Experimental capabilities at ATLAS/CARIBU for applied nuclear science

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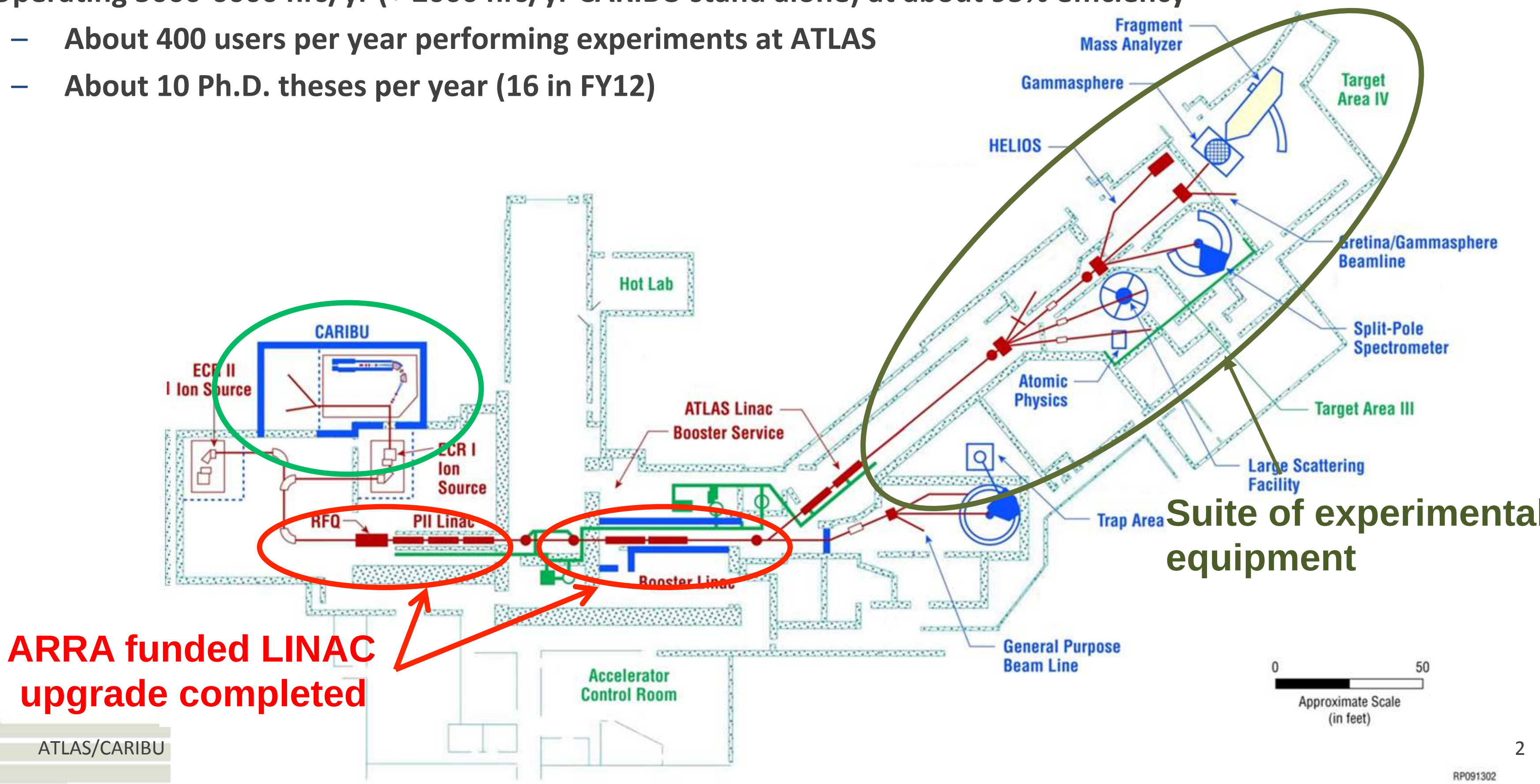
Nuclear Data Needs and Capabilities for Applications

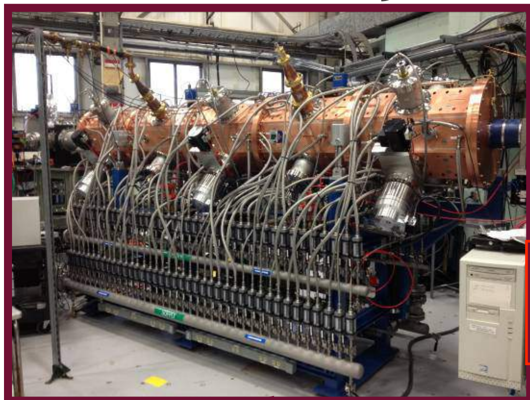
Berkeley, May 27-29, 2015

ATLAS facility

- Stable beams at high intensity and energy up to 10-20 MeV/u
- Light in-flight radioactive beams
  - *light beams, no chemical limitations, close to stability, acceptable beam properties*
- CARIBU beams
  - *heavy n-rich from Cf fission, no chemical limitations, low intensity, ATLAS beam quality, energies up to 15 MeV/u*
- State-of-the-art instrumentation for Coulomb barrier and low-energy experiments
- Operating 5000-6000 hrs/yr (+ 2000 hrs/yr CARIBU stand alone) at about 95% efficiency
  - About 400 users per year performing experiments at ATLAS
  - About 10 Ph.D. theses per year (16 in FY12)

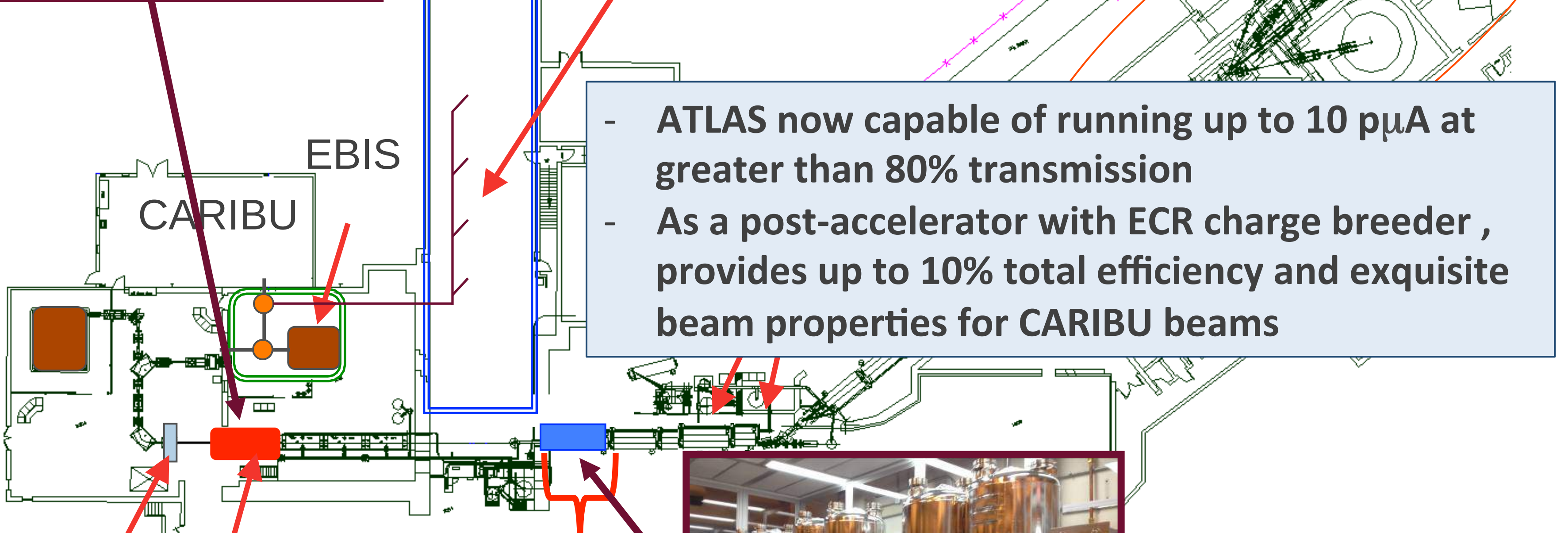


ATLAS layout after recent upgrades



Novel design from Accelerator R&D group

Removing tandem for new low-energy experimental hall for CARIBU



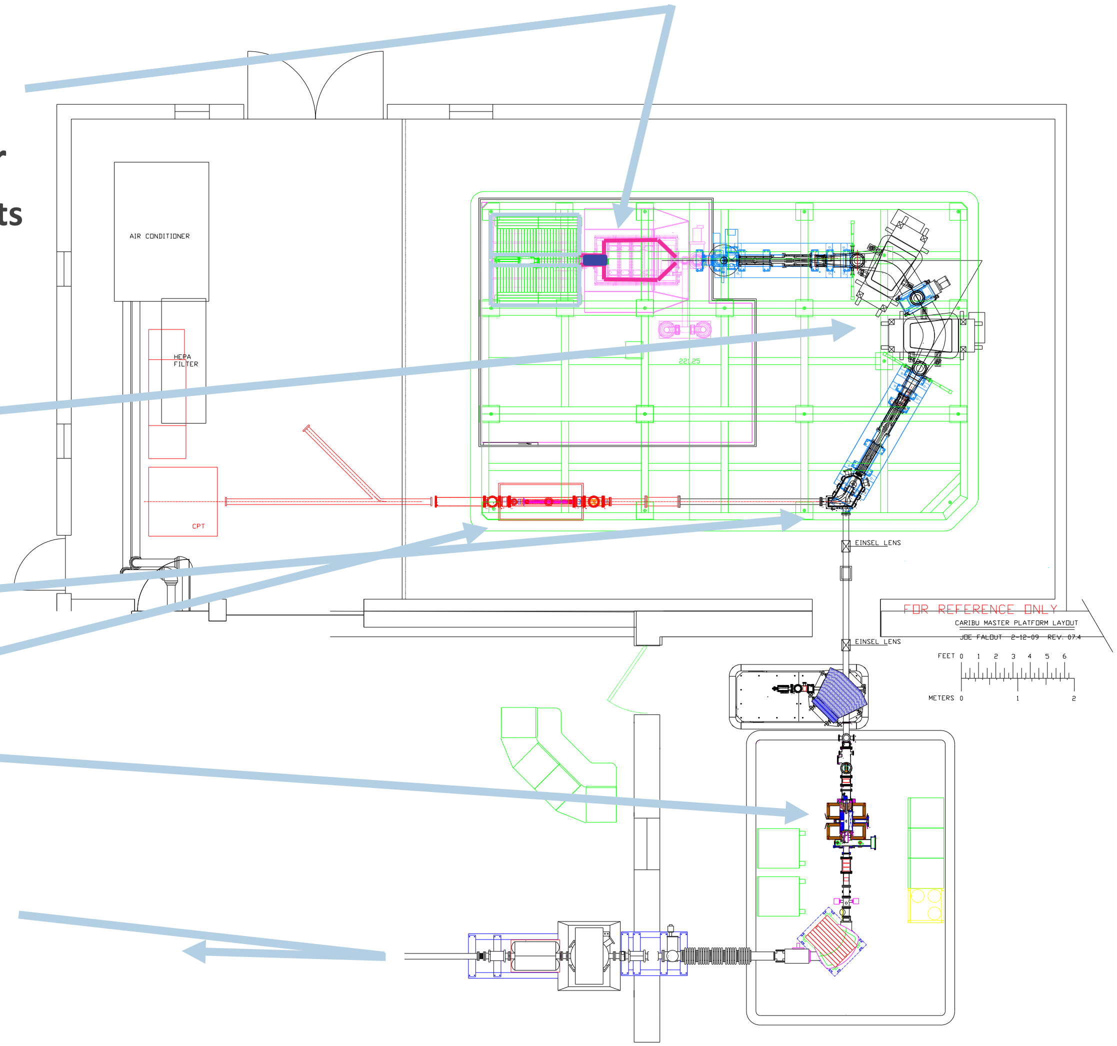
- **ATLAS now capable of running up to 10 pμA at greater than 80% transmission**
- **As a post-accelerator with ECR charge breeder , provides up to 10% total efficiency and exquisite beam properties for CARIBU beams**

World record performance

Neutron-rich beam source for ATLAS: CARIBU "front end" layout

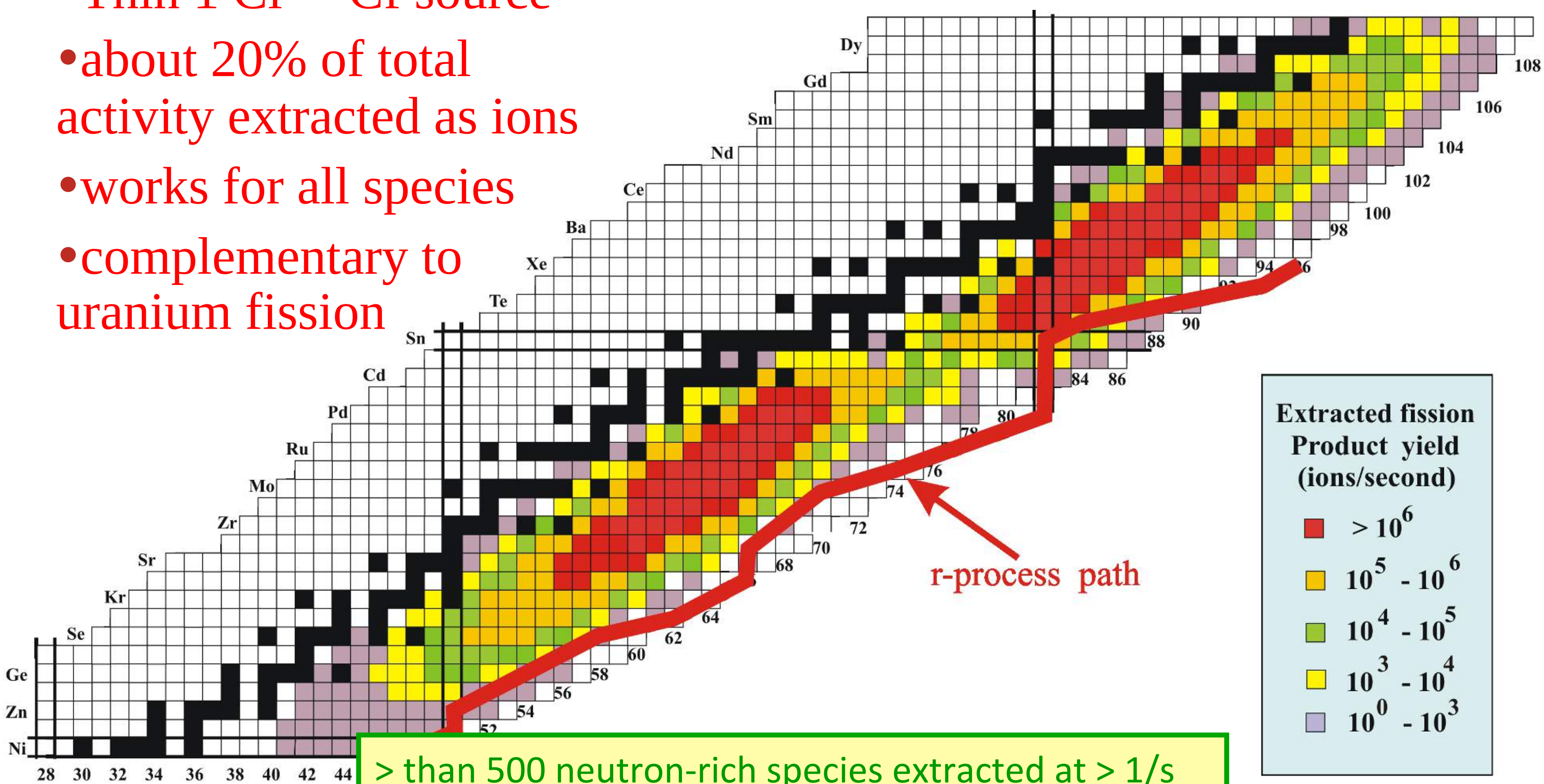
Main components of CARIBU

- **PRODUCTION**: "ion source" is ^{252}Cf source inside gas catcher
  - Thermalizes fission fragments
  - Extracts all species quickly
  - Forms low emittance beam
- **SELECTION**: Isobar separator
  - Purifies beam
- **DELIVERY**: beamlines and preparation
  - Switchyard
  - Low-energy buncher and beamlines
  - Charge breeder to Increase charge state for post-acceleration
  - Post-accelerator ATLAS and weak-beam diagnostics



Expected isotope yield distribution at low energy (50 keV)

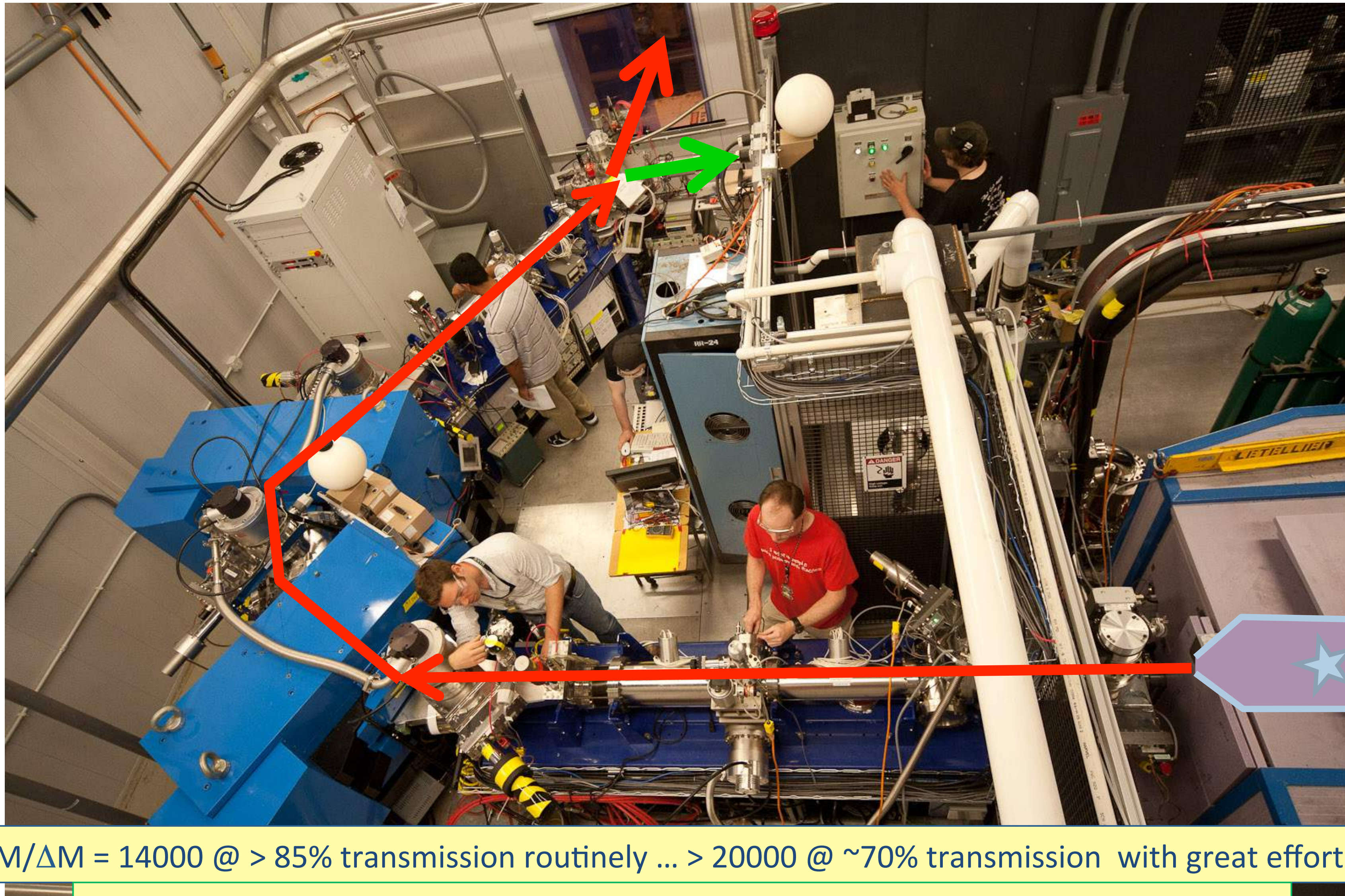
- Thin 1 Ci ^{252}Cf source
- about 20% of total activity extracted as ions
- works for all species
- complementary to uranium fission



> than 500 neutron-rich species extracted at > 1/s

> than 150 different neutron-rich species have been used for experiments at CARIBU already

Universal selection by compact CARIBU isobar separator



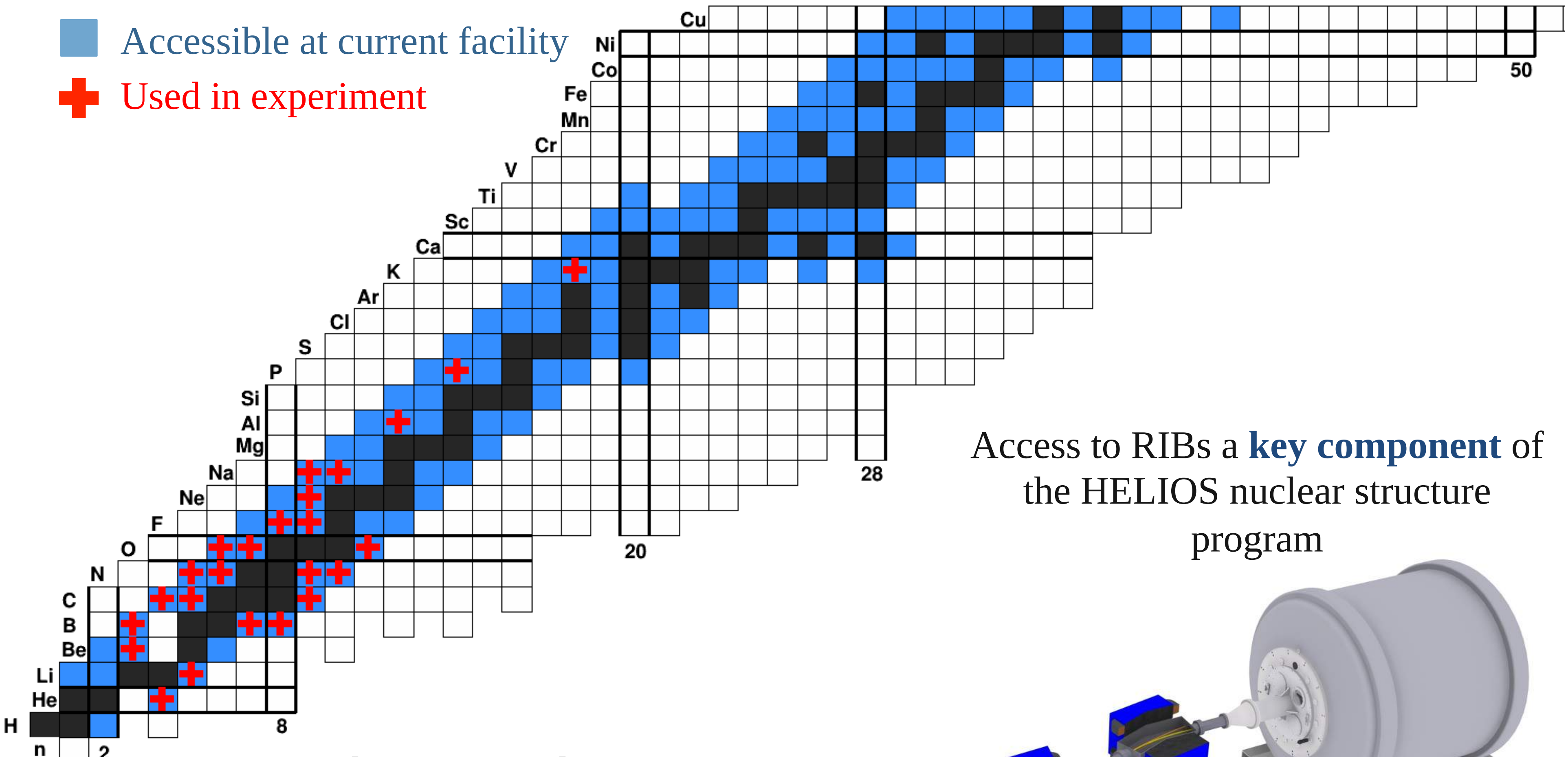
M/ΔM = 14000 @ > 85% transmission routinely … > 20000 @ ~70% transmission with great efforts

New MRTOF currently being commissioned for M/ΔM > 40000 @ > 50% transmission
-> should yield isotopically pure beams

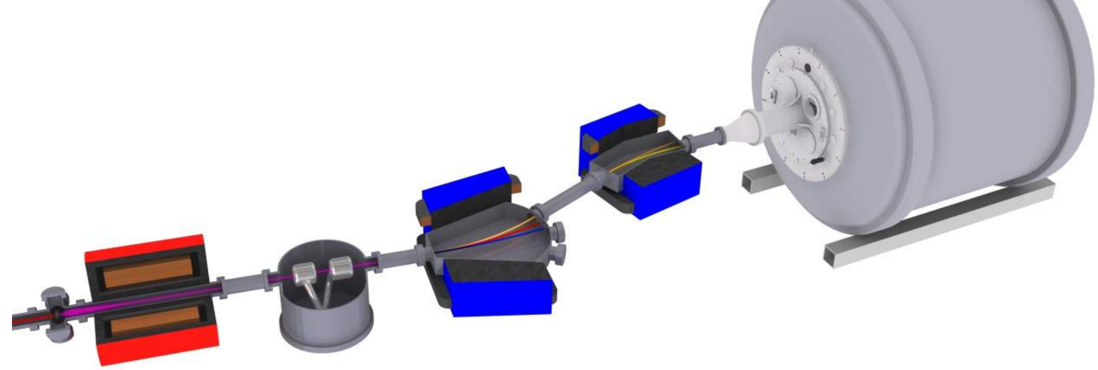
In-flight radioactive beams at ATLAS

Accessible at current facility

Used in experiment



Access to RIBs a **key component** of the HELIOS nuclear structure program



ATLAS upgrades, target and reaction techniques, will increase reach until arrival of the new in-flight separator **AIRIS**

ATLAS beams

- **Stable beams (protons to Uranium)**
  - up to 10 pμA, limited by ion source performance and radiation safety
  - Pulse separation of 82 ns or n X 82 ns with n=1, 2, 3, …
  - Pulse timing down to ~100 ps
  - Energy range from ~ 0.5 MeV/u up to 10-20 MeV/u depending on mass

Unique capabilities worldwide + coupled to unique instruments

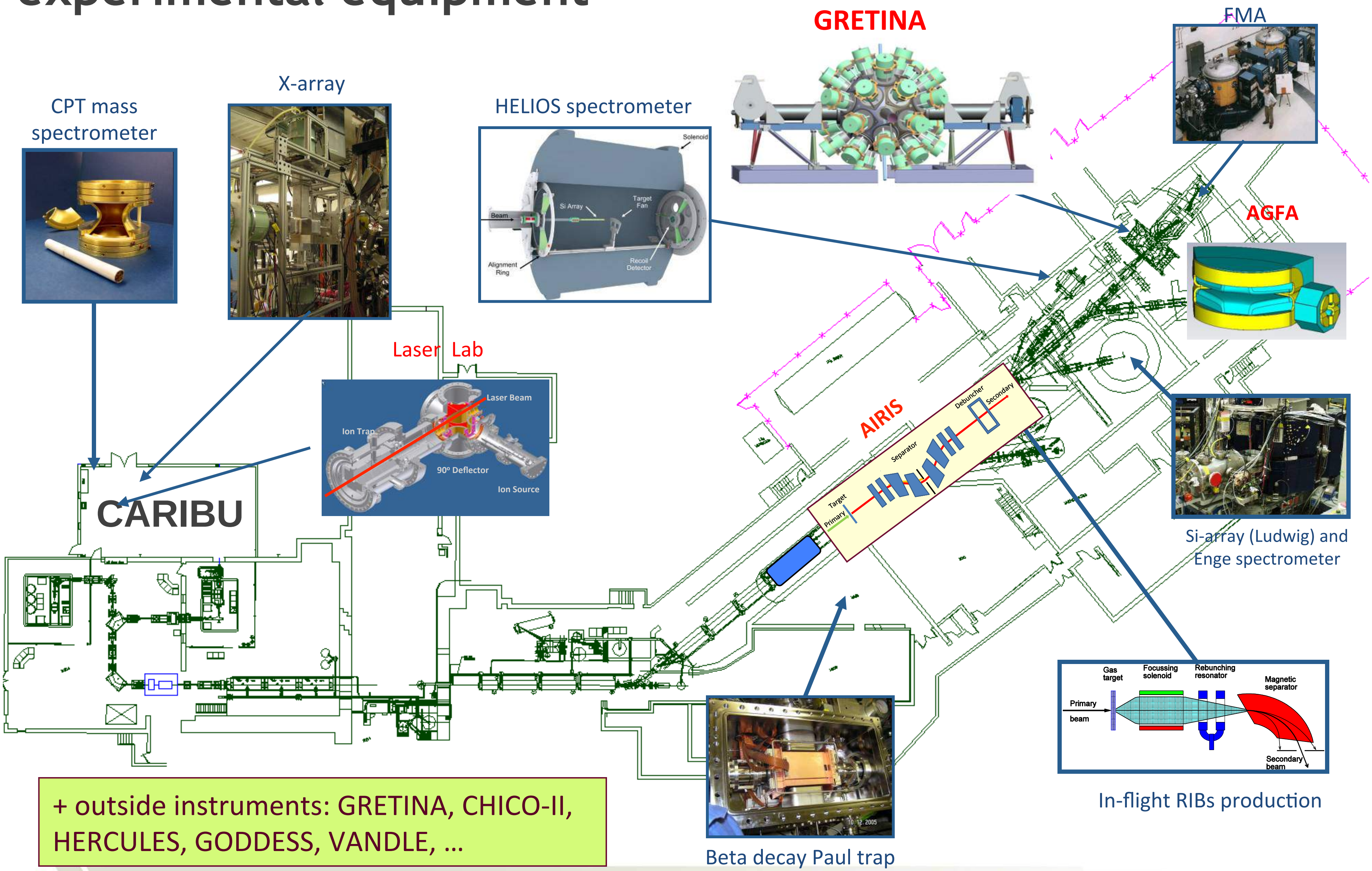
- **CARIBU beams have similar properties …. but much lower intensity**
  - All species, even the most refractory, are extracted efficiently

Most of the CARIBU beams (species and energy) are not available anywhere else. This will remain so at least until FRIB turns on.

- **In-flight radioactive beams: all light species, close to stability, but compromise between beam properties, intensity and purity**

A few other facilities worldwide can produce these beams but none have the ATLAS experimental equipment suite (e.g. HELIOS).

Main tools enabling the physics: ATLAS suite of experimental equipment

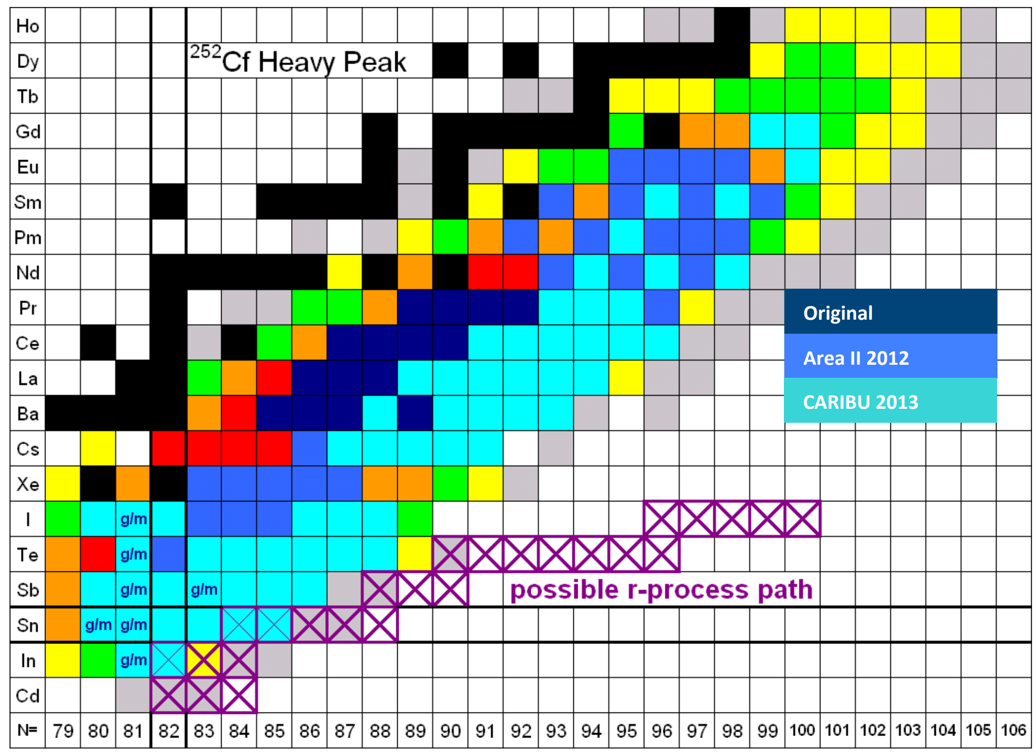


+ outside instruments: GRETINA, CHICO-II, HERCULES, GODDESS, VANDLE, …

Mass measurements of neutron-rich nuclides

- Masses determined via a measurement of the ions' cyclotron frequency
- Can measure the mass with a production rate of ~ 1 ion / s
- Mass precision ~ 10^{-6} to 10^{-8} (1 -100 keV/c^2) for masses approaching the *r* process

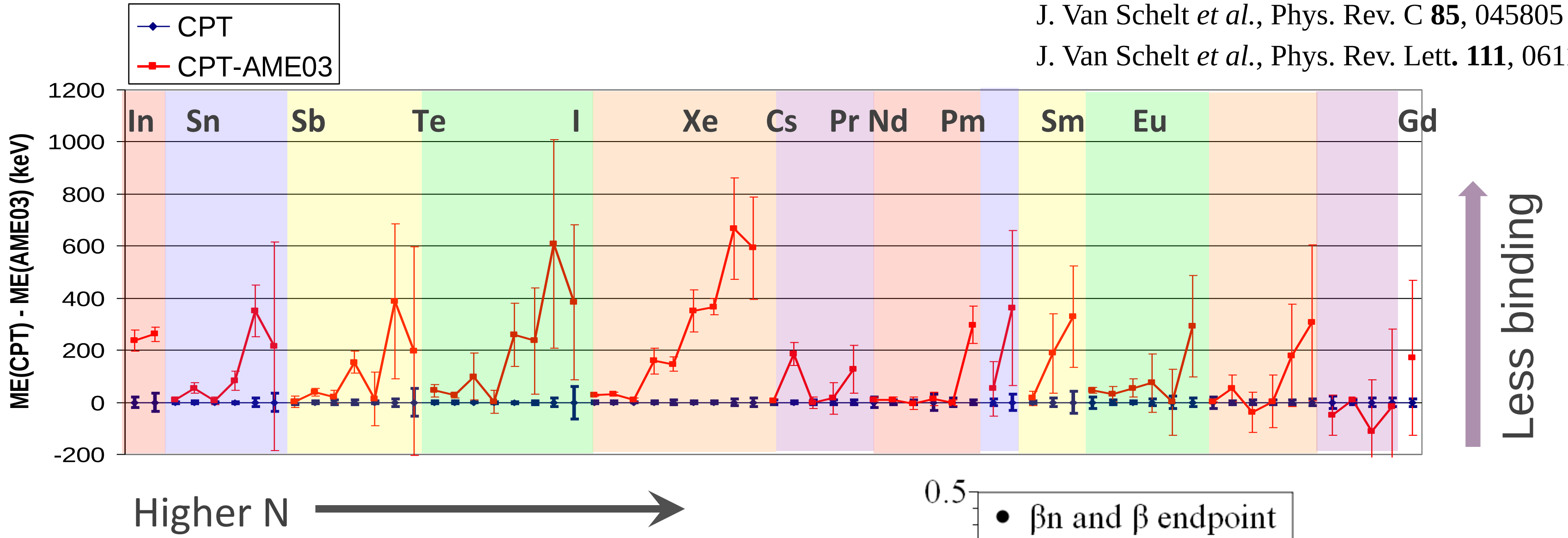
- Canadian Penning Trap (CPT) has measured more than 140 neutron-rich nuclides at CARIBU
- Currently reaching isotopes produced at below the 10^{-6} fission branch level
- For some nuclei, no prior information on the nuclide existed!



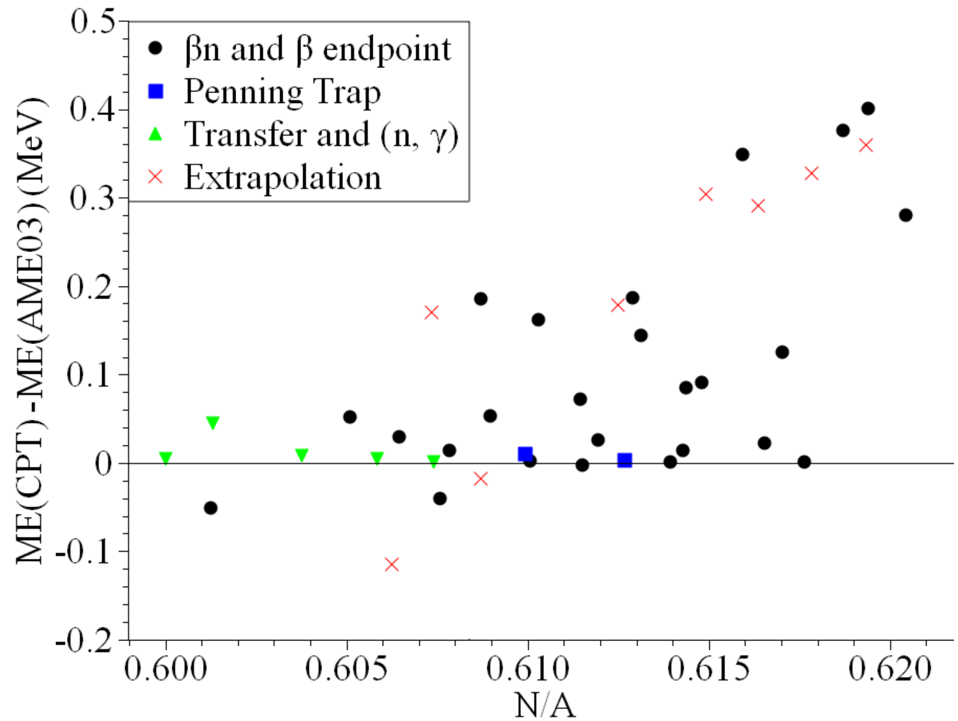
J. Van Schelt *et al.*, Phys. Rev. C **85**, 045805 (2012)
J. Van Schelt *et al.*, Phys. Rev. Lett. **111**,061102 (2013)

Comparison with the atomic mass evaluation

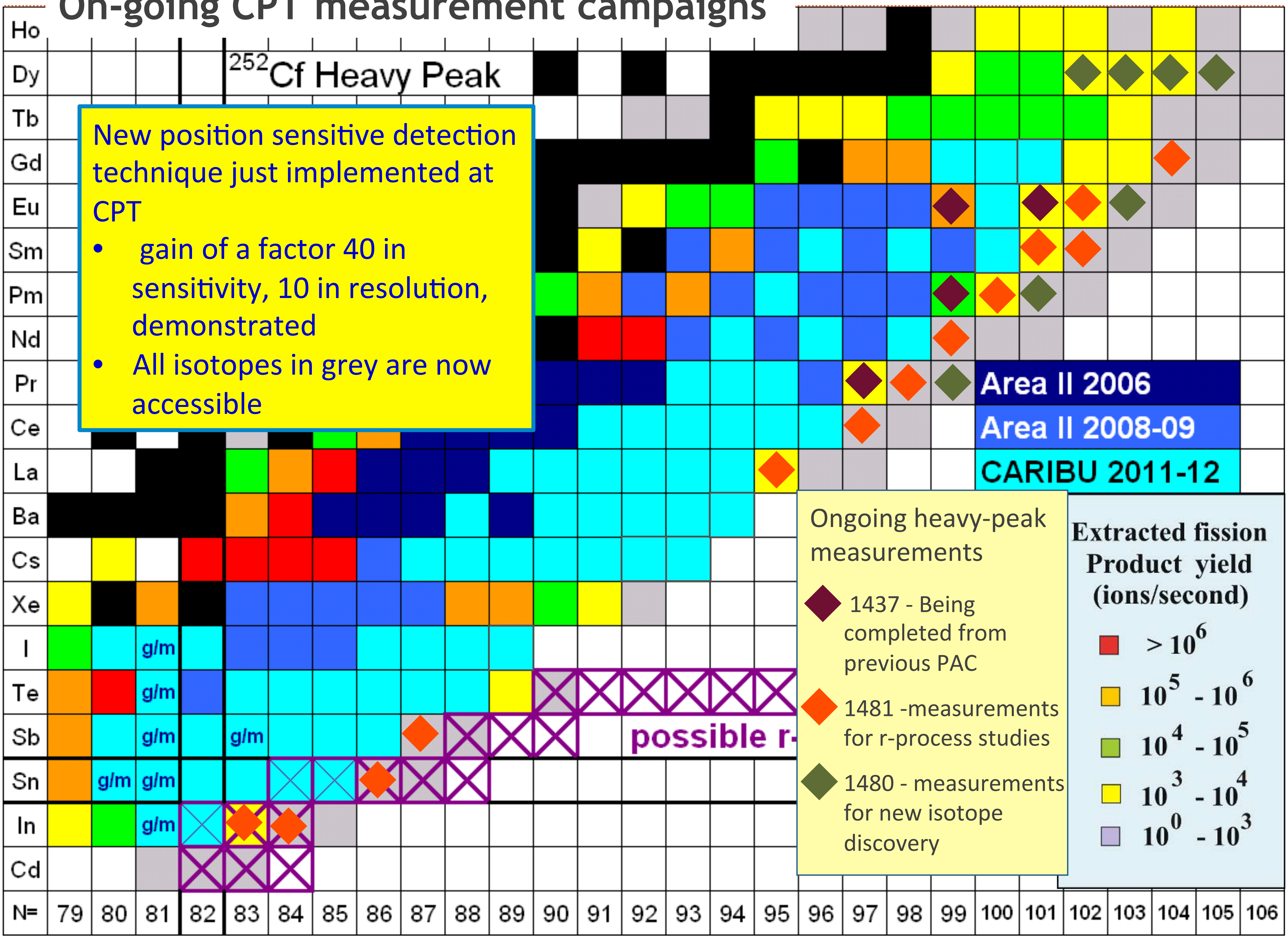
J. Van Schelt *et al.*, Phys. Rev. C **85**, 045805 (2012)
J. Van Schelt *et al.*, Phys. Rev. Lett. **111**, 061102 (2013)



- Trends indicate nuclei are less bound with neutron excess (affects the location of the r-process path)
- Good agreement with other Penning trap results and reaction Q value measurements
- Large disagreement with results obtained with β-decay measurements

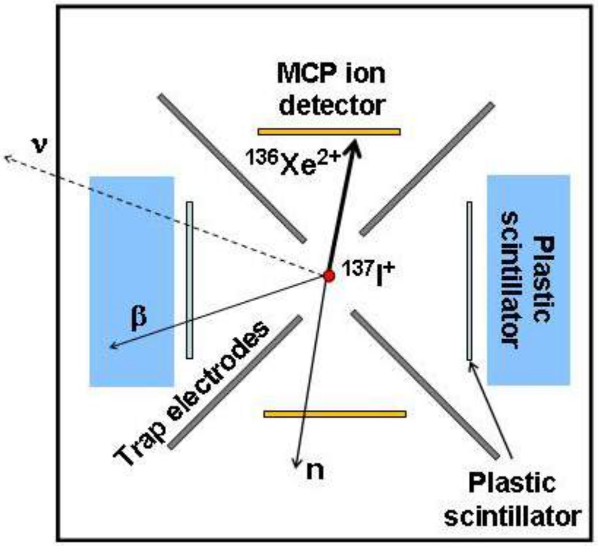


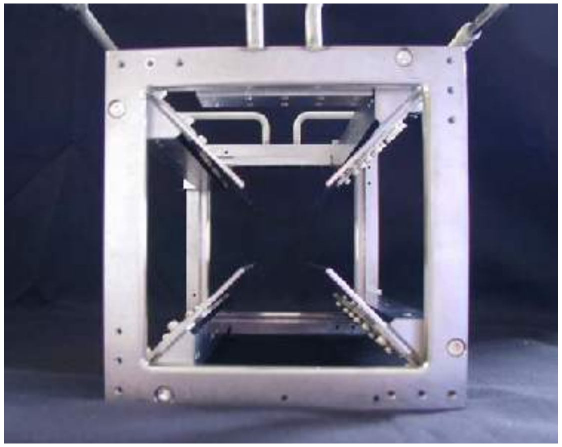
On-going CPT measurement campaigns



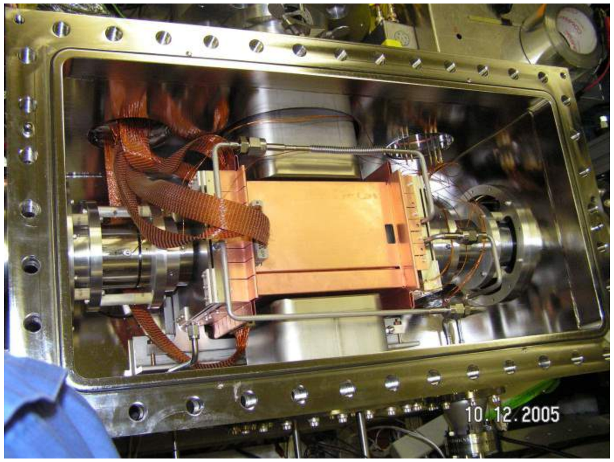
New technique for β-delayed neutron measurements

R.M. Yee *et al.*, Phys. Rev. Lett **110**, 092501 (2013) – ANL/LLNL/Berkeley/Chicago/Notre-Dame/McGill/Manitoba collaboration

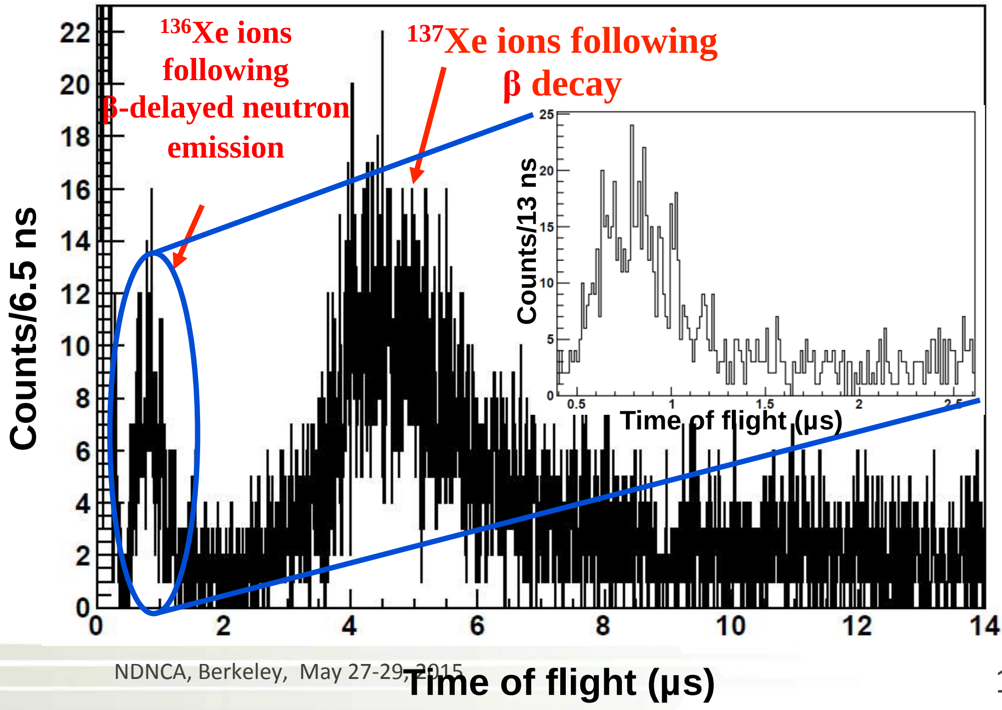




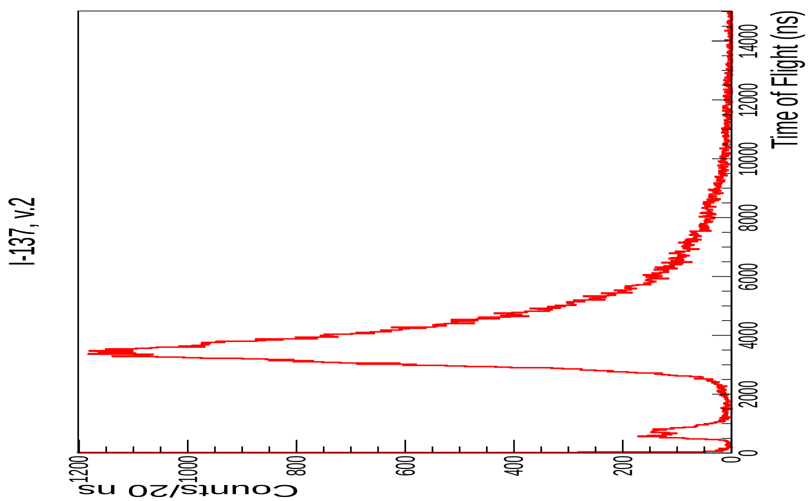
- Let ion decay from rest at center of ion trap (Paul trap)
- Surround ion trap (Paul trap) with plastic scintillators (to detect β's) and MCPs (to detect decay recoils)
- β-delayed neutron decay produces recoil detected by TOF with MCP

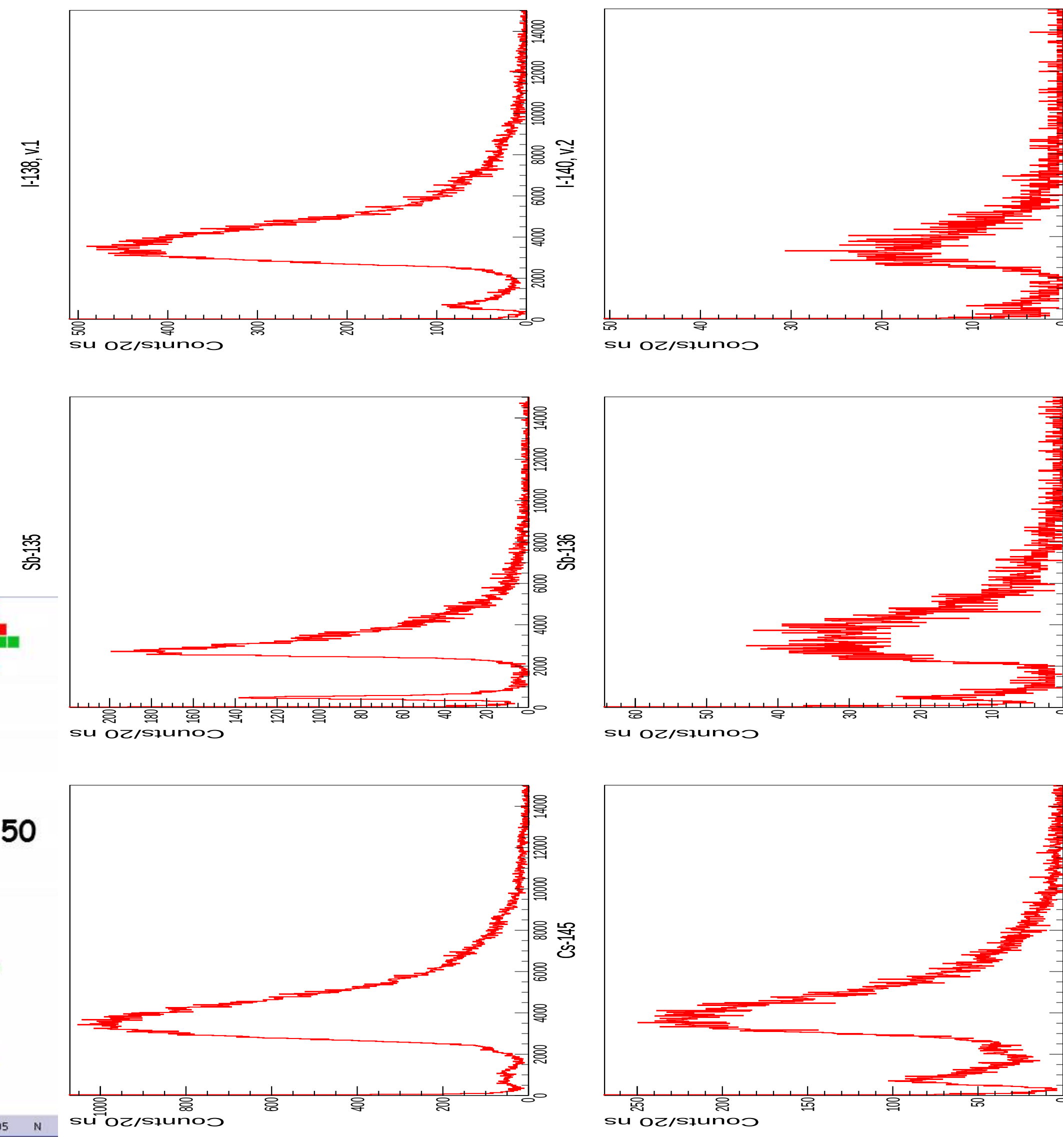


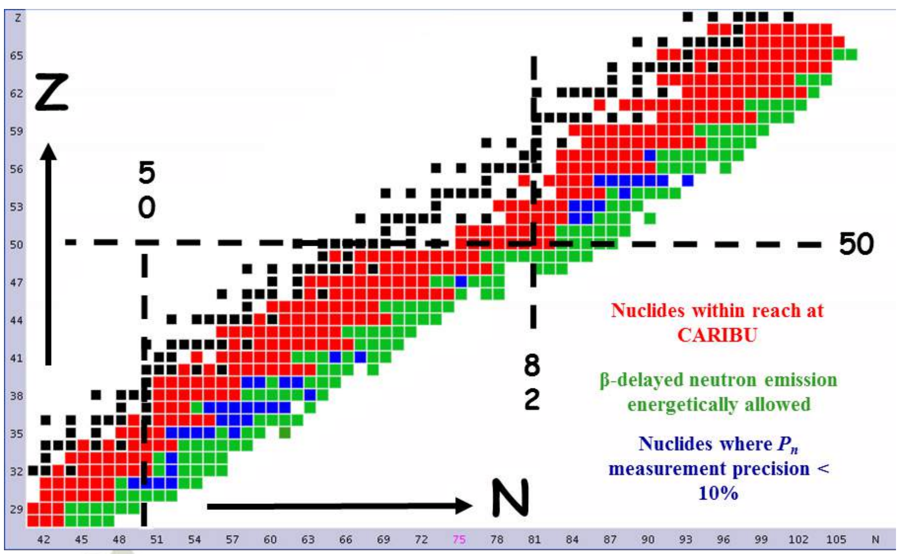
Trap chamber and instrumented trap



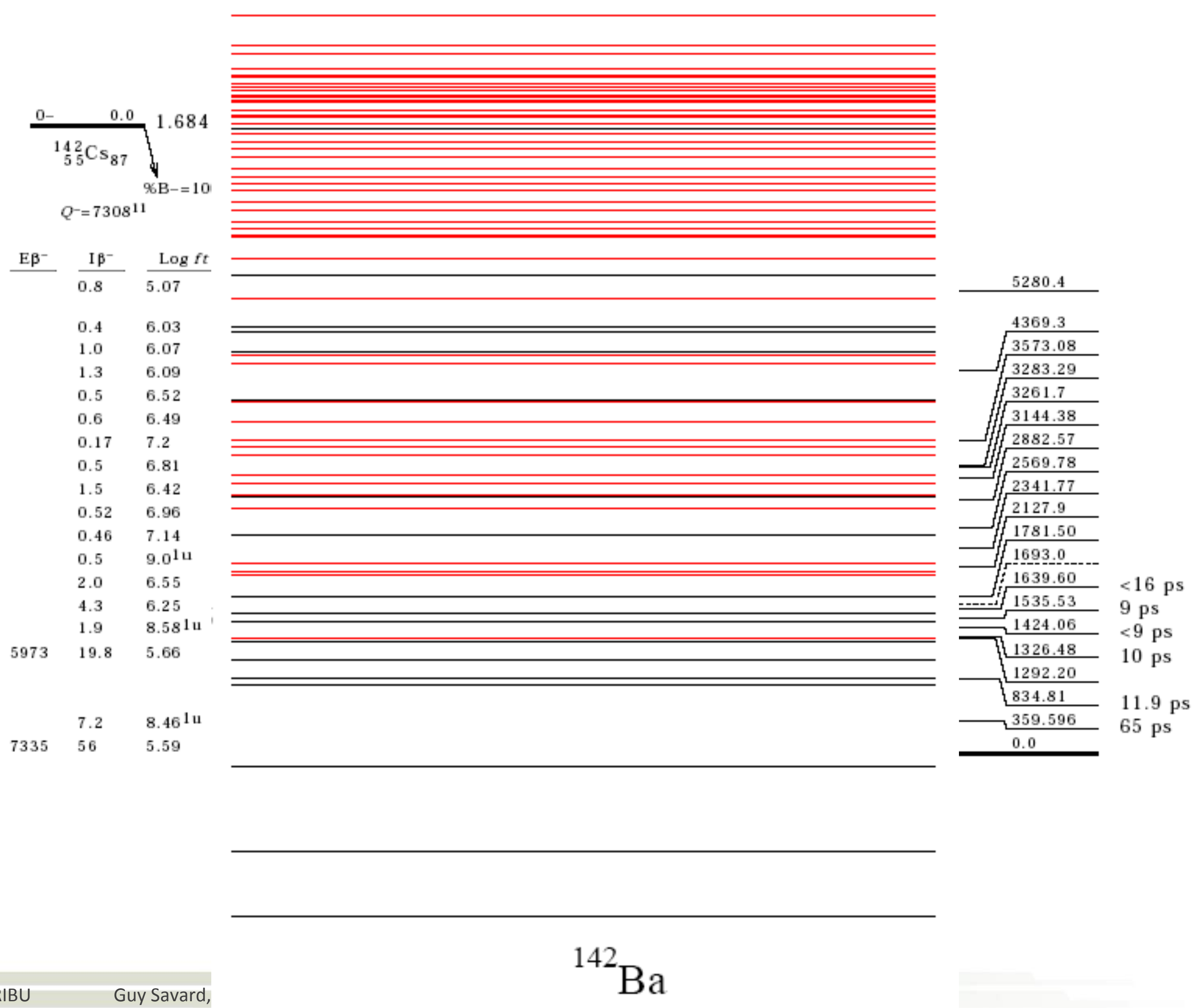
Preliminary spectra from fall 2013 beta-delayed neutron run



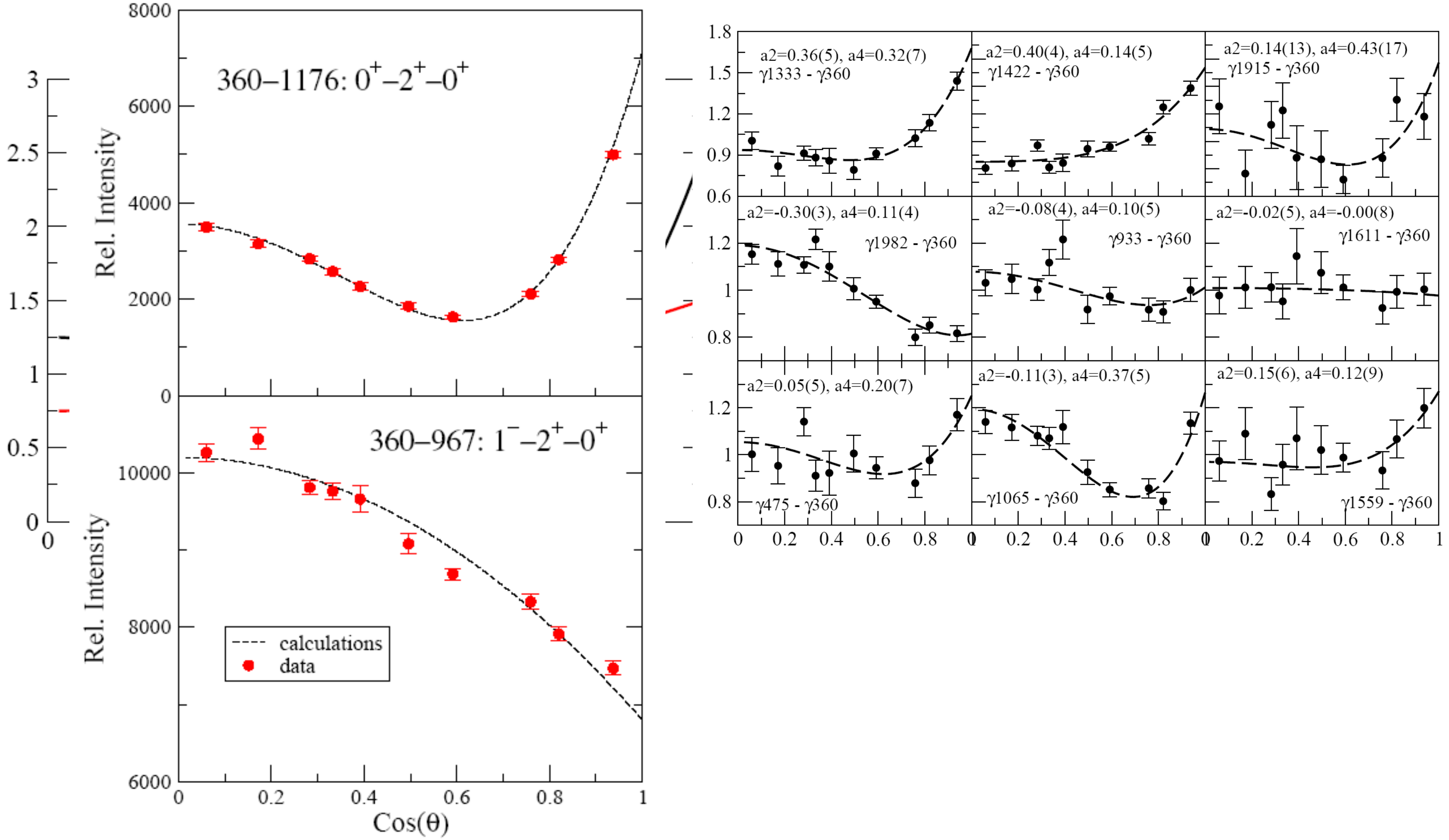




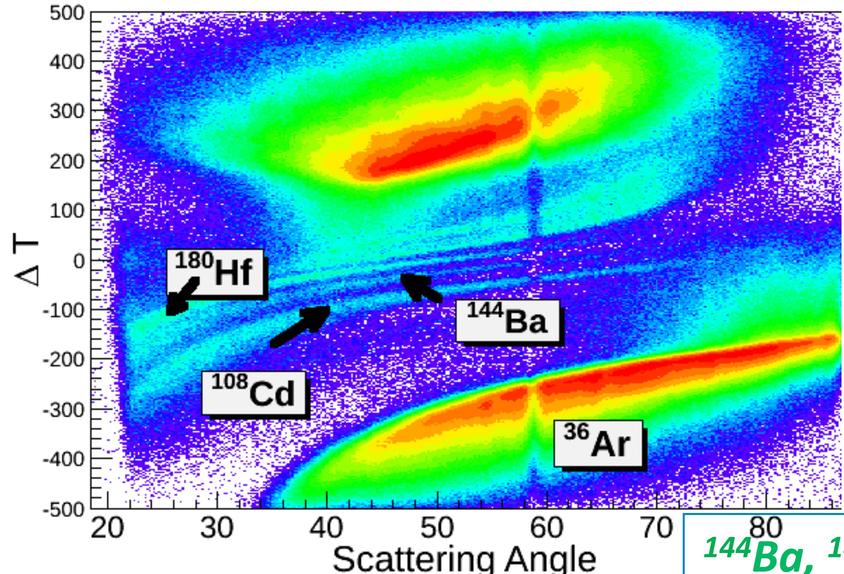
Decay spectroscopy at X-array or Gammasphere (or TAGS):
e.g.^{142}Cs in Gammasphere -> Expanded β-decay level scheme of ^{142}Ba

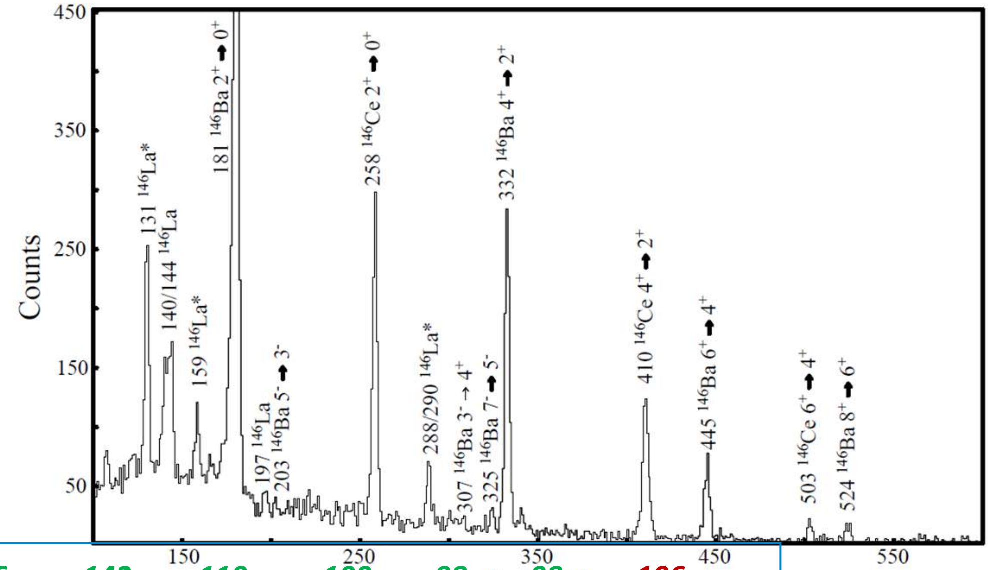


The power of Gammasphere: Spin-Parity Assignments via Angular Correlations



Coulomb excitation of CARIBU beams with GRETINA/CHICO2





^{144}Ba, ^{146}Ba, ^{142}Cs, ^{110}Ru, ^{100}Zr, ^{98}Zr, ^{98m}Y, ^{106}Mo

650-MeV ^{144}Ba + ^{208}Pb (1mg/cm^2) GRETINA + CHICO2 + CARIBU/ATLAS expt.

Rochester – LLNL – LBL- ORNL – Liverpool – Scotland – Ohio U – Tennessee – Georgia IT – Richmond - ANU –Washington – Toronto - Saclay – IHL Warsaw – GANIL – TU Darmstadt – Oslo – Notre Dame - ANL collab.

- GRETINA + CHICO2 provide excellent Doppler reconstruction
- charge breeder + upgraded ATLAS provide post-acceleration with ~10% total efficiency and exquisite beam properties

Current push forward for ATLAS

- Increasing efficiency with which programs are run
  - Pushing back beam limitations
    - Stable beams → higher intensity
    - In-flight radioactive beams → higher intensity, purity, and accessible to more experimental areas
    - CARIBU beams → higher intensity, purity
  - Pushing back rate limitations for essentially all experiments, including Gammasphere
  - Gaining higher efficiency for weak channels
  - Gaining access to other regions of the nuclear chart
  - Providing more beam hours and experimental stations

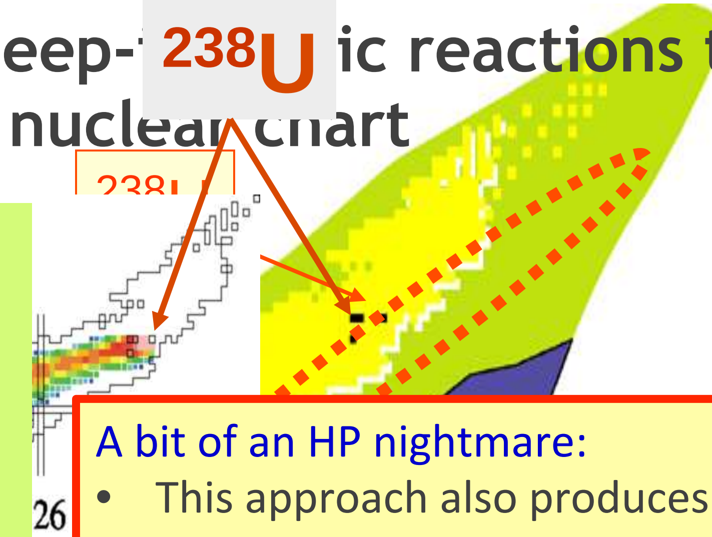
- Recent/current/possible upgrades addressing main limitations
  - ARRA funded intensity and efficiency upgrade of ATLAS (X10 in intensity) (FY13-14)
  - Digital Gammasphere (X4-12 in rate capabilities) (FY13-14)
  - EBIS charge breeder and larger low-energy experimental area for CARIBU (X 3 in intensity and higher purity) (FY14-15)
  - AGFA (X10 in acceptance for superheavies) (FY14-16)
  - AIRIS: New recoil separator for in-flight program (>100 in intensity and higher purity) (FY15-17)
  - Multi-user upgrade (FY16-20) ← Roughly $2 M

within baseline funding

Accessing new regions: deep-i[…]ic reactions to reach the […]t of the nuclear chart

238U

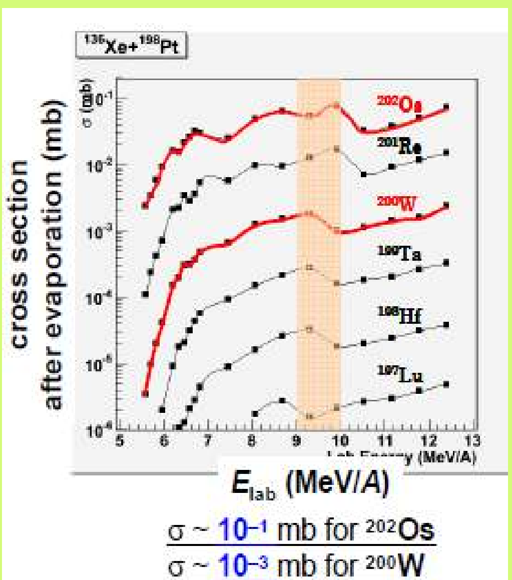
1 GeV/u $^{238}U + {}^{1}H$
Armbruster et al.



The Science:

- nuclear shell structure at the extremes
- r-process: second abundance peak, fission recycling and termination
- fission barriers of neutron-rich nuclei and symmetry energy
- connection of hot-fusion SHE island and mainland

Production through deep-inelastic reactions



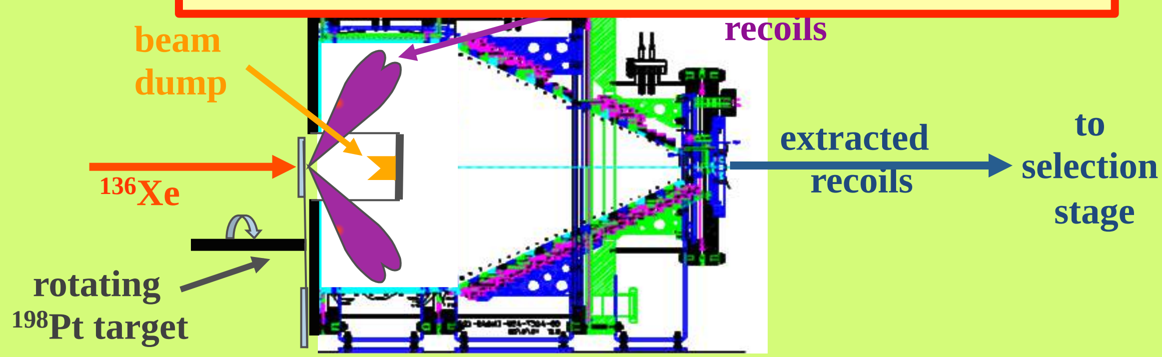
A bit of an HP nightmare:

- This approach also produces most of the heaviest isotopes, many alpha emitters

A huge potential applications payoff:

- We will be able to extract mass separated low-energy beams of almost all known heavy isotopes and use them for measurements similar to what we can do now at CARIBU for fission fragments

Effic[…] throu[…]



Access to ATLAS and Status

- ATLAS is the DOE low-energy nuclear physics national user facility
  - Running reliably and logging in a large number of operating hours in service of a large user community
  - Host to a broad science program
  - Adding new capabilities
    - CARIBU
    - Intensity upgrade
  - Improving its suite of experimental equipment
    - HELIOS, digital Gammasphere and DSSD, X-array
    - AGFA, AIRIS, N=126 factory, laser lab, beta-delayed neutron trap

- Experiments at ATLAS go through a PAC approval process
  - Typical PAC approval rate varies around 40%
  - Running is free for all approved experiments

- Facility is evolving to keep up with (and anticipate) the needs of the community … applications is one of these needs and is now a core component of the ATLAS long-range plan

- Other programs for applications not mentioned in talk: ATTA, MANTRA

Backup material

ATLAS multi-user upgrade … filling the gap

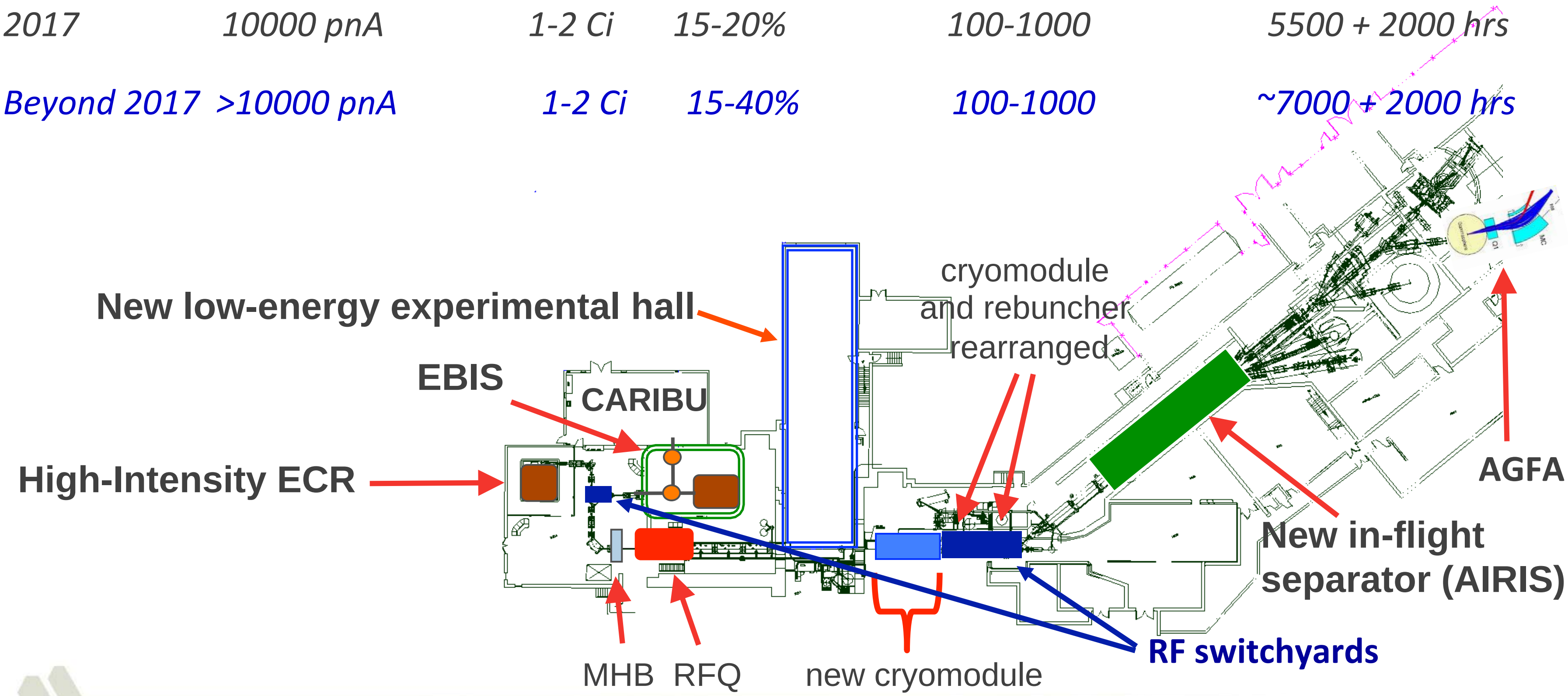
- Beamtime availability for low-energy community is under increasing pressure
  - In last few years, the low-energy community lost HRIBF and Yale (~ 4000-6000 hrs/yr)
  - Facilities outside the US (GSI, GANIL, RIKEN, ISOLDE) also have limited capabilities in coming years
- Further pressure on available beamtime to users from
  - Move to longer experiments with weak beams or low cross-section channels
  - ATLAS PAC oversubscribed by factor of ~ 3
- Specific characteristics of ATLAS and CARIBU can provide a cost efficient way to remedy this situation
  - With the EBIS breeder, the full CARIBU reaccelerated beam will be pulsed with a duty cycle of ~ 1%, leaving the accelerator "idle" for ~99% of the time.
  - The ATLAS linac can accelerate simultaneously ions of charge-to-mass ratio over a range of 10% or so as shown in the multiple-charge-state acceleration performed at ANL to demonstrate the original RIA/FRIB accelerator concept

ATLAS could be modified to simultaneously accelerate two beams … providing full fledged multi user capability (2 simultaneous users)

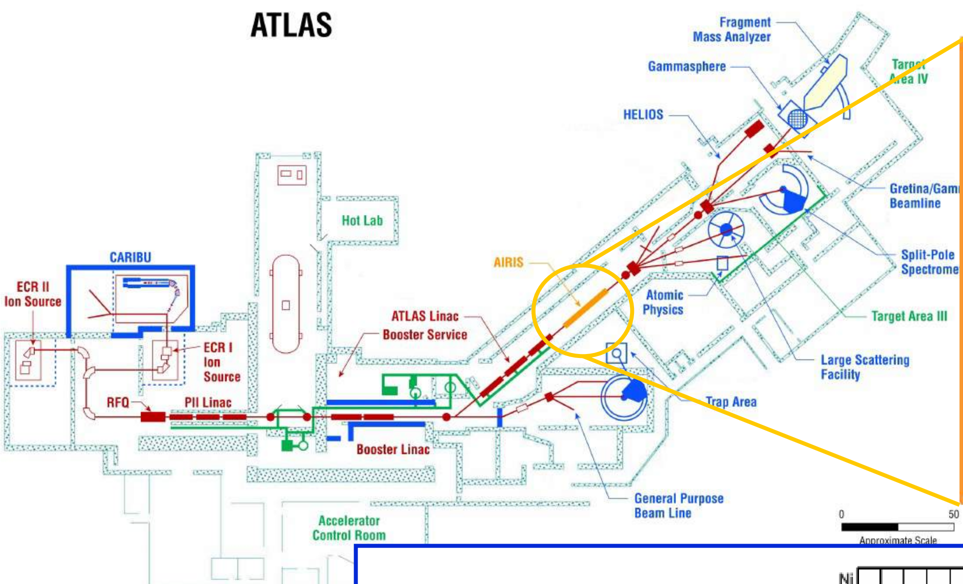
- **One full intensity CARIBU beam using 10-100 μs 30 times per second**
  - **Could accelerate 2 charge states to essentially double available intensity**
- **One ATLAS stable beam utilizing the remaining ~99% of the time**
  - **Available at the full intensity provided by the source**

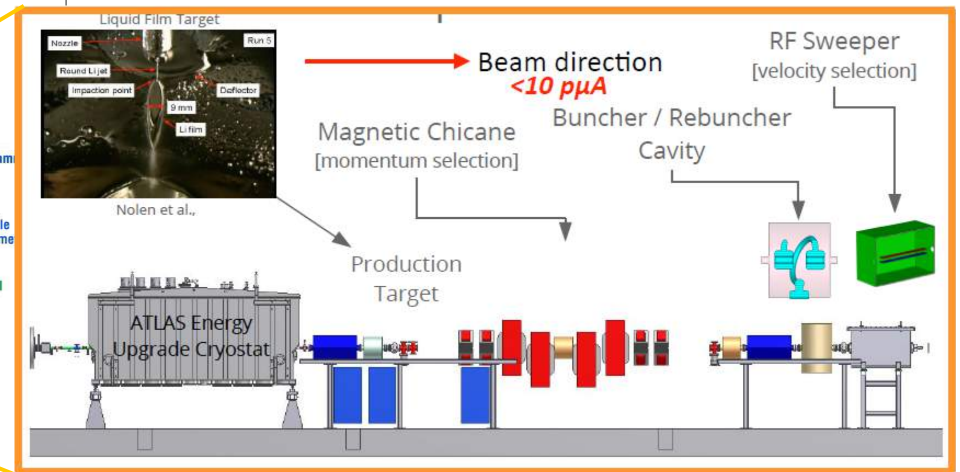
ATLAS layout: 2012 -> 2014 -> 2015 ->2017 -> 2020

	Stable beam	CARIBU		in-flight beams	beam hrs
	I_{max}	*source*	*reacc. eff.*	*relative yield*	*ATLAS+CARIBU low-E hrs*
2012	*200-500 pnA*	*0.3 Ci*	*3%*	*1*	*5500 + 2000 hrs*
2014	*10000 pnA*	*1 Ci* *	*8%*	*10*	*5500 + 2000 hrs*
2015	*10000 pnA*	*1-2 Ci*	*15-20%*	*10*	*5500 + 2000 hrs*
2017	*10000 pnA*	*1-2 Ci*	*15-20%*	*100-1000*	*5500 + 2000 hrs*
Beyond 2017	*>10000 pnA*	*1-2 Ci*	*15-40%*	*100-1000*	*~7000 + 2000 hrs*



AIRIS upgrade to the ATLAS facility

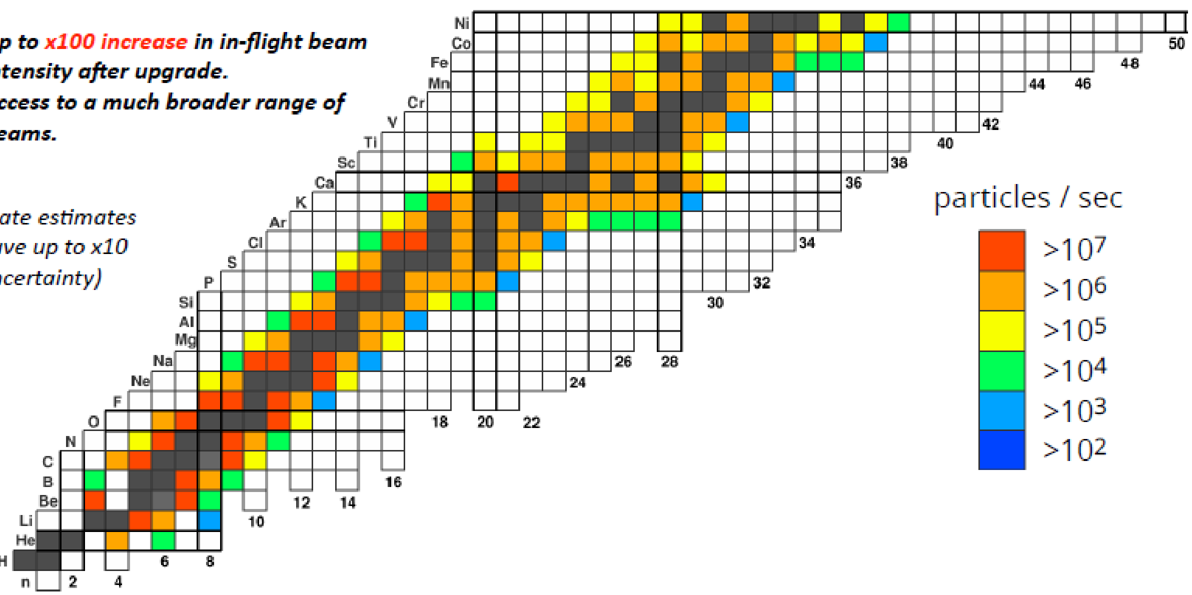




Up to** **x100 increase** **in in-flight beam intensity after upgrade.

Access to a much broader range of beams.

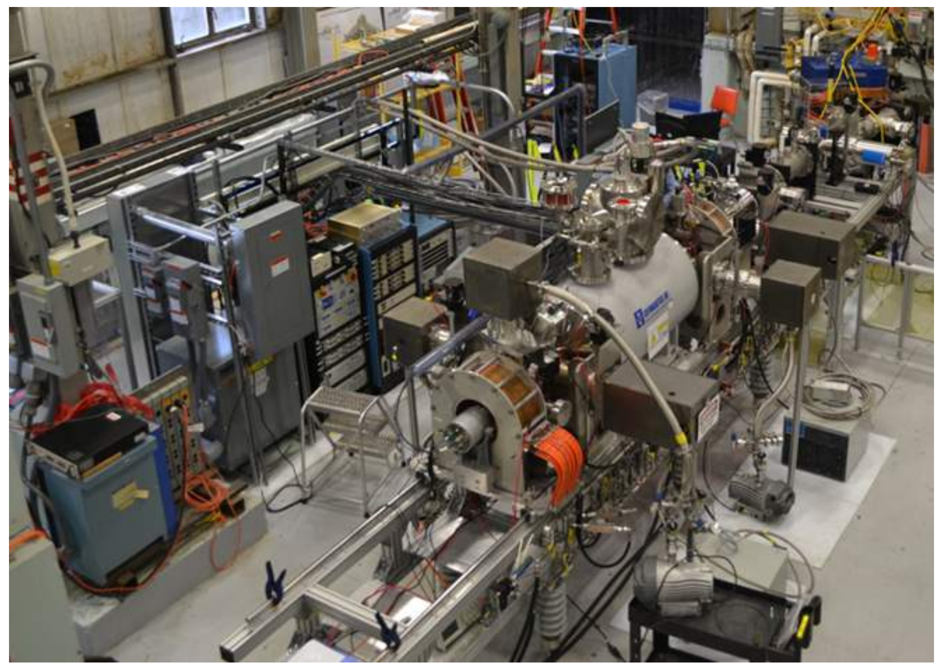
(Rate estimates have up to x10 uncertainty)



EBIS charge breeder upgrade

- Removing stable beam contamination of reaccelerated beams from ECR charge breeder
  - Concept developed and demonstrated by accelerator R&D group
  - Provides two important gains versus ECR charge breeding at CARIBU
    - Higher charge breeding efficiency demonstrated for pulse injection operation (ANL tests at BNL EBIS … and now operating off-line at ANL)
    - UHV system leads to stable beam background suppression

Factor 2-3 gain in intensity and large suppression of stable beam contaminants for reaccelerated CARIBU beams



AGFA: Argonne Gas-Filled Analyzer

Purpose:

- High efficiency separation
  - Gammasphere at target position
  - Evaporation residues
    - Super-heavy nuclei
    - ~^{100}Sn region
    - Spectroscopy at the p drip line
  - Deep-inelastic products
    - N-rich nuclei e.g. N~126
  - General purpose use

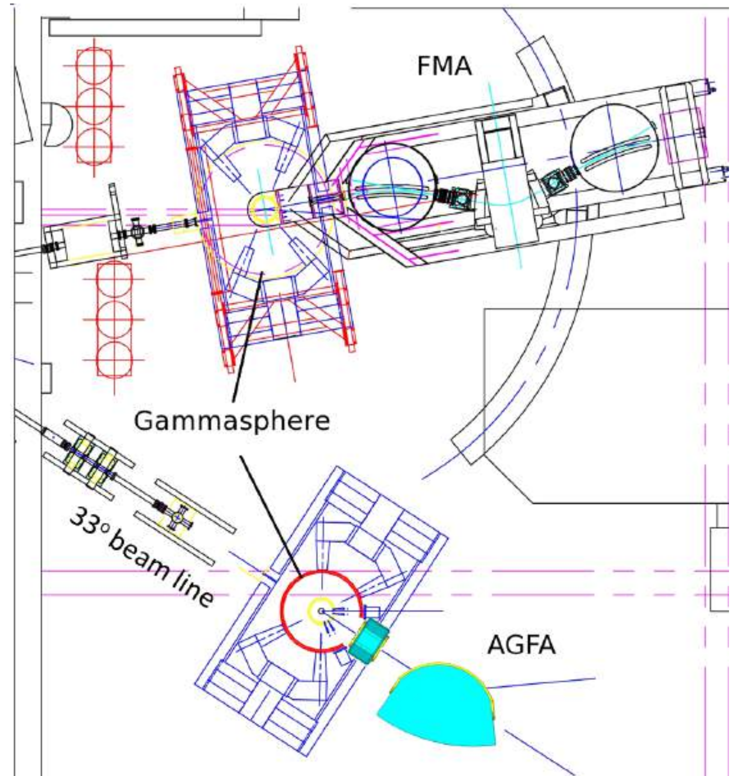
Status:

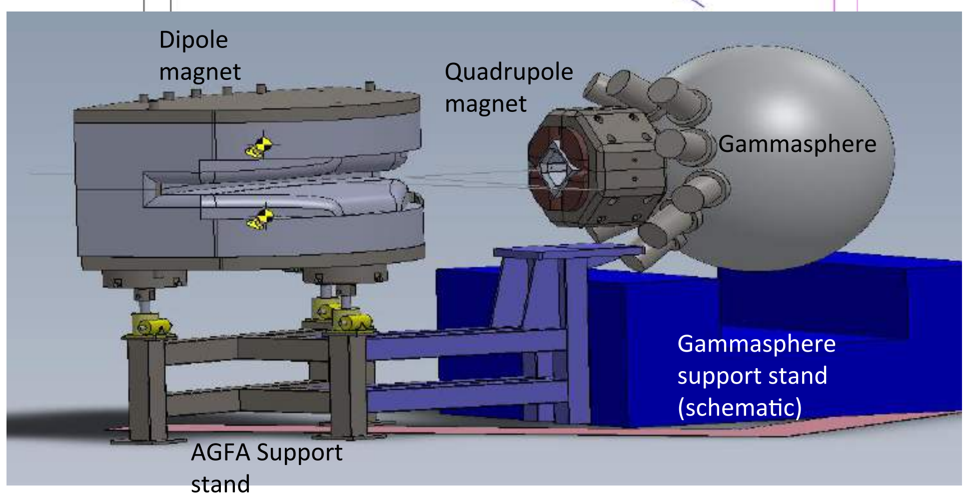
- DOE go ahead July 2013
- Management plan submitted Sept 2013
- ***Procurement of magnets ongoing***
- Planned completion Q2 FY2016

Cost: $1755k (incl. contingency)

AGFA: 50-95% Efficiency

FMA: Less efficiency, m/q measurement

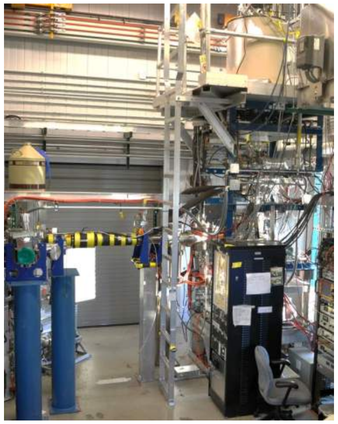




The CARIBU low-energy experimental area

- Delivers 1.5 kV to 10 kV beam to experimental stations
- Pulsed beams with rates from ~ 50 ms to seconds
- Low emittance
- Experimental stations:

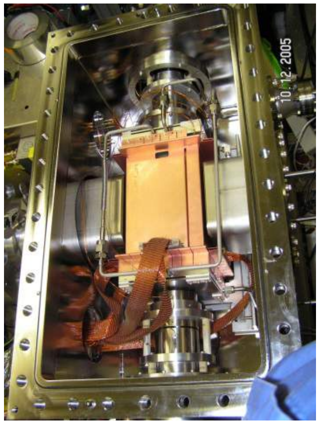
CPT (until 2016)



TAPE STATION (permanent)

X-ARRAY (Lowell)

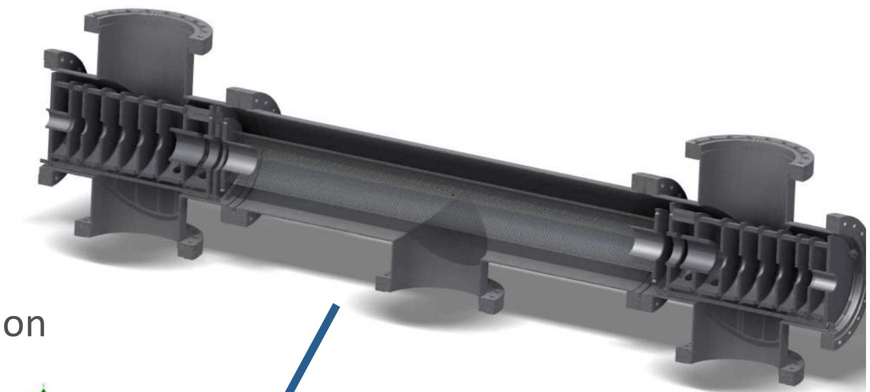
BPT (campaigns)

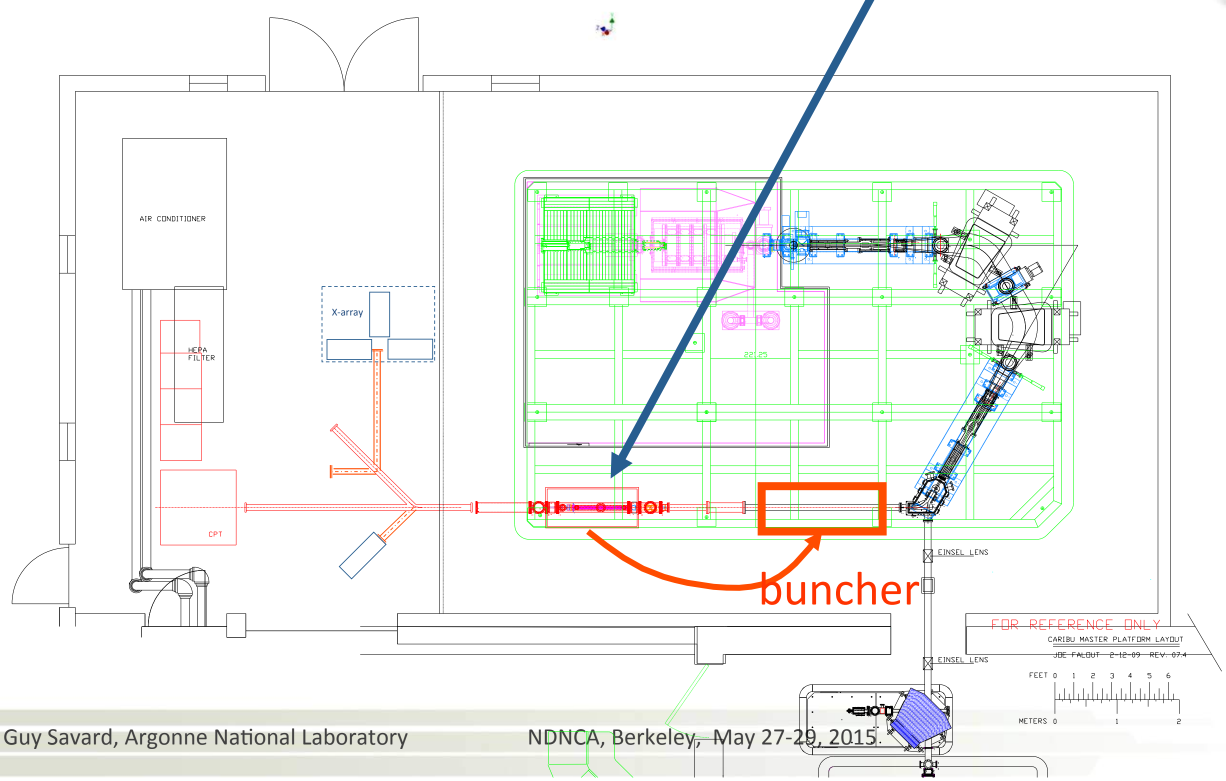


- Limited amount of space … experiments have to move out for others to move in

Better mass resolution

- Many experiments require better resolution than even the 20000 we hope to reach with the isobar separator
  - need different technology for that
    - → MR-TOF can yield above 100000 mass resolution with good transmission
    - → install an MR-TOF at CARIBU this year
      - -goal: > 40000 with > 50% transmission





What Species Have Been Extracted So Far

Gas catcher should be a "universal" approach … how diverse are the species that have been extracted so far:

- **Neutron-deficient isotopes**
  - **Cs, Xe, Te, Sb, Sn, In, Cd, Ag, Rh, Ru, Pd, Tc, Mo, Nb, Se, As, Ge, Ga, As, Zn, Co, Fe, V, Ti, K, Al, Mg, Na, O, C, B****
- **Neutron-rich isotopes**
  - **Nd*, Ce*, Pr*, La*, Ba*, Pm*, Sm*, Eu*, Gd*, Rh, Ru*, Tc, Mo, Nb*, Sr*, Cs, Xe, I, Te, Sb, Sn, In, Li****
- **Stable isotopes**
  - **Xe, Kr, Ar, Ne**

Essentially all attempted species, from the "easy" (alkali atoms and noble gases) up to the very refractory cases (Mo, Tc, Co, etc …) , have been extracted as singly or doubly charged ions with high efficiency !

****Difficulties for very light species (physics … not chemistry) but have succeeded at extracting ^{8}Li and ^{8}B as molecular ions (heating the gas catcher to get more contaminants)**