Overview of Accelerator Systems at FRIB/NSCL

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Outline of Lecture

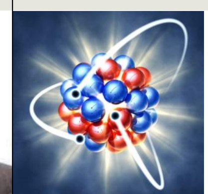
- Physics Research at FRIB and NSCL
  - Scientific Goals of FRIB/NSCL
  - Surveying Nuclear Landscape
- Accelerator System at FRIB
  - Specification of FRIB
  - Baseline Linac System
  - Superconducting RF Cavities
- ReAccelerator Facility at NSCL

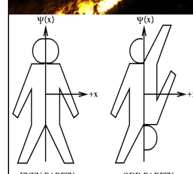
NSCL @ MSU

National Superconducting Cyclotron Laboratory (NSCL)

- Established in 1963, the NSCL is the nation's largest nuclear science facility that is on a university campus
- Home to the K500-K1200 Coupled Cyclotron Facility and the A1900 Projectile Fragment Separator
- MSU #1 ranked Nuclear Physics Program in the Nation
- Upgrade to the Facility for Rare Isotope Beams (FRIB) scheduled for 2022

Scientific Goals of the Laboratory

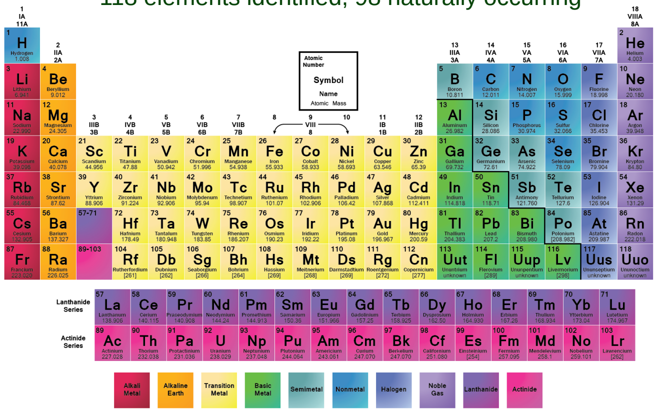


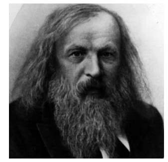


- Properties of Atomic Nuclei
  - Develop a predictive model of nuclei and their interactions
- Nuclear Processes in Cosmos
  - Origin of the elements; processes in the cosmic cauldrons
  - Stellar evolution, stellar explosions, and compact stars
- Test Fundamental Laws of Nature
  - Effects of symmetry violations are amplified in certain nuclei
- Societal Applications and Benefits
  - Advancing technology in a wide range of fields such as medicine, energy, material sciences, and national security

Periodic Table of Elements

- Elements ordered by atomic number (# protons)
  Maps chemical behavior of elements
- 118 elements identified, 98 naturally occurring



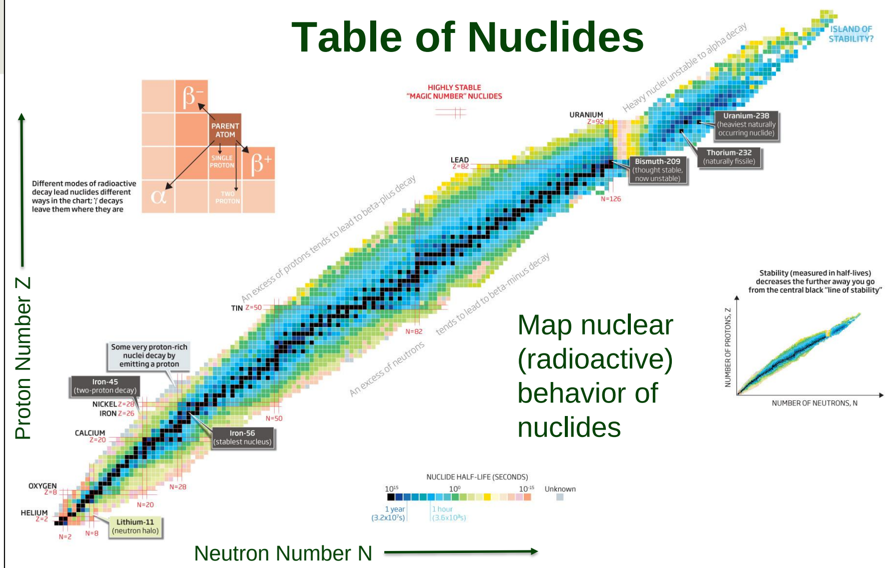


Dmitri I. Mendeleev
(1834 – 1907)

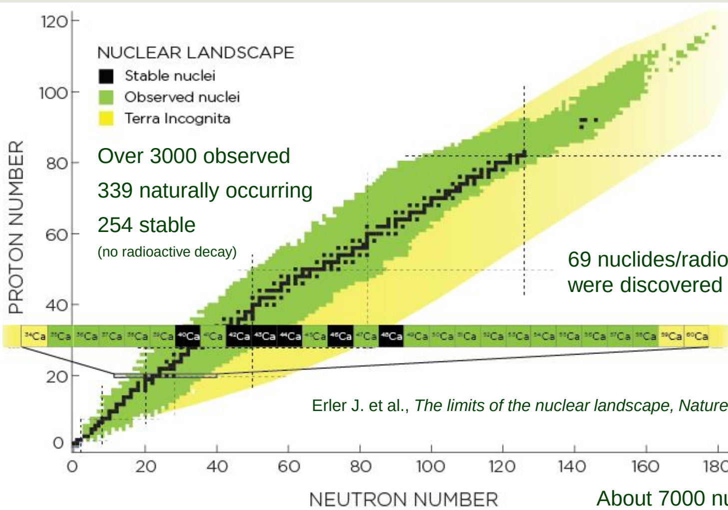
J. Lothar Meyer
(1830 – 1895)

Table of Nuclides

Map nuclear (radioactive) behavior of nuclides



Surveying the Nuclear Landscape



Over 3000 observed

339 naturally occurring

254 stable

(no radioactive decay)

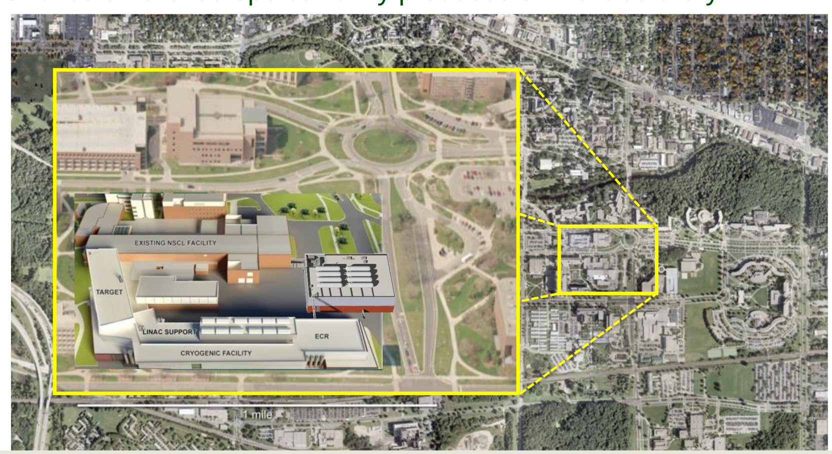
69 nuclides/radionuclides were discovered at the NSCL

Erler J. et al., *The limits of the nuclear landscape, Nature* ***486***, *509, (2012)*

About 7000 nuclides in all!

NSCL/FRIB on the MSU Campus

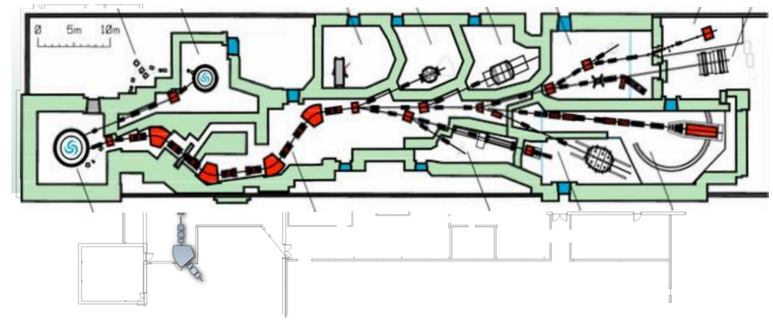
- Upgrade of NSCL to FRIB will boost beam intensities and extend the varieties of rare isotope currently produced at the laboratory



FRIB Specification

- Baseline Design of FRIB Driver Linac
  - Primary beams of stable ions up to Uranium-238
  - Ions are accelerated to energies ≥ 200 MeV/u
  - Beam power ≤ 400 kW on production target
  - Higher beam current by simultaneously accelerating several charge states (ex. $^{238}U^{76+}$, …, $^{238}U^{80+}$) while minimizing emittance
- Production Target and Fragment Separation System
  - Production and separation of Rare Isotope Beams (RIBs)
- Beam transport to experimental programs
  - Fast beams (~ 0.5c), Stopped beams (~ eV), Re-accelerated beams (0.3 – 12 MeV/u)

NSCL transition to FRIB

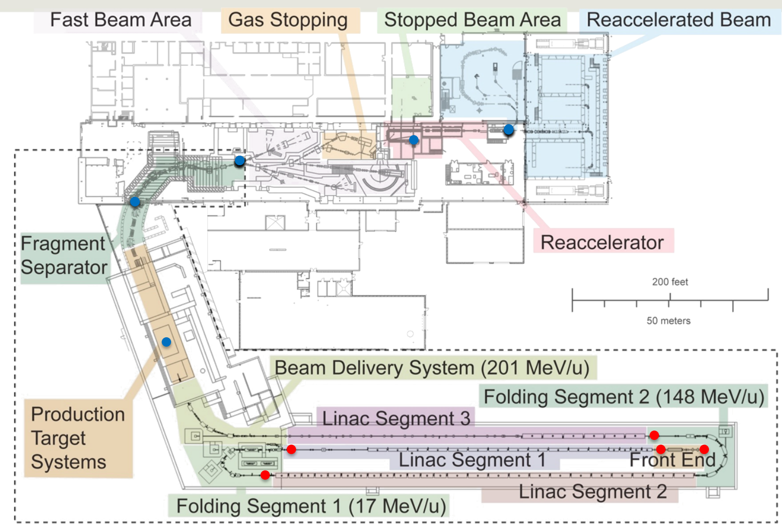


- Upgrade from NSCL to FRIB must minimize changes to existing experimental areas
- Allows post-production systems to be commissioned and ready before FRIB driver linac is completed

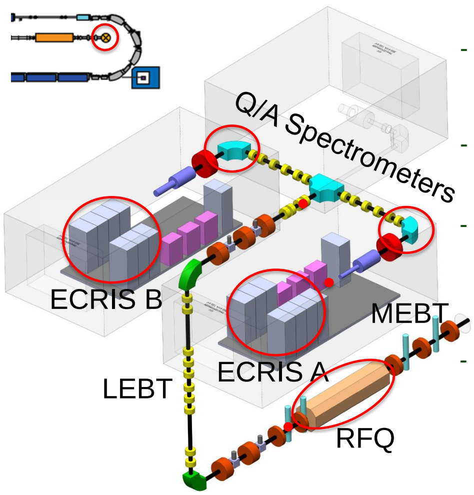
FRIB Challenges and Goals

- Robust ECR Ion Sources to deliver required beam currents
- Driver Linac accelerating all stable ions <u>up to Uranium</u>
- Produce beam on Production Target w/ spot size ~1 mm diameter
  - Optimized for high production yield while minimizing damage to target
- Design will allow for future upgrades to the facility for
  - Higher beam energies with extra space to add more SRF cavities
  - Light-Ion Injector and Isotope Separation On-Line (ISOL) Facility
- FRIB will push the limits of superconducting RF cavity, ECR ion source, charge stripping, and rare isotope beam (RIB) production technology

FRIB Layout and Operation

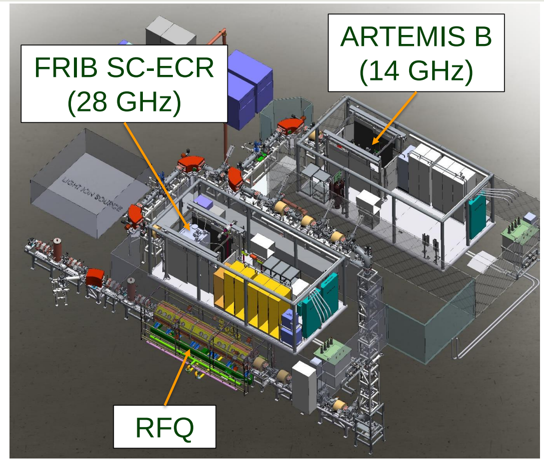


Front End

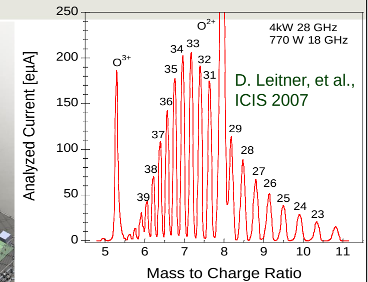


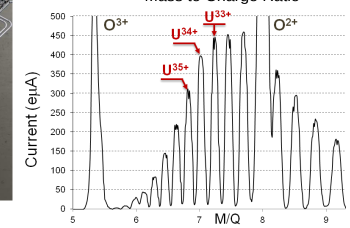
- DC beam of high charge state up to ^{238}U are produced by the ECRIS
- Selection through the Q/A spectrometer
- Selected ion species are accelerated, bunched, focused and matched in the Low Energy Beam Transport (LEBT) line into the RFQ
- RFQ focus and accelerate beams and the Medium Energy Transport (MEBT) matches beams into Linac Segment 1

FRIB ECR Ion Sources



Machicoane G., et al., Status of ECR ion sources for the Facility for Rare Isotope Beams, (2015).





Benitez J., et al., ECRIS 2012

FRIB SC-ECR Ion Source Parameters

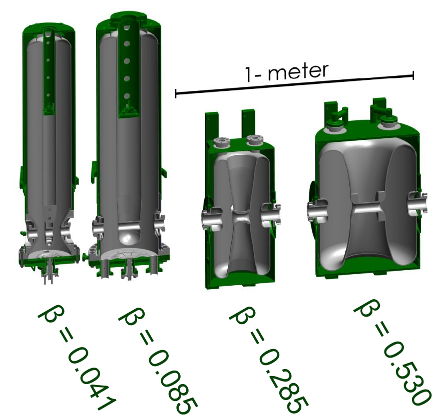
	Required Charge States	Required Beam Current (puA)	Extraction Energy (keV/u)
O	> 3	122	12
Ca	> 8	51	12
Kr	> 14	50	12
Xe	> 20	24	12
Pb	> 27, 28	23	12
U	> 33, 34	16	12

Pushing the limits of current ECR ion source technology!

Overview of SRF Cavities

Cavity Type	λ/4	λ/4	λ/2	λ/2
β_{opt}	0.041	0.085	0.285	0.530
f [MHz]	80.5	80.5	322	322
Aperture [mm]	30	30	40	40
V_a [MV]	0.81	1.62	1.90	3.70
E_p [MV/m]	30.8	33.5	33.3	26.5
B_p [mT]	54.5	68.7	59.6	63.2
T_c [K]	4.5	4.5	2.0	2.0
RF Drive [kW]	2	4	4	8
Number	19	115	80	162

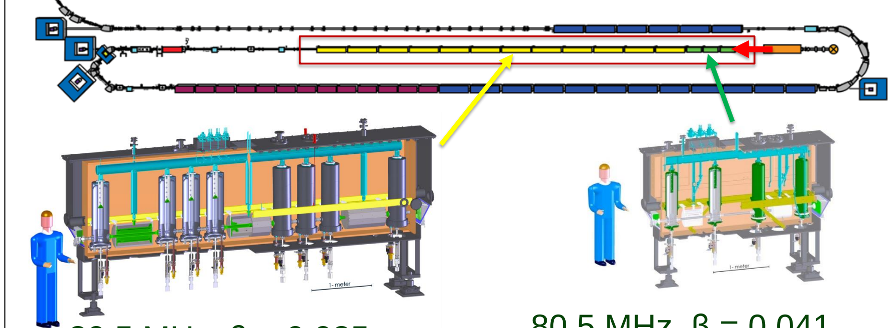
Compton C., et al., *Production Status of SRF Cavities for the FRIB project*, SRF (2015)



Saito K., et al., *FRIB Project: Moving to Production Phase*, SRF (2015)

Linac Segment 1

For $^{238}U^{33+}$ and $^{238}U^{34+}$, acceleration from 0.5 MeV/u to ~16.6 MeV/u

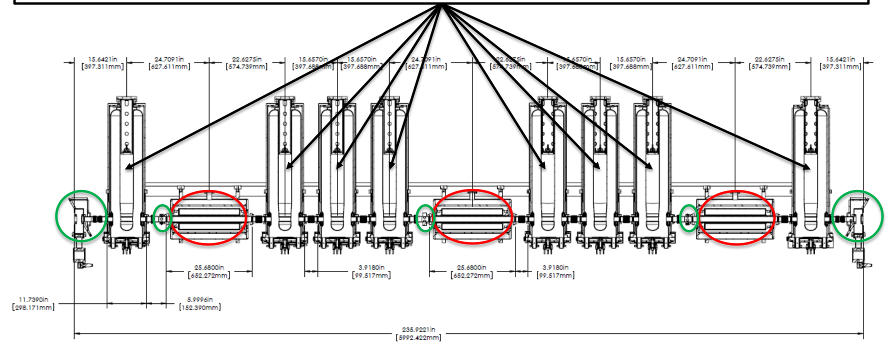


80.5 MHz, β = 0.085
11 QW (λ/4) Cryomodules

80.5 MHz, β = 0.041
3 QW (λ/4) Cryomodules

Inside a QW (λ/4) Cryomodule

Superconducting Niobium QW Cavities operating at 80.5 MHz

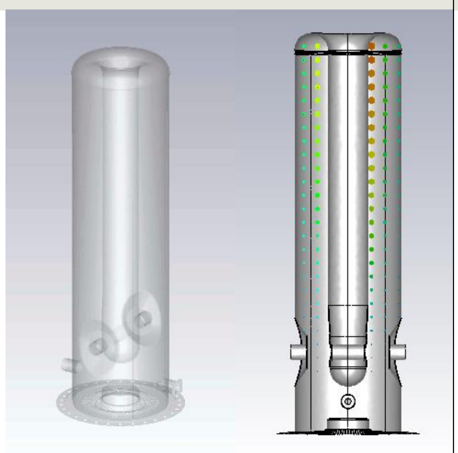


Superconducting Solenoid magnets for beam focusing + dipole for steering

Beam position monitors (BPM) and other beam diagnostics

Acceleration via RF Cavity

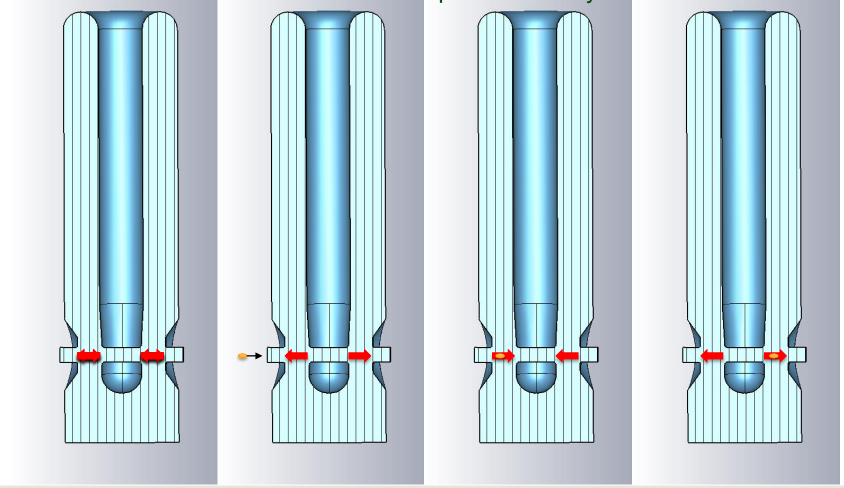
E-fields inside λ/4 β=0.085 Cavity



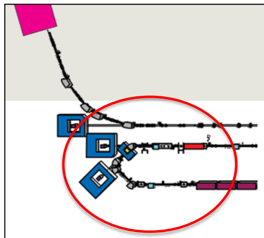
B-fields inside λ/4 β=0.085 Cavity

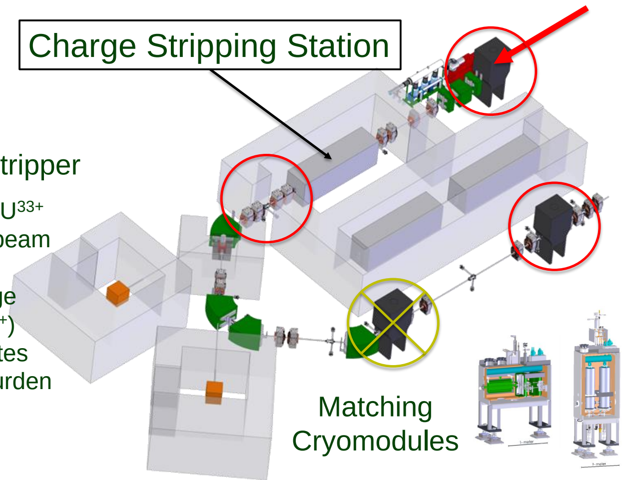
Acceleration via RF Cavity

E-fields inside λ/4 β=0.085 Cavity



Folding Segment 1

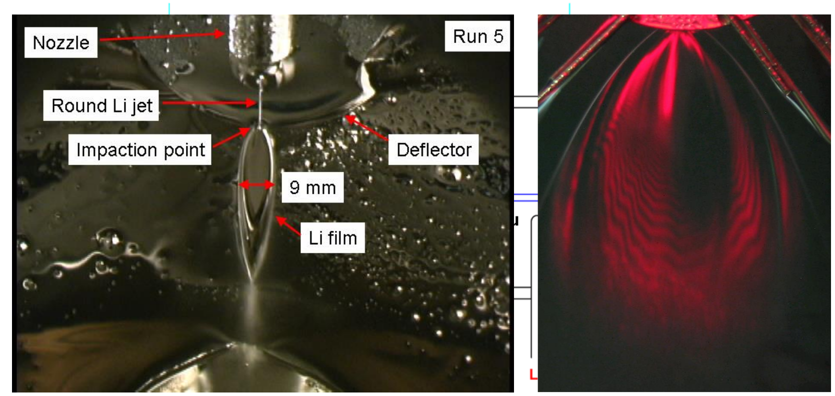




Liquid Li charge stripper

- Strip electrons off U^{33+} and U^{34+} primary beam
- Resulting beam peaking in 5 charge states (U^{76+} to U^{80+})
- Higher charge states ions will reduce burden on RF cavity performance

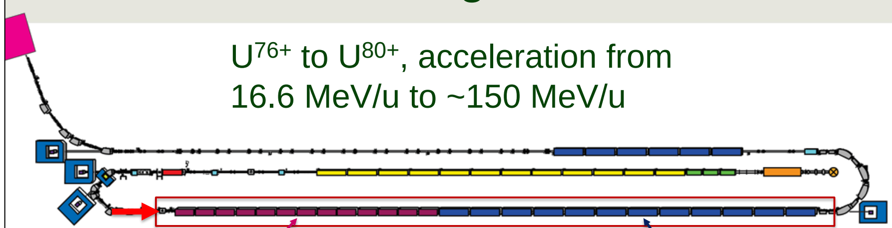
Liquid Lithium Stripper

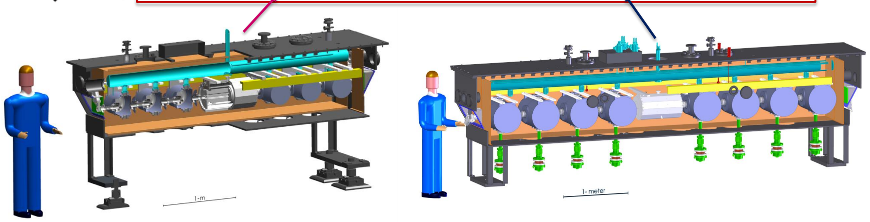


- Momozaki Y., Nolen J., et al., *Development of a liquid lithium thin film for use as a heavy ion beam stripper*, (2009).
- Marti F., et al., *Development of a Liquid Lithium Charge Stripper for FRIB*, (2015)

Linac Segment 2

U^{76+} to U^{80+}, acceleration from 16.6 MeV/u to ~150 MeV/u





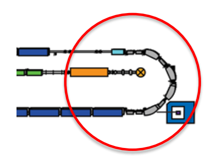
322 MHz, β = 0.285
13 HW (λ/2) Cryomodules

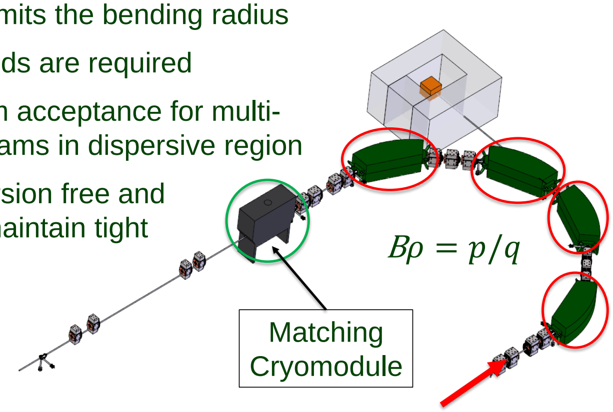
322 MHz, β = 0.53
13 HW (λ/2) Cryomodules

Folding Segment 2

Since tunnel width limits the bending radius

- Large dipoles fields are required
- Large momentum acceptance for multi-charge states beams in dispersive region
- Bends are dispersion free and isochronous to maintain tight particle bundle

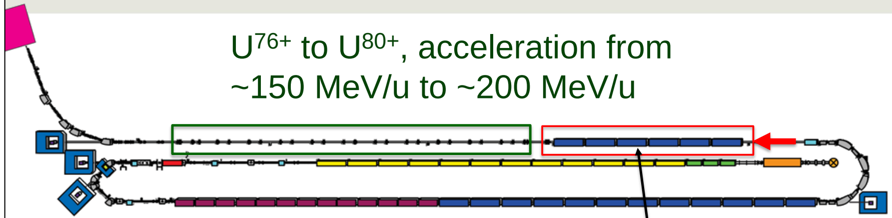




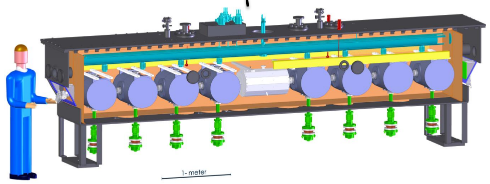
Superconducting bending magnets will be used

Linac Segment 3

U^{76+} to U^{80+}, acceleration from ~150 MeV/u to ~200 MeV/u



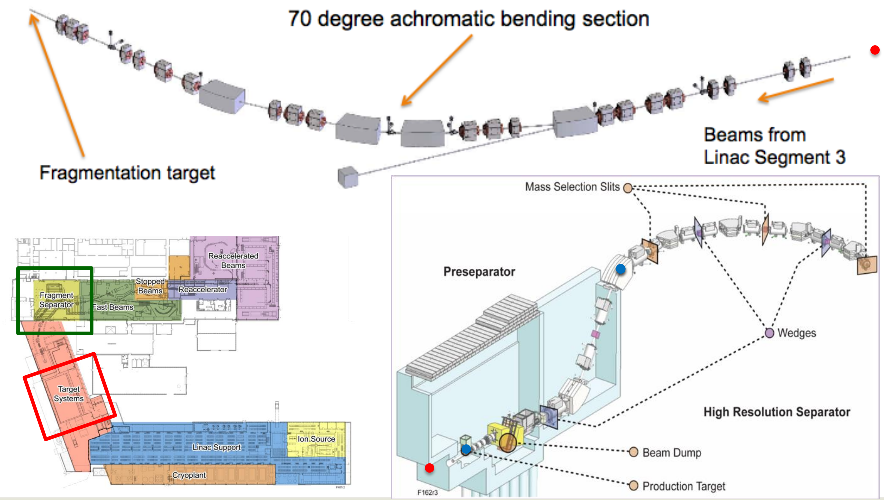
- High cavity performance is needed for required energy delivered on production target
- Possible lower charge states if He gas stripper is used in place of Li stripper



Additional space for up to 12 Cryomodules!

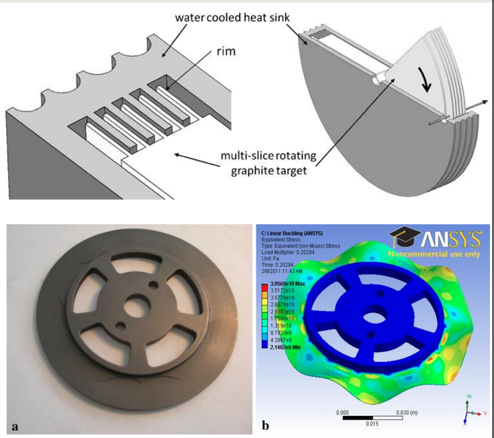
322 MHz, β = 0.530
6 HW (λ/2) Cryomodules

Production Target and Separator



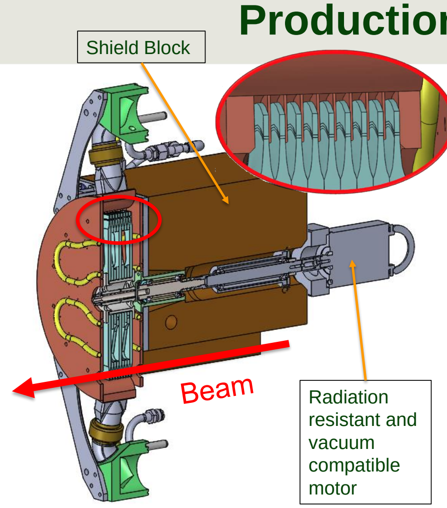
Production Target

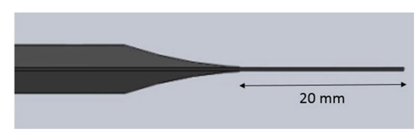
Total Beam Power	400 kW
Total Power in Target	90 kW
Power Deposition	60 MW/cm^3
Target Material	Graphite MERSEN 2360
Target Temp. Max.	1900°C
Slice Thickness	0.1 to 10 mm
Target Diameter	30 cm
Rotation Speed	5500 rpm
Max. Beam Extension	50 mm



Pellemoine F., et al., *Development of a production target for FRIB: thermo-mechanical studies*, J Radioanal Nucl Chem (2014)

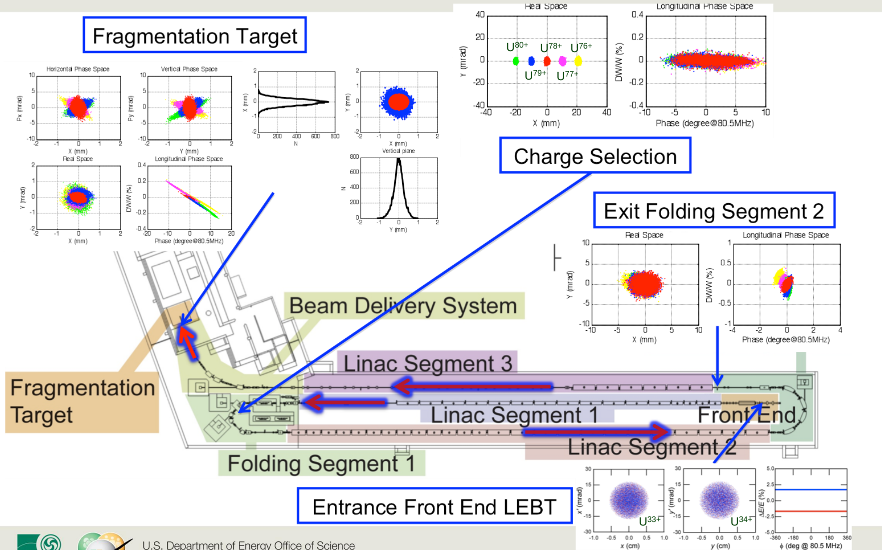
Production Target

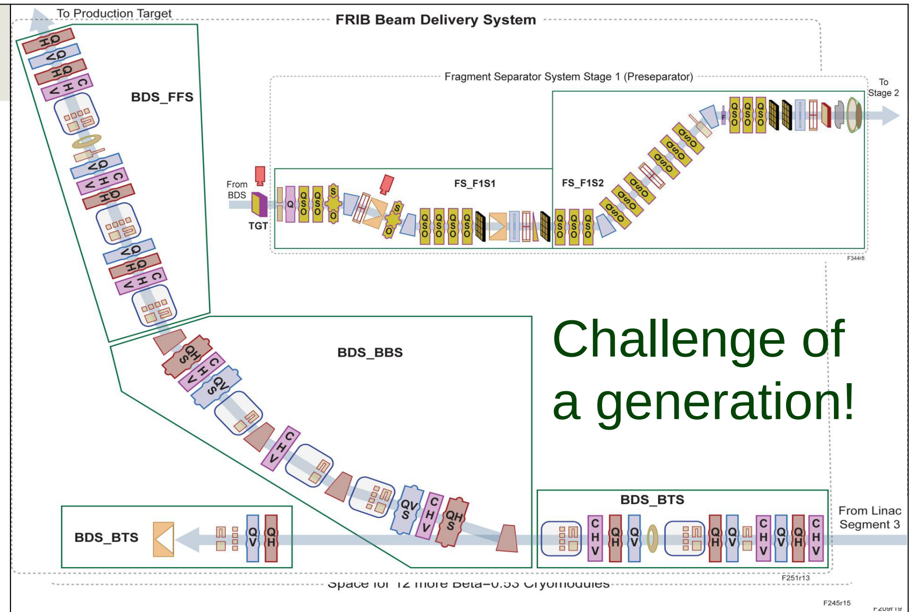




Avilov M., et al., A 50-kW prototype of the high-power production target for the FRIB, J Radioanal Nucl Chem (2014)

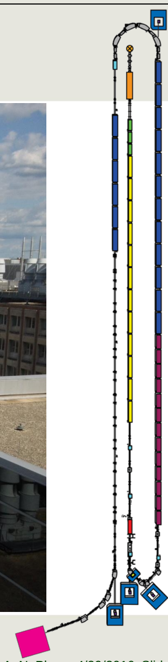
End-to-End Beam Simulations



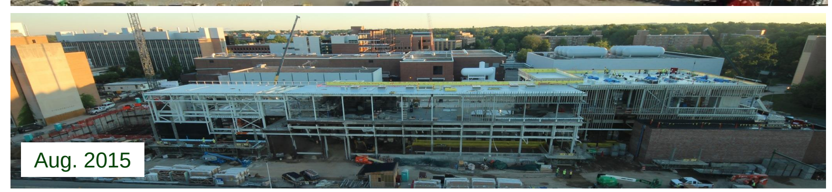


Challenge of a generation!

FRIB Construction

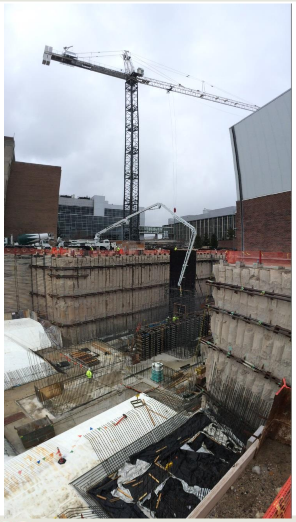


FRIB Construction



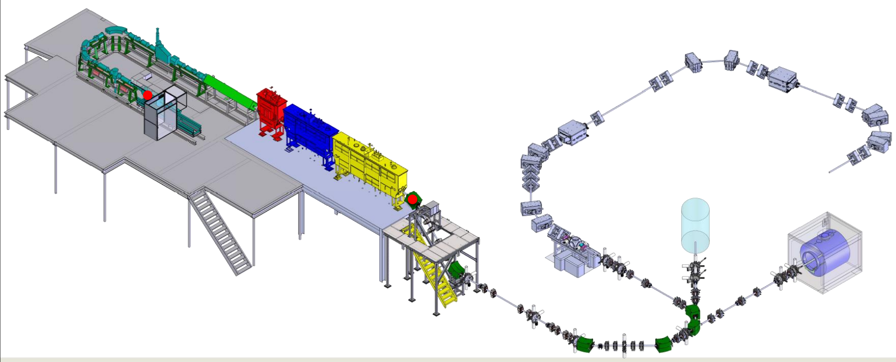
FRIB Construction

FRIB Construction

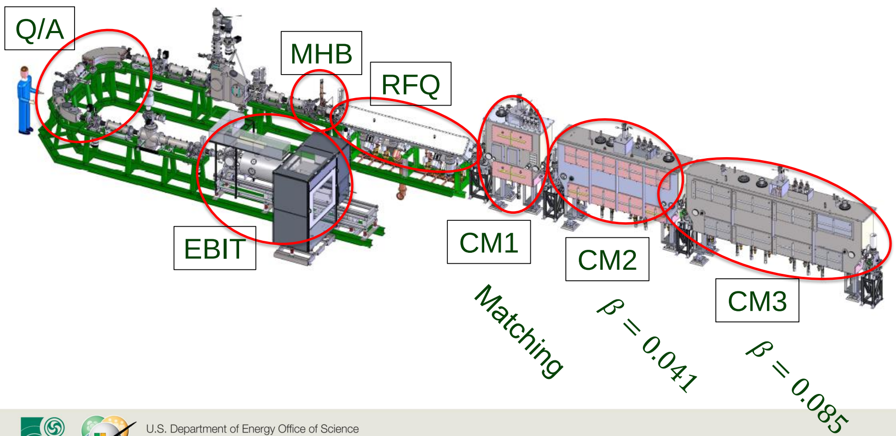


ReAccelerator @ MSU NSCL

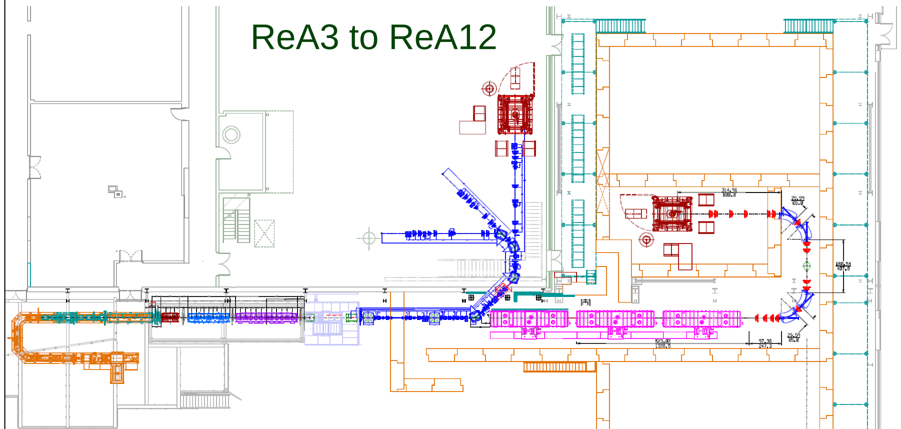
- ReA3 re-accelerates stopped/trapped ion beams to variable energies (~0.3–3 MeV/u for Uranium)
- It serves as a test bed for FRIB SRF technology
- Commissioning of ReA3 has been completed



ReAccelerator – Closer Look



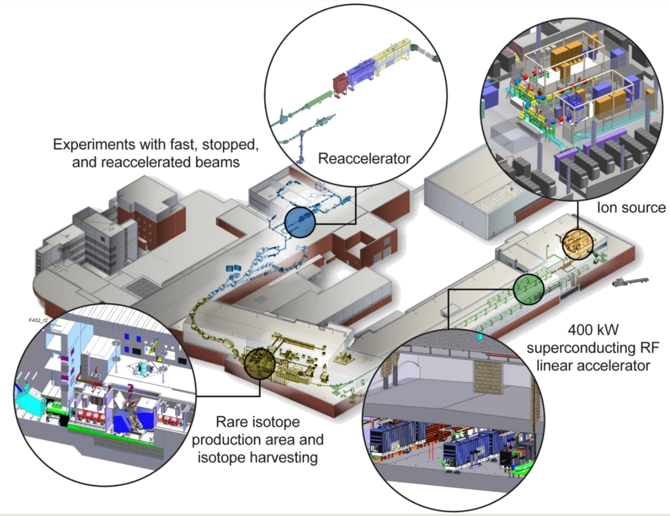
ReA Upgrade Strategy



By adding more cryomodules

U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

In Summary



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Thank you for your time!

Feel free to contact me
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