Overview of Accelerator Systems at FRIB/NSCL

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National Superconducting Cyclotron Laboratory

Outline of Lecture

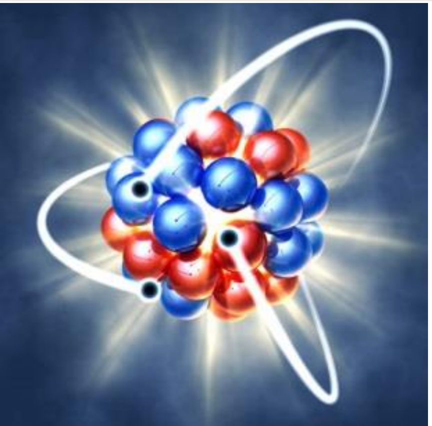
- Physics Research at FRIB and NSCL
  - Scientific Goals of FRIB/NSCL
  - Surveying Nuclear Landscape
- Accelerator System at FRIB
  - Specification of FRIB
  - Baseline Linac System
  - Superconducting RF Cavities
- ReAccelerator Facility at NSCL

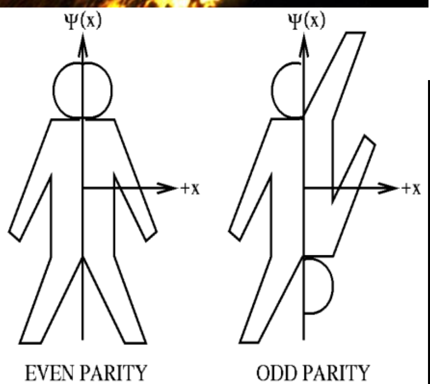
NSCL @ MSU

National Superconducting Cyclotron Laboratory (NSCL)

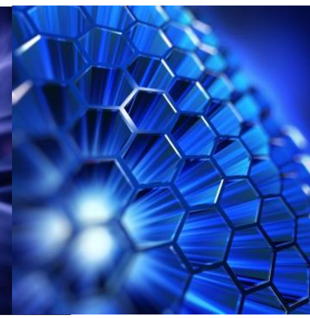
- Established in 1963, the NSCL is the nation's largest nuclear science facility that is on a university campus
- Home to the K500-K1200 Coupled Cyclotron Facility and the A1900 Projectile Fragment Separator
- MSU #1 ranked Nuclear Physics Program in the Nation
- Upgrade to the Facility for Rare Isotope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

Scientific Goals of the Laboratory



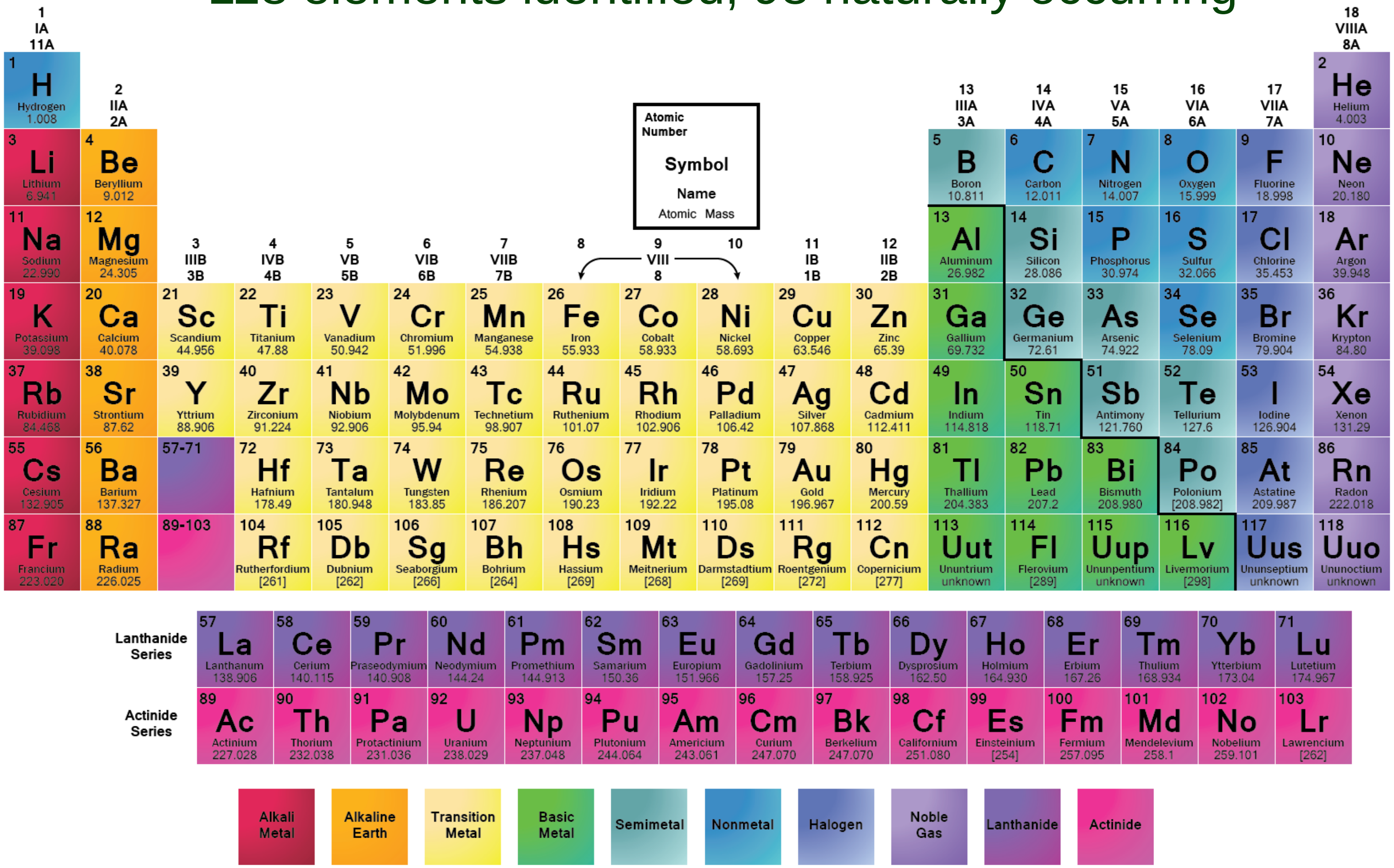


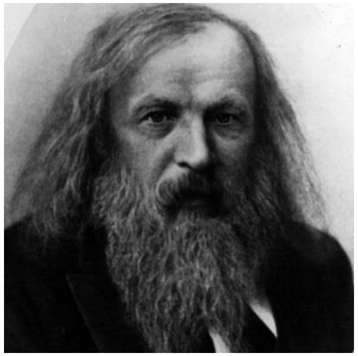
- <u>Properties of Atomic Nuclei</u>
  - Develop a predictive model of nuclei and their interactions
- <u>Nuclear Processes in Cosmos</u>
  - Origin of the elements; processes in the cosmic cauldrons
  - Stellar evolution, stellar explosions, and compact stars
- <u>Test Fundamental Laws of Nature</u>
  - Effects of symmetry violations are amplified in certain nuclei
- <u>Societal Applications and Benefits</u>
  - 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





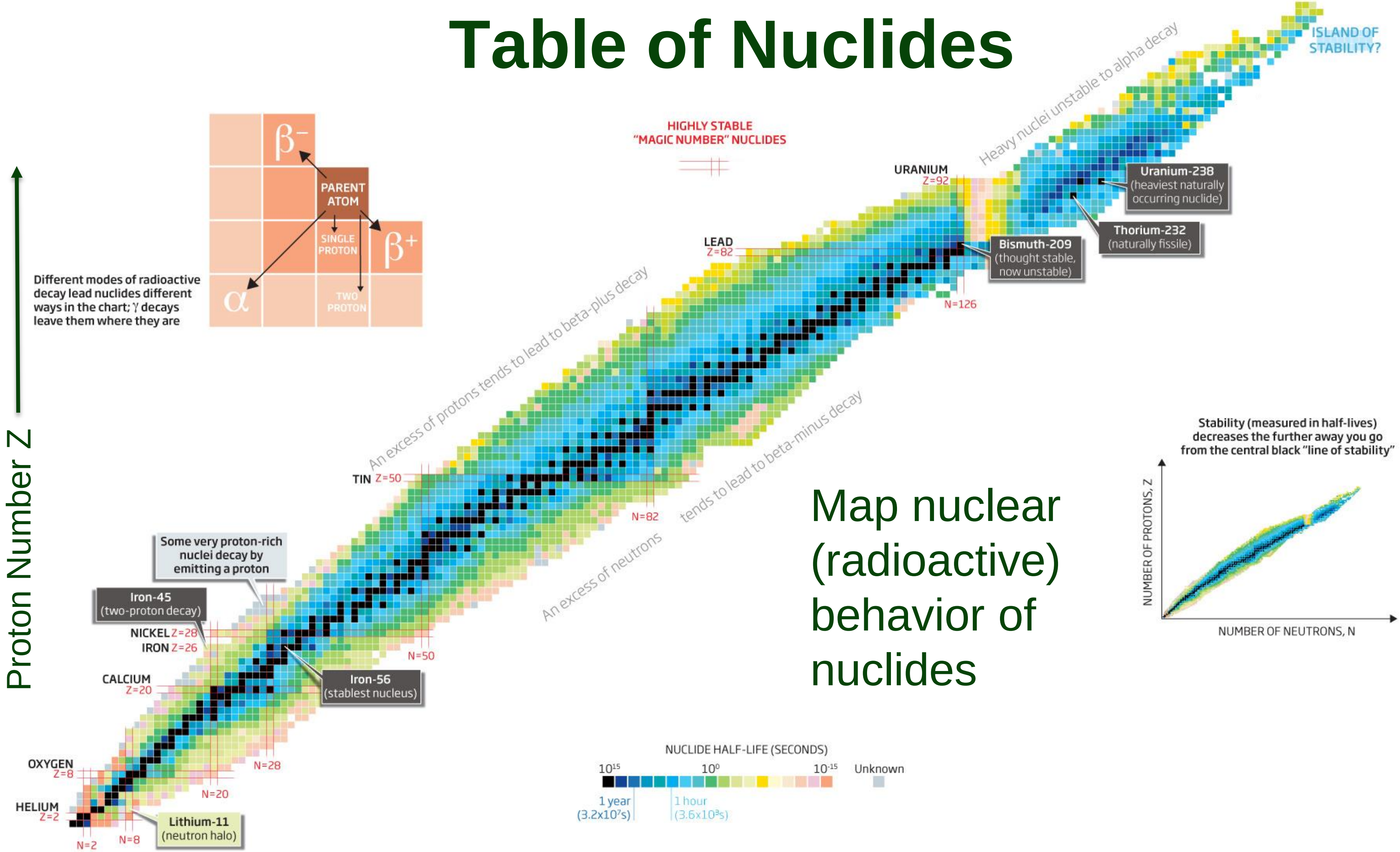
Dmitri I. Mendeleev
(1834 – 1907)

J. Lothar Meyer
(1830 – 1895)

NSCL

FRIB

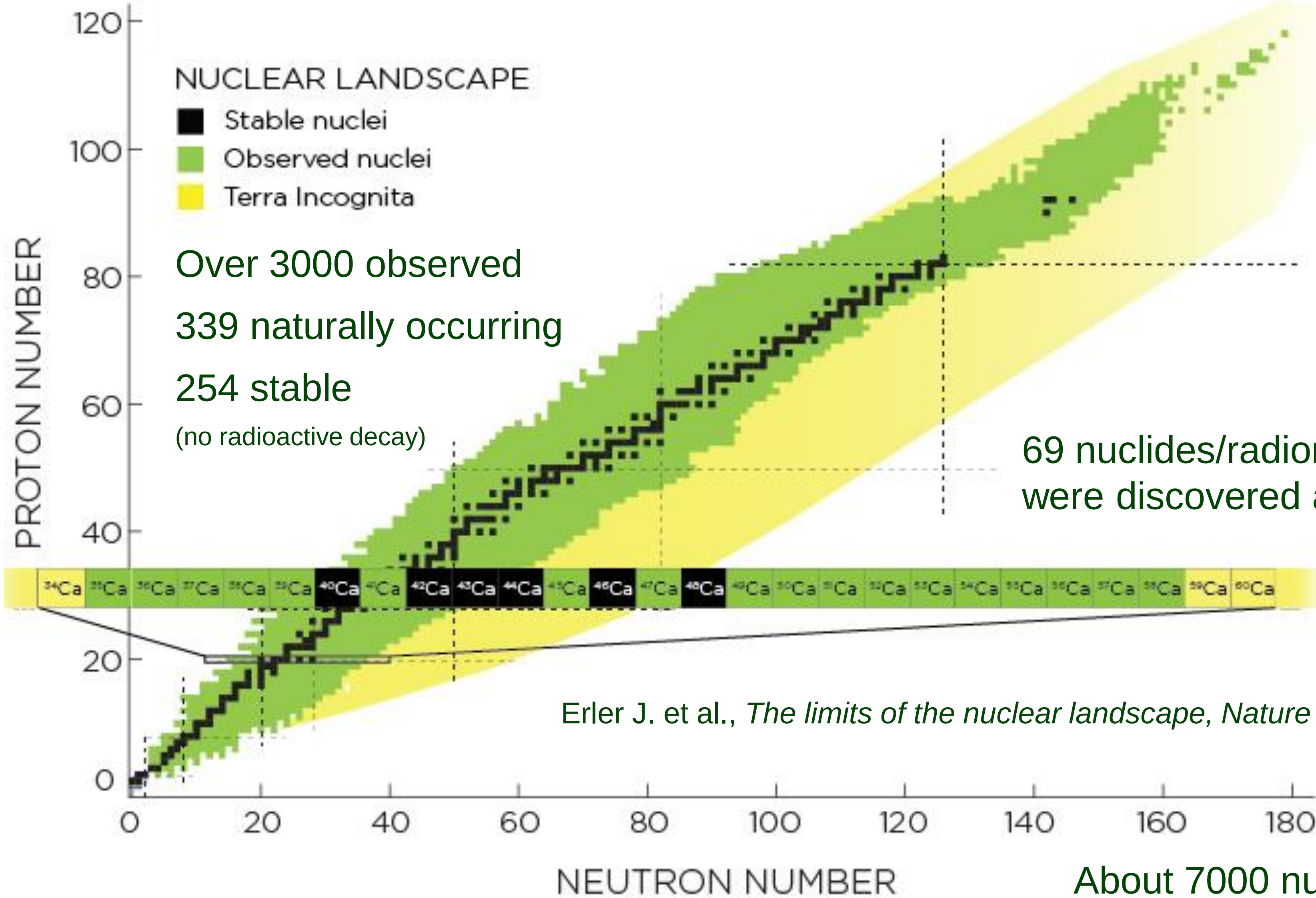
Table of Nuclides



Map nuclear (radioactive) behavior of nuclides

Neutron Number N

Surveying the Nuclear Landscape



Over 3000 observed

339 naturally occurring

254 stable

(no radioactive decay)

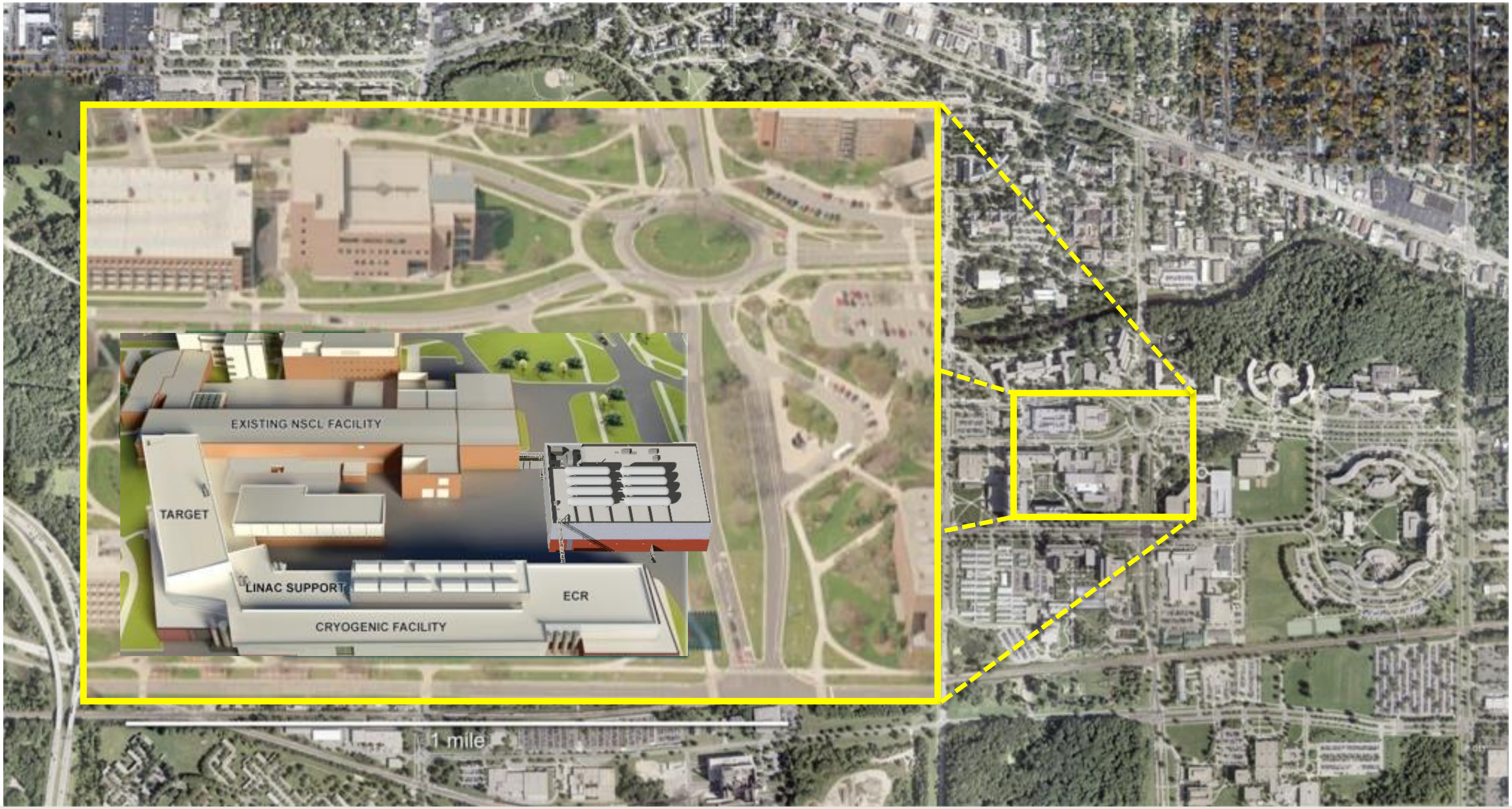
69 nuclides/radionuclides were discovered at the NSCL

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)

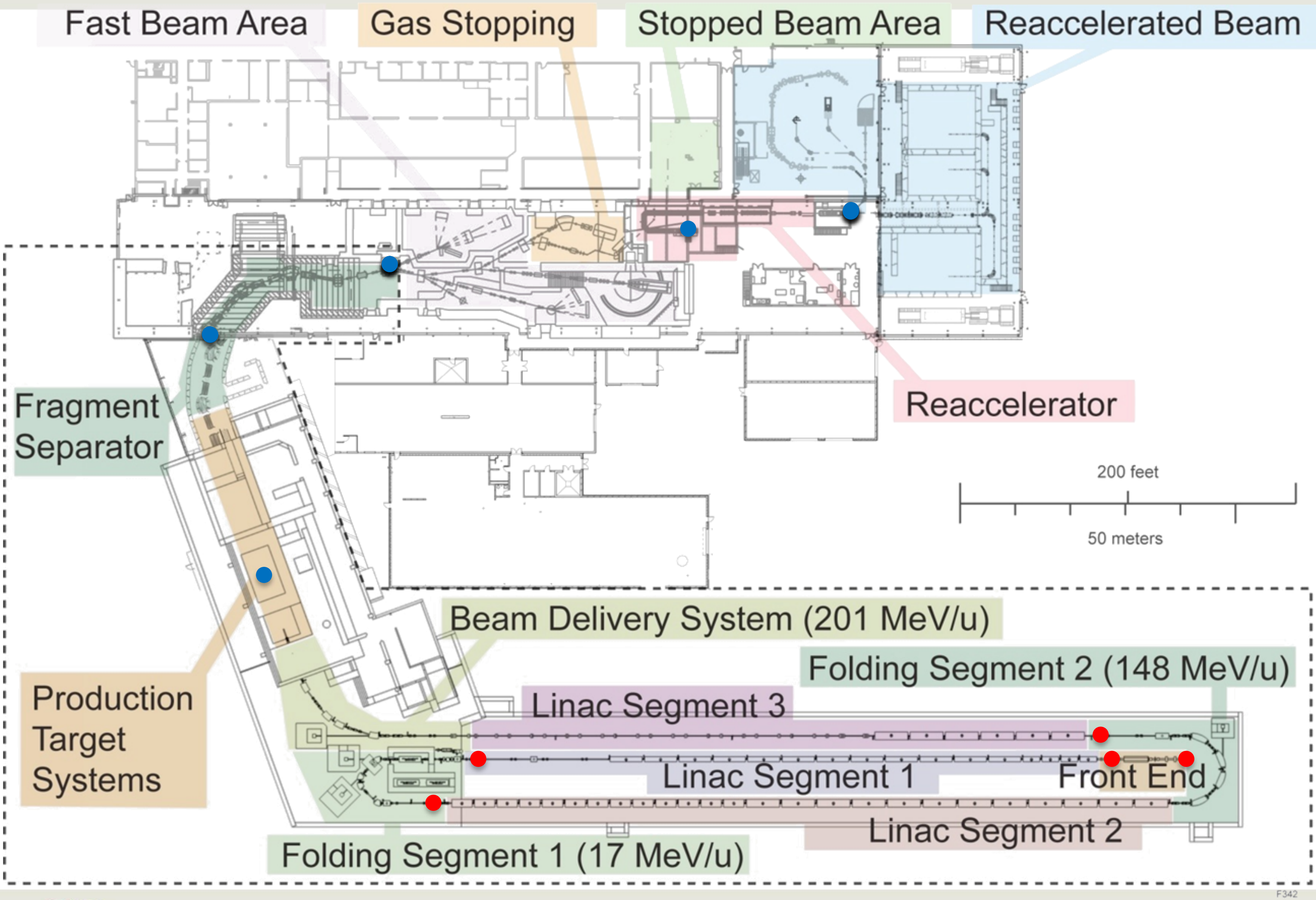
NSCL transition to FRIB

- 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

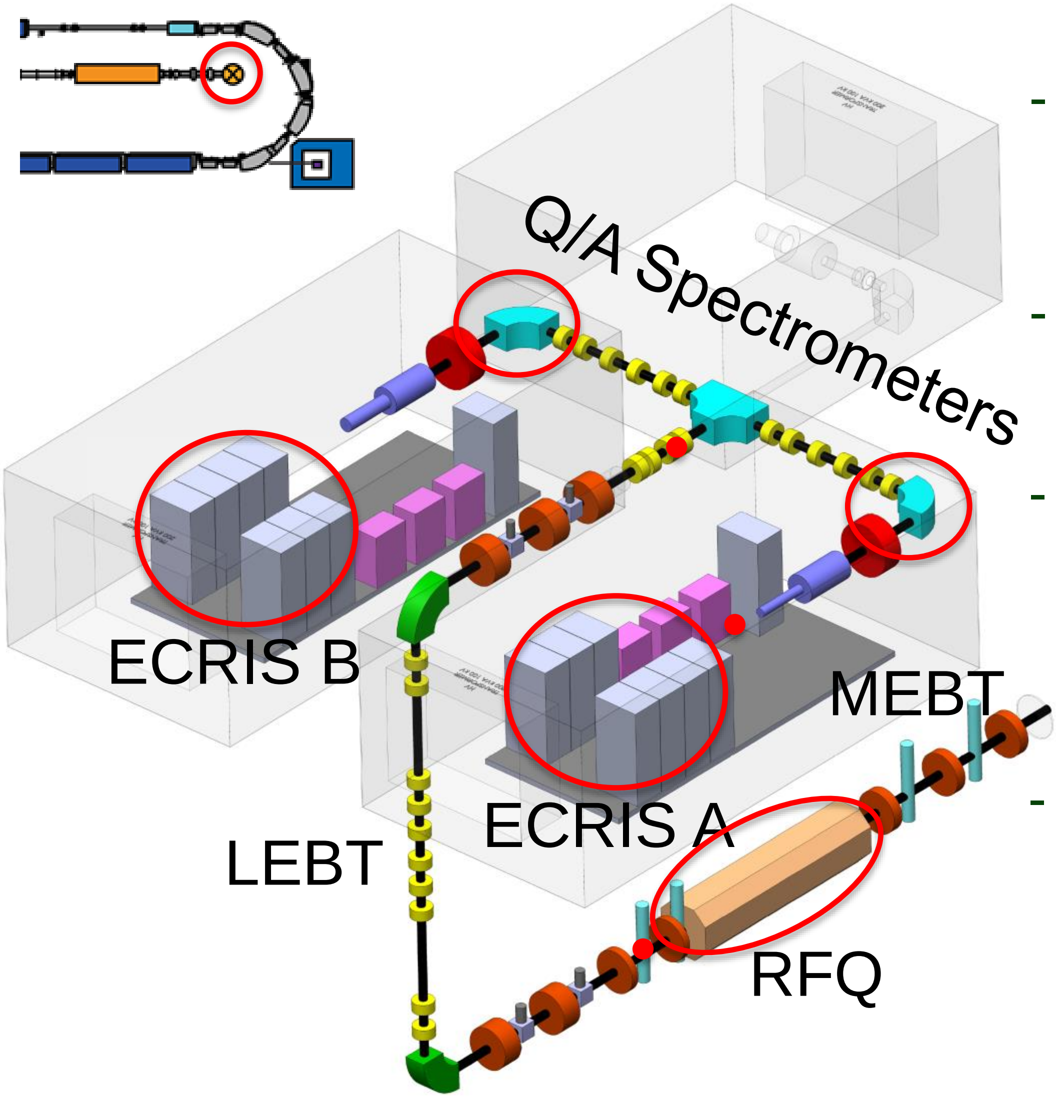
FRIB Challenges and Goals

- Robust ECR Ion Sources to deliver required beam currents
- Driver Linac accelerating all stable ions up to Uranium
- 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

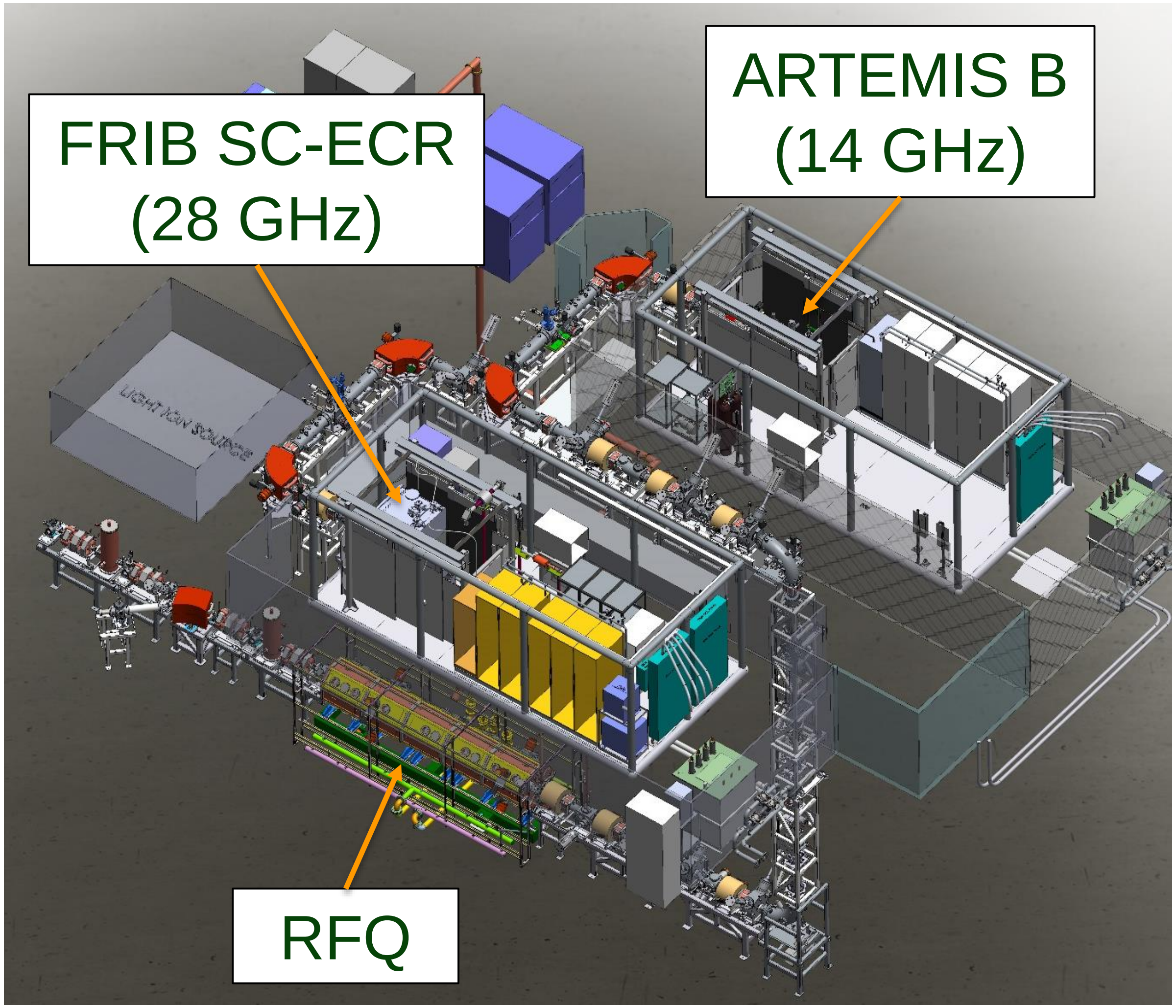


Front End

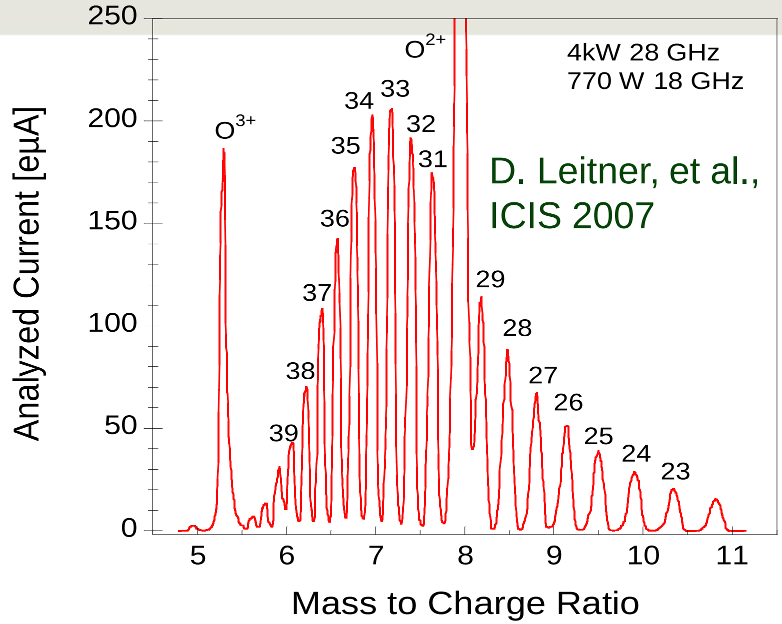


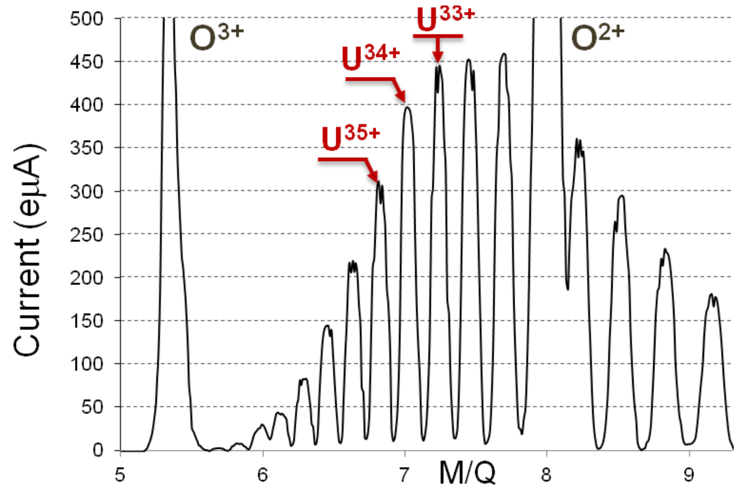
- DC beam of high charge state up to ^{238}U are produced by the ECRIS
- Selection through the Q/A spectrometer
- Selected ion species are accelerated, bunched, focused and matched in the Low Energy Beam Transport (LEBT) line into the RFQ
- RFQ focus and accelerate beams and the Medium Energy Transport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

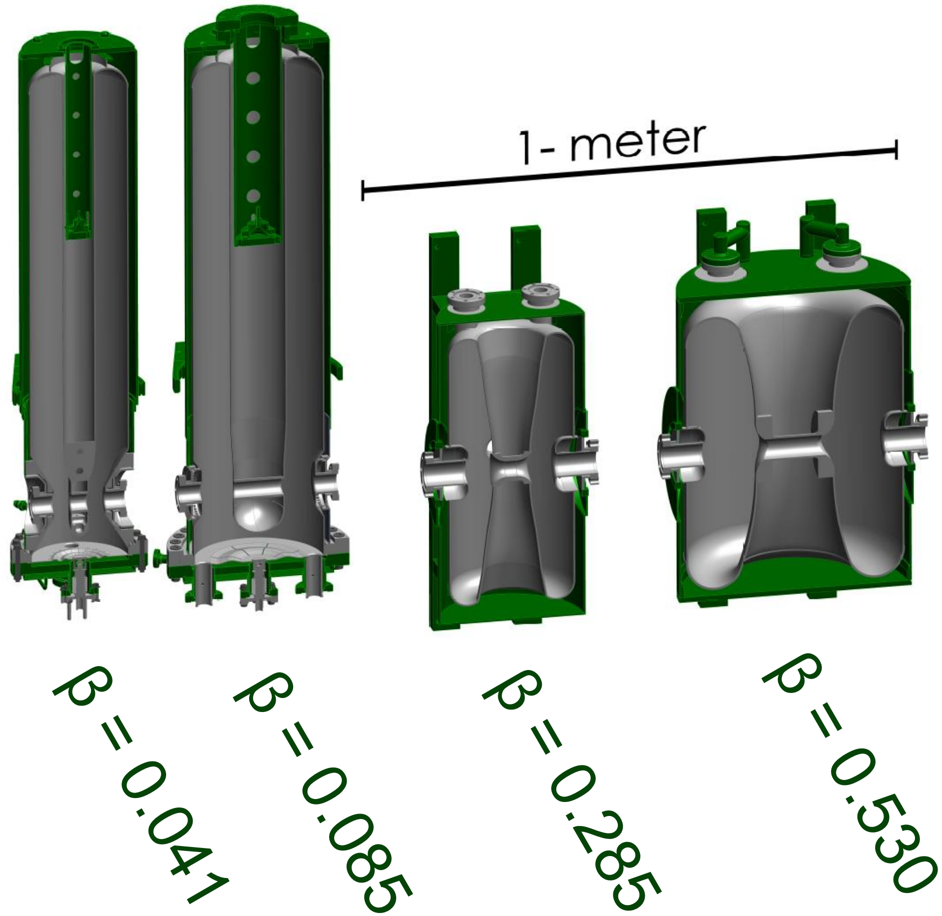
	Required Charge States	Required Beam Current (puA)	Extraction Energy (keV/u)
O	> 3	122	12
Ca	> 8	51	12
Kr	> 14	50	12
Xe	> 20	24	12
Pb	> 27, 28	23	12
U	> 33, 34	16	12

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

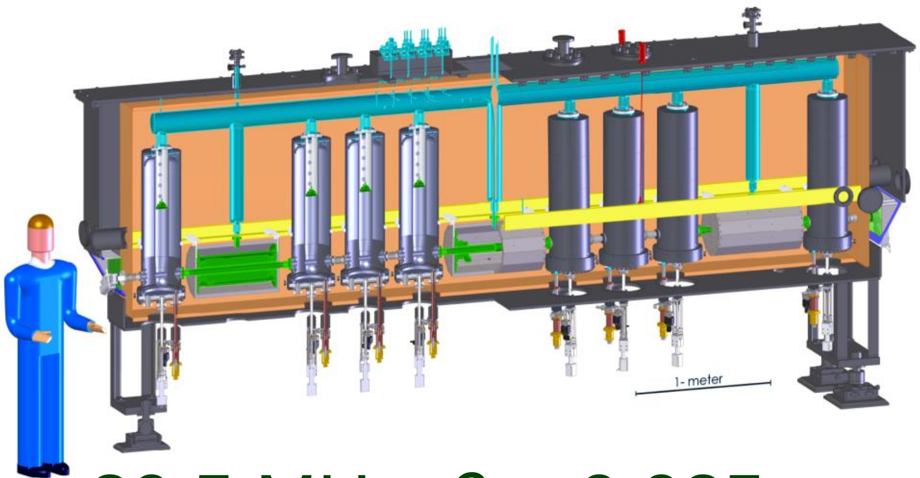
Compton C., et al., *Production Status of SRF Cavities for the FRIB project*, SRF (2015)



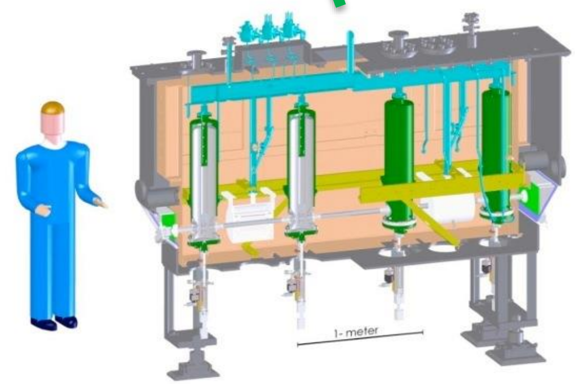
Saito K., et al., *FRIB Project: Moving to Production Phase*, SRF (2015)

Linac Segment 1

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



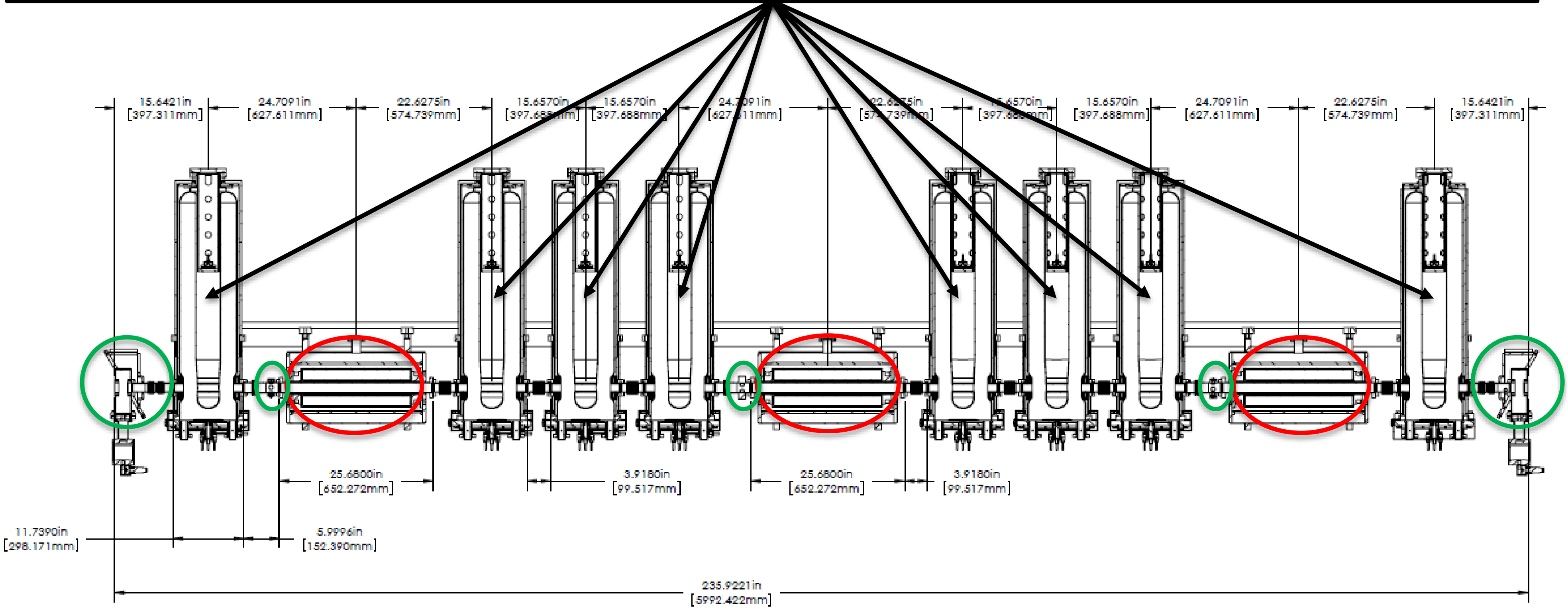
80.5 MHz, β = 0.085
11 QW (λ/4) Cryomodules



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

Inside a QW (λ/4) Cryomodule

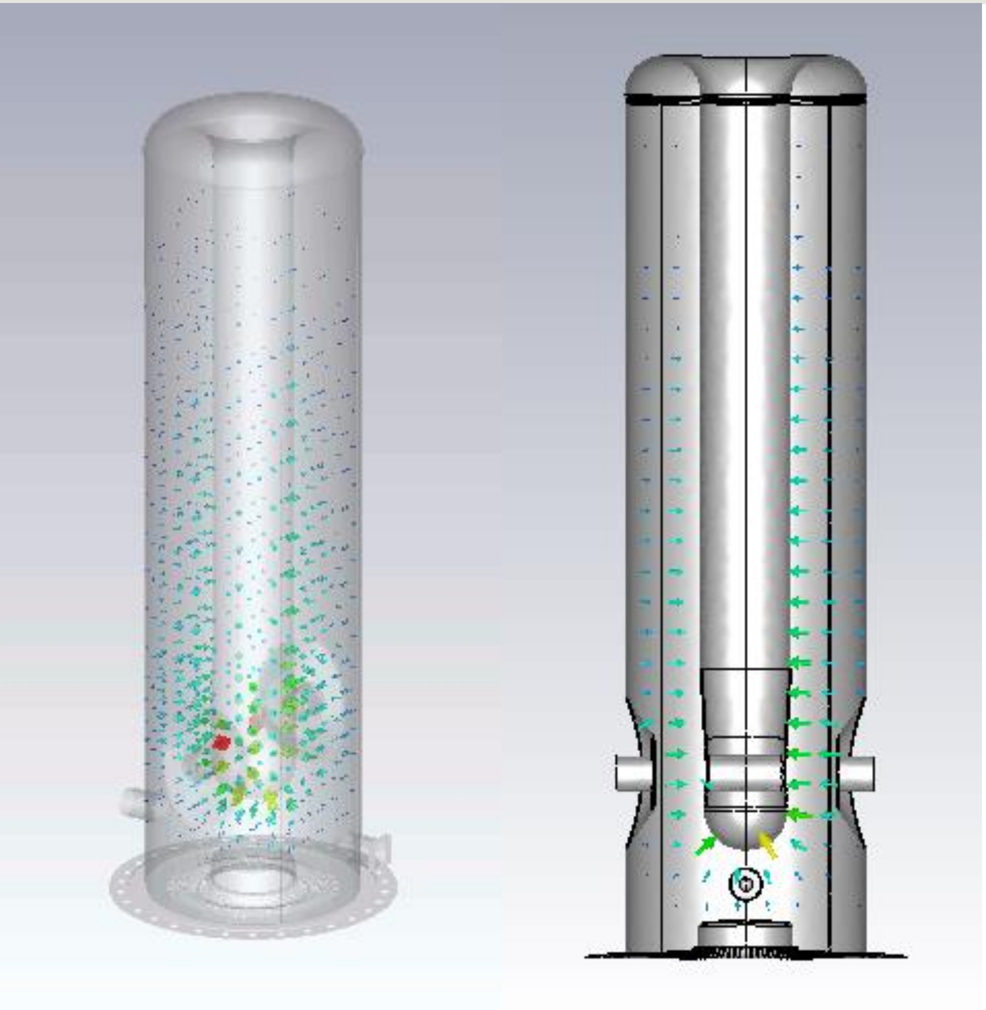
Superconducting Niobium QW Cavities operating at 80.5 MHz



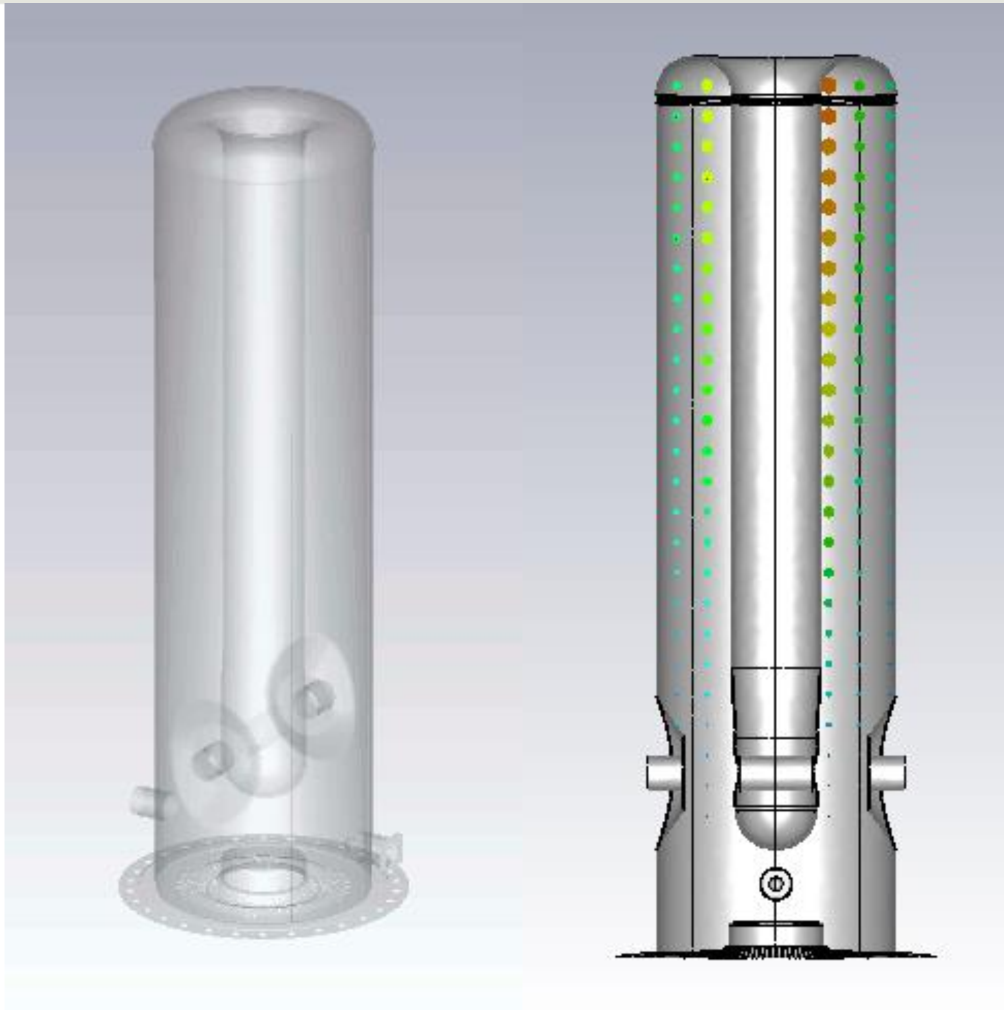
Superconducting Solenoid magnets for beam focusing + dipole for steering

Beam position monitors (BPM) and other beam diagnostics

Acceleration via RF Cavity



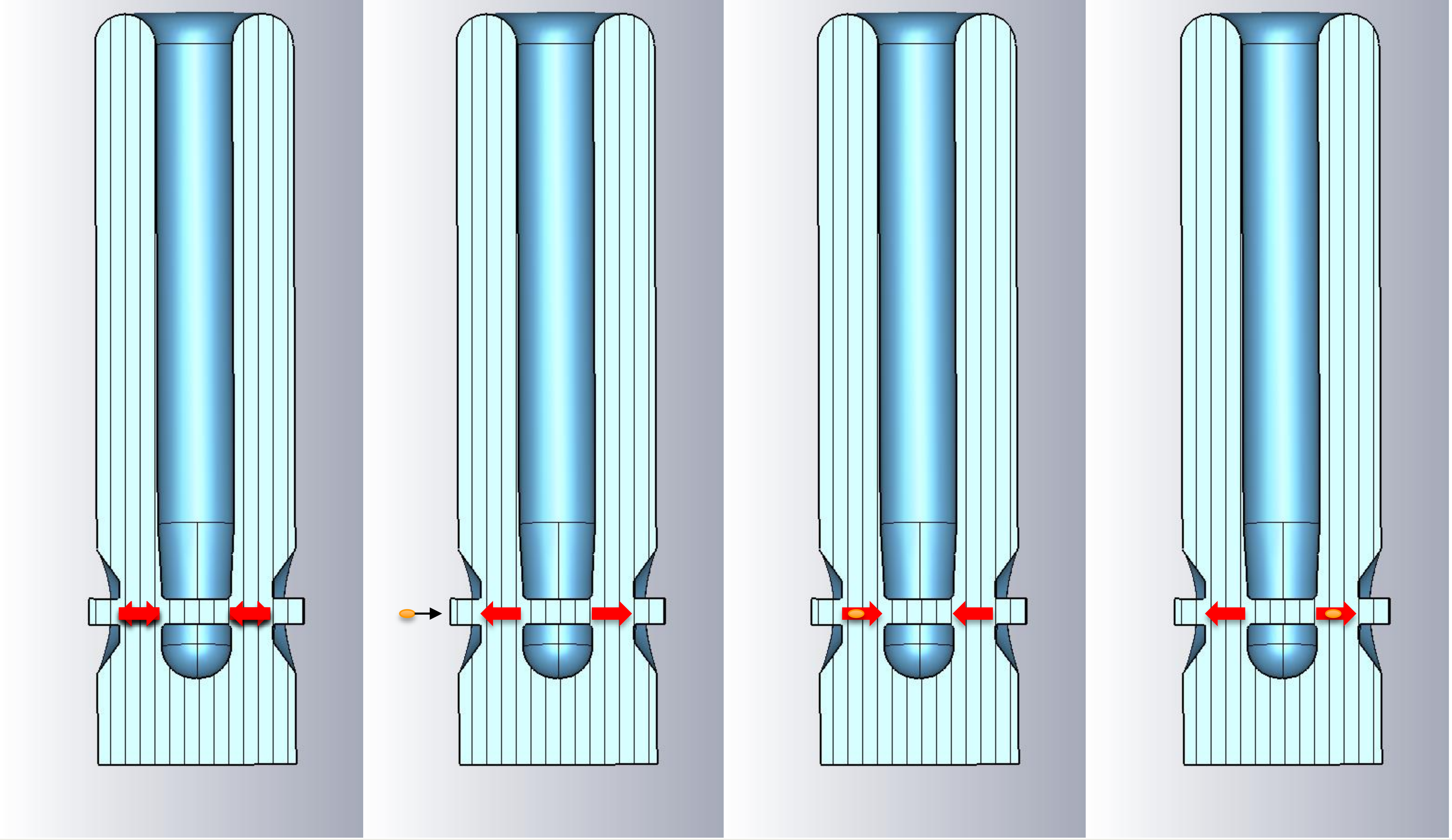
E-fields inside λ/4 β=0.085 Cavity



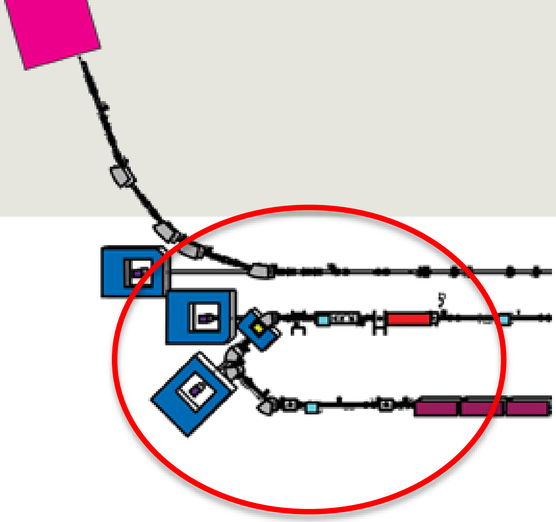
B-fields inside λ/4 β=0.085 Cavity

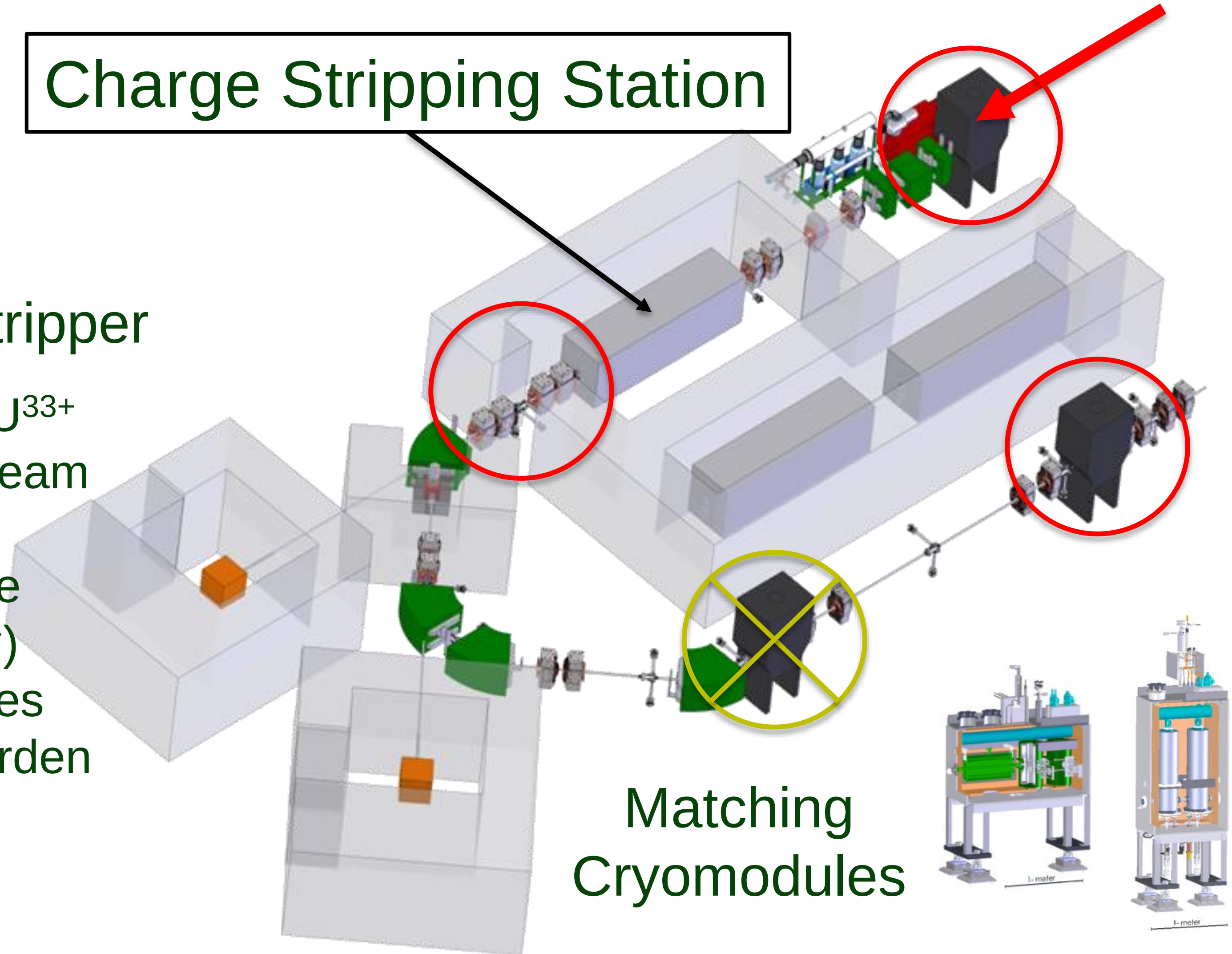
Acceleration via RF Cavity

E-fields inside λ/4 β=0.085 Cavity



Folding Segment 1



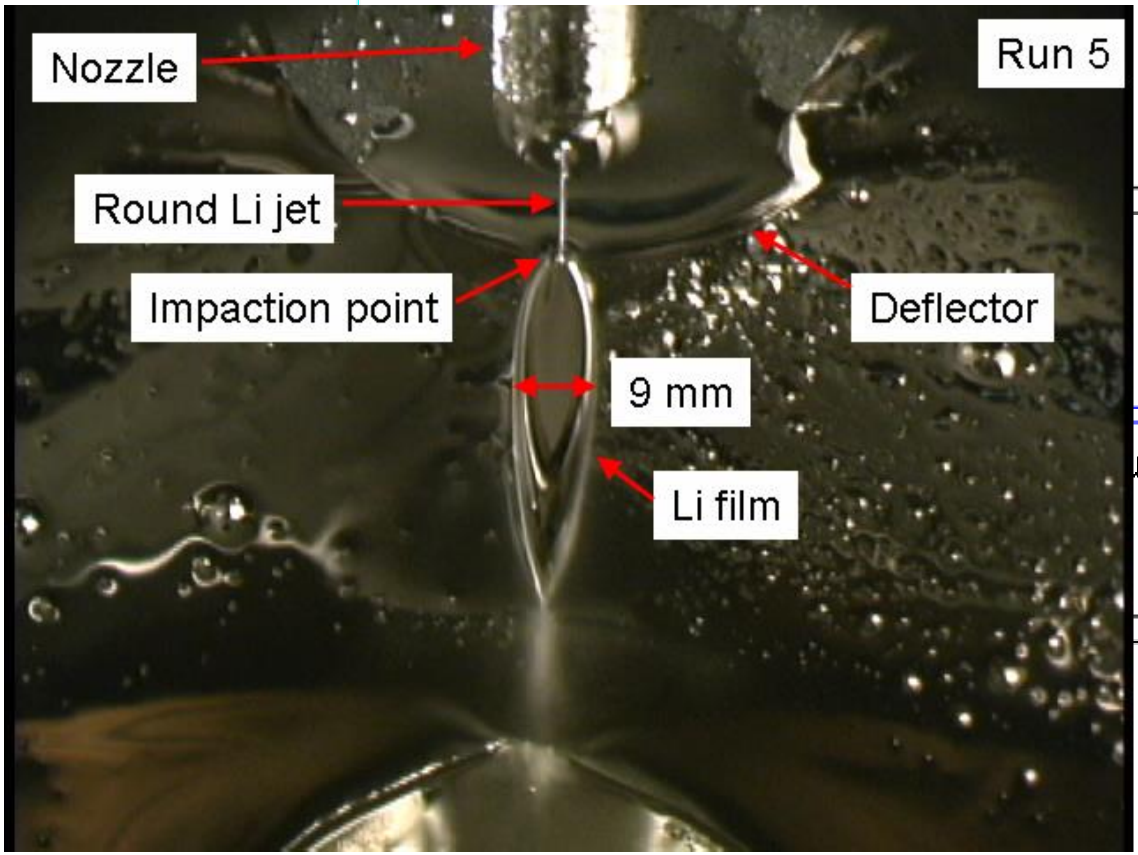


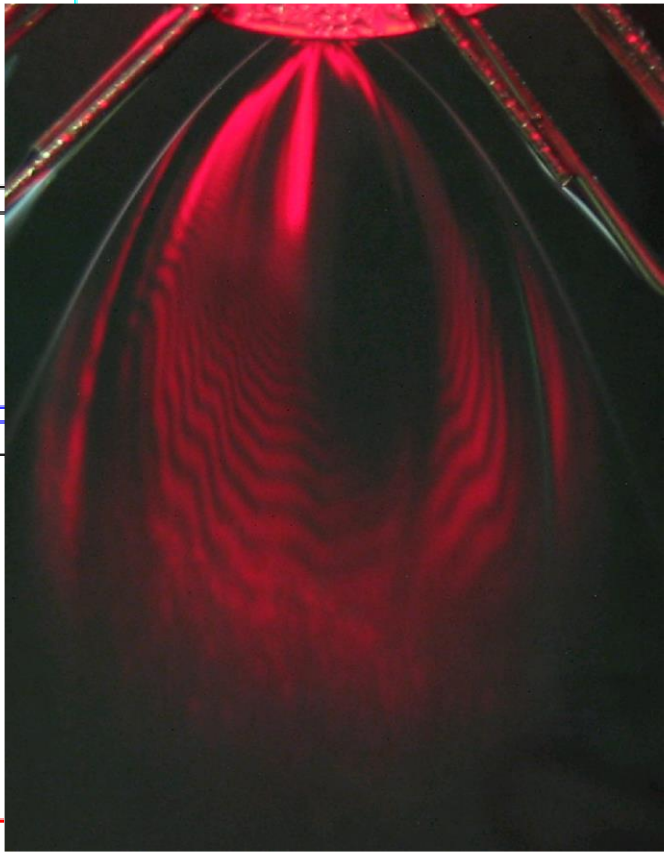
Liquid Li charge stripper

- 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

Matching Cryomodules

Liquid Lithium Stripper

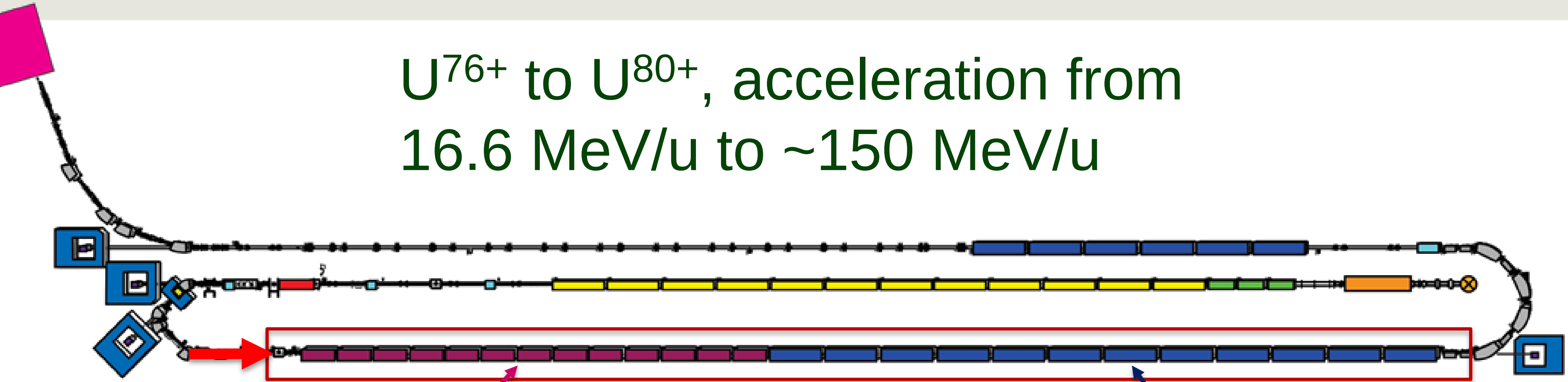


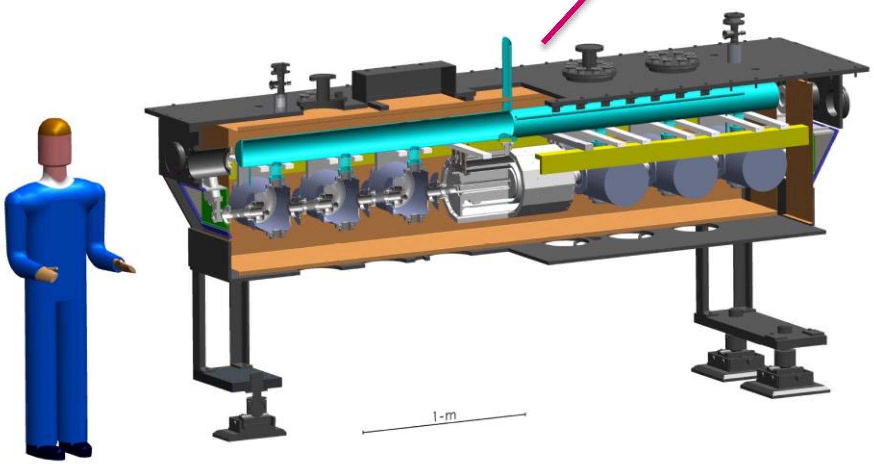


- Momozaki Y., Nolen J., et al., *Development of a liquid lithium thin film for use as a heavy ion beam stripper*, (2009).
- Marti F., et al., *Development of a Liquid Lithium Charge Stripper for FRIB*, (2015)

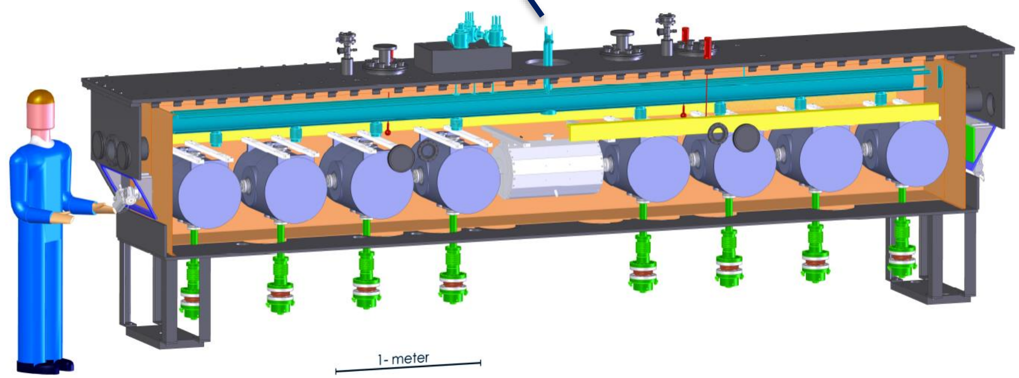
Linac Segment 2

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

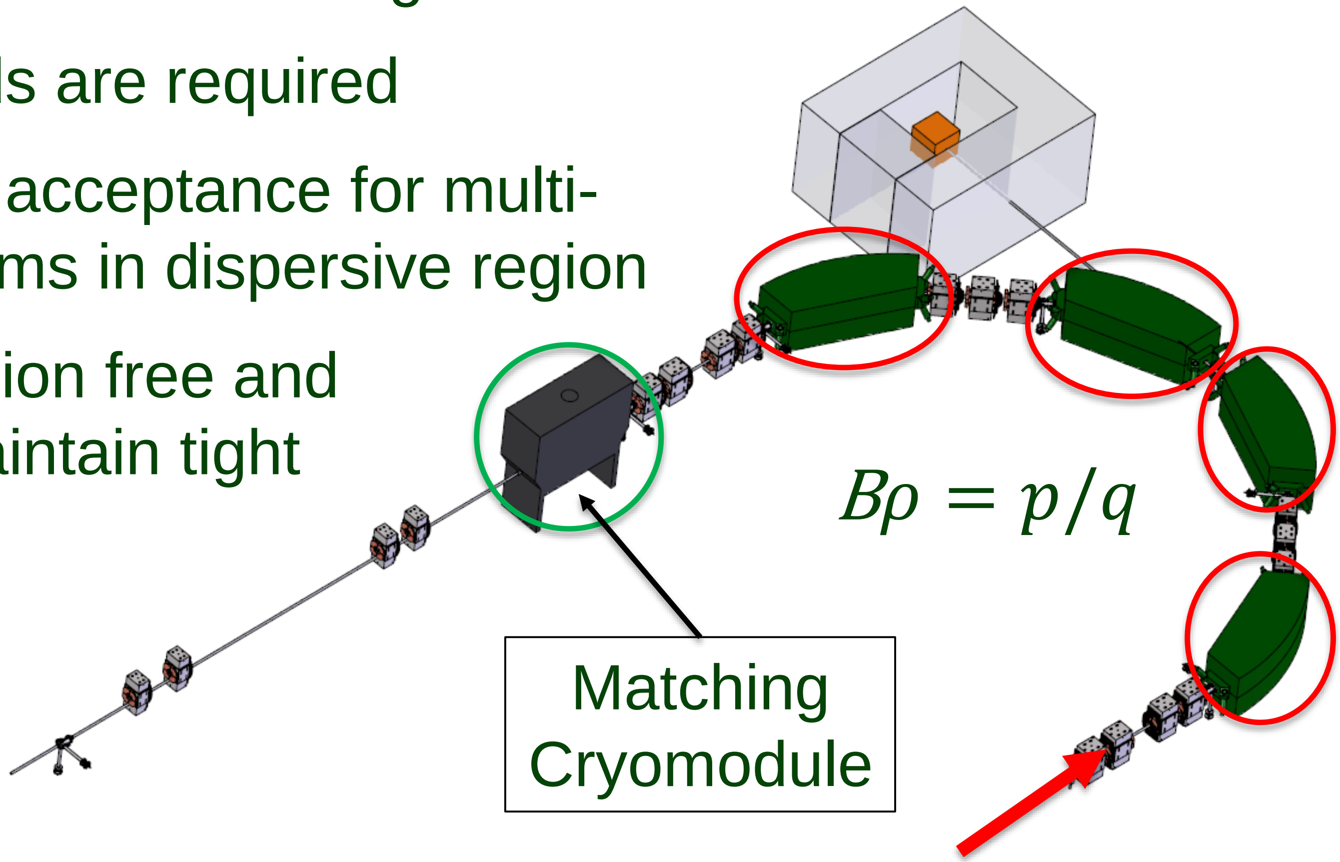


322 MHz, β = 0.53
13 HW (λ/2) Cryomodules

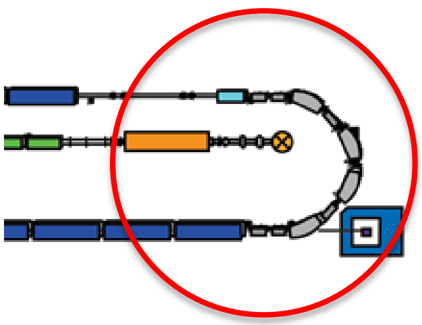
Folding Segment 2

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



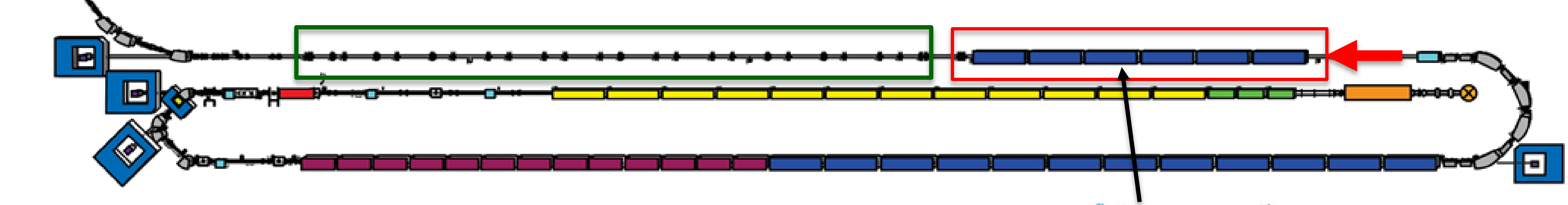
$$B\rho = p/q$$



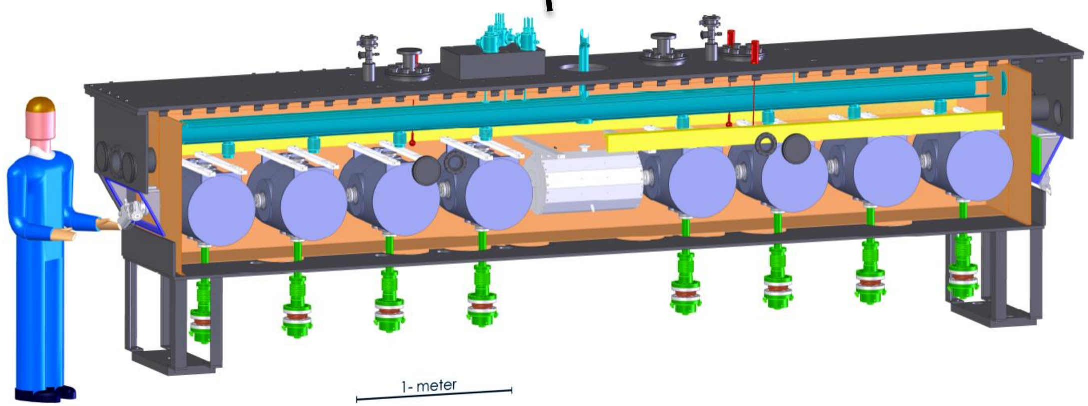
Superconducting bending magnets will be used

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

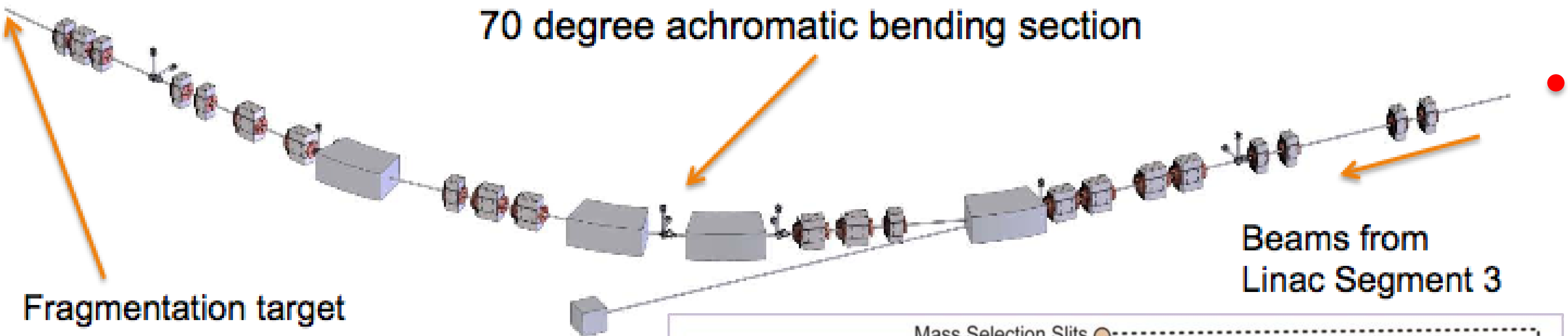


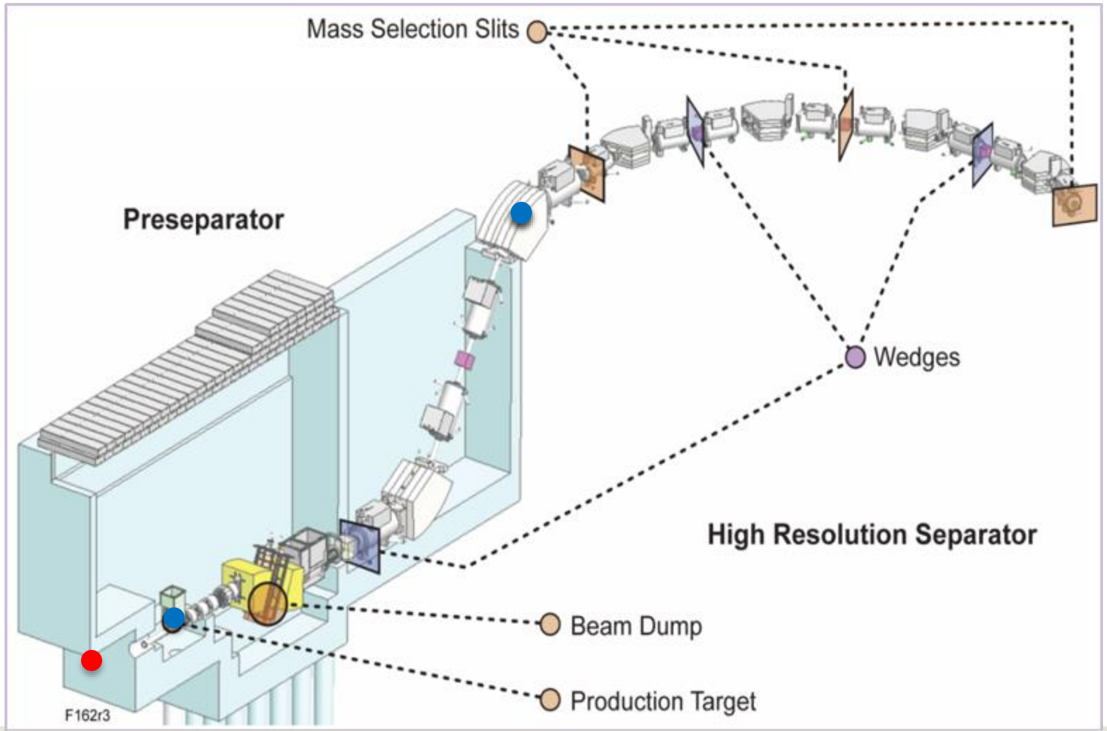
Additional space for up to 12 Cryomodules!

322 MHz, $\beta = 0.530$

6 HW ($\lambda/2$) Cryomodules

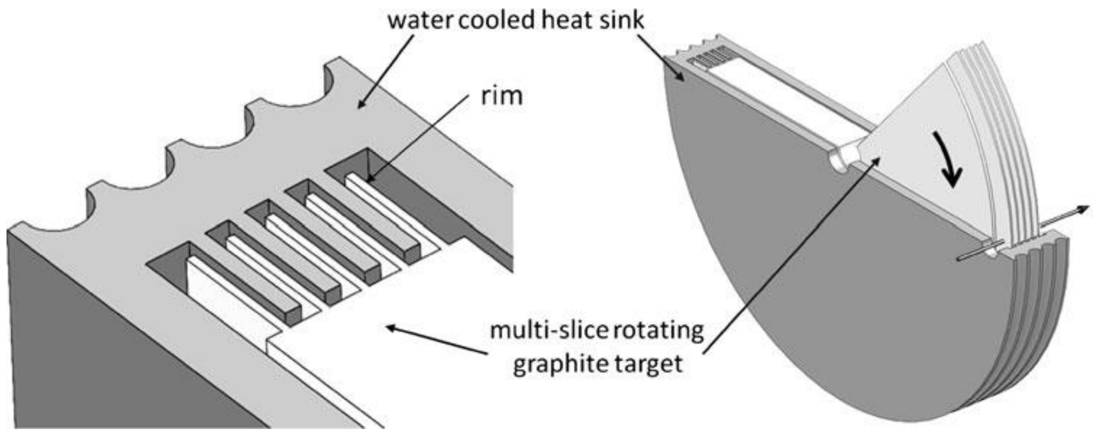
Production Target and Separator

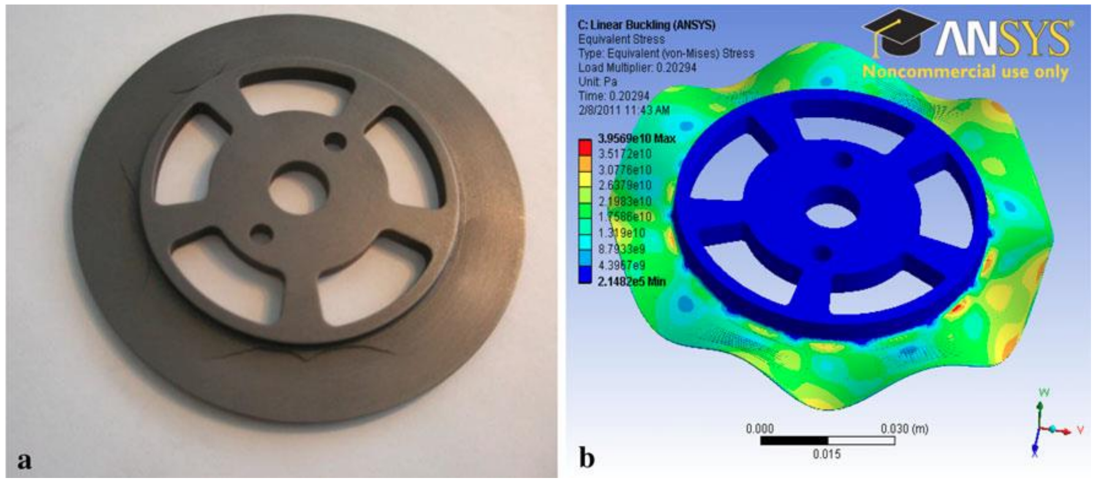




Production Target

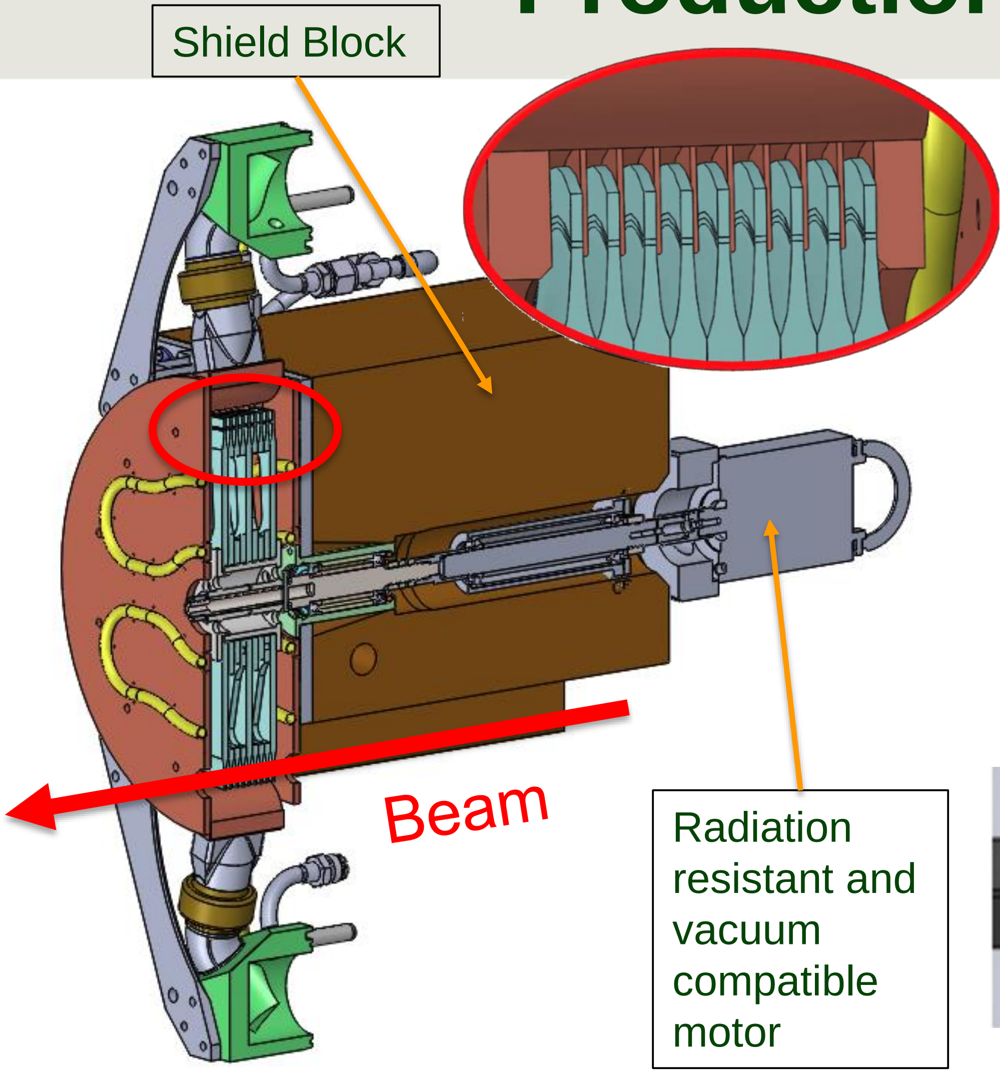
Total Beam Power	400 kW
Total Power in Target	90 kW
Power Deposition	60 MW/cm^3
Target Material	Graphite MERSEN 2360
Target Temp. Max.	1900°C
Slice Thickness	0.1 to 10 mm
Target Diameter	30 cm
Rotation Speed	5500 rpm
Max. Beam Extension	50 mm

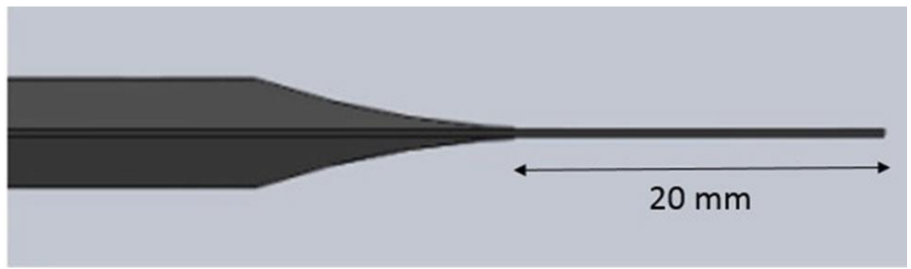




Pellemoine F., et al., *Development of a production target for FRIB: thermo-mechanical studies*, J Radioanal Nucl Chem (2014)

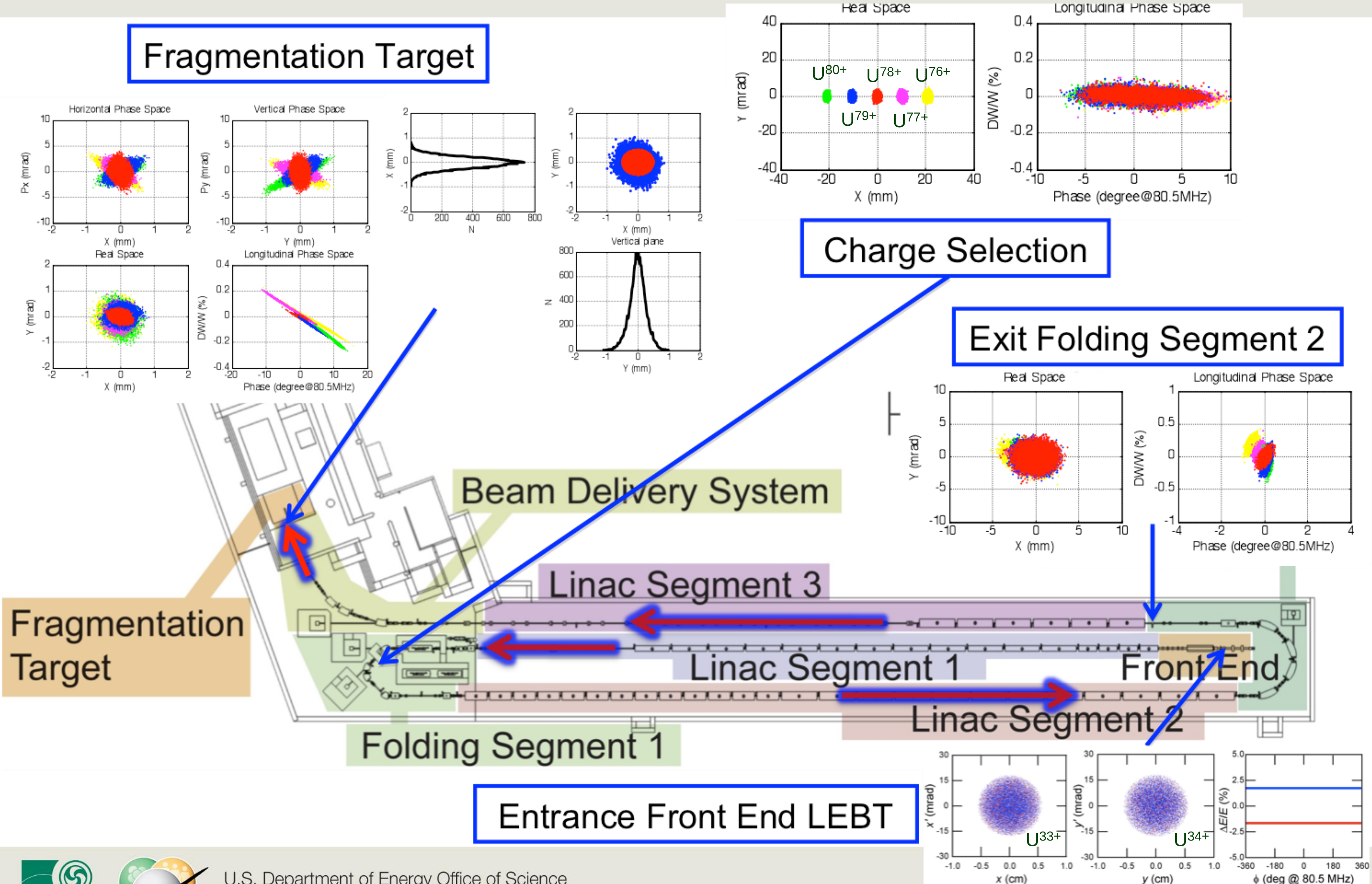
Production Target

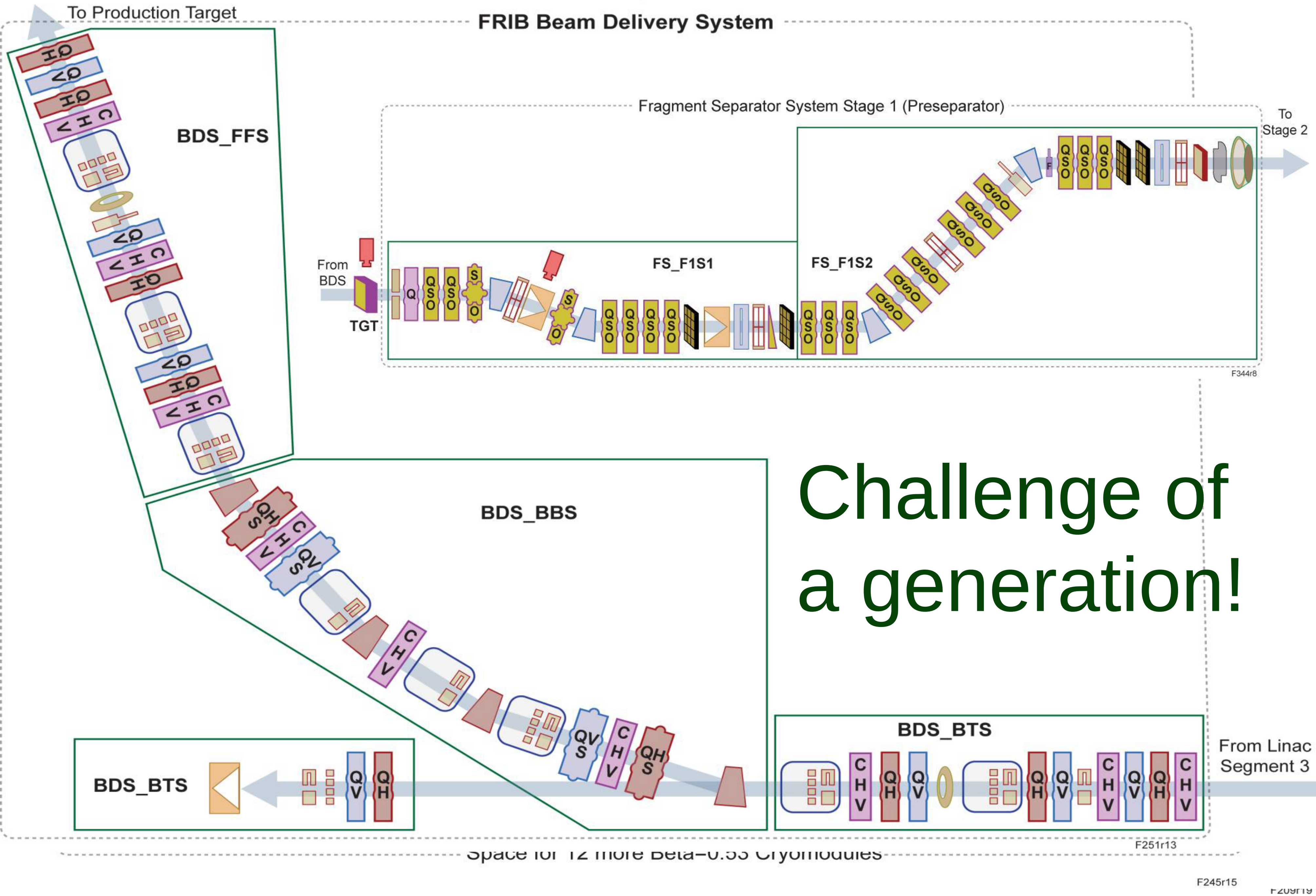




Avilov M., et al., A 50-kW prototype of the high-power production target for the FRIB, J Radioanal Nucl Chem (2014)

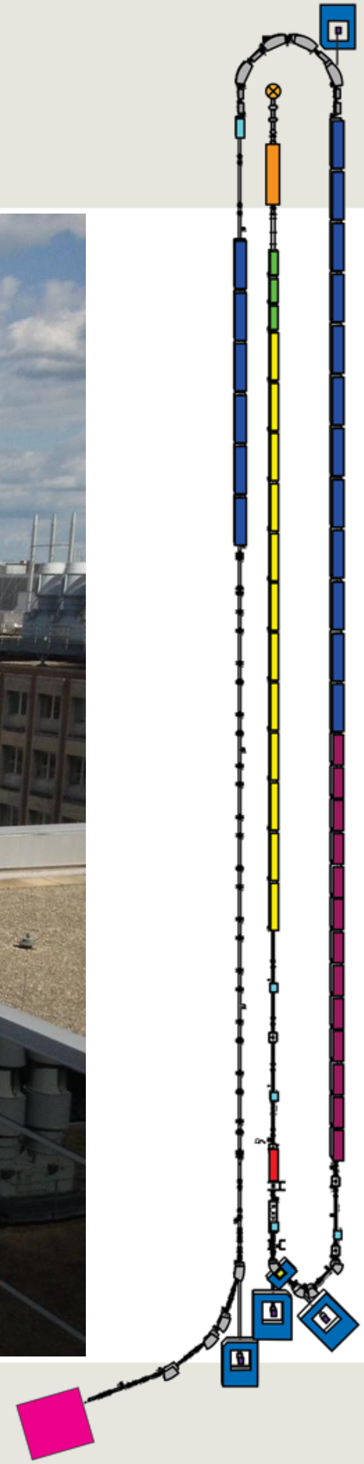
End-to-End Beam Simulations





Challenge of a generation!

FRIB Construction



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FRIB Construction

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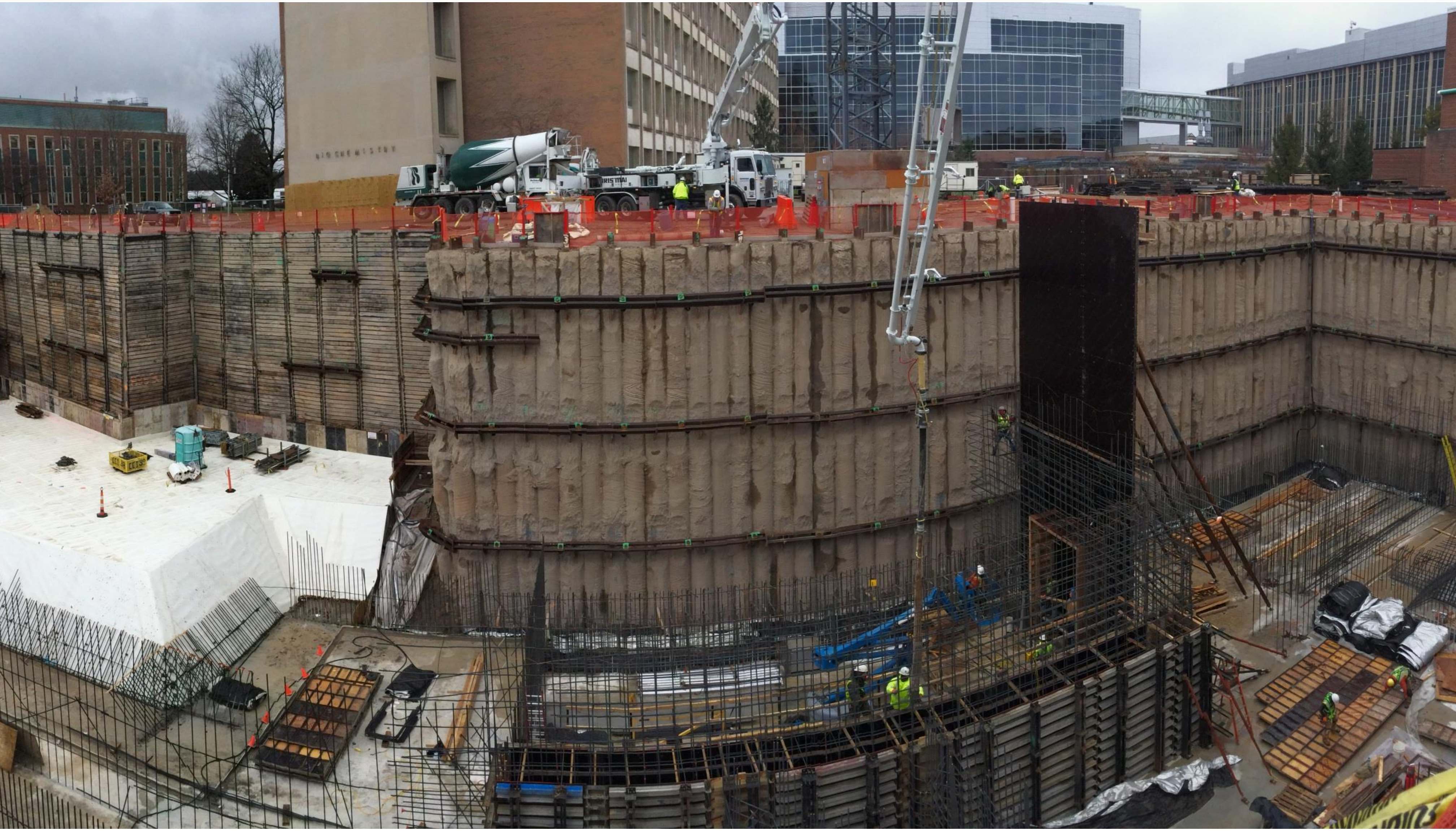
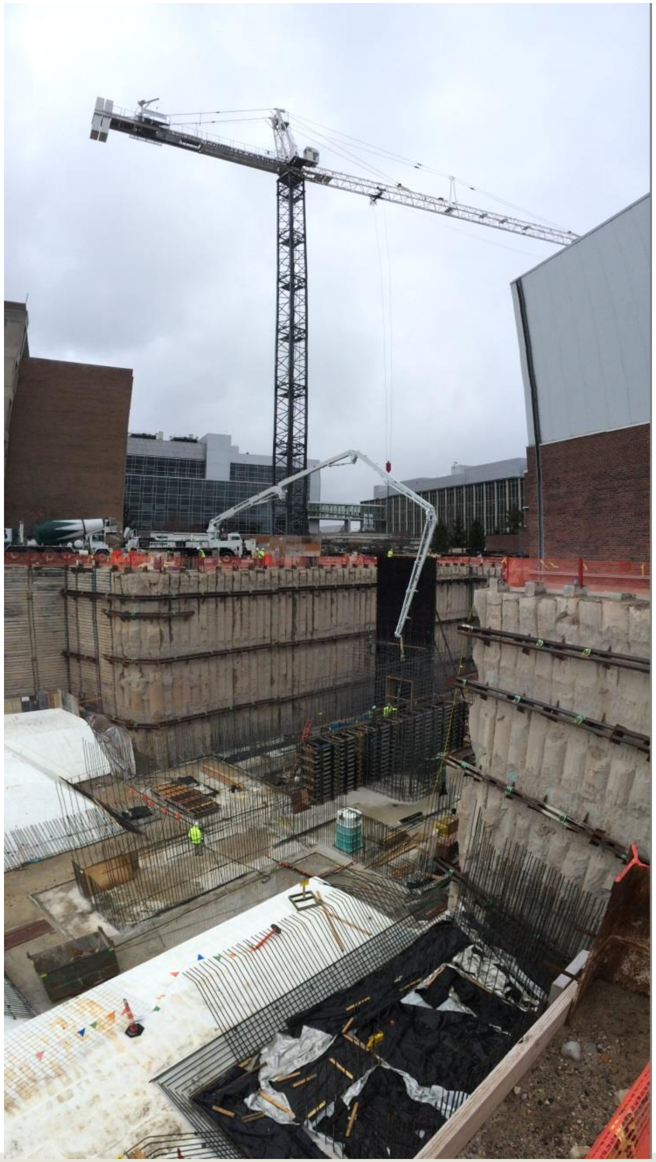
FRIB Construction

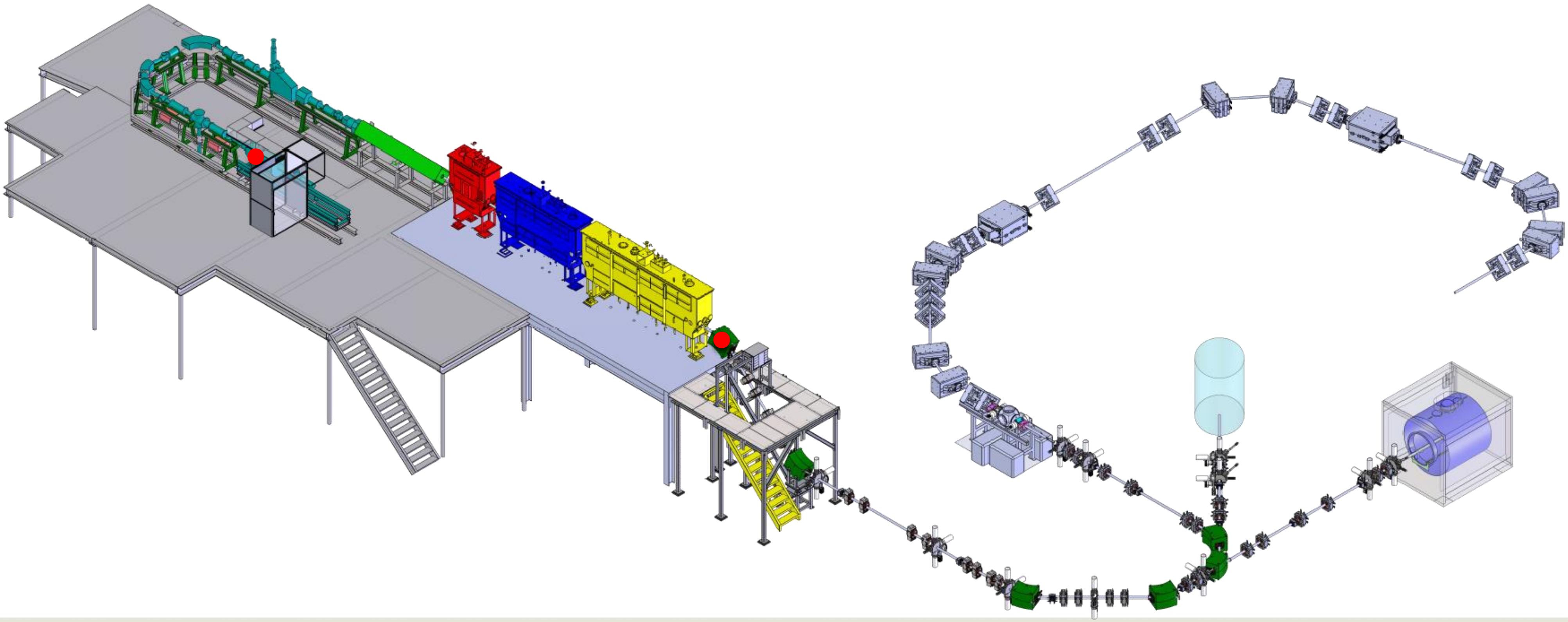


FRIB Construction

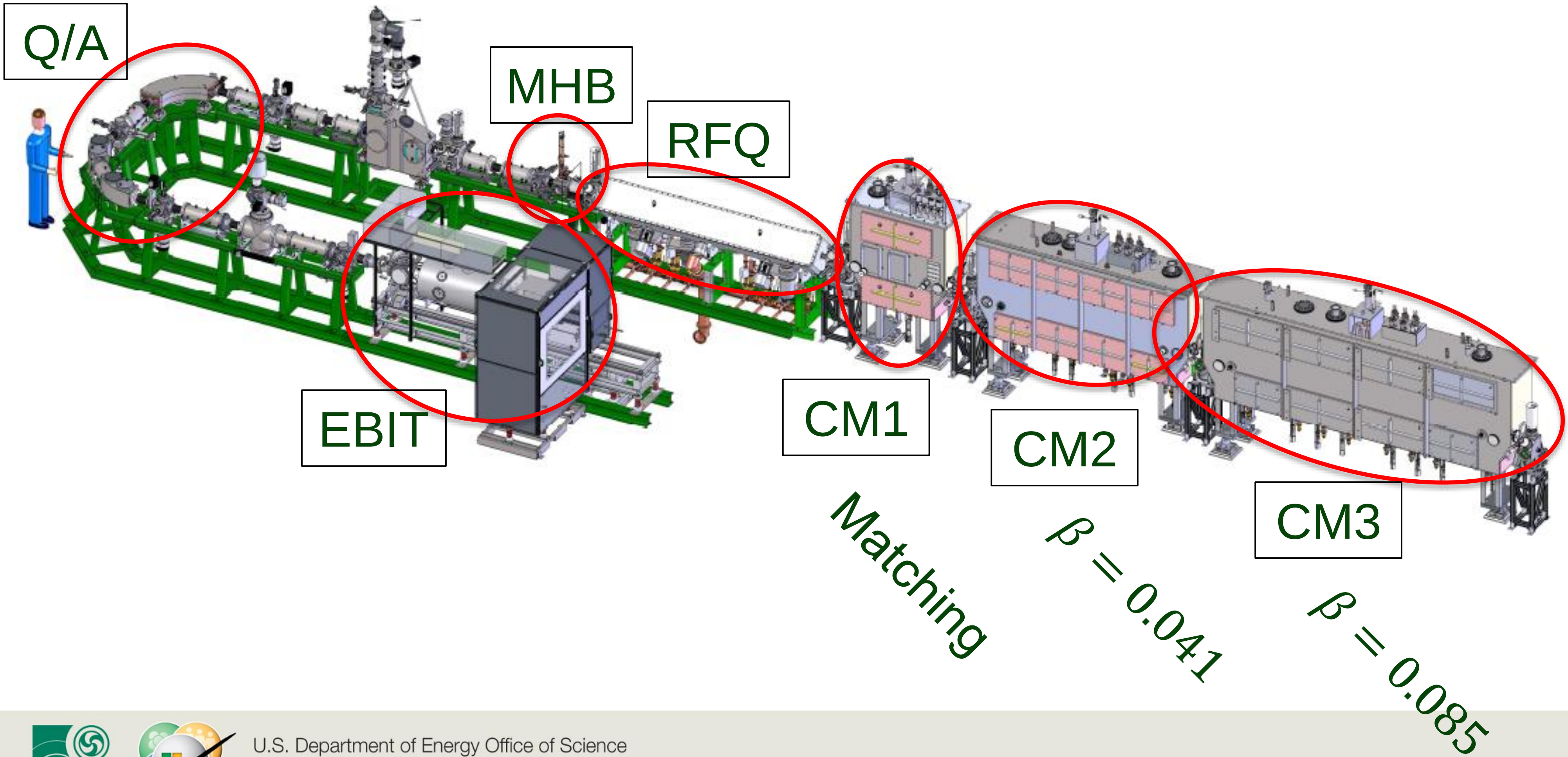


ReAccelerator @ MSU NSCL

- 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

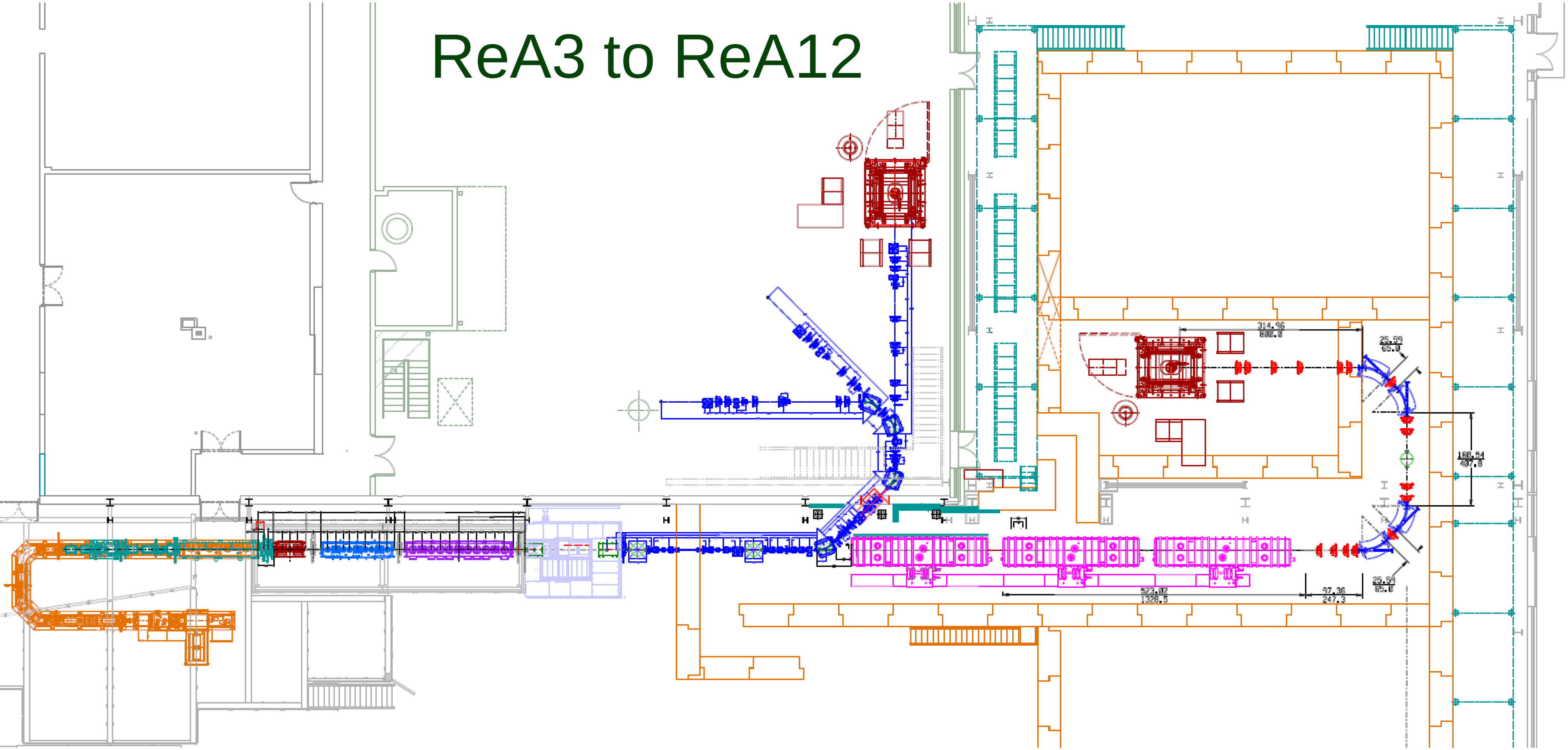


ReAccelerator – Closer Look



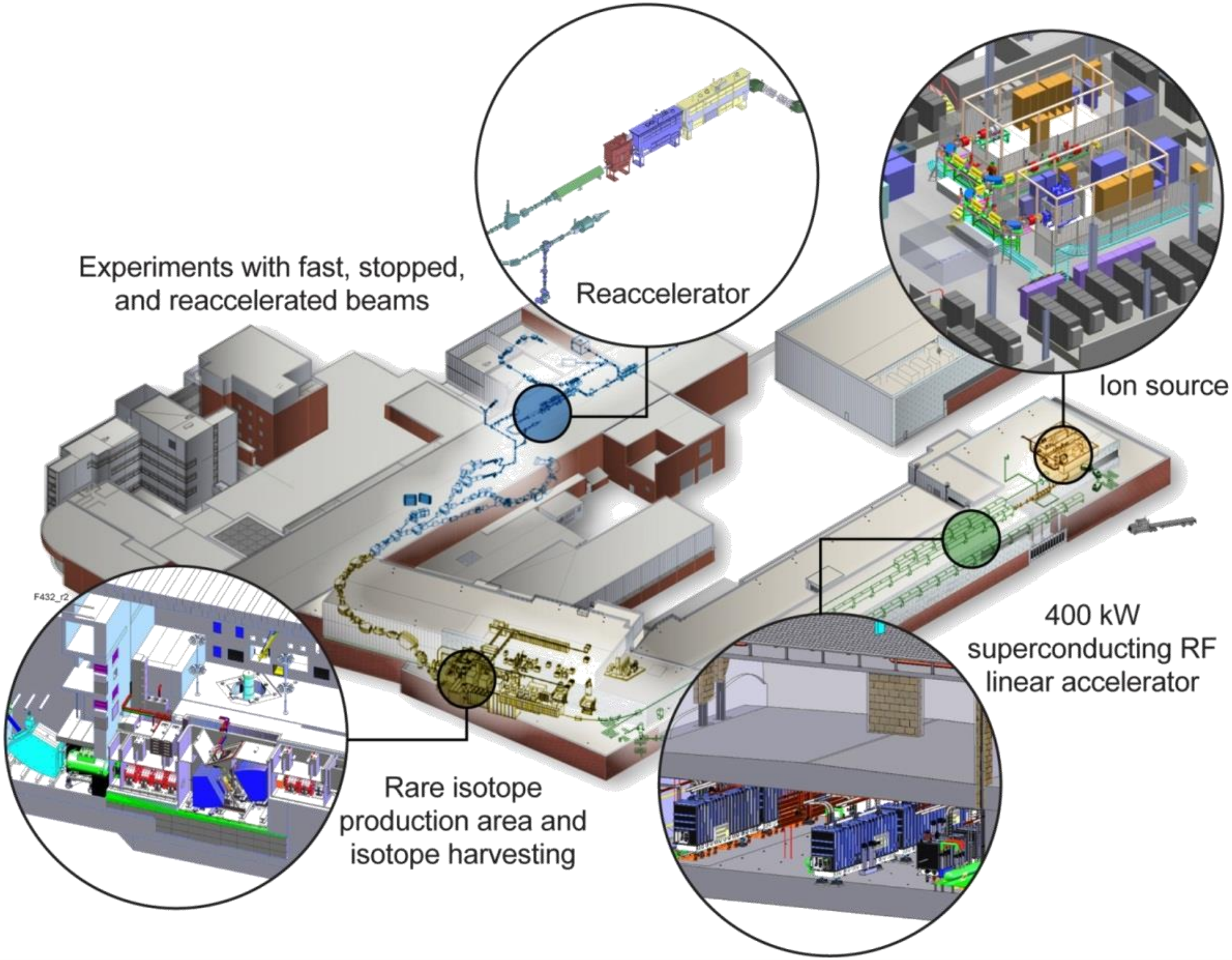
ReA Upgrade Strategy

ReA3 to ReA12



By adding more cryomodules

In Summary


Experiments with fast, stopped, and reaccelerated beams
Reaccelerator
Ion source
400 kW superconducting RF linear accelerator
Rare isotope production area and isotope harvesting
F432_r2

Thank you for your time!

Feel free to contact me
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