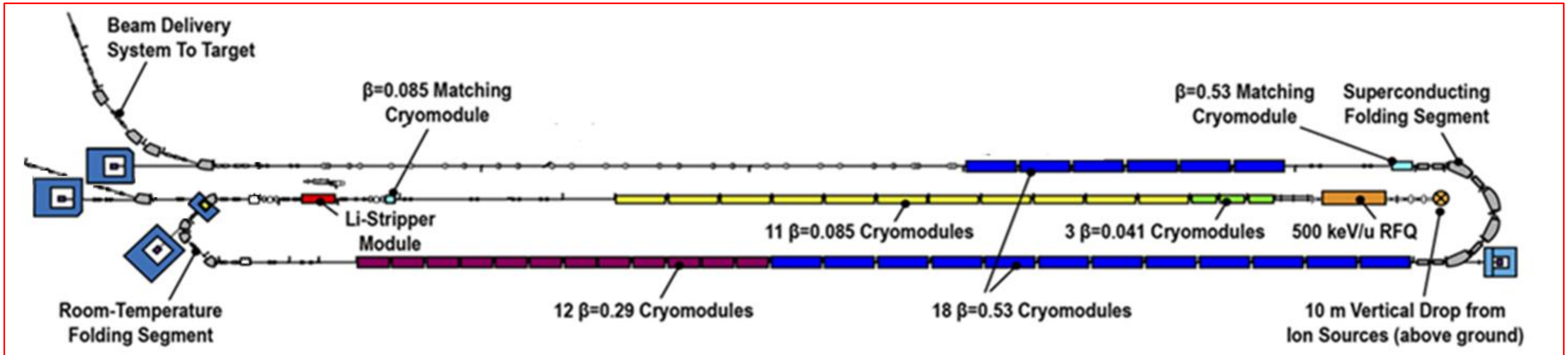


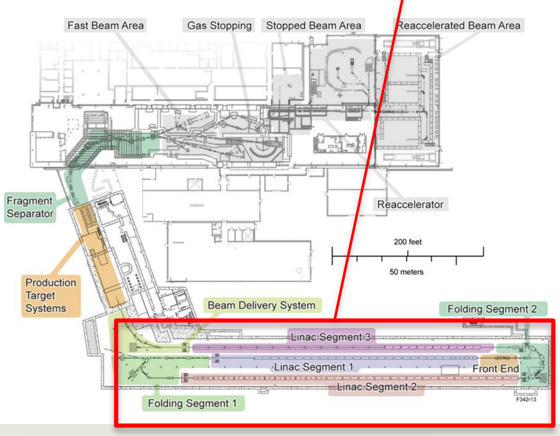
Phase	Commissioning Goals	Date
ARR1	• Accelerate Ar and Kr to 0.5 MeV/u • Generate Ar and Kr beam with > 25 eμA • Generate pulsed beam with chopper in LEBT	7/2017

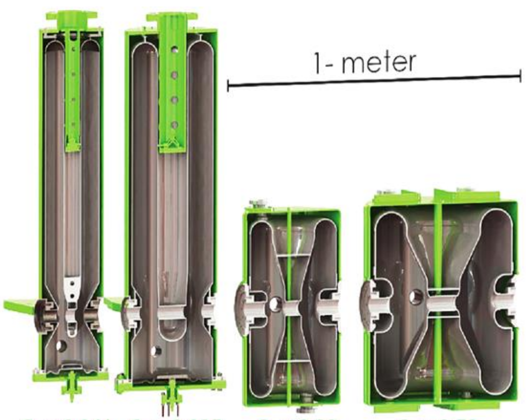
Linac and Folding Segments

Installation 2016-, Beam Commissioning 2018-

- Designed, constructed, tested, installed and commissioned 46 cryomodules and 4 superconducting dipole magnets







β_0 = 0.041 β_0 = 0.085 Quarter-Wave Resonators 80.5 MHz

β_0 = 0.29 β_0 = 0.53 Half-Wave Resonators 322 MHz

Quarter Wave Cryomodule				
β	*Type*	*Component Counts (baseline + spares)*		
		Cryomodules	*Cavities*	*Solenoids*
0.041	accelerating	3 + 1	12 + 4	6 + 2
0.085	accelerating	11 + 1	88 + 8	33 + 3
	matching	1 + 1	4 + 4	-
Half Wave Cryomodule				
0.29	accelerating	12	72	12
0.53	accelerating	18	144	18
	matching	1	4	-
TOTALS		46 + 3	324 + 16	69 + 5
2T Superconducting Dipole Magnets			4	

Preproduction Assembly Sequence (β=0.53)

All 46 Baseline Cryomodules Completed by May 2020

C1

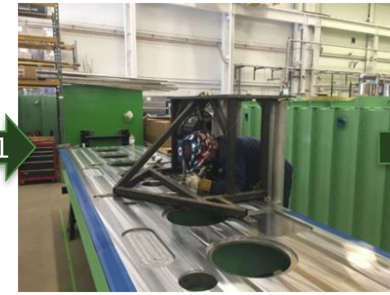
Completed cold mass assembly in clean room

C2

Cold mass assembly transport to cryomodule assembly area

C3

Cold mass ready for baseplate

1

Start baseplate assembly

2

Baseplate ready for cold mass

C4
3

Cold mass on baseplate

4

Completed cryogenic circuit

5

Thermal shield installation

6

Vessel cover installation

7

Tuner valve manifold installation

8


Transport to SRF High Bay

9

Transport into bunker

10

Transport to FRIB tunnel

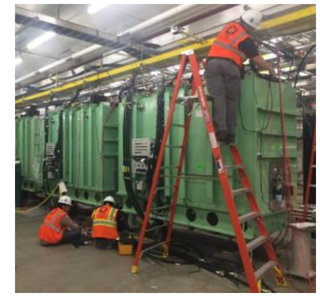
Cryomodule Installation in Linac Tunnel

Phased Installation and Commissioning for 5 Years

- Five-year cryomodule installation
  - First one (1st β=0.085) in 9/2016
  - Last one (18th β=0.53) in 6/2020
- Post-installation tasks
  - Alignment, Warm box installation, Cable termination, Interlock check, RF connection etc.

Moving cryomodule

Warm box Installation



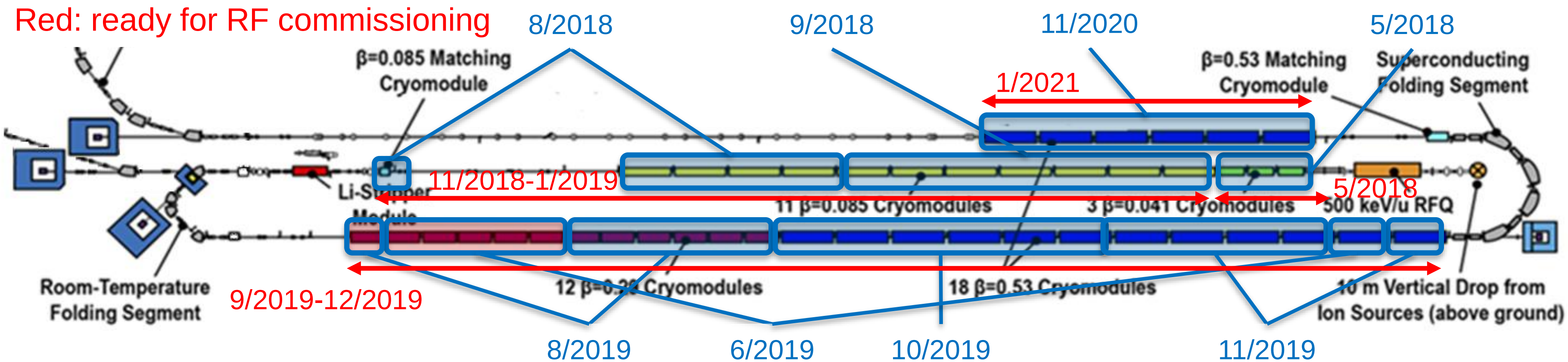
Cable termination

Cool down

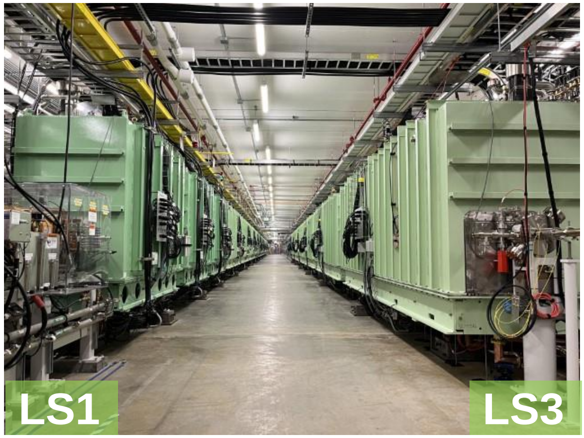
- Device Readiness Review (DRR)
  - Ensure beamline devices will safely meet performance requirements in prior to cool down and RF energization
  - Linac Segments ready for beam were reported to DOE as a level 2 milestone

Blue: cool down

Red: ready for RF commissioning

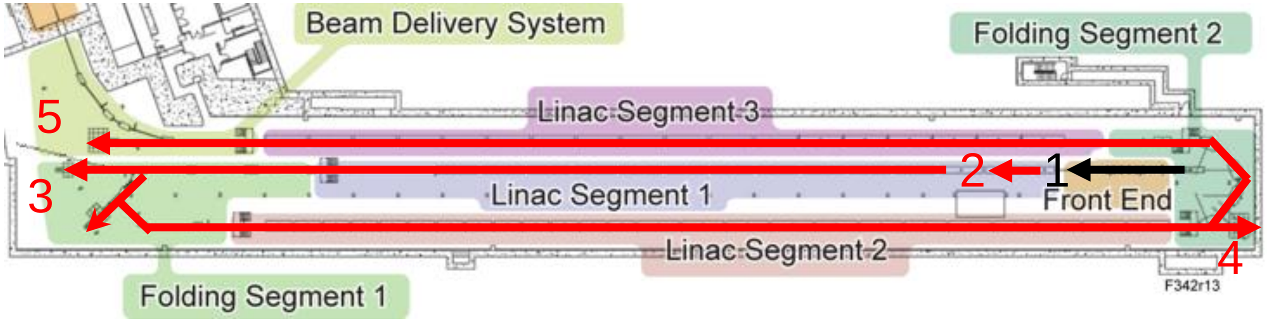


Beam Commissioning – ARR2 to 5
Became World's Highest Energy CW Hadron Linac



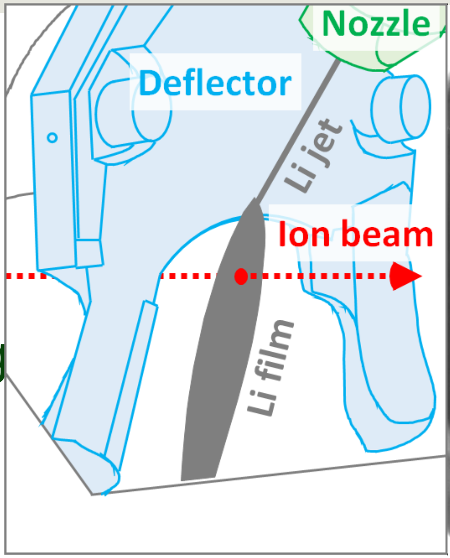
Phase	Commissioning Goals	Date
ARR2	• Accelerate Ar and Kr > 1.46 MeV/u • Demonstrate RF phase and amplitude tuning of second buncher in MEBT	5/2018
ARR3	• Accelerate Ar and Kr > 16 MeV/u • Charge stripping and selection of one charge state	2/2019
ARR4	• Accelerate Ar and Kr > 140 MeV/u (Ar accelerated to 204 MeV/u)	3/2020
ARR5	• Accelerate Kr > 200 MeV/u (Ar accelerated > 200 MeV/u at ARR04)	4/2021

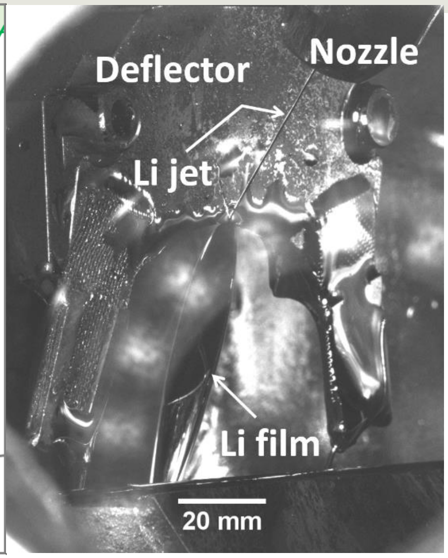
- Other achievements
  - Beam commissioning with lithium stripper (4/2021)

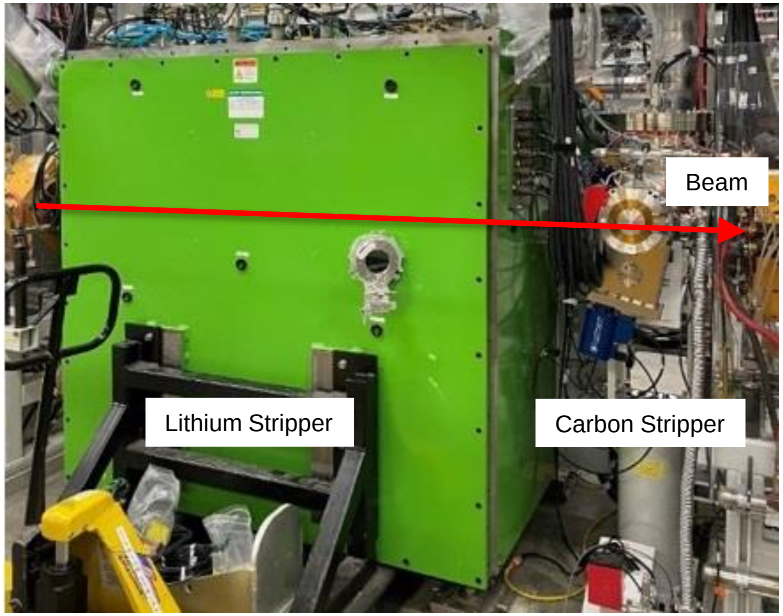


Liquid Lithium Charge Stripper Demonstrated with Ar, Xe and U beams

- Tested with 17 and 20 MeV/u Ar, Xe and U beams
- Tested with 10 pμA pulsed argon beam
  - Average beam power was limited by 500 W beam dump after LS1
- The film thickness measured by scanning the film position across the ion beam
  - 1 mg/cm^2 for Xe and Ar beams
  - 1.4 mg/cm^2 for U

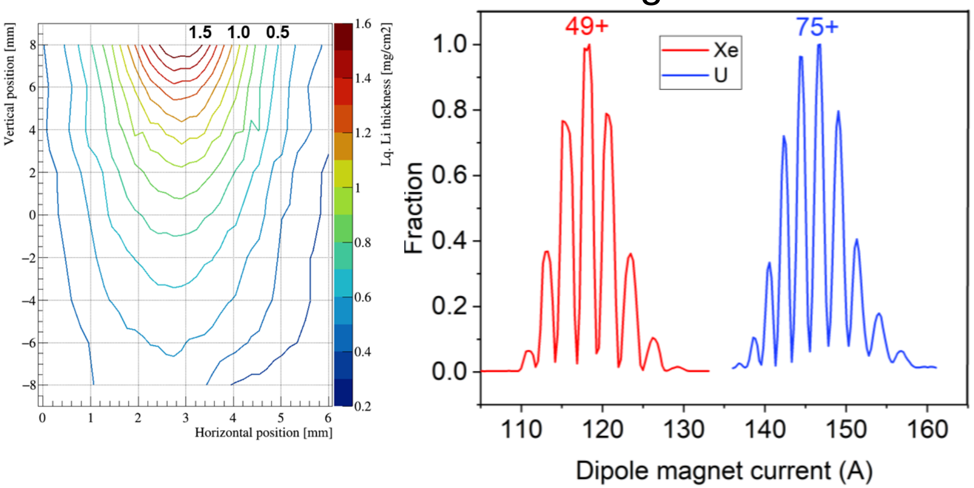






Li film thickness

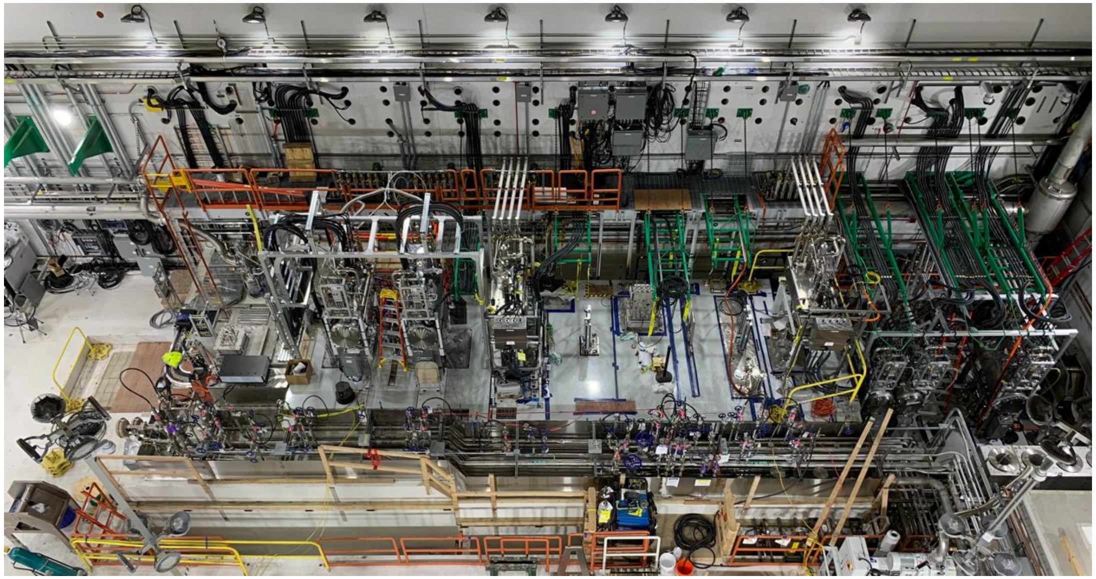
Charge distribution



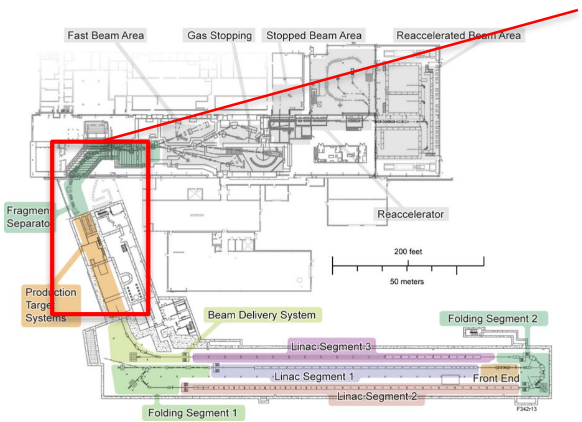
T. Kanemura, *et al., Phys. Rev. Lett.* **128**, 212301 (2022)

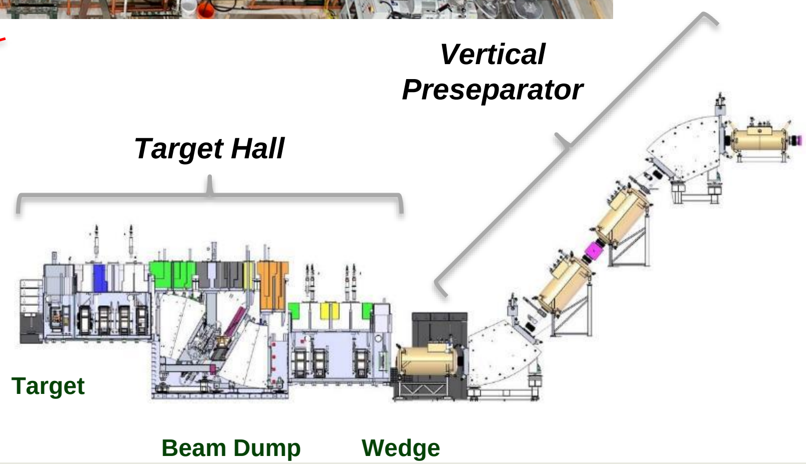
Target Hall and Fragment Separator
Installation 2016-, Beam Commissioning 2021-

Target Hall



Vertical Pre-separator



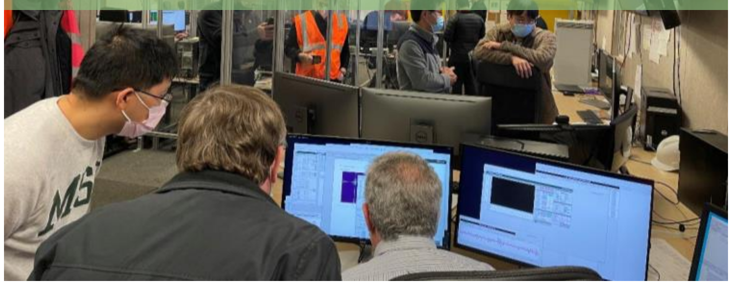


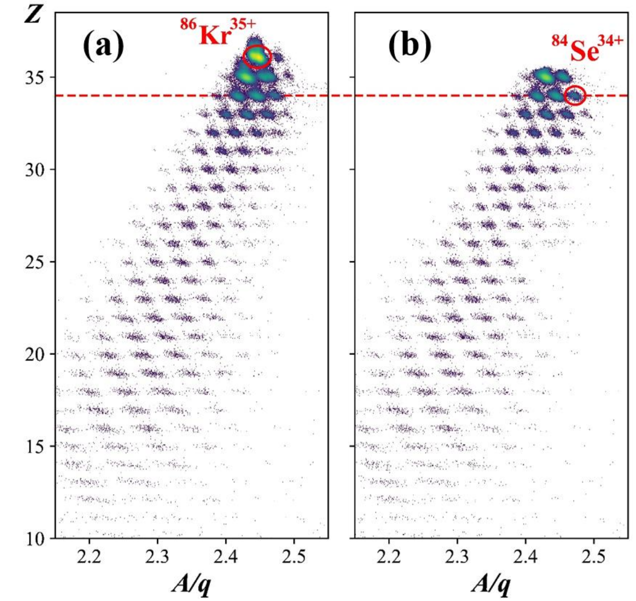
Beam Commissioning – ARR6 and 7

Demonstrated Key Performance Parameters (KPP)

Phase	Commissioning Goals	Date
ARR6	• Deliver Kr beam to the target • Produce, separate, and identify ^{84}Se isotopes	12/2021
ARR7	• Deliver Ar beam to the ARIS focal plane	1/2022

On 17:46, 11 December, 2021, ^{84}Se isotopes were produced





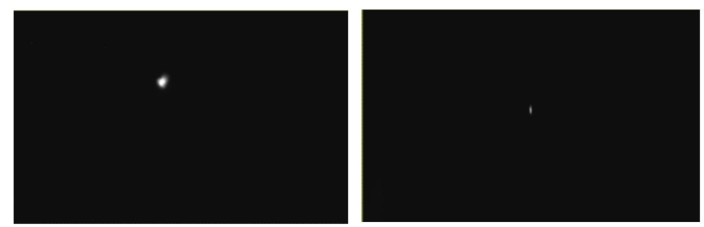
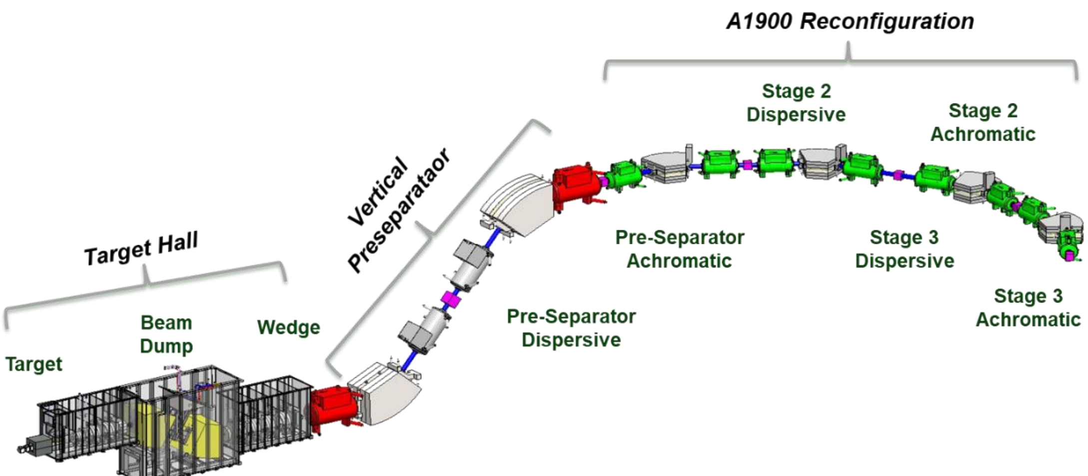
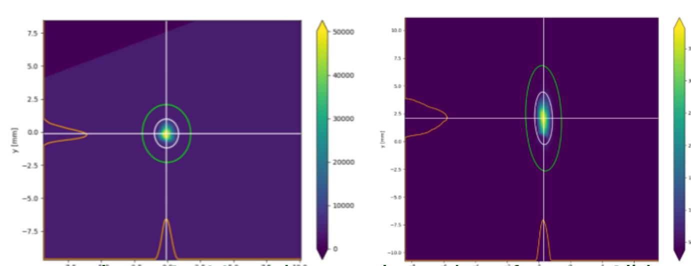


Figure 2. Screenshot of the beam images on the target (left) and DB5 (right) viewers.

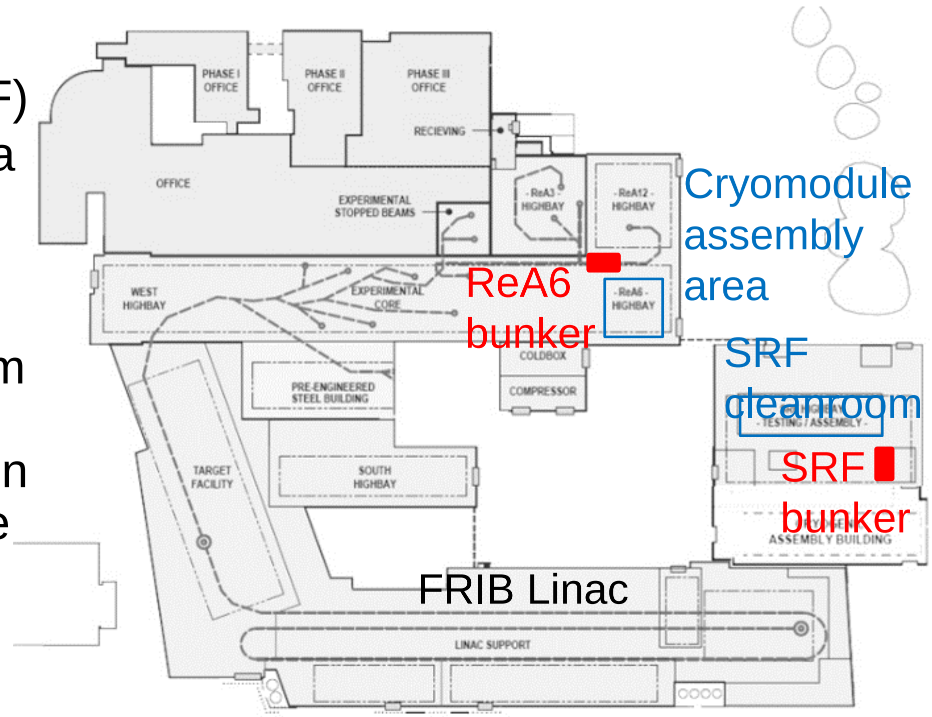




Lessons Learned for System Integration

Scaling up – from Small to Larger System

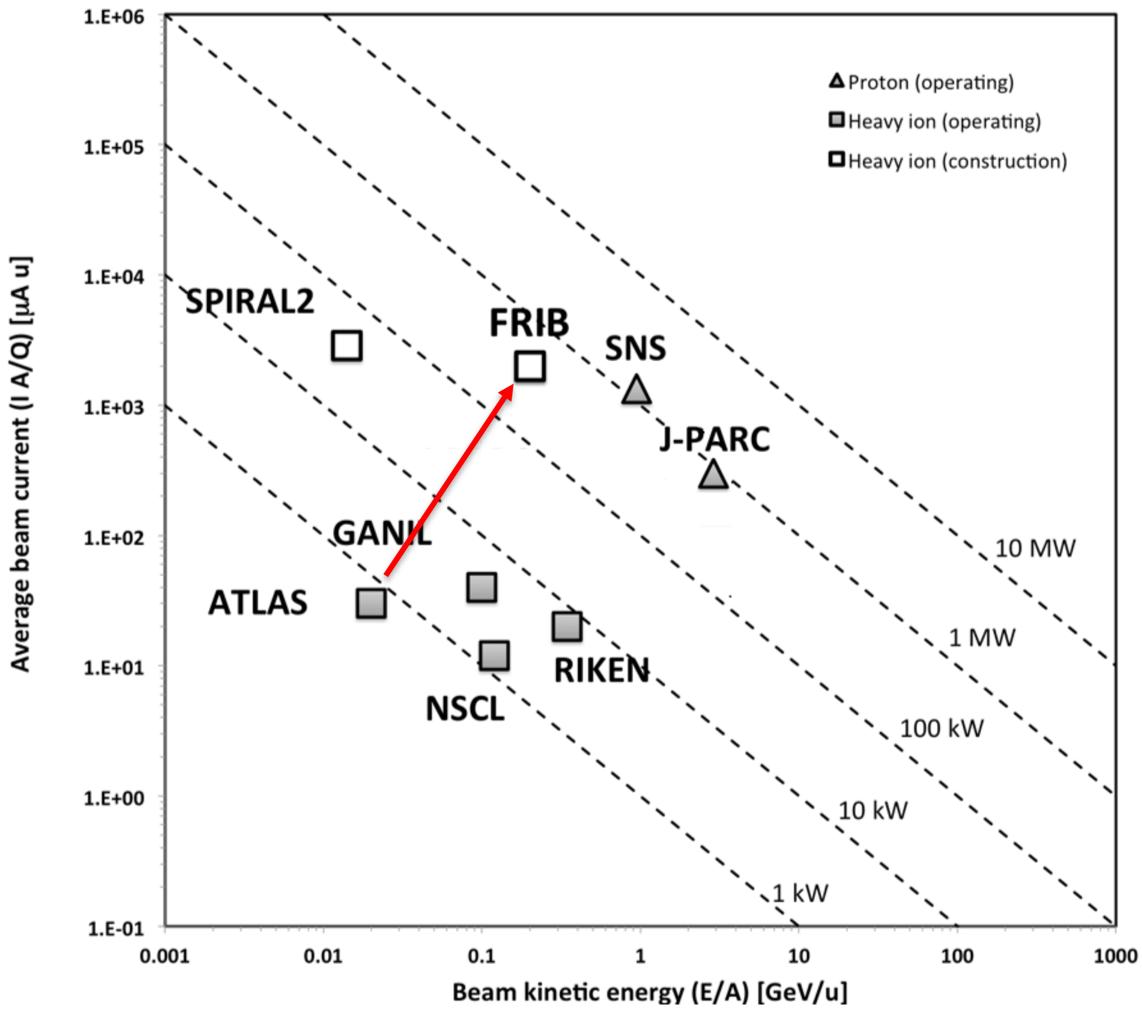
- Prototype, Testing, and Validation
  - Cryomodule Test Bunker (ReA6 and SRF)
  - ReA6 bunker was set up first to validate a FRIB prototype CM gave us a good opportunity to realize a prototype of the integrated FRIB accelerator system
  - Completed FRIB CMs undergo full system testing in bunkers before being accepted and delivered to the tunnel. This validation process minimized technical issues in the tunnel
- Scaling up: Small to Larger System
  - Phased commissioning plan allows us to start with small system and scale up to larger
  - At ARR3 β=0.085 QWRs commissioning proceeded at a rate of approximately 1 CM per day



Phase	Cryomodules	Cavity (in FRIB total)	Solenoid
ARR2	β=0.041 (1-3)	12	6
ARR3	+ β=0.085 (4-15)	104	39
ARR4	+ β=0.29, 0.53 (16-39)	272	63
ARR5	+ β=0.53 (40-47)	324	69

FRIB Heavy Ion Linac Joining the Proton Beam Power Front like SNS and J-PARC

- During the past decade, proton accelerators raised beam power to ~1 MW
  - SNS (USA): 1.4 MW pulsed; SRF linac/accumulator
  - J-PARC (Japan): 1 MW pulsed; warm linac/RCS
  - PSI (Switerland): 1.4 MW CW; cycrotron
- FRIB provided RI beams for the first experiment in 5/2022
  - Primary beam: 1 kW of ^{48}Ca
  - RI beams: ^{42}Si
- FRIB just starts over 6 years planned power ramp up to 400 kW



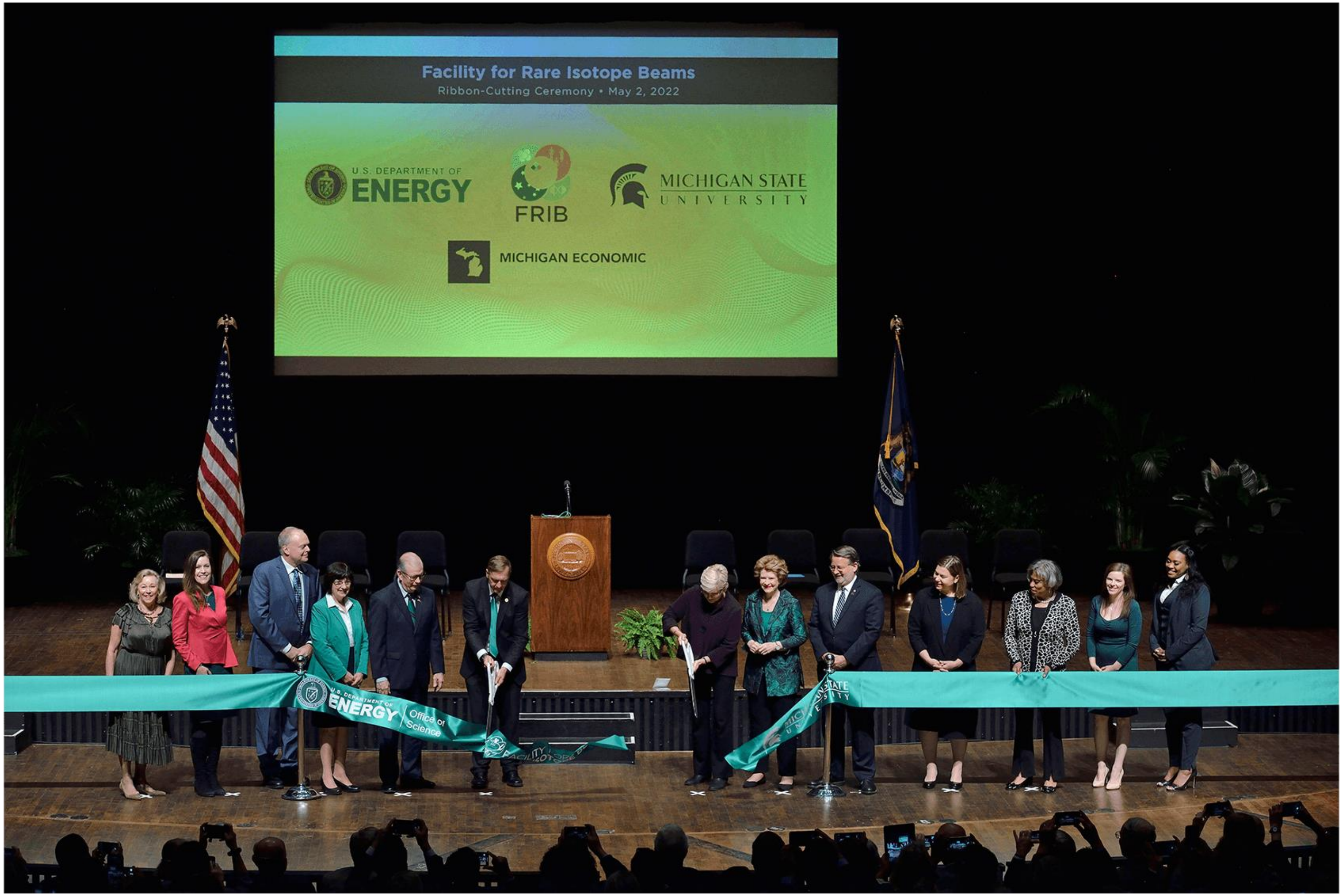
FRIB Built with Collaboration Including the Best in US and Worldwide Laboratories

- Argonne National Laboratory
  - Liquid lithium charge stripper; stopping of ions in gas; fragment separator design; beam dynamics; SRF
- Brookhaven National Laboratory
  - Radiation-resistant magnets; plasma charge stripper
- Fermilab
  - Diagnostics
- Jefferson Laboratory
  - Cryogenics; SRF
- Lawrence Berkeley National Laboratory
  - ECR ion source; beam dynamics
- Oak Ridge National Laboratory
  - Target facility; beam dump R&D; cryogenic controls
- Stanford National Accelerator Lab
  - Cryogenics
- Sandia
  - Production target
- Budker Inst. of Nuclear Physics (Russia)
  - Production target
- GANIL (France)
  - Production target
- GSI (Germany)
  - Production target
- IMP (China)
  - Magnets
- INFN Legnaro (Italy)
  - SRF
- KEK (Japan)
  - SRF technology; SC solenoid magnets
- RIKEN (Japan)
  - Charge strippers
- Soreq (Israel)
  - Production target
- Tsinghua University & CAS (China)
  - RFQ
- TRIUMF (Canada)
  - SRF; beam dynamics

Summary

- FRIB baseline was completed after 14-year project in 2022
- Accomplished phased beamline installation and commissioning over 5 years
  - Demonstrate and validate small system and then extend to more larger systems
  - Readiness review programs urged system owners to meet schedule milestones
- Started over 6 years power ramp up to 400 kW

Thank You for Your Attention



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