FRIB Project Status and Beam Instrumentation Challenges

Jie Wei
On Behalf of FRIB Accelerator Team & Collaboration

IBIC'17, Grand Rapids, August 21, 2017

MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661.
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.

Coauthors

- A. Aleksandrov[10], H. Ao[1], S. Beher[1], N. Bultman[1], F. Casagrande[1], J. Chen[1], S. Cogan[1], C. Compton[1], L. Dalesio[1], K. Davidson[1], K. Dixon[2], N. Eddy[9], A. Facco[1,4], F. Feyzi[1], V. Ganni[1], A. Ganshyn[1], P. Gibson[1], T. Glasmacher[1], W. Hartung[1], L. Hodges[1], K. Holland[1], K. Hosoyama[6], H.-C. Hseuh[1,7], A. Hussain[1], M. Ikegami[1], S. Jones[1], M. Kelly[3], R.E. Laxdal[1,5], J. LeTourneau[1], S. Lidia[1], G. Machicoane[1], I. Malloch[1], F. Marti[1], S. Miller[1], D. Morris[1], J. Nolen[1,3], P. Ostroumov[1], J. Popielarski[1], L. Popielarski[1], E. Pozdeyev[1], S. Prestemon[8], T. Russo[1], K. Saito[1], S. Stanley[1], H. Tatsumoto[1], R. Webber[1], M. Wiseman[2], T. Xu[1], Y. Yamazaki[1]

[1] Facility for Rare Isotope Beams, Michigan State University, USA

[2] Thomas Jefferson National Laboratory, USA

[3] Physics Division, Argonne National Laboratory, Argonne, IL USA

[4] INFN - Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy

[5] TRIUMF, Vancouver, Canada

[6] KEK, Tsukuba, Japan

[7] Brookhaven National Laboratory, Upton, USA

[8] Lawrence Berkeley National Laboratory, Berkeley, USA

[9] Fermi National Accelerator Laboratory, Batavia, USA

[10] Oak Ridge National Laboratory, Oak Ridge, USA

Acknowledgements

- We thank the FRIB Accelerator Systems Advisory Committee for their valuable guidance, colleagues who participated in FRIB accelerator peer reviews including G. Ambrosio, J. Anderson, D. Arenius, W. Barletta, G. Bauer, G. Biallas, J. Bisognano, S. Bousson, S. Caspi, M. Champion, M. Crofford, C. Cullen, D. Curry, R. Cutler, G. Decker, J. Delayen, J. Delong, G. Dodson, H. Edwards, J. Error, J. Fuerst, F. Kornegay, K. Kurukawa, J. Galambos, J. Galayda, G. Gassner, J. Gilpatrick, C. Ginsburg, S. Gourlay, M. Harrison, S. Hartman, S. Henderson, G. Hoffstaetter, J. Hogan, S. Holmes, M. Howell, R. Kersevan, A. Hodgkinson, N. Holtkamp, H. Horiike, C. Hovater, H. Imao, R. Janssens, R. Keller, J. Kelley, P. Kelley, J. Kerby, A. Klebaner, J. Knobloch, R. Lambiase, M. Lamm, Y. Li, C. LoCocq, C. Luongo, K. Mahoney, J. Mammosser, T. Mann, W. Meng, N. Mokhov, Y. Momozaki, G. Murdoch, W. Norum, H. Okuno, S. Ozaki, R. Pardo, S. Peggs, R. Petkus, C. Pearson, F. Pellemoine, T. Peterson, C. Piller, J. Power, T. Powers, J. Preble, J. Price, D. Raparia, A. Ratti, T. Roser, M. Ross, R. Ruland, J. Sandberg, R. Schmidt, W.J. Schneider, D. Schrage, I. Silverman, K. Smith, J. Sondericker, W. Soyars, C. Spencer, R. Stanek, M. Stettler, W.C. Stone, J. Stovall, H. Strong, Y. Than, J. Theilacker, Y. Tian, J. Tuozzolo, V. Verzilov, R. Vondrasek, P. Wanderer, P. Wright, H. Xu, L. Young, and A. Zaltsman, and colleagues who advised and collaborated with the FRIB team including A. Burrill, A.C. Crawford, K. Davis, X. Guan, P. He, Y. He, A. Hutton, S.H. Kim, P. Kneisel, R. Ma, K. Macha, G. Maler, E.A. McEwen, S. Prestemon, J. Qiang, T. Reilly, R. Talman, J. Vincent, X.W. Wang, J. Xia, Q.Z. Xing

- The FRIB accelerator design is executed by a dedicated team of the FRIB Accelerator Systems Division with close collaboration with the Experimental Systems Division headed by G. Bollen, the Conventional Facility Division headed by B. Bull, the Chief Engineer's team headed by D. Stout, and supported by the project controls, procurements, ES&H of the FRIB Project, by NSCL, and by MSU

- Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661 and the National Science Foundation under Cooperative Agreement PHY-1102511

Outline

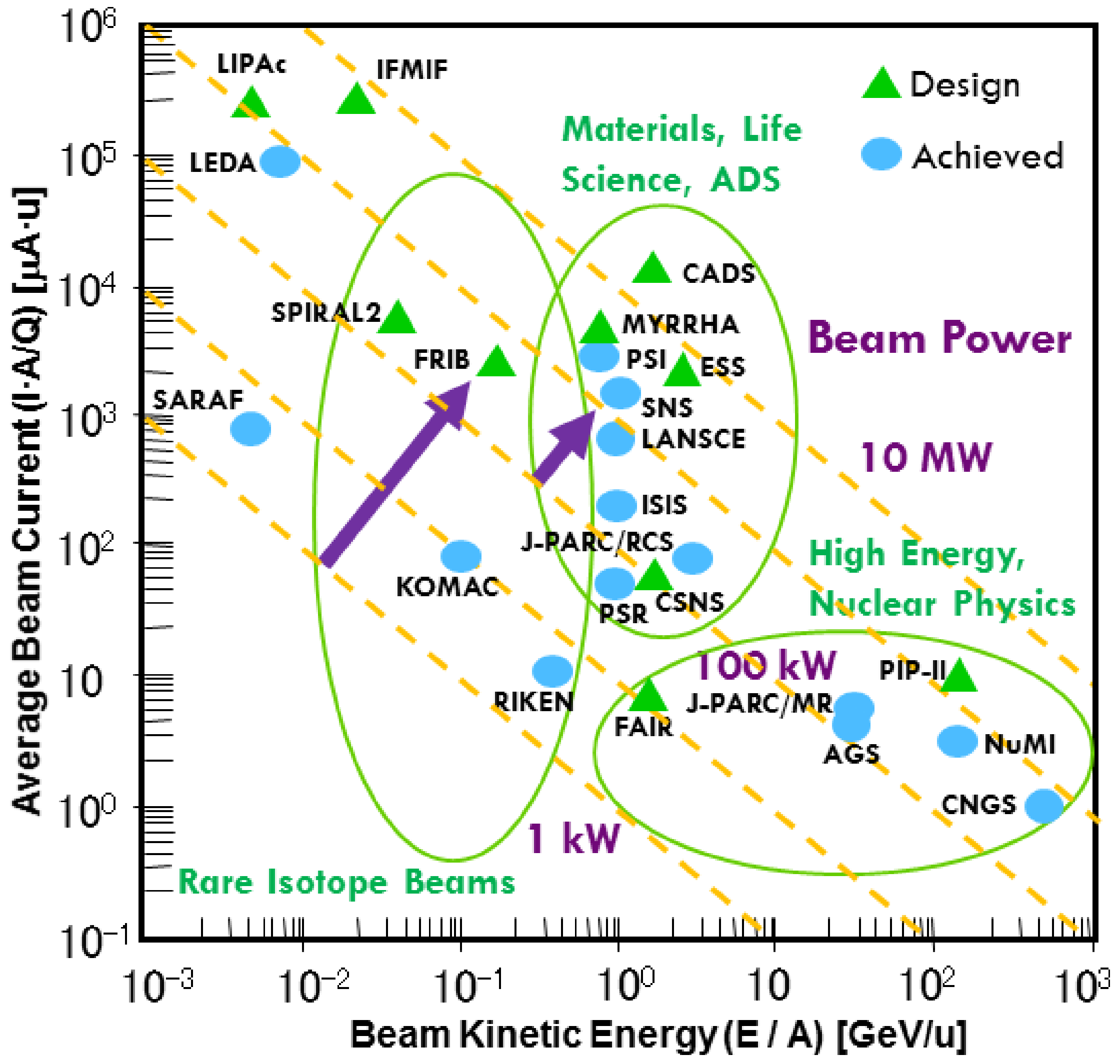
- Introduction
- Major technology developments
  - Integrated cryogenics and superconducting RF cryomodule
  - Liquid lithium charge stripping
  - Multi-time-scale machine protection
- Beam instrumentation challenges
- Accelerator project status
  - Long-lead procurements and production infrastructure
  - Construction, installation and commissioning
  - Operations and upgrades
- Team, collaboration, and baseline execution
- Summary

- Introduction

Accelerator at Beam-power Frontier

Among Three Major Frontiers: Energy, Power, Brightness

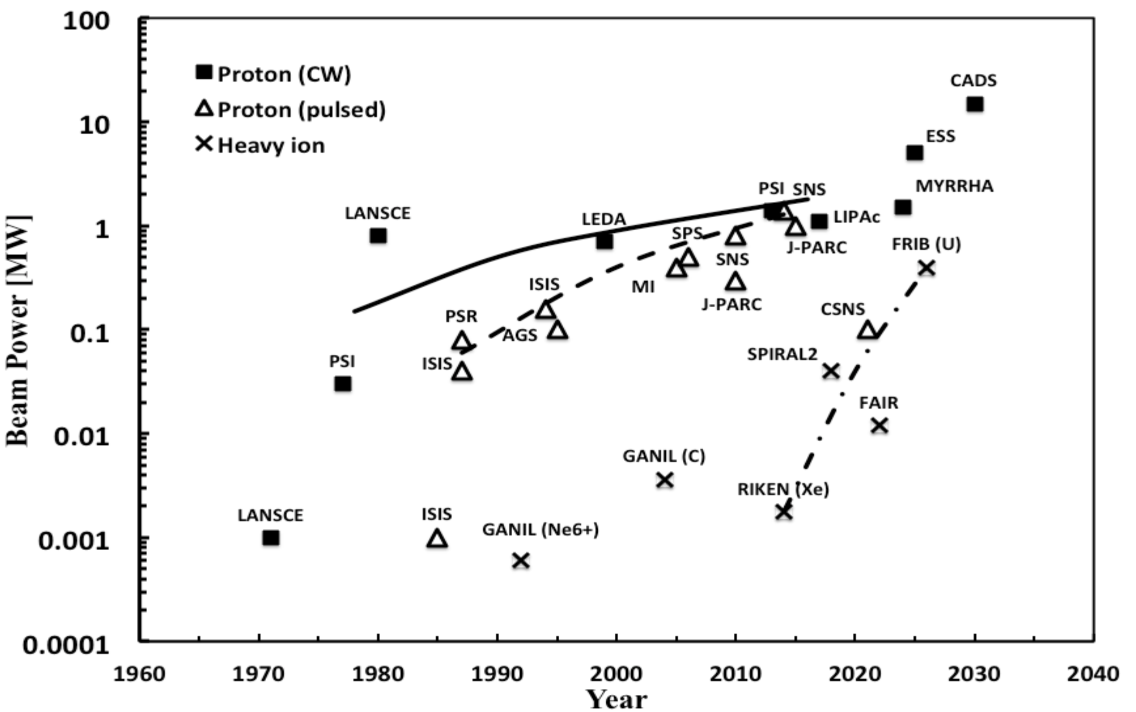
- High energy, nuclear physics (ν, K factories)
  - 1 ~ 400 GeV proton
  - Linac + Synchrotron
- Material, life science, (SNS) accelerator-driven subcritical systems (ADS)
  - 0.5 ~ 3 GeV proton
  - Cyclotron, linac, rapid cycling synchrotron, accumulator
- Rare isotope beams (RIB)
  - 0.01 ~ 1 GeV/u heavy ion
  - Linac, cyclotron, synchrotron
- Material irradiation; isotope
  - ~0.02 GeV/u deuteron; linac



FRIB Physical and Engineering Challenges

Raising Heavy-ion Power Frontier by Two Order-of-magnitudes

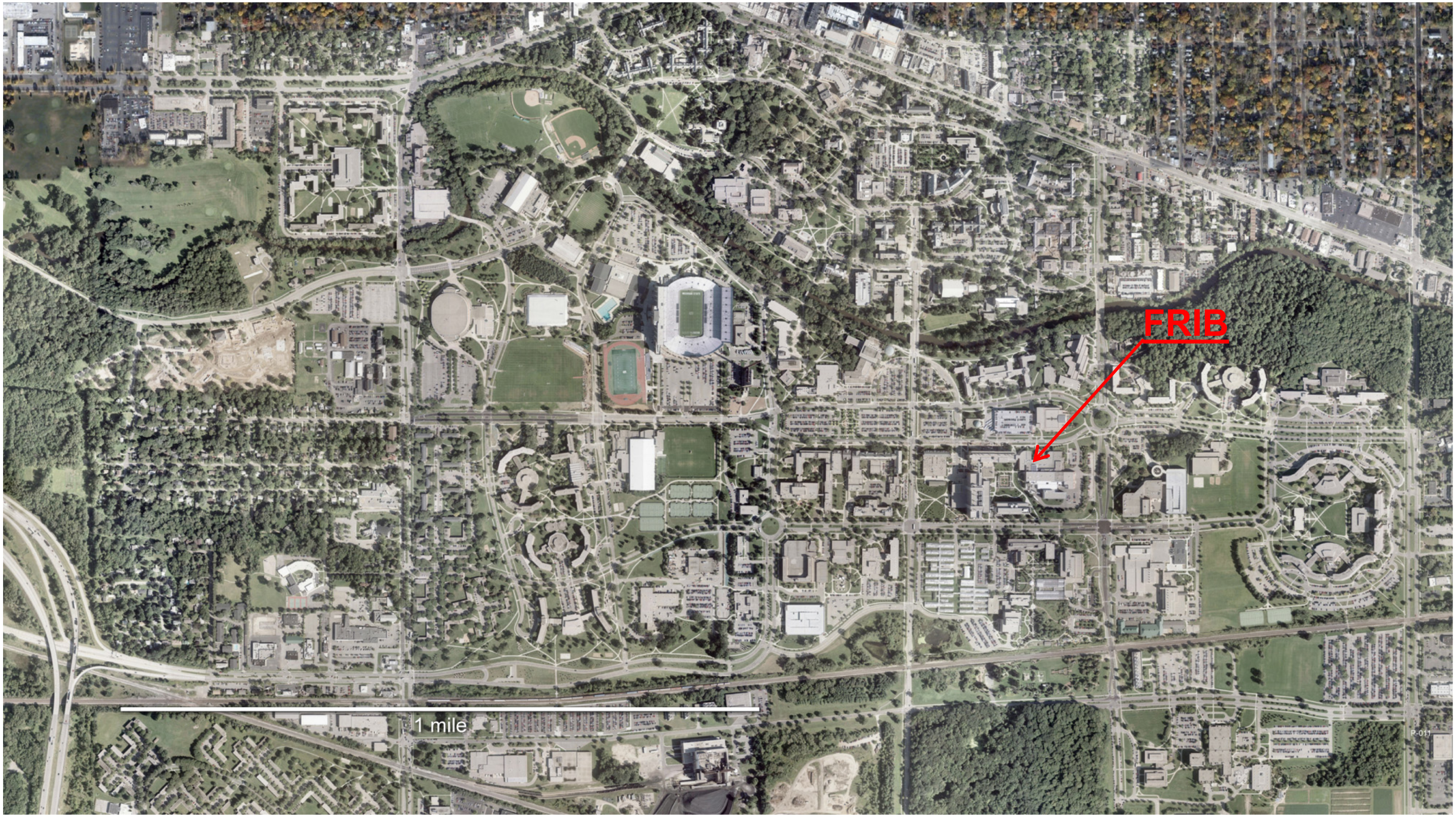
- SNS raised pulsed proton power frontier by one order-of-magnitude
  - Physical challenges: electron cloud mitigation; beam loss control
  - Engineering challenges: 1st full-scale superconducting RF proton linac; high-power target
- FRIB will raise heavy-ion power frontier by two order-of-magnitudes



- Physical challenges
  - Machine protection for high-power, low-energy heavy ions
  - Simultaneous acceleration of multiple charge-state beams
- Engineering challenges
  - Full-scale low-β SRF linac
  - Liquid lithium charge stripper

Michigan State University

57,000 People; 93 km^2 Area; 552 Buildings; US$1.8B Annual Revenue



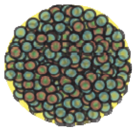
FRIB Project at Michigan State University
Project of $730M ($635.5M DOE, $94.5M MSU)

- 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

Growth from more than 500 employees today at NSCL, MSU

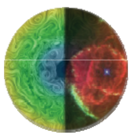
More than 1200 registered user at NSCL user group and at FRIB user organization

The Science of FRIB is Endorsed by NSAC and NRC



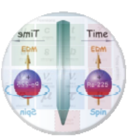
Properties of nuclei

- Develop a predictive model of nuclei and their interactions
- Understand the nuclear force in terms of QCD
- Many-body quantum problem: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.



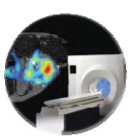
Astrophysical processes

- Chemical history of the universe
- Model explosive environments
- Properties of neutron stars, EOS of asymmetric nuclear matter



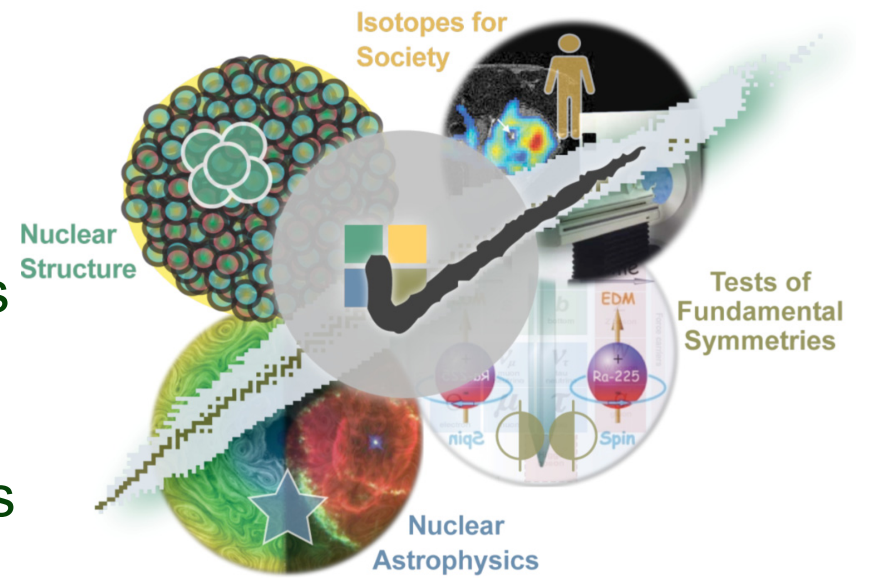
Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei

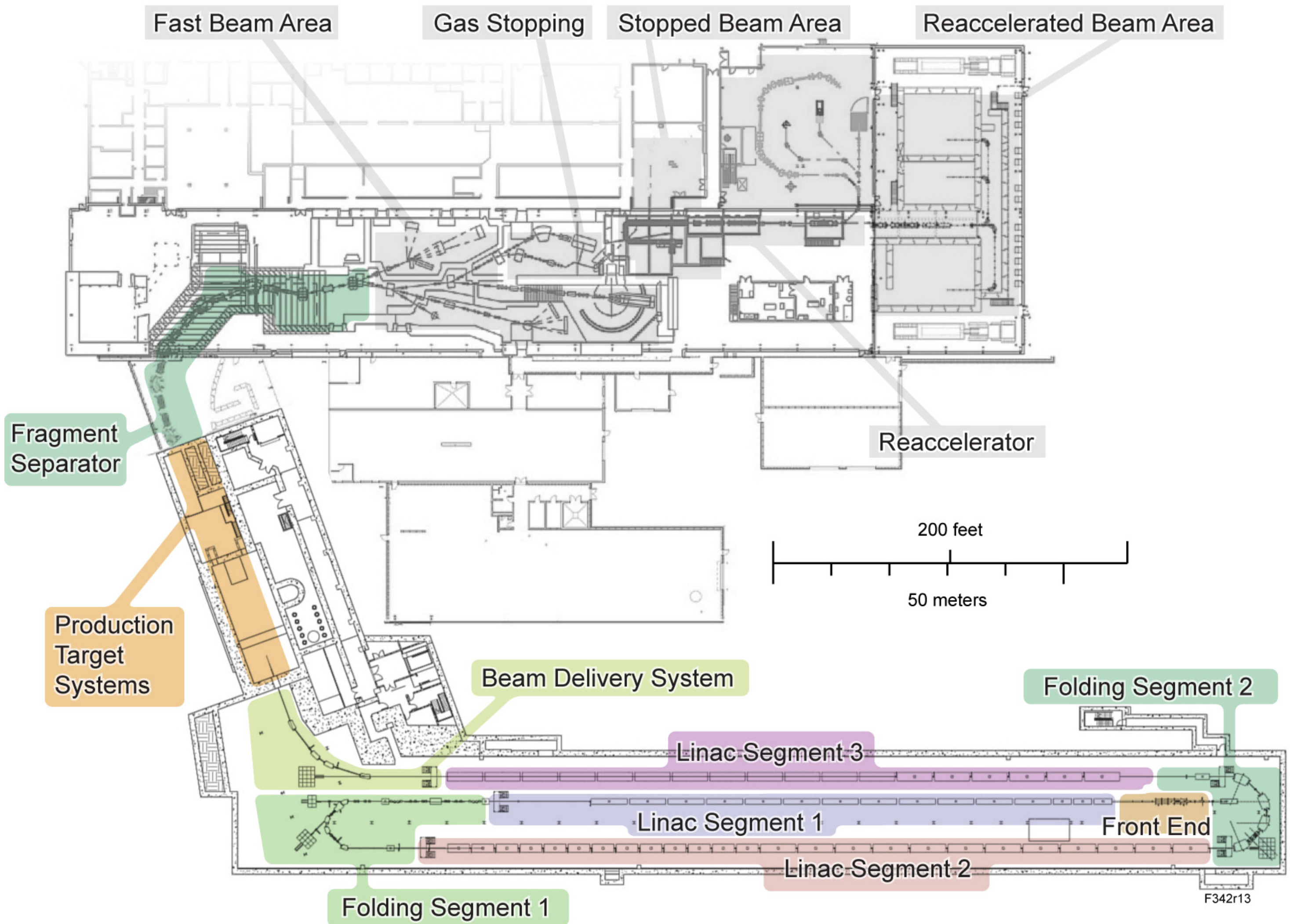


Societal applications and benefits

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

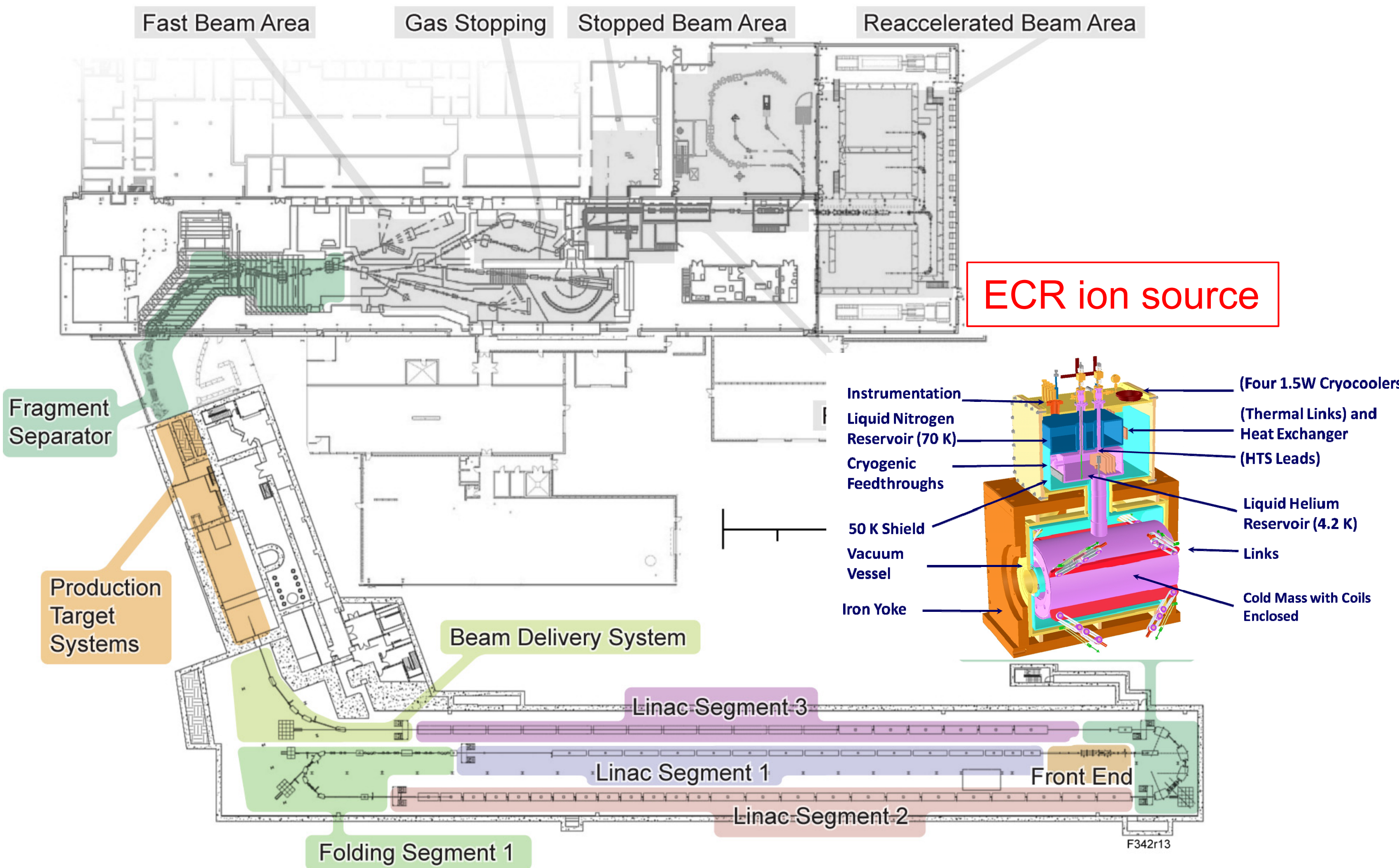


FRIB Accelerator Complex Subsystems



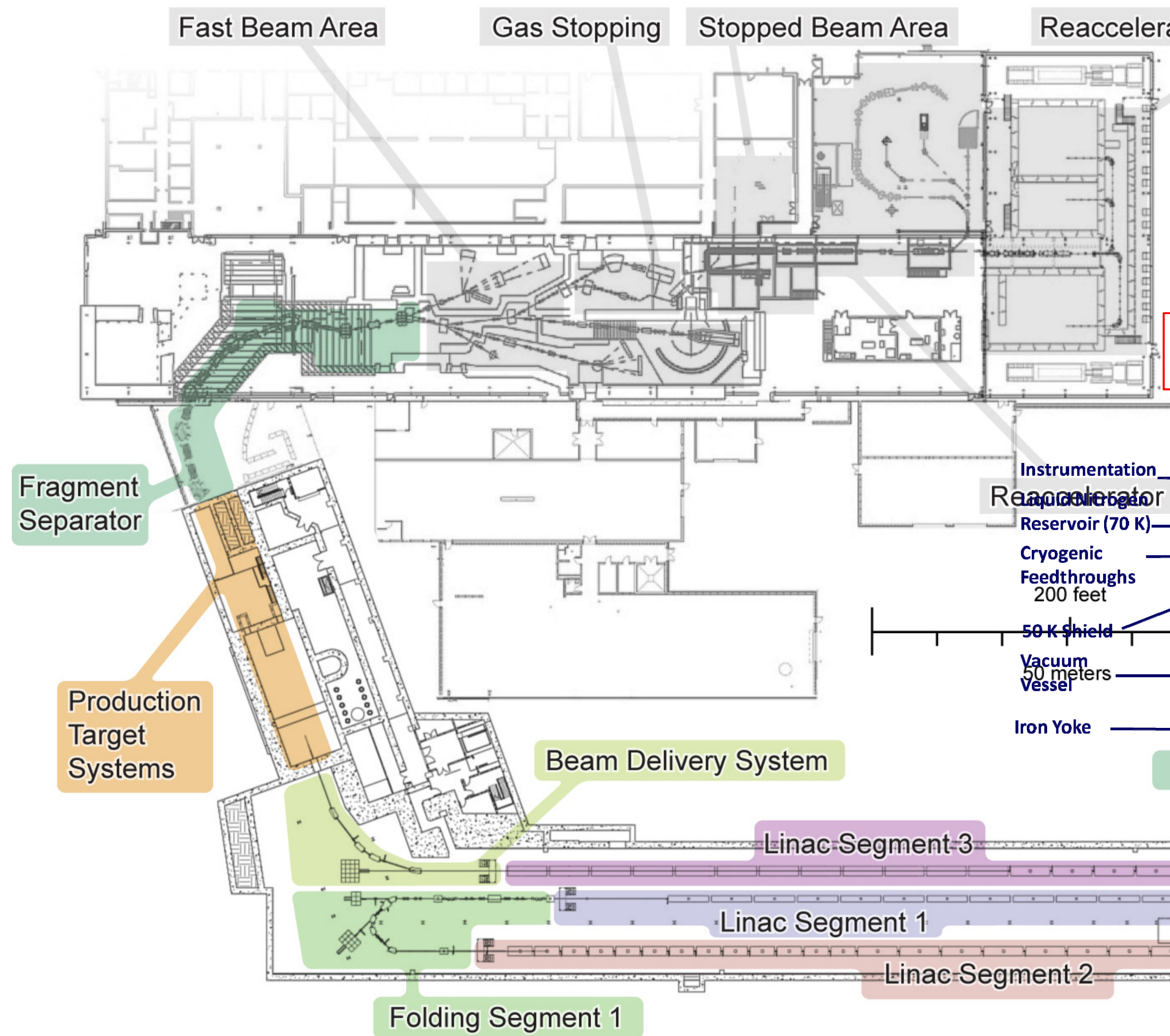
J. Wei, et al., IBIC'17, Slide 11

FRIB Accelerator Complex Subsystems

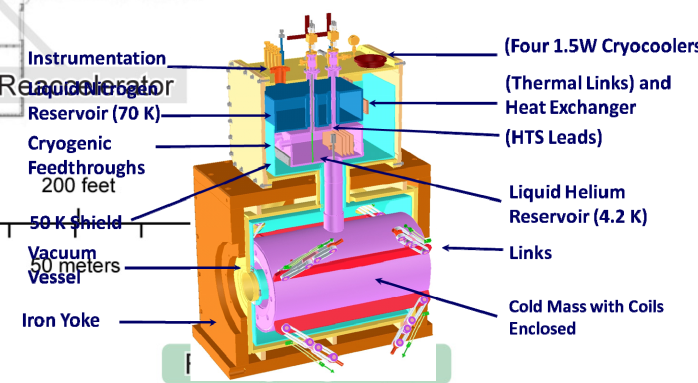


J. Wei, et al., IBIC'17, Slide 12

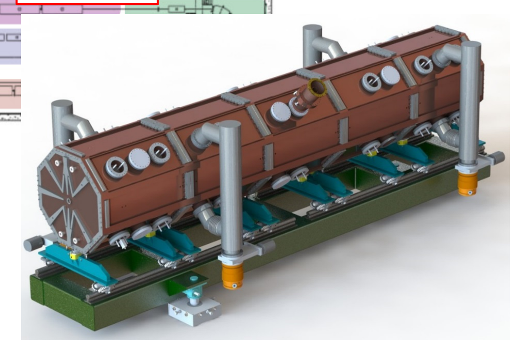
FRIB Accelerator Complex Subsystems



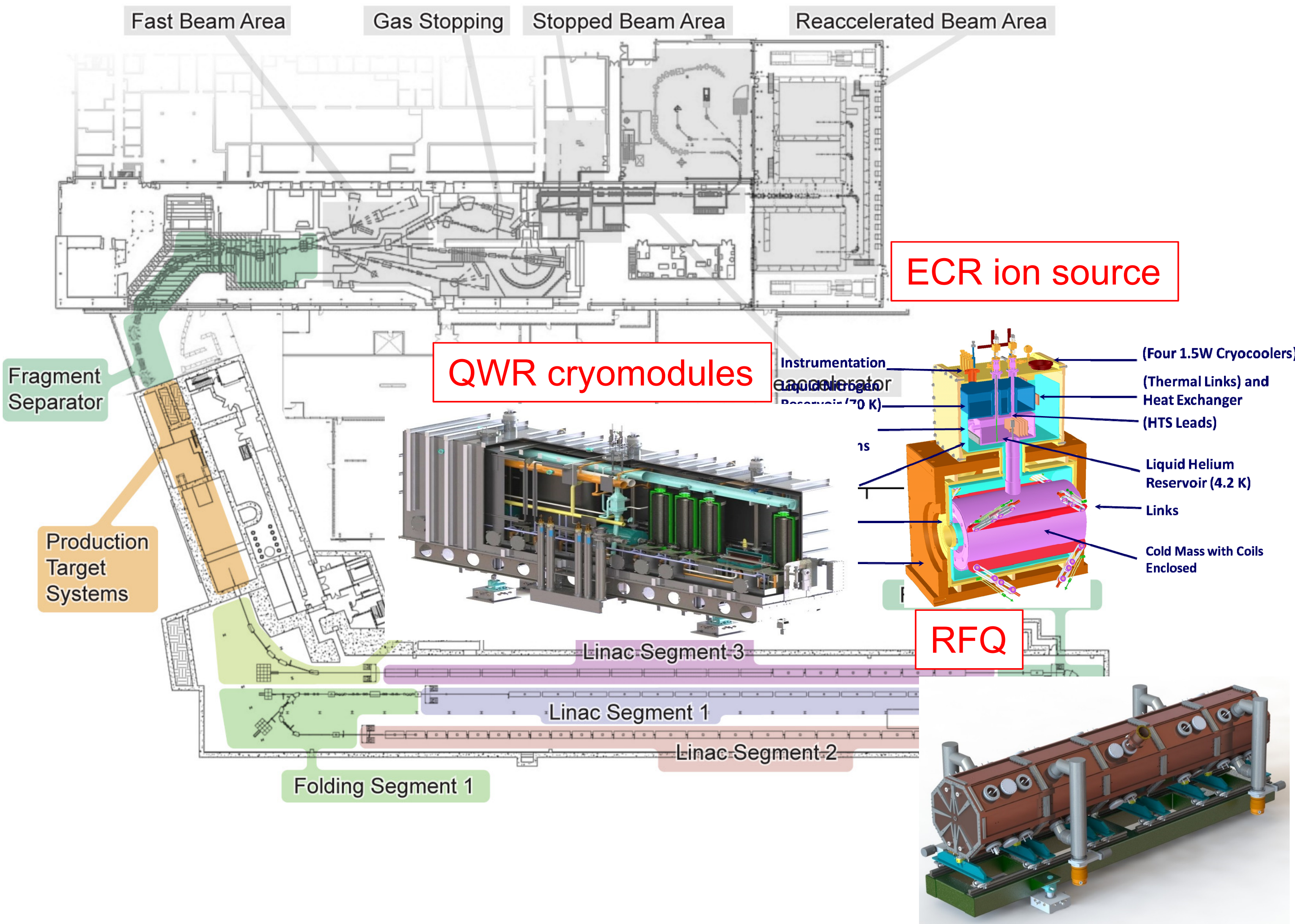
ECR ion source



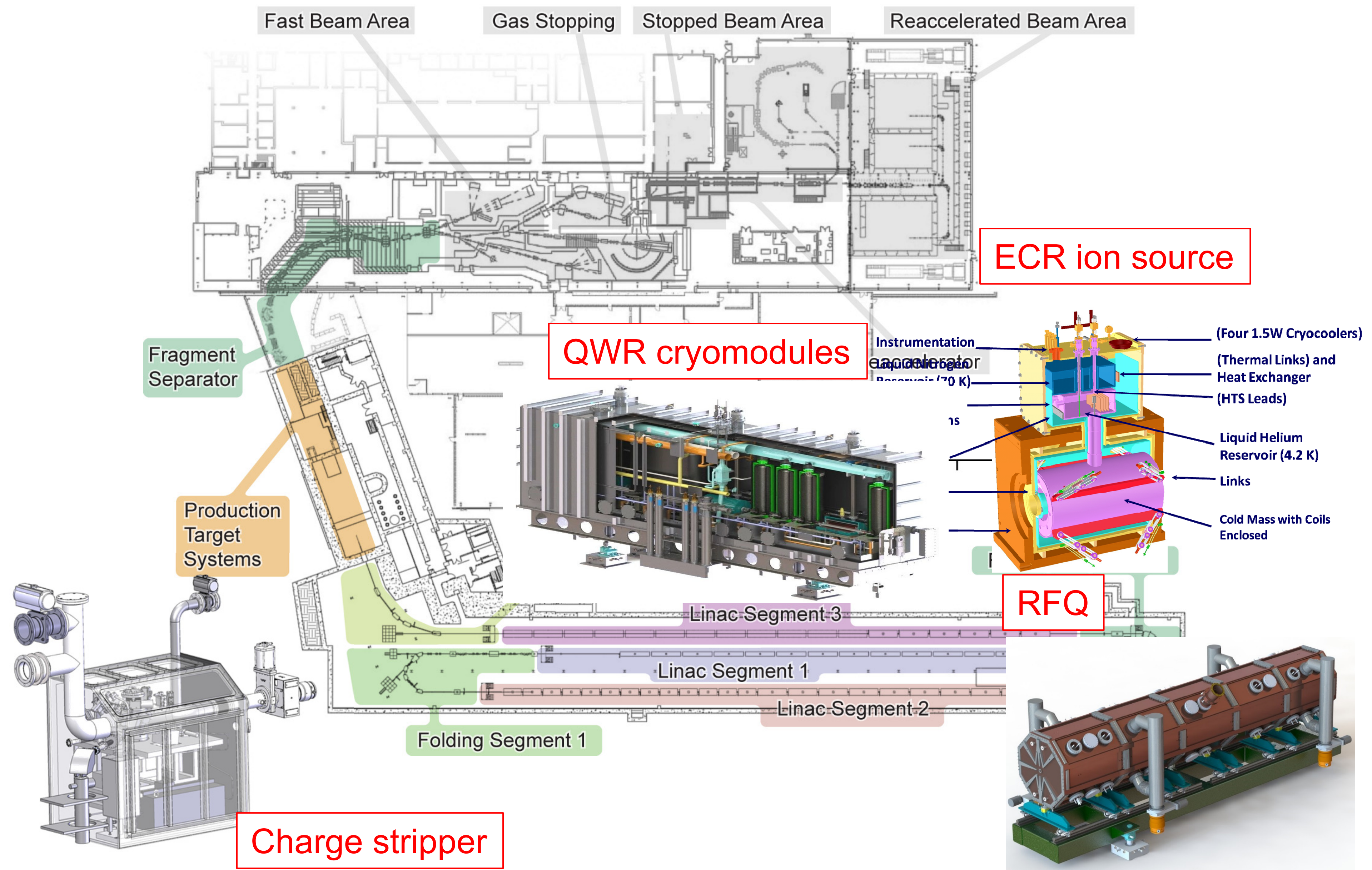
RFQ



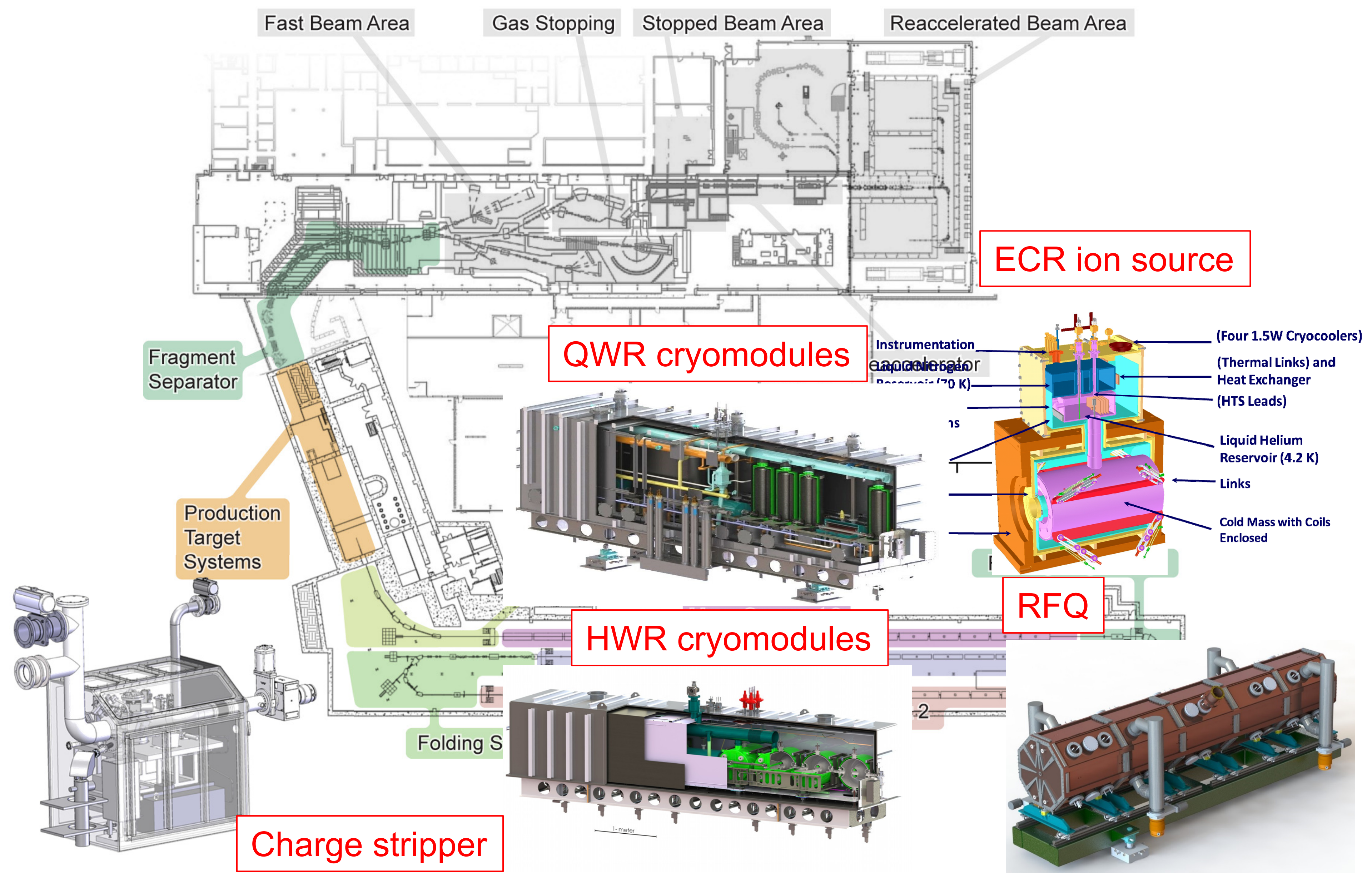
FRIB Accelerator Complex Subsystems



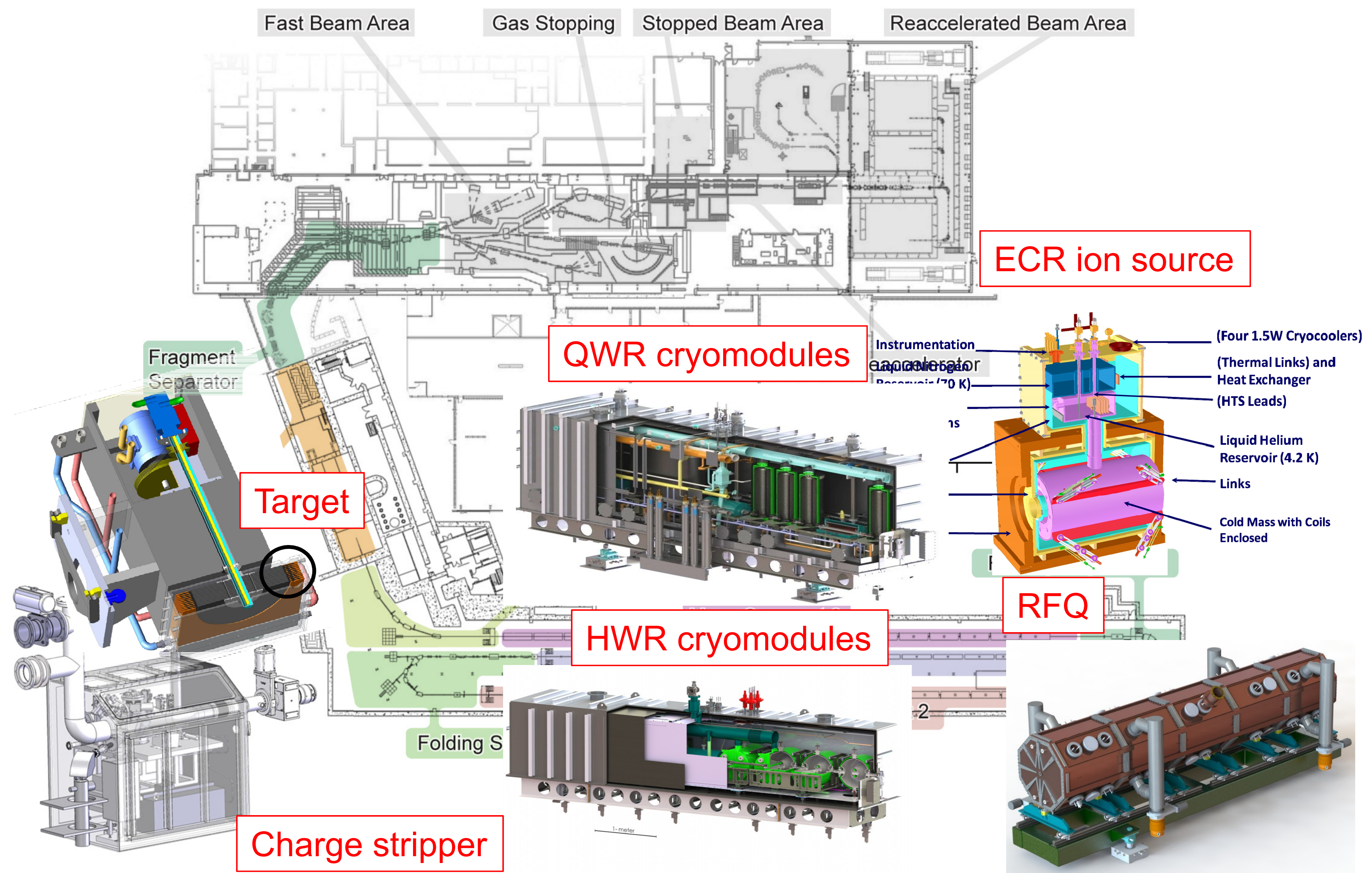
FRIB Accelerator Complex Subsystems



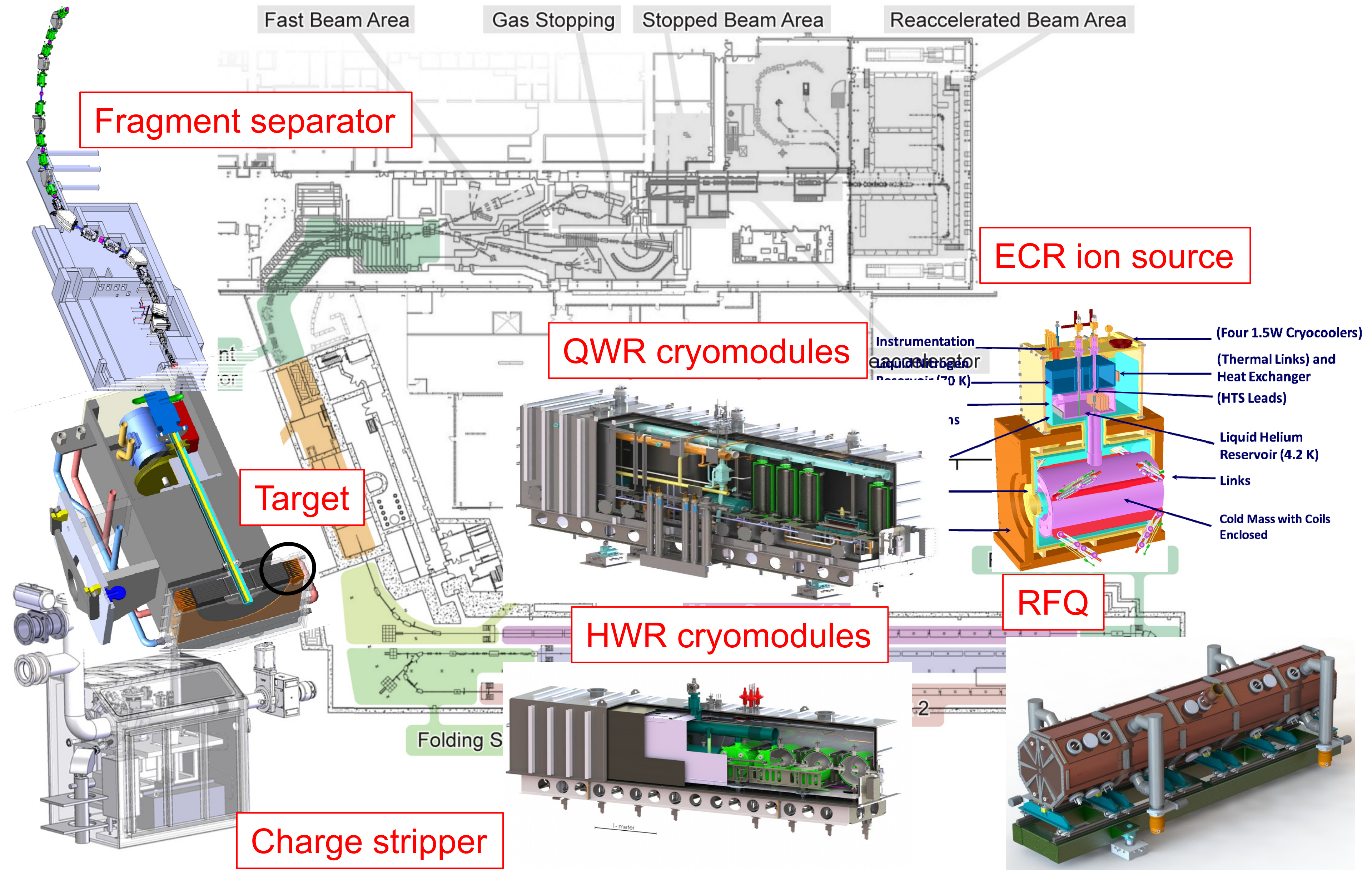
FRIB Accelerator Complex Subsystems



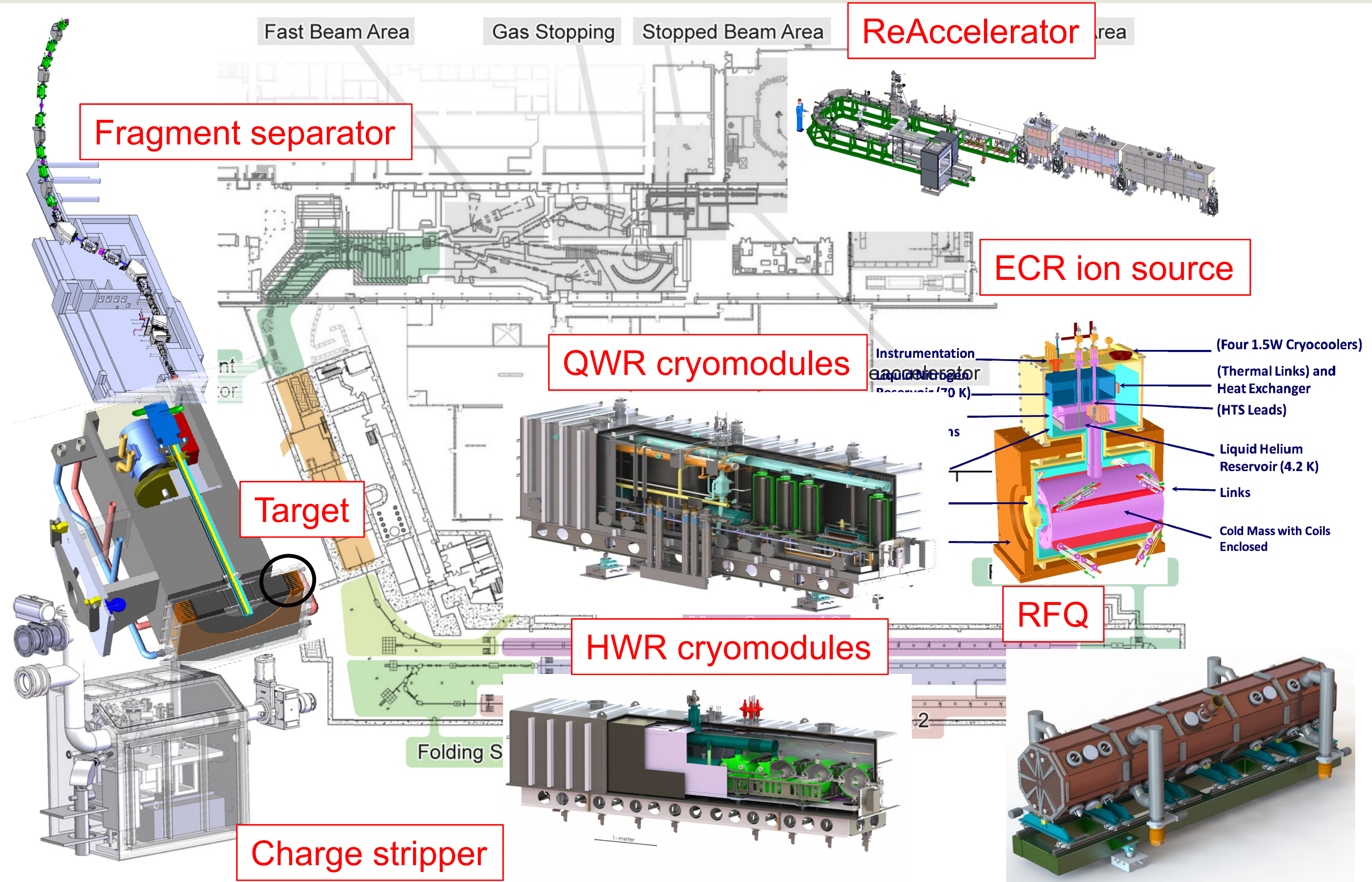
FRIB Accelerator Complex Subsystems



FRIB Accelerator Complex Subsystems



FRIB Accelerator Complex Subsystems



FRIB Civil Construction Site

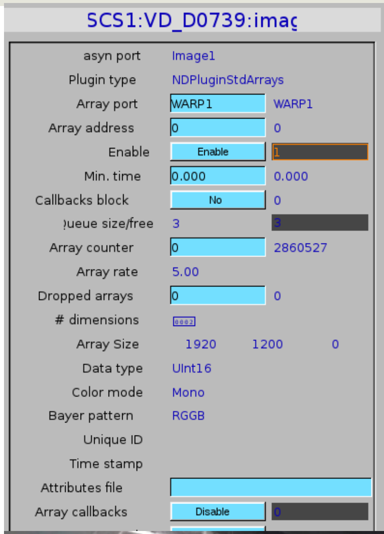
Accelerator Civil Construction Completed

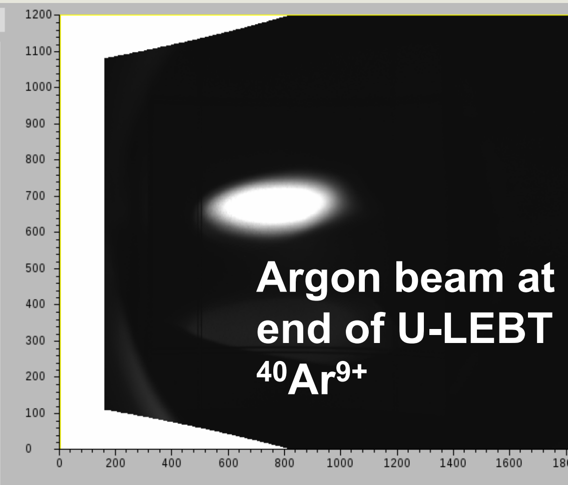
FRIB Accelerator Tunnel Installation Started

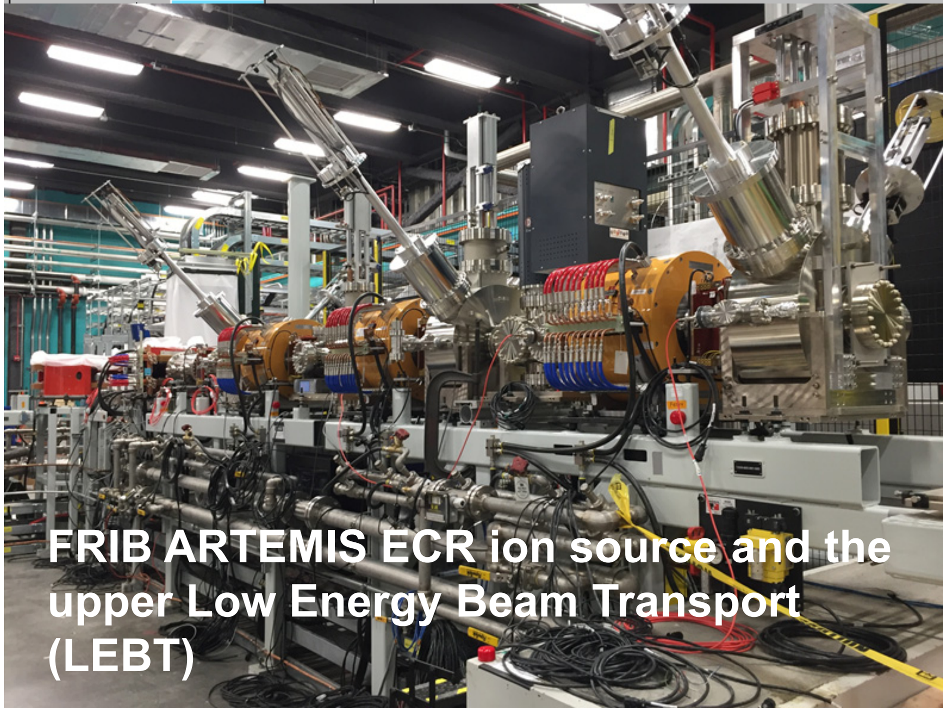
Transported Beam Through U-LEBT at 100% Efficiency
Conducted 1st Accelerator Readiness Review (ARR01)

- Focused efforts
  - Coordination between civil construction and accelerator technical teams
  - Integration of supporting infrastructure
  - Interface of various subsystems
  - Hazard mitigation and passive/active interlock implementation
- Issues and mitigations
  - Continually needed culture changes in configuration management and work control

Objective Measures	Date
Building Beneficial-occupancy-date (BOD)	3/2017
ARTEMIS ion source device readiness review	Done, 9/2016
FRIB first beam from ARTEMIS ion source	Done, 10/2016
FRIB Ar beam threaded to end of upper LEBT	Done, 4/2017







All β=0.041 Cryomodules Installed in Tunnel
Device Readiness Preparation for ARR02 in May 2018

- Focused efforts
  - Constructed and bunker tested all four β=0.041 cryomodules including one spare
  - Installed and aligned all three cryomodules in tunnel to specification (< 1 mm)
    - » Extended efforts between Accelerator Physics and Mechanical Engineering teams
  - Developed cable routing and termination procedures for electrical installation
- Issues and mitigations
  - Learned lesson in transporting cryomodule enforcing stay-clear zone and using mock-up to verify clearances

Objective Measures	Date
Production QWR for β=0.041 coldmass #1 certified	Done, 5/2016
Production β=0.041 cryomodule #1 tested	Done, 10/2016
All β=0.041 cryomodules installed in tunnel	Done, 4/2017
Spare β=0.041 cryomodule built and tested	Done, 4/2017
Cryoplant tested for operations	3/2018
Cryogenic distribution for LS2 tested	3/2018
Device Readiness Review DRR02	4/2018
Accelerator Readiness Review ARR02	5/2018


The three β=0.041 cryomodules under installation in the FRIB tunnel

- Major Technology Development

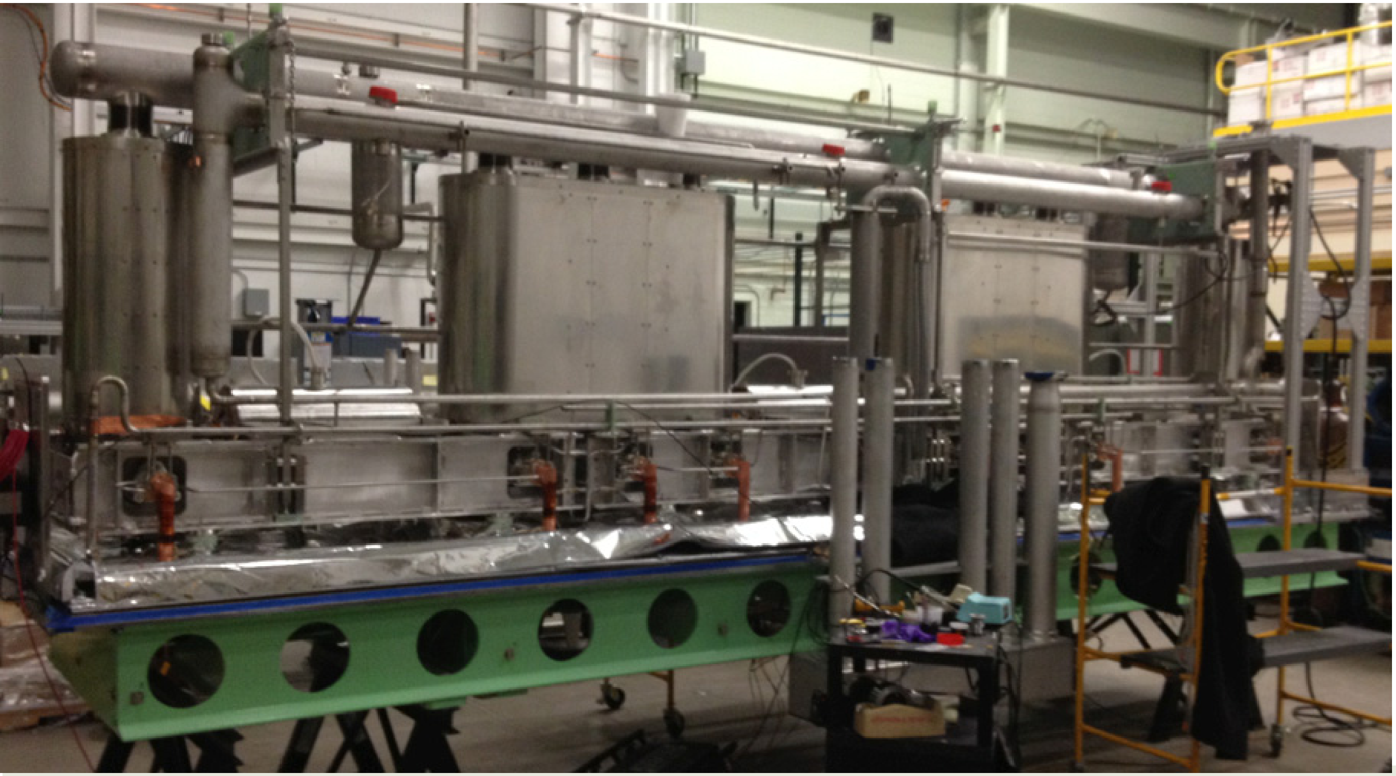
Integrated Cryogenics

- Cost significant: cryogenics systems accounts for ~ 20% linac cost
- 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

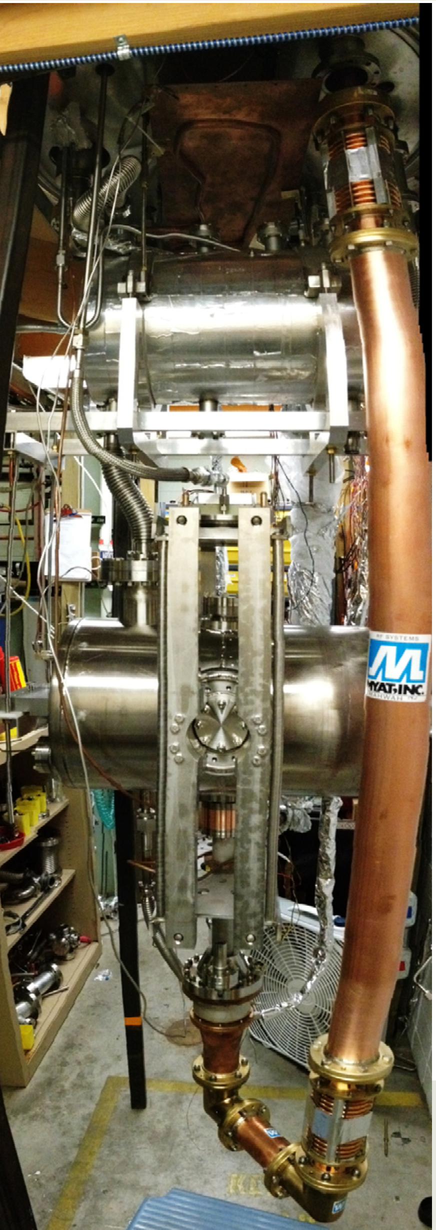
Bottom Up Cryomodule

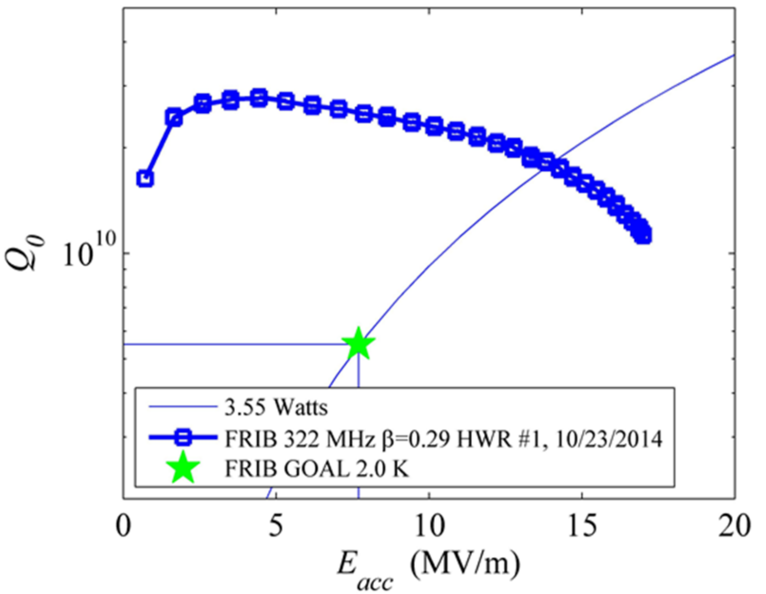
- Facilitate assembly efficiency; simplify alignment; and allow U-tube cryogenic connections for maintainability
  - Resonators and solenoids supported from the bottom
  - Cryogenic headers are suspended from the top for vibration isolation

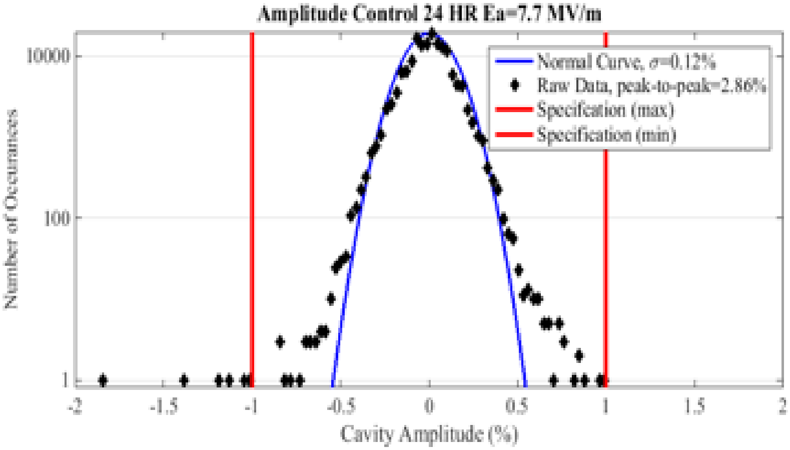


- All resonators operate at 2 K
- All solenoids operate at 4.5 K
- Local magnetic shielding for 1.5 μT remnant field

Low-β Superconducting RF





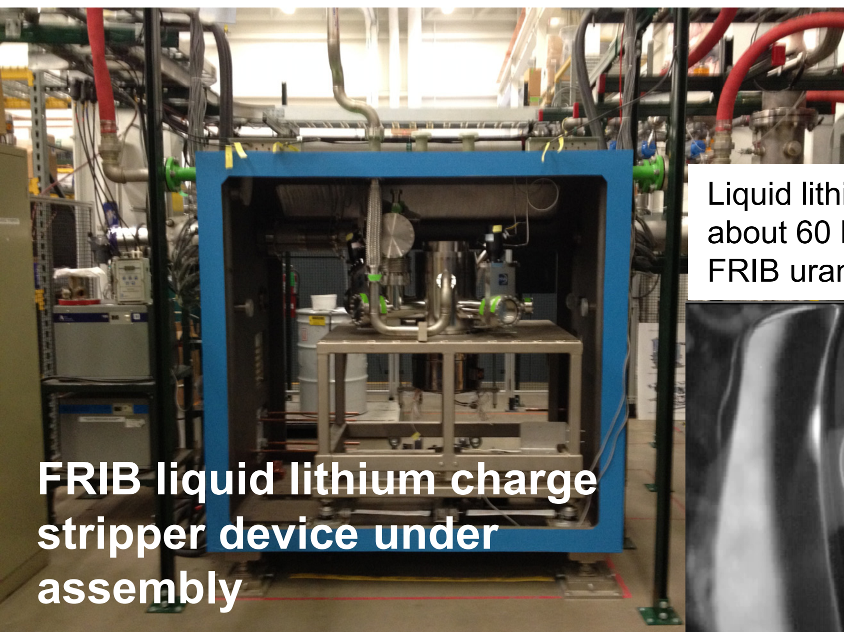


- Superconducting RF starting from 0.5 MeV/u
- Optimum performance at low production cost
  - cavity geometries
  - material
  - mechanical solutions
- Designs validated
  - Vertical dewar tests
  - Integrated tests of the cavity, power coupler, tuner, and ancillary systems
  - Assembled cryomodule testing in the bunker

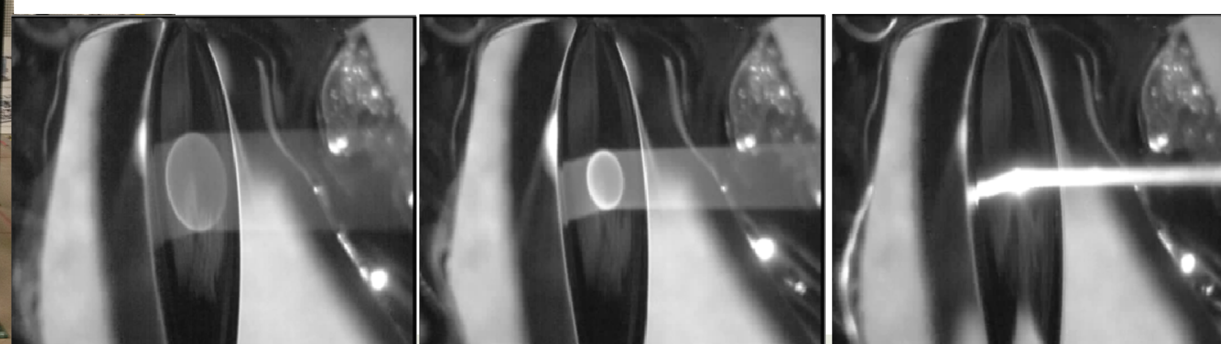
Liquid Lithium Charge Stripper
Electrostatic Pump for Lithium Circulation Tested Recently

- Liquid lithium film established with controllable thickness and uniformity
- LEDA Ion Source (IS) beam commissioned at MSU
  - Beam commissioned at MSU after restoring with new cooling and power supply system after more than 10 years of storage
- Beam power tests on liquid lithium film successfully performed at ANL
  - The film sustained ~200% of FRIB maximum power density deposition

Los Alamos NATIONAL LABORATORY EST. 1943 Argonne NATIONAL LABORATORY


FRIB liquid lithium charge stripper device under assembly

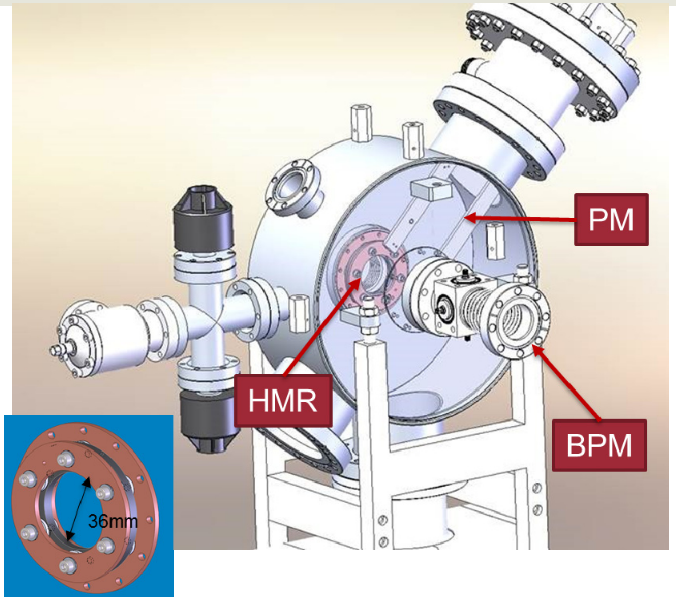
Liquid lithium film flowing at high speed (~ 50 m/s) intercepting a proton beam of about 60 kV at ANL. The test produced power deposition densities similar to the FRIB uranium beams.

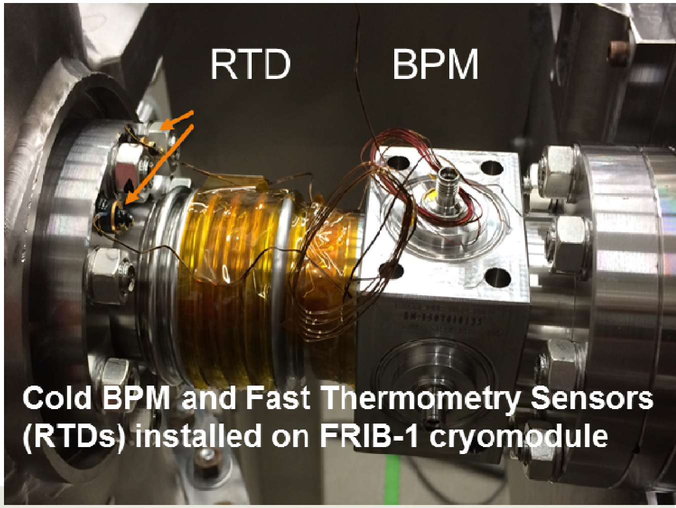


Machine Protection

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
- Machine Protection Systems relies operationally on novel designs
  - 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

- Beam instrumentation challenges

Beam Instrumentation Challenge Examples

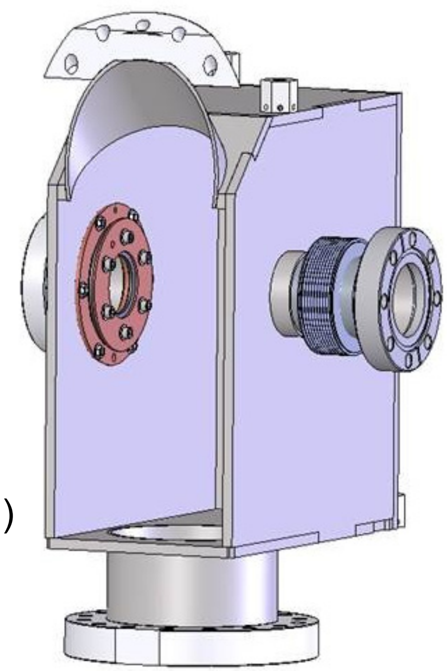
- Machine protection challenge due to intense heavy-ion beams with
  - Low detection sensitivity on low-energy heavy ions
  - Short range, high power concentration
- Prevention of slow degradation of superconducting RF cavities under "slow" beam loss conditions
- Beam diagnostics with simultaneous acceleration of
  - Multi-charge-state beams (e.g. $^{238}U^{76+}$, $^{238}U^{77+}$, $^{238}U^{78+}$, $^{238}U^{79+}$, $^{238}U^{80+}$,)
  - Both heavy and light ions (e.g. $^{238}U^{79+}$, H_3^+)
- Charge selection/scraping of high-power waste beams
  - Up to 40 kW scraped beam requiring rotating-target beam selector
- Beam position monitoring on high-power target and feedback on accelerator
- Folded accelerator geometry causing radiation cross-talk issue from high energy linac sections that confound low energy beam loss measurements
- Wide dynamics range on both primary & secondary beams; both cw & pulsed
- Frequent change of user (every 1 – 2 weeks) demanding different ion beams
- Availability requirement demanding fast beam tuning with SRF cavities

Loss Detection and Machine Protection
Multi-time Scale Mitigation Necessary

- Low-energy ions has low detection sensitivity & high impact
- Must mitigate both acute & chronic beam loss (by beam inhibition)

Mode	Time	Detection	Mitigation
FPS	~35 µs	LLRF controller Dipole current monitor Differential BCM Ion chamber monitor Halo monitor ring Fast neutron detector Differential BPM	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

- Halo monitor ring developed
- Differential BCM used
- Thermo-sensors designed



Z. Liu et al, Nucl. Instrum. Meth. A767, 262 (2014)

Fast Protection System Time Budget

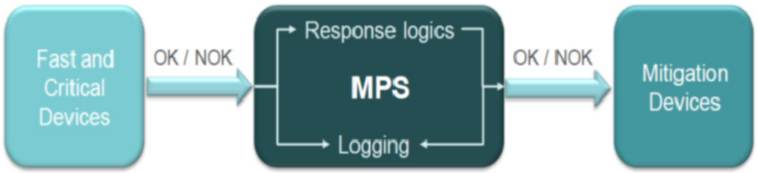
10 μs
Sensing and indicating error condition to FPS (include cable delay)

10μs
FPS Response Time
From Input OK/NON to output to mitigation device

5 μs
Mitigation Action (include cable delay)

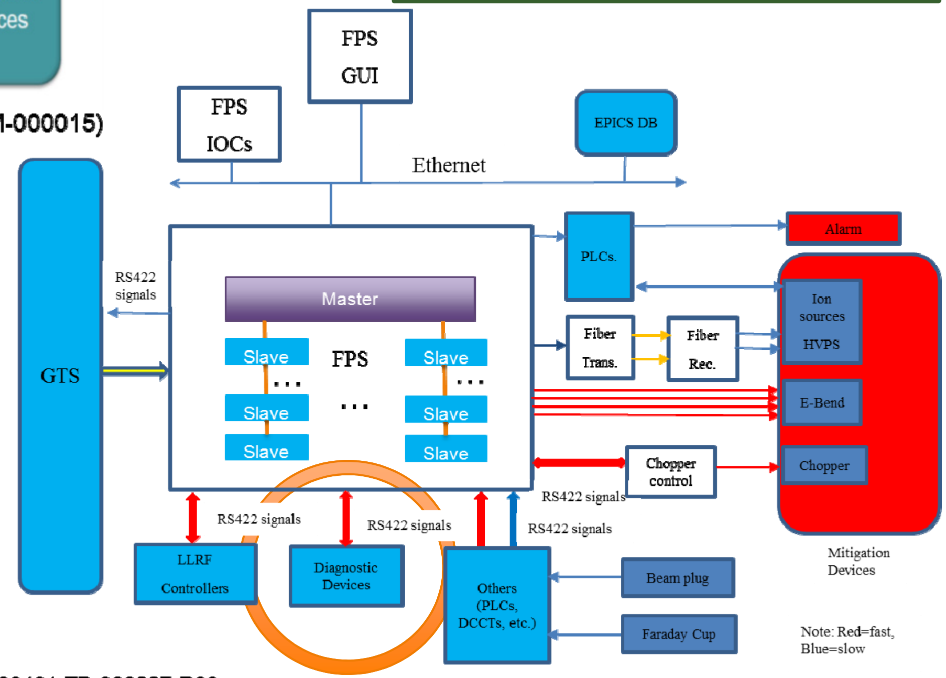
10 μs
Beam mitigation time

Time budget includes sensing, signal trans-mission, logic, and mitigation



Systems Requirement Document for Machine Protection Systems (T30400-CM-000015)

- Diagnostics interface to MPS is implemented at the board and chassis level
- Thresholds are compared at various sensitivity/time-averaged stages
- Special purpose FMC cards are used with FGPDBs to send & receive to MPS network



T30401-TD-000227-R005
Machine Protection System Architecture and Interfaces

MPS Architecture Diagram

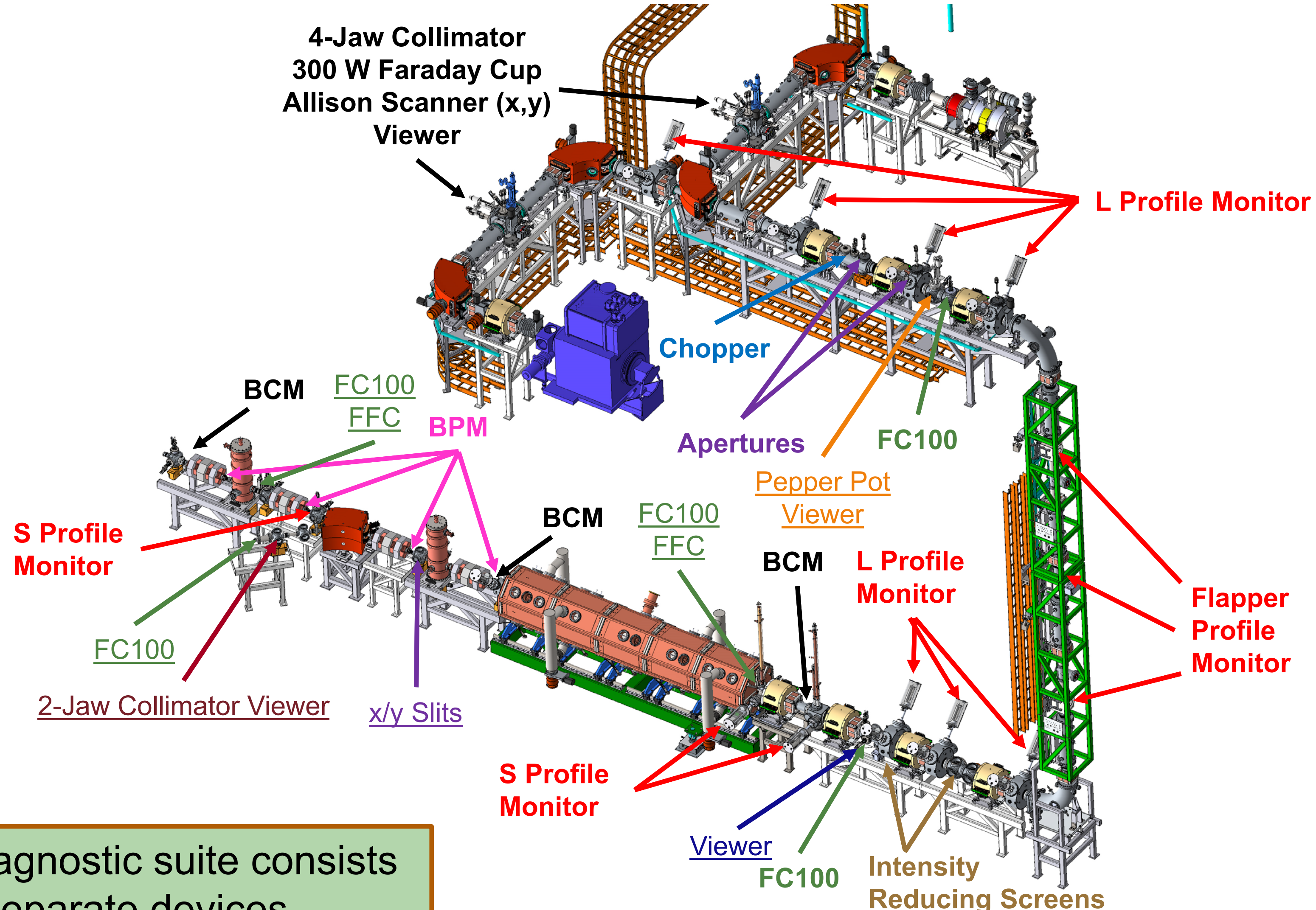
Scope of Driver Linac Diagnostics

Accelerator Systems - Diagnostics	TOTAL	FE	LS1	FS1	LS2	FS2	LS3	BDS
Beam Position Monitor	**150**	4	39 + 20	18	24	12	20	13
Beam Current Monitor (ACCT)	**12**	3		5		2		2
Beam Loss Monitor – Halo Monitor Ring	**17**		17	8	24	4	13	
Beam Loss Monitor - Ion Chamber	**47**			8		12	15	12
Beam Loss Monitor - Neutron Detector	**24**	1	9	1	12		1	
Beam Loss Monitor – Fast Thermometry System	**240**		192		48			
Profile Monitor (Lg., Sm. Flapper)	**42**	7L/4S/3F	2S	4L/7S		2L/2S	4S	2L/5S
Bunch Shape Monitor	**1**			1				
Allison Emittance Scanner (2 axis)	**2**	2						
Pepper pot emittance meter	**1**	1						
Faraday Cup	**7**	7						
Fast Faraday Cup	**2**	2						
Viewer Plate	**5**	5						
Selecting Slits System - 300 W	**5**	5 axes						
Collimating Apertures - 100 W	**2**	2						
Intensity Reducing Screen System	**2**	2						

559 total diagnostic devices

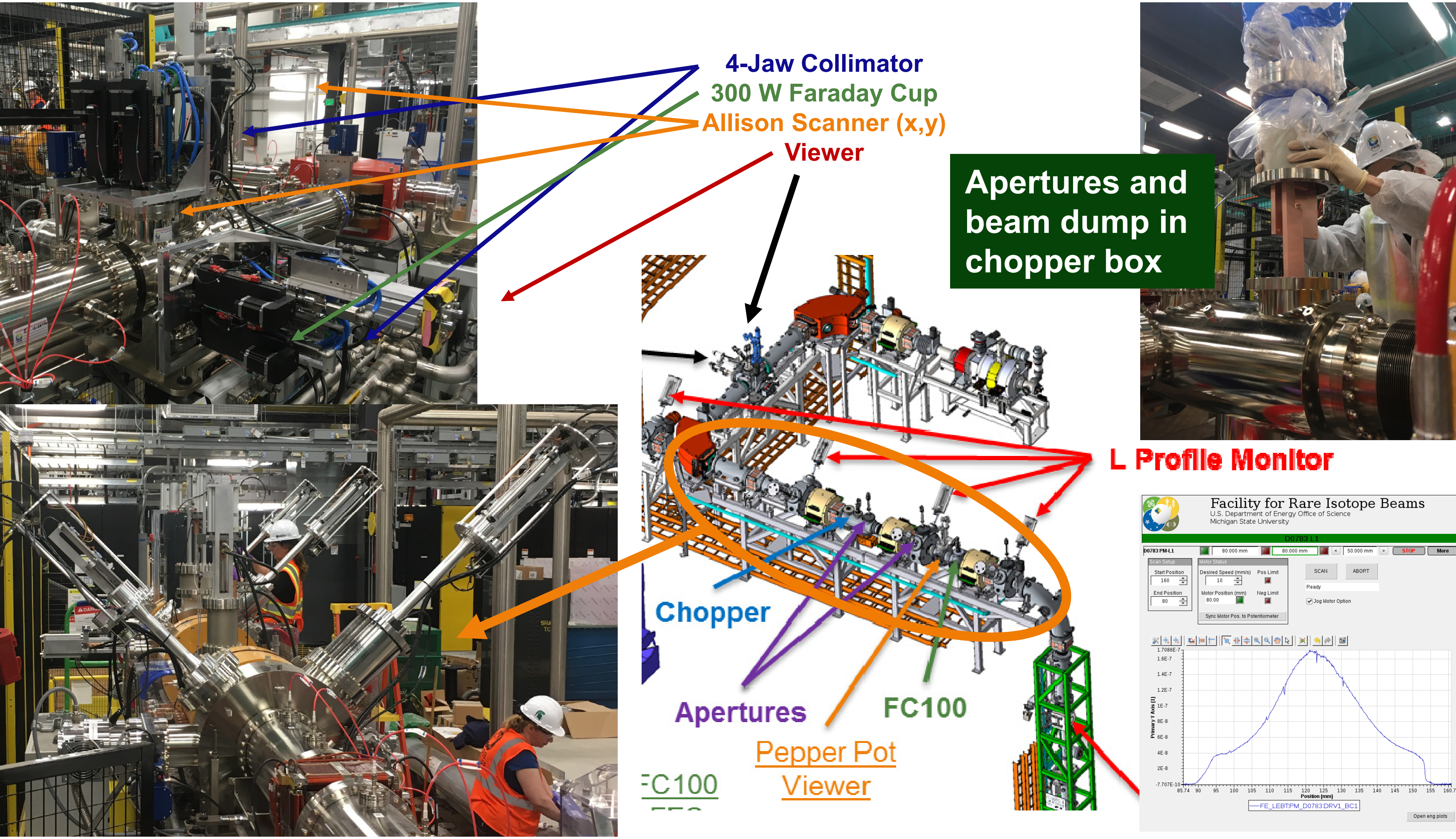
Front End Diagnostics Scope

FRIB LEBT Is About 40 m Long



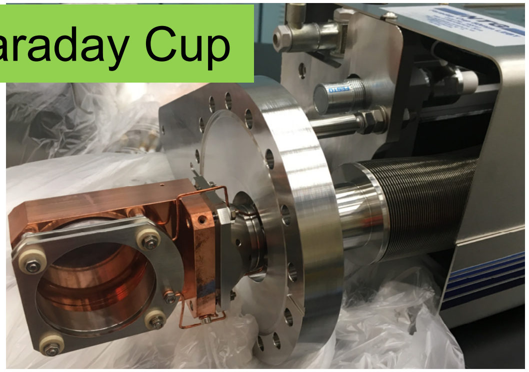
Front End diagnostic suite consists of 48 separate devices
24 devices are highest priority and required for commissioning

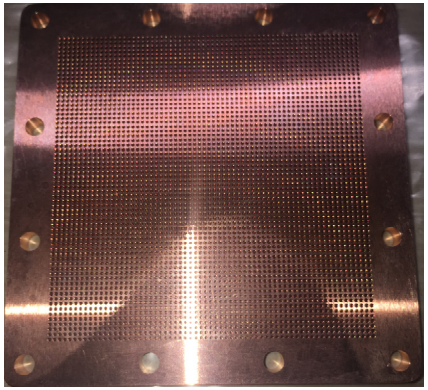
Upper LEBT Devices Installed

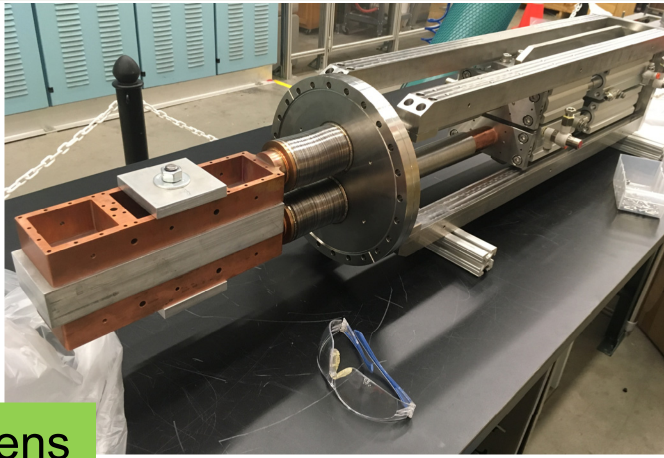


Lower LEBT and MEBT Diagnostics Installation in Progress

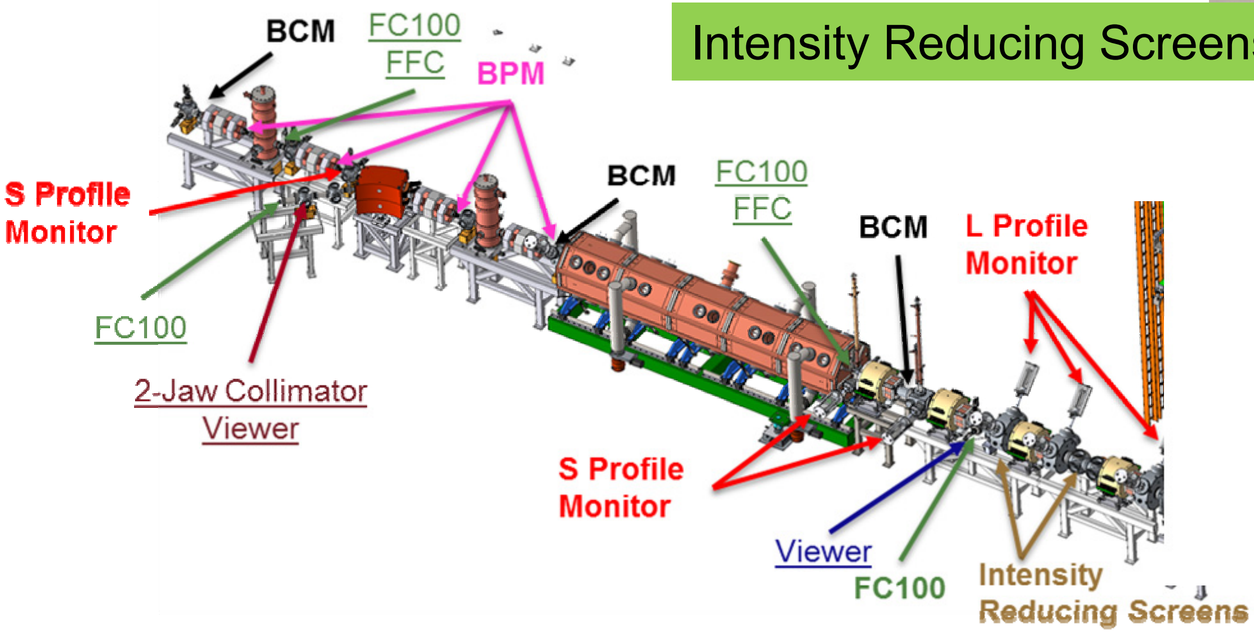
Faraday Cup







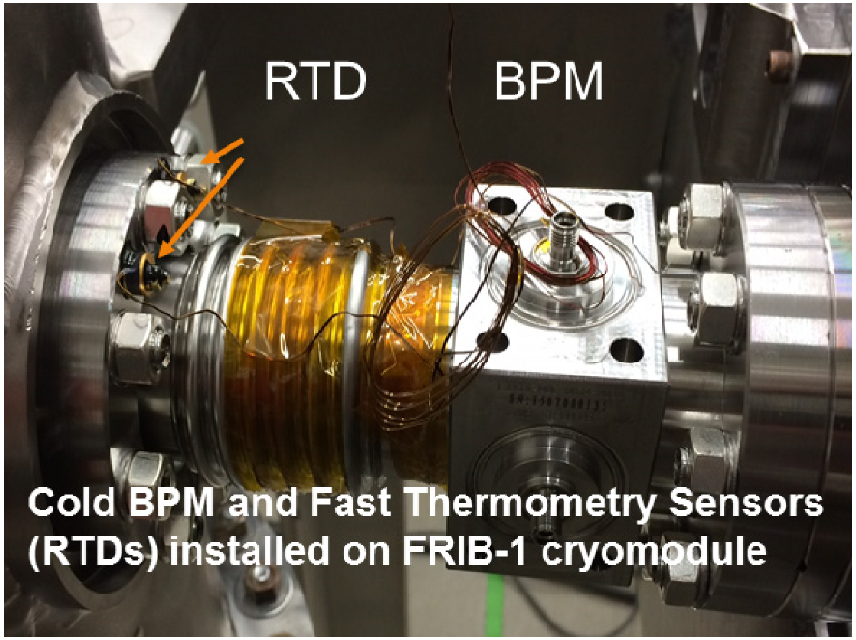
Intensity Reducing Screens



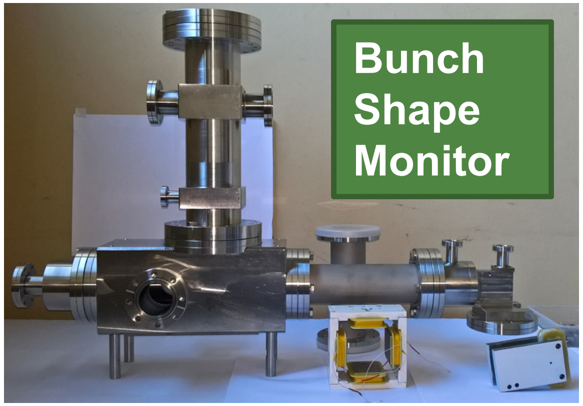
Profile Monitors

Linac Devices in Production and Ready to Install

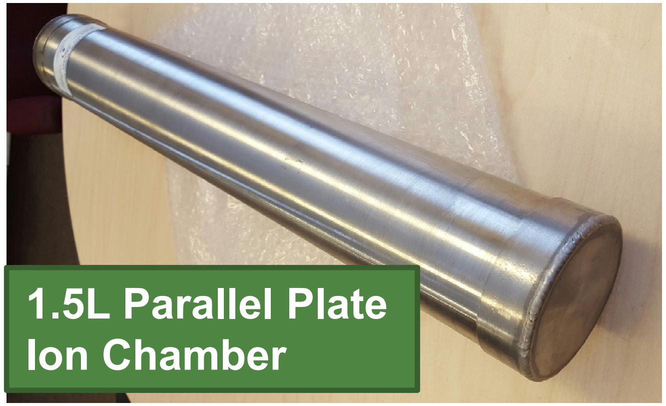
- Installation is progressing in Linac Segment 1 cryomodules
- Warm vacuum devices on hand or in production for installation
  - Halo monitor rings
  - Profile monitors
- Secondary radiation monitors ready for installation



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



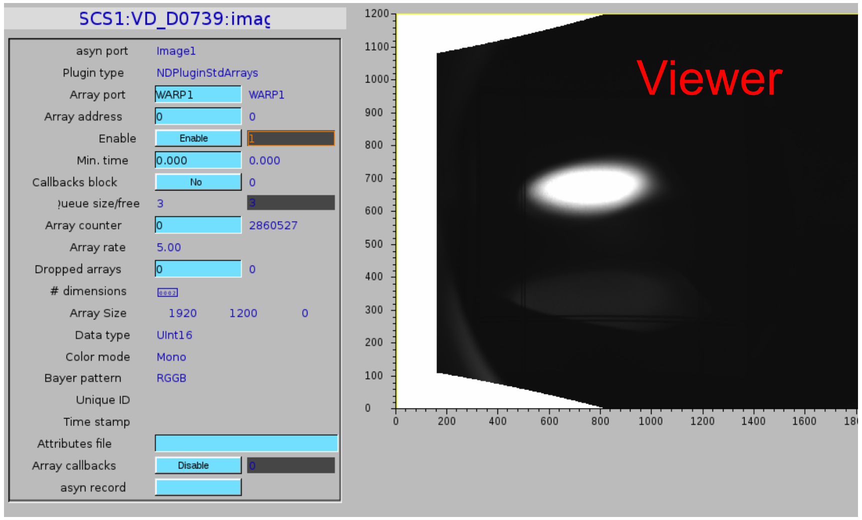
Bunch Shape Monitor



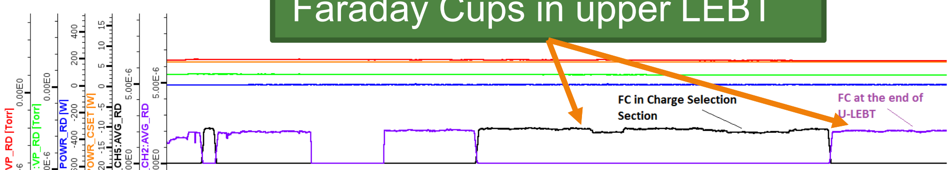
1.5L Parallel Plate Ion Chamber

Scintillator-based Neutron Detector

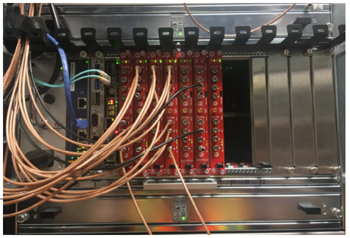
Diagnostics In Place to Support LEBT Tuning



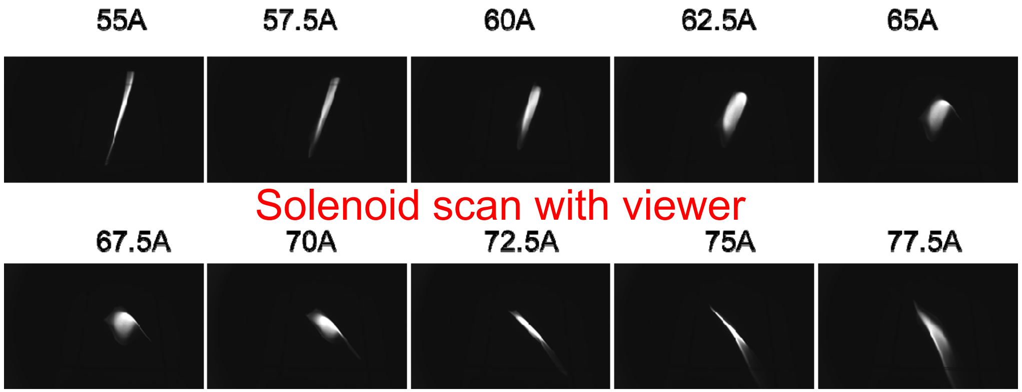
Faraday Cups in upper LEBT

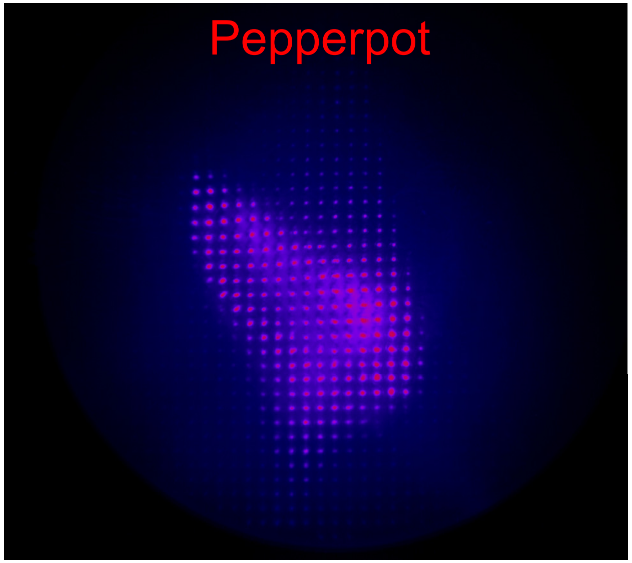


- Faraday Cup collector signal read back into MTCA picoammeter boards.
- Local EPICS IOC in MTCA chassis.



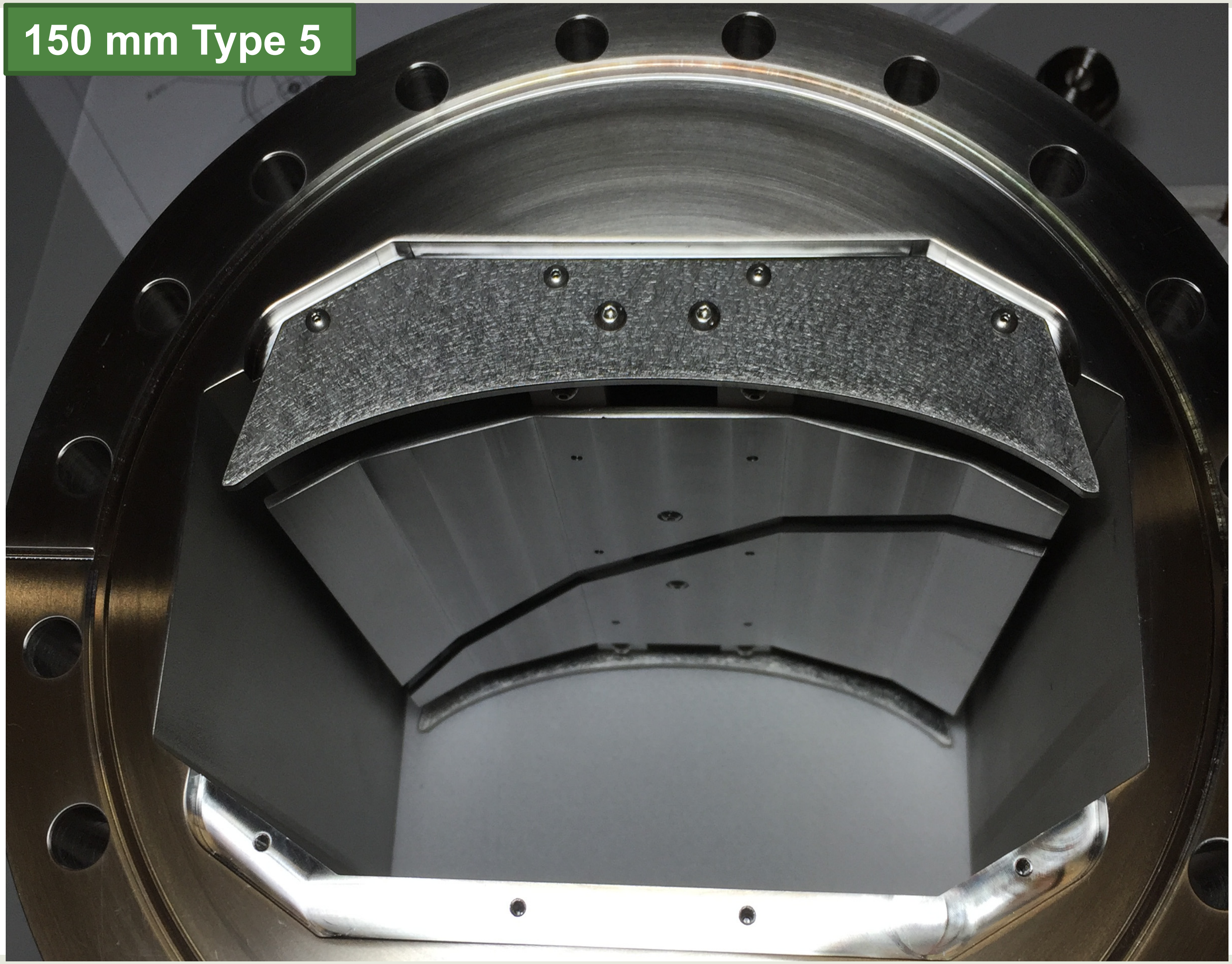
Ethernet cameras supply images via EPICS *AreaDetector.* Image data processed and stored locally.





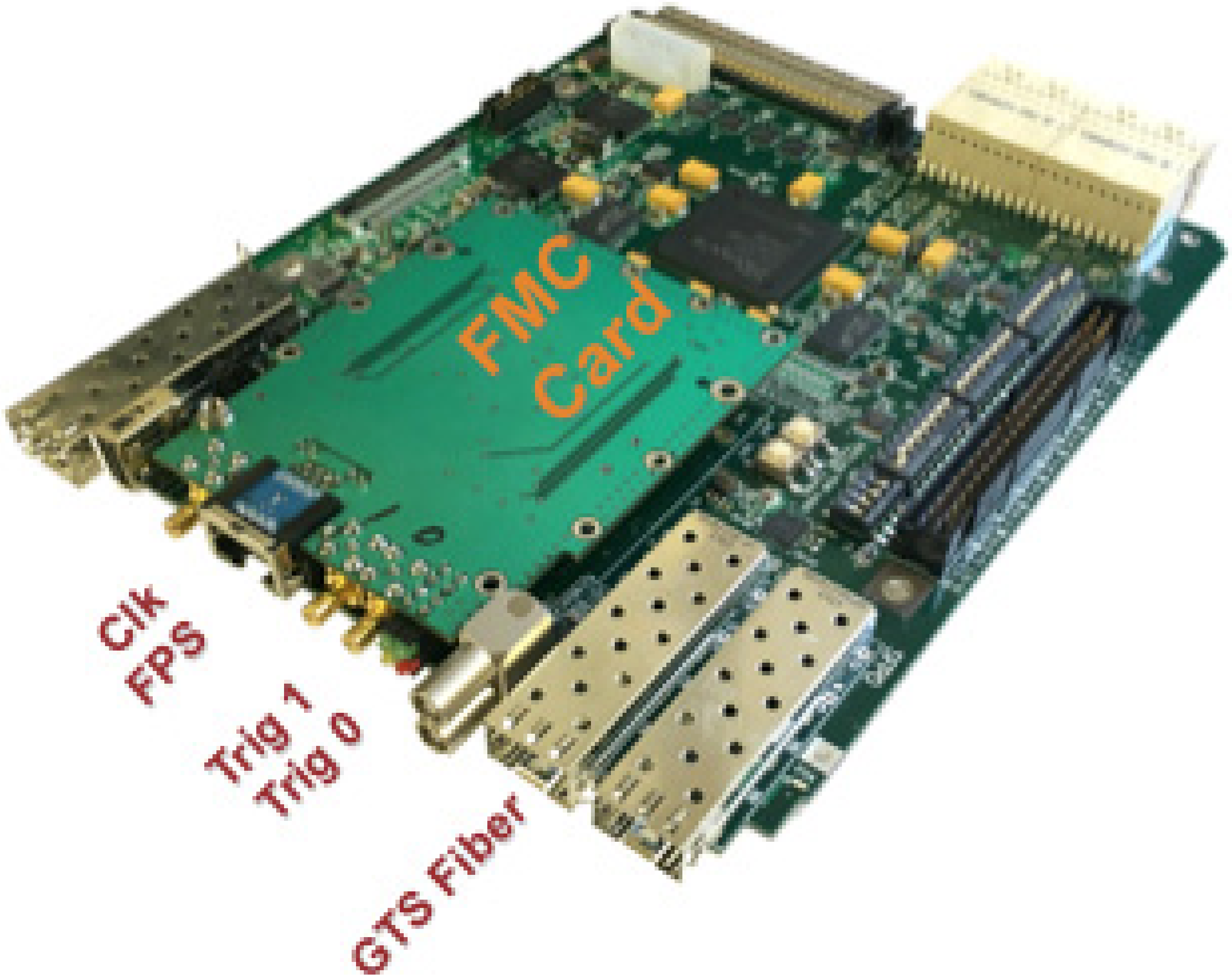
Elliptical Beam Position Monitor
Multi-charge-state Beam in Folding Segment Dispersive Sections

150 mm Type 5



FRIB General-purpose Digital Board (FGPDB)

Shared by Machine Protection Controls, Diagnostics, Low-level RF



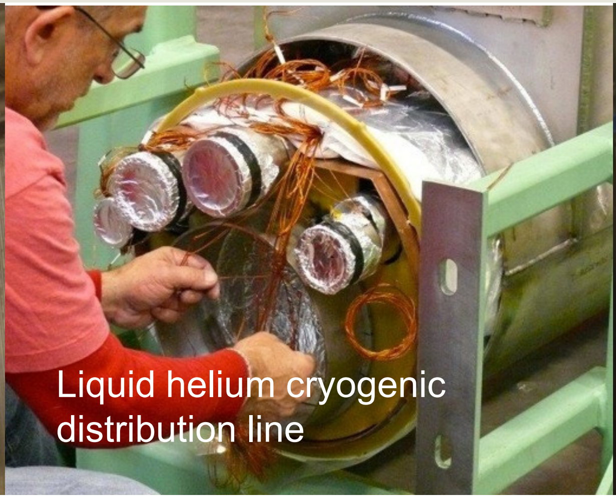
- Accelerator project status

FRIB Accelerator Construction Status

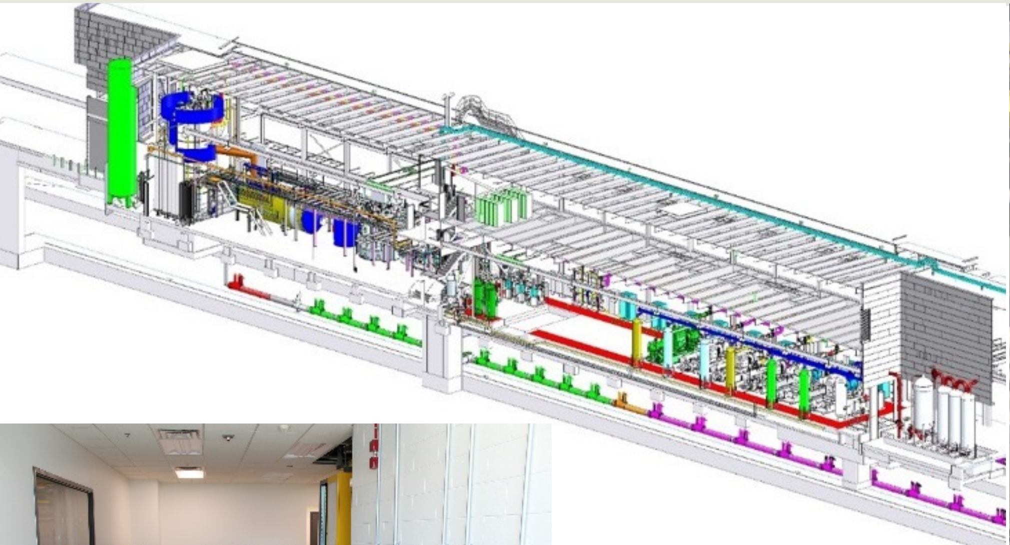
- Technical construction officially started in 2014 (CD-3b)
  - 35% for in-house labor: critical processing and assembly; one-of-a-kind
  - 65% for material, work-for-others efforts at partner laboratories, and procurements from industries
- Major accelerator long-lead procurements prepared prior to CD-2/3a
  - 4.5 K cryogenic refrigeration “cold box”
  - Cryogenic distribution
  - Niobium material for SRF cavities
  - Pre-production of the SRF cavities
  - Radio frequency quadrupole linac (RFQ)
  - Electron Cyclotron Resonance ion source (ECR)
- Currently, 94% of major procurements (>US$50k) are spent or committed

Long-lead Procurements Started in 2012

About 15% of Total Procurements Proceeded Before CD-3b



Cryoplant On Track to Operate in 2018



80.5 MHz, 5-segment, 4-vane RFQ Tuned

"SRF High Bay" Constructed at MSU

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

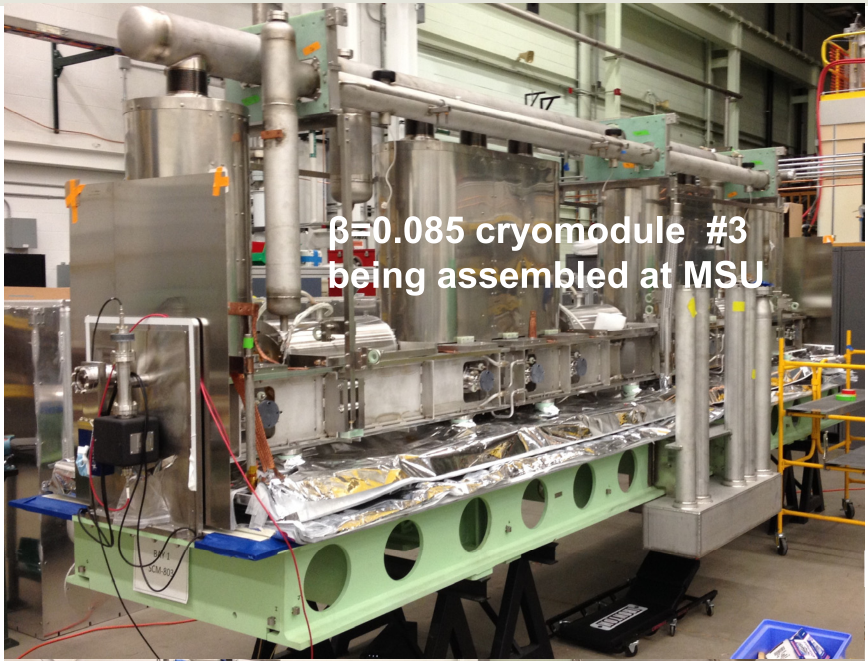
- Production throughput:
  - 5 cavity per week
  - > 1 coldmass per month

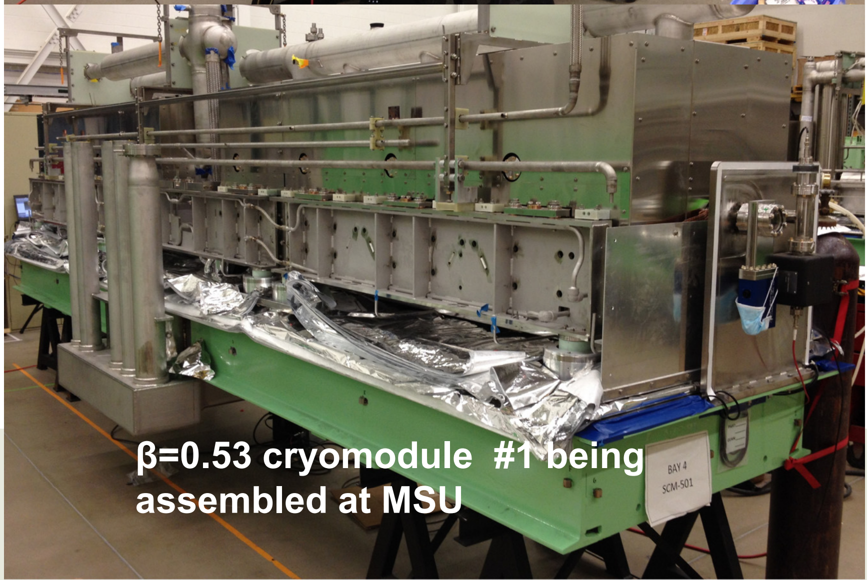
Five Cryomodule Assembly Bays in Parallel

Producing 1.5 Cryomodules Per Month at Peak at MSU

Six Types of Cryomodules Being Assembled

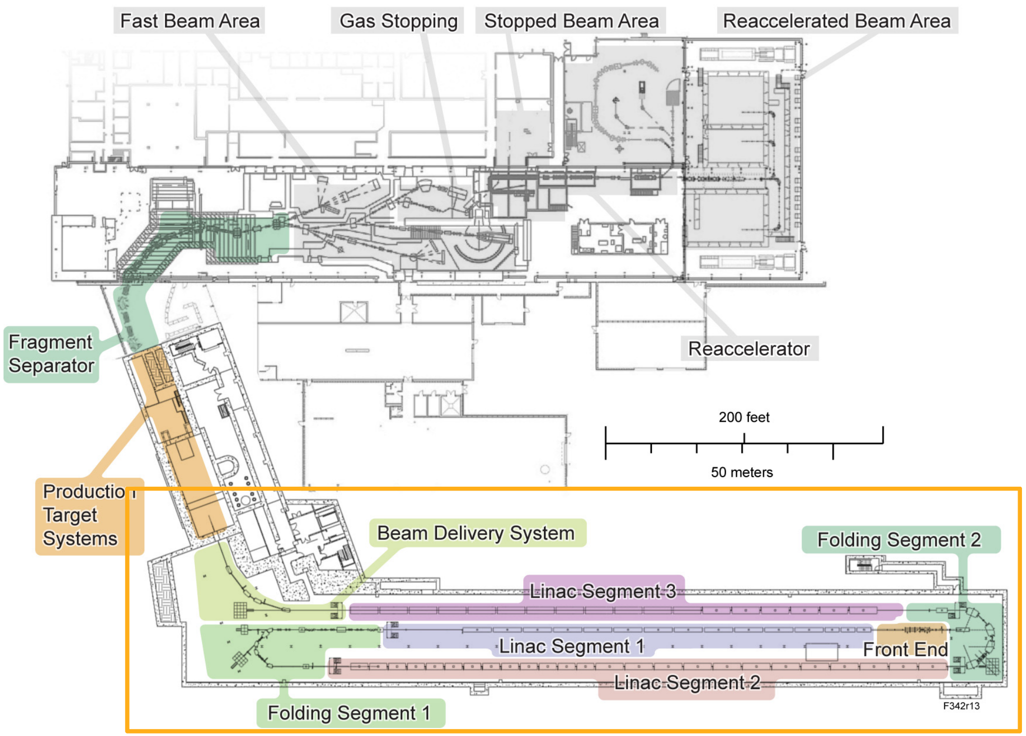
Five Assembly Lines in Parallel at Peak





Proceed to Commissioning & Early Operations

Upgrade Studies Launched on β=0.65 SRF Cavities



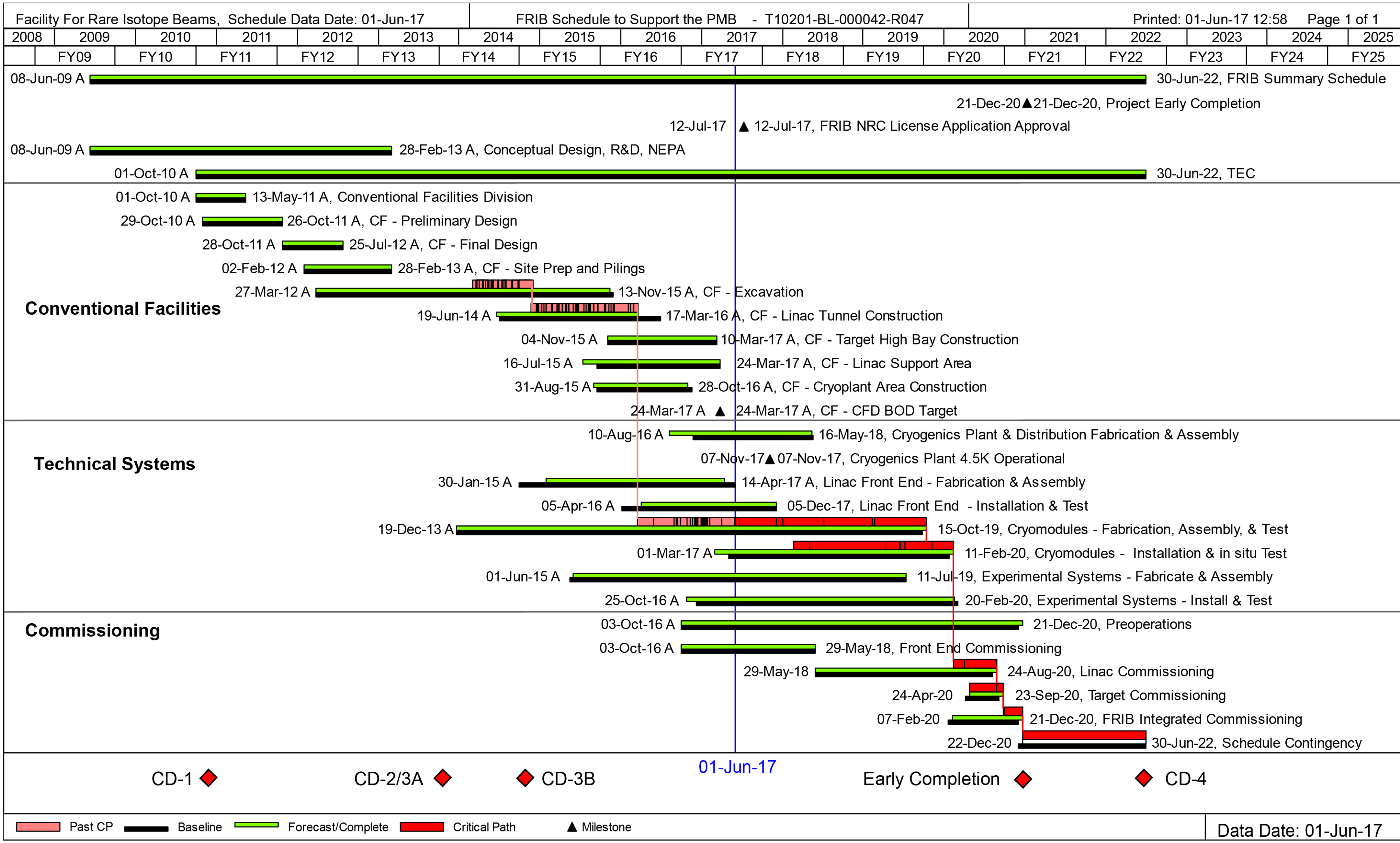
- Delivers FRIB accelerator as part of a DOE-SC national user facility with high reliability & availability
- Accelerate ion species up to ^{238}U with energies of no less than 200 MeV/u
- Provide beam power up to 400 kW
- Satisfy beam-on-target requirements

- Option for energy upgrade to >400 MeV/u by filling vacant slots with ~ 12 cryomodules
- Maintain Isotope Separation On-Line (ISOL) option
- Upgradable to multi-user simultaneous operation of light / heavy ions with addition of a light-ion injector

- Team, collaboration, and baseline execution

FRIB Integrated Master Schedule

Critical Path Shown in Red



Work Continually Been Reviewed
All Comments and Recommendations Tracked and Addressed

- Project Reviews
  - Accelerator Systems Advisory Committee (Ozaki) – 2/11; 11/11; 6/12; 12/12; 6/13; 12/13; 4/14; 12/14; 6/15; 12/15; 5/16; 11/16, 5/17
  - MSU Independent Reviews – 4/12 (Holtkamp); 4/14 (Harrison)
  - Lehman/Meador Review – 3/11; 9/11; 4/12; 10/12; 6/13; 6/14; 3/15; 11/15; 6/16; 12/16
- Accelerator Systems external peer reviews and workshops since CD-1
  - 10/2010: Accelerator Alignment External Review
  - 01/2011: Cryomodule Heat Source External Review
  - 02/2011: Machine Protection, Diagnostics Timing
  - 04/2011: Accelerator Lattice External Review
  - 05/2011: Diagnostics External Review
  - 05/2011: Electrical Grounding Workshop
  - 07/2011: Controls External Review
  - 08/2011: Cryogenic External Review
  - 08/2011: SRF External Review
  - 08/2011: Cryomodule (0.53) External Review
  - 08/2011: Front End External Review
  - 10/2011: Magnets External Review
  - 10/2011: Charge Stripper External Review
  - 11/2011: Installation, Pre-ops, Commissioning
  - 12/2011: RF & Power Supply External Review
  - 01/2012: Diagnostics Preliminary Design Peer Review
  - 01/2012: Personnel Protection System Workshop
  - 01/2012: Vacuum, Beam Dump, Collimator Review
  - 02/2012: Lithium Stripper Safety Review
  - 07/2012 SRF Subsystem Review
  - 09/2012: Utility Interface External Review
  - 09/2012 Final Engineering Design Approach Review
  - 11/2012: HP Source Magnet/Coldmass Workshop
  - 11/2012: FRIB Vacuum Workshop
  - 02/2013: ReA coupler, SRF fabrication, TDCM, ETCM
  - 03/2013: Magnet Shielding Workshop
  - 07/2013: RF and Power Supplies Intermediate
  - 07/2013: Personnel Protection System Intermediate
  - 08/2013: ARTEMIS Ion Source / HV Platform Inter. Design
  - 09/2013: ReA6 Cryomodule Project Status Review
  - 10/2013: QWR Prototype Cryomodule Final Design
  - 10/2013: Lithium Charge Stripper Intermediate Design
  - 10/2013: MPS and GTS Intermediate Design Review
  - 10/2013: Alignment Intermediate Design Review
  - 11/2013: Cryodistribution Intermediate Design Review
  - 11/2013: HWR Cryomodule Intermediate Design
  - 11/2013: ASD Room-temperature Dipole Magnet Interm.
  - 11/2013: ASD Superconducting Magnet Final Design
  - 11/2013: ASD RT Optical Element Intermediate Design
  - 11/2013: Diagnostics Intermediate Design Review
  - 11/2013: MEBT Bunch Preproduction Review
  - 11/2013: Low-level Controls Intermediate Design
  - 01/2014: FRIB In-depth Technical Interface Series
  - 03/2014: Cryomodule Maintenance Workshop
  - 03/2014: Machine Protection Systems Workshop
  - 03/2014: ESH Advisory Committee Review
  - 03/2014: Prelim. Start-up & Commissioning Plan Review
  - 04/2014: ARTEMIS Ion Source / HV Platform Final Design
  - 05/2014: ASD RT Magnet Final Design Review
  - 06/2014: 0.53 HWR Cryomodule Final Design Review
  - 06/2014: Cryomodule SC solenoid Final Design review
  - 08/2014: RF and Power Supply Final Design Review
  - 08/2014: Lithium Stripper Final Design Review
  - 09/2014: ECR Cold Mass Design Review
  - 09/2014: Alignment Network Final Design Review
  - 09/2014: Vacuum In-progress Design Review
  - 09/2014: Cryoplant and Cryodistribution Final Design Review
  - 11/2014: ICFA Workshop on High Power Hadron beams
  - 02/2015: ASD Diagnostics Final Design Review
  - 02/2015: ESHAC Review
  - 05/2015: EVMS Review
  - 05/2015: Vacuum Final Design Review
  - 05/2015: Personnel Protection System In-progress Review
  - 05/2015: Front End Controls Final Design Review
  - 07/2015: Front End Diagnostics Intermediate Design Review
  - 08/2015: Controls Network In-Process Review
  - 08/2015: Time Critical Front End Controls In-Process Review
  - 09/2015: Phase I Personnel Protection System 90% Review
  - 09/2015: MPS, GTS and Central Control 90% Review
  - 09/2015: Hardware Controls Final Design Review
  - 10/2015: ASD Beam Dump Final Design Review
  - 01/2016: DOE Review on FRIB Operations Cost
  - 01/2016: 0.041 Cryomodule Final Design Review
  - 01/2016: LEBT Beam Plug Final Design Review
  - 01/2016: High Power ECR Cryostat Review
  - 03/2016: ESHAC Review
  - 03/2016: β=0.085 Matching Cryomodule Intermediate Design Review
  - 04/2016: EVMS Review
  - 05/2016: ASD Diagnostics Electronics Final Design Review
  - 06/2016: β=0.085 Matching Cryomodule Final Design Review
  - 08/2016: FRIB 2K Cold Box Final Design Review
  - 08/2016: β=0.29 Cryomodule Preliminary Design Review
  - 09/2016: ARTEMIS Device Readiness Review
  - 09/2016: ECR Cryostat Final Design Review
  - 03/2017: β=0.53 Matching Cryomodule Preliminary Design Review
  - 06/2017: Pre-Accelerator Readiness Review (Front End)
  - 07/2017: Accelerator Readiness Review (Front End)

Continue to Leverage Collaborations
WFO Contracts Being Executed with Partner Laboratories

- 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, database
- 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
  - Diagnostics; controls
- SLAC**
  - Cryogenics**, SRF multipacting**, physics modeling

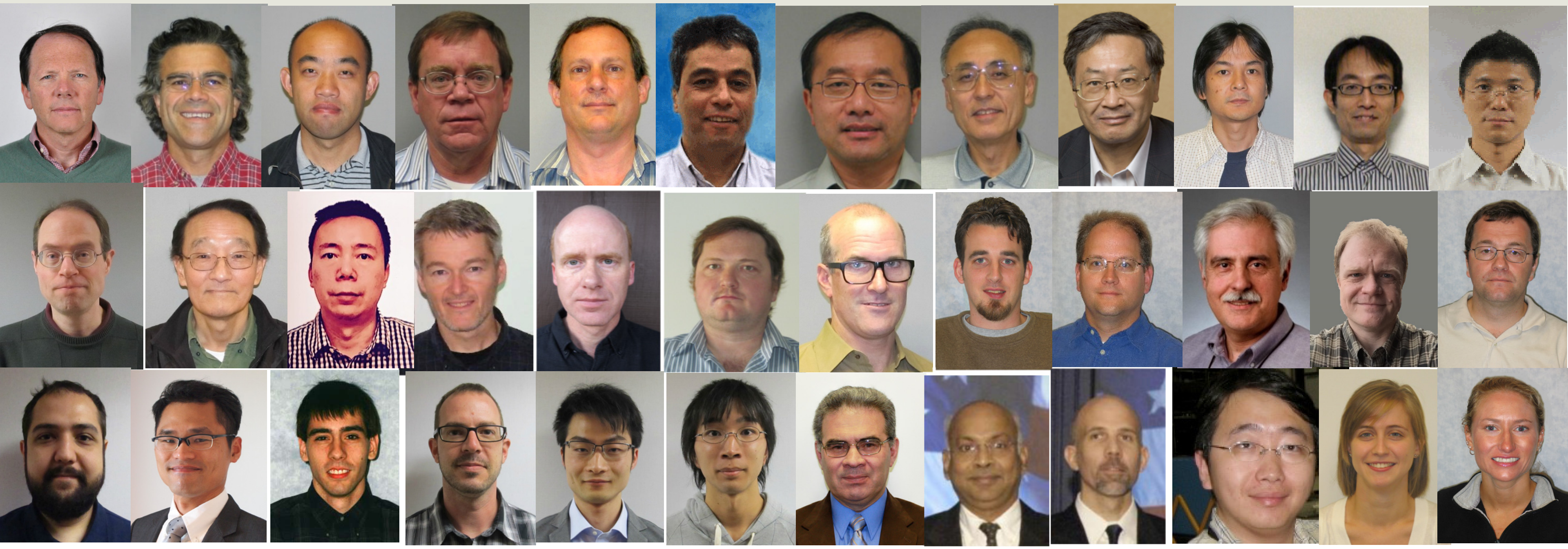
- RIKEN
  - Helium gas charge stripper
- TRIUMF
  - Beam dynamics design, physics modeling **
  - SRF, QWR etching**
- INFN
  - SRF technology
- KEK
  - SRF technology, SC solenoid prototyping
- IMP
  - Magnets
- Budker Institute, INR Institute
  - Diagnostics
- Tsinghua Univ. & CAS
  - RFQ
- ESS
  -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

* Under discussion or in preparation

** Completed

Red: Active/actively planned WFO contract

Attracted World Experts in Key Areas
With Culture Background from About 20 Countries



- Attracted seasoned leaders in accelerator physics and engineering
  - H. Ao (J-PARC), N. Bultman (LANL), F. Casagrande (ORNL), J. Chen (PPPL), D. Chabot (BNL), L. Dalesio (BNL), A. Facco (INFN), F. Feyzi (Wisconsin), K. Fukushima (U. Hiroshima), V. Ganni (JLab), A. Ganshyn (Cornell), P. Gibson (ORNL), W. Hartung (Cornell), S.H. Kim (ANL), P. Knudsen (JLab), Y. Hao (BNL), H.-C. Hseuh (BNL), A. Hussain (BNL), M. Ikegami (J-PARC), T. Kanemura (JAEA), R.E. Laxdal (TRIUMF), S. Lidia (LBNL), S. Lund (LLNL), G. Machicoane, A.C. Morton (TRIUMF), J. Nolen (ANL), D. Omitto (BNL), P. Ostroumov (ANL), E. Pozdeyev (BNL), T. Russo (BNL), K. Saito (KEK), H. Tatsumoto (J-PARC), J. Wei (BNL/THU), T. Xu (ORNL), Y. Yamazaki (KEK), T. Yoshimoto (TIT/KEK)

Summary

- FRIB Project is three years into full technical construction
  - Overall accelerator systems construction is 72% complete in cost
  - Major procurement is 94% spent or committed
- Accelerator design meets FRIB performance requirements
  - Accelerator lattice footprint frozen since 2011
  - All major technology developments are completed
  - Optimized for availability, maintainability, reliability, tunability, upgradability
- Phased approach in meeting beam instrumentation challenges
  - Machine protection challenges highlighted
- An excellent team is in place to lead accelerator systems delivery
- FRIB is looking for dedicated fellows & seasoned colleagues to join the project, and also welcomes collaboration in all forms

Thank You!