Advances of the FRIB Project

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On Behalf of FRIB Accelerator Team & Collaboration

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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 commissioning
- Technical issue resolution
- Infrastructure growth
- Power ramp up and upgrade
- Summary

- Acknowledgement
- References

Introduction

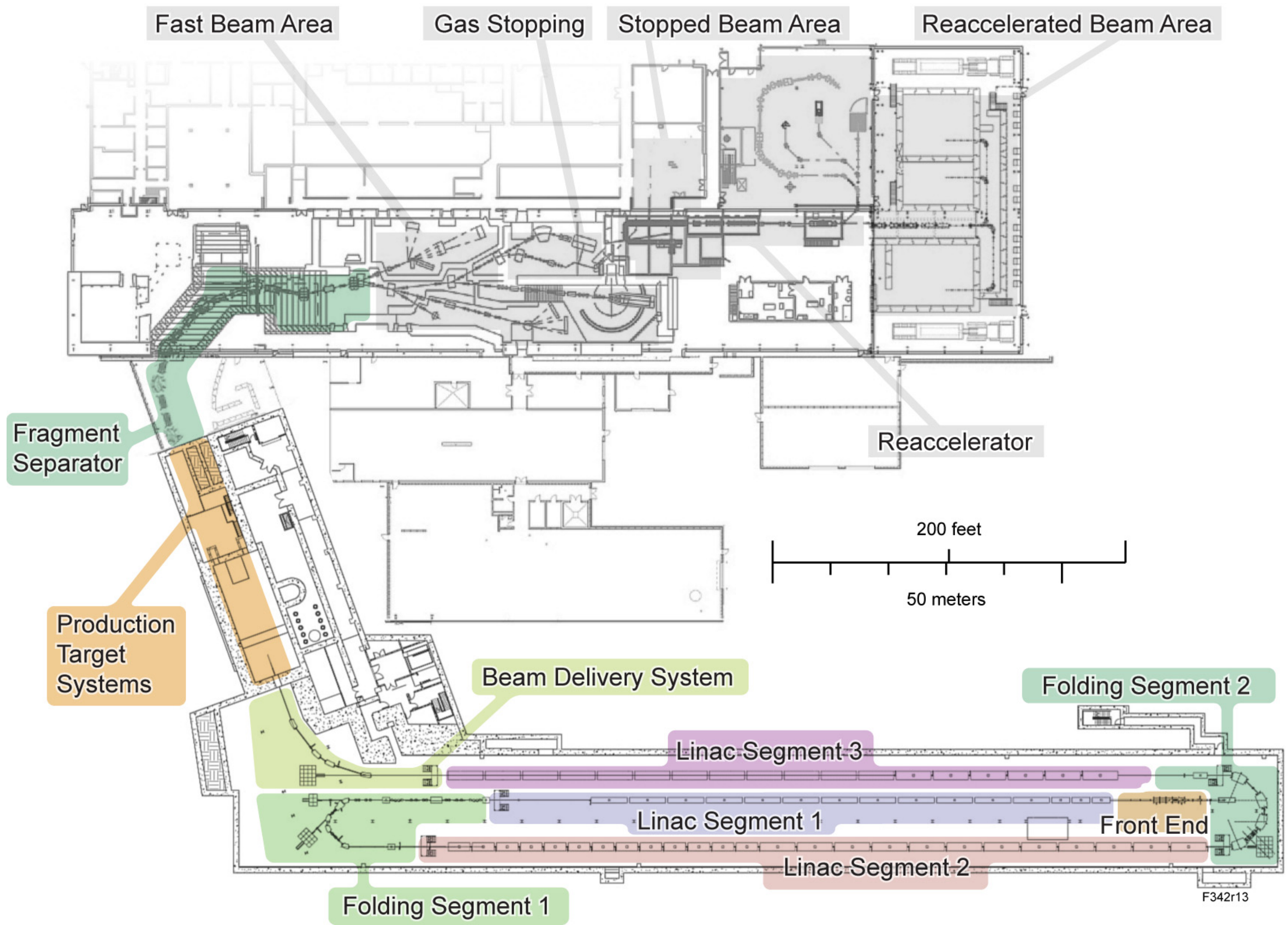
- FRIB Project constructs a $730 million national user facility funded by the U.S. Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- Planned completion date is June 2022, managing to early completion in 2021
- FRIB will be a DOE-SC scientific user facility for rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC

FRIB Technical Construction Started in 2014

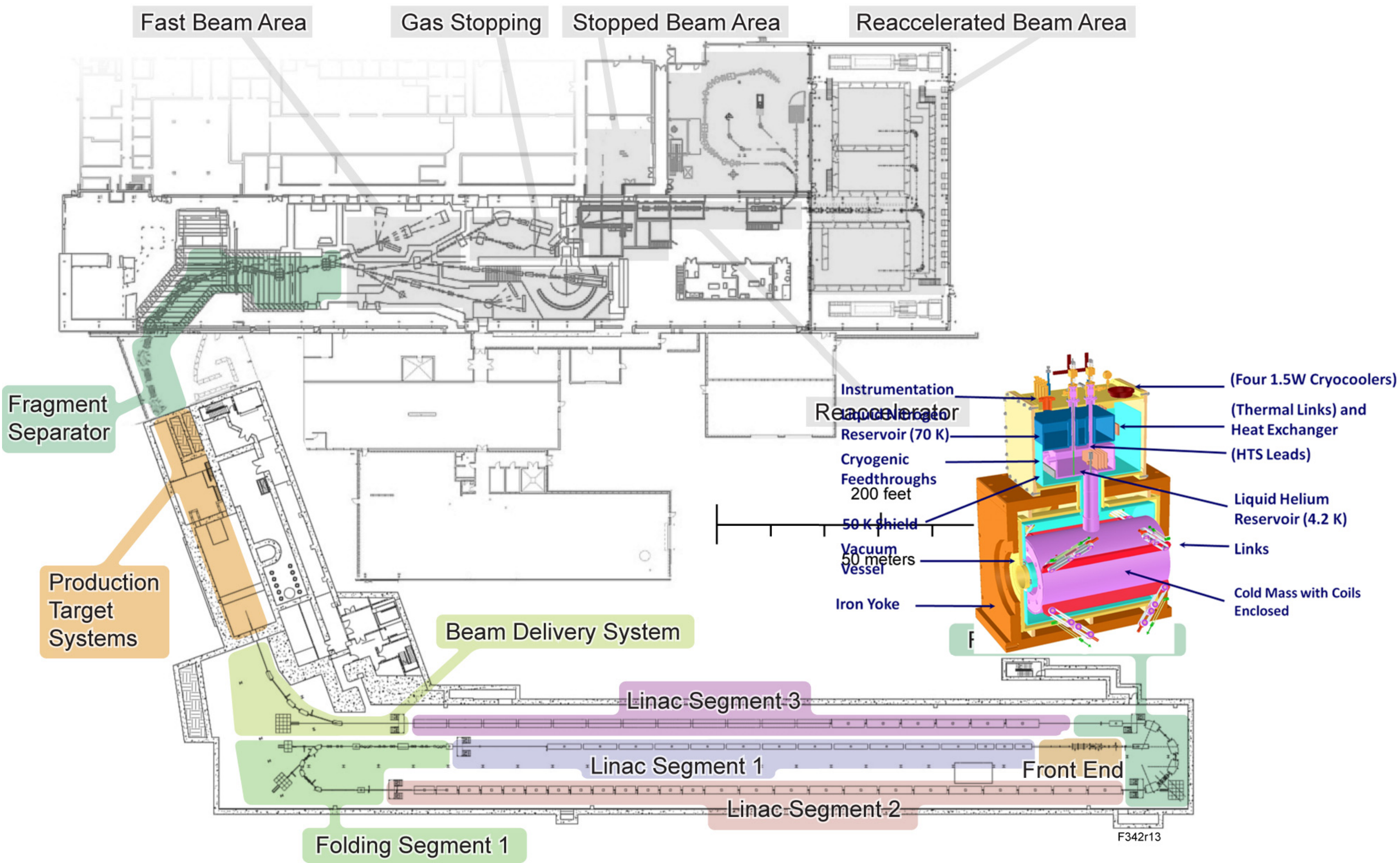
CD-3a in 2012 (Long Lead Procurements); CD-3b in 2014 (All)

FRIB Civil Construction Is Complete – Now Installing & Commissioning Accelerator

FRIB Accelerator Complex Subsystems



FRIB Accelerator Complex Subsystems



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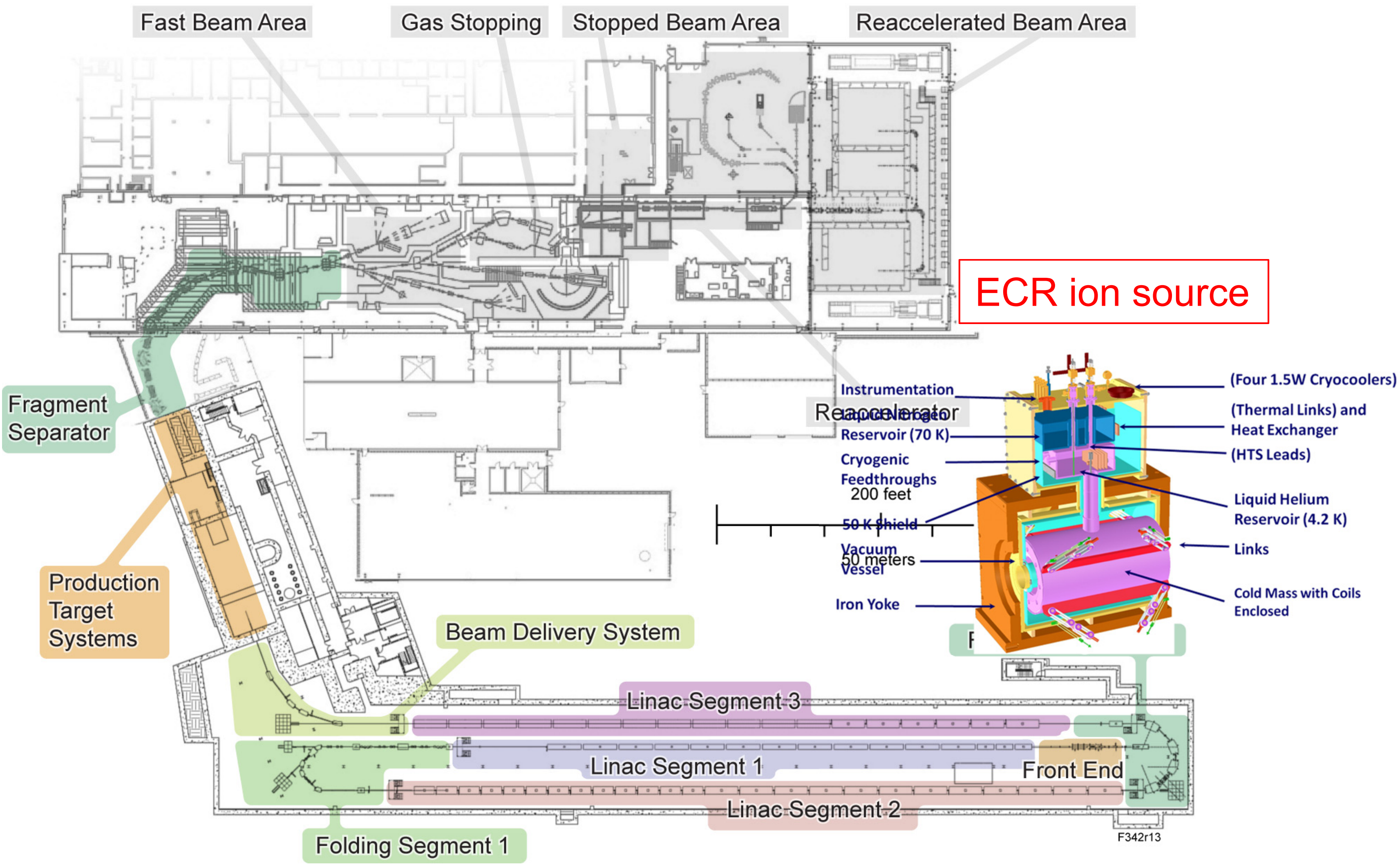

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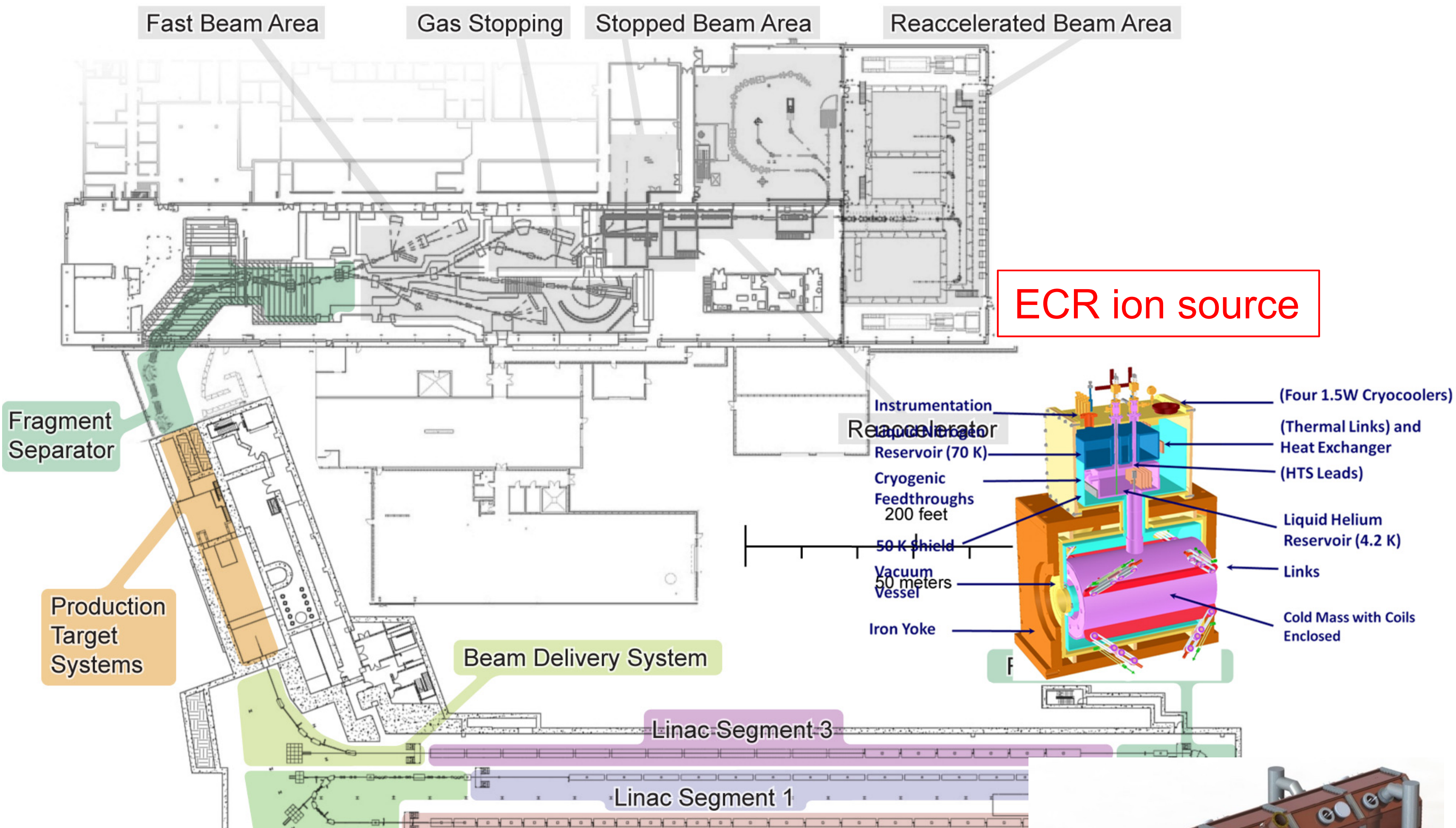

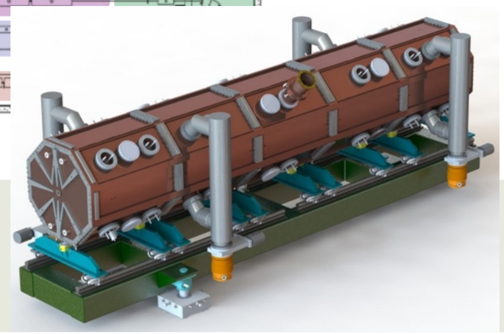

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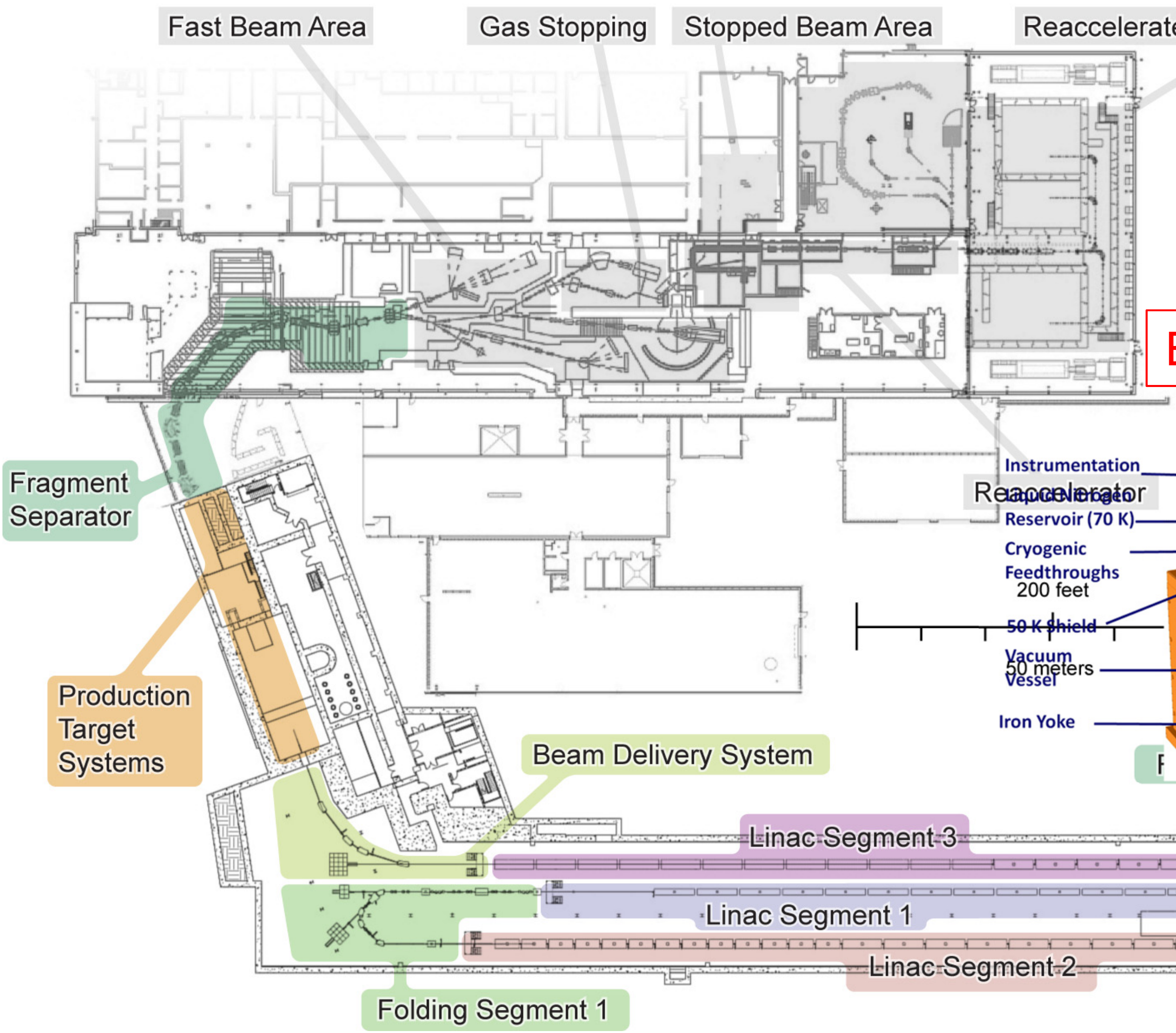
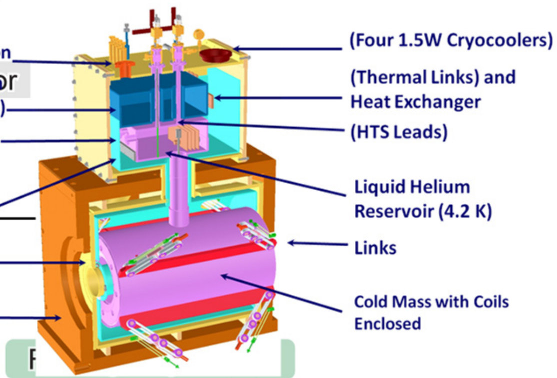
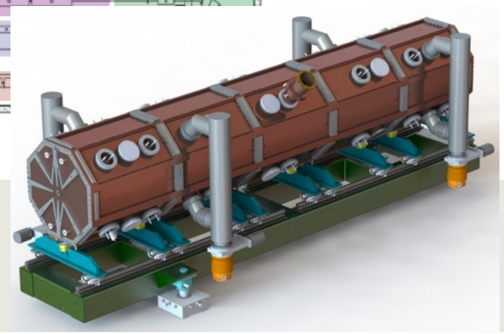


ECR ion source



RFQ



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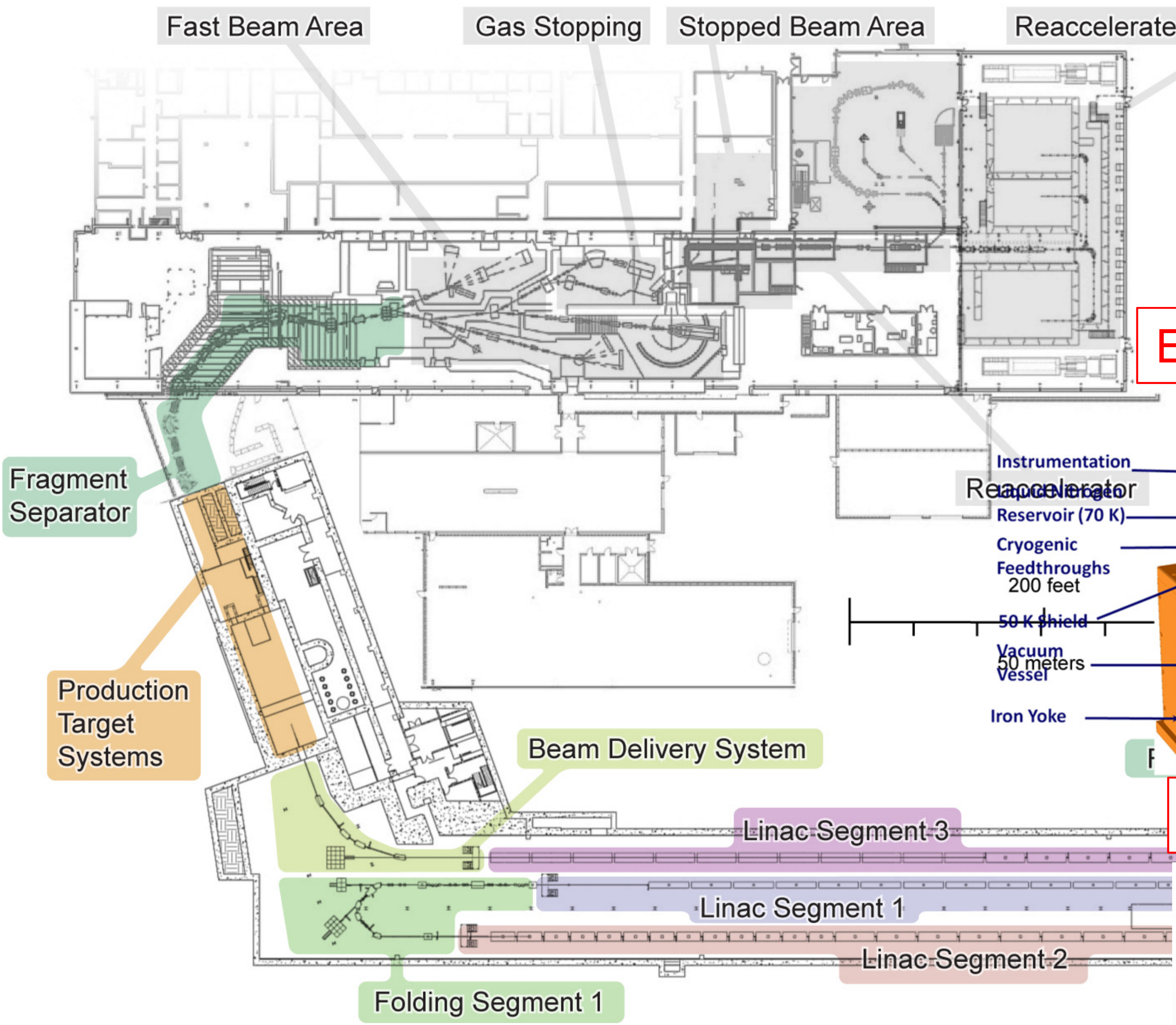

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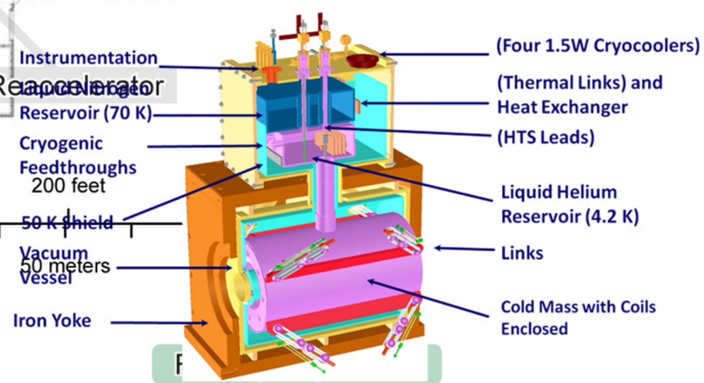

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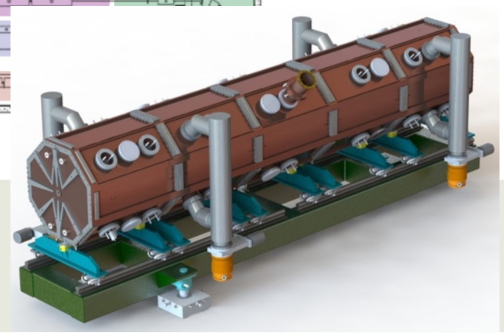

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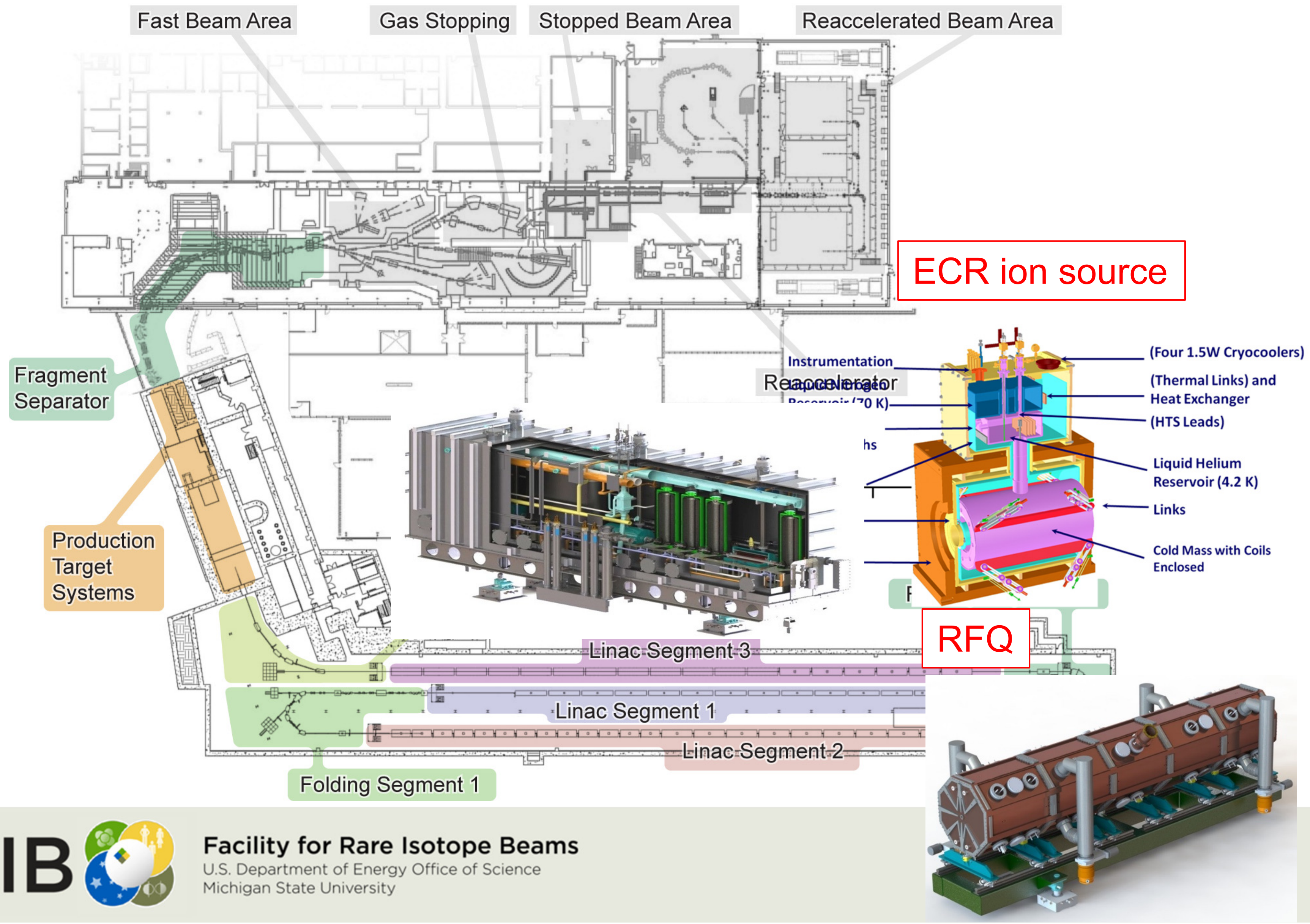

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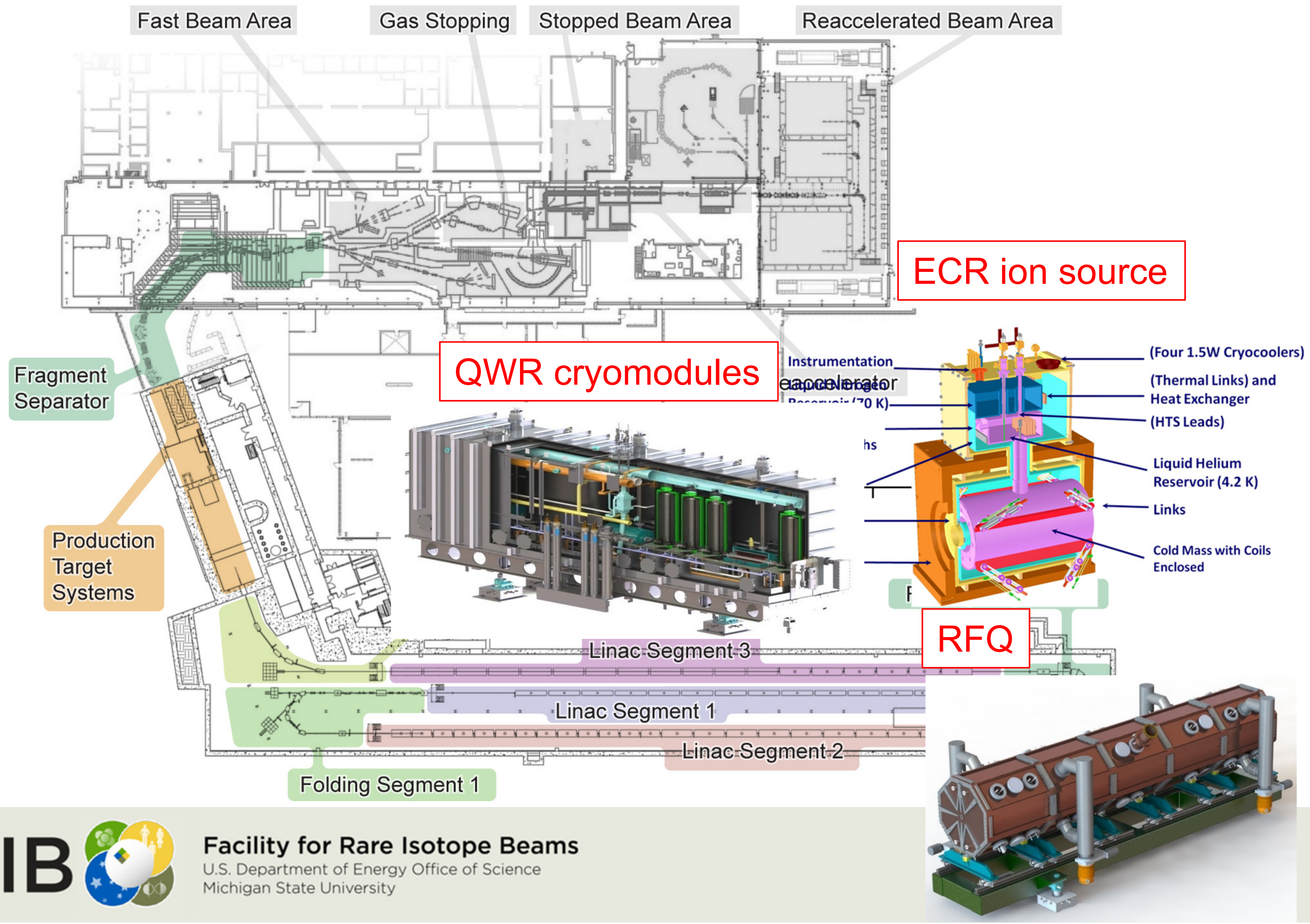

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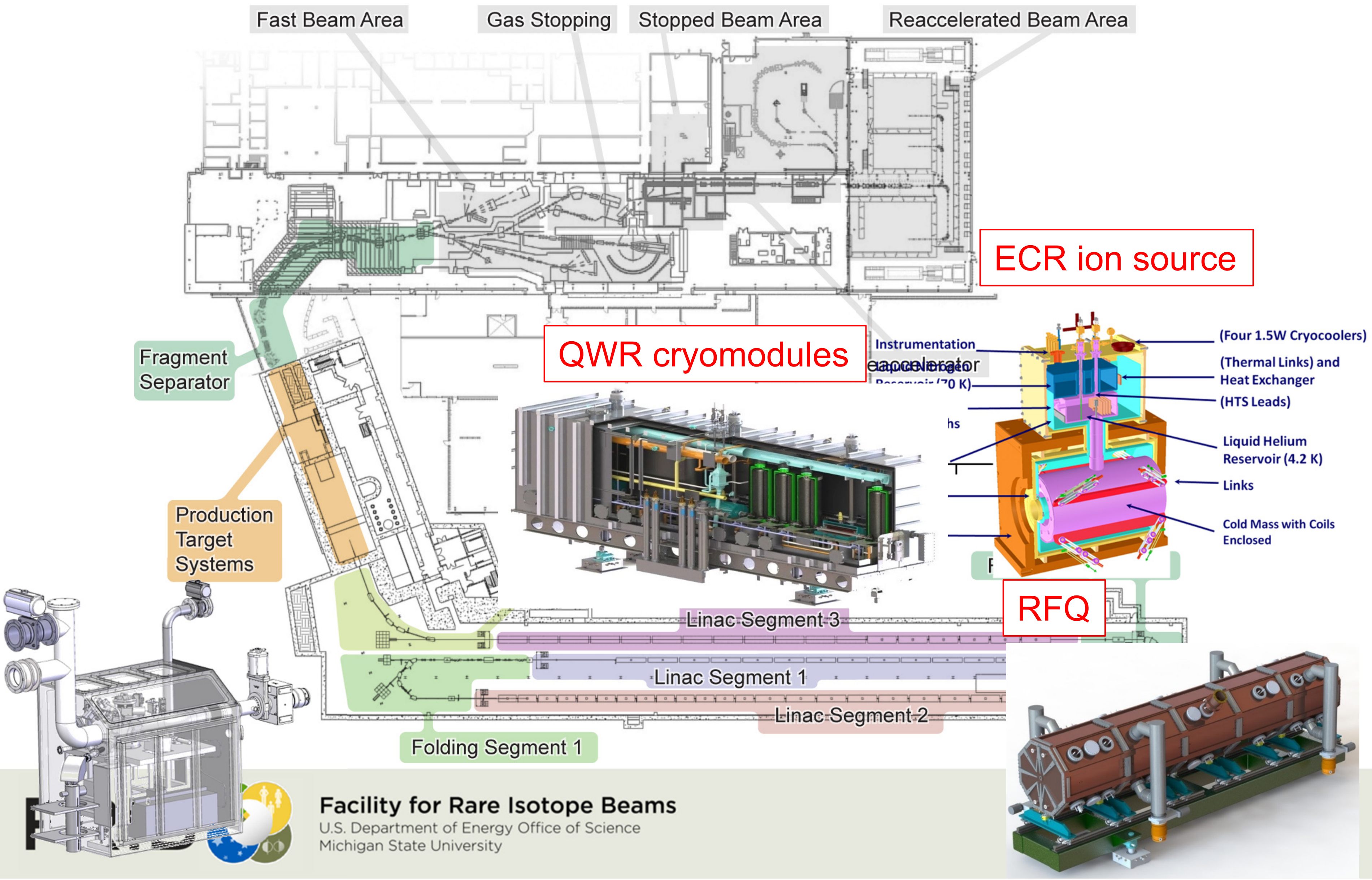

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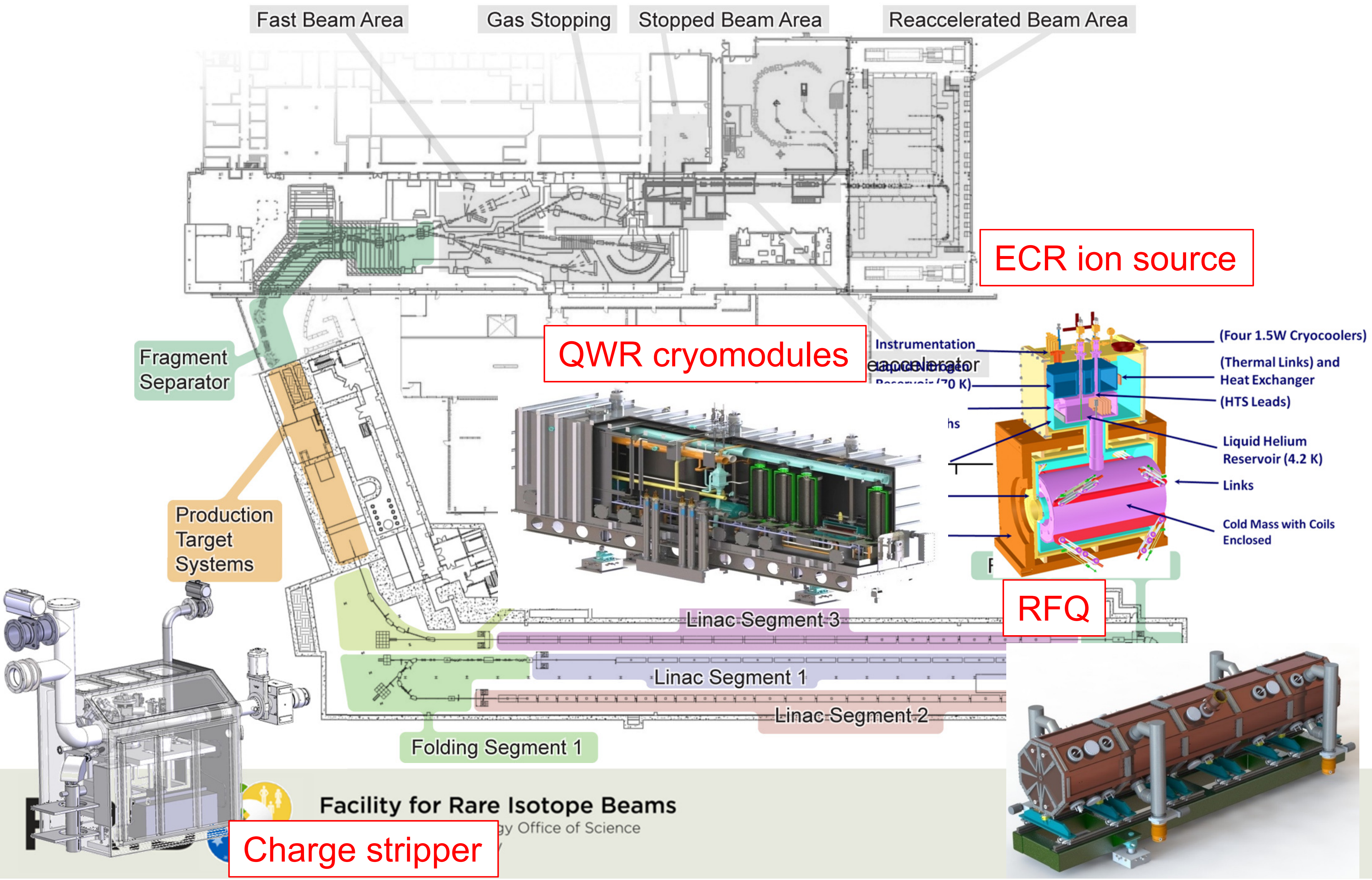

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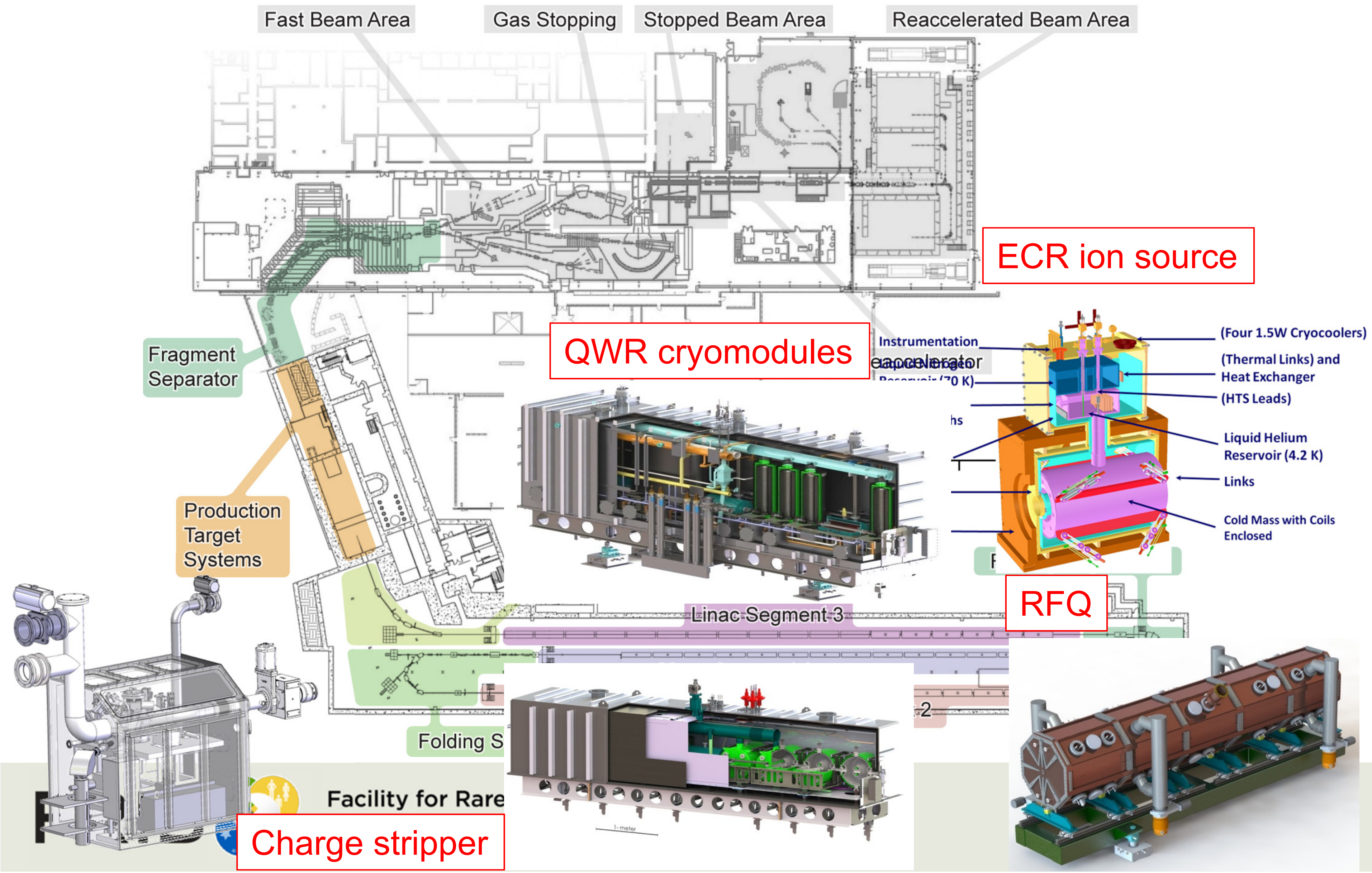

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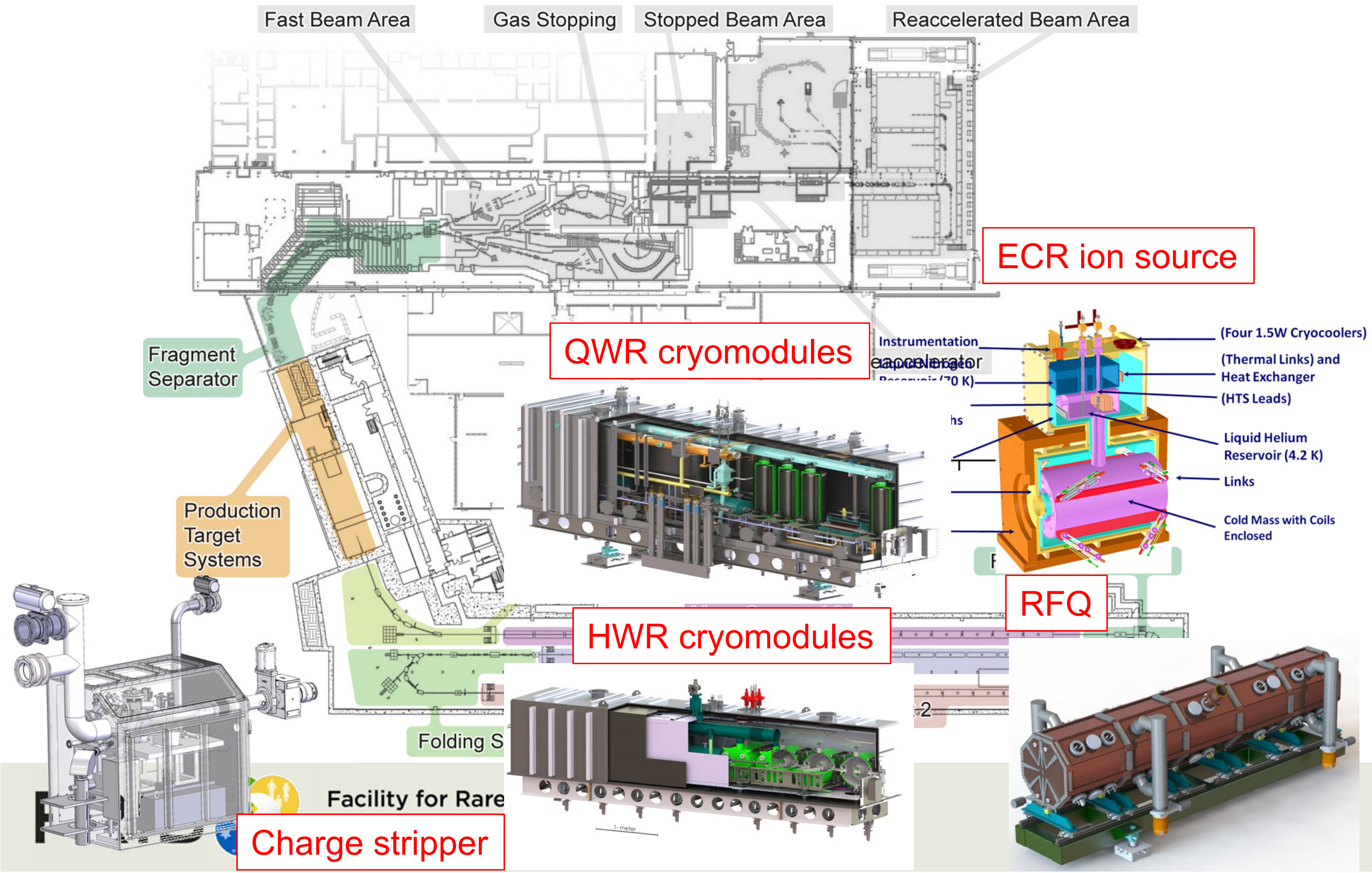

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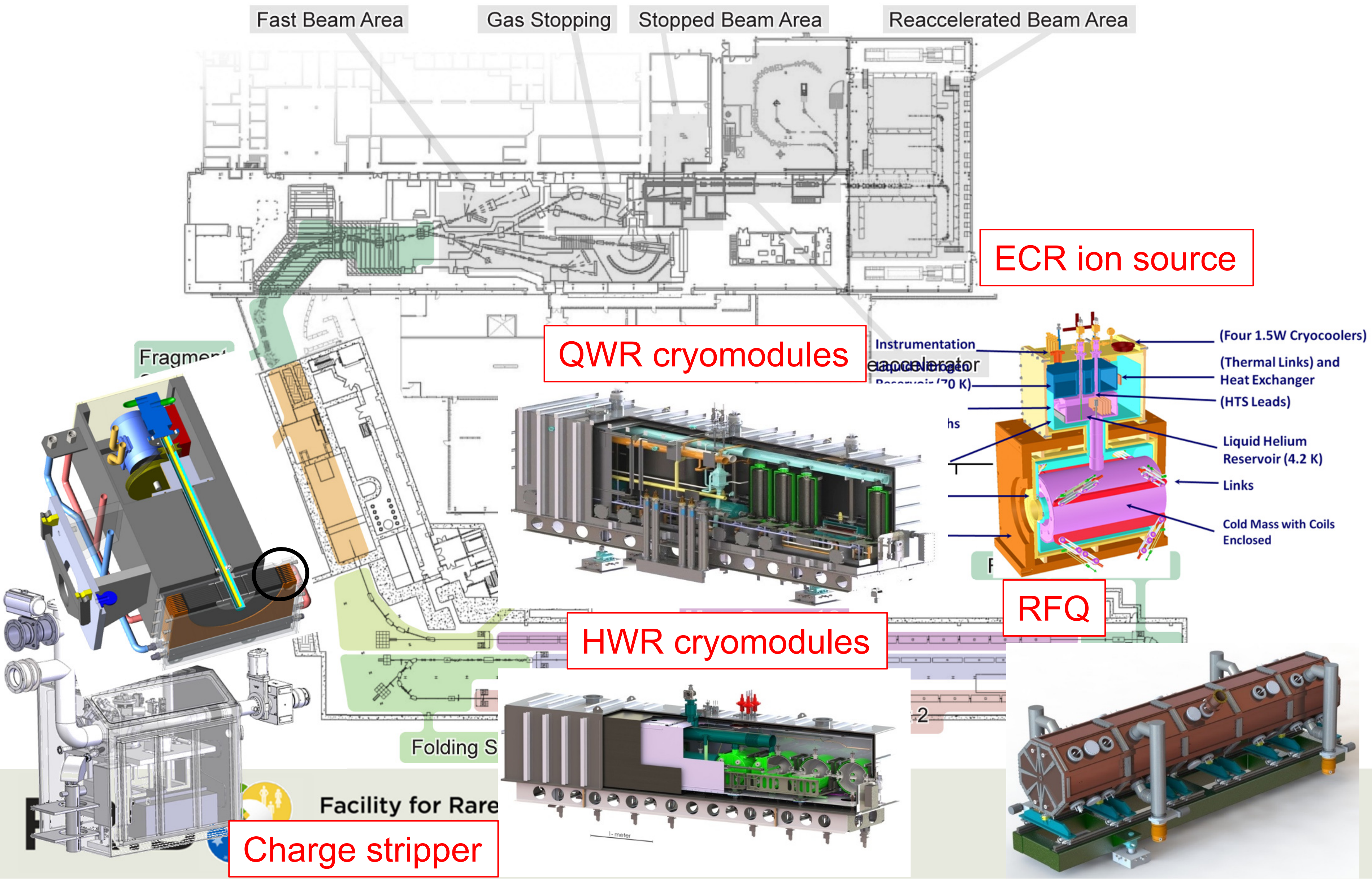

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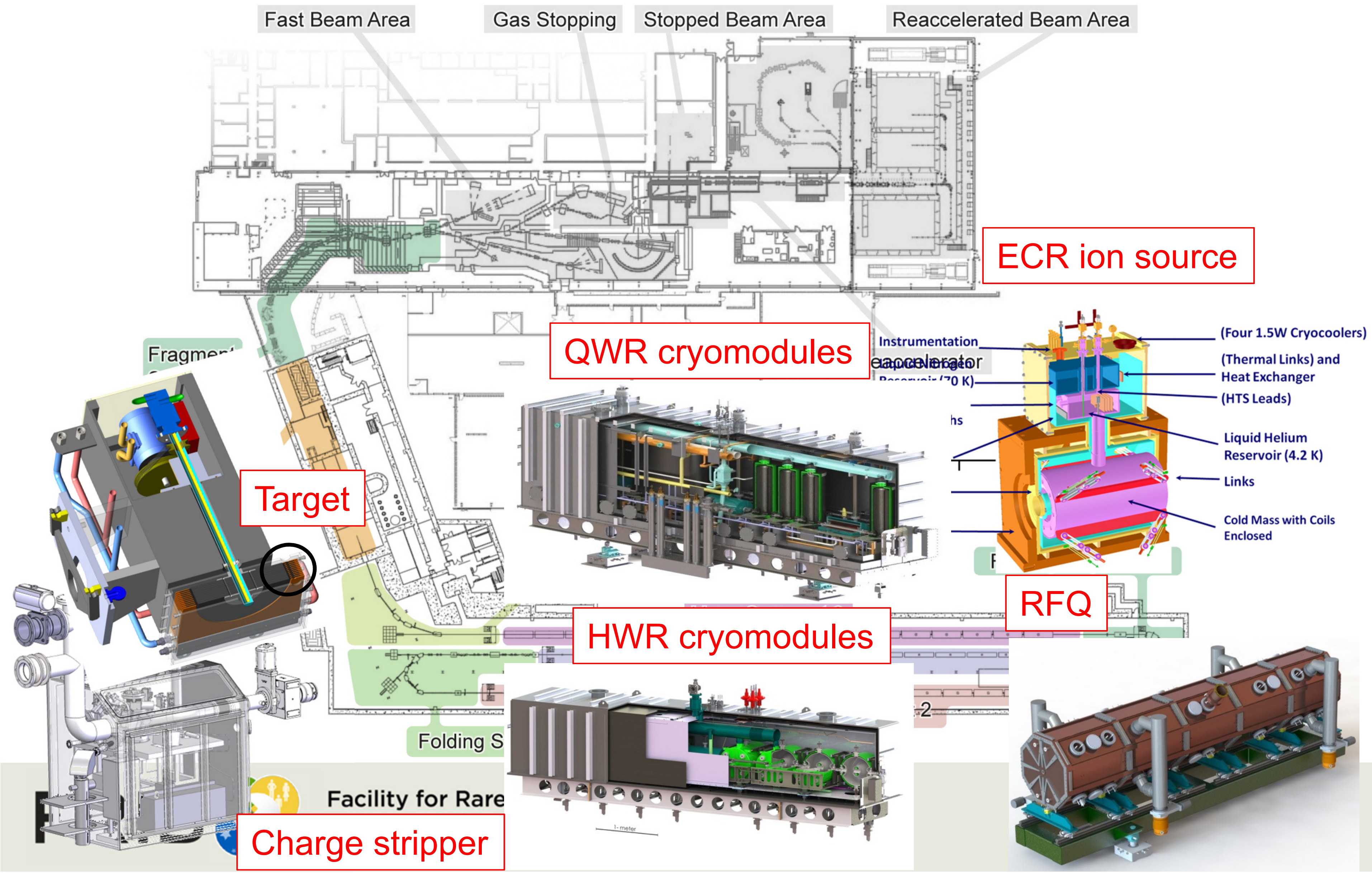

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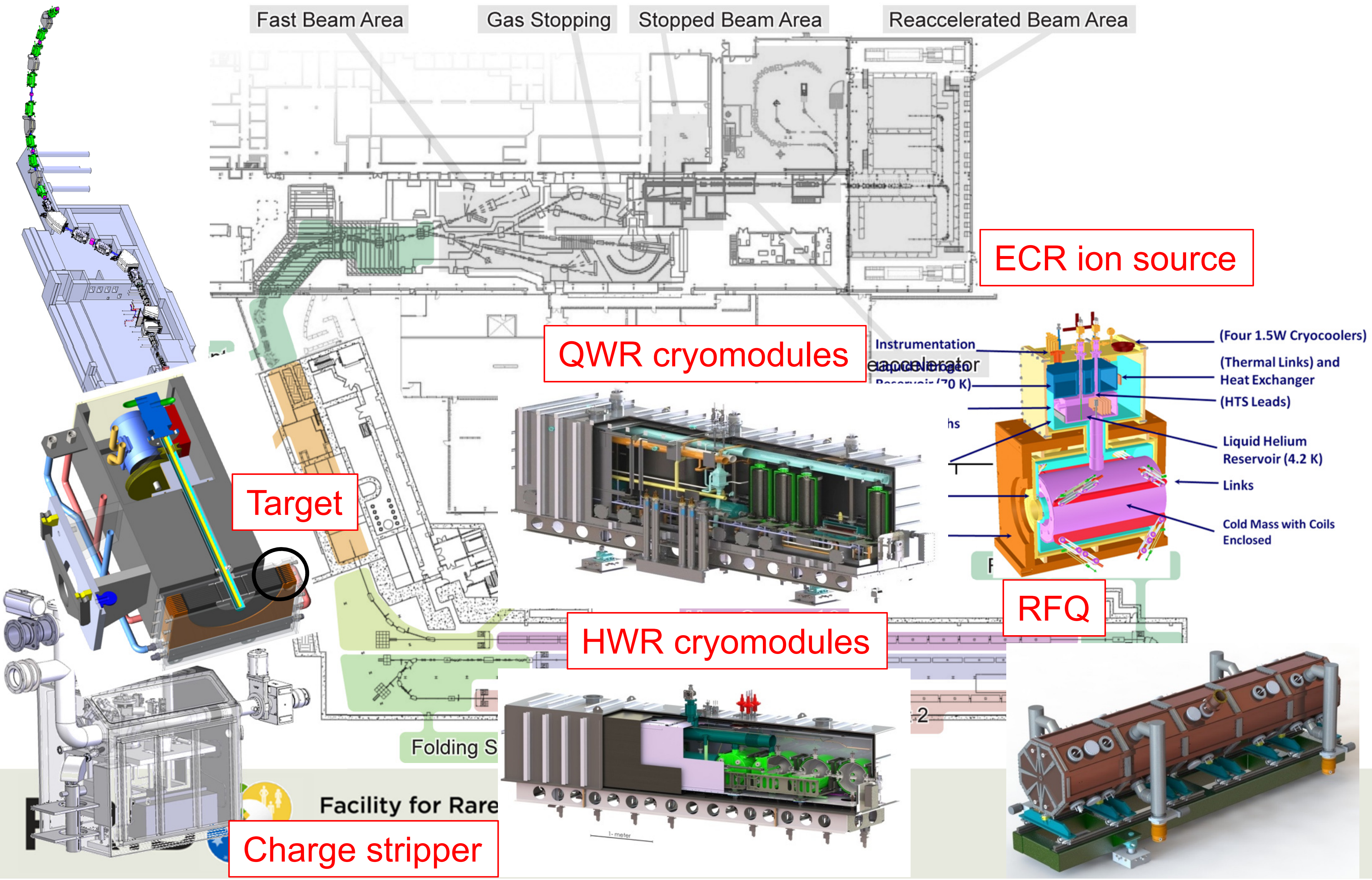

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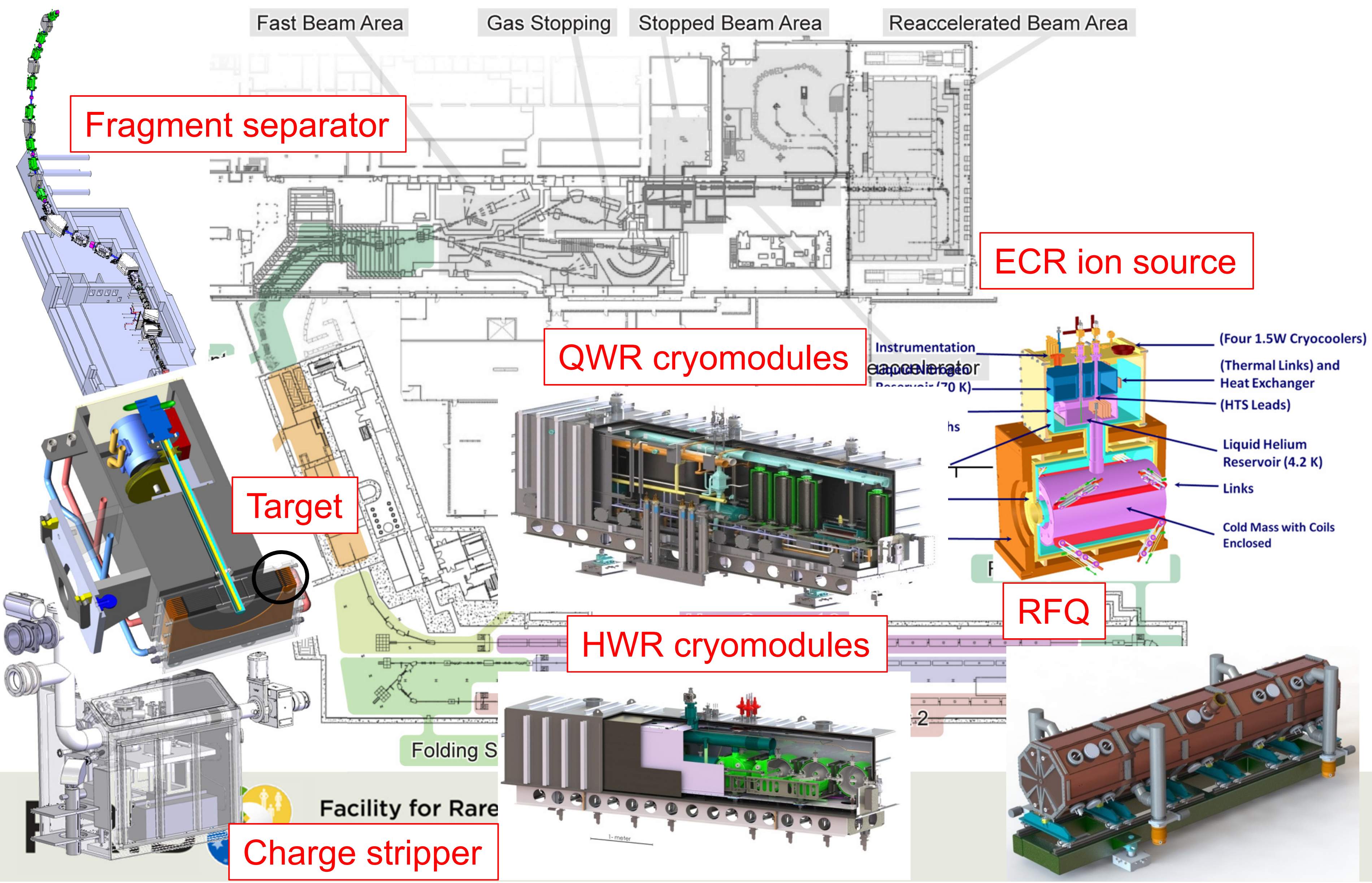

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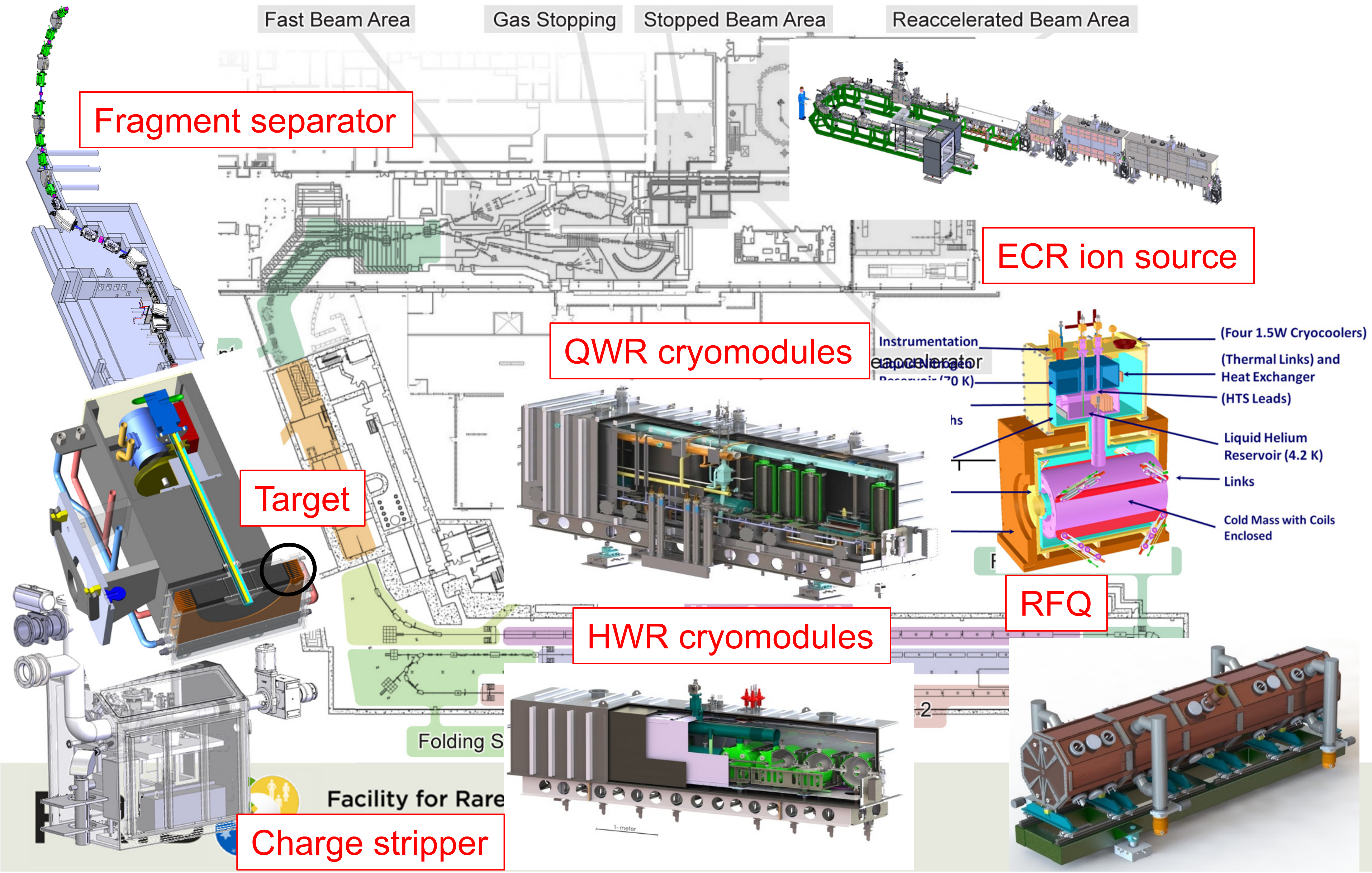

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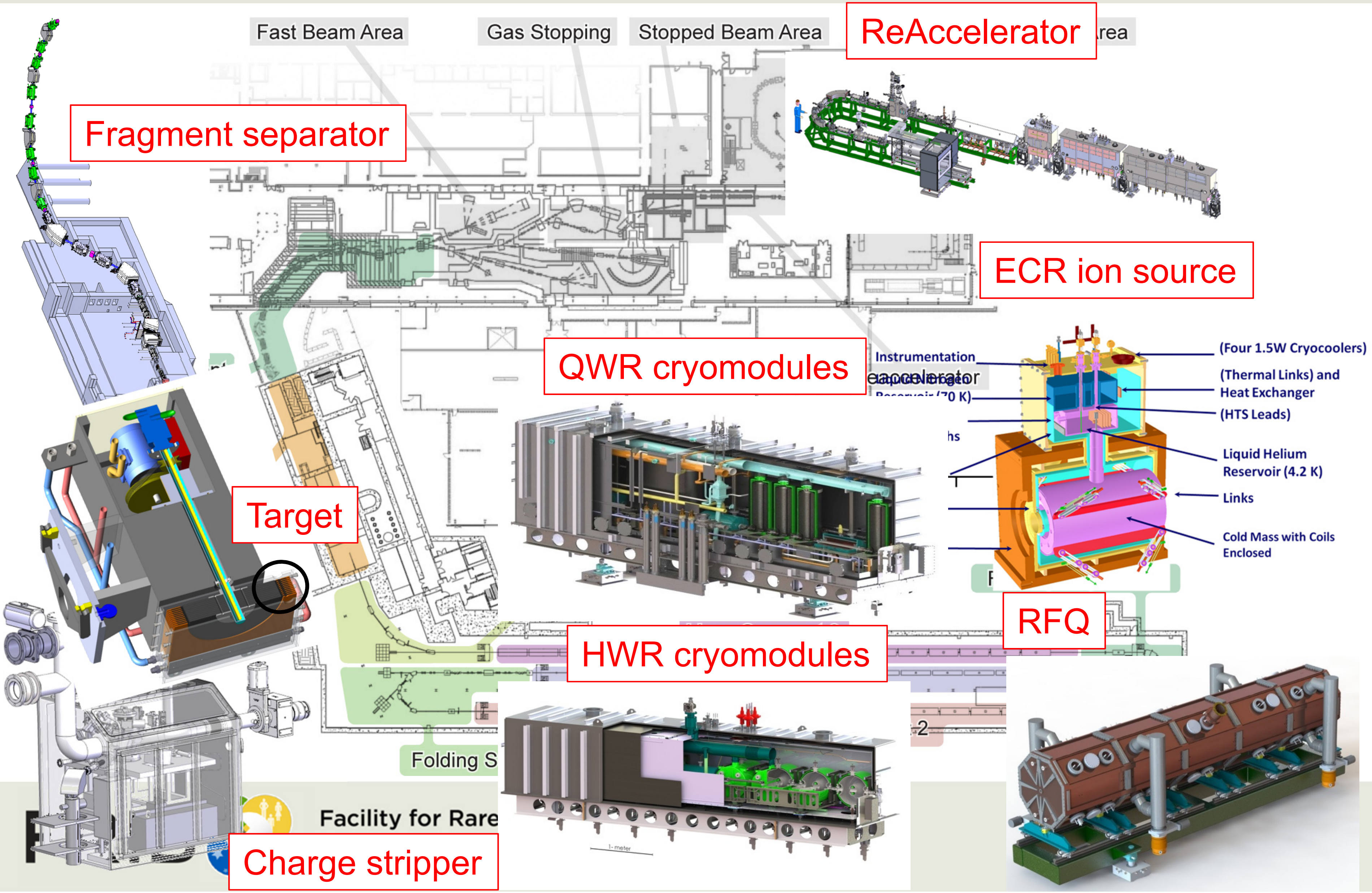


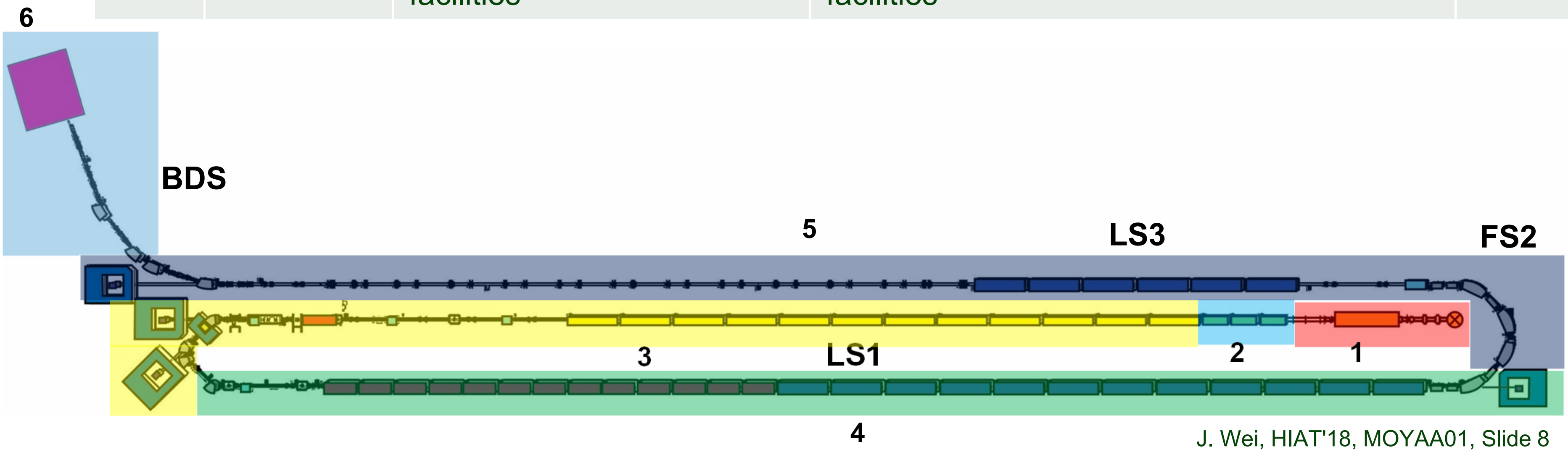
Started Beam Commissioning in 2017 While Installation Proceeds

FRIB Lower LEBT, RFQ, MEBT, and β=0.041, 0.085, 0.29 and 0.53 cryomodules installed

Phased Commissioning

Two Accelerator Readiness Reviews Completed

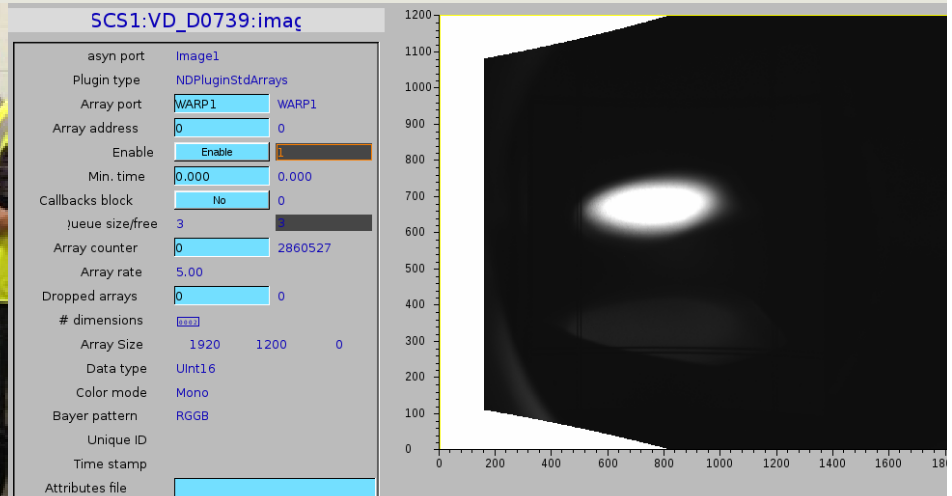
ARR	E [MeV/u]	Area with beam	Strategic goal	Date
1 ✓	0.5	Ion Source, LEBT, RFQ, MEBT	Integrate linac room temperature systems together with civil engineering & utilities	07/2017
2 ✓	~ 2	Plus β=0.041 cryomodules	Integrate with cryogenics & cryomodules operating at 4 K temperature	05/2018
3	~ 20	Plus β=0.085 cryomodules	Operate as radiation generating facility with 15 cryomodules; test charge stripping	02/2019
4/5	~ 200	Plus β=0.29, 0.53 cryomodules	Operate all 46 cryomodules at 2 K cryogenics temperature	12/2020
6	~ 200	Plus target, beam dump	Integrate with experimental systems	09/2021
Final	~ 200	Plus reconfigured existing facilities	Integrate with all reconfigured existing facilities	12/2021



Front End Commissioned with Ar & Kr Beams

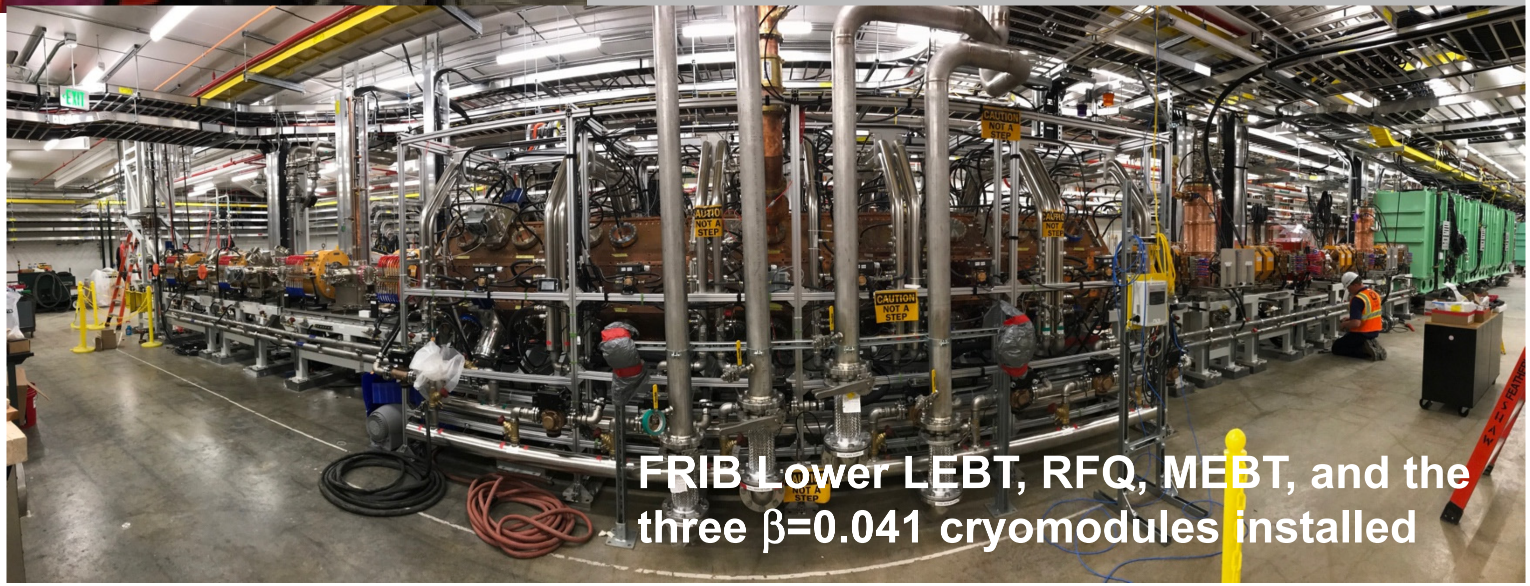
Meeting Key Performance in Two Days at Full Expected Efficiency

ARR01 commissioning in the FRIB front end control room



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

Liquid Helium Produced in FRIB Cryoplant

Cryogenics On Track to Support ARR02 in May 2018

- Focused efforts
  - Benefiting from experience and lessons learned at JLab and SNS
  - Benefiting from collaboration with JLab
  - Established MSU Cryogenic Initiative with Ganni and Knudsen
  - One of the four focus areas of DOE 2017 Traineeship grant sole award to MSU

Helium refrigeration system in commission

Objective Measures	Date
System utilities in place	Done, 6/2017
Cryogenic plant ODH system complete	Done, 8/2017
Warm compressor commissioning	Done, 9/2017
Tunnel ODH system complete	Done, 11/2017
Cryogenic plant 4 K operational	Done, 12/2017
Cryogenics ready for LS1 cryomodules, 4 K	Done, 5/2018
2 K cold box commissioning	12/2018
Folding Segment 2 ready for 1st SC magnet	12/2018
Experimental area cryo install/commissioning	10/2020
Experimental area magnet cool down start	11/2020

November 16, 2017, first helium liquid in FRIB 4 K cold box dewar

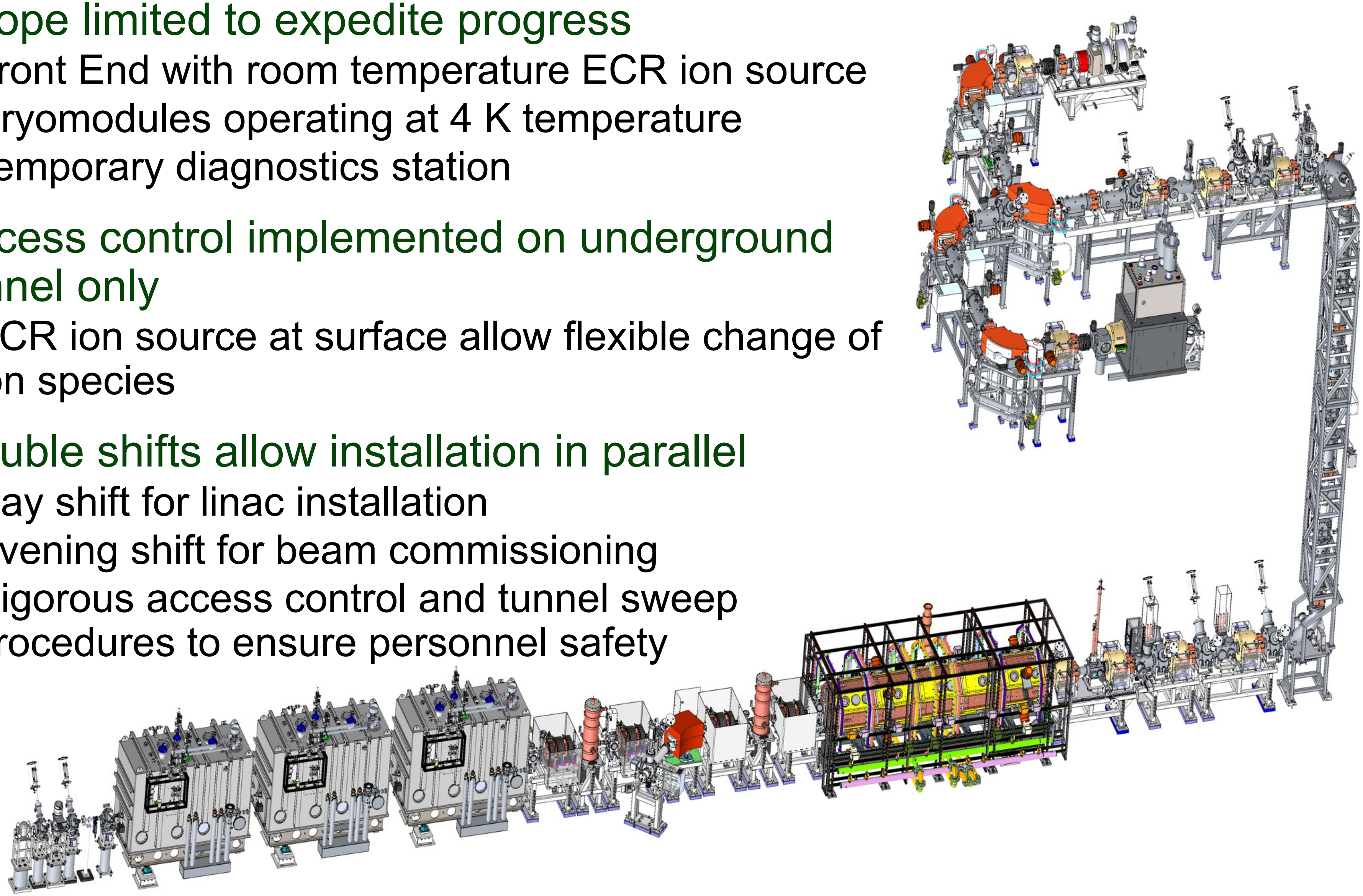
Integrated Cryogenics Is Key to

- 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-tubed for maintenance
- 4-2 K heat exchangers housed inside cryomodules

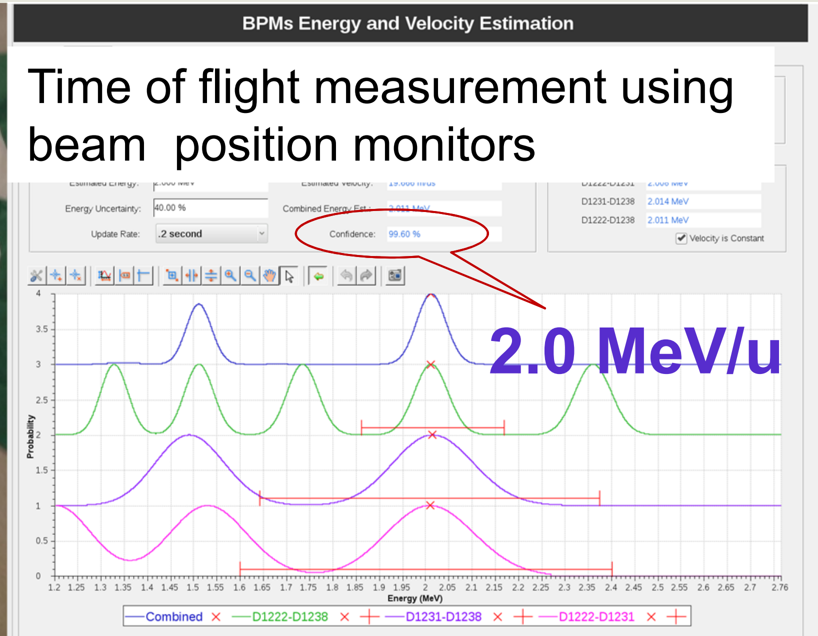
ARR02 Commissioning Conducted in Parallel to Linac Installation

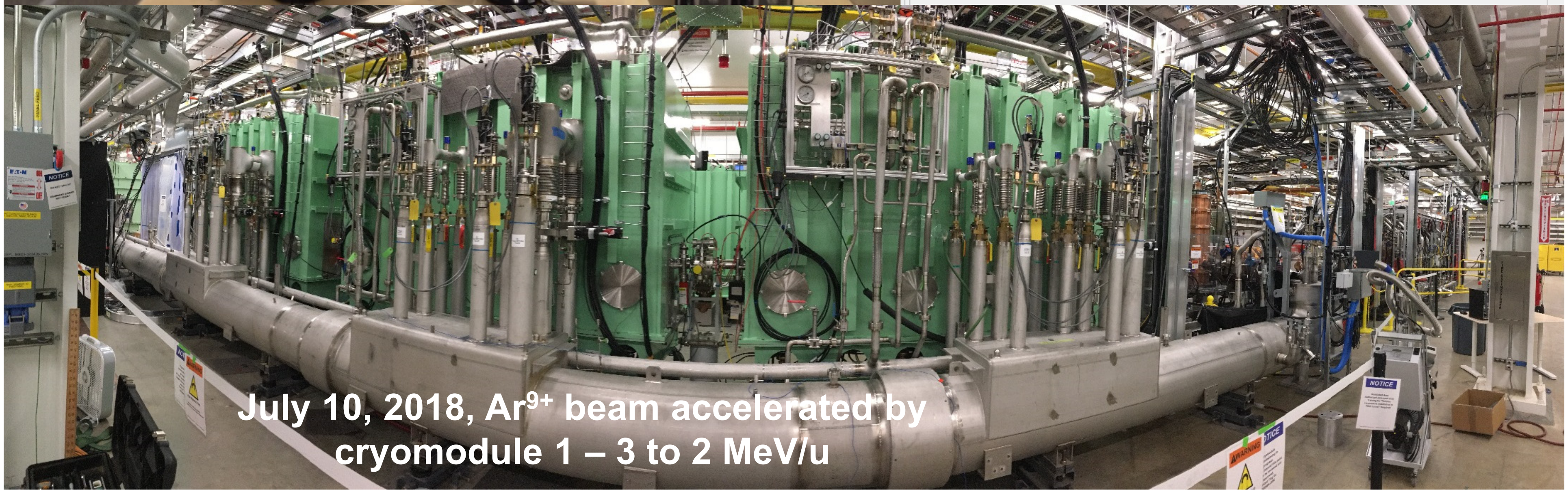
- Scope limited to expedite progress
  - Front End with room temperature ECR ion source
  - Cryomodules operating at 4 K temperature
  - Temporary diagnostics station
- Access control implemented on underground tunnel only
  - ECR ion source at surface allow flexible change of ion species
- Double shifts allow installation in parallel
  - Day shift for linac installation
  - Evening shift for beam commissioning
  - Rigorous access control and tunnel sweep procedures to ensure personnel safety



Cryomodule 1 – 3 Key Performance Achieved in 3 Days upon Authorization

ARR02 commissioning in the FRIB temporary control room

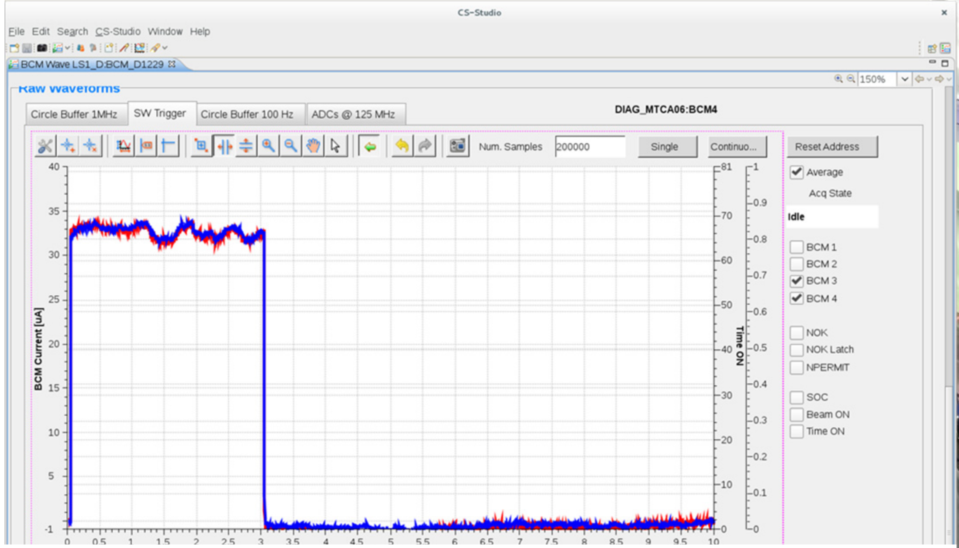




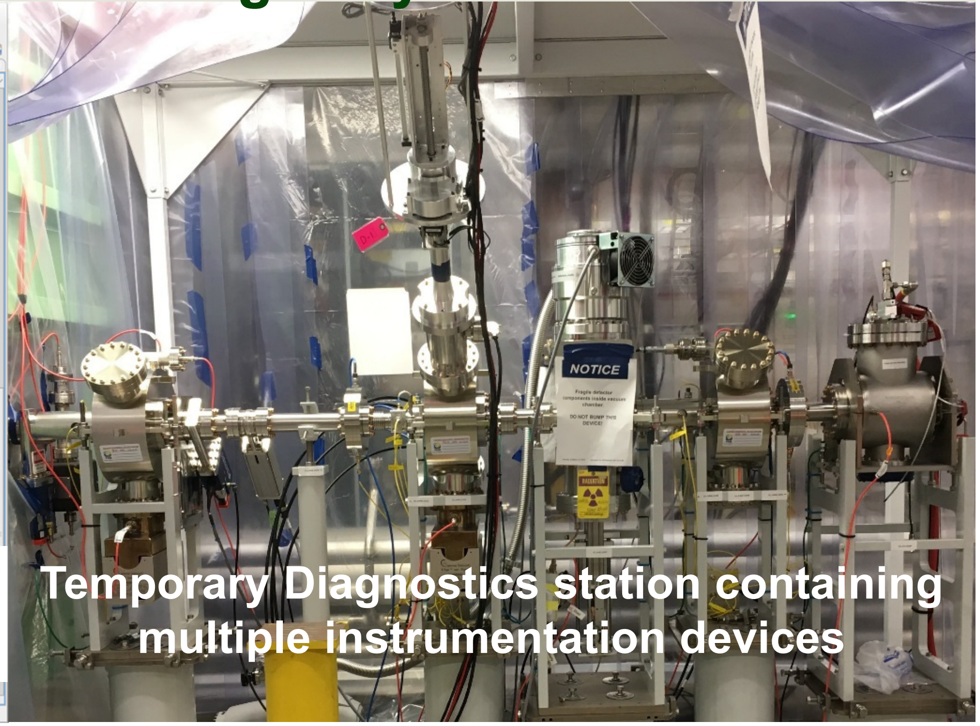
July 10, 2018, Ar^{9+} beam accelerated by cryomodule 1 – 3 to 2 MeV/u

Towards Higher Beam Duty / Power

Accelerated 66 W Beam to 1.5 MeV/u
100% Beam Transmission through Cryomodules



Demonstration of 30% beam duty, 33 µA peak current, 3 ms pulse length at 100 Hz



Temporary Diagnostics station containing multiple instrumentation devices

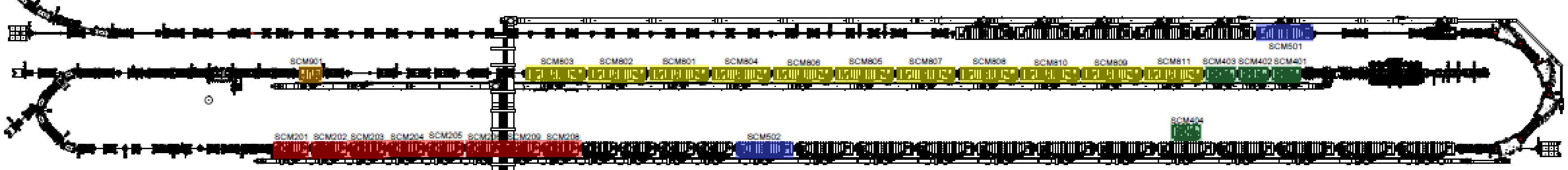
- 33 µA Ar^{9+} accelerated to 1.5 MeV/u with 30% duty factor
  - Further increase of duty factor was limited by outgassing from the Faraday Cup (FC) mounted on the temporary diagnostics station
- Can produce 38 kW on target if accelerated to the design energy in Continuous Wave (CW) mode

On Track towards ARR03

Scope Defined: 15 Cryomodules Accelerating Beams to 16 MeV/u

- ARR committee scheduled to meet January 23 – 25, 2019
  - F. Kornegay (Chair), J. Anderson (FNAL), D. Cossairt (FNAL), D. Curry (ORNL), G. Dodson (ORNL), M. Howell (ORNL), A. Zaltsman (BNL)

- Focus: hardware readiness
  - » Device Readiness Reviews (DRR03) leading to the ARR03
- Focus: people readiness
  - » Staff roles and responsibility; qualification, certification, and authorization
- Focus: system/documentation readiness
  - » Work plan/control, QA/QC, training, radiation protection, configuration control



- Color indicates: installed cryomodules

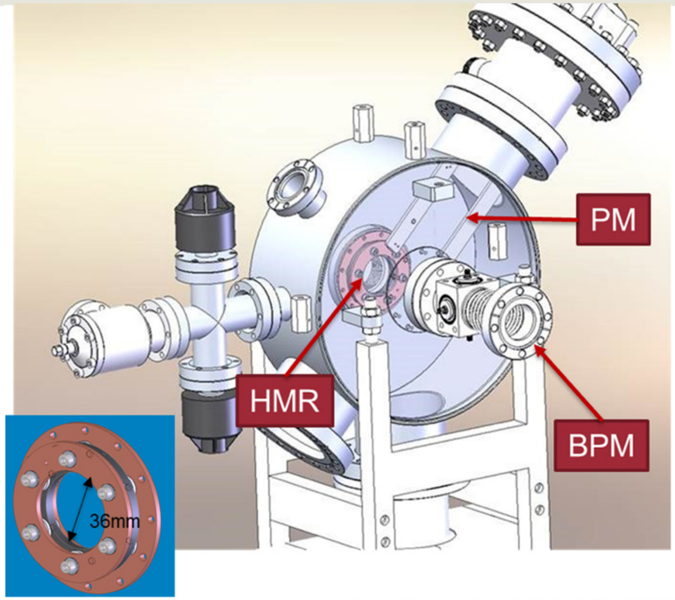
Technical Issue Resolution

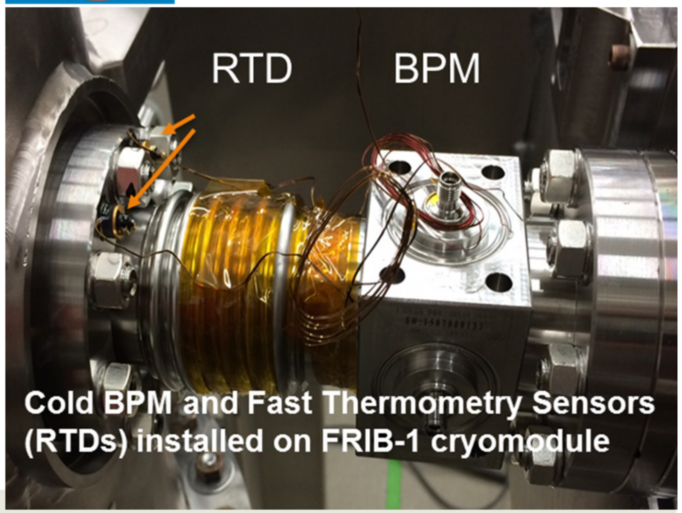
- Machine protection and low-sensitivity beam loss detection
- High-power charge stripping
- Microphonics suppression

Machine Protection Challenge

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
  - Differential current monitors for beam inhibit
  - 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

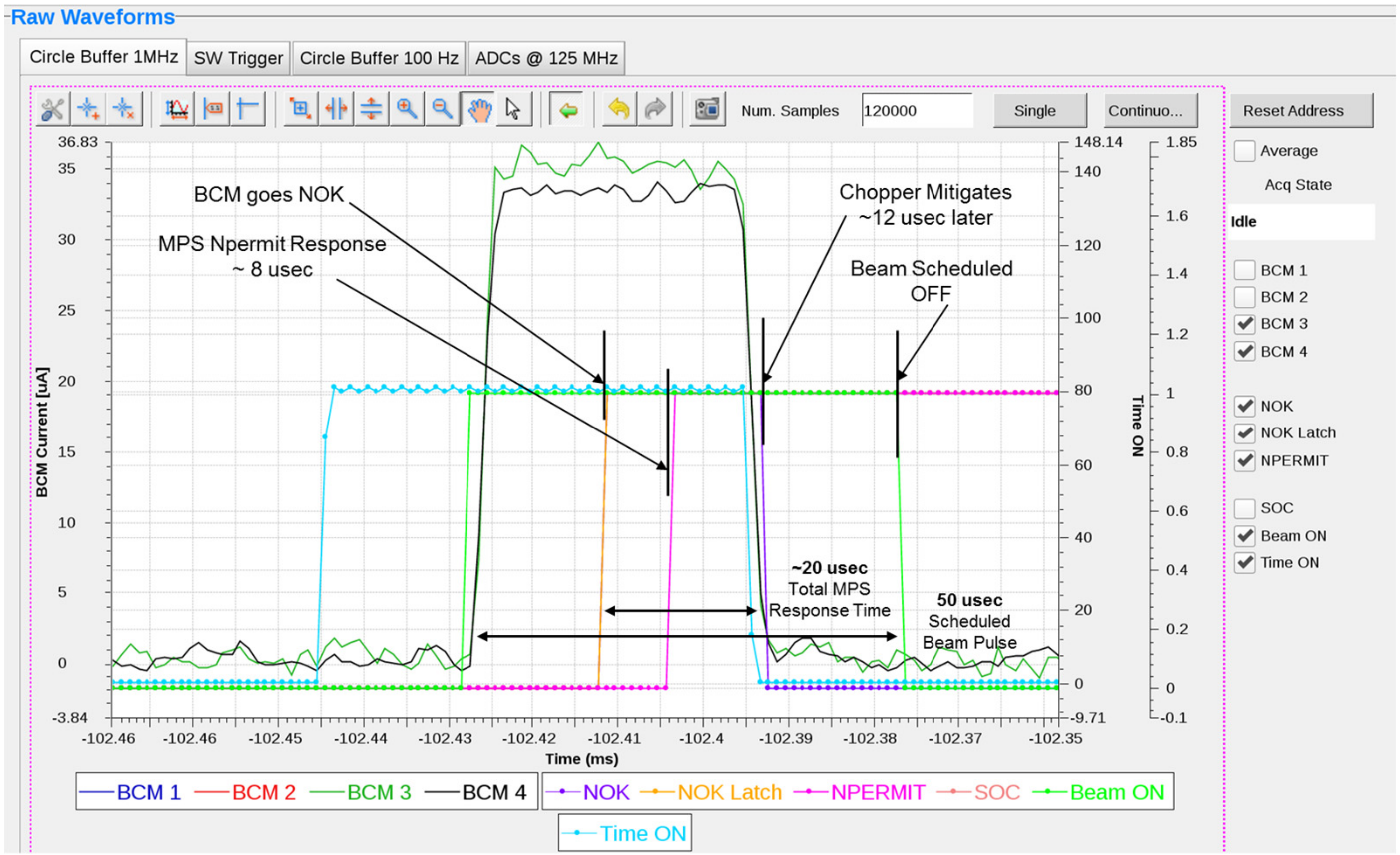
Machine Protection Practiced at ARR02
Multi-time Scale Mitigation Needed for Higher Beam Energy

- Mitigation of both acute & chronicle beam loss is needed for ARR03 and higher beam energy and power
- ARR02 is used to test and commission various MPS schemes

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

- ARR02 MPS steps
  - Use beam attenuator to reduce beam intensity by a factor of ~ 100
  - Commission both beam chopper and chopper monitor before skipping attenuator
  - Commission differential current monitor for beam inhibit
  - Test halo monitor ring and thermometry monitoring sensitivity

Machine Protection System Validated



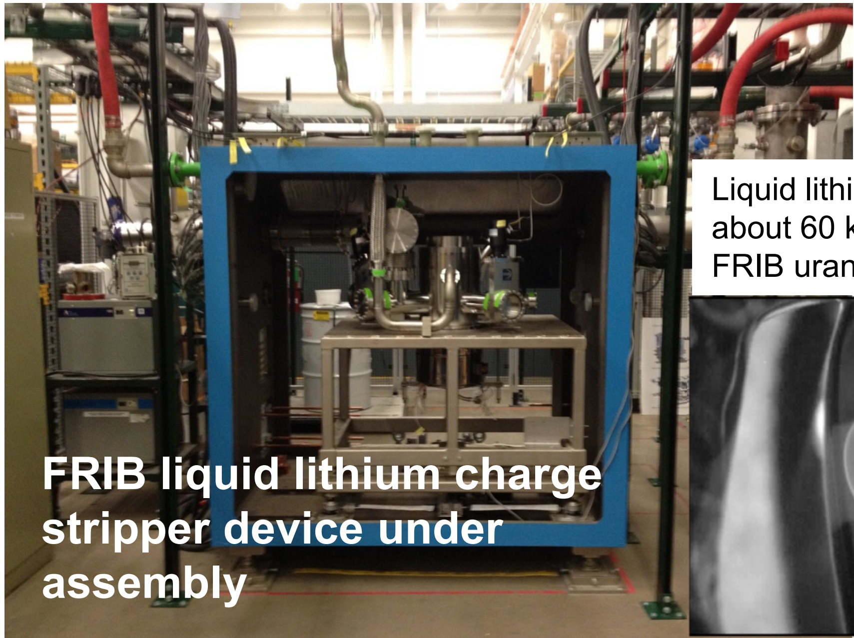
Demonstration of fast machine protection system responding within 35 µs

- Required response time of 35 µs demonstrated
  - Fault event detected in 15 µs; beam mitigated 20 µs later
  - Validated chopper function in fail safe mode
  - Redundancy in beam inhibit tested
    - » Ion source high voltage
    - » Electrostatic bend high voltage deflectors
    - » Beam plug in fail safe mode

High-power Charge Stripping Challenge
Carbon Foil; Helium Gas; Liquid Helium

- 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

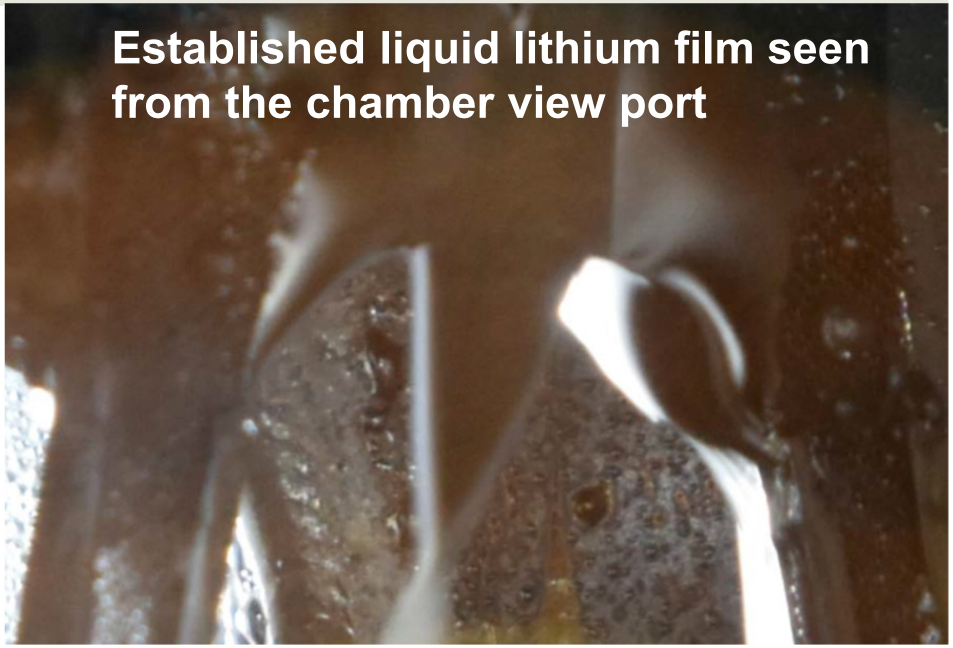
Los Alamos NATIONAL LABORATORY EST. 1943 Argonne NATIONAL LABORATORY



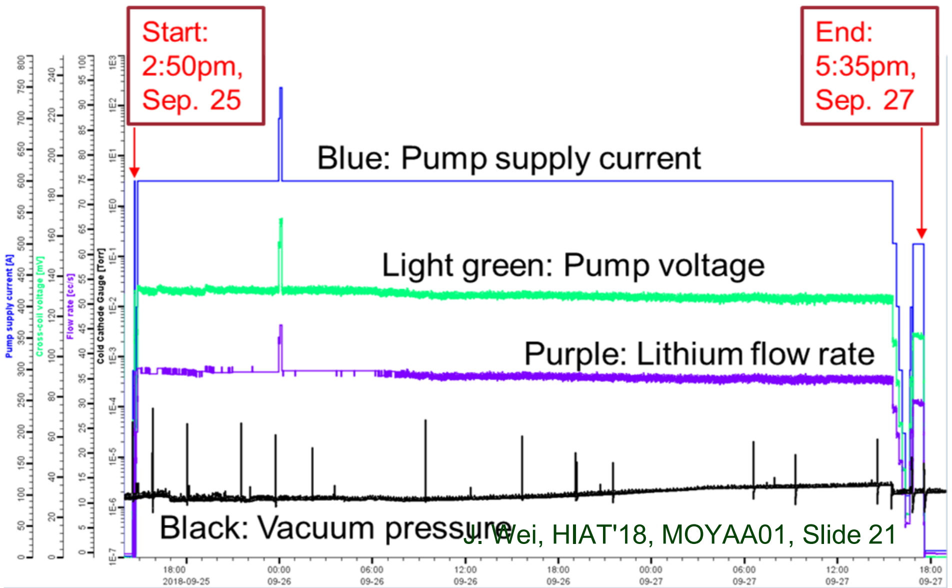
Liquid lithium film flowing at high speed (~ 50 m/s) intercepting a proton beam of about 60 kV at ANL. The test produced power deposition densities similar to the FRIB uranium beams.

Liquid Lithium Stripper Film Established
50 Hour Continuous Operations Completed

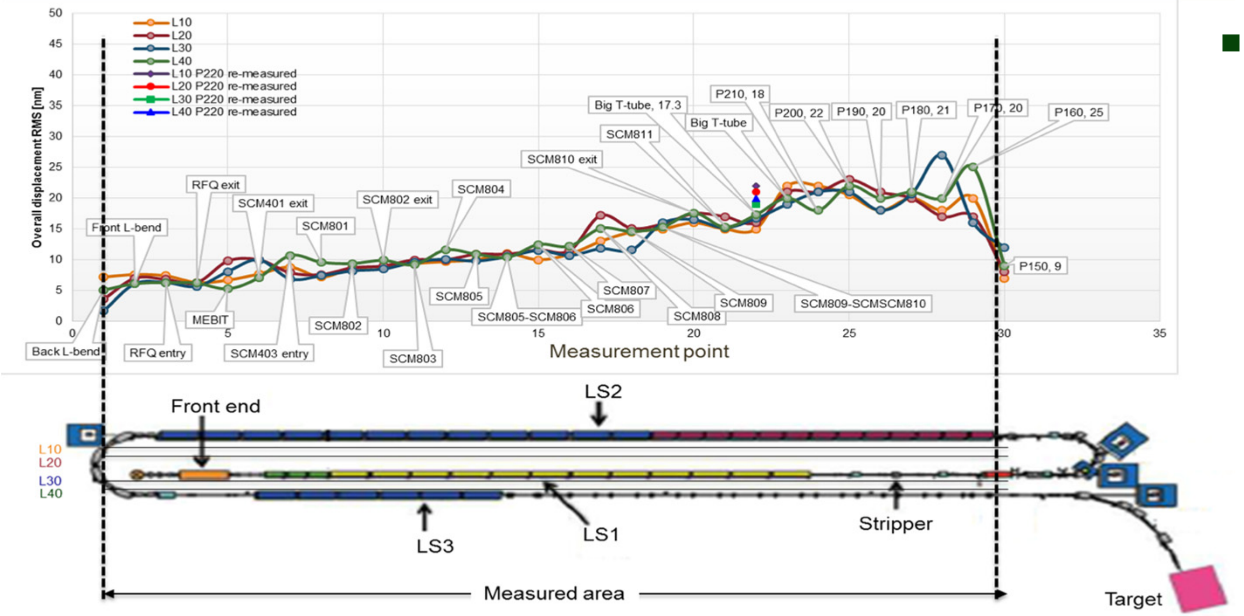

Loading of solid lithium stock


Established liquid lithium film seen from the chamber view port


Night shift during the 50-hour run



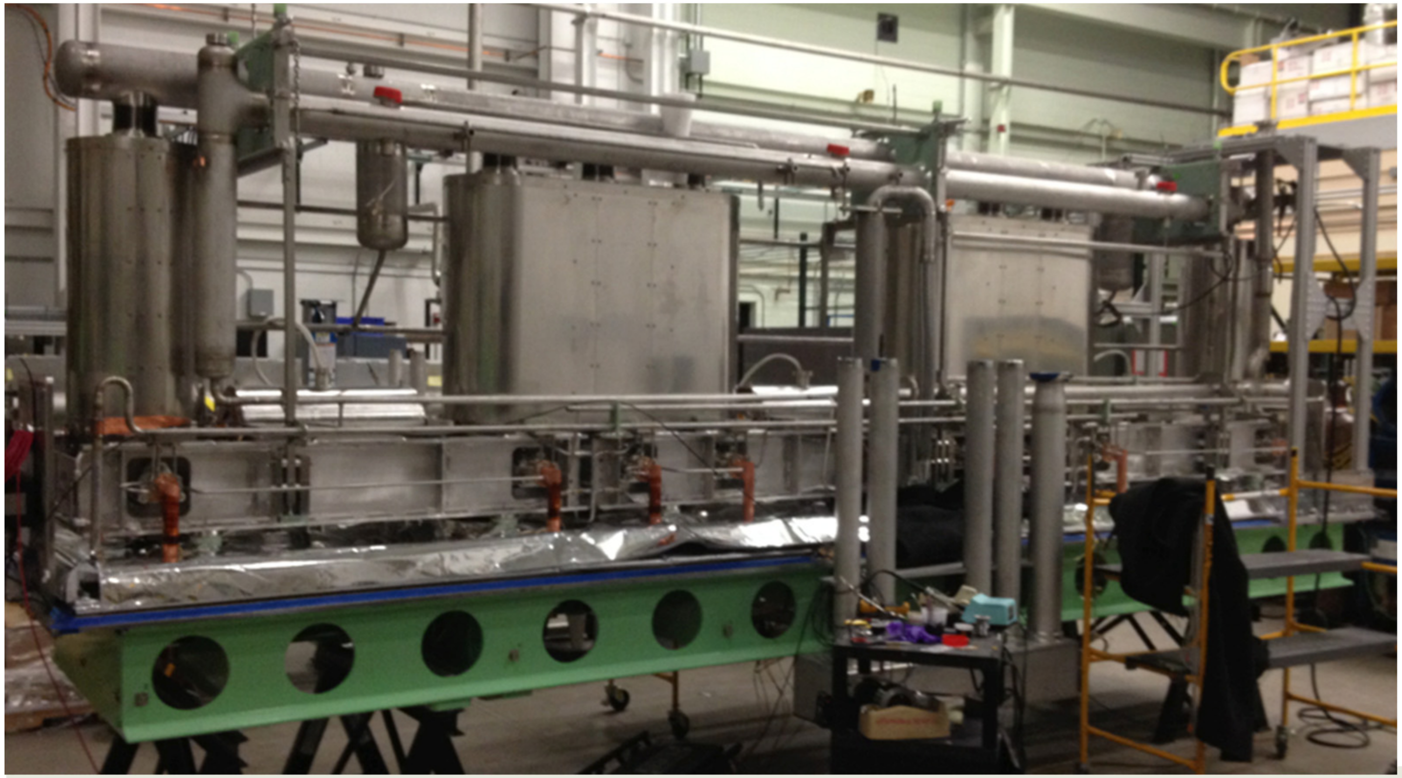
Microphonics Suppression Challenge
Successfully Locking Cavities at Operating Frequency



- Precautions in compressor design & installation mitigated microphonics concerns
  - Verified by tunnel measurement of vibration at multiple occasions
  - Confirmed by beam commissioning
- Promptly resolved cavity locking issue upon initial cool down
  - Iteration on valve controls logic
  - Provision for liquid helium supply from 10,000 liter Dewar

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

Infrastructure Growth

- The MUS ryogenics Initiative
- SRF Highbay & Cryogenics Assembly Building
- World wide recruitment of subject matter experts for high-power accelerator science and engineering

MSU Cryogenic Initiative Addresses National Need

Design of Large Cryoplants 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)

College of Engineering
MICHIGAN STATE UNIVERSITY

Cryogenic Initiative Focuses: Education, R&D, Facility Support

- Education
  - University courses
  - US Particle Accelerator School courses
  - Conference tutorial class
- Research & development
  - Main compressor efficiency improvements
  - Low level impurity removal
  - Small 2 K system for laboratory use

- Facility support
  - FRIB Cryoplant, cryo-distribution, cryomodule and superconducting magnets
  - National needs in major projects: LCLS-II, PIP-II, electron ion collider
  - World wide demands in cryogenics for large accelerator projects

"SRF High Bay" Constructed at MSU

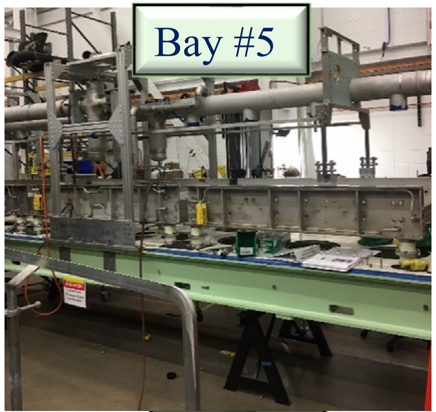
Infrastructure Investment for FRIB Construction & SRF Research

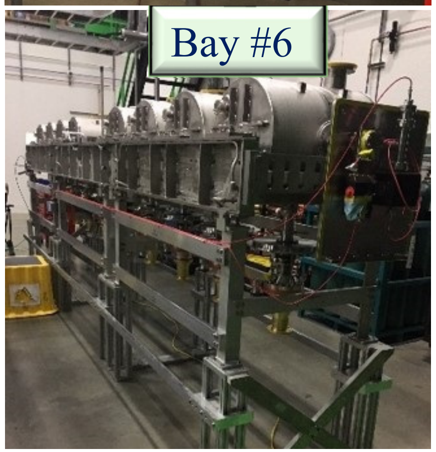
Objective Measures	Date
Ready-for-equip.	01/2014
Beneficial occu.	05/2014
Clean 1st cavity	07/2014
Coord. measure.	09/2014
Degassing furnace	10/2014
Etch 1st Cavity	12/2014
Cryogenics system	09/2015
RF test 1st cavity	11/2015
Vertical test area	01/2016
Cryomodule test	09/2016

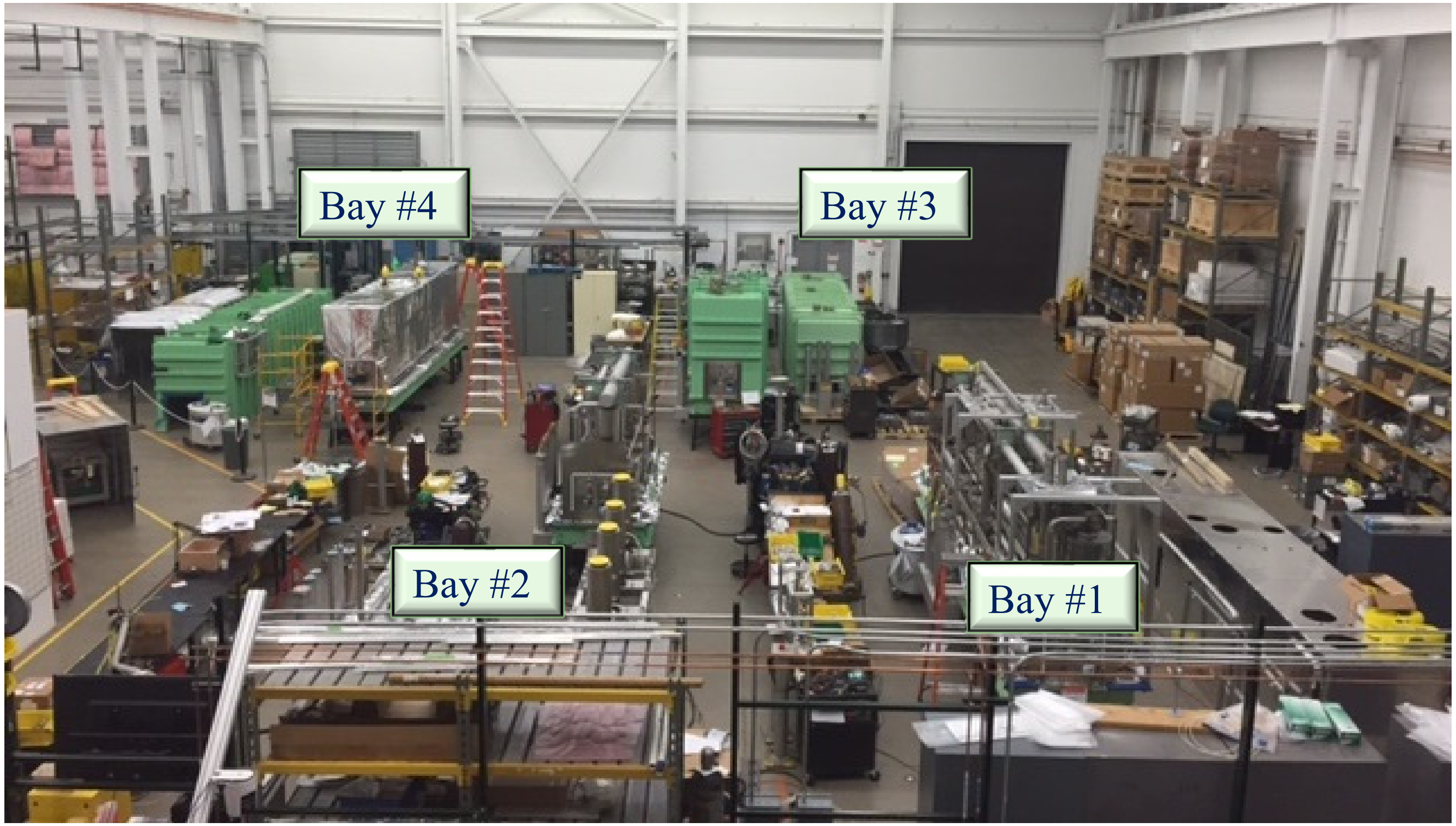
- Production throughput:
  - 5 cavity per week
  - ~ 1.5 coldmass per month

Six Cryomodule Assembly Bays in Parallel

Producing > 1 Cryomodules Per Month at MSU



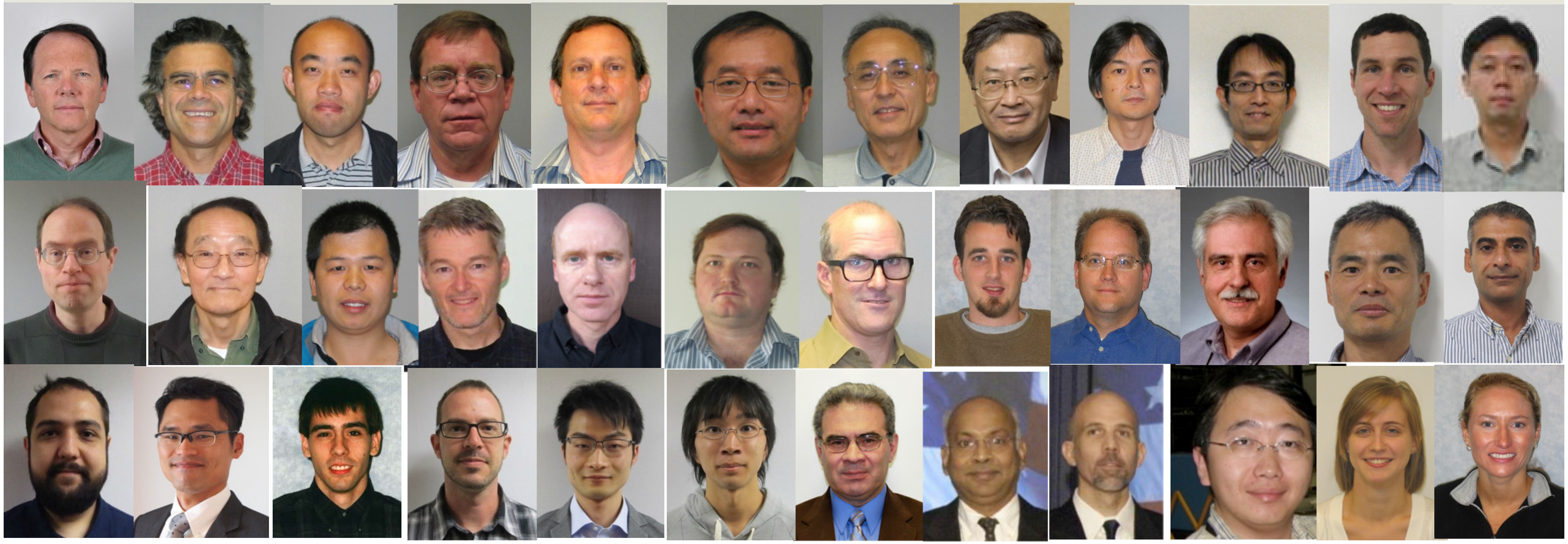




- MSU-funded SRF infrastructure:
  - **SRF Highbay**, 2500 m^2 with full processing and certification capacity of testing 5 cavity per week and assemble 1.5 coldmass per month
  - Cryomodule assembly area housing 6 parallel assembly lines yielding > 1 cryomodule per month
  - **Cryogenic Assembly Building**, 1440 m^2 for future cryomodule and magnet maintenance

Attracted World Experts in Key Areas

With Culture Background from ~ 30 Countries



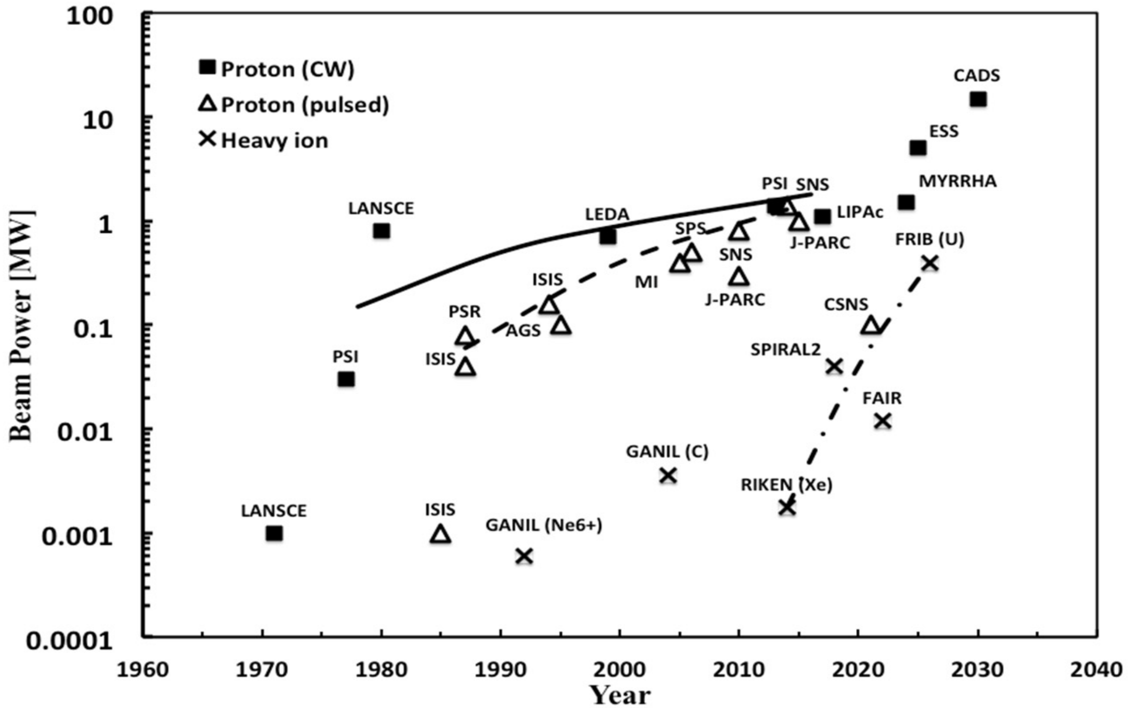
- Attracted seasoned leaders in accelerator physics and engineering
  - H. Ao (J-PARC), N. Bultman (LANL), F. Casagrande (ORNL), J. Chen (PPPL), D. Chabot (BNL), L. Dalesio (BNL), A. Facco (INFN), K. Fukushima (U. Hiroshima), V. Ganni (JLab), A. Ganshyn (Cornell), P. Gibson (ORNL), W. Hartung (Cornell),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

Power Ramp Up and Upgrade

- Power ramp up challenges
- Upgrade preparation

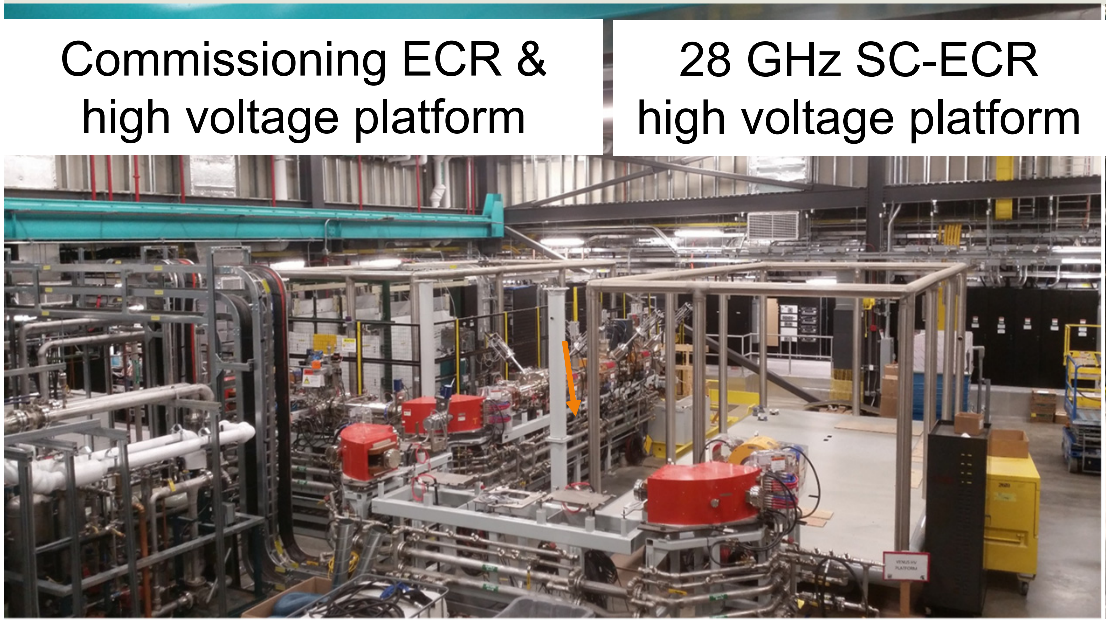
FRIB Physical and Engineering Challenges
Raising Heavy-ion Power Frontier by Two Order-of-magnitudes

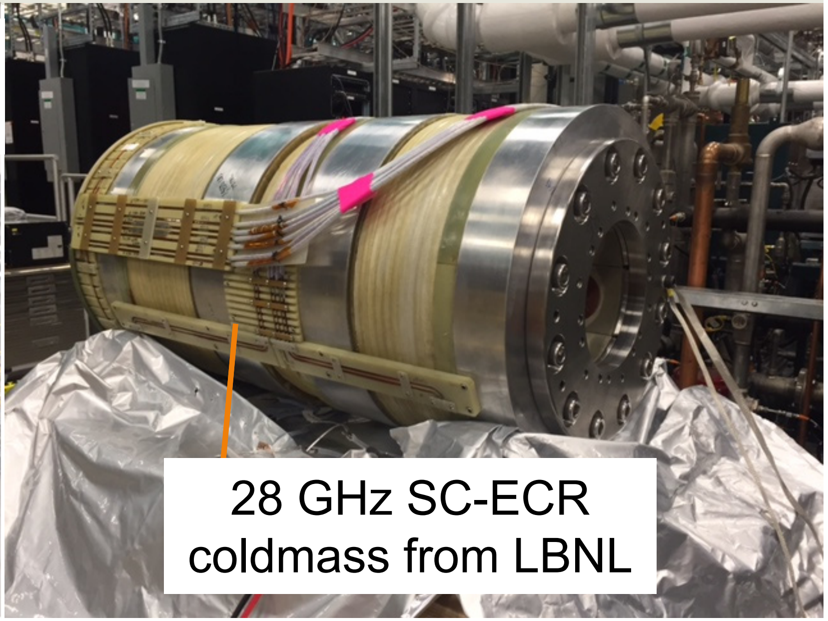
- SNS raised pulsed proton power frontier by one order-of-magnitude
  - Physical challenges: electron cloud mitigation; beam loss control
  - Engineering challenges: 1st full-scale superconducting RF proton linac; high-power target
- FRIB will raise heavy-ion power frontier by two order-of-magnitudes



- 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

Hardware Requirements for Beam Power and Accelerator Availability Ramp Up

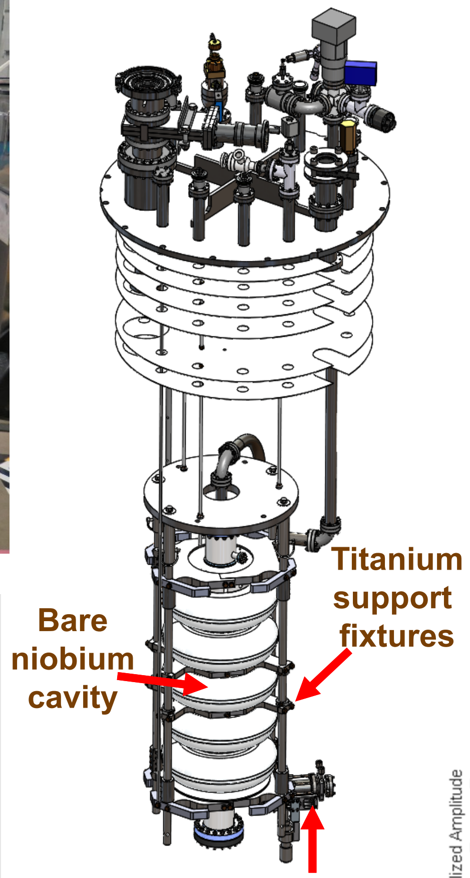




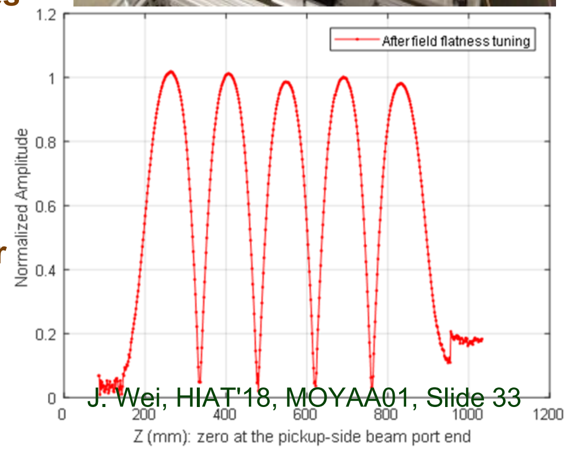
- Hardware upgrades from commissioning to full power operations
  - 28 GHz superconducting ECR ion source
  - Liquid lithium charge stripper fully operational
  - High-power charge selector (rotating disc for heat dissipation)
  - Beam collimation system of scrapers and collectors
- Operational experience necessary for high availability and reliability
  - Highly reliable machine protection and alarming systems
  - Automated tuning and fault recovery
  - Ion source development for user demands and flexibility

Energy Upgrade with β=0.65 Elliptical Cavity
In-house Certification for FRIB Upgrade Prototype Cryomodule

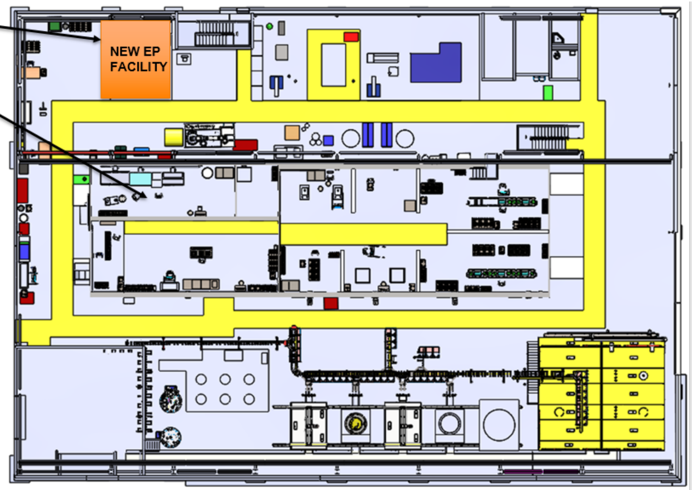
Dunk Test Insert for 644 MHz Upgrade Cavity



Field profile measurement after bulk EP, baking, and tuning



- New EP Facility
- Existing BCP Etching Facility



Summary

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
- IMP, CAS (China)
  - Room temperature magnet
- Tsinghua University (China)
  - RFQ
- TRIUMF (Canada)
  - SRF; beam dynamics

FRIB Project Started in June 2009 and Will Be Complete before 2022

- FRIB Project is about 87% complete, on budget, and being managed to early completion in 2021, CD-4 is in June 2022
- Beam commissioning is proceeding in parallel with installation
  - Frontend is complete – accelerated argon and krypton beams
  - 4K cryoplant operational and making liquid helium
  - More than 50% of needed 49 cryomodules are completed and installed
  - Beams are accelerated through first 3 cryomodules in 2018
- 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
- 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

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Thank You!