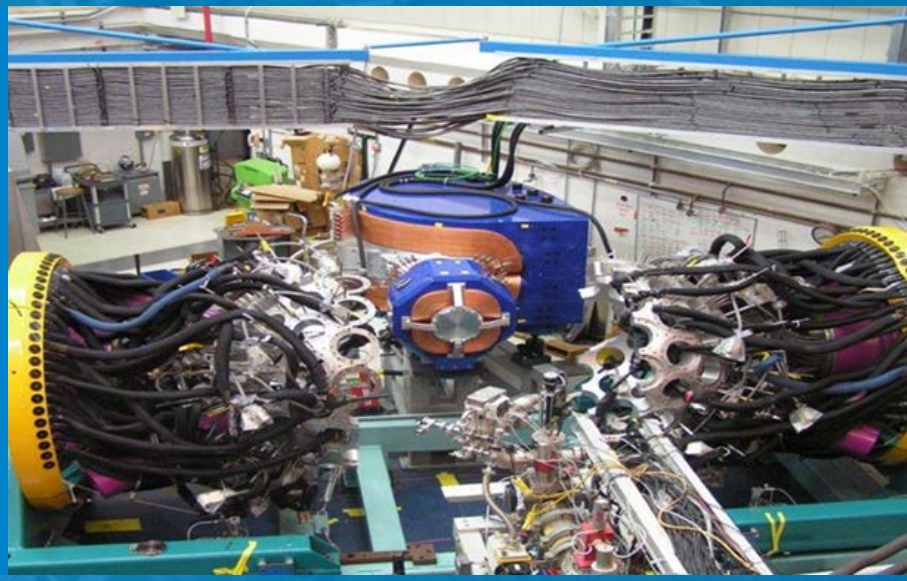
10TH AUGUST 2018

ATLAS OVERVIEW AND STATUS



GUY SAVARD
Director of ATLAS

U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

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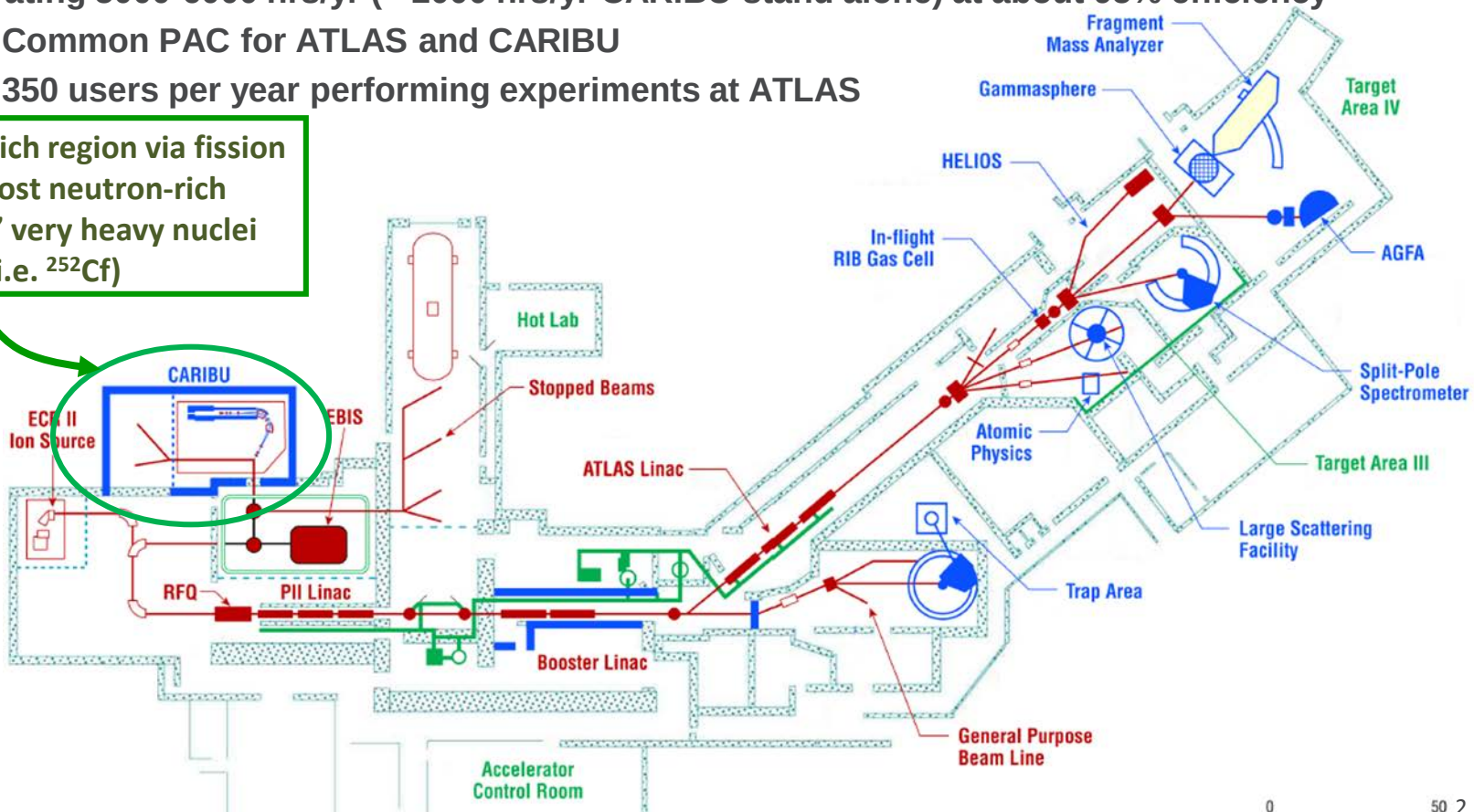
ATLAS/CARIBU FACILITY

- 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
  - Common PAC for ATLAS and CARIBU
  - 350 users per year performing experiments at ATLAS

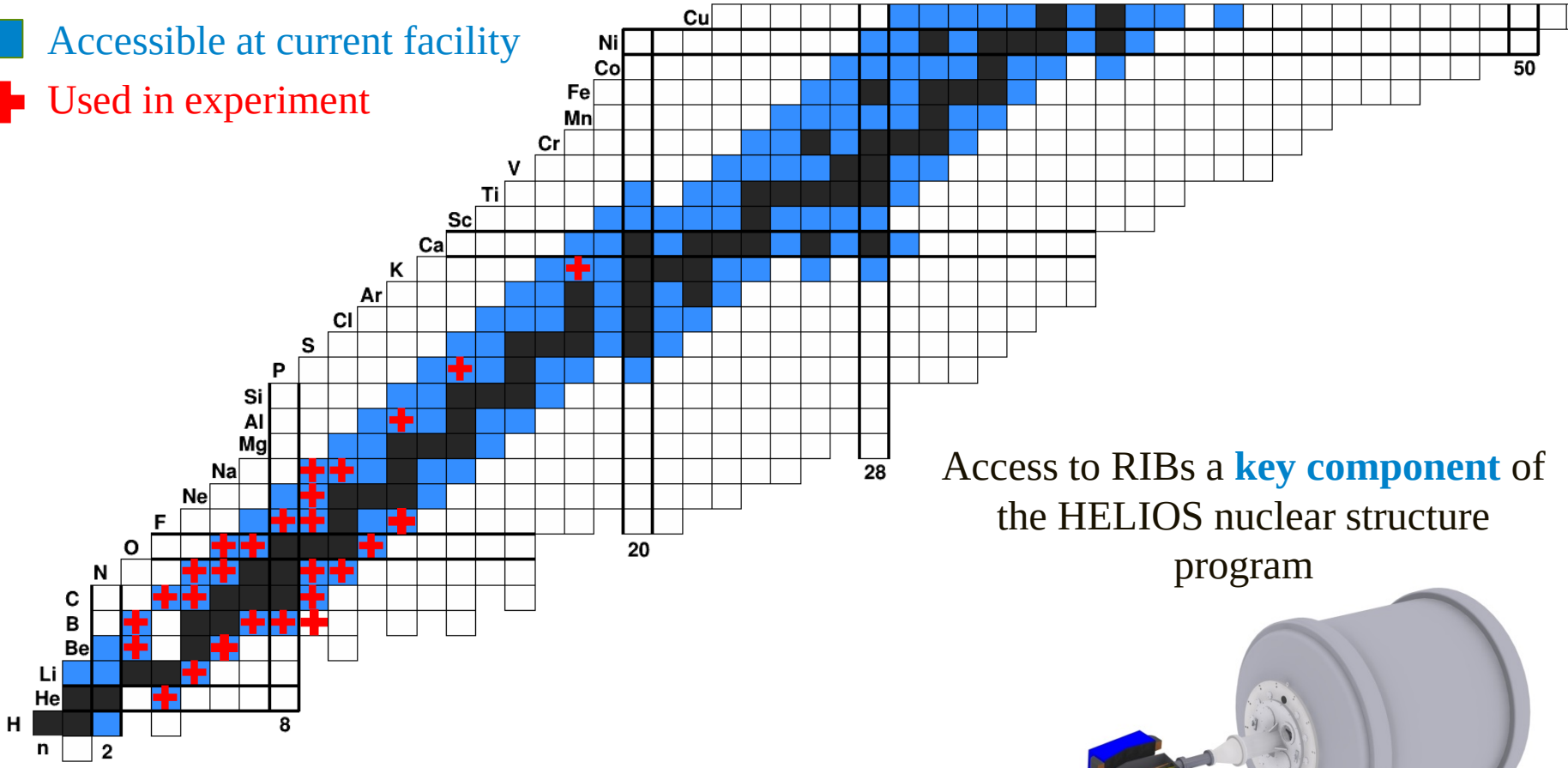
Access to n-rich region via fission of the most neutron-rich "available" very heavy nuclei (i.e. ^{252}Cf)



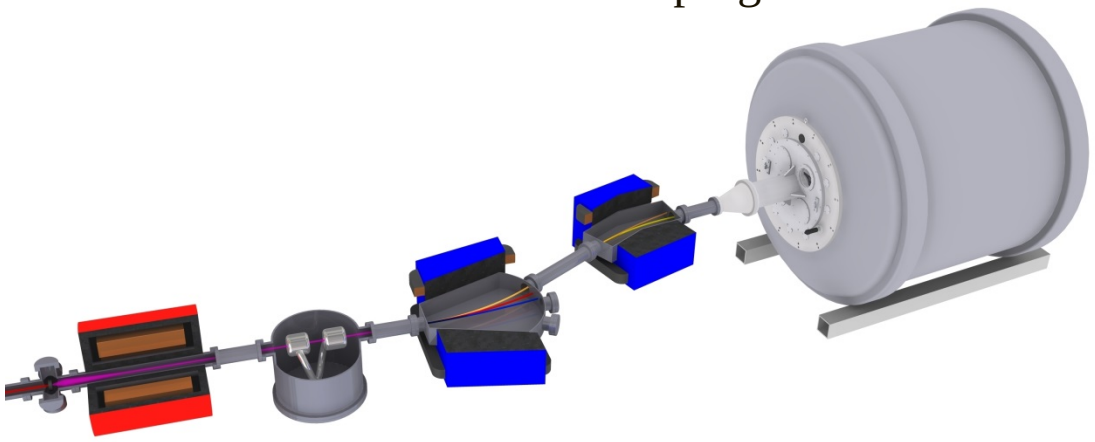
IN-FLIGHT RADIOACTIVE BEAMS AT ATLAS

Accessible at current facility

Used in experiment



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

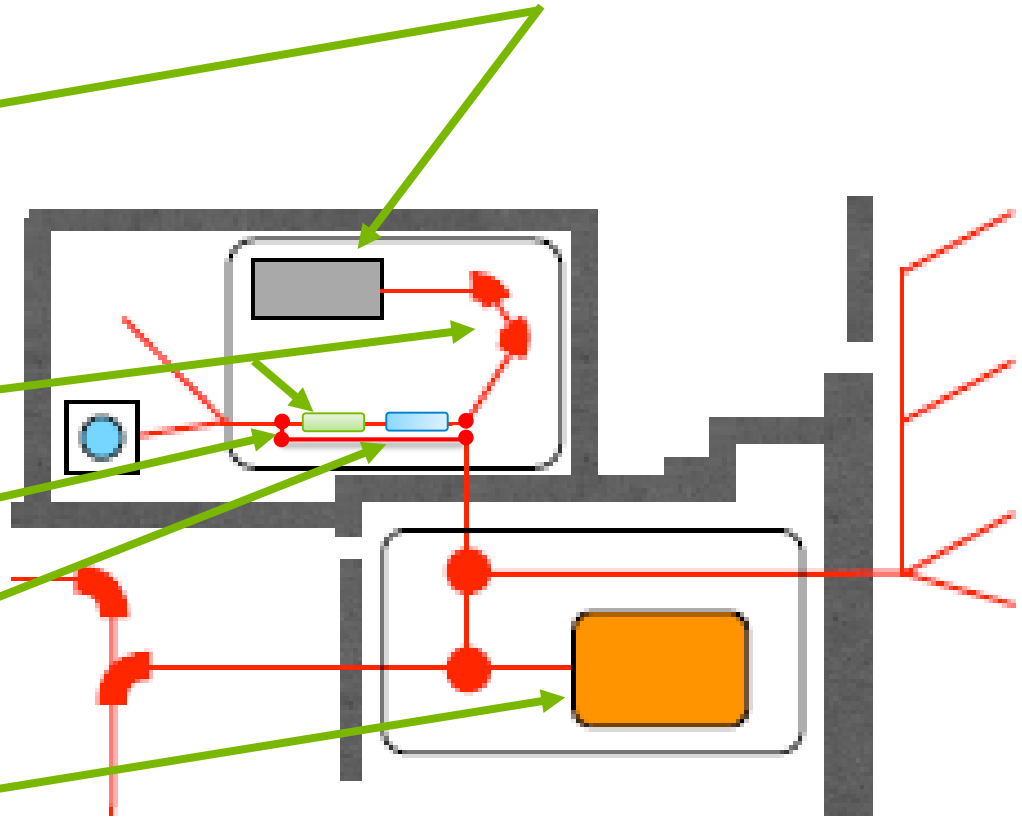


ATLAS upgrades, target and reaction techniques, will increase reach until arrival of the new in-flight separator **AIRIS**

NEUTRON-RICH BEAM SOURCE FOR ATLAS: CARIBU "FRONT END" LAYOUT

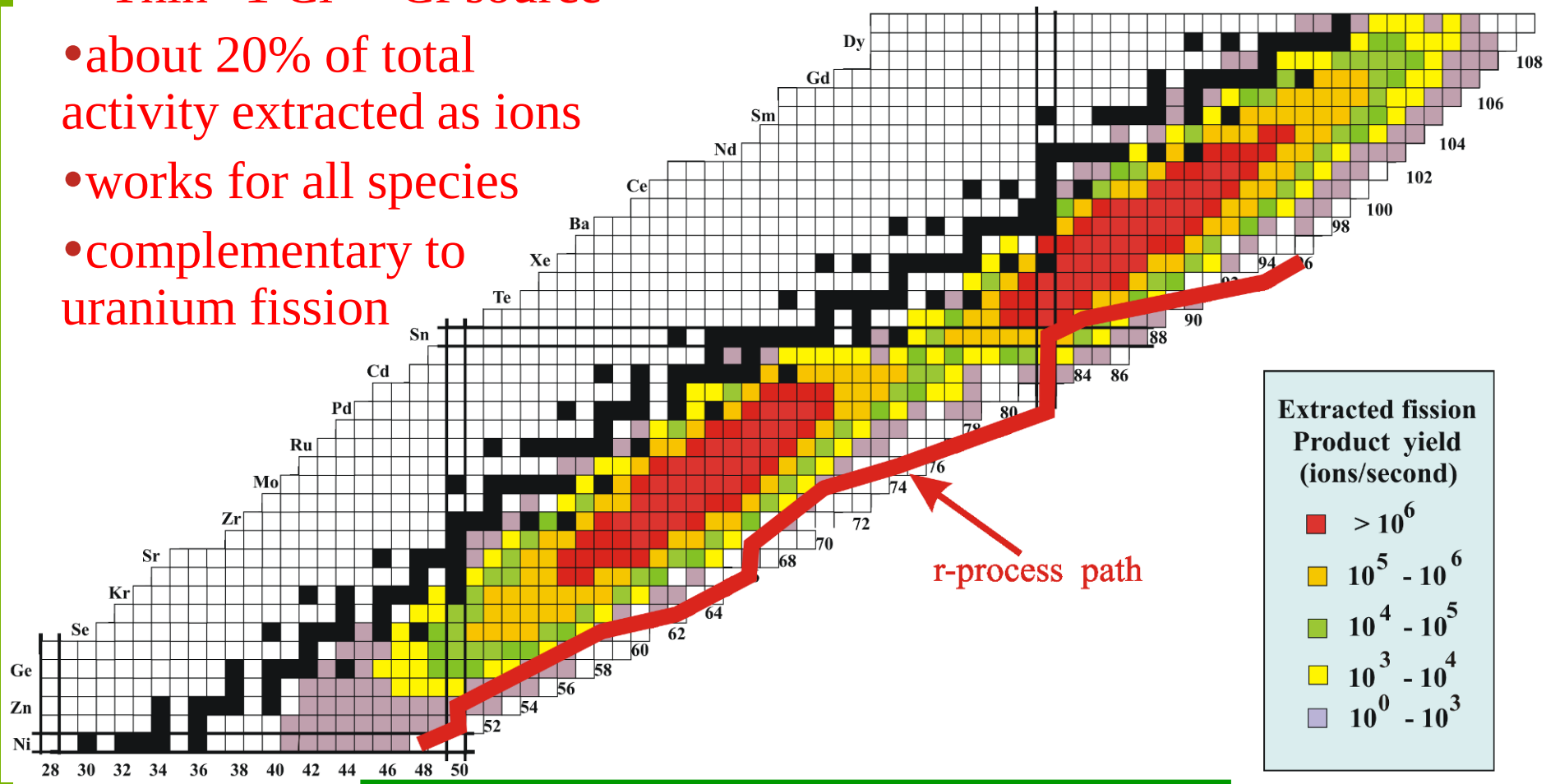
Main components of CARIBU

- **PRODUCTION: "ion source" is ^{252}Cf source inside gas catcher**
  - **Thermalizes fission fragments**
  - **Extracts all species quickly**
  - **Forms low emittance beam**
- **SELECTION: Isobar separator and MR-TOF**
  - **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

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.

- **In-flight radioactive beams: all light species, close to stability, but some compromises 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).

ATLAS Facility Performance

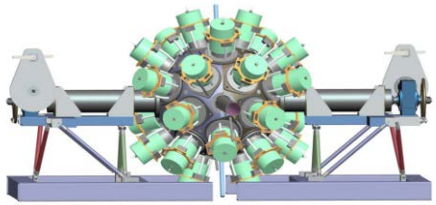
Operating Statistics

Machine Operation ATLAS	FY2012	FY2013 Booster	FY2014 Upgrade	FY2015	FY2016	FY2017	FY2018 (Proj.)
Research Hours (on Target)	5848	3345	2801	5559	4953	4318	5200
Beam Study Hours	924	152	228	56	352	310	300
Tuning/Restore	911	607	786	671	855	840	400
Total Delivered Hours	**7683**	**4104**	**3815**	**6286**	**6160**	**5468**	**5900**
Unscheduled failure hours	706	487	248	479	433	452	400
Total Scheduled Hours	8389	4591	4063	6765	6593	5920	6300
Availability (%)	91.6	89.4	93.9	92.9	94.4	92.4	93.7
CARIBU							
Research Hours	1074	1980	2131	1884	2820	2260	2000
Beam Study Hours	360	340	172	376	464	204	300
Total Delivered Hours	1434	2320	2303	2260	3284	2464	2300

- FY17-18: Install existing permanent magnet ECR ion source to provide more flexibility and development time for ion sources
- FY17: Cryogenics group complete by mid-March, return to 7 day/week operations 3/1/2017
- FY18: Little flexibility in schedule to make hours due to:
  - Shut down of facility for 2 weeks in Dec. 2017 due to ARIS issue
  - Long beginning of year shutdown to install main components of AIRIS
- FY19 – FY24 : continue delivering 5900 hours/year under scenario 1, more once the MUU is operational in scenario 2

MAIN TOOLS ENABLING THE PHYSICS: ATLAS SUITE OF EXPERIMENTAL EQUIPMENT

GAMMASPHERE/GRETINA

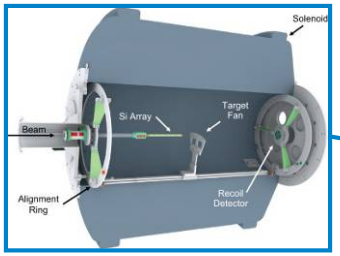


FMA

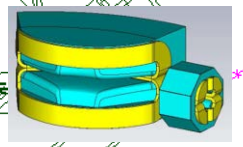
CPT mass spectrometer

X-array

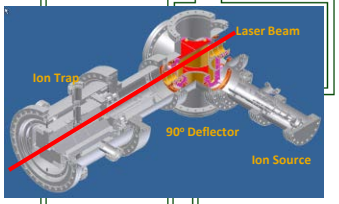
HELIOS spectrometer



AGFA

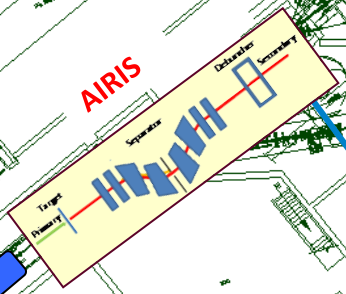


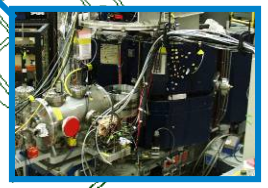
Laser Lab



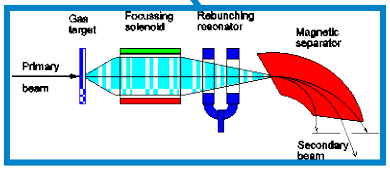
CARIBU

AIRIS

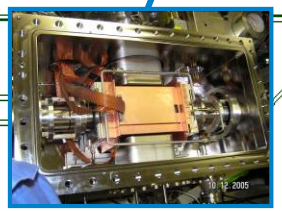




Si-array (Ludwig) and Enge spectrometer



In-flight RIBs production



Beta decay Paul trap

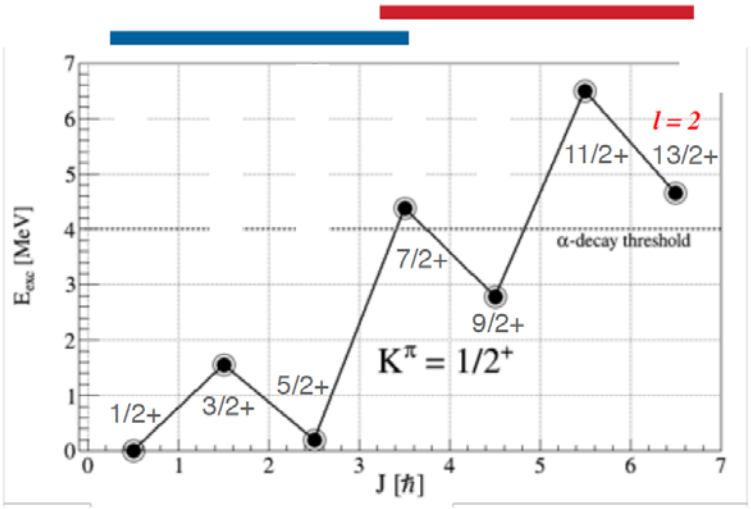
+ outside instruments: GRETINA, CHICO-II, HERCULES, GODDESS, VANDLE, …

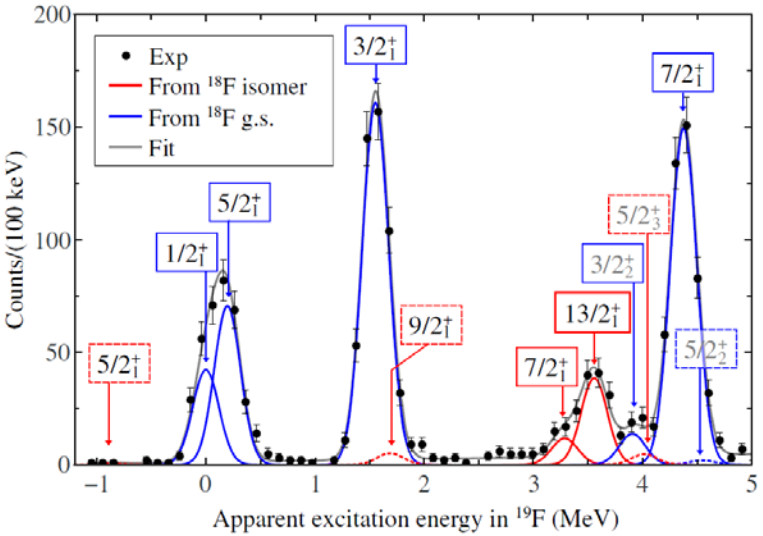
Neutron adding on ^{18g,18m}F in inverse kinematics

Single-particle probe of an aligned spin state

Testing the single-particle & collective descriptions of nuclear levels

- production, transport, & reactions on a $T_{1/2}$ ~ 160 ns isomer **(5^+)** & **(1^+)** g.s. beam





Technical achievements:

- Development of isomeric beams via the in-flight method @ ATLAS
- Transfer reactions on isomeric beams w/ HELIOS

D. Santiago Gonzalez et al, PRL 120 (2018)

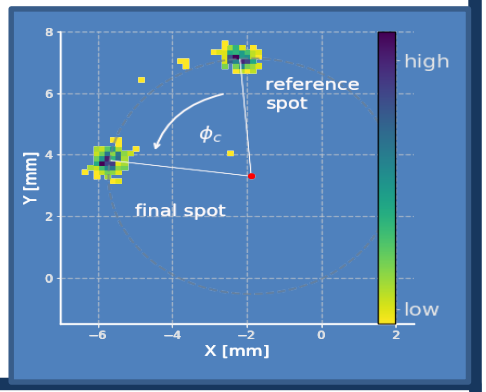
CPT mass measurements at CARIBU using Phase-Imaging Ion Cyclotron Resonance (PI-ICR)

PI-ICR technique:

- Determine cyclotron frequencies by measuring the phase advance of orbital motion over a period of free motion in the Penning trap

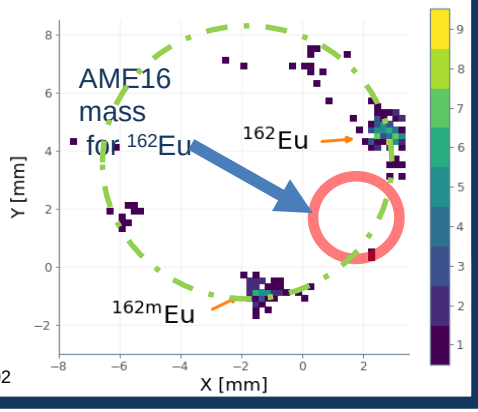
$$\nu_c = \frac{\phi_c + 2\pi N}{2\pi t_{\mathrm{acc}}}$$

- Compared to TOF-ICR this technique is faster, offers higher resolution and improved sensitivity.
- Excellent low-rate capability (as low as ~1 ct/hr)



Isomer discoveries:

- Several long-lived isomeric states in rare-earth isotopes have been identified (eg. ^{160,162}Eu[1])
- β-decay spectroscopy was then conducted on these states



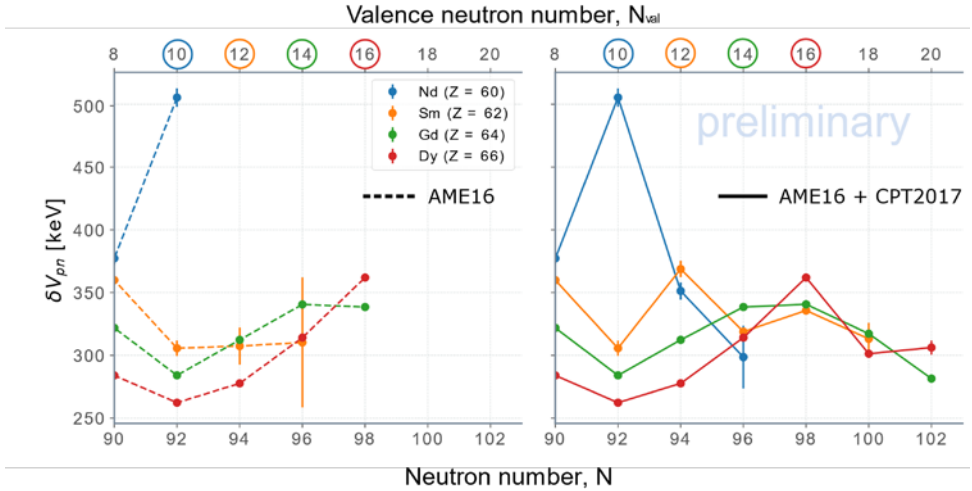
[1] D. Hartley et al. **PRL 120** (2018) 182502

p-n interaction in the rare-earth region:

- Double differences in masses isolate the average interaction between the last two protons and neutrons of a nucleus. For even-even nuclides this metric is given by:

$$\delta V_{pn} = \frac{1}{4}[S_{2N}(Z,N) - S_{2N}(Z-2,N)]$$

- In this region maxima in δV_{pn} are expected near $Z_{val} = N_{val}$ (circled below)



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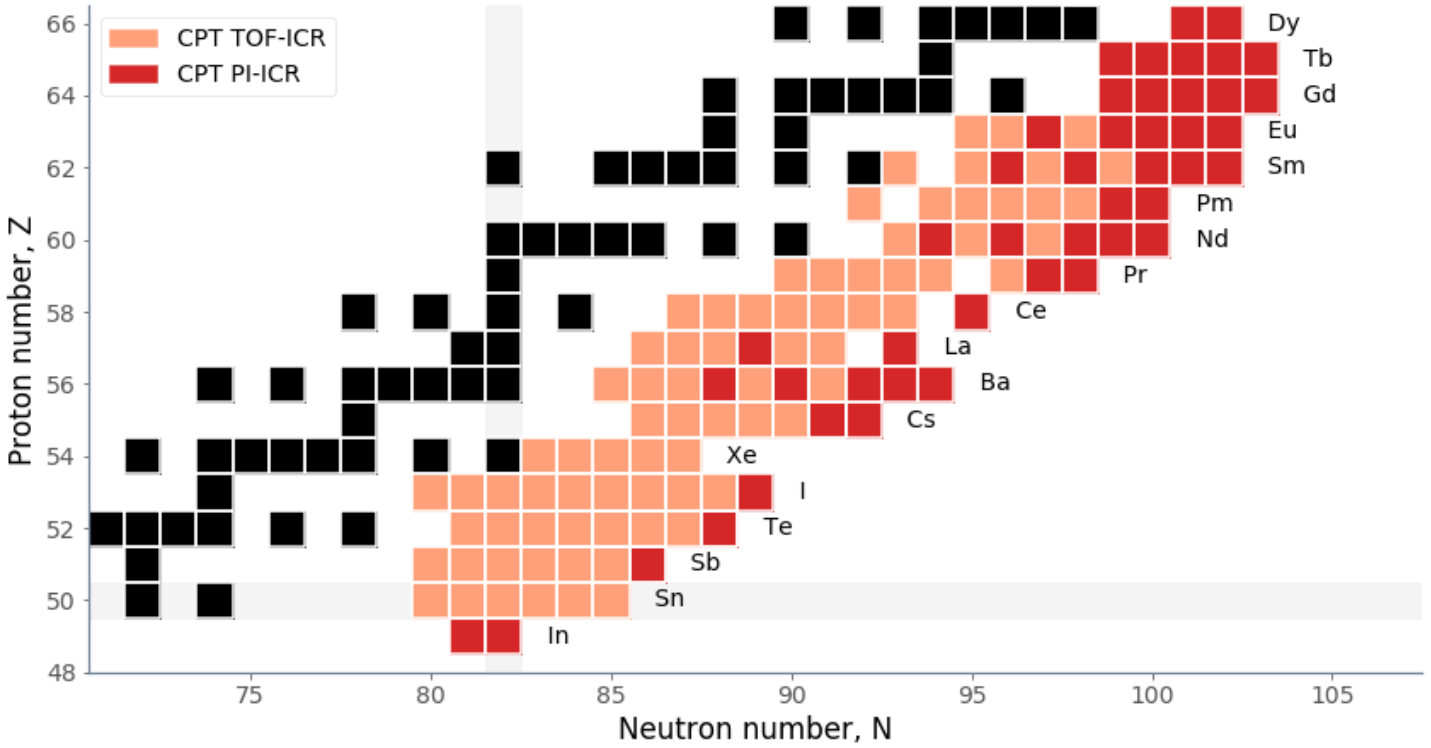
Increased efficiency also allows mass measurements further from stability



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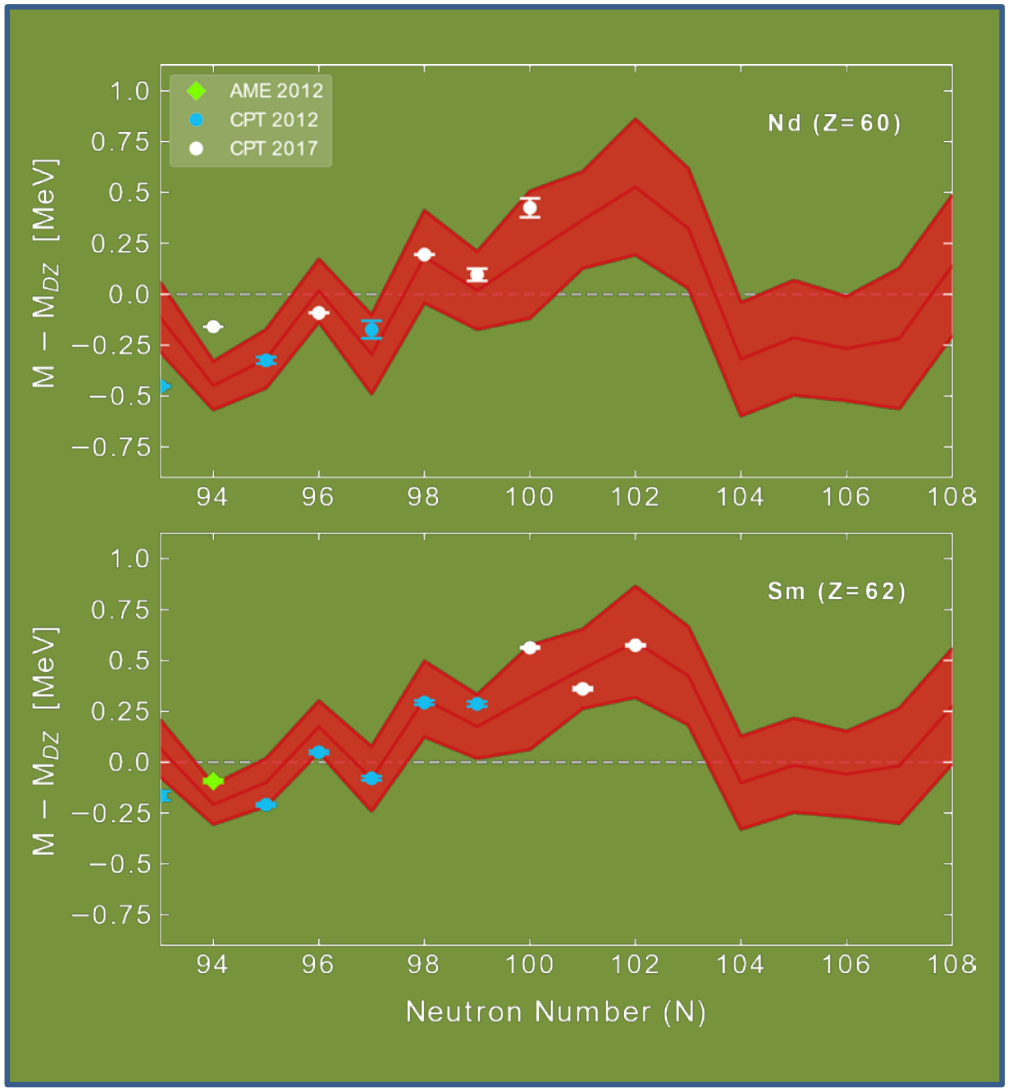
Nd and Sm masses for dynamical formation of rare-earth peak

Takeaway:

- See good agreement between experiment and theory given this scenario
- Rare-earth peak can be created through dynamical mechanism
- Need to measure more masses and calculate further mass surfaces under different astrophysical conditions

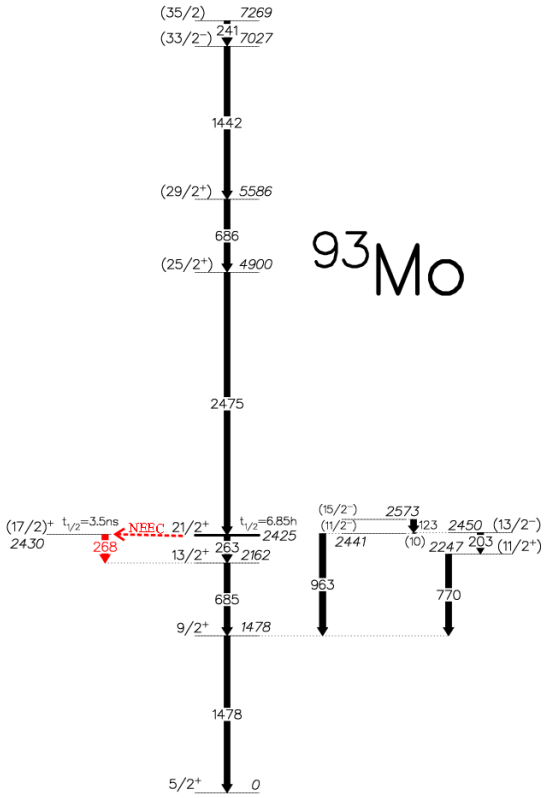
Orford et al, **PRL 120** (2018) 262702

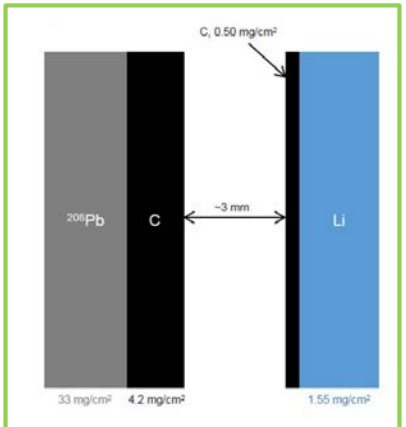


First Experimental Evidence of Nuclear Excitation by Electron Capture (NEEC)

C. J. Chiara *et al.*, Nature **554** , 216 (2018)

- NEEC is theorized to occur when an electron captured into an atomic vacancy excites the nucleus to a higher-lying state when the KE of the electron + binding energy matches the nuclear energy difference.
- NEEC has never been confirmed experimentally even though many studies have been undertaken.
- An experiment was constructed utilizing Gammasphere to look for evidence of NEEC in ^{93}Mo.
- Due to a long-lived isomer in ^{93}Mo (~7 hrs), gamma-rays associated with the feeding and decay of the isomer should not be in fast coincidence with each other.
- The observation of coincidences between these feeding and decay gamma-rays implies that the isomer is being depleted by excitations to a state ~5 keV higher in energy
- This excitation has been ascribed as confirmation of NEEC.

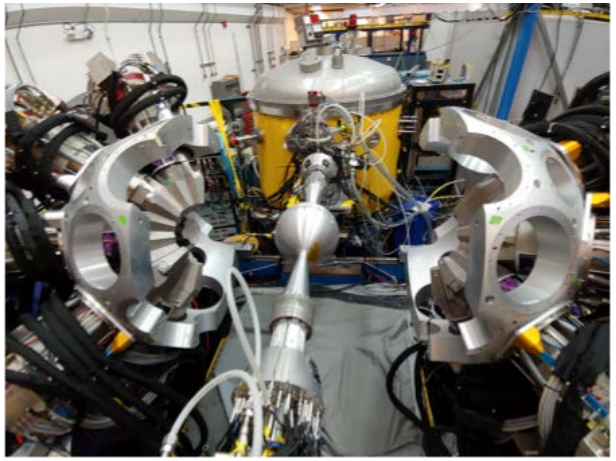




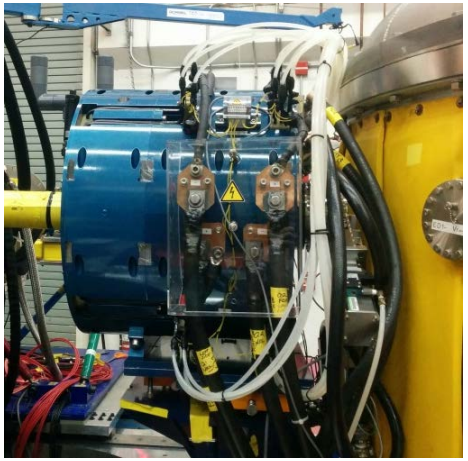
GRETINA/FMA CAMPAIGN ONGOING

STATUS

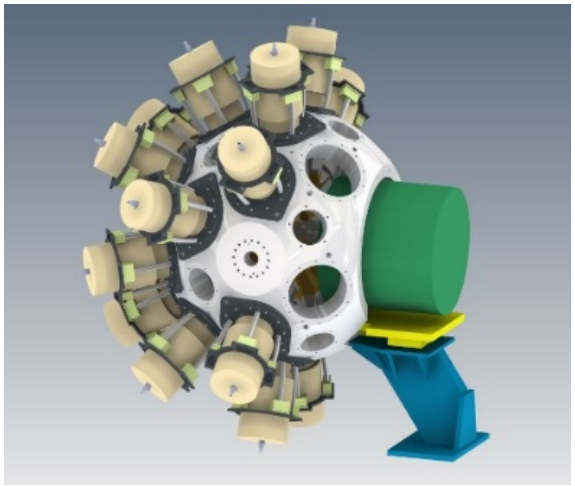
- New quad fitting inside GRETINA shell installed in fall 2017
- 12 msr FMA solid angle, presently 2 msr with Gammasphere
- GRETINA using two hemispheres at 90^{o} to the beam axis (11 clusters)
- New support frame for GRETINA use with the FMA at up to 30 cm or with CHICO
- GRETINA/FMA campaign Oct 2017 – March 2019



GRETINA on Gammasphere support



New Quad on FMA



GRETINA surrounding new quad

THE PATH FORWARD FOR ATLAS: CONTINUED PUSH TOWARDS HIGHER EFFICIENCY AND SENSITIVITY

- 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
- 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 (~X 2 in intensity and higher purity) (FY14-17)
  - AGFA (X10 in acceptance for superheavies) (FY15-17)
  - AIRIS: New recoil separator for in-flight program (>100 in intensity and higher purity) (FY16-18)
  - New larger low-energy experimental area for CARIBU (FY17-18)
  - N=126 factory (FY17-19)
  - Multi-user upgrade (FY18-20)

ATLAS Upgrades: Present Status (Active Projects)

Tandem to north end of vault (AIP)
Moved in 6/2017
Provide space to start new stopped beam facility

FY18: New low-energy experimental hall (AIP)

ECR2

CARIBU

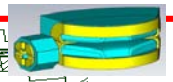
EBIS

PII

BOOSTER

ATLAS

FY17:AGFA



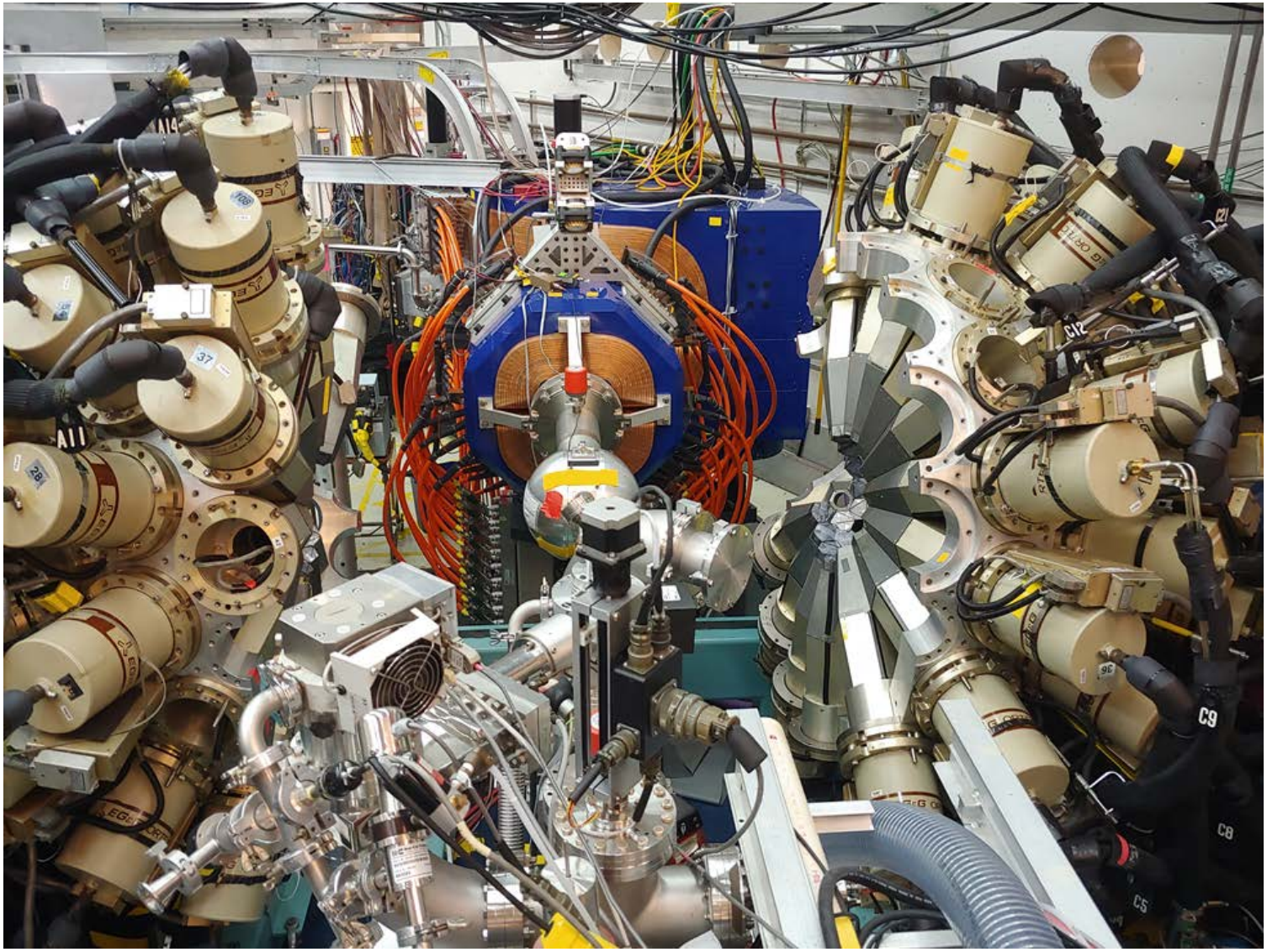
FY18: New in-flight separator (AIRIS)

FY18: Permanent Magnet ECR (light beams) (CE)

- **Energy Upgrade Cryostat AIP Improvement (AIP)**
  - 4 year funding started in FY16
  - Add one new resonators (8 total)
  - Retire VCX phase control – go to driven system
  - Gain ~4 MV

Priority to improving unique capabilities and flexibility of facility

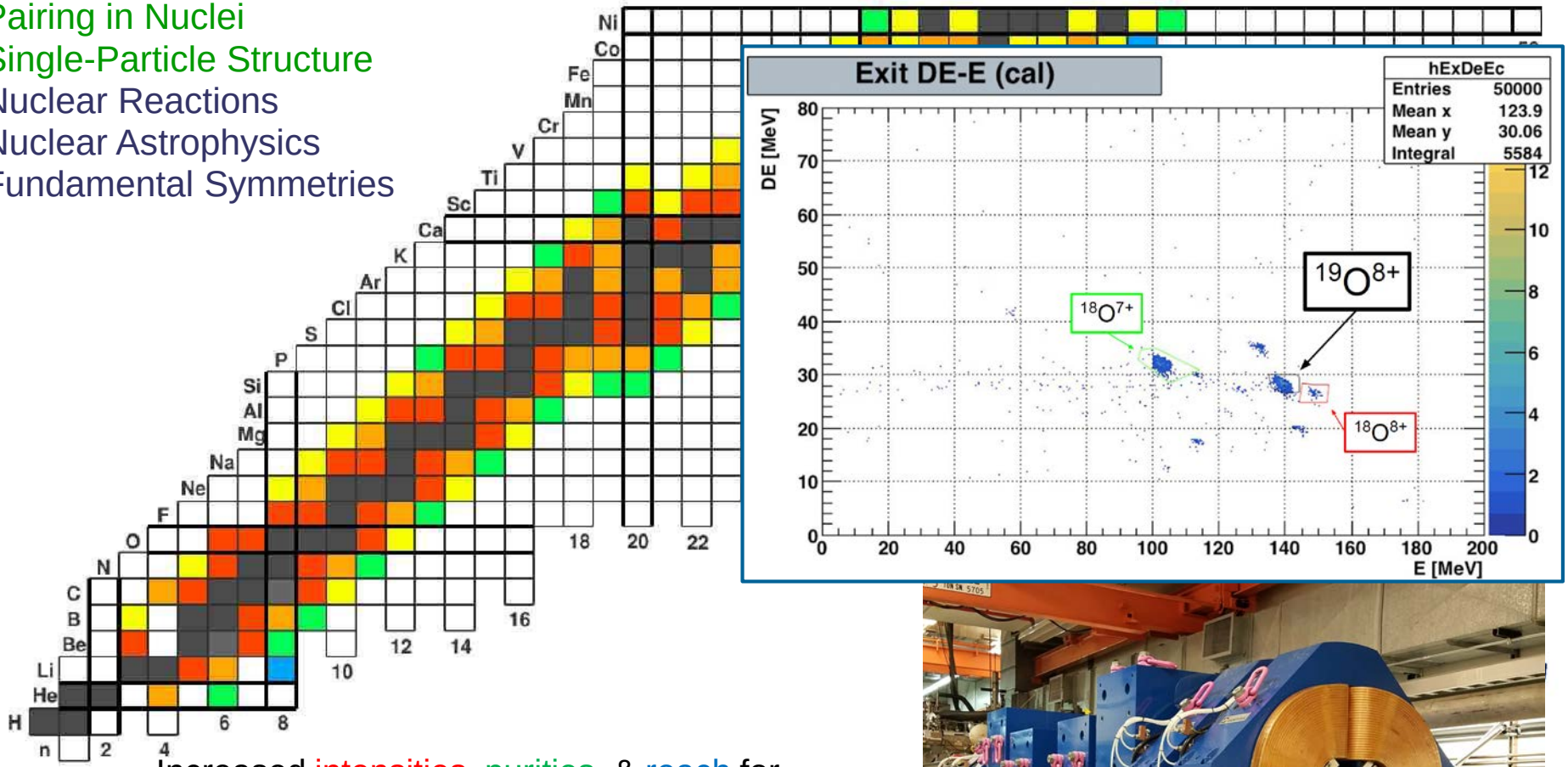
The AGFA gas filled spectrometer has now been commissioned and used for first experiments



ESTIMATED BEAM RATES AT AIRIS EXIT

- Collective Nuclei
- Pairing in Nuclei
- Single-Particle Structure
- Nuclear Reactions
- Nuclear Astrophysics
- Fundamental Symmetries

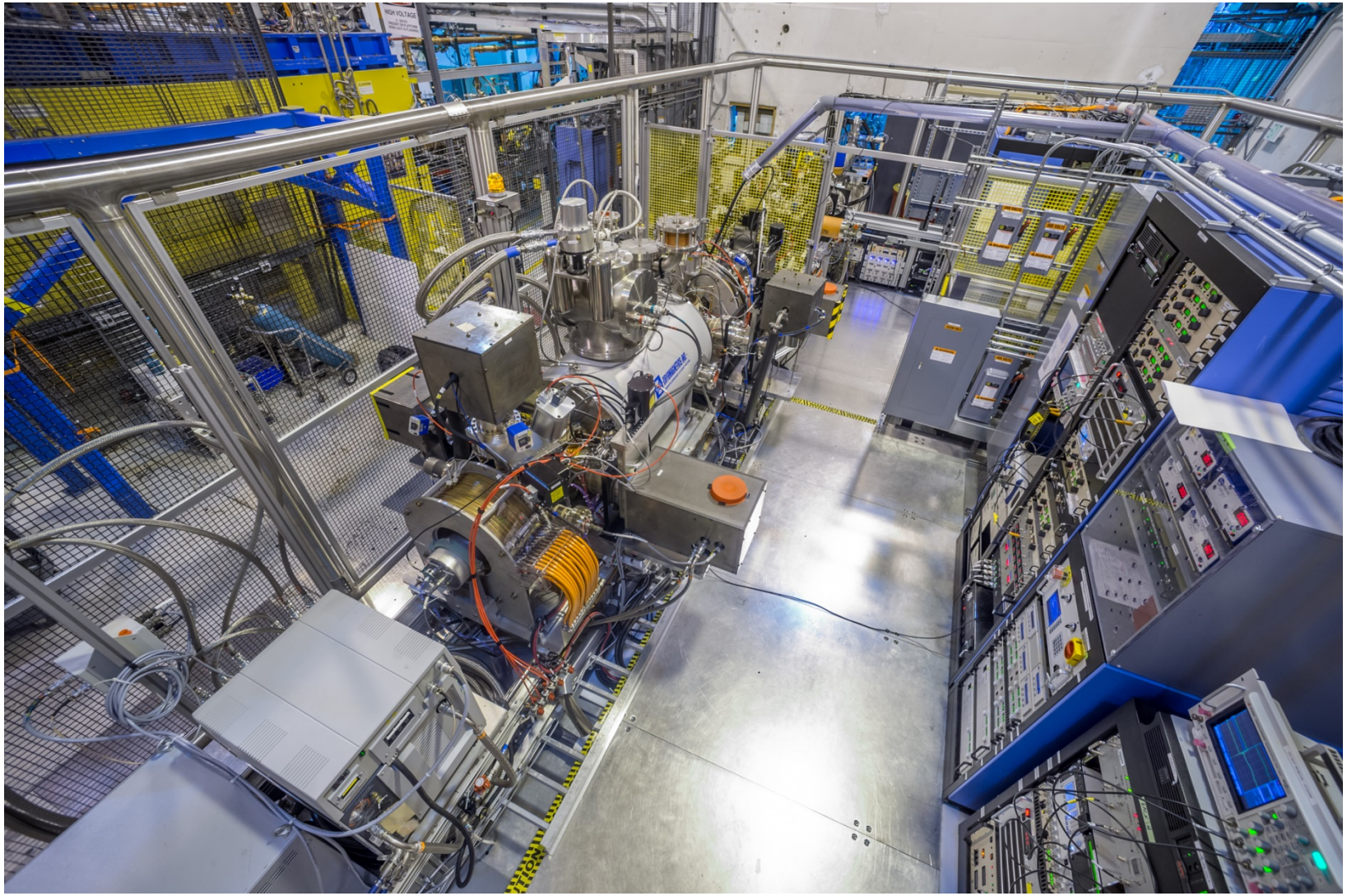
Uncertainties up to one order of magnitude



- Increased intensities, purities, & reach for ATLAS in-flight beams
- Accessibility to more experimental areas

More info at https://www.phy.anl.gov/airis/

EBIS CHARGE BREEDER AT ATLAS



Reaccelerated CARIBU beams properties optimized over the last year

- Purity
  - Typically 80% of beam is radioactive beam, as opposed to ~1% with ECR

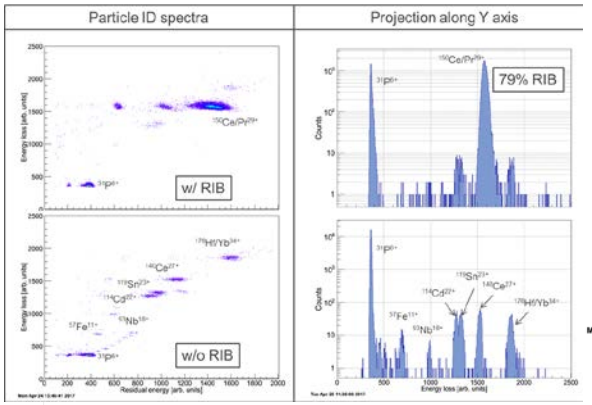
    (acceptable for most experiments)

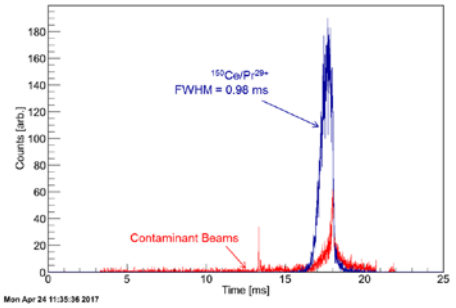
- Time structure
  - Can now be stretched without losses from ~ 20 us to 10 ms

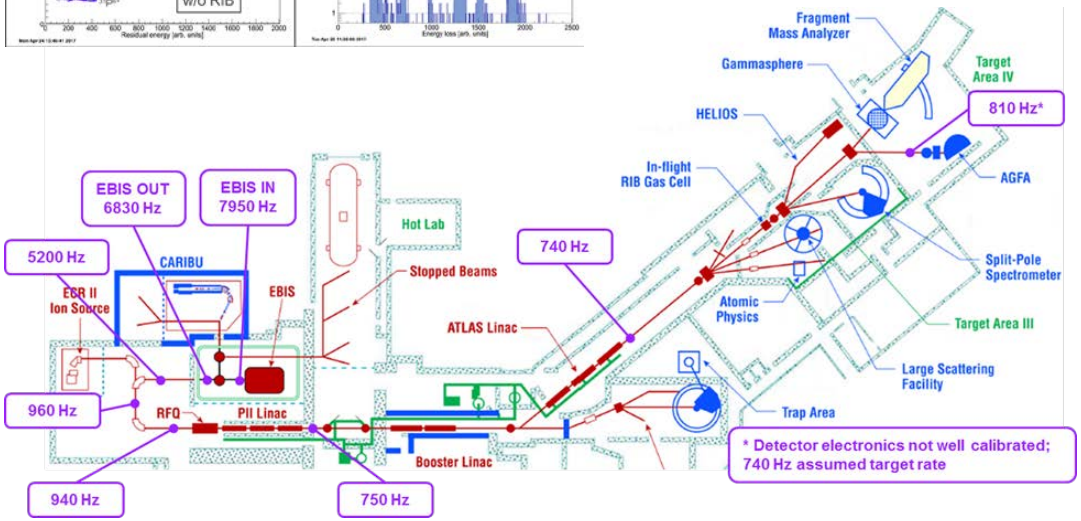
    (instantaneous rate now acceptable for most experiments)

- Transmission
  - 70-80% from EBIS platform to target

    (theoretical limit ~ 83%)

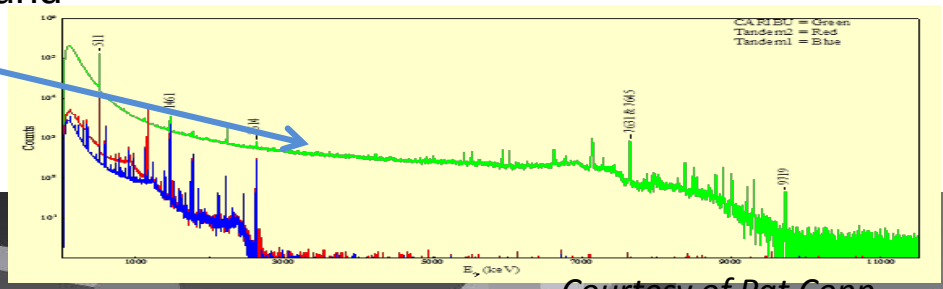




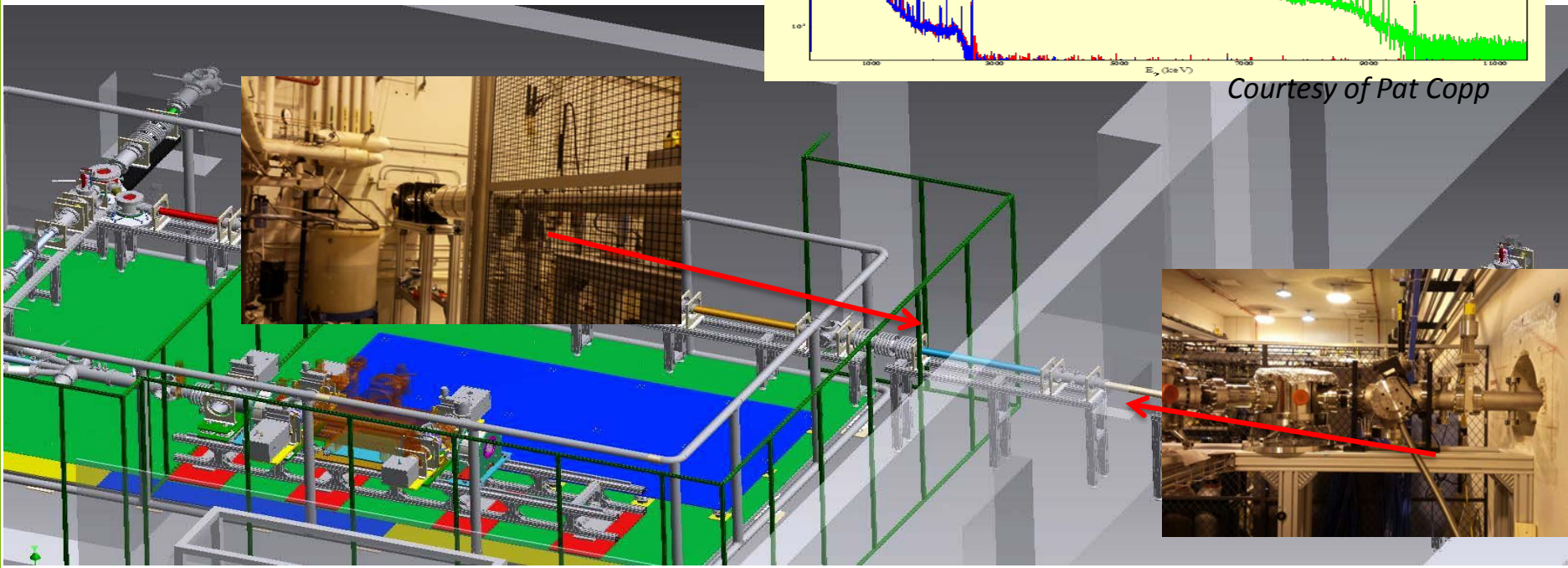


Coming next for CARIBU: new larger lower-background low-energy experimental area

- Tandem moved to north end of hall last summer
- Services in place and beamline components installation ongoing
- New experimental area expected to be available later this spring
  - ~ 2 orders of magnitude lower background



Courtesy of Pat Copp



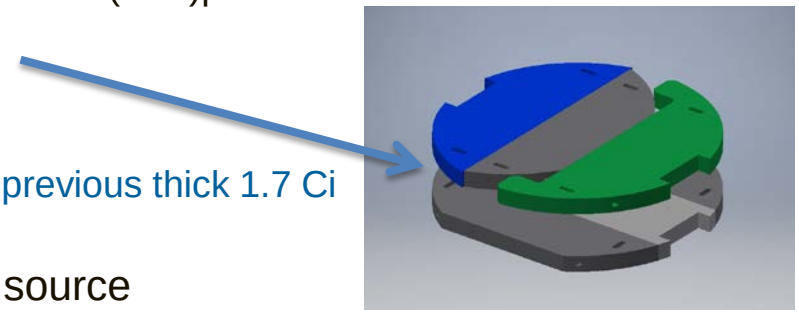
CARIBU source: delivery, present & future

- The 1.7 Ci source, installed at CARIBU in May 2014, needed to be replaced
  - Decayed to ~ 0.59 Ci + too thick (~11% release) → effectively 0.06 Ci

- R&D effort with ORNL to obtain a better source gave mixed results
  - depositions with analogs at ORNL have yielded thinner deposits but no clear effect of heating
  - a 3-plate source configuration with a larger area was developed at ANL
  - these developments could in principle lead to a factor of ~5 gain
  - actual 252Cf deposition however yielded irreproducible results
    - First (side)plate was a success → 0.52 Ci with 40-50% release
    - Next 3 attempts yielded no usable deposits

- Delays started to encroach on ATLAS schedule and we needed to move forward
  - designed a modified holder to accept the one successful (side)plate
  - arrived at ANL in March 2018
  - Installed in May 2018

  - Yield with thinner 0.5 Ci source similar to that with previous thick 1.7 Ci

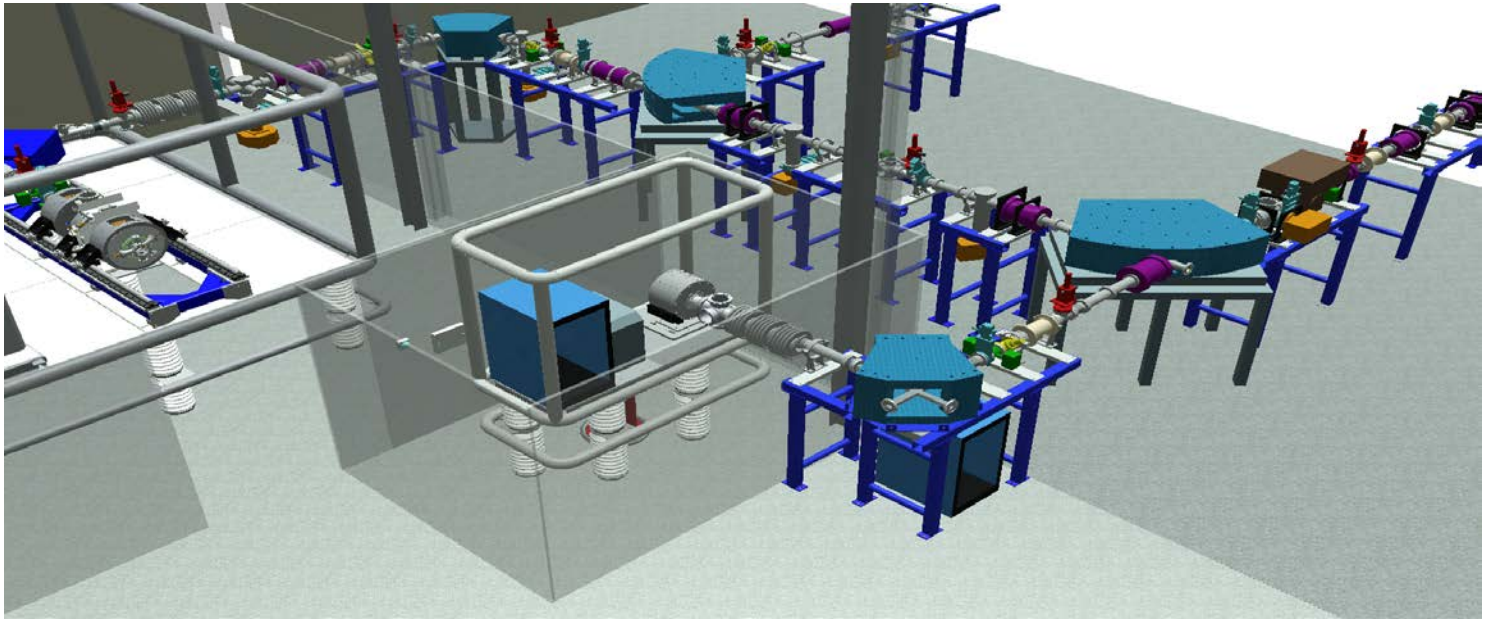


- Need to look at better future options for CARIBU source

AIP investment in a neutron-generator-based source of fission fragments to obtain more reliable and higher intensity access to fission products

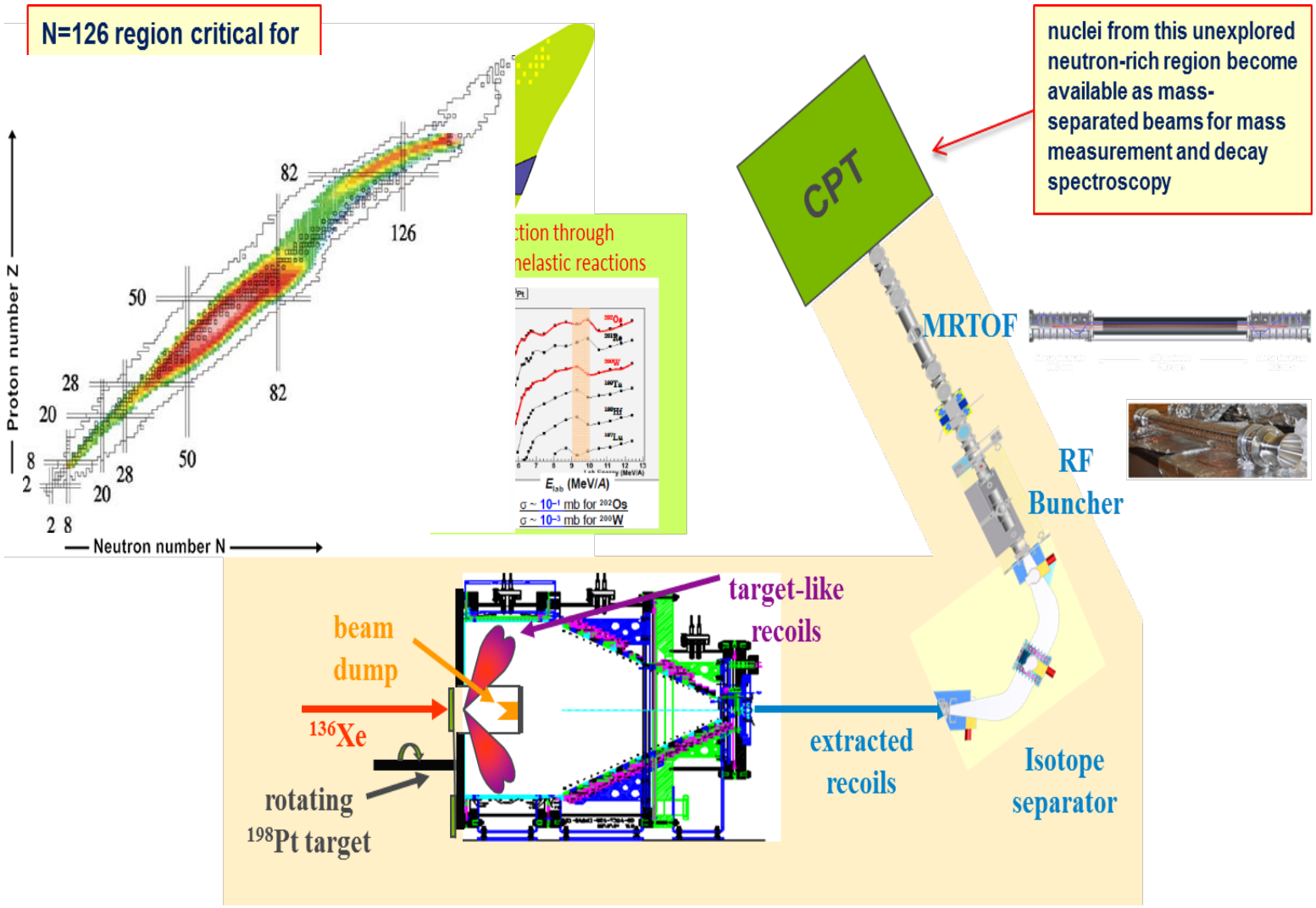
Installation of new light-ion ECR source at PII LEBT

- **Re-purposed items:** Ion source, HV platform/p.s., 90 degree dipole/p.s., HV transformers, accelerator tubes, magnetic steerer, interlocks, TWTA, turbo/forepumps, control sys interface hardware, vacuum pipe/slits/bpm/fc/bellows etc.
- **New items needed:** Electrical feed, chiller, electrostatic quad triplet, integrated ECR exit steerer, vacuum valves/diagnostics interface, control system hardware, 2nd freq. TWTA

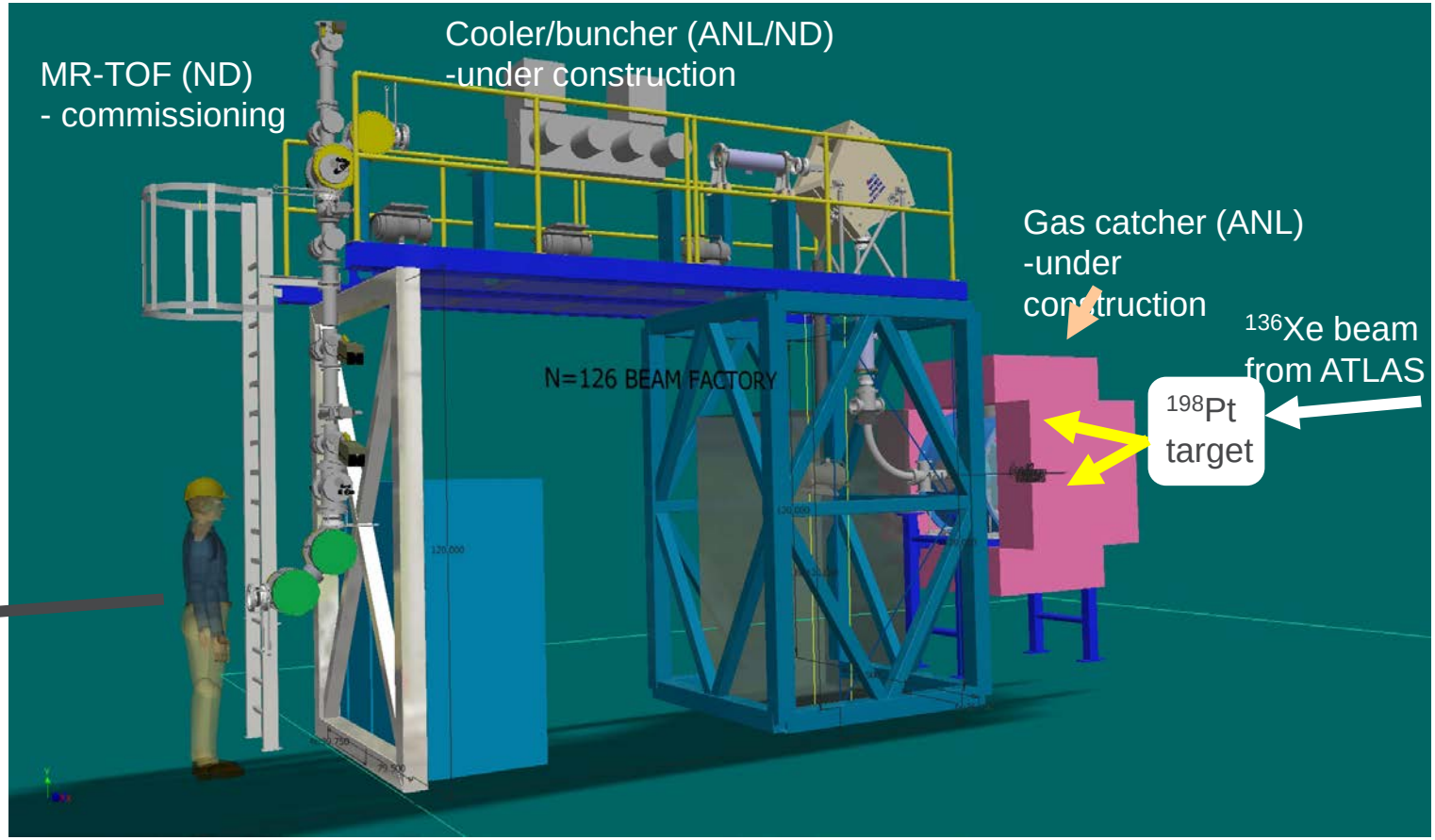


Expected to be operational by end of summer for light ions and "special" beams …. i.e. ^{14}C, ^{225}Ra, …

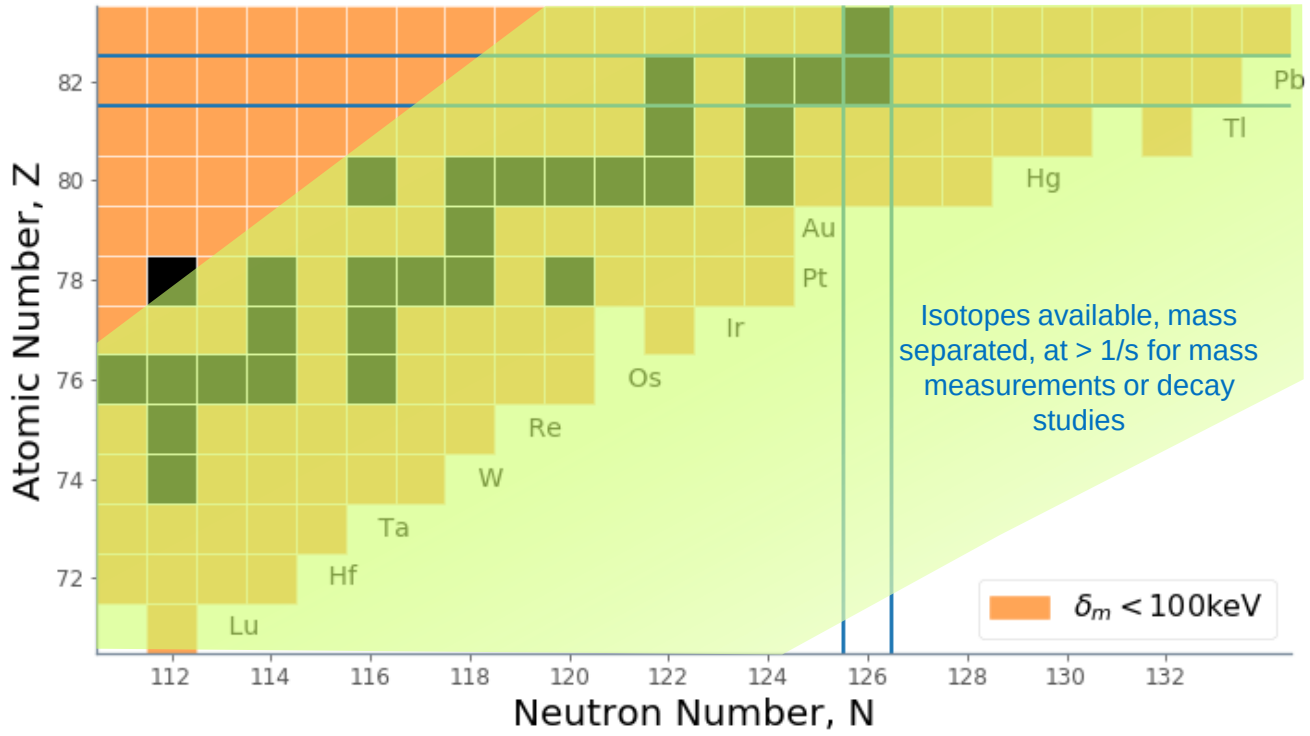
ACCESSING ISOTOPES OF INTEREST FOR THE LAST R-PROCESS ABUNDANCE PEAK: THE N=126 FACTORY



The N=126 factory



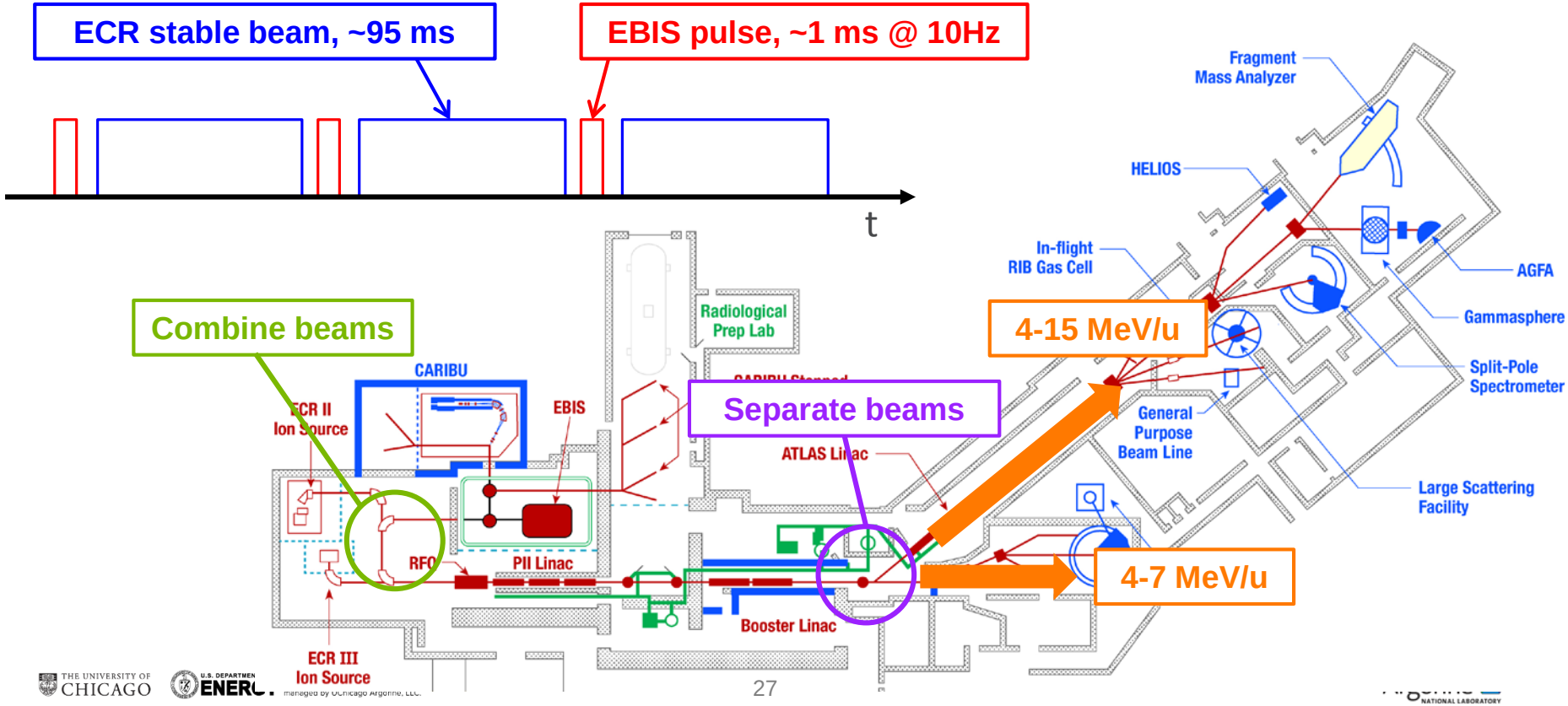
EXPECTED REACH OF N = 126 FACTORY



Note: N=126 factory will also be used for mass measurements around the termination of the rp-process using fusion-evaporation

ATLAS MULTI-USER UPGRADE

- EBIS beams represents 1-3% duty factor
- Combine pulsed EBIS beam with stable ECR beam
  - Address high demand on facility
  - Enable long duration experiments
  - Maximize efficient accelerator usage



STATUS

- ATLAS is the DOE low-energy nuclear physics national user facility
  - Running reliably and logging in a large number of operating hours
  - Accomplishing its current science goals
  - A coherent upgrade program to add accelerator and experimental capabilities that build on each other to provide new capabilities to better address the community's evolving science goals
    - Improving suite of experimental equipment
      - HELIOS, digital Gammasphere and DSSD, X-array
      - **AGFA,** N=126 factory, laser lab, beta-delayed neutron trap
    - **Improving purity of reaccelerated beams: CARIBU + ATLAS upgrade+ EBIS charge breeder (+ new Cf source)**
    - **Improving background for decay work: CARIBU + MRTOF + new low-energy (+ new Cf source)**
    - **Improving in-flight beams: AIRIS + ATLAS upgrade + new high power targets**
- Providing unique capabilities to a broad user community
  - unique experiments with stable beams
  - exploring the path and bridging the gap to the reaccelerated beam program at FRIB
  - providing access to new regions of interest that will not be readily accessible to FRIB