The FRIB SC-Linac: Installation and Phased Commissioning

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On Behalf of FRIB Accelerator Team & Collaboration

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MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

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Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

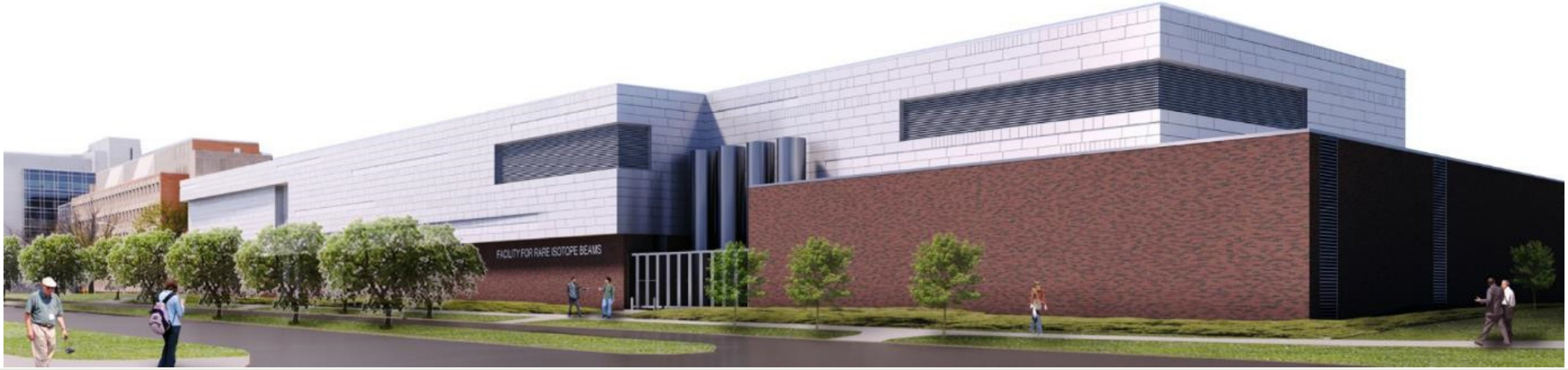
Outline

- Introduction
- Phased beam commissioning and strategic planning
- Design and construction evolution
- Installation and preparation
- Operations coordination and maintenance infrastructure
- Summary

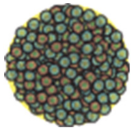
Introduction

Facility for Rare Isotope Beams Project On Track for Early Completion in 2021

- 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
- Planned completion date is June 2022, managing to early completion in 2021
- FRIB will be a DOE-SC scientific user facility for rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC

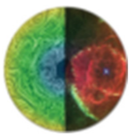


FRIB Enables Scientists to Make Discoveries



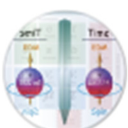
Properties of atomic nuclei

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



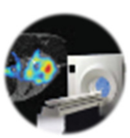
Astrophysics: What happens inside stars?

- 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

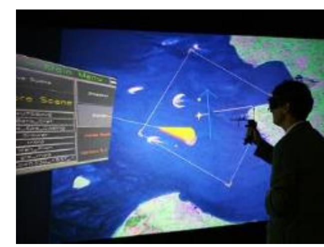
Science is aligned with national priorities articulated by

- 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)

Basic Research in Rare Isotopes Leads to Applications for Society

- Medical applications
  - Isotopes for medical research
  - Medical imaging and treatment of cancer and tumors
- Energy
  - Reliable calculation of fission and energy generation
  - Allow mechanisms of radiation damage to be studied in detail
  - Sensitive probes for the development of new materials, e.g. lithium-film batteries

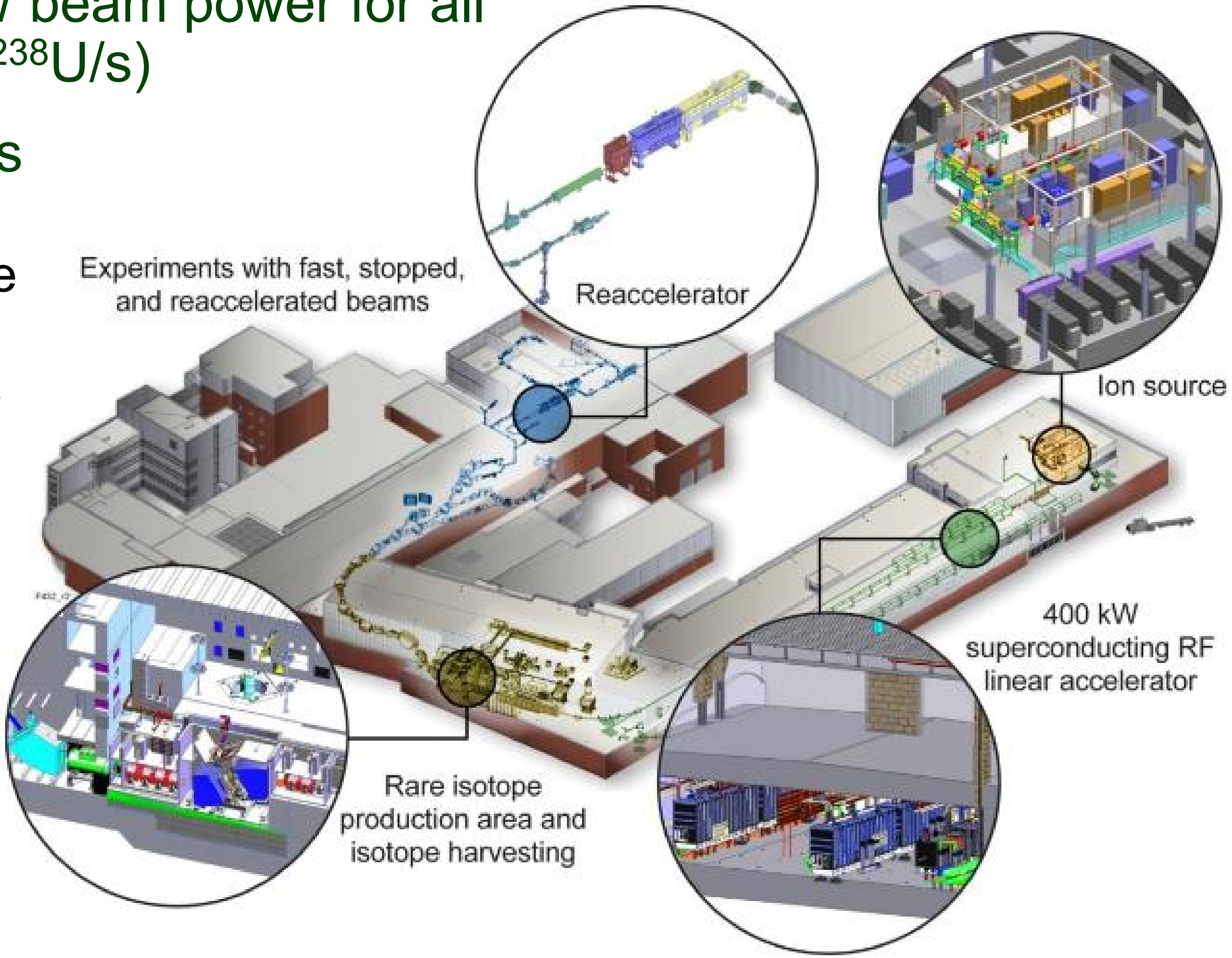
- Homeland security and defense
  - Detectors at borders and throughout the country to detect nuclear material and components
  - Nuclear scanning techniques to screen cargo and luggage
  - Nuclear forensic methods to track and trace nuclear material



- Workforce
  - Development of talent for technical, medical, security, and industrial fields

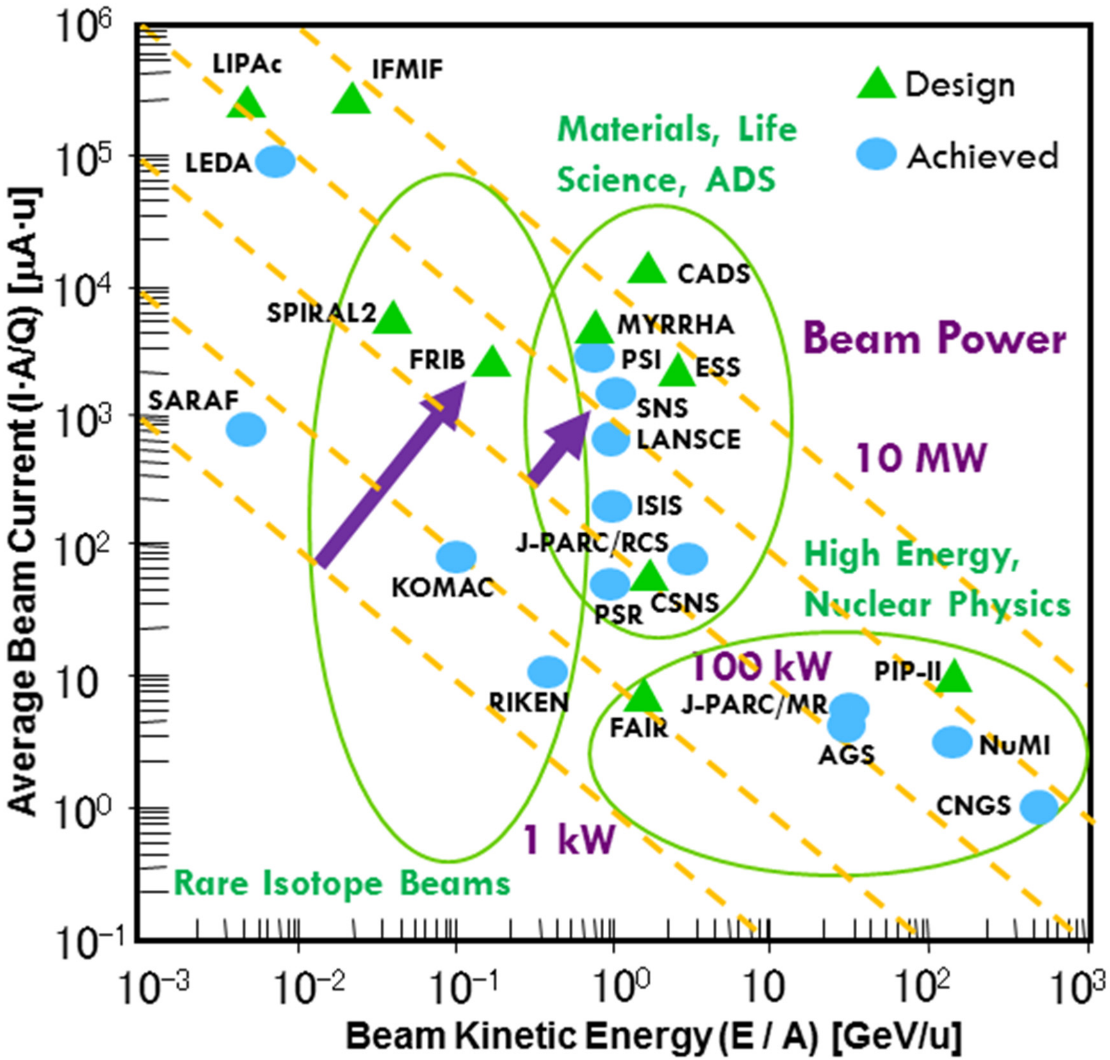
FRIB Optimized for Science
with Fast, Stopped and Reaccelerated Rare Isotope Beams

- Key feature is 400 kW beam power for all ions (8pμA or 5x10^{13} ^{238}U/s)
- 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



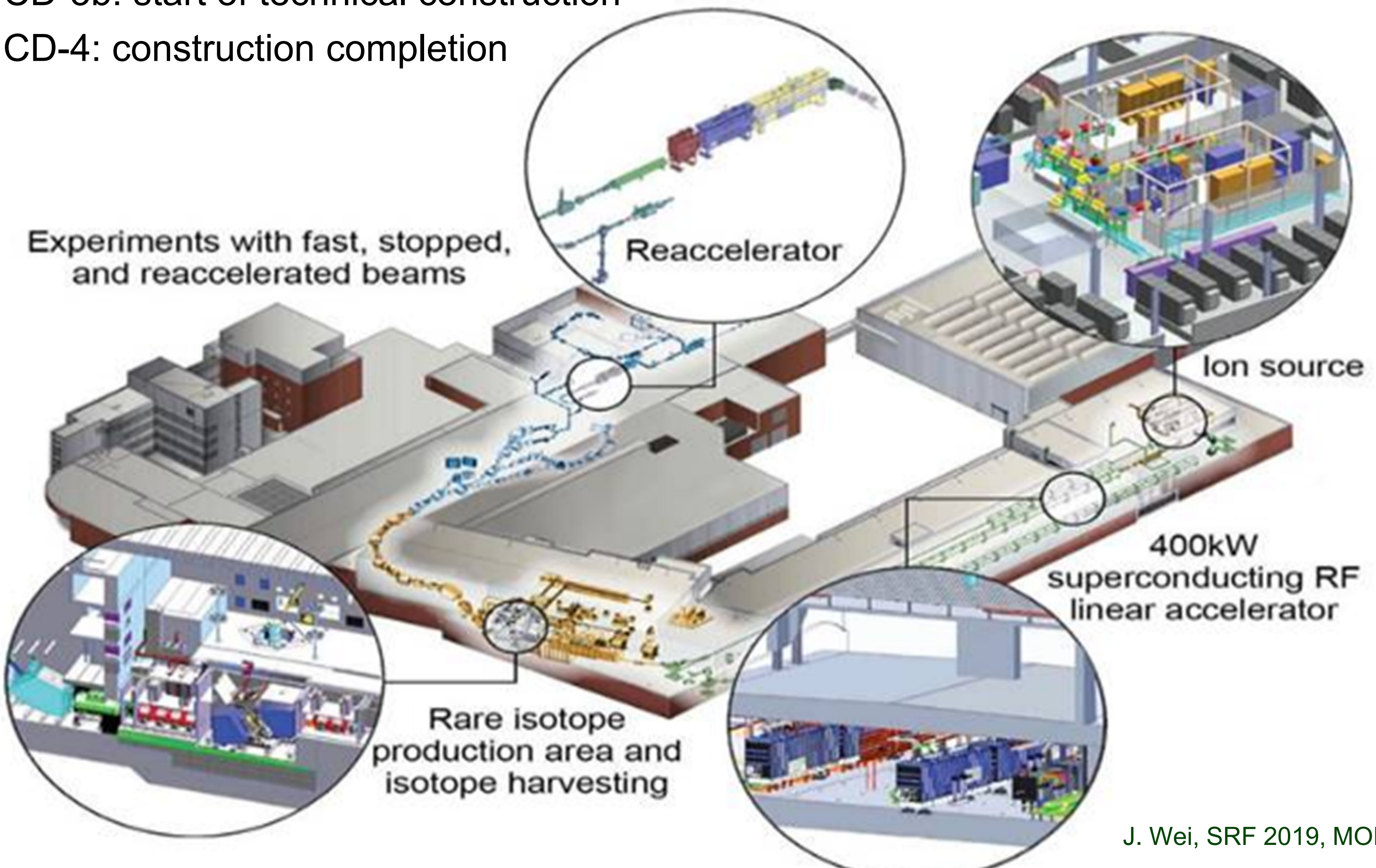
FRIB at Accelerator Power Frontier
among Three Major Frontiers: Energy, Power, Brightness

- FRIB will provide more beam power by two-to-three orders of magnitude over existing heavy-ion facilities
- Past experience for less-complex proton machines indicates steep learning curve
- Successful early operation is key to achieving desired power ramp-up profile
- Beam losses will limit power ramp-up, mitigation takes time and experience

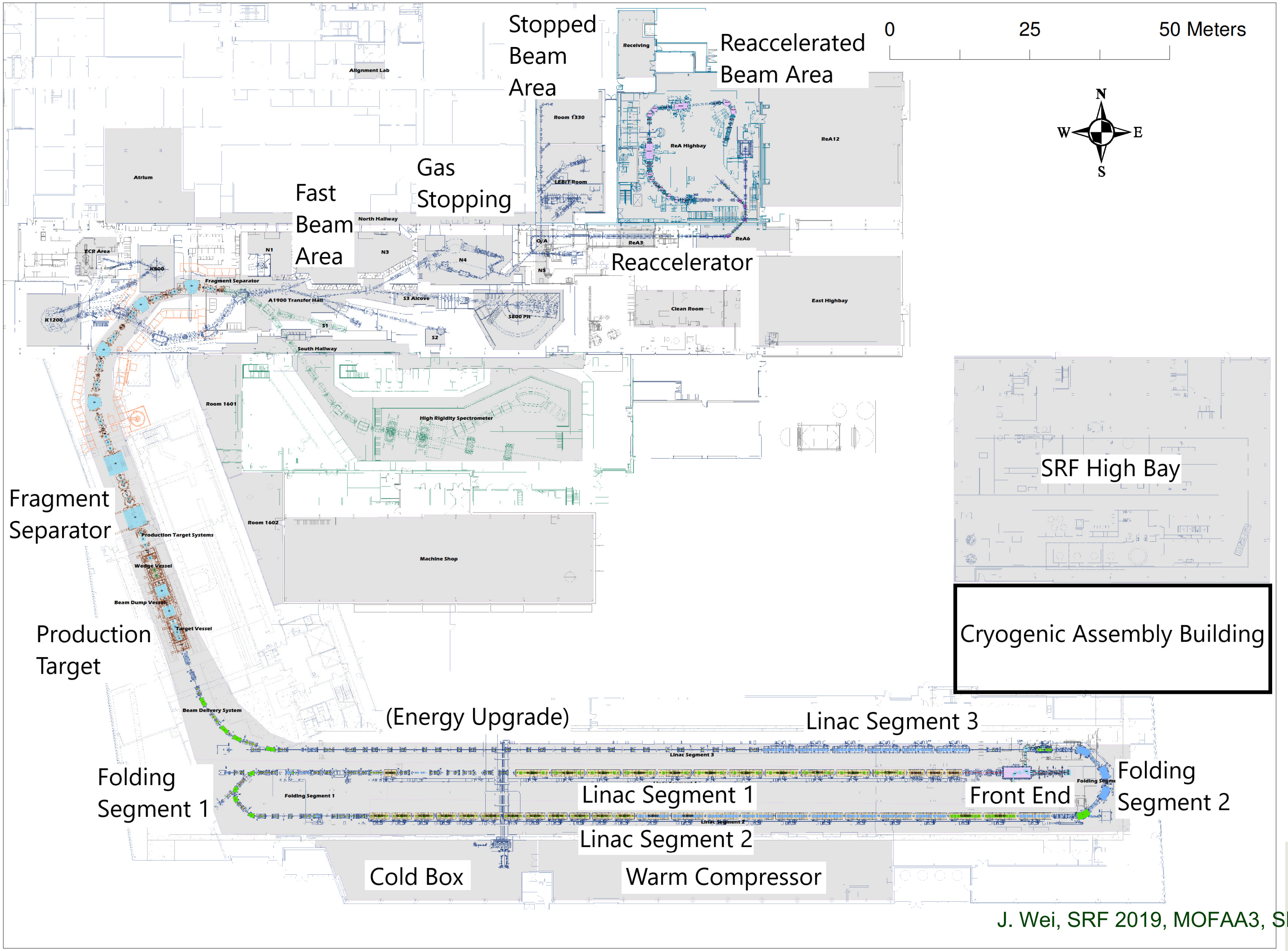


FRIB Project at Michigan State University
Project of $730M ($635.5M DOE, $94.5M MSU)

- 2008-12: DOE selects MSU to establish FRIB
- 2009-6: DOE and MSU sign corresponding cooperative agreement
- 2010-9 CD-1: conceptual design complete & preferred alternatives decided
- 2013-8 CD-2/CD-3a: performance baseline, start of civil construction & long lead procurement
- 2014-8 CD-3b: start of technical construction
- 2022-6 CD-4: construction completion



FRIB Accelerator Complex Subsystems



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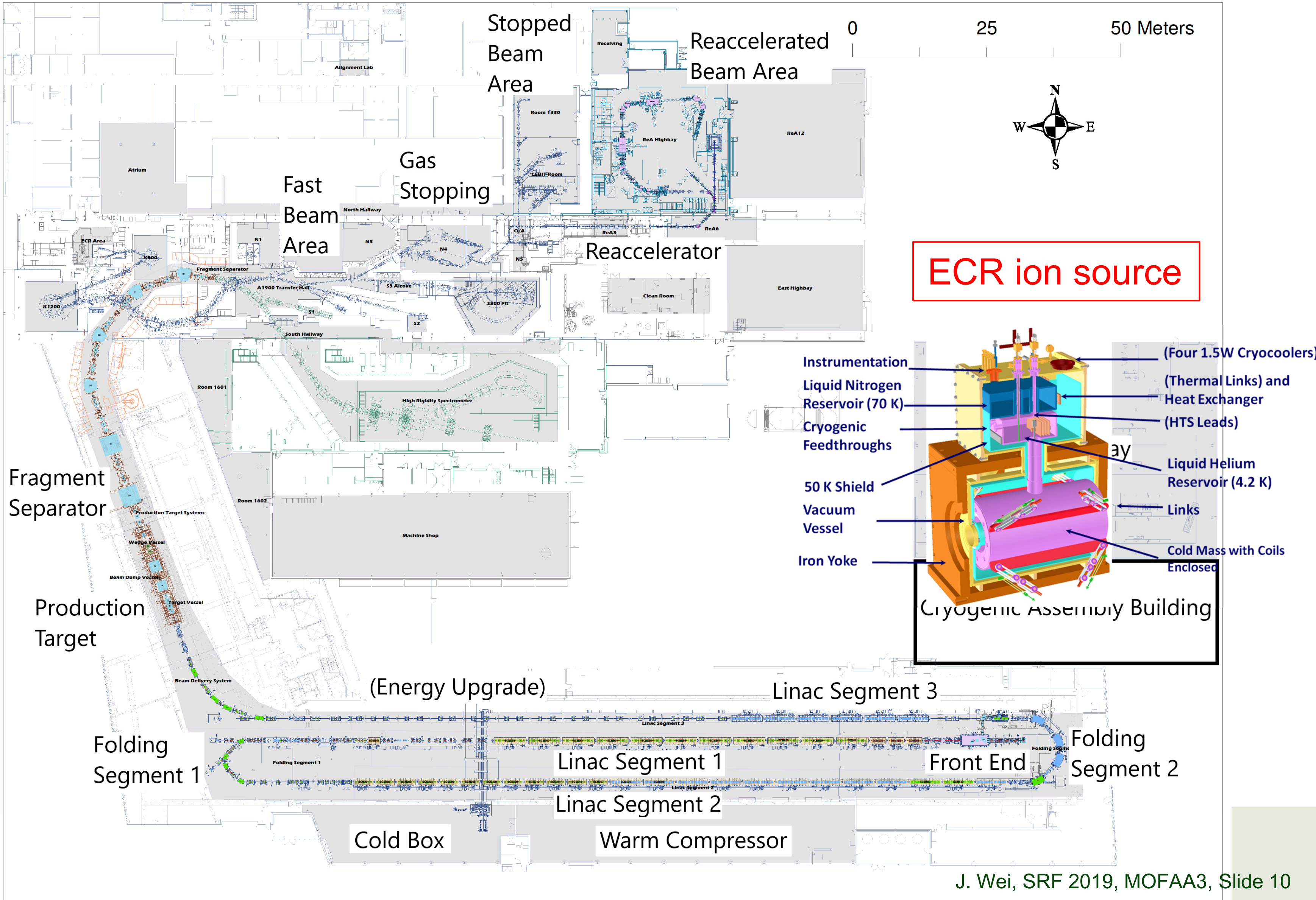

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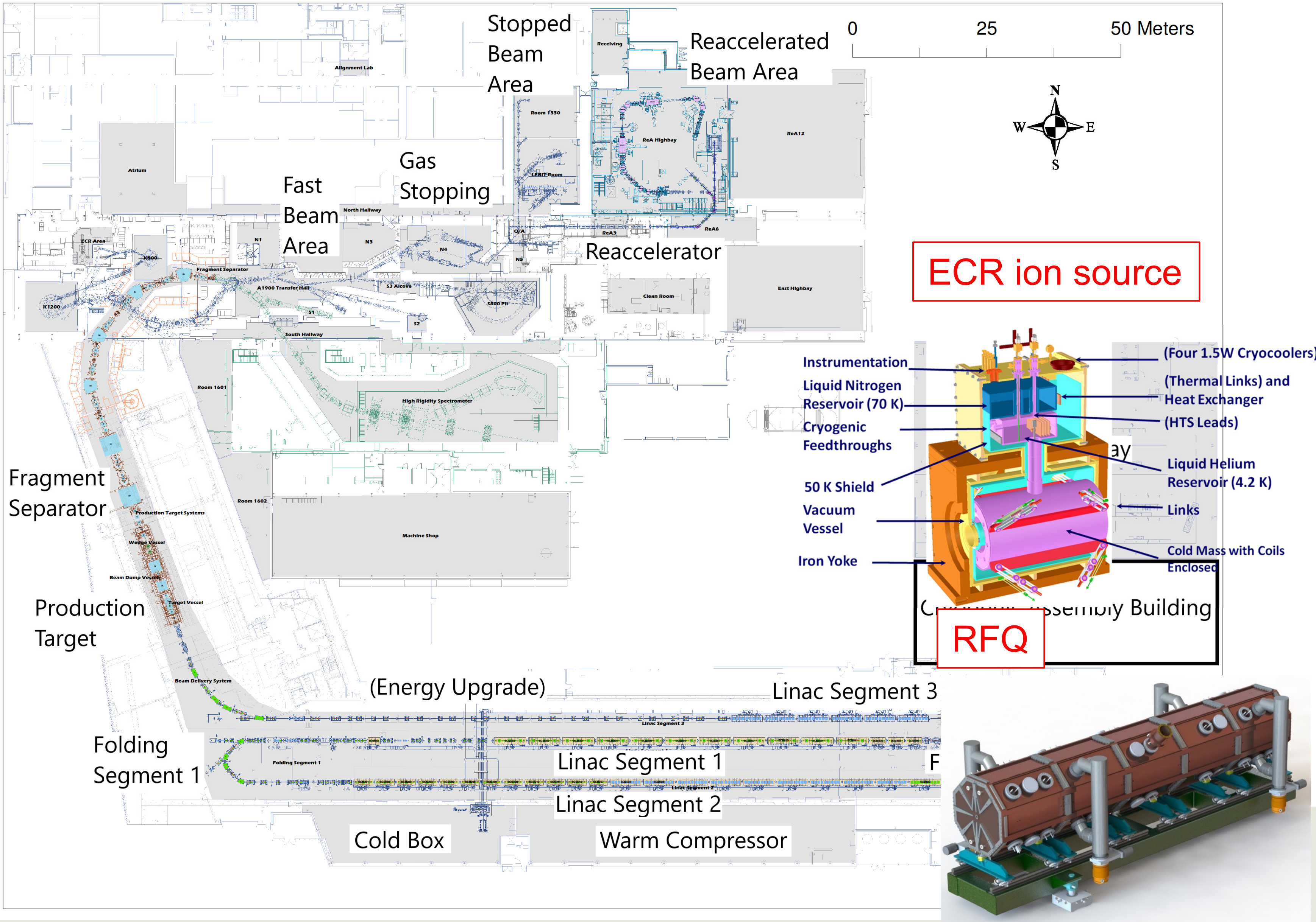

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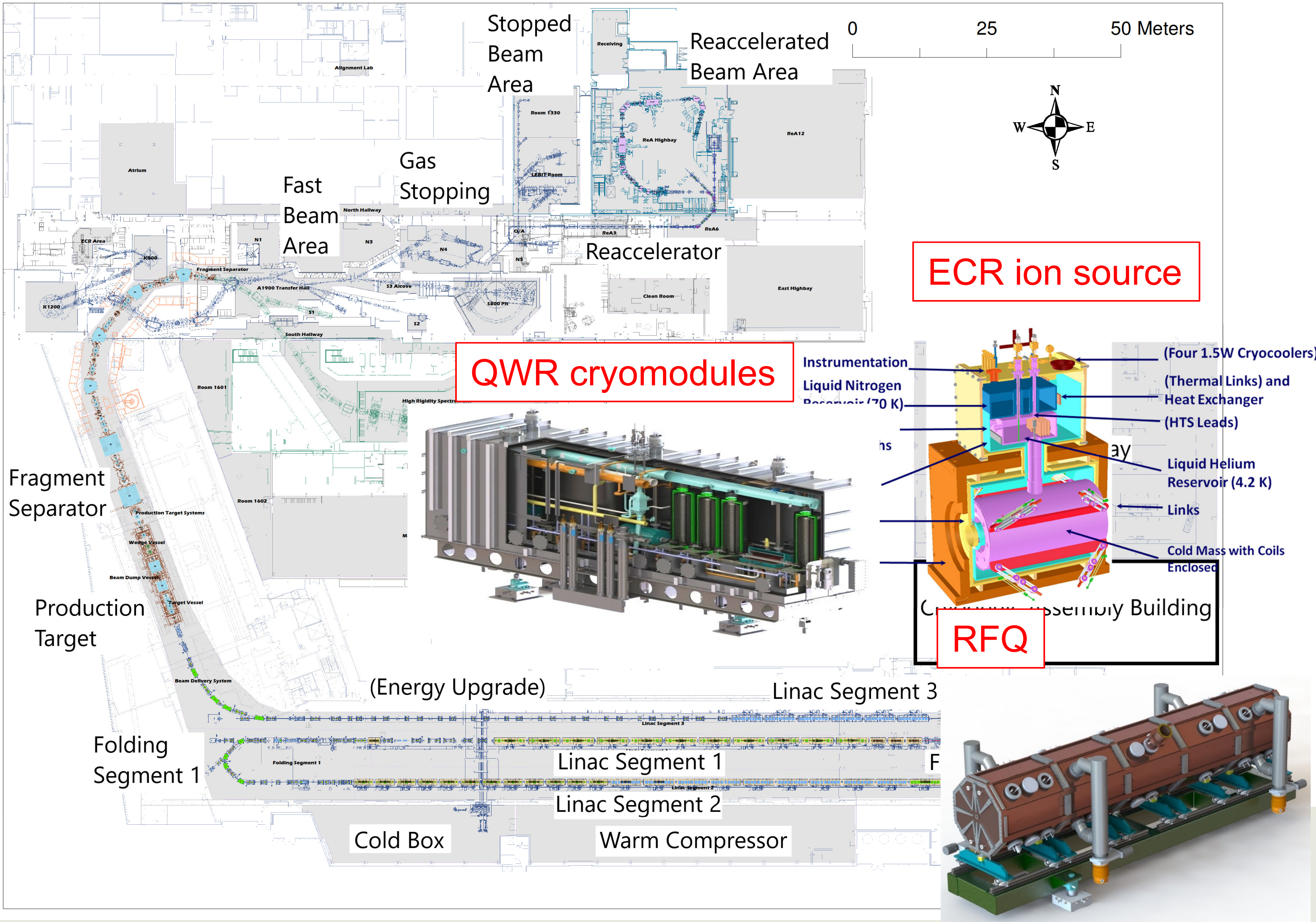

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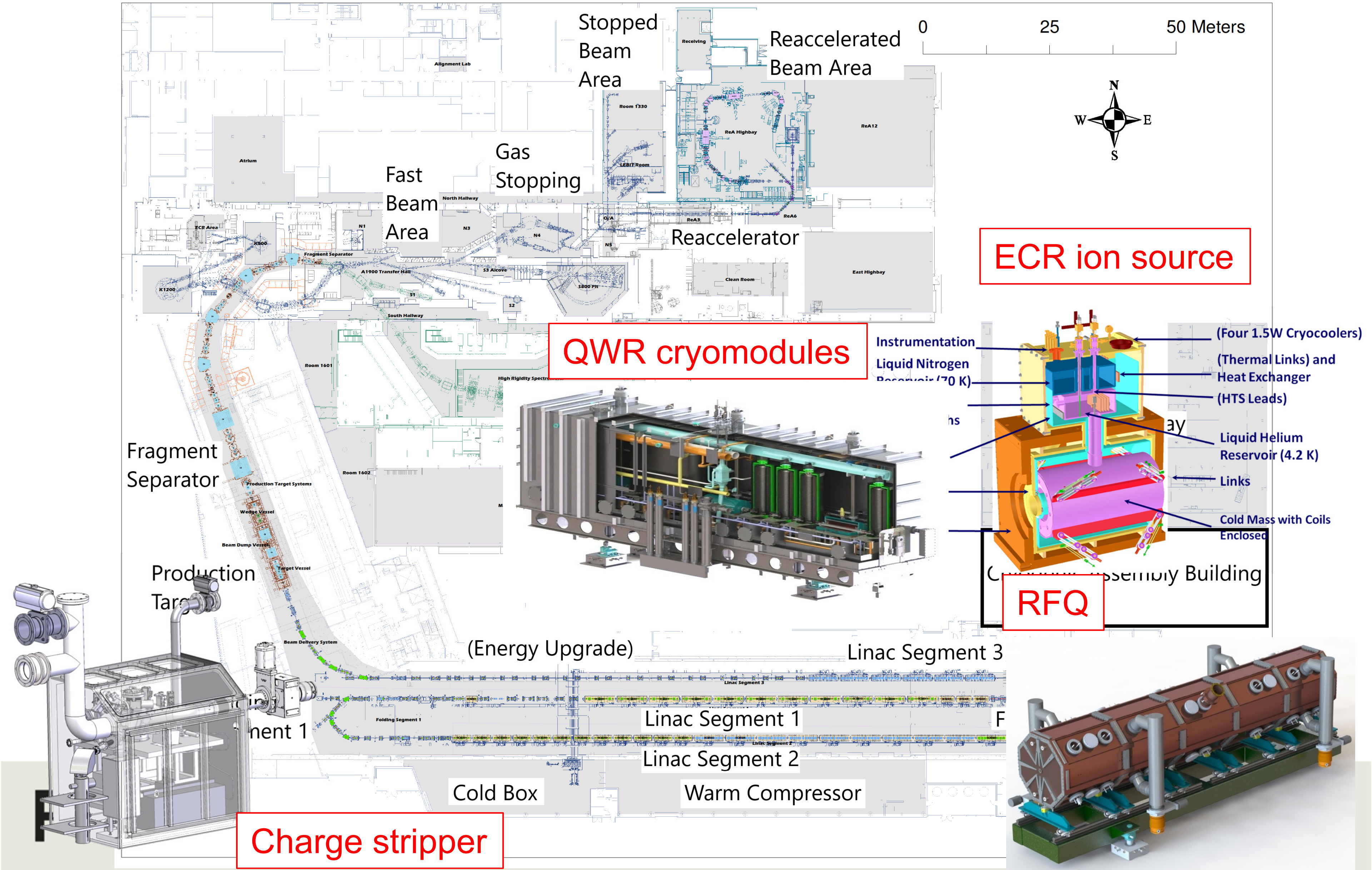

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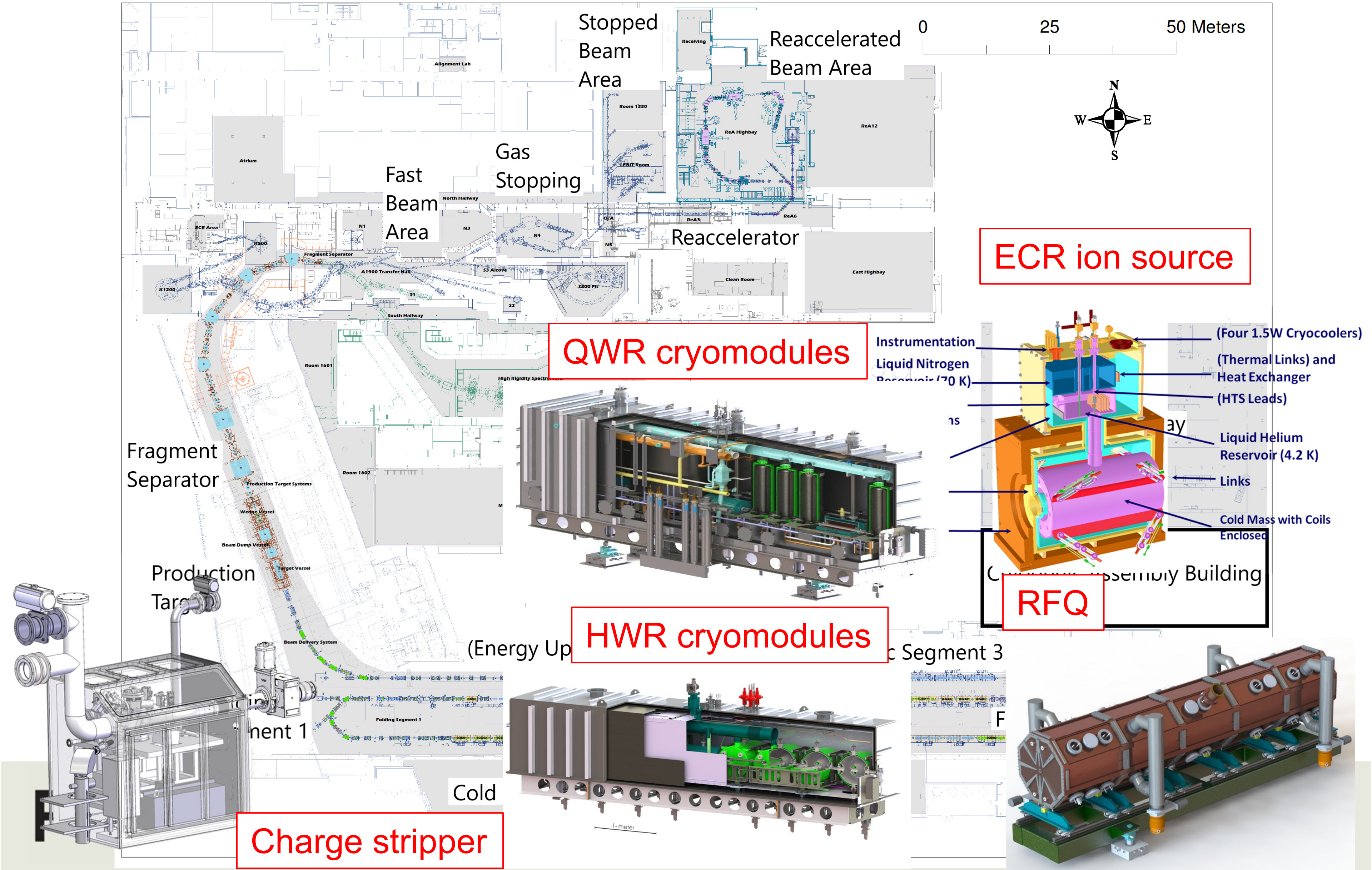

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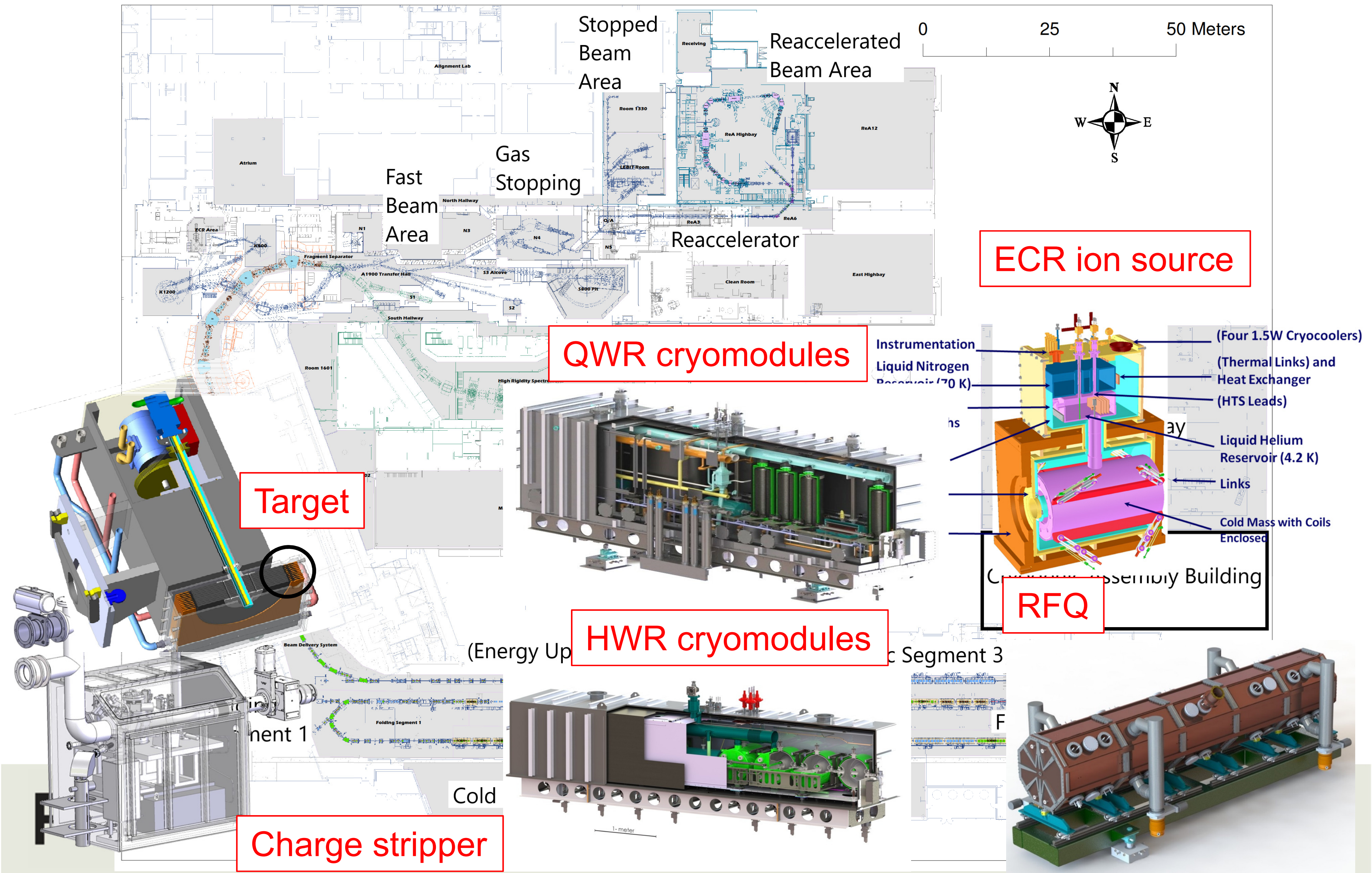

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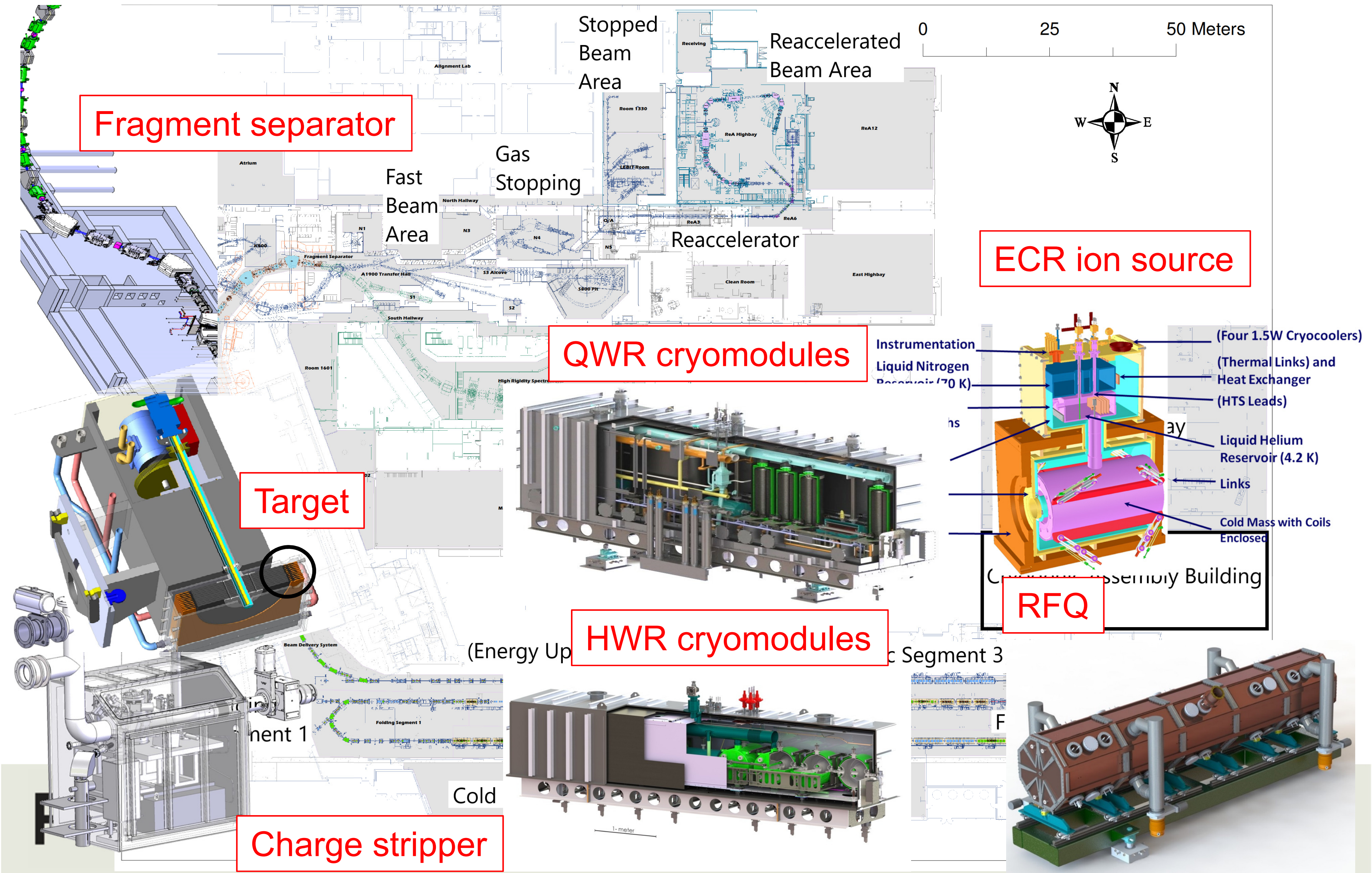

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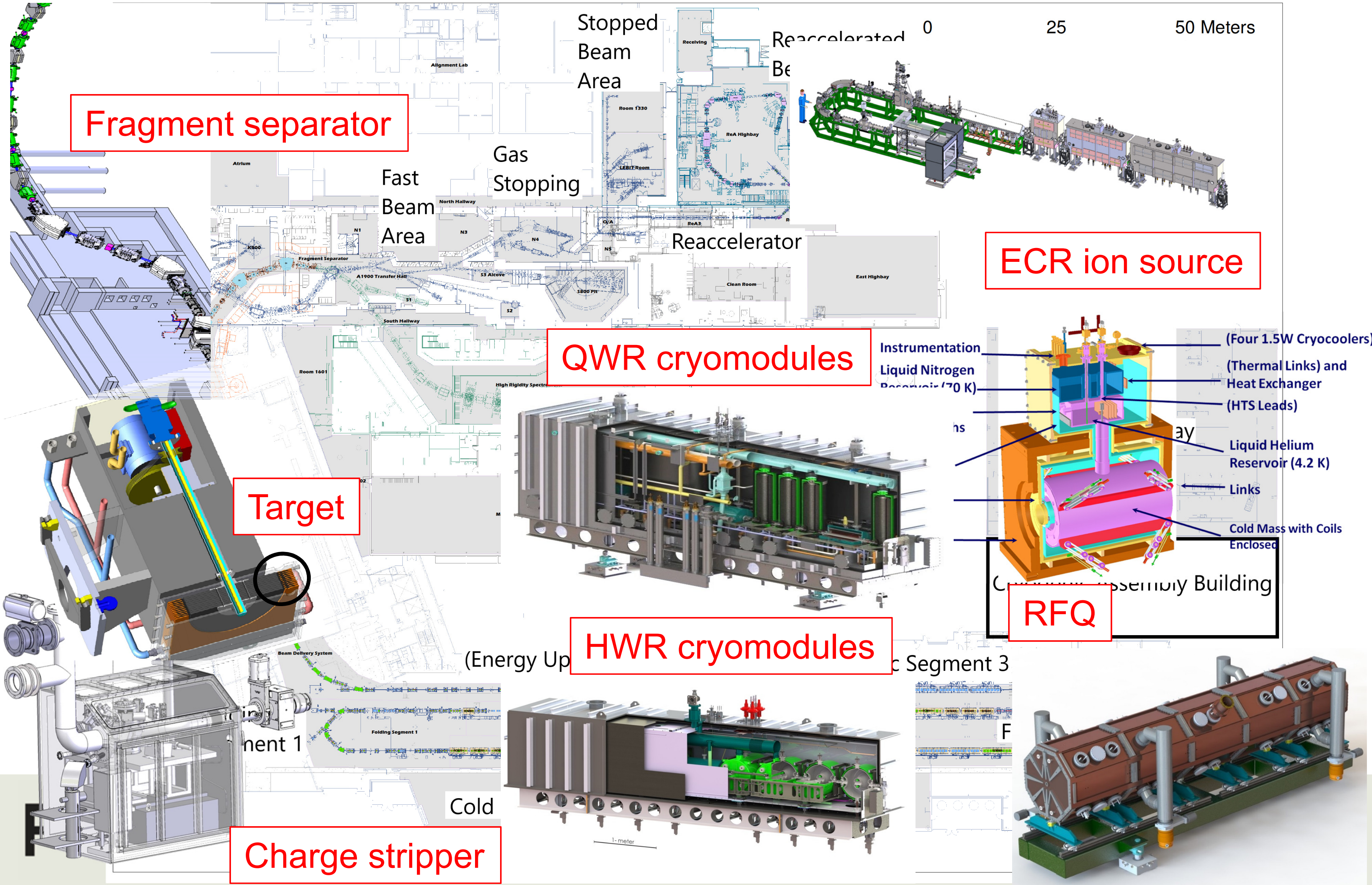
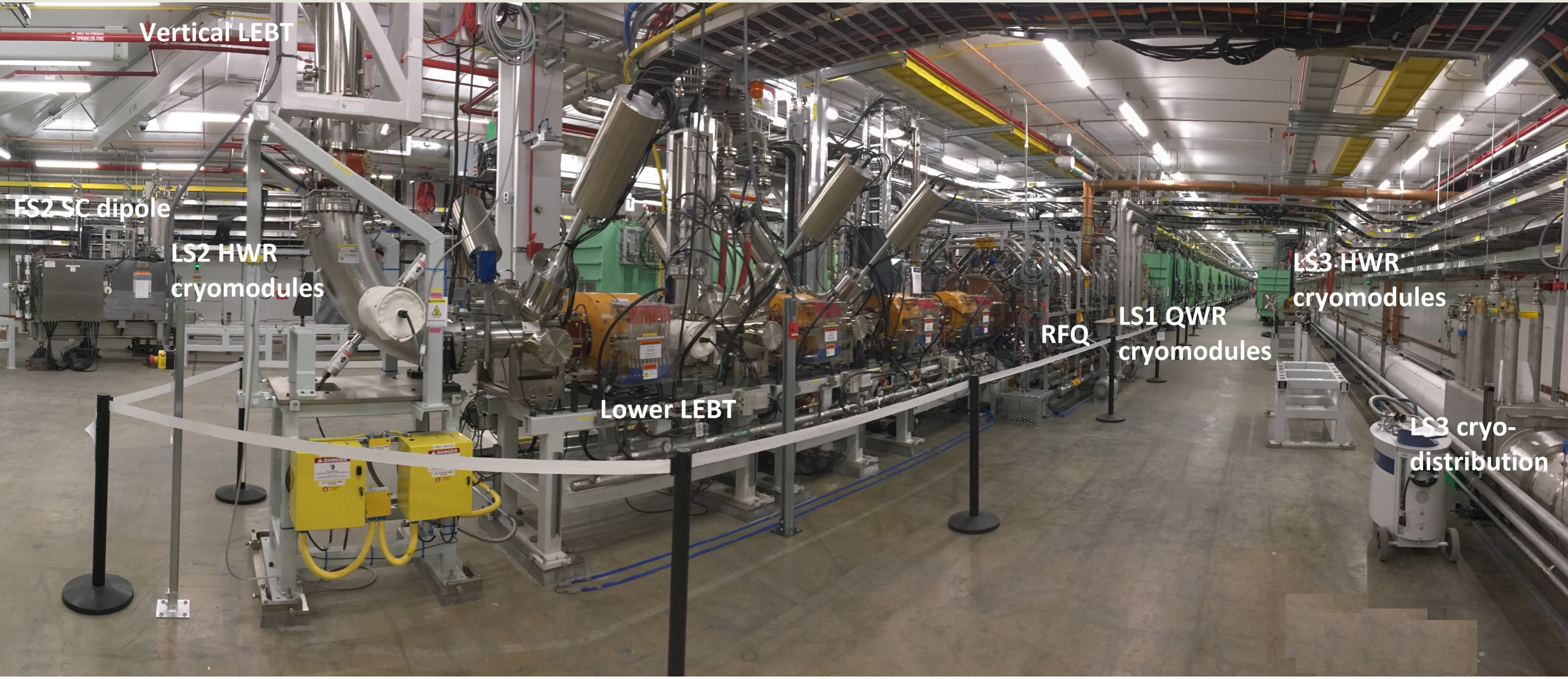


Civil Construction: March 2014 - March 2017

Accelerator Tunnel Installation Proceeding

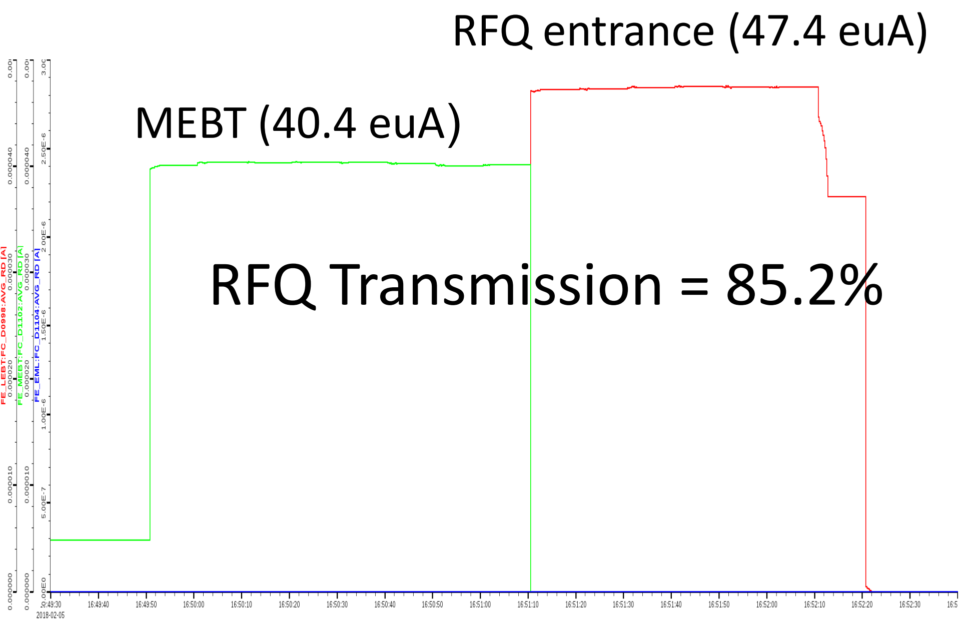


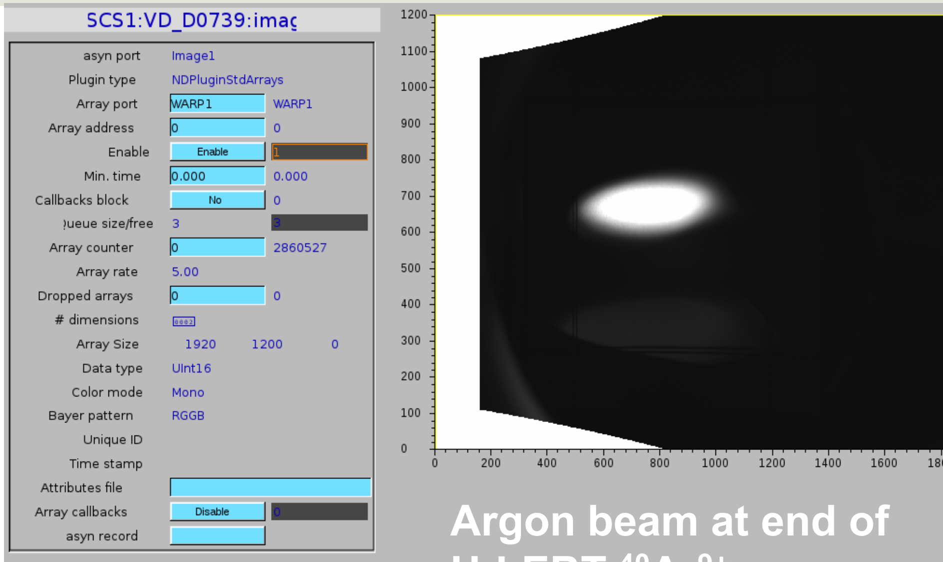
- FRIB linac tunnel is ~ 10 m underground for prompt radiation shielding
- Accelerates all stable ions (proton to uranium) above 200 MeV/u with upgrade to 400 MeV/u in continuous wave (CW) or pulsed modes

Phased beam commissioning and strategic planning

2017: Front End Beam Commissioned (ARR1)

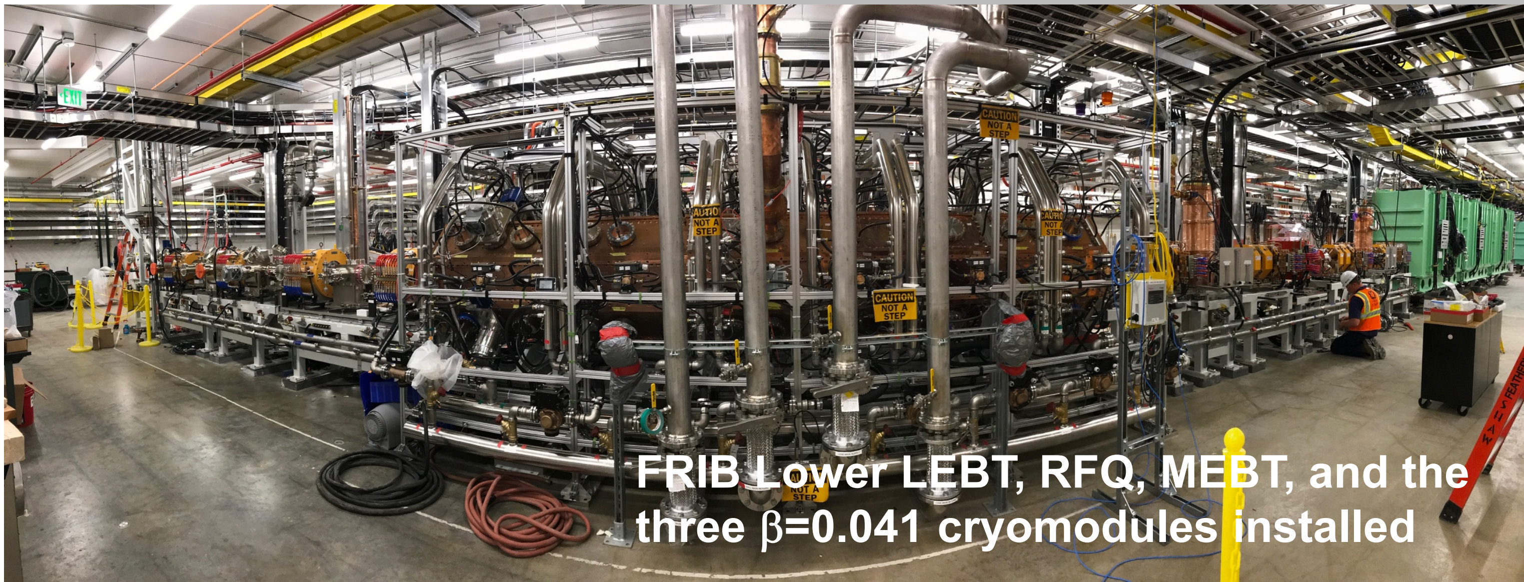
Integrate Warm Systems with New Civil Infrastructure





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

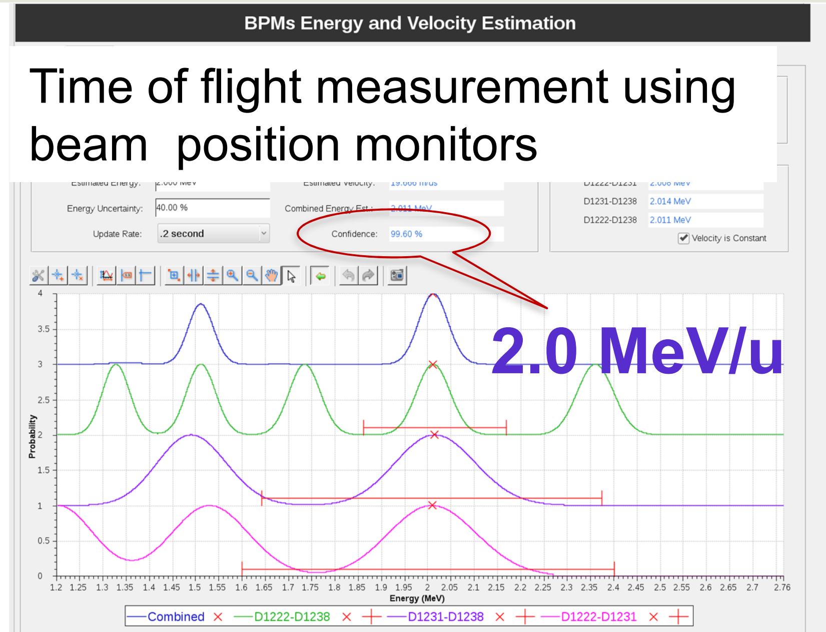
- Beam based measurement & RF calibration in agreement within 1%

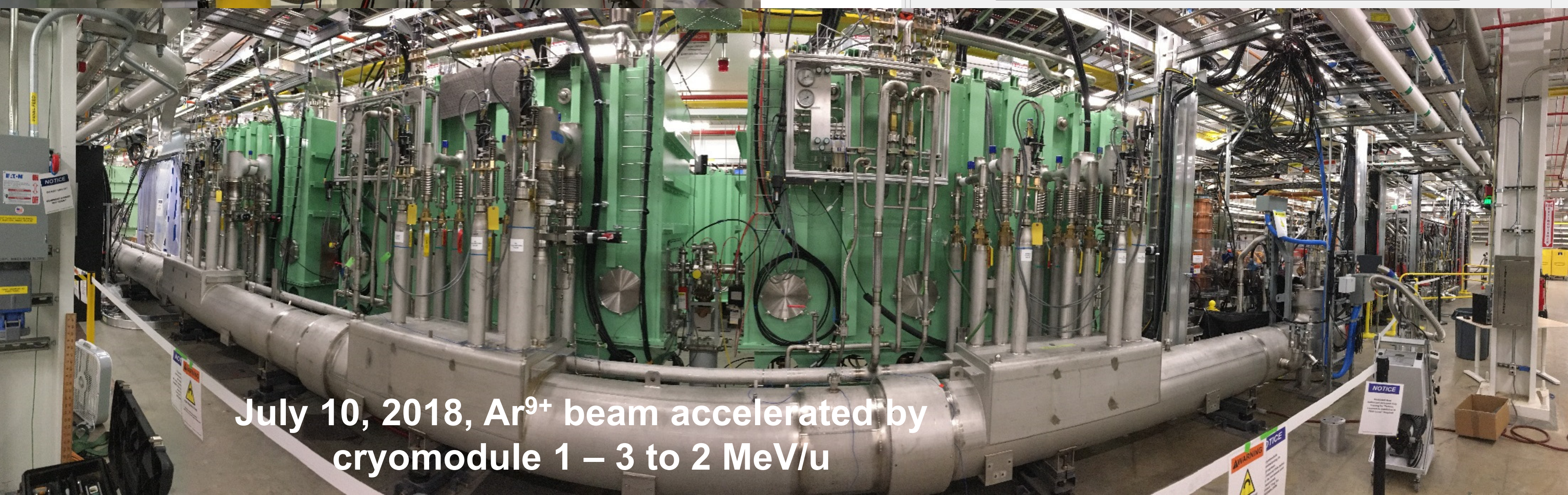


FRIB Lower LEBT, RFQ, MEBT, and the three β=0.041 cryomodules installed

2018: Accelerate Beams > 2 MeV/u (ARR2)

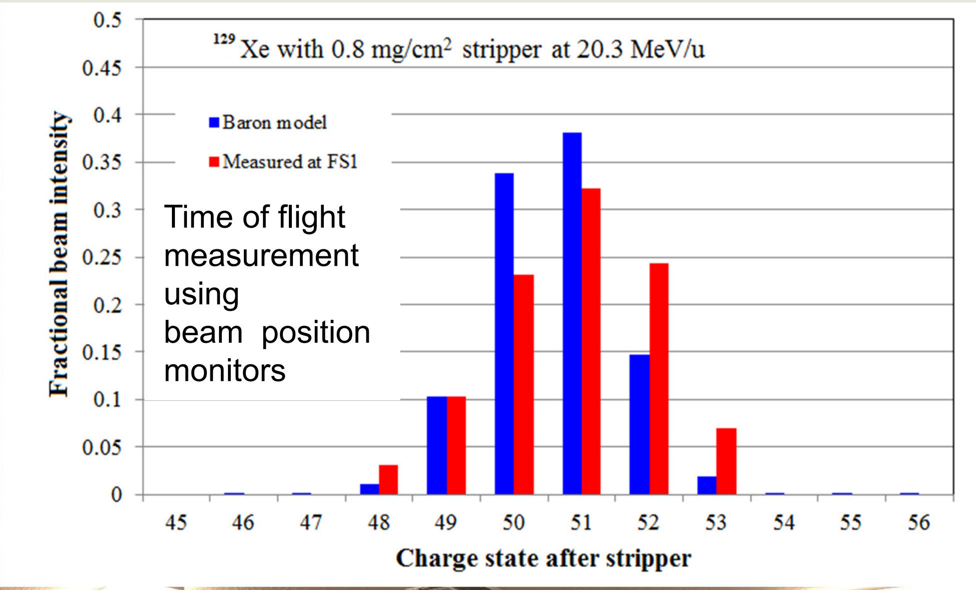
Integrated Cryogenic and Cryomodule Systems





2019: Accelerate Beams > 20 MeV/u (ARR3)

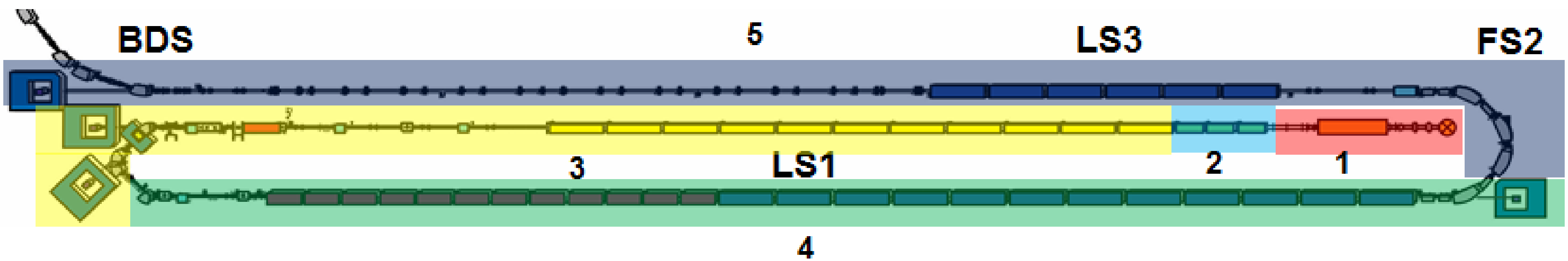
FRIB Became World's Highest Energy CW Hadron Linac



Phased Commissioning towards Completion

2020 Goal: Accelerate Beams > 200 MeV/u (ARR4)

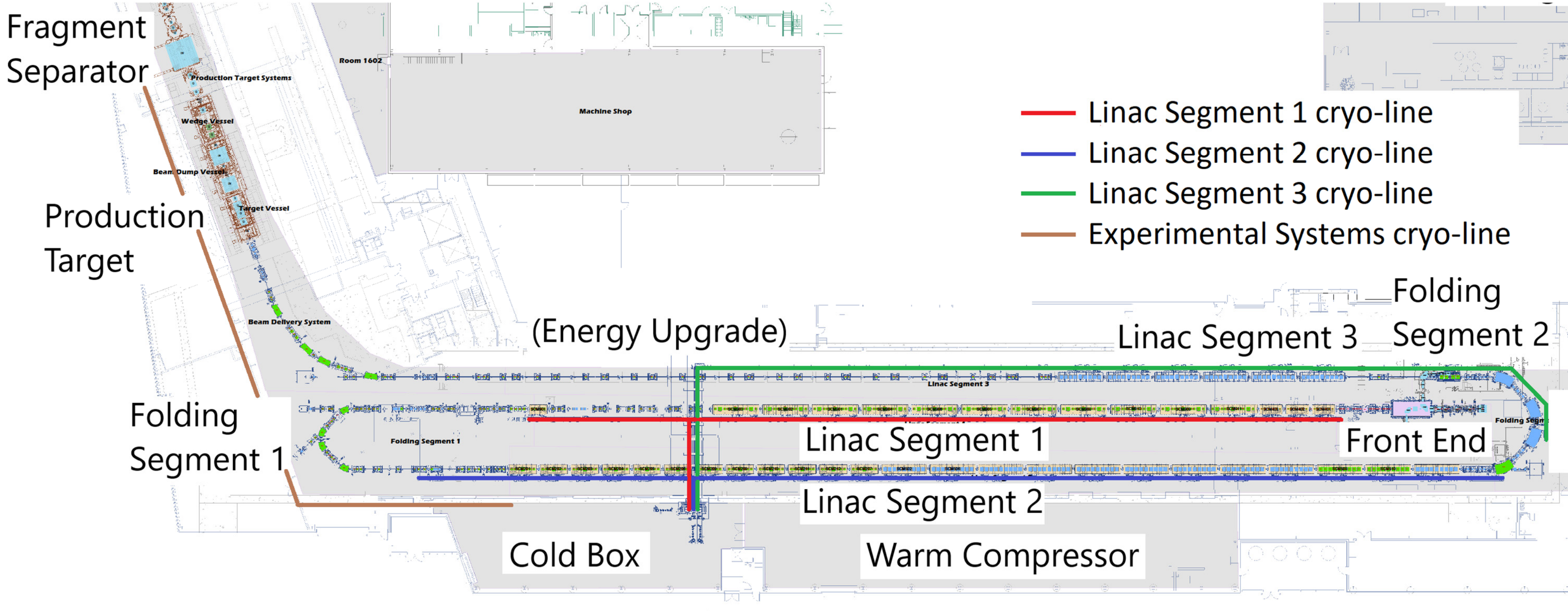
Phase	Area with beam	ARR	
ARR1	Ion source, Low Energy Beam Transport (LEBT), RFQ, Medium Energy Beam Transport (MEBT)	07/2017	✓
ARR2	Linac Segment (LS) 1 (β=0.041 cryomodules)	05/2018	✓
ARR3	Rest of LS1 and first dipole of Folding Segment (FS) 1	02/2019	✓
ARR4	**Rest of FS1, LS2, and part of FS2 to straight dump**	**03/2020**	
ARR5	FS2, LS3, part of Beam Delivery System (BDS) to straight dump	12/2020	
ARR6	BDS, target hall pre-separator	09/2021	
ARR Final	Prior post-start Items, vertical pre-separator (outside target hall), reconfigured A1900, entire facility	12/2021	



Strategy Facilitating Phased Commissioning

Allowing Each Area at Totally Different Project Phase

- LS1: operations; LS2: commissioning; LS3: construction; ESD: design



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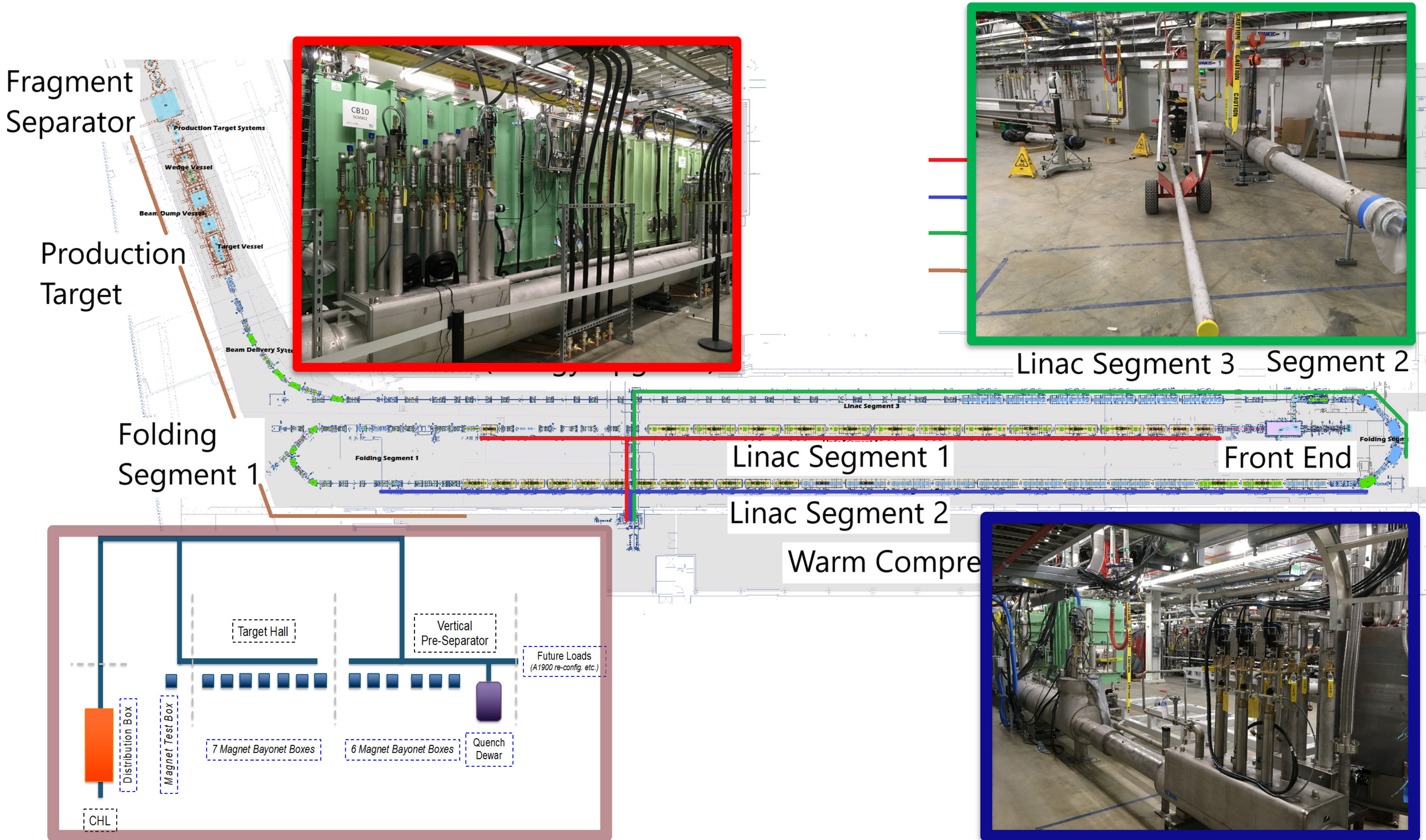
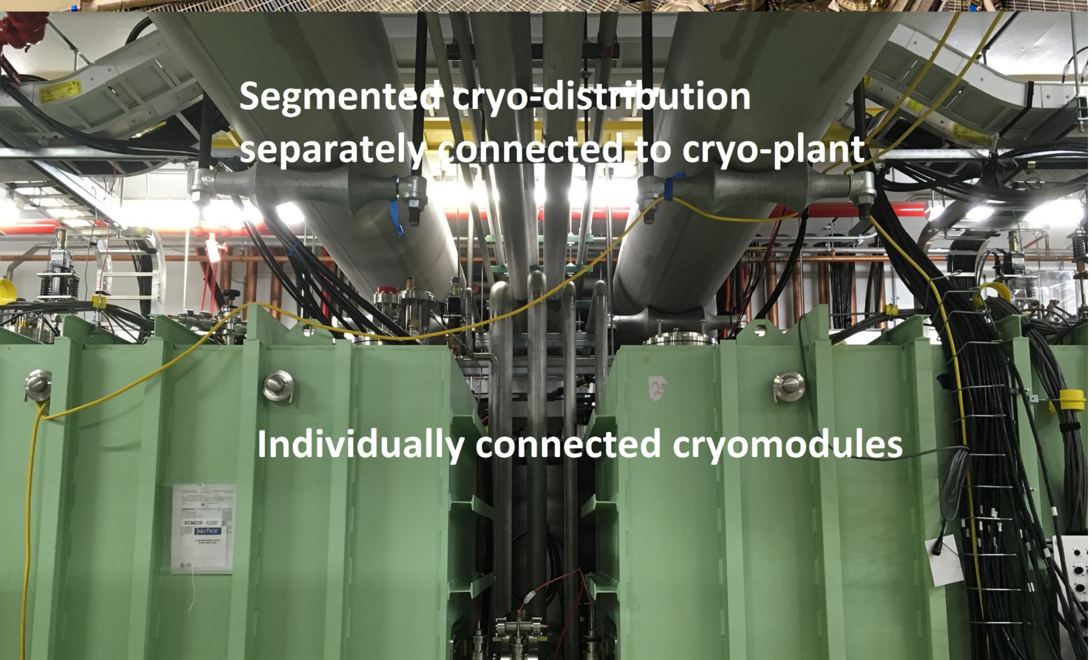


Design and construction evolution

Integrated Cryogenics



- Dramatic recovery over early setback in the attempt to procure a turn-key system
- An integrated design of the cryogenic refrigeration, distribution, and cryomodule systems is key to efficient SRF operations
  - Ganni cycle: floating pressure process
  - Distribution lines segmented
  - Cryomodules connected with U-tubes: maintenance
  - 4-2 K heat exchangers housed inside cryomodules

Helium Refrigeration System Operational

All Cryomodules in Linac Segment 1 Cooled Down to 2 K

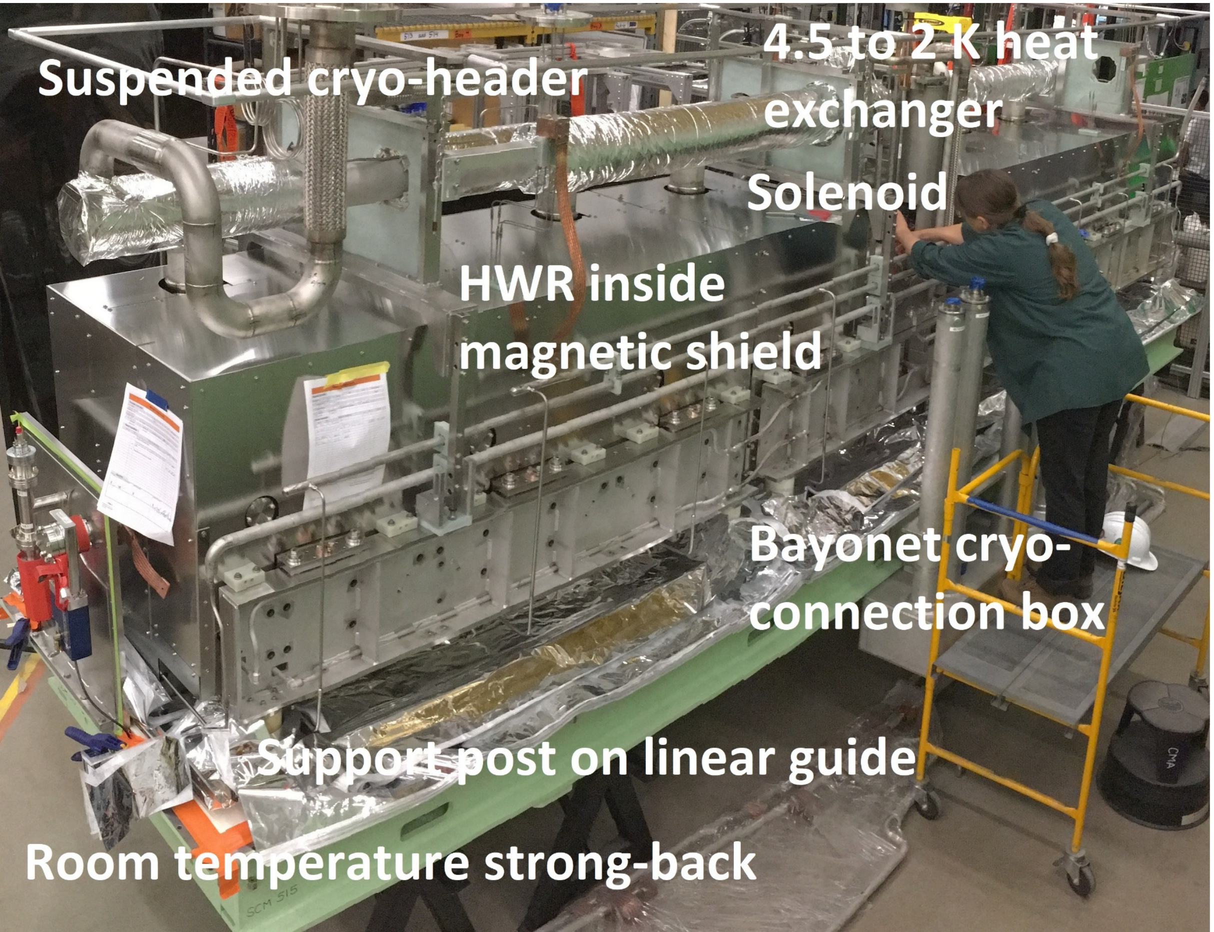
2 K cold box commission on December 2018

2 K cold box installation August 2018

Both Linac Segment 1 and 2 cryo-lines cool down since March 2019

Bottom Up Cryomodule

- Facilitate assembly efficiency; simplify alignment; and allow U-tube cryogenic connections for maintainability
  - Resonators and solenoids supported from the bottom
  - Cryogenic headers are suspended from the top for vibration isolation



- All resonators operate at 2 K
- All solenoids operate at 4.5 K
- Local magnetic shielding for 1.5 μT remnant field

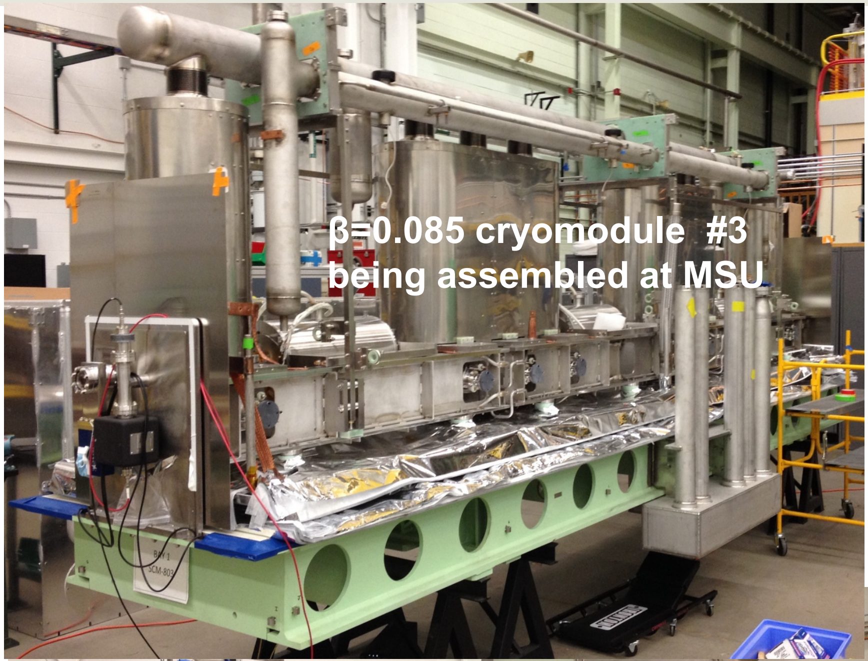
WETEA5: S. Miller et al, FRIB cavity and cryomodule performance, comparison with the design and lessons learned

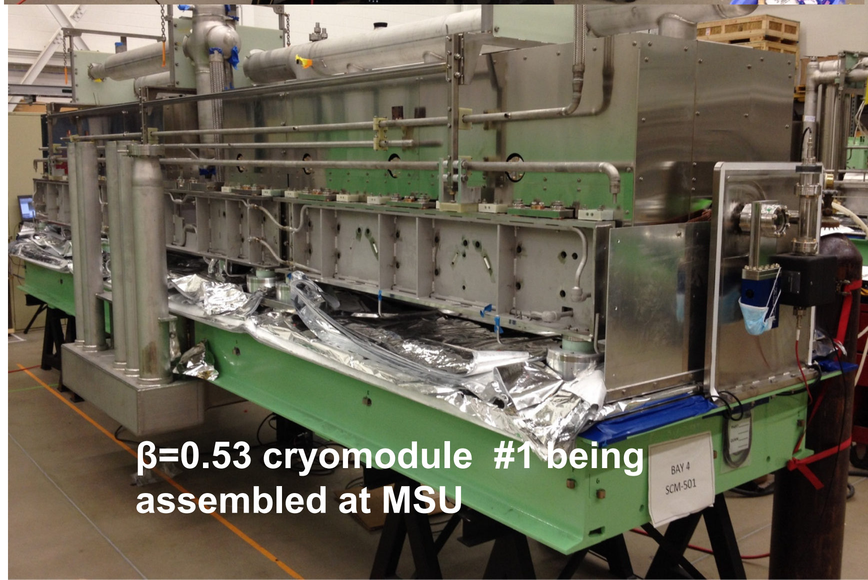
Six Cryomodule Assembly Bays in Parallel
Producing ~ 1.5 Cryomodules Per Month at MSU

THP098: C. Compton et al, The FRIB superconducting cavity production status and findings concerning surface defects

Six Types of Cryomodules Being Assembled

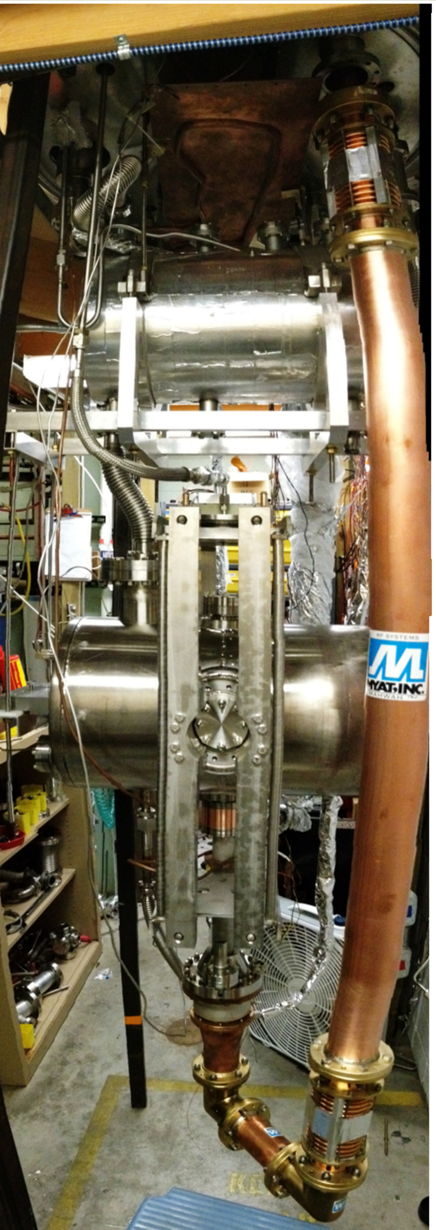
β=0.041, 0.085, 0.29, 0.53 for Baseline; β=0.65 for Upgrade

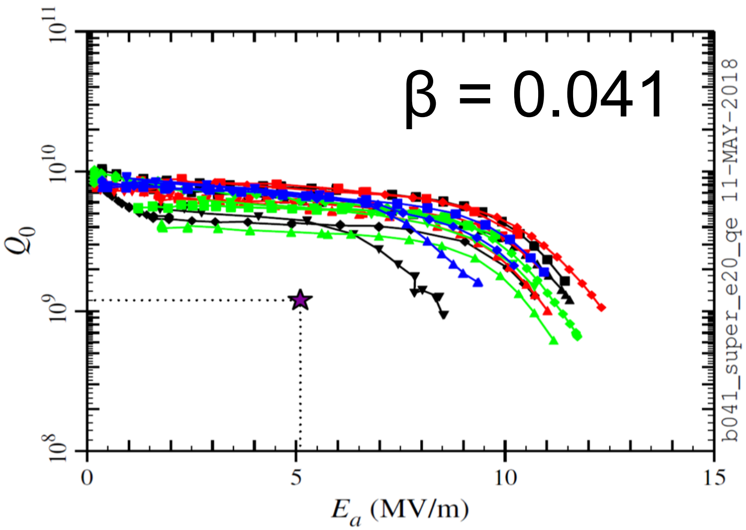


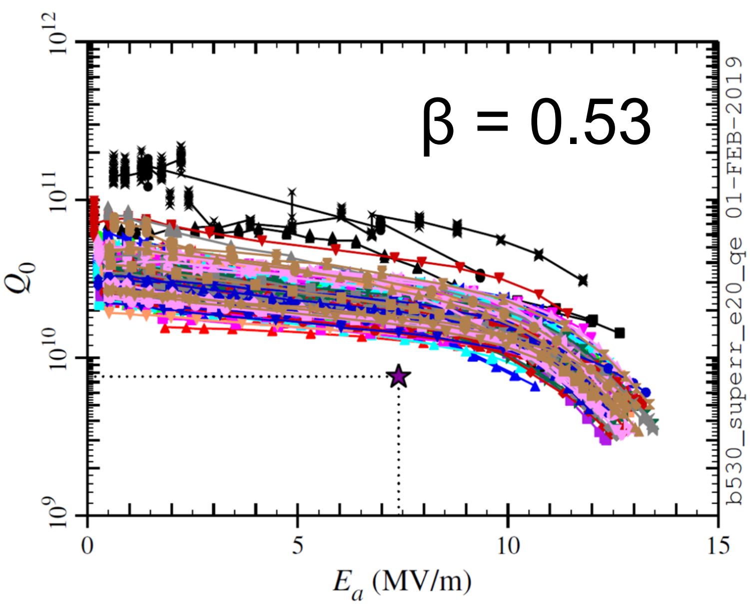


Low-β SRF

Development Intensified since 2011 Overcoming Early Challenges







- Superconducting RF starting from 0.5 MeV/u
- Optimum performance at low production cost
  - geometry; material; mechanical solutions
- Designs fully validated
  - Vertical Dewar tests
  - Integrated tests of the cavity, power coupler, tuner, and ancillary systems
  - Assembled cryomodule 100% tested in bunker
  - Beam tested

MSU/FRIB Contributions to SRF 2019

MOP071: J. Popielarski *et al*, FRIB coupler performance and lessons learned.

MOP072: K. Saito *et al*, FRIB solenoid package in cryomodule and local magnetic shield.

TUP089: M. Xu *et al*, FRIB LS1 cryomodule's solenoid commissioning.

TUP090: S-H. Kim *et al*, Performance of quarter wave resonators in the FRIB superconducting driver linear accelerator.

TUP091: C. Compton *et al*, Production Status of Superconducting Cryomodules for the Facility for Rare Isotope Beams.

TUP092: K. Elliott *et al*, Experiences of superconducting radio frequency coldmass production for the FRIB linear accelerator.

TUP093: E. Matzgar *et al*, Summary of FRIB cavity processing in the SRF coldmass processing facility and lessons learned.

WETEA5: S. Miller *et al*, FRIB cavity and cryomodule performance, comparison with the design and lessons learned.

THP061: W. Hartung *et al*, Performance of FRIB production quarter-wave and half-wave resonators in Dewar certification tests.

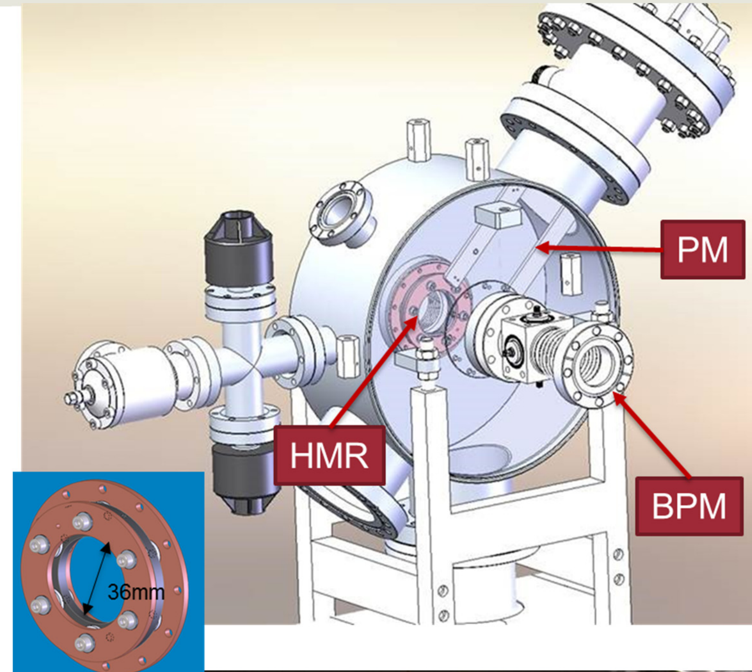
THP062: W. Chang *et al*, Progress in FRIB cryomodule bunker tests.

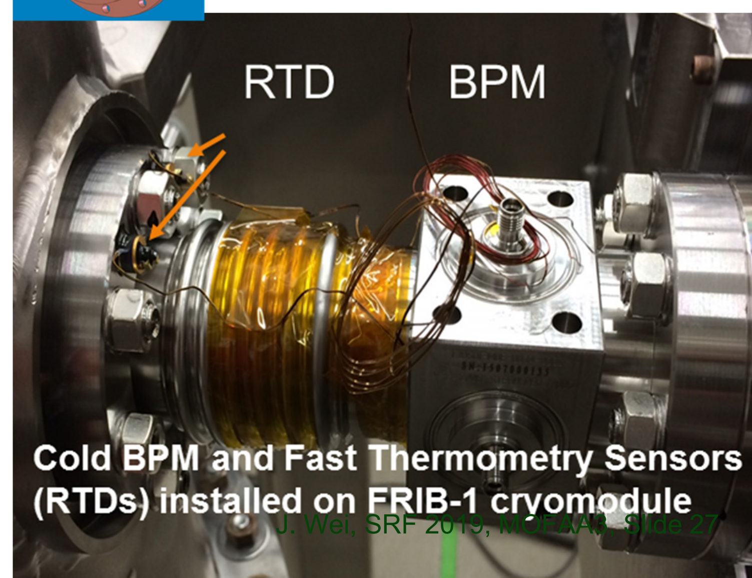
THP063: S. Shanab *et al*, Investigating the possibility of 1.3 GHz SRF cavity for medium-beta heavy ion multi-charge-state beams.

THP098: C. Compton *et al*, The FRIB superconducting cavity production status and findings concerning surface defects.

Machine Protection System (MPS)
Low Sensitivity & Short Range of Intense Heavy-ion Beams

- Uranium ion stopping range is about 30 times shorter than proton’s
  - Uranium ion energy deposition density in material is more severe than protons
- Uranium beam is about 30 times more difficult to detect than protons
  - Further complicated by signal interference in the folded layout
- MPS of multi time scale is needed to mitigate both acute & chronicle beam loss
  - Both prompt damage and long-term degradation of SRF resonators
- Innovative detection techniques developed
  - Halo monitor ring and thermometry sensors for high-sensitivity loss detection
  - Current monitoring modules for critical magnet power supply inhibition





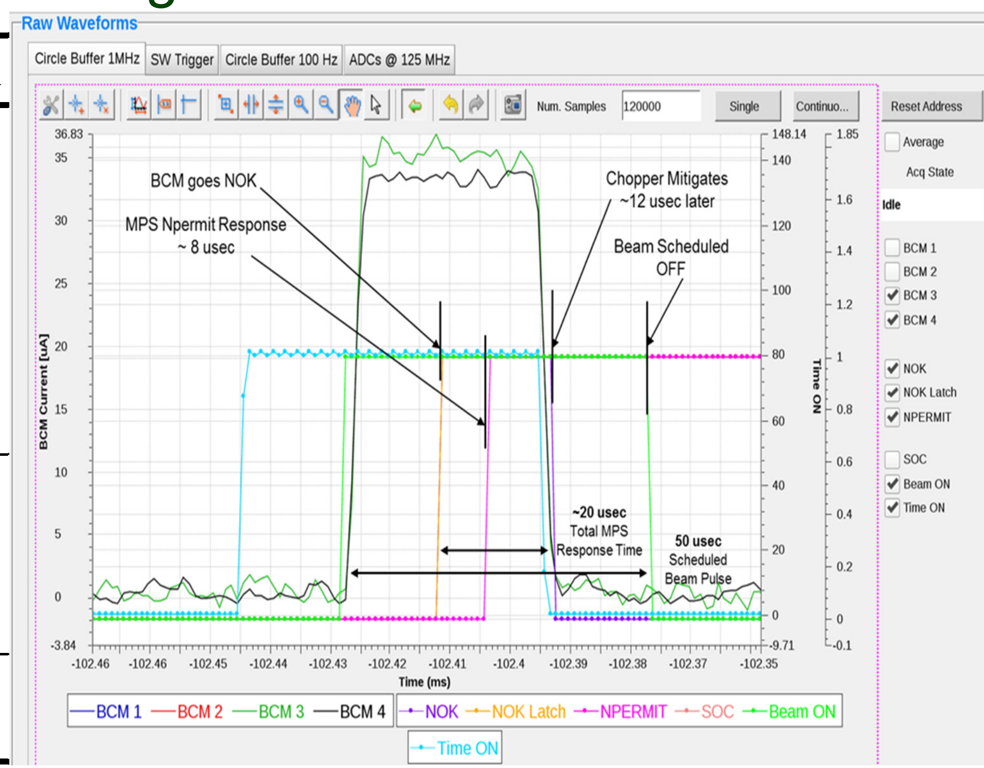
Cold BPM and Fast Thermometry Sensors (RTDs) installed on FRIB-1 cryomodule

Fast Machine Protection Validated

Differential BPM Readings Inhibits Beam within 35 μs

- Validated chopper and chopper monitoring system to limit beam power
- Commissioned differential BPM system for fast (< 35 μs) MPS
- Halo monitor ring ring provided rich signal for both ion and electrons
- Thermometry sensors responded to beam loss with 0.1 K sensitivity
- Run permit system under commissioning

Mode	Time	Detection	Mitigation
FPS	~35 μs	LLRF controller Dipole current monitor Differential BCM Ion chamber monitor Halo monitor ring Fast neutron detector	LEBT bend electro-static deflector
RPS (1)	~100 ms	Vacuum status Cryomodule status Non-dipole PS Quench signal	As above; ECR source HV
RPS (2)	>1 s	Thermo-sensor Cryo. heater power	As above



Installation and preparation

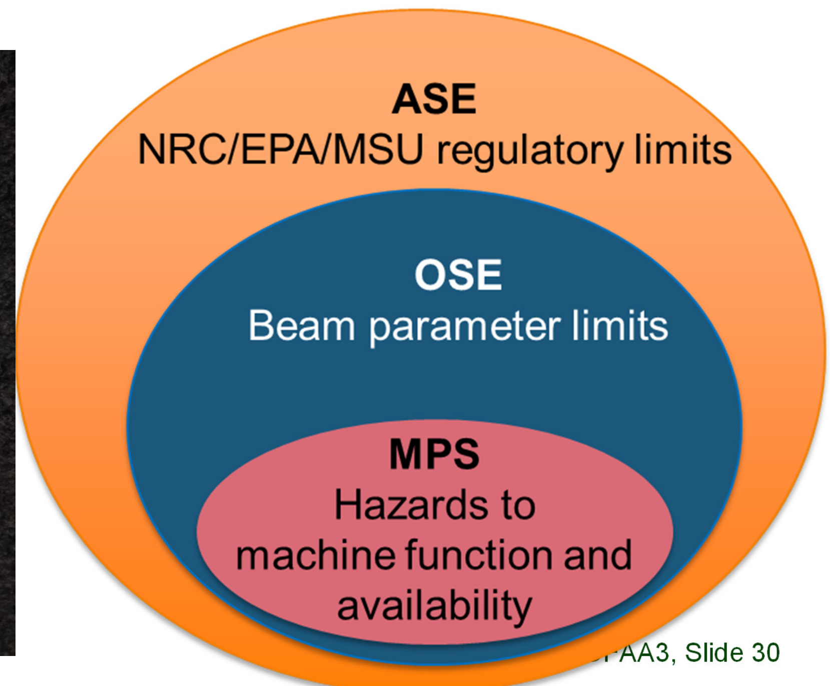
Personnel Protection System Establishment

Determine Accelerator & Operations Safety Envelope (ASE/OSE)

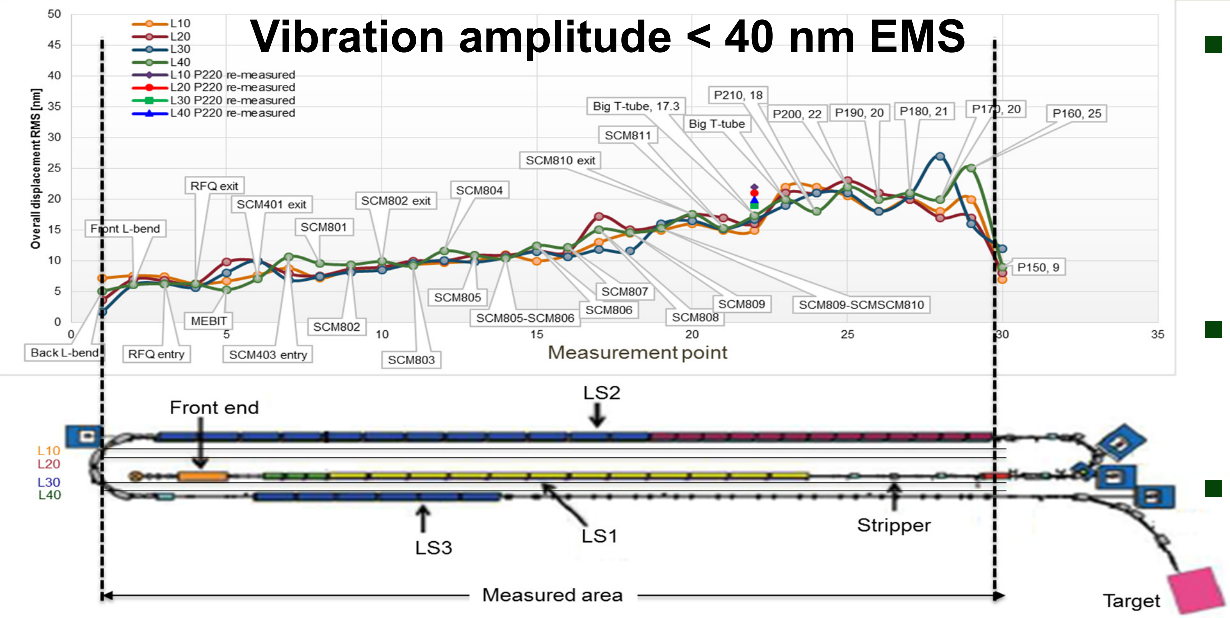
- Oxygen Deficiency Hazard (ODH) mitigation for cryogenic environment
  - No nitrogen cryogen allowed in the FRIB tunnel
  - Separate ODH zones for cryo-plant, tunnel, rack room
- Access Control System to FRIB tunnel: 10 m underground for shielding
- Radiation Control System for prompt radiation and fault conditions
- Physically separated PPS controls network for reliability, cyber security

PPS rack for ODH

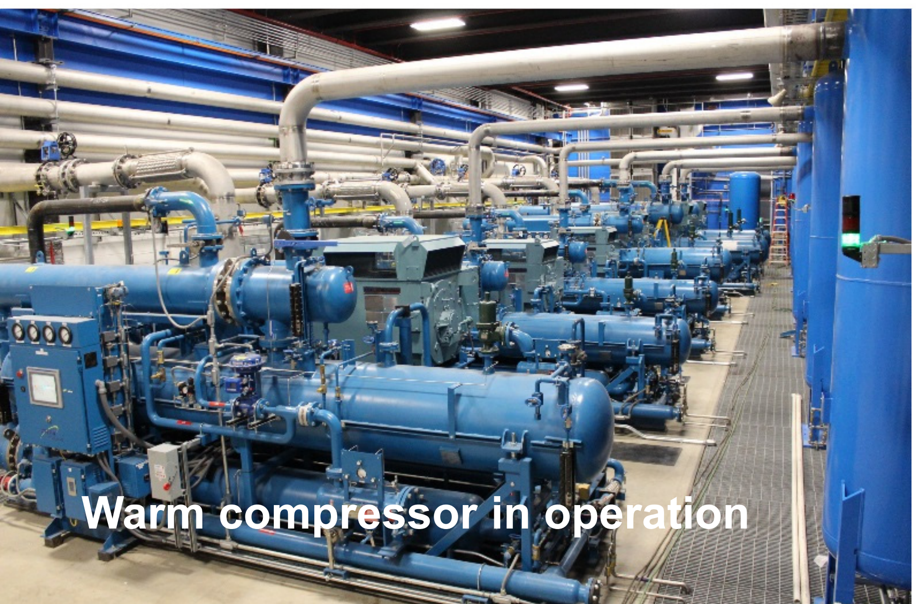
ODH monitor for linac tunnel



Microphonic Mitigation
Provisions at Resonator, Cryomodule, Cryogenics Design



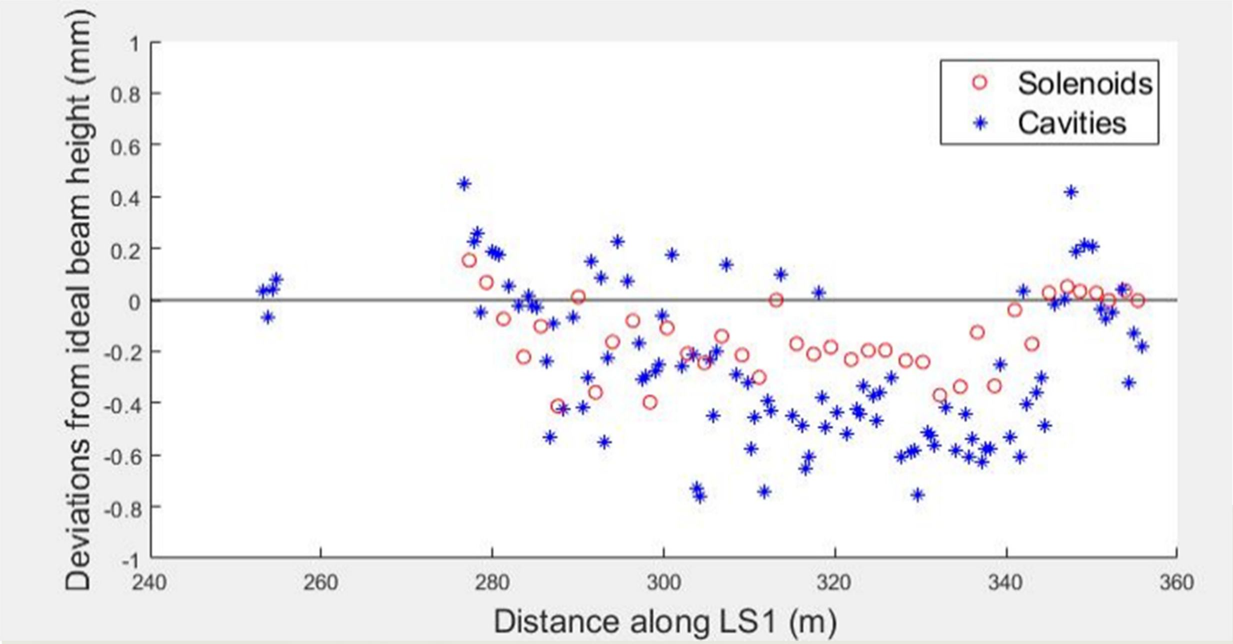
- Previsions in compressor design & installation verified by tunnel vibration measurements
- Detailed resonator and cryomodule designs
- Additional design features
  - QWR mechanical damper
  - Cryo-header attachment to top cover to suppress low freq. mechanical modes
  - All resonators run at 2 K

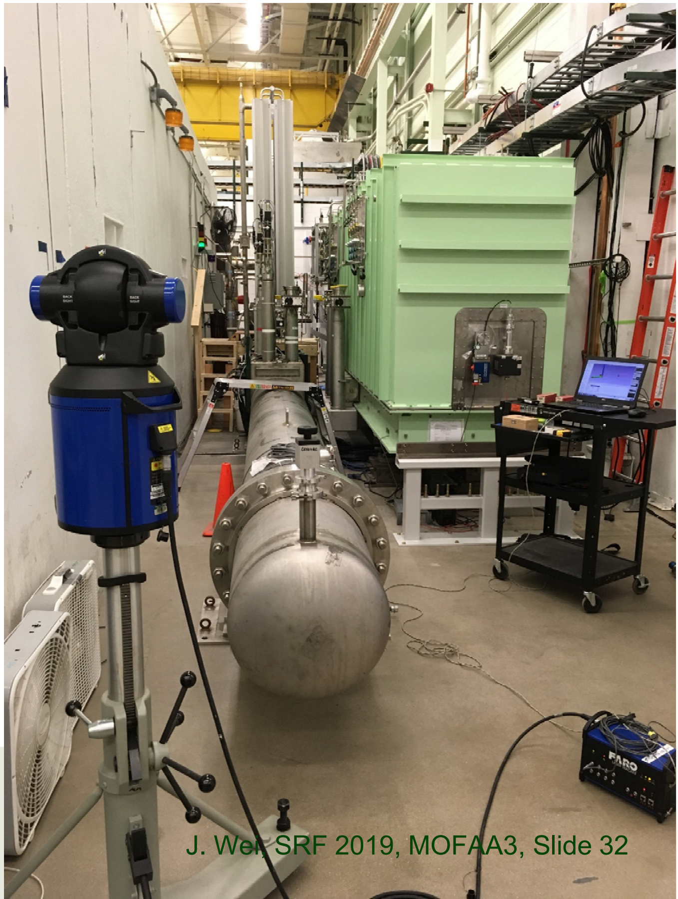


- Promptly resolved cavity locking issue upon initial cool down
  - Iteration on valve controls logic
  - Provision for liquid helium supply from 10,000 liter Dewar

Survey and Alignment
"Bottom-up" Cryomodule Design Minimizes Manual Intervention

- Satisfactory beam commissioning achieved without in-field alignment adjustments of individual sub-components (resonators & solenoids)
  - Correctors at < 25% full strength to control orbit deviation < +/- 1 mm
- Standardized fabrication tolerance & assembly procedure executed
  - Fiducials measured during coldmass assembly
  - Thermal offset corrections account for cool-down
  - Least-square fit line through magnetic centers of the solenoids to characterize CM alignment

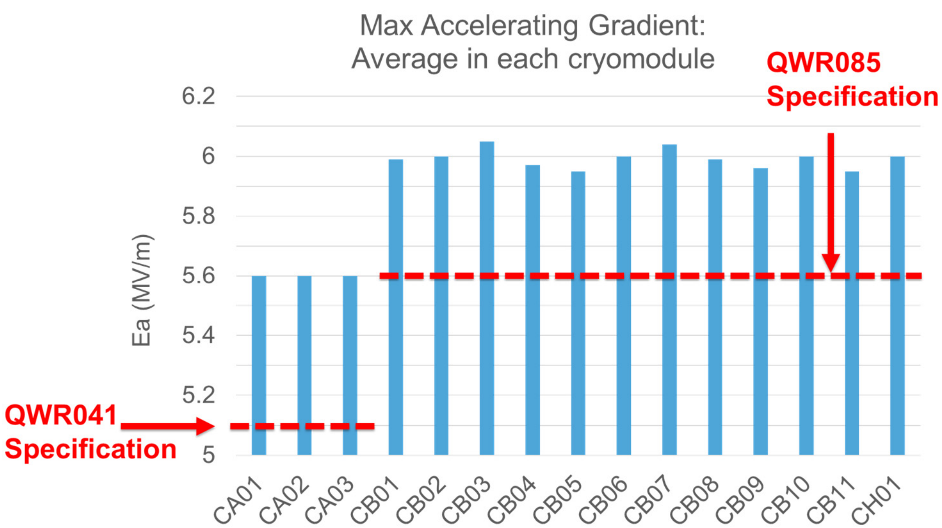




Cryogenic Installation and Cool Down

- Conducting final assembly and tests on site avoids complications
- Phased cool down commissioning of cryo-distribution lines to support various phases of accelerator beam commissioning
- Individual cryomodule installation, tests, and cool down (dictated by controls and interlock configuration)

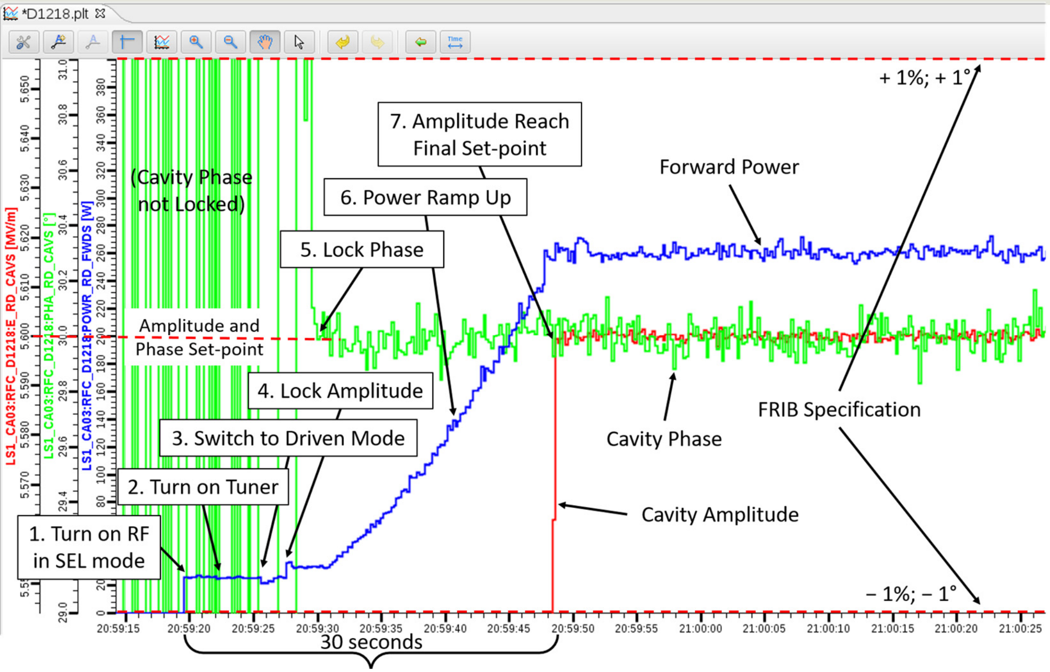
Device energization and RF conditioning



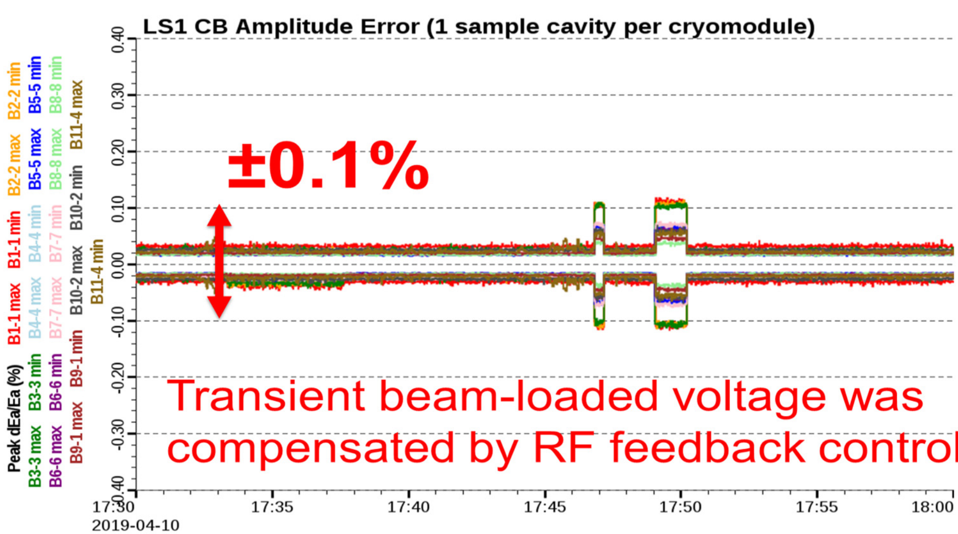
- Rigorous tests and thorough preparation ensures prompt SRF commissioning
  - Resonators, couplers, solenoids etc. 100% cold tested at working temperature
  - Cryomodules 100% bunker tested
- Cryomodule (containing up to 8 QWRs and solenoids) typically commissioned at the rate of one per day
- All SRF resonators and SC solenoids perform above design specifications

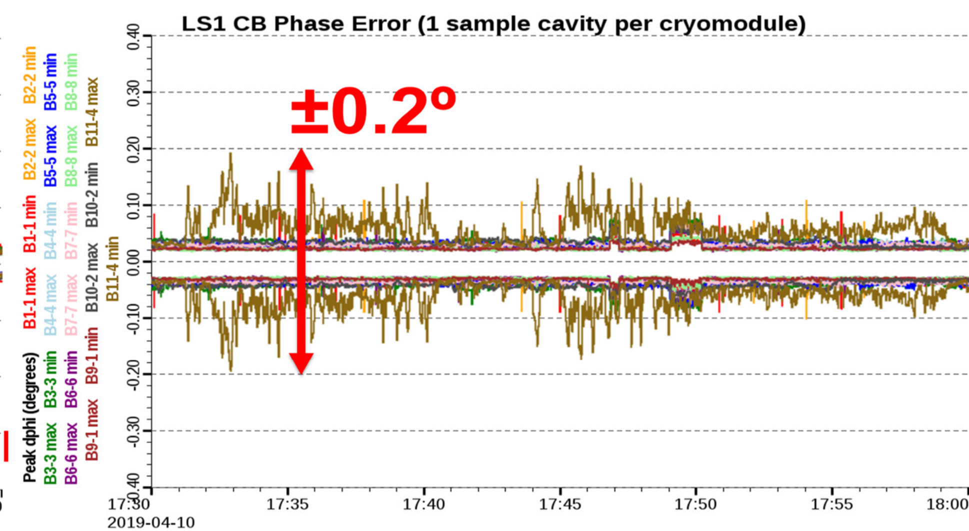
TUP090: S-H. Kim *et al*, Performance of quarter wave resonators in the FRIB superconducting driver linear accelerator.

Low-level RF Controls and Automation



- Amplitude and phase errors:
  - Achieved < $\pm 0.1\%_{pk\text{-}pk}$ < $\pm 0.2^{o}_{pk\text{-}pk}$
  - Specifications: <$1\%_{pk\text{-}pk}$, < $\pm 1^{o}_{pk\text{-}pk}$
- Automated turn-on of resonators
  - ~ 30 s per resonator
  - Turn on all 104 QWR cavities in ~ 20 min.
- No issue with frequency locking





Operations coordination and maintenance infrastructure

Interlaced Installation and Commissioning

Demands Operational Discipline and Close Coordination

- Commissioning shifts
  - Access Control System prevents access into the shielded enclosure while the Radiation Control System interlock ensures that there is no prompt radiation through temporary penetrations, including the transport shaft and unsealed conduits
  - Before the transition to an installation shift, a radiation survey is done and areas of radio-activation are secured
- Installation shifts
  - Daily work control planning is implemented for all tasks in the linac tunnel, with specified locations, times, and personnel
  - When switching back to commissioning, the operator-in-charge ensures that the operational conditions are restored and search-and-evict is conducted following the established procedures

"SRF High Bay" Constructed at MSU
Infrastructure Investment for FRIB Construction & SRF Research

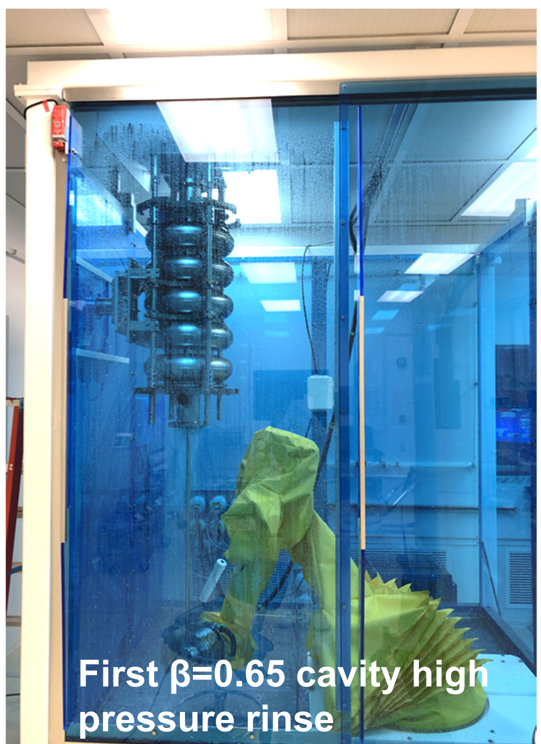
Objective Measures	Date
Ready-for-equip.	01/2014
Beneficial occu.	05/2014
Clean 1st cavity	07/2014
Coord. measure.	09/2014
Degassing furnace	10/2014
Etch 1st Cavity	12/2014
Cryogenics system	09/2015
RF test 1st cavity	11/2015
Vertical test area	01/2016
Cryomodule test	09/2016

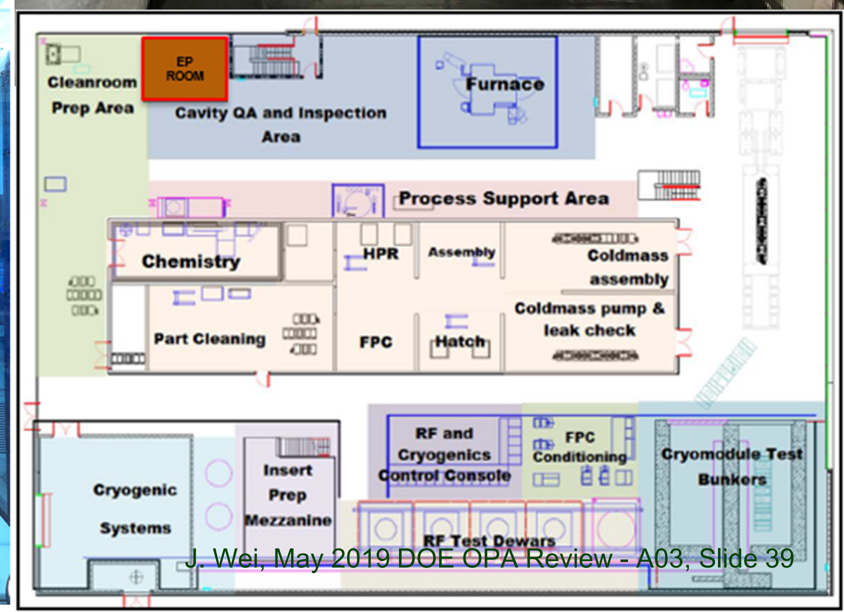
- Production throughput:
  - 5 cavity per week
  - > 1 coldmass per month

MSU Funded Cryogenics Assembly Building and SRF Electropolishing Facility Proceeding

- Cryogenics Assembly Building (CAB) Beneficial Occupancy Date August 2019
  - Cryogenics team to fabricate experimental distribution components
  - SC magnet team to assemble SCD1 and SCD2 magnets
  - Cryomodule team to conduct cryomodule maintenance
- Electro-polishing (EP) expected to be established at MSU early 2020 for FRIB upgrade & research
  - One β=0.65 elliptical cavity EP processed at ANL
  - One β=0.65 elliptical cavity to be BCP processed at MSU in May 2019


Cryogenic Assembly Building (CAB) interior


First β=0.65 cavity high pressure rinse



MSU Cryogenic Initiative Addresses National Need

Design of Large Cryogenic Plants and Training of Cryogenic Engineers

- 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.
- Led by Prof. Rao Ganni (formerly Jefferson Laboratory)
- 14 engineering students enrolled in first class, fall 2017 (5 graduate, 9 undergraduate)

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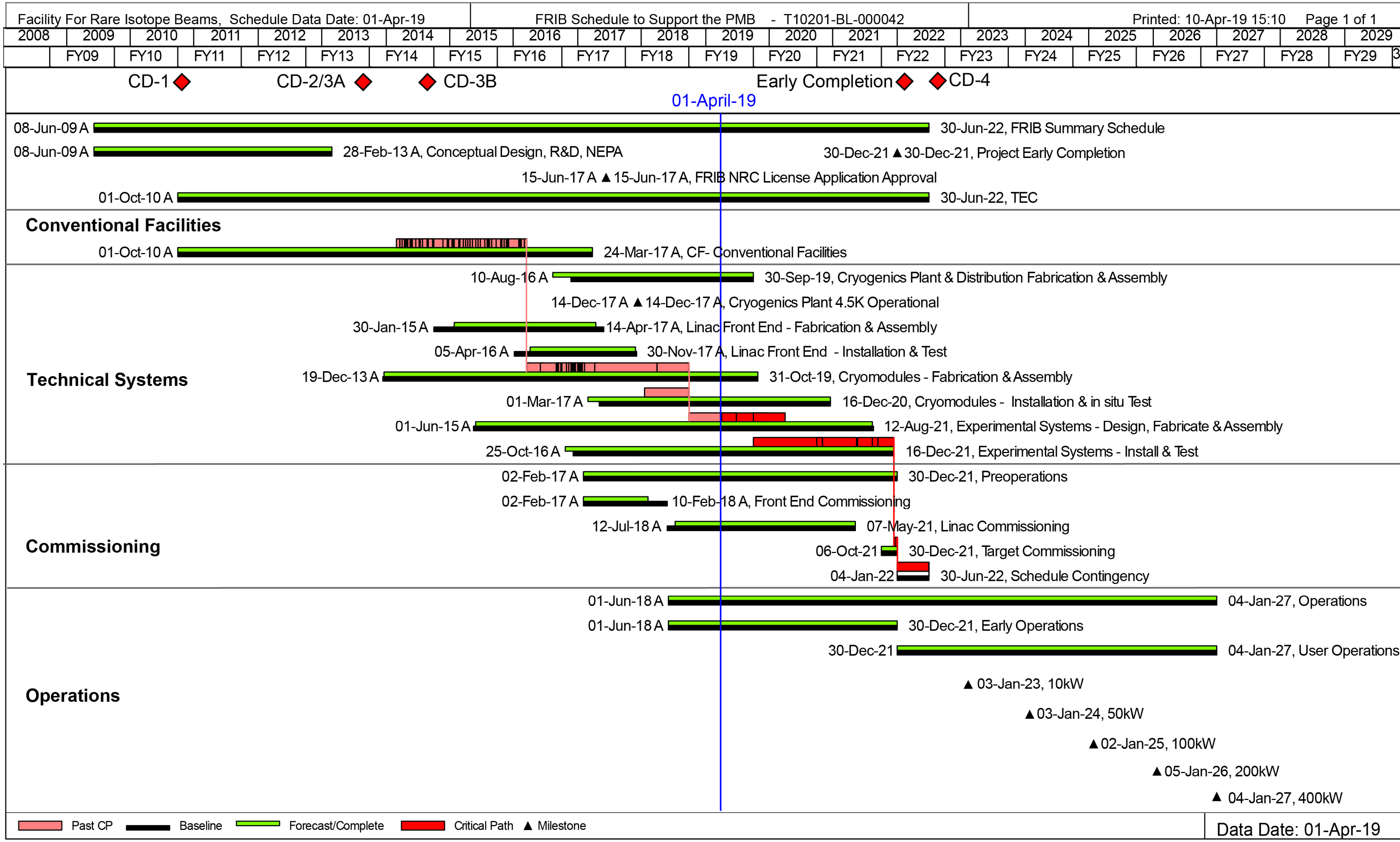
Summary

Schedule Integrated and On Track

Focusing on Critical Path; Accelerating Commissioning Schedule



We Thank the SRF Community for Your Help in Enabling FRIB Development

- Help from some key SRF experts in critical efforts and important advice to keep FRIB SRF development on track
  - Weekly SRF teleconferences continuously from 2011 (until today with weekly participation from A. Facco and R. Laxdal; earlier days P. Kneisel)
- Benefits from exchanges, visits, workshops and conferences
  - SRF conferences
  - TTF meetings
  - Visits to CEA Saclay and other laboratories
- Collaborations with other laboratories
  - TRIUMF, JLab, FNAL, …
- Work-for-others contracts with other laboratories
  - JLab, ANL, …
- Industrial providers pertaining to accelerator and SRF establishments
- We intend to return the favor by sharing with the community our lessons learned and experiences gained

We Cannot Build FRIB Alone and Are Working with the Best in US and Worldwide

- 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
- 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

Conclusion

- Nearly five years after the start of technical construction, FRIB is progressing on schedule and on cost, with beam commissioning completed through the first 15 of 46 superconducting cryomodules, and with heavy ions of Ne, Ar, Kr and Xe accelerated above 20 MeV/u.
- The next phase of beam commissioning (ARR4) scheduled after March 2020 aims at accelerating these heavy ion beams to about 200 MeV/u using the 15 QWR CMs and 24 HWR CMs.
- Operations for scientific users is expected to start as planned in 2022.

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References

- [1] J. Wei *et al.*, *International Journal of Modern Physics E* **28**, 1930003 (2019).
- [2] J. Wei *et al.*, in *Proc. HIAT 2012, Chicago*, p. 8.
- [3] M. Johnson *et al.*, in *Proc. IPAC 2012, New Orleans*, p. 2507.
- [4] S. Miller *et al.*, "FRIB cavity and cryomodule performance, comparison with the design and lessons learned," WETEA5, these proceedings.
- [5] T. Xu *et al.*, in *Proc. SRF 2017, Lanzhou*, p. 345.
- [6] V. Ganni *et al.*, in *Proc. CEC-ICMC 2013*, **59**, p. 323.
- [7] A. Facco *et al.*, in *Proc IPAC 2012, New Orleans*, p. 61.
- [8] A. Facco *et al.*, in *Proc. SRF 2013, Paris*, p. 873.
- [9] S. Stark *et al.*, in *Proc. LINAC 2016, East Lansing*, p. 535.
- [10] S. Miller *et al.*, in *Proc. SRF 2013, Paris*, p. 825.
- [11] M. Ikegami, in *Proc. IPAC 2015, Richmond*, p. 2418.
- [12] F. Casagrande, in *IPAC 2015, Richmond*, THYB1.
- [13] C. Compton *et al.*, "The FRIB superconducting cavity production status and findings concerning surface defects," THP098, these proceedings.
- [14] E. Metzgar *et al.*, "Summary of FRIB cavity processing in the SRF coldmass processing facility and lessons learned," TUP093, these proceedings.
- [15] W. Hartung *et al.*, "Performance of FRIB production quarter-wave and half-wave resonators in Dewar certification tests," THP061, these proceedings.
- [16] K. Elliott *et al.*, "Experiences of superconducting radio frequency coldmass production for the FRIB linear accelerator," TUP092, these proceedings.
- [17] W. Chang *et al.*, "Progress in FRIB cryomodule bunker tests," THP062, these proceedings.
- [18] J. Popielarski *et al.*, "FRIB coupler performance and lessons learned," MOP071, these proceedings.
- [19] K. Saito *et al.*, "FRIB solenoid package in cryomodule and local magnetic shield," MOP072, these proceedings.
- [20] M. Xu *et al.*, "FRIB LS1 cryomodule's solenoid commissioning," TUP089, these proceedings.
- [21] C. Compton *et al.*, "Production status of superconducting cryomodules for the Facility for Rare Isotope Beams," TUP091, these proceedings.
- [22] S. Kim *et al.*, "Performance of quarter wave resonators in the FRIB Superconducting driver linear accelerator", TUP090, these proceedings.
- [23] D. Morris *et al.*, in *Proc. IPAC 2018, Vancouver*, p. 1765.
- [24] J. Vincent *et al.*, *Nucl.Instrum. Meth. Phys. Res. A* **643**, p. 11 (2011).
- [25] J. Crisp *et al.*, in *Proc. NAPAC 2013, Pasadena*, p. 1187.
- [26] Z. Liu *et al.*, *Nucl. Instrum. Meth. Phys. Res. A* **767**, p. 262 (2014)
- [27] 7th MicroTCA Workshop for Industry and Research, Hamburg (2018), https://mtcaws.desy.de
- [28] S. Cogan *et al.*, in *Proc. IBIC 2016, Barcelona*, p. 572.
- [29] M. Konrad, in *Proc. PCaPAC 2016, Campinas*, p. 105.
- [30] A. Li *et al.*, in *Proc. LINAC 2018, Beijing*, p. 336.
- [31] S. Lidia, in *Proc. IBIC 2014, Monterey*, p. 239.
- [32] A. Li *et al.*, in *Proc. LINAC 2016, East Lansing*, p. 956.
- [33] M. Konrad *et al.*, in *Proc. PCaPAC 2016, Campinas*, p. 145.
- [34] E. Pozdeyev *et al.*, in *Proc. LINAC 2018, Beijing*, p. 615.
- [35] P. Ostroumov *et al.*, *Phys. Rev. Accel. Beams* **22**, 040101 (2019).
- [36] L. Popielarski *et al.*, in *Proc. LINAC 2014, Geneva*, p. 954.

Thank You!