Exotic Beam Summer School: Accelerators and Beams

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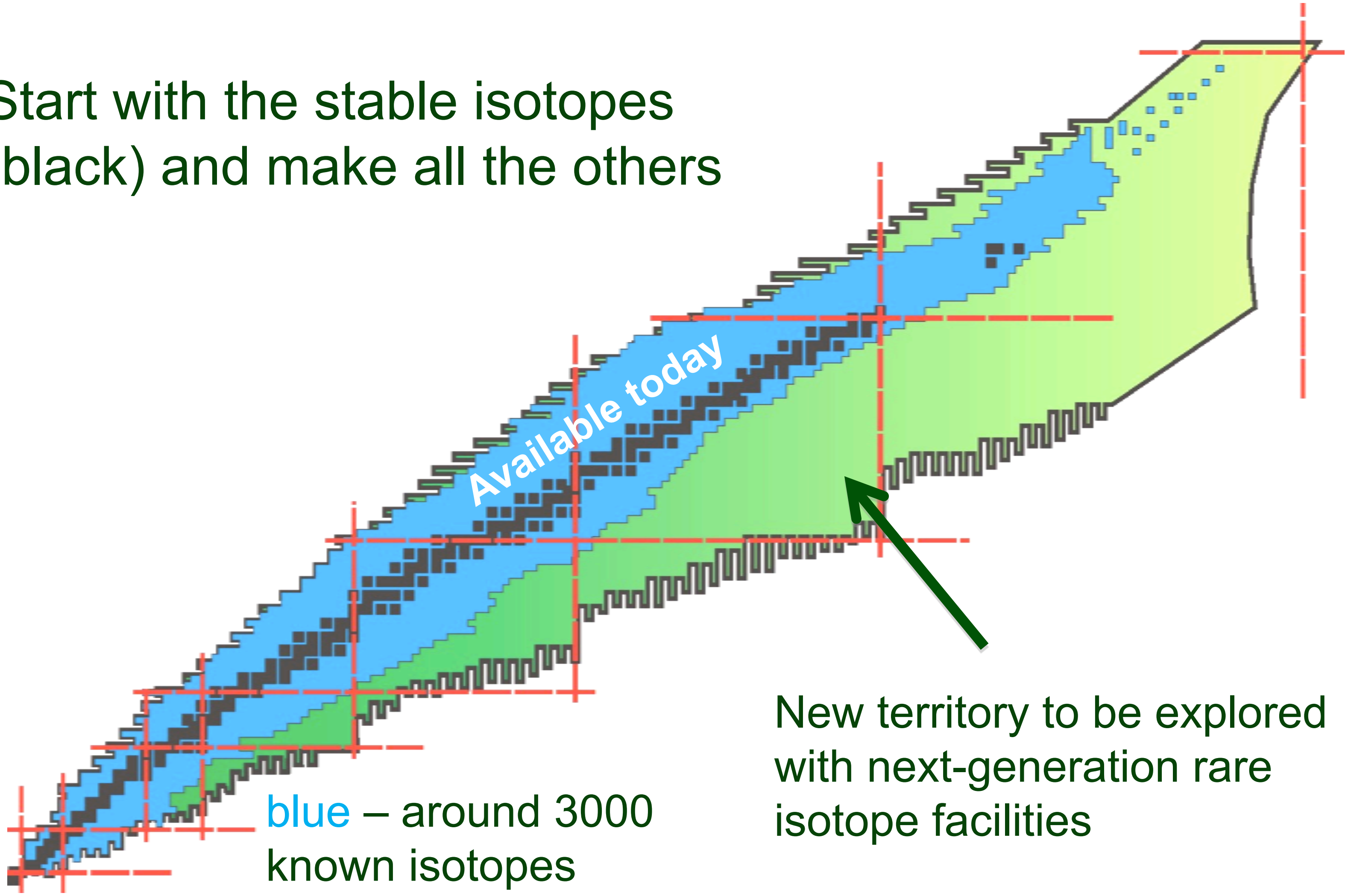
FRIB Chief Scientist

U.S. DEPARTMENT OF ENERGY

Office of Science

Accelerators are used to produce important isotopes and make beams of them

Start with the stable isotopes (black) and make all the others



blue – around 3000 known isotopes

New territory to be explored with next-generation rare isotope facilities

Rare Isotope Production Mechanisms

- There are a variety of nuclear reaction mechanisms used to add or remove nucleons (jargon)
- Spallation
- Fragmentation
- Coulomb fission (photo fission)
- Nuclear induced fission
- Light ion transfer
- Fusion-evaporation (cold, hot, incomplete, …)
- Fusion-Fission
- Deep Inelastic Transfer
- Charge Exchange

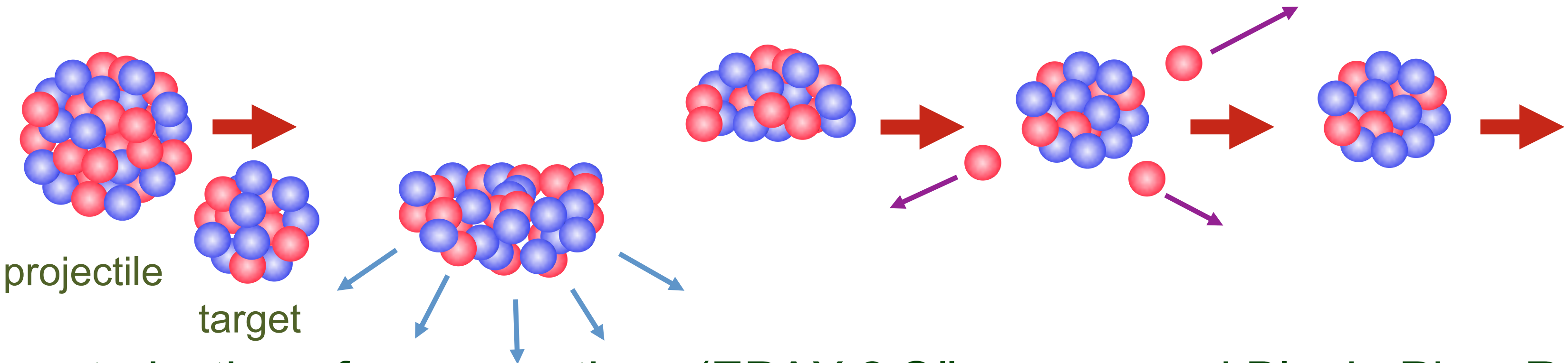
There is no best method. Many still have interesting physics question relevant to their application to produce rare isotopes.

Production Mechanisms – High Energy

- Fragmentation (used at NSCL, GSI, RIKEN, GANIL, FRIB)
  - Projectile fragmentation of high energy (>50 MeV/A) heavy ions
  - Target fragmentation of a target with high energy massive ion. In the heavy ion reaction mechanism community this would include *intermediate mass and target fragments*.
- Spallation (ISOLDE, TRIUMF-ISAC, EURISOL, SPES, …)
  - Name comes from spalling or cracking-off of target pieces.
  - Major ISOL mechanisms, e.g. ^{11}Li made from spallation of Uranium.
- Fission (HRIBF, ARIEL, ISAC, JYFL, …)
  - There is a variety of ways to induce fission (photons, protons, neutrons (thermal, low, high energy)
  - The fissioning nuclei can be the target (HRIBF, ISAC) or the beam (GSI, NSCL, RIKEN, FAIR, FRIB).
- Coulomb Breakup (GSI) At beam velocities of > 200 MeV/u the equivalent photon flux is so high the GDR excitation cross section is many barns.
- Charge Exchange (GSI, NSCL, FRIB) a neutron or proton can change its charge with a proton or neutron; cross sections can be ≈mb at >100 MeV/u

Fragmentation (Projectile)

- Pictorial model (above 50 MeV/u)



- Parameterization of cross sections (EPAX 2 Sümmerer and Blank, Phys.Rev. C61(2000)034607)
  - Parameters fit to experimental data (exponential form function of removed nucleons)
  - Energy independent cross sections (true above 50 MeV/u or so)
  - Production cross section does not depend on the target (rates do)
- More detailed models (e.g. ABRABLA (K-H Schmidt *et al.* - See http://www-win.gsi.de/charms/)
- Intranuclear Cascade Model (J.Cugnon, C.Volant and S.Vuillier, Nucl.Phys. A620 (1997) 475)

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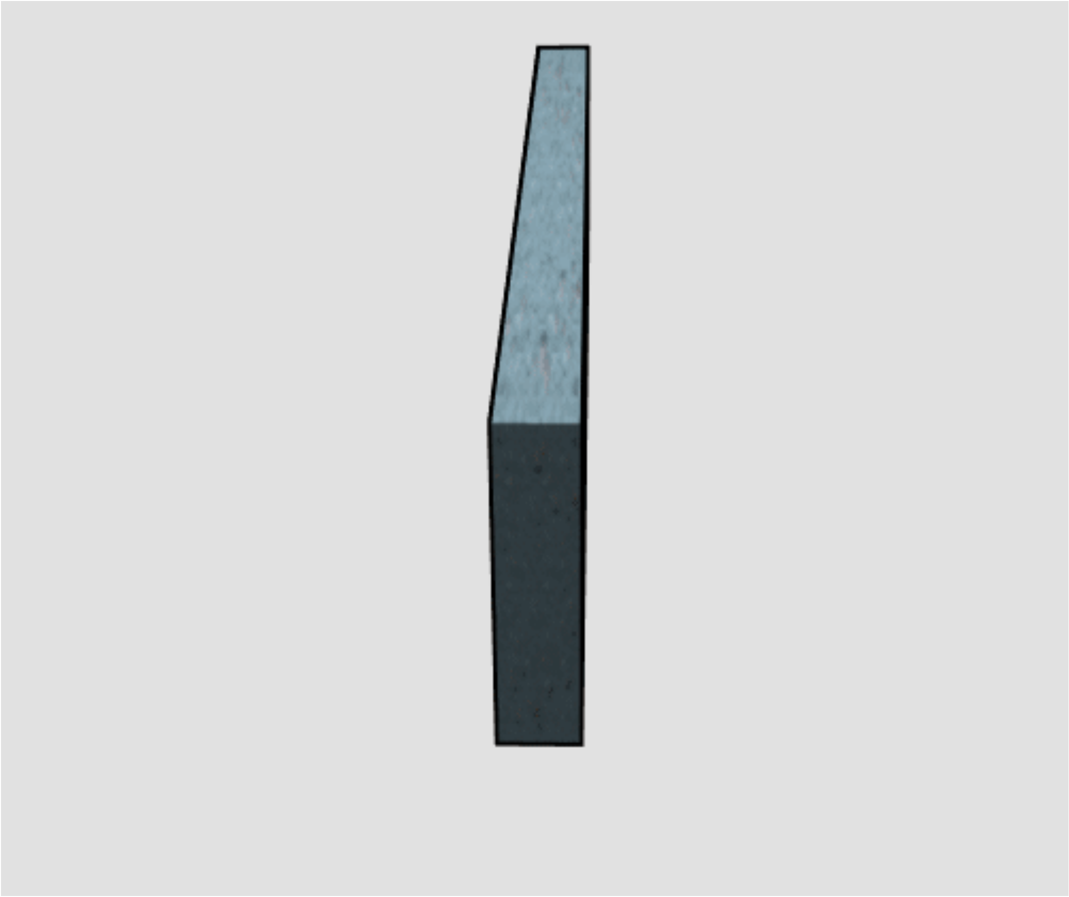
Spallation



From Wikimedia Commons: http://en.wikipedia.org/wiki/File:Spallation.gif

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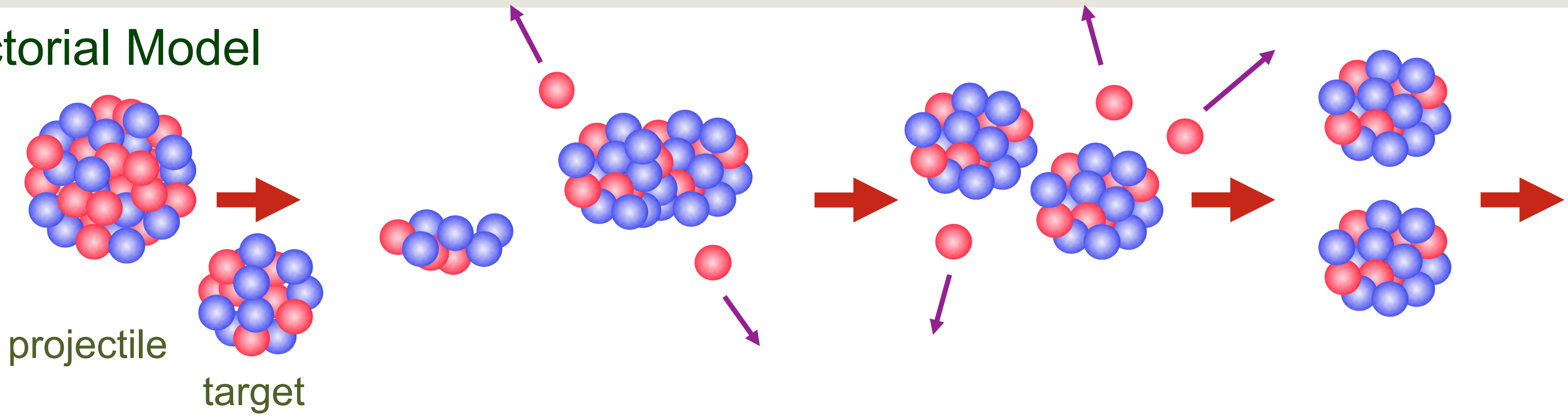
Fission

- Pictorial Model



- ABRABLA - See http://www-win.gsi.de/charms/ for excellent details (Schmidt et al.) – J. Benlluire et al. Phy. Rev. C 78 054605 (2008)
- LISE++ Fission Models (Tarasov et al.) LISE++
- The initial fragmentation step produces a wide range of excitation energies
- Can use photons, protons, nuclei, etc. to induce the fission
- Observation: For 500 MeV/u ^{238}U the fragmentation and fission cross sections are approximately equal

Production Probability

- The probability of production of a fragment is related to its production cross section:

$$P = \frac{N(\tau)}{N_0} = \left(1 - e^{-\frac{\tau N_a \sigma}{A_t}}\right)$$

τ target thickness (g/cm^2)
N_a Avagodro's number
A_t target mass number
σ production cross section

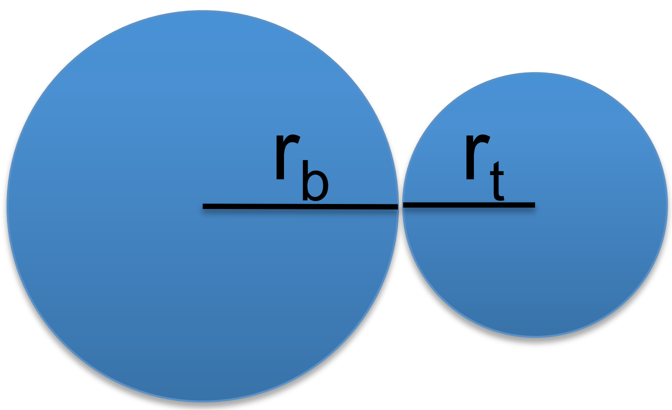
- For production cross sections of 1 mb and target thickness of 1 g/cm^2 the production probability (and fragment rate) is high:

$$P = \frac{N(\tau)}{N_0} = \left(1 - e^{-\frac{1 \cdot 6.022\times 10^{23} \cdot 1\times 10^{-27}}{9}}\right) = 7 \times 10^{-5}$$

- Beam of 10^{14}/s beam would yield $7\text{x}10^{9}$ /s

Cross sections for production

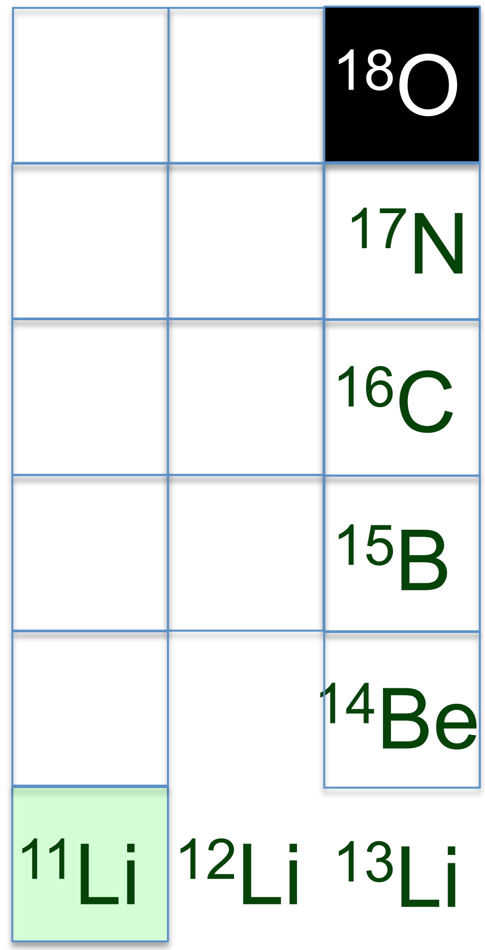
Beam (into page) Target



$$\sigma = \pi\left(r_t + r_b\right)^2 \approx 600\ mb$$

Actual: $^{16}O + ^{12}C$ interaction cross section: 1000 mb (measured at 970 MeV/u)

Note: Above around 300 MeV/u the interaction length is shorter than the electronic stopping range of the ^{16}O



One nucleon removal
Around 50 mb
(light nuclei)

P ≈ 5%

2n removal
5 mb
P = .5%

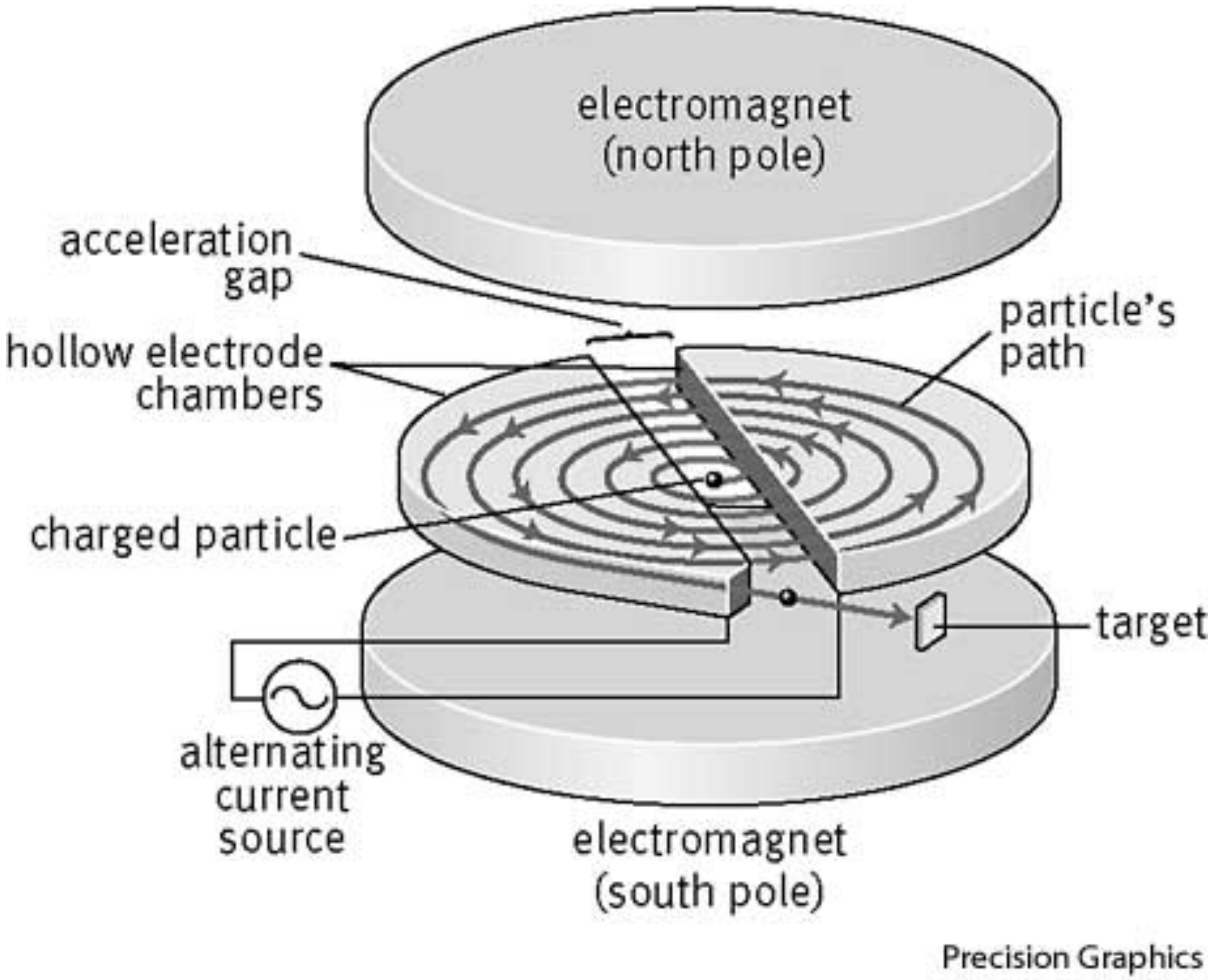
And so on
Rule of thumb
.1 x for each neutron removed

Accelerators

- The particle accelerator used for production is often called the "driver"
- Types
  - Cyclotron (NSCL, GANIL, TRIUMF (proton driver), HRIBF (proton driver), RIKEN RIBF)
  - Synchroton (GSI, FAIR-GSI)
  - LINAC (LINear ACcelerator) (FRIB, ATLAS - ANL
  - Others like FFAGs (Fixed-Field Alternating Gradient) are currently not used
- Main Parameters
  - Top Energy (e.g. FRIB will have 200 MeV/u uranium ions)
  - Particle range (TRIUMF cyclotron accelerates hydrogen, hence is used for spallation)
  - Intensity or Beam Power (e.g. 400 kW = $8x6x10^{12}$/s x 50GeV
  - Power = pμA x Beam Energy (GeV)   (1pμA = $6x10^{12}$ /s)

Cyclotrons

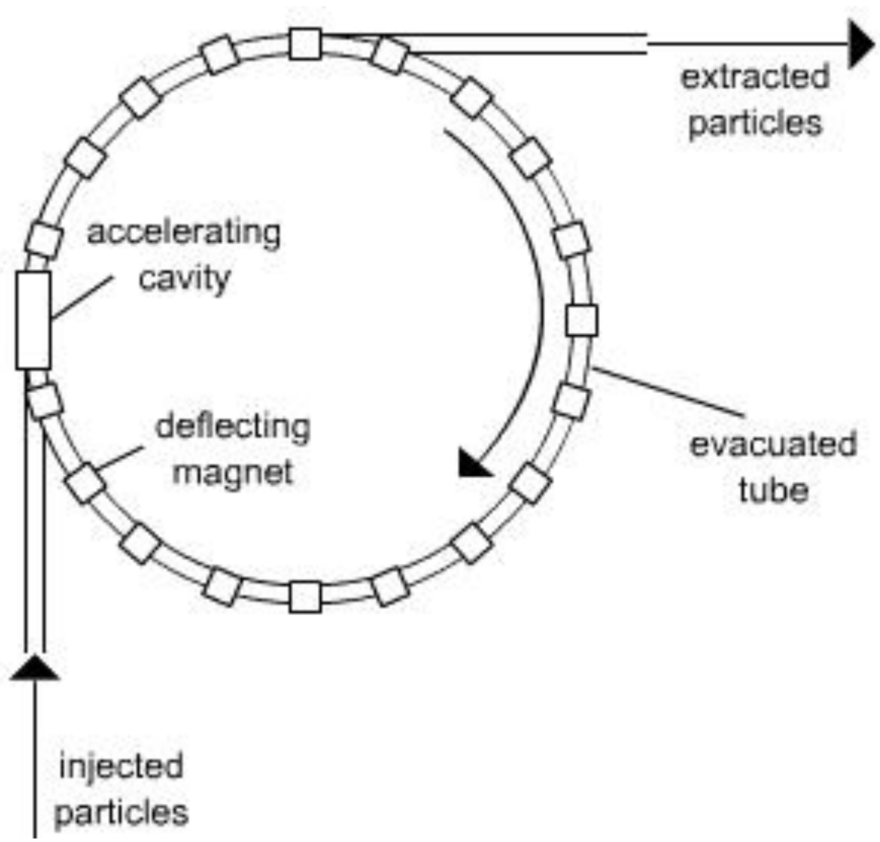
- Relatively easy to operate and tune (only a few parts.
- Tend to be used for isotope production and places where reliable and reproducible operation are important
- Intensity is moderately high, acceleration efficiency is high, cost low
- Relativity is an issue, so energy is limited to a few hundred MeV/u.
- RIKEN Superconducting Ring Cyclotron 350 MeV/u



http://images.yourdictionary.com/cyclotron

Synchrotron

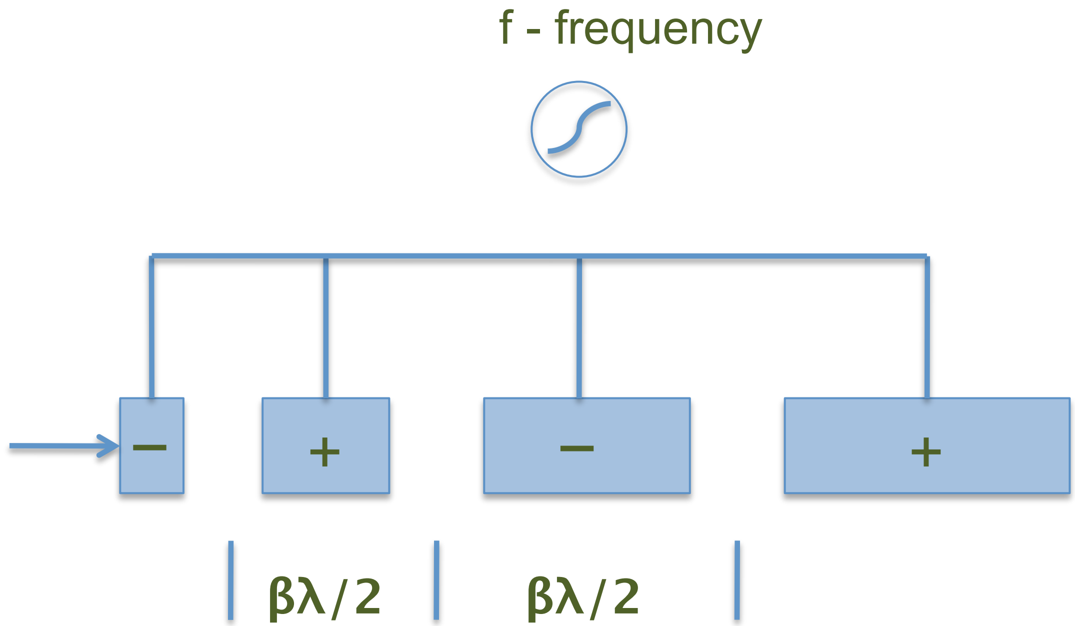
- Can achieve high energy at modest cost – tend to be used to deliver the highest energies
- Beam is accelerated in bunches
- Beam is accelerated internally and then ejected
- Intensity is limited by the Coulomb force of particles within a bunch (Space Charge)
- The magnets must ramp and this can be difficult to do quickly for superconducting magnets



http://universe-review.ca/R15-20-accelerators.htm

Linear Accelerator - LINAC

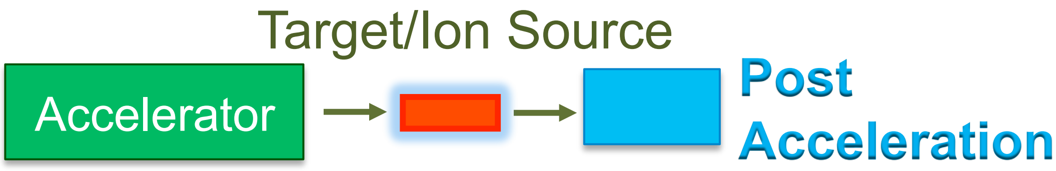
- There are many difference types
- At the right is the principle behind the drift tube linac introduced by Alverz
- Intensity can be very high
- Tuning can be difficult and complicated
- FRIB will have around 400 separate cavities
- Cost can be high
- Used to provide the highest intensities
- Electron linacs are widely used for medical applications

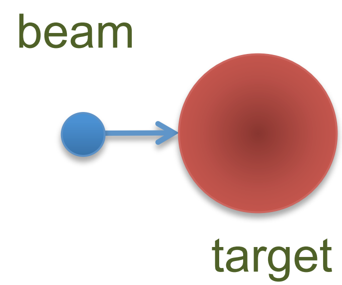


B = (v/c)

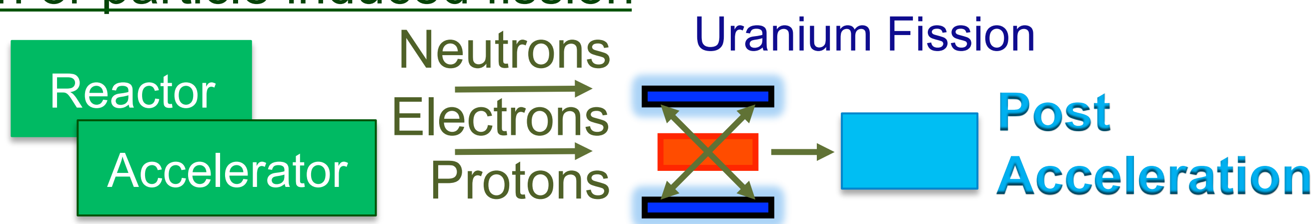
Rare Isotope Beam Production Techniques

- Target spallation and fragmentation by light ions (ISOL – Isotope separation on line)

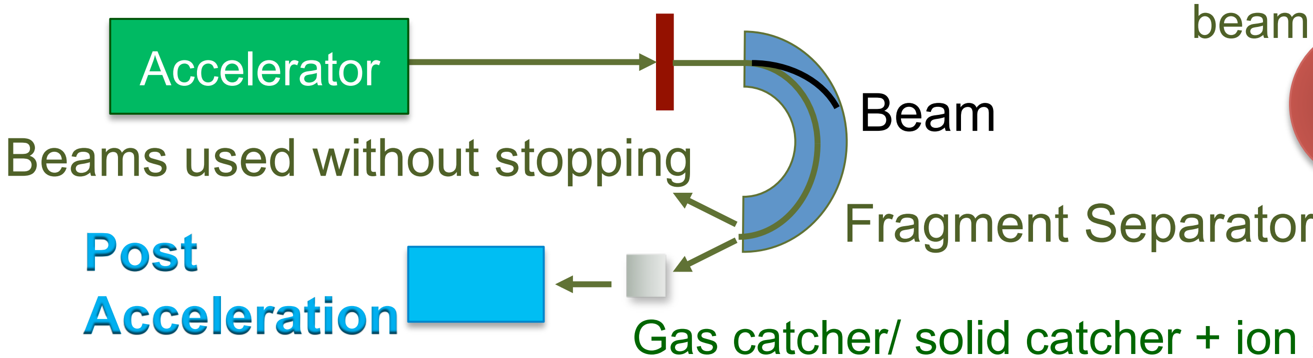


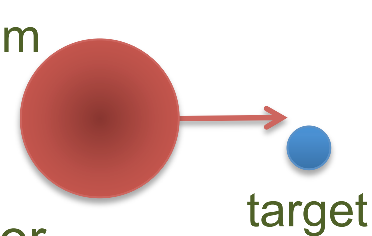


- Photon or particle induced fission

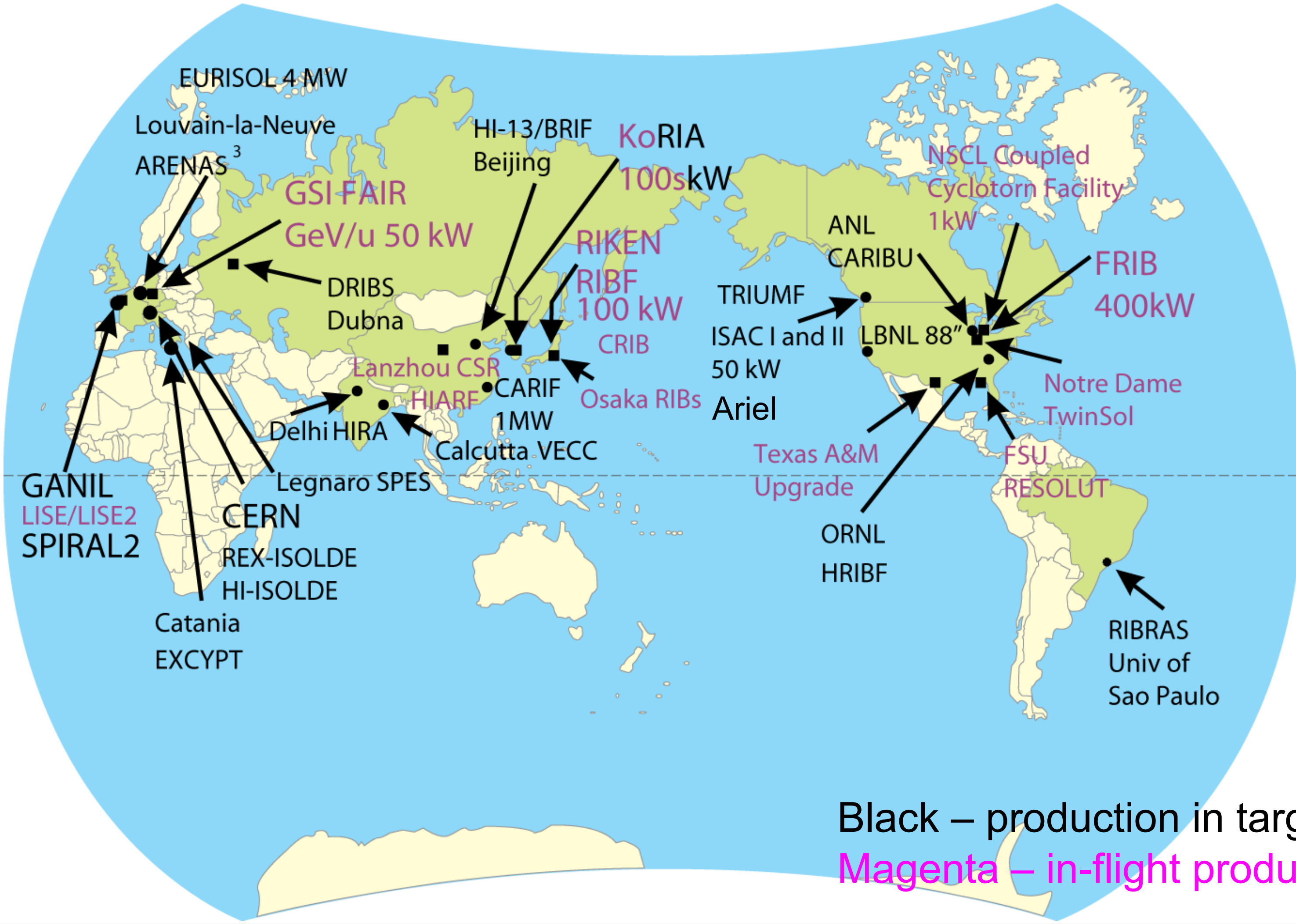


- In-flight Separation following nucleon transfer, fusion, projectile fragmentation/ fission





World view of rare isotope facilities



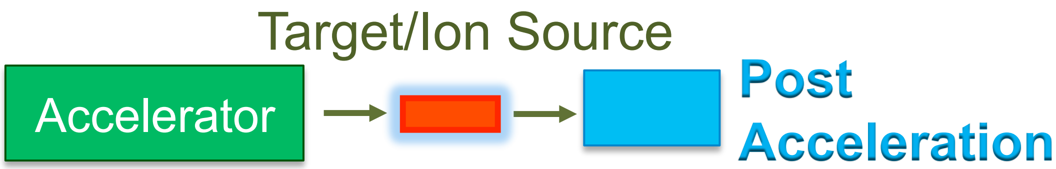
Black – production in target

Magenta – in-flight production

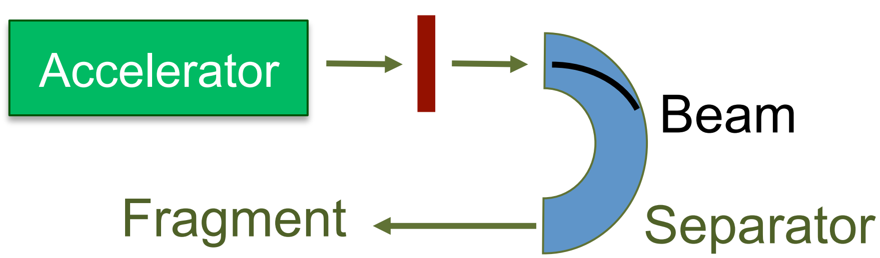
Jargon

- ISOL

400kW protons at 1 GeV is 2.4×10^{15} protons/s



- In-flight (projectile fragmentation is one production mechanism)



Less chemistry involved; beams at high energy

Advantages/Disadvantages of ISOL/In-Flight

In-flight:

GSI
RIKEN
NSCL
FRIB
GANIL
ANL
RIBBAS …

- Provides beams with energy near that of the primary beam
  - For experiments that use high energy reaction mechanisms
  - Luminosity (intensity x target thickness) gain of 10,000
  - Individual ions can be identified
- Efficient, Fast (100 ns), chemically independent separation
- Production target is relatively simple

ISOL:

HRIBF
ISAC
SPIRAL
ISOLDE
SPES
EURIOSOL

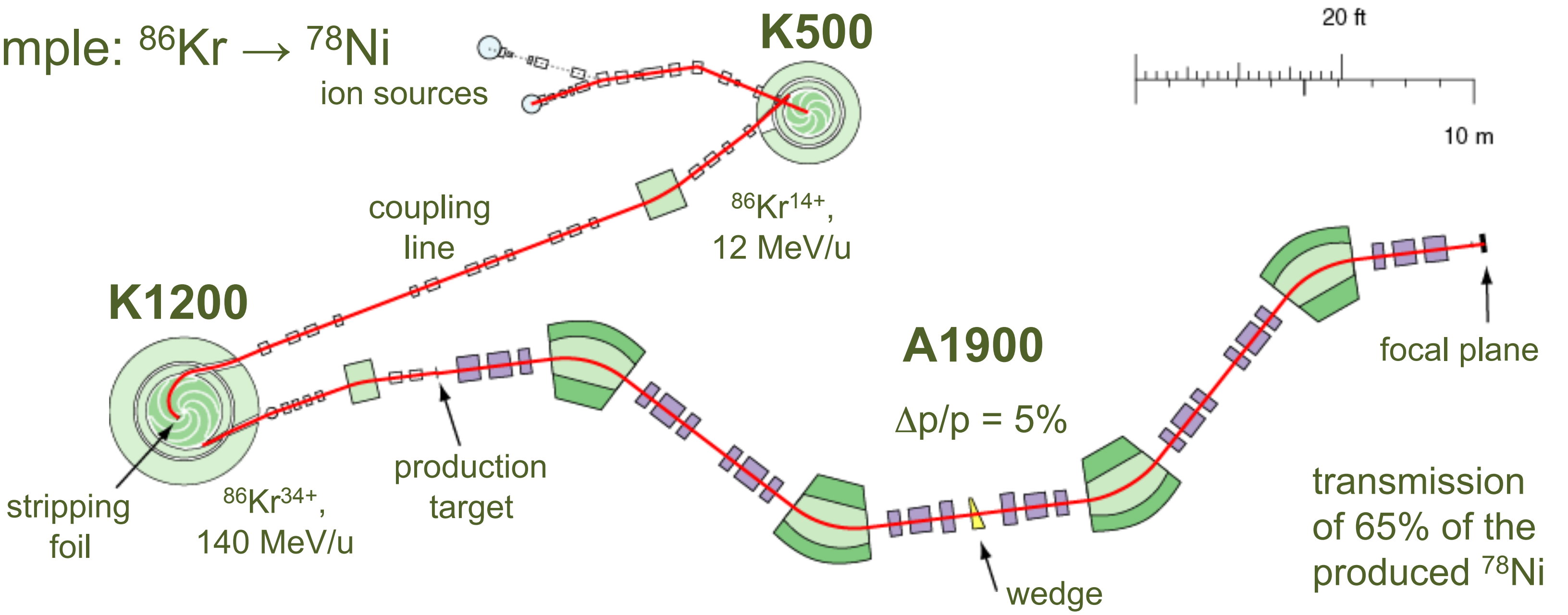
- Good Beam quality (π mm-mr vs. 30 π mm-mr transverse)
- Small beam energy spread for fusion studies
- Can use chemistry (or atomic physics) to limit the elements released
- 2-step targets provide a path to MW targets
- High beam intensity leads to 100x gain in secondary ions

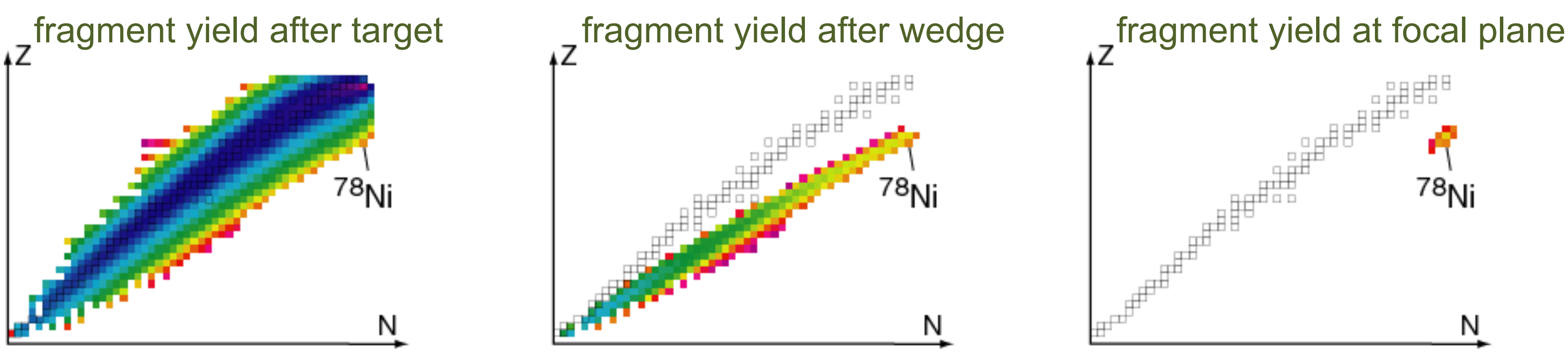
400kW protons at 1 GeV is 2.4×10^{15} protons/s

In-Flight Production Example: NSCL's CCF

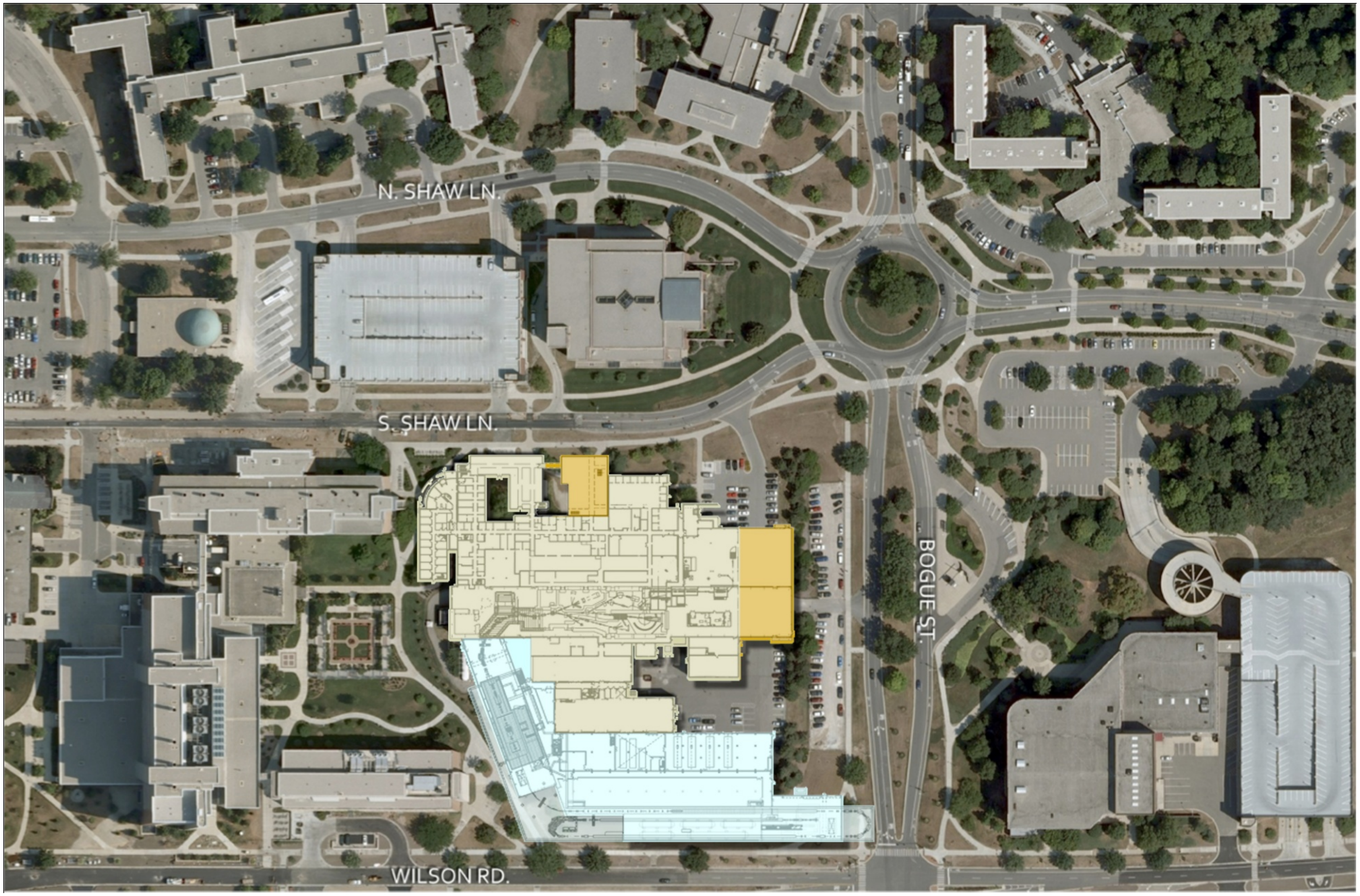
D.J. Morrissey, B.M. Sherrill, Philos. Trans. R. Soc. Lond. Ser. A. Math. Phys. Eng. Sci. 356 (1998) 1985.

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





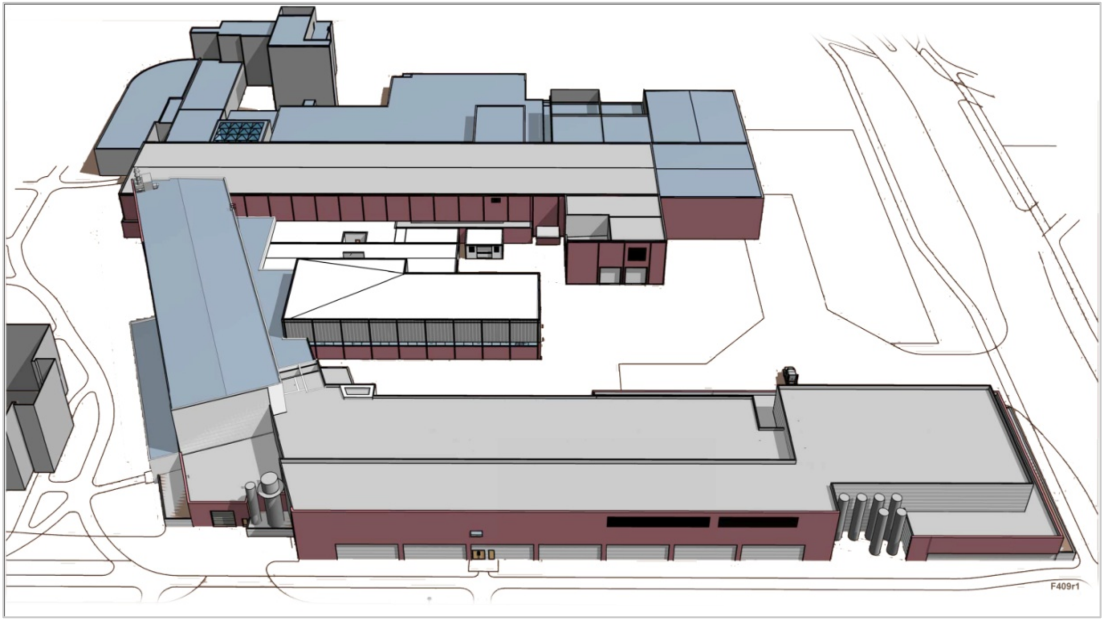
Facility for Rare Isotope Beams, FRIB - USA



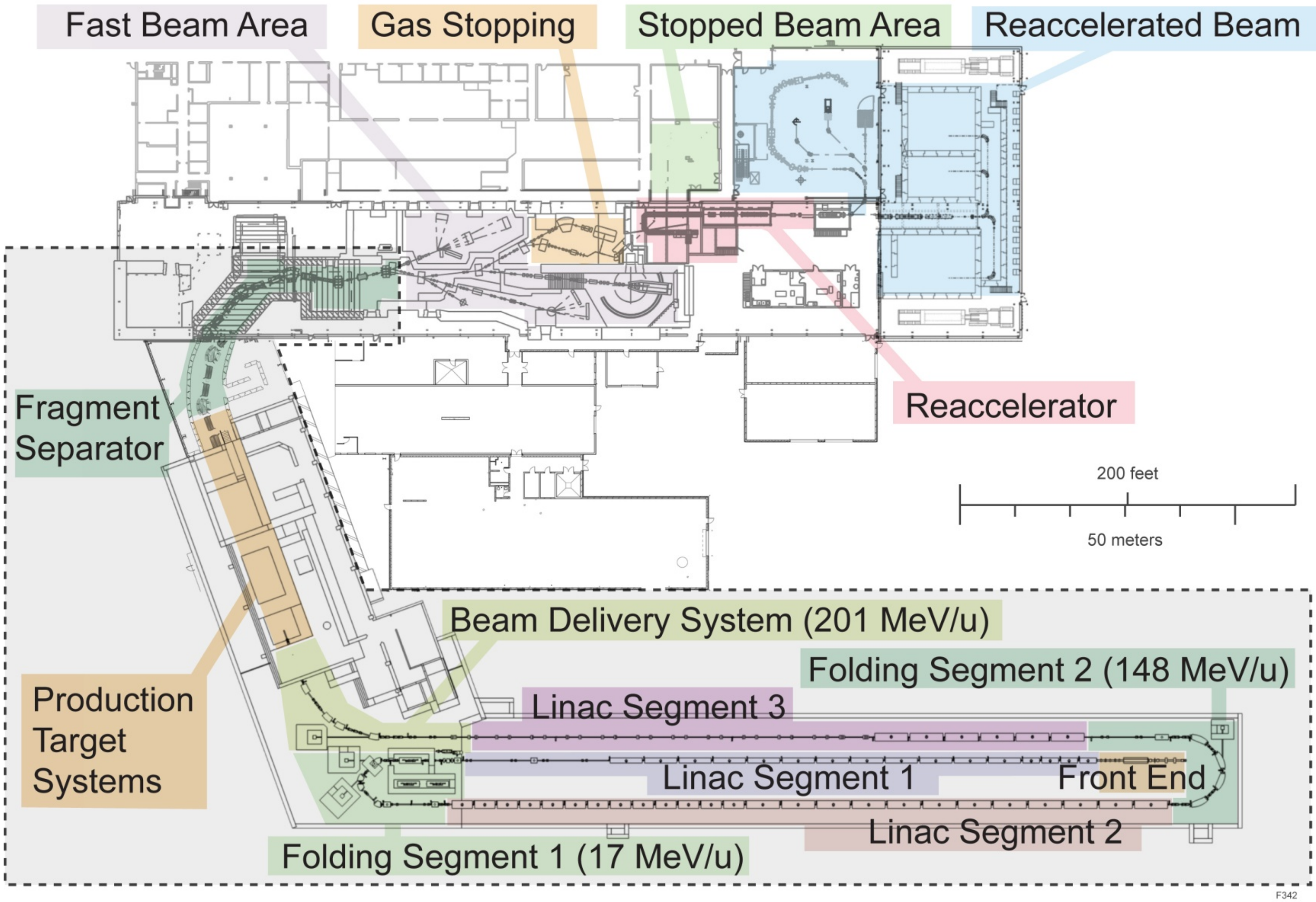
US Community's Major New Initiative – Facility for Rare Isotope Beams

- Laboratory Director Konrad Gelbke, Project Director Thomas Glasmacher
- Estimate of TPC $614.5M
- Project completion in 2020, managed for early completion in 2018
- Key features (unique)
  - 400 kW heavy ion beams
  - Efficient acceleration (multiple charge states)
  - Stopped and reaccelerated, separated beams
- Space for
  - Reaccelerated beams, uranium to 12 (15) MeV/u
  - Isotope harvesting

FRIB

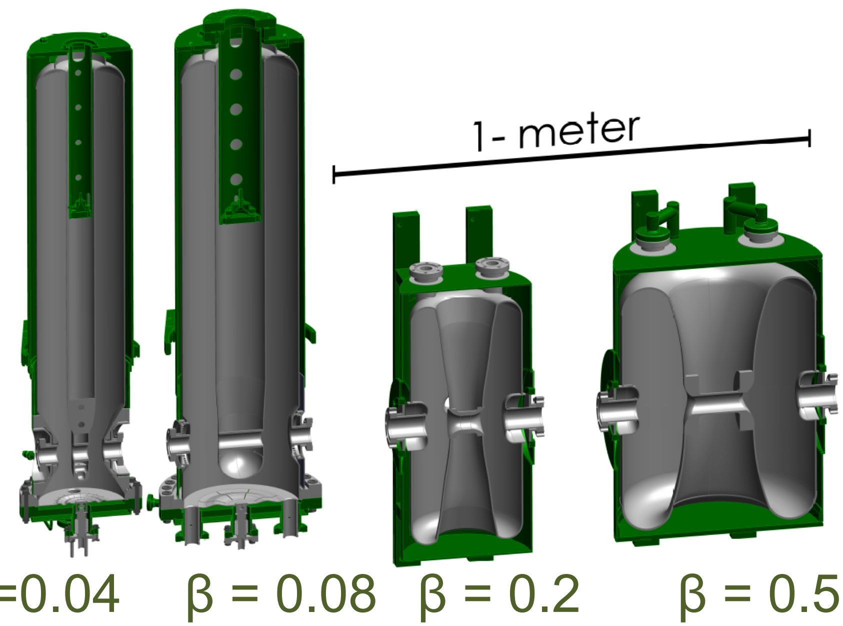


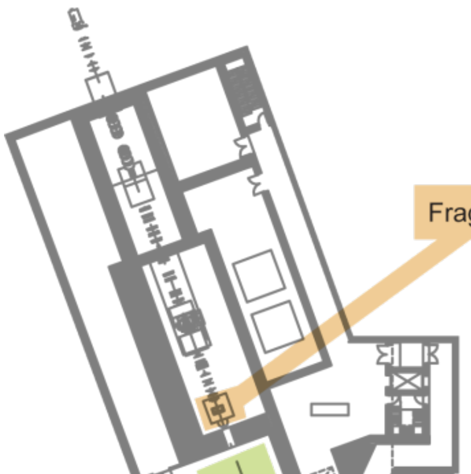
FRIB Facility Layout

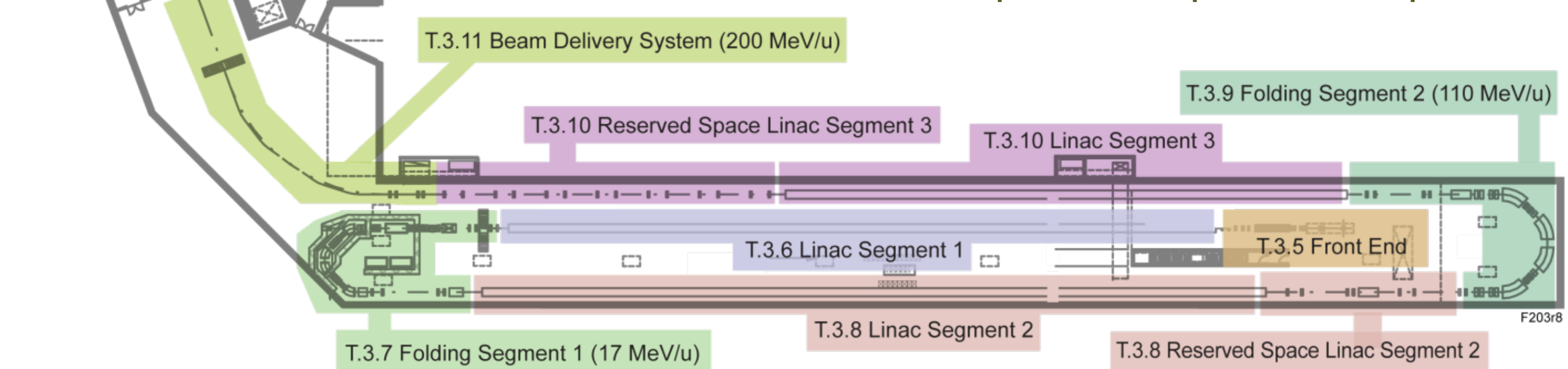


Details of the FRIB Accelerator

Superconducting
RF cavities
4 types
≈ 344 total
E_{peak} ≈ 30 MV/m

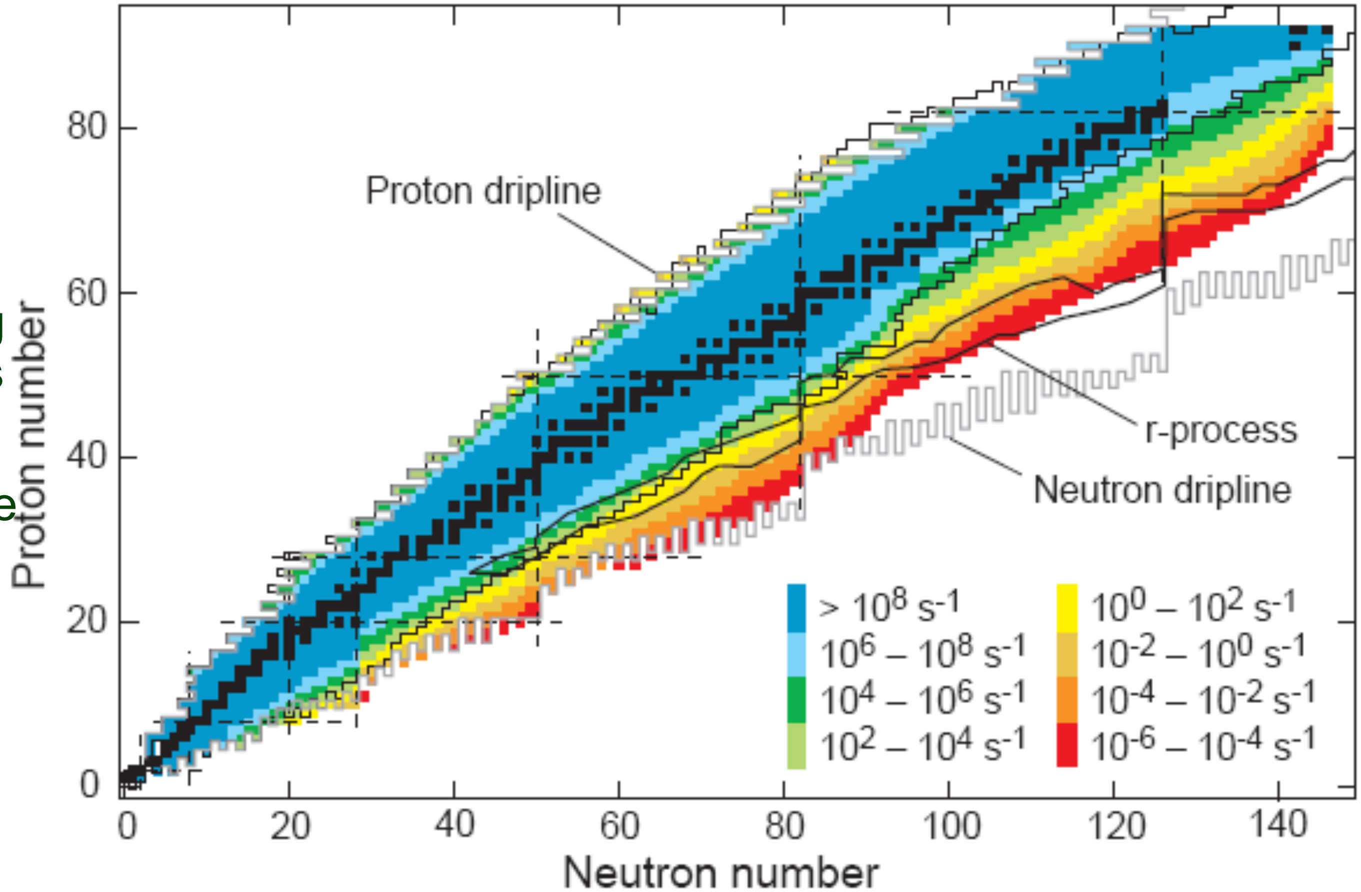






What New Nuclides Will FRIB Produce?

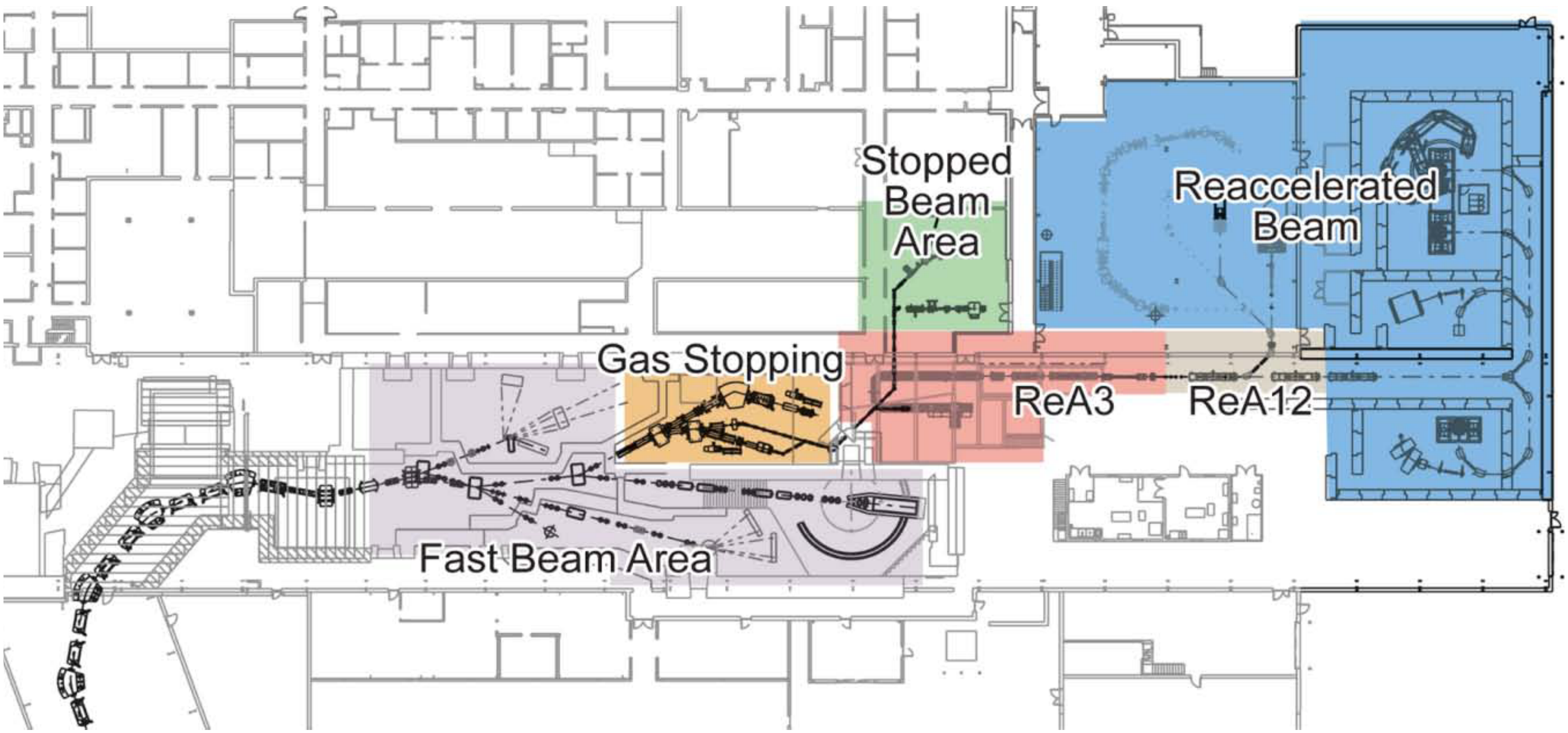
- FRIB will produce more than 1000 NEW isotopes at useful rates (4500 available for study)
- Theory is key to making the right measurements
- Exciting prospects for study of nuclei along the drip line to mass 120 (compared to 24)
- Production of most of the key nuclei for astrophysical modeling
- Harvesting of unusual isotopes for a wide range of applications



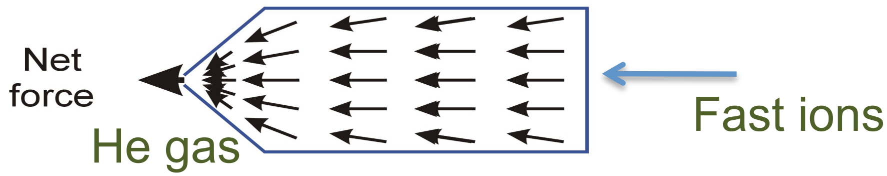
Rates are available at http://groups.nscl.msu.edu/frib/rates/

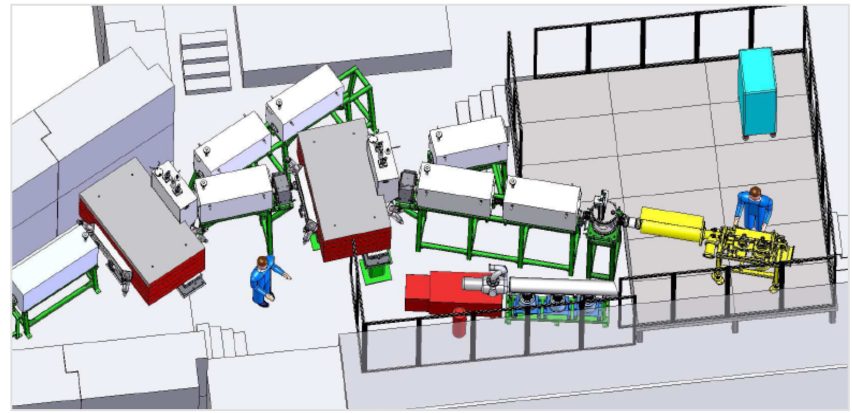
Notional Equipment Layout for Fast, Stopped, and ReA3-ReA12

- FRIB experimental areas will use existing NSCL augmented by a new ReA12 experimental area (funded by MSU, to be completed Sept 1, 2011)
- ReA12 Upgrade is essential for much of the science of FRIB



Key FRIB component: Beam Stopping

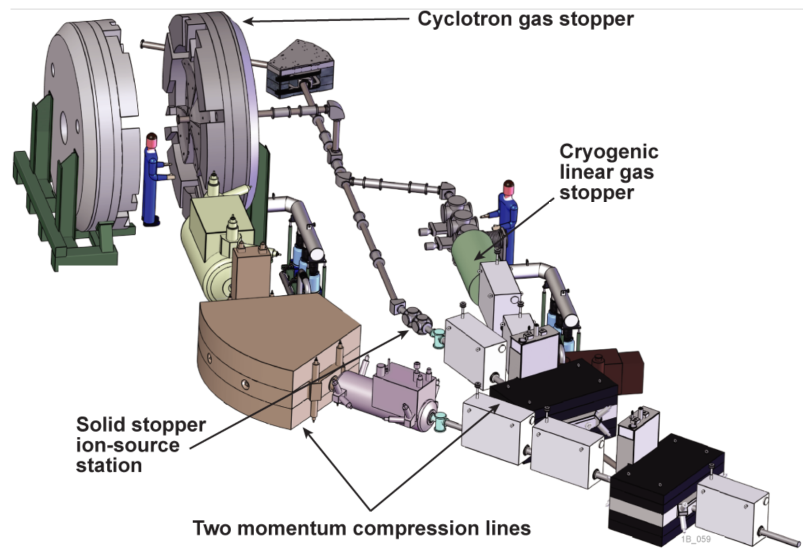




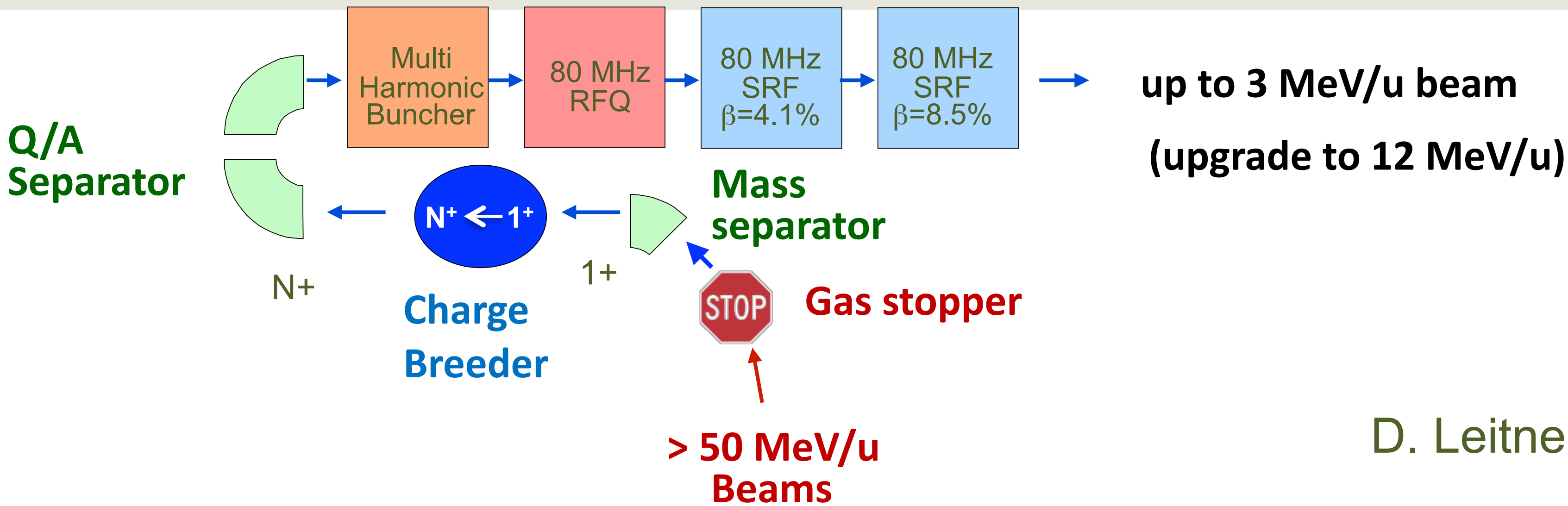
G. Savard, ANL, D. Morrissey NSCL
LLN, GSI, et al.

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

- Cyclotron gas stopper
- Linear gas stopper
- Solid stopper (LLN (Belgium), KVI (Netherlands))



ReAccelerator (3 MeV/u) (ReA3): Concept



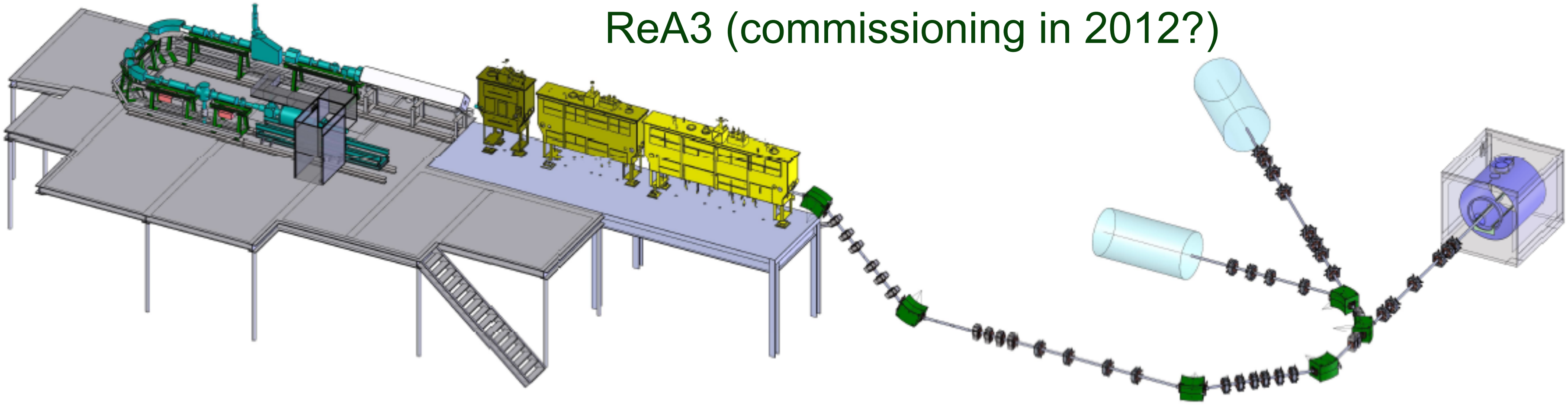
D. Leitner

Requirements		
Ion efficiency for all elements	> 20 %	EBIT charge breeder + high efficiency linac
Beam rate capabilities	10^8 ions/sec	Hybrid EBIS/T charge breeder
High beam purity		A1900, EBIT CB, Q/A
Low energy spread, short pulse length	1keV/u, 1nsec	Multiharmonic external buncher and tight phase control in SRF linac

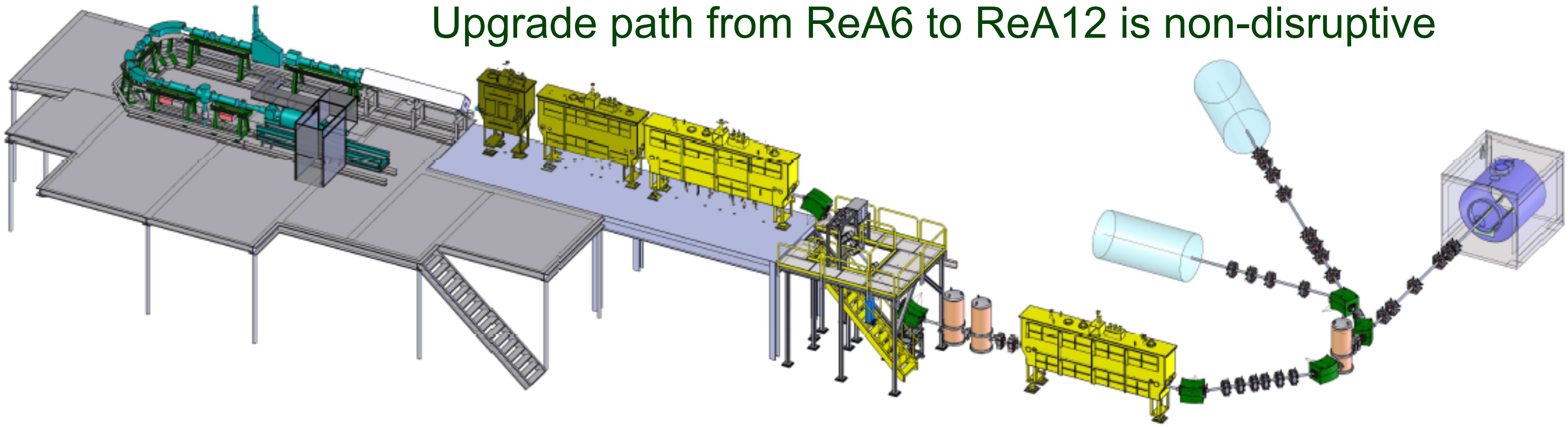
Energy upgrade of ReA3

High priority for NSCL/FRIB user community

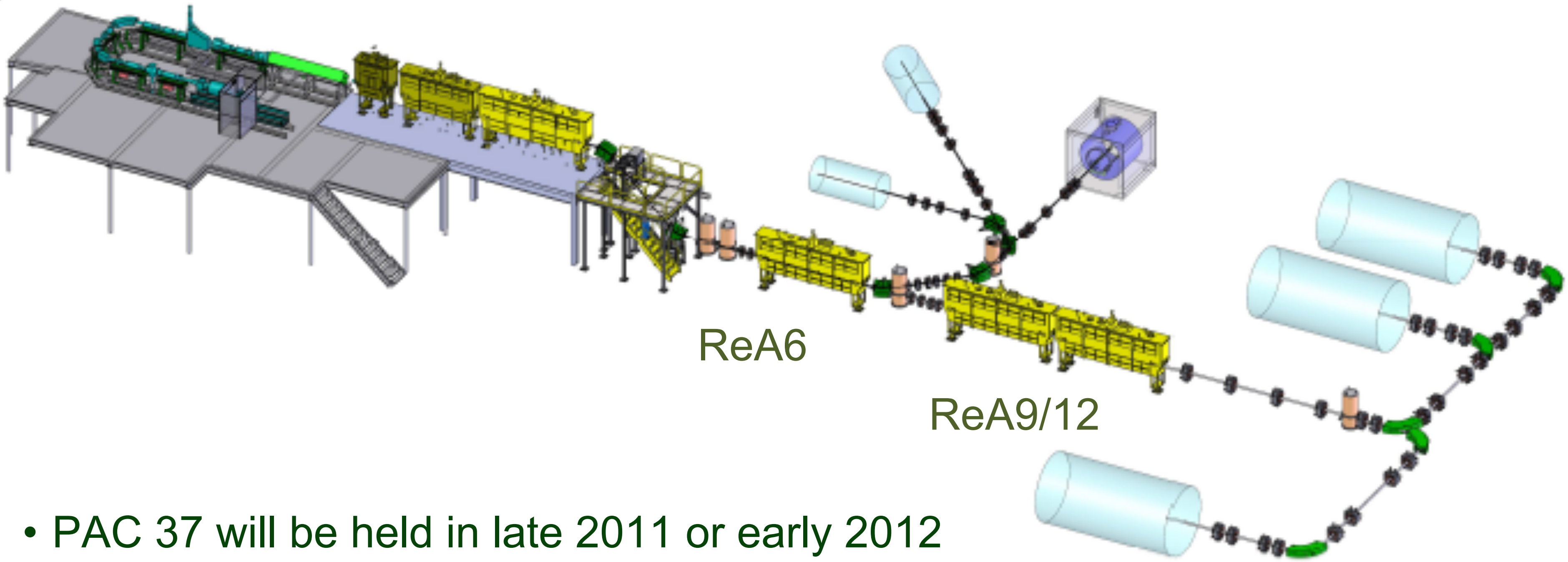
ReA3 (commissioning in 2012?)



Upgrade path to ReA6 requires minor disruption of ReA3 operations
Upgrade path from ReA6 to ReA12 is non-disruptive

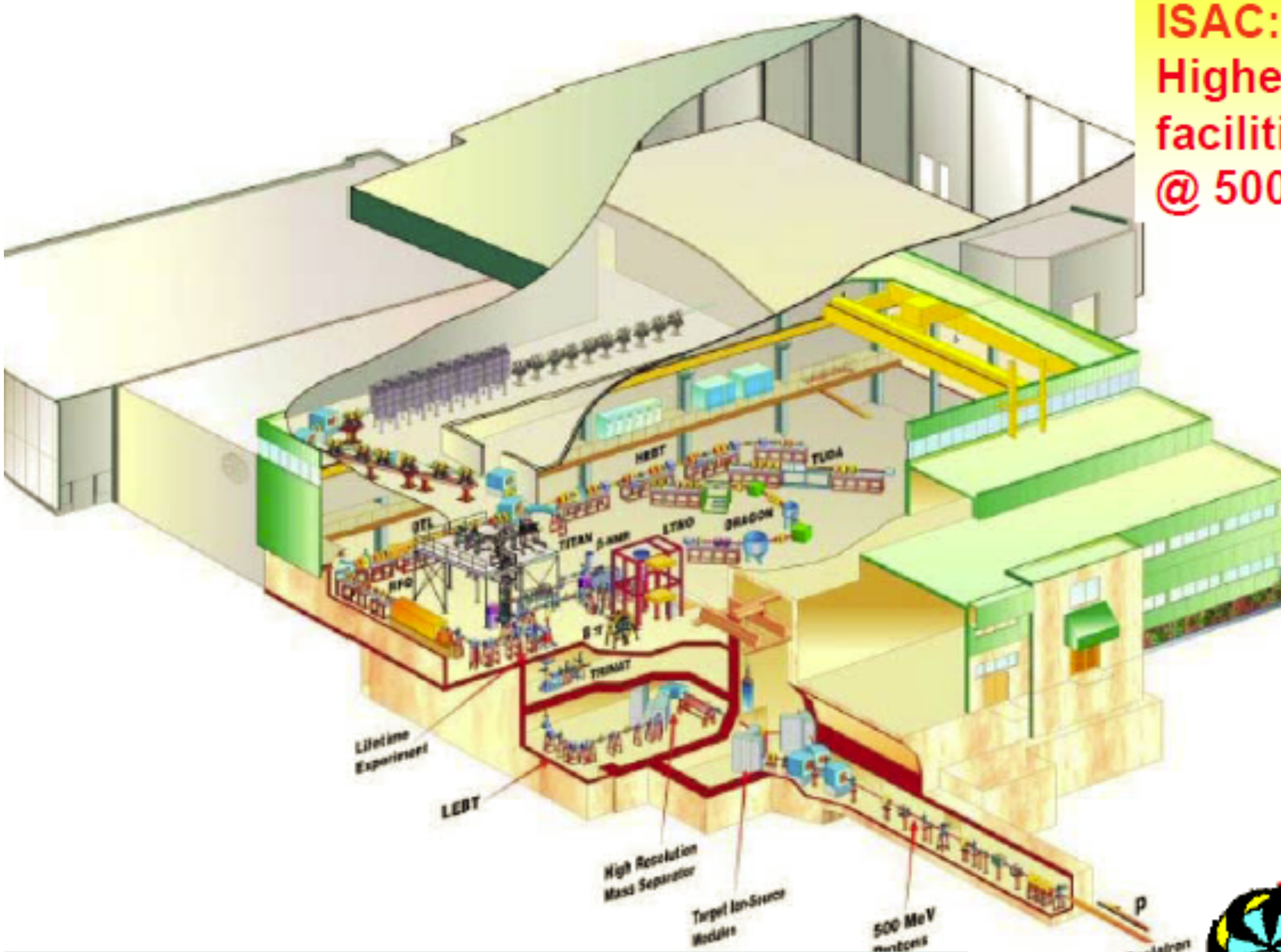


ReA3 and Upgrade Path to Higher Energies
(ReA6 and ReA12)



- PAC 37 will be held in late 2011 or early 2012
  - Proposals for reaccelerated beam experiments with ReA3 will be accepted
  - Continue to accept proposals for fast and stopped beam experiments
- Earliest start of (small scale) user program January 2013
- Operations budget has been approved by NSF
- Funding proposal has been submitted to NSF (pending)

ISAC @ TRIUMF



ISAC:
Highest power for On-Line facilities, we go up to 100μA @ 500MeV DC proton

ISAC has 3 exper. areas:

- Low energy (60keV)
- ISAC I (up 1.8 MeV/u)
- ISAC II (up to 16MeV/u, presently upgraded)

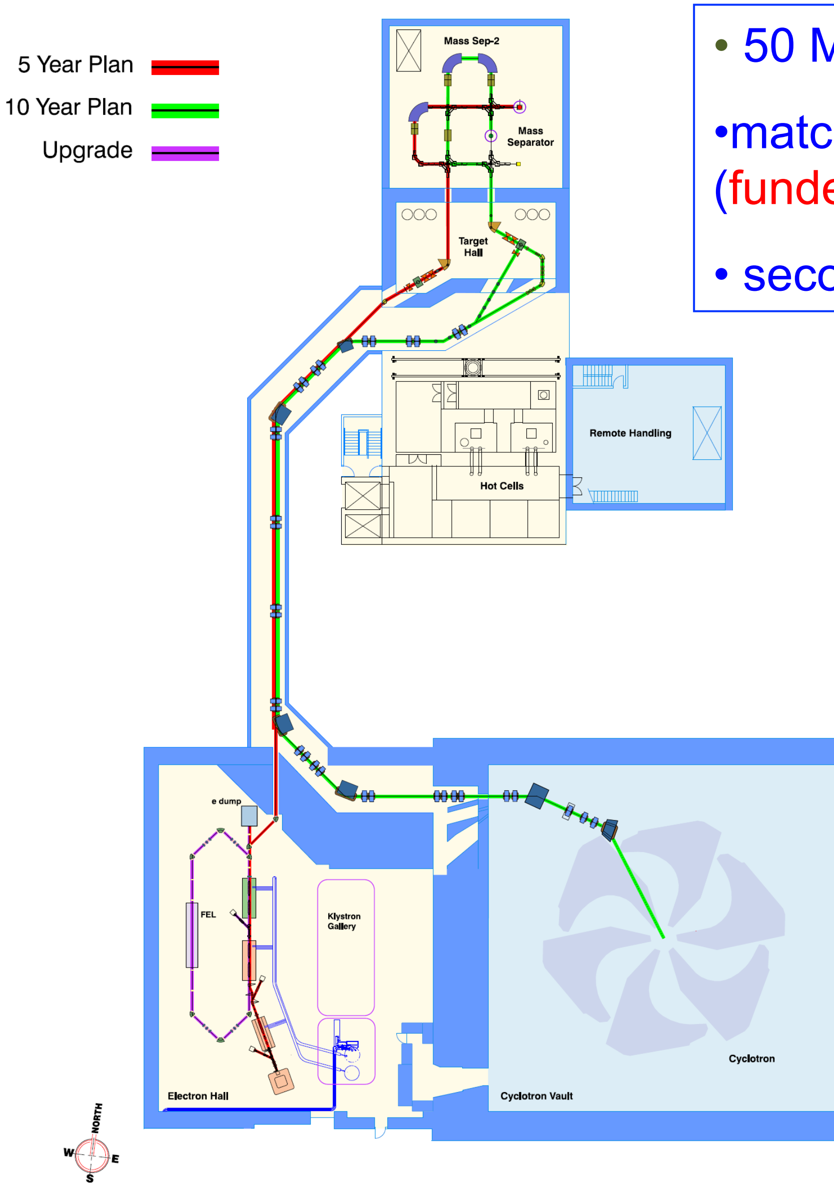
Suite of experimental stations:

- TRINAT, Beta-NMR, 8pi, tape-station, TITAN, Co-linear laser spec, polarised beam line, etc
- DRAGON, TUDA, TACTIC, GPS,
- TIGRESS, EMMA (2011), HERACLES

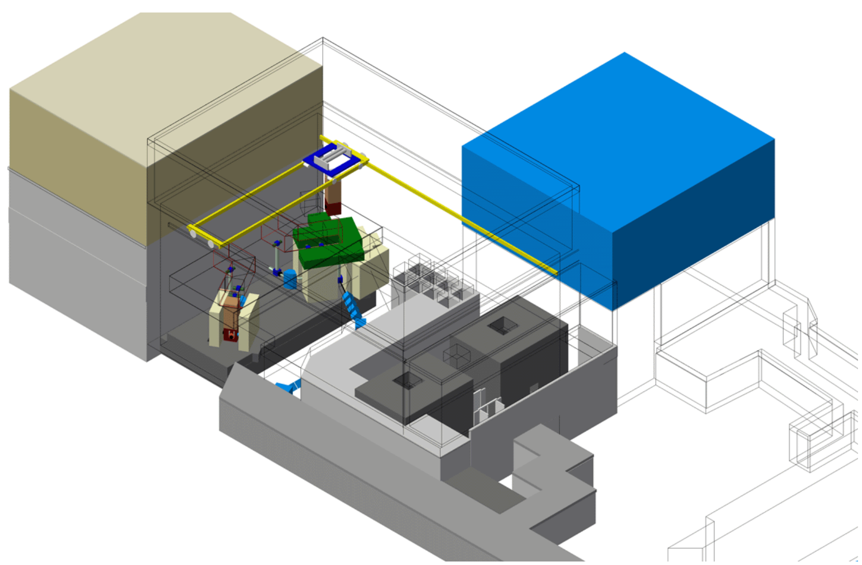
Target material for beam production includes U (UO and UC license)
Ion sources: surface, laser, FEBIAD, ECR (test)
TRIUMF part of collaborations for target and ion source R&D

Gordon Ball, TRIUMF

Present status of the Ariel Project



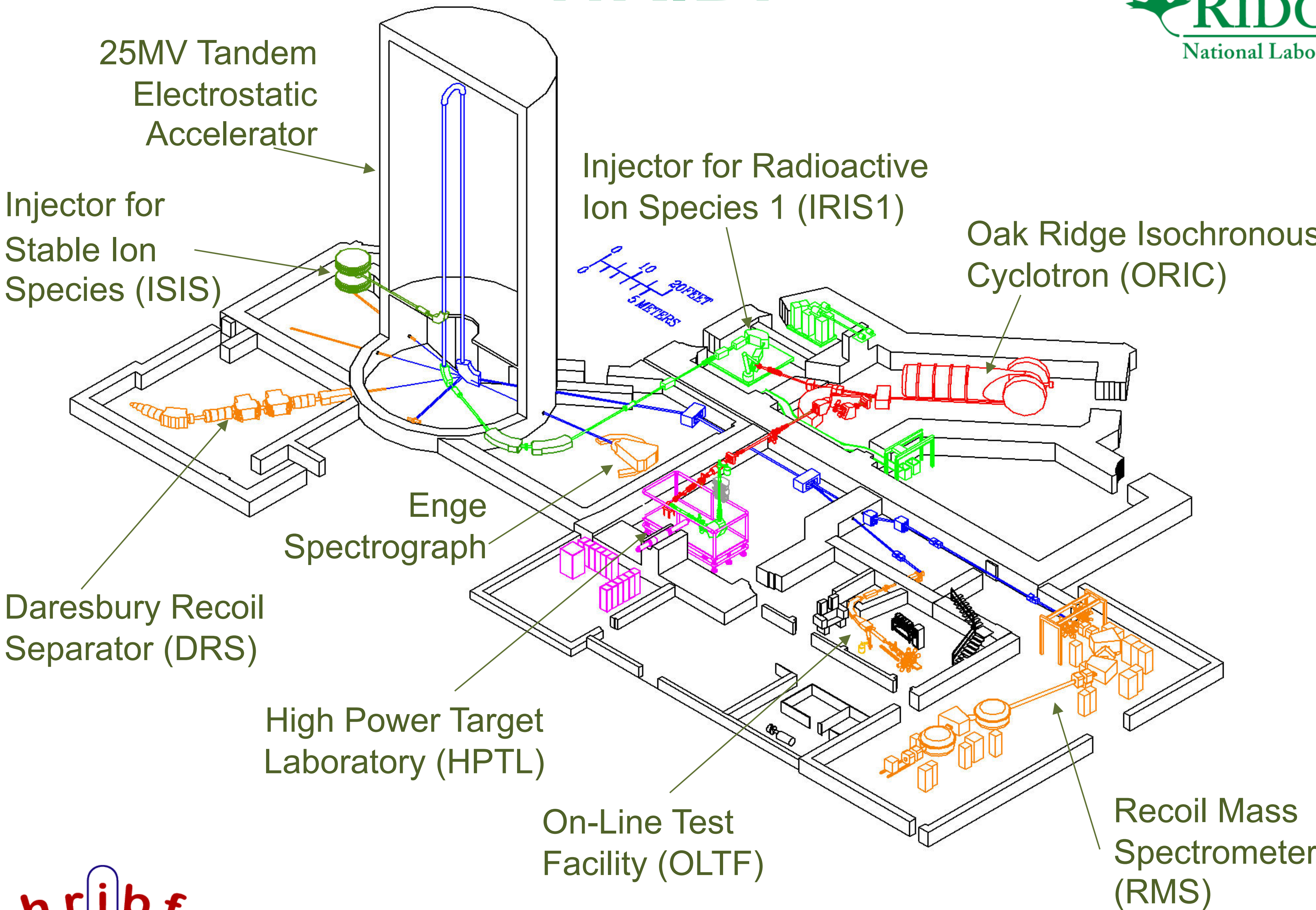
- 50 MeV, 500 kW superconducting e-linac funded
- matching funding from BC province for buildings (funded June 2010)
- second proton beamline deferred until next 5YP



Gordon Ball, TRIUMF

HRIBF

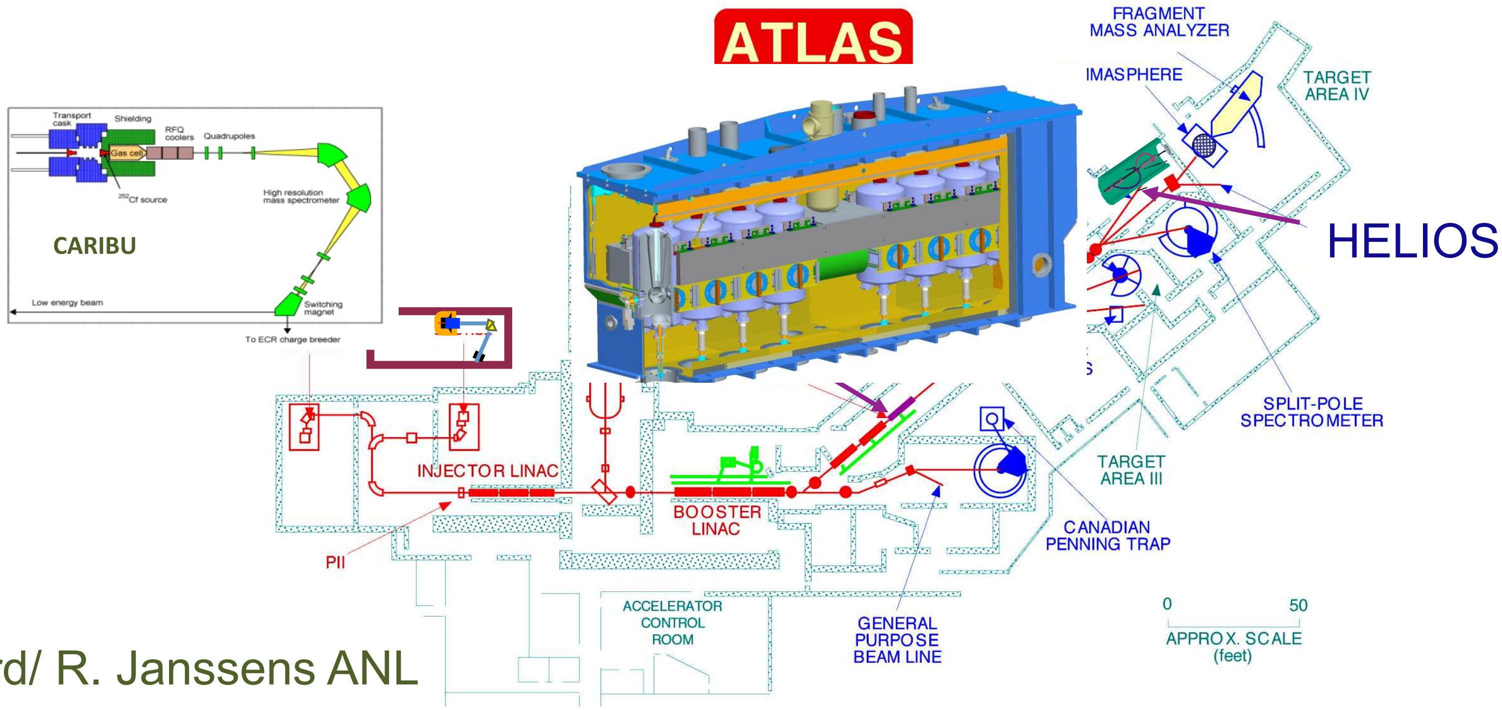
Oak Ridge National Laboratory



hribf
Holifield Radioactive Ion Beam Facility
Oak Ridge National Laboratory

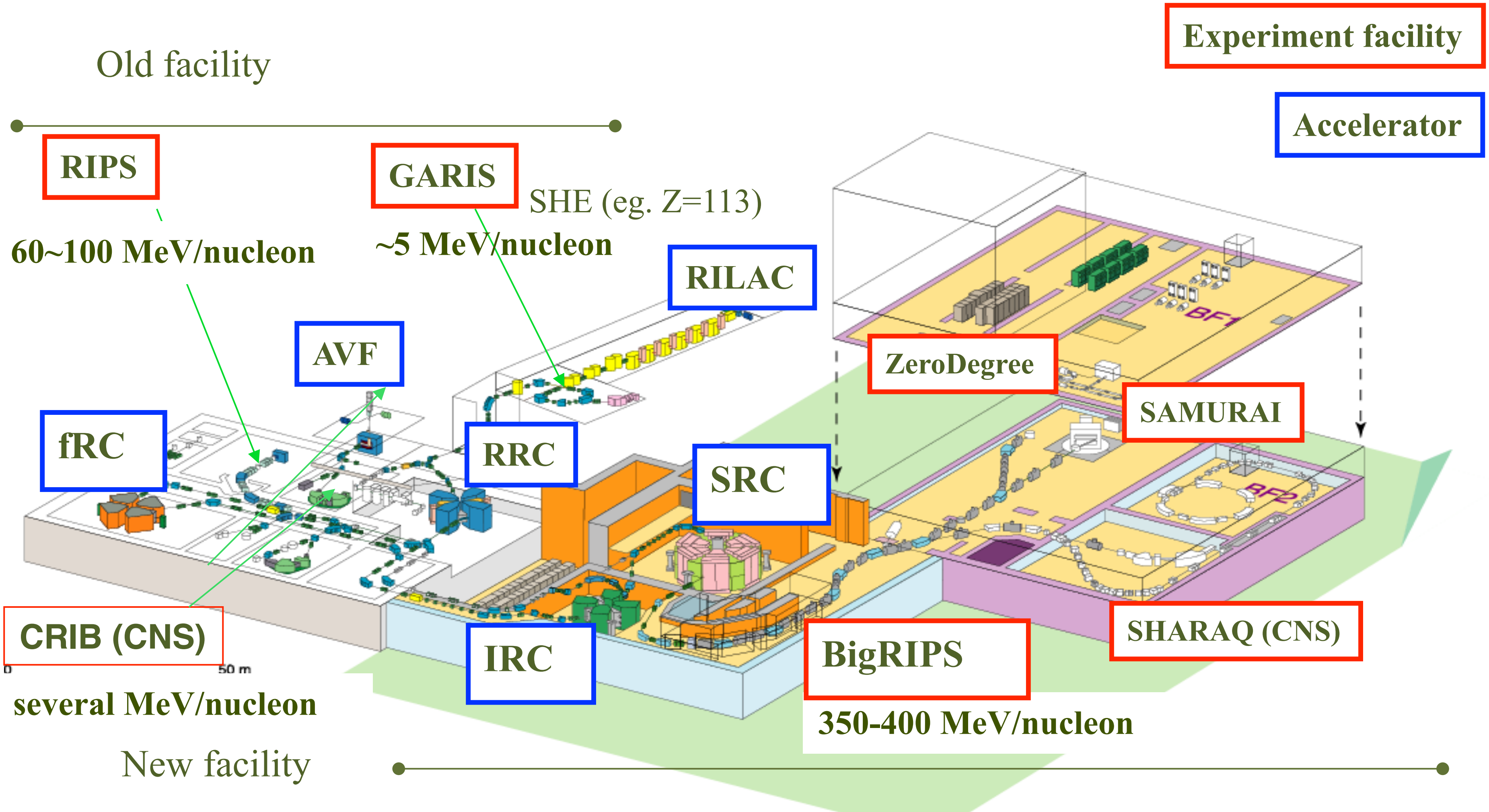
Argonne National Laboratory: CARIBU & Energy Upgrade & HELIOS: Unique Synergy

- Fission products of ^{252}Cf spontaneous fission stopped in gas and accelerated
- CARIBU gives access to exotic beams not available elsewhere.
- Physics with beams from CARIBU (1 & 2 nucleon transfer reactions) needs the new energy regime opened by the Energy Upgrade (12 MeV/u) .
- Solenoid Spectrometer greatly expands the effectiveness of both the fission fragment beams and the existing in-flight RIB program at these higher energies.



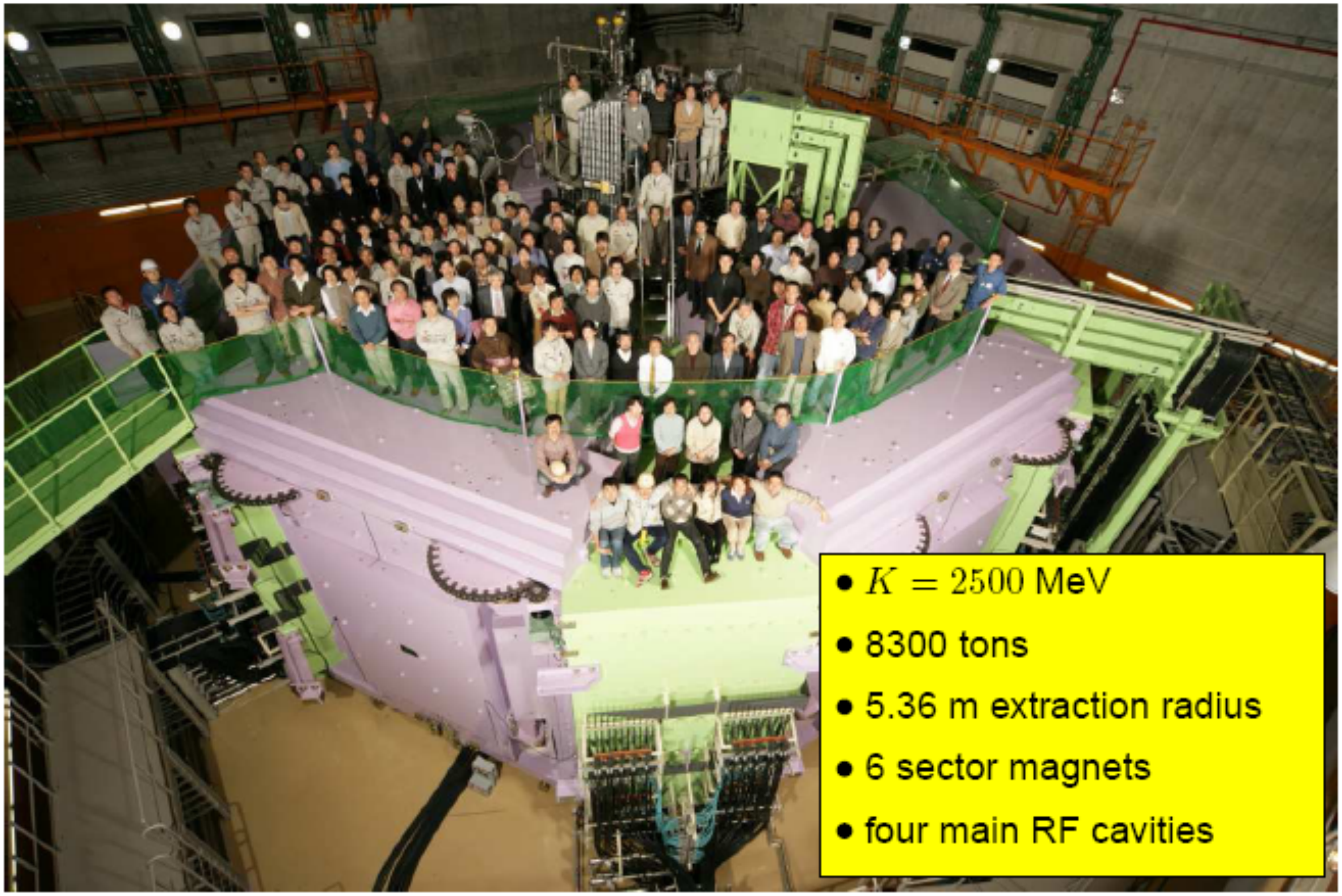
G. Savard/ R. Janssens ANL

RIKEN RI Beam Factory (RIBF)



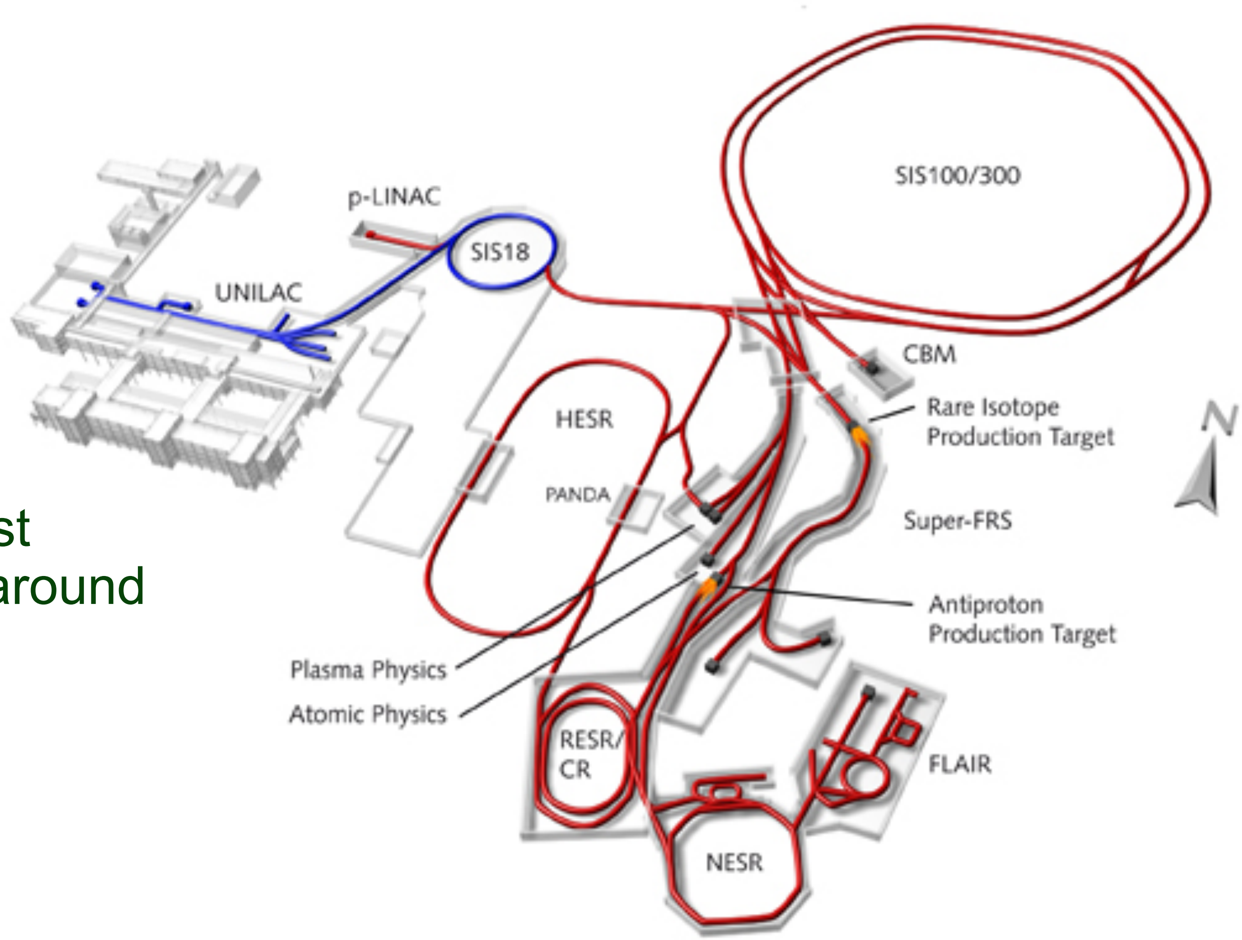
Intense Heavy Ion beams (up to U) up to 345*A*MeV at SRC
Fast RI beams by projectile fragmentation and U-fission at BigRIPS
Operation since 2007

SRC: World Largest (Heaviest) Cyclotron



Facility for Antiproton and Ion Research

- Beams at 1.5 GeV/u
- 10^{12}/s Uranium
- Research
  - Compressed matter
  - Rare isotopes
  - Antiproton
  - Plasma
  - Atomic physics
- Completion of the first stages are planned around 2018



http://www.fair-center.de/index.php?id=1

Closing Thoughts

- We have entered the age of designer atoms – new tool for science
- FRIB (and other facilities) 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
- There are significant challenges remaining in modeling and understanding the best production mechanism