Technical Challenges in Design and Construction of Facility for Rare Isotope Beam (FRIB)

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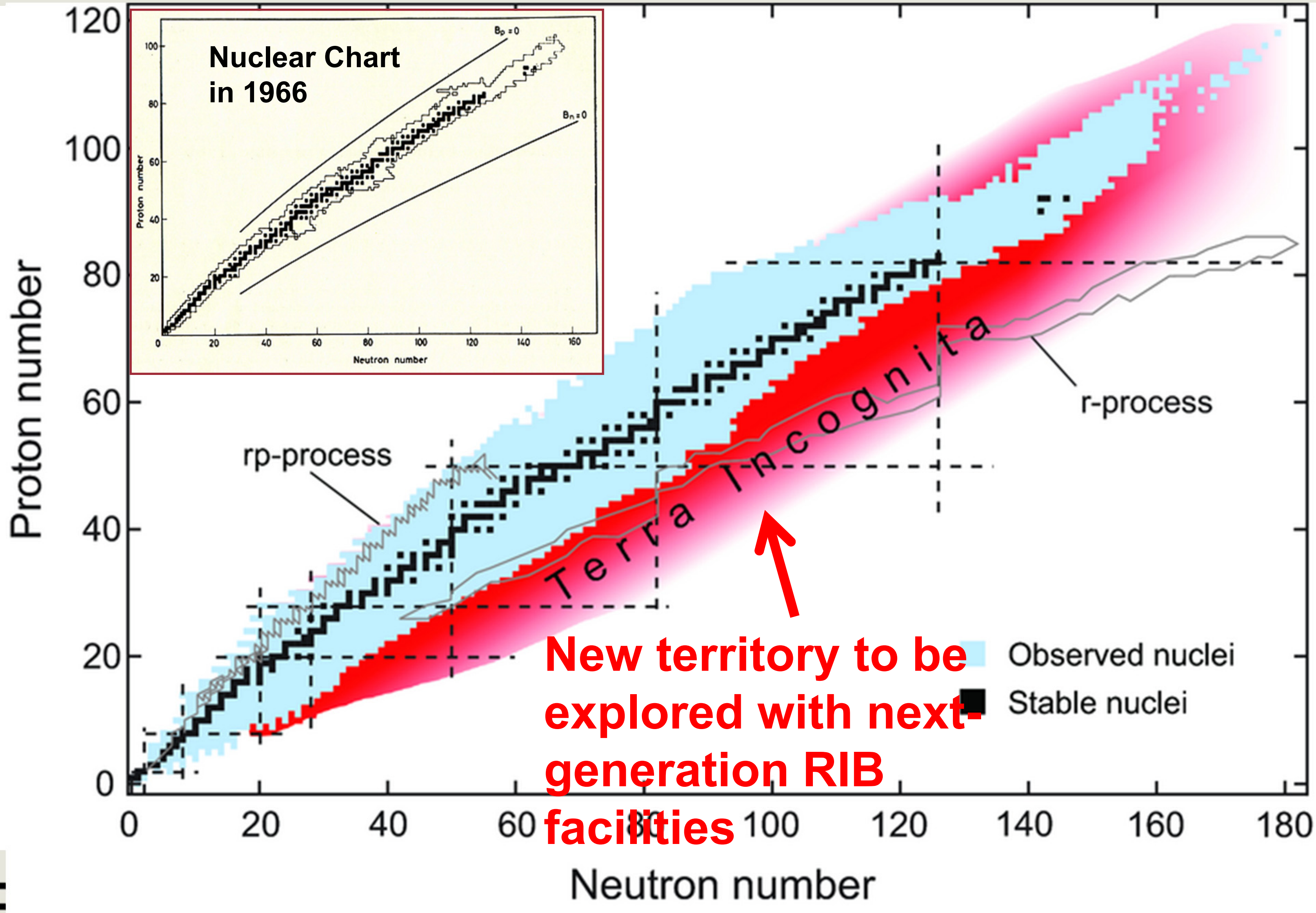
Outline

- Project numbers
- Science
- Facility overview
- FRIB by parts
- Summary

FRIB Project Numbers

- **June 2009**
  - Cooperative Agreement (DOE Contract with MSU)
- **July 2010**
  - Conceptual Design Report
- **August 2010**
  - CD-1 (Approve Alternative Selection and Cost Range)
- **June 2012** (planned)
  - CD-2 (Approve Performance Baseline)
- **2020**
  - CD-4 (Project Complete)
  - **2018 (early finish)**

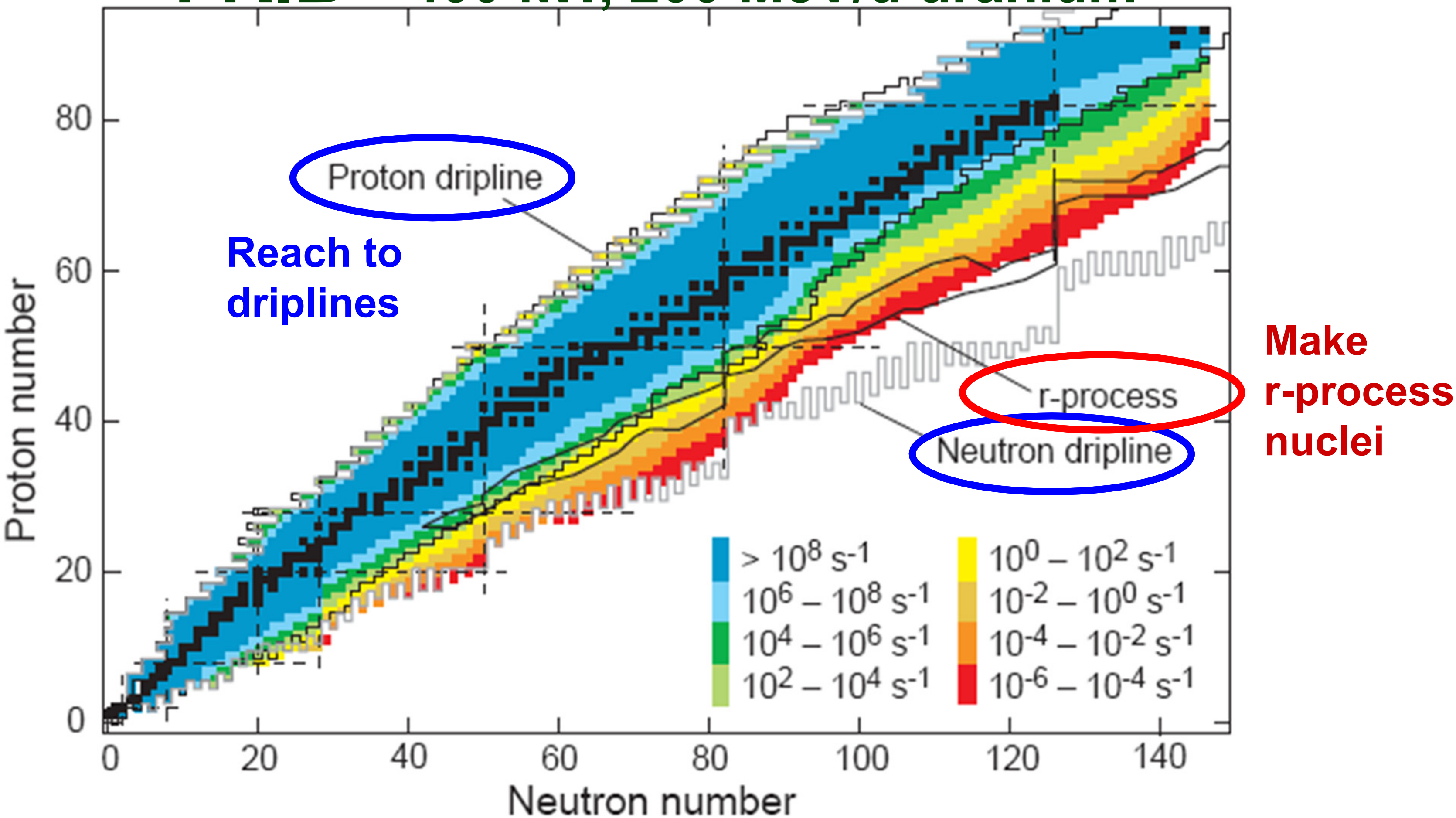
Domain of FRIB Research



High Beam Rates are Needed to Do the Science

Next-generation high-power (>100 kW) RIB facilities are the key

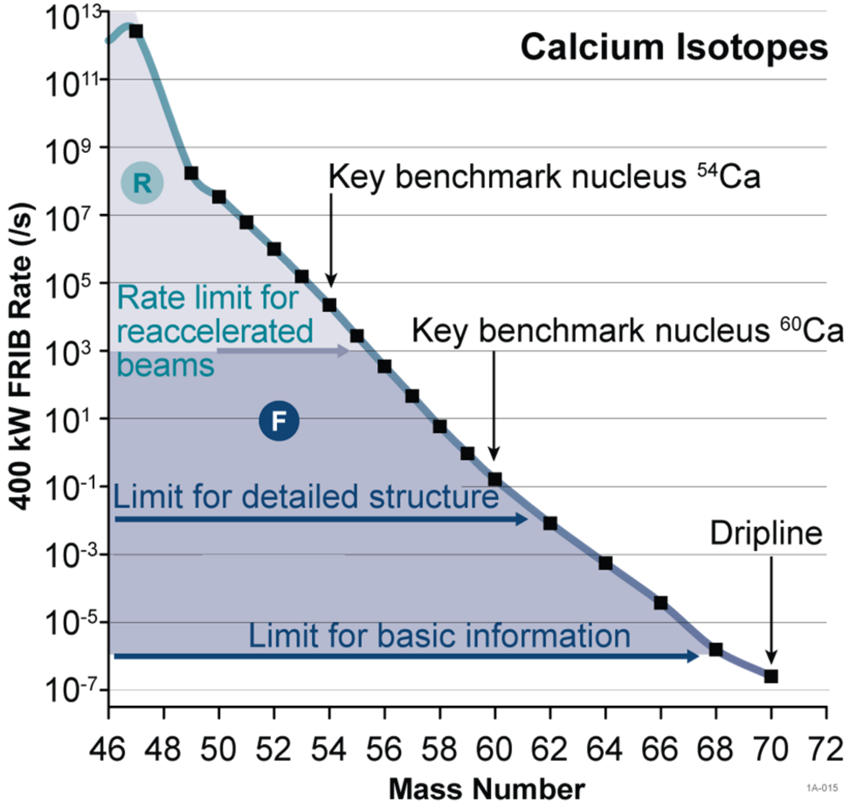
FRIB 400 kW, 200 MeV/u uranium



Gain factors of 10-10000 over operational facilities

Fast, stopped, and reaccelerated beams are needed to do the science

- Fast beams (>100 MeV/u) F
  - Farthest reach from stability, nuclear structure, limits of existence, EOS of nuclear matter
- Stopped beams (0-100 keV)
  - Precision experiments – masses, moments, symmetries
- Reaccelerated beams R (0.2-20 MeV/u)
  - Detailed nuclear structure studies, high-spin studies
  - Astrophysical reaction rates

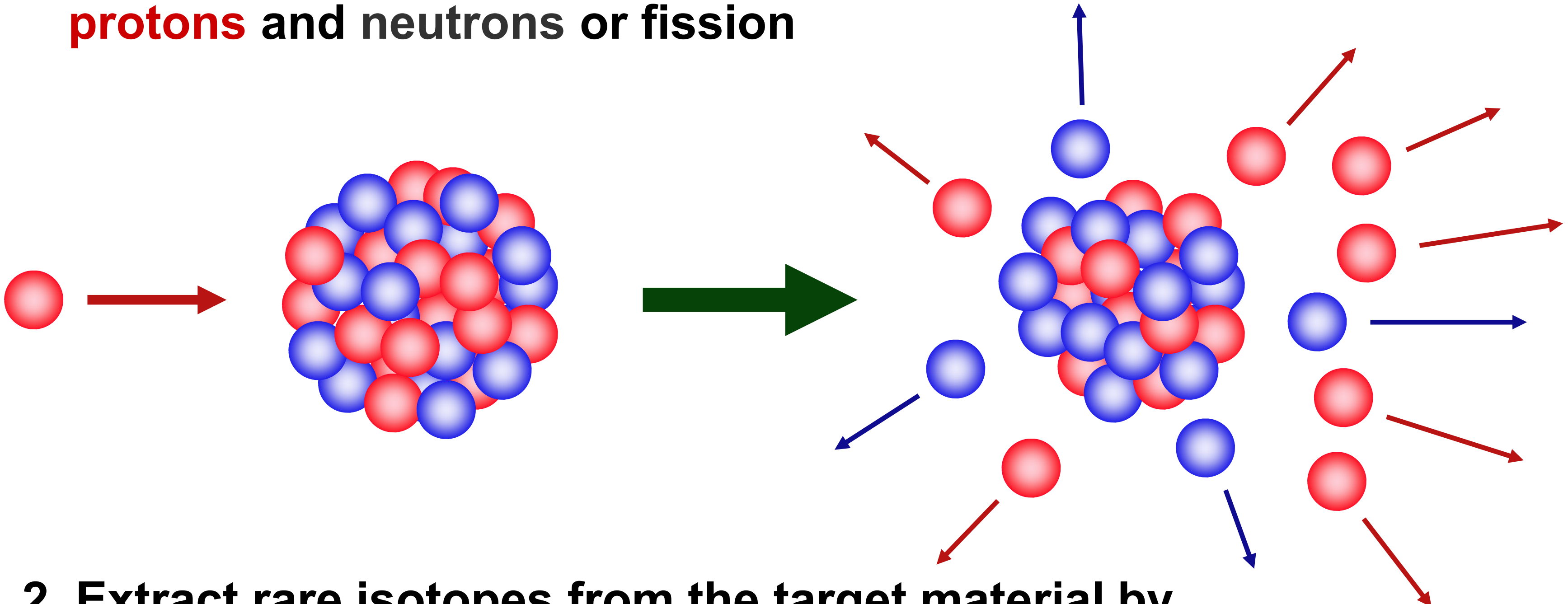


Production of Rare Isotopes at Rest

Isotope Separation On Line (ISOL technique)

Not in baseline but potential for implementation maintained

1. Bombard a thick target of heavy nuclei with energetic light particles, e.g. 1 GeV protons, to achieve random removal of protons and neutrons or fission

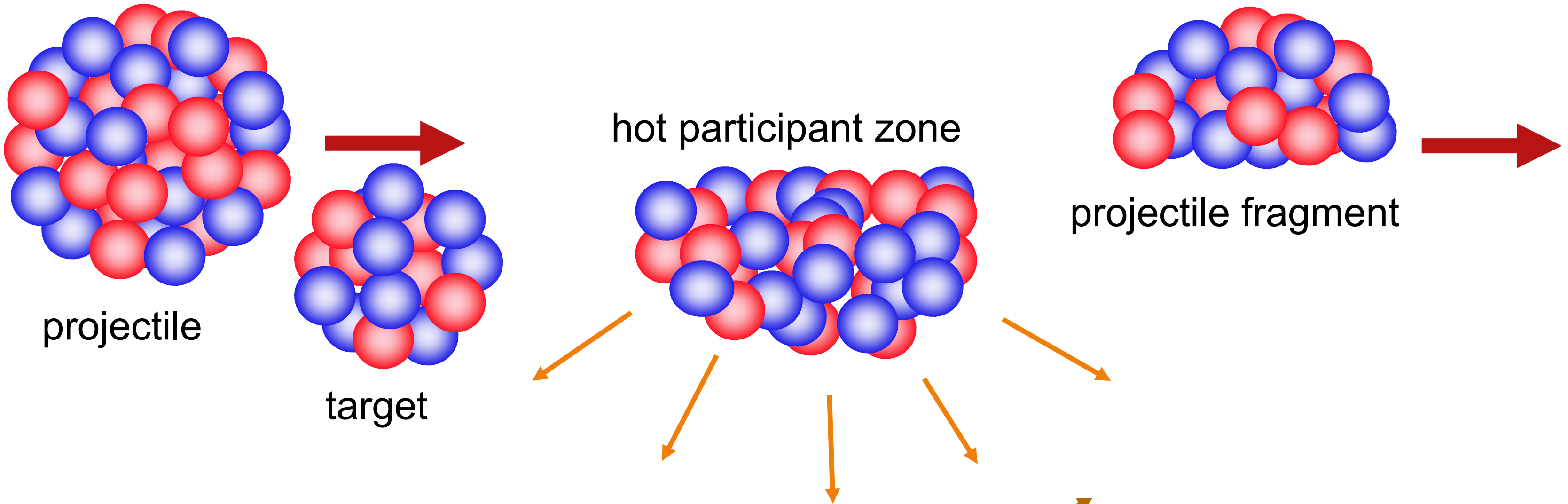


2. Extract rare isotopes from the target material by diffusion or effusion; ionize and accelerate them to the desired energy beam of high quality

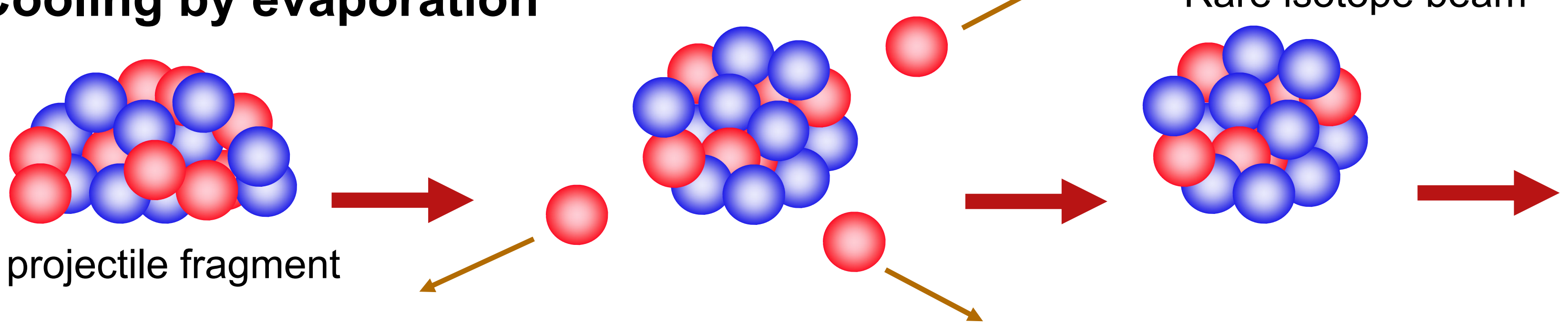
Production of Rare Isotopes in Flight

Baseline Approach

1. **Accelerate heavy ion beam to high energy and pass through a thin target to achieve random removal of protons and neutrons in flight**

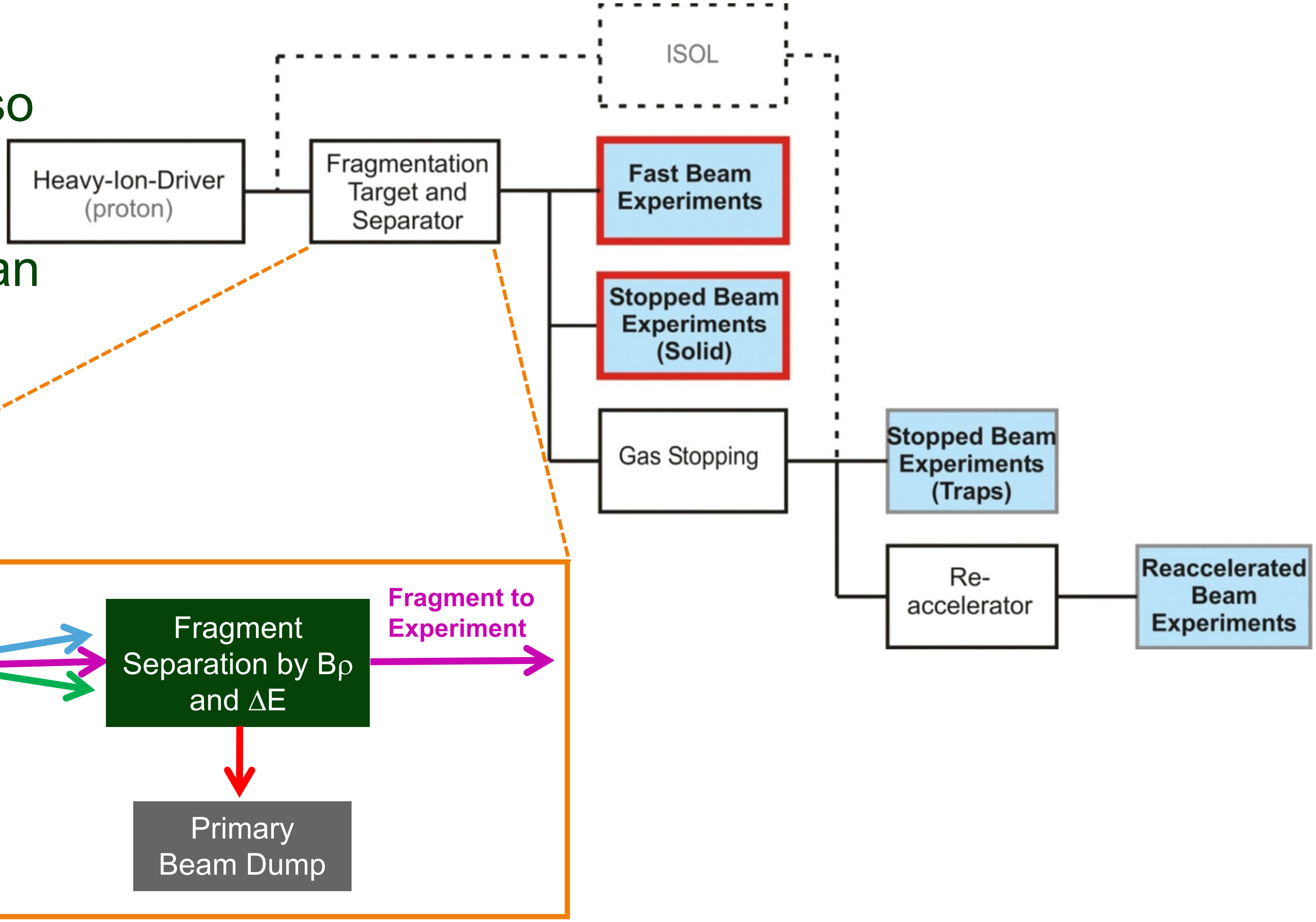


2. **Cooling by evaporation**



FRIB Rare Isotope Beams

- Heavy-ion linac can also accelerate light ions needed for an ISOL facility



FRIB Specifications

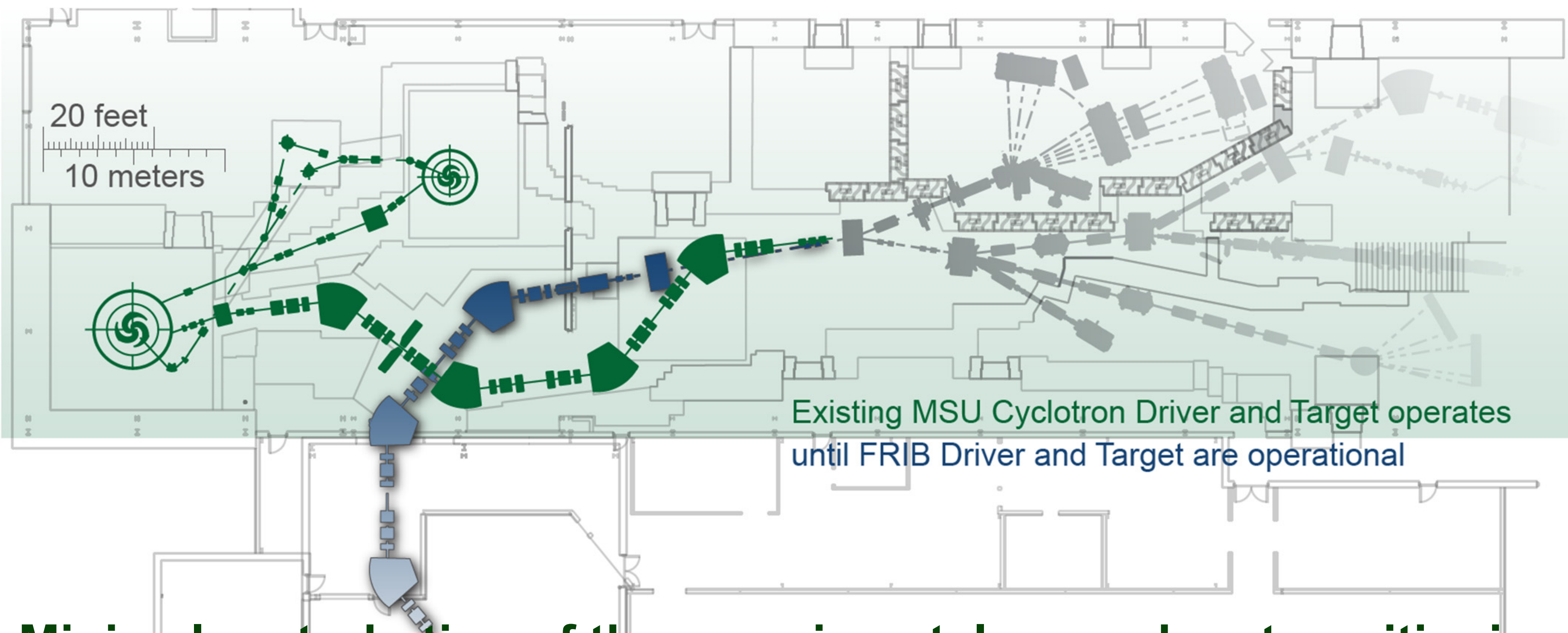
Baseline

- Driver Linac
  - Stable ions up to ^{238}U
  - Energies ≥200 MeV/u
  - Beam power ≤400kW
- Production Target and Fragment Separator System
- Experimental systems for experimental program – use rare isotopes
  - At velocity (~0.5*c*) (Fast)
  - Stopped
  - Reaccelerated

Maintain upgrade options

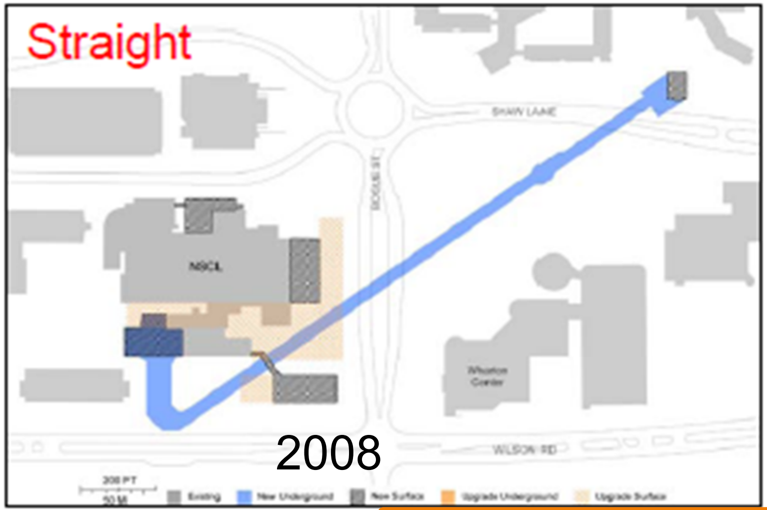
- Energy upgrade to ≥400 MeV/u for ^{238}U
- ISOL target system & light-ion injector

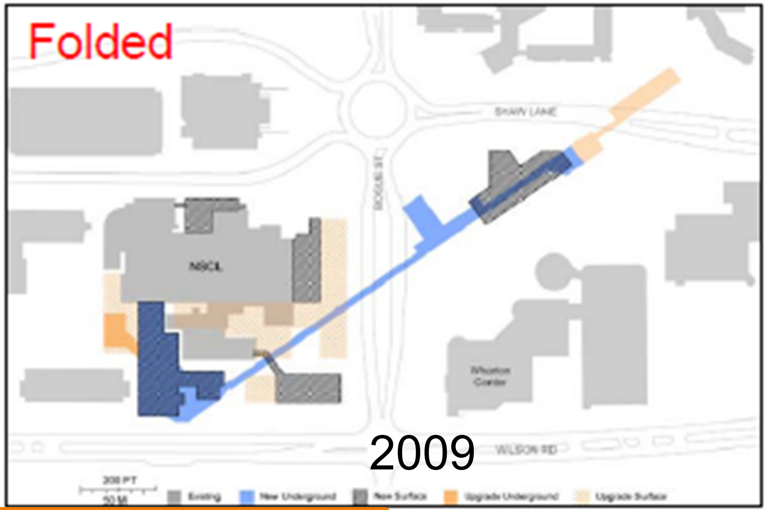
Present NSCL Facility Offers Substantial Advantages & Challenge



- **Minimal perturbation of the experimental area when transitioning from NSCL to FRIB operations**
- Post-production elements commissioned before FRIB driver linac complete - ensures world-class scientific research program at start of FRIB operation

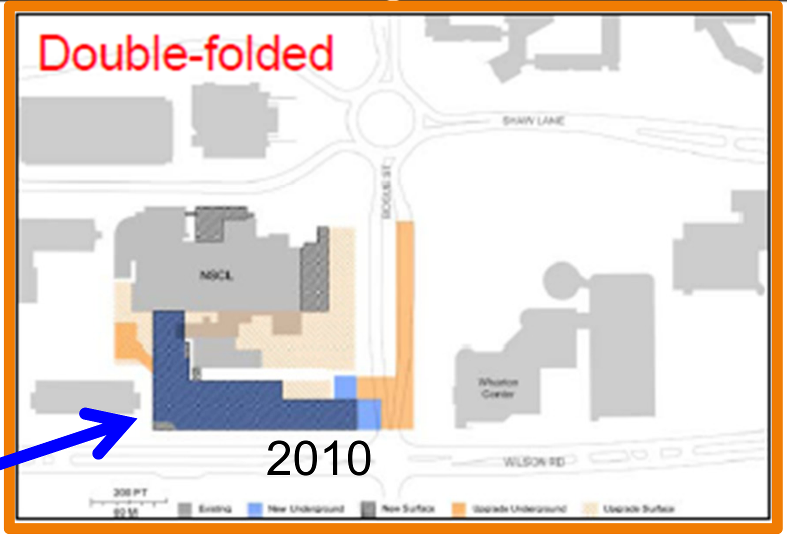
Challenge - Configuration



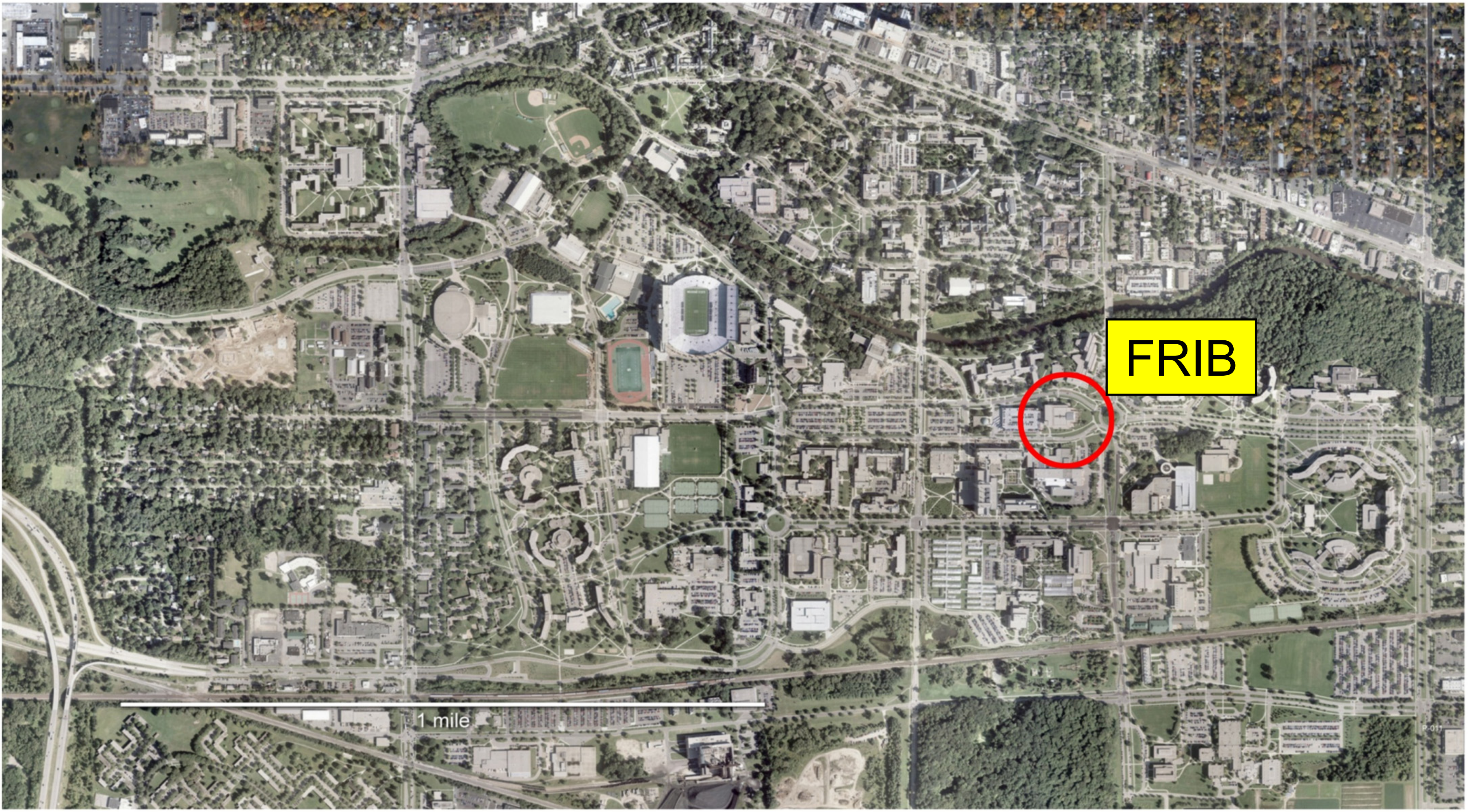


Many geometries possible

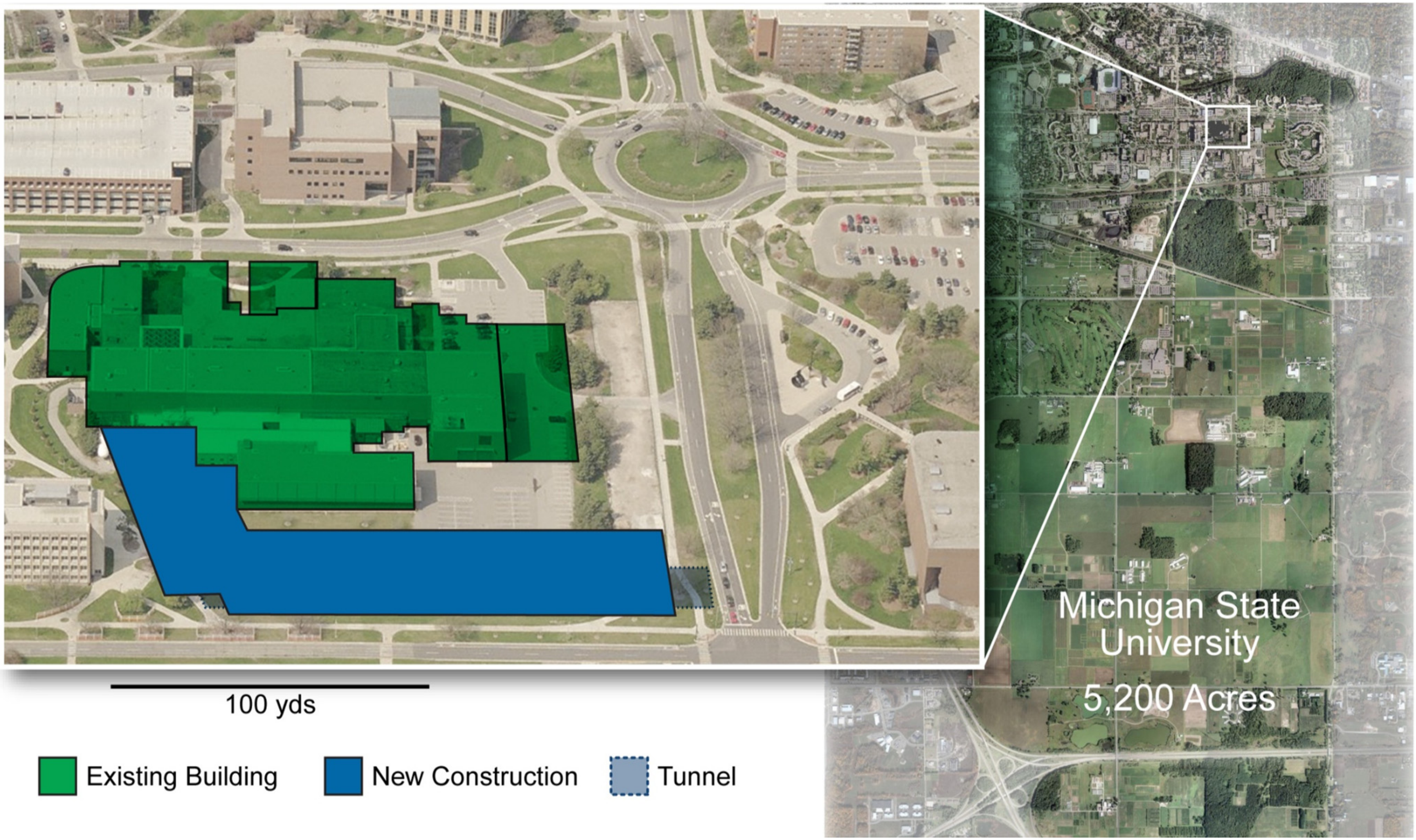
- Driven by minimum cost meeting baseline and maintaining upgrade potential
- **Compact geometry best**



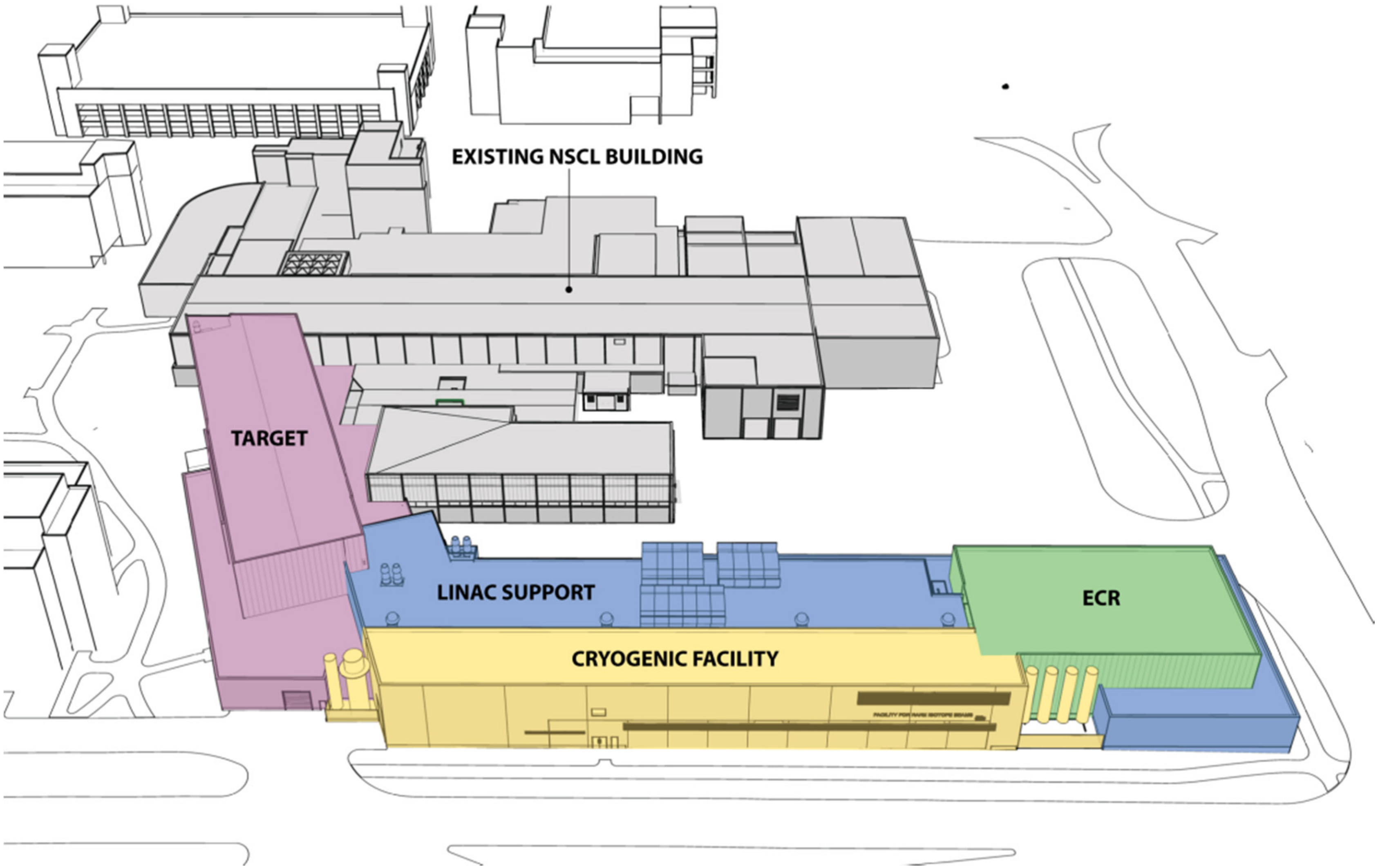
Welcome to Michigan State University
57,000 people; 36 sq mi; $1.8B annual revenue; 552 buildings



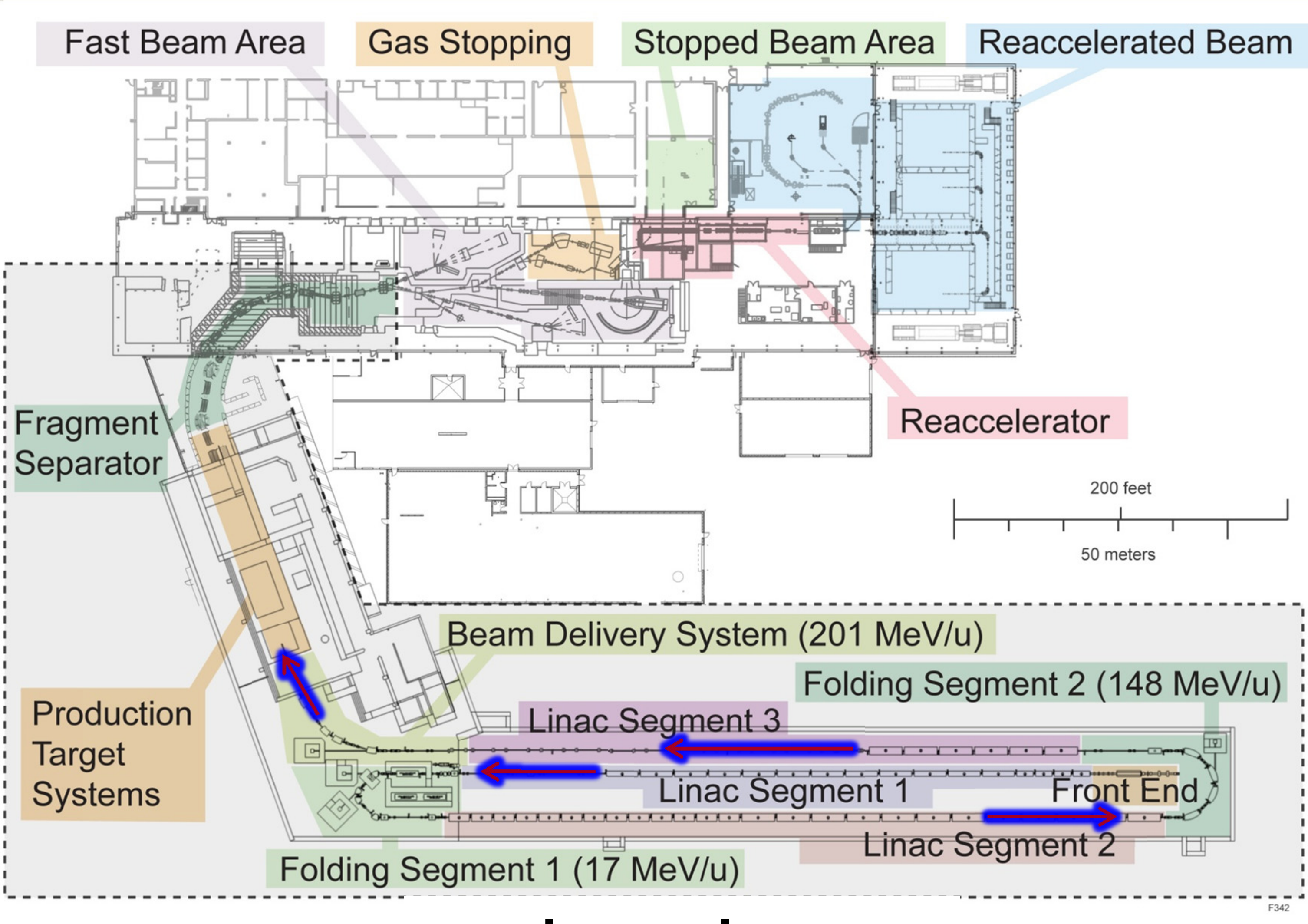
FRIB on Campus



FRIB Layout

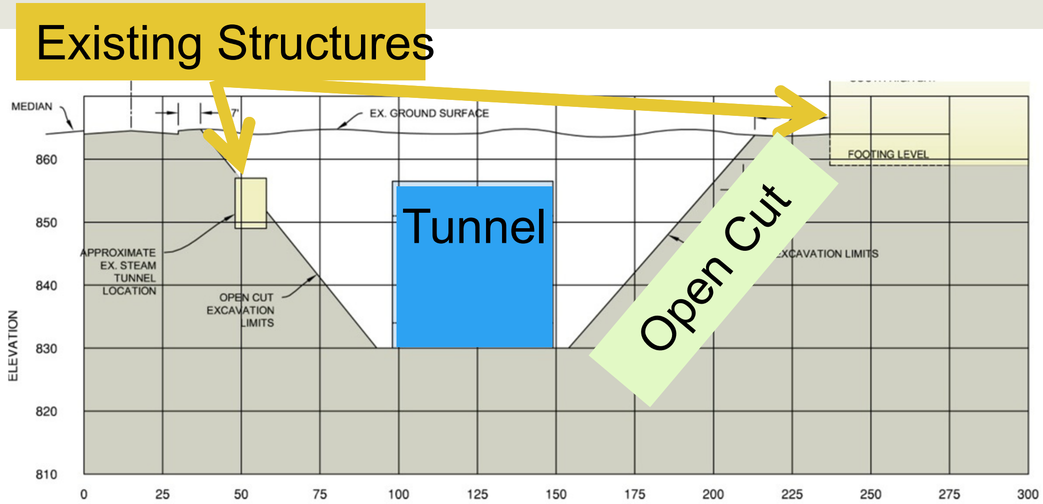

EXISTING NSCL BUILDING
TARGET
LINAC SUPPORT
ECR
CRYOGENIC FACILITY

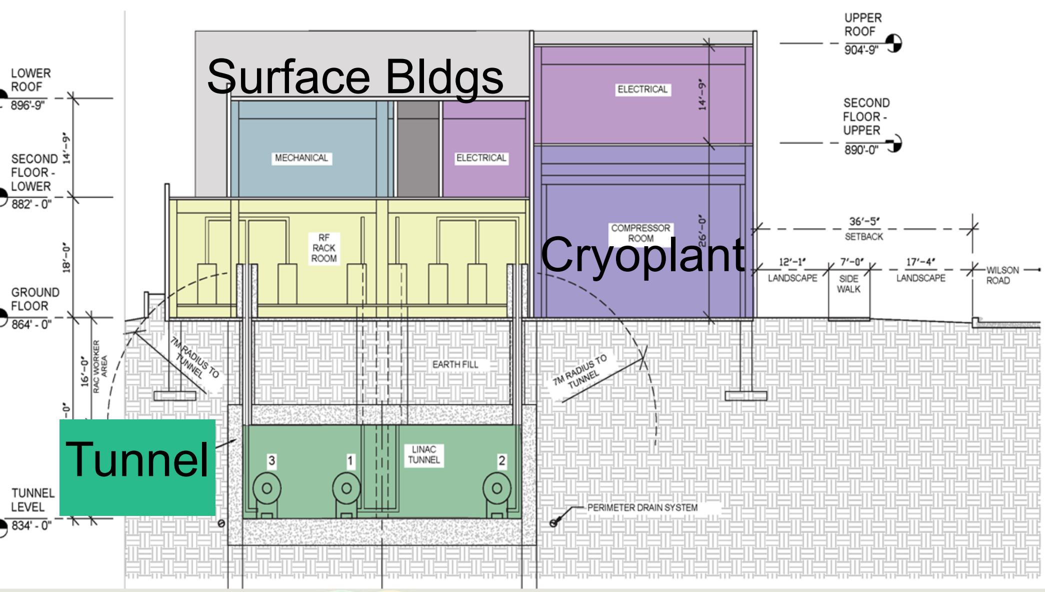
Facility Layout



uranium values given

Challenge – Conventional Construction Cost





Site tunnel to allow open cut – minimize earth retention (reduced cost)

Support buildings directly above tunnel

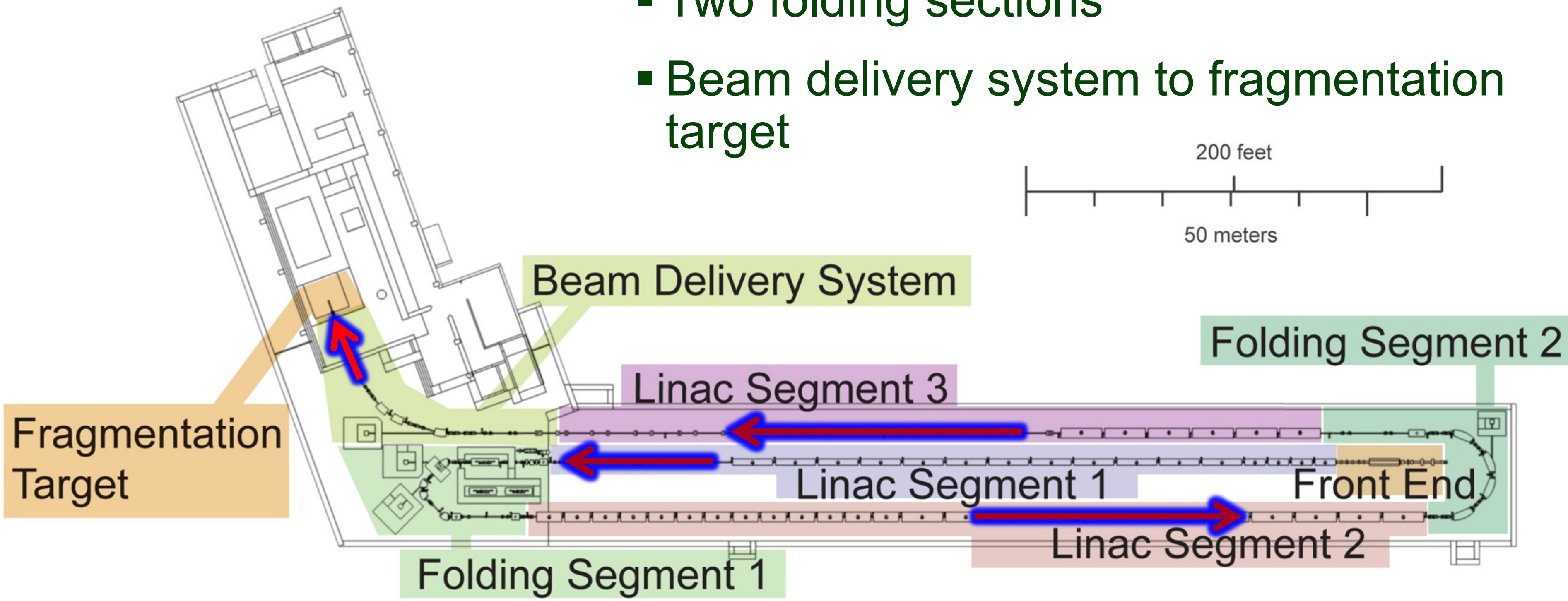
- Controlled area - reduced shielding - less depth reduced cost
- Routing from tunnel to support more efficient - reduced cost
- Tunnel support columns maintain integrity at reduced cost
- Cryoplant proximity - reduced cost - microphonics ok using commercial dampers for rotating machinery

Driver Linac

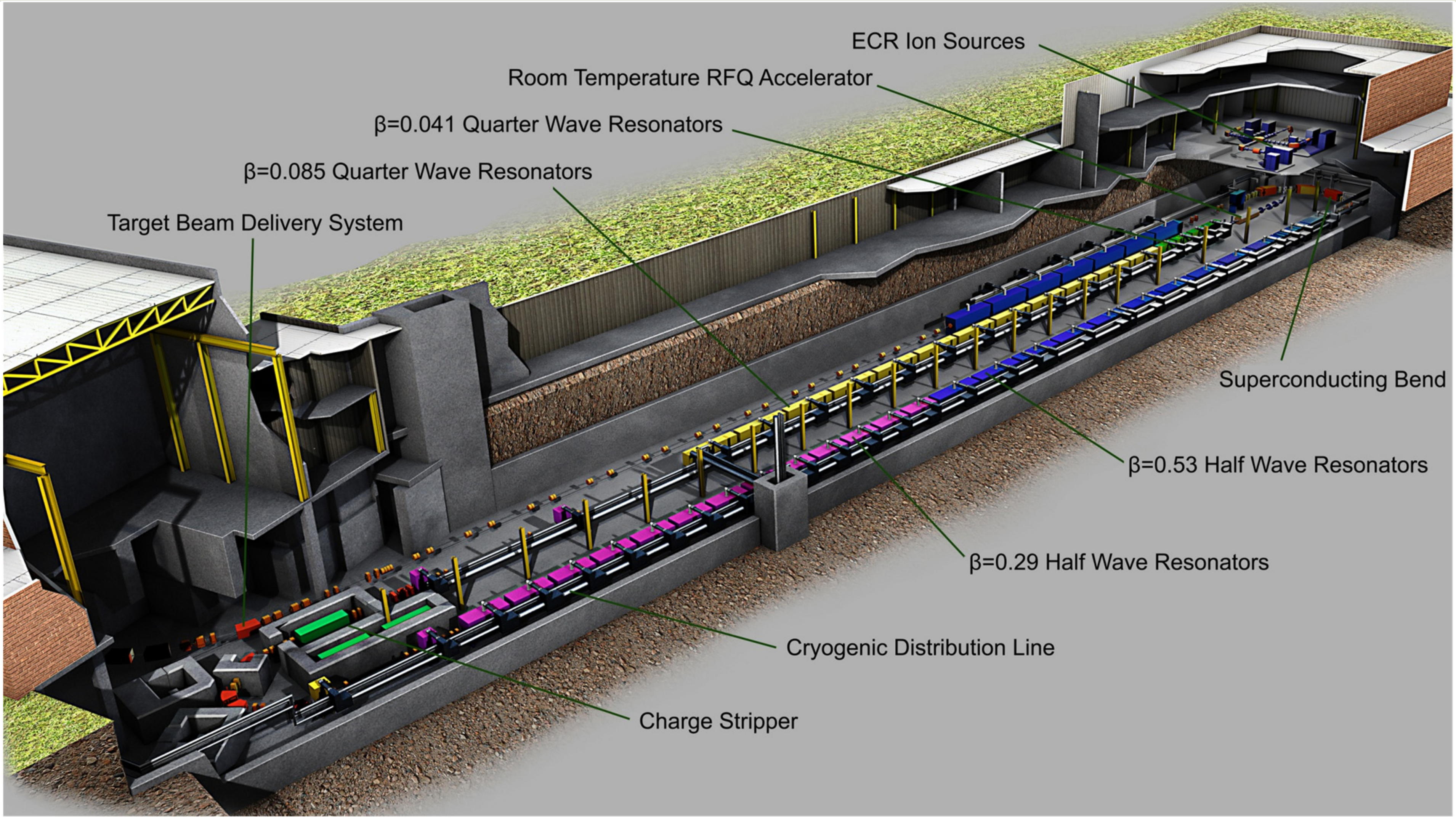
Compact layout to minimize conventional construction costs

Primary Segments

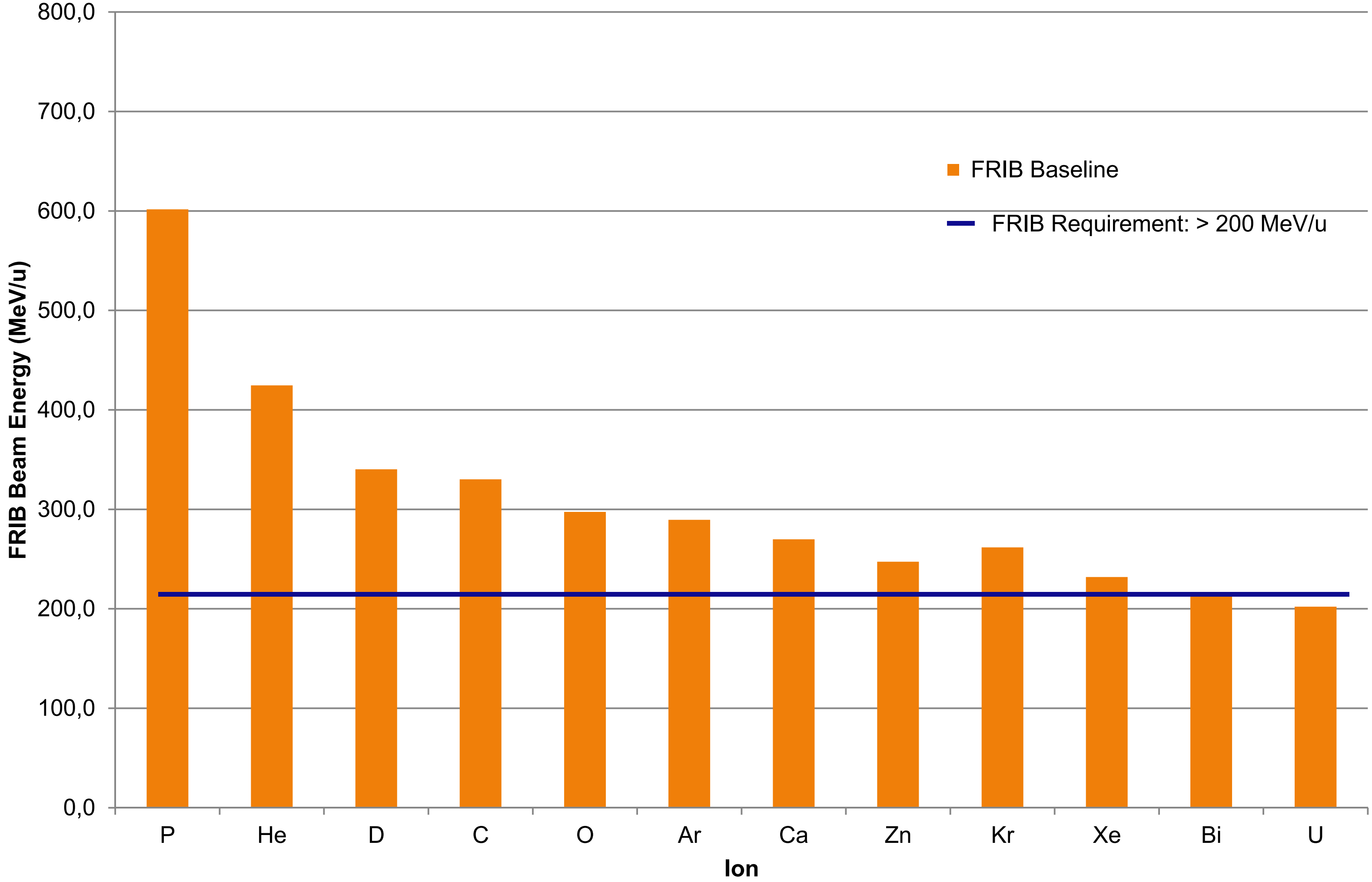
- Front end
- Three superconducting linac segments
- Two folding sections
- Beam delivery system to fragmentation target



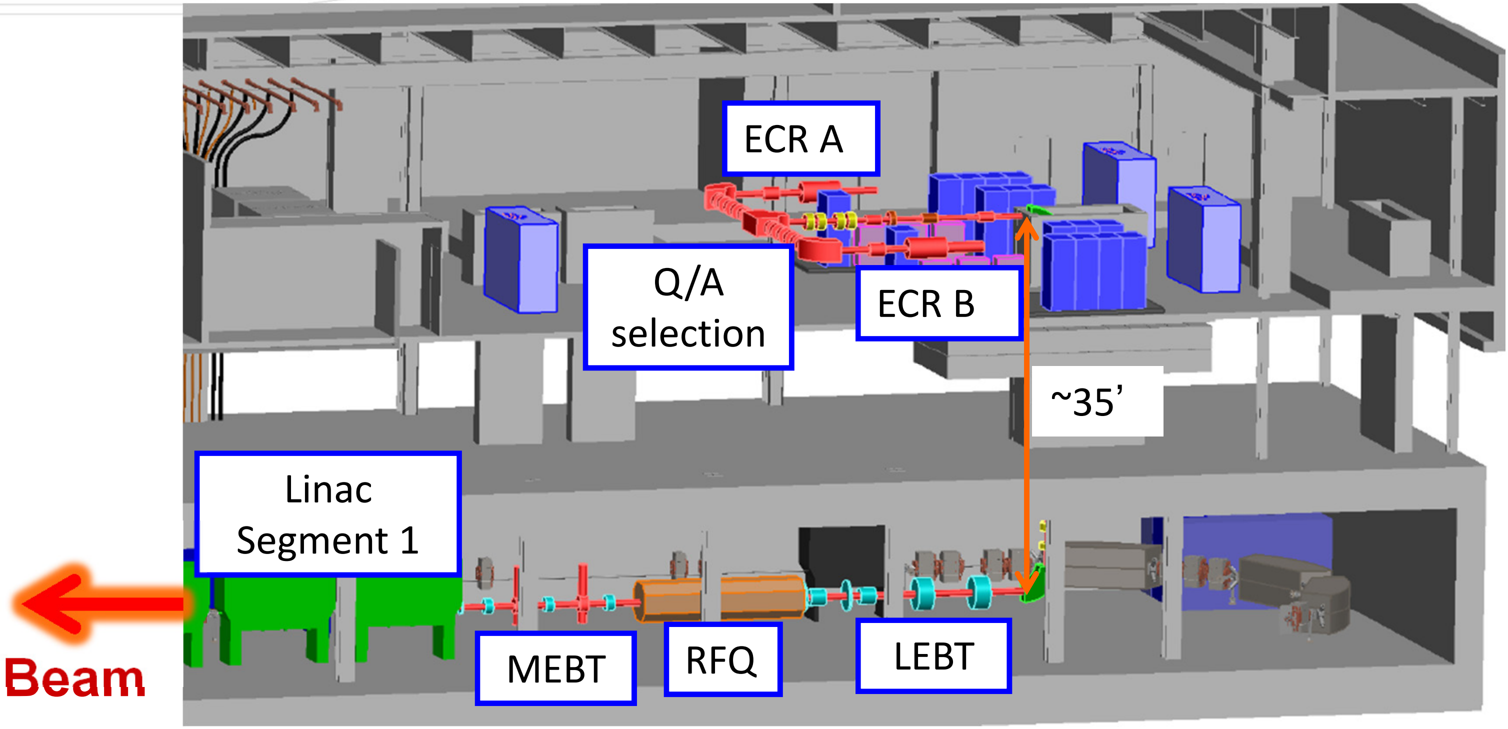
Driver Linac



FRIB Driver Linac Performance



Driver Linac Front End



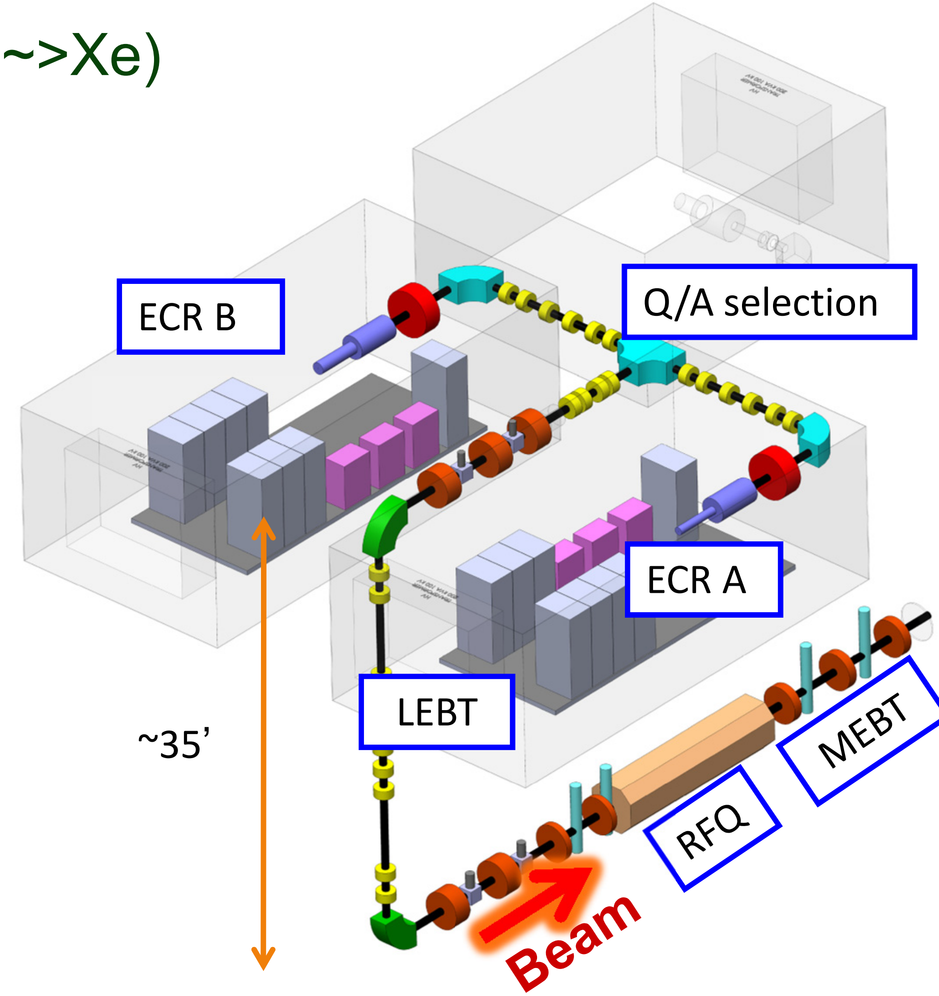
Front End Challenges

Heavy ion currents sufficient for 400 kW

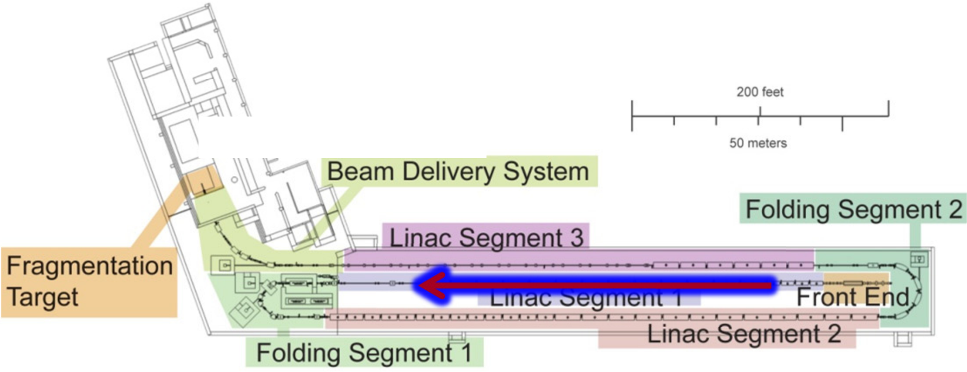
- Two charge-states for heavier ions (~>Xe) (e.g. 33+ & 34+ for U)

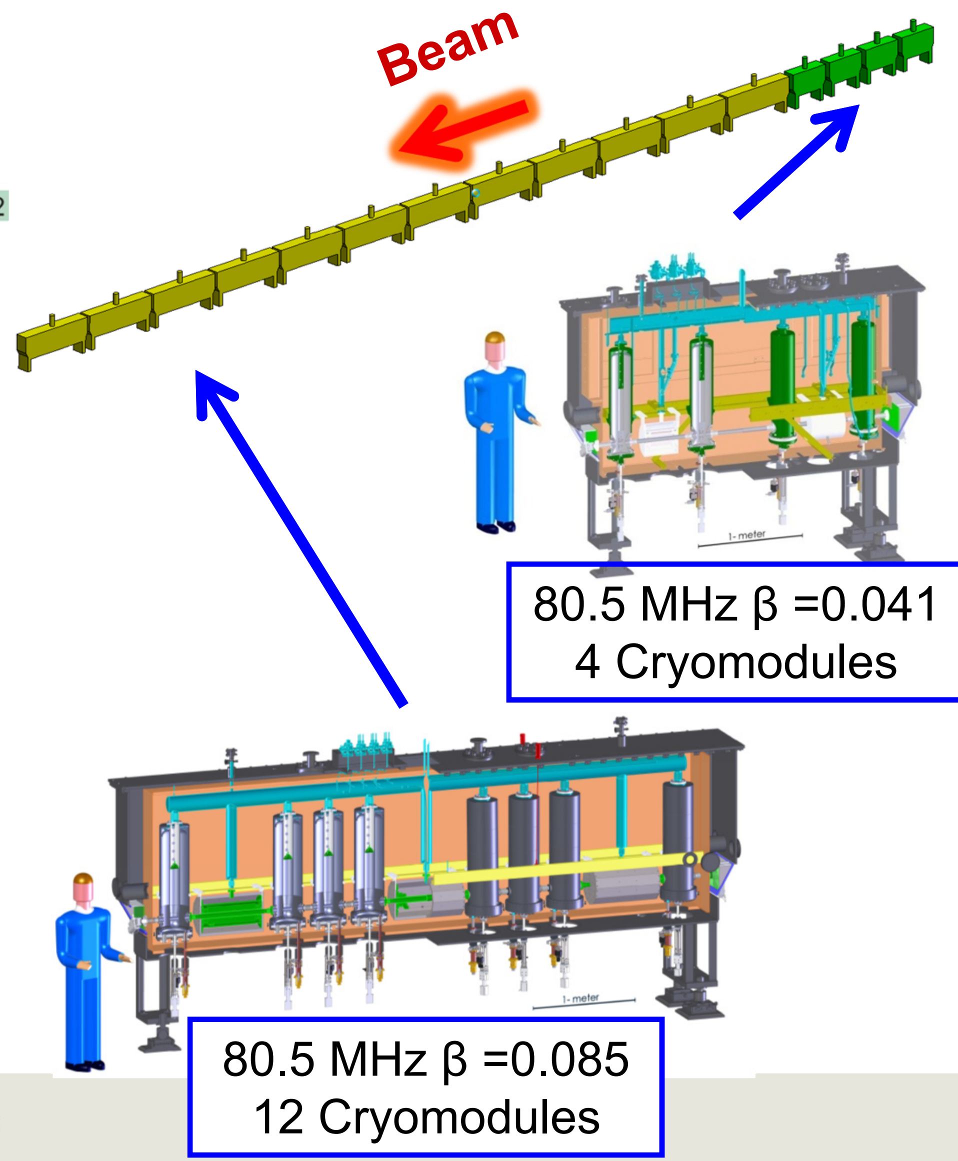
Multi-charge state beams increase effective longitudinal emittance

- Create & maintain low longitudinal emittance by
  - Bunching in LEBT – external to RFQ
  - MEBT providing 6-D Match into superconducting linac



Driver Linac Segment 1





- Uranium acceleration
  - Two charge-states 33+ & 34+,
  - From 0.3 MeV/u to ~16.6 MeV/u
- Transverse focusing
  - SC solenoids with dipole correctors
    - » Effective lengths: 0.2 or 0.5 m

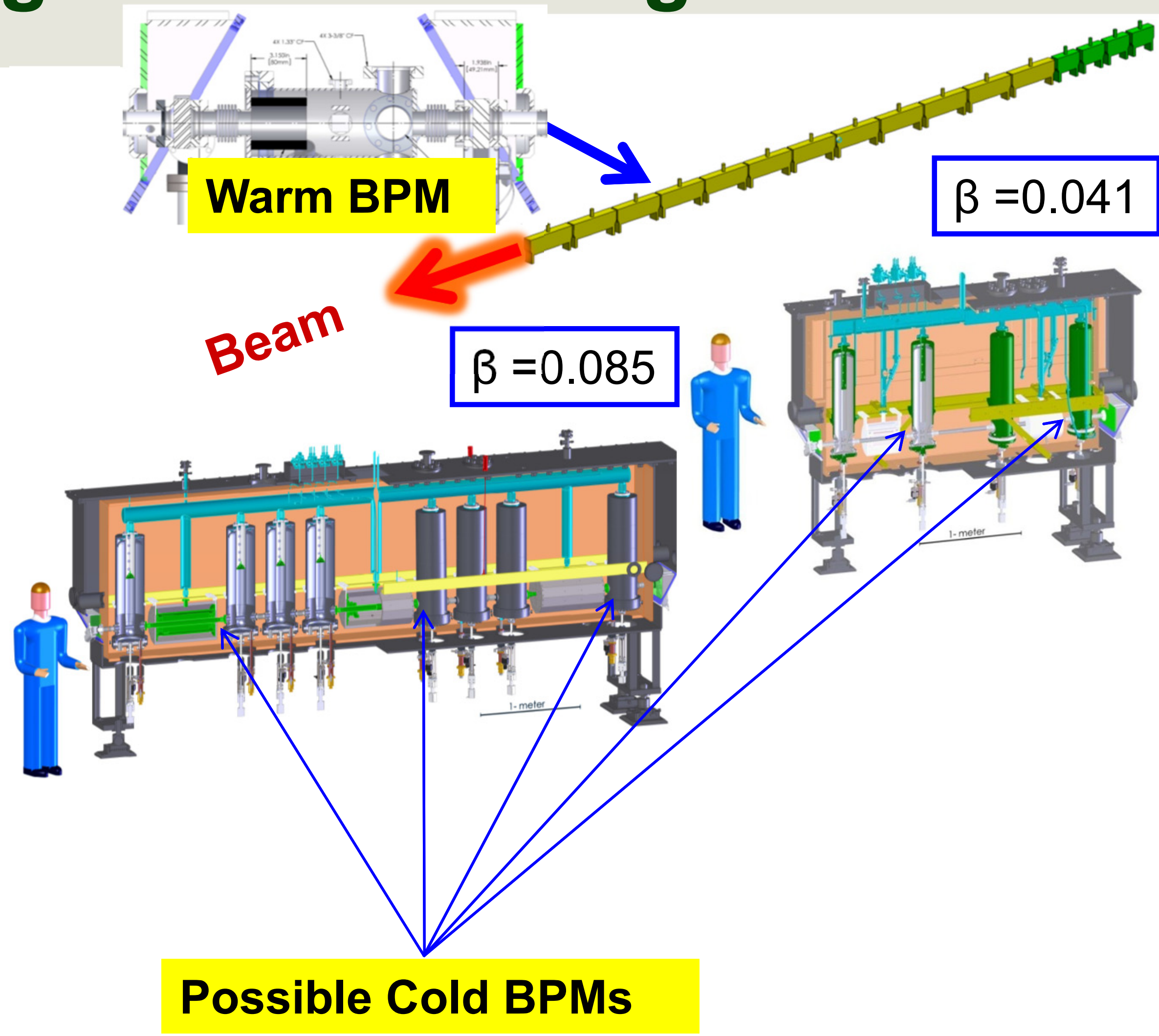
Linac Segment 1 Challenges

80.5 MHz λ/4 resonator performance

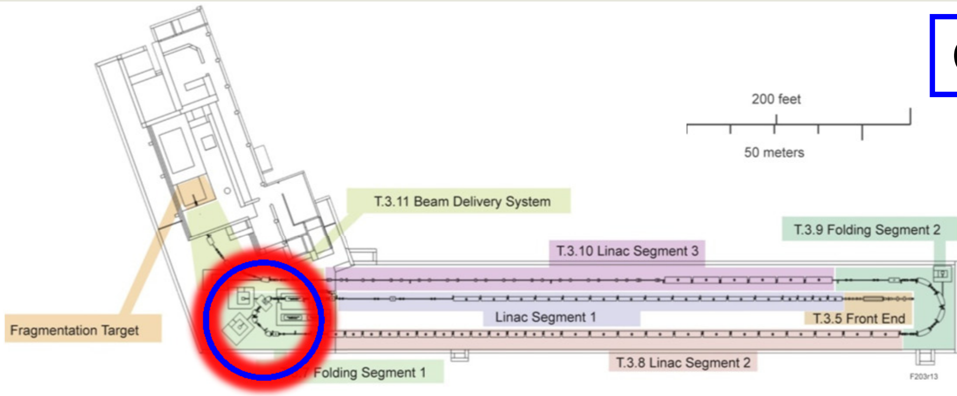
- Operate at 2 K (as opposed to 4.5 K)
  - Reduces "Q-slope"
  - Reduces microphonics by more stable He bath pressure

Low energy beam – central trajectory sensitivity

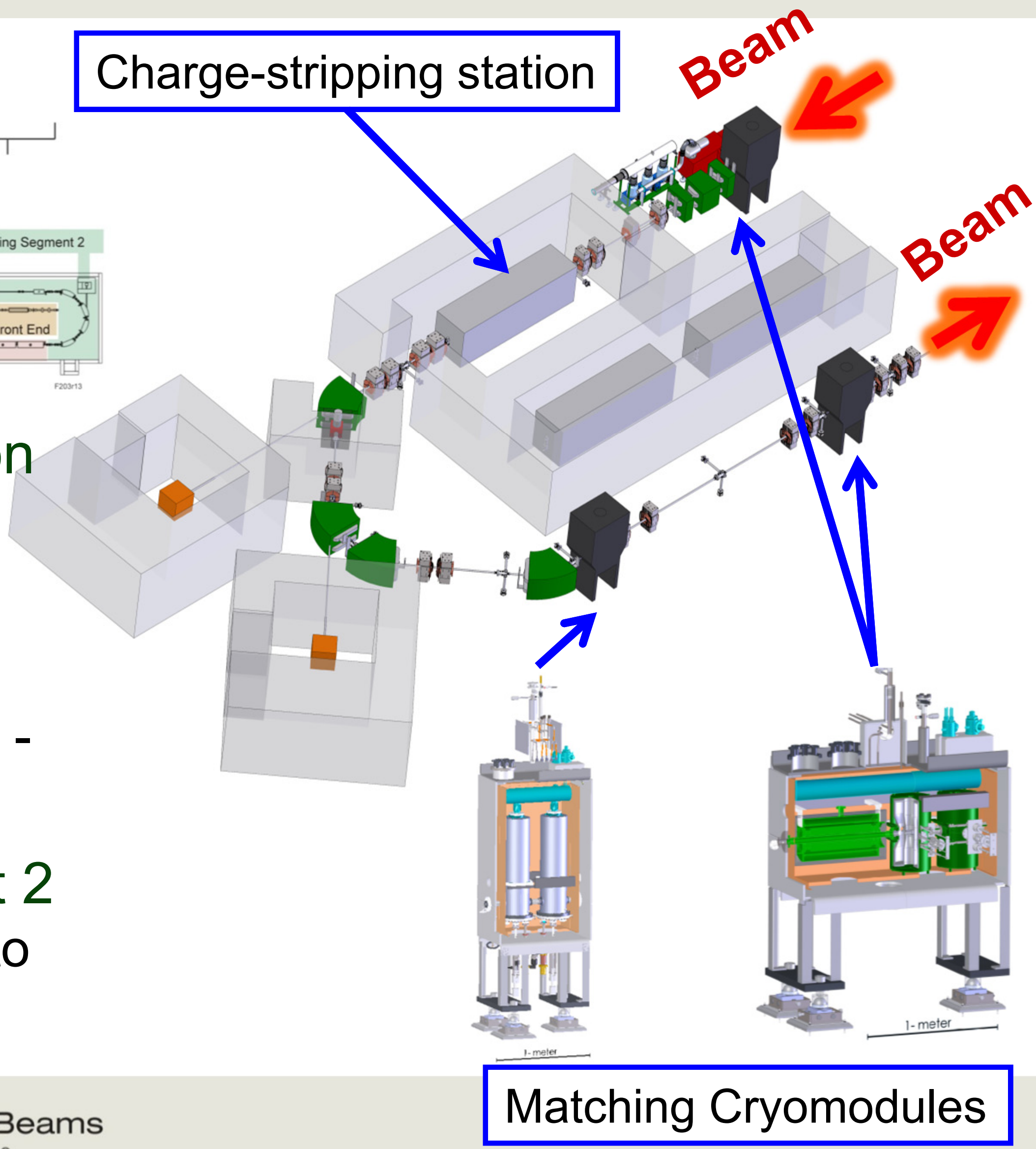
- Warm region for diagnostics: 0.38 m
- Cold BPMs near each solenoid under evaluation



Driver Linac Folding Segment 1



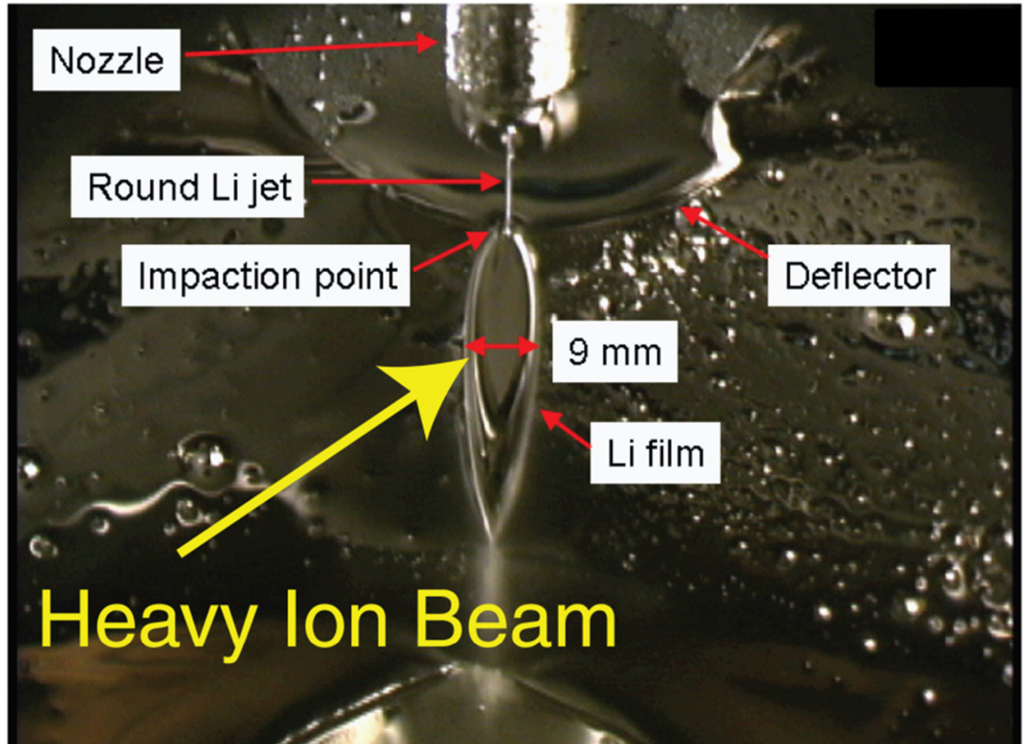
- Charge-stripping for acceleration efficiency
  - Stripping energy: ~ 16.6 MeV/u
- Charge selection
  - Stripping to 5 charge states for U - 76+ to 80+, 5
- 6-D matching to Linac Segment 2
  - Single frequency change – 80.5 to 322 MHz

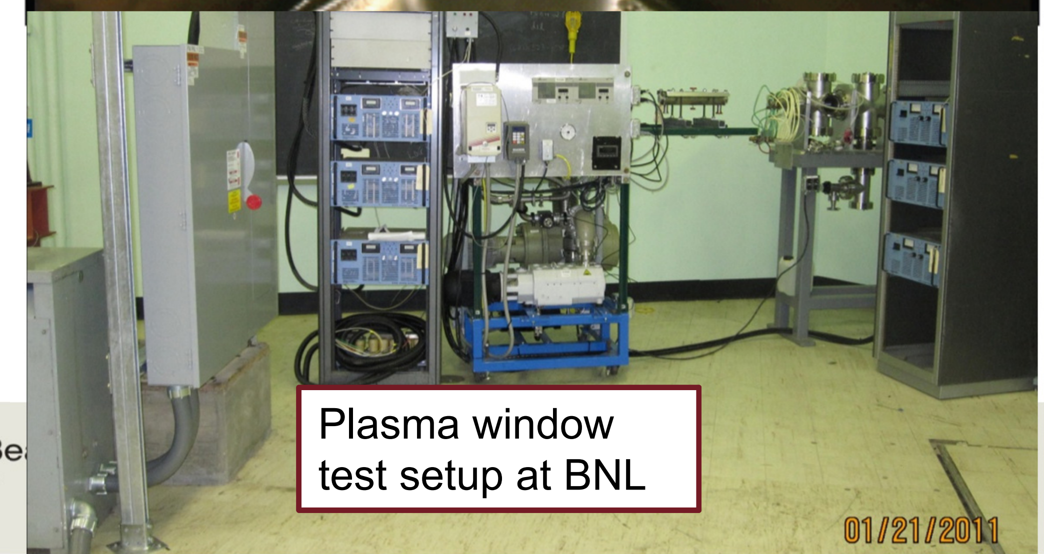


Folding Segment 1 Challenges [1]

Need to strip beam with high power density (~kW/mm^2, ~MW/mm^3)

- Liquid Li stripper R&D at ANL
  - Demonstrated reasonable parameters – ion beam tests remain
- He gas contained by plasma windows – 2nd alternative
  - R&D at BNL underway
  - Lower charge state than Li – space provided for 3 additional cryomodules



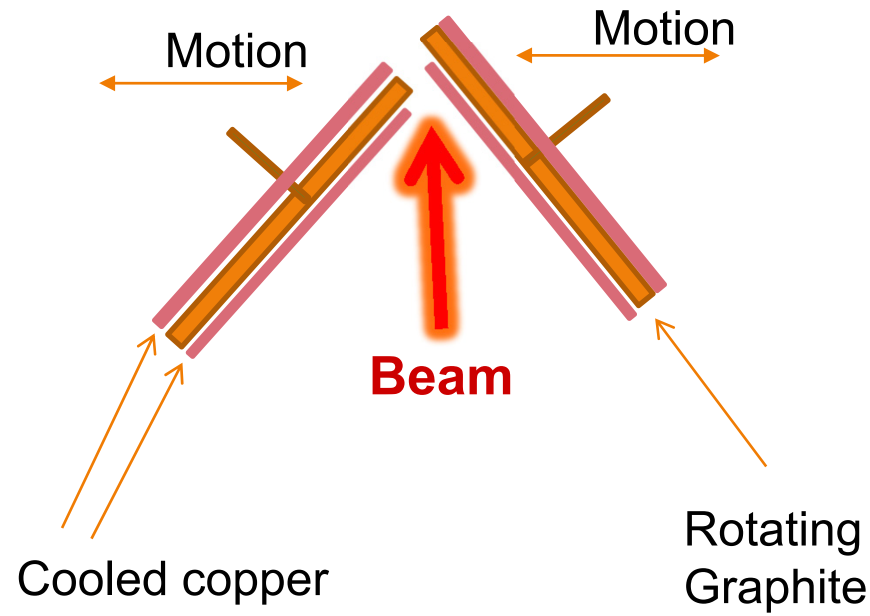


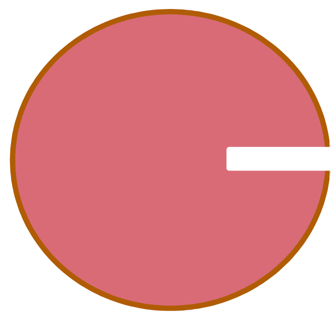
Plasma window test setup at BNL

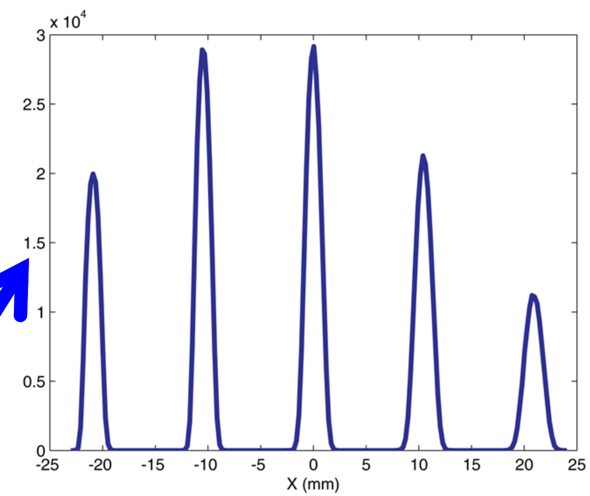
Folding Segment 1 Challenges [2]

Need to collimate beam with high power density (~kW/mm^2, ~MW/mm^3)

- Routine continuous losses of ~10 kW
  - E.G. – Accelerate 5 charge states of U - ~10 kW of beam power in other charge states
- Production target challenge similar
  - Engineering design under development for collimator using two rotating wheels following production target design

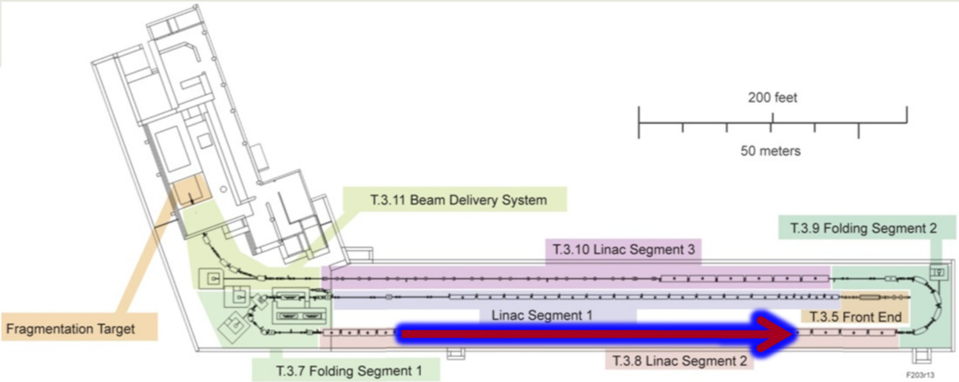






For U - ~10 kW per charge state (+76 to +80) separated by ~1 cm

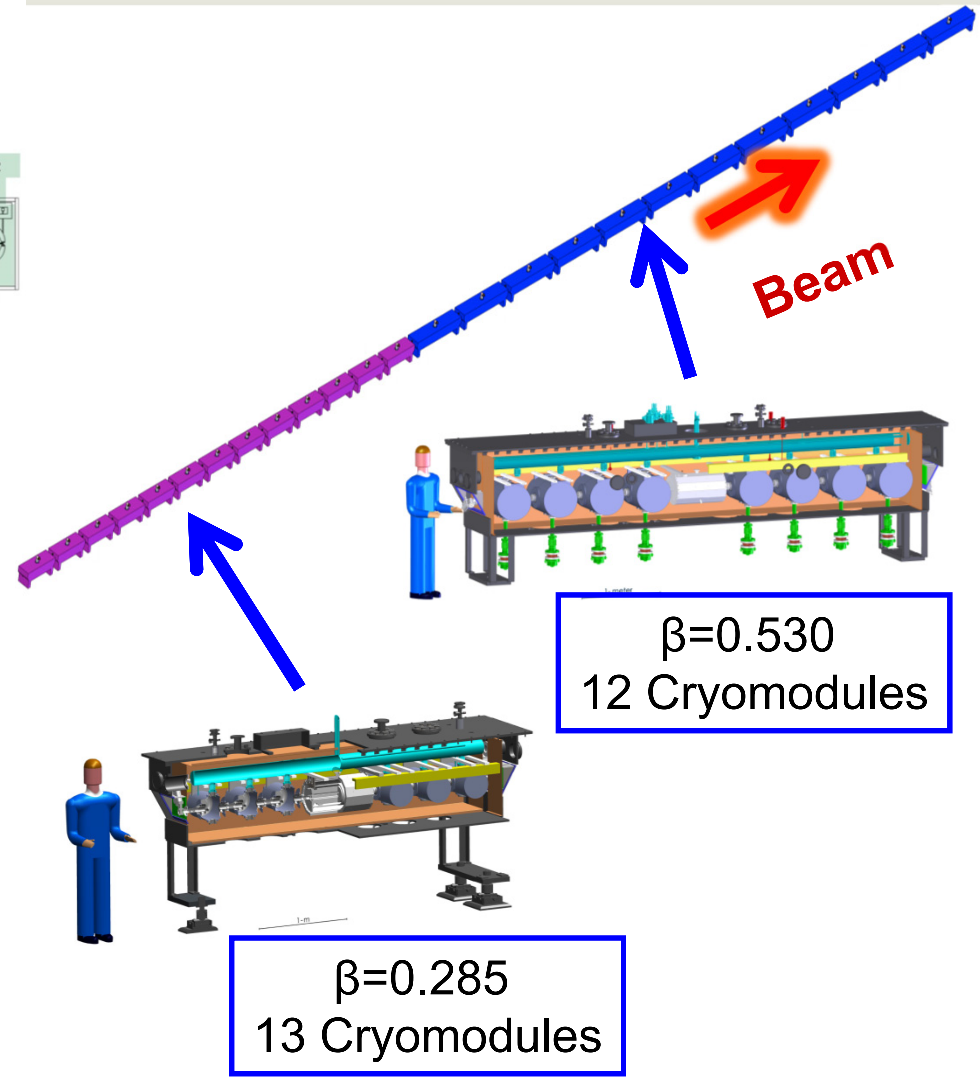
Driver Linac Segment 2



- λ/2 cryomodules – 322 MHz
- Uranium beam acceleration
  - From ~16.4 MeV/u to ~149 MeV/u
- Warm region: 0.38 m
  - BPMs and other beam diagnostics devices

Challenge

- λ/2 performance
  - Space for additional cryomodules in Linac Segment 3

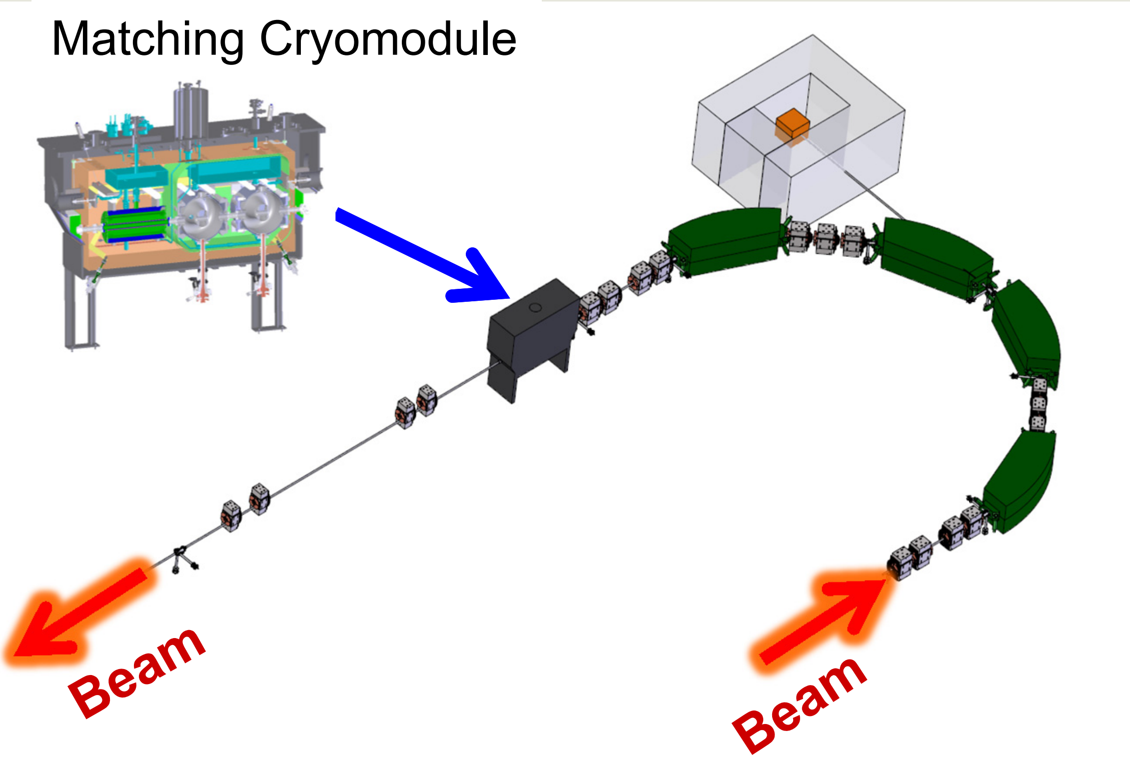


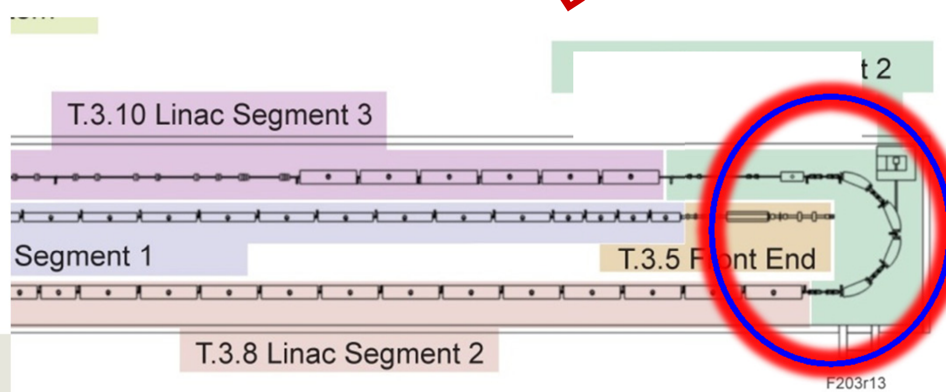
Driver Linac Folding Segment 2

- Multi-charge state beams
- 180 degree beam direction change
- No charge stripping

Challenges

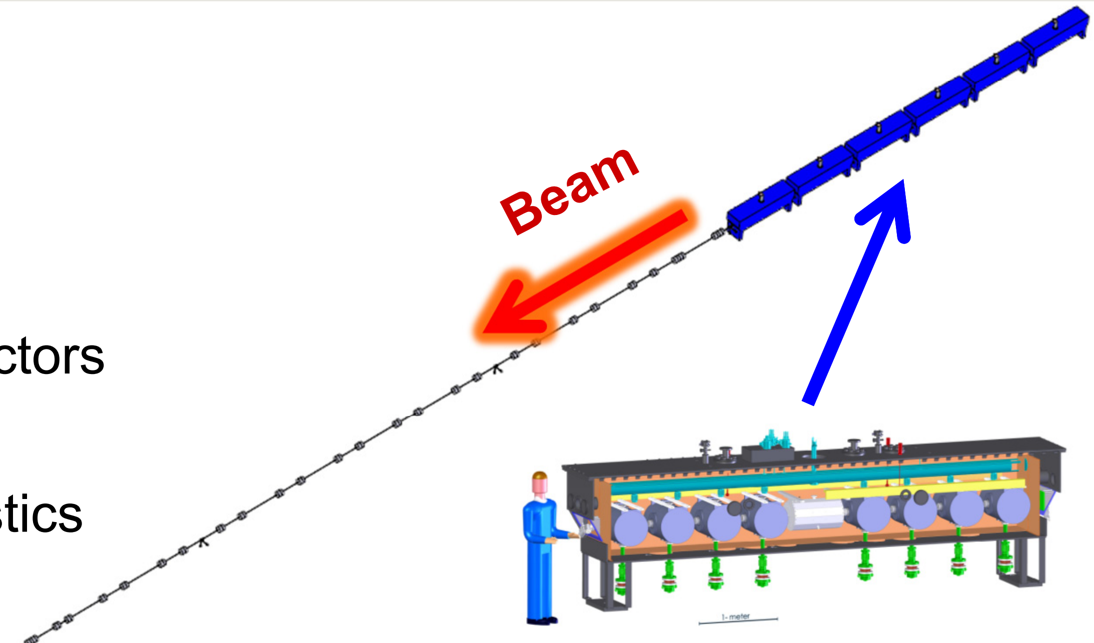
- Tunnel width set by bend diameter
  - Need to minimize bend diameter while retaining beam quality
- Large momentum spread from multi-charge states & dispersive regions require high magnetic field quality





Driver Linac Segment 3

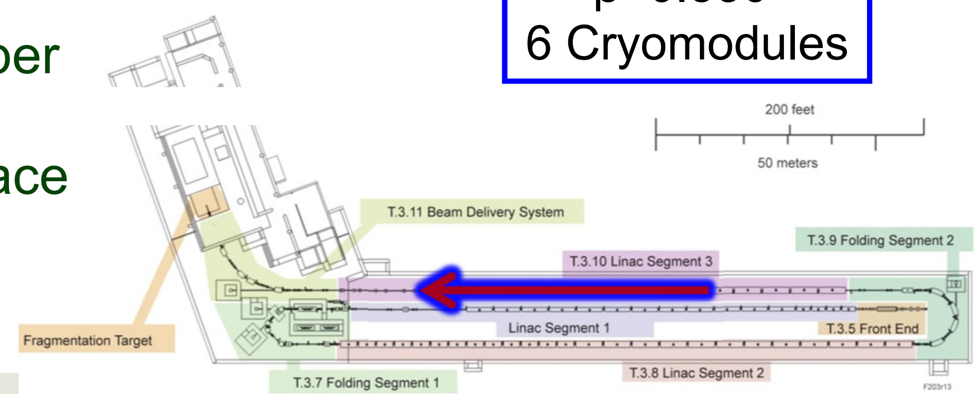
- λ/2 cryomodules
- Uranium beam acceleration:
  - From ~149 to ~ 200 MeV/u
- Transverse focusing
  - SC solenoids with dipole correctors
- Warm region: 0.38 m
  - BPMs and other beam diagnostics devices



β=0.530
6 Cryomodules

Challenges

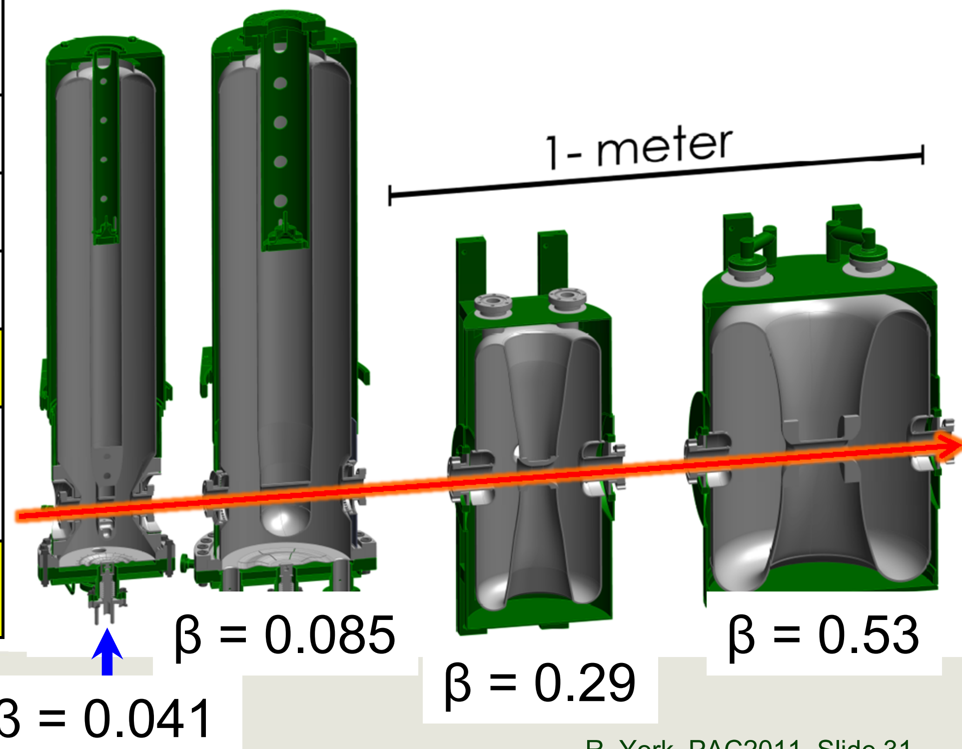
- λ/2 performance & possible lower charge states if He in lieu of Li stripper is required
- Both met by providing additional space for up to 12 cryomodules



Driver Linac SRF Cavities

- Only 4 cavity types
- 1 frequency transition (between Linac Segment 1 and 2)

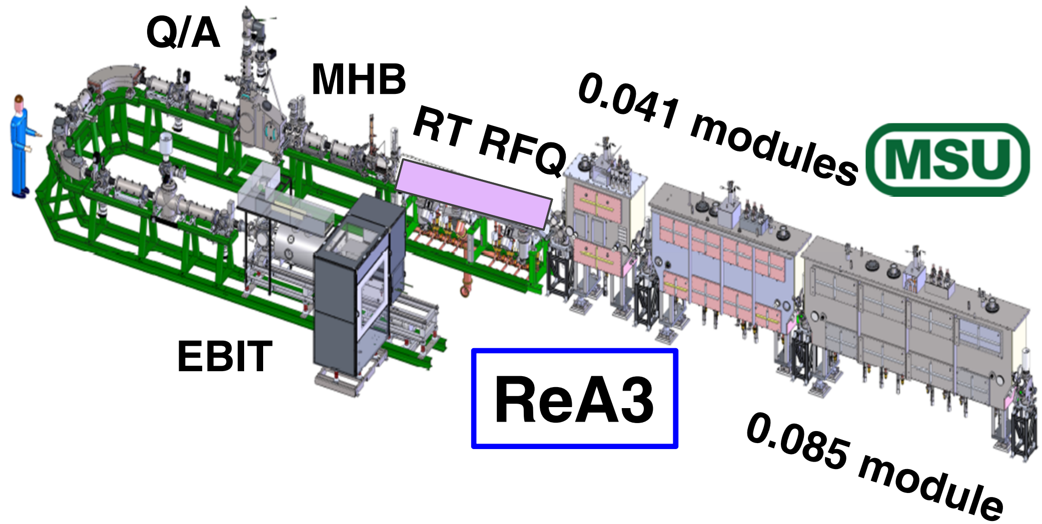
Type	⌊ /4	⌊ /4	⌊ /2	⌊ /2
®$_{opt}$	**0.041**	**0.085**	**0.285**	**0.530**
f(MHz)	**80.5**	**80.5**	**322**	**322**
Aperture (mm)	30	30	30	40
V_a (MV)	0.81	1.62	1.90	3.70
E_p (MV/m)	30.0	31.5	31.5	31.5
B_p (mT)	53	71	75	77
T(K)	**2.0**	**2.0**	**2.0**	**2.0**
RF Drive (kW)	**2**	**4**	**4**	**8**
Number	**16**	**100**	**82**	**147**

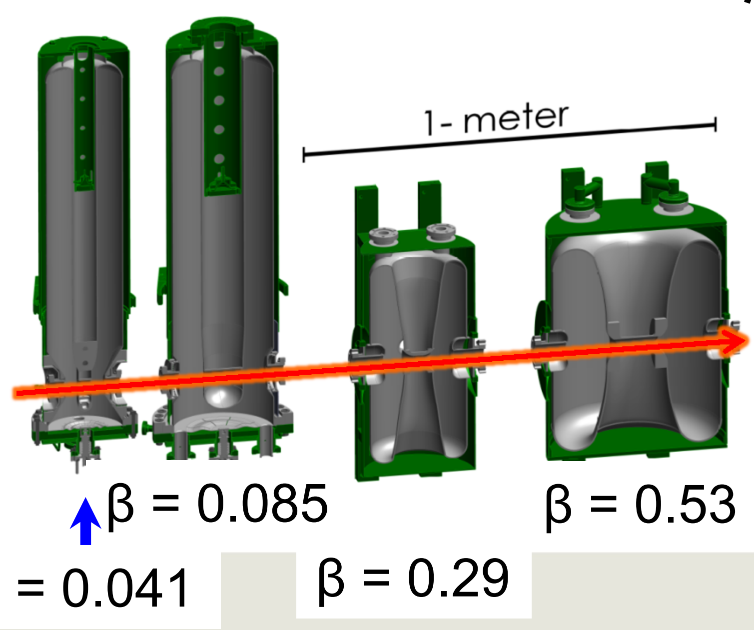


Driver Linac SRF Cavities Challenges

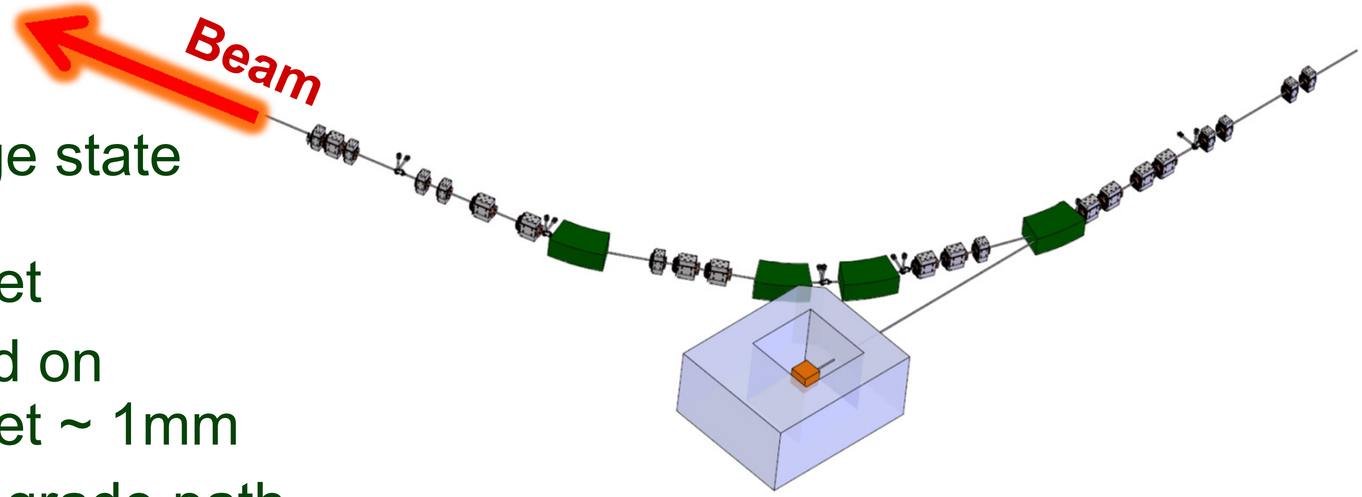
Complex (compared to e.g. elliptical) geometry – more challenging

- To manufacture
  - Technology transfer program
- To process & operate
  - R&D and systems testing
  - ReA3 – utilizing 15 of λ/4 cavities provides test bed
  - λ/2 β=0.53
    - » 5 under test
    - » Prototype systems test 2011
  - λ/2 β=0.29 follow from β=0.53





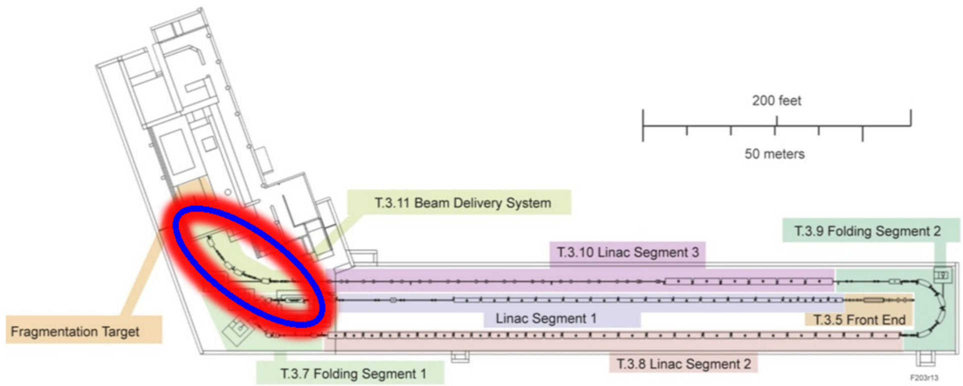
Driver Linac Beam Delivery System



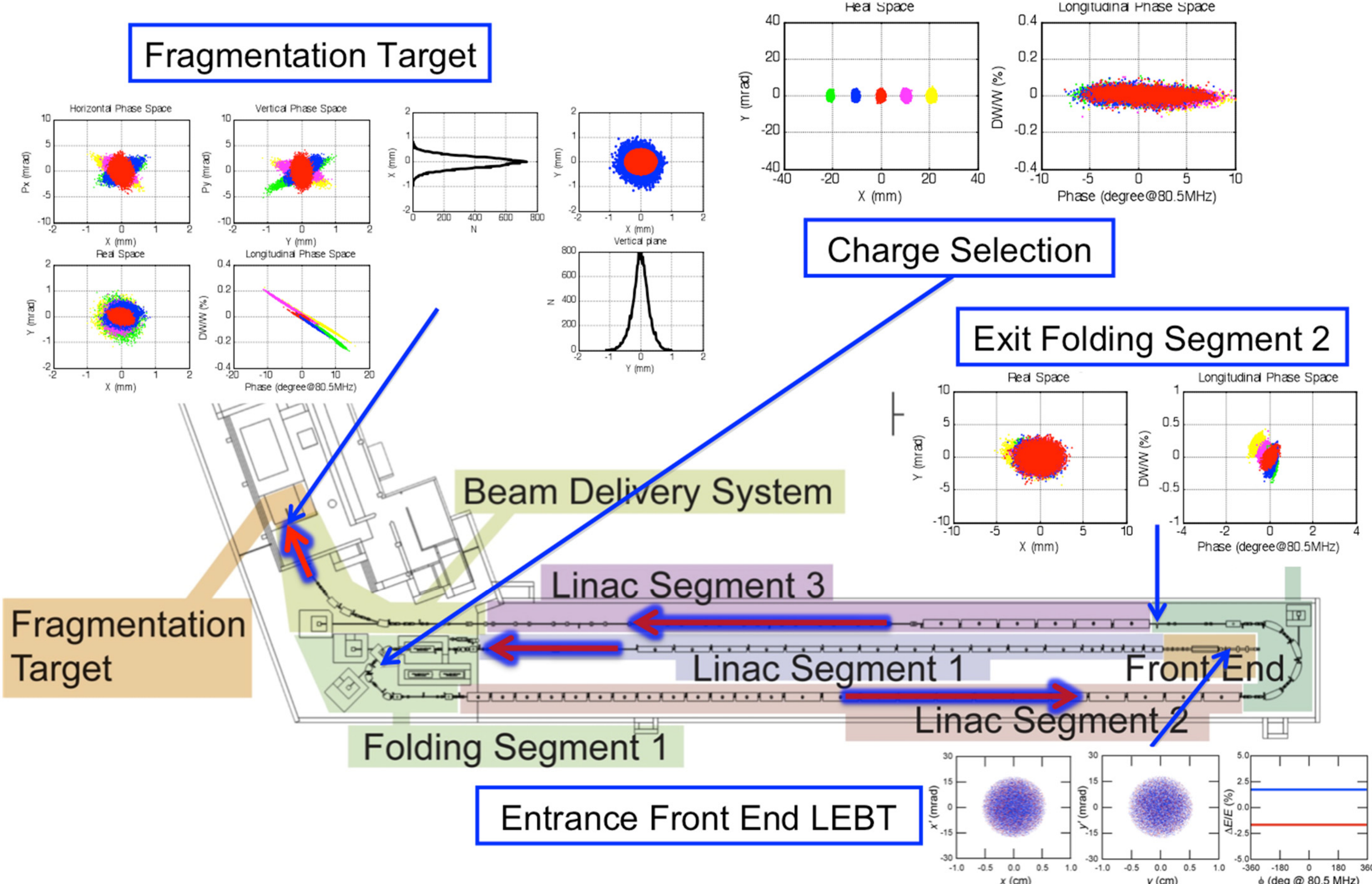
- Deliver multi-charge state beams to a single fragmentation target
- Beam size required on fragmentation target ~ 1mm
- Satisfy possible upgrade path
  - Higher beam energy
  - Multiple targets

Challenge

- 90% of particles within 1mm spot size given multi-charge state momentum spread

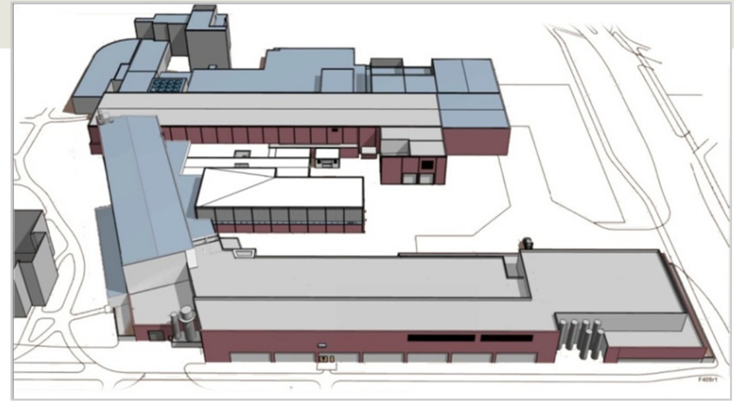


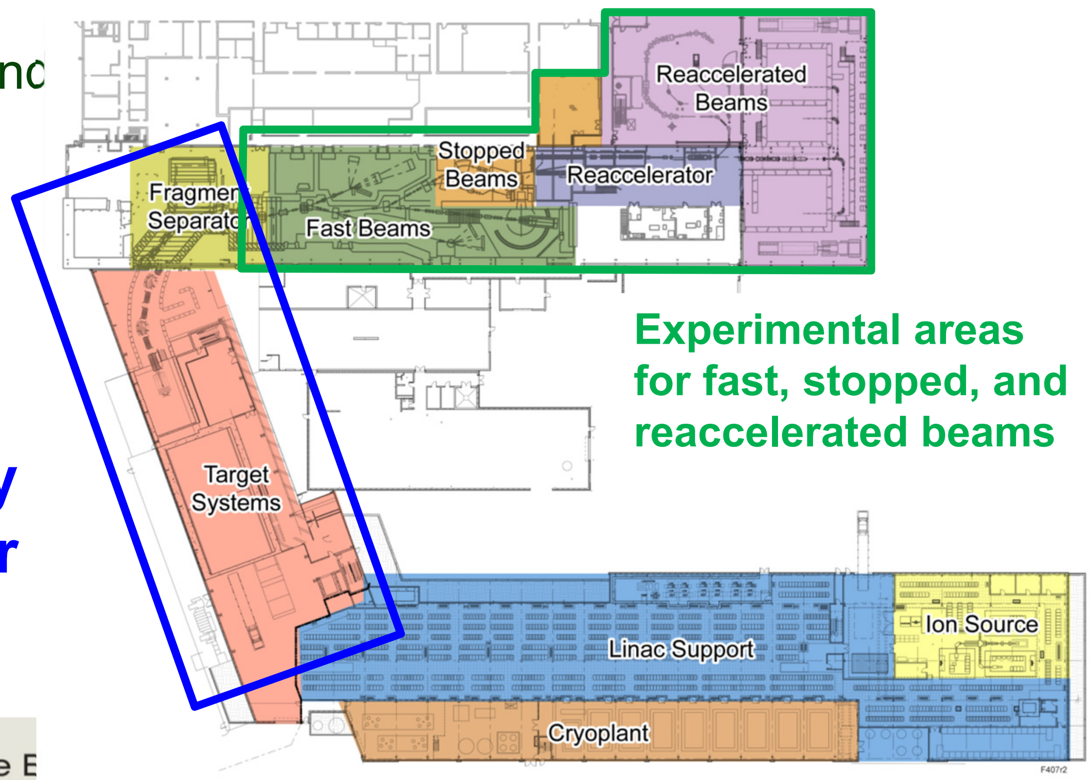
End-to-End Beam Simulations



Experimental Systems

- Rare isotope production with primary beams up to 400 kW, 200 MeV/u uranium
- Fast, stopped and reaccelerated beam capability
- Experimental areas and scientific instrumentation for fast, stopped and reaccelerated beams



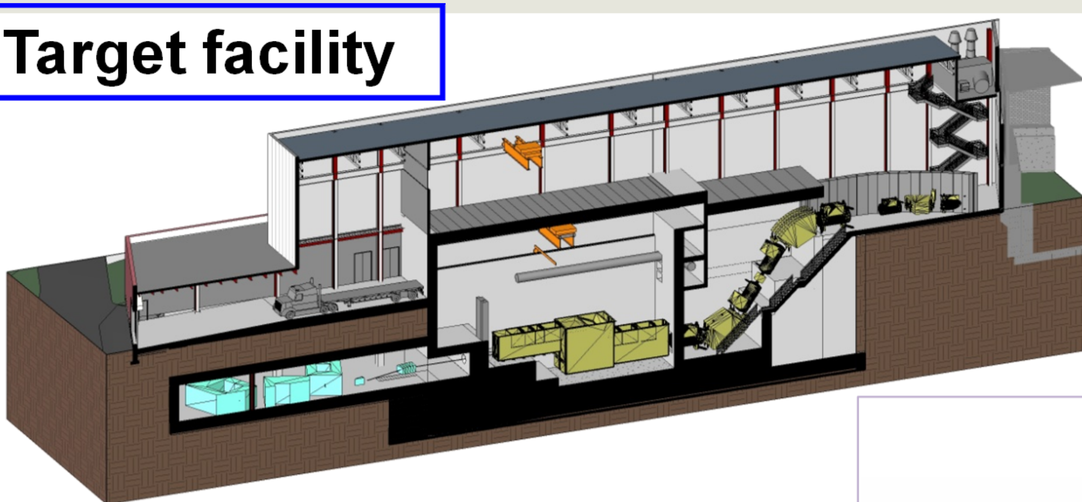


Experimental areas for fast, stopped, and reaccelerated beams

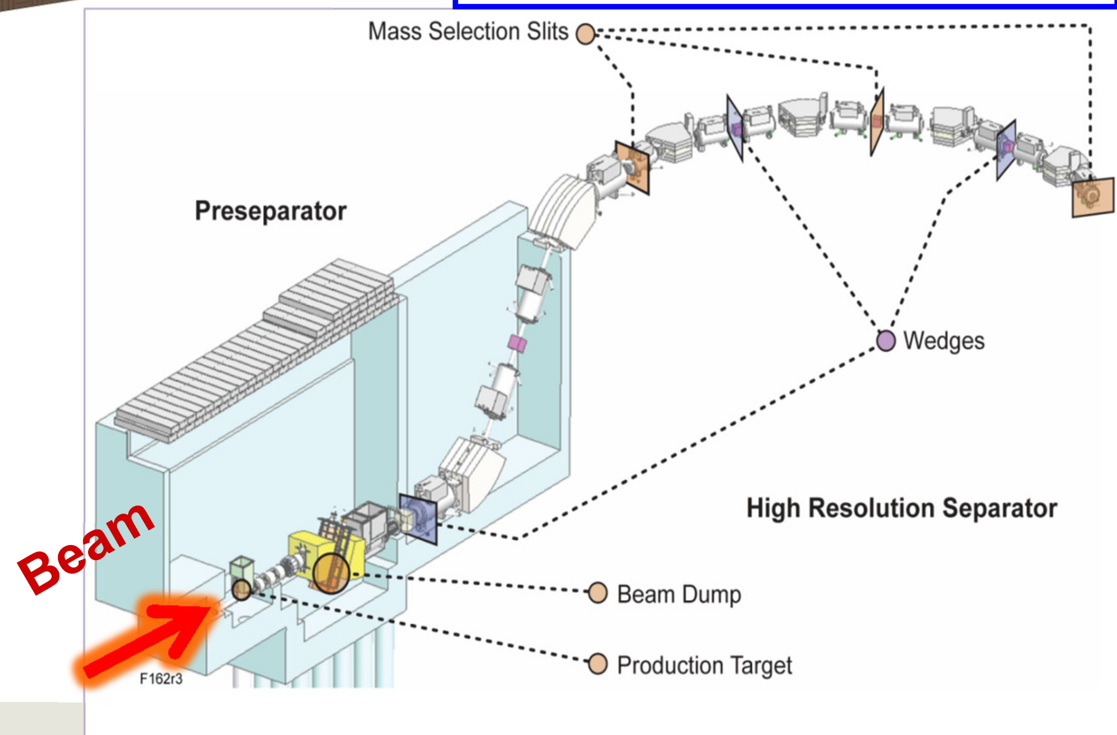
Production target facility + fragment separator

FRIB Beam Production Facilities

Target facility



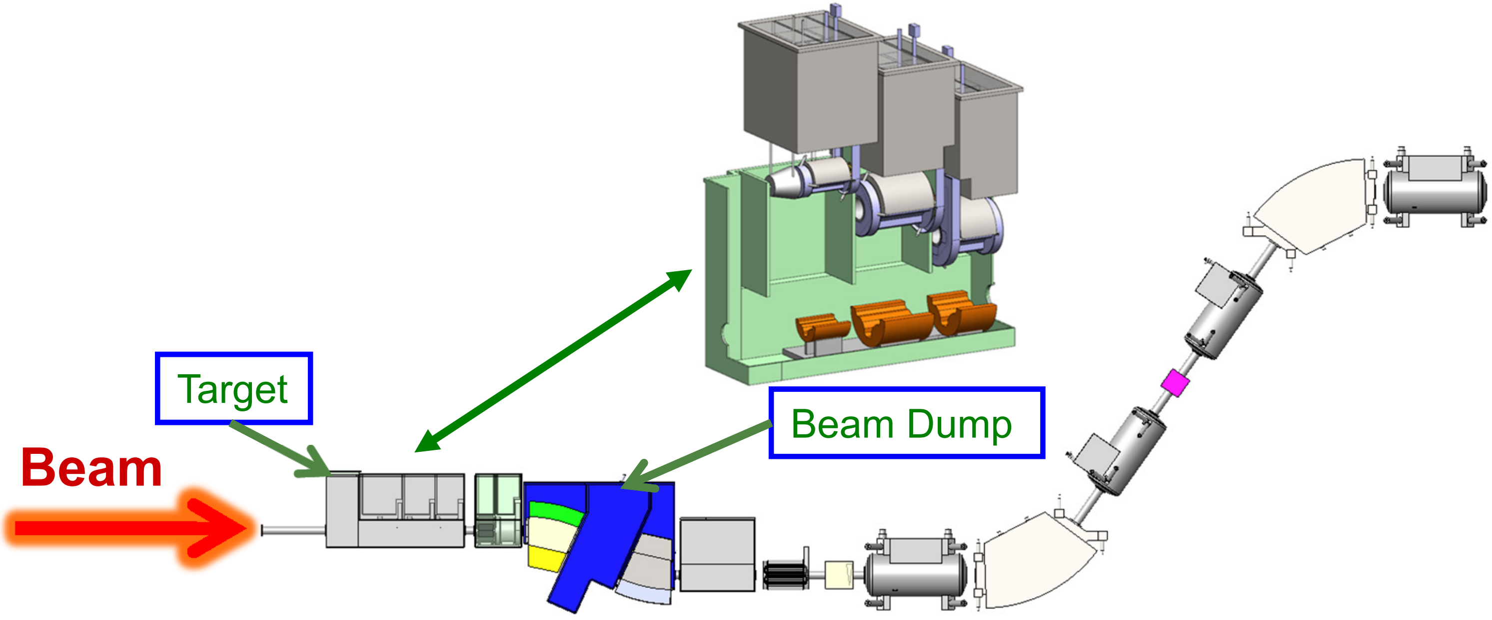
Fragment Separator



Beam Production Challenges [1]

Select rare isotopes with high efficiency and high beam purity in high radiation environment

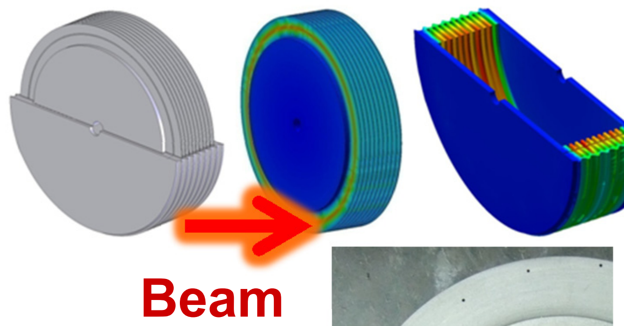
- Design
  - Pre-separator with remote handling capability for 1st separation & to have highest radiation in confined area
  - Optics design uses 3 stage separation – high purity

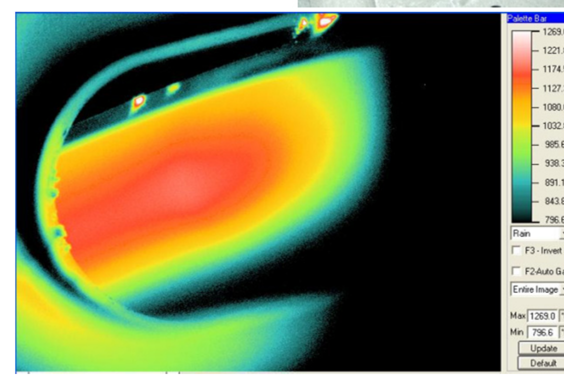


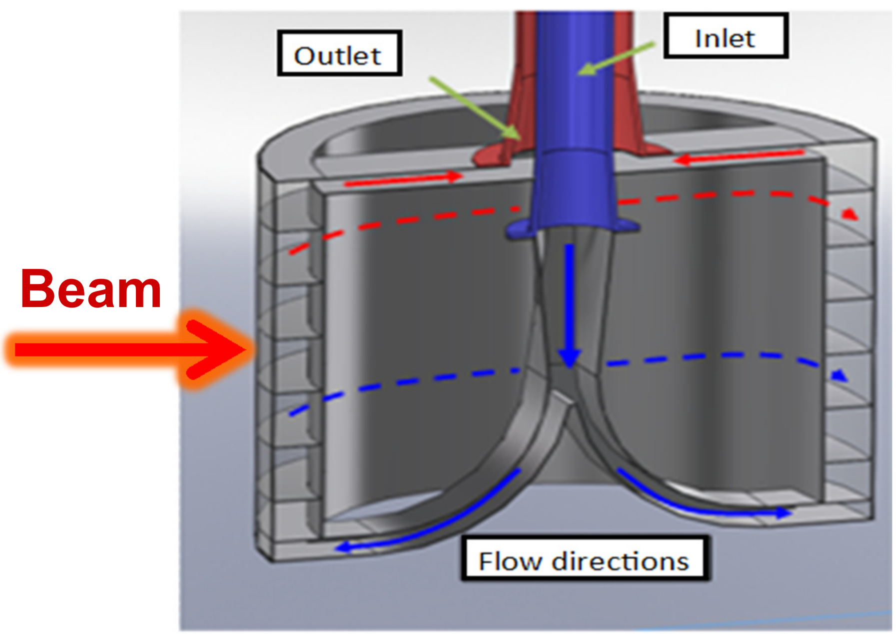
Beam Production Challenges [2]

High power density at production target and beam dump

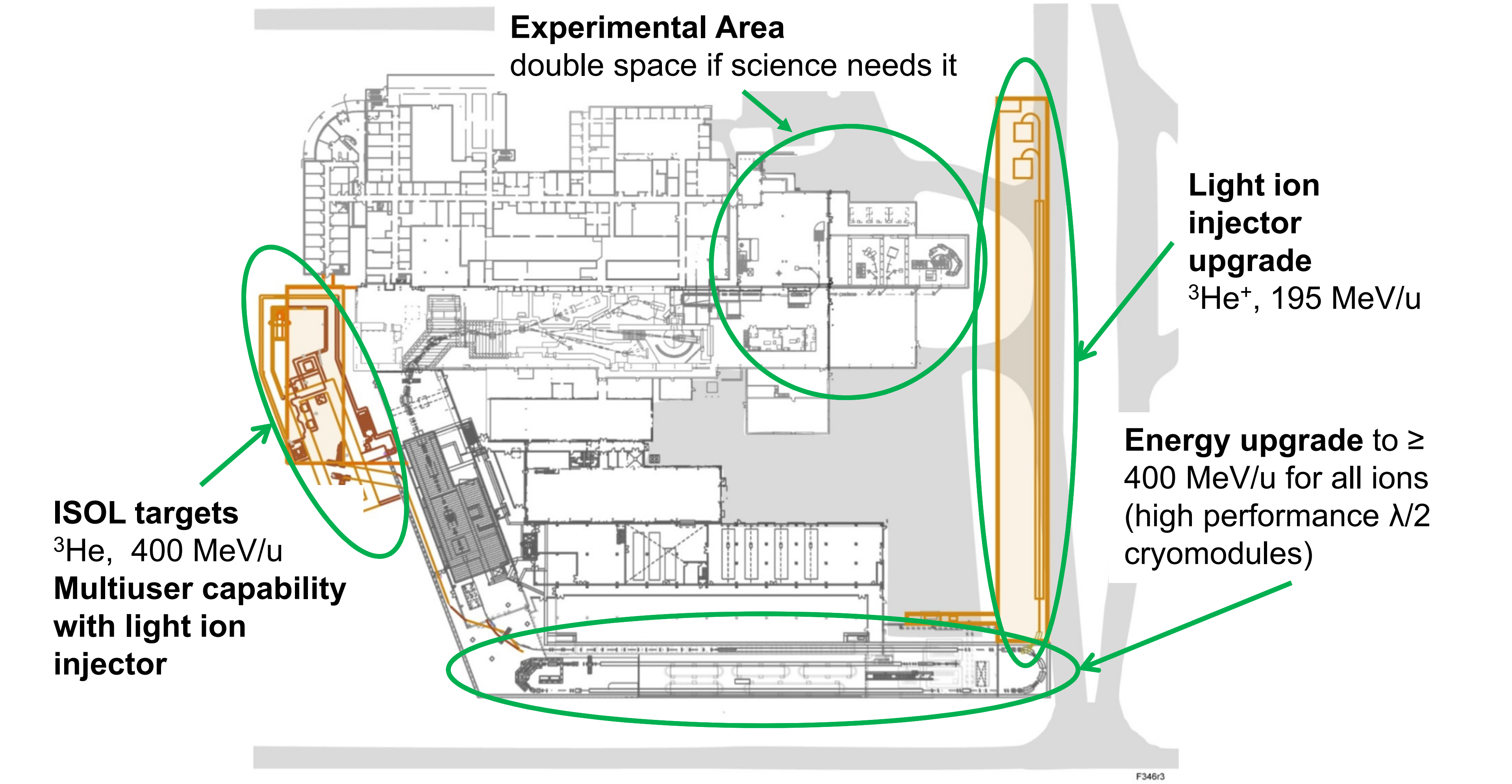
- Production target – rotating graphite
  - Up to 200 kW beam power
- Beam dump
  - Up to 400 kW beam power







Science-Driven Upgrade Options Remain



Summary

FRIB challenges identified and mitigated (or in process of)

- Linac 400 kW beam power for heavier ions - multi-charge state acceleration
- High power density from heavy ion / matter interaction
  - Linac stripper & charge selection R&D
  - Production target & beam dump R&D
- Linac beam energy & quality
  - Linac accelerating cavity performance R&D
  - 90% of beam within 1mm on production target - end-to-end simulations
- Facility near NSCL
  - Layout provides baseline and maintains upgrade potential