ATLAS

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Scientific Director of ATLAS

Argonne National Laboratory
&
University of Chicago

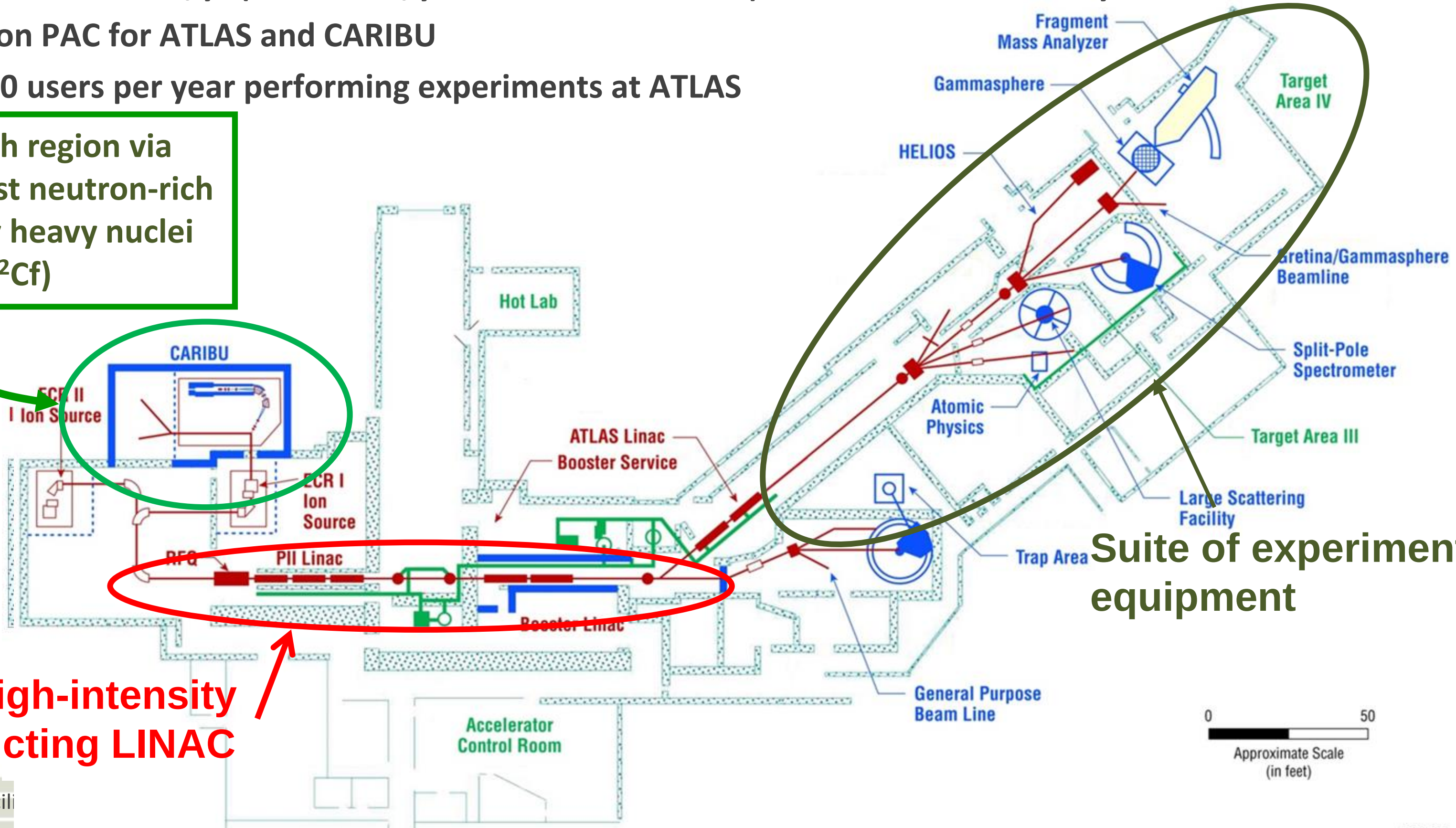
Presentation to the Low Energy Community Meeting

South Bend, August 12, 2016

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
  - 350-400 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)



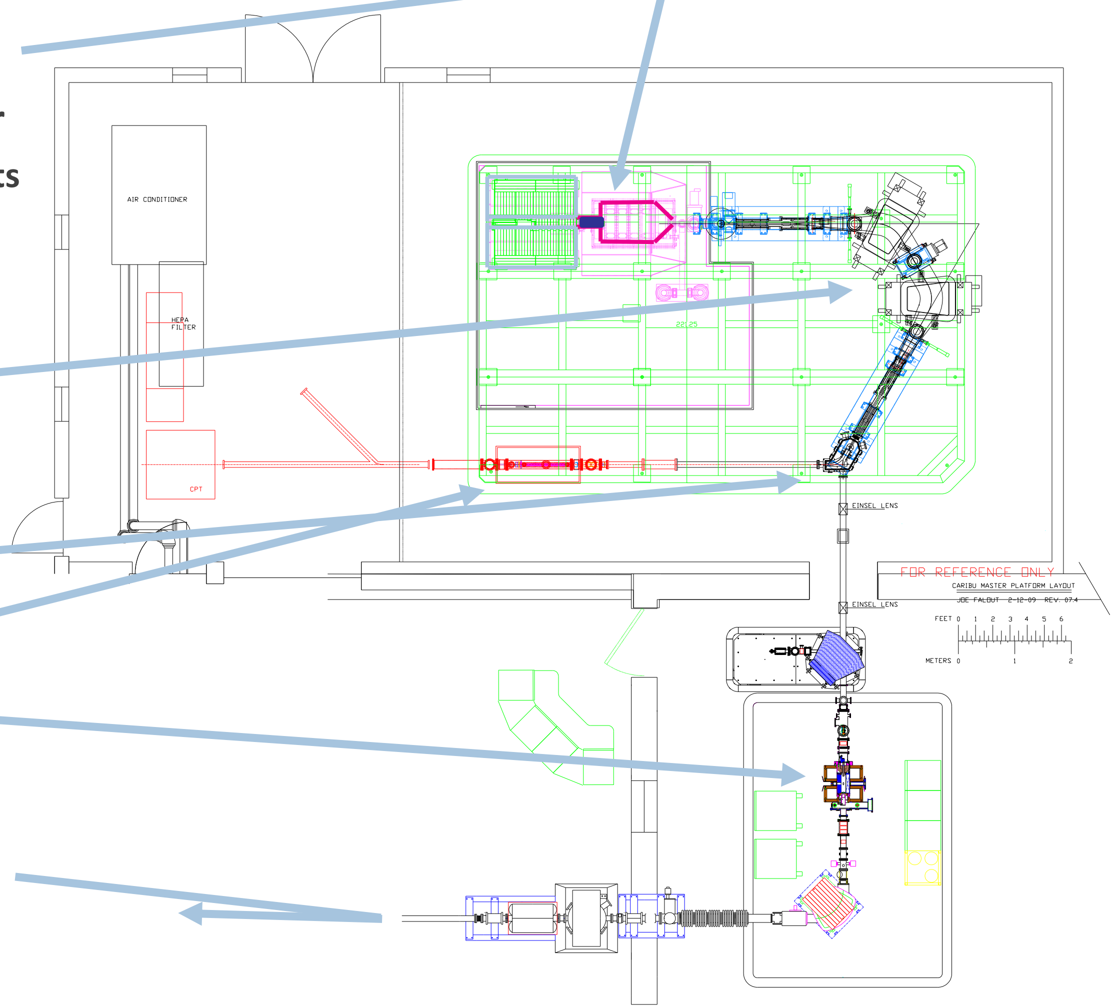
Suite of experimental equipment

Upgraded high-intensity superconducting LINAC

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

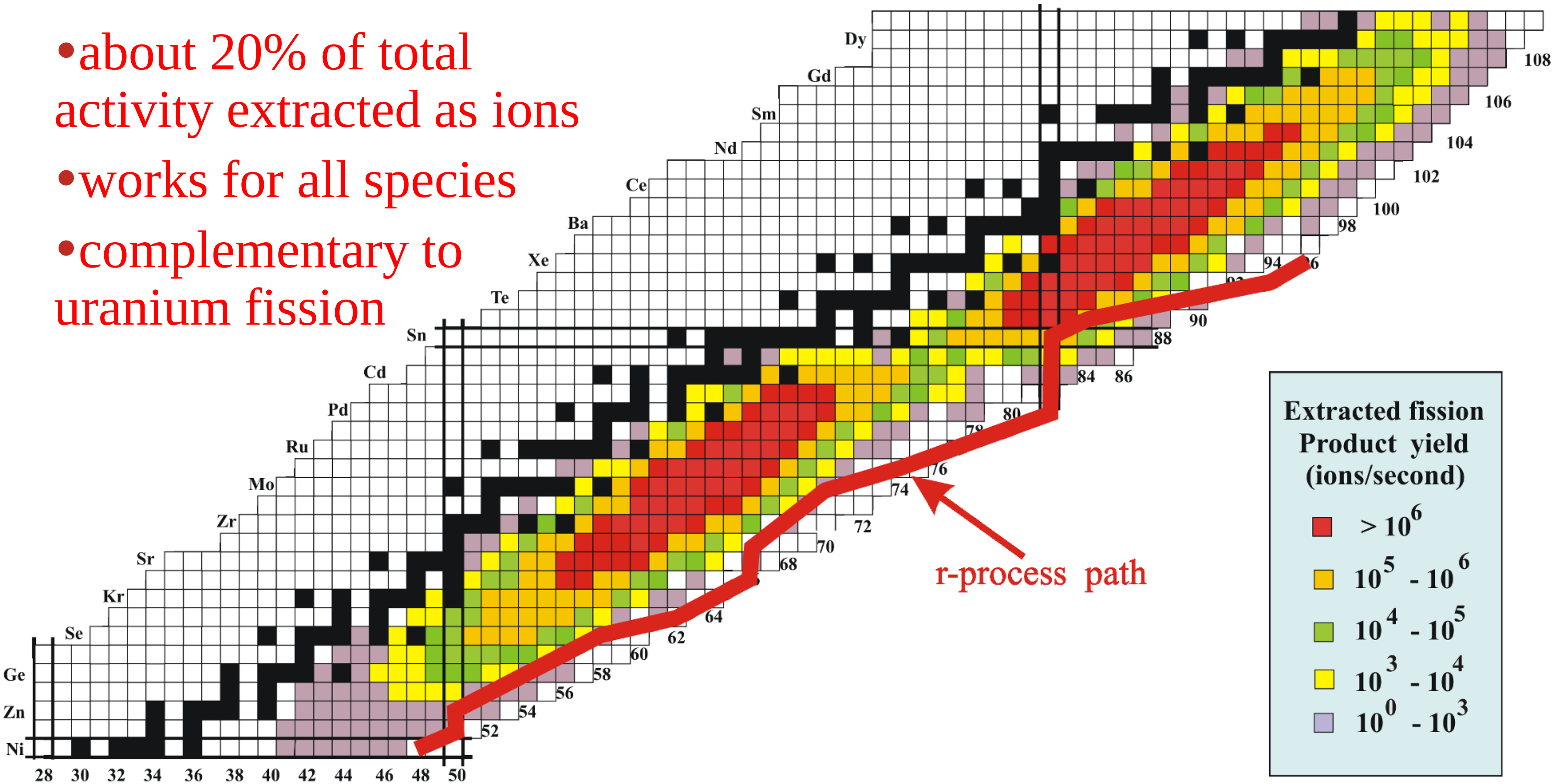
Main components of CARIBU

- **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



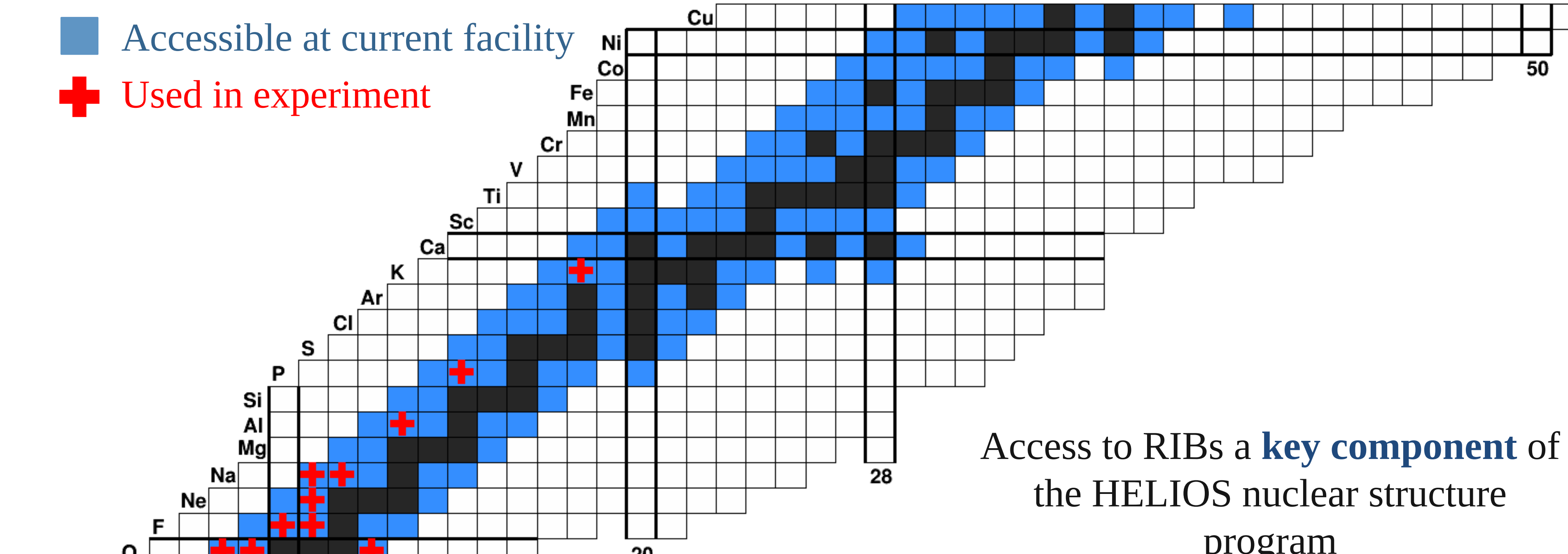
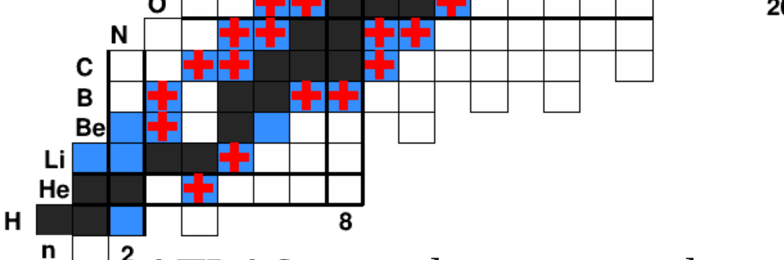
Expected isotope yield distribution at low energy (50 keV)

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

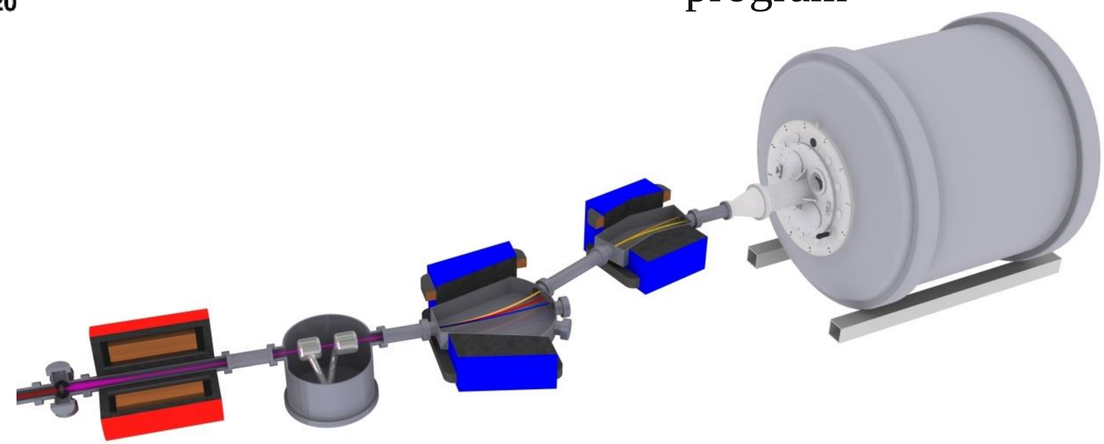


> than 500 neutron-rich species extracted at > 1/s

In-flight radioactive beams at ATLAS

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

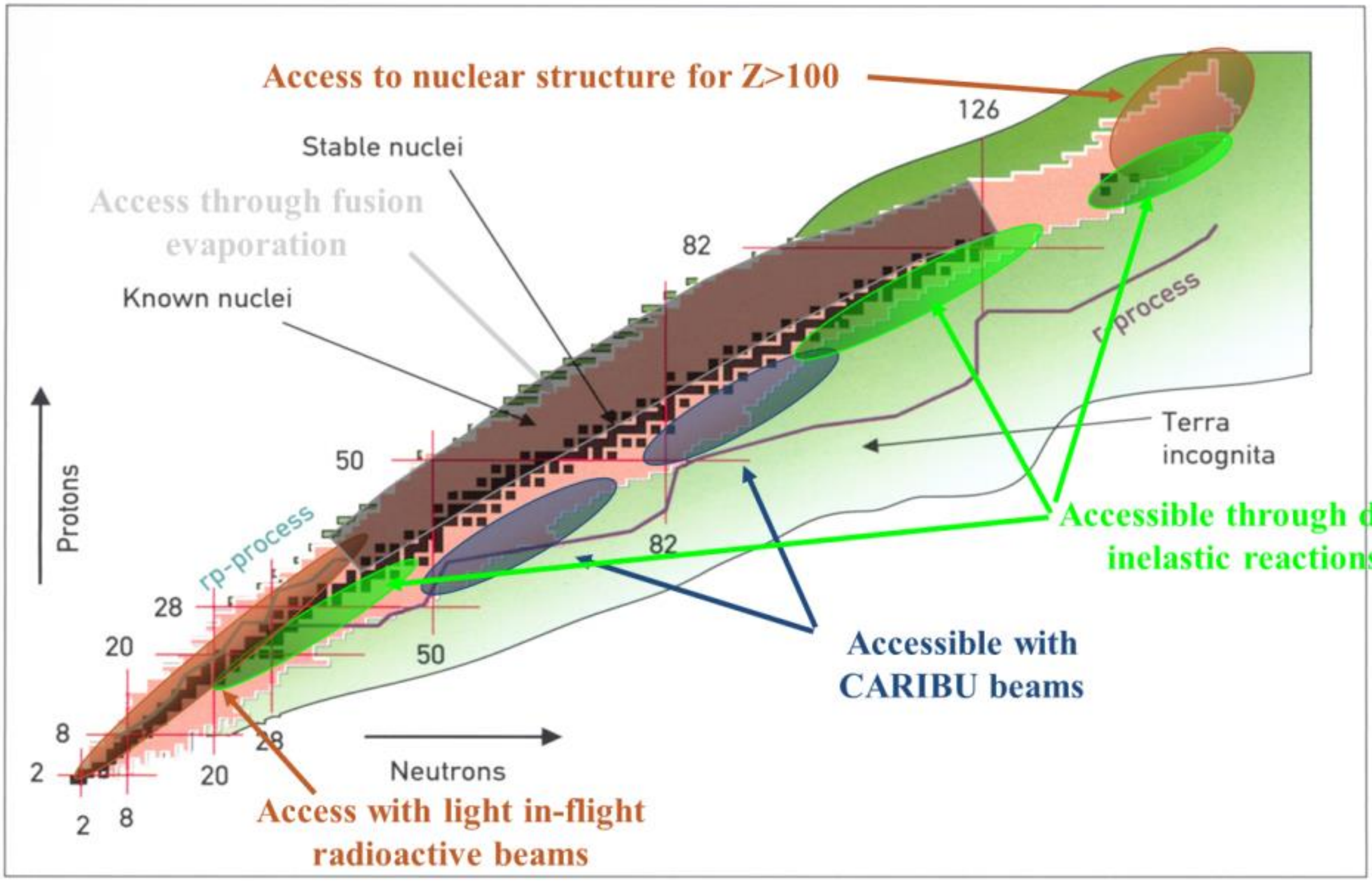
- **CARIBU beams have similar properties …. but much lower intensity**
  - All species, even the most refractory, are extracted efficiently

Most of the CARIBU beams (species and energy) are not available anywhere else.

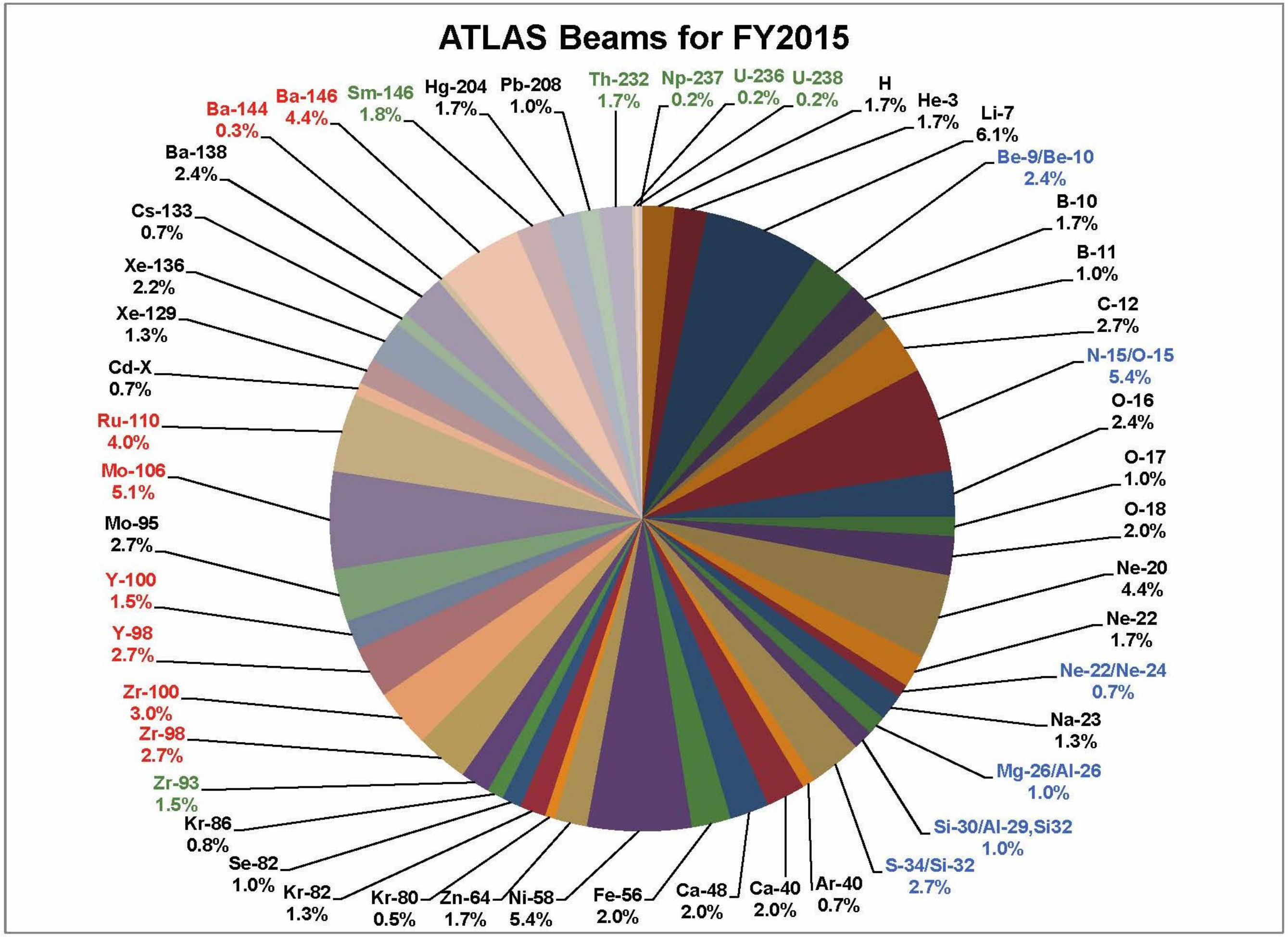
- **In-flight radioactive beams: all light species, close to stability, but some compromises between beam properties, intensity and purity**

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

ATLAS: broad isotope reach through various reaction mechanisms



ATLAS Beams for FY2015



Label Legend

Red: CARIBU

Blue: In-flight

Green: AMS

Black: Stable

54 Different Beams and Beam Configurations

23% of beam time for accelerated CARIBU runs

(Last CARIBU accelerated beam run May 10, 2015: 39% of beam time over 7+ months)

13% of beam time for In-Flight Radioactive Beams

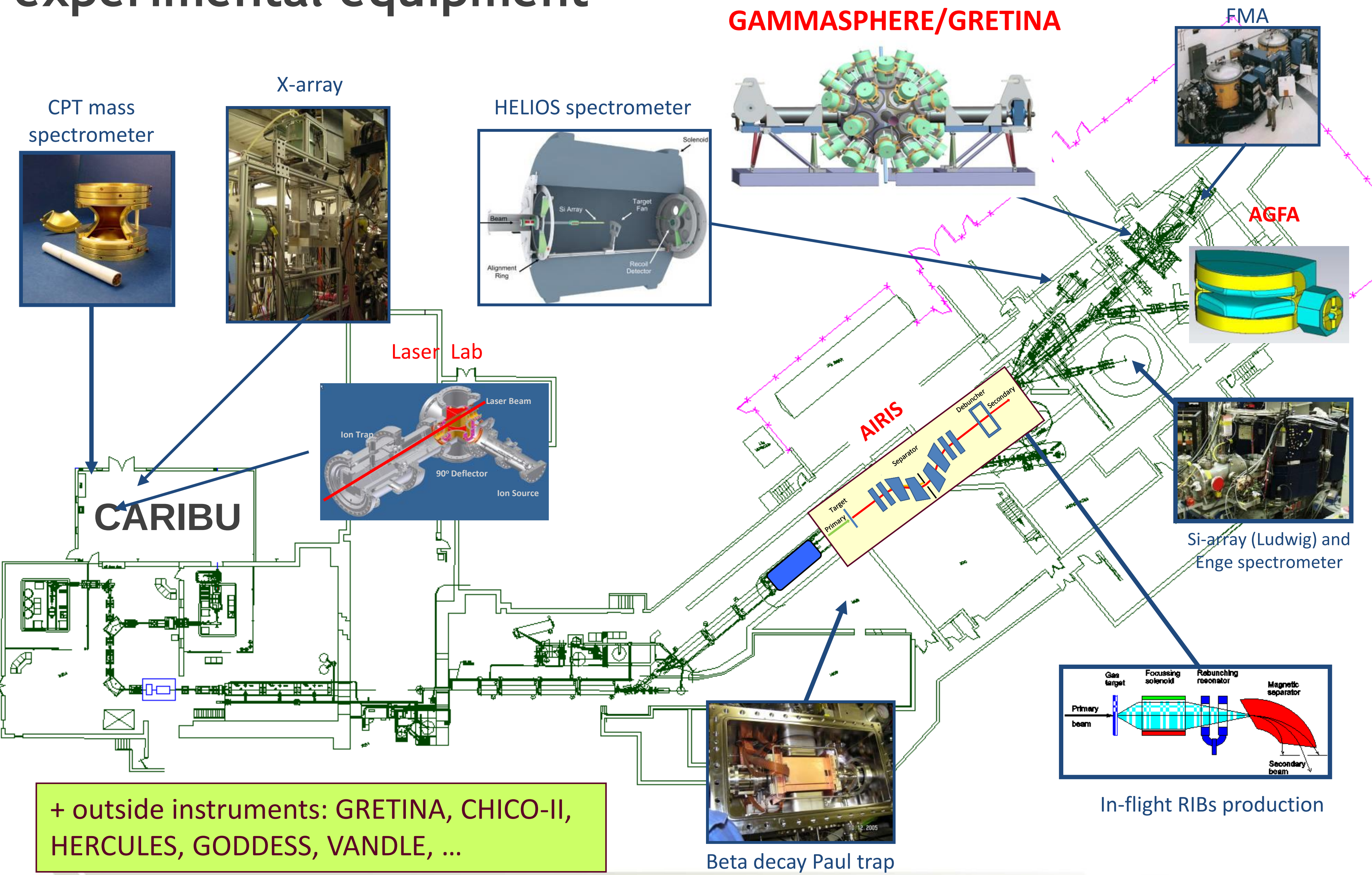
ATLAS Facility Performance

Operating Statistics

Machine Operation ATLAS	FY2010	FY2011	FY2012	FY2013 Booster	FY2014 Upgrade	FY2015	FY2016 (Proj.)
Research Hours (on Target)	4892	3742	4774	3345	2801	5959	5500
Accelerator Devel. Hours	403	997	564	152	228	56	500
Total R & D Hours	**5295**	**4739**	**5338**	**3497**	**3029**	**6015**	**6000**
Total Operating Hours	5944	5470	6140	4104	3814	6686	6600
Scheduled Maintenance	671	944	509	561	279	409	500
Experimental Downtime	517	419	648	487	248	479	500
Availability (%)	89.5	92.9	91.6	89.4	93.9	93.3	93
CARIBU (low-energy)							
Research Hours			1074	1980	2131	1884	1750
Beam Study Hours			360	340	172	376	250
Total Delivered Hours			1434	2320	2303	2260	2000

- FY13-14: Booster reconfiguration downtime kept operating hours low
- FY14: Six day operation due to staff resignations and retraining requirements
- FY15: Resumed 7-day operation in November 2014
- FY15: Complete focus on operation and CARIBU development
- FY16: Commission EBIS and learn how to operate new pulsed source
- FY16: Only one stable-beam ion source: Reduced overall scheduling flexibility

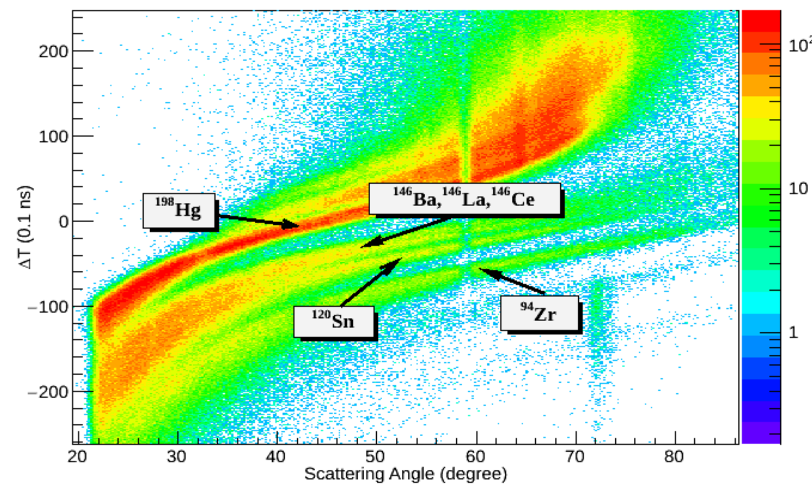
Main tools enabling the physics: ATLAS suite of experimental equipment

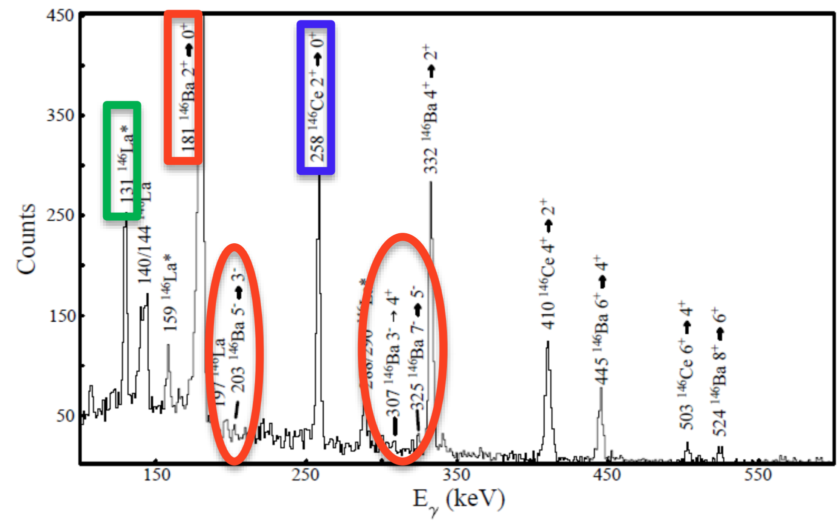


+ outside instruments: GRETINA, CHICO-II, HERCULES, GODDESS, VANDLE, …

Recent highlight : Coulomb excitation of ^{144,146}Ba → Direct measurements of B(E3) strengths

- Strong Octupole Correlations in both ^{144}Ba and ^{146}Ba;
- In ^{144}Ba, B(E1) strength is two orders of magnitude larger than it is in ^{146}Ba;
- Separation of ^{144,146}Ba from contaminants other than isobars made by the measured two-body kinematics: Time-of-flight difference vs. scattering angle;
- γ energy resolution is nearly a factor of 2 improvement compared to that of GS/CHICO;
- The B(E3:3^{-}→0^{+}) strengths are determined to be 46(+25/-34) and 48(+21/-29) *W.U.* for ^{144}Ba and ^{146}Ba, respectively;
- The measured B(E3) strengths are larger than the largest values predicted by various models;
- The measured E3 strengths are the same in ^{144}Ba and ^{146}Ba, despite the two orders of magnitude difference in B(E1) strengths in these two nucleus. The results demonstrate, for the first time, the significant impacts of the shell effects on the nuclear intrinsic dipole moments.





B. Bucher, S. Zhu, C. Y. Wu et al., PRL116,112503(2016)
B. Bucher, S. Zhu, C. Y. Wu et al., in preparation

Recent lowlight: Apparently we helped kill Marty McFly

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Pear-shaped nuclei discovery challenges time travel hopes

By Kenneth Macdonald
BBC Scotland Science Correspondent

23 June 2016 | Scotland

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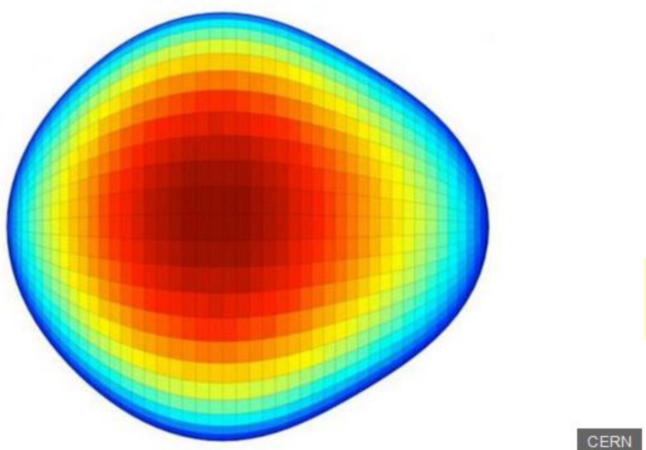


The pear shape was first discovered in the nucleus of the isotope Radium-224

The finding has since been confirmed in a second study, this time of the nucleus of Barium-144. The study also involved Dr Scheck and was led by Ching-Yen Yu from the Lawrence Livermore National Laboratory in California.

Dr Scheck says the pear shape shouldn't be there, according to the currently-accepted model of physics.

He says: "Further, the protons enrich in the bump of the pear and create a specific charge distribution in the nucleus.

"This violates the theory of mirror symmetry and relates to the violation shown in the distribution of matter and antimatter in our universe."

Direction in time

In other words, a pear-shaped nucleus points to why our Universe contains so much more matter than antimatter.

But that's not all it points to.

Dr Scheck says: "We've found these nuclei literally point towards a direction in space. This relates to a direction in time, proving there's a well-defined direction in time and we will always travel from past to present."

So time travel would appear to be a non-starter.

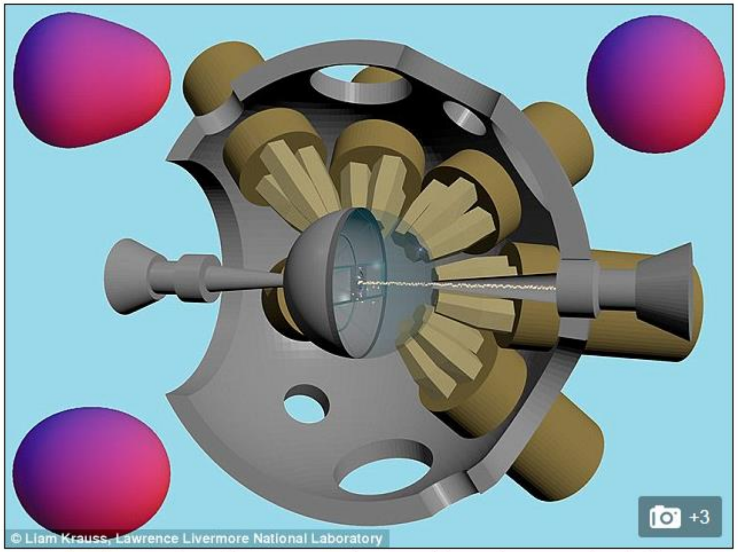
When it rains it pours ....

 Thursday, Aug 11th 2016 1AM 75°F 4AM 74°F 5-Day Forecast

Daily Mail .com Science & Tech

Have hopes of time travel gone pear shaped? Researchers say discovery of fruit-shaped nuclei could make it impossible

- Researchers confirmed the pear-shaped nuclei of isotope Barium-144
- The pear shape goes against the accepted symmetry-based model
- Scientists say it may relate to the symmetry violation seen with antimatter
- And, they say shape points in direction that relates to time –past to present



Researchers have confirmed the existence of an unusual form of atomic nuclei, challenging the fundamental theories of physics – and it could send hopes for time travel swirling down the drain. The image illustrates the device used to differentiate the pear (top left) from spherical (upper right) or ellipsoidal (lower left) shapes

TGD diary

Daily musings, mostly about physics and consciousness, heavily biased by Topolo background.

WEDNESDAY, JULY 20, 2016

Pear-shaped Barium nucleus as evidence for large parity breaking effects in nuclear scales?

Pieces of evidence for nuclear physics anomalies continue to accumulate. Now there was a popular article telling about the discovery of large parity breaking in nuclear physics scale. What have been observed is pear-shaped ^{144}Ba nucleus not invariant under spatial reflection. The arXiv article speaks only about octupole moment of Barium nucleus difficult to explain using existing models. Therefore one must take the popular article managing to associate the impossibility of time travel to the unexpectedly large octupole moment with some caution. As a matter fact, pear-shapedness has been reported earlier for Radon-220 and Radium-224 nuclei by ISOLDE collaboration working at CERN (see this and this).

The popular article could have been formulated without any reference to time travel: the finding could be spectacular even without mentioning the time travel. There are three basic discrete symmetries: C,P, T and their combinations. CPT is belived to be unbroken but C,P, CP and T are known to be broken in particle

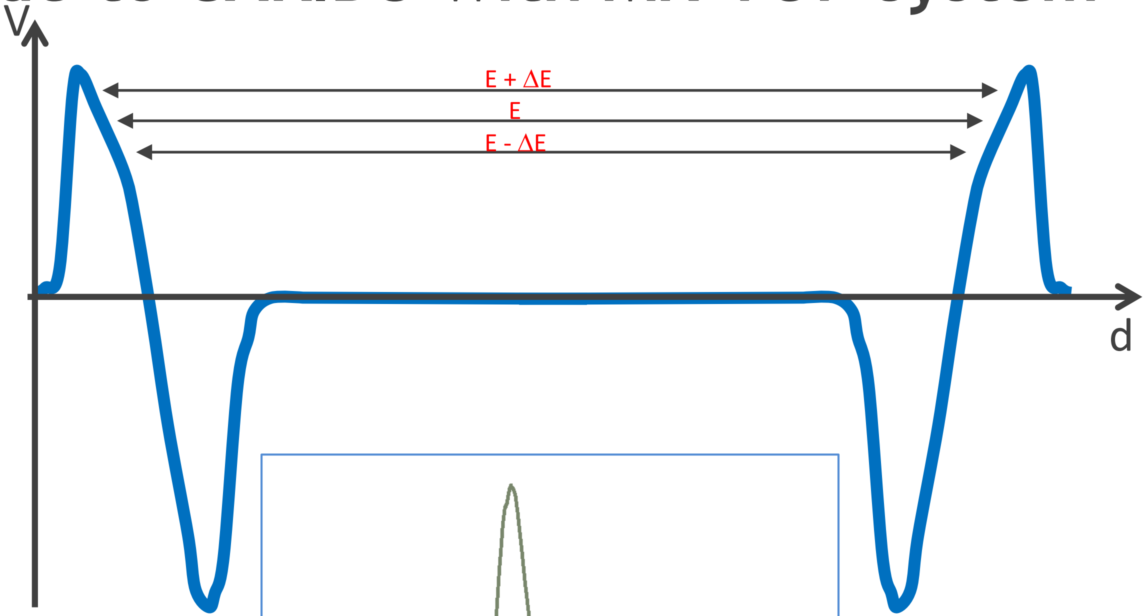
Highlight: Purity upgrade to CARIBU with MR-TOF system

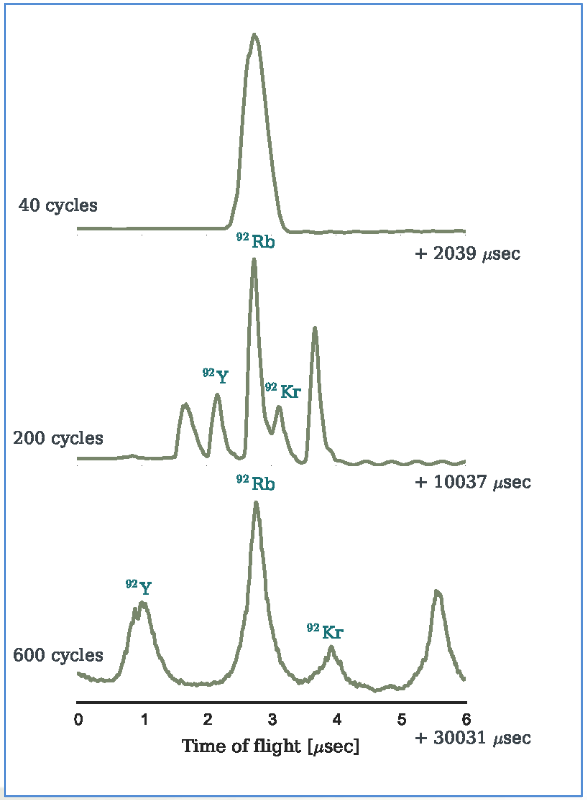
'Fast' isobar separation:

- **~ 1.3 m long MR-TOF**
- **Based on ISOLTRAP/ISOLDE design**

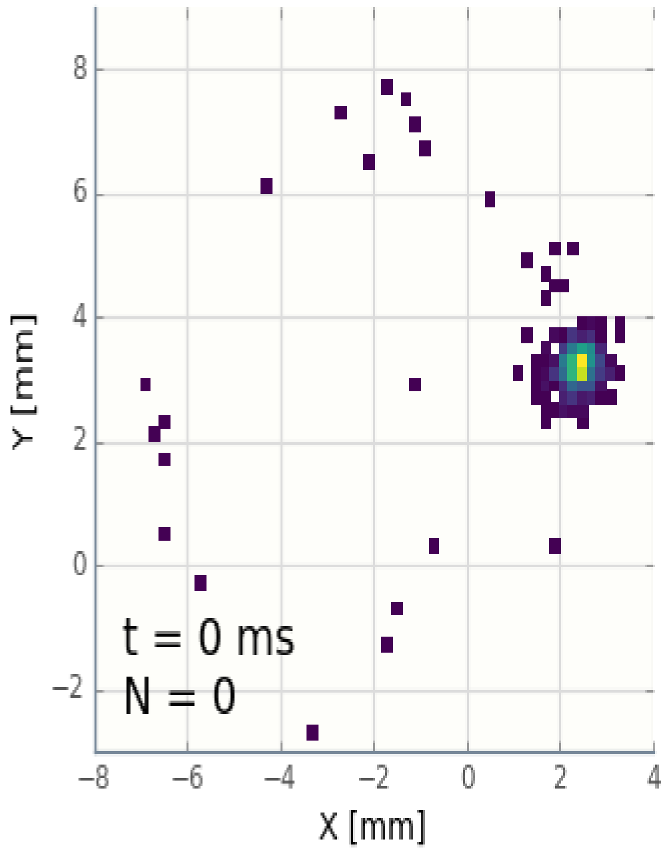
R.N. Wolf *et al.*, NIM A **686**, 82 (2012).

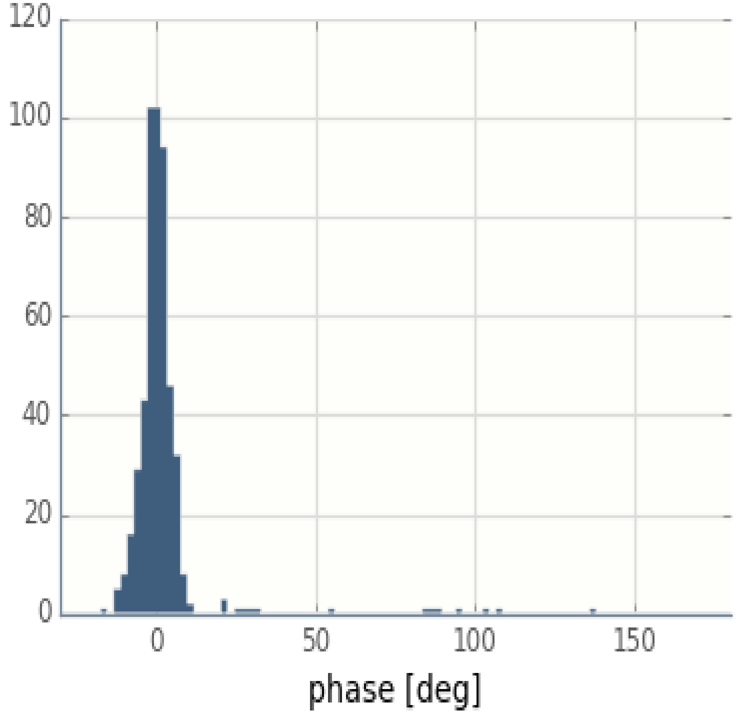
- **Goals:**
  - **resolving power > 40,000**
  - **transmission > 50%**
- **Status:**
  - **Installed December 2014 …. as a facility component available for all experiments**
  - **Used in routine operation with low-energy beams for over a year now**
  - **Current performance: R ~ 50,000 - 150,000 with ≥ 50% transmission in 10 - 30 ms**





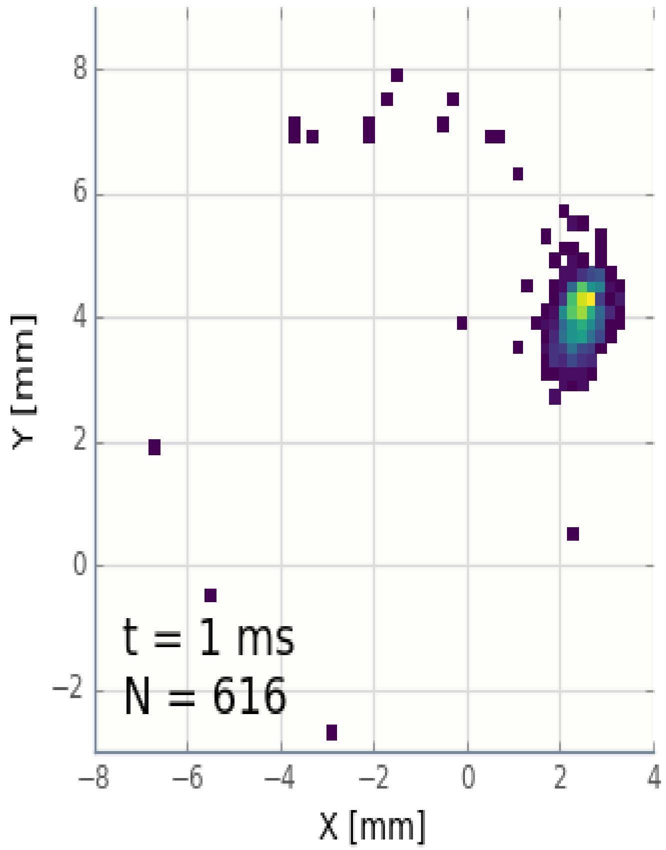
Combined with PI-ICR signal in Penning traps: enhanced resolution and sensitivity

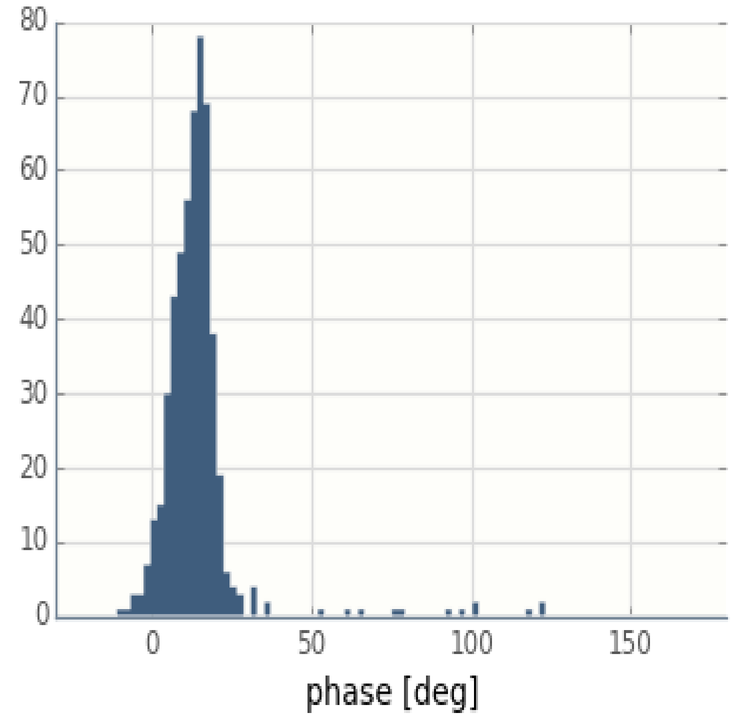




Evolution of PI-ICR signal

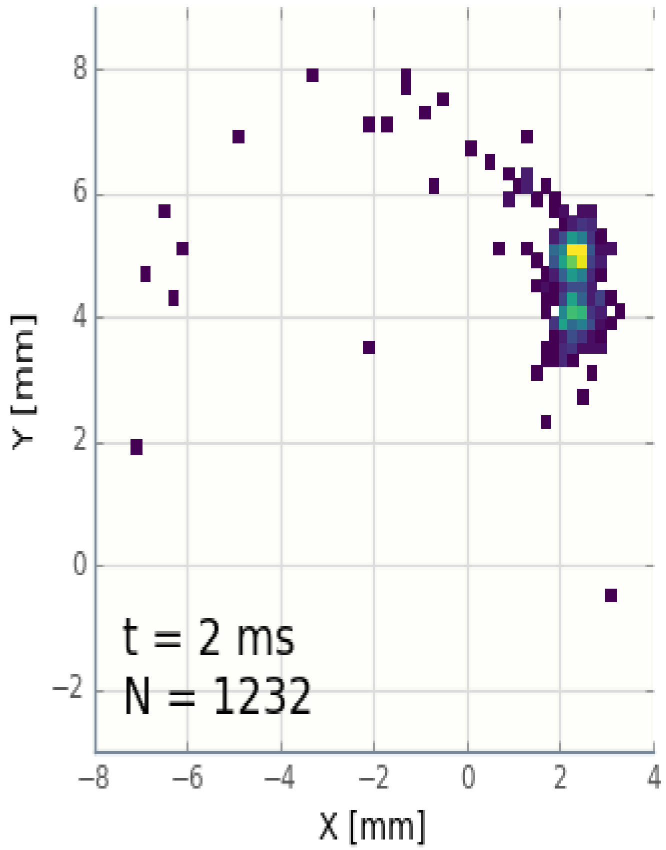
PI-ICR Resolution

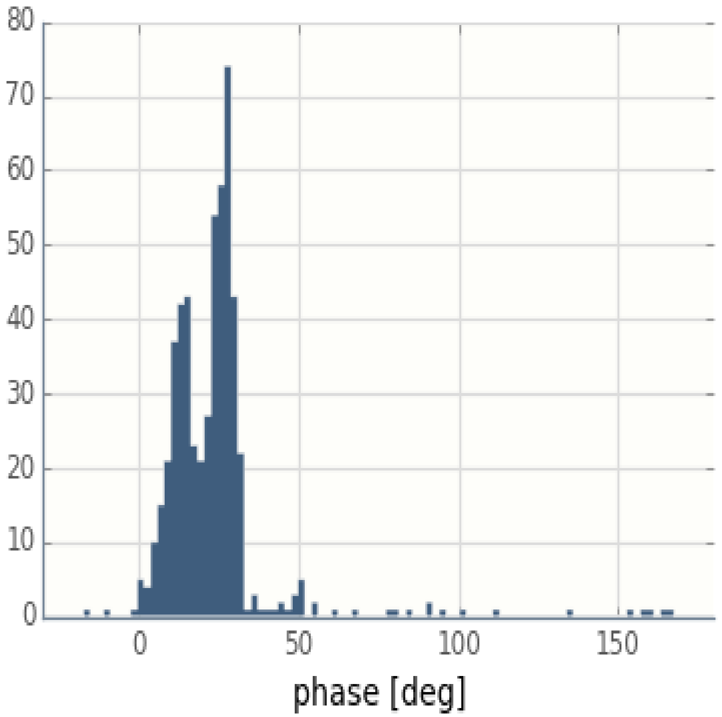




Evolution of PI-ICR signal

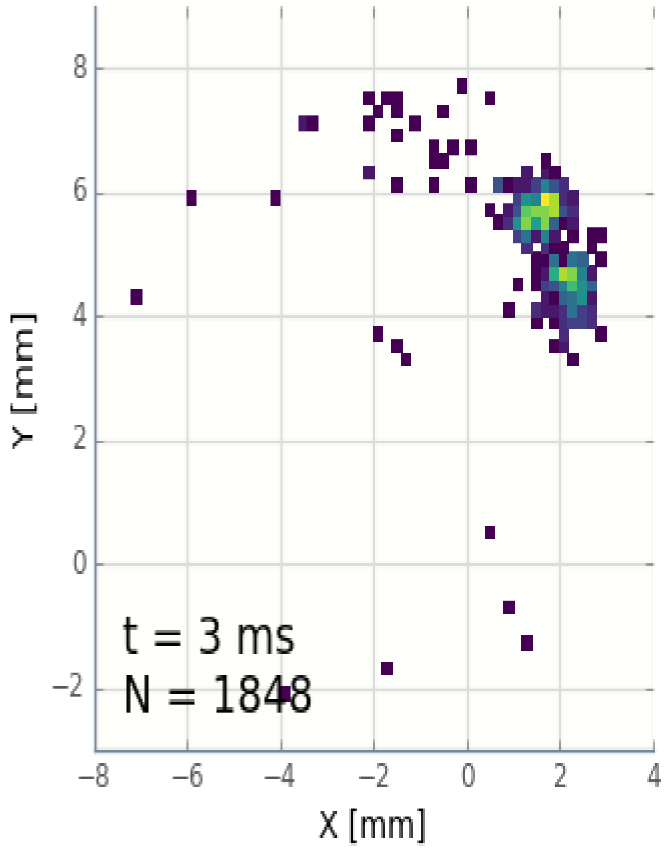
PI-ICR Resolution

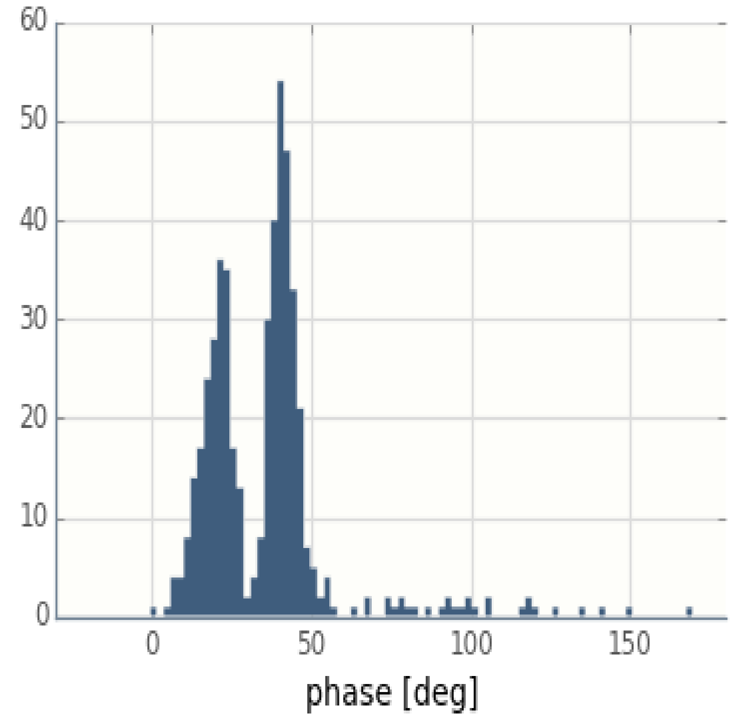




Evolution of PI-ICR signal

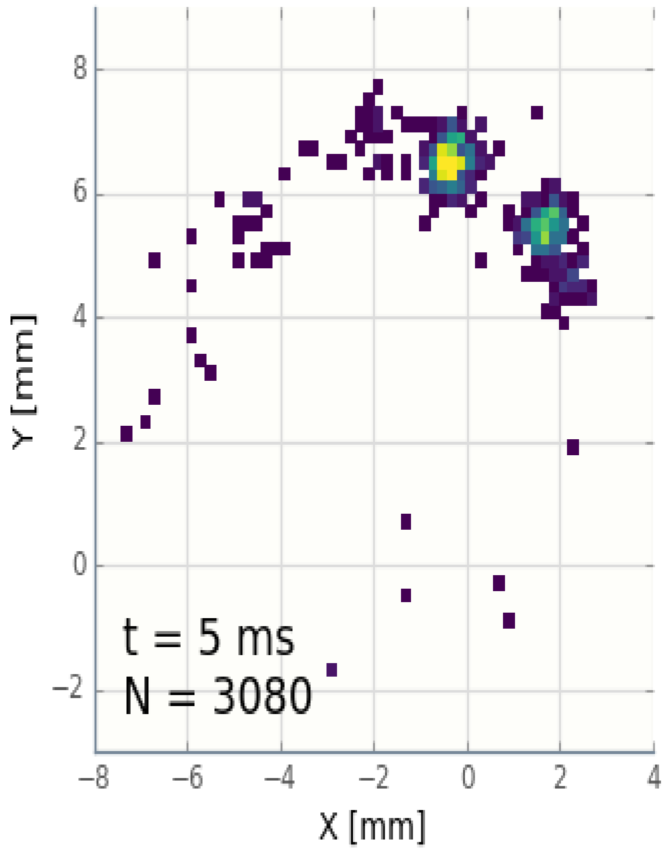
PI-ICR Resolution

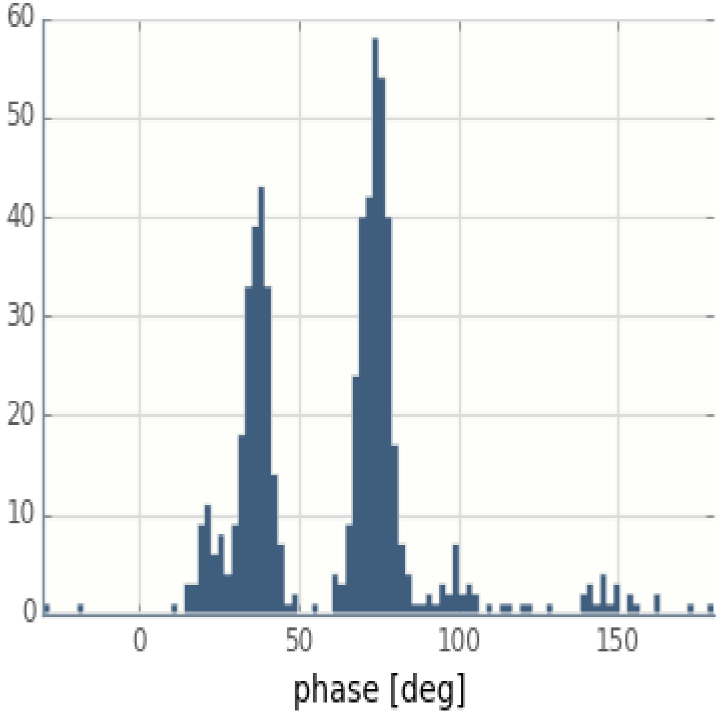




Evolution of PI-ICR signal

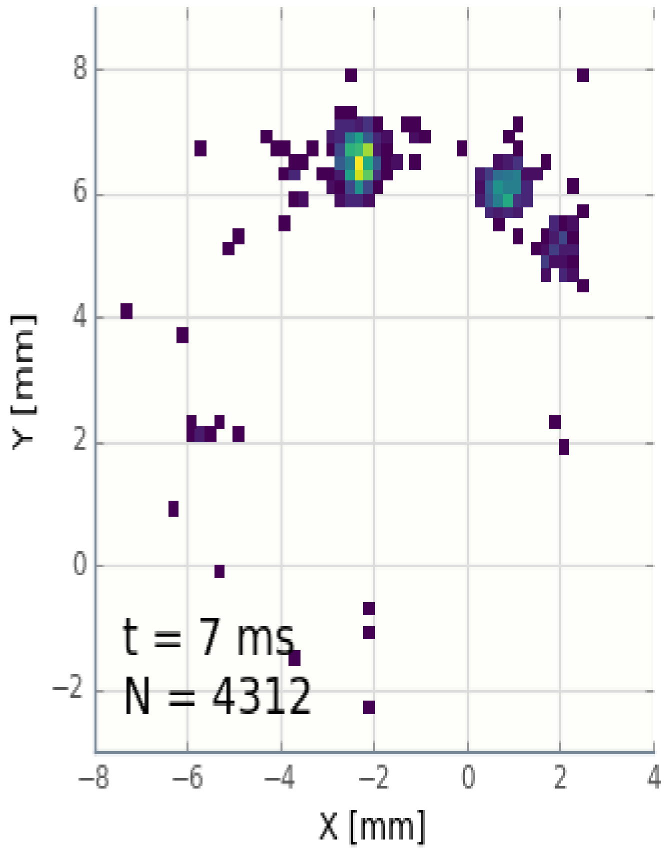
PI-ICR Resolution

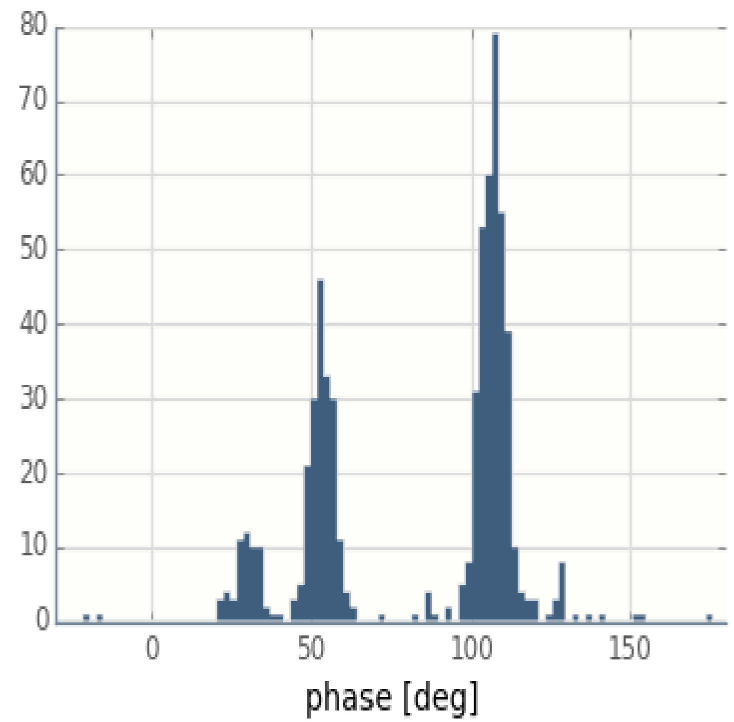




Evolution of PI-ICR signal

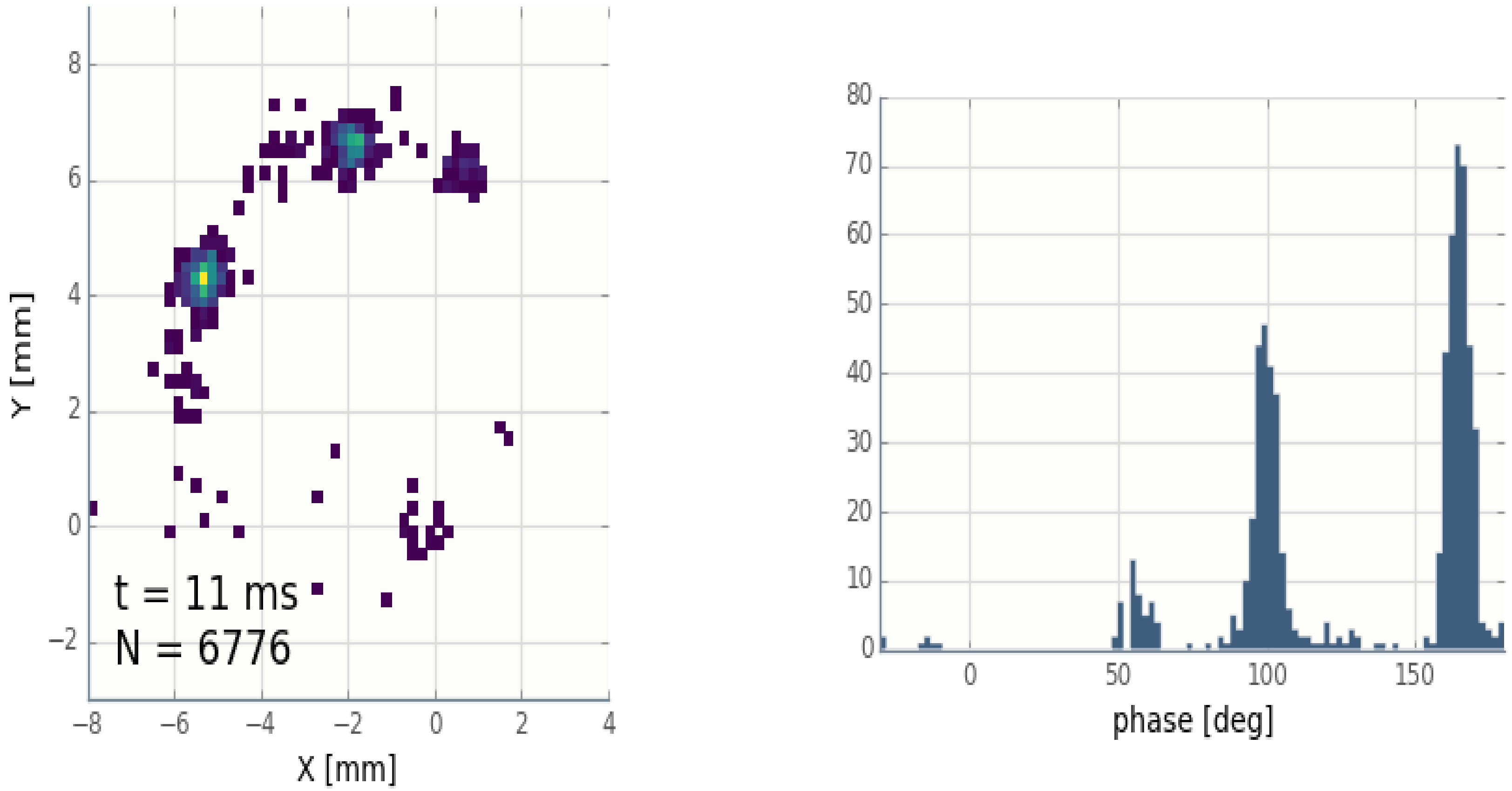
PI-ICR Resolution



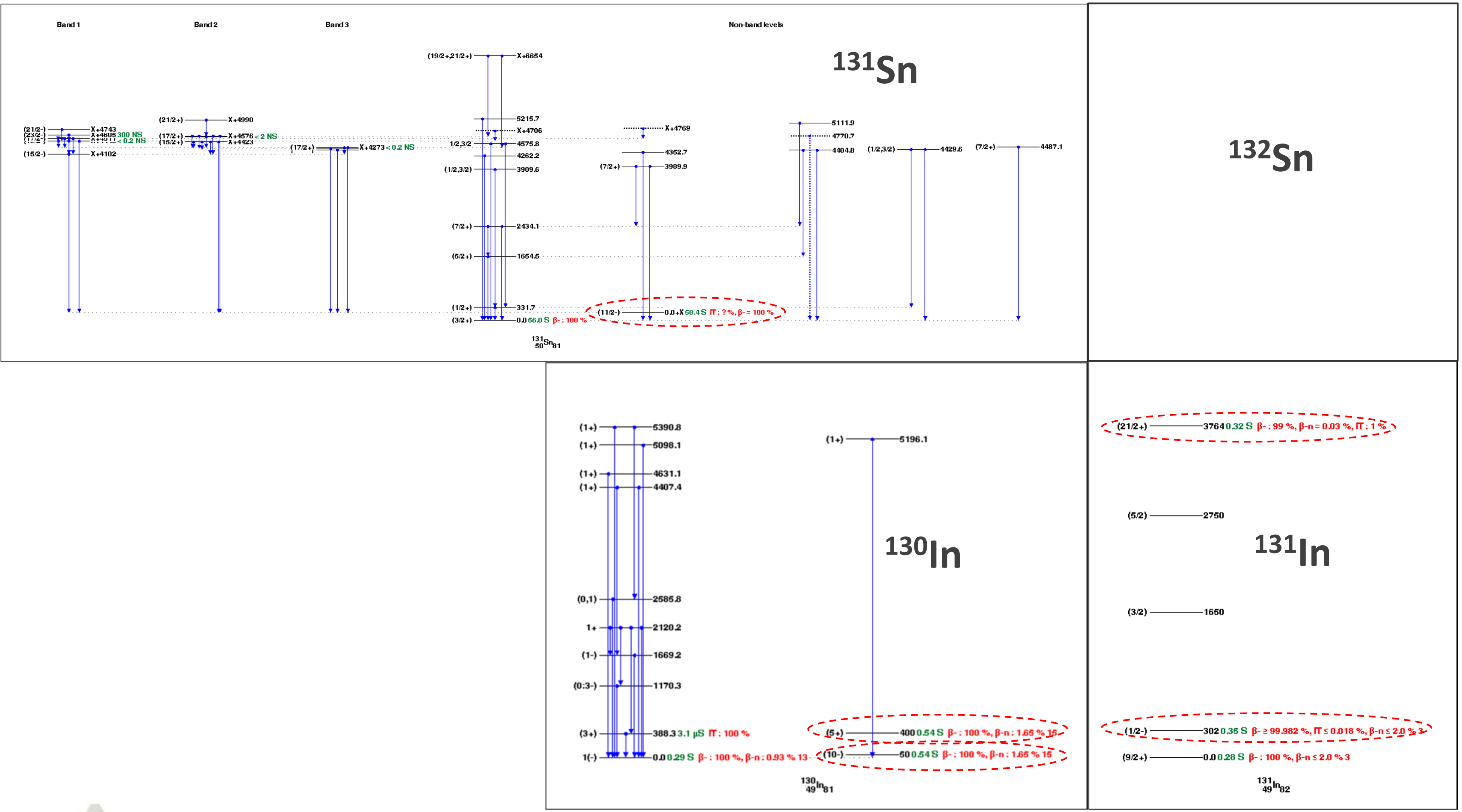


Evolution of PI-ICR signal

PI-ICR Resolution

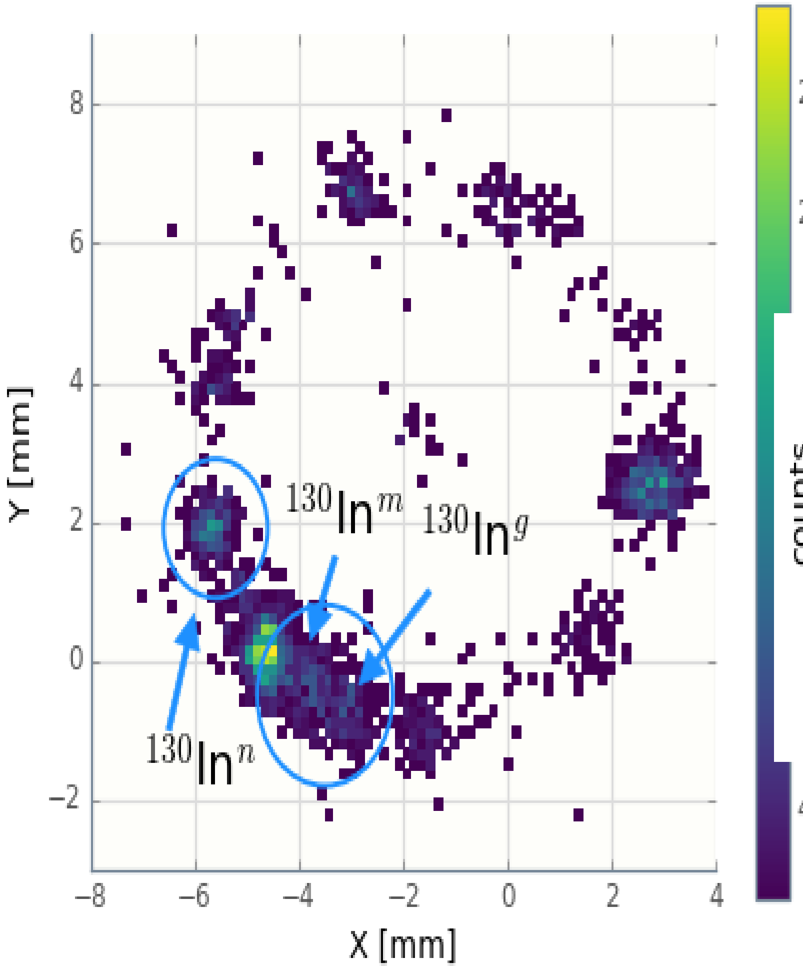


p-hole - n-hole interaction around ^{132}Sn



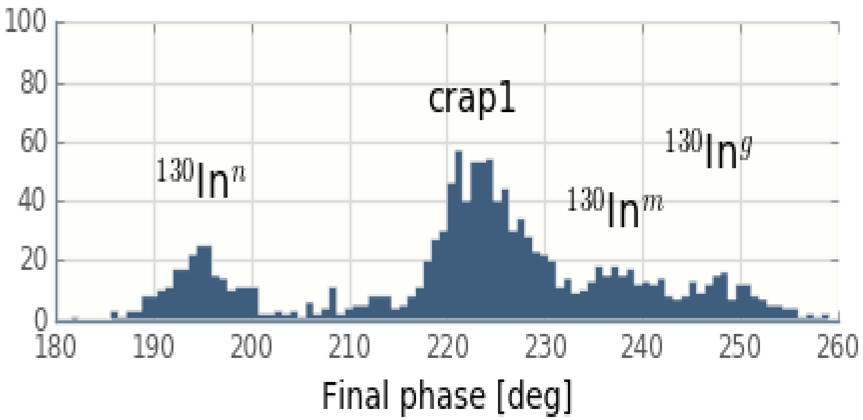
Isomer separation

75 ms wc excitation ^{130}In



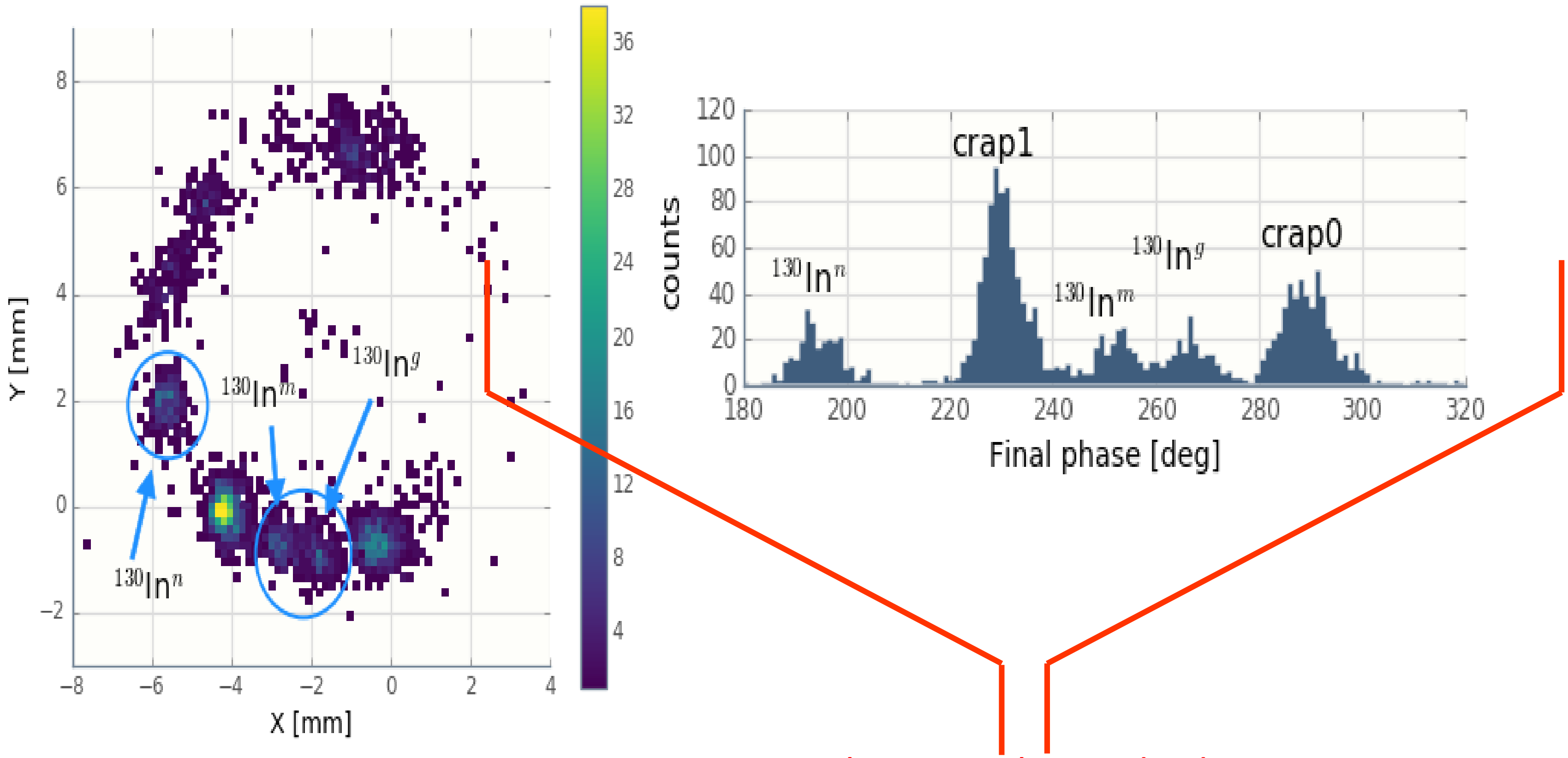
tacc = 75ms

Can almost completely resolve the two states.



Isomer separation

97.075 ms wc excitation ^{130}In

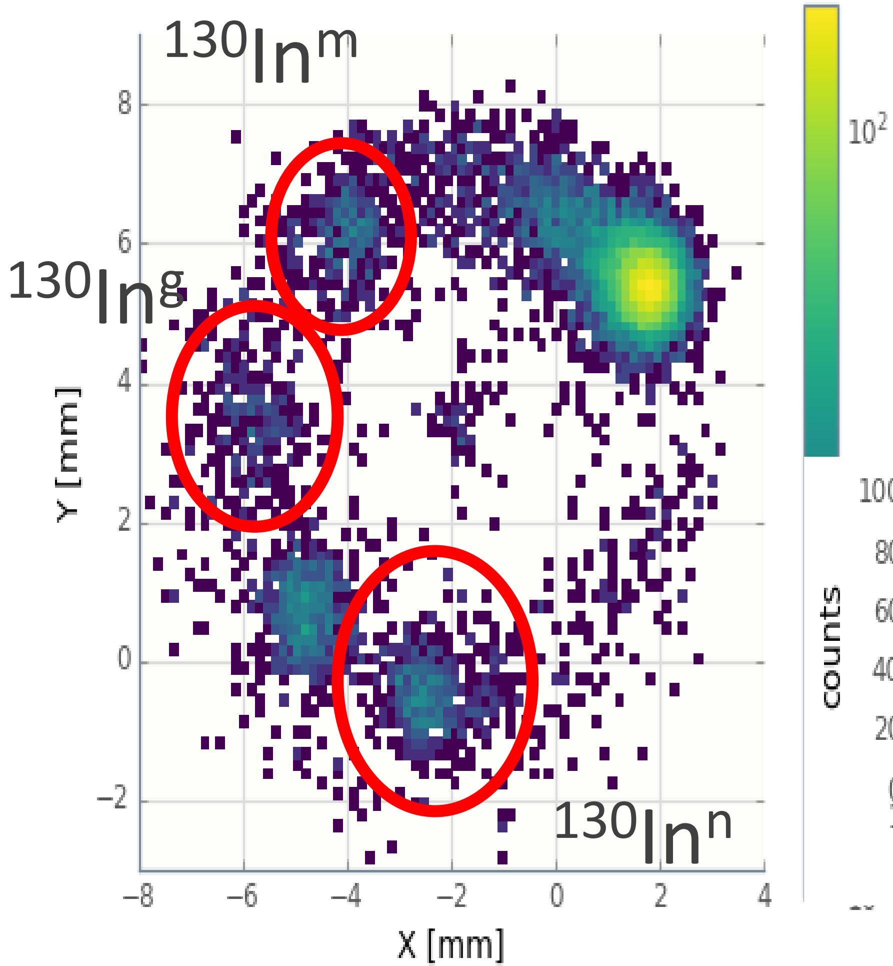


tacc = 97.075ms
Excitation energy ~50 keV.
Resolution of ~1.8million in 100ms.

Resolution with standard excitation ~70000
→ 25 times worst ←

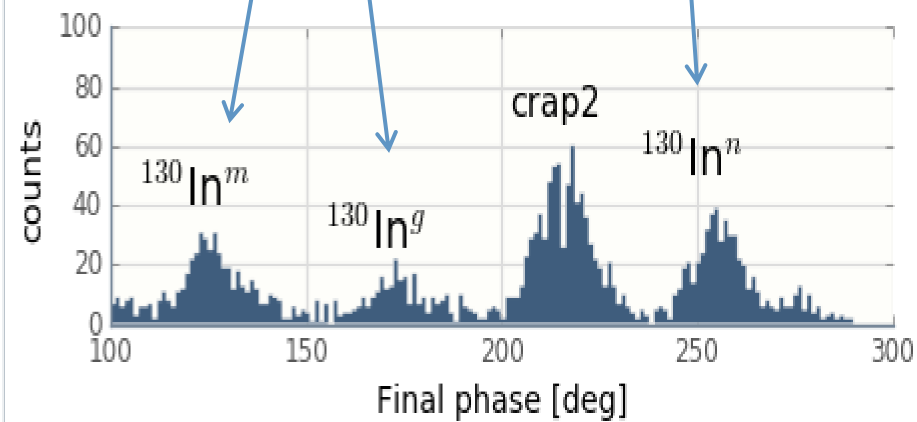
Isomer separation

347.965 ms wc excitation ^{130}In



g,m on same turn, n is not.

In-g decayed a bit compared to 100ms files.



Continued push towards higher efficiency and sensitivity 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

- 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 2-3 in intensity and higher purity) (FY14-16)
  - AGFA (X10 in acceptance for superheavies) (FY14-17)
  - AIRIS: New recoil separator for in-flight program (>100 in intensity and higher purity) (FY16-18)
  - Multi-user upgrade (FY17-20) ← ~ $ 2-3 M

within baseline funding

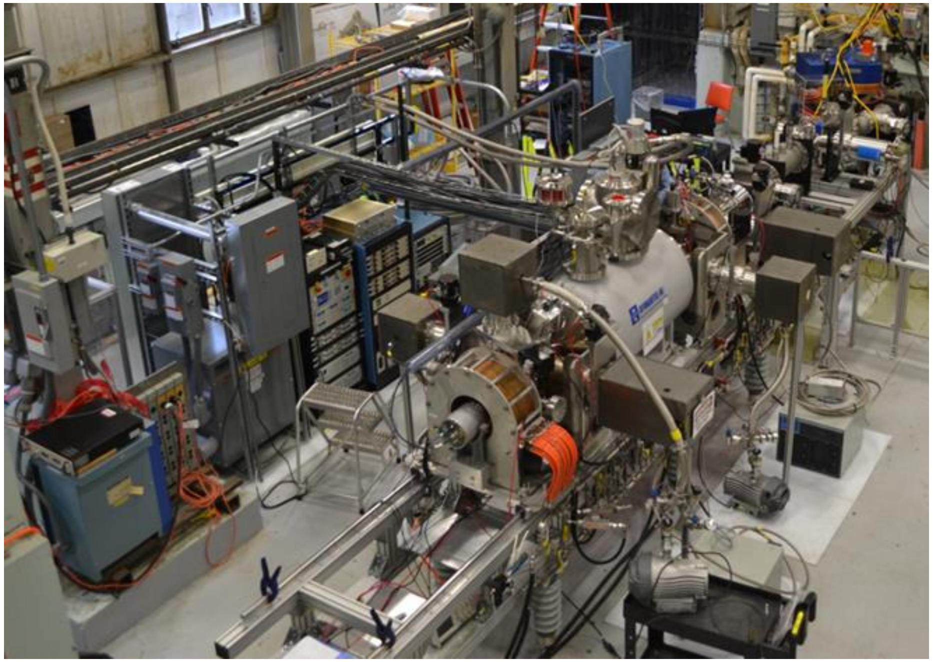
EBIS charge breeder upgrade

- 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

- Main goal: suppression of stable beam contaminants
- As a bonus, gain in intensity for reaccelerated CARIBU beams
  - Light fission peak

    17-21% (25-30% X 0.7) for EBIS+buncher vs 4-6% for ECR
  - Heavy fission peak

    16-20% (20-25% X 0.8) for EBIS+buncher vs 8-12% for ECR

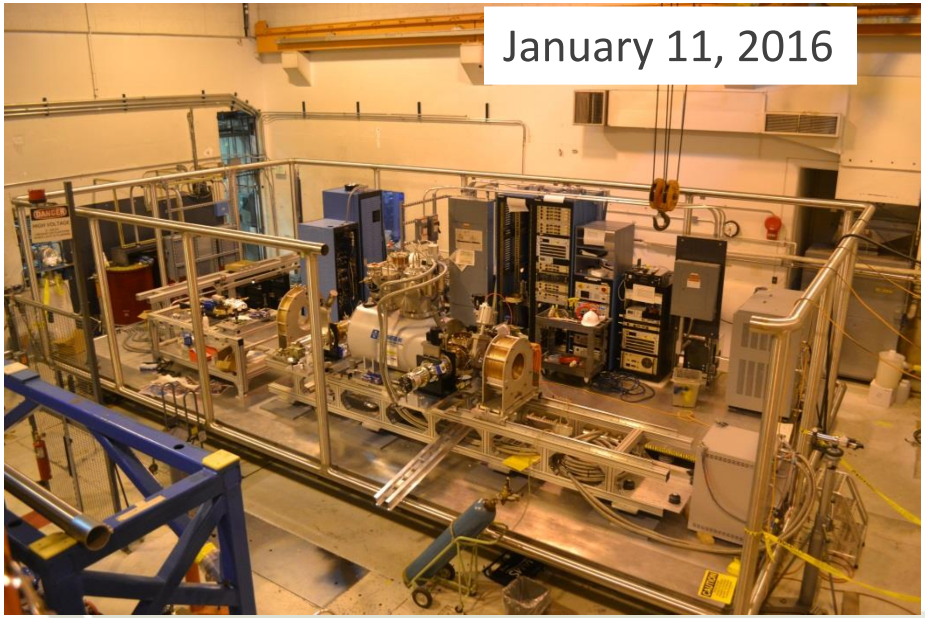


ATLAS Upgrades: EBIS Charge Breeder

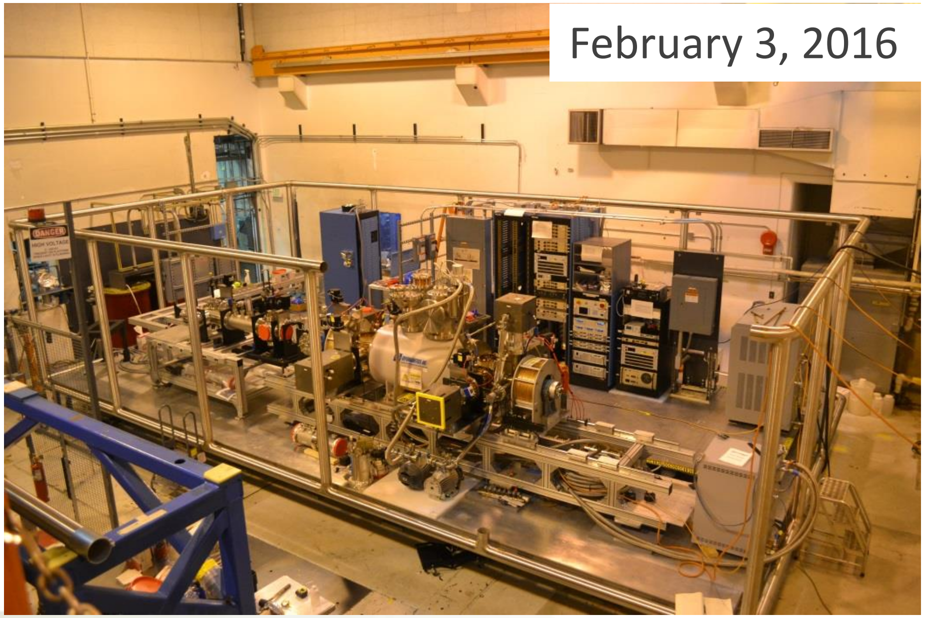
EBIS Installation at ATLAS

September 23, 2015

December 1, 2016



January 11, 2016



February 3, 2016

EBIS status:

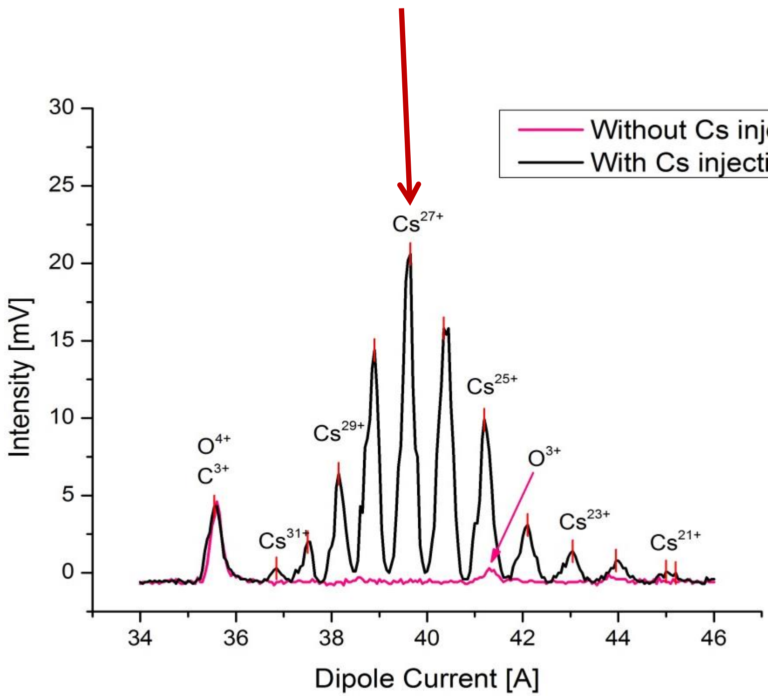
- stable beam charge bred and reaccelerated through ATLAS
- low background demonstrated

EBIS charge breeder operating

- Charge distribution narrower than with ECR CB → higher efficiency in one M/Q
- Beam dominated by charge bred injected beam, not background from the source

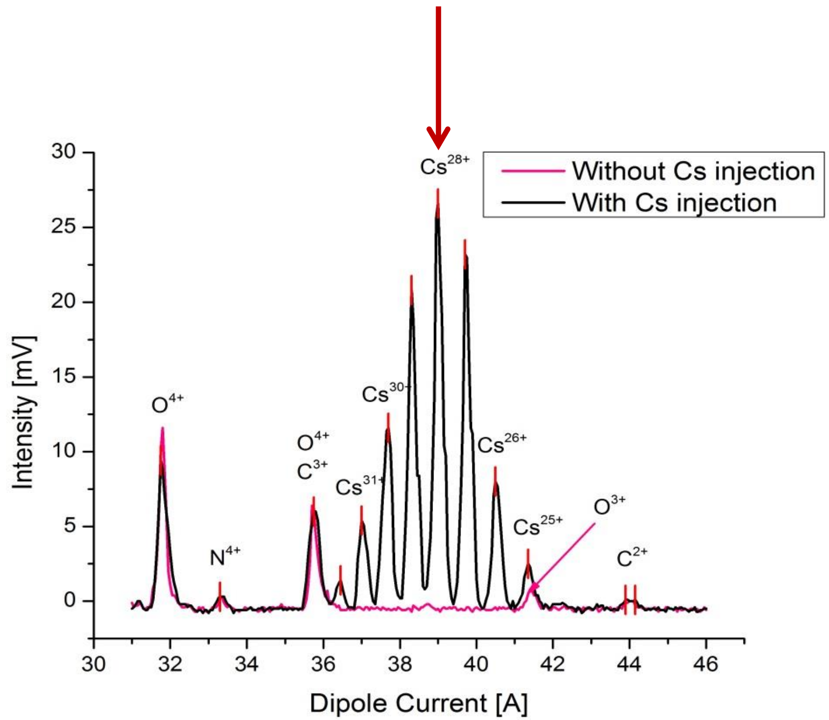
20 msec

Cs^{27+}, M/Q=4.925



30 msec

Cs^{28+}, M/Q=4.75

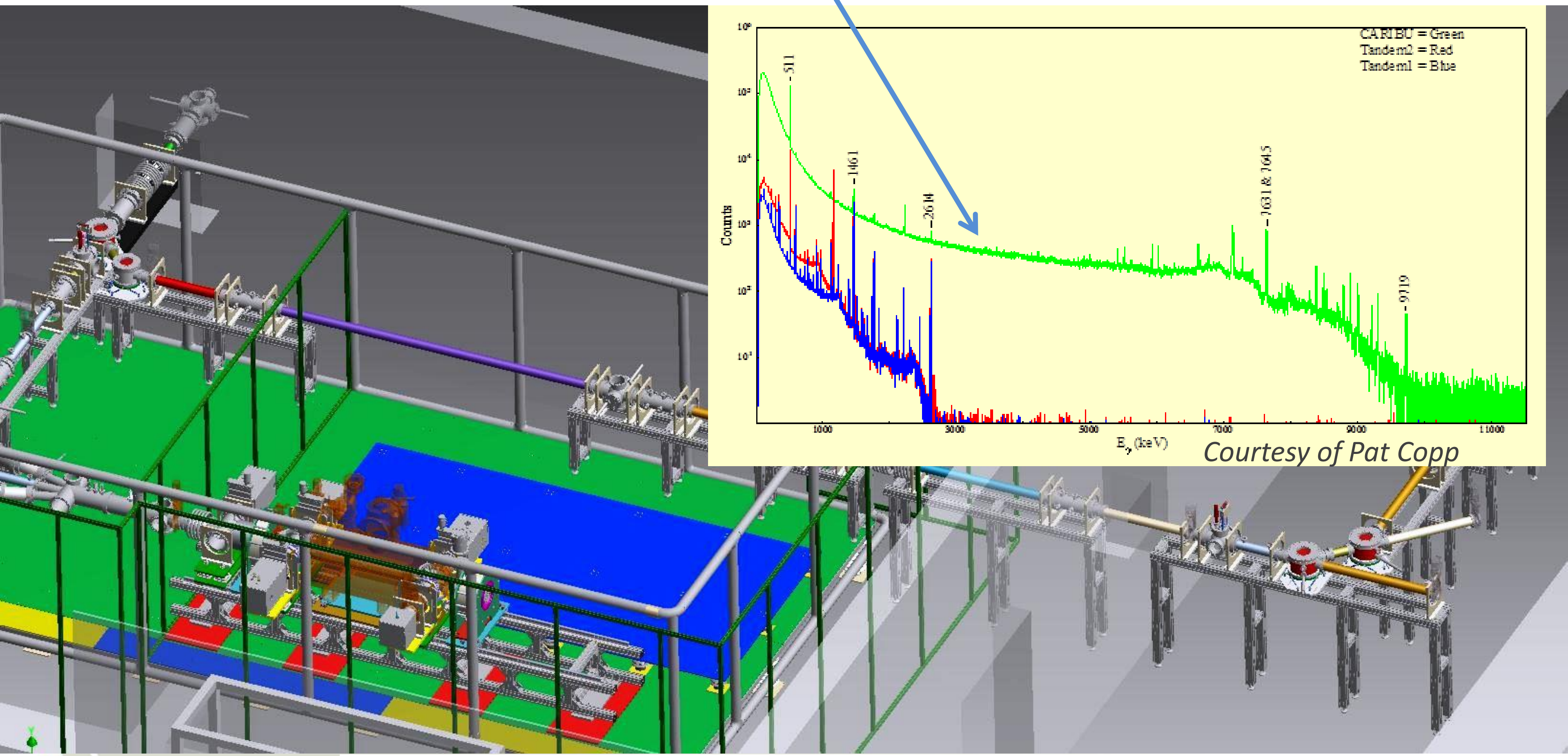


EBIS status:

- first EBIS charge bred CARIBU beam through ATLAS in 2 weeks
- these beams available for coming PAC (deadline Sept 12 2016)

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

- Tandem removal in preparation … planned for Nov 2016
- Beamline designed and components construction ongoing
- New experimental area expected to be available in March 2017
  - ~ 2 orders of magnitude lower background

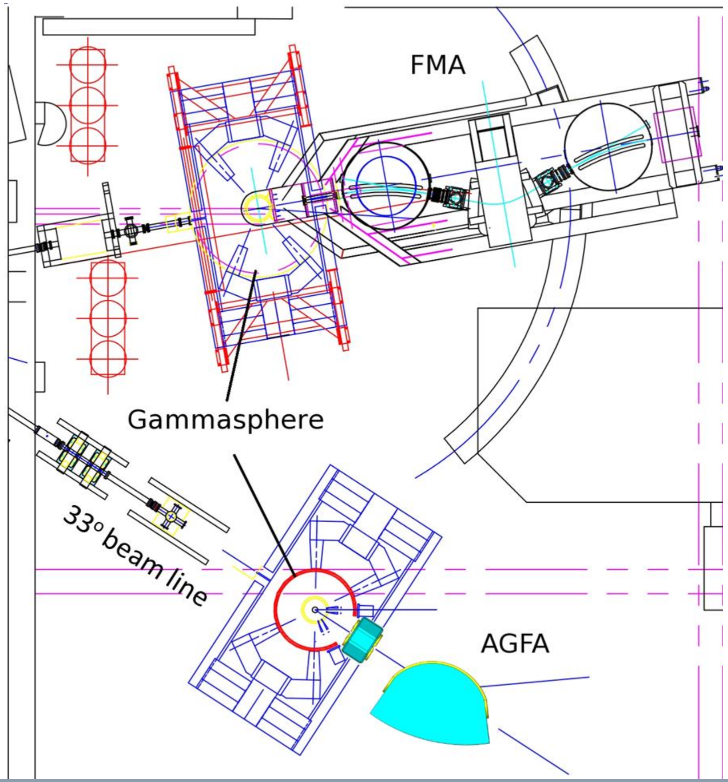


Courtesy of Pat Copp

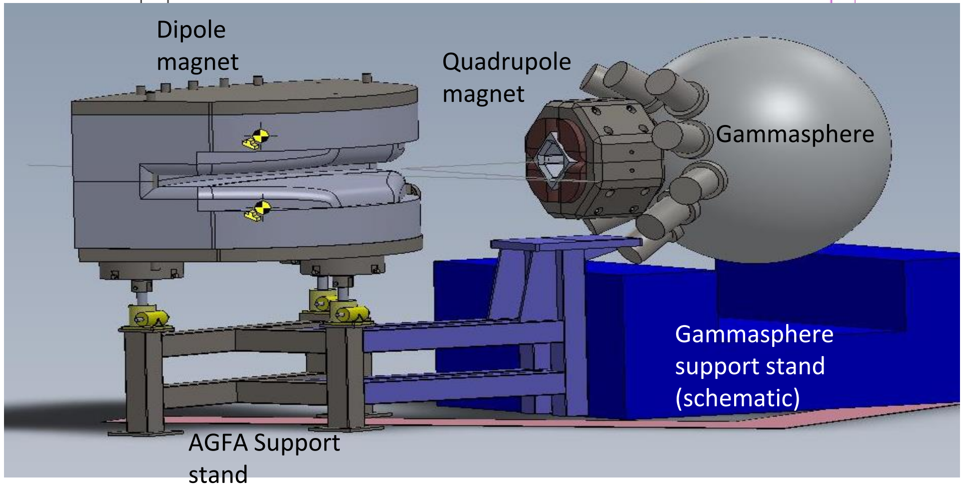
AGFA: Argonne Gas-Filled Analyzer

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



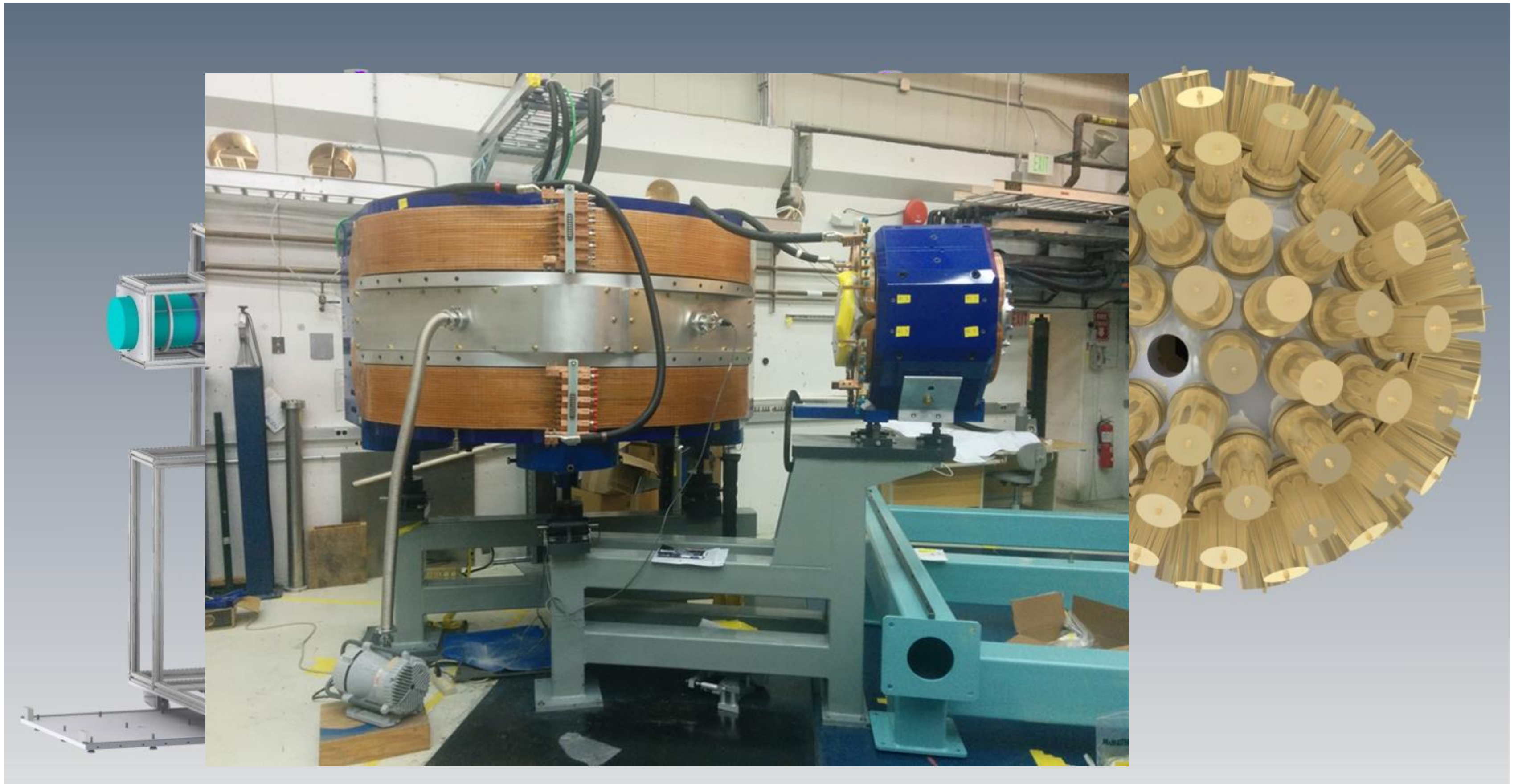
Large distance from target to entrance quadrupole provides ability to run with full GAMMASPHERE for high gamma-recoil coincidence efficiency



AGFA: 50-95% Efficiency

FMA: Less efficiency, m/q measurement

AGFA detection systems



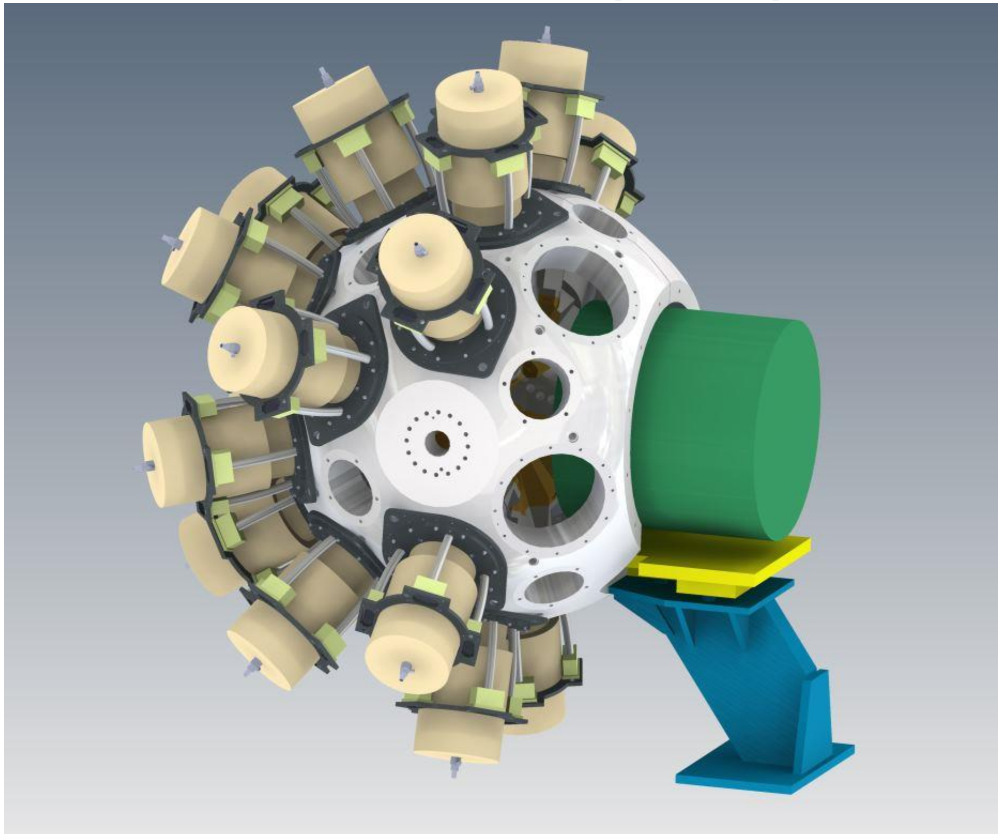
Large target-separator distance - prompt γ-ray spectroscopy with a 4π Ge array

Compact focal plane – efficient decay spectroscopy

Short flight path – short-lived activities

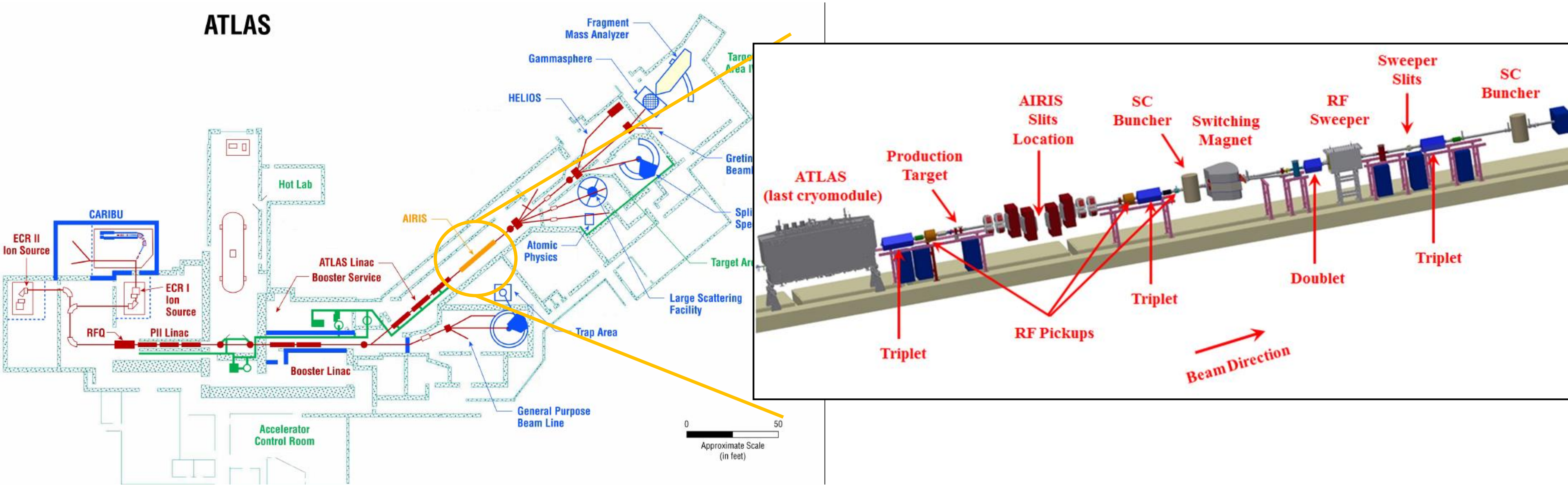
under budget, ahead of schedule, on-line commissioning planned for March 2017

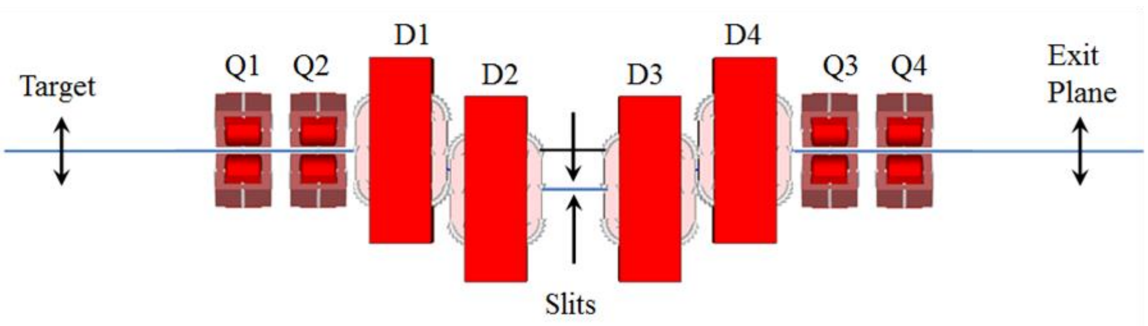
Enhanced sensitivity at the proton-drip line: GRETINA with new FMA entrance quadrupole

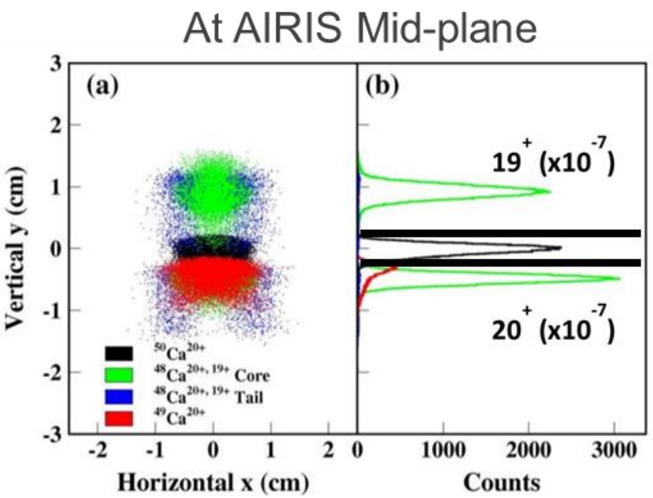


- Will fit inside GRETINA frame (most forward detector ring removed)
- Larger solid angle 12 msr (8 msr with FMA alone now, 2 msr with GS)
- Two hemis at 90 degrees to the beam axis (>10 clusters)
- high γ-ray efficiency, high recoil detection efficiency, superior Doppler correction, polarization
- **Will be available for 2017 GRETINA campaign at ATLAS**

AIRIS upgrade to the ATLAS facility



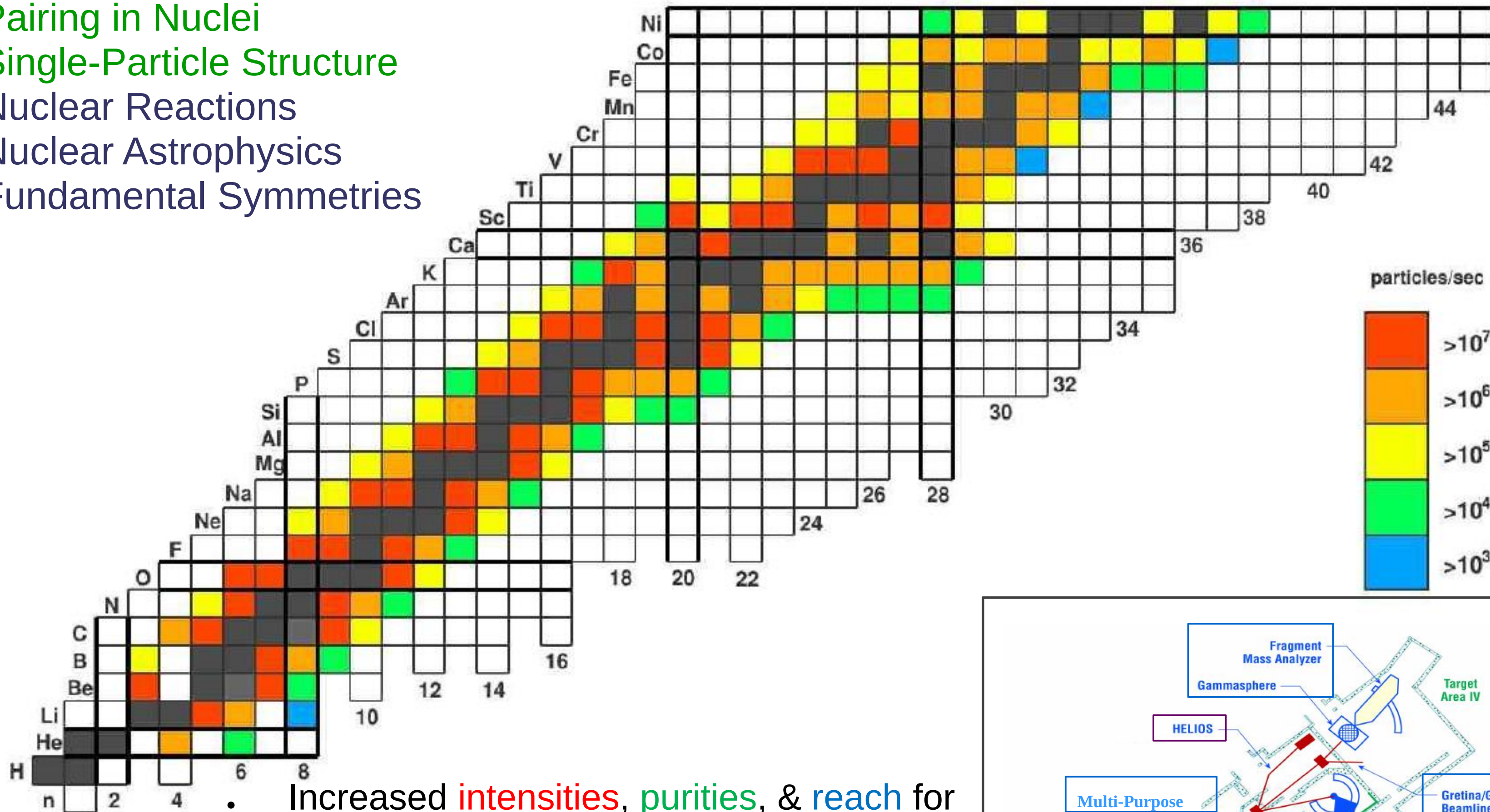




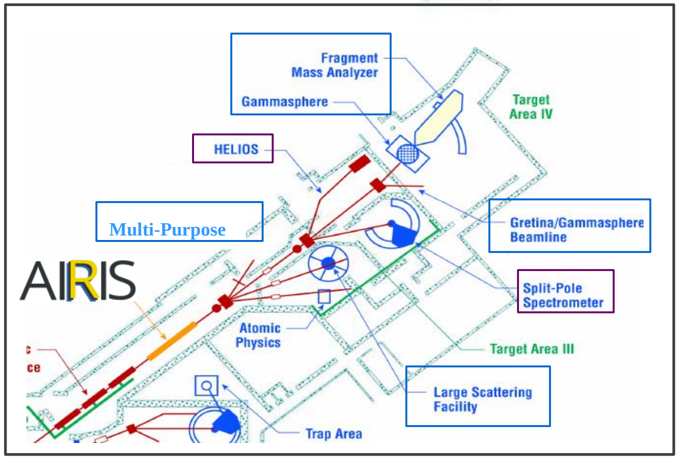
Estimated Beam Rates at AIRIS Exit

- 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

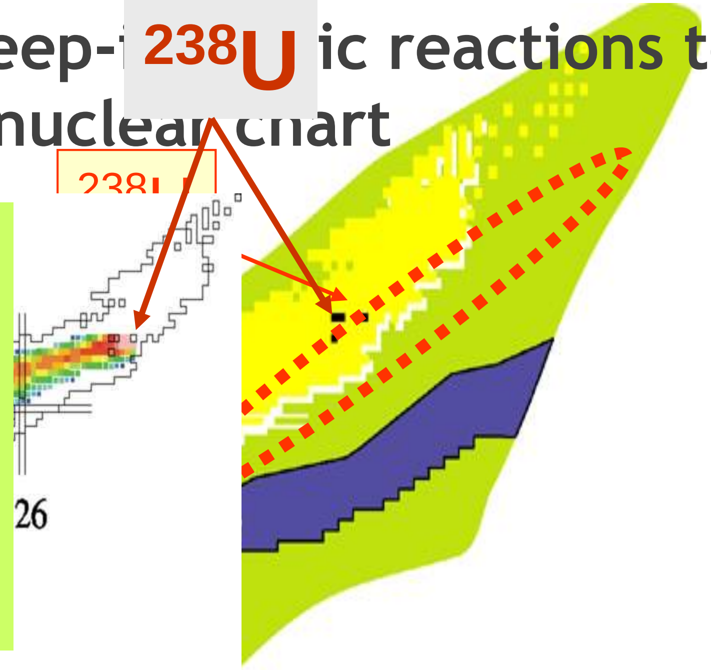


More info at https://www.phy.anl.gov/airis/

Accessing new regions: deep-i ic reactions to reach the st of the nuclear chart

^{238}U

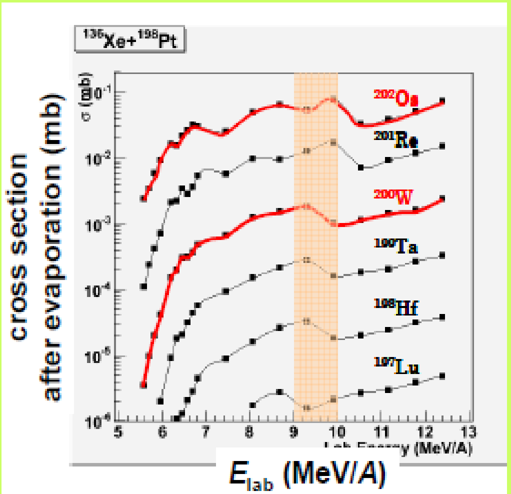
1 GeV/u ^{238}U + ^{1}H
Armbruster et al.



The Science:

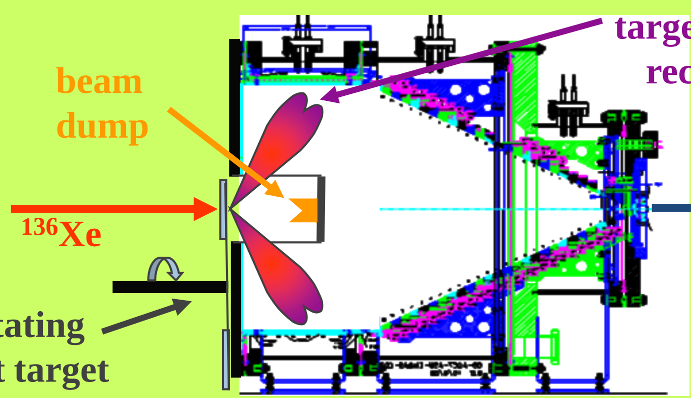
- nuclear shell structure at the extremes
- r-process: second abundance peak, fission recycling and termination
- fission barriers of neutron-rich nuclei and symmetry energy
- connection of hot-fusion SHE island and mainland

Production through deep-inelastic reactions



$\sigma \sim 10^{-1}$ mb for ^{202}Os
$\sigma \sim 10^{-3}$ mb for ^{200}W

Efficient thermalization, extraction and separation through a CARIBU like large gas catcher and separator



ATLAS Multi-User Upgrade

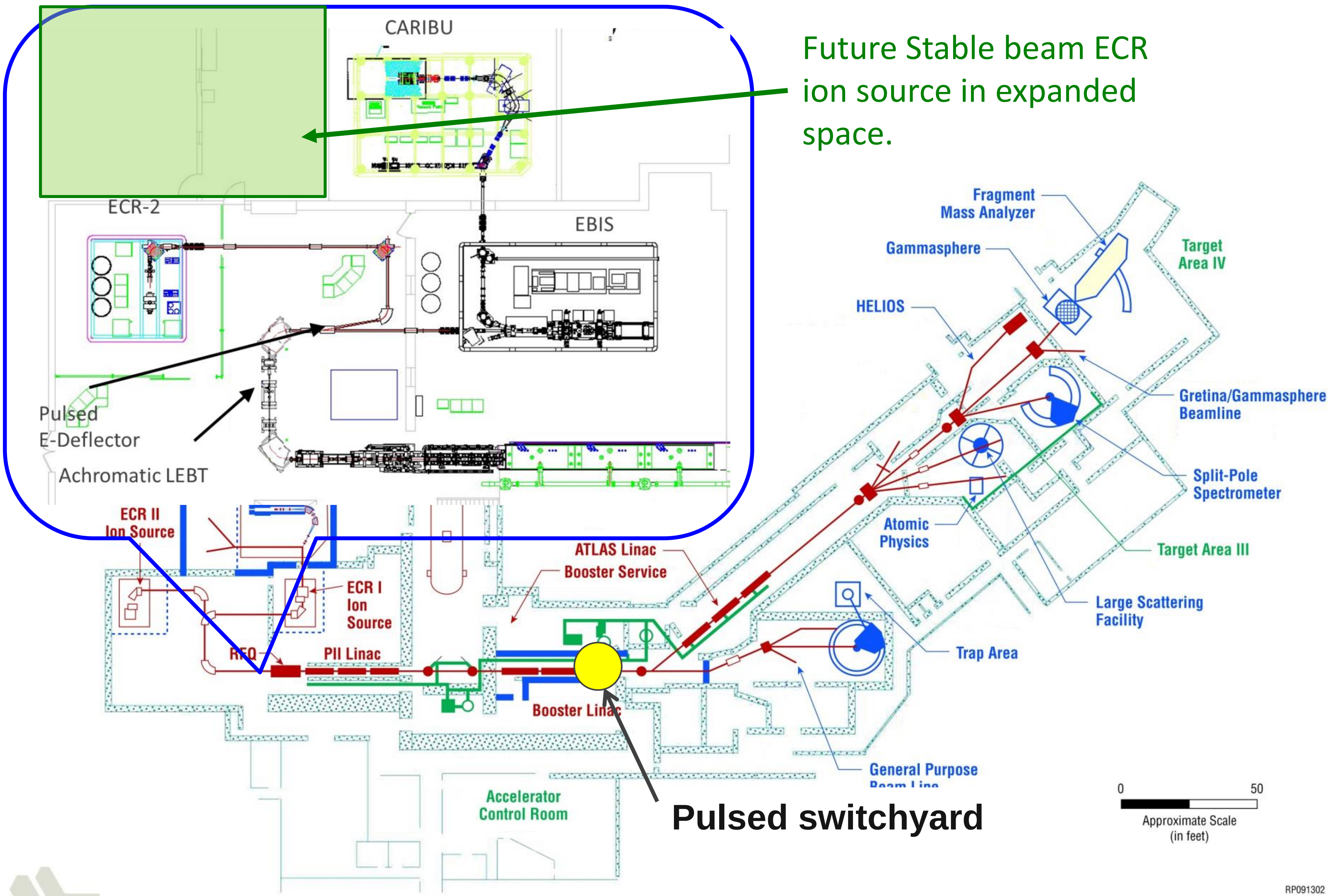
- Specific characteristics of the upgraded ATLAS and CARIBU can provide a cost efficient way to remedy this situation
  - With the EBIS breeder, the full CARIBU reaccelerated beam will be pulsed with a duty cycle of 1-3%, leaving the accelerator "idle" for 97-99% of the time
  - The ATLAS linac can accelerate simultaneously ions with similar charge-to-mass ratio within 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 10-1000 μs 30 times per second**
    - **Pulse structure is intrinsic to our EBIS charge breeder approach**
  - **One ATLAS stable beam utilizing the remaining 97-99% of the time**
    - **Available at the full intensity provided by the ECR source**

- **Favorable S&T review and encouragement to prepare a proposal for Fall 2016**
- **Received support from the Laboratory (Development funds)**

Concept development for the ATLAS Multi-User Upgrade (funded by LDRD): <u>New achromatic LEBT and pulsed switchyard</u>



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 science goals
  - Adding new capabilities
    - CARIBU
      - **EBIS charge breeder → addresses purity issues for reaccelerated beams**
      - **MRTOF + new low-energy area → purity and low background**
  - Improving its suite of experimental equipment
    - HELIOS, digital Gammasphere and DSSD, X-array
    - **AGFA, AIRIS,** N=126 factory, laser lab, beta-delayed neutron trap

- 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

- **Next ATLAS/CARIBU PAC deadline Sept 12 2016**

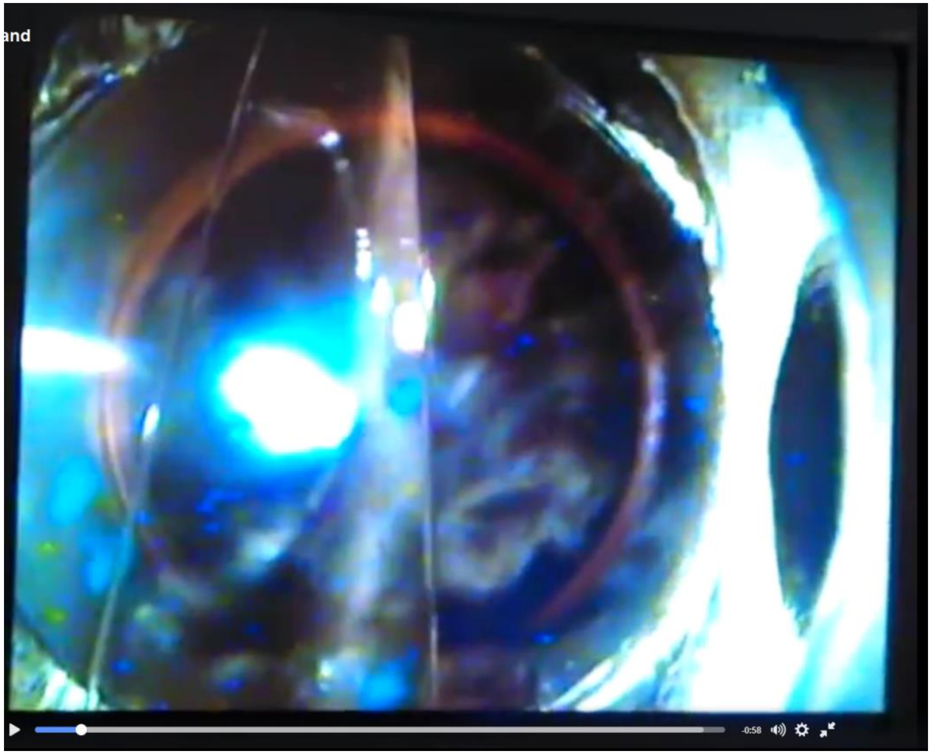
Backup slides

High-intensity liquid film target

As part of the AIRIS project, we have developed a liquid film target to handle the higher beam intensities ATLAS can now provide after the intensity and efficiency upgrade

After initial off-line tests, a final design with colliding jets and double differential pumping system was built and tested on-line at ATLAS

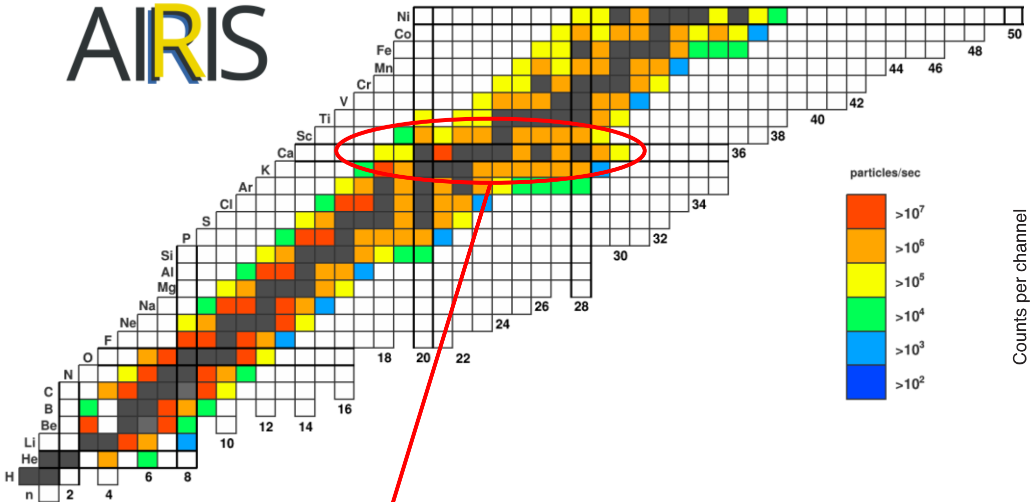
- Hydrogen target (pump oil CH_2 chains)
- High intensity test
  - ^{40}Ar at 10-15 uA
  - ran stably over 4 days test run with no noticeable deterioration
  - > 20 times higher intensity than what present gas targets can take
  - no noticeable degradation of beamline vacuum
- Hydrogen target now demonstrated, now testing for best deuterated compound for deuterium target



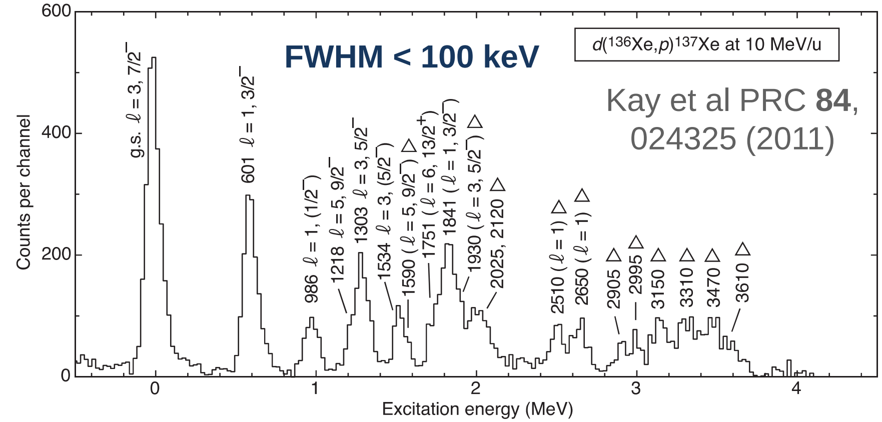
Main research thrusts: Nuclear structure

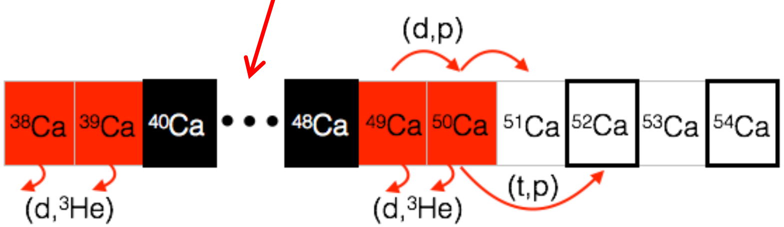
Single-particle transfer program with Helios at ATLAS in coming years

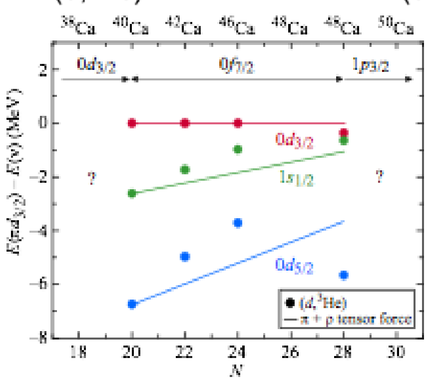
AIRIS

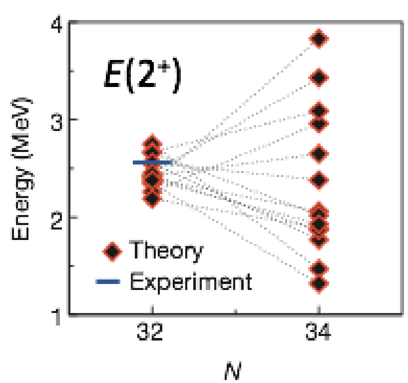


CARIBU

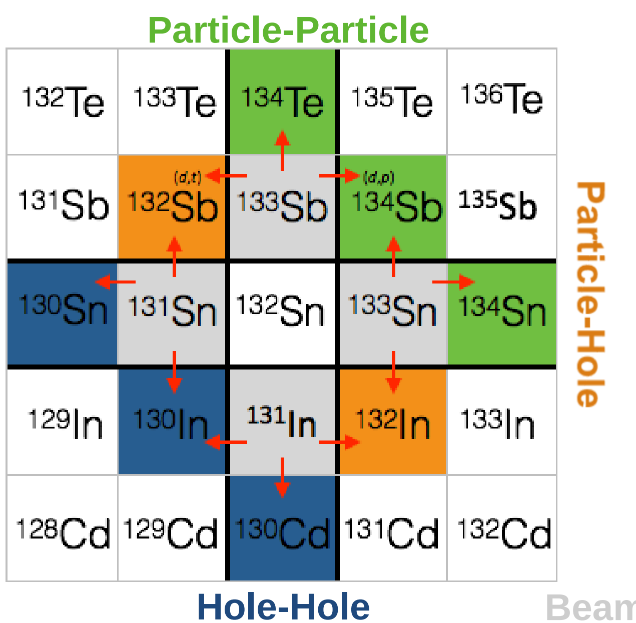








Steppenbeck *et al.*, Nature 502, 207 (2013)

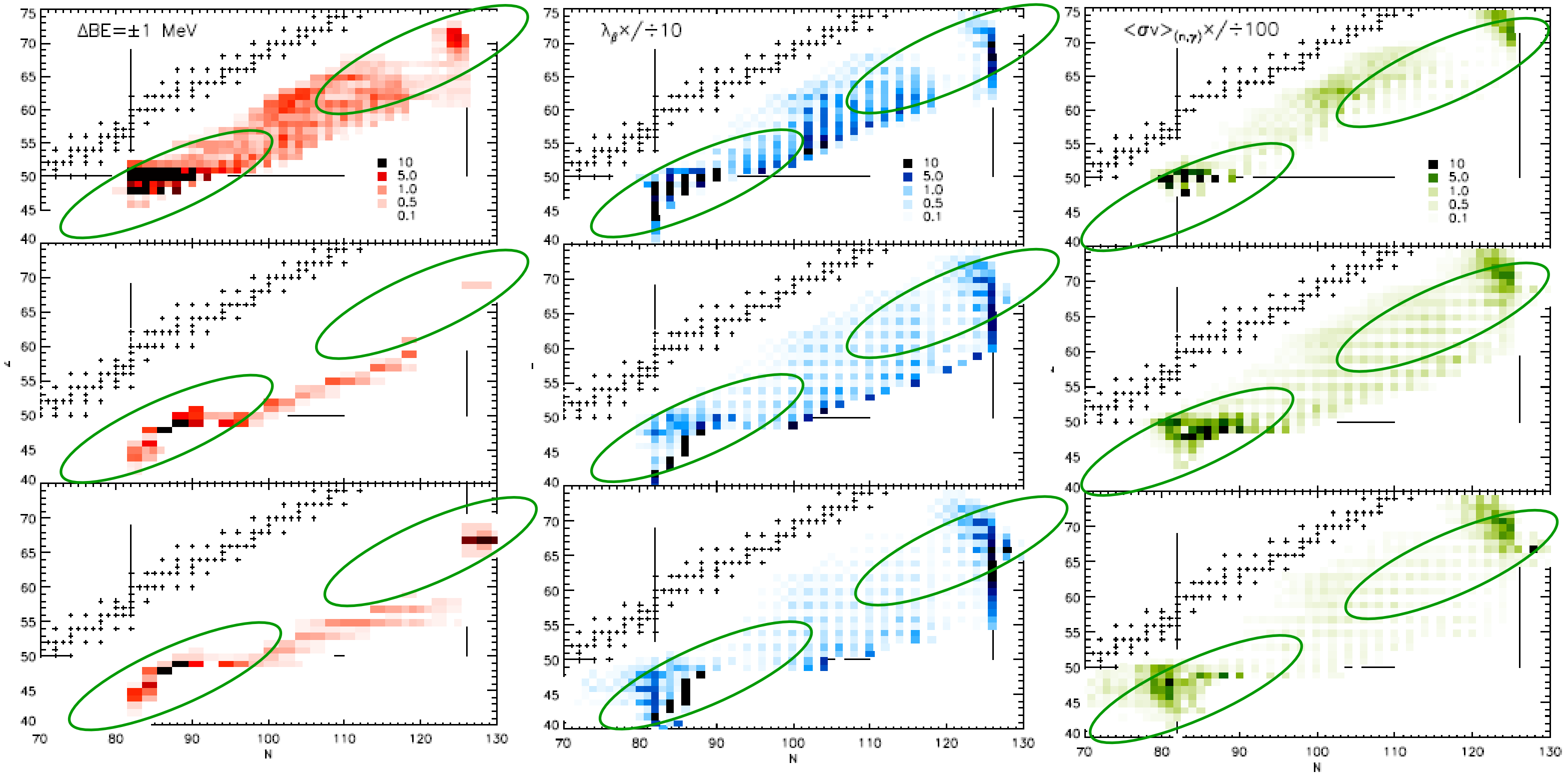


R-process sensitivity to nuclear physics input

Hot r-process

Supernova neutrino-driven wind cold r-process

Neutron-star merger cold r-process



binding energy | neutron-capture rate | lifetime

From R. Surman, M. Mumpower et al, arXiv:1039.0059v1

Clear regions of interest for most scenarii … need to make them accessible experimentally

Main research thrusts: Nuclear astrophysics

Accessing new regions for r-process and rp-process measurements