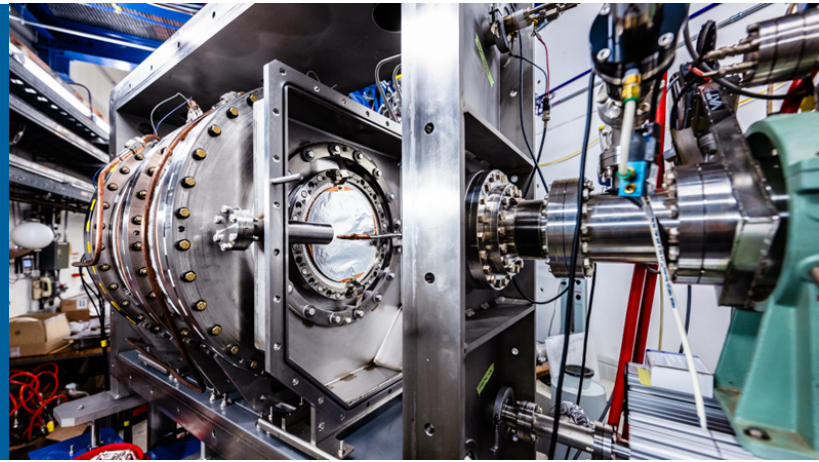
SSNET 2024 Conference

November 4-8, 2024

Orsay, France

Argonne NATIONAL LABORATORY

PROGRESS AT THE ATLAS FACILITY

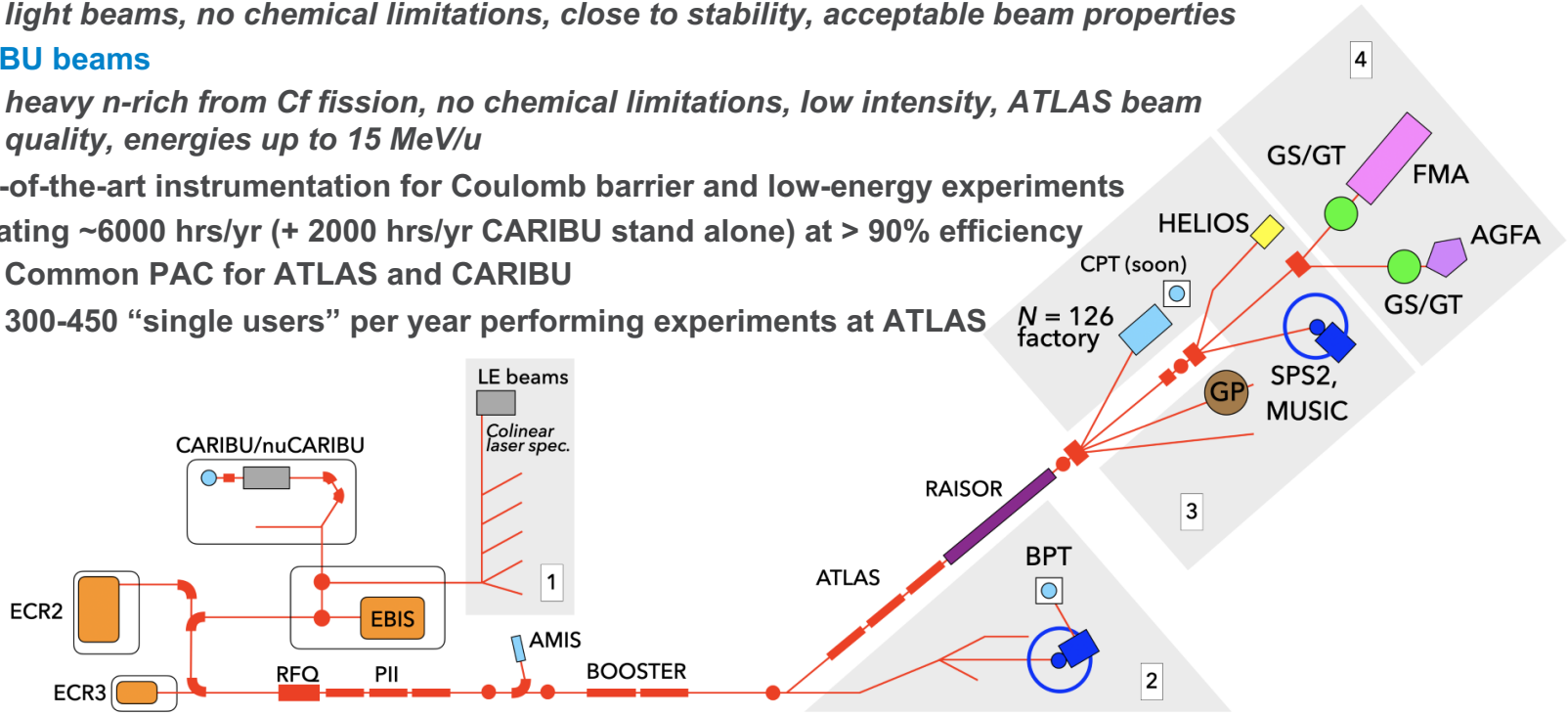


GUY SAVARD
Argonne National Laboratory
and University of Chicago

November 4, 2024

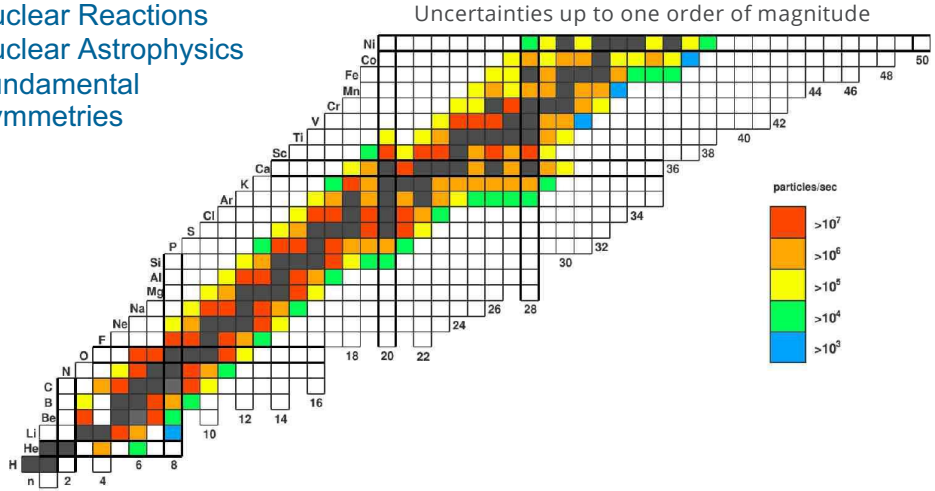
ATLAS/CARIBU FACILITY

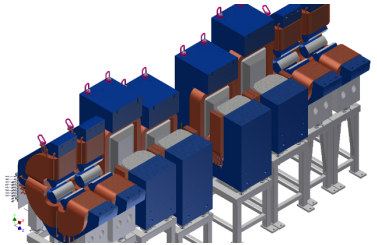
- **DOE nuclear physics national user facility**
- Stable beams at **high intensity** and energy up to 10-20 MeV/u
- Light in-flight radioactive beams with **RAISOR**
  - *light beams, no chemical limitations, close to stability, acceptable beam properties*
- **CARIBU beams**
  - *heavy n-rich from Cf 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 ~6000 hrs/yr (+ 2000 hrs/yr CARIBU stand alone) at > 90% efficiency
  - Common PAC for ATLAS and CARIBU
  - 300-450 “single users” per year performing experiments at ATLAS

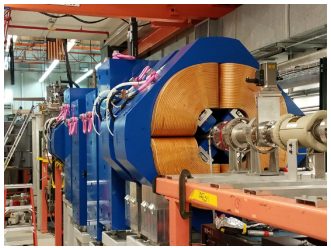


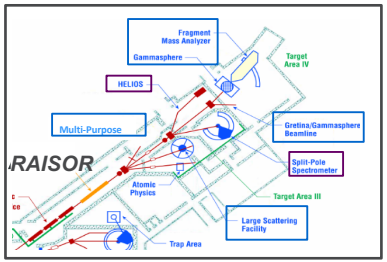
LIGHT IN-FLIGHT RADIOACTIVE BEAMS WITH RAISOR

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







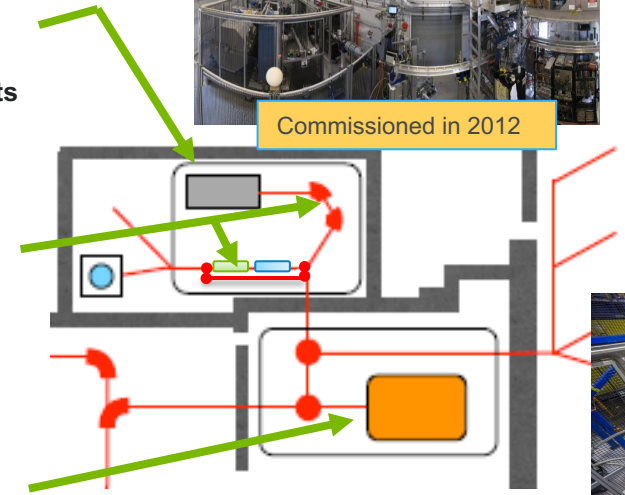


- Increased intensities, purities, & reach for ATLAS in-flight beams
- Momentum selection (magnetic chicane) followed by velocity selection (RF sweeper) → A/q selection
- Accessibility to more experimental areas

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
  - Low-energy buncher and beamlines
  - Charge breeder to Increase charge state for post-acceleration
  - Post-accelerator ATLAS and weak-beam diagnostics

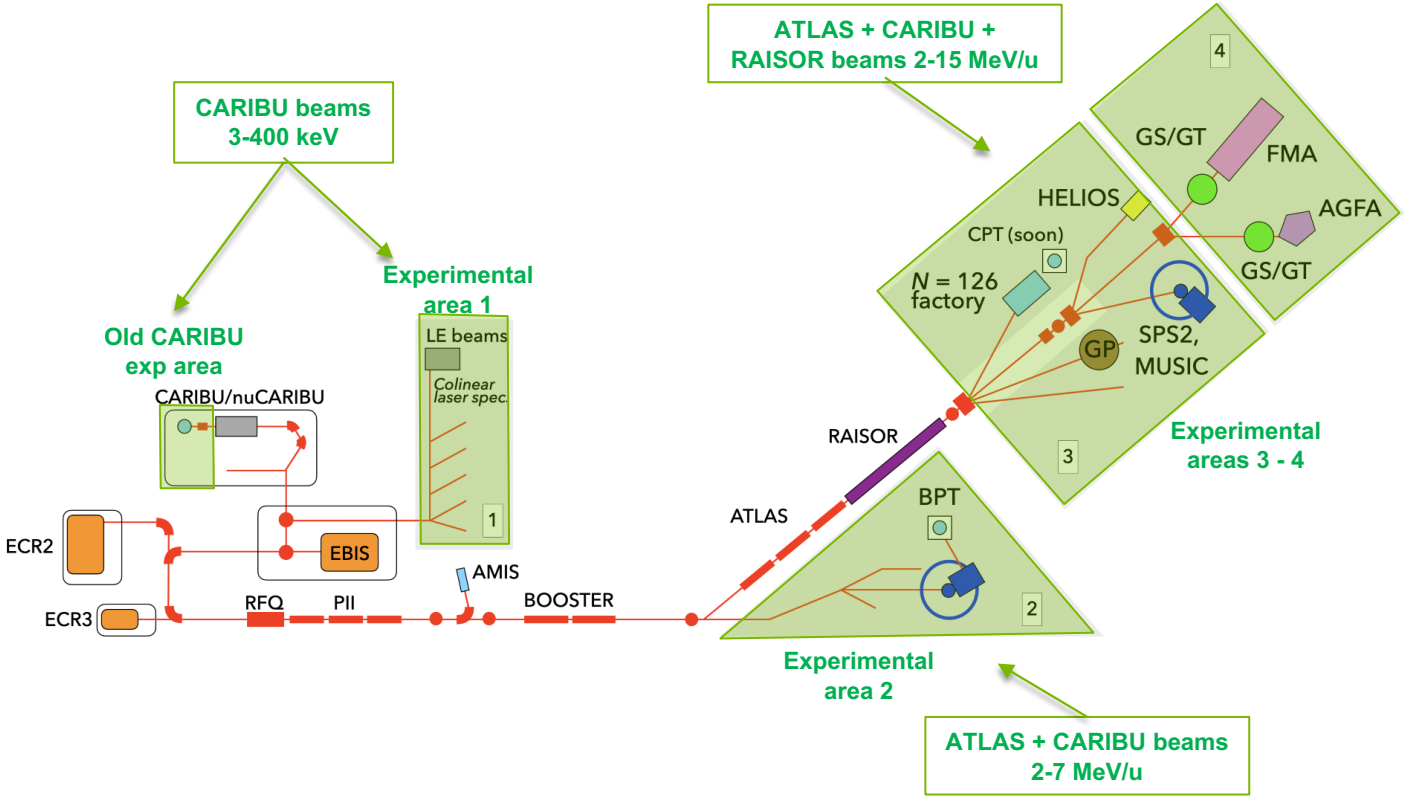


Commissioned in 2012

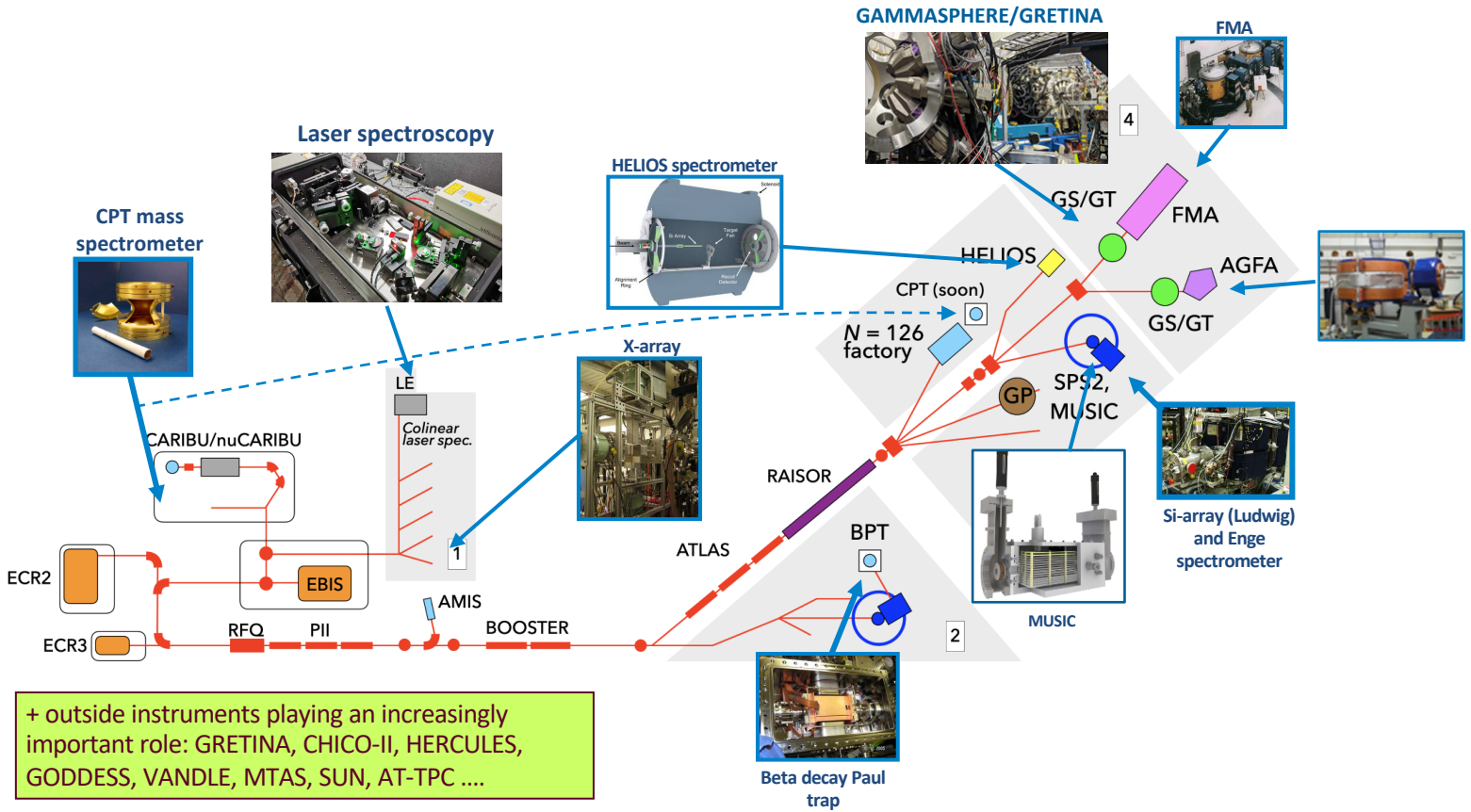
Commissioned in 2020

Commissioned in 2017

LAYOUT OF ATLAS FACILITY

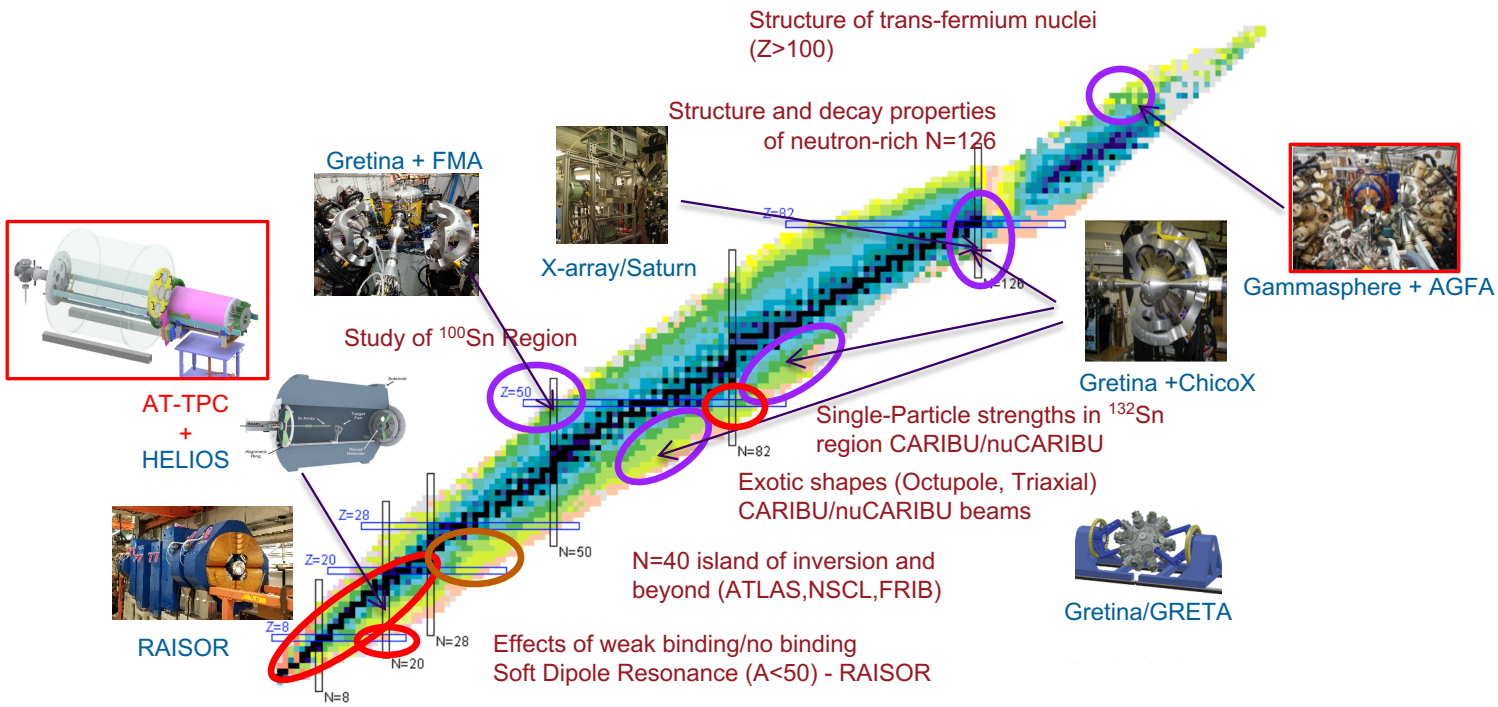


DISTRIBUTION OF EXPERIMENTAL EQUIPMENT

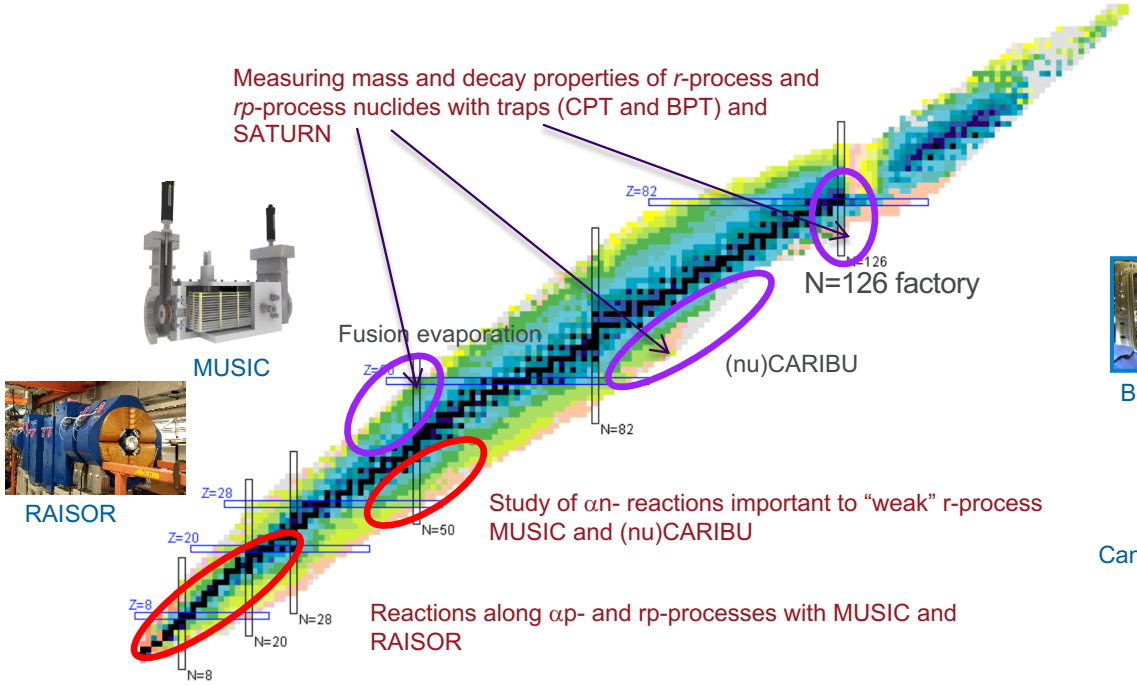


+ outside instruments playing an increasingly important role: GRETINA, CHICO-II, HERCULES, GODDESS, VANDLE, MTAS, SUN, AT-TPC ….

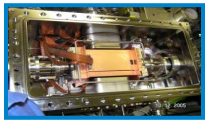
MAIN NUCLEAR STRUCTURE RESEARCH TOPICS AND TOOLS



MAIN NUCLEAR ASTROPHYSICS RESEARCH TOPICS AND TOOLS



X-Array/SATURN



Beta-Decay Paul Trap

Canadian Penning Trap

ATLAS FACILITY PERFORMANCE

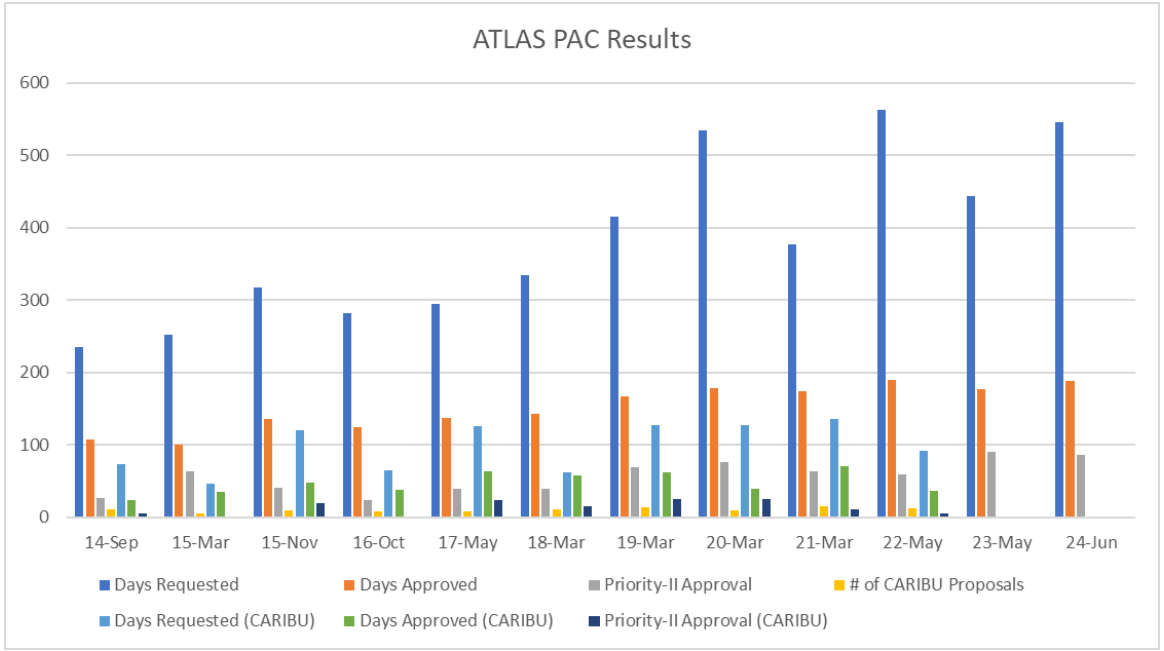
Operating Statistics

Machine Operation ATLAS	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025 (proj)
Research Hours (on Target)	4953	4318	4497	5377	3640	4071	4808	3887	4851	4750
Beam Study Hours	352	310	255	296	203	394	643	1145	217	350
Tuning/Restore	855	840	995	1100	685	1018	975	737	1086	750
Total Delivered Hours	**6160**	**5468**	**5747**	**6773**	**4528**	**5483**	**6426**	**5769**	**6154**	**5850**
Unscheduled failure hours	433	452	612	594	206	675	363	913	291	450
Total Scheduled Hours	6593	5920	6359	7367	4734	6158	6789	6682	6445	6300
Availability (%)	94.4	92.4	90.4	91.9	95.6	89.0	94.7	86.3	95.5	92.9
CARIBU										
Research Hours	2820	2260	652	1068	862	1328	2264	1971	1072	1400
Beam Study Hours	464	204	240	296	138	264	232	148	124	700
Total Delivered Hours	3284	2464	892	1332	1000	1592	2496	2119	1196	2100

ATLAS+CARIBU delivered	**9444**	**6932**	**6639**	**8105**	**5528**	**7075**	**8922**	**7888**	**7350**	**7950**	**hours**

- FY20: operating hours reduced due to COVID shutdown for 3 months followed by restart at 5 days/wk without outside users
- FY21: targeted 5350 hours for ATLAS due to budget reduction and to allow removal of 109 MHz cryostat
- FY22: targeted 5800 hours for ATLAS due to reduced budget and to allow reinstallation of 109 MHz cryostat
- FY23: targeted 5950 hours for ATLAS but reduced hours delivered due to power failure event in summer 2023
- FY24 – FY28 : plan for ~6000 delivered hours for ATLAS in FY24 and returning to > 6000 hours/year starting in FY25, assuming adequate budget

BEAM TIME REQUEST CONTINUES GROWING

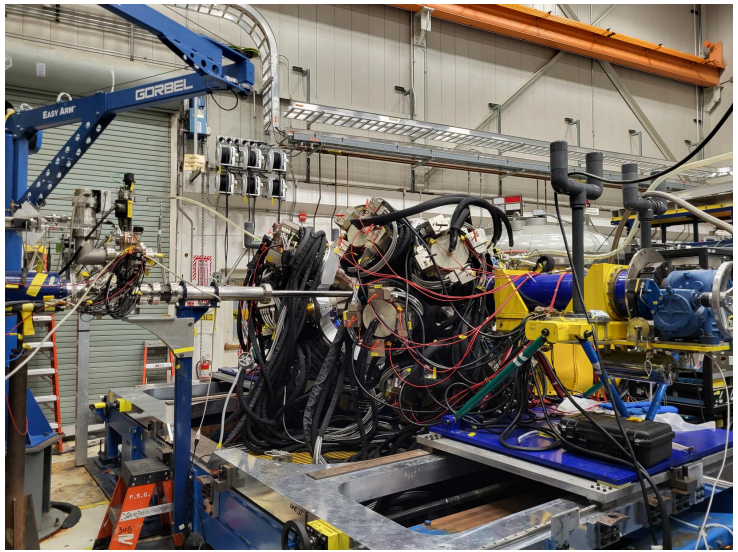


PAC Statistics:

- Trends persist, i.e., high number of proposals & oversubscription by a factor of ~3
- Continue to operate with priority I & II modes to optimize efficiency of program
- Keep enough backlog to allow additional needed flexibility in scheduling
- For this last PAC meeting, record number of proposals and 546 days requested

GRETINA CAMPAIGN

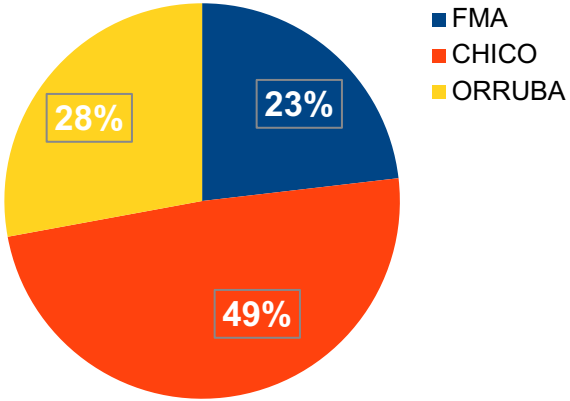
Equipment was delivered in May/June from FRIB…

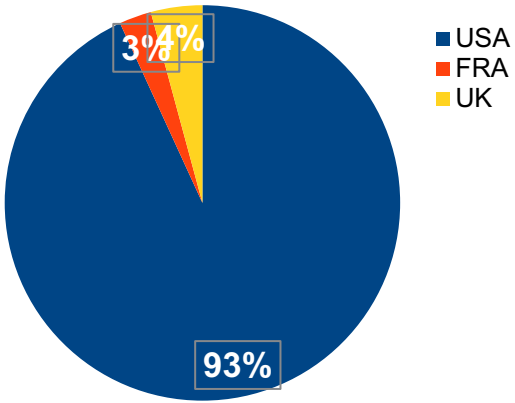


... and installation completed in a month and a half, commissioning experiment took place at the end of July

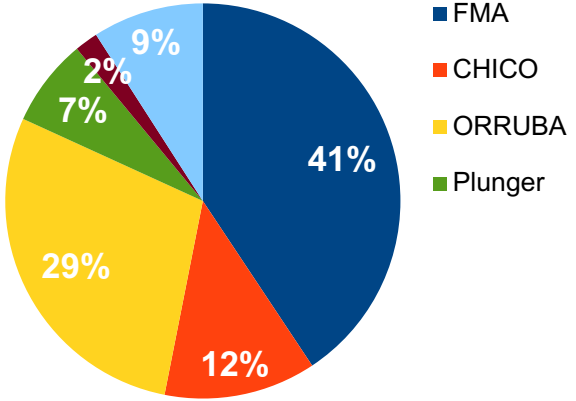
GRETINA CAMPAIGNS IN NUMBERS

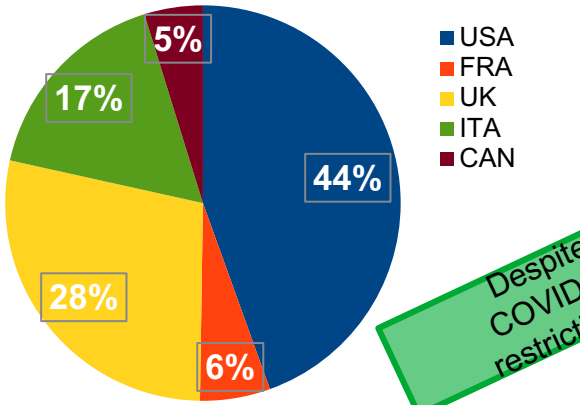
2018/2019 Campaign: 190 days/1.5 year





2021/2022 Campaign: 209 days/1.5 year

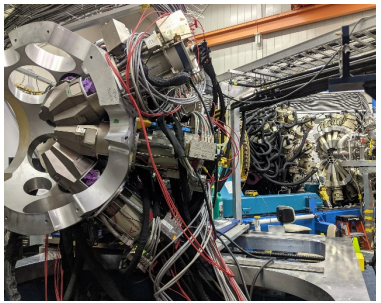




Despite COVID19 restrictions!

*numbers based on main-PI affiliation

CURRENT GRETINA CAMPAIGN IN NUMBERS



(last) GRETINA campaign at ATLAS

- Installation of the array in June-July
- Experimental campaign started in early August!

74 requests submitted during the last PAC:

over the 32 projects devoted to γ-ray spectroscopy,

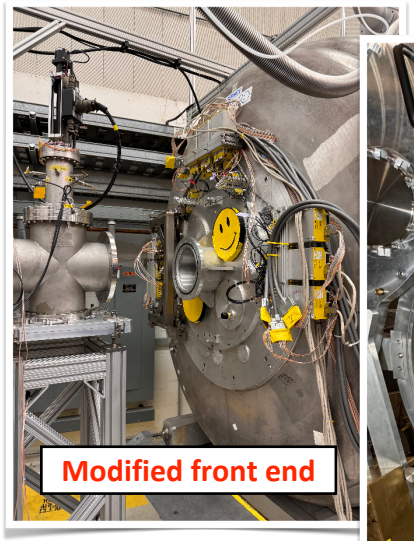
18 proposals required GRETINA for a total of **103 days**.

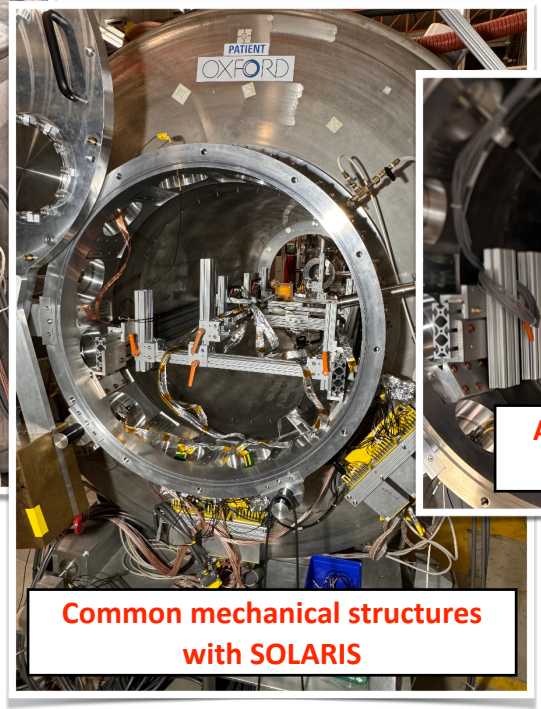
11 proposals approved for a total of **81 days**
+ **additional 91 days** from previous PACs
= more than **170 days/year** (70% stable ion beams)

ATLAS tries to provide as much access as possible to GRETINA for the community while the device is at Argonne… and hopes to do the same for GRETA in the future

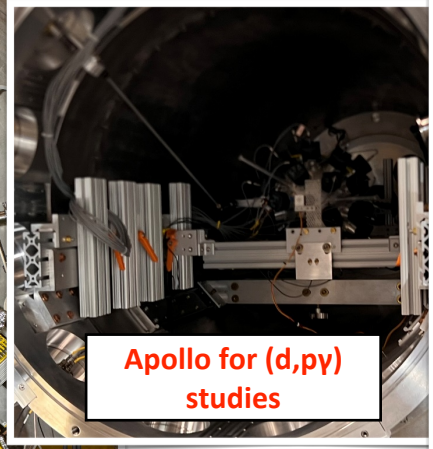
HELIOS progress

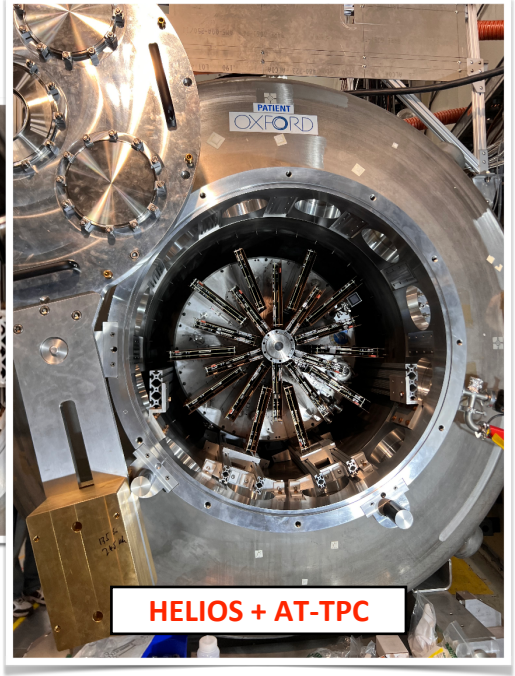
Focus since ~2021: HELIOS has been iteratively upgraded to enable new capabilities as SOLARIS came into being … take advantage of the unique capabilities of both facilities and common equipment/instrumentation


Modified front end



Common mechanical structures with SOLARIS


Apollo for (d,pγ) studies

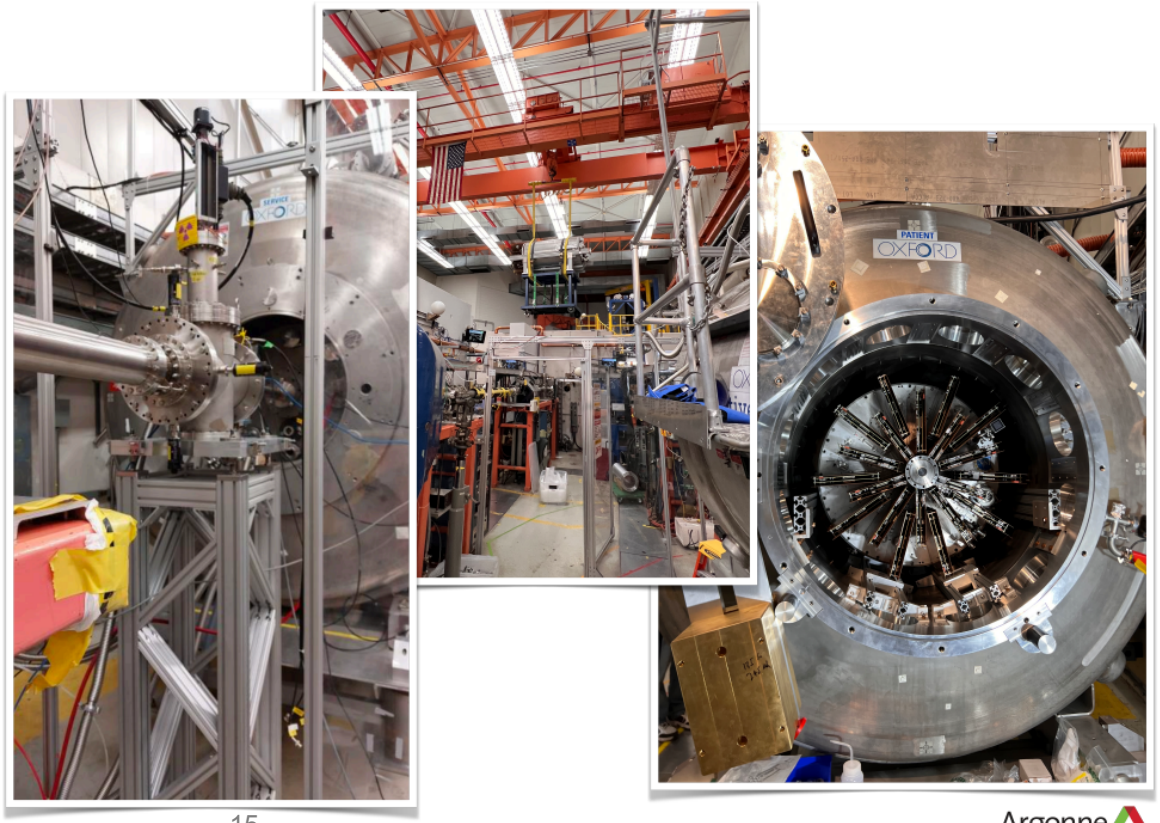


HELIOS + AT-TPC

The first AT-TPC campaign, 2023 (a second will occur later in 2025)

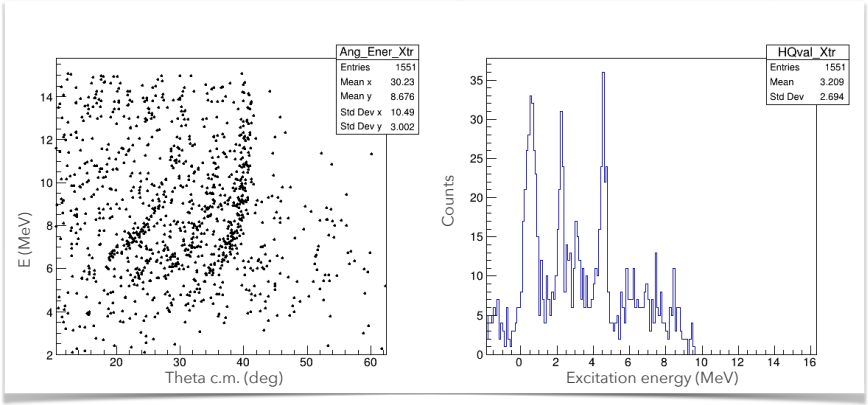
At Argonne from March through November 2023, seven experiments

12Be + p	RAISOR
15C + p,d	RAISOR
14C + p,a	ECR3
16C + p,d	RAISOR
16C + a	RAISOR
136Xe + p	"nuCARIBU" (ECR2, EBIS)
7Be + d	RAISOR

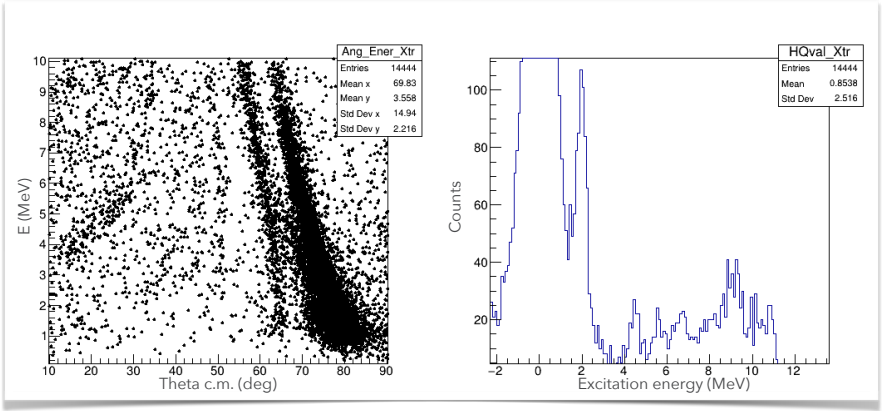


World-unique capabilities

Short-lived in-flight (ground states and isomers) beams are one of the exceptional powers of RAISOR. Vast arrays of physics opportunities with both silicon mode and hugely extended reach with the AT-TPC … for example, ^{12}Be (12.5 ms g.s., 230 ns isomer) at ~100 pps(!)



^{12}Be(p,d)^{11}Be at 10 MeV/u

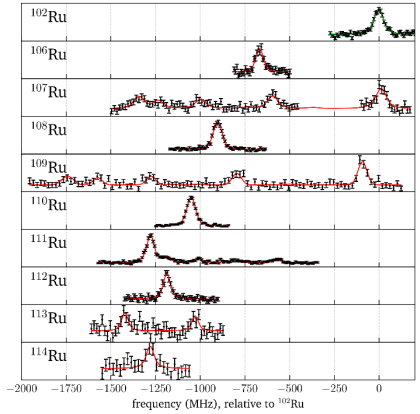


^{12}Be(p,p')^{12}Be* at 10 MeV/u

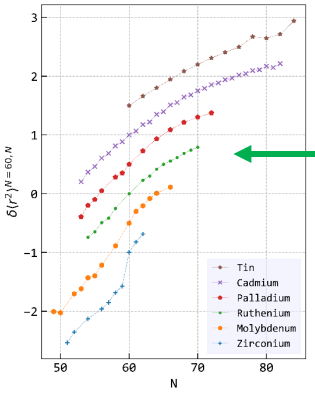
In 2025, AT-TPC will have a ^{3}He gas insert, PAC approved experiments for (^{3}He,d) studies

ATLANTIS: COLLINEAR LASER SPECTROSCOPY

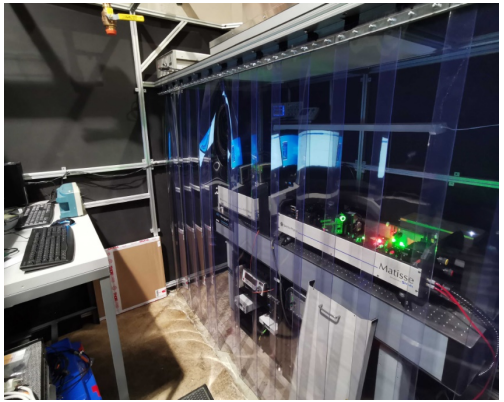
- Probed over 33 isotopes of 4 different elements during first two campaigns
- Many radioactive isotopes had never been investigated with laser spectroscopy before
- “Complete” data sets for Ru, complementary Pd data, and first hints of Rh and Tc
- Plans for neutron-rich La, Zr, Nd, Ce, Tc (approved)
- “Copy” of this setup at the N=126 Factory will allow access to neutron-rich heavy elements (ex: Pt)



Nuclear Charge Radii:



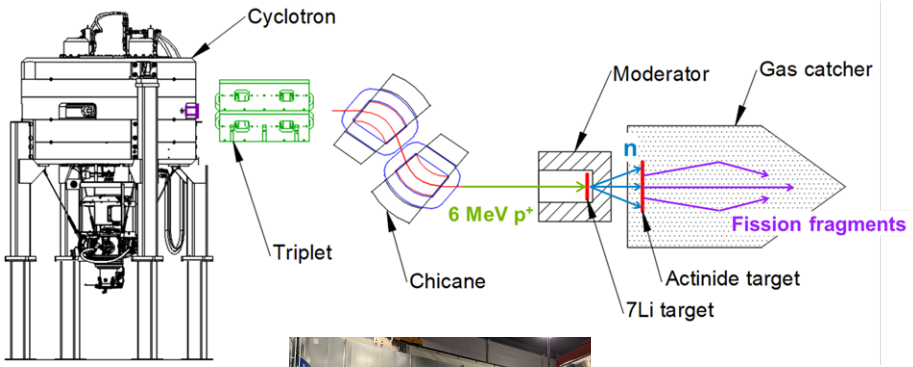
First laser spectroscopy investigation of neutron-rich ruthenium

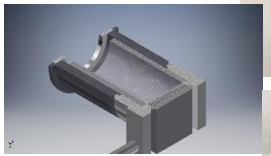


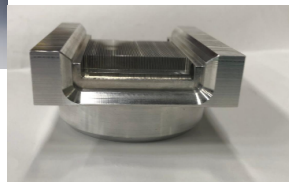
$$\delta\nu_i^{A,A'} = \nu_i^{A'} - \nu_i^{A} = F_i\,\delta\langle r^2\rangle^{A,A'} + M_i\,\frac{m'_A - m_A}{m'_A m_A}$$

nuCARIBU (fission-fragment beams)

- Move from spontaneous fission of ^{252}Cf to neutron-induced fission of actinides (starting with ^{235}U)
  - Higher yield
  - Easier to maintain and operate
- Serving all areas of ATLAS
  - seven low-energy beam lines in area 1
  - ~6 MeV/u beams in area 2
  - up to 12 MeV/u beams in areas 3 & 4
- Major programs in Coulomb excitation (GS and GRETINA and in the future Clarion), and with the AT-TPC and HELIOS, direct reaction studies and resonant elastic scattering
- Cyclotron commissioning completed, triplet and chicane installed, ^{7}Li neutron generator tested online at ATLAS, working on SAD/ASE approval with goal of extracted radioactive beam by end of year





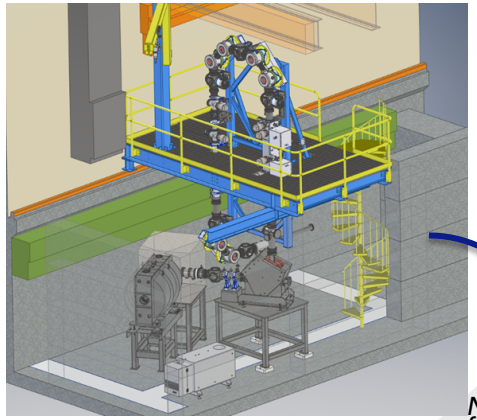


N = 126 Factory (multi-nucleon transfer beams)

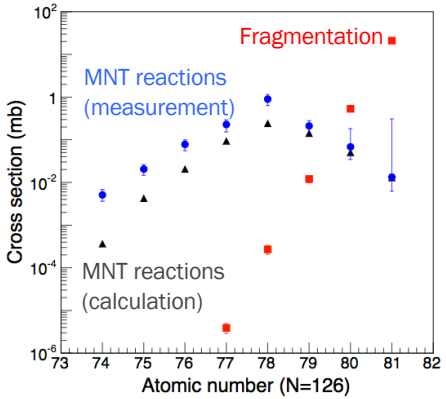
Adapt universality of CARIBU concept to a different reaction mechanism

Novel powerful yet very compact RIB facility

- *production (MNT reactions)*
- *Cooling (gas catcher)*
- *Pre separation (magnetic)*
- *Bunching (RFQ buncher)*
- *Final separation (MRTOF)*
- *Beam delivery*



NEW CAPABILITY ENABLED BY GAS CATCHERS: N=126 FACTORY … MULTI-NUCLEON TRANSFER TO PRODUCE NEUTRON-RICH HEAVY ISOTOPES

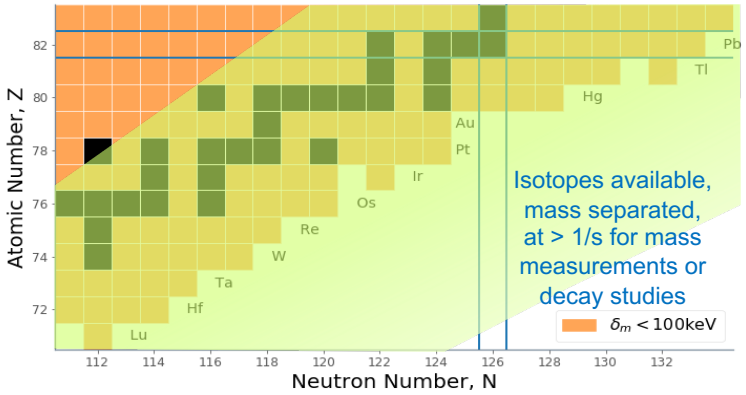


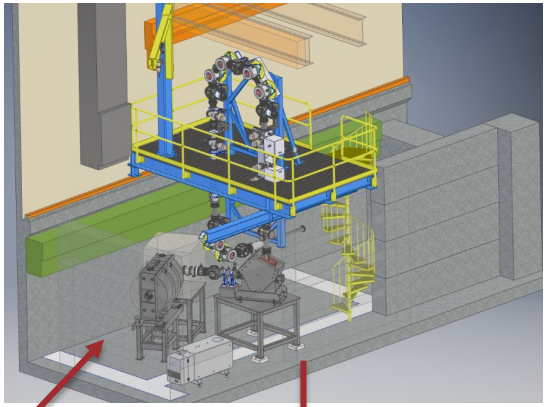
Hirayama *et al.*, EPJ Web Conferences **109,** 08001 (2016)

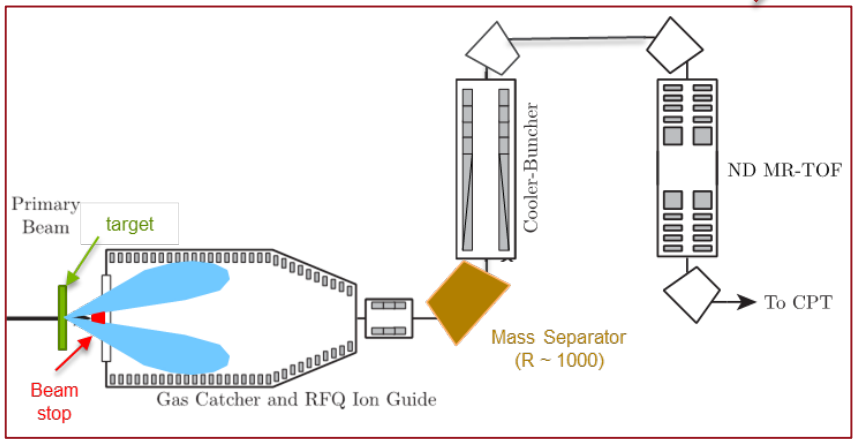
^{208}Pb + ^{9}Be at 1 GeV/u (best fragmentation reaction cross-sections for N = 126)

versus

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

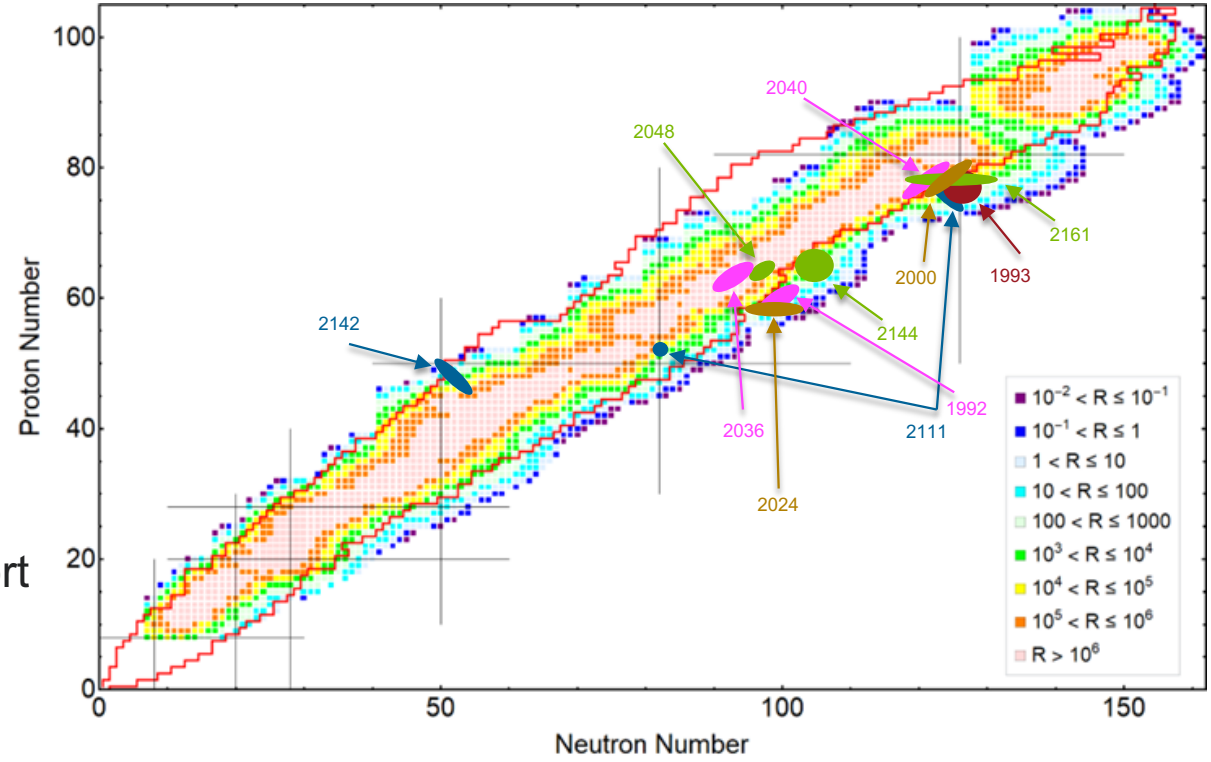






The ‘Everything’ Factory

- Initially targeting the N=126 region below Pb, this technique promises extraordinary reach via specific choices of beams and targets
- Early focus of approved experiments on mass measurements, decay spectroscopy, and laser spectroscopy
- Future ambitions to transport to area 1 and potentially consider re-acceleration

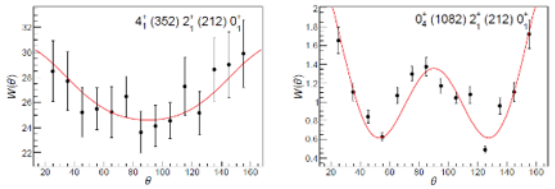


BETA DECAY FACTORY IN AREA 1

Gammasphere Decay Station

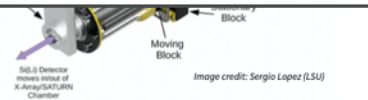
- β–γ coincidences for proper feeding intensities
- γ–γ, γ–γ–γ for level structure determination and spin assignments from angular correlations
- Red
  crys
  Arra
- Calc
  exci
  bas
- Gar
  prov
  contact @ 4, 8 and 20 MeV full range

γ ray angular correlations following ^{100}Y beta decay with Gammasphere

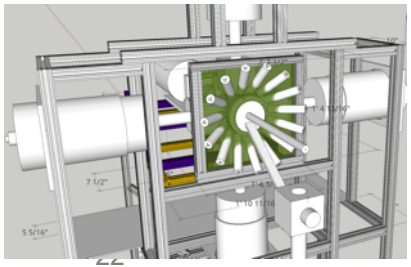


Saturn/X-Array Upgrades

- $LaBr_3$ to measure lifetimes – 2 rings, 15 1”x1” crystals each ring.
- Conversion electron measurements utilizing Laces



1 LaBr3 Ring @ X-Array

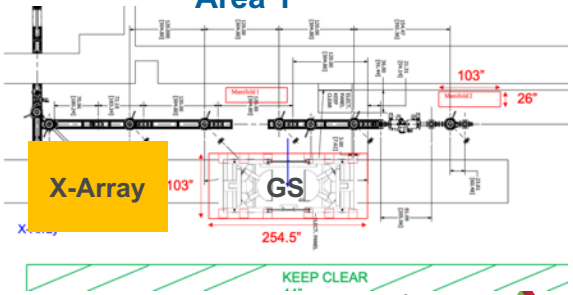


Beta Decay Factory

- Gammasphere upgrade project allows for relocation of device to Area 1.
- Using nuCARIBU, we estimate 2 orders of magnitude increase in implanted ions.

50-50 parent decays

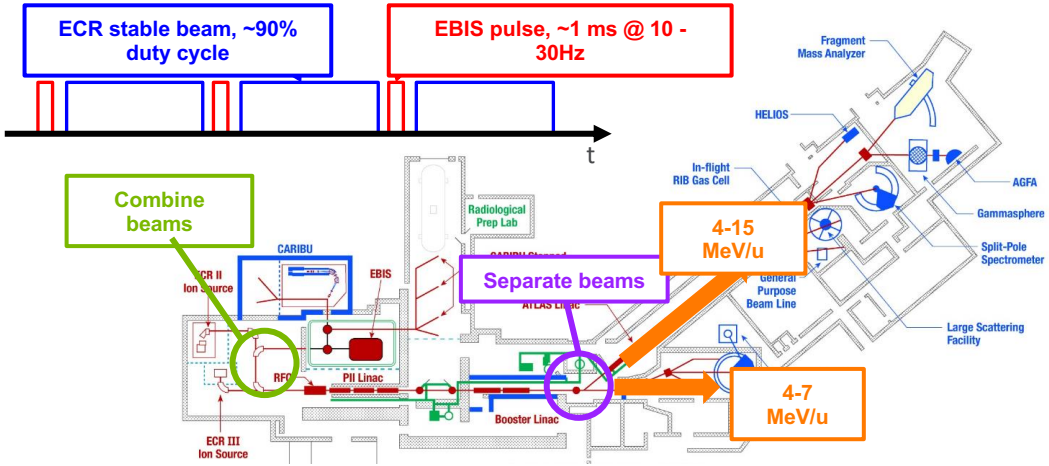
Area 1



Decay Workshop to be held at Argonne **in early 2025** to gauge interest in moving Gammasphere to Area 1 for use in decay studies using isotopes extracted from *nu*CARIBU – details to follow.

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



Great flexibility (2 different beams at different energies) to increase beam hour delivered by ~3000 hours per year

OUTLOOK

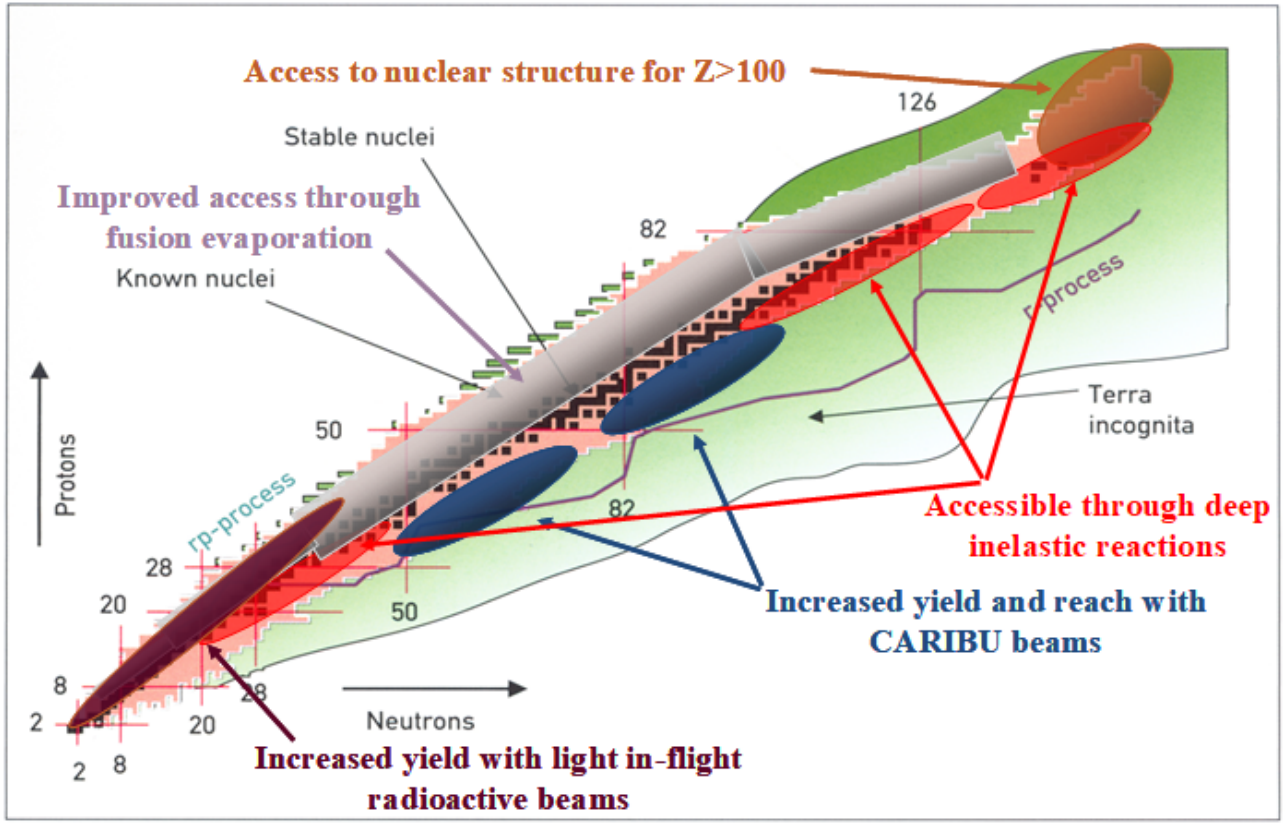
- ATLAS is the DOE nuclear physics stable beam national user facility
  - Running reliably and logging in a large number of operating hours
  - Accomplishing its current science goals
  - Demand for beamtime remains high and is increasing

- ATLAS has followed the coherent plan developed with the community to add accelerator and experimental capabilities that build on each other to provide new capabilities that better address the community's evolving science goals

The new equipment and capabilities are seeing a lot of use and producing the science they were designed for

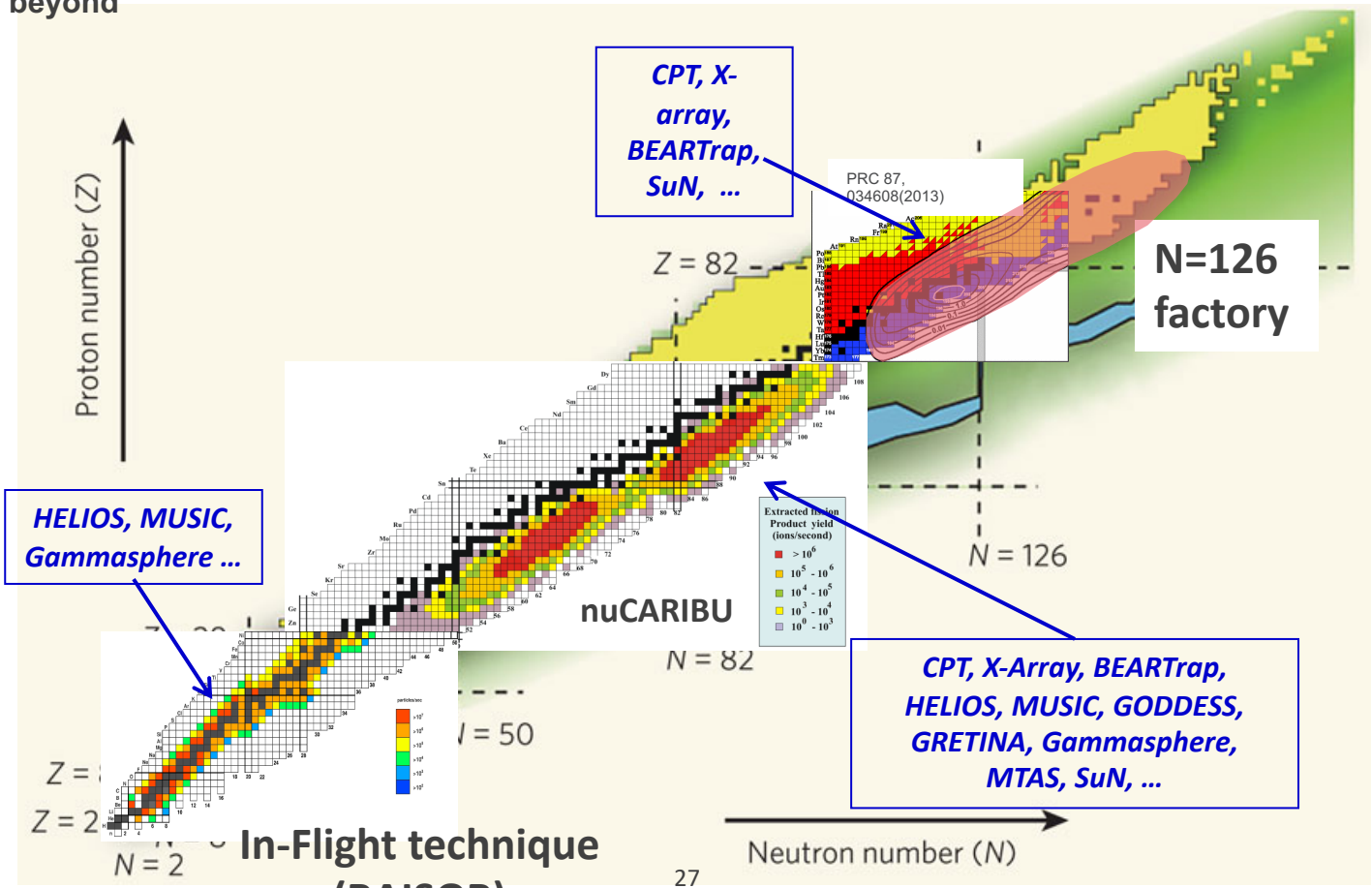
- ATLAS is working to put in place the remaining elements of this plan while continuing to provide operating hours and world leading capabilities to its users. This plan includes the completion of nuCARIBU, the N=126 factory and the AMUU, all within the next two years, uniquely positioning ATLAS to serve the nuclear physics community in the coming decade.

PHYSICS REACH OF ATLAS

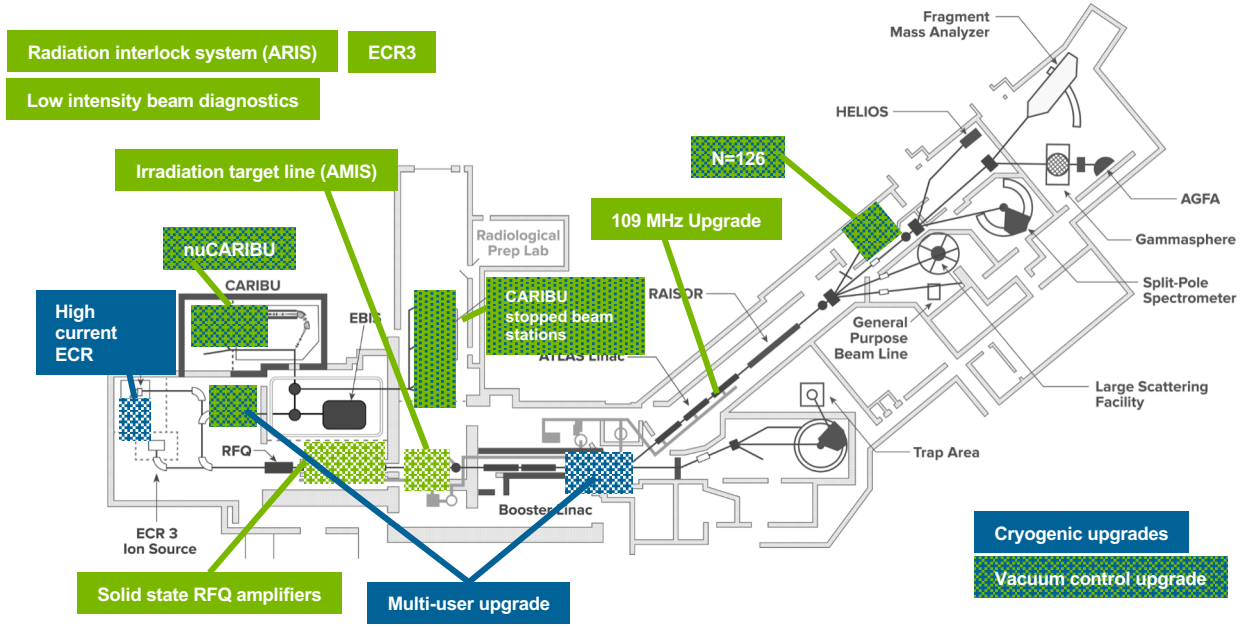


World- leading program in Nuclear astrophysics

Accessing new regions for r-process and rp-process measurements …. 10 years and beyond



ATLAS UPGRADES IN PAST FEW YEARS

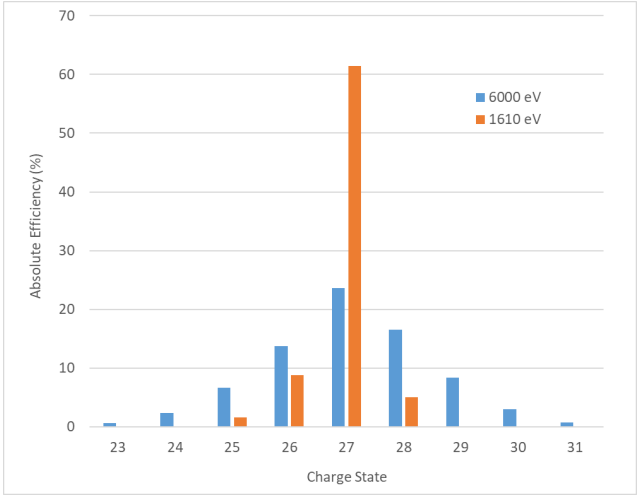


EBIS CHARGE BREEDER UPDATE

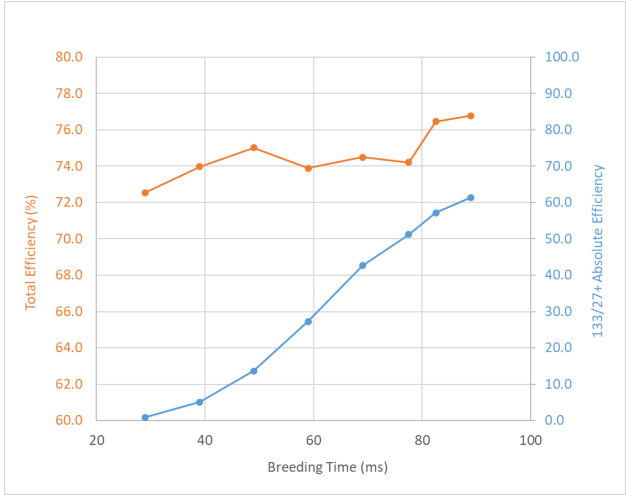
	Shell	Ionization Energy
+26	[Ar]3d104s	916.1 eV
+27	[Ar]3d10	1592

Closed shell breeding

EBIS Operating Parameters	
Solenoid field	5.5 T
Magnetic field on cathode	0.15 T
Cathode diameter	4.2 mm
Drift tube diameter	20 mm
Electron energy	1610 eV
Electron current	0.17 A
Effective electron current density in trap	280 A/cm^2
Trap length	0.5 m
Charge capacity	2.2x10^{10}
Injection time	50 μs
Repetition rate	10 Hz
Duty cycle	90 %
EBIS bias	20 kV
Pressure	1x10^{-10} torr



Absolute efficiencies for 6000 eV electron beam energy and 1610 eV electron beam energy.

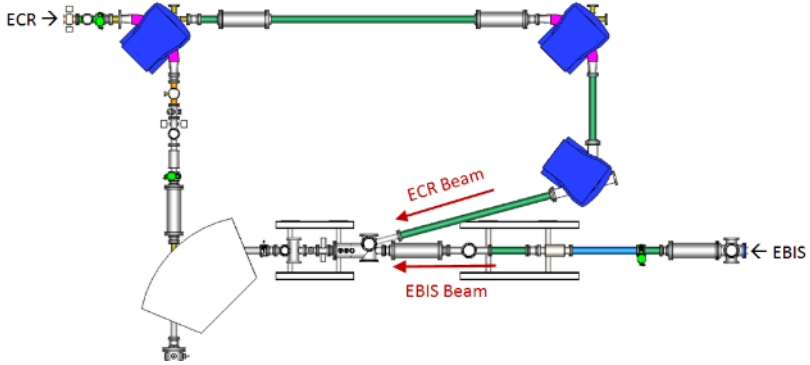


133/27+ absolute efficiency and EBIS total efficiency for 1610 eV electron beam energy.

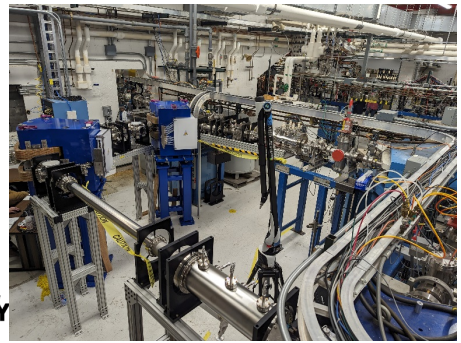
- ANL EBIS design incorporated closed-shell breeding technical requirements
- 10 Hz rep rate and high duty cycle allows long breeding times
- New electron gun from 3M (collaborative effort between ANL, BNL, and MSU) has performed well

MAIN COMPONENTS FOR MULTI-USER UPGRADE

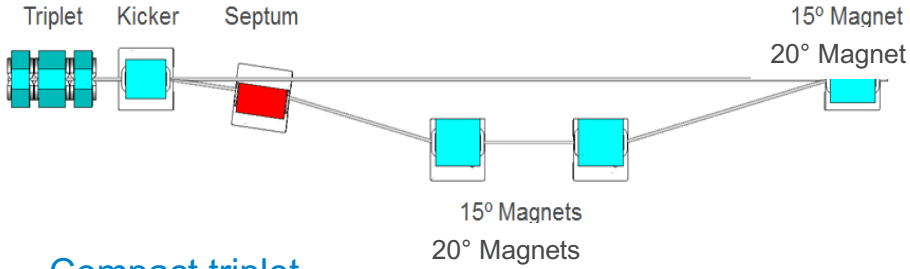
LEBT Injection



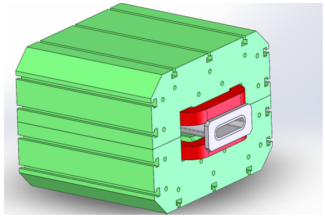
- Pulsed electric deflector
- Two electrostatic sextupoles
- Two 80 deg dipoles



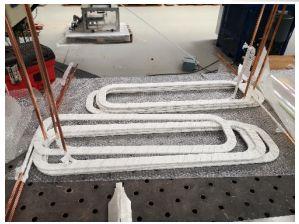
Booster Switchyard



- Compact triplet
- Pulsed kicker-magnet - 10°
- Septum-magnet - 10°

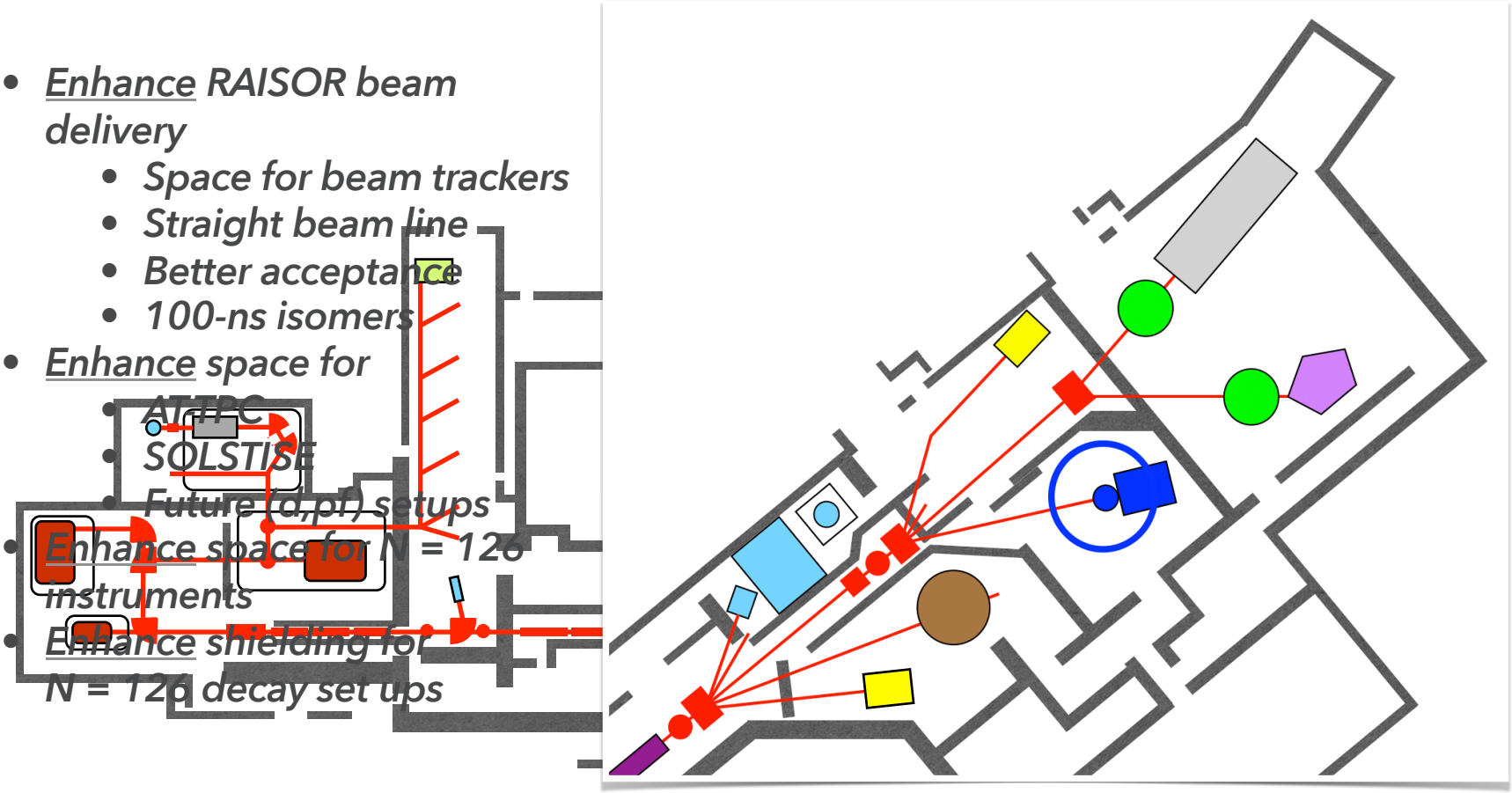


The technically challenging part



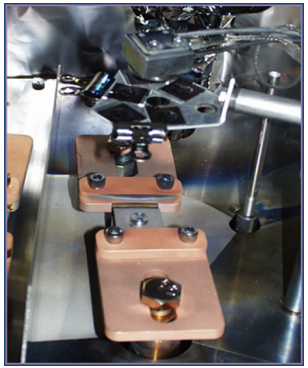
Next phase of HELIOS's evolution *(all about beams)*

- *Enhance RAISOR beam delivery*
  - *Space for beam trackers*
  - *Straight beam line*
  - *Better acceptance*
  - *100-ns isomers*
- *Enhance space for*
  - *ATTPC*
  - *SOLSTISE*
  - *Future (d,p!) setups*
- *Enhance space for N = 126 instruments*
- *Enhance shielding for N = 126 decay set ups*



CATS (Center for Accelerator Target science)

Goals:
- Production of targets for the community
- Training for individual investigators and students
- R&D for new techniques/targets
- Library of existing targets

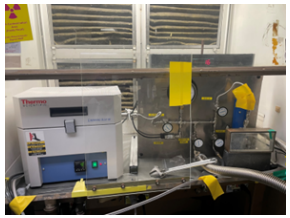


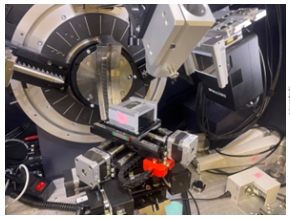
Recent production: 2021: 570 targets (34% external)
2022: 372 targets (24% external)
2023: 703 targets (43% external)
First half of 2024: 598 targets (54% external *(FSU, LSU, ND, TAMU, LLNL, BNL, ORNL, LBNL, JYFL, INFN, FRIB, JLAB, CFC))*

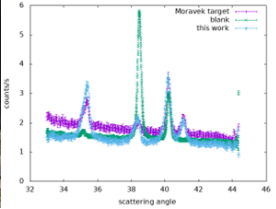
Bi-annual Nuclear Target Development Summer School (NTDSS) (most recently held in July 2024, 20 students)

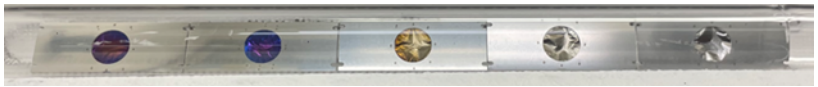
Recent R&D: Tritiated titanium for (t,p) reactions

- Tests with deuterated titanium and analysis via x-ray diffraction have been successful.
- Targets containing tritium have been produced and tested with HELIOS.

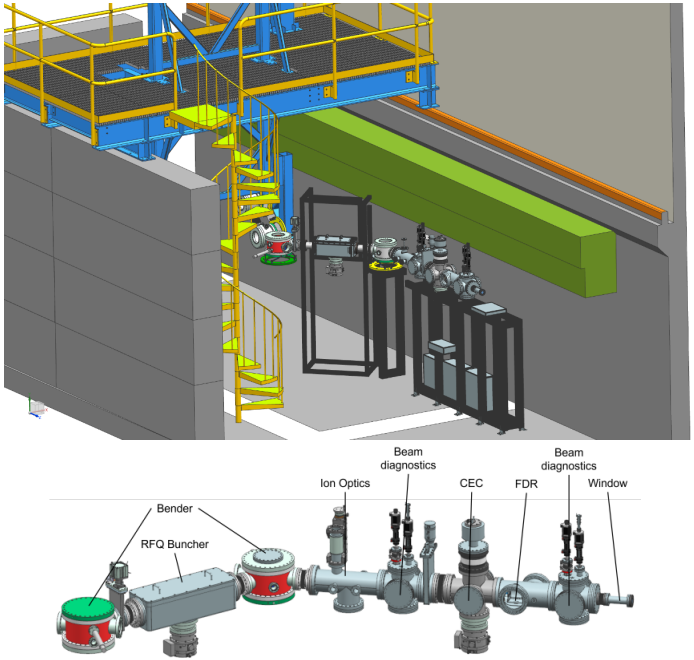




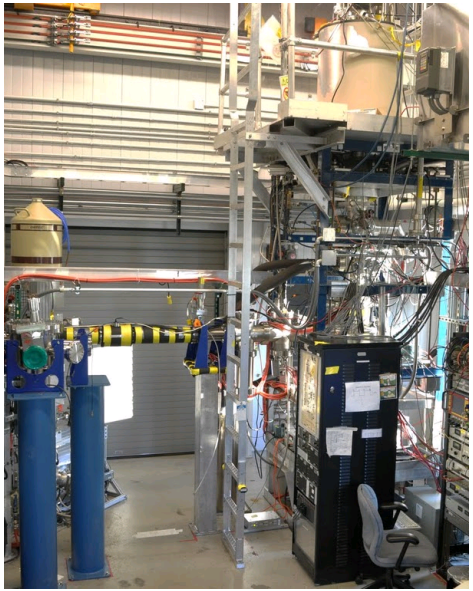




EXPERIMENTAL EQUIPMENT FOR N=126



Laser spectroscopy

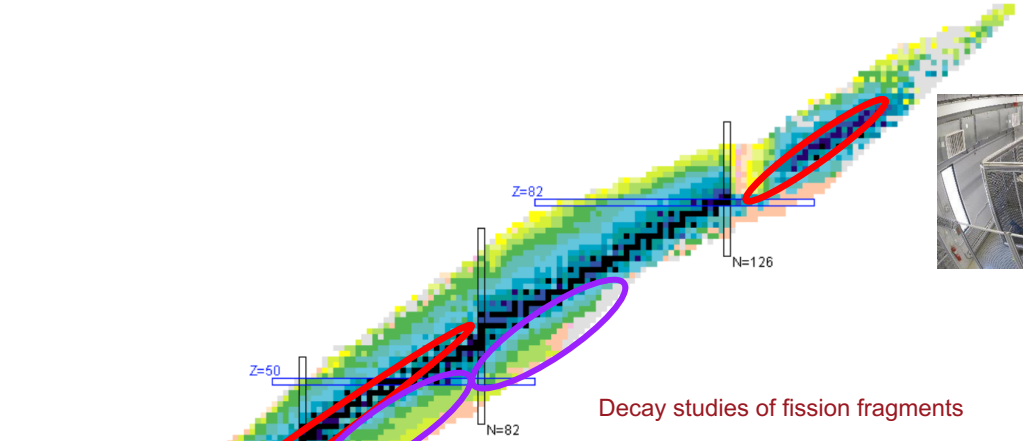


CPT mass spectrometer

X-array

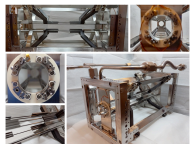
+ SuN, LACES, ….

NUCLEAR PHYSICS APPLICATIONS AND FUNDAMENTAL SYMMETRY RESEARCH TOPICS AND TOOLS



Irradiation damage studies of materials

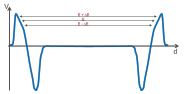
Beta-neutrino correlation



BPT Mk IV

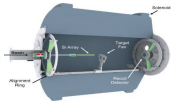
Fission fragment distribution

(nu)CARIBU



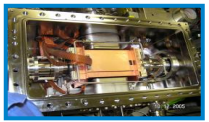
MR-TOF

HELIOS

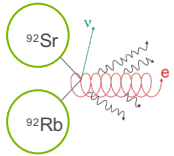


Decay studies of fission fragments

Gammasphere + X-array



Beta-Decay Paul Trap



CRES spectrometer