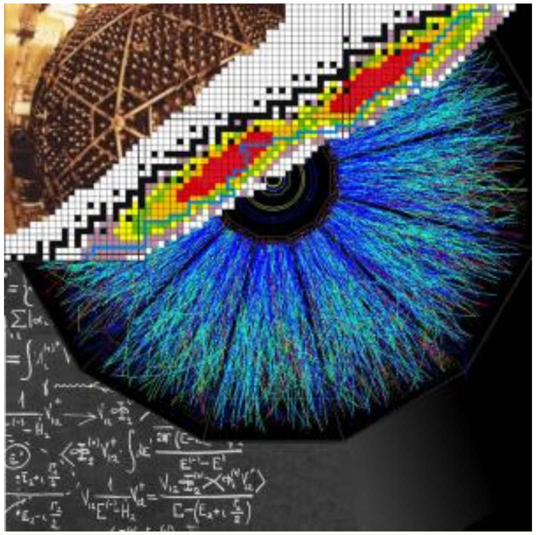
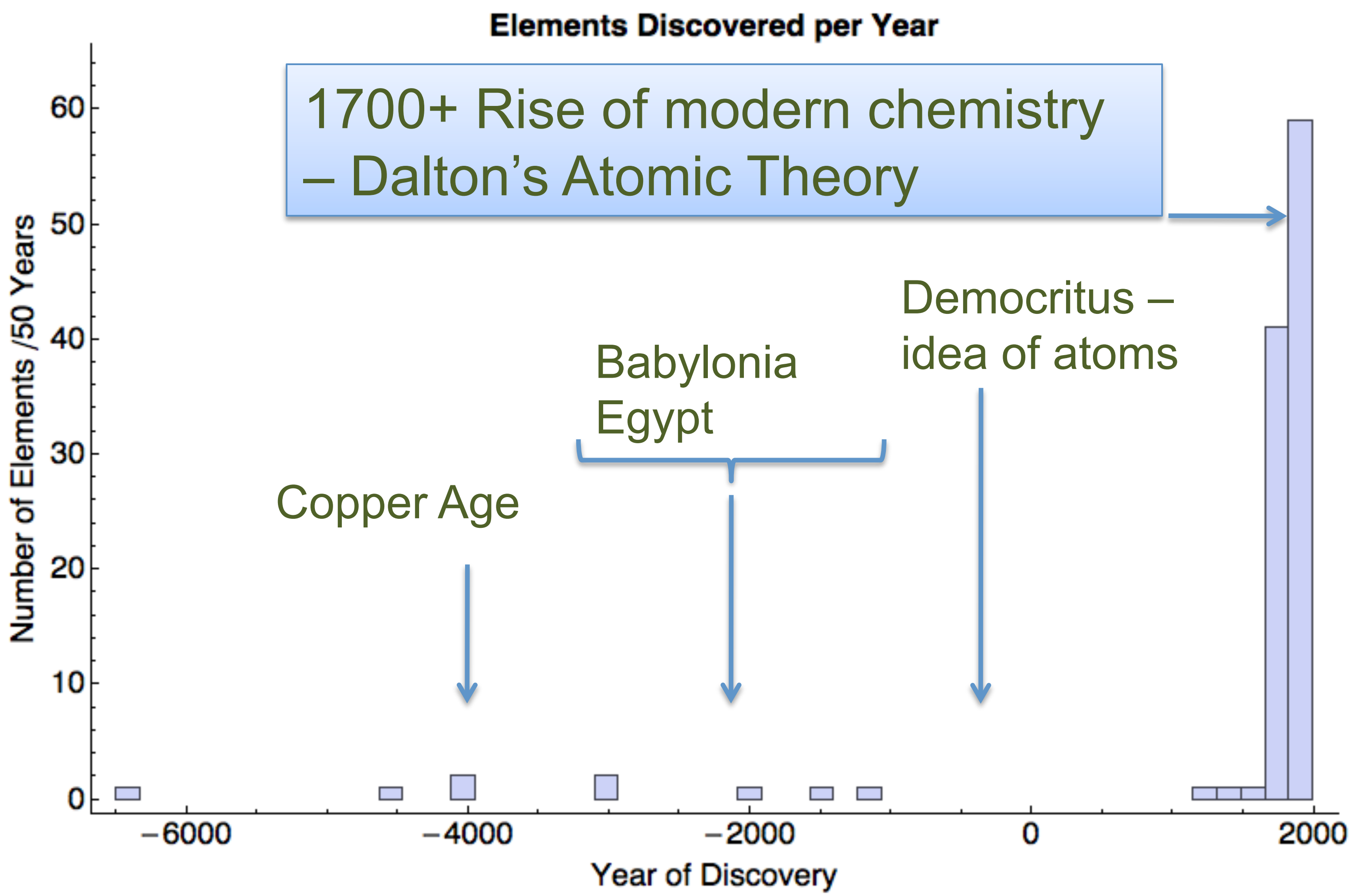
The Future at FRIB



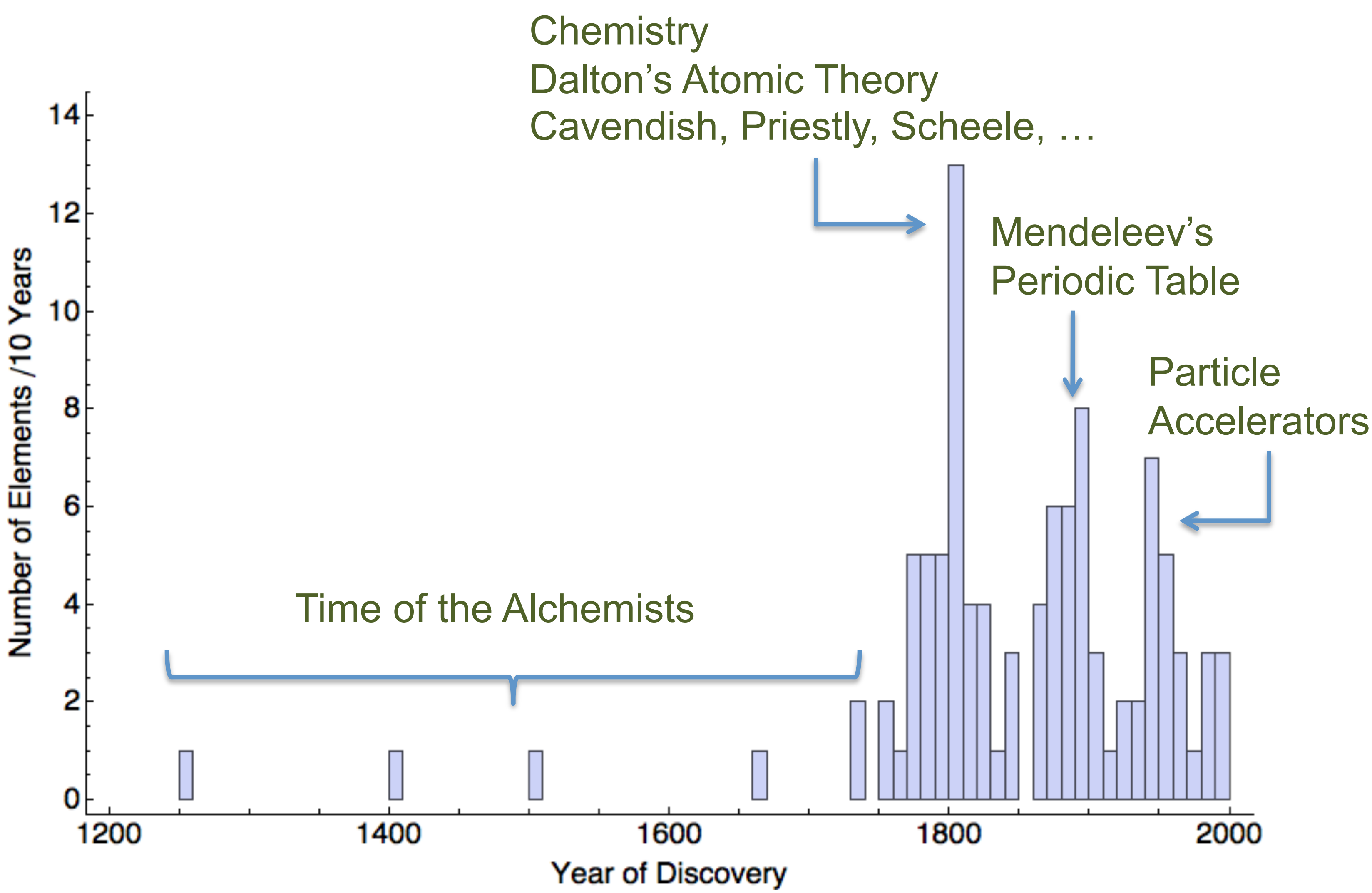
Gary Westfall

Michigan State University

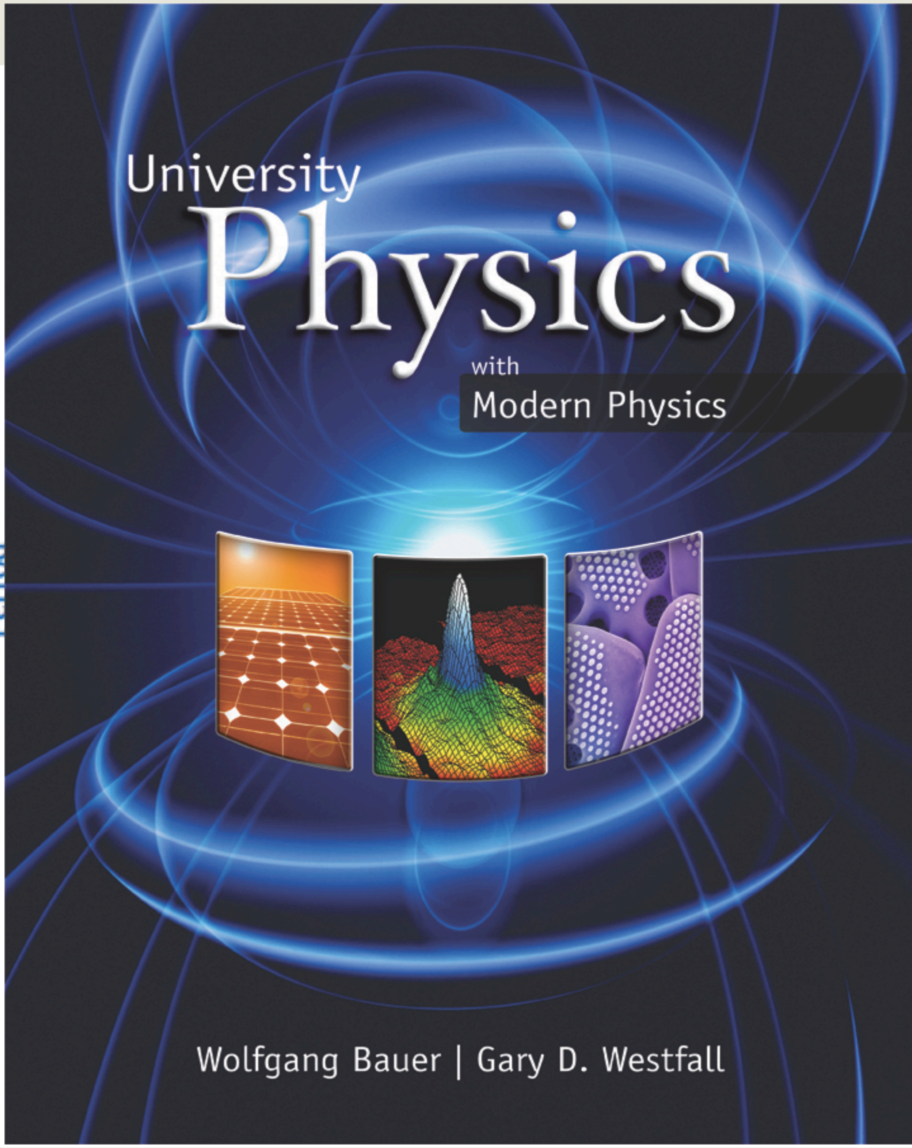
History of Element Discovery

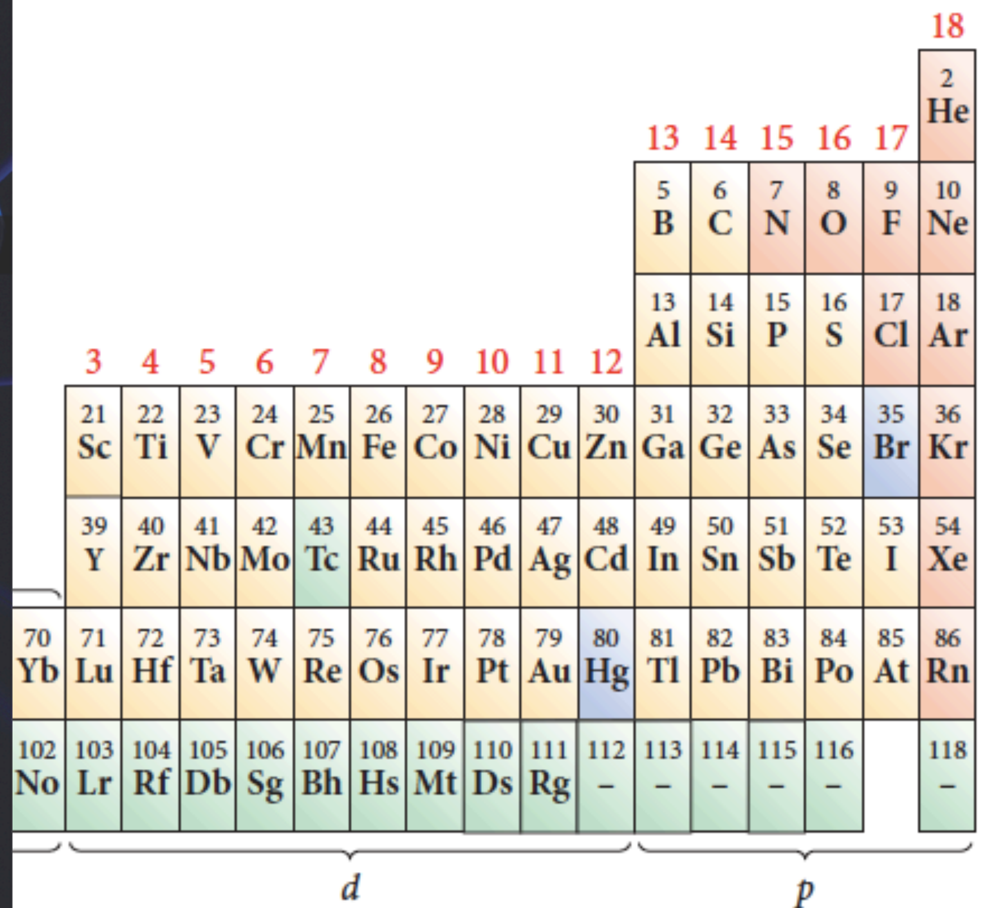


The history of element discovery 1200-2000



Periodic Table of the Elements

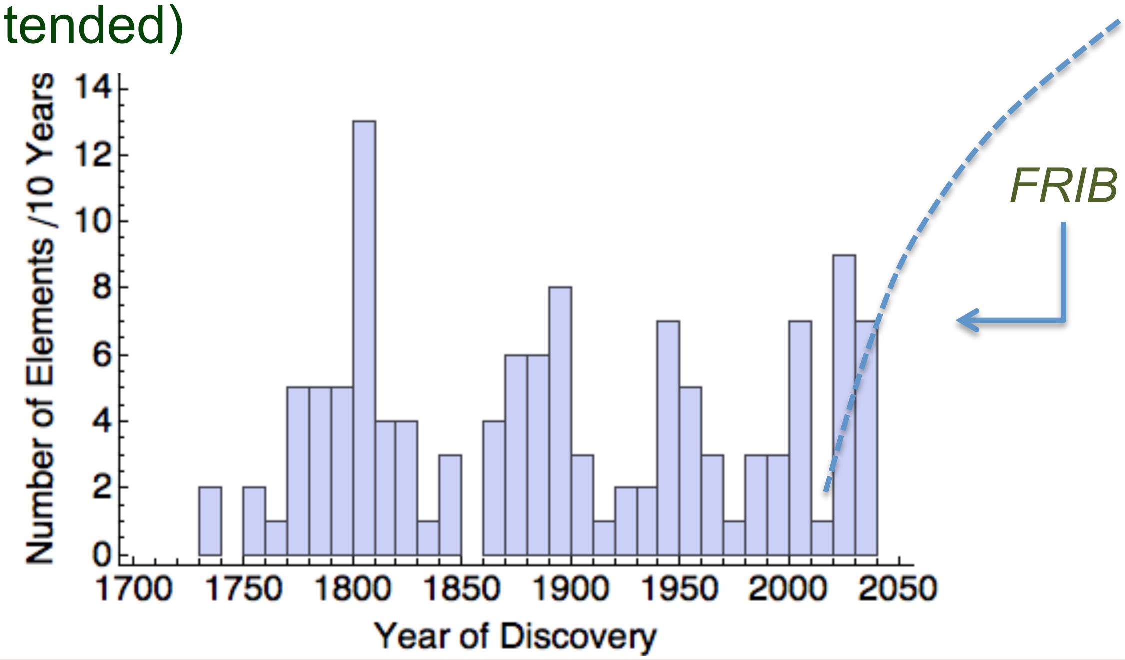




How many elements are possible?

- We do not know. So far we have "discovered" 118 elements. (The last six have not been officially sanctioned.)
- We think elements up to 300 are possible, but don't know the limit
- This is one of the questions we can address at FRIB with an advanced capability to produce new neutron-rich isotopes
- FRIB is a modern equivalent to the Philosopher's Stone (no religious or mystical connotation intended)

50 Years from now (not so likely but dreaming)…



A question

Where do gold atoms come from?

Where do all atoms come from? (H, He, Li from the Big Bang; the rest from stars)

When did people first create gold atoms from something else?

- *1924 Editors of Scientific American* "Gold can be extracted from mercury, but mercury cannot be transmuted into gold."
- "It was not until 1941 that gold was actually prepared from a base metal. By bombarding mercury with fast neutrons, Sherr, Bainbridge, and Anderson obtained three radioactive isotopes of gold. Even that did not fulfill the dream of the alchemists; the gold was radioactive and the process did not produce wealth; it consumed it." *A Philatelic Ramble Through Chemistry* (Heilbronner and Miller; Verlag 1998)

THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 60, NO. 7 OCTOBER 1, 1941 SECOND SERIES

Transmutation of Mercury by Fast Neutrons

R. SHERR AND K. T. BAINBRIDGE, *Research Laboratory of Physics, Harvard University, Cambridge, Massachusetts*

AND

H. H. ANDERSON, *Mallinckrodt Laboratory, Department of Chemistry, Harvard University, Cambridge, Massachusetts*

(Received August 13, 1941)

Where are Gold atoms made?

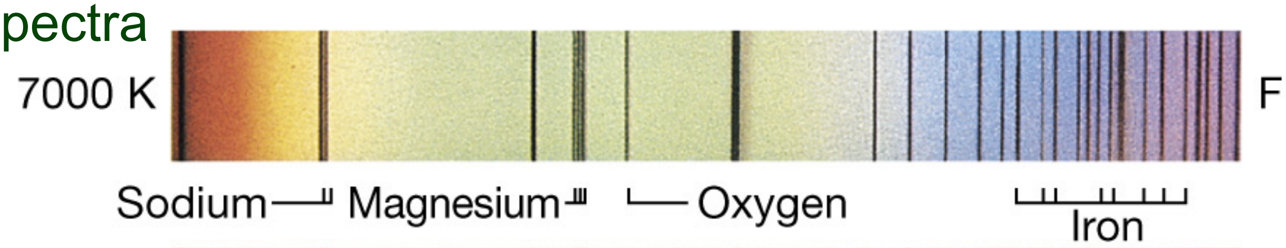
- We don't know
- We do know it is related to the processes of stars
- The most likely site is supernovae explosions where stars that are more than 10 times the mass of our Sun explode
- Supernova 1994D

Galaxy NGC 4526
53 million light years from Earth

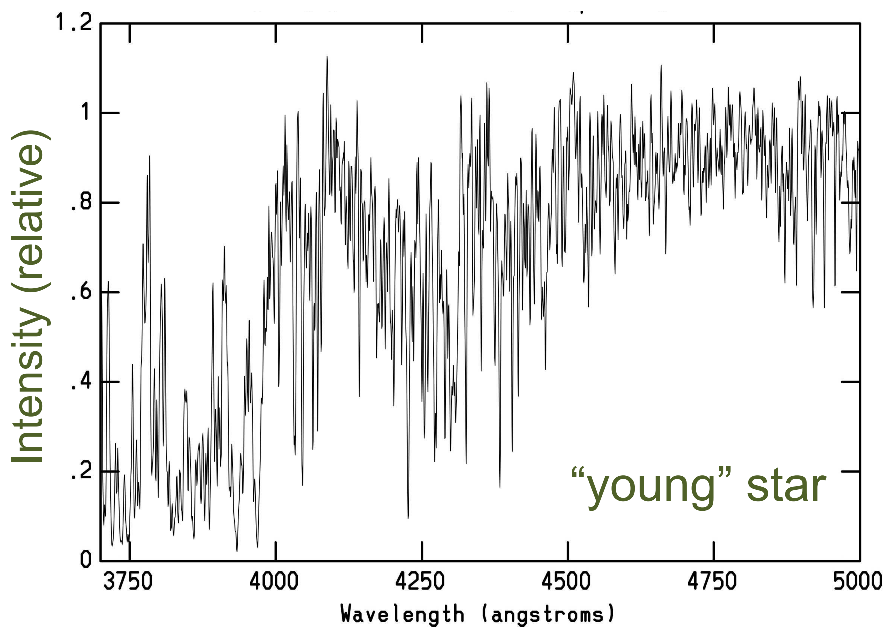
- To learn where gold was made, we need to study unusual atoms that do not normally exist on Earth – We need FRIB to make them!

Where do atoms come from? A hint from stellar spectra

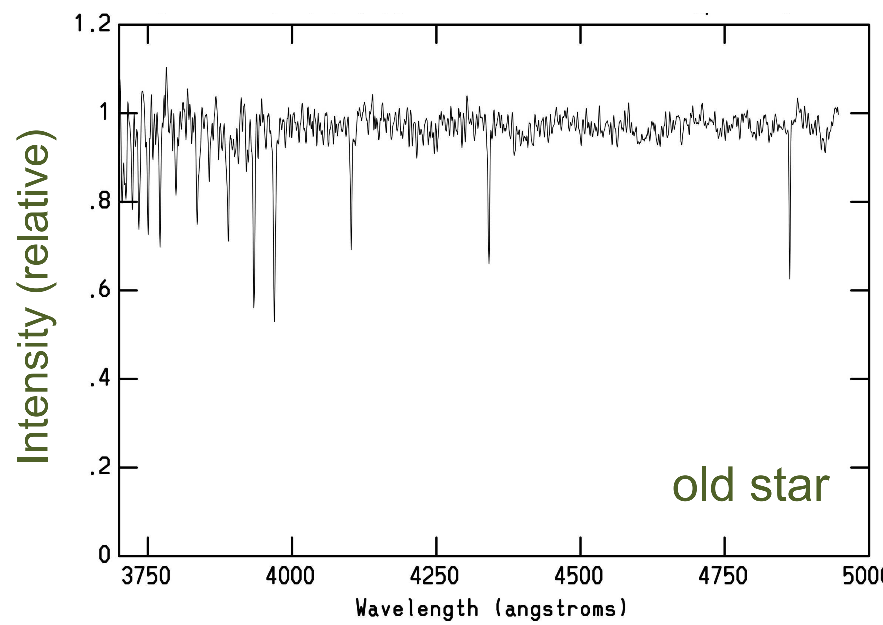
- Stellar absorption spectra



- Not all stellar absorption spectra of the same surface temperature are identical



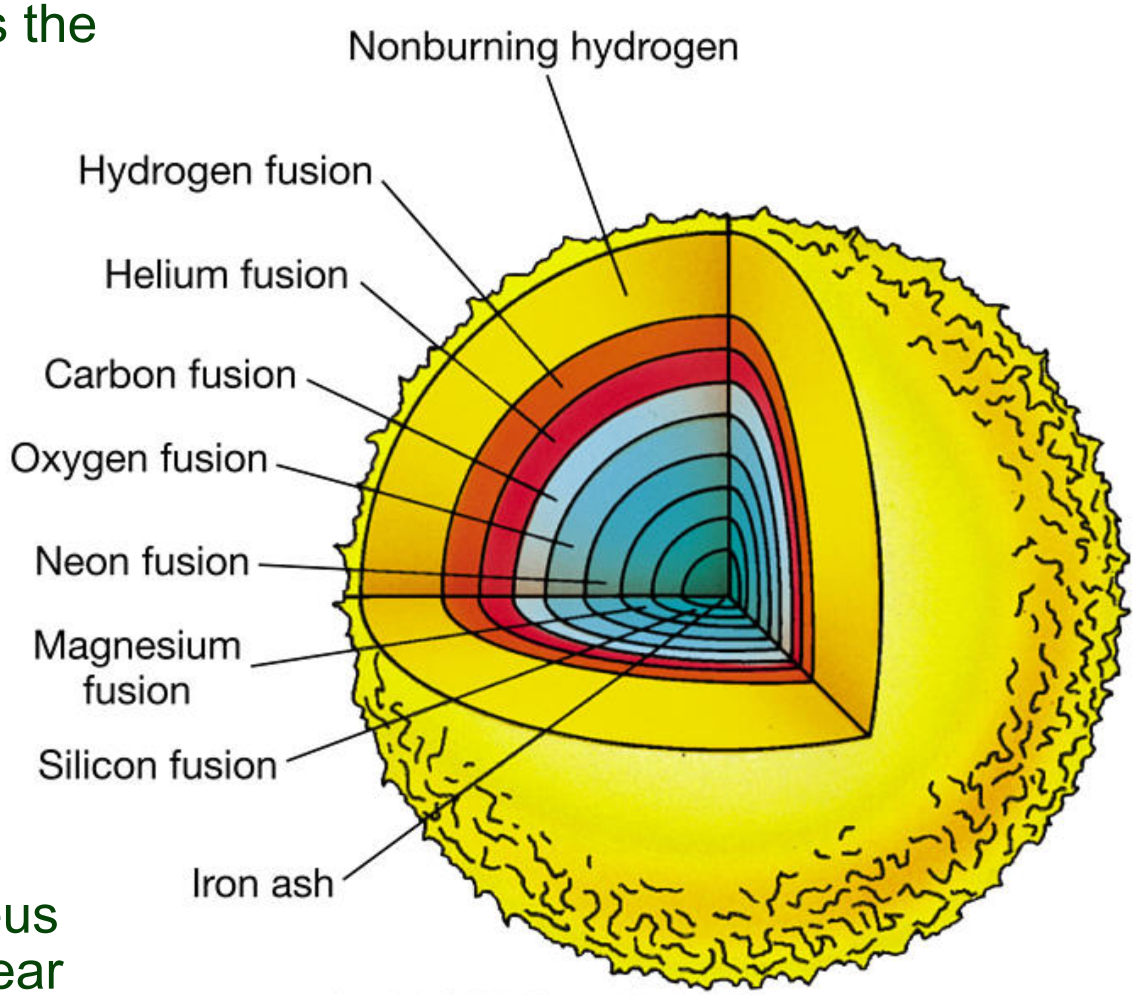
T=4800 K; elements like our sun



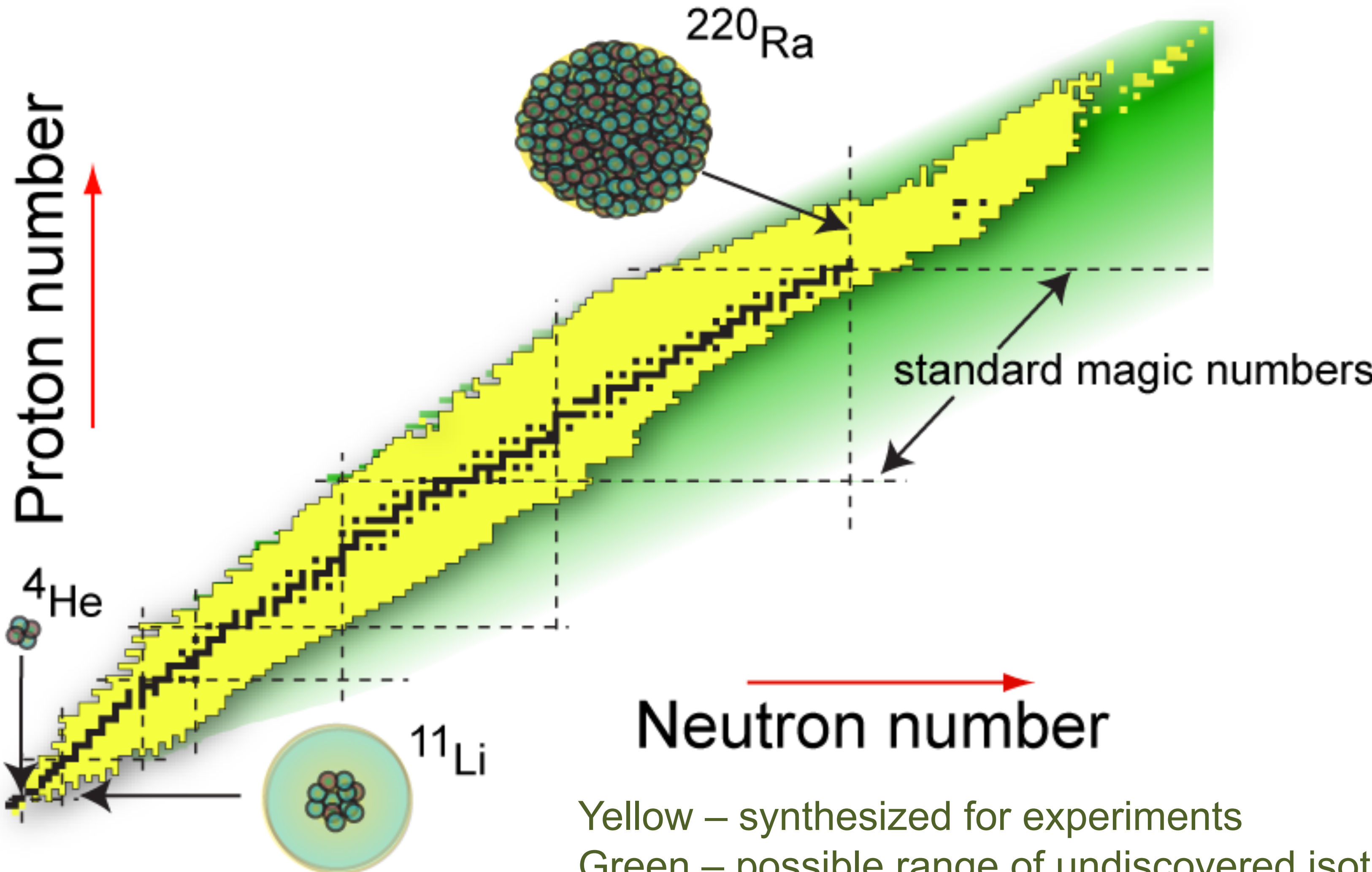
T=4700 K; only 1/10,000 heavy elements

Stellar evolution of massive stars

- Stars with more than 8 times the mass of our Sun develop multiple burning layers
- Hydrogen to helium
- Helium to carbon
- Carbon to oxygen, neon, magnesium
- Oxygen to neon
- Neon to magnesium
- Magnesium to Silicon
- Silicon to Iron
- Iron is the most bound nucleus and has no exothermic nuclear reactions

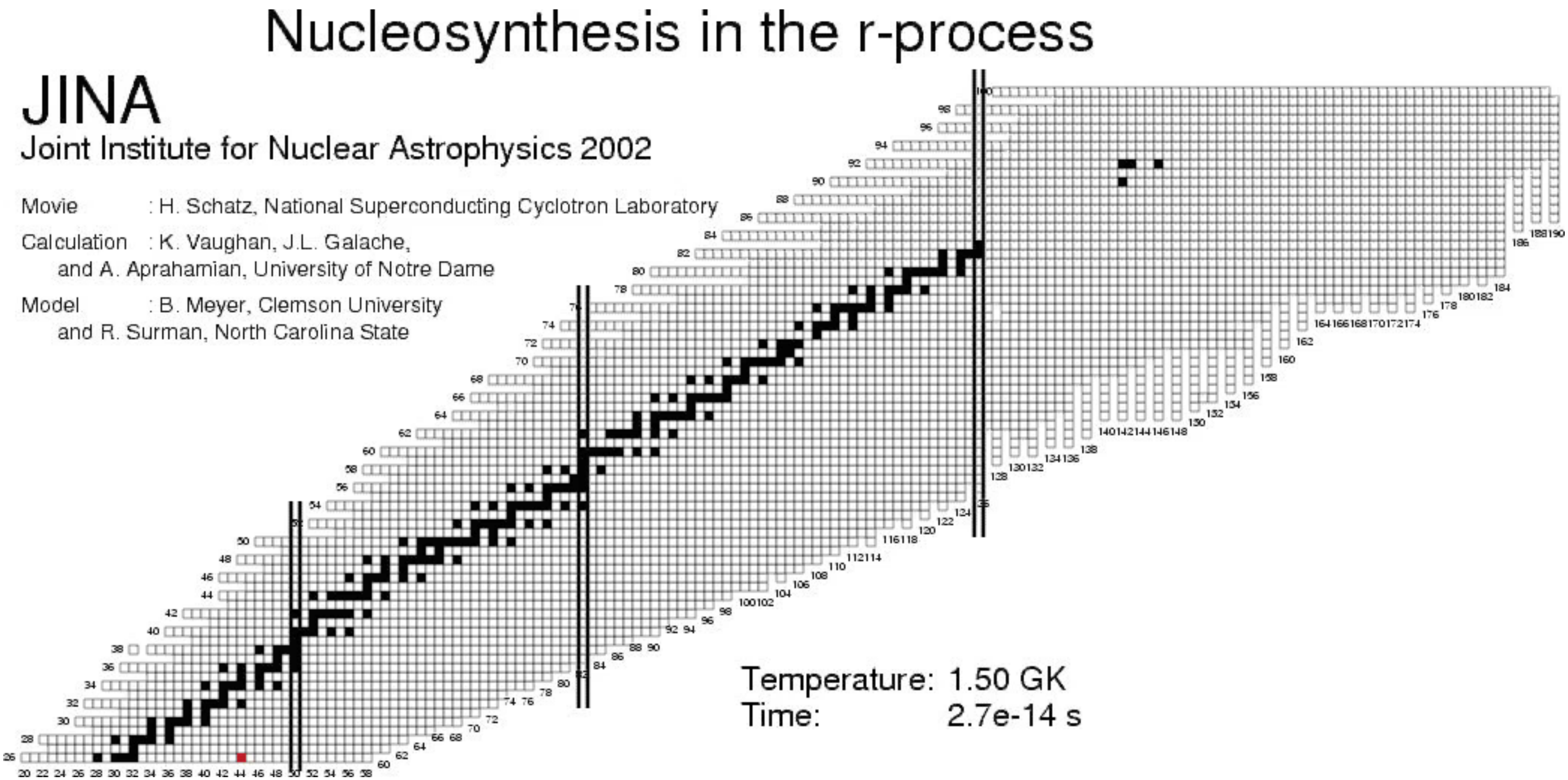


Isotope Chart – Chart of Nuclides



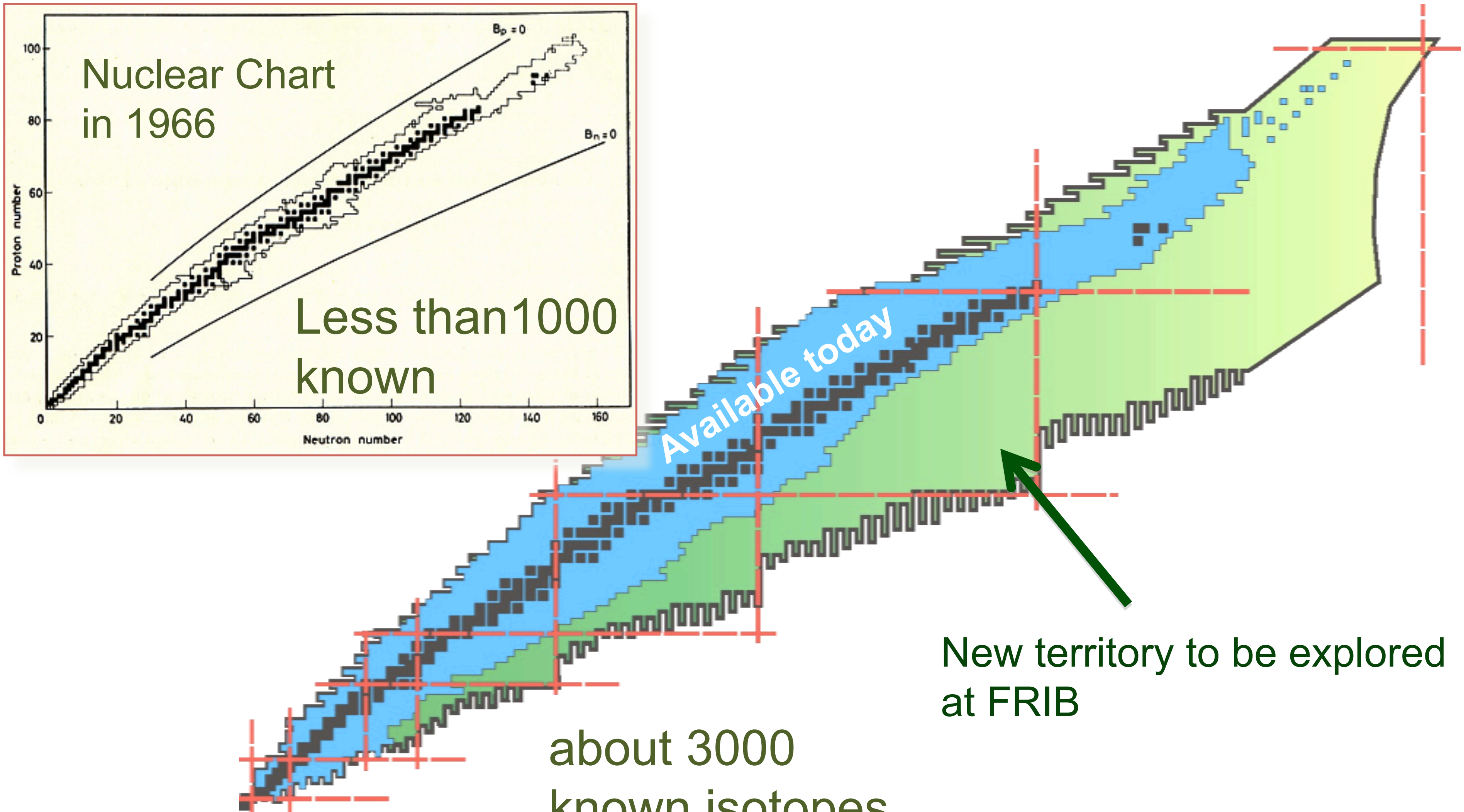
Yellow – synthesized for experiments
Green – possible range of undiscovered isotopes

About Half of Heavier Elements must be made in an r-Process



Nuclear physics shapes the characteristic final abundance pattern for a given r-process model

The availability of rare isotopes over time



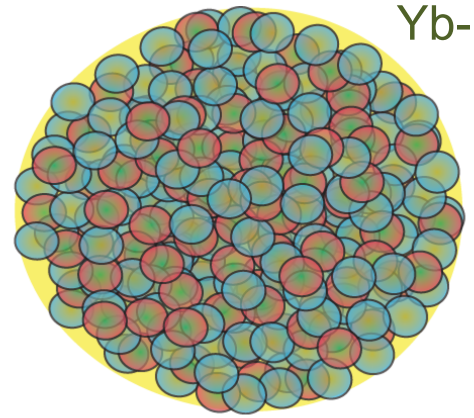
New territory to be explored at FRIB

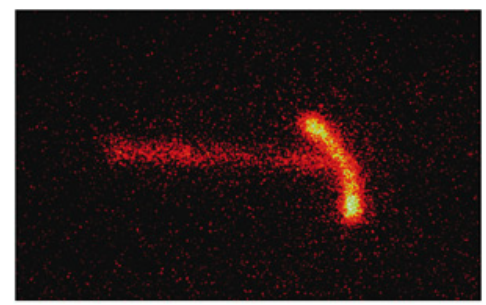
about 3000 known isotopes

Designer atomic nuclei

- Designer Nuclei: The possibility for a researcher to order a nucleus that has a specified number of neutrons and protons
- To make progress in nuclear physics, some astrophysics, and some high energy physics we need such a capability
- There are about 263 stable combinations found in nature, with about 1500 others studied in some detail. **In 10 years** we may have the capability to extend that to 5000 isotopes.
- Most combinations of neutrons and protons are radioactive; sometimes it is the novel radioactivity that is interesting
- Designer Nuclei ←→ Rare Isotopes

Yb-196

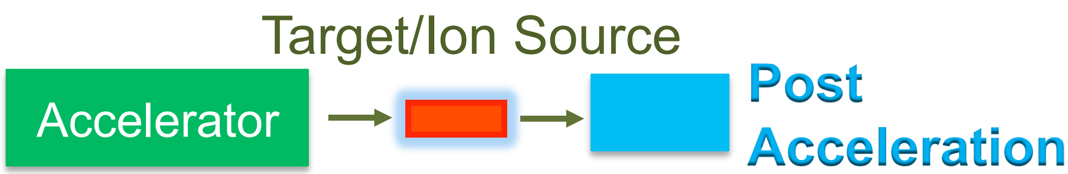


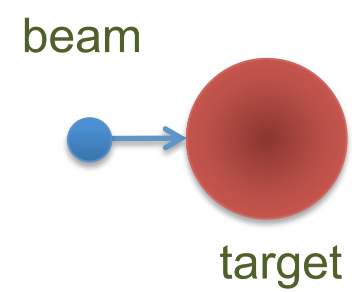


^{45}Fe two-proton decay: K Miernik *et al.* 2007 Phys. Rev. Lett. 99 192501

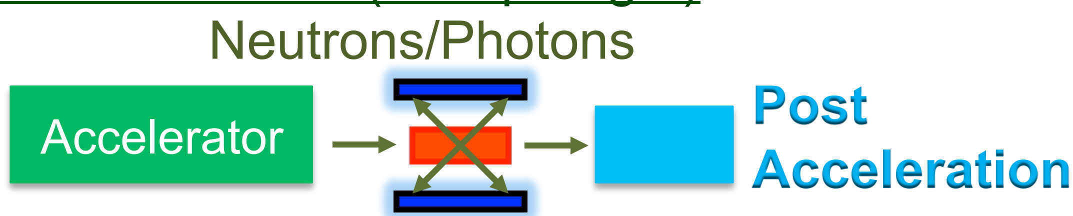
Rare Isotope Production Techniques using Accelerators

- Target spallation and fragmentation by light ions

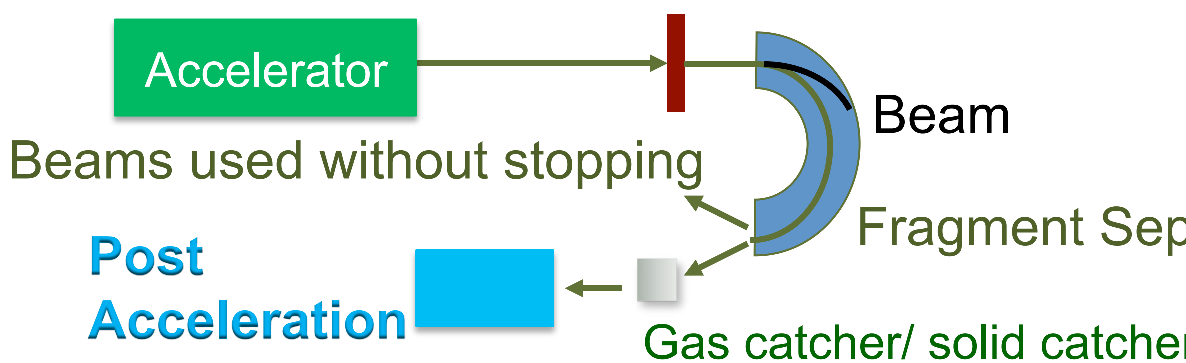


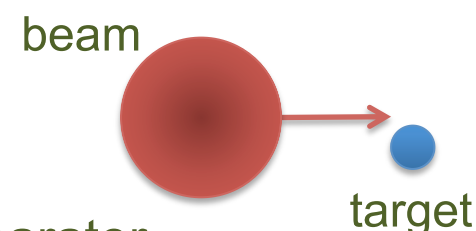


- Neutron induced fission (2-step target)



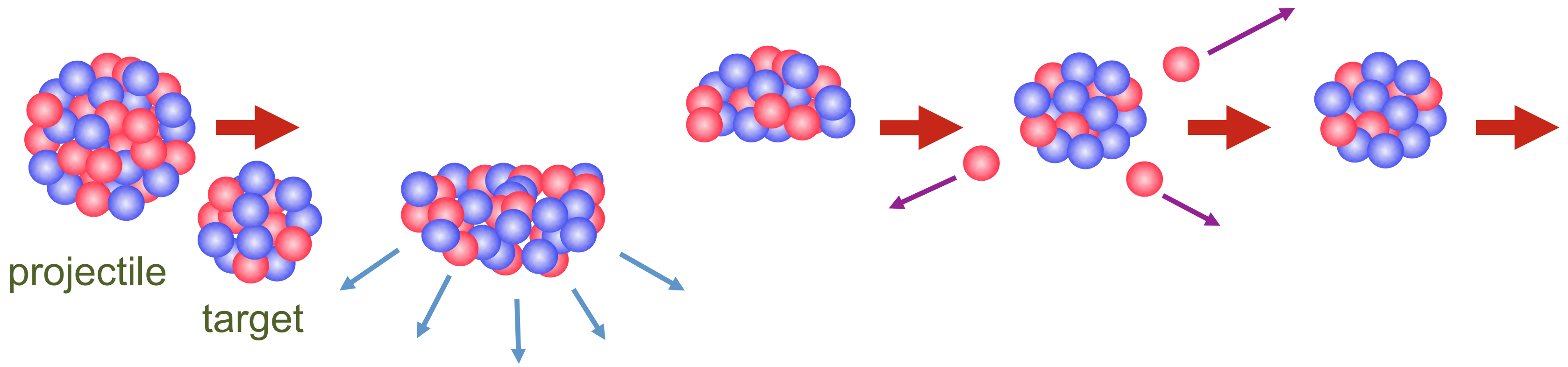
- In-flight Separation following projectile fragmentation/fission (Used by FRIB)





Production of Rare Isotopes in Flight

1. Cartoon of the production process - fragmentation (fission is also used)



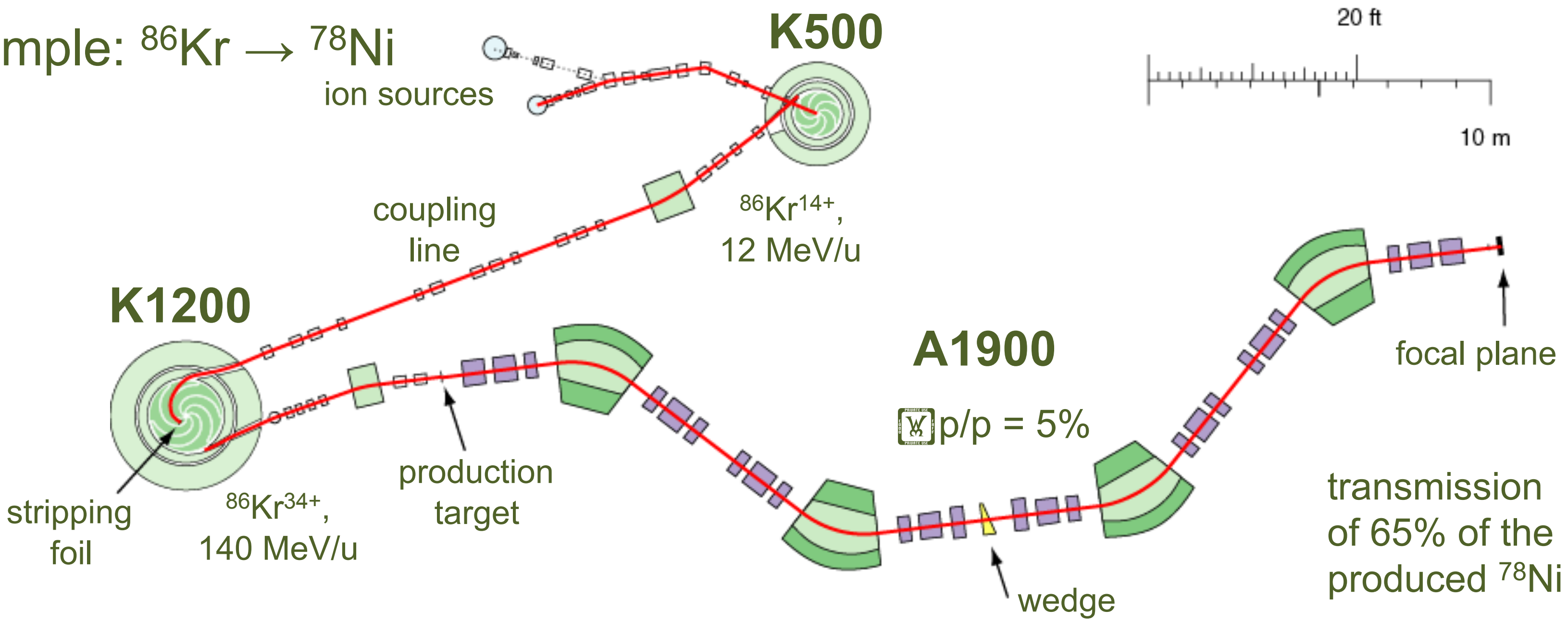
2. The production cross section for the most exotic nuclei is extremely small; but, facilities have tremendous sensitivity. The projectile intensity at the next generation facilities (^{48}Ca 400 kW, ≅ 2x10^{14} ion/s) is such that the cross section that corresponds to one atom/week is 3x10^{-20} b (30 zeptobarns, 3x10^{-48} m^{2})

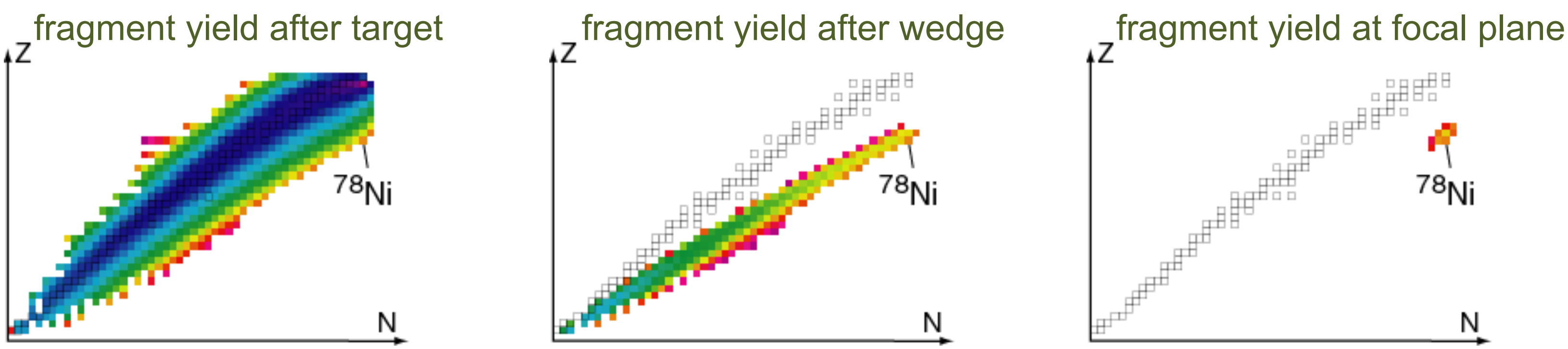
3. Neutrino elastic scattering cross sections are

$$\sigma_{\upsilon_e e^- \rightarrow \upsilon_e e^-} = 9.5 \cdot 10^{-49}\ m^2 \left(\frac{E_\upsilon}{1\, MeV} \right)$$

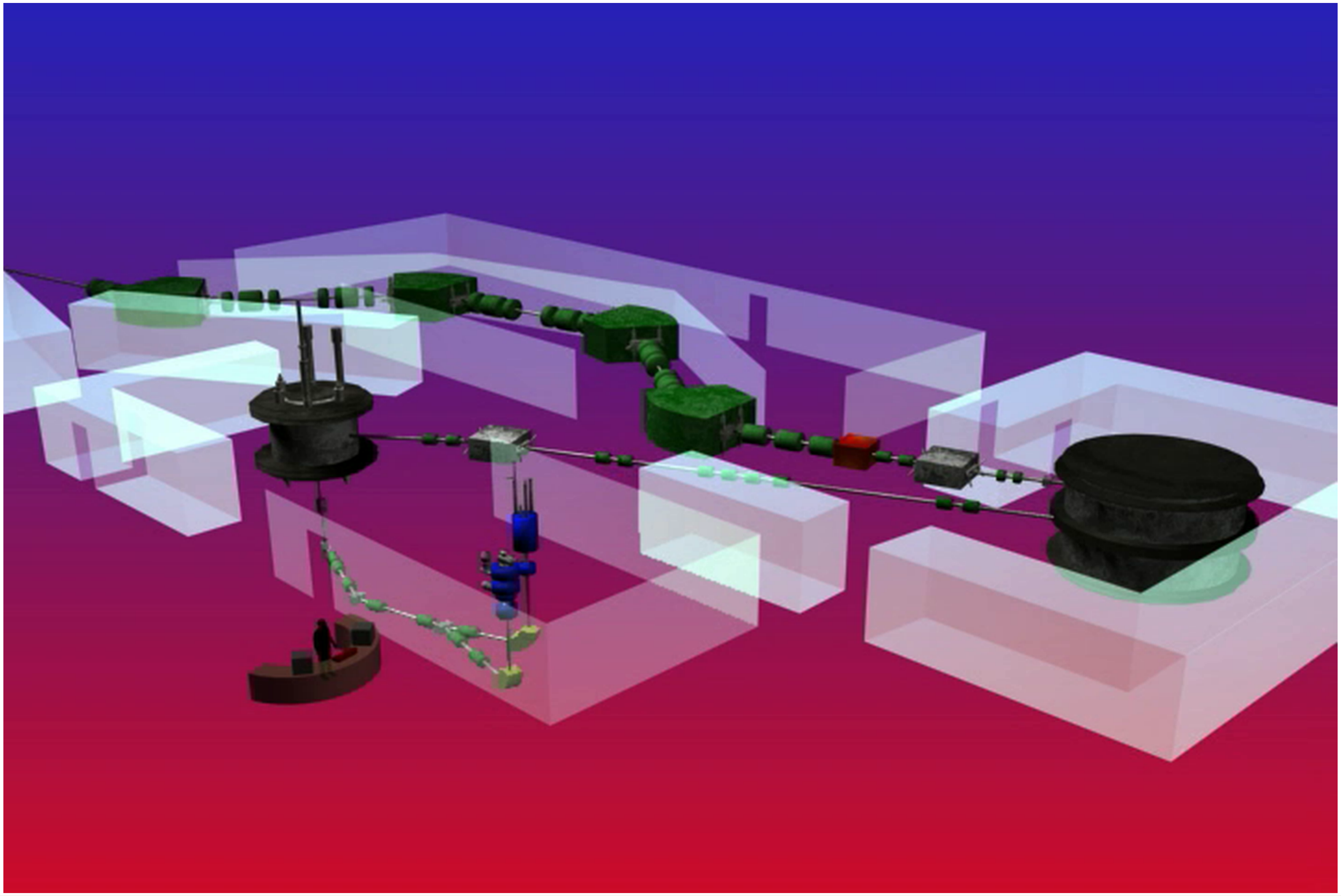
In-Flight Production of Rare Isotopes
Example: NSCL's CCF

Example: $^{86}Kr \rightarrow {}^{78}Ni$

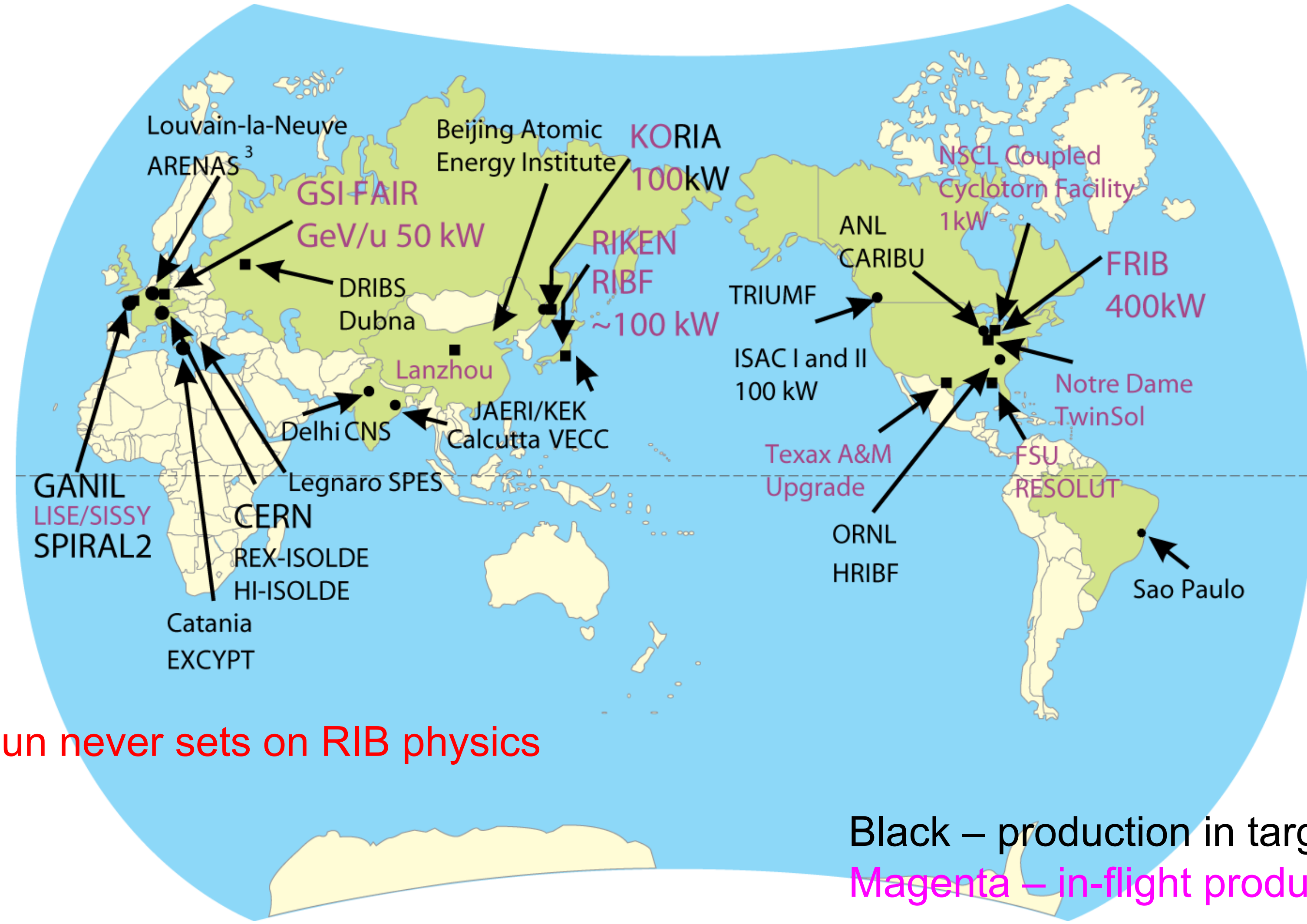




Production of rare isotopes – Example from the NSCL



World view of rare isotope facilities

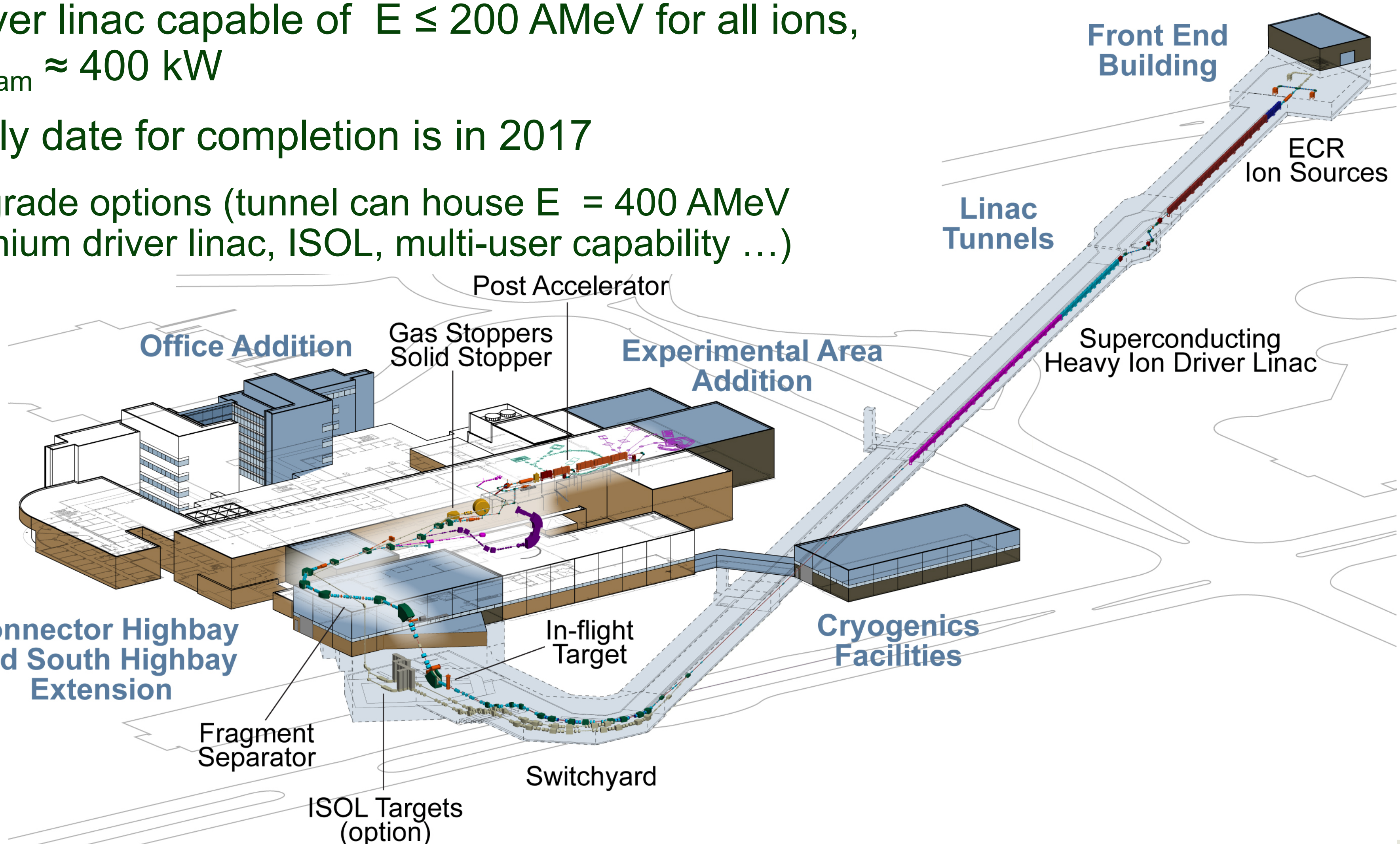


The Sun never sets on RIB physics

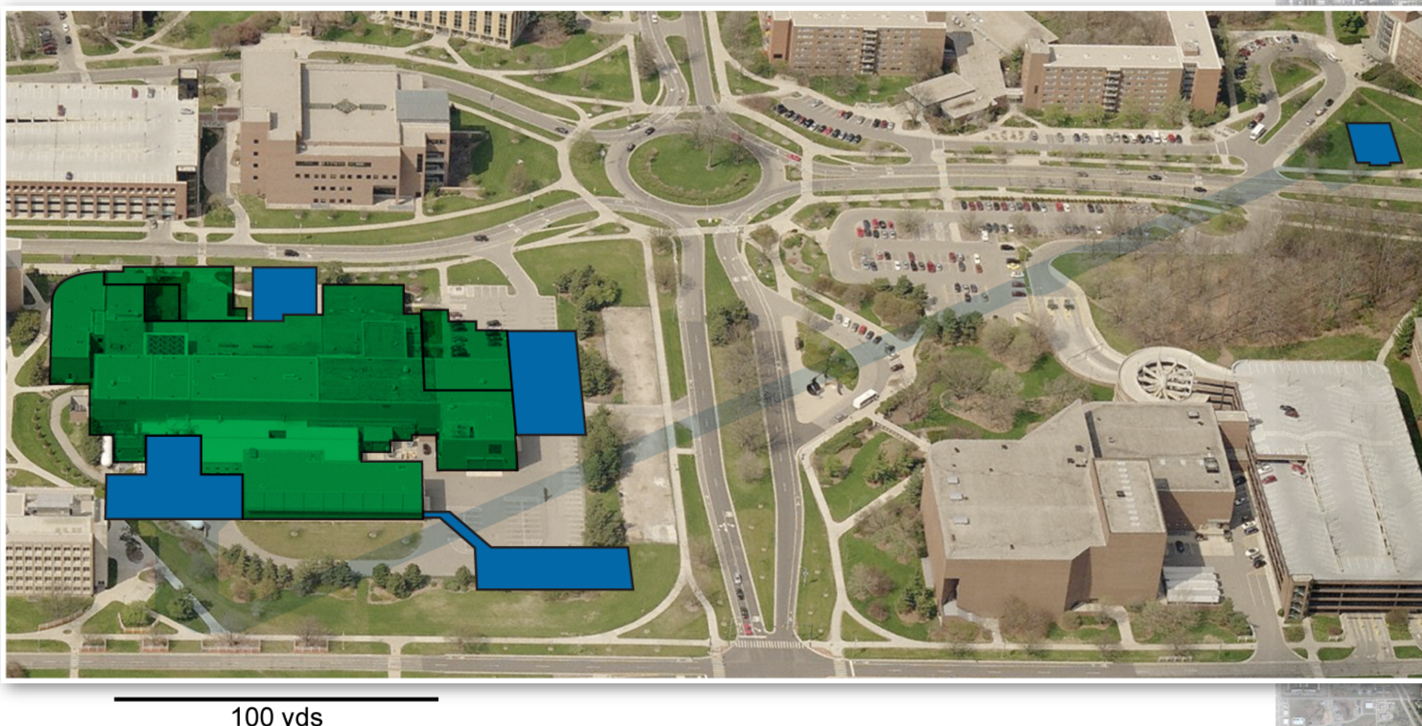
Black – production in target
Magenta – in-flight production

Facility for Rare Isotope Beams, FRIB Broad Overview

- Driver linac capable of E ≤ 200 AMeV for all ions, P_{beam} ≈ 400 kW
- Early date for completion is in 2017
- Upgrade options (tunnel can house E = 400 AMeV uranium driver linac, ISOL, multi-user capability …)

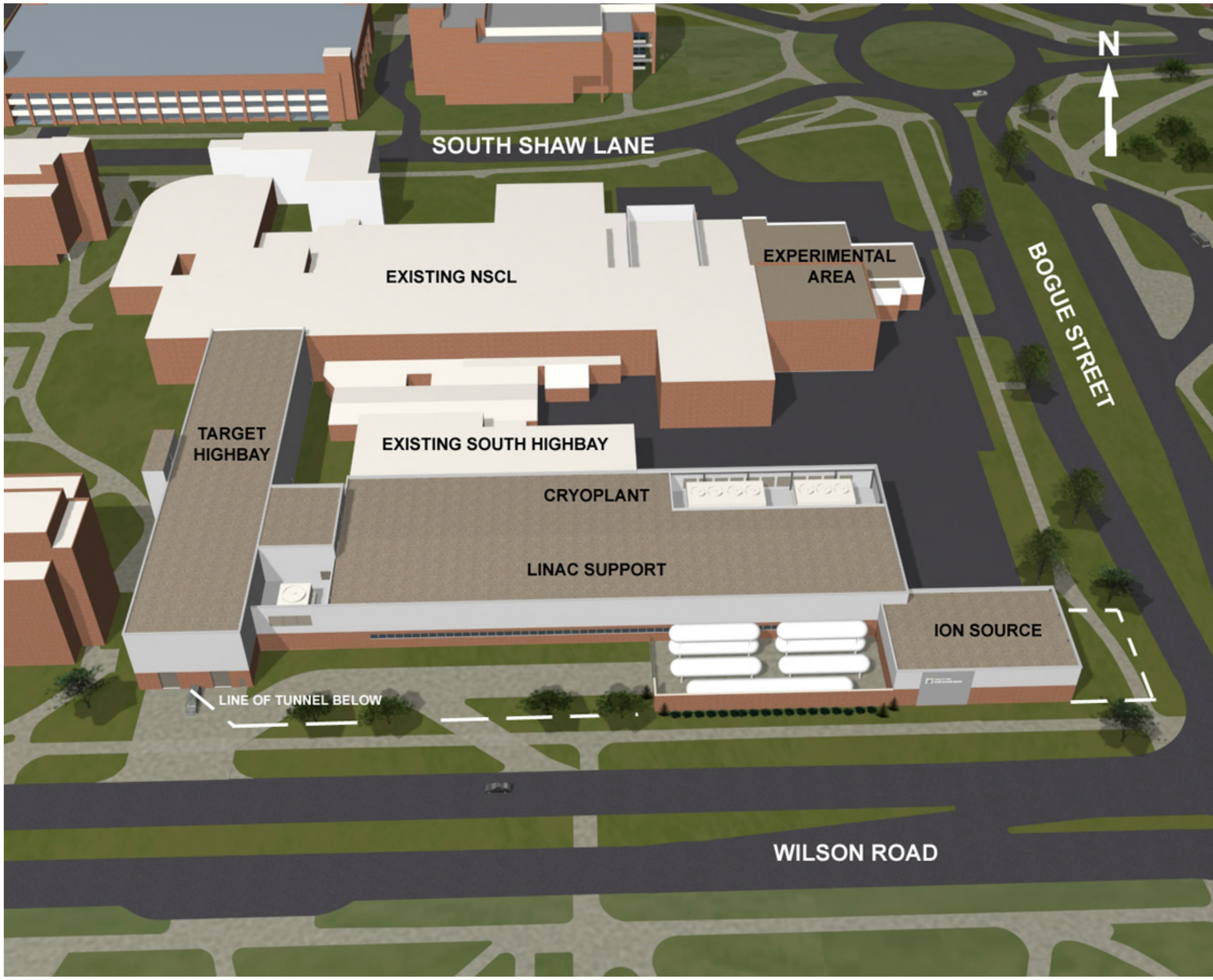


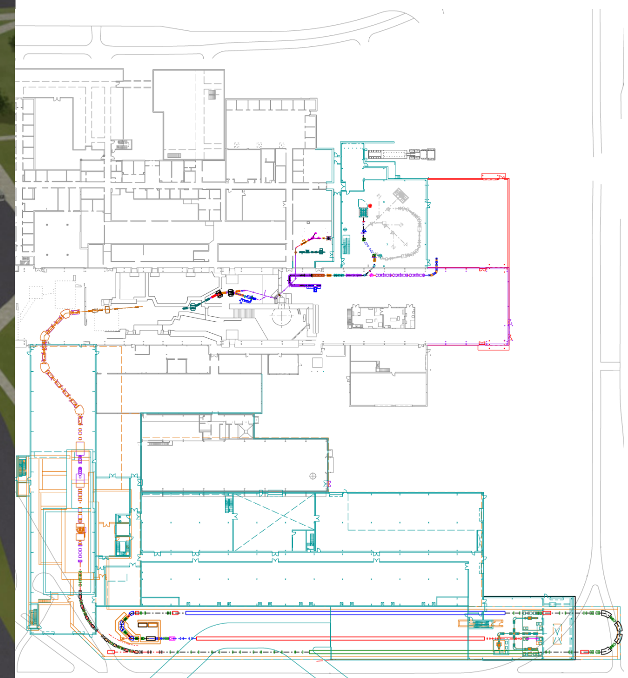
Facility placement on MSU campus



- Adjoining NSCL facility on 10.5 acre site

Compact, more cost-effective solution

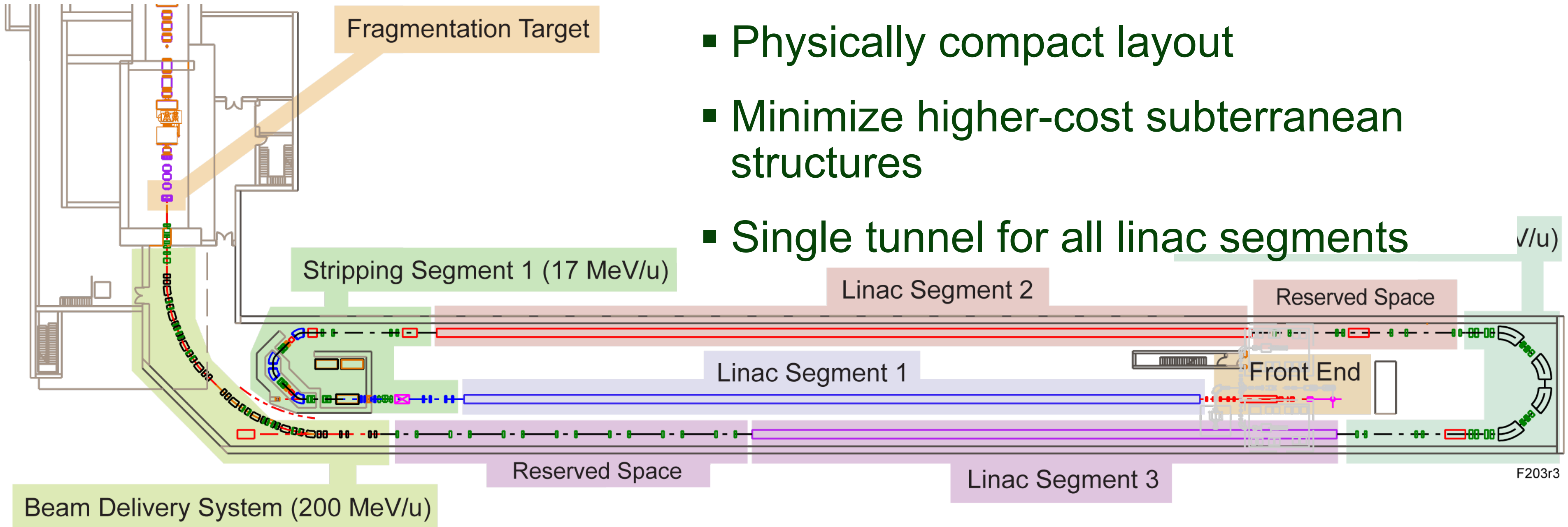


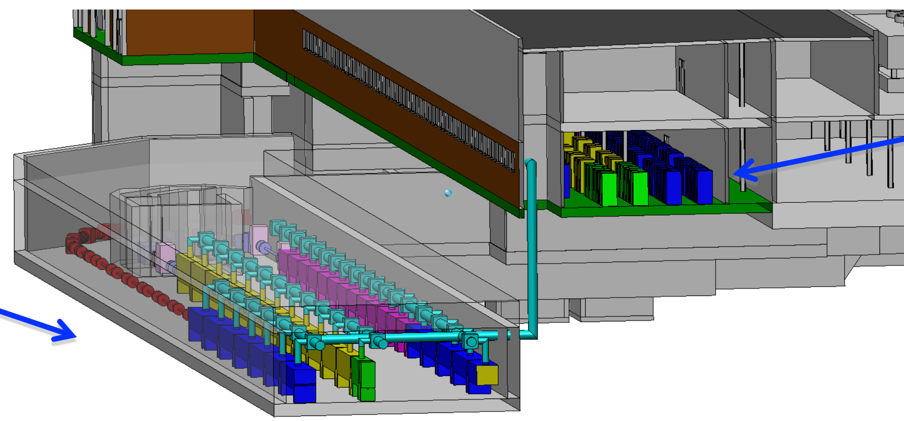


Rough (not base-lined) TPC range $550M to $600M

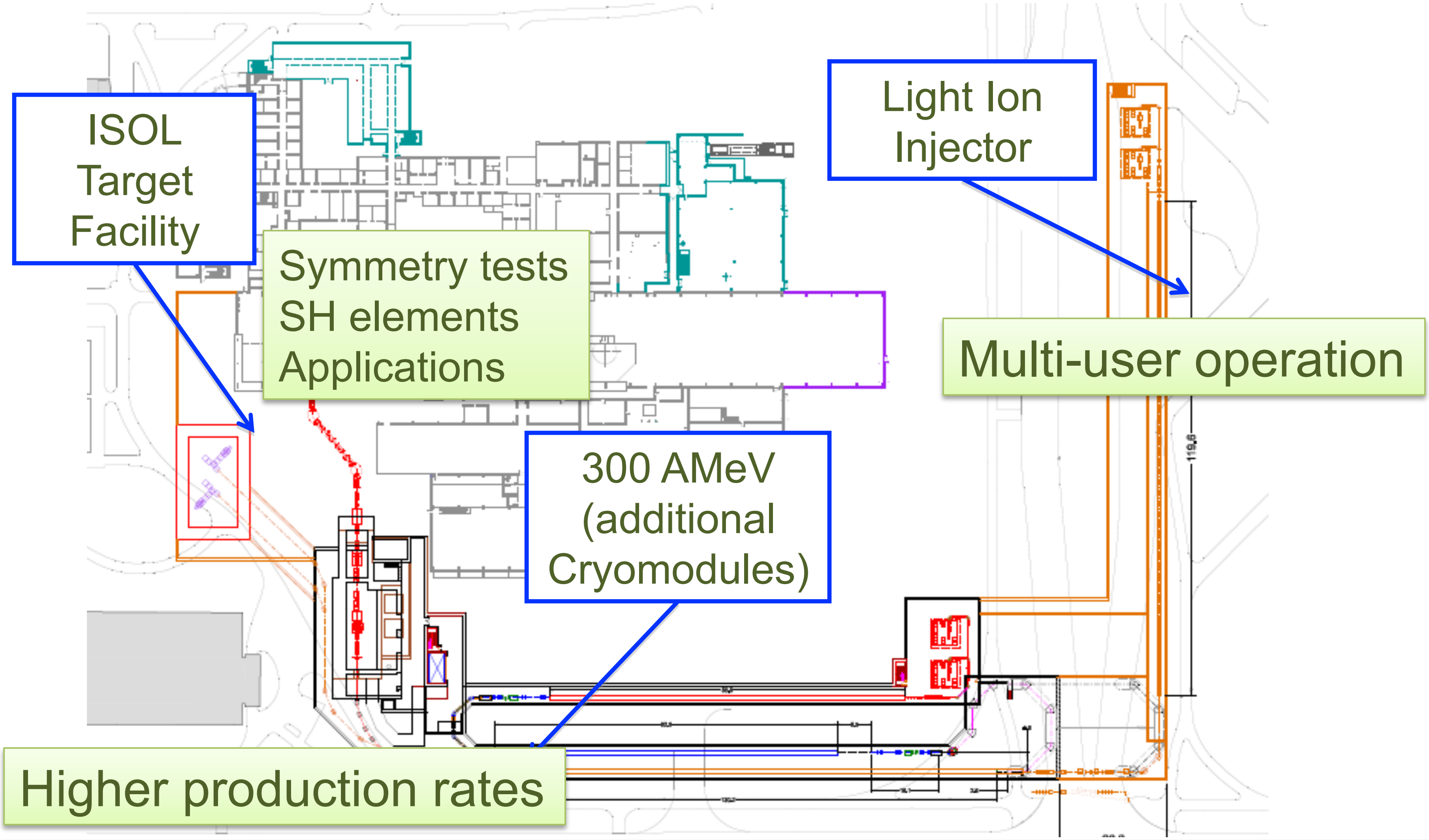
Folded FRIB LINAC details

- Physically compact layout
- Minimize higher-cost subterranean structures
- Single tunnel for all linac segments



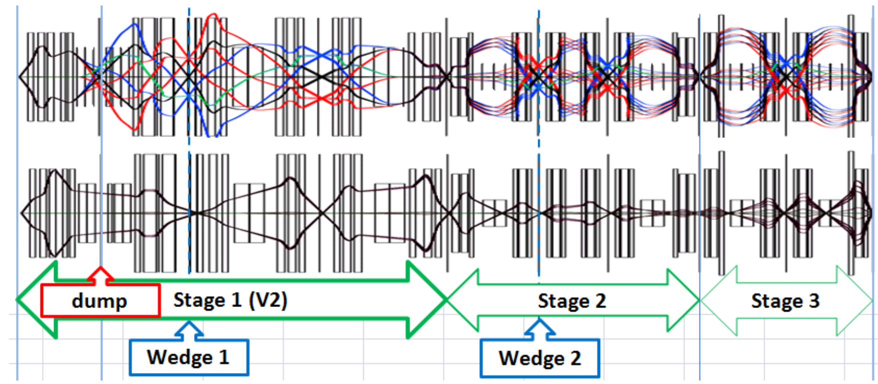


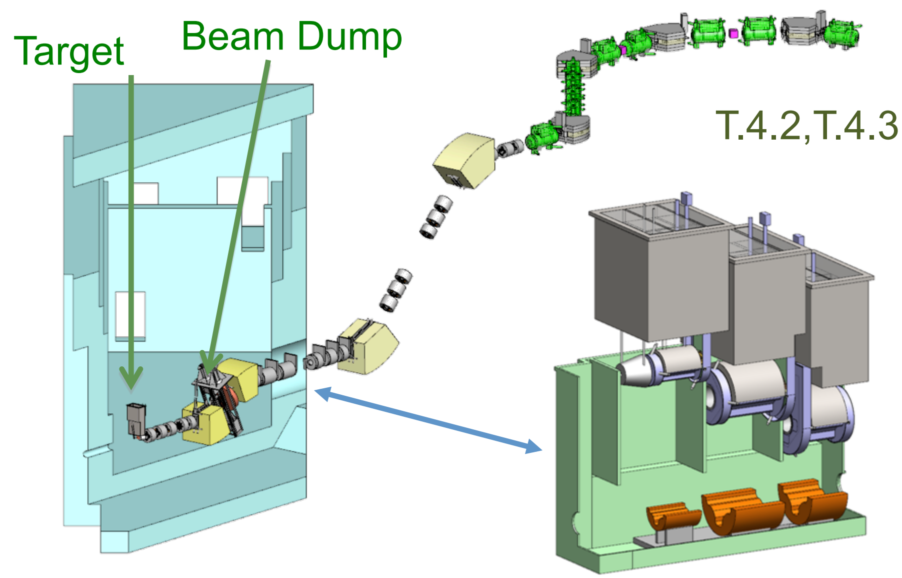
FRIB Facility Upgrade Options



Fragment Separator Conceptual Design

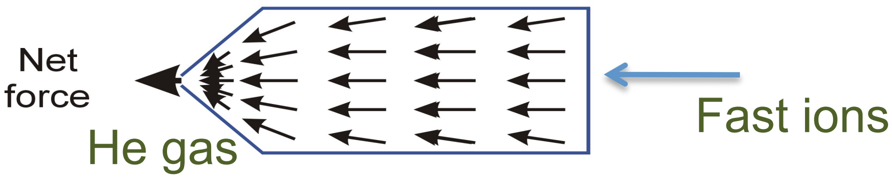
- Optics design
  - Separator concepts that have 50% collection efficiency and provide rare isotope beams with high rate and purity
  - Match beam distribution acceptance
  - Momentum spread of 5% (compressed from 15%)
  - Verified with calculations up to 3rd order, different codes used to benchmark results
- Mechanical design
  - Realistic concepts that consider radiological aspects and remote-handling needs
- Radiation transport studies
  - Radiation fields
  - Component activation

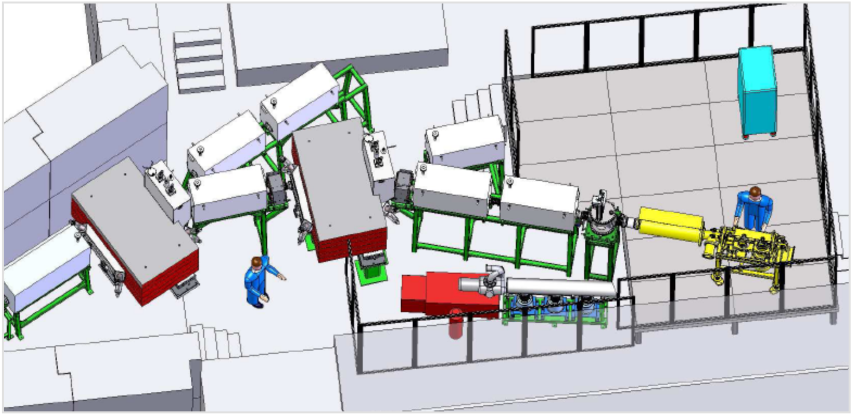




Key FRIB component: Beam Stopping

Concepts develop at ANL by G. Savard *et al.*

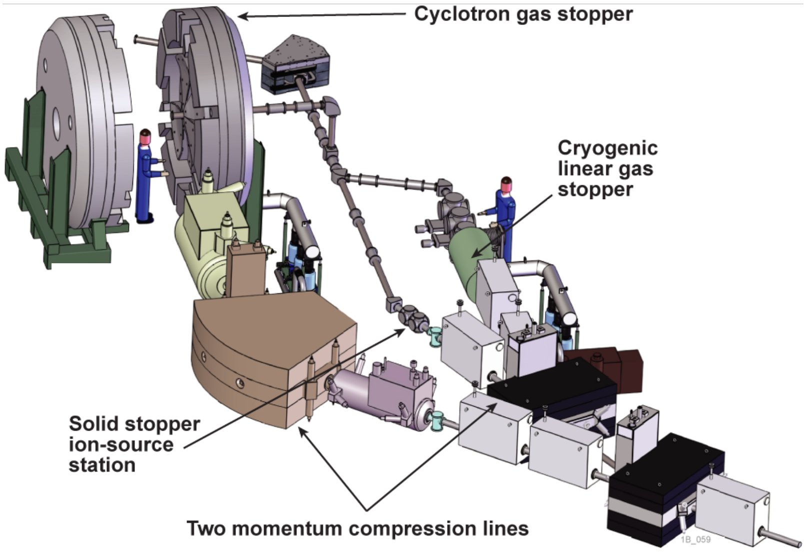




Beams for precision experiments at very low-energies or at rest and for reacceleration

- Cyclotron gas stopper
- Linear gas stopper
- Solid stopper (FRIB)

- Phase 1 (by 2011), two momentum compression lines
  - MSU linear cryogenic gas cell and
  - ANL gas catcher (FRIB R&D)
- Phase 2 (after 2012):
  - One linear gas stopper
  - Gas-filled cyclotron stopper (funded as NSF-MRI)
  - Solid-stopper/reionizer (FRIB)

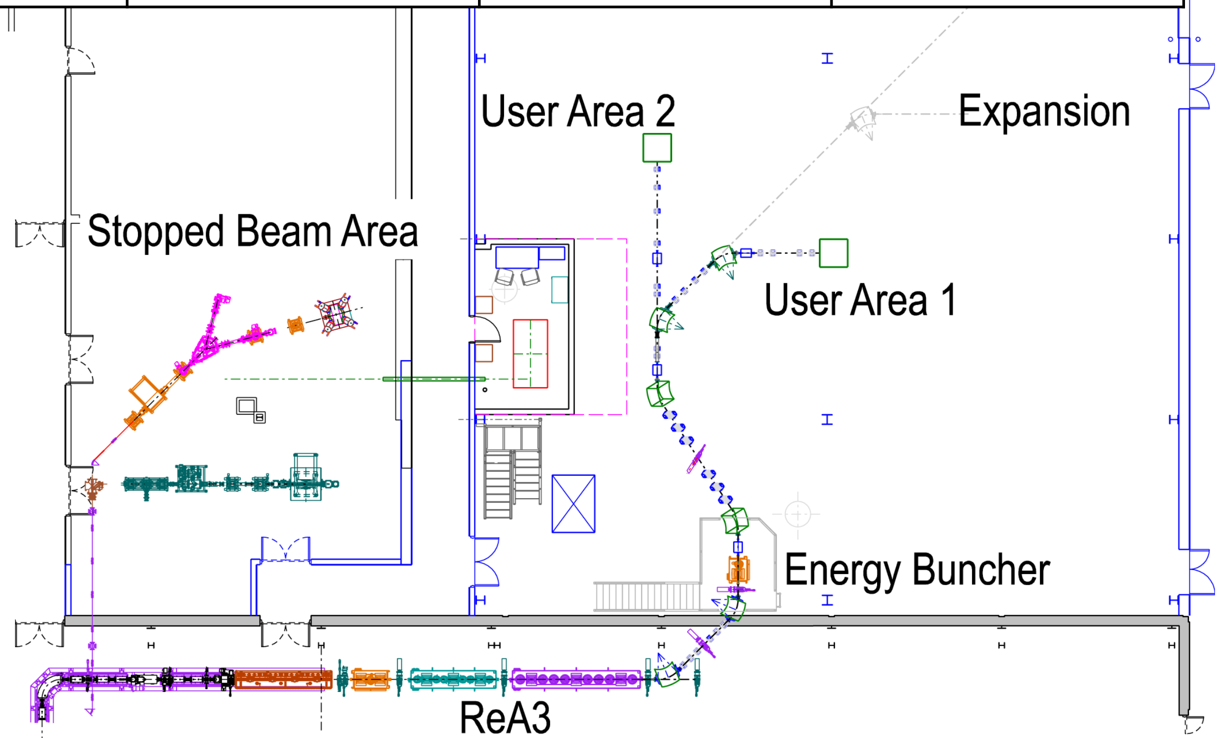


Stopped and Reaccelerated Beams Areas

operational by the end of 2010 with first experiments in 2011

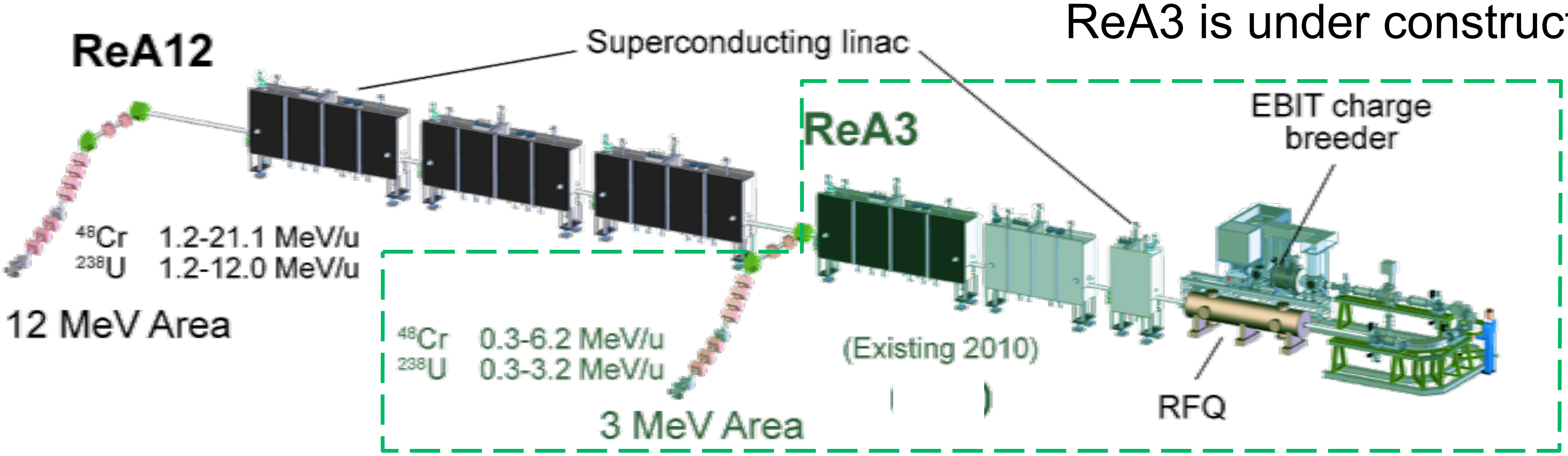
Q/A	Final Energy (AMeV)		
	Deceleration	Acceleration (Design gradient)	Acceleration (FRIB gradient)
0.20	0.3	2.4	3.8
0.25	0.3	3.0	4.6
0.50	0.3	6.0	9.4

- Initial layout with 2 beam lines; expandable to 6.
- Initial equipment
  - ANASEN (LSU/FSU)
  - AT-TPC (MSU/LLNL/LBL/St Mary's/Catania/GANIL/
  - Coulex
  - LENDA
  - Etc.
- 23 Letters of intent at last PAC



ReA12 - Reaccelerator 12 AMeV

ReA3 is under construction



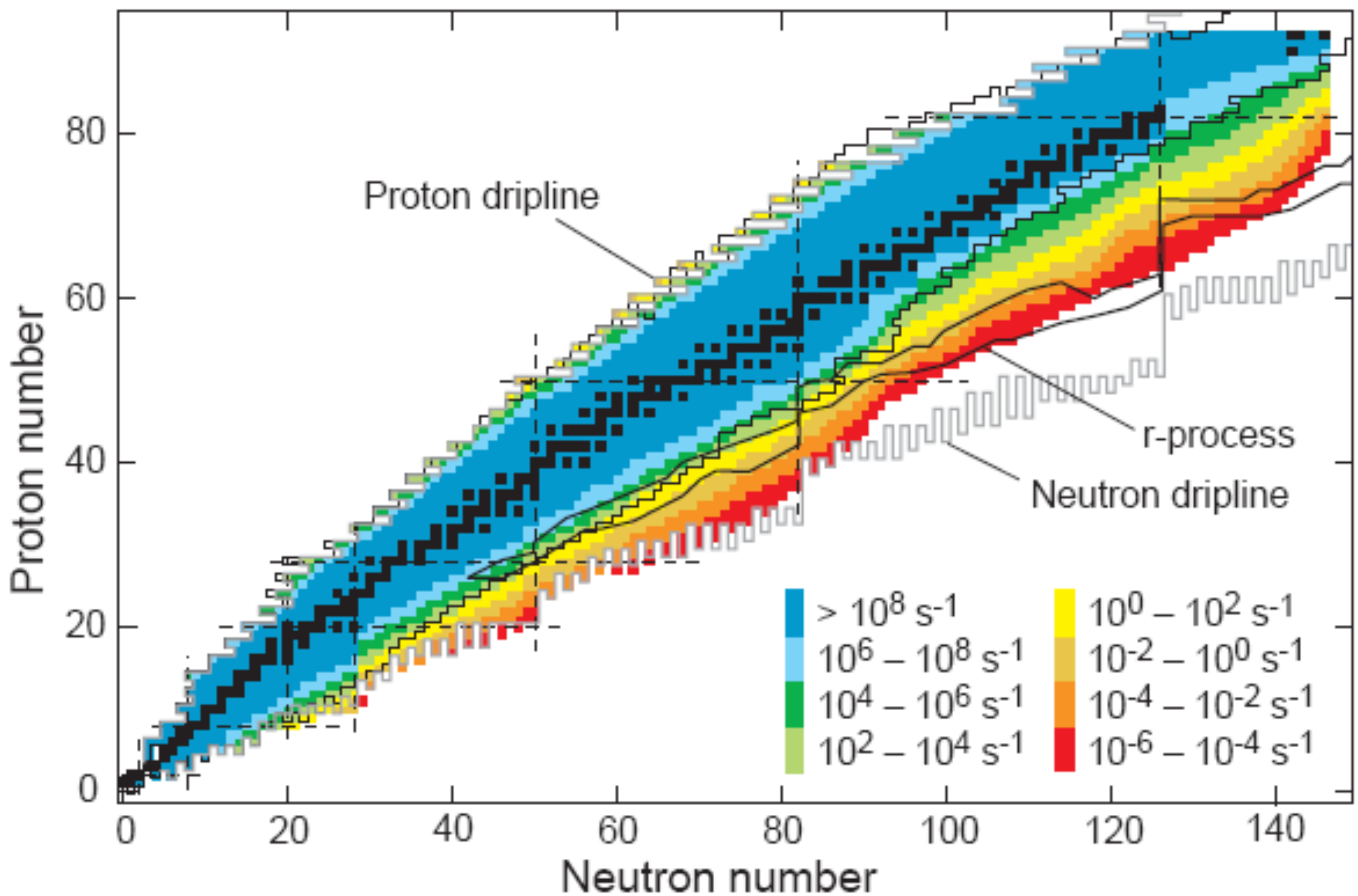
- ReA3 in operation by 2011
  - 0.3-3.2 AMeV for uranium
- Upgrade to ReA12 by adding cryomodules already designed and previously constructed
  - 1.2-12 AMeV for uranium
- Priority to fund outside the FRIB project

Schedule for FRIB Completion

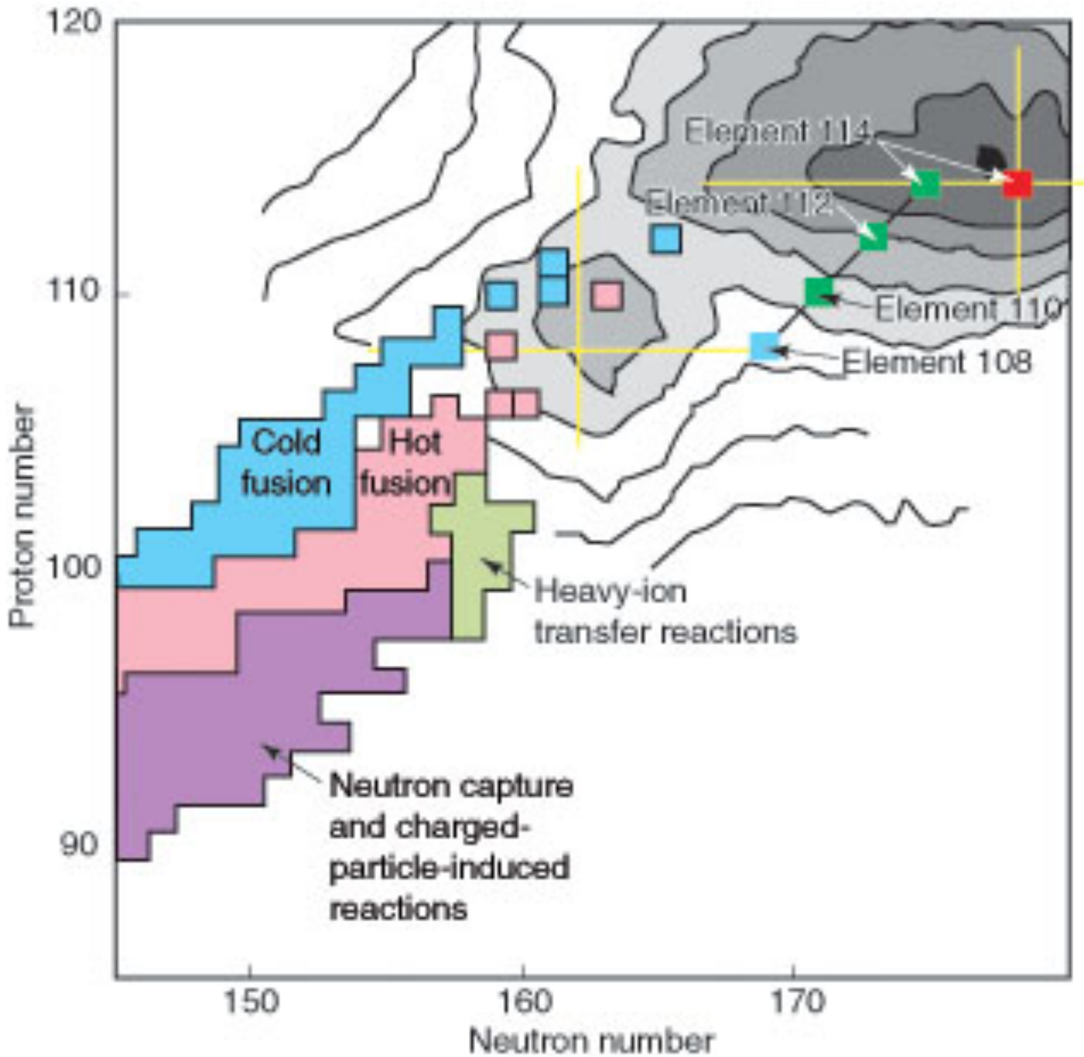
- The project will be run under the spirit of DOE order 413.3a
- 2010 – Approval of the conceptual design, start of preliminary design
- 2011 – Approval to start final design
- 2013 – Final design approved, start of construction
- 2018 – Project is complete

What new atomic nuclei will FRIB produce?

- FRIB will produce more than 1000 NEW isotopes at useful rates (5000 available for study)

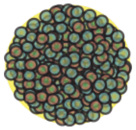


How to make Superheavy Elements



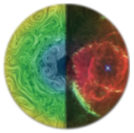
LLNL

The Science of FRIB



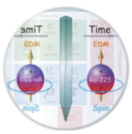
Properties of nuclei (nuclear structure)

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



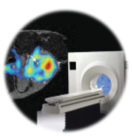
Nuclear processes in the universe

- Chemical history of the universe, (explosive) nucleo-synthesis
- Properties of neutron stars, EOS of asymmetric nuclear matter



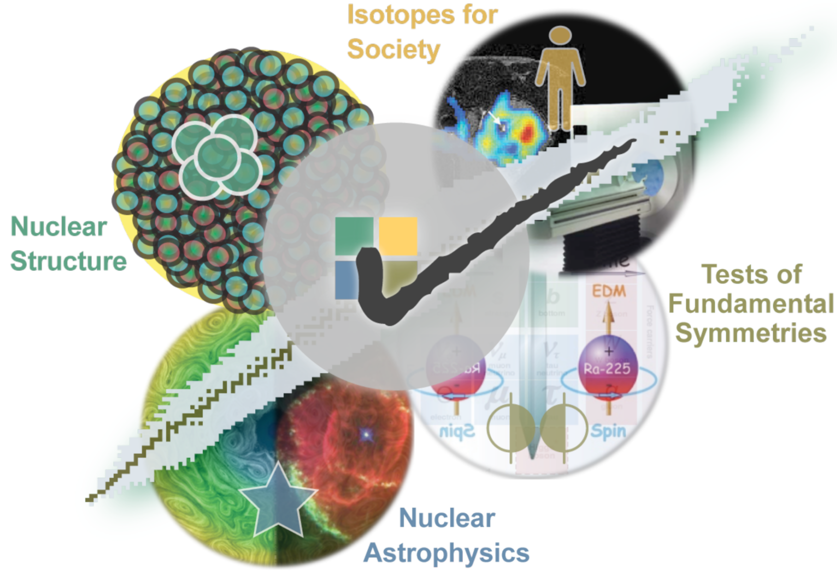
Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei



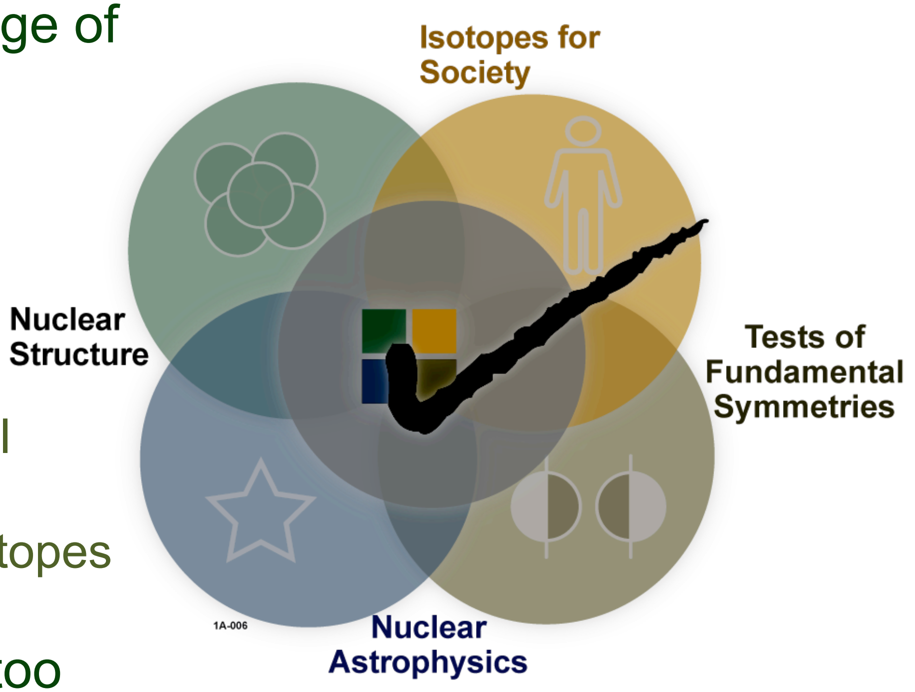
Societal applications and benefits

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



Summary

- We have entered the age of designer atoms – new tool for science
- FRIB will allow production of a wide range of new designer isotopes
  - Necessary for the next steps in accurate modeling of atomic nuclei
  - Necessary for progress in astronomy (chemical history, mechanisms of stellar explosions)
  - Opportunities for the tests of fundamental symmetries
  - Important component of a future U.S. isotopes program
- FRIB represents a vital part of the (not too far) future of nuclear physics

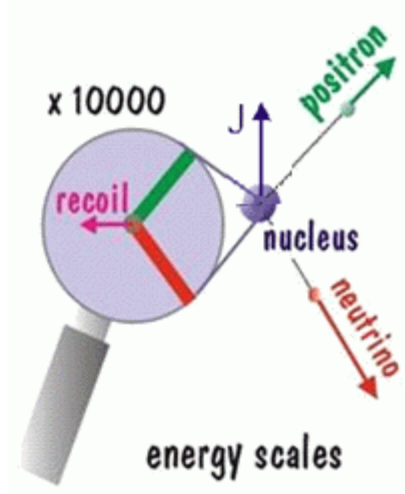


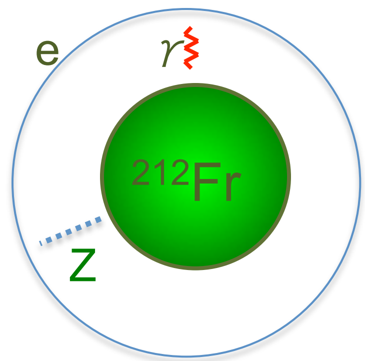
The Five-Minute Rap Version

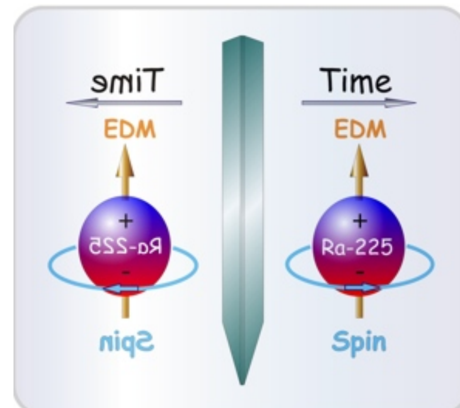
- Rare Isotope Rap by Kate McAlpine (MSU physics major)

Tests of Nature's Fundamental Symmetries

- Angular correlations in β-decay and search for scalar currents
  - Mass scale for new particle comparable with LHC
  - ^{6}He and ^{18}Ne at 10^{12}/s
- Electric Dipole Moments
  - ^{225}Ac, ^{223}Rn, ^{229}Pa (30,000 more sensitive than ^{199}Hg; I > 10^{10}/s)
- Parity Non-Conservation in atoms
  - weak charge in the nucleus (francium isotopes; 10^{9}/s)
- Unitarity of CKM matrix
  - V_{ud} by super allowed Fermi decay
  - Probe the validity of nuclear corrections







$$\begin{vmatrix} \mathbf{V_{ud}} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix}$$

Rare Isotopes For Society

- Isotopes for medical research
  - Examples: ^{47}Sc, ^{62}Zn, ^{64}Cu, ^{67}Cu, ^{68}Ge, ^{149}Tb, ^{153}Gd, ^{168}Ho, ^{177}Lu, ^{188}Re, ^{211}At, ^{212}Bi, ^{213}Bi, ^{223}Ra (DOE Isotope Workshop)
  - β-emitters ^{149}Tb, ^{211}At: potential treatment of metastatic cancer
  - Cancer therapy of hypoxic tumors based on ^{67}Cu possible is a source would be available
- Reaction rates important for stockpile stewardship and nuclear power – related to astrophysics network calculations
  - Determination of extremely high neutron fluxes by activation analysis
  - Rare isotope samples for (n, γ), (n,n'), (n,2n), (n,f) e.g. $^{88,89}Zr$
    - » Same technique important for astrophysics
  - More difficult cases studied via surrogate reactions (d,p), (^{3}He,α xn) …
- Tracers for Geology (^{32}Si), Condensed Matter (^{8}Li), material studies, …
- Special isotopes for homeland security applications (β-delayed neutron emitters to calibrate detectors, etc.)

Challenges

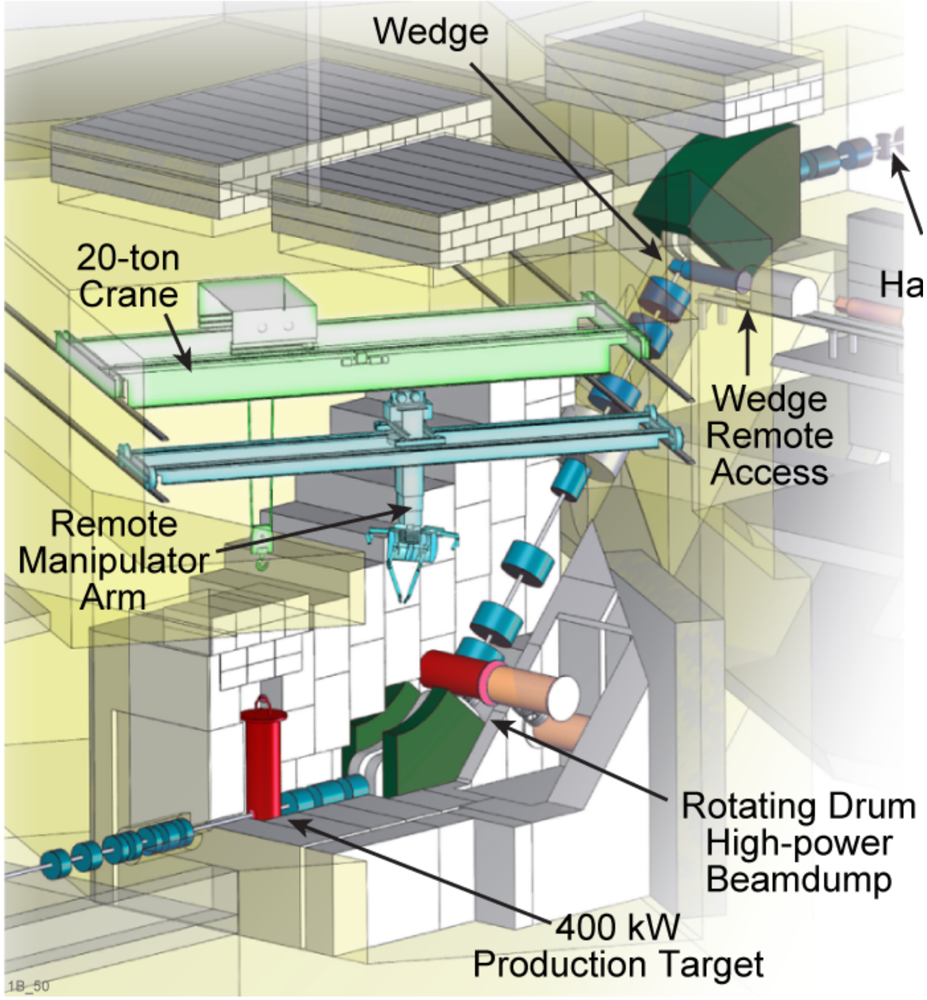
FRIB will have the highest-power heavy ion accelerator in the world: 400 kW, 200 AMeV uranium, higher energies for lighter beams

- 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?

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
  - 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

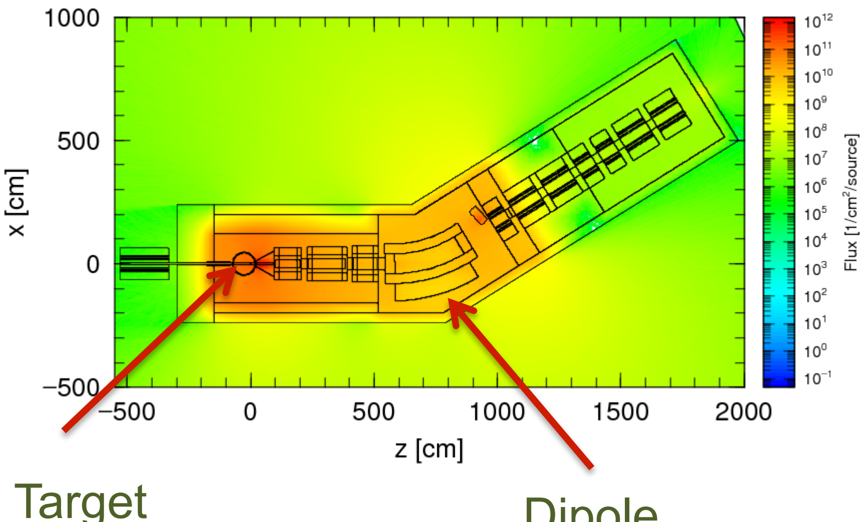


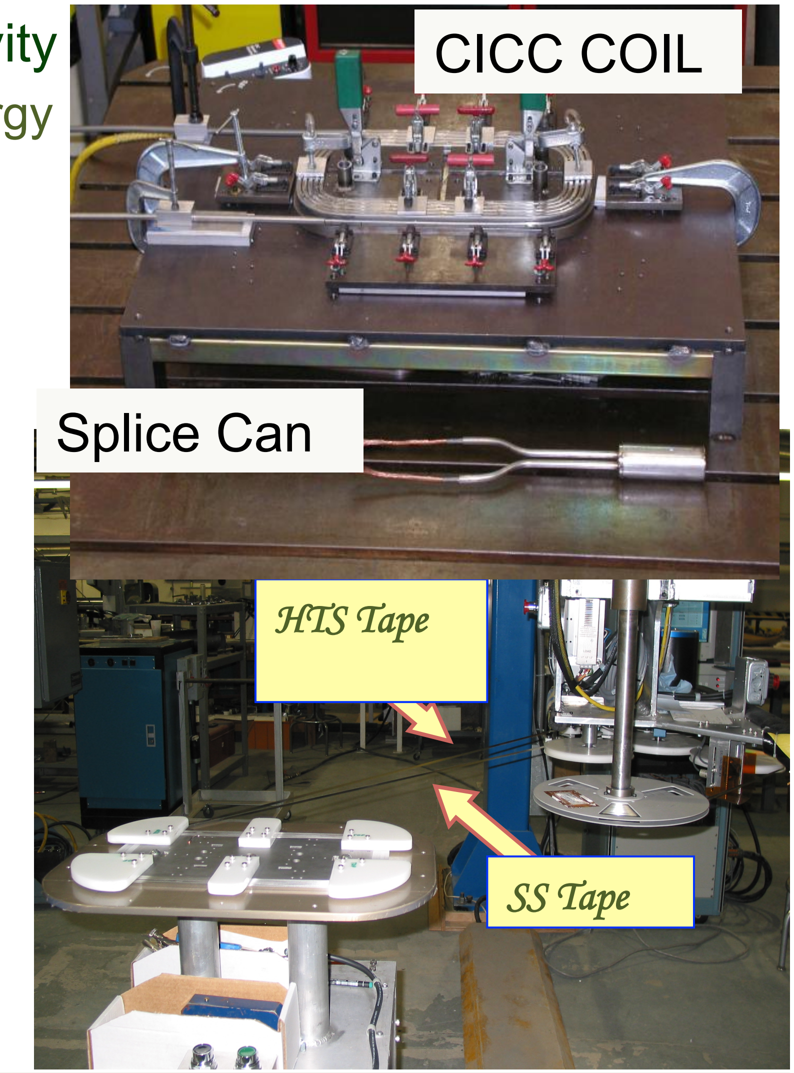
Challenges

- Accelerating technology using superconductivity
  - Allows higher electric fields to reach higher energy
  - Lower operating costs
  - How do we optimize the accelerating cavities?
- Superconducting technology for magnets

Neutron fluence on first quad:

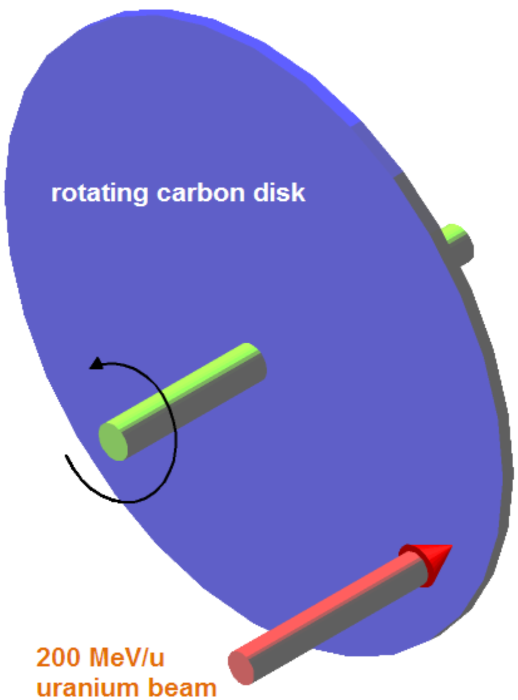
2.5×10^{15} n/cm^2 per year (1 MGy/yr) at 400 kW





Rare Isotope Production Target

- High reliability - long lifetime
- Ideally one single target concept for all beam
- 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)

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