INTERNATIONAL CONFERENCE ON ELECTROMAGNETIC ISOTOPE SEPARATORS AND RELATED TOPICS

EMIS XVIII

CERN GENEVA / SWITZERLAND / 16 - 21 SEPTEMBER 2018

THE N=126 FACTORY: A NEW FACILITY TO PRODUCE VERY-HEAVY NEUTRON-RICH ISOTOPES

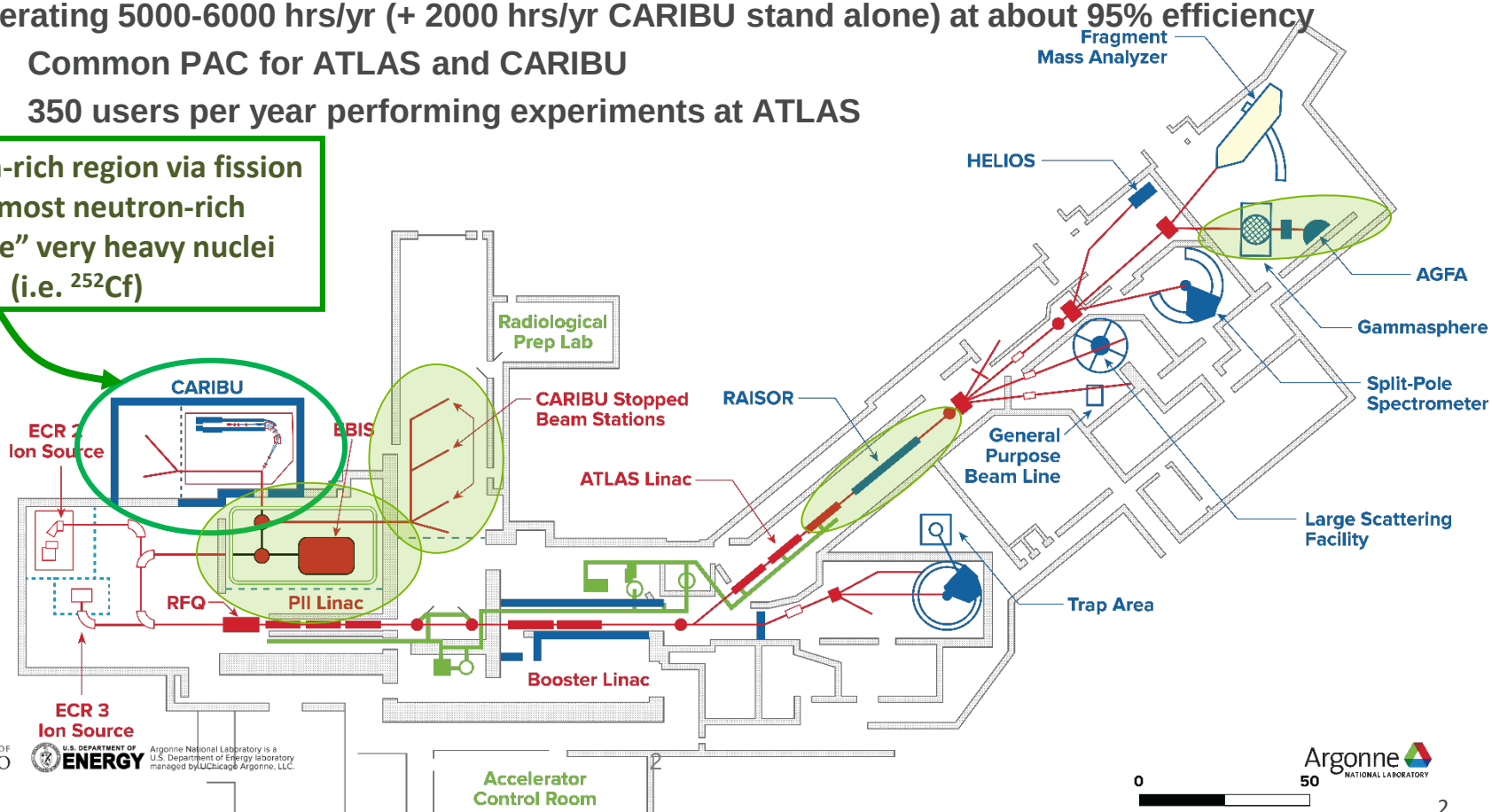
GUY SAVARD
Argonne National Laboratory

SEPTEMBER 20 2018

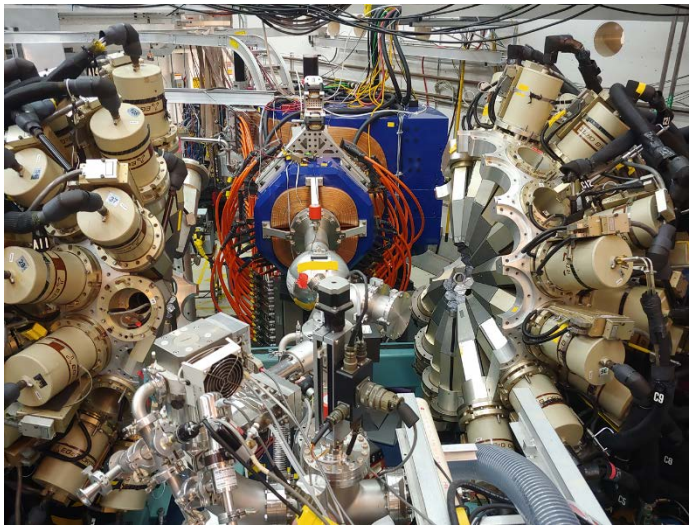
ATLAS/CARIBU FACILITY

- 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

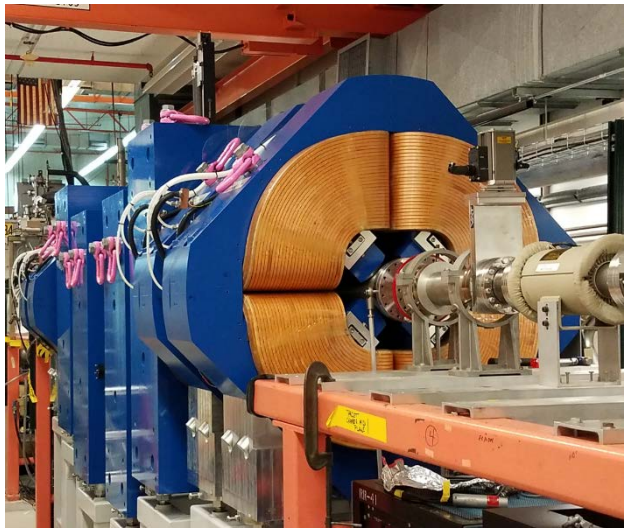
Access to n-rich region via fission of the most neutron-rich "available" very heavy nuclei (i.e. ^{252}Cf)



NEW TOYS AT ATLAS SINCE LAST EMIS CONFERENCE



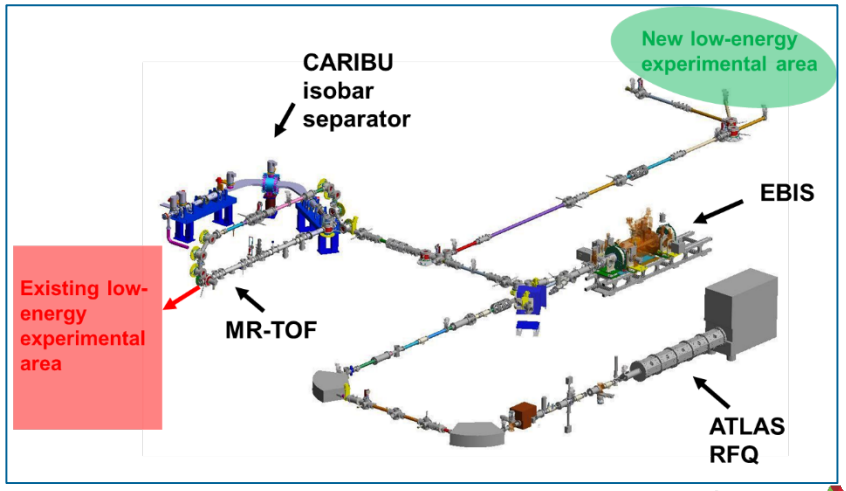
AGFA gas-filled spectrometer



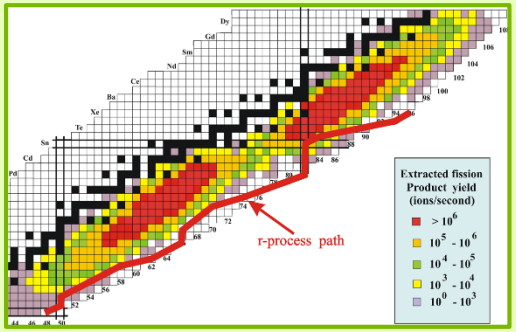
AIRIS in-flight separator

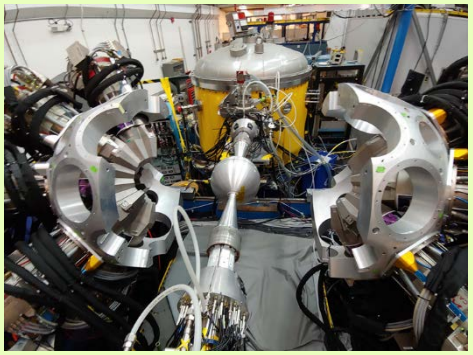
EBIS charge-state breeder

new CARIBU low-energy area



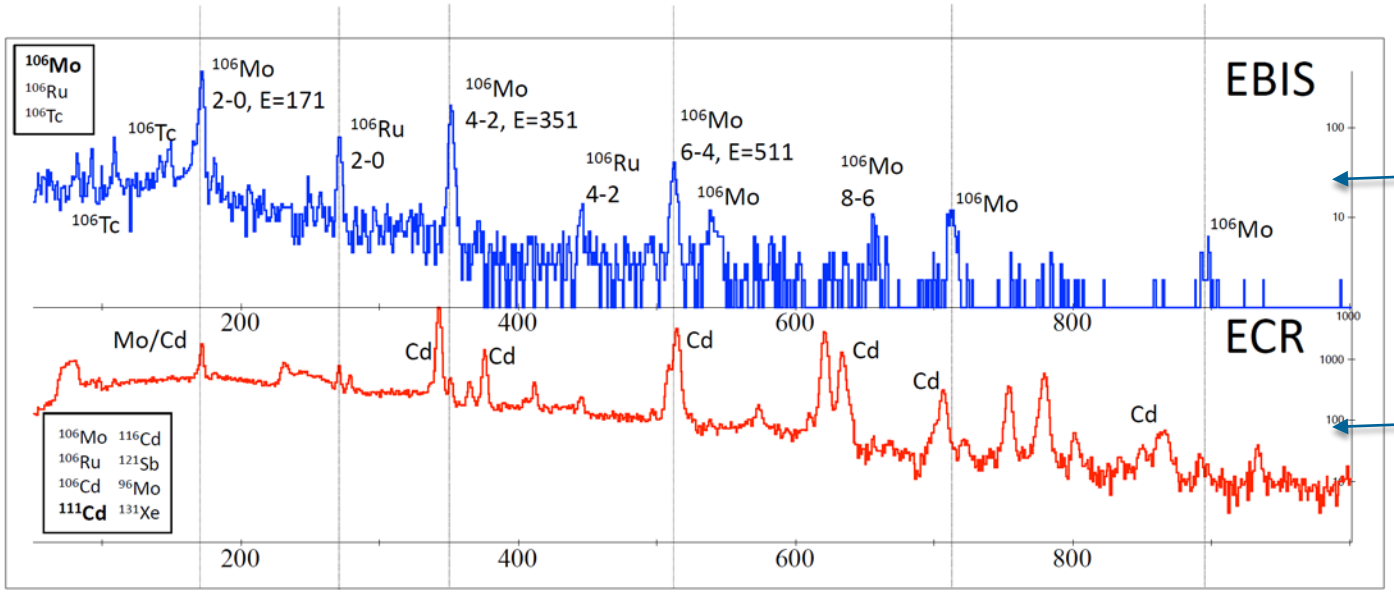
Experiments this month with reaccelerated CARIBU beams using EBIS : Coulomb excitation of ^{104,106}Mo, ^{110}Ru, ^{100}Zr





CARIBU + EBIS charge breeder + GRETINA + CHICO2

EBIS vs ECR Beam Quality: ^{106}Mo (408 MeV) + ^{208}Pb

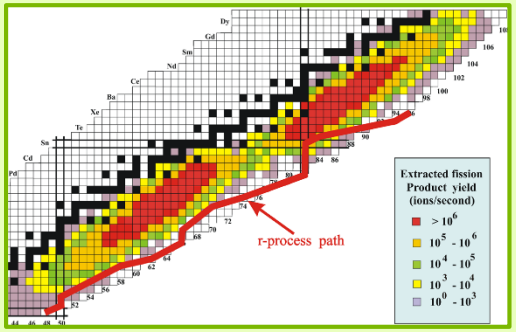


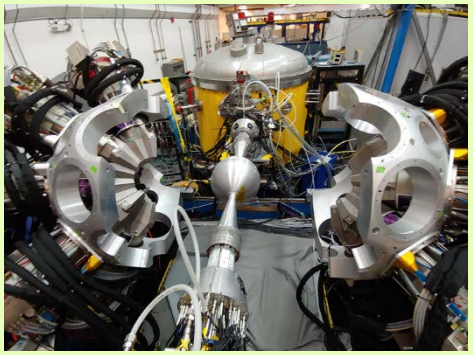
Now

vs

Last EMIS

Experiments this month with reaccelerated CARIBU beams using EBIS : Coulomb excitation of ^{104,106}Mo, ^{110}Ru, ^{100}Zr





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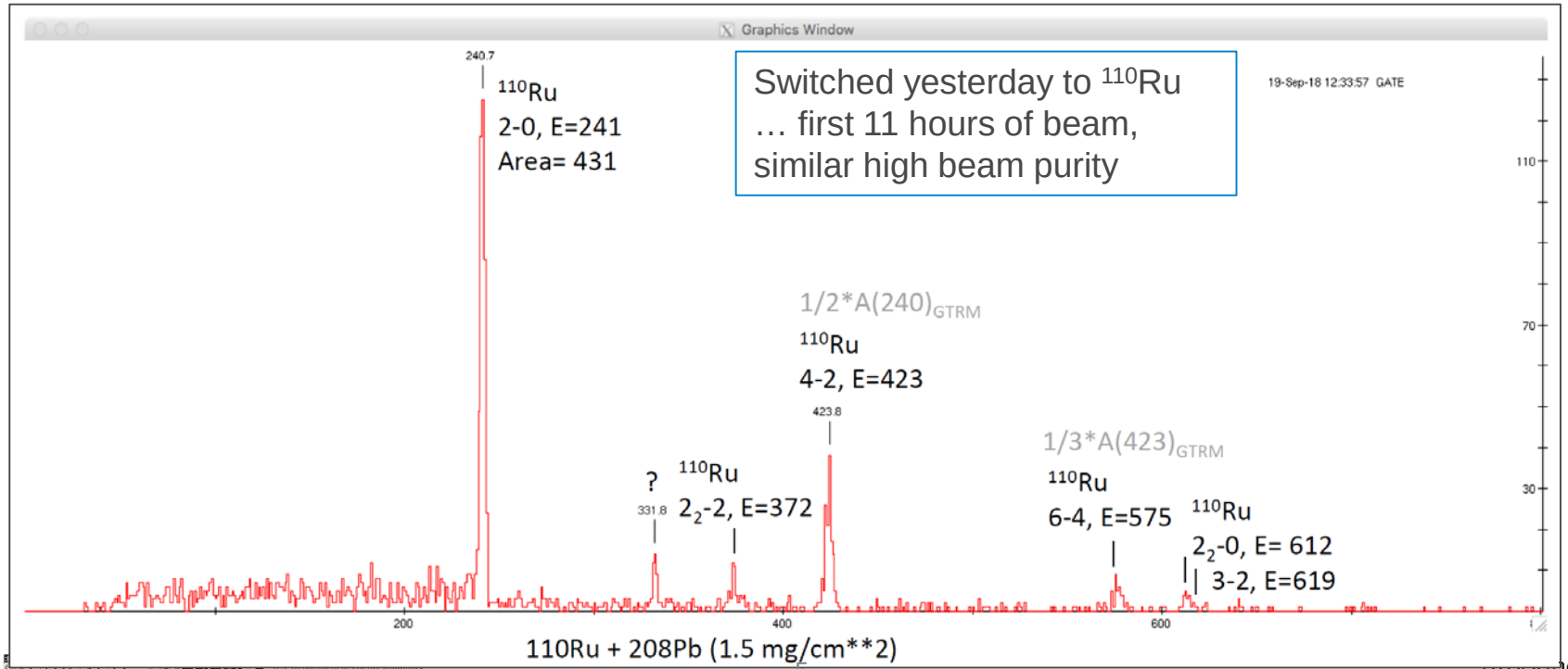

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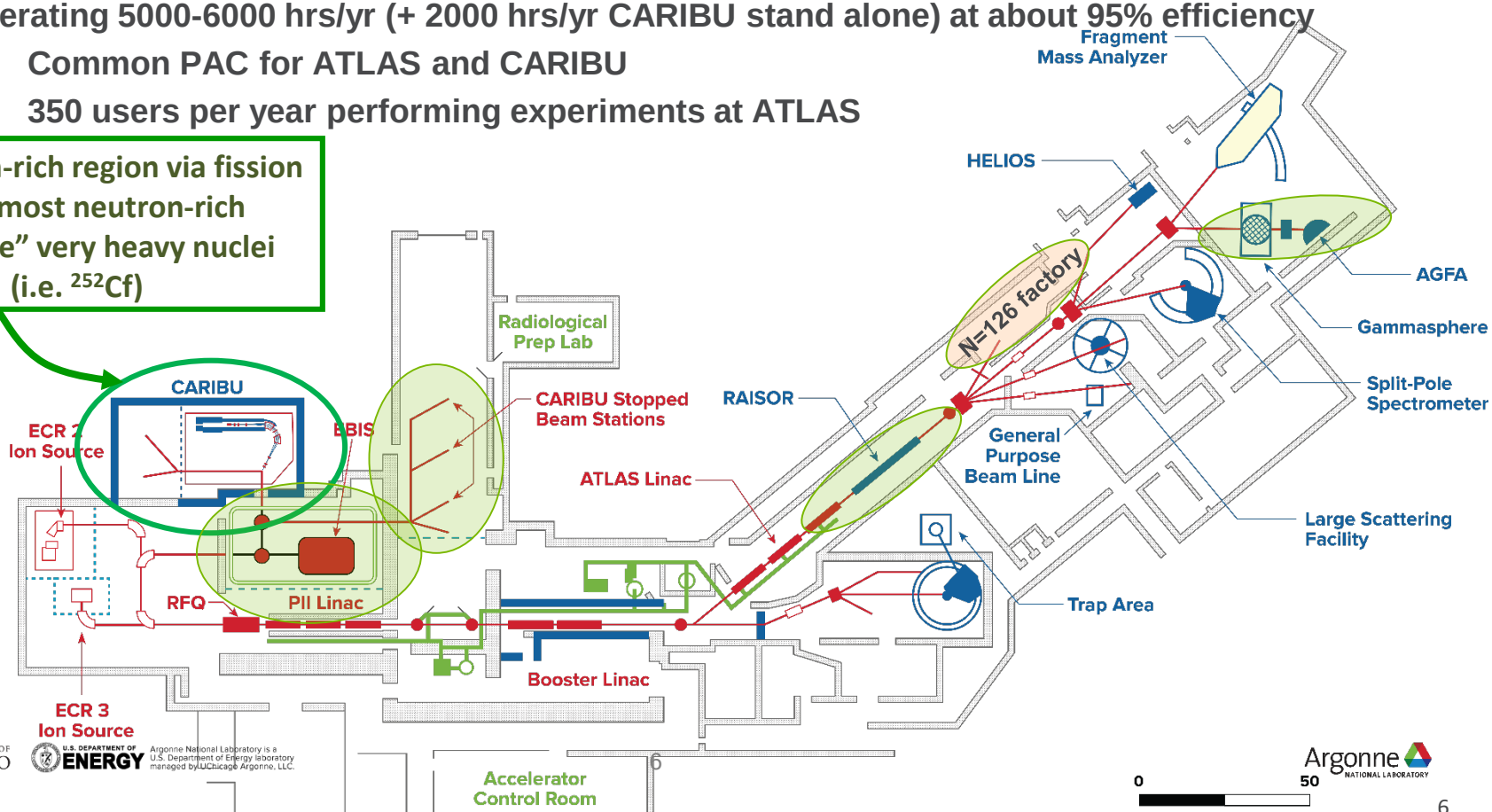


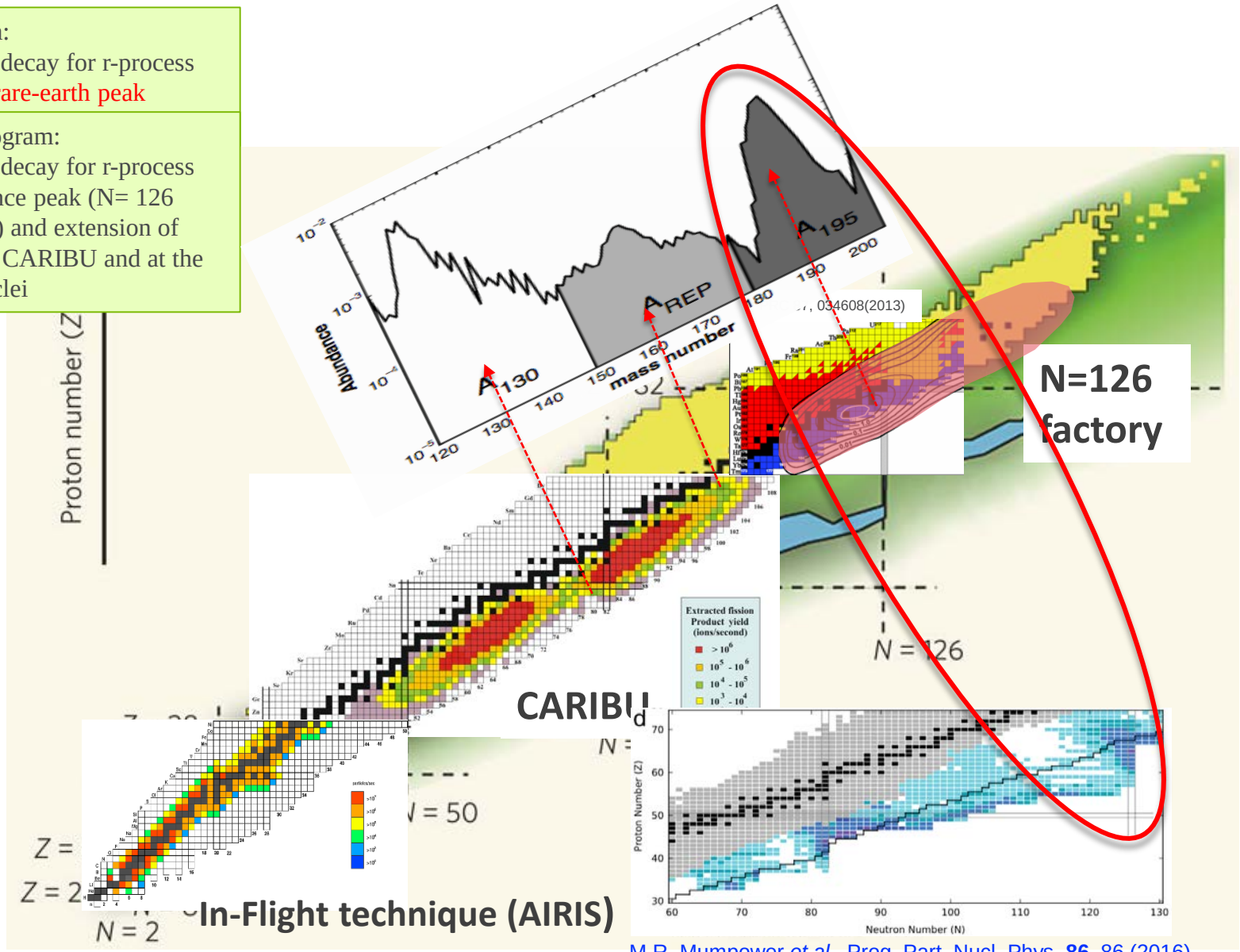
R-PROCESS STUDIES AT ATLAS

Current program:

- Masses and decay for r-process (N=82 and rare-earth peak

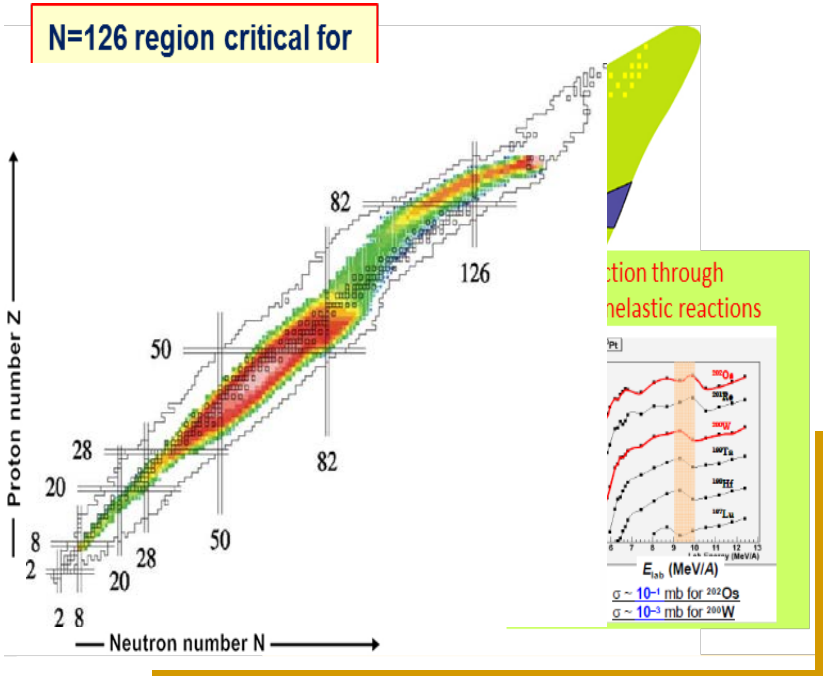
Next 5 years program:

- Masses and decay for r-process last abundance peak (N= 126 peak region) and extension of work above CARIBU and at the heaviest nuclei

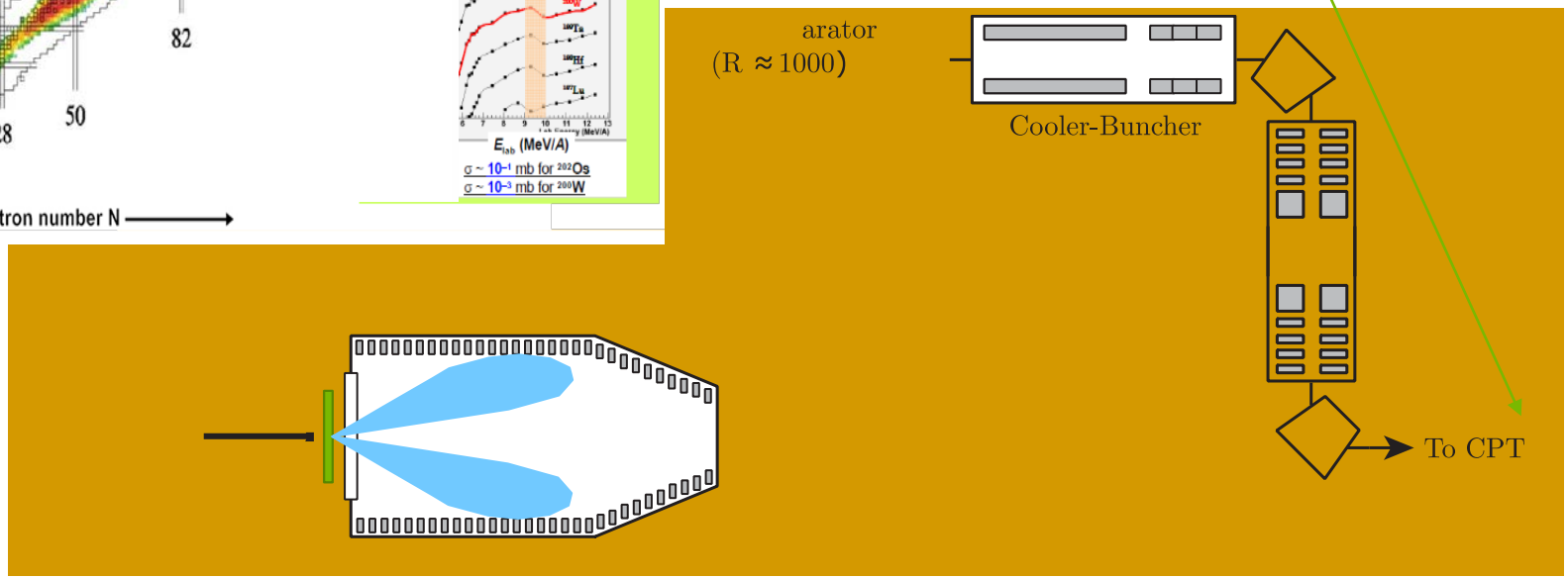


M.R. Mumpower *et al.*, Prog. Part. Nucl. Phys. **86**, 86 (2016)

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



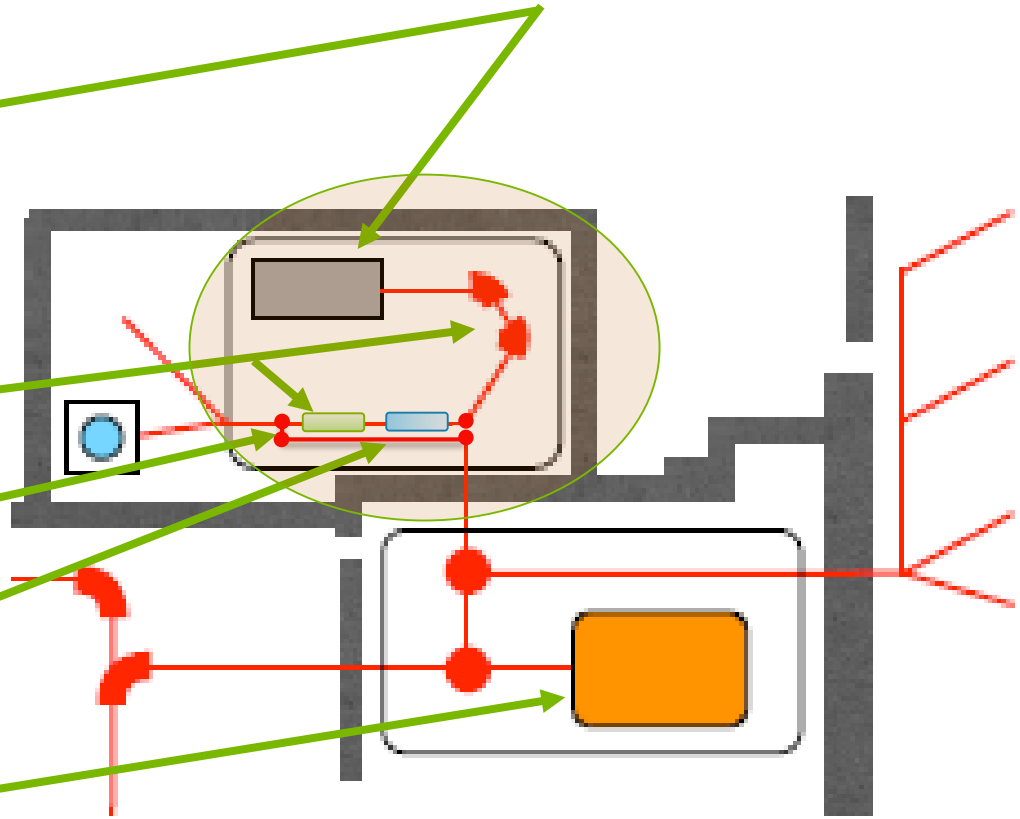
Makes these critical nuclei available as a good quality mass separated low-energy beam



AN EXAMPLE OF HOW TO DEAL WITH SPACE-CHARGE: CARIBU "FRONT END" LAYOUT

Main components of CARIBU

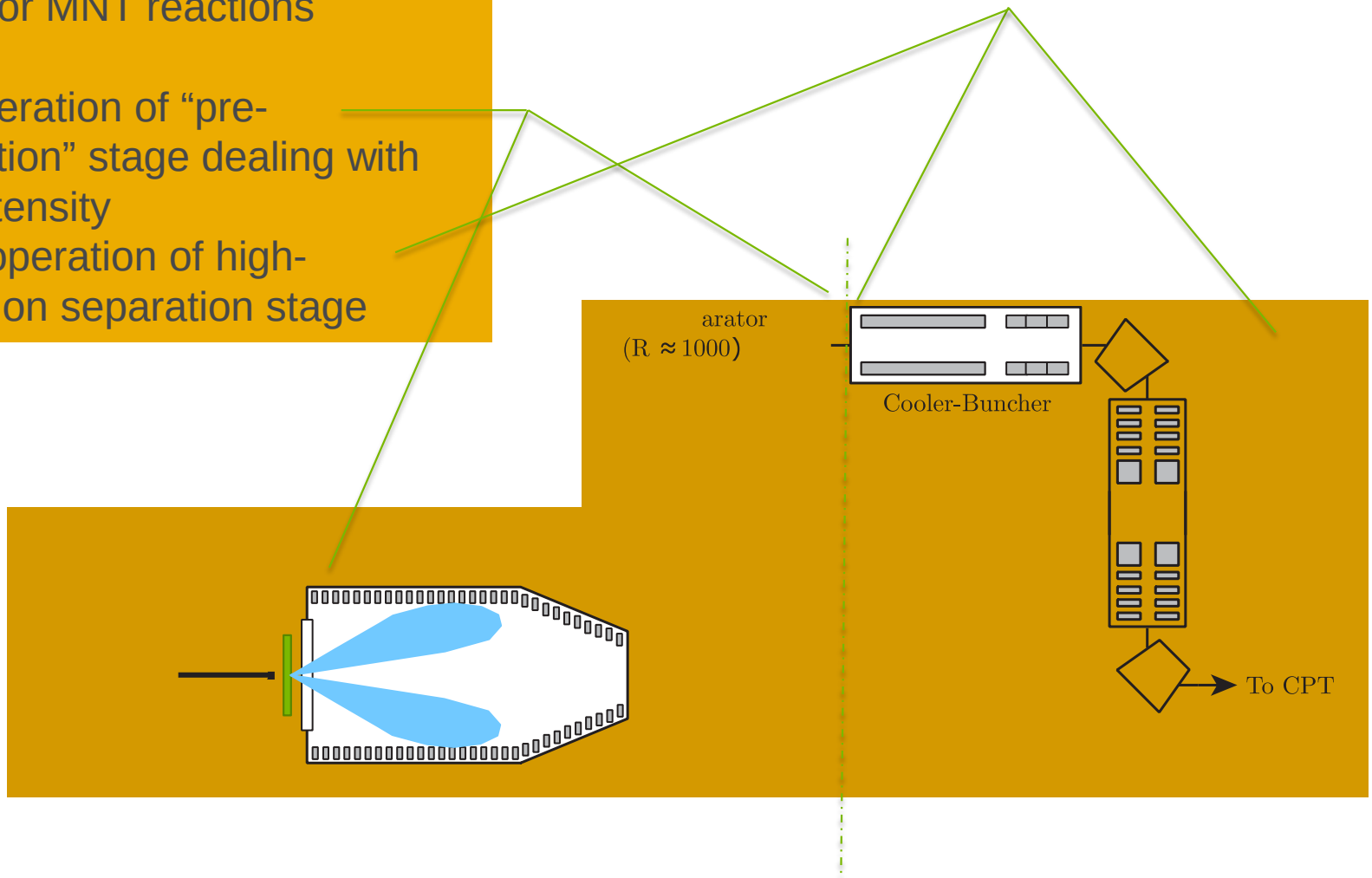
- PRODUCTION: "ion source" is ^{252}Cf source inside gas catcher
  - Thermalizes fission fragments
  - Extracts all species quickly
  - Forms low emittance beam
- SELECTION: Isobar separator and MR-TOF
  - Purifies beam
- DELIVERY: beamlines and preparation
  - Switchyard
  - Low-energy buncher and beamlines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



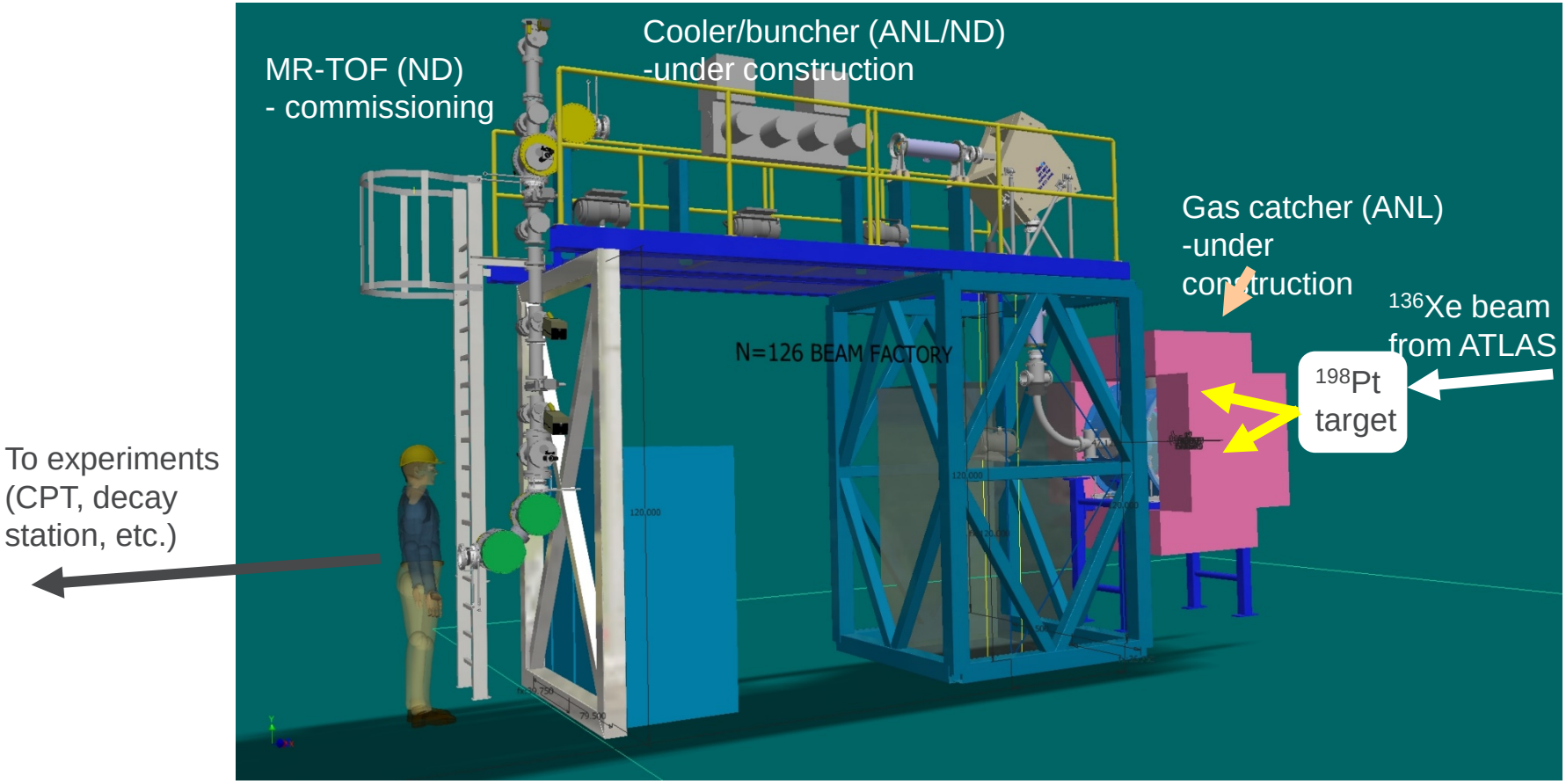
ACCESSING ISOTOPES OF INTEREST FOR THE LAST R-PROCESS ABUNDANCE PEAK: THE N=126 FACTORY

N=126 factory design is a simplified CARIBU for MNT reactions

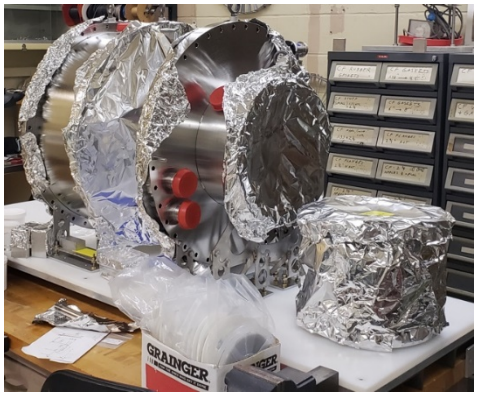
- CW operation of “pre-separation” stage dealing with high intensity
- Pulse operation of high-resolution separation stage

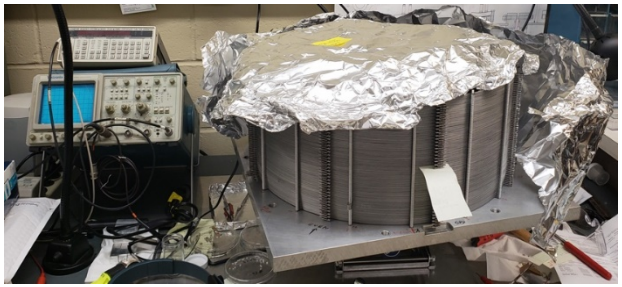


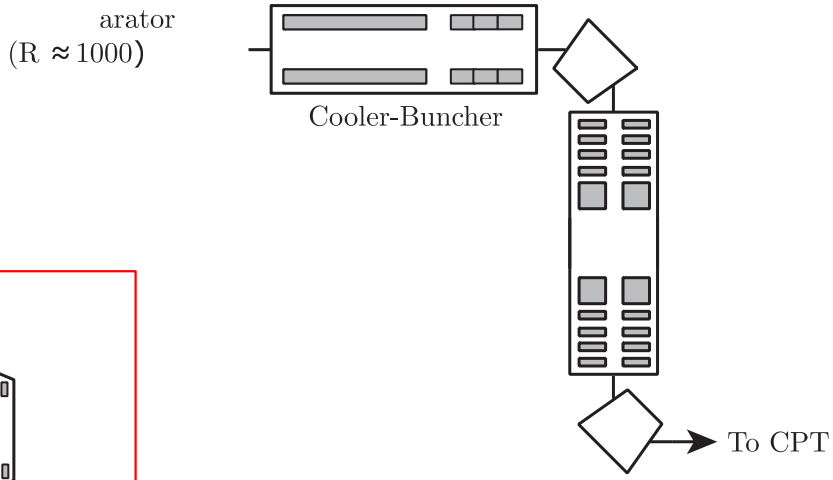
The N=126 factory

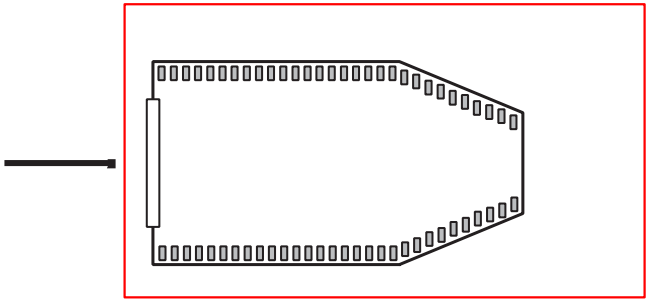


THE N=126 FACTORY: HIGH-INTENSITY GAS CATCHER SYSTEM

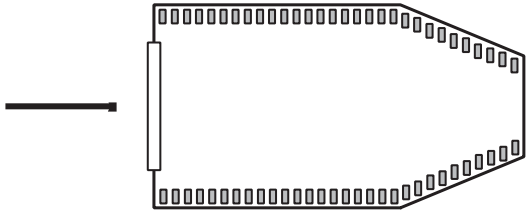


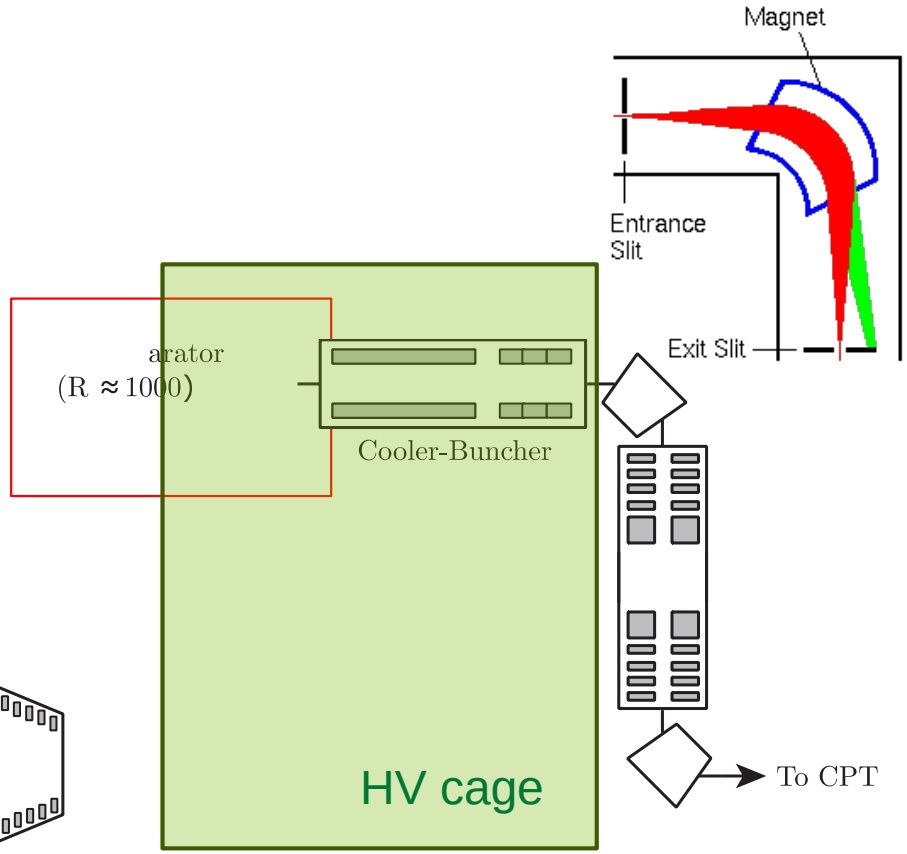






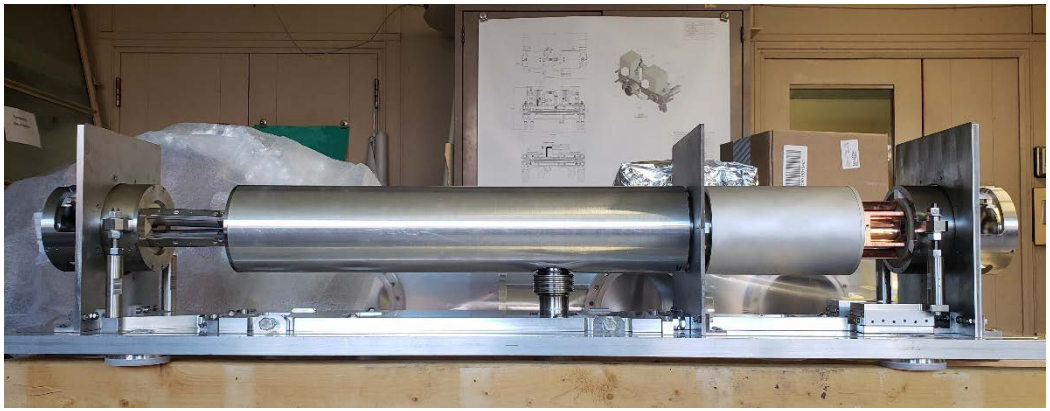
THE N=126 FACTORY: ISOBAR SEPARATOR

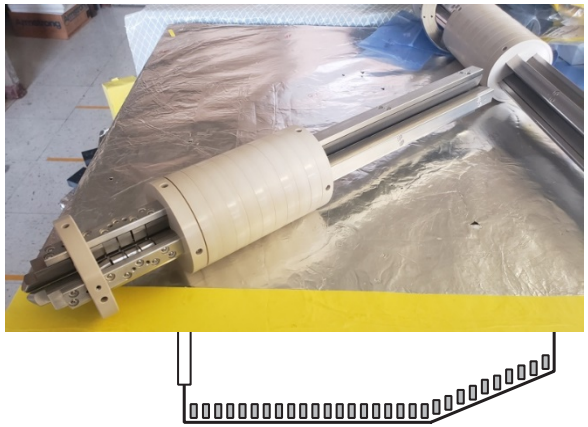


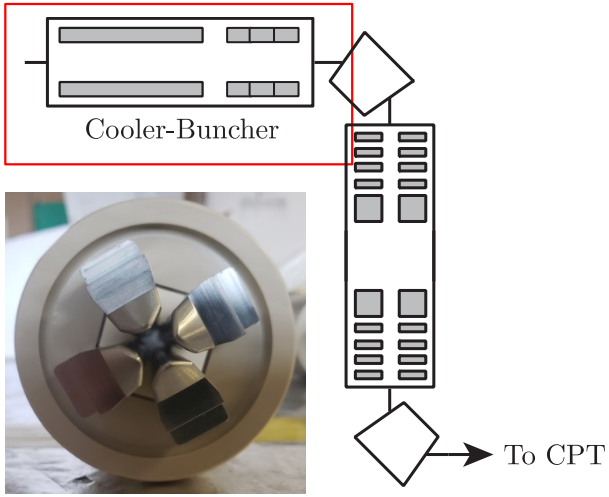


THE N=126 FACTORY: RFQ BUNCHER

Valverde, Adrian

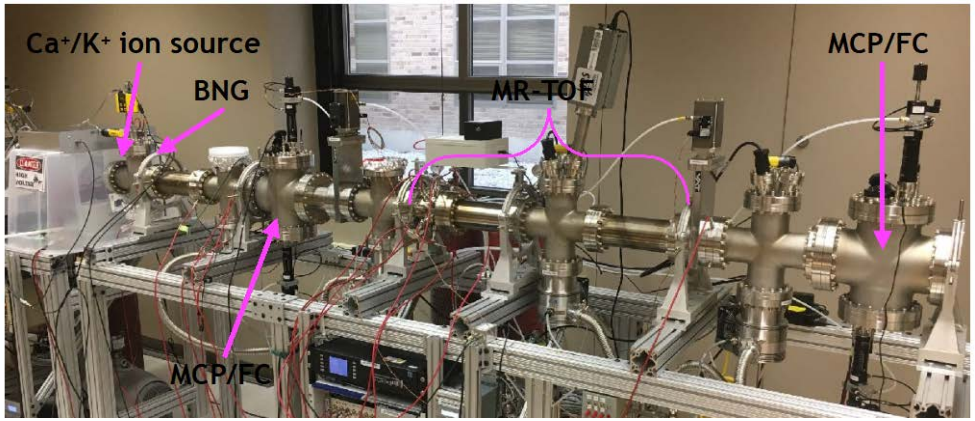


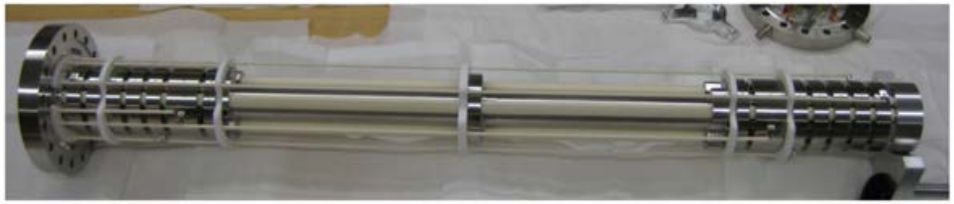


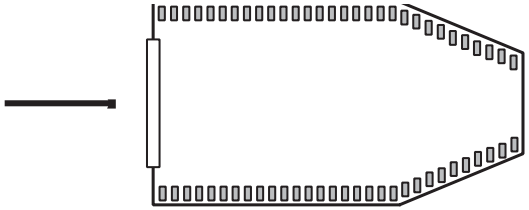


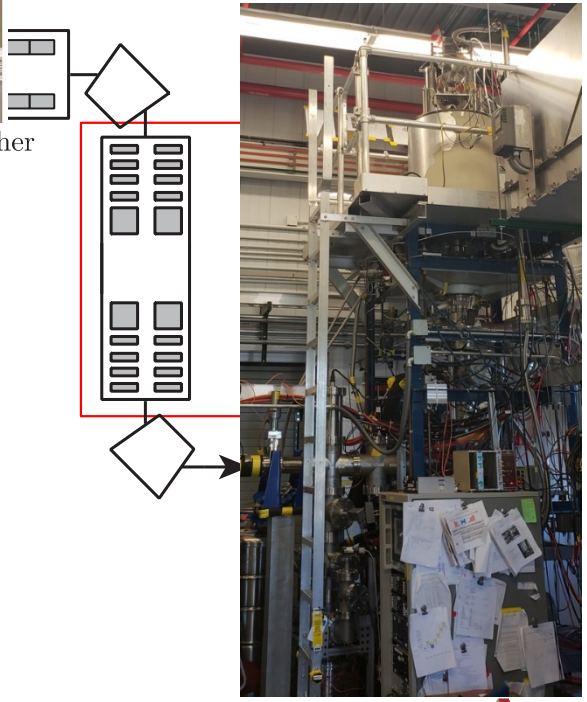
THE N=126 FACTORY: MRTOF SYSTEM BEING COMMISSIONED AT NOTRE-DAME

Kelly, James M.

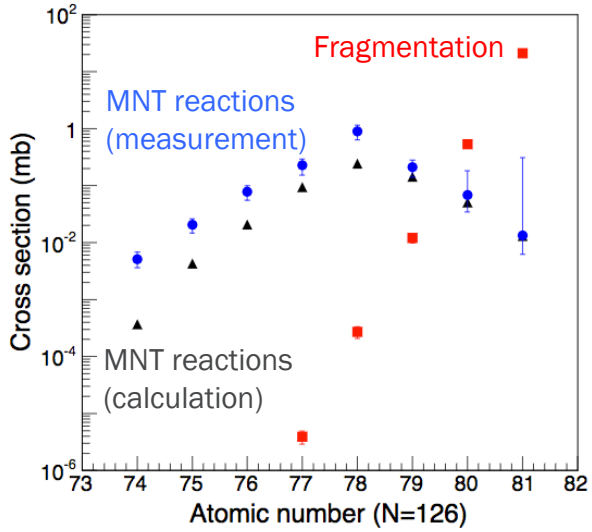






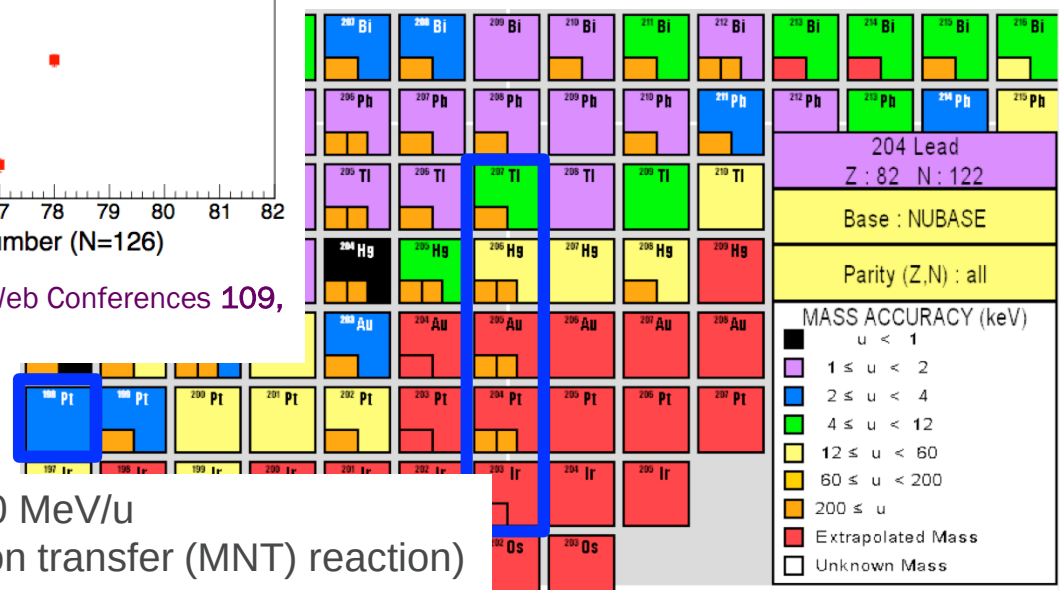


CROSS-SECTION FOR MULTI-NUCLEON TRANSFER VERSUS FRAGMENTATION



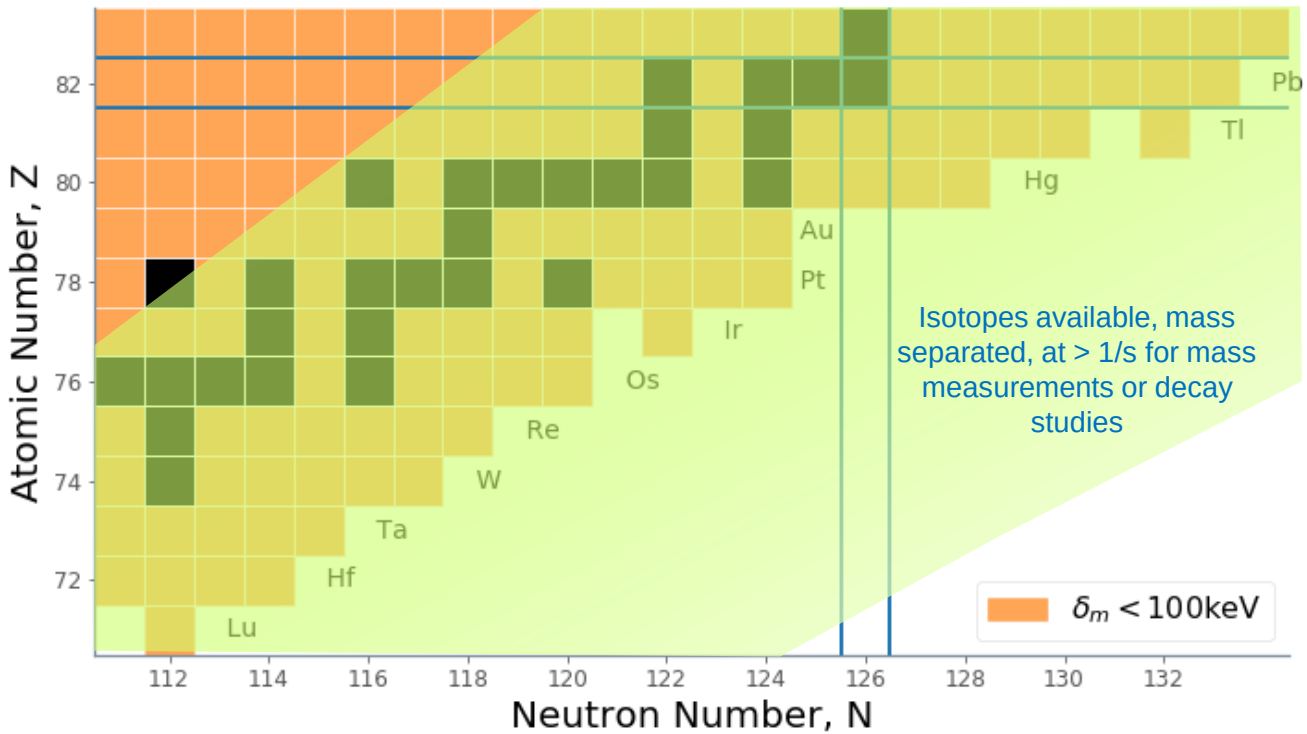
Hirayama *et al.*, EPJ Web Conferences **109**, 08001 (2016)

^{208}Pb + ^{9}Be at 1 GeV/u (fragmentation reaction with best cross-sections for N = 126)

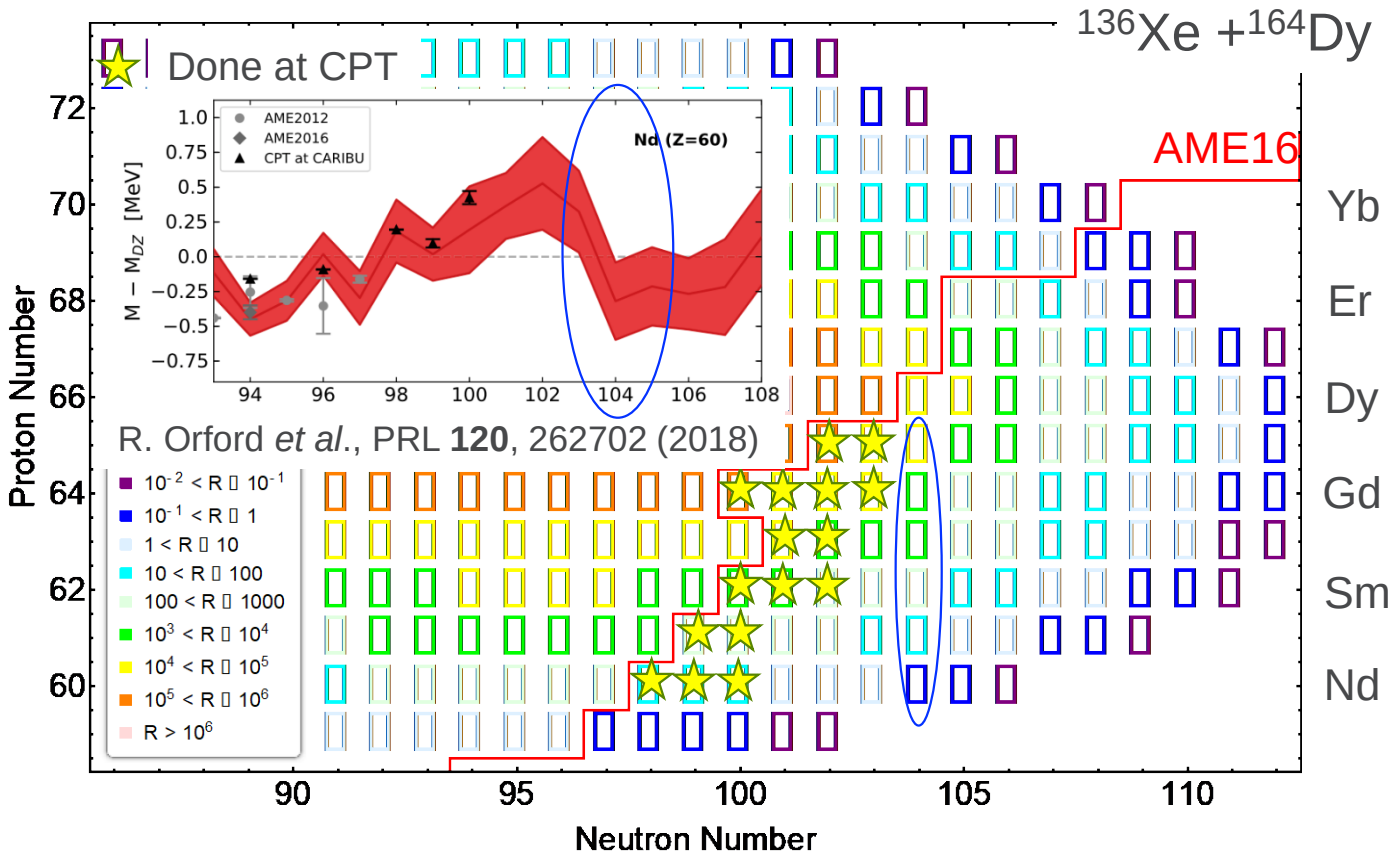


^{136}Xe + ^{198}Pt at 10 MeV/u
(best multi-nucleon transfer (MNT) reaction)

EXPECTED REACH OF N = 126 FACTORY … AROUND N=126



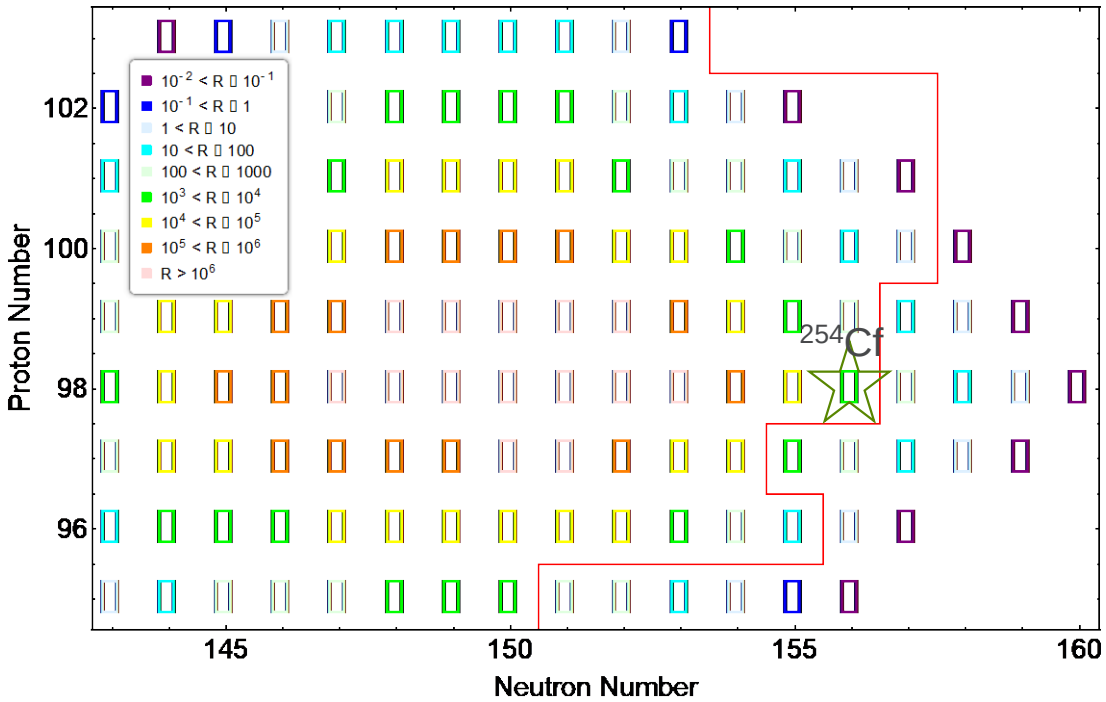
What can the N=126 factory do near the rare earth fission peak?



Major extension over what is possible now in this region … can map the possible kink at N=104.

MEASUREMENTS ON VERY HEAVY NUCLEI

$^{136}Xe + ^{251}Cf$ (50 mCi)

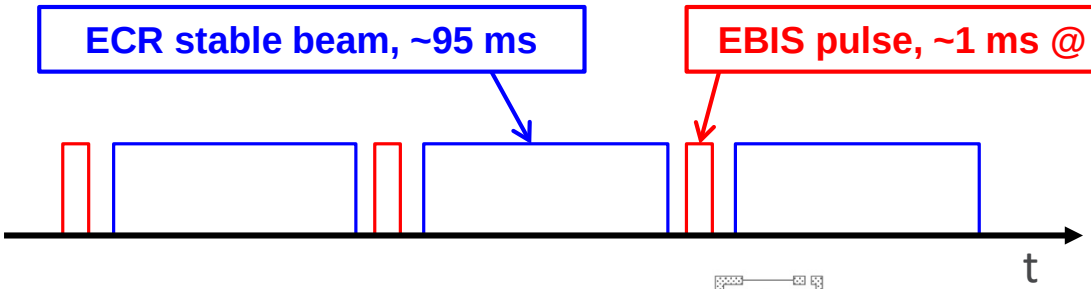


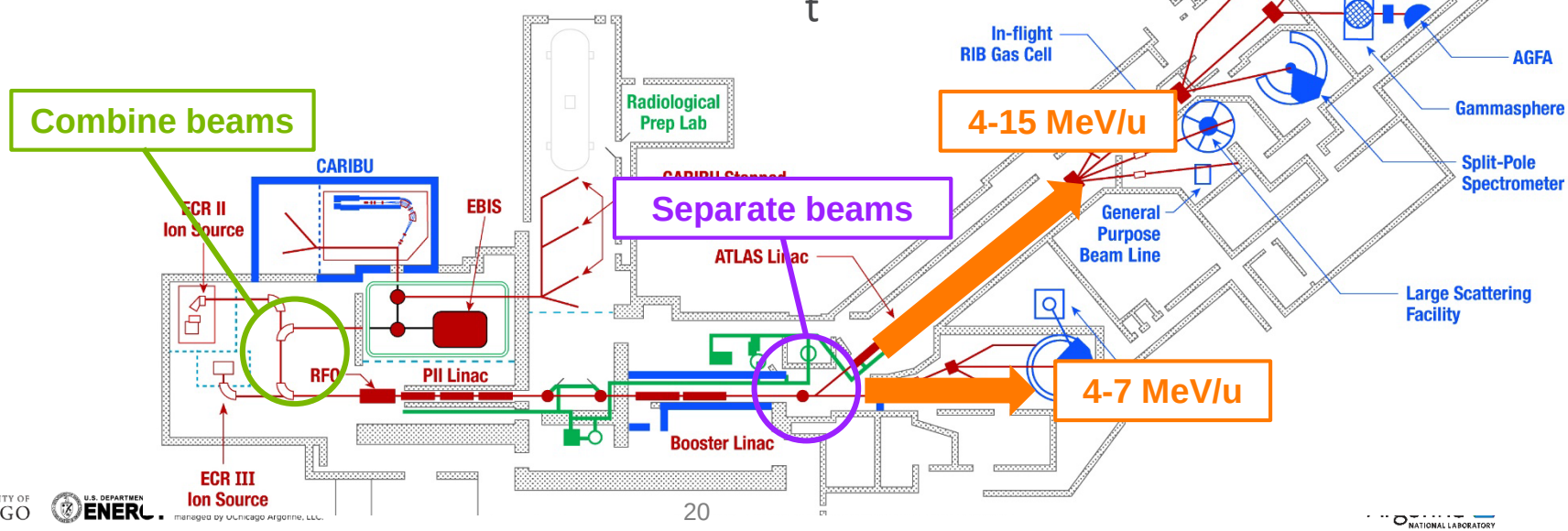
$^{238}U + ^{248}Cm$
for very n-rich Z~100

	Z																																			
Rf	**104**	-4.0	-3.0	-2.4	-1.8	-1.3	-0.8	-0.3	0.0	0.4	0.7	0.9	1.1	1.2	1.2	1.1	0.9	0.6	0.0	-0.8	-1.4	-2.7	-3.6	-5.8	####	####	####	####	####	####	####	####				
Lr	**103**	-1.7	-1.1	-0.5	0.0	0.4	0.8	1.2	1.5	1.7	1.9	2.0	2.1	2.2	2.3	2.2	2.1	1.9	1.6	1.1	0.7	-0.2	-1.0	-2.0	-3.3	-6.1	####	####	####	####	####	####				
No	**102**	-0.2	0.3	0.7	1.2	1.5	1.8	2.1	2.4	2.6	2.8	2.9	3.0	3.1	3.1	2.8	2.9	2.6	2.5	2.0	1.8	0.9	0.3	-0.6	-1.7	-3.1	-4.9	-7.5	####	####	####	####				
Md	**101**	0.8	1.2	1.6	2.0	2.3	2.6	2.8	3.1	3.3	3.5	3.6	3.7	3.8	3.8	3.6	3.7	3.3	3.3	2.7	2.3	1.9	1.4	0.8	0.1	-0.8	-1.9	-3.2	-4.8	-6.7	####	####				
Fm	**100**	1.6	2.0	2.3	2.7	3.0	3.3	3.5	3.8	4.0	4.2	4.3	4.4	4.3	4.5	4.3	4.4	4.0	4.0	3.4	3.1	2.7	2.3	1.8	1.2	0.5	-0.2	-1.0	-2.1	-3.6	-5.6	####				
Es	**99**	2.1	2.5	2.9	3.2	3.5	3.8	4.1	4.3	4.6	4.8	4.9	5.0	4.9	5.1	4.9	5.0	4.7	4.5	4.2	3.9	3.5	3.1	2.6	2.1	1.6	1.0	0.3	-0.6	-1.8	-3.2	-5.2				
Cf	**98**	2.7	3.2	3.5	3.9	4.2	4.5	4.7	4.9	4.9	5.3	5.2	5.5	5.4	5.7	5.5	5.7	5.5	5.5	4.9	4.6	4.2	3.8	3.3	2.8	2.3	1.8	1.2	0.5	-0.4	-1.5	-3.2				
Bk	**97**	3.0	3.4	3.8	4.1	4.5	4.8	5.0	5.3	5.3	5.7	5.7	6.0	5.9	6.3	6.2	6.3	6.4	6.3	5.9	5.4	4.9	4.4	3.9	3.4	3.0	2.4	1.9	1.3	0.5	-0.4	-1.6				
Cm	**96**	3.4	3.9	4.2	4.5	4.6	5.0	5.1	5.5	5.5	5.9	5.9	6.3	6.3	6.8	6.9	7.3	7.9	248Cm	6.6	6.1	5.6	4.9	4.4	3.9	3.4	2.8	2.3	1.6	0.8	-0.1	-1.3				
Am	**95**	3.4	3.9	4.2	4.6	4.6	5.1	5.1	5.5	5.5	5.8	5.8	5.9	6.0	6.1	6.2	6.3	6.4	6.4	5.9	5.4	5.0	4.6	4.2	3.7	3.2	2.8	2.3	1.7	1.0	0.1	-1.1				
Pu	**94**	3.4	3.8	3.9	4.4	4.4	4.8	4.9	5.2	5.2	5.5	5.4	5.5	5.6	5.6	5.6	5.6	5.5	5.3	5.1	4.7	4.4	4.1	3.7	3.3	2.8	2.2	1.6	0.9	0.0	-0.3	-1.4				
Np	**93**	3.2	3.6	3.7	4.1	4.1	4.5	4.5	4.8	4.8	4.9	4.9	5.0	5.0	5.0	4.9	4.9	4.8	4.6	4.4	4.2	3.9	3.6	3.2	2.8	2.4	1.9	1.3	0.6	-0.3	-0.6	-1.8				
U	**92**	2.6	3.1	3.2	3.6	3.7	4.0	4.0	4.3	4.2	4.3	4.4	4.4	4.4	4.4	4.3	4.2	4.1	3.9	3.6	3.2	2.6	2.6	1.9	1.9	1.1	1.0	0.1	-0.2	-1.2	-1.6	-2.8				
Pa	**91**	2.4	2.8	2.9	3.2	3.2	3.4	3.5	3.5	3.6	3.7	3.7	3.7	3.7	3.7	3.6	3.5	3.4	3.2	2.9	2.6	2.1	2.0	1.4	1.3	0.6	0.4	-0.5	-0.8	-1.9	-2.5	-4.8				
Th	**90**	1.9	2.1	2.2	2.6	2.6	2.7	2.8	2.9	2.9	3.0	3.0	3.0	3.0	2.9	2.8	2.7	2.5	2.3	1.8	1.8	1.2	1.2	0.5	0.3	-0.5	-0.8	-2.0	-2.6	-4.4	-5.7	####				
Ac	**89**	1.1	1.4	1.5	1.7	1.8	1.9	2.0	2.1	2.2	2.2	2.3	2.3	2.2	2.2	2.1	1.9	1.7	1.5	0.9	1.0	0.3	0.3	-0.6	-0.8	-1.9	-2.4	-5.0	####	####	####	####				
Ra	**88**	-0.1	0.2	0.4	0.6	0.8	1.0	1.1	1.2	1.3	1.3	1.3	1.3	1.3	1.2	1.0	0.8	0.4	0.0	-0.7	-0.9	-1.8	-2.1	-3.2	-3.7	-5.3	####	####	####	####	####	####				
		135	**136**	**137**	**138**	**139**	**140**	**141**	**142**	**143**	**144**	**145**	**146**	**147**	**148**	**149**	**150**	**151**	**152**	**153**	**154**	**155**	**156**	**157**	**158**	**159**	**160**	**161**	**162**	**163**	**164**	**165**	**N**			

NEXT BIG STEP AT ATLAS: MULTI-USER UPGRADE

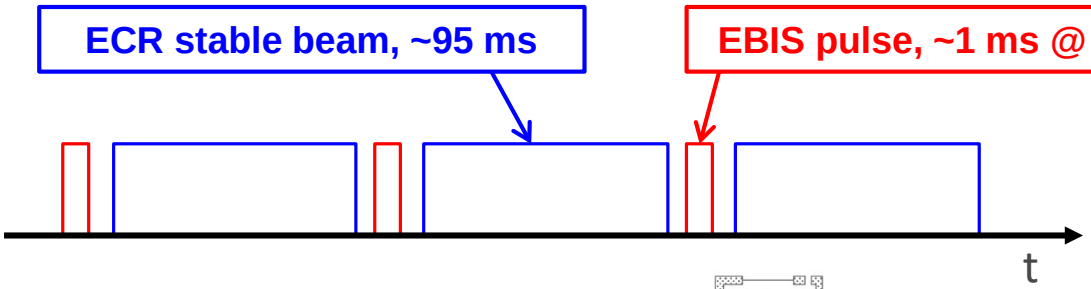
- EBIS beams represents 1-3% duty factor
- Combine pulsed EBIS beam with stable ECR beam
  - Address high demand on facility
  - Enable long duration experiments
  - Maximize efficient accelerator usage

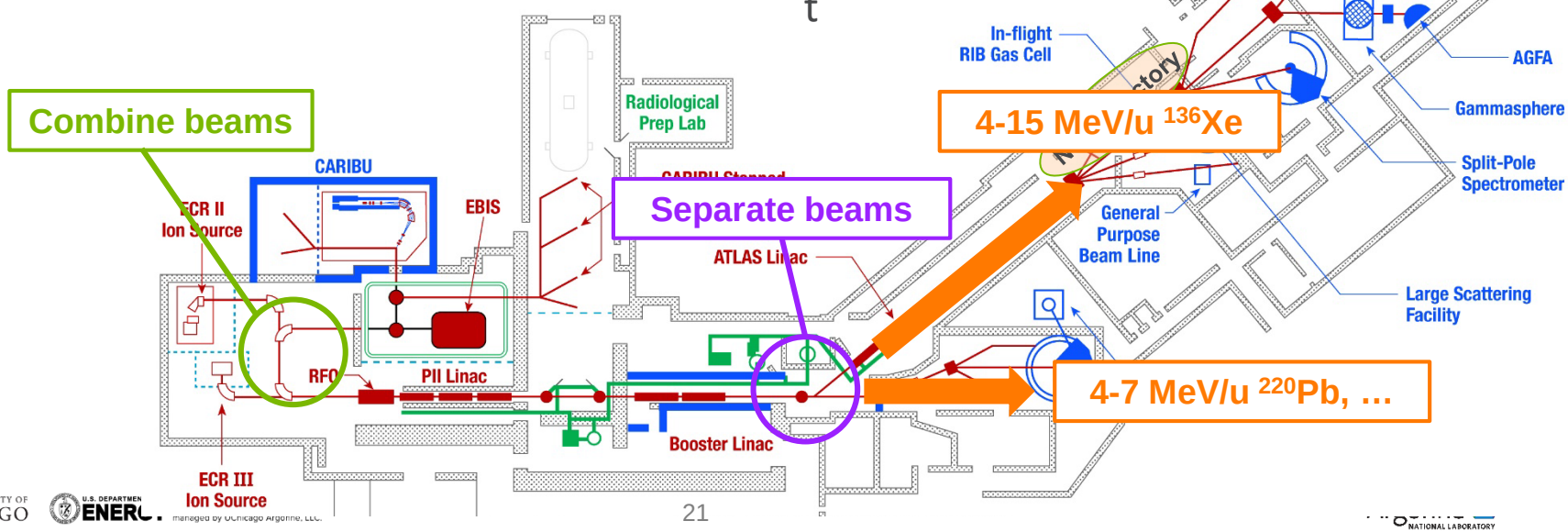




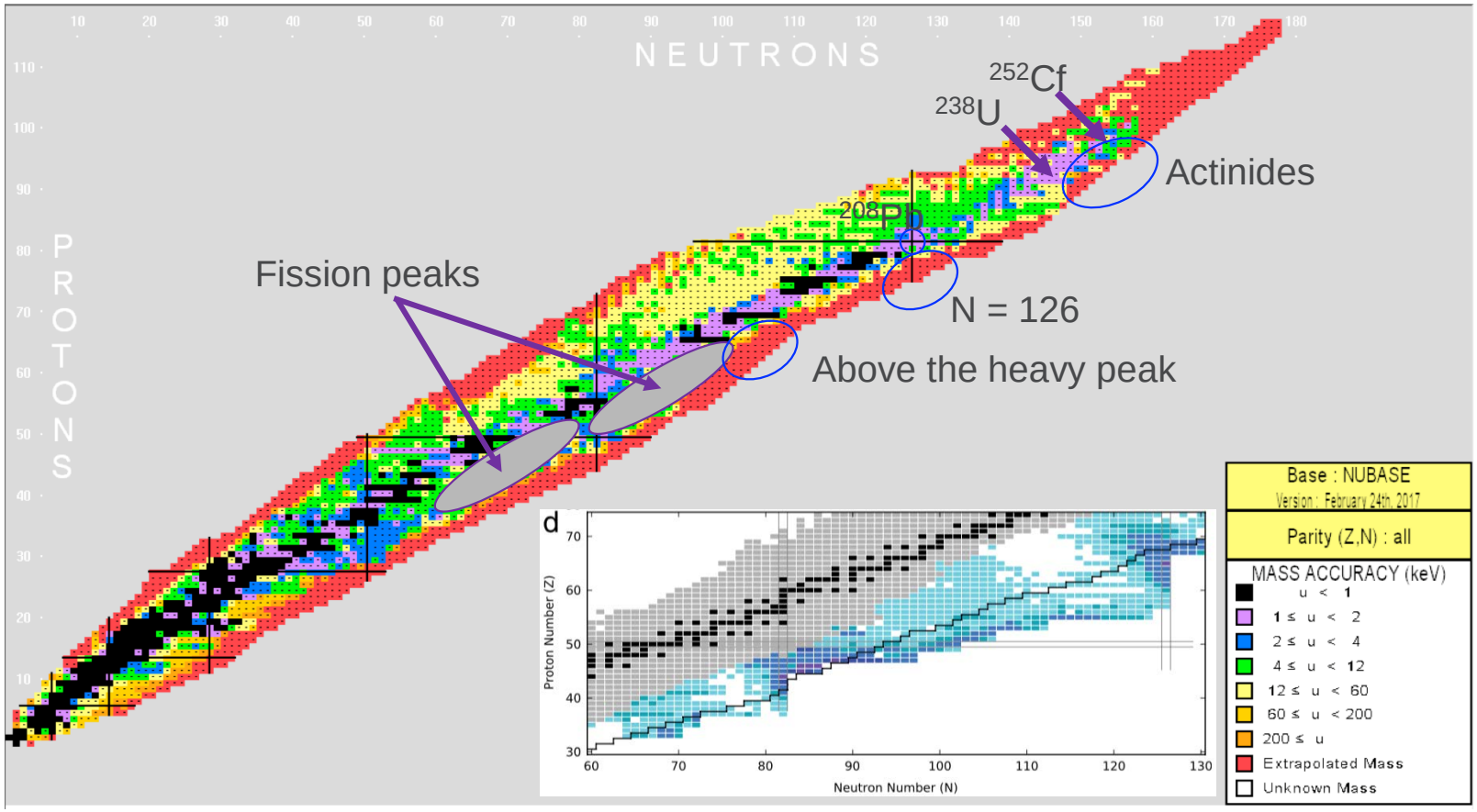
ATLAS MUU OPENS UP TOTALLY NEW POSSIBILITIES FOR R-PROCESS STUDIES

- Use stable beam 95% of duty cycle to produce N=126 isotopes
- Feed back N=126 isotopes into EBIS and reaccelerate in 1-3% of duty cycle
- Provides Coulomb energy beams of N=126 nuclei to address fissionability of nuclei in this region … critical to understand fission recycling in r-process





What region can it cover for the r-process?



+ longer term, insight into fissionability of heaviest neutron-rich nuclei

CONCLUSIONS / STATUS

- More nuclear physics inputs needed to better understand the astrophysical r-process
  - Large ongoing project at ATLAS/CARIBU on N=82 and rare-earth peak regions
  - Next step is the N=126 abundance peak

- Atomic masses are the most important nuclear data input for r-process abundance calculations … they can be measured with very low yield.

- The N = 126 beam factory aim to produce nuclei of importance for the r-process that are difficult of access: N = 126 shell, above fission peaks, and actinides.

- Beam factory gas catcher, isobar separator, cooler-buncher and MRTOF are under assembly.

- The N=126 factory can do a lot more than N=126 nuclei.

Collaboration

Argonne NATIONAL LABORATORY

M. Burkey, J.A. Clark, A.F. Levand, Y. Liang, G. Savard, B.J. Zabransky

THE UNIVERSITY OF Chicago

McGill

F. Buchinger, R. Orford

M. Brodeur, J.M Kelly, A. Valverde

UNIVERSITY OF MANITOBA

D. Ray, K.S. Sharma