The Facility for Rare Isotope Beams Project – Accelerator Challenges and Progress

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On Behalf of FRIB Accelerator Team & Collaboration

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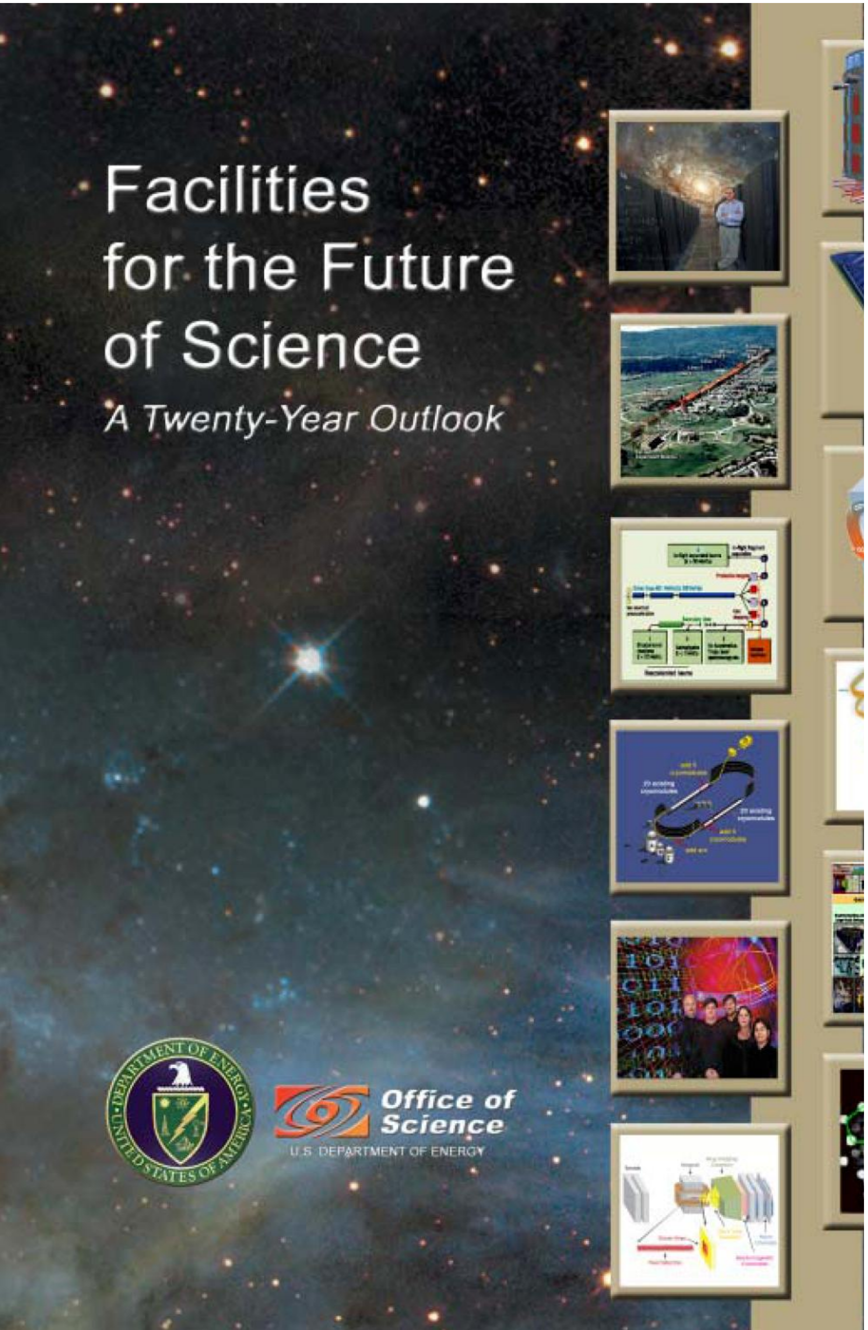
Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Outline

- Introduction
- Design philosophy
- Accelerator physics challenges
- Technology challenges
- Accelerator design
- Subsystem design and acquisition
- Future perspectives
- Acknowledgements

DOE Science Facility 20 Year Outlook



Facilities for the Future of Science:
A Twenty-Year Outlook

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FRIB Project at MSU
Project of $680M ($585.5M DOE, $94.5M MSU)

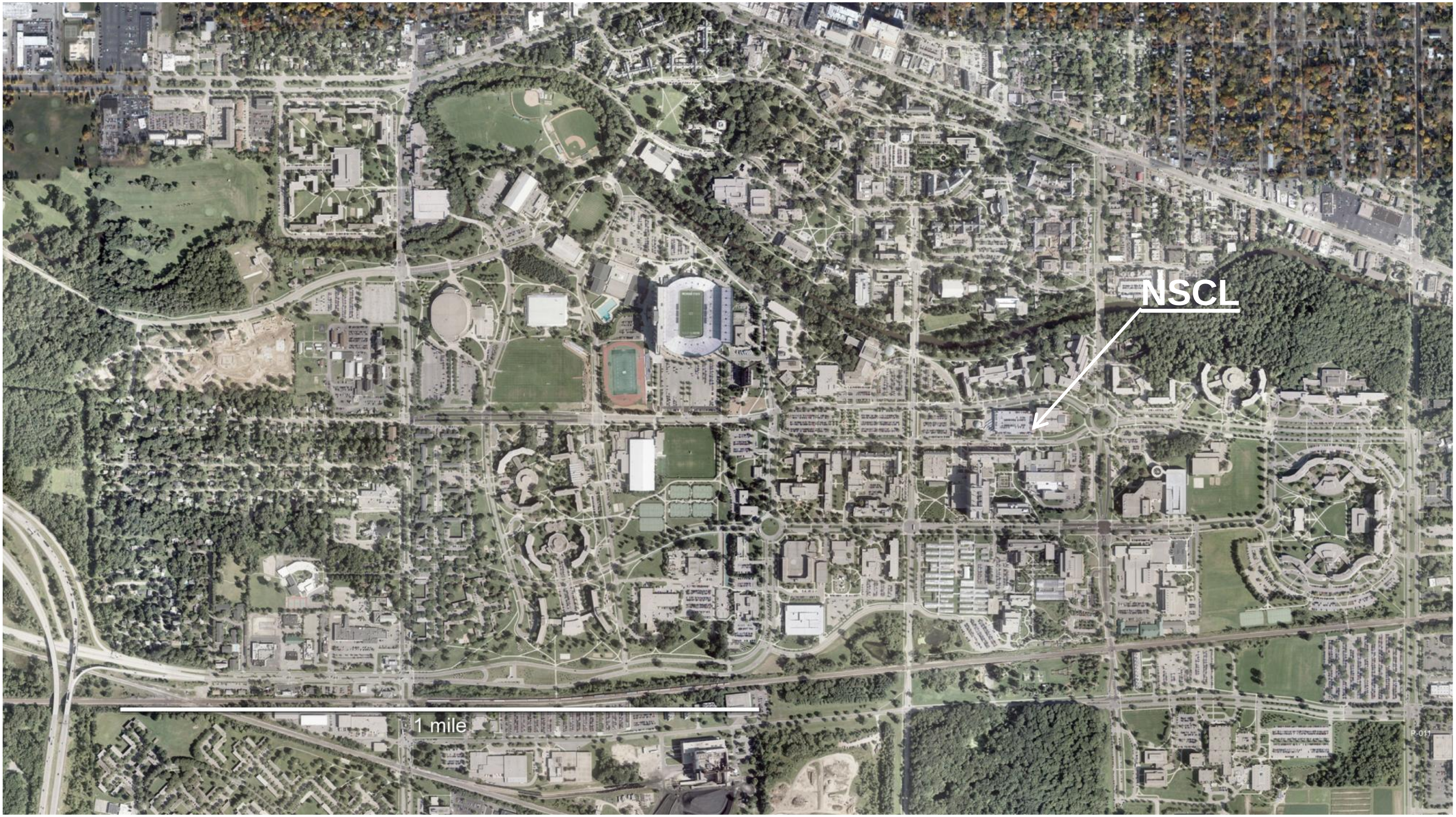
- Dec. 2008: DOE selects MSU to establish FRIB
- June 2009: DOE and MSU sign corresponding cooperative agreement
- Sept. 2010: CD-1 granted; conceptual design complete & preferred alternatives decided
- April 2012: performance baseline & start of conventional facility construction readiness completed

Growth from more than 500 employees today at NSCL, MSU

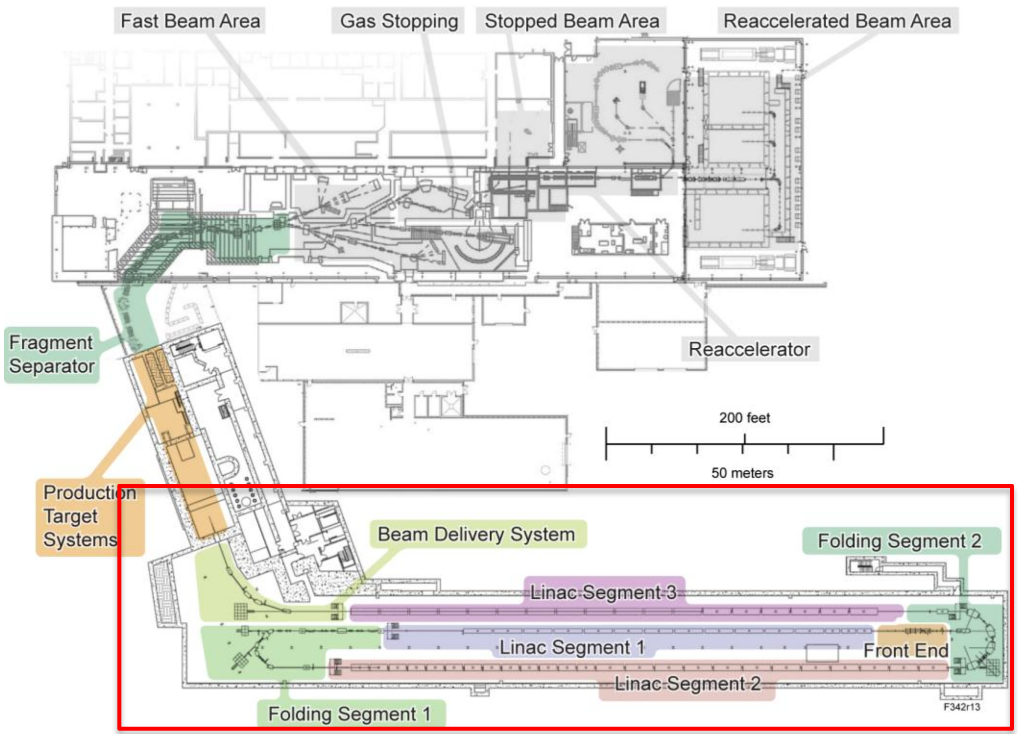
More than 1200 registered user at NSCL user group and at FRIB user organization

Michigan State University

57,000 people; 36 sq mi; $1.8B annual revenue; 552 buildings

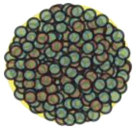


FRIB Accelerator Design Requirements



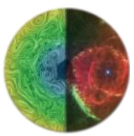
- Delivers FRIB accelerator as part of a DOE-SC national user facility with high reliability & availability
- Accelerate ion species up to ^{238}U with energies of no less than 200 MeV/u
- Provide beam power up to 400 kW
- Satisfy beam-on-target requirements
- Energy upgrade by filling vacant slots with 12 SRF cryomodules
- Maintain ISOL option
- Upgradable to multiuser simultaneous operation of light/heavy ions with addition of a light-ion injector

The Science of FRIB is Endorsed by NSAC and NRC



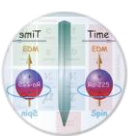
Properties of nuclei

- 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.



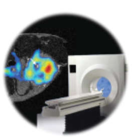
Astrophysical processes

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



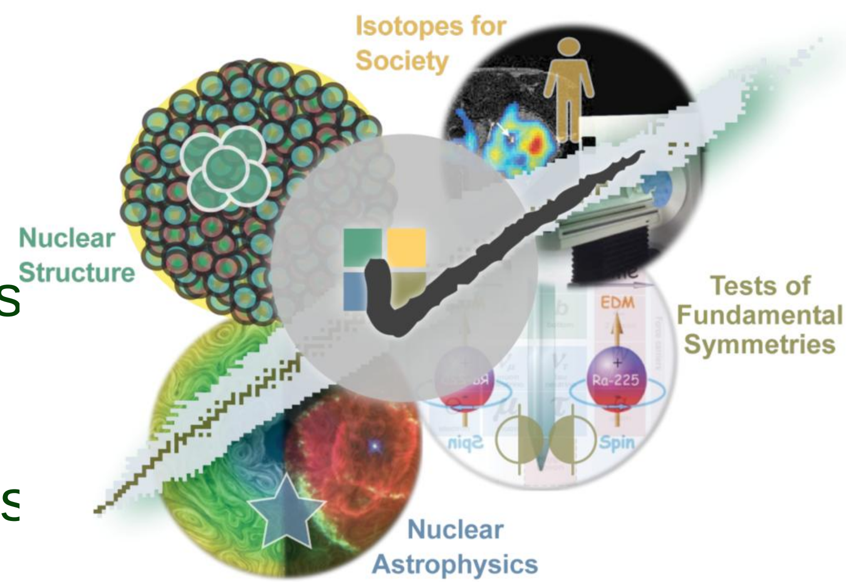
Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei



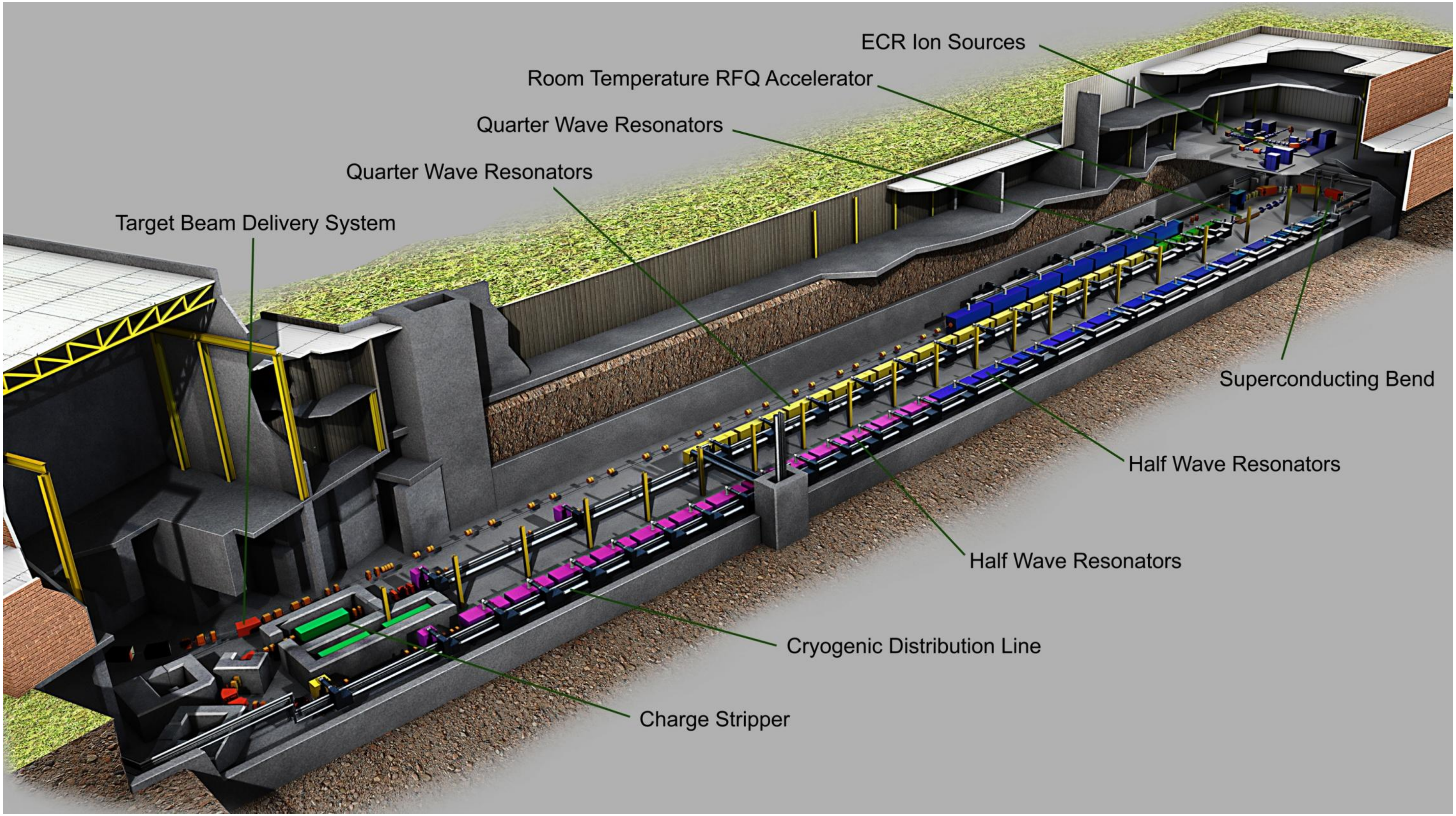
Societal applications and benefits

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



FRIB Civil Design Completed

Close Integration Between Accelerator & Civil Designs



Accelerator Design Philosophy

- A full-energy linac driver to provide beam quality that user desires
  - Full-scale CW linac using superconducting RF low-β cavities
- Meet stringent requirements demanded by experimental programs
  - Up to 400 kW of beams are focused to a diameter of 1 mm (90%)
  - Energy spread of 1% (95% peak-to-peak), and bunch length of < 3 ns
  - Intensity range of 10^8 – diagnostics & controls requirements
- Support FRIB as a national scientific user facility
  - Availability
  - Maintainability
  - Reliability
  - Tunability
  - Upgradability

Accelerator Availability & Upgradability
Design Supports Multiple Operational Scenarios

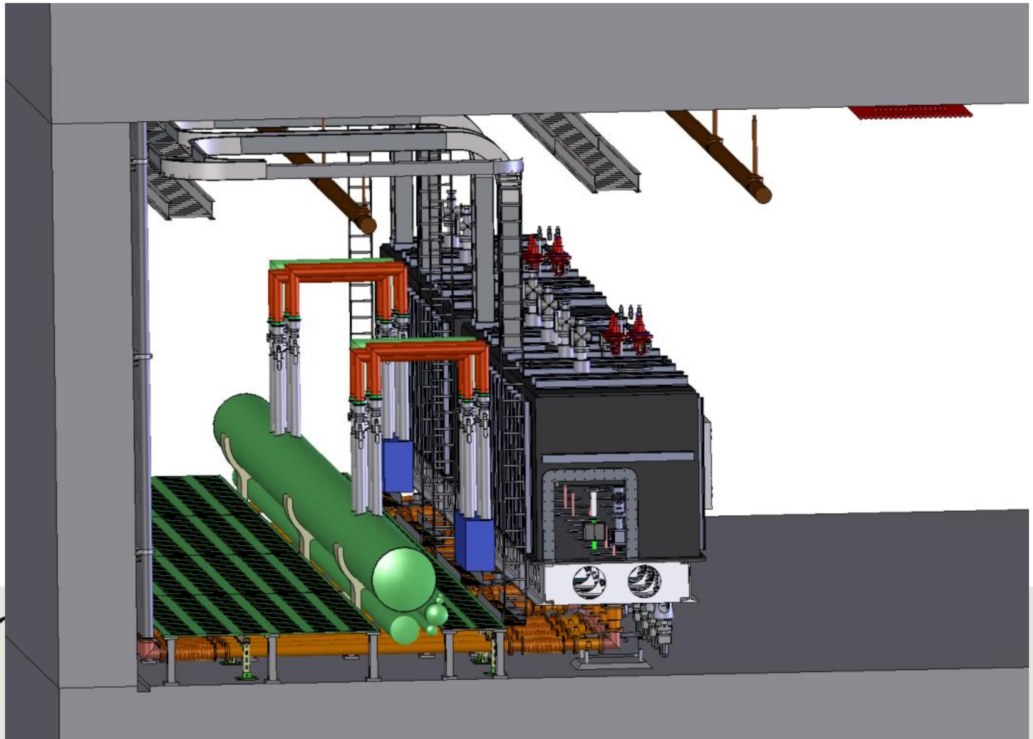
- Baseline scenario (200 MeV/u, 400 kW) with liquid Li stripper for U^{78+}
  - Multiple ion sources for enhanced availability
- Alternative scenario with He gas stripper for U^{71+}
  - Folding segment optics accommodates both stripping scenarios
- Fault scenario tolerated – comparable to SNS day-1 condition
  - Tolerate 20% cavity underperformance; single cryomodule failure; lower stripping efficiency (charge state down to U^{63+})
- Upgrade scenarios to 300 and 400 MeV/u supported

^{238}U beam

Scenario	Charge state (average)	Energy [MeV/u] (baseline)	Energy [MeV/u] (baseline + + 3 C.M.)	Energy [MeV/u] (baseline + + 12 C.M.)	Energy [MeV/u] (baseline + 12 C.M.) (35% gradient enh. for β=0.29 & 0.53)
Proposed					
Baseline	78+	202	228	306	413
Alternative	71+	179	202	275	375
Fault	63+	155	176	247	342

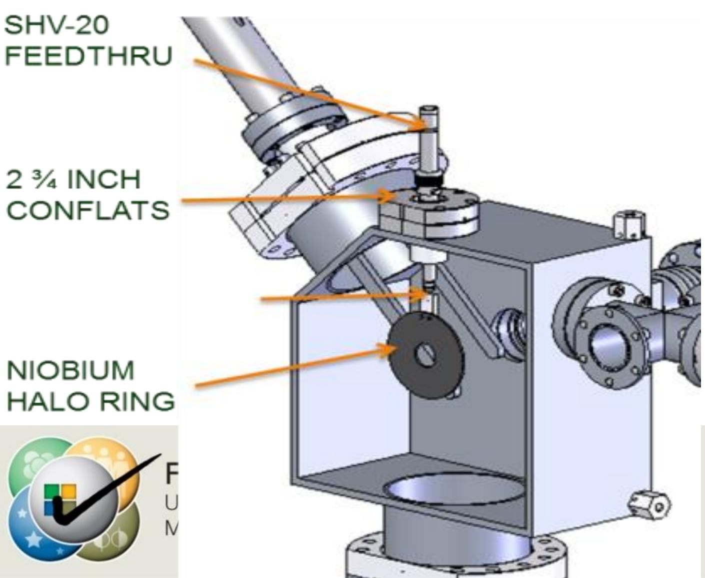
Accelerator Maintainability

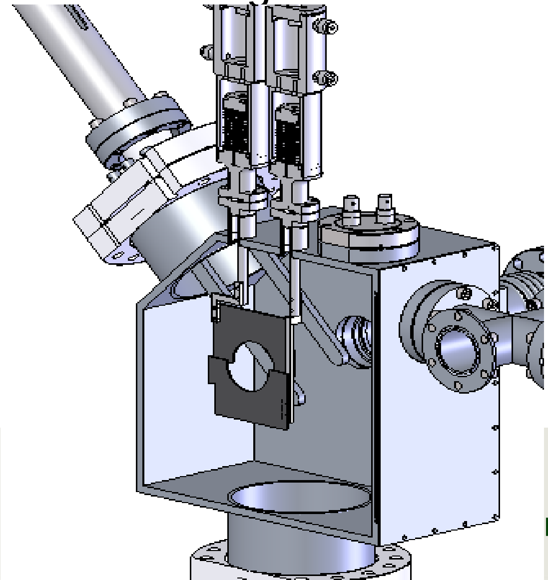
- Limit uncontrolled beam loss below 1 W/m for all ion species
  - Proton: activation below 1 mSv/h; ^{238}U: machine protection & cryo load req.
- Ion sources placed at grade level 10 m above tunnel
- Adopt bayonet/U-tube and integrate heat exchanger/JT valve to cryomodule improving individual cryomodule maintainability
  - Integrated designs of cryomodule, cryogenic distribution, and cryogenic plant



Accelerator Reliability
Machine Protection on Acute and Chronic Beam Losses

- Addressing key reliability and availability aspects
  - Prevent permanent accelerator component damage
  - Minimize beam loss and residual activations
  - Reduce long and frequent beam interruption, e.g. solenoid quench, cryogenic load raise
- Beam loss detection is challenging: gas monitor insensitive to low energy HI beam; signal crosstalk due to folding linac footprint
  - Damages to accelerator components may occur in 40 μs; MPS budget is 35 μs: 15 μs diagnostic, 10 μs control, and 10 μs beams in pipe
- Machine protection on acute (fast) chronic (slow) beam loss
  - Monitor beam loss using halo scraper rings at warm region between cryomodules
  - Gas chamber detection on acute beam loss at high energy
  - Beam current monitor at entrance and exit of each linac segments

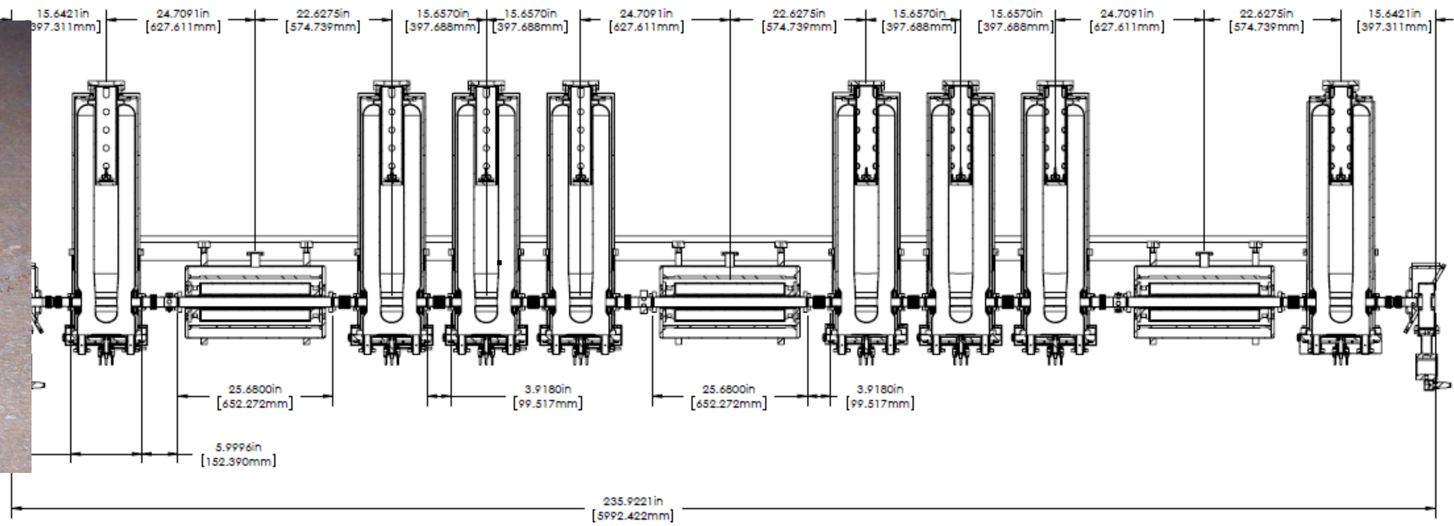




FRIB

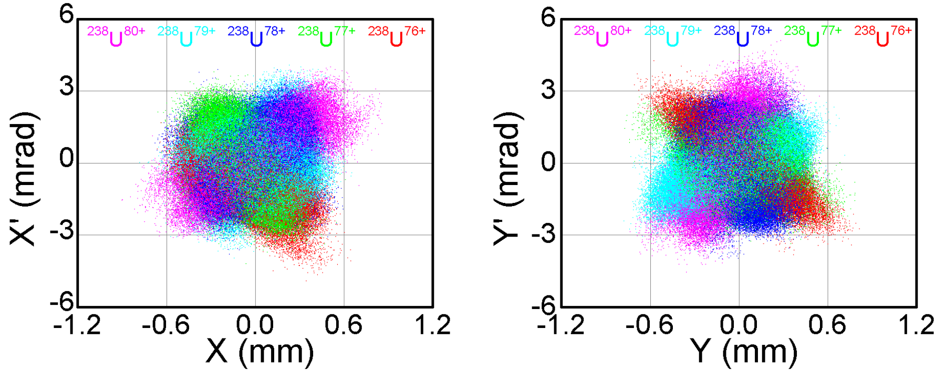
Accelerator Tunability
Example: Linac Segment 1 Cold BPM for On-line Tuning

- CD-1 lattice design did not allow tuning of whole machine at once
  - Lattice only allowed one-at-a-time steering making tuning operationally impractical (warm BPM at unfavorable phase-advance locations)
- Implement 39 “cold” beam position monitors (BPM) – allowing practical beam steering for increased accelerator availability
  - Cold BPM facilitates response-matrix-based on-line tuning for greatly improved machine availability



Accelerator Physics Challenges

- Combined challenges of heavy-ion & high-power accelerator
  - Fractional uncontrolled beam loss at 10^{-6} per m level
  - Protons: activation & shielding issues; ^{238}U: material damage & heat load
- Limited aperture of accelerating structures (low-β vs. elliptical cavity)
- Simultaneous acceleration & overlapping of multi-charge-state beams
  - Achromatic optics design (transverse) & cavity placement (longitudinal)
  - Diagnostics and control capabilities
- Accurate alignment of "cold" elements in cryomodules
  - 9-T solenoid & BPM to be aligned to < 1 mm under cryogenic condition
- Stringent beam-on-target requirements
  - Requiring corresponding beam diagnostics & control



Technology Challenges

- Charge stripping
  - Solid foils unable to survive on the high-power, high-charge-state beams
  - Collaboration with ANL on liquid-lithium stripping film (low vapor pressure)
  - Collaboration with BNL on plasma window to contain helium-gas stripper
    - » Also benefit from development progress at RIKEN on helium gas stripping
- Superconducting RF
  - > 10 years of development at MSU on low-β SRF, benefiting from seminar work at INFN
  - Collaboration with JLab and ANL
    - » subcomponent development & processing
  - Benefit from consultations with world experts from INFN, TRIUMF, JLab, ANL, FNAL etc.
- Collaboration with major institutes and laboratories world-wide on key accelerator subsystems

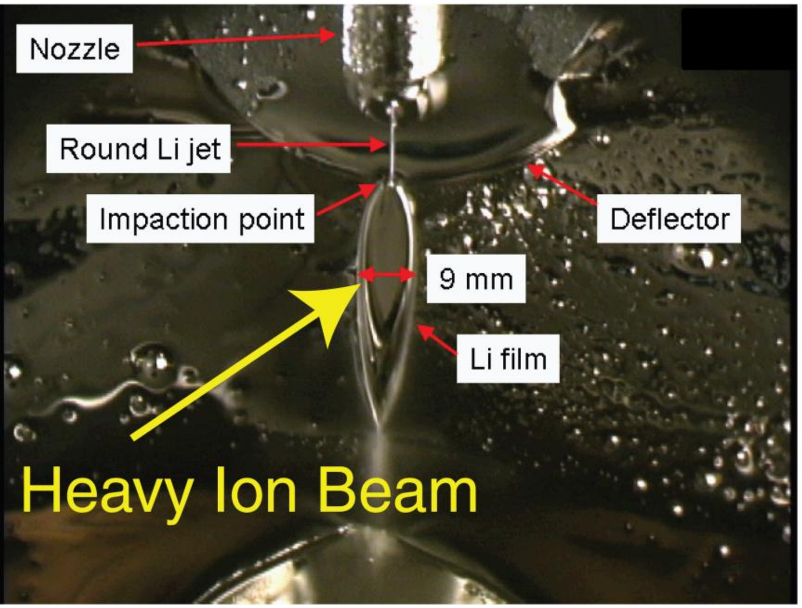
FRIB Accelerator Systems Division Key Collaborators

- ANL
  - Liquid lithium stripper
  - Beam dynamics verification
  - β=0.29 HWR design and prototype*
- BNL
  - Plasma window & charge stripper, physics modeling, database
- FNAL
  - Diagnostics
- JLab
  - Cryogenics systems design
  - QWR & HWR hydrogen degassing
  - PANSOPHY e-traveler
  - HWR processing & certification*
- LANL
  - Proton ion source, RFQ
- LBNL
  - ECR ion source; beam dynamics**
- ORNL
  - Diagnostics, controls
- SLAC**
  - Cryogenics**, SRF multipacting**, physics modeling
- RIKEN
  - Helium gas charge stripper
- TRIUMF
  - Beam dynamics design, SRF, physics modeling
- INFN
  - SRF technology
- KEK
  - SRF technology
- IMP
  - Magnets*
- Budker Institute, INR Institute
  - Diagnostics
- Tsinghua Univ. & CAS
  - RFQ*
- ESS
  - AP*

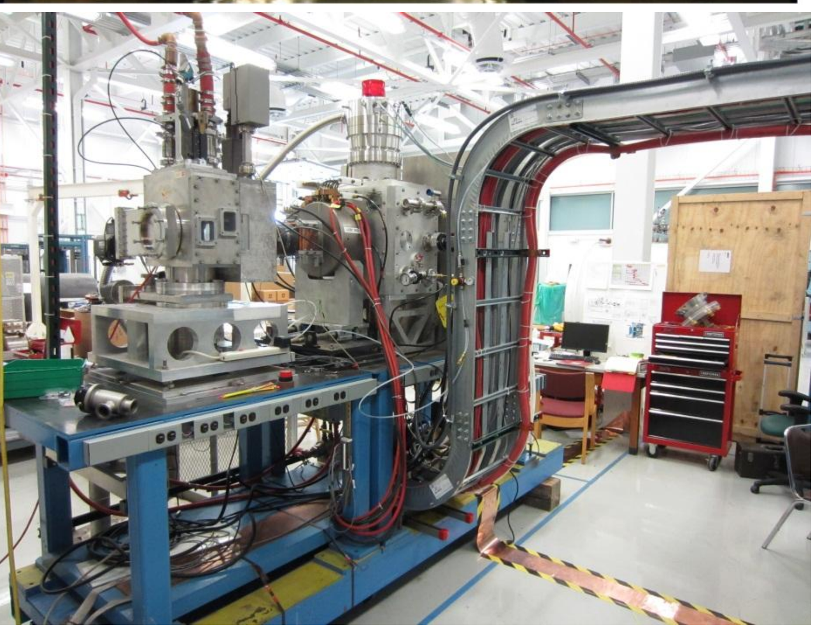
* Under discussion or in preparation

** Completed

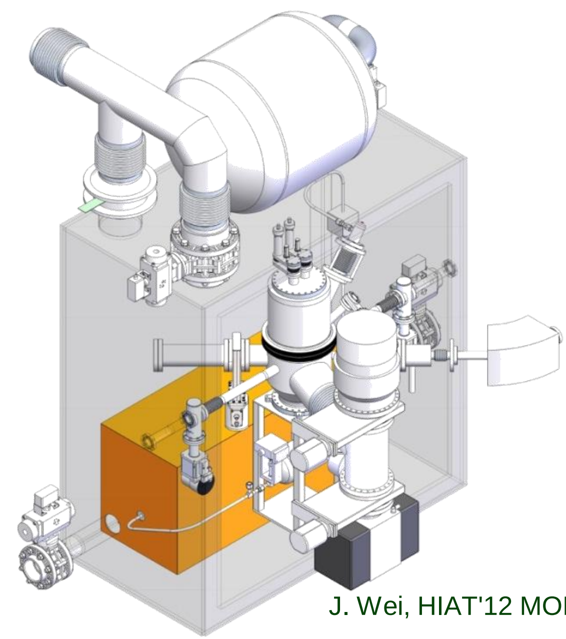
Charge Stripping Developments



- Liquid lithium film established at ANL with controllable thickness & uniformity
- High-power beam test pursued with LEDA source
  - LANL proton source shipped to MSU for beam tests of the lithium film at ANL
- Li film tests at MSU on density effects

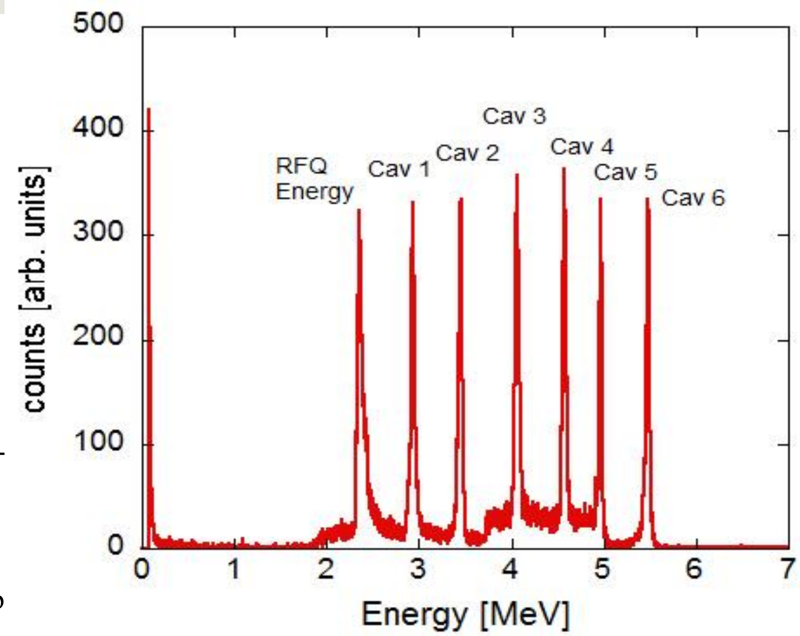


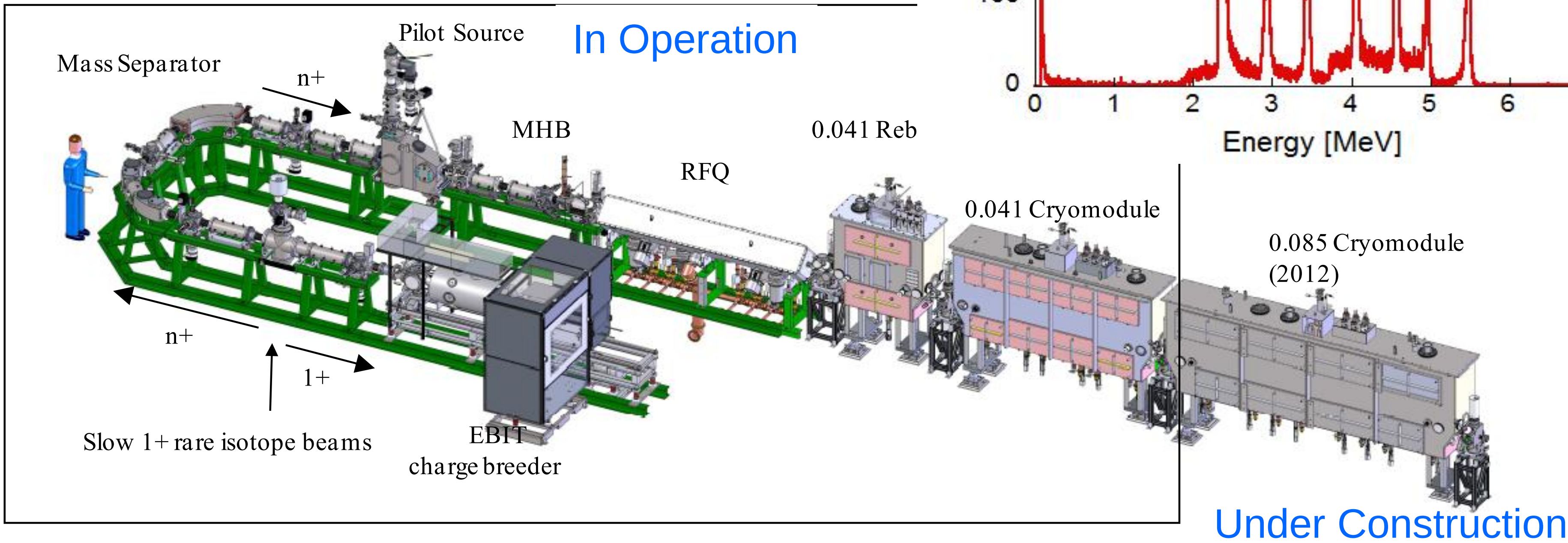
Argonne NATIONAL LABORATORY



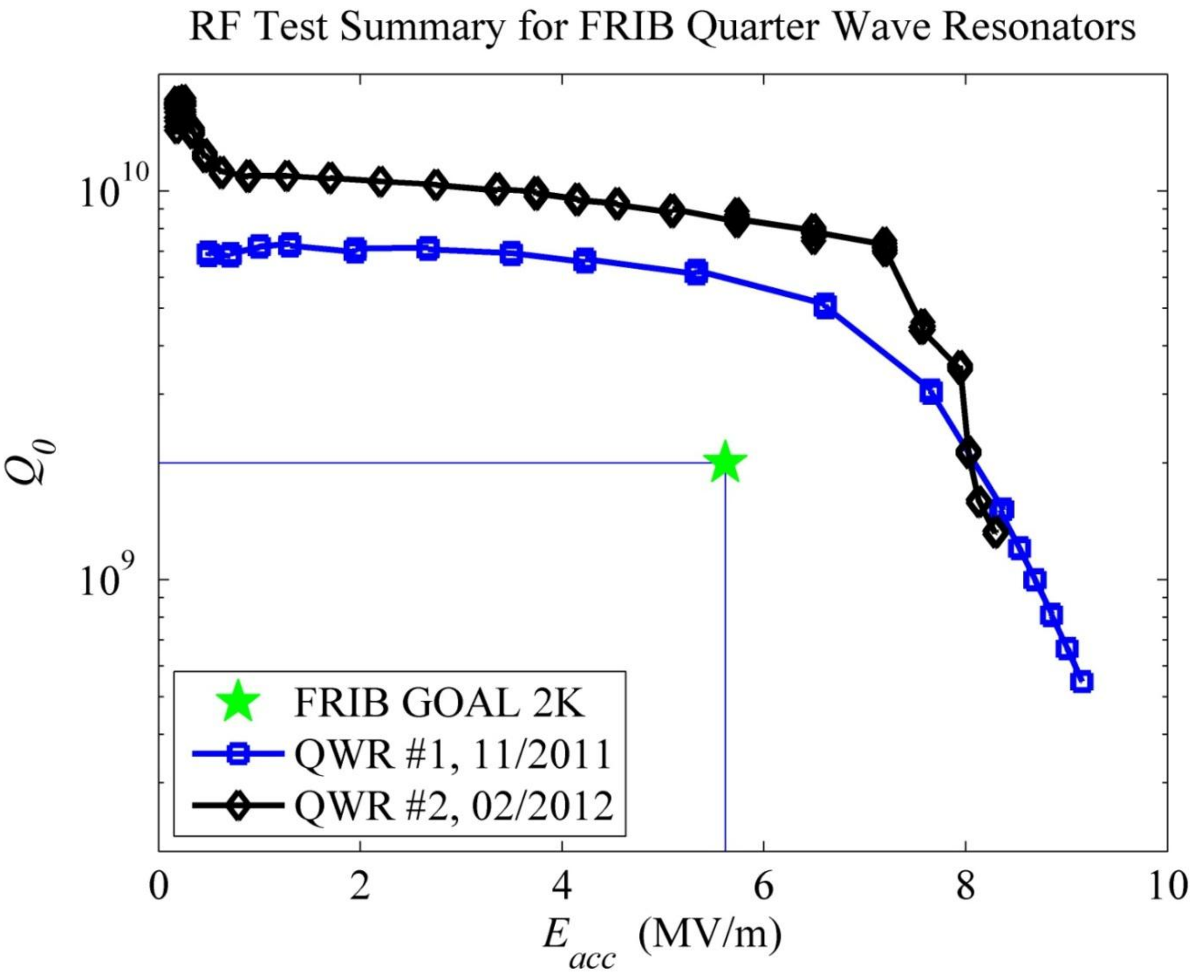
ReA3 Linac: Two Cryomodules in Operation, One (β=0.085) Under Construction

- Since Apr 2011: β=0.041 cryomodule accelerated H_2^+, He^+, He^{2+}, Ne^{8+} beams at design energies
- Experience learned under unfavorable operating conditions
  - Platform vibration, 4.5 K operation, etc.



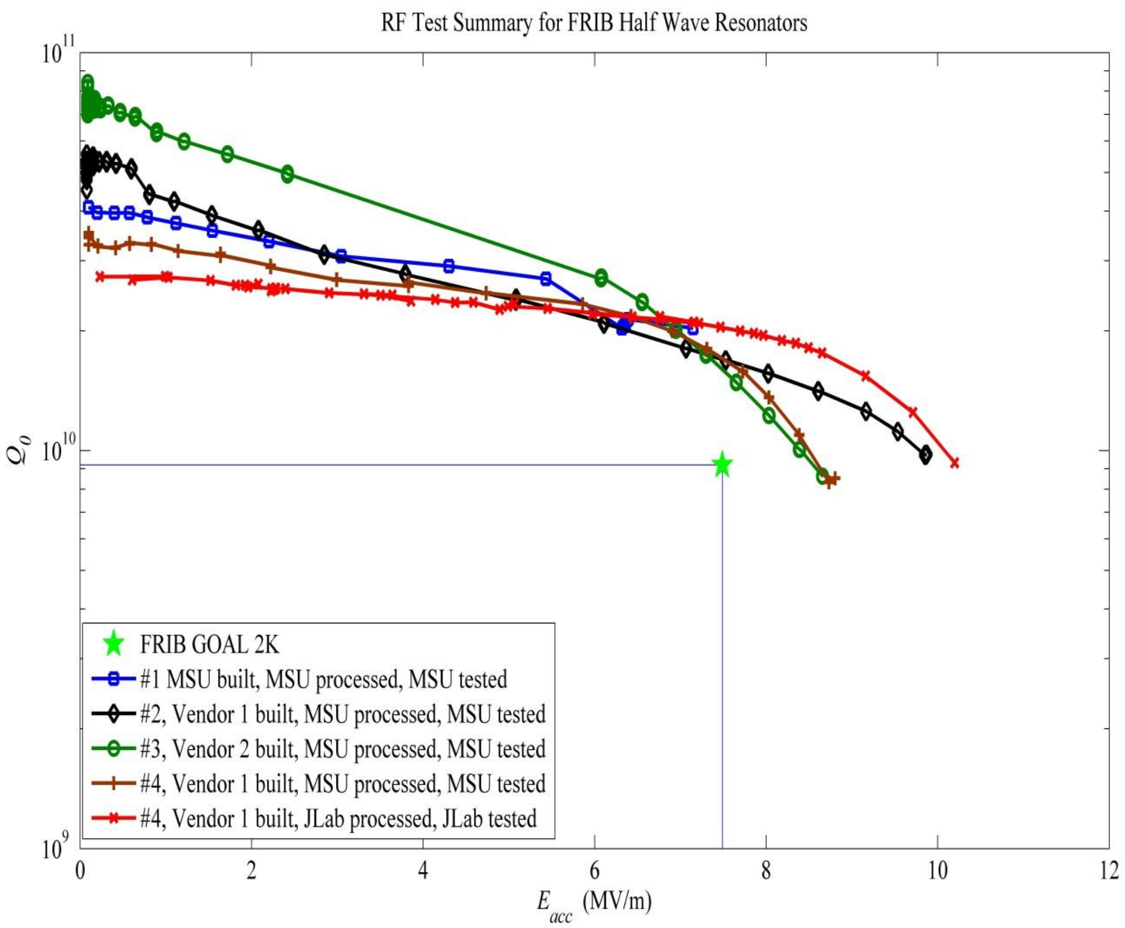


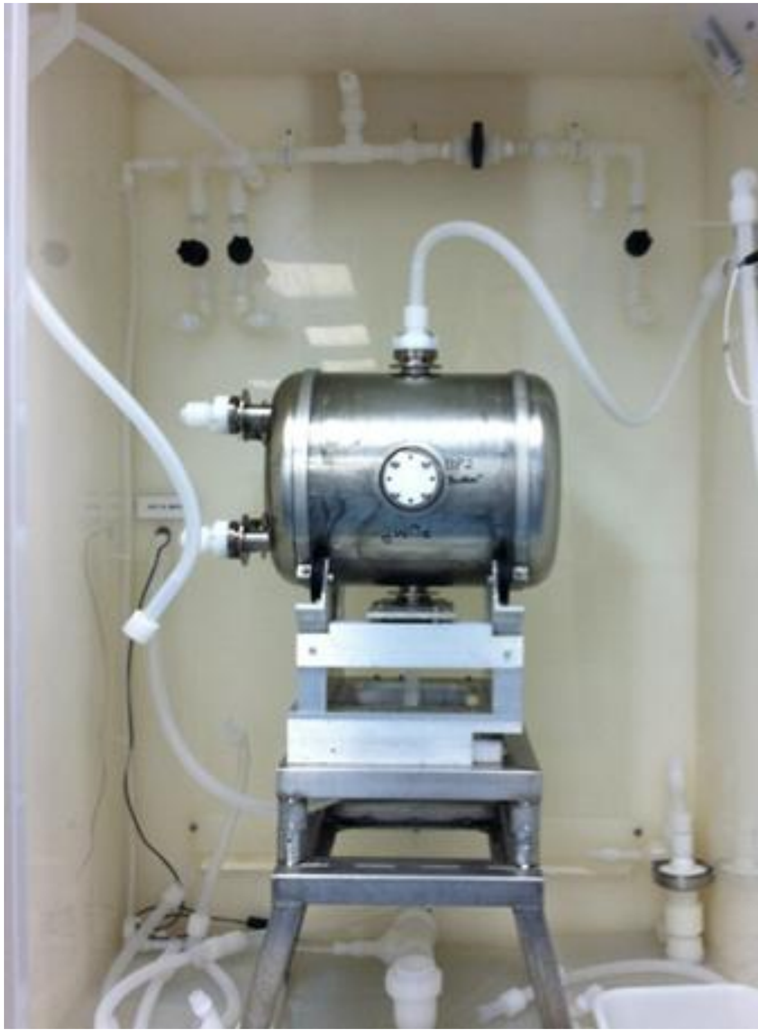
Successful Prototyping of β=0.085 QWRs
Significant Margin Allowed 10% Design Gradient Increase



Margin of about a factor of 3 in Q, 40% in E field

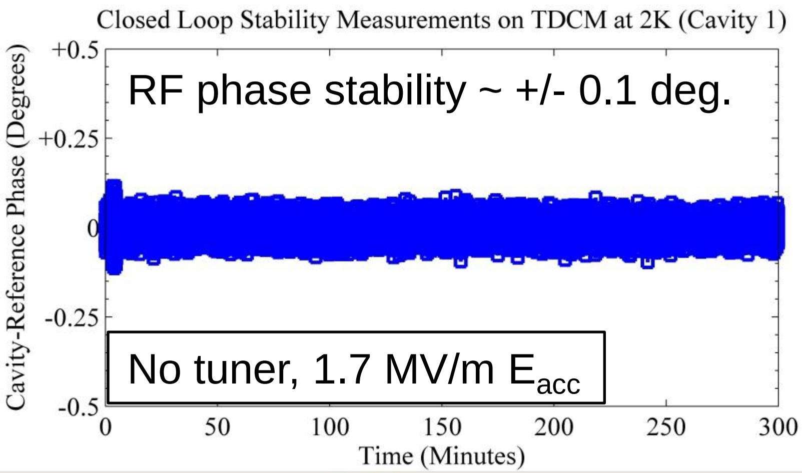
R&D Completed: β=0.53 HWR SRF Cavities
Vendor Fabricated Cavities Meet Performance Goals





Test results independently verified at JLab

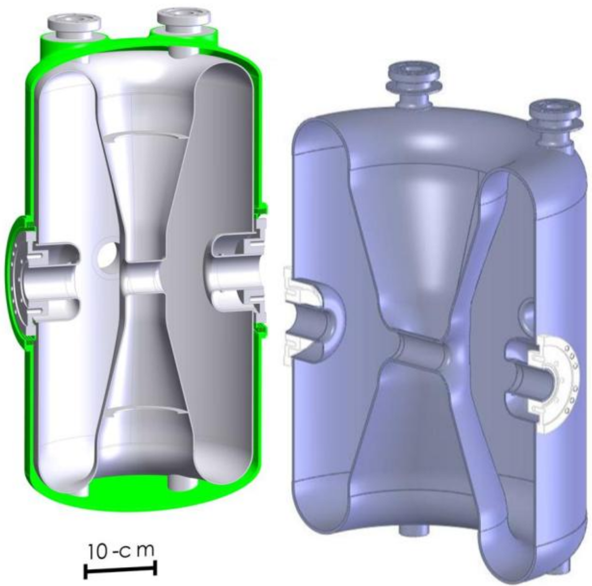
β=0.53 Prototype Cryomodule Tests
Successfully Meeting R&D Milestones in SRF Tests



- FRIB Technology Demonstration Cryomodule R&D milestones completed
  - TDCM operates stably at 2 K temperature with excellent cryogenic stability
  - Cavities continually locked to design frequency; excellent low-level RF control
  - Coupler operated at full CW power (4.5 kW) in full reflection within specified cryogenic load
  - Magnetic shielding efficiency demonstrated
  - Ancillary components (cavity, low-level control, coupler, tuner) operating
- Lessons learned to benefit the design of FRIB preproduction cryomodules
  - Team coordination, engineering culture enforcement, magnetic material management, tuner noise, coupler/cavity multipacting, solenoid lead heat load/pressure drop, NSCL cryogenics issues

SRF Acquisition Strategy Established
Active Vendor Engagement is Key to Procurement Success

- FRIB actively expanding vendor base; risk sharing to reduce cost
  - Material (Nb, NbTi) order at final contracting stage with 3 providers
  - Largest SRF cavity order to a domestic provider: 174 β=0.53 HWRs
    - » 3 vendors delivered FRIB cavities; 7 vendors responded to recent HWR request-for-proposal (RFP)
    - » 174 cavities awarded in 3 production steps of 2-cavity, 10-cavity, and mass production (with 10% excess)
  - β=0.29 pre-production HWR: awarded to 2 vendors (2 cavities each)
  - β=0.085 pre-production QWR: RFP released
- Monitoring and acceptance procedures established to assure quality



Cryoplant Acquisition Strategy Established
Same Key Individuals Delivered SNS Cryoplant

- FRIB and JLab agreed on Work-for-others agreement for FRIB cryoplant design/acquisition and in future support)
  - Similar to collaboration framework of SNS cryoplant acquisition
  - Design closely referring to that for JLab's 12 GeV upgrade
  - Separate procurements of cold boxes, compressors, auxiliary subsystems
  - MSU responsible for procurements – in full support of JLab team's needs
- FRIB recruited Fabio Casagrande from SNS to lead FRIB team and work with Dana Arenius' team at JLab
  - A strong FRIB cryogenics team is crucial in the integration, commissioning, and maintenance of the system
  - MSU Controls team is responsible for the cryogenic controls

Attracted World Experts in Key Areas
Aggressively Strengthened Technical Team Leadership

- Recruited top SRF experts in the world
  - A. Facco (INFN) and K. Saito (KEK)




- Built cryogenics team to leverage SNS success
  - Recruited F. Casagrande (ORNL) to head Cryogenics Department
  - JLab cryogenics team is closely engaged under FRIB/JLab WFO agreement
- Recruited seasoned linac world expert to head Accelerator Physics
  - Y. Yamazaki is ASD Deputy Director; consolidated AP Department

Successful in Building-up Accelerator Team

Recruited 20 Core Team Leaders/Members (Examples)

Name	MSU Date	FRIB Position	Prior Project & Leadership Experience
Wei	9/2010	ASD Director	RHIC, US-LHC, SNS, CSNS, CPHS
Yamazaki	11/2011	ASD Deputy Director	TRISTAN, KEKB, J-PARC
Leitner M	9/2010	ASD Project Engineer	LBNL (SNS, VENUS IS, HIFS-VNL, NDCX-II)
Bultman	1/2012	Front End Project Engineer	LANL (SNS, DARHT, GTA)
Casagrande	12/2011	Cryogenics	INFN/CERN (ICARUS, EA), MIT/Bates, SNS
Chu	2/2011	Application Software	SNS, LCLS
Gibson	4/2011	Installation/Integration	SNS
Leitner D	10/2010	Commissioning	LBNL (88' Cyclotron, VENUS IS, DIANA)
Marti	7/1979	Charge stripper area	MSU (K100, K250, K500, K1200, ReA3)
Ozelis	3/2012	Cryomodule Project Engineer	FNAL (VTCF), JLab (SNS, CEBAF 12 GeV, FEL)
Peng	7/2011	Controls	SNS, LCLS
Pozdeyev	10/2009	Front End FS/BDS Area	VEPP2M, JLab FEL, BNL (RHIC, FEL, e-RHIC)
Russo	7/2011	Electrical Engineering	BNL (AGS/Booster, RHIC, SNS, LBNE)
Saito	2/2012	SRF	KEK (TRISTAN, KEKB, J-PARC, STF, ILC-GDE)
Webber	10/2011	Diagnostics	SSC, TEVATRON, FNAL Instrumentation
Zeller	10/1979	Magnet	MSU (K500, K1200, S800, CCP, A1900, RIA)
Zhang	2/2011	Linac Area	SNS

ASD Organization Ready for Scope Delivery

Area & Control Account Managers Integrating Scope

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ACCELERATOR SYSTEMS DIVISION
DIRECTOR – **J. Wei**
DEPUTY DIRECTOR – Y. Yamazaki
PROJECT ENGINEER – M. Leitner
PROJECT ELECTRICAL ENGINEER – T. Russo
SENIOR ADVISORS – A. Facco, J. Nolen
Administrative Support – A. McCausey

- **FRONT END** – **E. Pozdeyev**; PROJECT ENGINEER – N. Bultman
  - ION SOURCE – **G. Machicoane (M)**
  - RFQ – **E. Pozdeyev**
- **COMMISSIONING** – **D. Leitner**
  - REACCELERATOR* – **D. Leitner**; S. Krause (M), A. Lapierre (M), F. Montes (M), S. Nash (M), G. Perdikakis, R. Rencsok (M), A. Rodriguez, S. Schwarz (M), W. Wittmer
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  - MECHANICAL ENGINEERING INTEGRATION TEAM – **B. Lang**; M. Shuptar
  - VACUUM & INSTALLATION – **P. Gibson**; R. Kersevan
  - SURVEY & ALIGNMENT – **M. Leitner**
  - FABRICATION & MANUFACTURING – **M. Williams**; J. Simon
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    - TUNER TEAM – S. Miller
    - SOLENOID AND SHIELDING TEAM – S. Chouhan
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  - OPERATION – **F. Casagrande**; A. Chiesa, A. McCartney, E. Swanson (M), M. Thrush
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  - GLOBAL SYSTEMS – **S. Peng**
- **ACCELERATOR PHYSICS** – **Y. Yamazaki**; LATTICE MANAGER – Q. Zhao
  - BEAM DYNAMICS – **Y. Yamazaki**; M. Syphers, X. Wu, Q. Zhao
  - FRONT END AREA – **E. Pozdeyev**
  - LINAC SEGMENT AREA – **Y. Zhang**; Z. Liu
  - CHARGE STRIPPER & TRANSPORT AREA – **F. Marti**
  - REACCELERATOR AREA – **D. Leitner**; B. Durickovic, W. Wittmer

WFO contracts with
JLab, ANL, BNL, FNAL

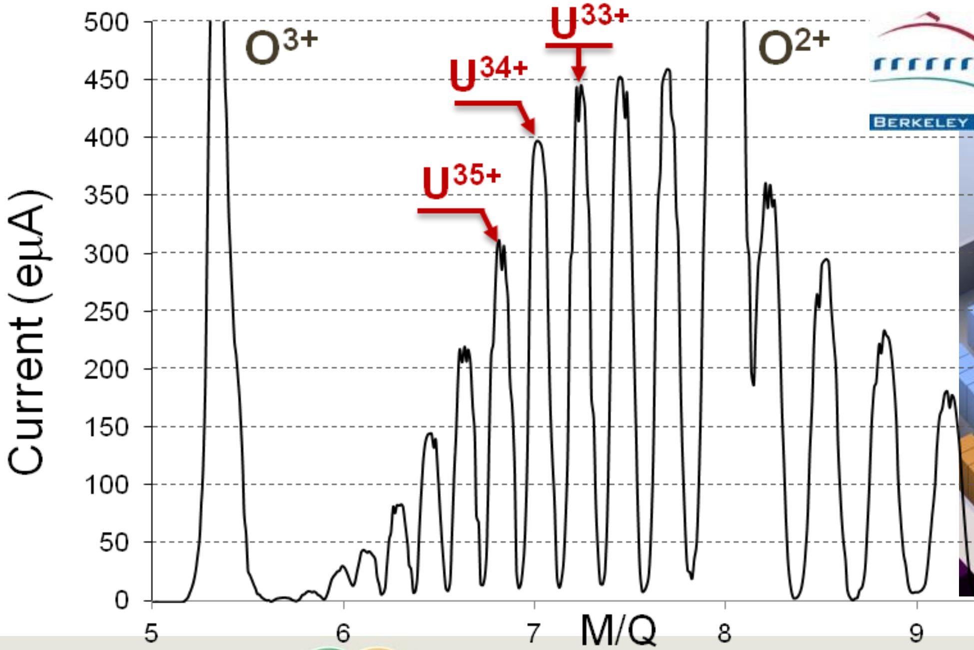
Argonne NATIONAL LABORATORY · BROOKHAVEN NATIONAL LABORATORY · Jefferson Lab · Fermilab

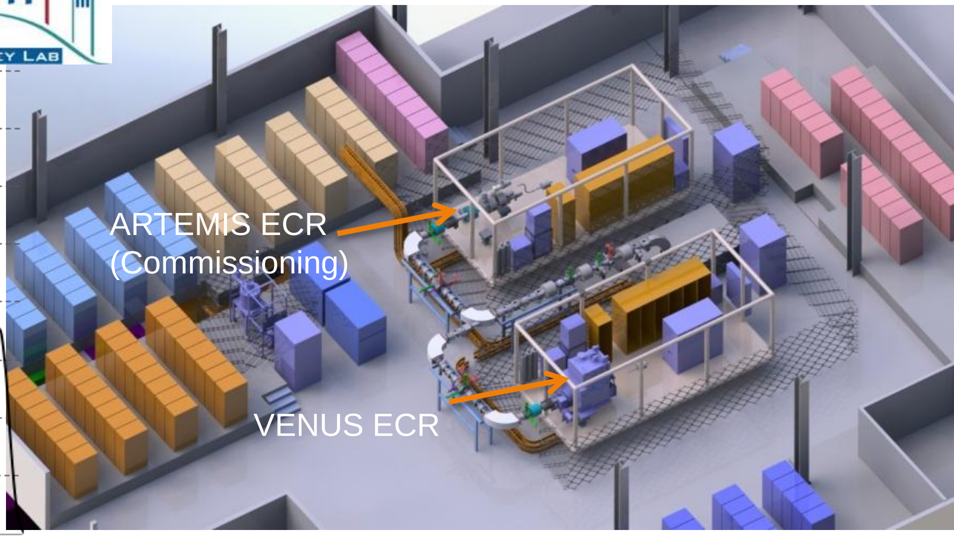
Collaboration with
ANL, BNL, FNAL, JLab,
LBNL, ORNL, SLAC, RIKEN,
TRIUMF, INFN, IMP, INR,
THU, ESS

- WFO contracts in place
  - JLab: 1) Cryoplant design and acquisition; 2) SRF processing
  - ANL: 1) Liquid lithium beam test; 2) SRF cavity coupler design
  - BNL: Plasma window performance improvement
  - FNAL: Beam position monitor diagnostics

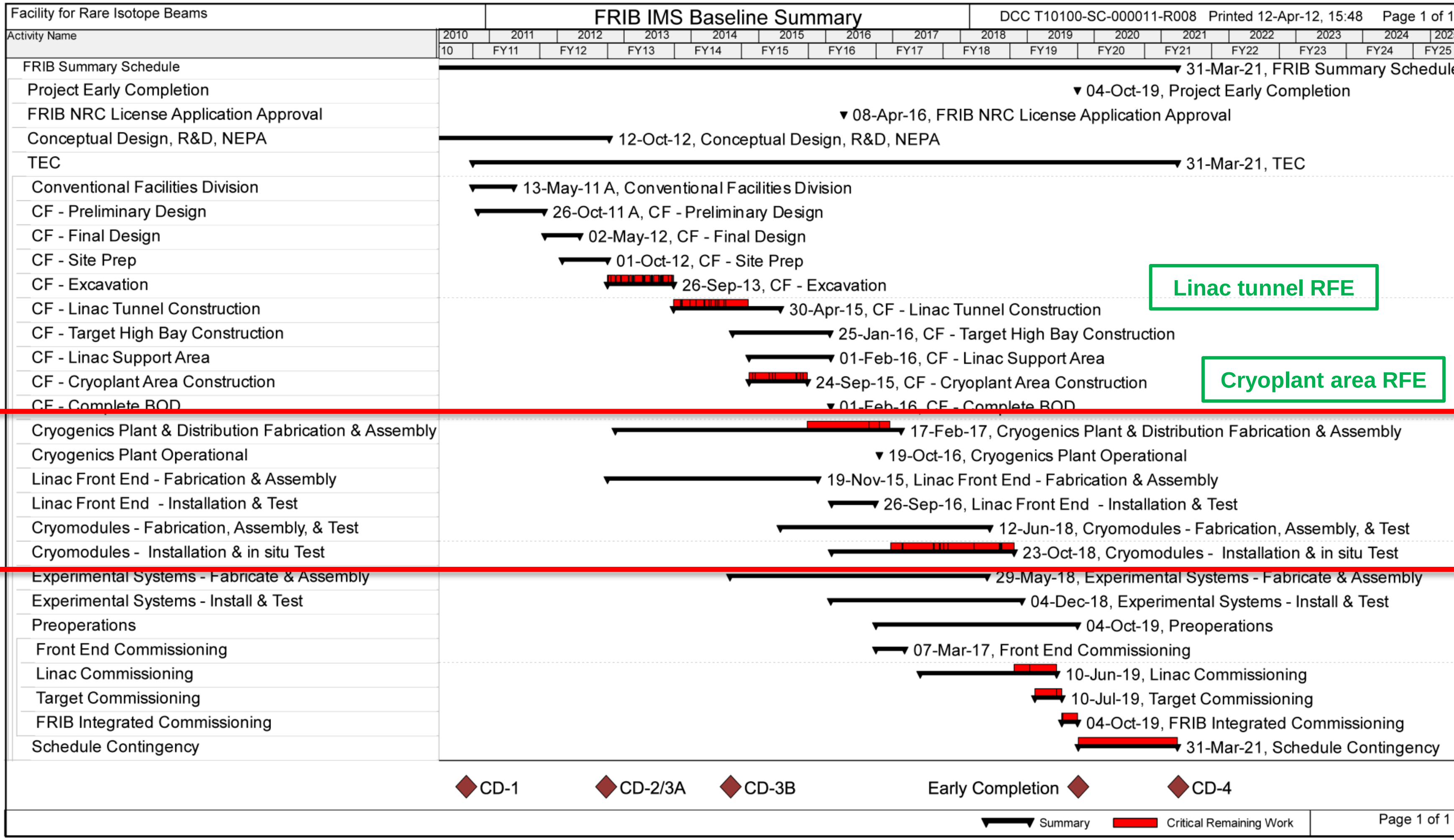
Early Front End Establishment Planned
Ion Sources at LBNL and MSU Demonstrated Performance

- Two ECRs to cover FRIB Project's commissioning & operation needs
  - ECRIS based on ARTEMIS design running at MSU is to be tested in FRIB configuration in 2012; adequate for commissioning & light ion operations
  - High-performance superconducting ECRIS is based on VENUS design; LBNL/VENUS source delivered twice FRIB ^{238}U required intensity in 2011
    - » Team and expertise established at MSU
    - » Fabrication of ECR sextupole/solenoid coils and assembly of cold mass planned





ASD Integrated in Project Schedule



Summary

- FRIB project is proceeding with scope, schedule and cost baselined and ready for civil construction start
- Accelerator design meets FRIB performance requirements
  - Accelerator lattice footprint frozen since June 2011
  - Detailed developments continue on critical components- charge stripper and SRF
  - System designs optimized and value engineered for availability, maintainability, reliability, tunability, and upgradability
- Acquisition strategy has been meeting performance, cost & schedule requirements
- 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!

Coauthors

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