FRIB

The Facility for Rare Isotope Beams

The Latest DOE NP User Facility Coming Online

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U.S. DEPARTMENT OF ENERGY | Office of Science

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Disclaimer/Acknowledgements

- FRIB is the result of many people's work over many years
  - Too many to list
- Content of many slides borrowed from colleagues who know more about it than I do.

Outline

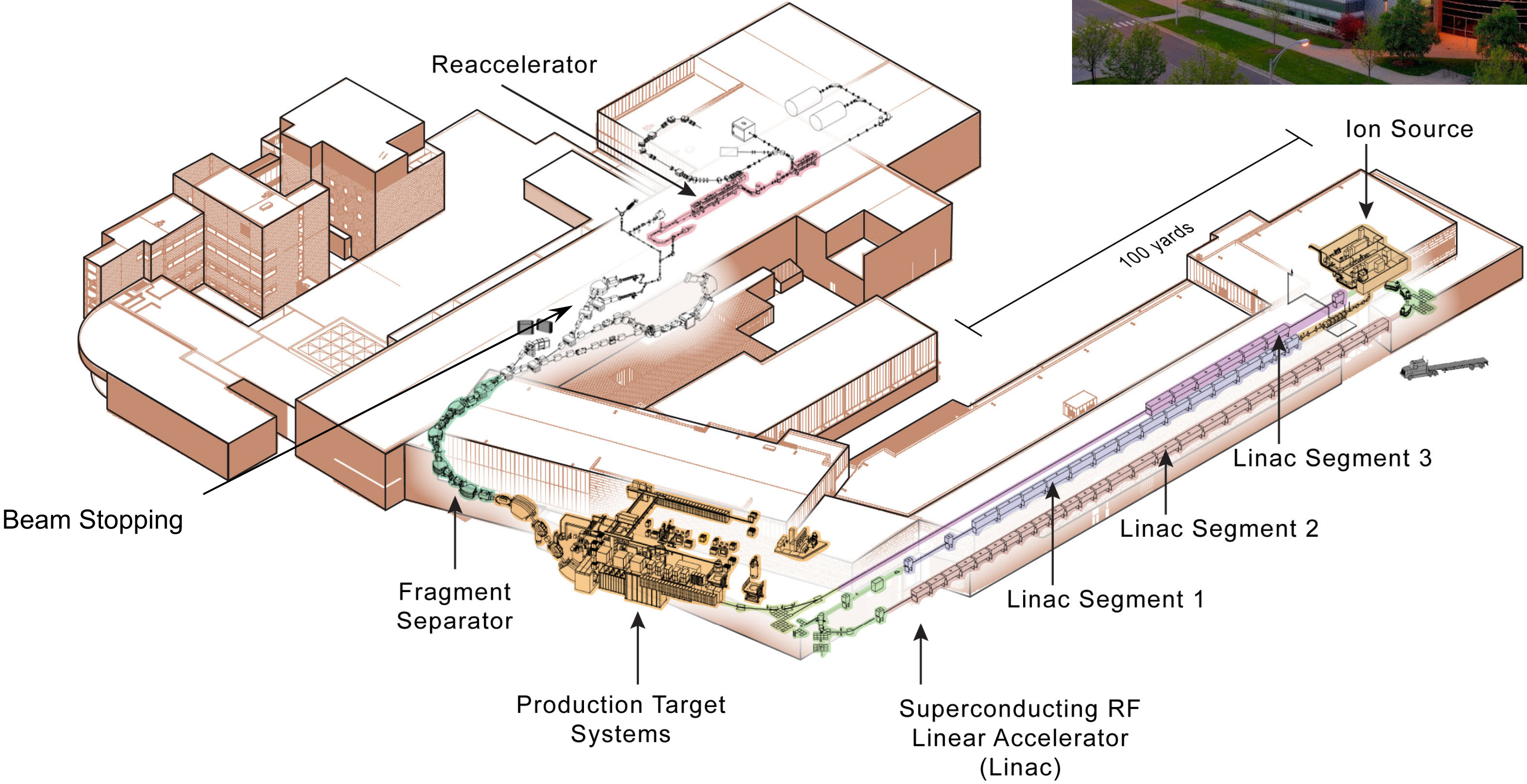
- What is FRIB?
- Why rare-isotope beams?
- Why FRIB?
- How does FRIB work?
- Status and Outlook
- Machine learning examples

What is FRIB?

- The Facility for Rare Isotope Beams (FRIB) is an accelerator facility that provides beams of rare isotopes for experiments.
- In a nut shell:
  - Linear accelerator for large variety of primary beams
    - From ^{16}O at 320 MeV/u
    - To ^{238}U at 200 MeV/u
  - Generate rare isotope by impinging those beams onto production targets
    - Targets are “thin”: primary beam is not stopped
  - Separate desired isotope(s) from primary beam and other isotopes
  - Utilize purified rare isotope beam at experiments
    - “Fast” beam: beam directly to experiment
    - “Stopped” beam: after stopping in gas and extraction/transport at few kV
    - “Reaccelerated” beam: after stopping and subsequent reacceleration to few MeV/u
- FRIB will provide the highest intensity rare-isotope beams in the world

FRIB Layout Overview

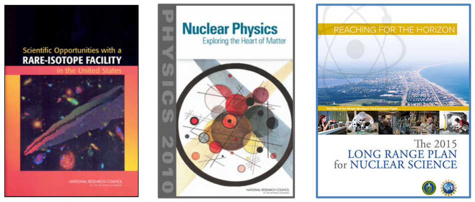
- FRIB on the campus of Michigan State University



Why Rare Isotope Beams?

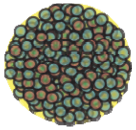
Rare isotope research answers questions posed by the NRC and NSAC

- Science drivers (thrusts) from NRC RISAC 2007
- Intellectual challenges from NRC Decadal Study 2013
- Overarching questions from NSAC Long Range Plan 2015


Scientific Opportunities with a RARE-ISOTOPE FACILITY in the United States

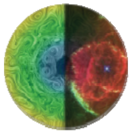
PHYSICS 2010 Nuclear Physics Exploring the Heart of Matter

REACHING FOR THE HORIZON The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE



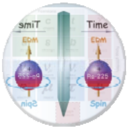
Properties of nuclei

- Develop a predictive model of nuclei and their interactions
- Many-body quantum problem: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.
- The limits of elements and isotopes



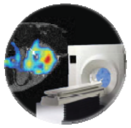
Astrophysical processes

- Origin of the elements in the cosmos
- Explosive environments: novae, supernovae, X-ray bursts …
- Properties of neutron stars



Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei

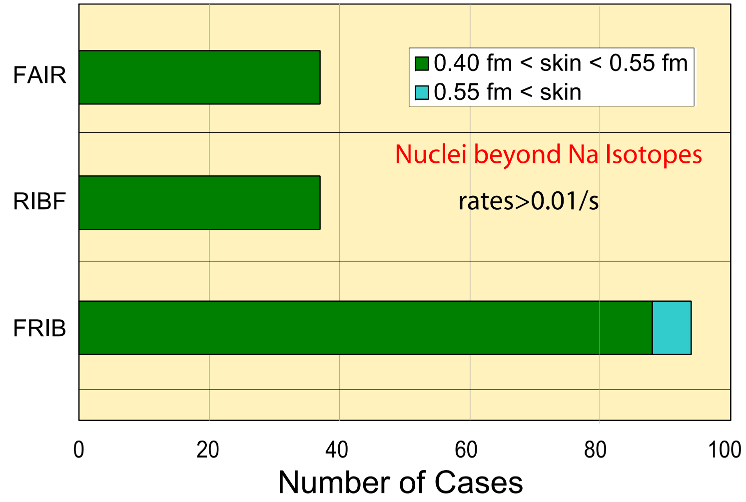


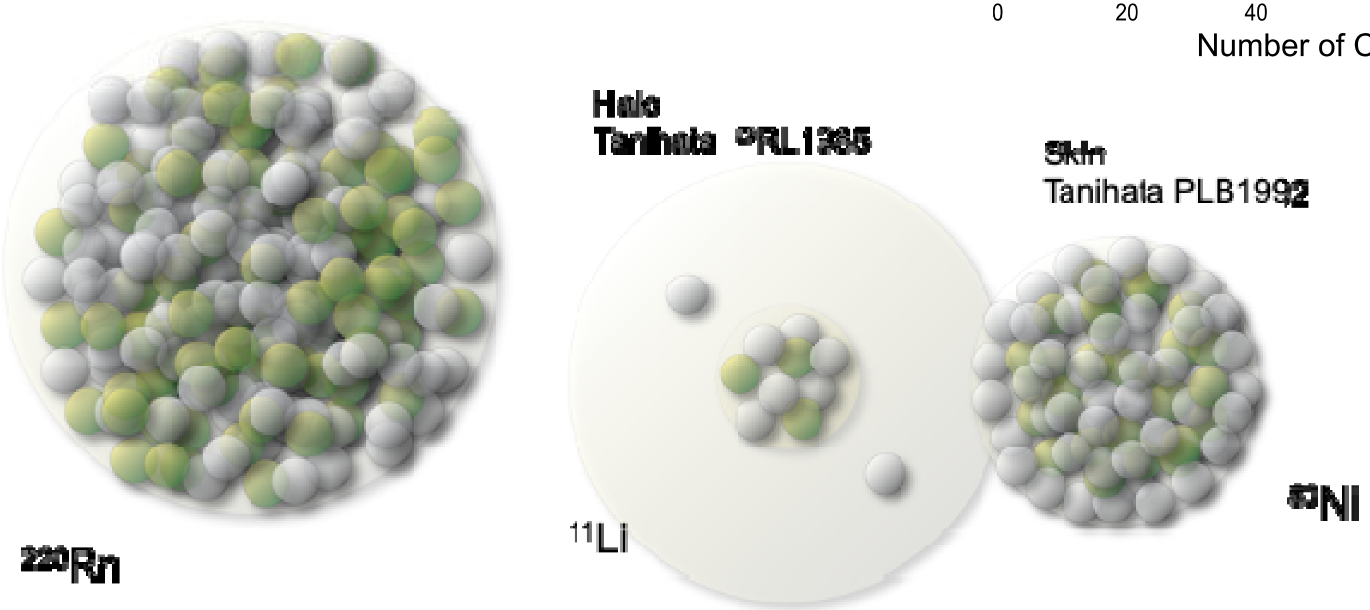
Societal applications and benefits

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

Properties of Nuclei – Example (1)

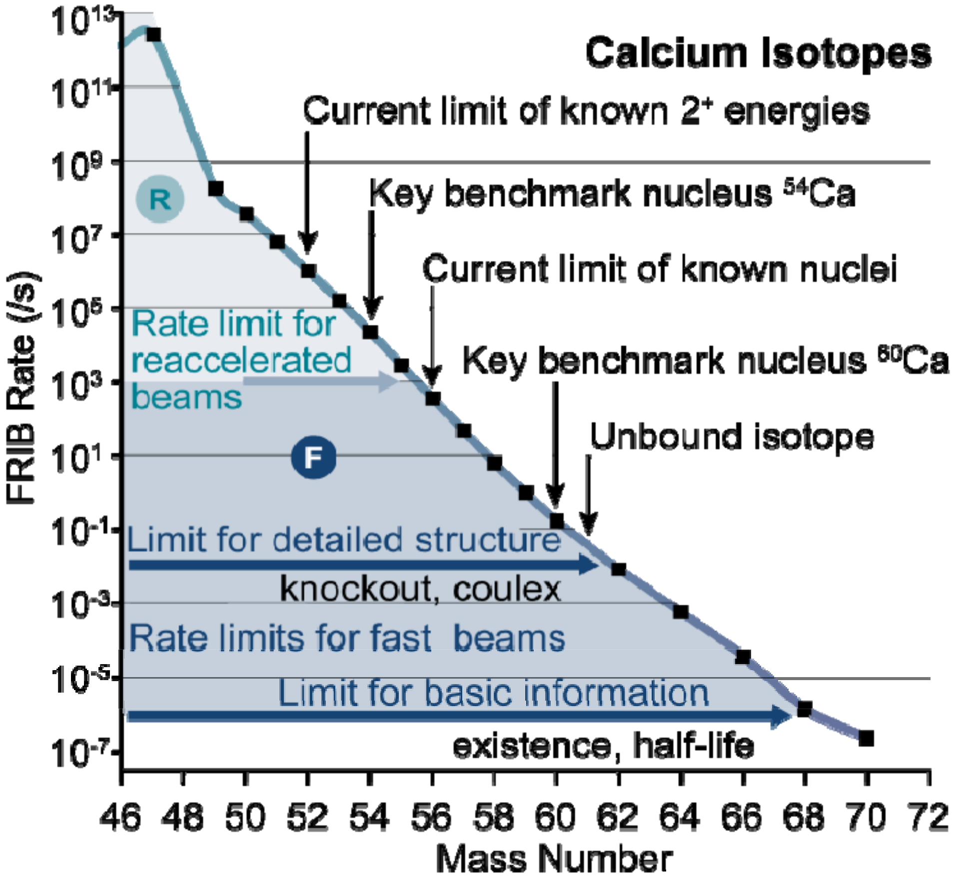
- Access to isotopes with unusual neutron/proton ratios is key to improved understanding of nuclear force, nuclear structure, and limits of stability
- Example: neutron halos and skins
  - FRIB provides first access to ^{80}Ni and a ^{11}Li intensity exceeding 10^8 particles per second
- FRIB will allow study of extreme >0.5 fm neutron skins.





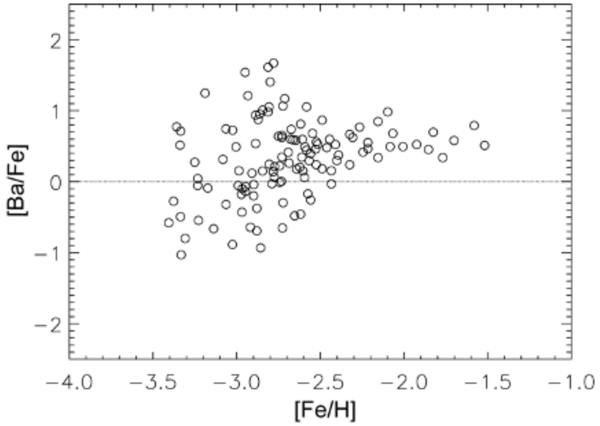
Properties of Nuclei – Example (2)

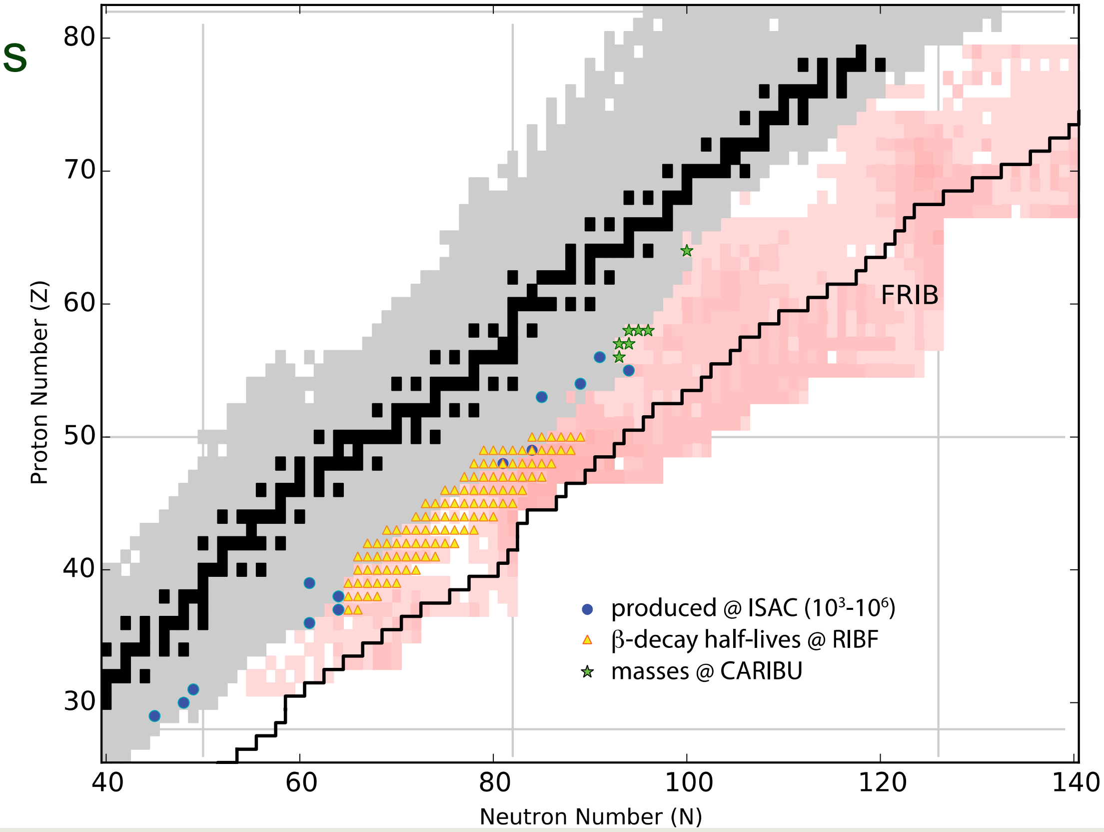
- FRIB provides access to key neutron-rich Ca isotopes with intensities sufficient to measure crucial observables (masses, half-lives, decay properties, excitations…). It will be the only facility with ^{60}Ca yields above 0.01/s. FRIB will reach ^{64}Ca.



Astrophysical Processes

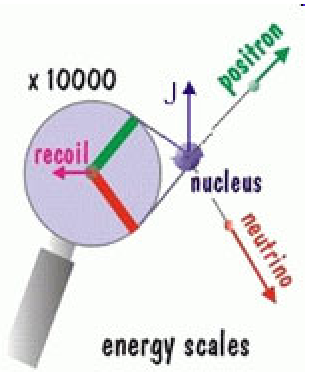
- Astrophysical r-process goes through rare isotopes presently inaccessible to experiments
  - FRIB will make many of these accessible for the first time
- Properties of these isotopes are essential to understand r-process abundances
  - See Mumpower et al. 2015
    - » DOI: 10.1103/PhysRevC.92.035807
- Example: [Ba/Fe] ratios in early stars

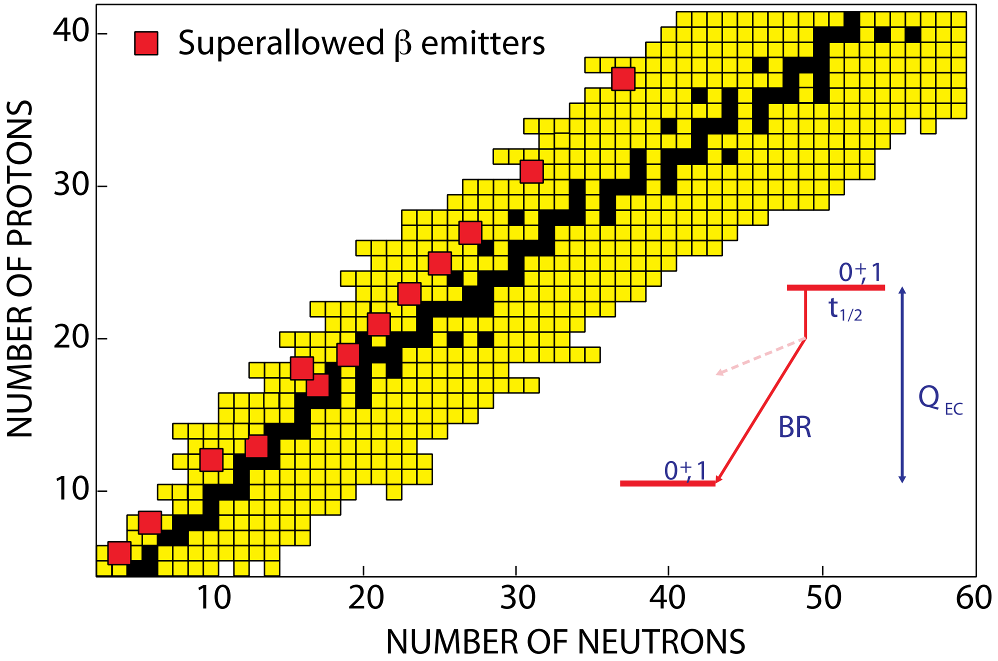




Test of Fundamental Symmetries - Examples

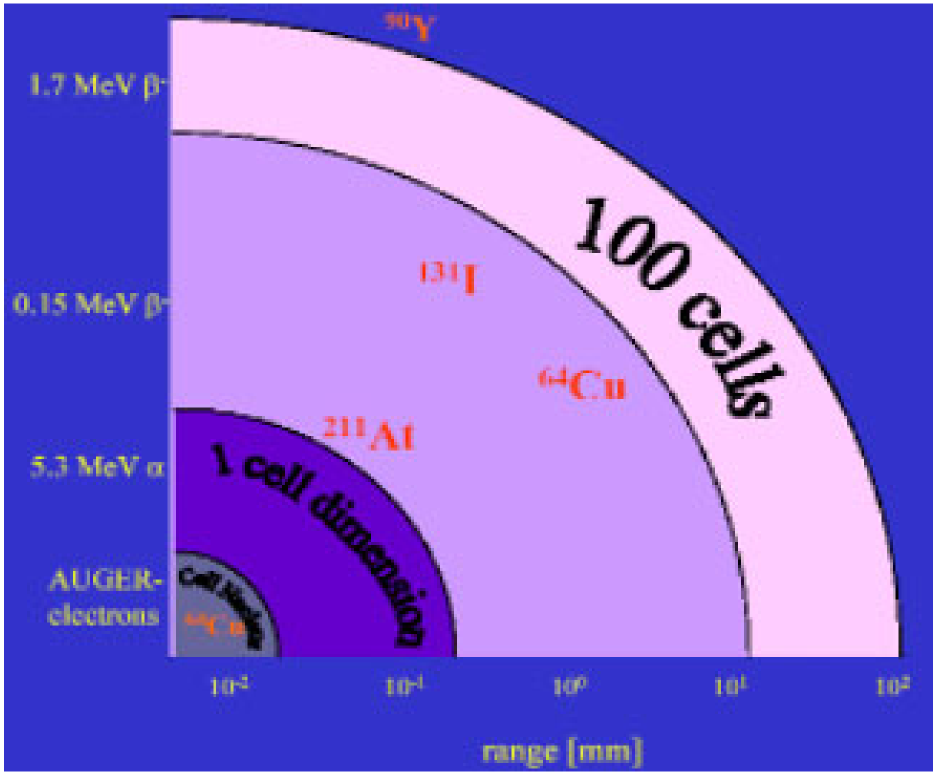
- Superallowed beta emitters to test the CKM matrix unitarity
- Angular correlations in β-decay and search for scalar currents
- Parity Non-Conservation in atoms (e.g. Francium)
- Atomic Electric Dipole Moment (EDM)
  - Rare isotopes 30,000x more sensitive than ^{199}Hg
  - ^{225}Ra: first measured by Parker et al.
    - » DOI 10.1103/PhysRevLett.114.233002
  - ^{223}Rn: FRIB estimated to yield 40 times more particle rate than world leading experiment





Societal Applications: Targeted Cancer Therapy

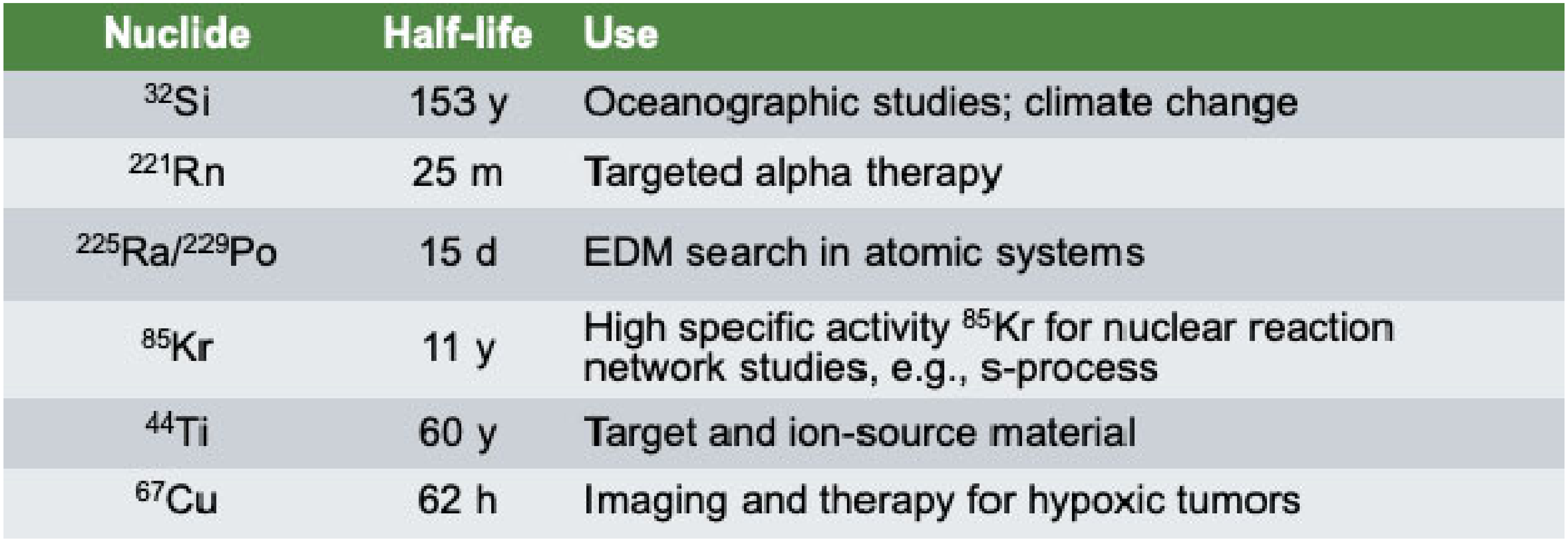
- Modern targeted therapies in medicine take advantage of knowledge of the biology of cancer and the specific biomolecules that are important in causing or maintaining the abnormal proliferation of cells
- These radionuclides have been relatively difficult to get in sufficient quantities[1]. The short-lived alpha emitters are particularly in demand, especially ^{225}Ac, ^{213}Bi, and ^{211}At.
- Pairs, e.g., ^{67}Cu (treatment) and ^{64}Cu (dosimetry) are particularly interesting
- FRIB can supply many isotopes via parasitic harvesting



[1] Isotopes for the Nation's Future: A Long Range Plan, NSACIS 2009

Sample Isotopes for Societal Applications

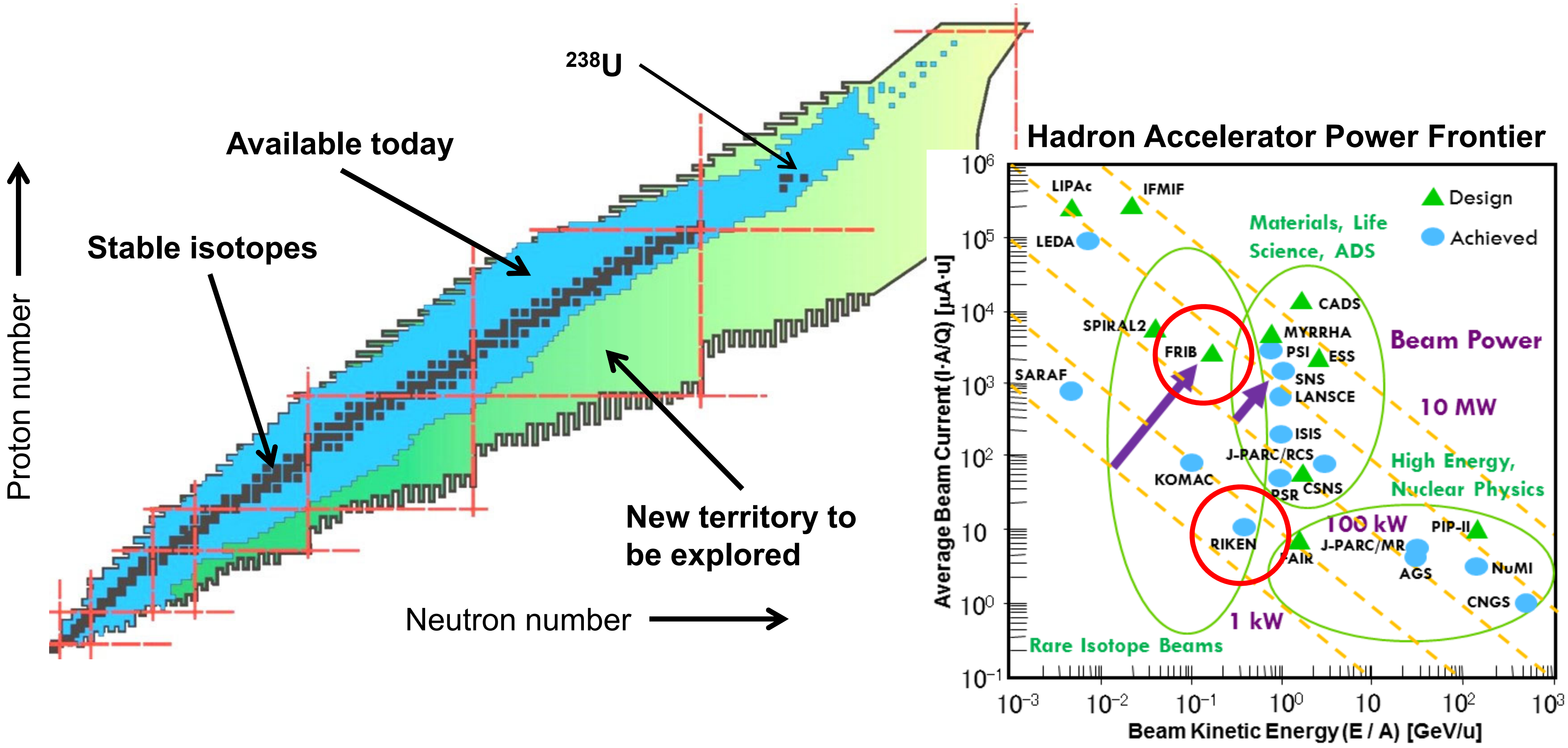
- Workshops on Applications of Isotopes from FRIB
  - E.g. Sep/Oct 2010, Santa Fe, NM; July 2012, East Lansing



Nuclide	Half-life	Use
^{32}Si	153 y	Oceanographic studies; climate change
^{221}Rn	25 m	Targeted alpha therapy
^{225}Ra/^{229}Po	15 d	EDM search in atomic systems
^{85}Kr	11 y	High specific activity ^{85}Kr for nuclear reaction network studies, e.g., s-process
^{44}Ti	60 y	Target and ion-source material
^{67}Cu	62 h	Imaging and therapy for hypoxic tumors

Why is FRIB Needed?

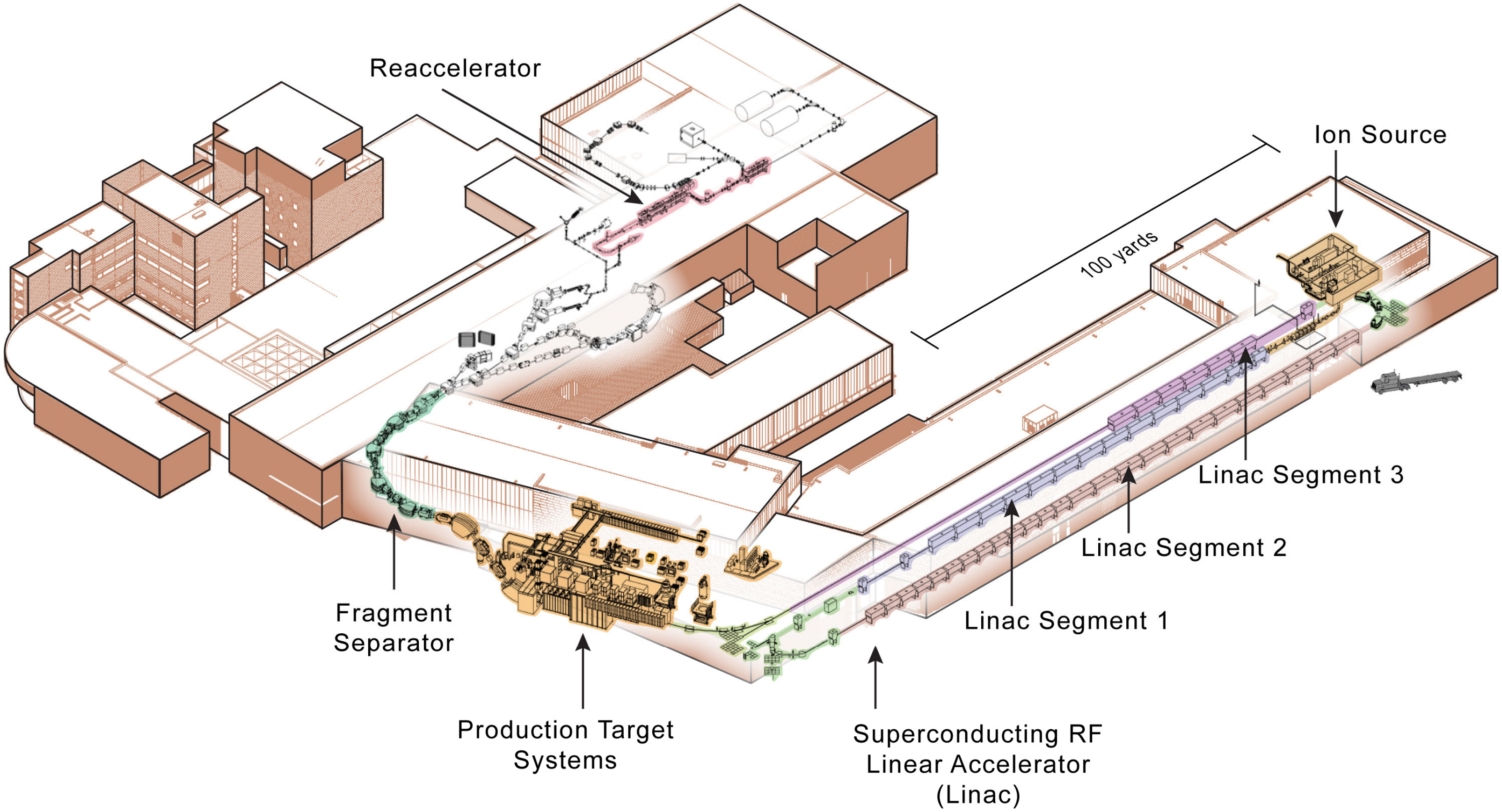
- FRIBs unprecedented beam power will yield the highest rare isotope beam intensities and expand the reach of rare isotopes available for research.



J. Wei, MPLA 31 (2106)

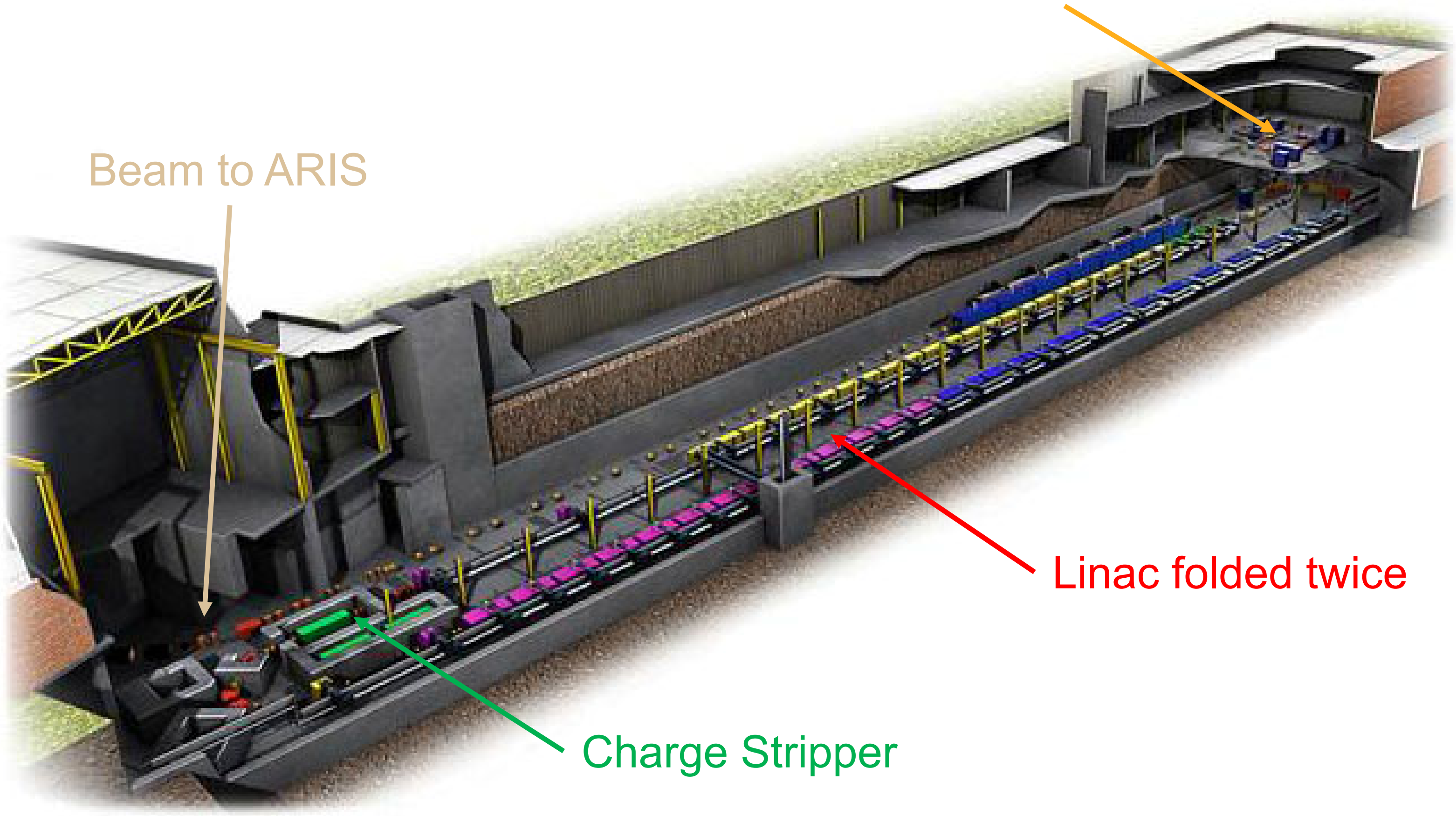
How Does FRIB Work?

- Revisit facility overview



FRIB Superconducting RF Linac

- Superconducting RF linac



Front end

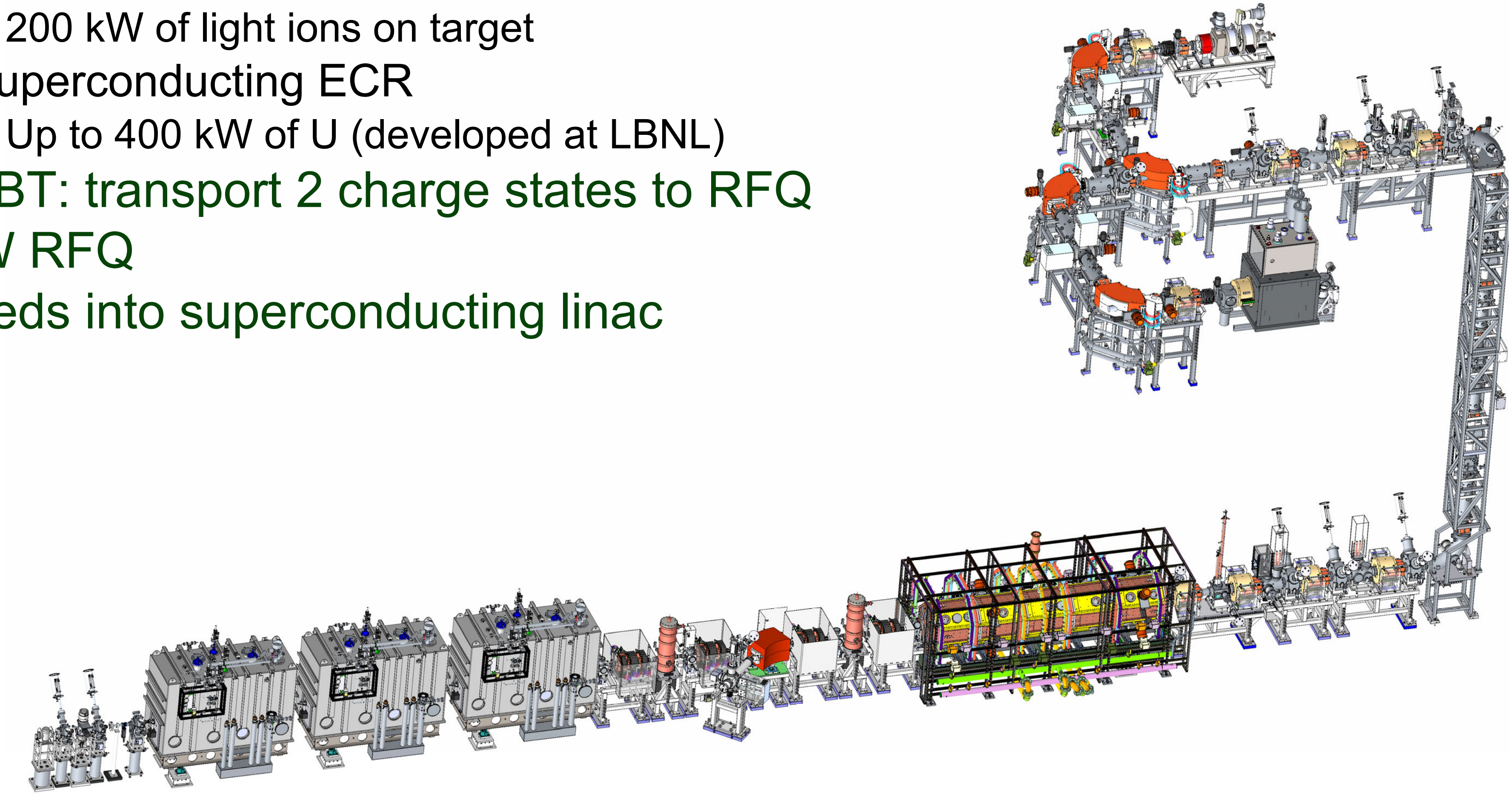
Beam to ARIS

Linac folded twice

Charge Stripper

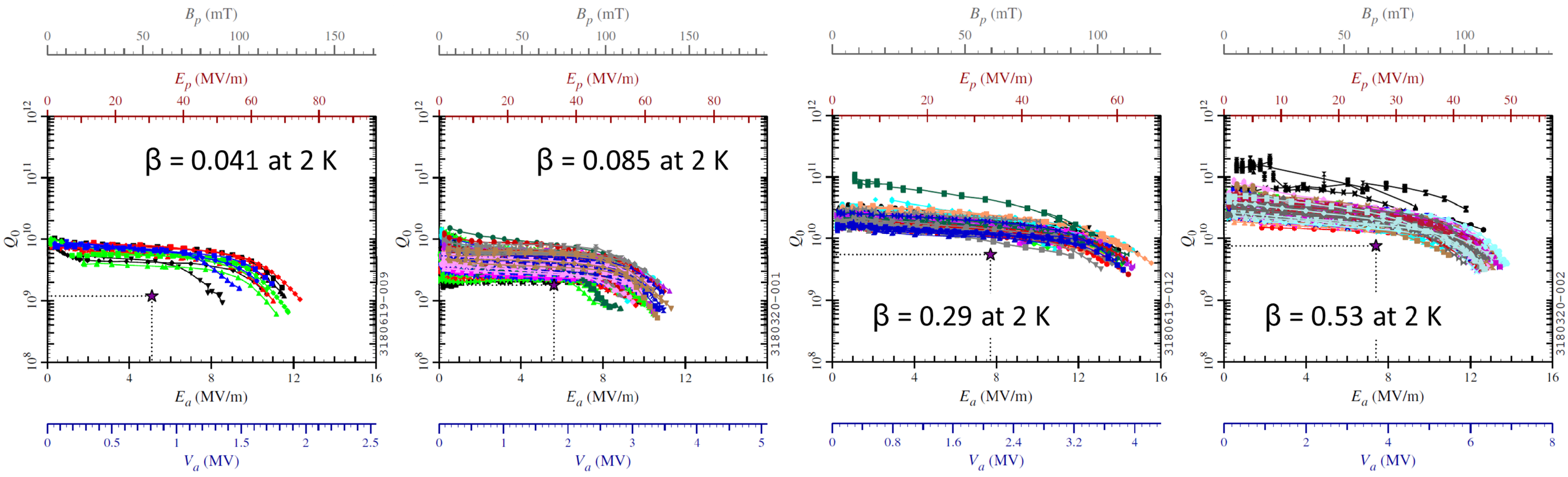
Linac Front End

- Two ECR ion sources:
  - Room temperature ECR
    - 200 kW of light ions on target
  - Superconducting ECR
    - Up to 400 kW of U (developed at LBNL)
- LEBT: transport 2 charge states to RFQ
- CW RFQ
- Feeds into superconducting linac



Superconducting RF Resonators

- 324 SC resonators (4 types) and 46 cryomodules
  - All cavities exceed specifications

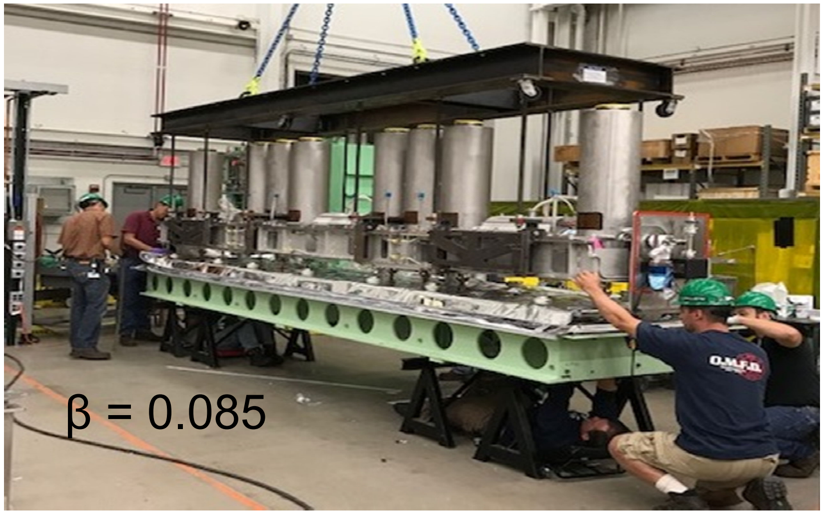


Linac Segment 1

Linac Segment 2

Linac Segments 2+3

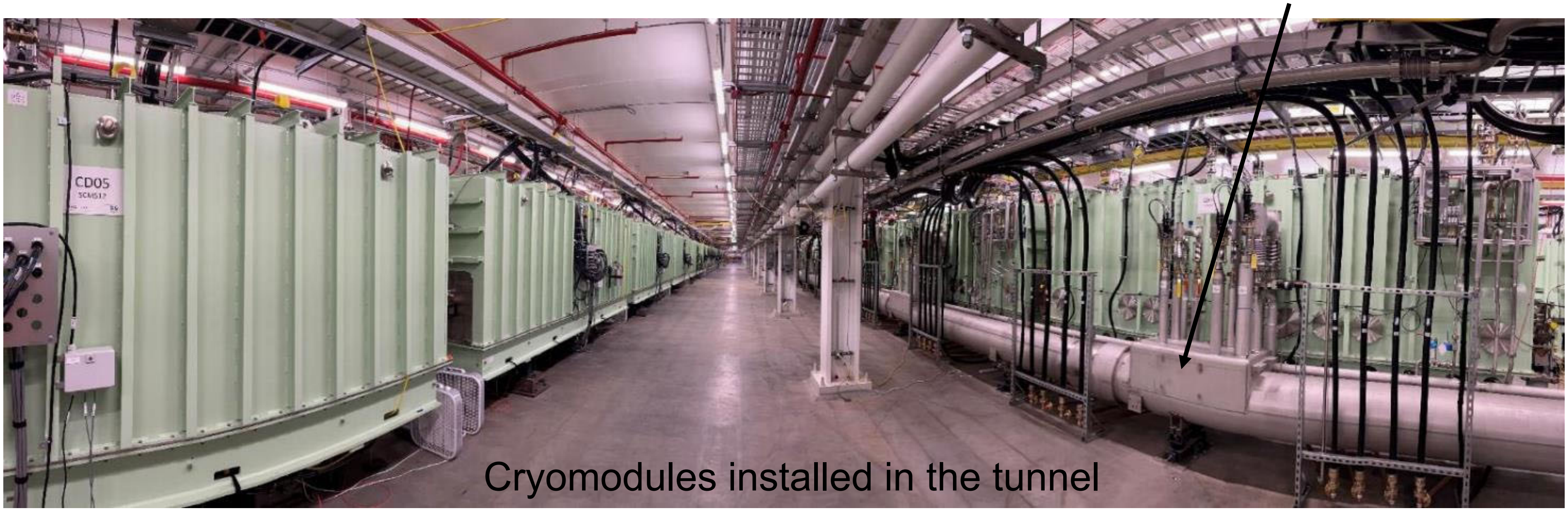
SRF Cryomodules



β = 0.085

β = 0.53

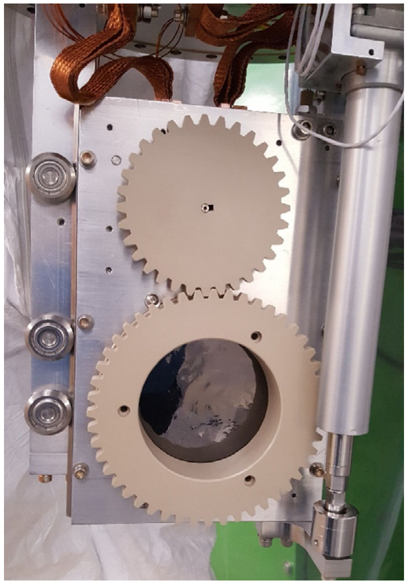
Cooling line from FRIB cryoplant located above the tunnel

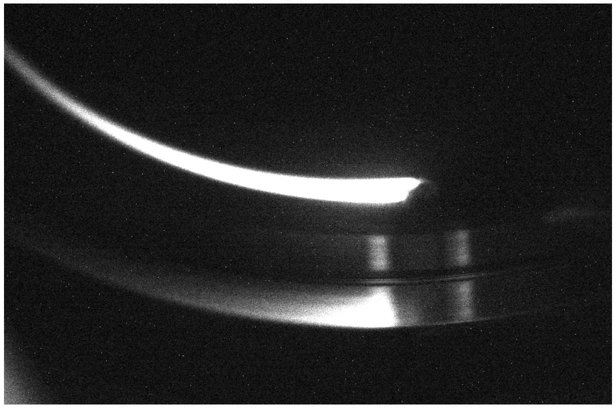


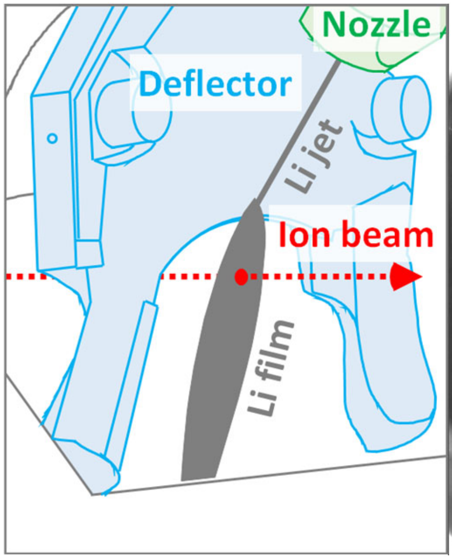
Cryomodules installed in the tunnel

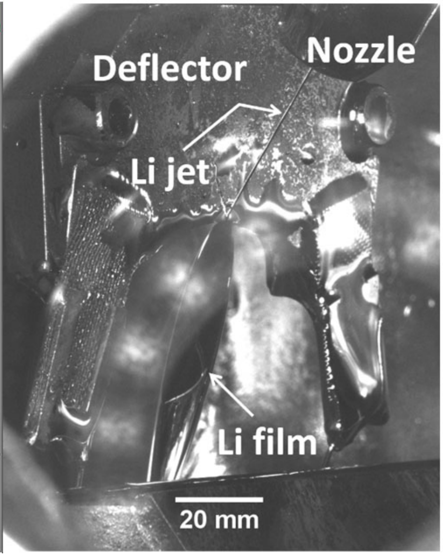
Charge Stripping

- Stripping ions at ~ 20 MeV/u for efficient acceleration
- Rotating Carbon Foil up to 10 kW Beam on Target
  - 100 mm diameter foil, rotating and up-down motion
  - Tested with 440 W ^{86}Kr beam on the stripper
- Liquid Lithium Charge Stripper for 400 kW
  - Closed loop liquid lithium system
  - Tested with 10 pμA pulsed argon beam



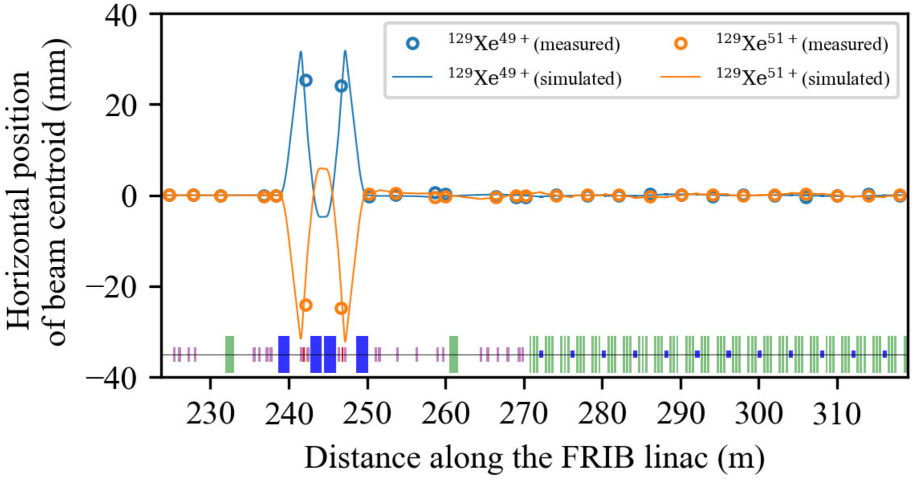


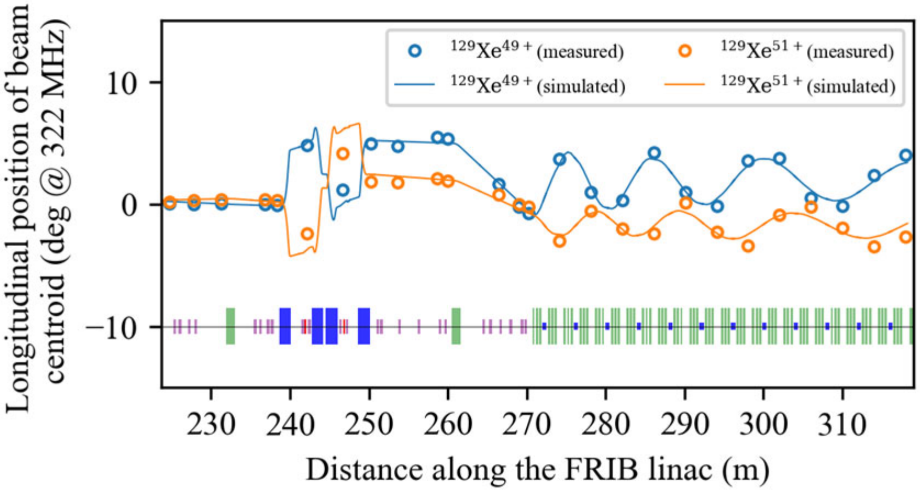




Multi Charge-State Acceleration

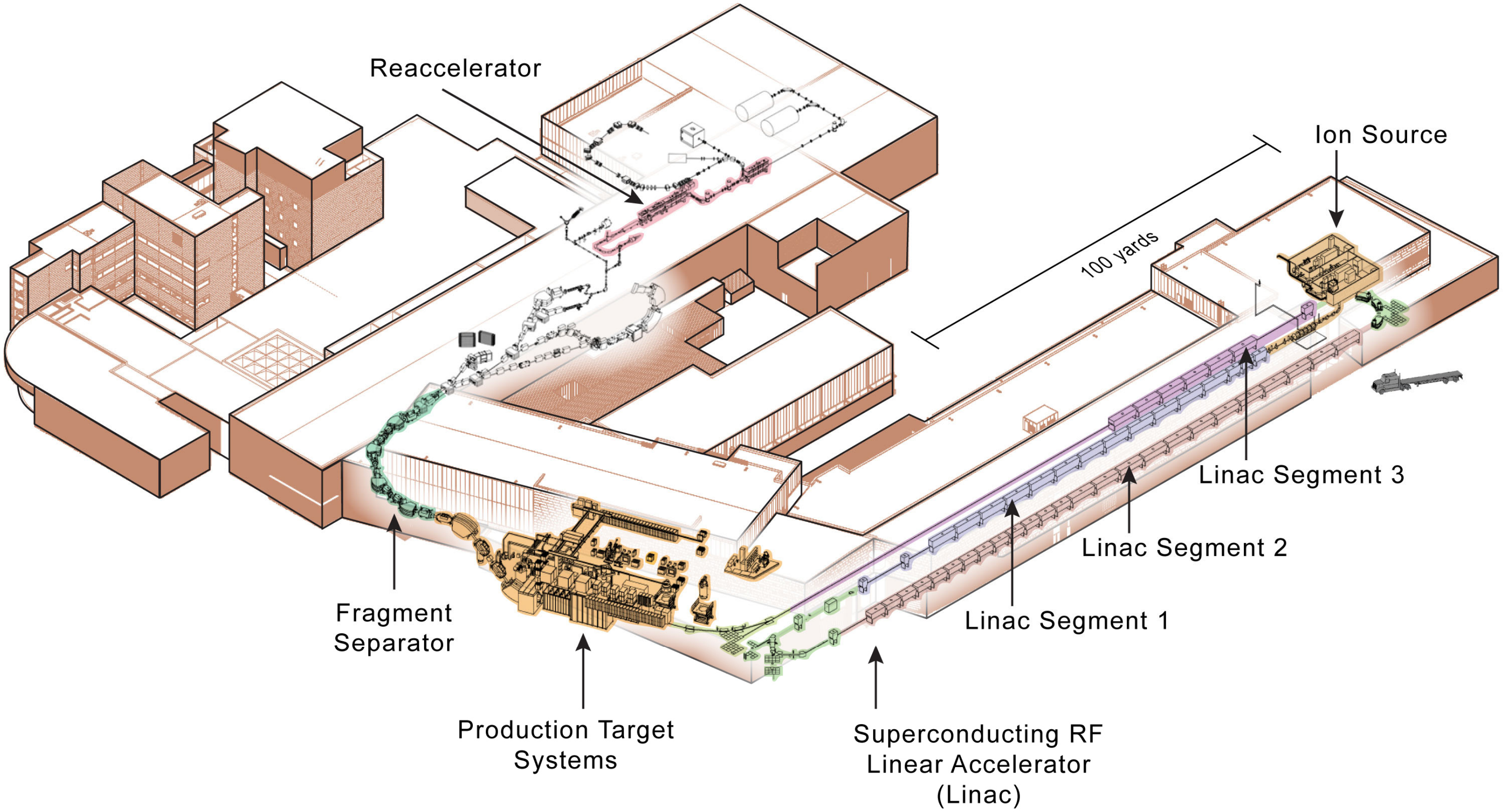
- Five charge states to be accelerated after charge stripper for 400 kW Uranium beam
- Demonstrated factor of 2.5 increase of beam intensity with three charge states acceleration of Xenon
  - Stripping efficiency into 49+, 50+, 51+ = 76.5%
  - Good agreement with simulation





Production and Selection of Rare Isotopes

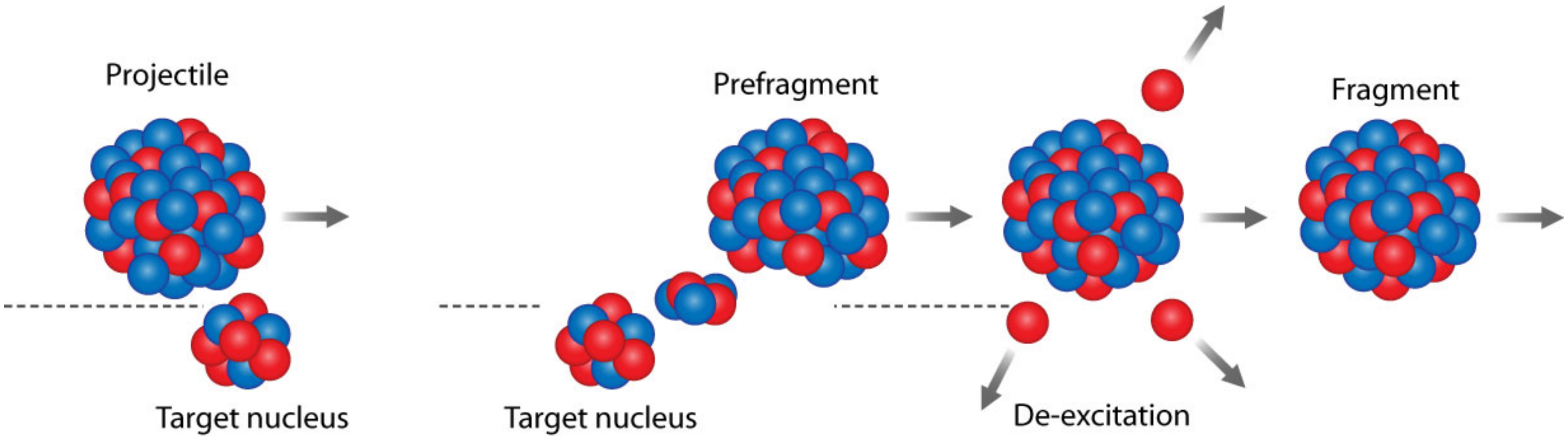
- Revisit facility overview (for the last time ☺)



Production of Rare Isotopes at FRIB [1]

Projectile Fragmentation

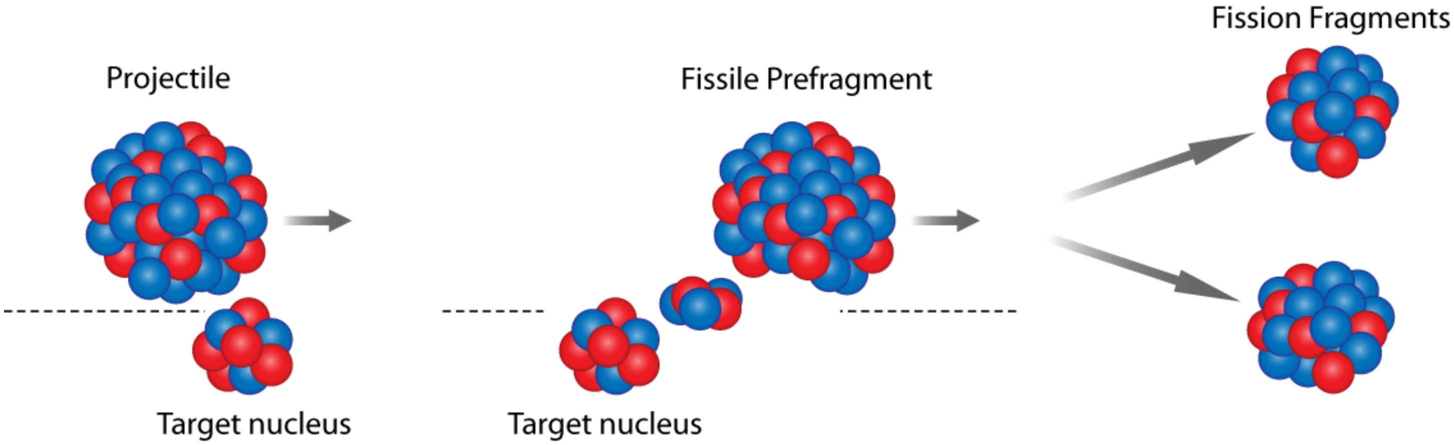
- In projectile fragmentation a target nucleus scrapes some nucleons of a projectile nucleus
- The prefragment de-excites by releasing neutrons (and/or gammas)
- Statistical process results in many different rare isotopes
  - Produces "all" nuclides possible by proton and neutron removal
- Yield for a given nuclide varies strongly with the choice of projectile



Production of Rare Isotopes at FRIB [2]

Induced Fission

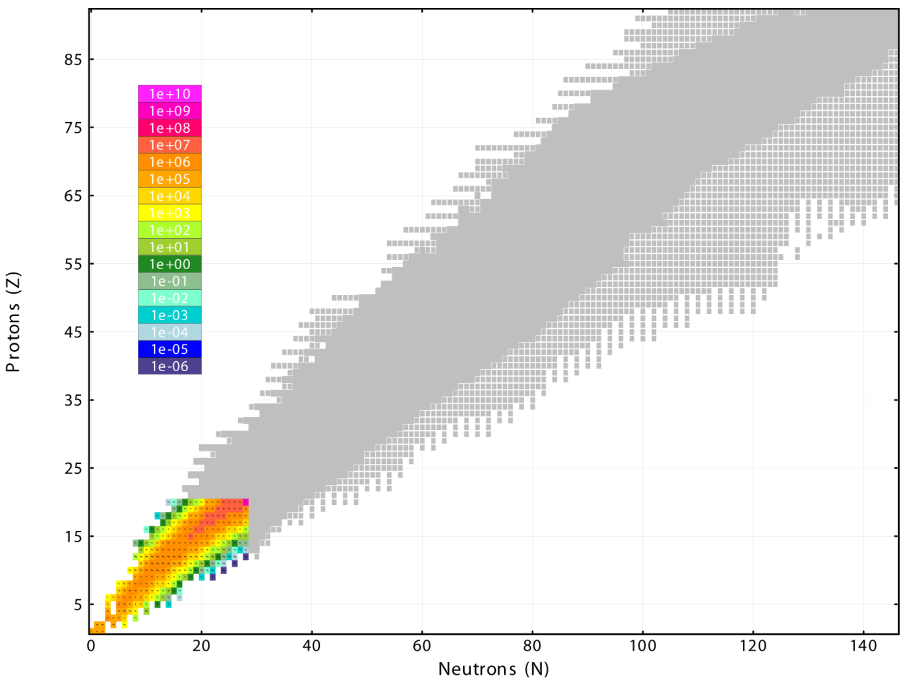
- Excited prefragments from uranium projectiles can also fission
- Produces two medium-mass fission fragments per incoming uranium projectiles that fissions
  - Fission fragments are neutron rich because uranium is more neutron rich than stable medium-mass nuclides
    - » 238/92 is 18 neutrons more than 2 times 110/46 (heaviest stable Pd isotope)



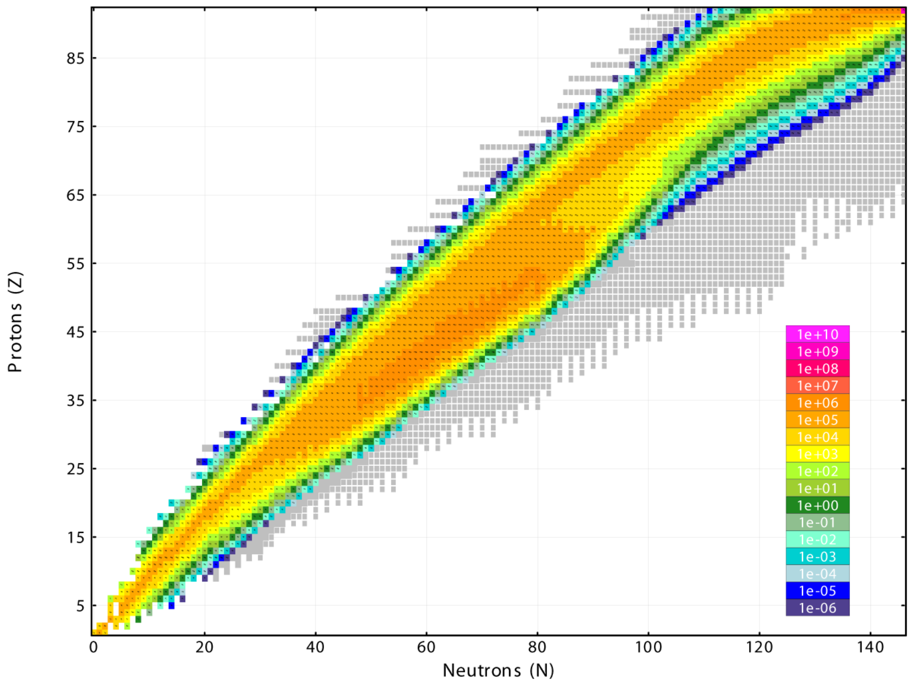
Output from Target – Need for Separation

- Reactions in Target Produce Many Different Rare Isotopes
  - Uranium produces nearly all possible nuclides, but not all with high intensity
  - Light beams produce only light rare isotopes, but with higher yield
  - We use different primary beams to enhance the yield for a desired secondary beam
- **We need to separate the desired nuclide(s) from contaminants**

Yields from ^{48}Ca beam (1 pnA)

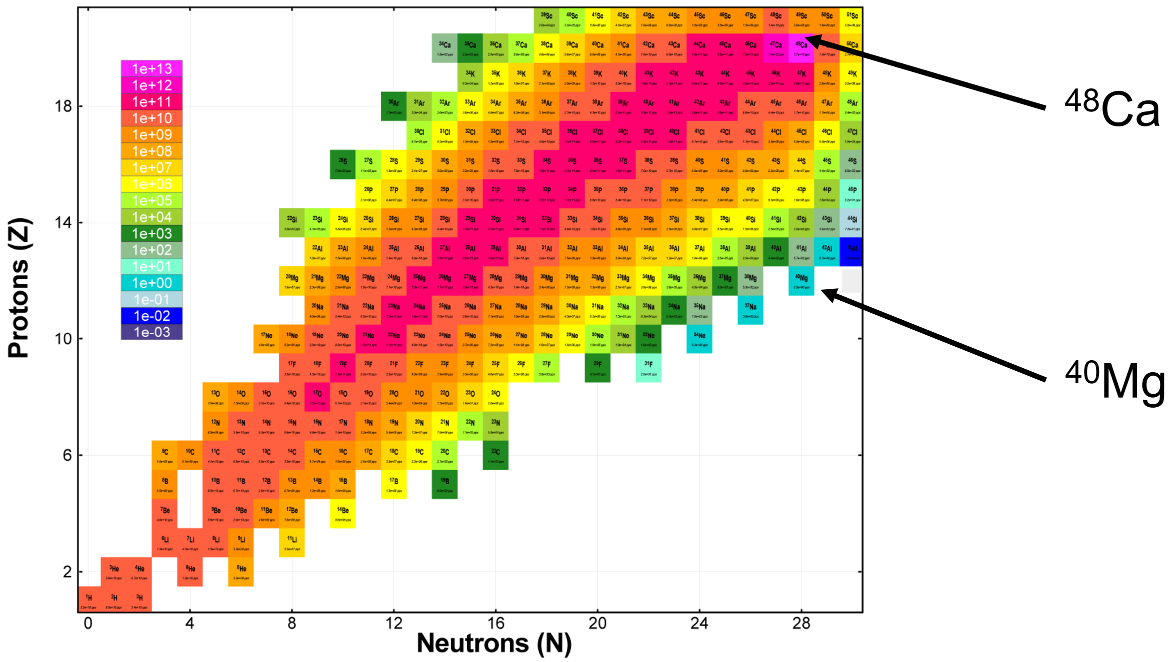


Yields from ^{238}U beam (1 pnA)



Need for Separation - Example

- Example: generate ^{40}Mg from ^{48}Ca beam
- Desired isotope: ^{40}Mg → 5.5 particles per second
- Everything coming from target → $1.85 \cdot 10^{14}$ particles per second
  - About 90% of that is “unreacted” ^{48}Ca

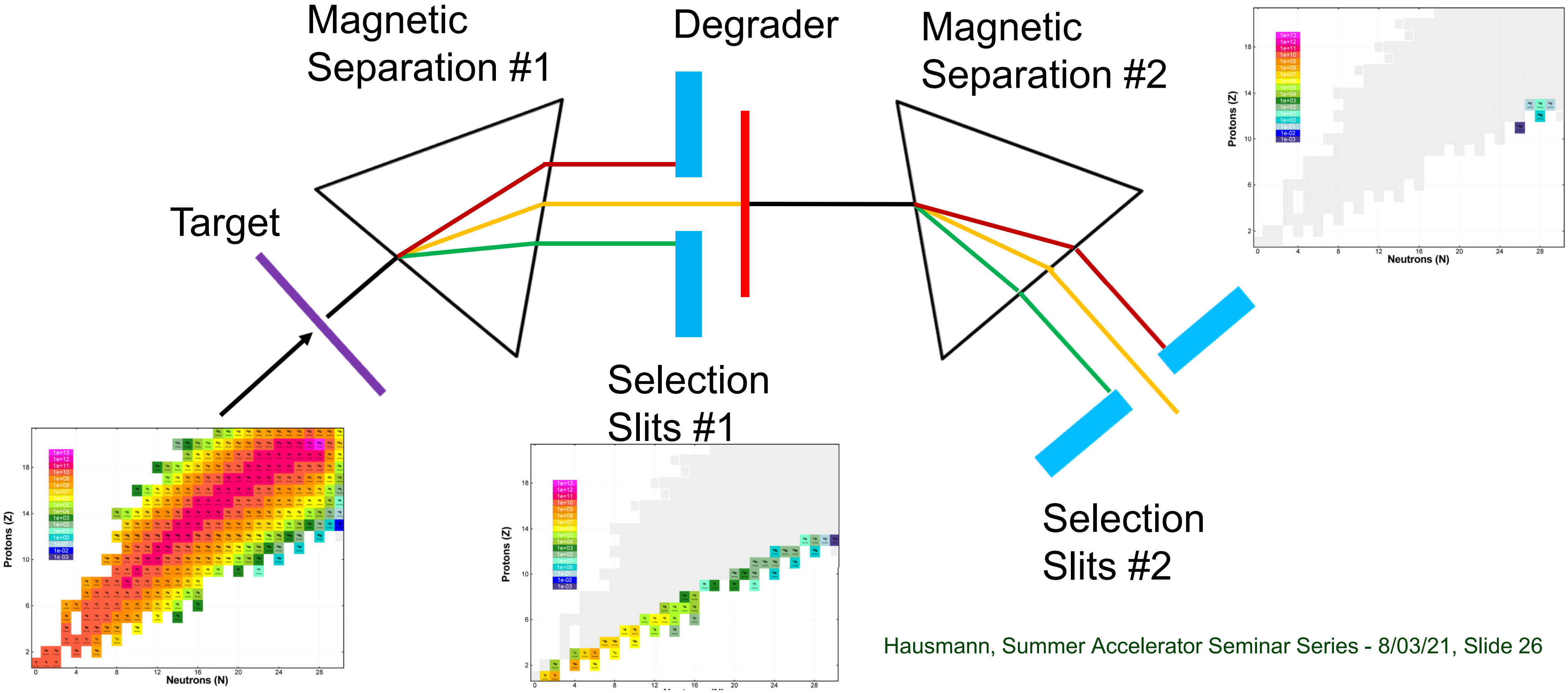


^{48}Ca

^{40}Mg

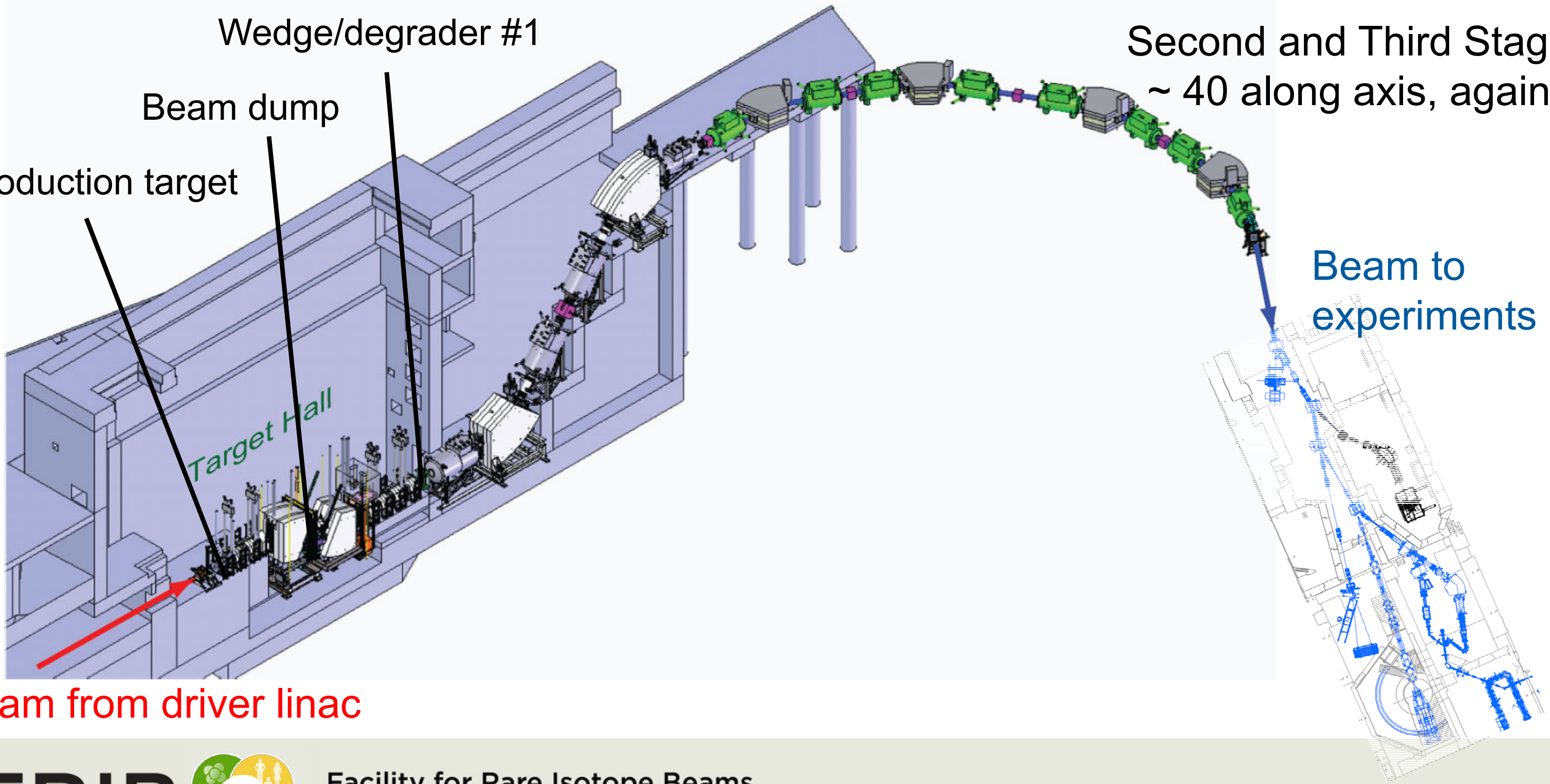
Separation In a Nutshell

- Separation in three steps ($B\rho - \Delta E - B\rho$ method)
  - Select different beams from target by magnetic rigidity (roughly by A/Z)
  - Change the magnetic rigidities by sending beams through degrader
    - Energy loss ~ Z^2
  - Select by magnetic rigidity again



Fragment Separator

- Dipole magnets to bend and disperse beam
- Quadrupole magnets to focus beam



Wedge/degrader #1

Beam dump

Production target

Second and Third Stage
~ 40 along axis, again

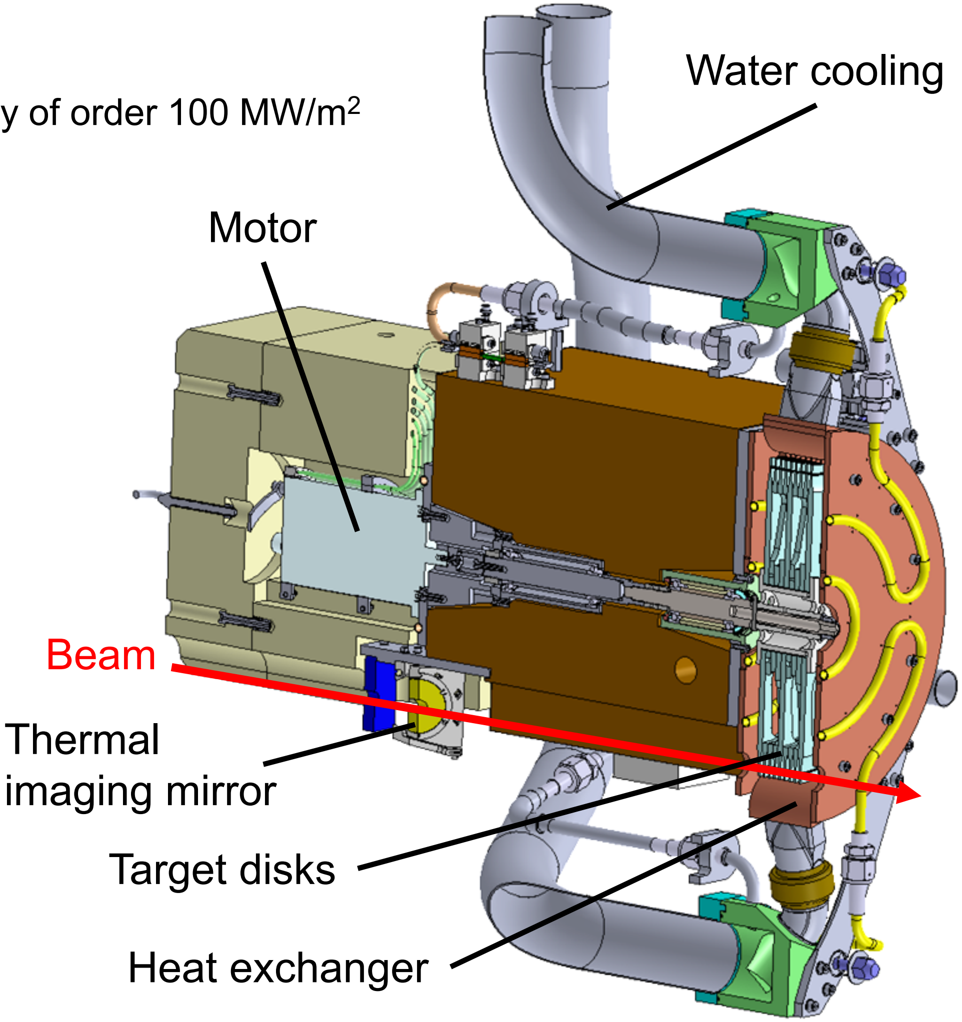
Beam to
experiments

Beam from driver linac

Production Target

- Shooting primary beam through a target
  - Deposit about 25% of beam energy in target
    - 100 kW in a 1 mm diameter spot → power density of order 100 MW/m^2
- Multi-slice rotating graphite disk target
  - Up to 9 slices; 30 cm diameter;
  - Beam hits the rim of the disks
  - Disks rotate at 5000 rpm
  - Radiative cooling to fins on both sides
  - Graphite temperature 1500 - 1900ºC
    - Low enough to control sublimation
    - High enough to anneal radiation damage
- Prototype tested with electron beam

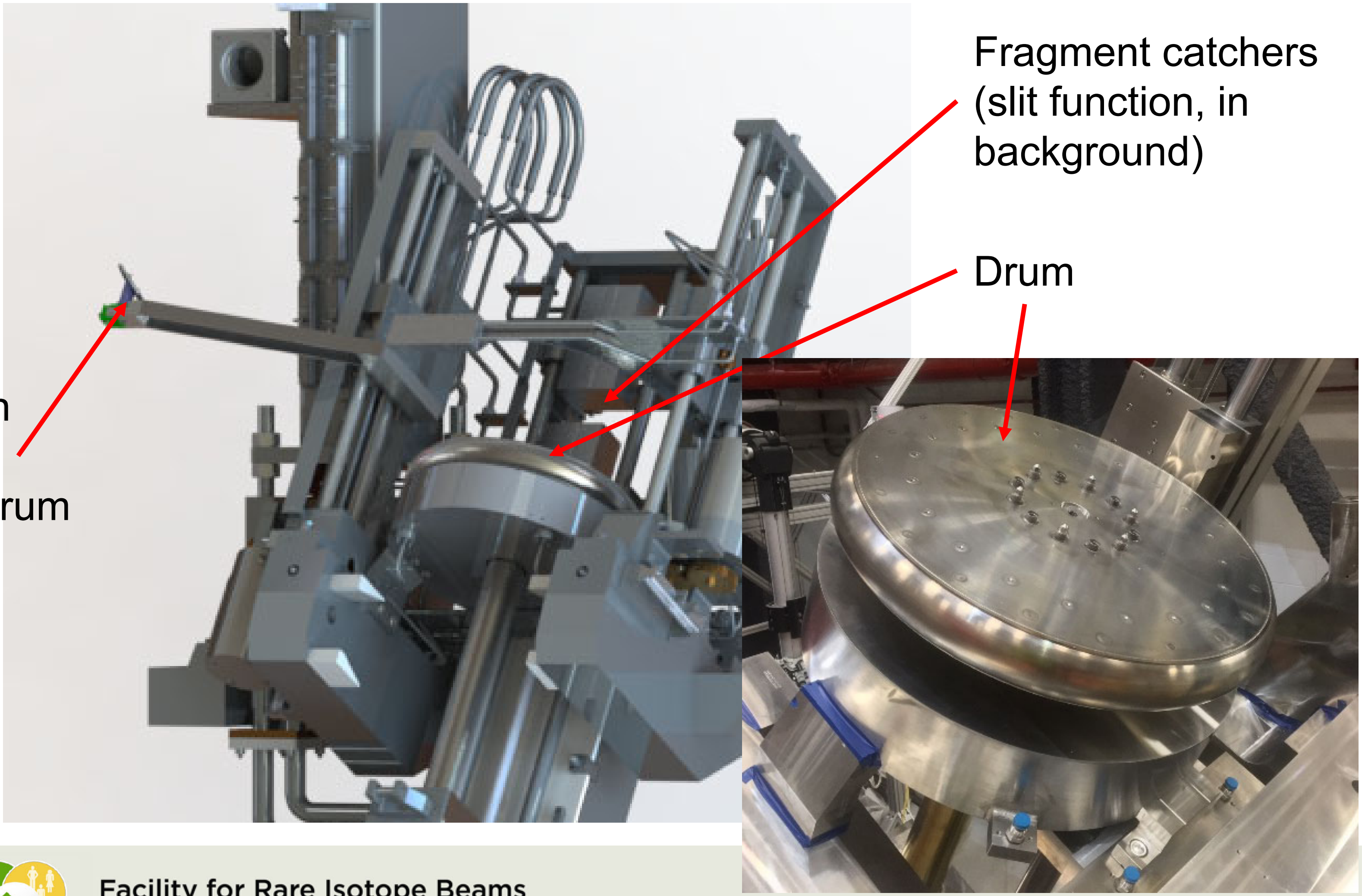
Prototype target with five disks



Target assembly design

Beam Dump

- Water filled rotating drum: opportunity for isotope harvesting



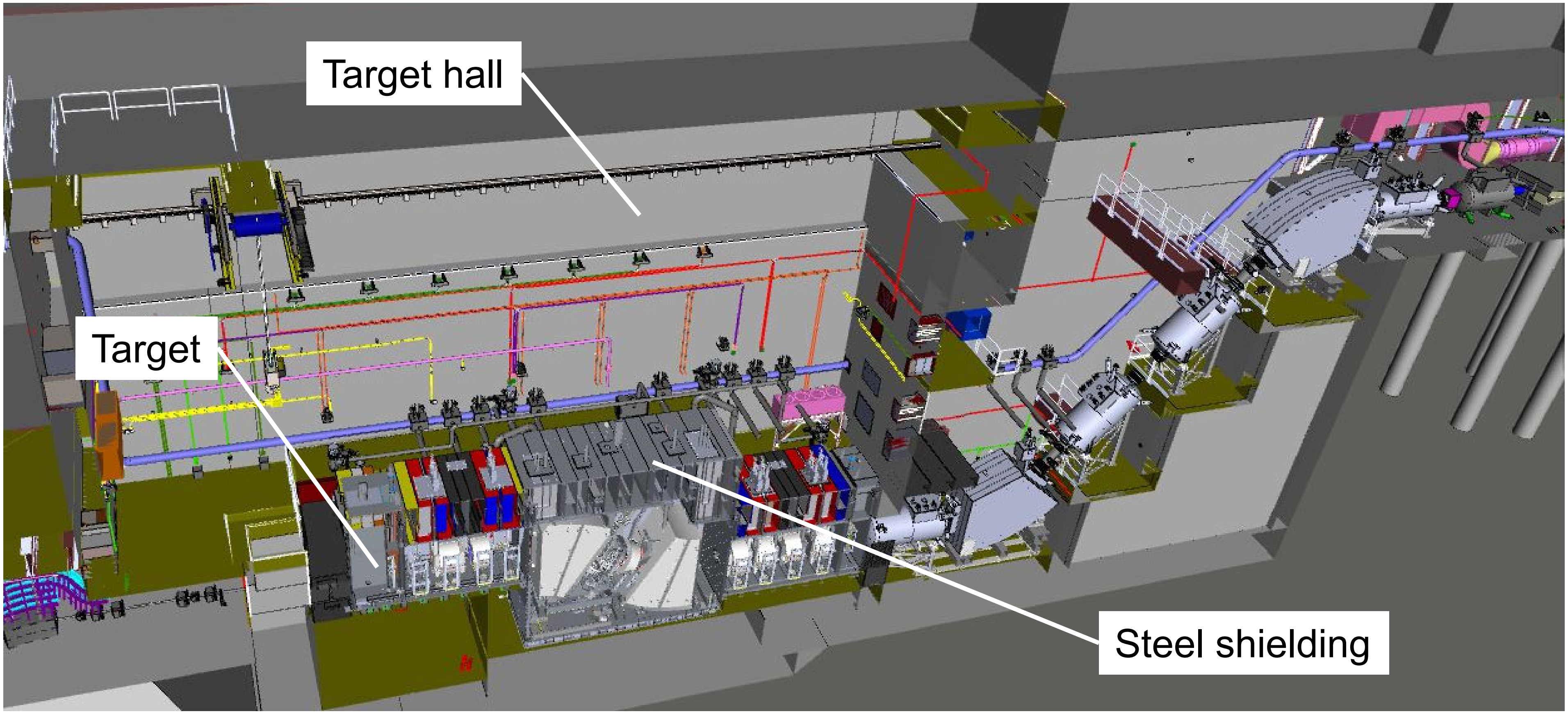
Fragment catchers (slit function, in background)

Drum

Mirror to watch beam heat signature on drum

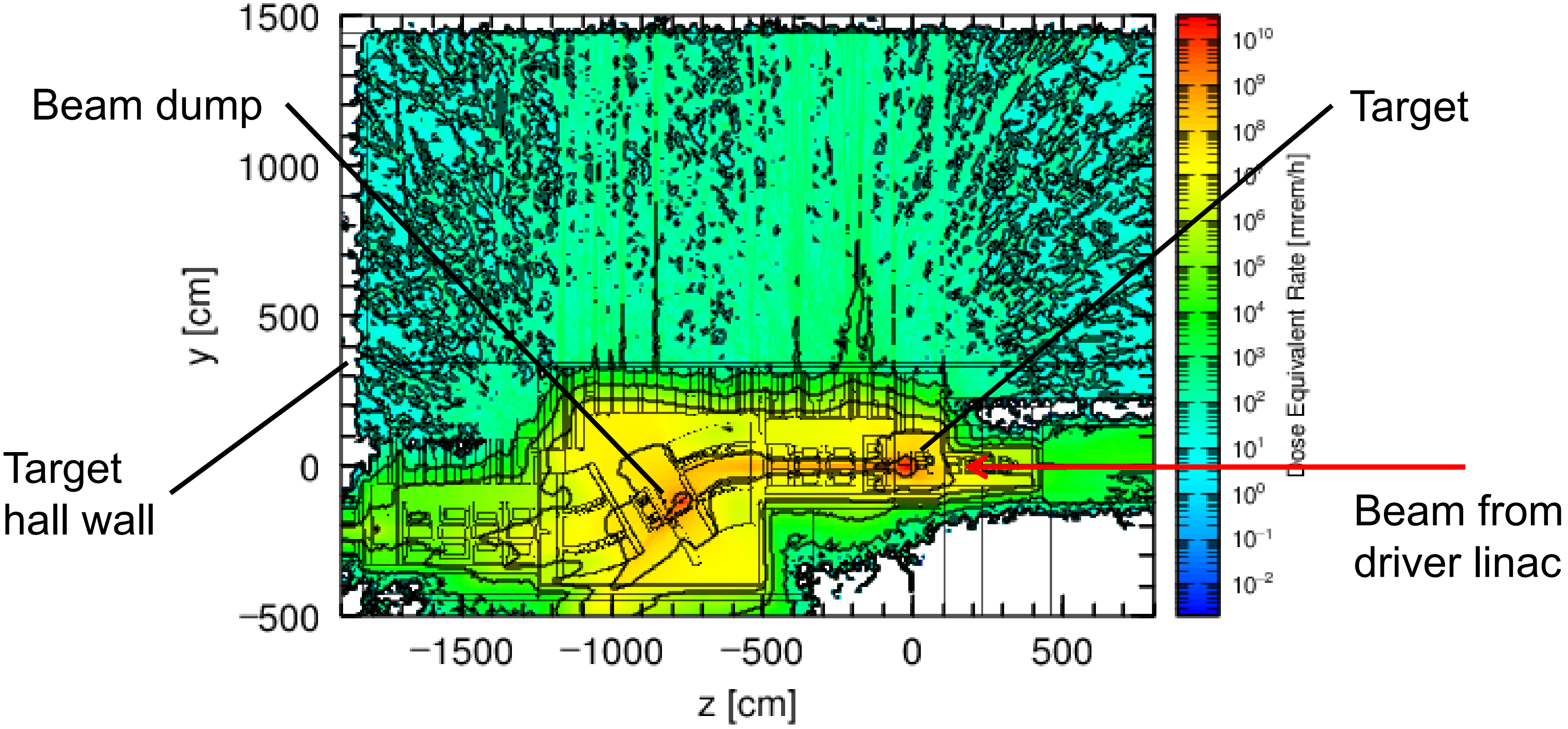
Preseparator with Vacuum Vessels

- 3D model shows cut through three large vessels in target hall
  - Placing equipment inside of large vacuum vessels avoids handling vacuum connections
  - Steel reentrant shielding over the top (1.5 m) allows hands-on maintenance above shielding
  - Remote handling to access components from top of vessels when shielding removed



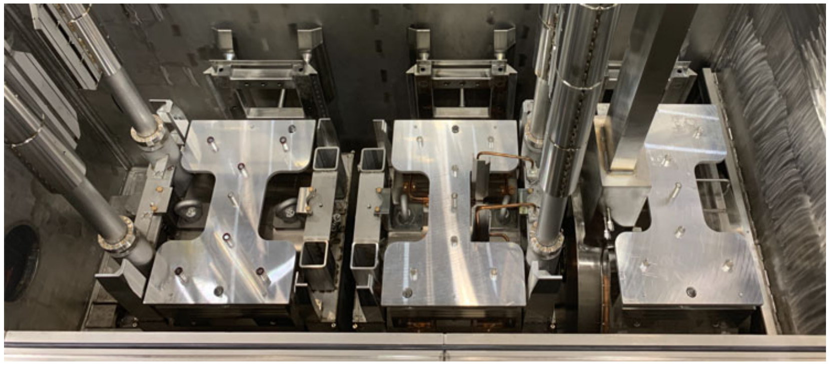
Radiation Fields in Target Hall

- Dose rates near target can exceed 10^9 mrem/h
- Reentrant shielding reduces radiation levels by ~5 order of magnitude
  - Side view of target hall area from radiation transport calculation
  - Target hall walls and ceiling (removable roof beams) absorb most of remaining radiation

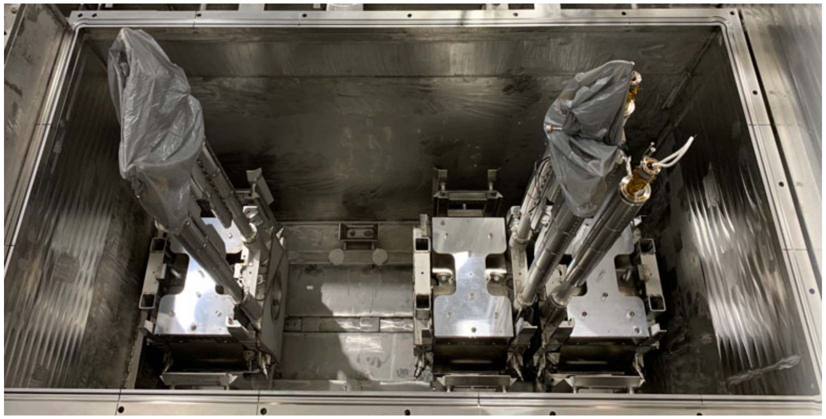


Preseparator Magnets

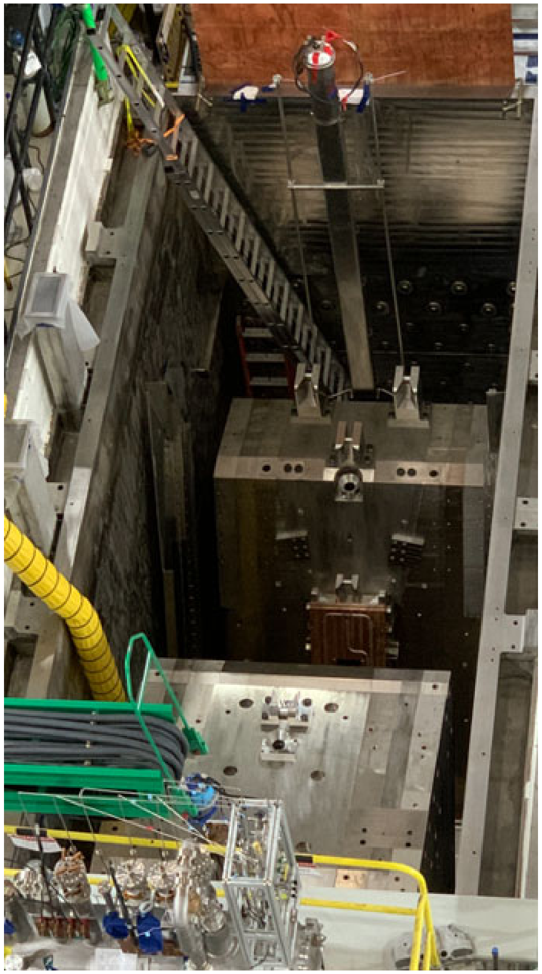
WIQ1,2,3 in target magnet vessel



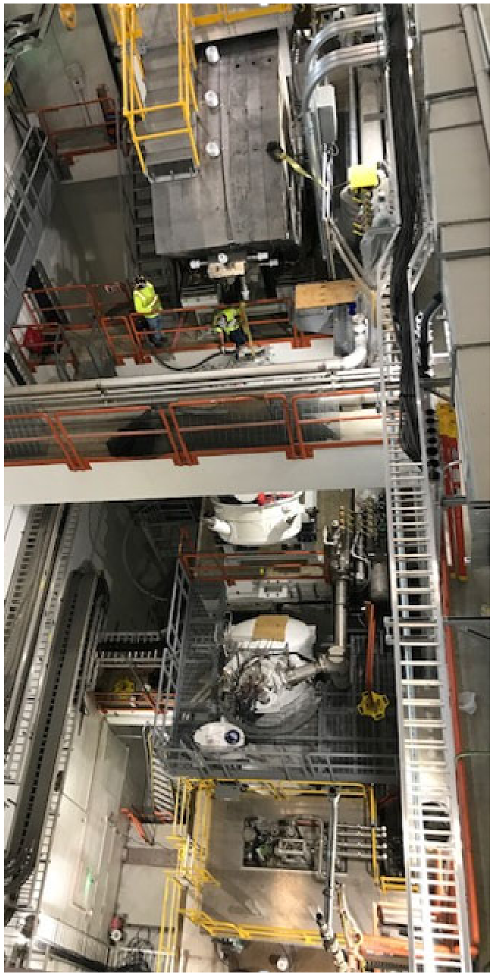
WIQ4,5,7 in wedge magnet vessel



SCD1 and SCD2 Dipole

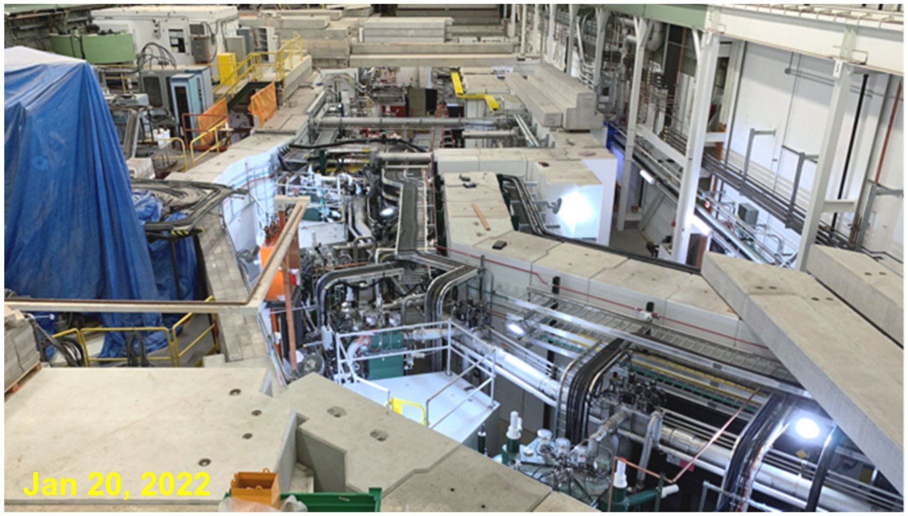


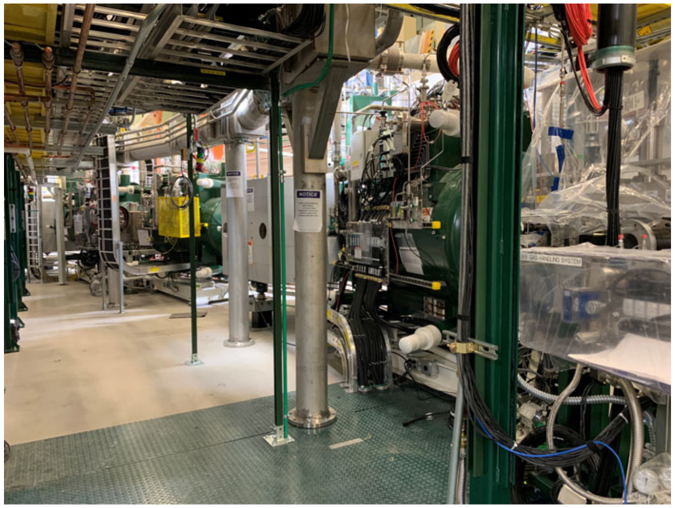
Vertical Preseparator



Fragment Separator Installed

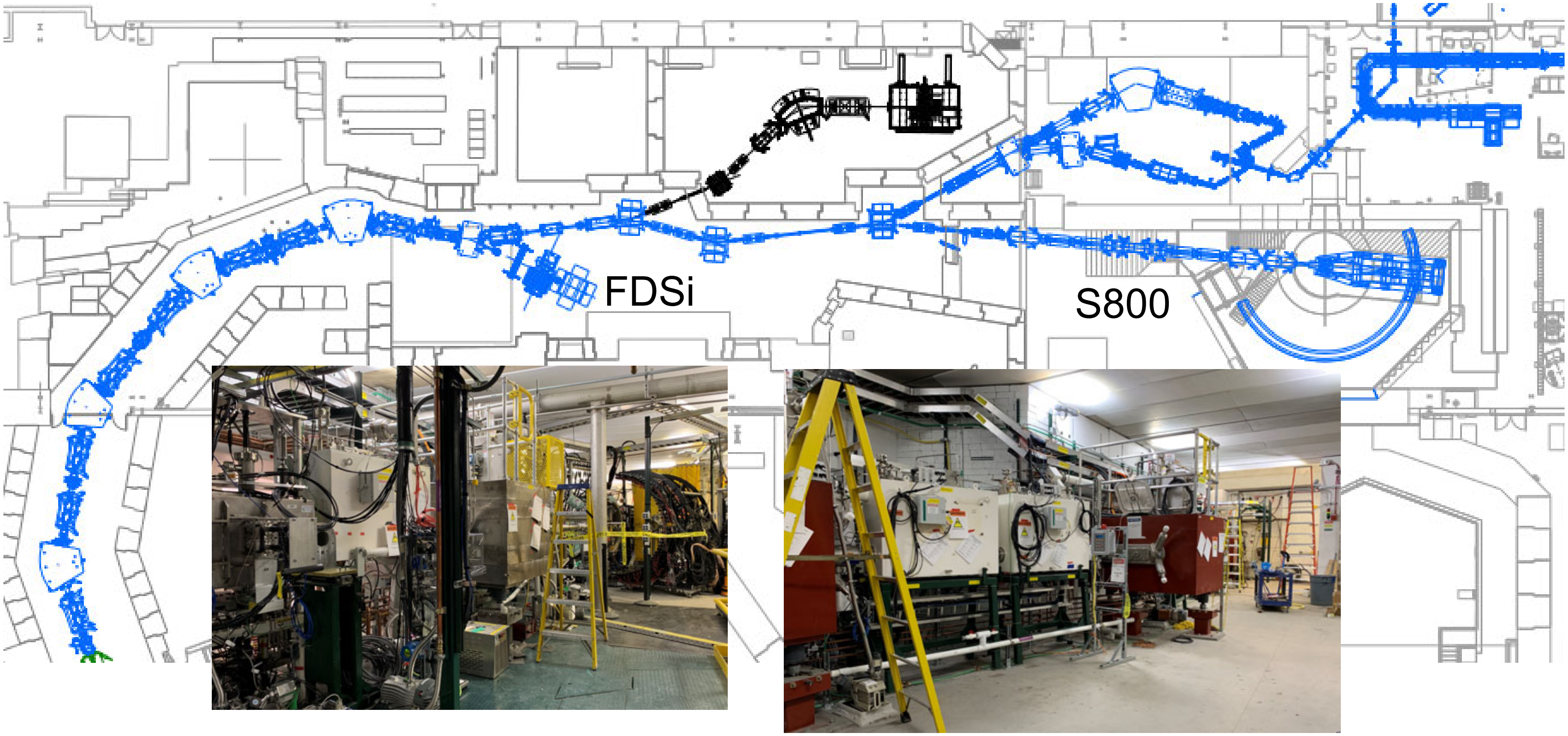

Jan 25, 2021


Jan 20, 2022



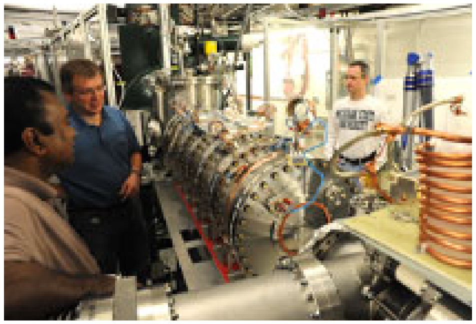
Beamlines Installed
Beamline to FDSi Being Commissioned

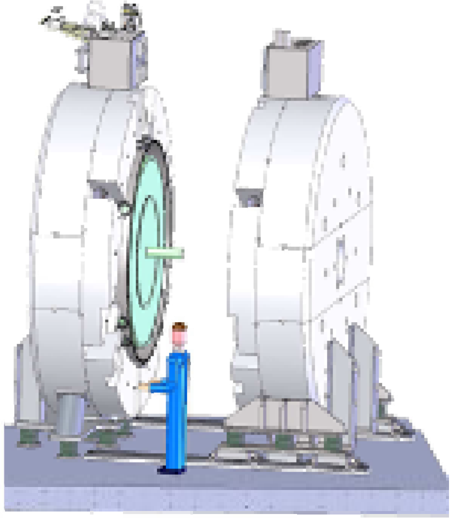
- Transport Beamlines to FDSi and S800 installed

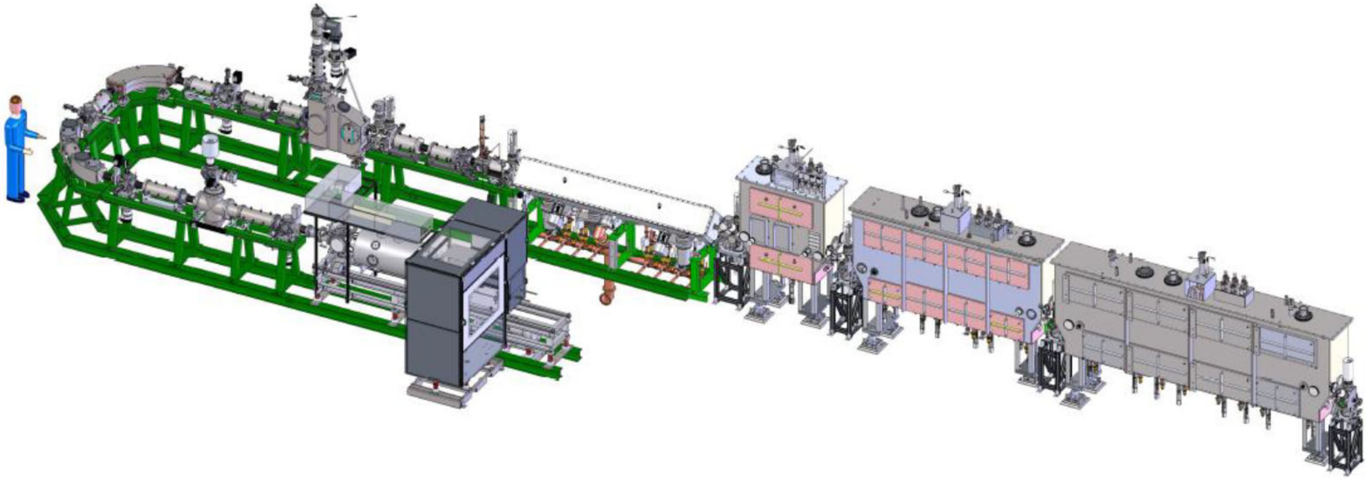


At the End of the Beamline

- “Fast” beam experiments use beam directly
  - Initial operation with S800 Spectrograph and “FDSi” decay station
- Stopped beams
  - Multifaceted approach including linear gas stoppers and cyclotron gas stopper
- Reaccelerator: ReA 3/6 (upgradeable to 12)
  - Reacceleration of stopped rare isotope beams to 3/6/12 MeV/u





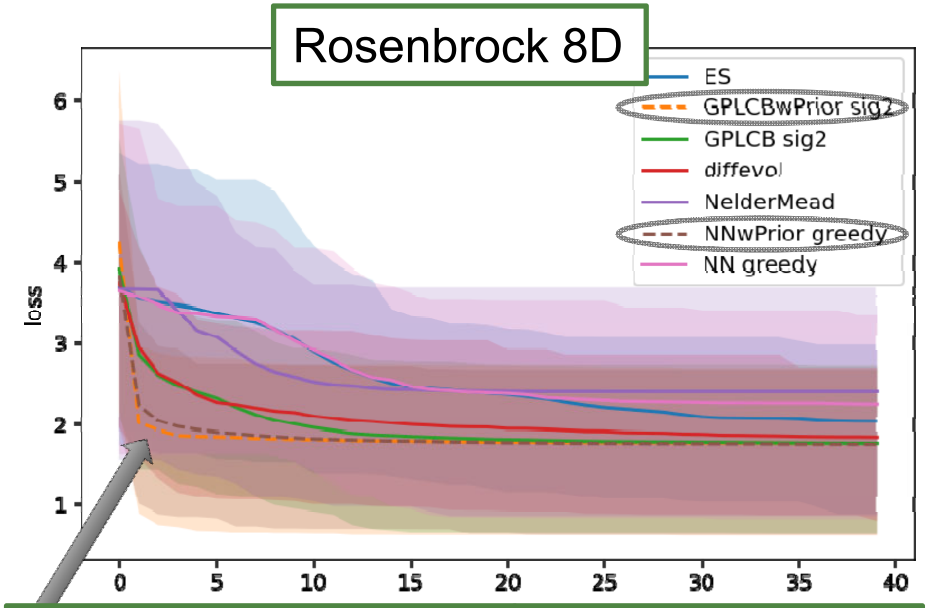


FRIB Status and Outlook

- FRIB project completed
  - First beam to end of fragment separator in January 2022
  - CD-4 review with DOE OPA in February 2022
    - Recommended CD-4
- First experiment scheduled in May 2022
  - Initial beam power 1 kW
- Plan to ramp up power to 400 kW by 2028

Machine Learning Example 1
Cold Restart Beam Tune Optimization

- Significant beam drift after cold start of the ion source requires retuning
- Developing machine learning (ML) algorithm to expedite tuning
  - Benchmarked optimization methods with 8D test function (4 decision parameters and 4 randomly chosen to represent uncontrollable environmental variables
- Used 20,000 randomly chosen 8D data to train model
- Resulted in near instant tuning in the model
- Application in real beamline in the future

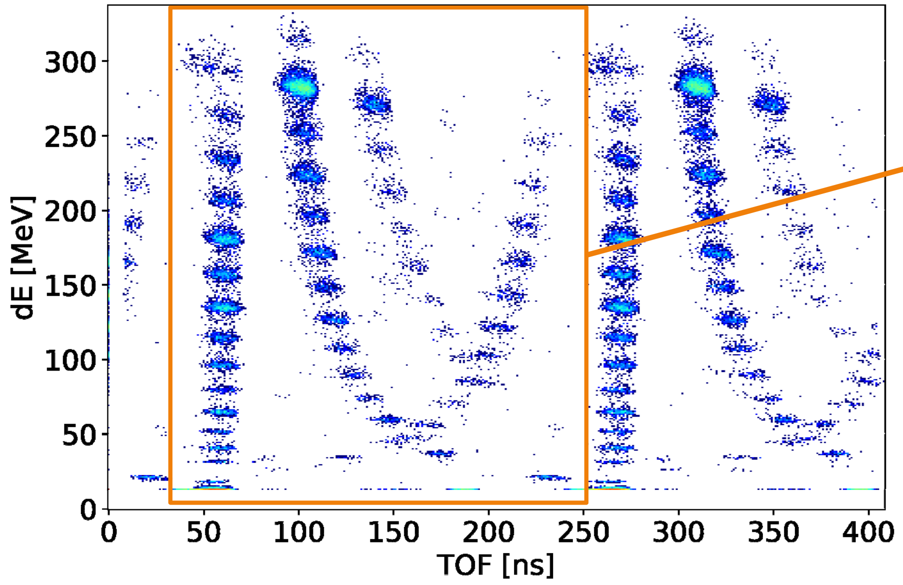


20,000 randomly chosen 8D data is used to train prior model

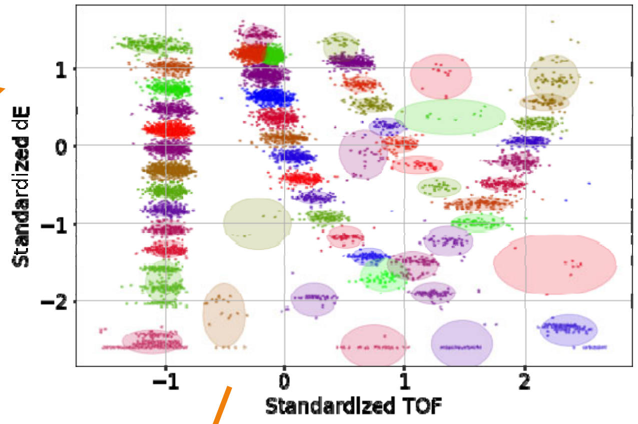
Machine Learning Example 2

Particle Identification

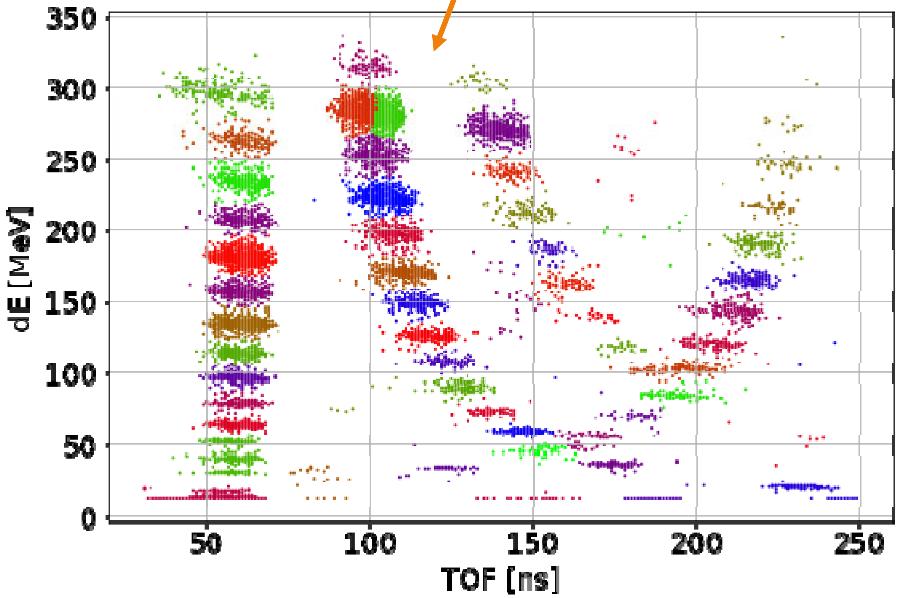
- Particle identification needed to deliver correct rare-isotope beam



Scaled and run through Bayesian Gaussian Mixture Model



Rescaled

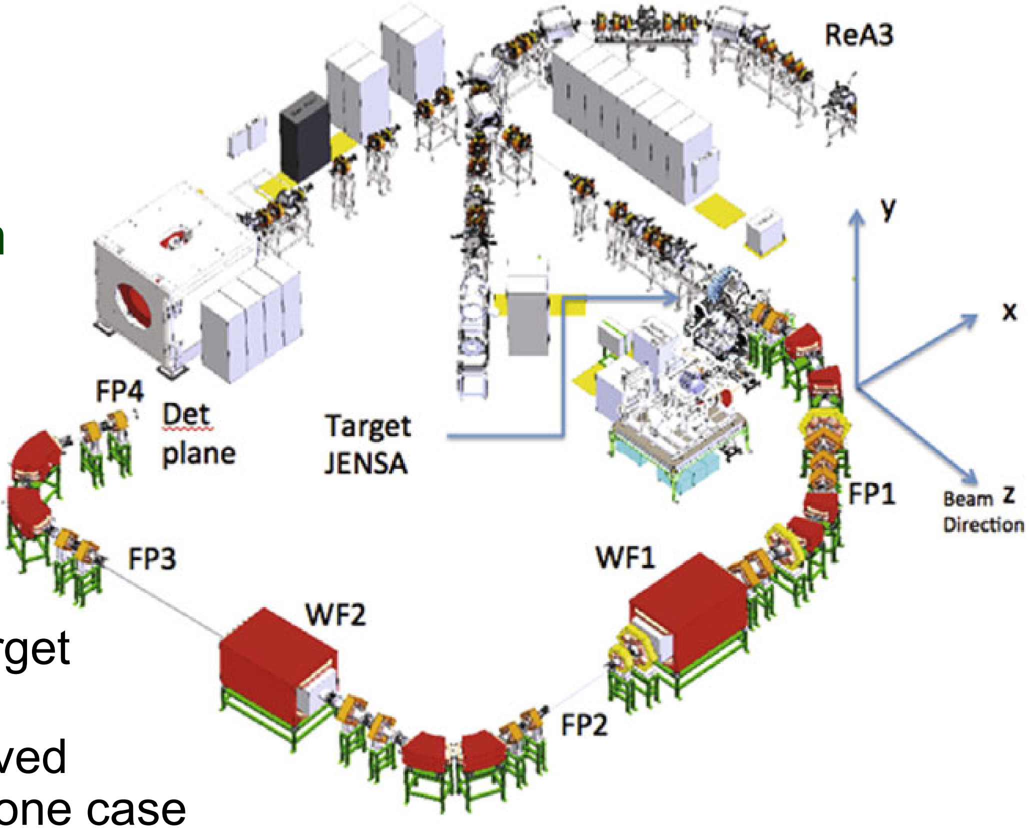


- First test of Bayesian Gaussian Mixture Model on measured particle-identification spectrum
- Many species isolated correctly
- Some issues with very high/low intensities require additional development

Machine Learning Example 3

Bayesian Optimization of Recoil Mass Separator

- S. A. Miskovich et al.: https://arxiv.org/pdf/2202.01978.pdf
- SEparator for Capture Reactions (SECAR)
- Suppression of unreacted beam by factor 10^{13} required
- Used Bayesian optimization with a Gaussian process to tune beam
  - Beam on target position and angle
  - Focusing/beam rejection
- No previous tunes used as training data
- First results
  - Successfully optimized beam on target faster than manual tune
  - Confirmed design optics and improved relevant beam spot size by 32% in one case



Thank You for Your Attention!