Materials issues in design, construction and operation of FRIB

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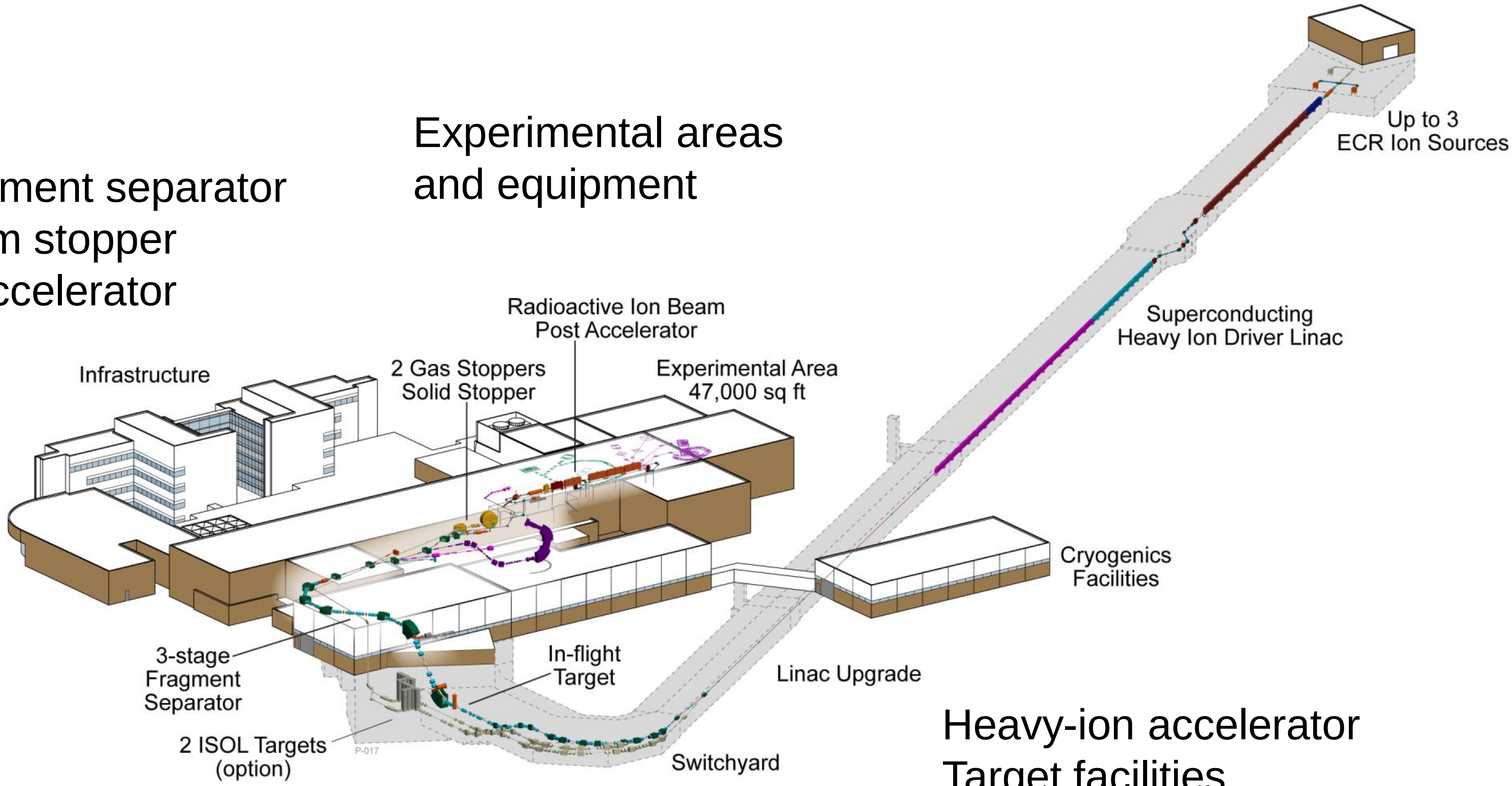
U.S. DEPARTMENT OF ENERGY
Office of Science

Facility for Rare Isotope Beams

World-leading next-generation rare isotope beam facility in the US

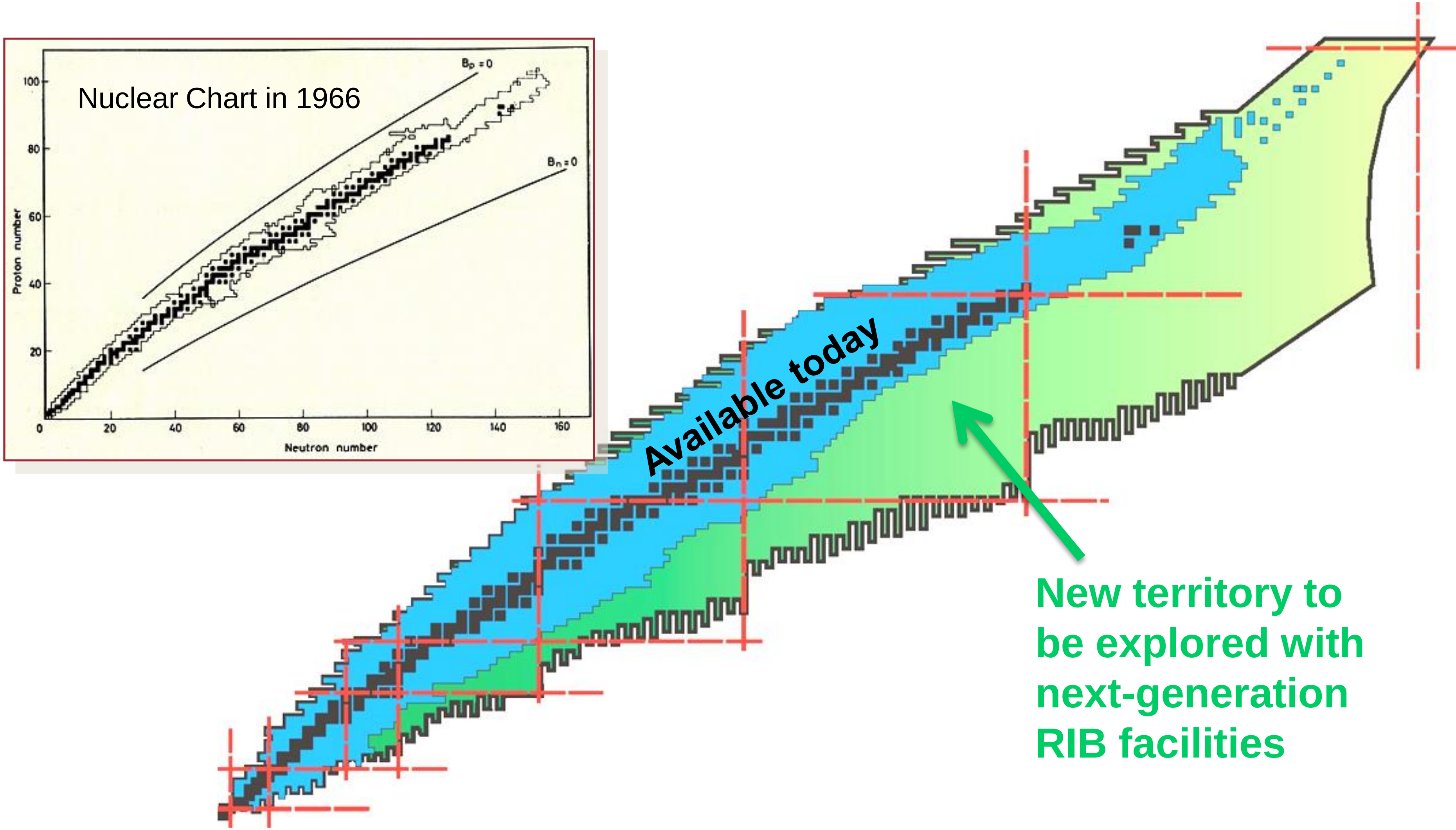
Experimental areas
and equipment

Fragment separator
Beam stopper
Reaccelerator



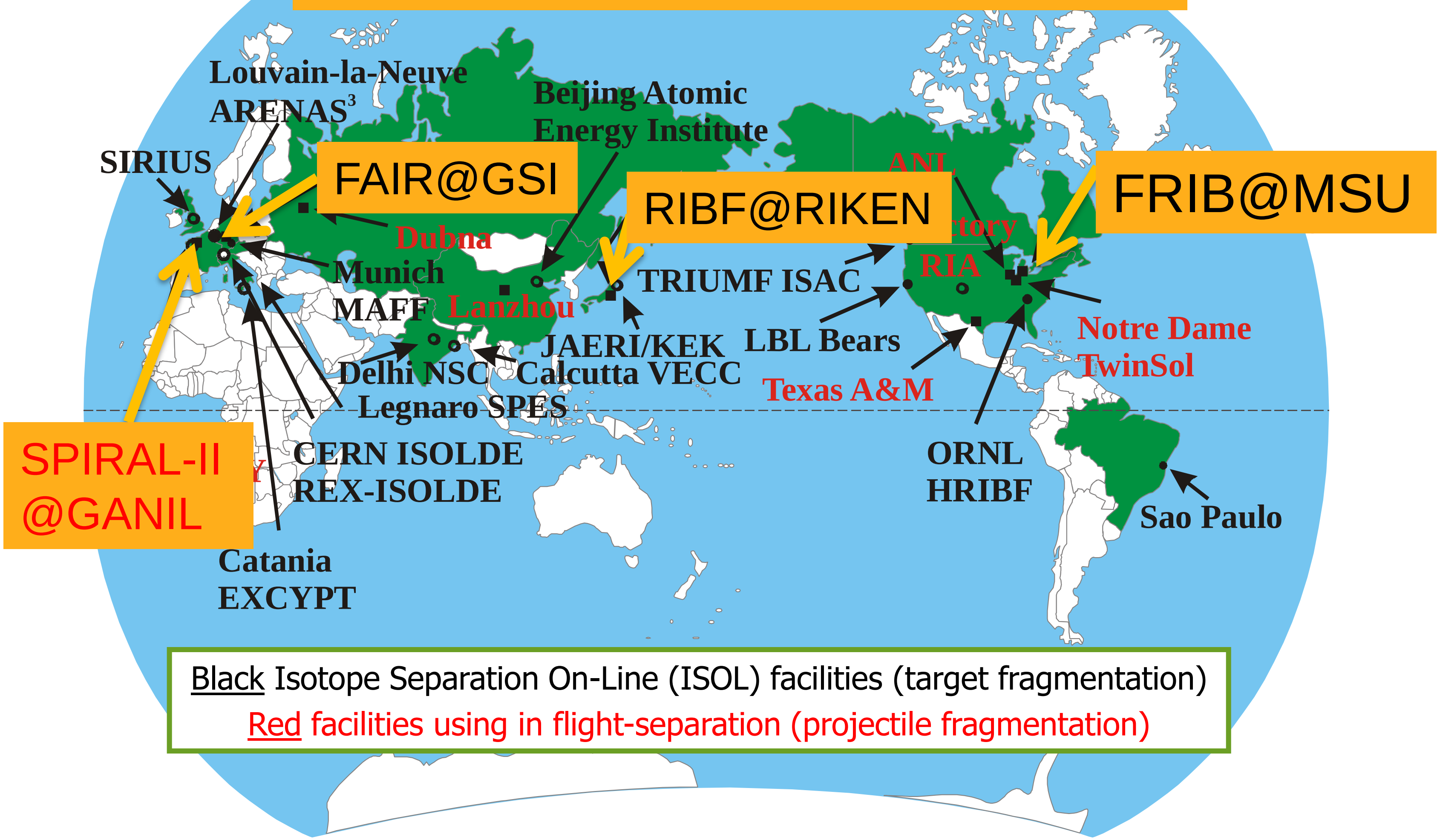
Heavy-ion accelerator
Target facilities

Need for Rare Isotopes



World Wide Effort in Rare Isotope Science

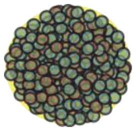
Next Generation RIB Facilities



<u>Black</u> Isotope Separation On-Line (ISOL) facilities (target fragmentation)

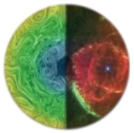
<u>Red</u> facilities using in flight-separation (projectile fragmentation)

Rare Isotope Science and Applications



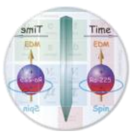
Properties of nucleonic matter

- Classical domain of nuclear science
- Many-body quantum problem: intellectual overlap to mesoscopic science – how to understand the world from simple building blocks



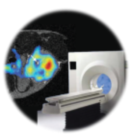
Nuclear processes in the universe

- Energy generation in stars, (explosive) nucleo-synthesis
- Properties of neutron stars, EOS of asymmetric nuclear matter



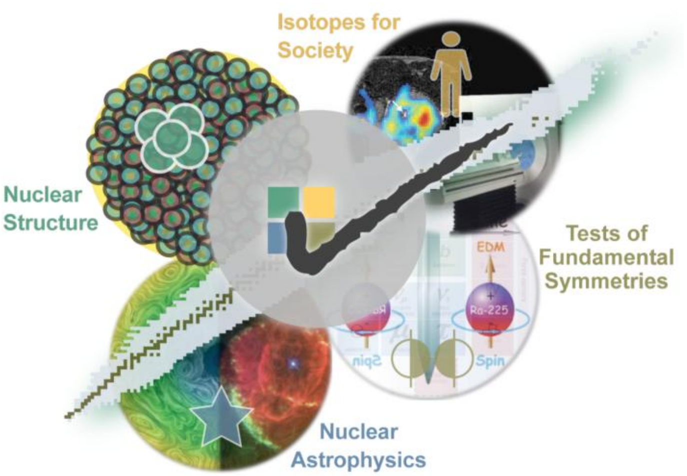
Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei



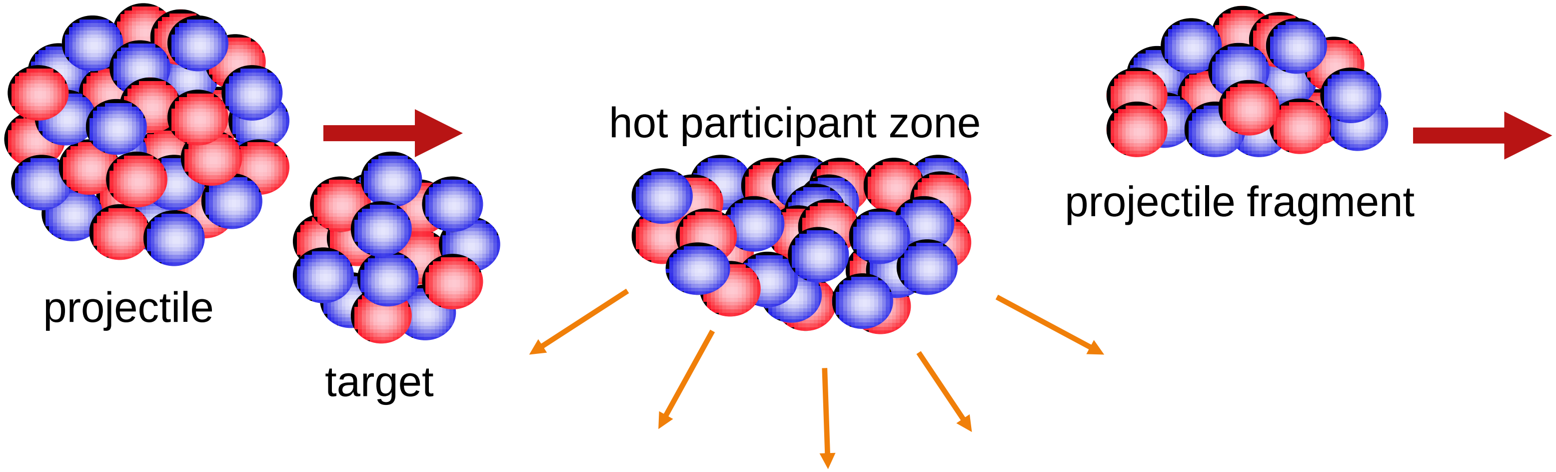
Societal applications and benefits

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

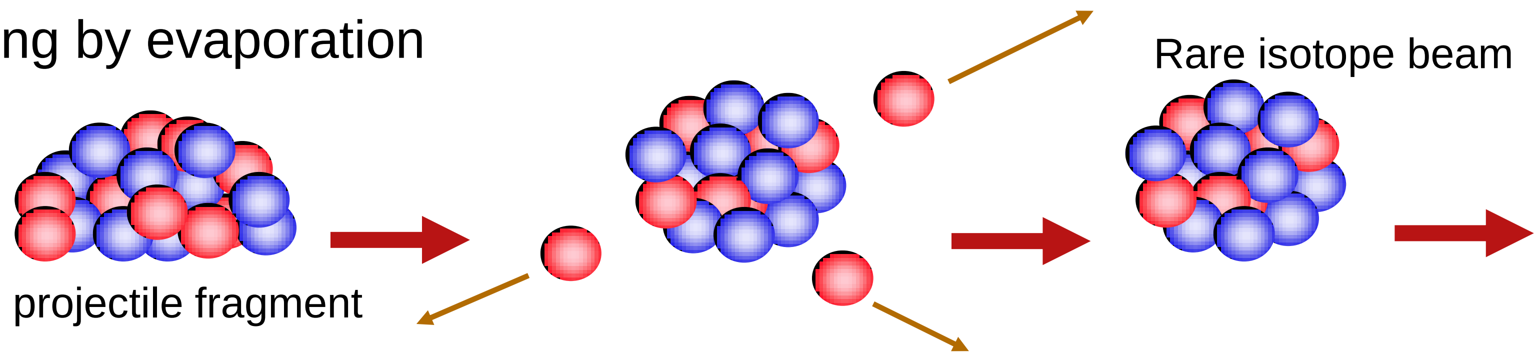


Production of Rare Isotopes af FRIB: In-flight Production

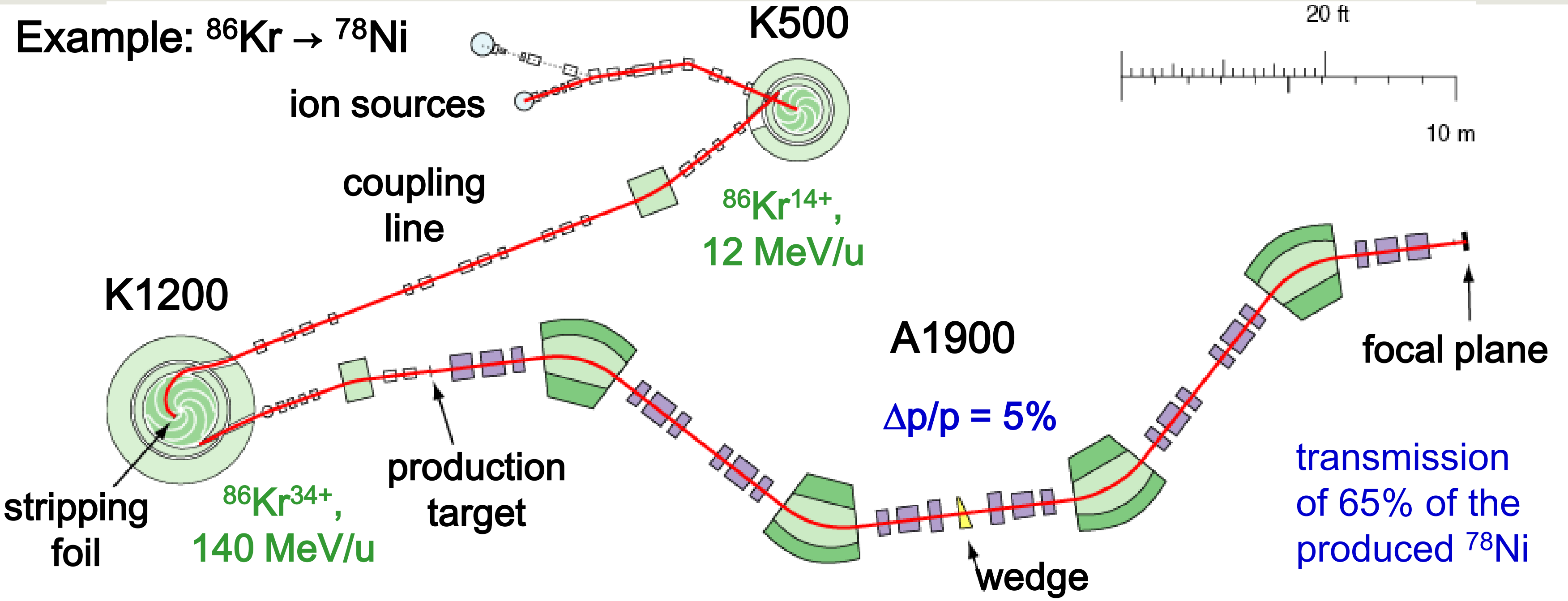
1. Accelerate heavy ion beam to high energy and pass through a thin target to achieve random removal of protons and neutrons in flight



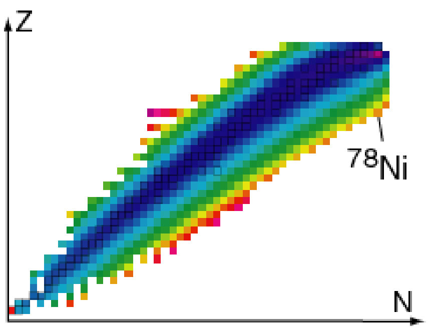
2. Cooling by evaporation



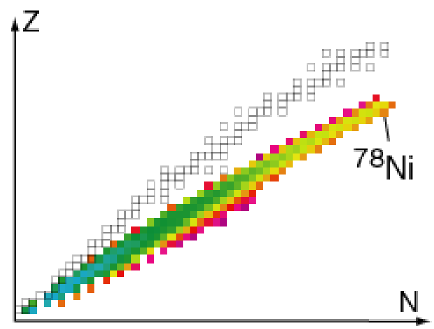
Example: In-Flight Production at NSCL



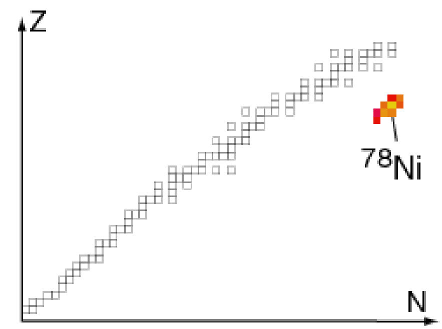
fragment yield after target



fragment yield after wedge



fragment yield at focal plane



FRIB - Historical Background

1999: ISOL Task Force Report – proposes Rare Isotope Accelerator (RIA) concept

2003: RIA ranks 3rd in DOE 20-year Science Facility Plan

2005: DOE cancels draft of RIA-RFP (request for proposal)

- Rare Isotope Science Assessment Committee (RISAC) of the Academies to assess science case for rare isotope beam facility

2006: DOE cancels RIA and pursues a lower cost option

- RISAC endorses construction of a facility for rare isotope beams (FRIB) based upon a 200 MeV driver-linac

2007: NSAC makes construction of FRIB the 2nd highest priority for nuclear science

2008: DOE issues a Financial Assistance Funding Opportunity Announcement (FOA) for FRIB and selects the MSU application following a merit review and evaluation process (Dec. 11)

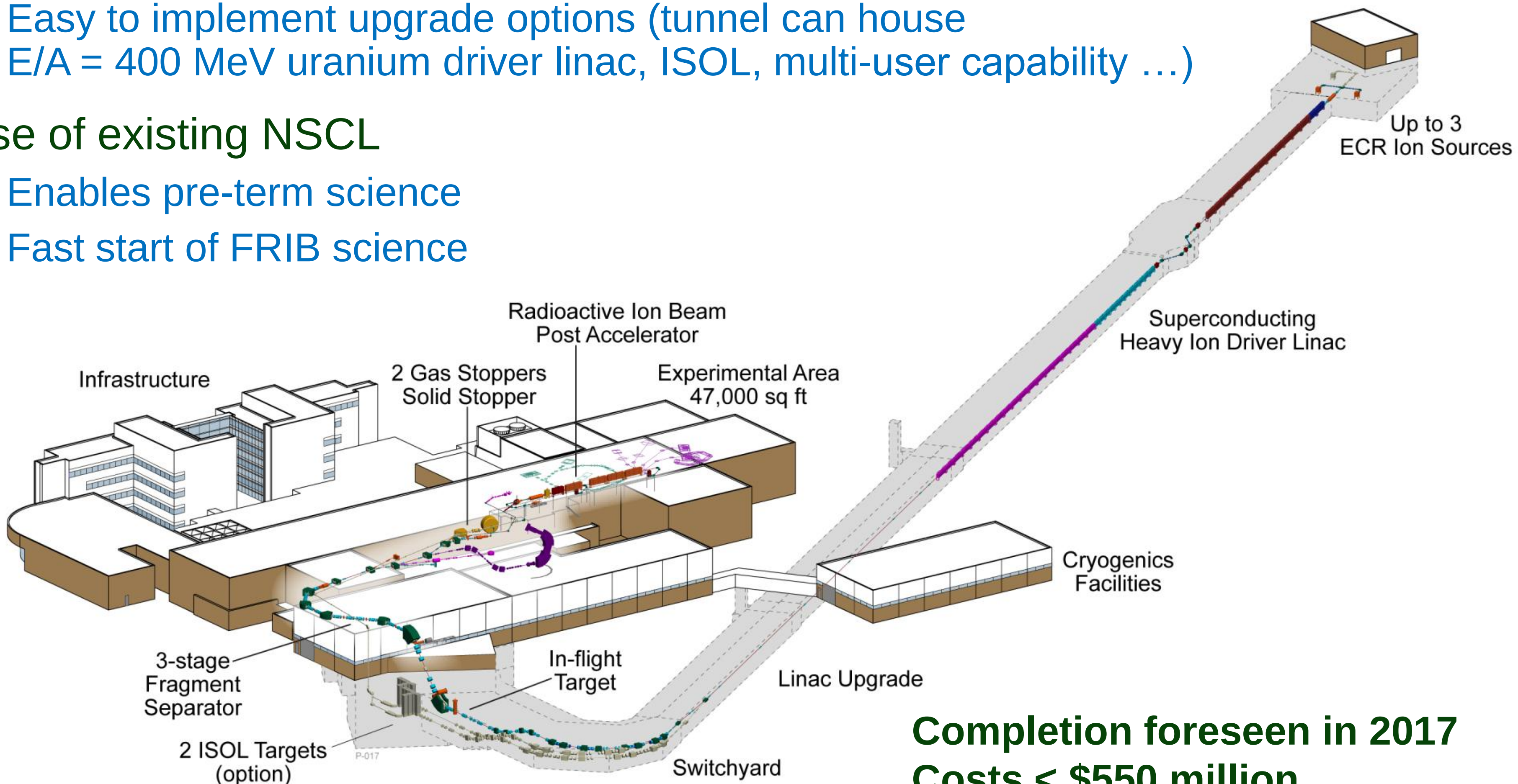
2009: Cooperative agreement between DOE and MSU to build FRIB

Specifications from DOE FRIB Funding Opportunity Announcement

- 200 MeV/u, 400 kW superconducting heavy-ion driver linac
- Initial capabilities should include fragmentation of fast heavy-ion beams combined with gas stopping and reacceleration
- Capable of world-class scientific research program at start of operation
- Accommodate 100 users at a time, 400-500 per year
- Designed, built and commissioned for a total project cost of $\leq$ 550 M$

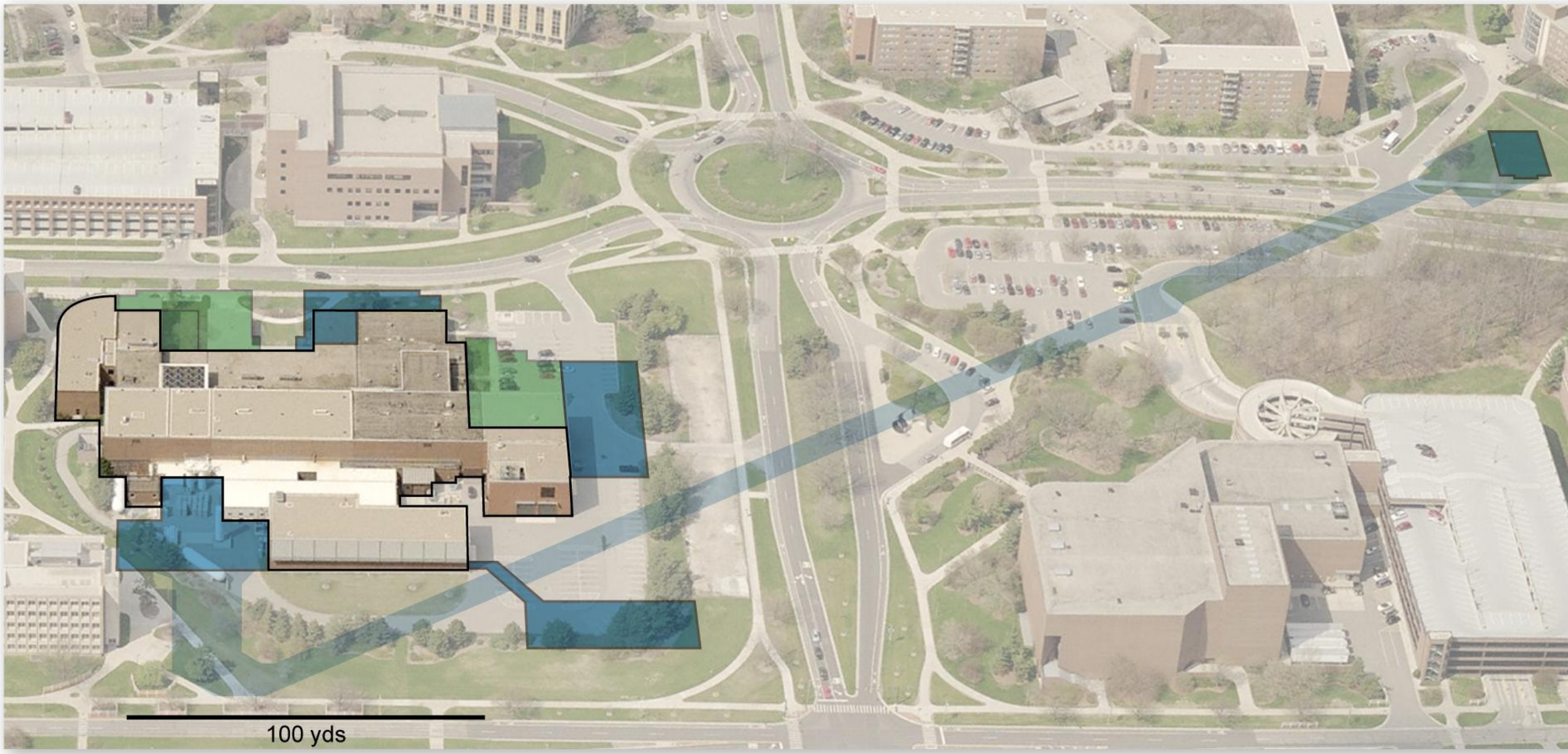
MSU-Proposed FRIB

- Driver linac with E/A ≥ 200 MeV for all ions, P_{beam} ≥ 400 kW
  - Easy to implement upgrade options (tunnel can house E/A = 400 MeV uranium driver linac, ISOL, multi-user capability …)
- Use of existing NSCL
  - Enables pre-term science
  - Fast start of FRIB science



Completion foreseen in 2017
Costs < $550 million

FRIB Location on the MSU Campus



P-010b

Challenges

FRIB will have the highest-power heavy ion accelerator in the world: 400 kW, 200 MeV/u uranium, higher energies for lighter beams

- High power density in matter
  - Primary heavy ion beam interacts with material in targets, beam dumps, etc.
  - Deposited power densities up to 100 MW/cm^3
  - Which materials are suitable?
- High radiation fields
  - Radiation damage of materials due to secondary particles (protons, neutrons)
    - Damage quite well-known, can be calculated
  - Radiation damage of material due to primary heavy ion beam
    - Radiation damage due to heavy-ion matter interaction not well known, uncertain model predictions in relevant energy regime
  - Which materials are suitable? Path forward to better data and improved models?
- High rare isotope beam rates
  - High beam rates are key to new science
  - Detector systems needed that are radiation tolerant and fast – new materials?
  - Fast solid catcher systems for low-energy beam production – what are the best materials?

Superconducting RF Driver LINAC

400 kW, 200 MeV/u uranium, 610 MeV protons

Venus (LBNL) type ECR ion sources + LEBT+ RFQ-Linac

<u>SRF LINAC:</u>

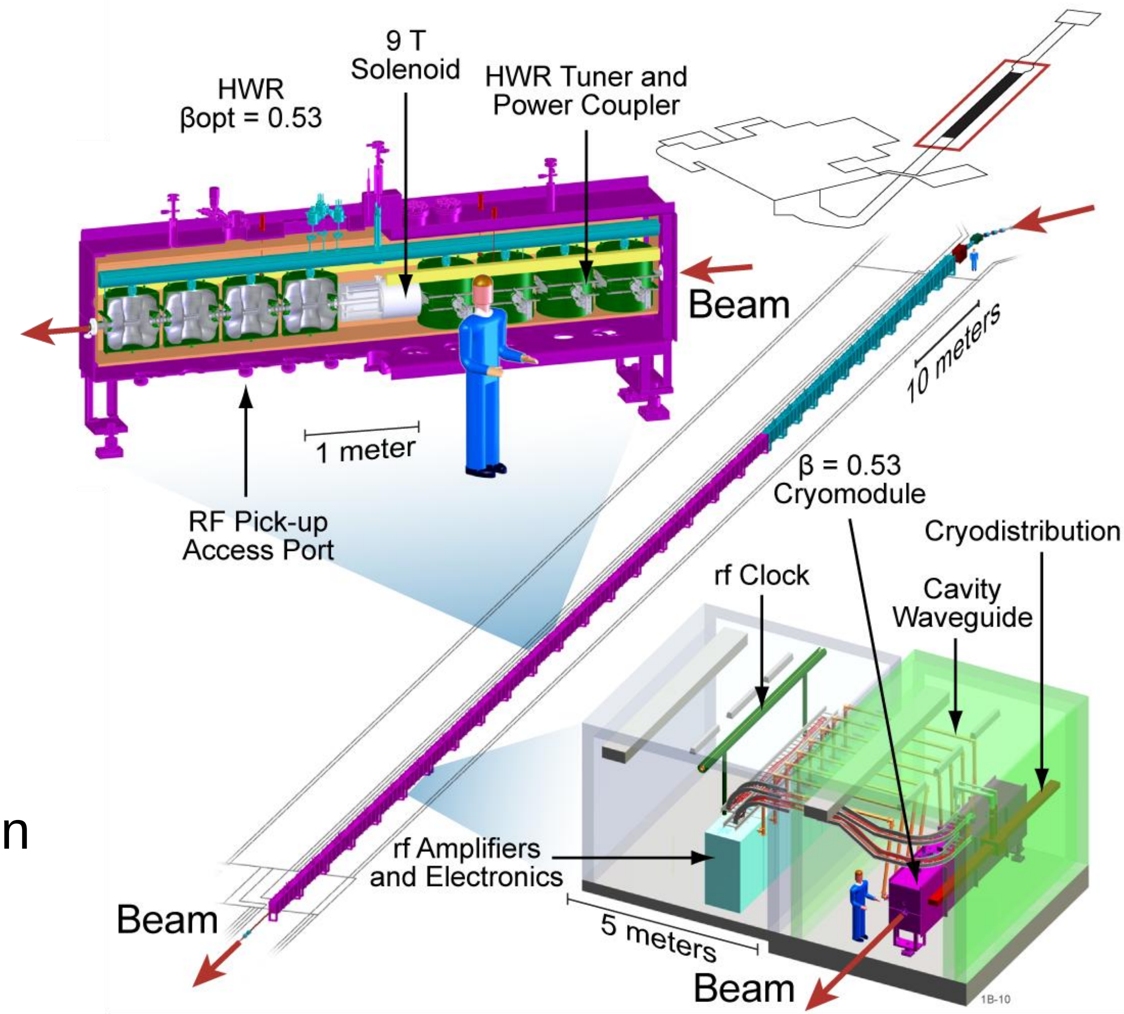
Two types of quarter-wave Resonators (QWRs) at 80.5 MHz

One stripping station

Two types of Half-wave Resonators (HWRs) at 322 MHz

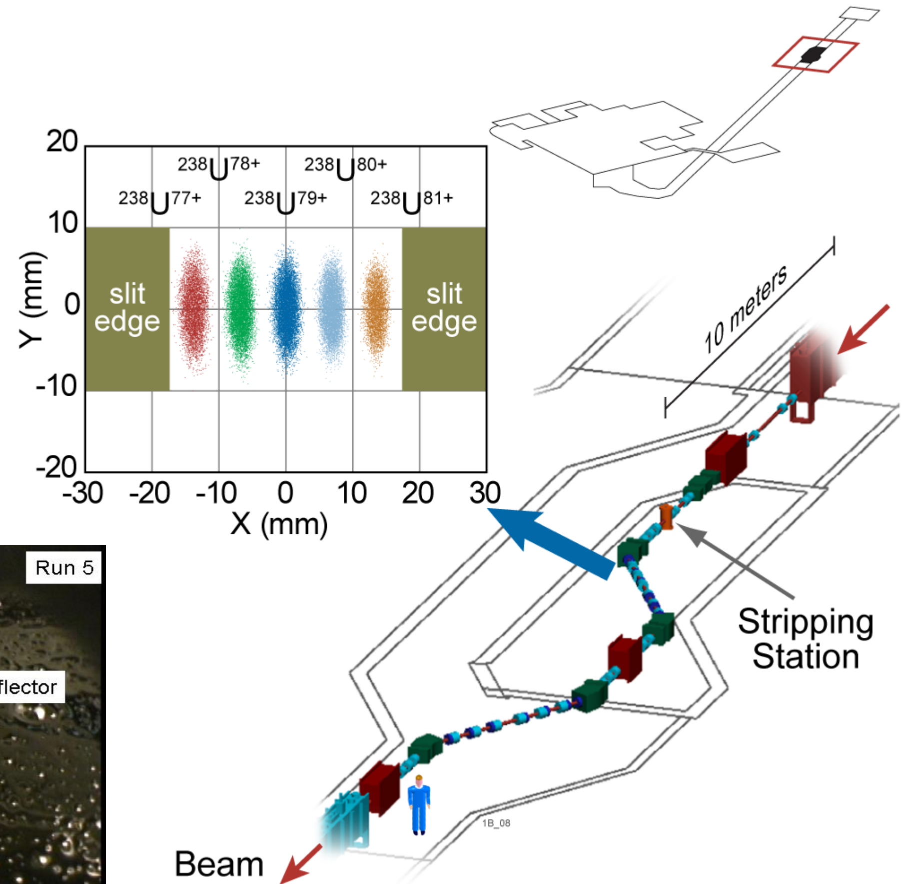
Multi-charge state acceleration

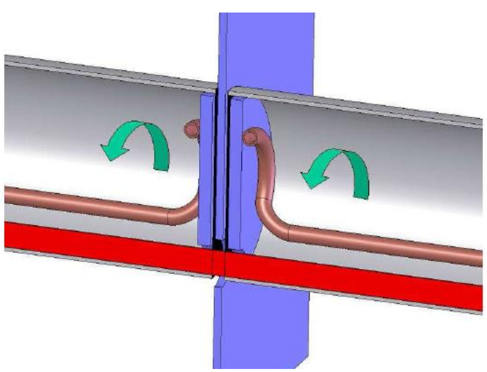
Upgradable to 400 MeV/u



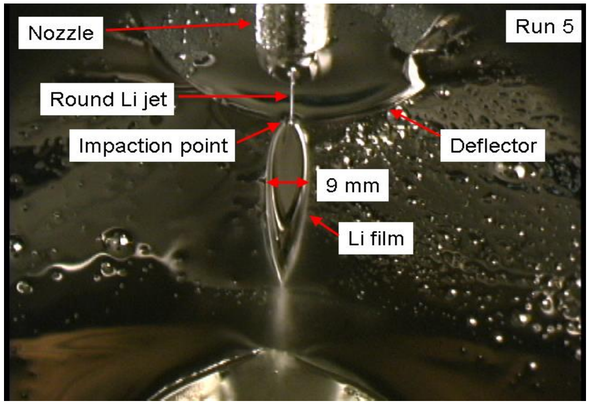
Material Issues Beam Stripper

- Increase the charge state of the ions being accelerated
  → reduced total voltage installed in the accelerator
  → reduced cost
- A thin media is inserted in the beam





Solid carbon stripper

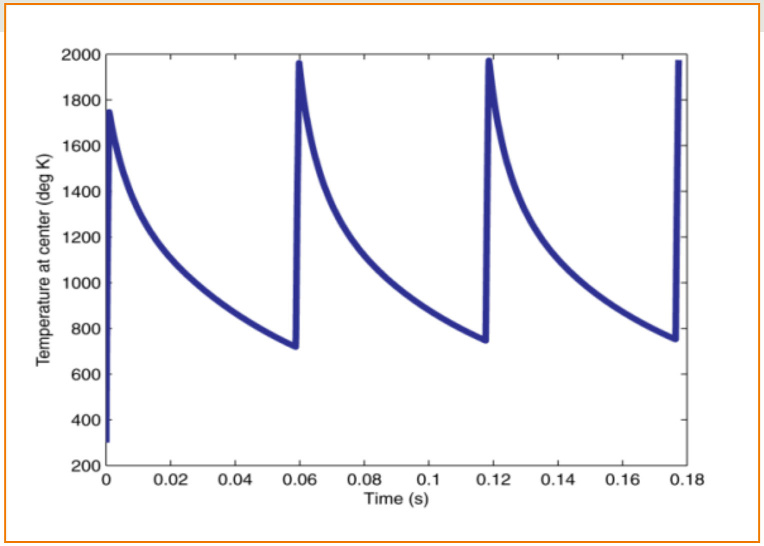


Li thin film

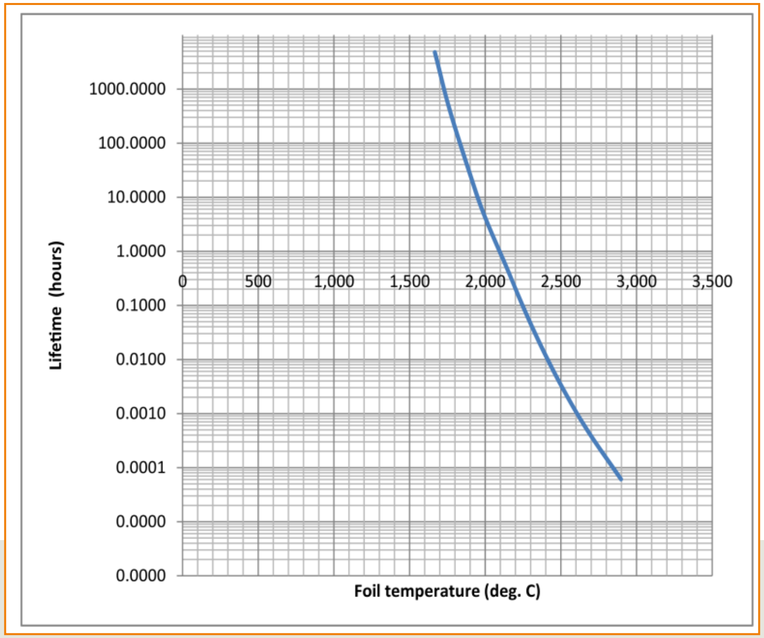
R&D: F. Marti (MSU), J. Nolen (ANL)

Why is it challenging to use carbon foils?

- Power density
  - Uranium beam power at stripper energy (17.5 MeV/u) is ~ 50 kW
  - Carbon foil equilibrium thickness is ~ 500 μg/cm^2 (2.2 μm thick)
  - Power deposited on the stripper foil ~ 660 W
  - For 5 mm diameter beam power density ~ 3.8 kW/mm^3
  - 100 mm radius, 2000 rpm, T>2000K , ΔT>400K



- Thermal and mechanical issues
  - Sublimation
  - Thermal stress
  - Foils tend to get thinner for heavy ions
  - The typical failure modes are foil thinning (energy changes) and foil tearing

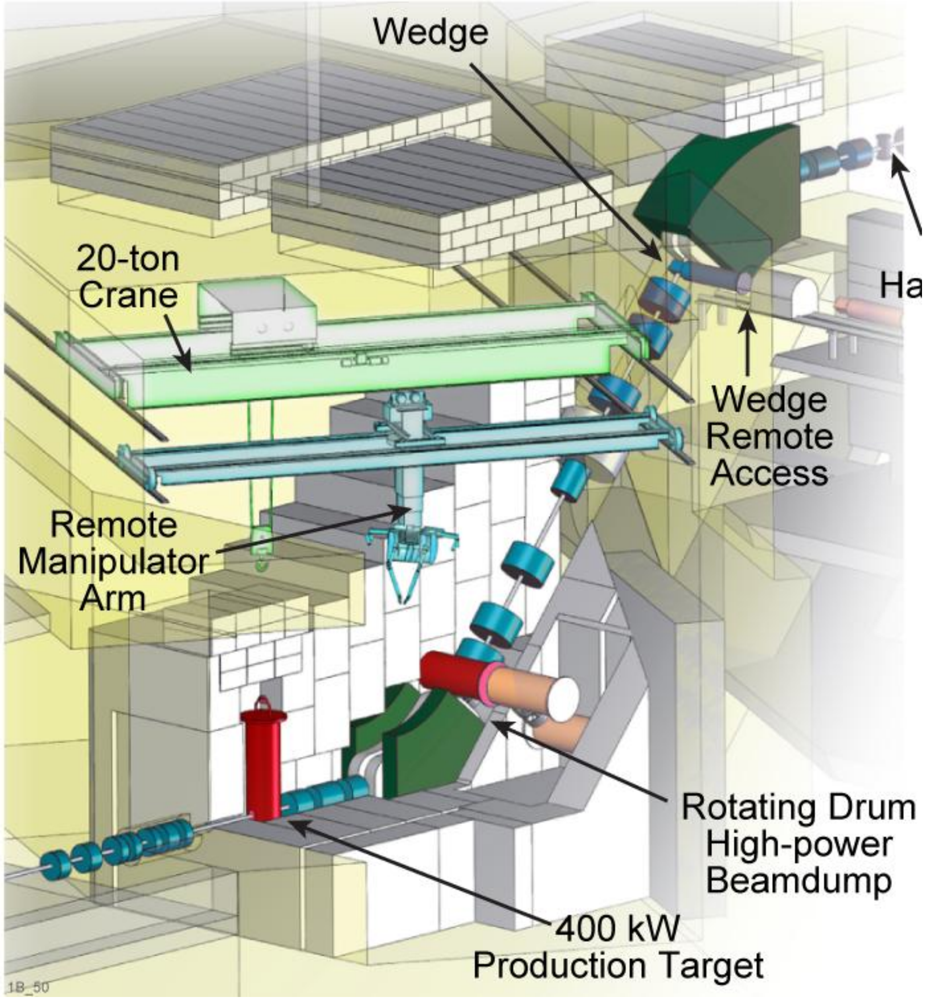


- Radiation damage
  - Deformation of lattice causes internal pressure in the foil

Production Target Facilities and Separator

- Self-contained target building
- State-of-the-art full remote-handling to maximize efficiency
- Target applicable to light and heavy beams (about 1/3 of power lost in target)
  - Rotating solid graphite target foreseen
  - Liquid-Li target (optional) for use with uranium beams
- Beam dump for unreacted primary beam for up to 400 kW beam power

High-power density, high radiation issues

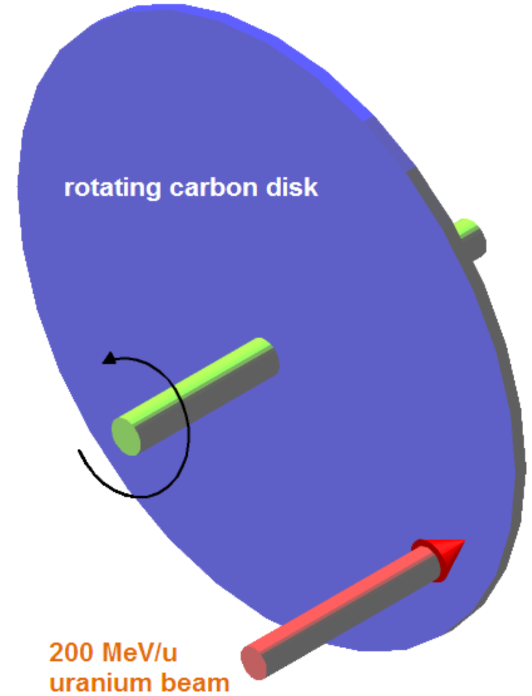


Rare Isotope Production Target

- High reliability - long lifetime
- Ideally one single target concept for all beams
- Beam power 400 kW at 200 MeV/u
- 200 kW in a ~ 0.6 - 8 g/cm^2 target
- 1 mm diameter beam-spot
  - max extension in beam direction ~ 50 mm
- Very high power density: ~ 20 - 60 MW/cm^3

Two solutions will be evaluated

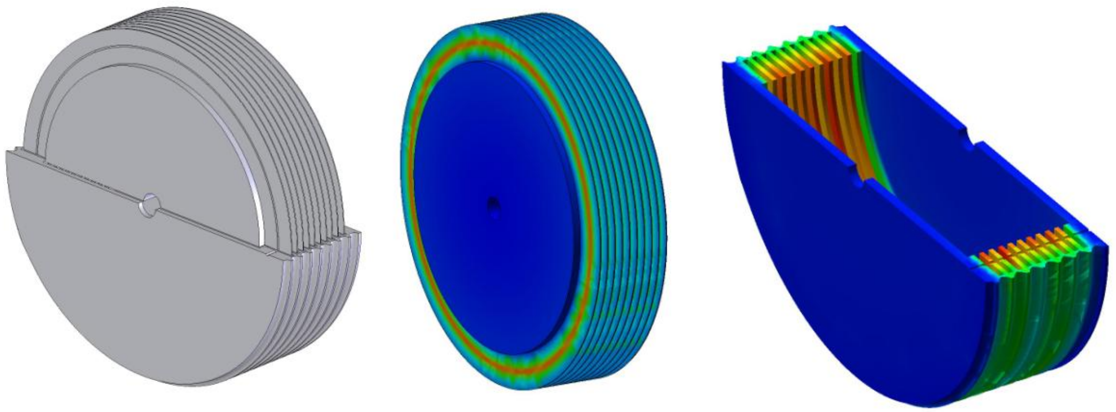
- PRIMARY
  - Production target using carbon-based material
- SECONDARY
  - Liquid Lithium Production Target
    (not suitable for light beams due to low density)

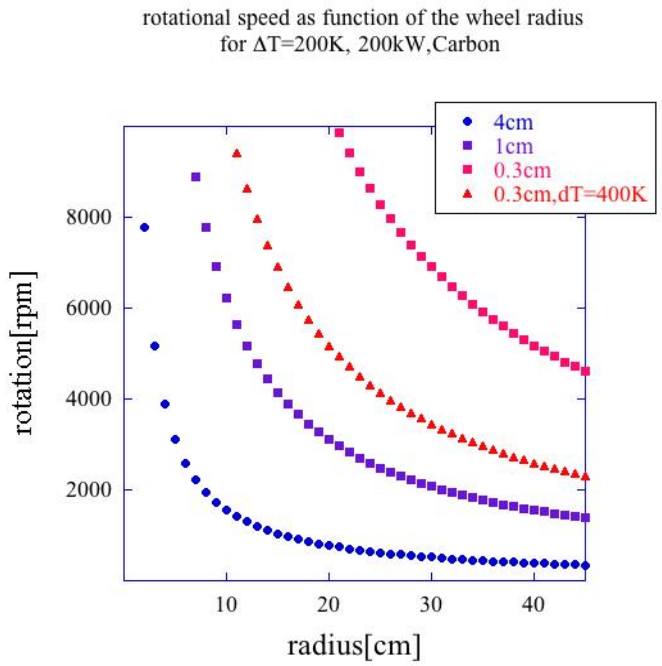


R&D: W. Mittig (MSU)

Radiation-Cooled Multi-Slice Target

- Multi-slice target for increased radiation area
- Example: 200 kW, beam radius 1 mm, 10 slices of 1 mm thickness, spacing 5 mm, wheel diameter 20 cm, 8000 rpm





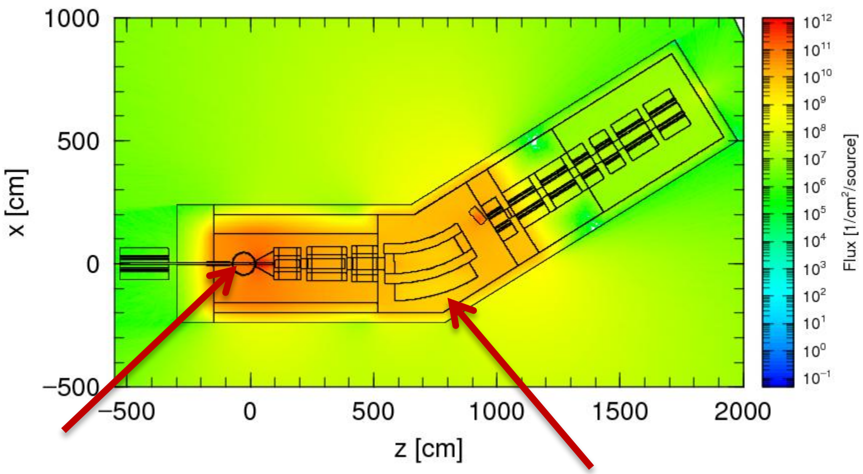
Material issues
•Thermal stress and mechanical integrity
•Radiation damage

Radiation Resistant Magnets

- Options
  - Radiation resistant magnets and metal-oxide Cable-In-Conduit-Conductor (CICC) NbTi
  - Radiation resistant magnets using High Temperature Superconductors (HTS) YBCO

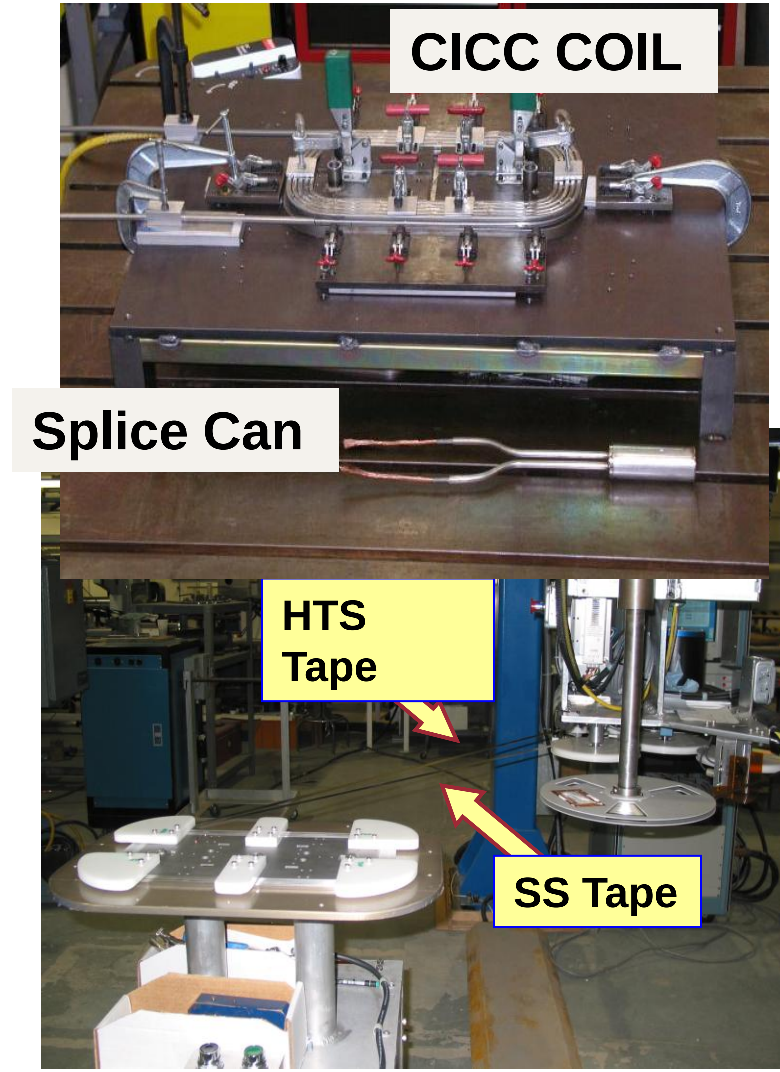
Neutron fluence on first quad:

2.5 x10^{15} n/cm^2 per year (1 MGy/yr) at 400 kW



Target

Dipole

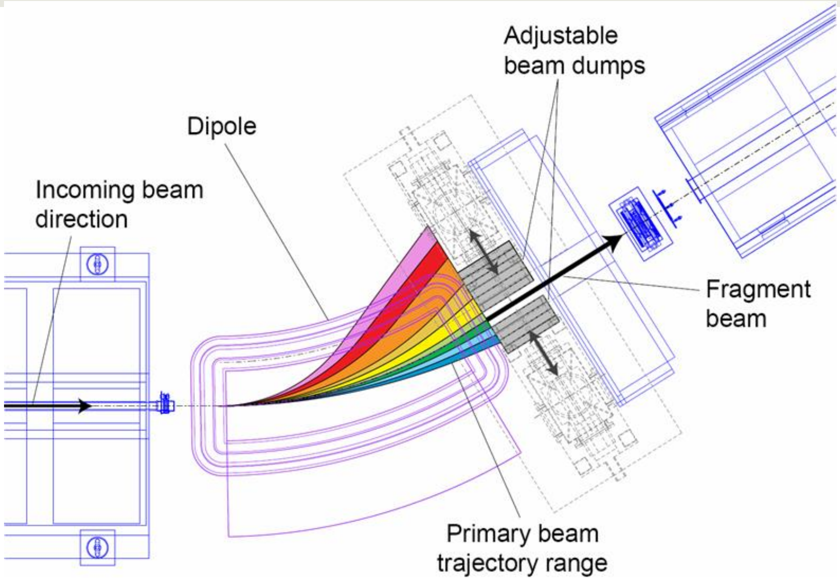


HTS Materials Issues

High Temperature Superconductors (HTS) need to operate in high radiation environments

- Only a few irradiation studies
  - High-energy protons => actual damage in target area from neutrons
  - Comparing protons to neutrons not easy
  - Irradiations done at room temperature
- Assumptions made:
  - Materials behave like Nb_3Sn => no annealing of damage at room temp.
  - If materials behave like NbTi => much annealing at room temp
    - » This leads to overestimation of radiation resistance and problems
- Displacements per atom (dpa)
  - Would be useful for comparing different irradiation systems, if we knew what it meant.
    - » Dpa calculated independent of temperature => annealing ignored
    - » Is there a way to use it?

Beam dump – stopping the primary beam



Requirements

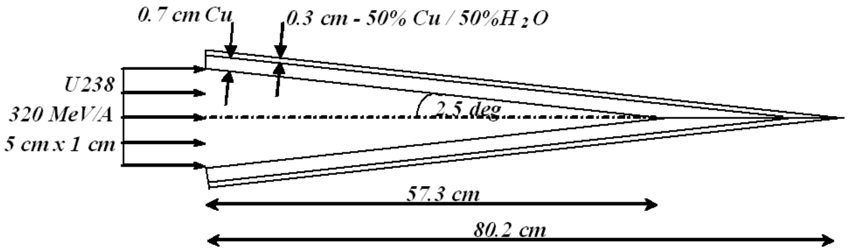
- High power capability
  - Absorb up to 400 kW
- Long-lived or rapidly replaceable
  - >>1 year desirable
  - Remote-handling capable
- Adjustable position

Material issues

- High-power density
- Radiation damage

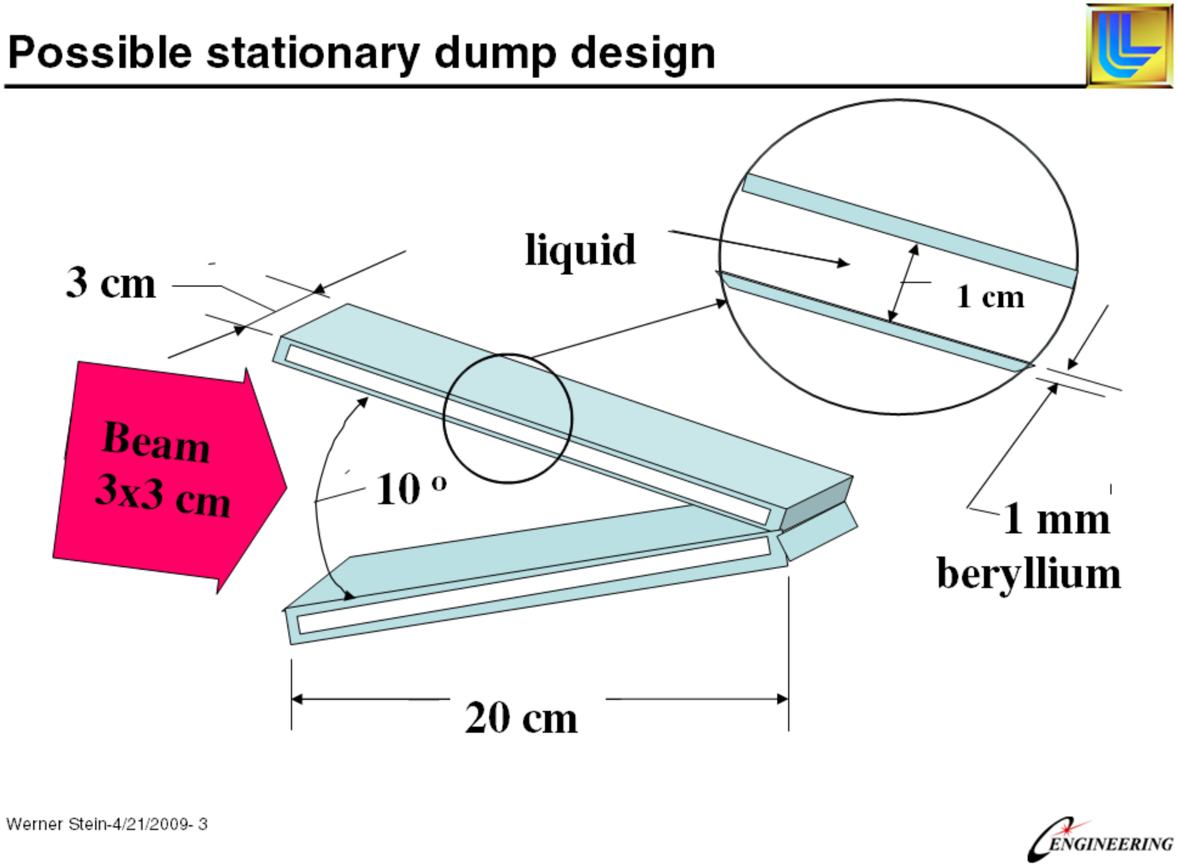
Example: Copper dump (water cooled):
Lifetime due to radiation damage
<<1 month at 400 kW

The fragmentation line beam dump model consists of two intersecting slabs.



Previous R&D studies

- Al or Be-window stationary liquid-cooled dump
  - Lifetime due to radiation damage ~ 3 months at 400 kW

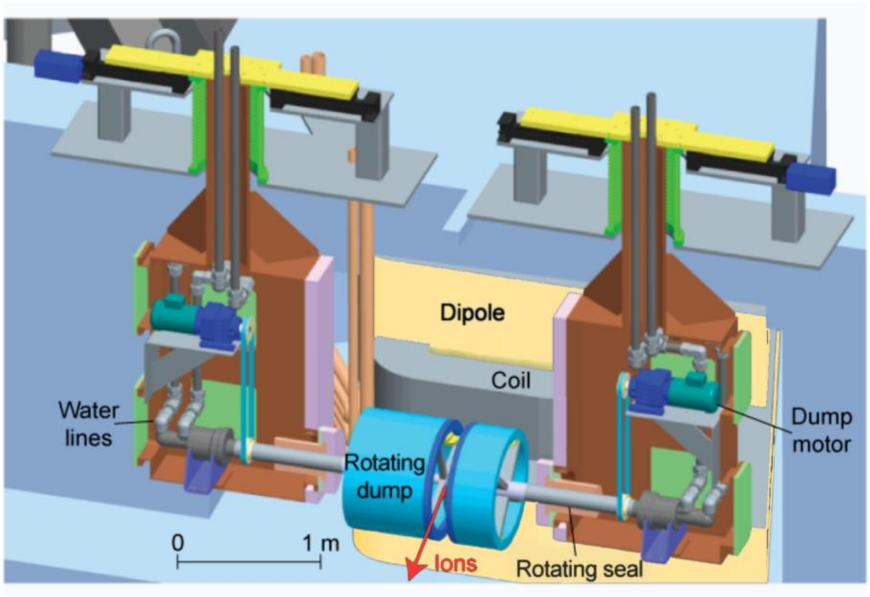


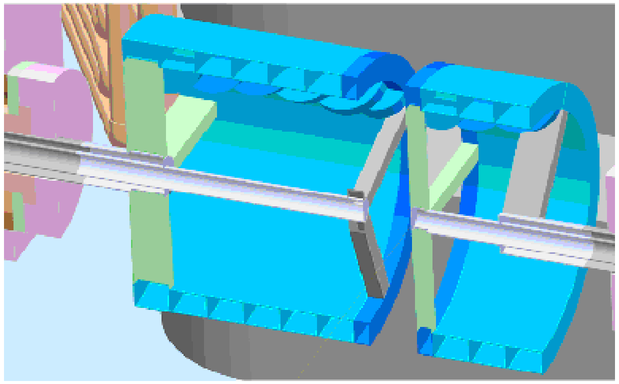
Promising Concept

Rotating water-filled aluminum cylinder dump

- Beam stops in water, not in Al of shell
- Rotating shell- reduced thermal and radiation damage issues
- Simple models used to assess lifetime, thermal properties
  - Indicate lifetimes of years for drum (< 1 dpa/y, 5 dpa limit)
  - Indicate 400 KW power capability (400 - 600 rpm, 240 gpm water flow)

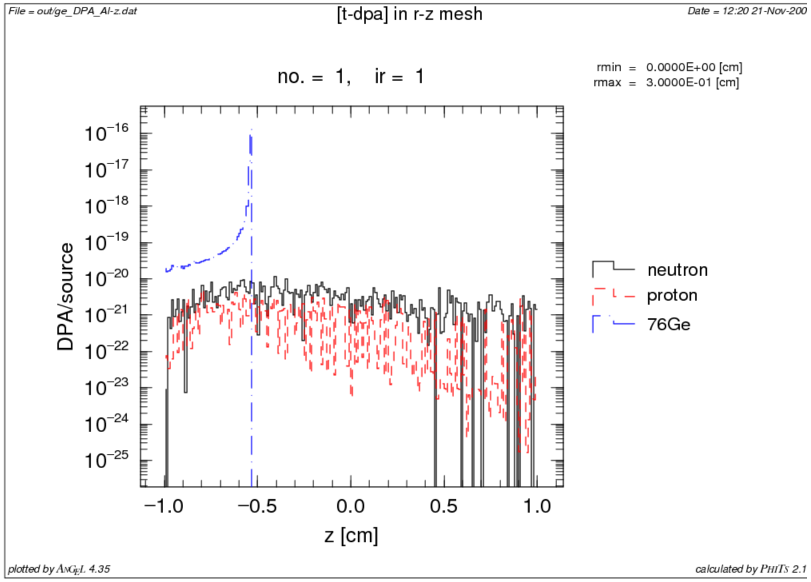
- Alternative coolants? Gallium, tin? Understand material compatibility.



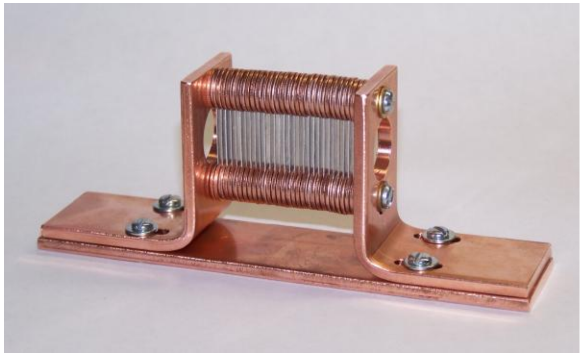


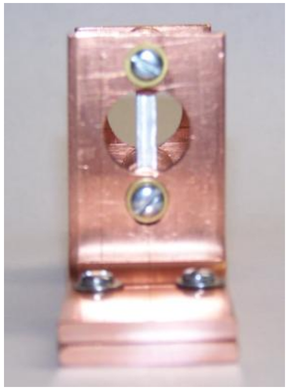
Radiation Damage Experiment at NSCL/ORNL

- Present radiation transport codes:
  - Poor predictions of radiation damage for heavy ions.
  - Only nuclear elastic and inelastic collisions contribute to the atomic displacement.
  - No contribution from electro-magnetic processes. Latter could explain increased damage in case of fast heavy ions: Swift Heavy Ion Effect (SHI)



- Goal of experiment: determine role of SHI Effect.
  - ^{76}Ge at 130 MeV/nucleon on stack of aluminum foils (NSCL)
  - Material Analysis: Electric resistivity, Vicker's Hardness, TEM (ORNL)
  - Results not conclusive. Next: water-cooled target for higher doses.



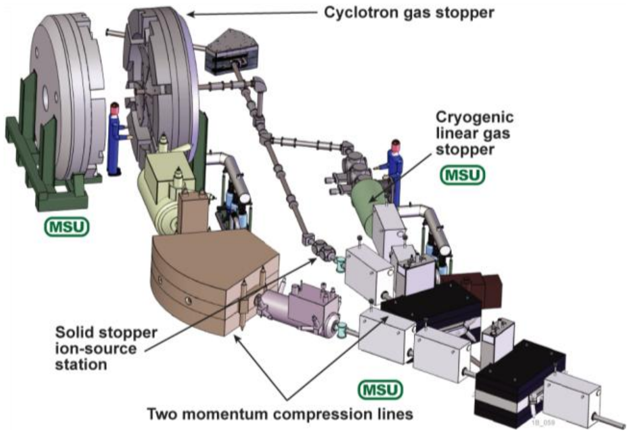


M. Kostin (MSU)

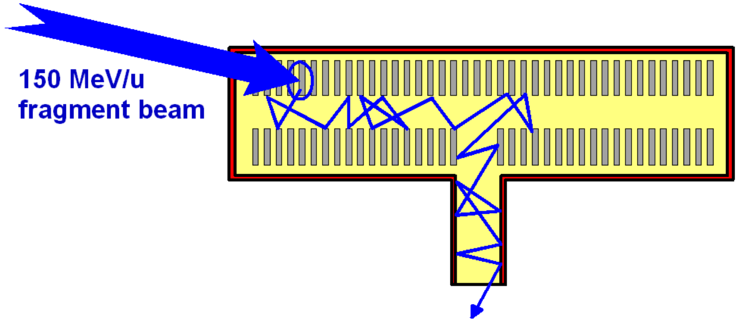
Beam Stopping

Beams for precision experiments at very low-energies or at rest

Penning trap mass measurements, laser spectroscopy
+ reacceleration of rare isotopes



- Cyclotron gas stopper
  - Best for light and medium heavy isotopes
- Cryogenic linear gas stopper
  - Best for heavy isotopes
- **Solid stopper**
  - For special elements and very high beam rates
  - Example: ^{15}O, I >10^{10}/s

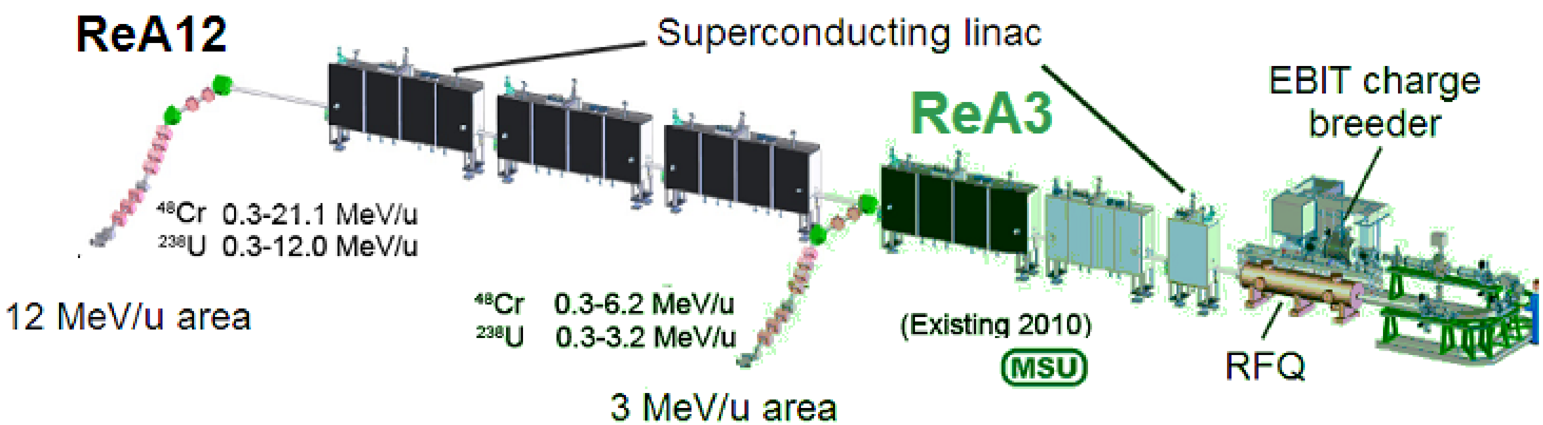


Suitable materials:

- Molecule formation desired or not (example $^{12}C^{14}O$, $^{12}C^{14}O_2$)
- High temperature for fast release
- Problems similar to those for ISOL beam production

Reacceleration

Reaccelerated beams of rare isotopes from projectile fragmentation



ReA3 is under construction

Advanced n+ reaccelerator with EBIT charge breeder

– High-intensity EBIT as $1^+ \rightarrow n^+$ charge breeder

– Modern linear accelerator – RT RFQ+ SRF linac

  » Energies 0.3-3 MeV/u and 0.3-12 MeV/u uranium

  » Higher energies for lighter ions

Detector systems

- Detector systems are needed for beam diagnostics and experiments. Desired properties: Radiation resistant, fast, high beam rate capability, and others.
- FRIB challenge are orders of magnitude higher beam rates compared to existing facilities

Example: NSCL beam monitor (NSCL is a 1-4 kW facility, FRIB 400 kW)

new camera

after 9 months use

radiation estimate in target area:

neutron equiv. dose for 15pnA Kr beam (0.2 kW):

1 Rad / hour @ 50 cm distance

stolz@nscl.msu.edu 2006-05

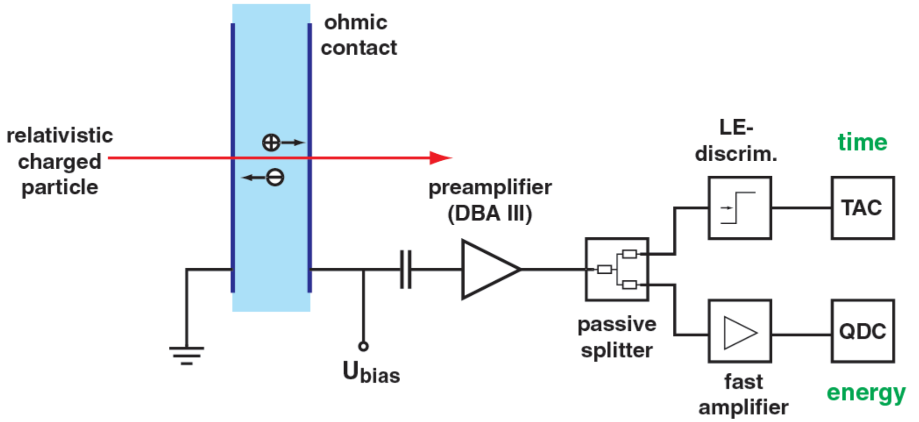
Radiation-hard CID cameras (CID8710D1M, Thermo CIDTEC)

remote electronics in shielded area

radiation tolerance: >1MRad (γ)

camera lifetime ~ 1 year

Diamond as charged particle detector



Physical Property at 300 K	*Diamond*	*Silicon*
band gap [eV]	5.45	1.12
Electron mobility [cm^2 /Vs]	2200	1500
Hole mobility [cm^2 /Vs]	1600	600
Breakdown field [V/m]	10^7	$3x10^5$
Resistivity [Ω cm]	$>10^{13}$	$2.3x10^5$
Dielectric constant ε_r	5.7	11.9
Thermal conductivity [W/cm K]	20	1.27
Lattice constant [Å]	3.57	5.43
Energy to remove an atom from the lattice [eV]	80	28
Energy to create an e-h pair [eV]	13	3.6

→ very fast, radiation-hard detectors

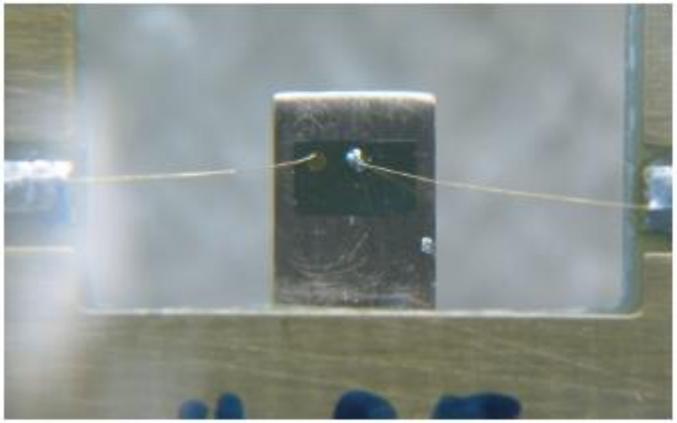
A. Stolz, B. Golding

grown at MSU (B. Golding)

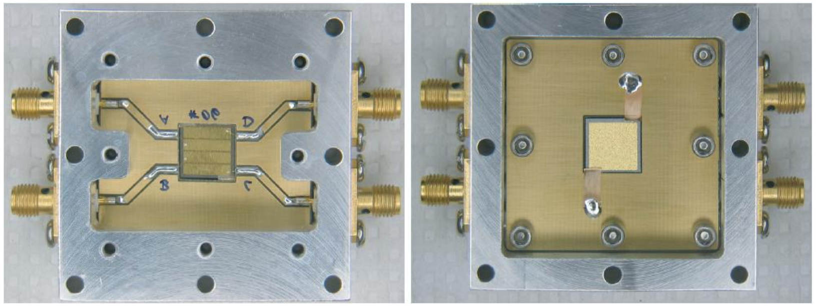
hetero-epitaxie CVD

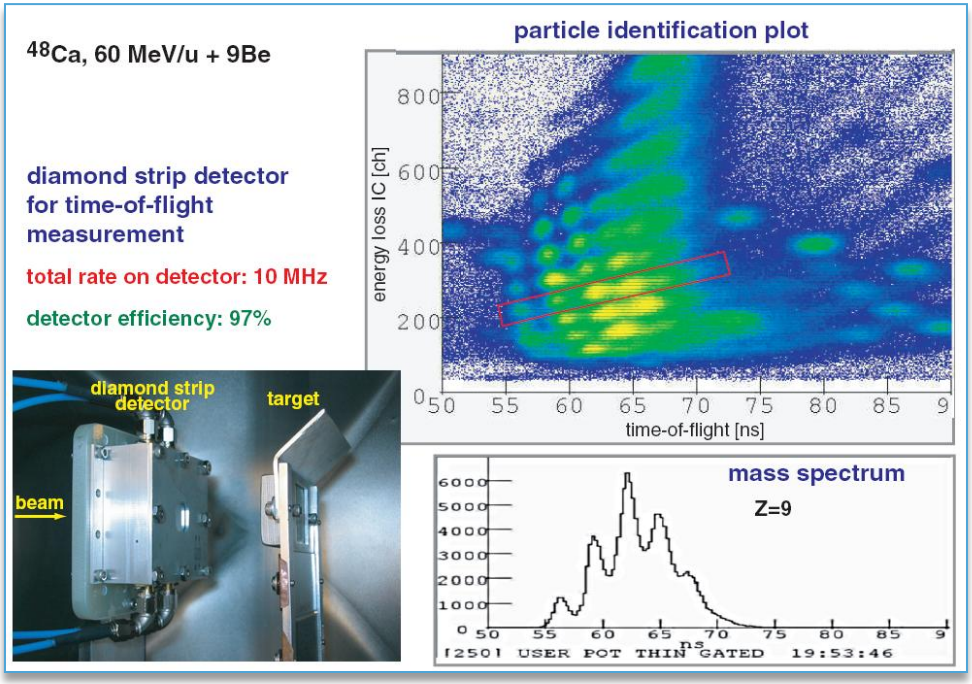
thickness 20 μm

Ir back layer (300 Å)



Segmented diamond detectors





Excellent timing resolution (20 ps)
High beam rate capability 10^7 ions/(s mm^2)

Desirable for FRIB:

- Larger size (30 cm x 2 cm)
- High homogeneity
- Higher segmentation (1 mm pitch)

Summary

- FRIB will allow major advances in nuclear science and nuclear astrophysics
  - Significant opportunities for the tests of fundamental symmetries
  - Potential for important societal applications
  - Campus-based location offers important educational and collaboration benefits
- Realization of FRIB requires R&D to reduce technical risk
  - High risks directly related to material properties
    - » High-power density in material
    - » High radiation that lead to material damage
  - Are there alternative materials?
  - Do we understand properties?