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nuCARIBU: UPGRADE OF THE CARIBU FACILITY AT ARGONNE

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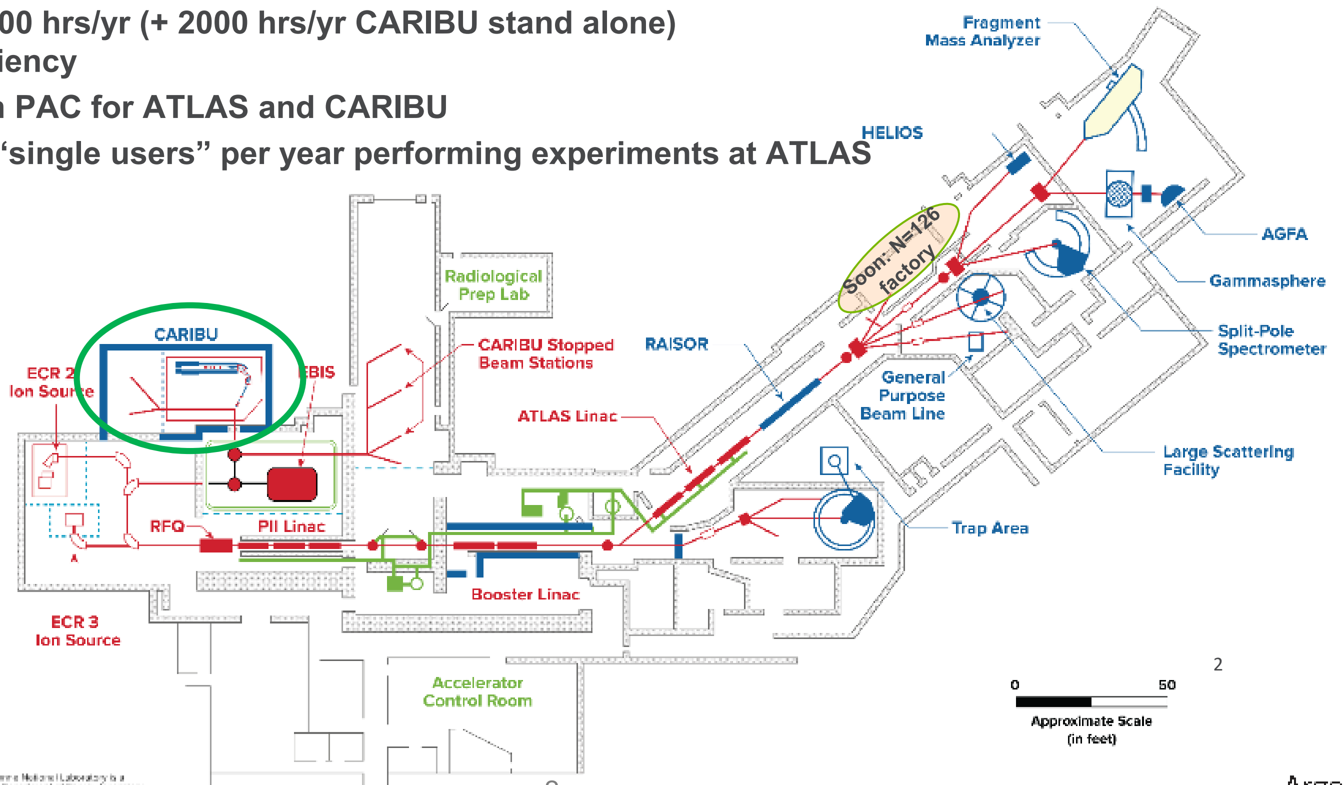
U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY

ATLAS/CARIBU FACILITY

- ATLAS is the DOE nuclear physics stable beam 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
  - 200-400 "single users" per year performing experiments at ATLAS



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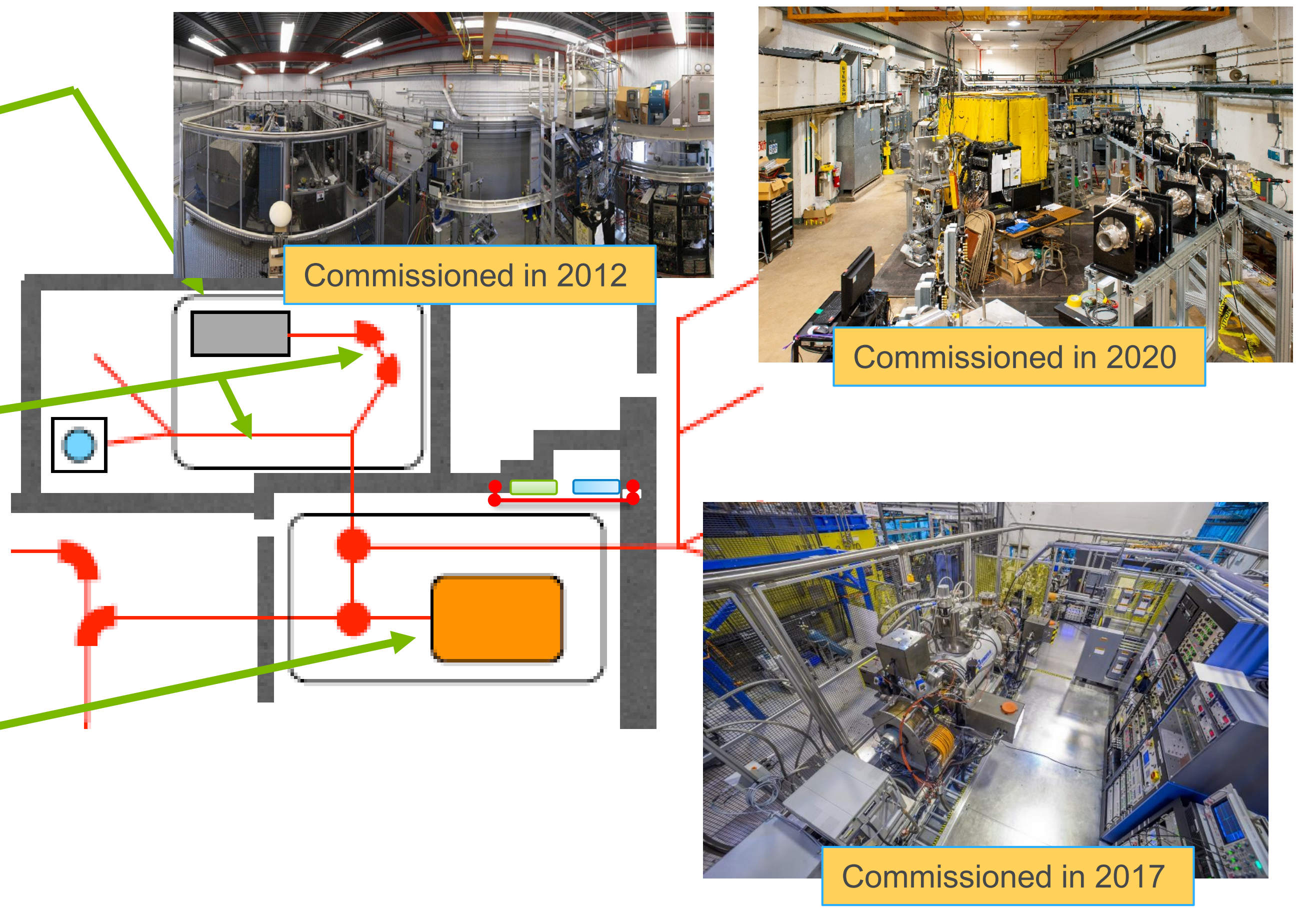
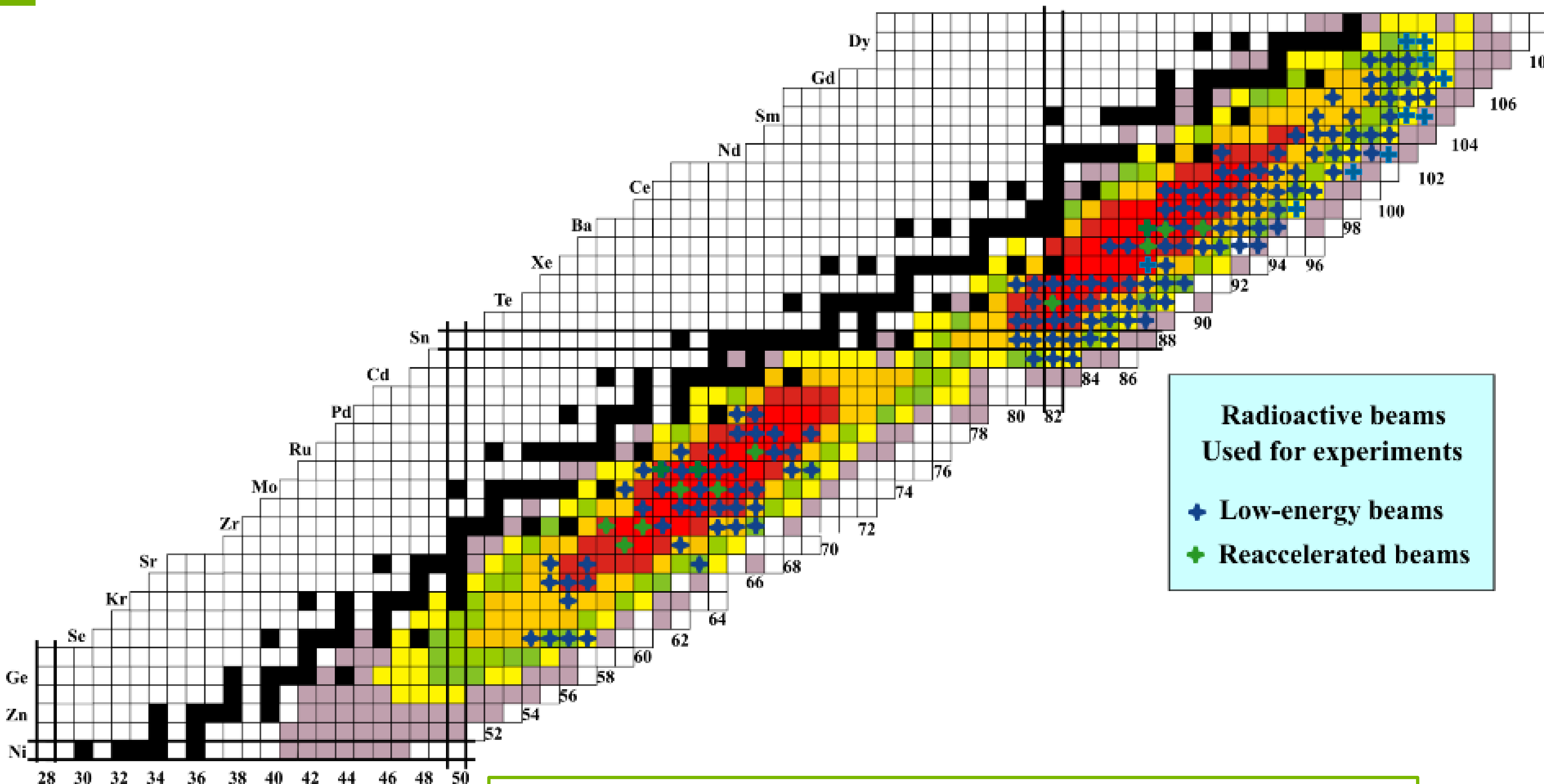
NEUTRON-RICH BEAM SOURCE FOR ATLAS: CARIBU “FRONT END” LAYOUT

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



CARIBU BEAMS DELIVERED TO EXPERIMENTS SO FAR

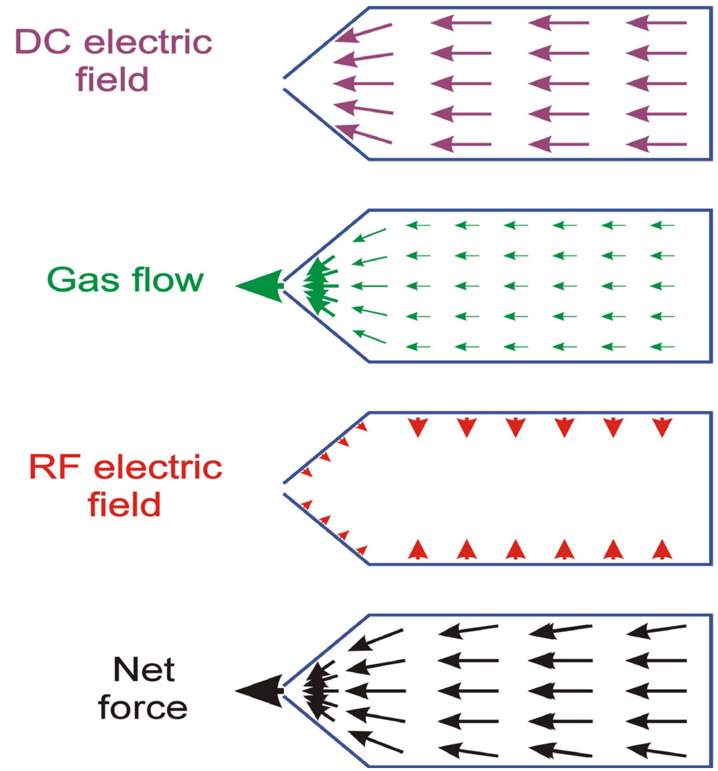


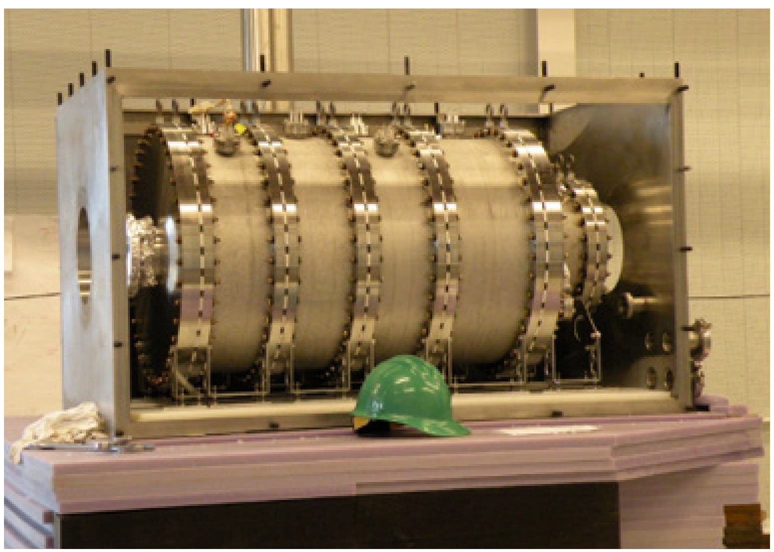
All of these beams now available in the new low-background low-energy area (Area 1)

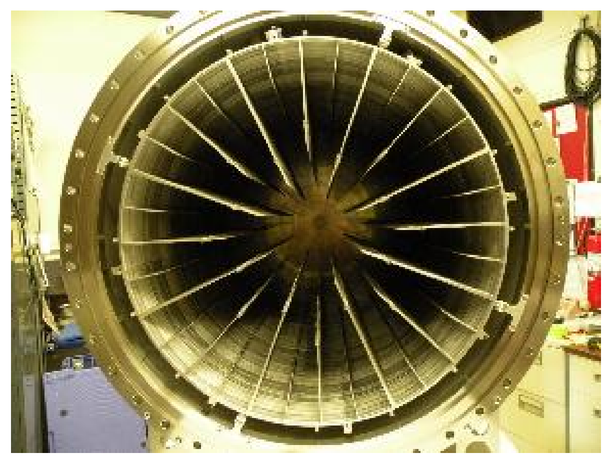
GAS CATCHER 101

A combination of forces working together is required to obtain

- Fast extraction times over the full volume
- High efficiency over the full volume
- Tolerance to high intensity





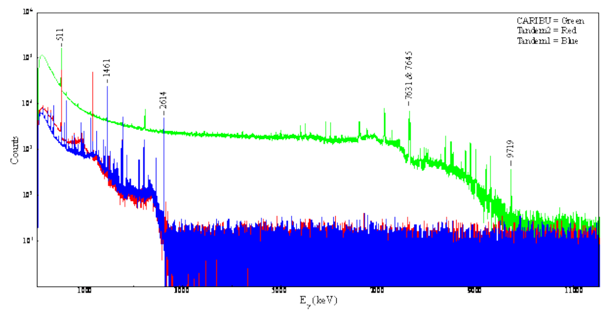


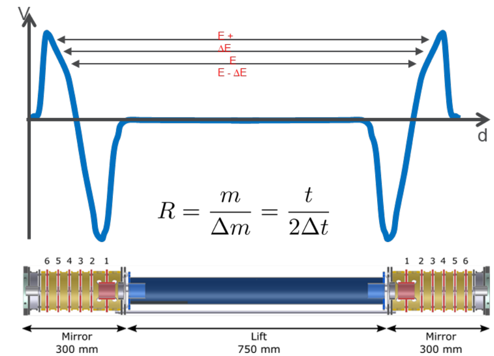
CARIBU IS A CENTRAL COMPONENT OF THE ATLAS AND WORLDWIDE LOW-ENERGY NUCLEAR PHYSICS RESEARCH PORTFOLIO

Capabilities further enhanced by recent upgrades

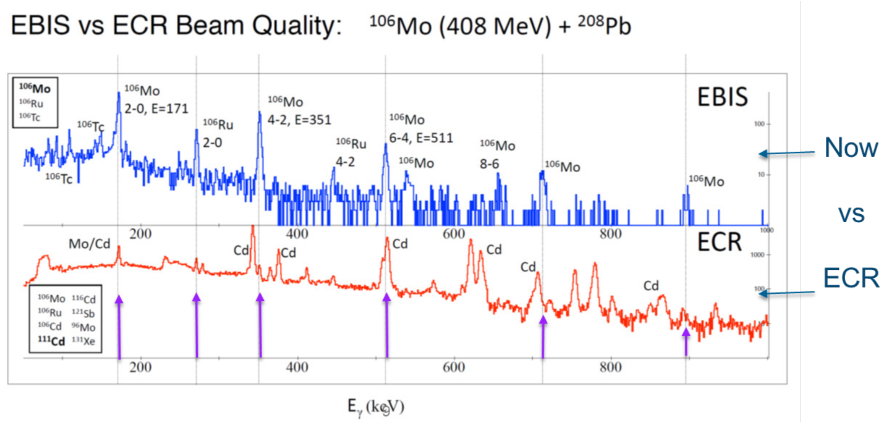
- Unique neutron-rich beams not available anywhere else

- Large low-energy experimental area, low background, pure beams





- Clean reaccelerated neutron-rich beams



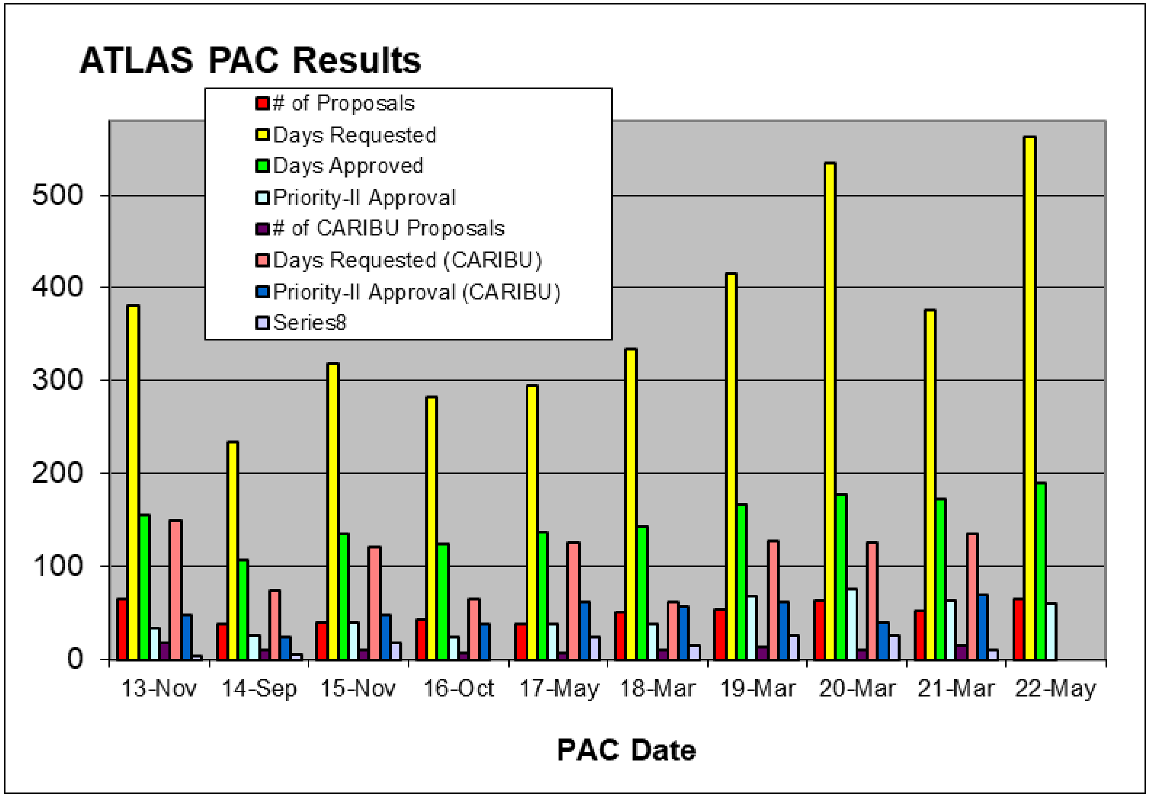
ATLAS FACILITY PERFORMANCE

Operating Statistics

Machine Operation ATLAS	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022 (proj.)
Research Hours (on Target)	4953	4318	4497	5377	3640	4071	4750
Beam Study Hours	352	310	255	296	203	394	350
Tuning/Restore	855	840	995	1100	685	1018	700
Total Delivered Hours	**6160**	**5468**	**5747**	**6773**	**4528**	**5483**	**5800**
Unscheduled failure hours	433	452	612	594	206	675	450
Total Scheduled Hours	6593	5920	6359	7367	4734	6158	6250
Availability (%)	94.4	92.4	90.4	91.9	95.6	89.0	92.8
CARIBU							
Research Hours	2820	2260	652	1068	862	1328	1700
Beam Study Hours	464	204	240	296	138	264	300
Total Delivered Hours	3284	2464	892	1332	1000	1592	2000

- FY20: operating hours reduced due to COVID-19 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: target 5800 hours for ATLAS due to reduced budget and to allow reinstallation of 109 MHz cryostat
- FY23 – FY28 : plan for 5920 delivered hours in FY23 assuming president's request and returning to > 6000 hours/year starting in FY24

PAC STATISTICS



<u>PAC Statistics</u>:

- 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

CARIBU KEY BEAMLINE ELEMENTS

Capabilities and limitations

Low-energy beamline
Transmission: ~100%

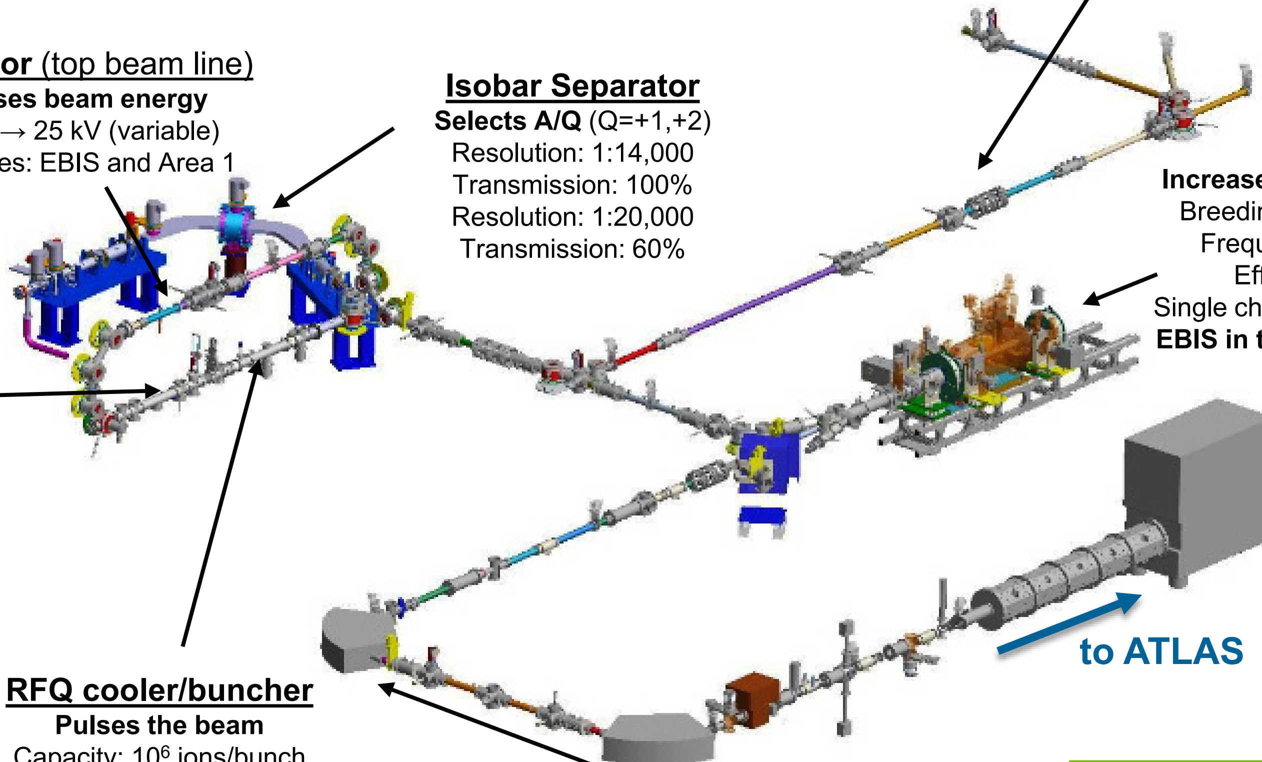
Elevator (top beam line)
Raises beam energy
2 kV → 25 kV (variable)
Services: EBIS and Area 1

Isobar Separator
Selects A/Q (Q=+1,+2)
Resolution: 1:14,000
Transmission: 100%
Resolution: 1:20,000
Transmission: 60%

EBIS
Increases charge state
Breeding time: 20 ms
Frequency: 10 Hz
Efficiencies:
Single charge state ~20%
EBIS in to Target 5-15%

^{252}Cf source and gas catcher not shown

MR-TOF
Improves beam purity
Capacity: 10^4 ions/bunch
Resolution: 1:100,000
Transmission: **<50%**
(depends on # of cycles)
Hold-up time: 10-15 ms (variable)
Can be bypassed
(100% transmission, no hold-up)



RFQ cooler/buncher
Pulses the beam
Capacity: 10^6 ions/bunch
Ejection period: 50-100 ms (variable)
Pulse width: ~100 ns
Transmission: >70% for +2, ~50% for +1

Dipole Magnets
Resolution: 1:400
Transmission: 100%

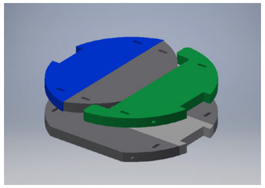
HIGH VOLTAGE PLATFORMS ARE NOT SHOWN IN THIS VIEW

Image credit: Rick Vondrasek

All components, except maybe for the RFQ buncher, are performing at state-of-the-art level

CARIBU SOURCE: PRESENT AND FUTURE

- Present situation:
  - Source needs to be changed roughly every 3 years and it has proven very challenging to obtain a good thin ^{252}Cf source
    - The 1.7 Ci source, installed in May 2014, needed to be replaced in 2017
    - R&D at ORNL and a 3-plate source configuration with a larger area developed at ANL to try to resolve the thickness issue
    - actual ^{252}Cf deposition however yielded irreproducible results
      - First (side)plate was promising → 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
    - installed at ANL in May 2018



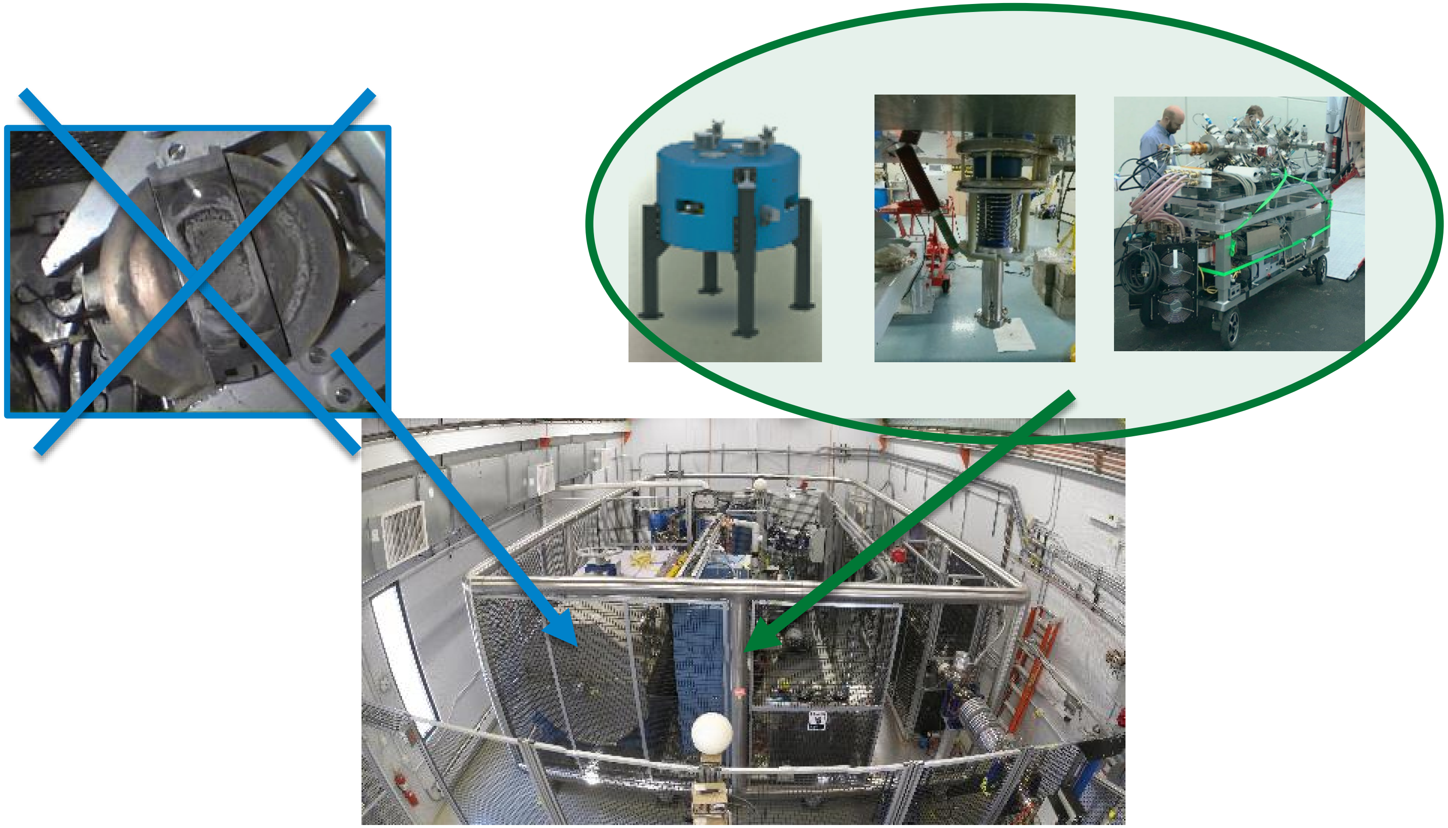
- There was one more attempt at ORNL in early February 2020, unfortunately it also did not succeed … a better approach is needed

Proposed solution: nuCARIBU, a neutron-generator-based source of fission fragments to obtain more reliable and higher intensity (goal is factor of 5-10 gain) access to fission products … to be implemented in two years.

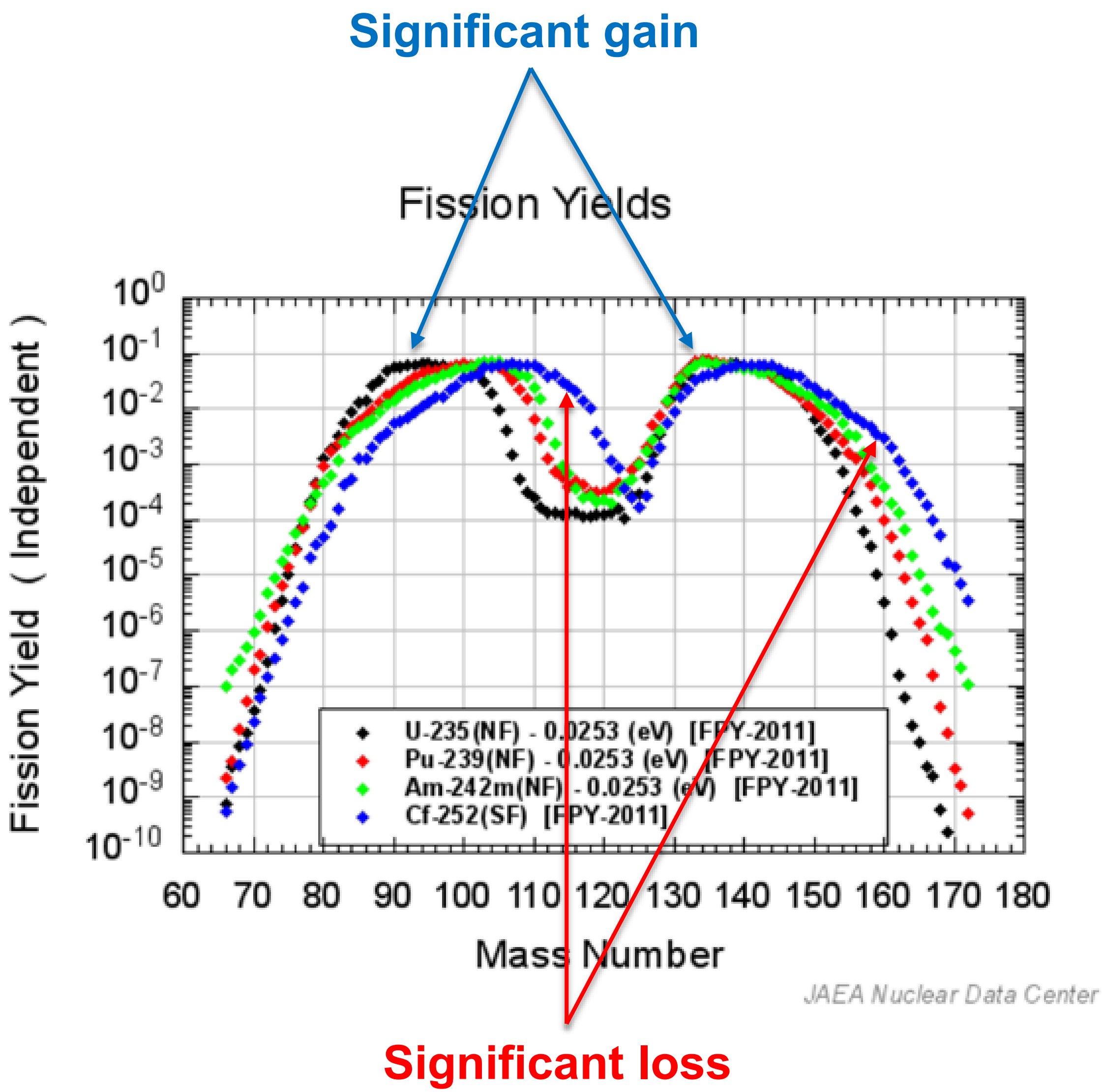
- In the meantime, a group of experts looked at the source production method and proposed some changes and a different approach for a last source. That attempt took place in Feb 2022 … no success … again! An AAR is ongoing at ORNL but we cannot wait anymore and are moving on.

NEUTRON GENERATOR UPGRADE TO CARIBU

- Replace ^{252}Cf source by neutron-induced fission on actinide foils
  - More reliable source of fission products
  - Operationally easier to maintain and operate
  - Gain an order of magnitude in overall fission rate … i.e. ~ 10^9 fission/sec vs current ~ 5 X10^7 fission/sec
  - Higher fission yield feeding in the ^{132}Sn region or above ^{78}Ni region



CHANGES IN FISSION DISTRIBUTION



DIFFERENT MATERIAL CAN BE USED DEPENDING ON REGION OF INTEREST

- ^{235}U available at 93% purity has been identified and is available as a metal for rolling. Will be used first.

- ^{239}Pu, ^{242m}Am and other fissionable isotopes are also available but more difficult to handle

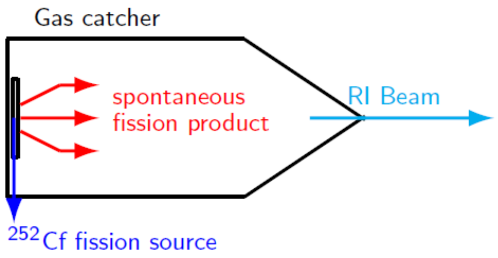
- Different fissioning isotopes allow to optimize yield to particular region

	fissioning material			
	252Cf	239Pu	235U	229Th
isotope				
82Ge	5.4E-05	2.7E-04	1.3E-03	1.2E-02
90Se	4.1E-05	1.2E-05	1.3E-04	6.2E-05
110Ru	3.62%	0.57%	0.01%	1.4E-04
132Sn	0.14%	0.48%	0.59%	0.11%
164Gd	2.6E-04	1.7E-05	4.3E-08	7.9E-12

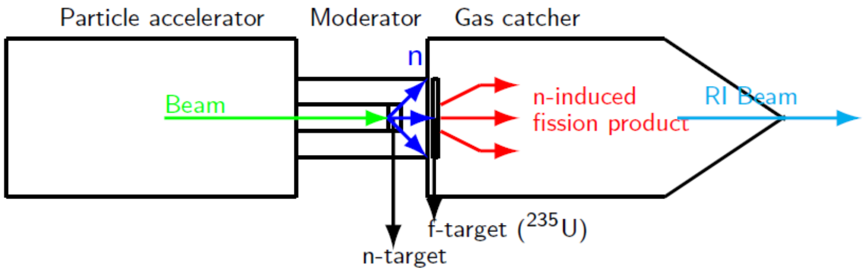
- Significant gains over ^{252}Cf in some region from relative yield, enhanced further by higher fission rate, but losses in heaviest region

MODIFICATION TO FACILITY

- CARIBU

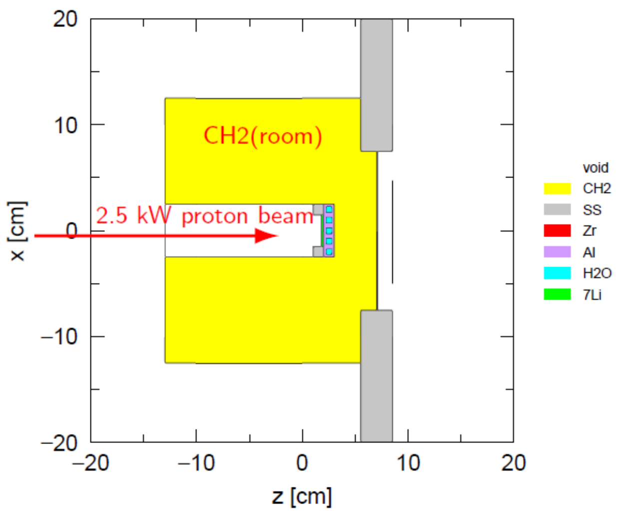


- nuCARIBU



- ^{252}Cf fission source
  - ✓ fission rate $\approx 5 \times 10^7$
  - ✓ Source has to be replaced every 3 years
  - ✓ very challenging to obtain a good thin ^{252}Cf foil

- A neutron-generator-based source
  - ✓ will resolve the issues caused by using the ^{252}Cf foil while making the system easier to maintain and operate since the main source of radioactivity will now be able to be turned off
  - ✓ expect more reliable and higher intensity, $\approx$ 20 times

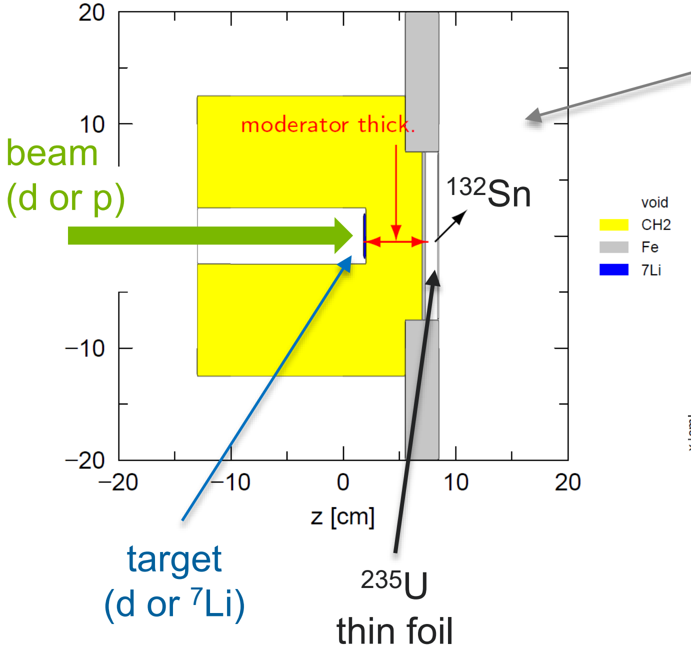


- 2.5 kW proton beam (5 MeV and 0.5 mA) on the target, after Ti window
- 3 cm thick CH2 moderator
- room temperature moderator
- 1mm thick Zr window and 5 mm distance between U foil and Zr window

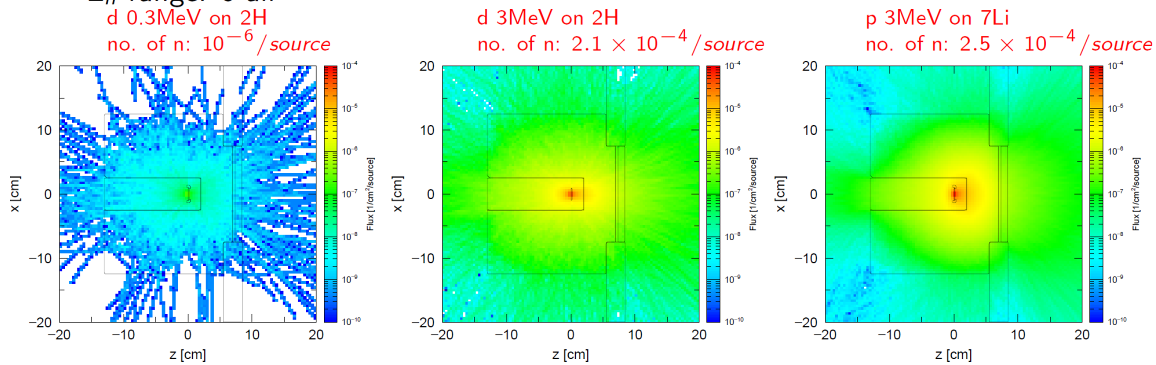
NEUTRON-GENERATOR OPTION STUDIES

Looking at D-D (300 keV and 3 MeV) and p-^{7}Li (3 MeV … or higher)

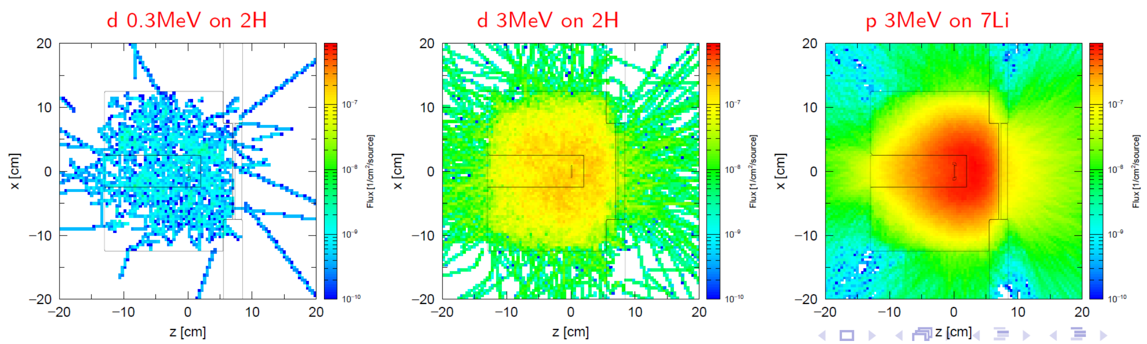
- Geometry



- E_n range: 0-all



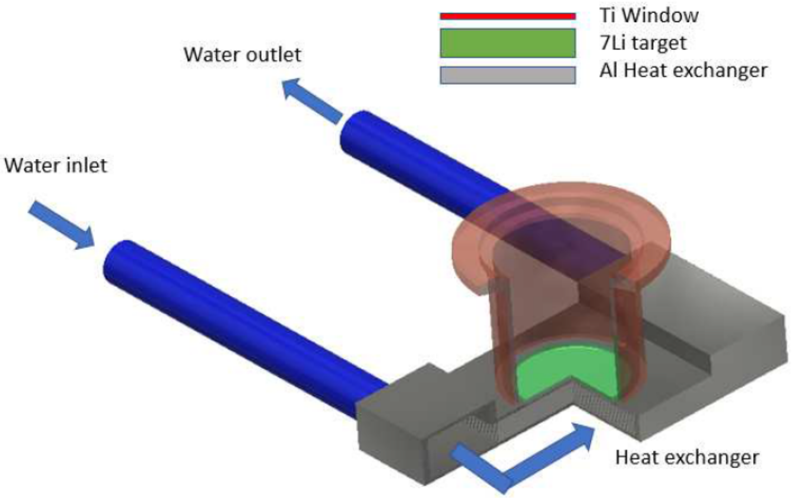
- E_n range: 0 - 10eV



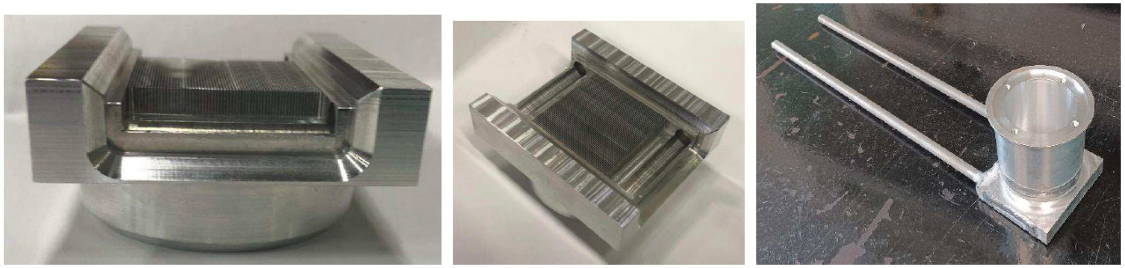
Simulations by Jeongseog Song

HIGH POWER LITHIUM TARGET

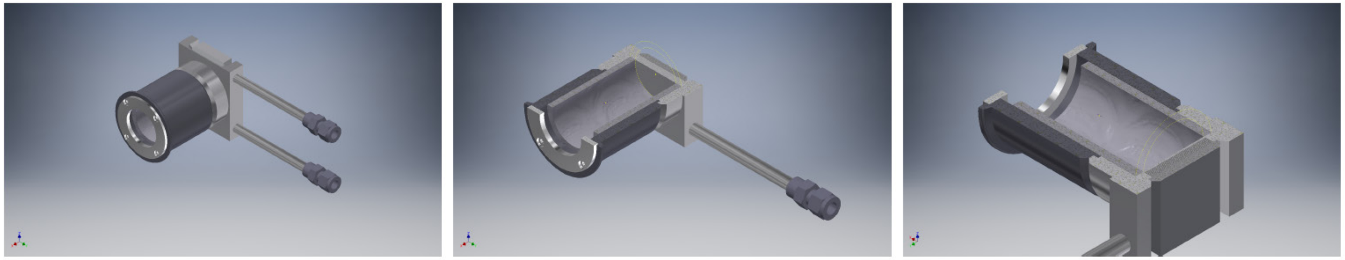
- 6 MeV proton beam at 0.5 mA (3 kW)
  - p energy after 50 um Ti window -> 5 MeV
- Li target
  - high neutron production cross-section
  - low melting point (180.5 C), need a window
- Water cooling system
  - water speed in the channels 2-10 m/s
  - water flow ~ 10 gpm
- Microchannel heat exchanger
  - material Al
  - channel width 1 cm to 0.25 mm



- pictures of prototype



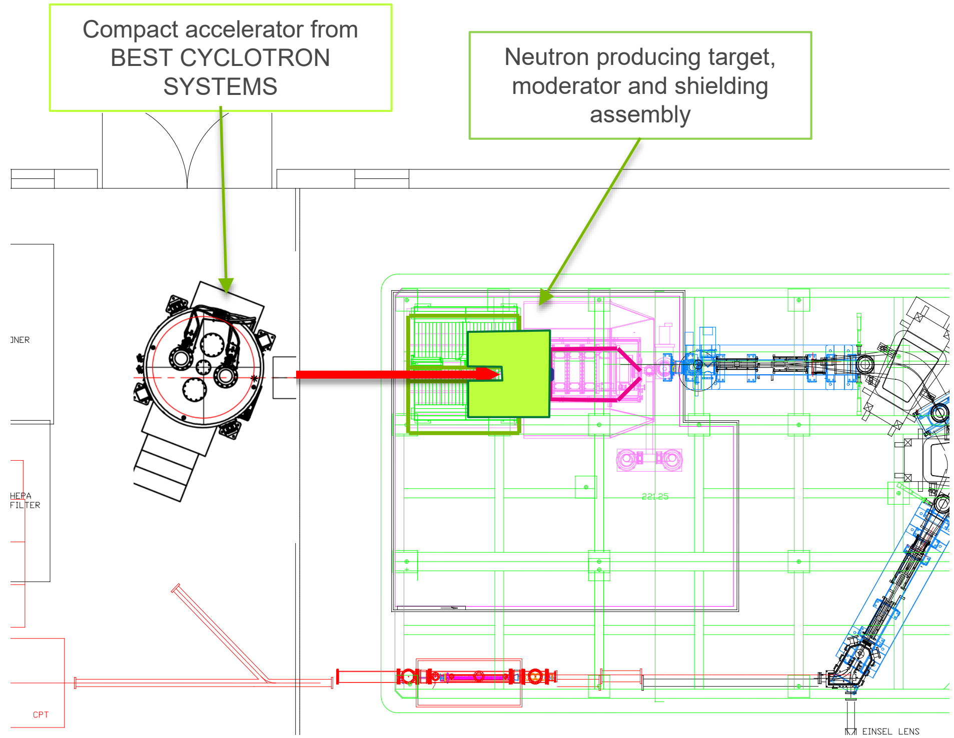
- 3D drawings of prototype



SELECTED P-7LI OPTION FOR NUCARIBU

Low-energy cyclotron

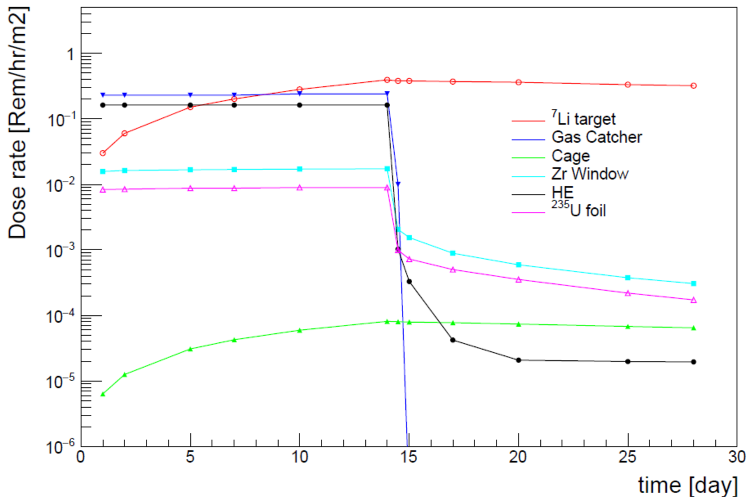
- 6 MeV compact proton cyclotron
- Can obtain sufficient current and higher energy so can afford to put it off the platform (lose 150 keV in energy)
- Can cover the ^{7}Li target
- Is the less expensive option
- Easier to bring in services since off of HV platform
- Space available
- CARIBU shutdown shorter since less work on platform



Cyclotron is now on-site

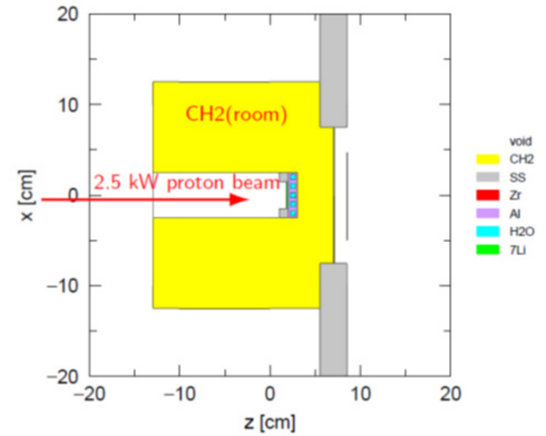
TWO IMPORTANT ISSUES: PROMPT RADIATION AND ACTIVATION OF COMPONENTS

- Simulations performed by PHITS 3.27
  - ✓ Radiation from activation
  - ✓ Without shielding
  - ✓ DCHAIN results with PHITS output

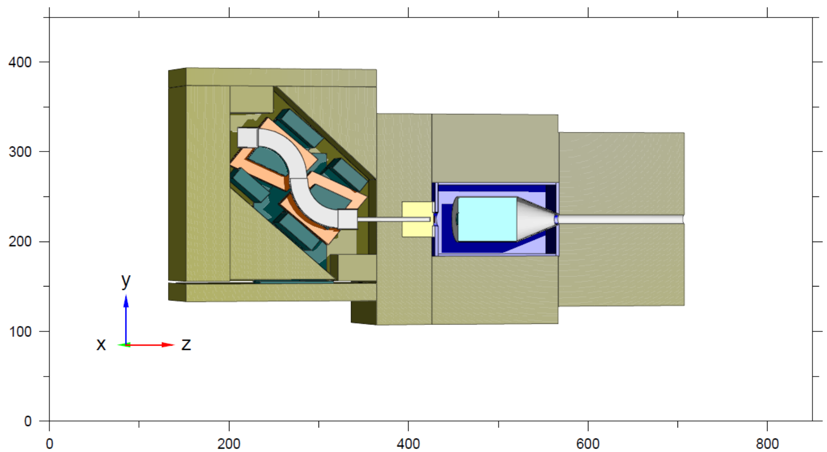


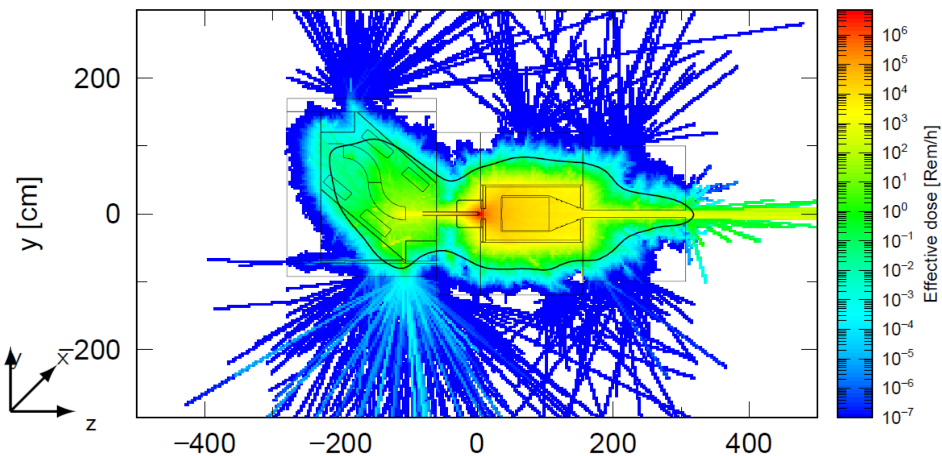
- dominent nuclides

comp.	nucl.	half-life
Li tgt	7Be	53.22 d
G.C	56Mn	2.58 h
Cage	59Fe	44.5 d
Zr win.	93Y	10.18 h
HE	28Al	2.25 m



- Geometry
  - ✓ B-CH2 shielding

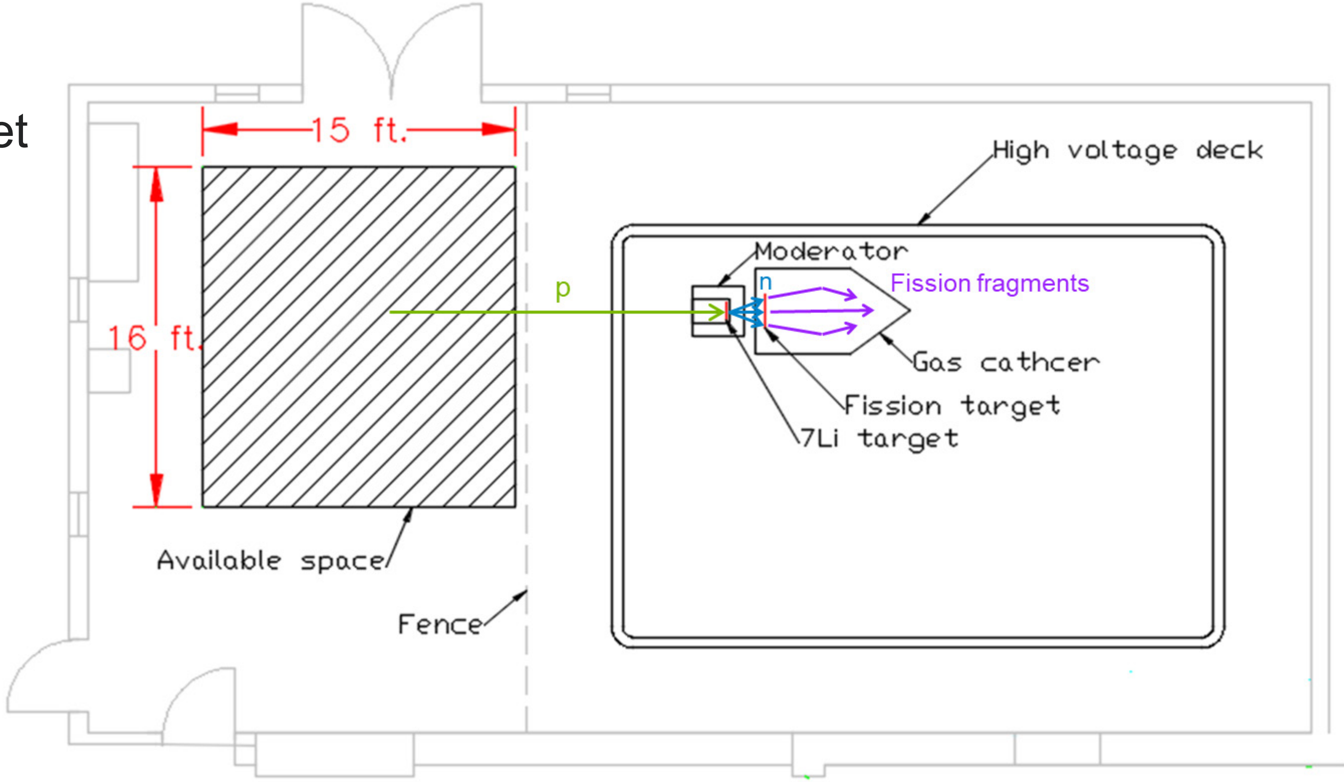




nuCARIBU SCOPE

neutron-induced fission of actinide foils

- Proton accelerator
- Transport system
- ^{7}Li n-production target
- Moderator
- Actinide target
- Facility modifications
  - Utilities
  - Gas catcher
  - Controls

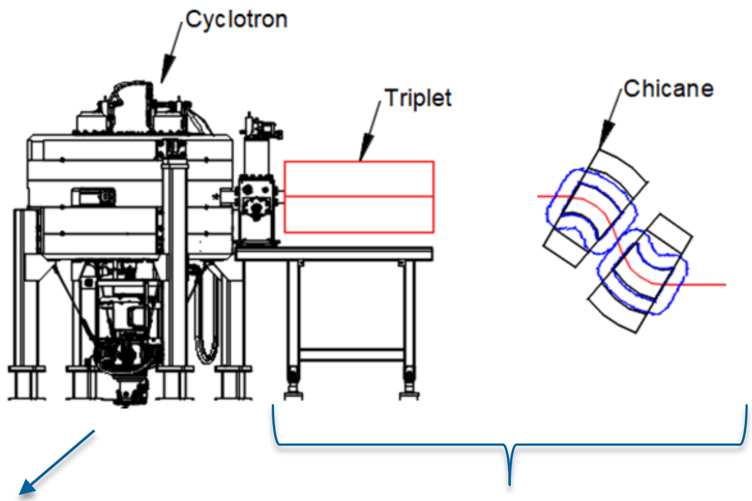


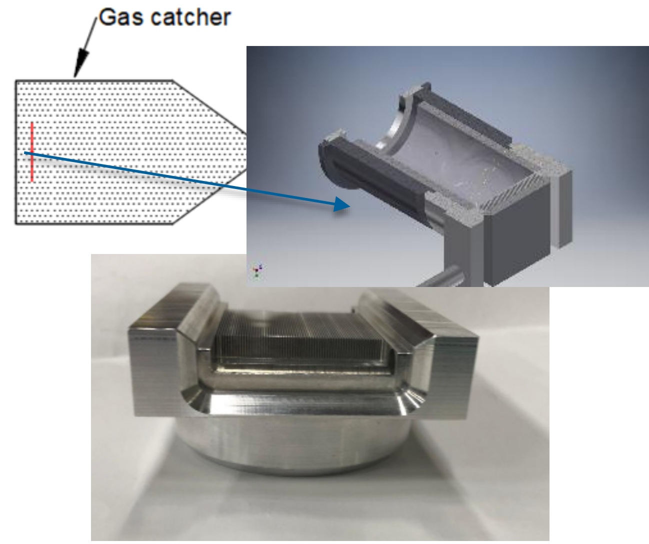
LAYOUT IN THE CARIBU HV PLATFORM

Neutron-generator would go on the North-West corner of the CARIBU HV platform where source transport cask currently resides

NUCARIBU PROGRESS

Neutron generator



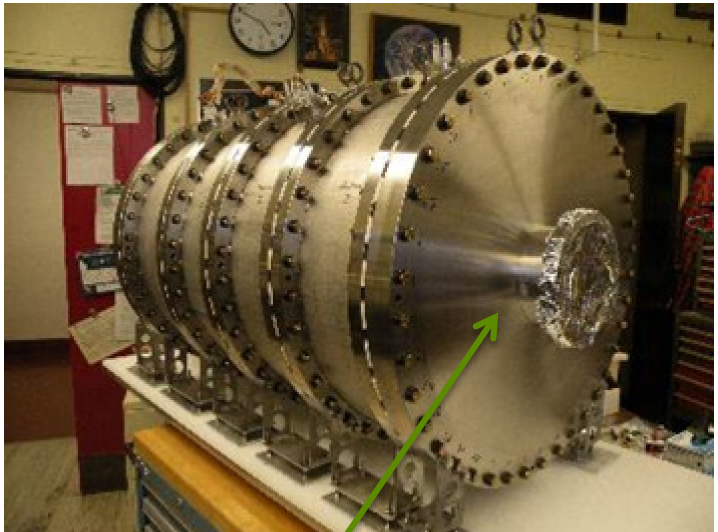


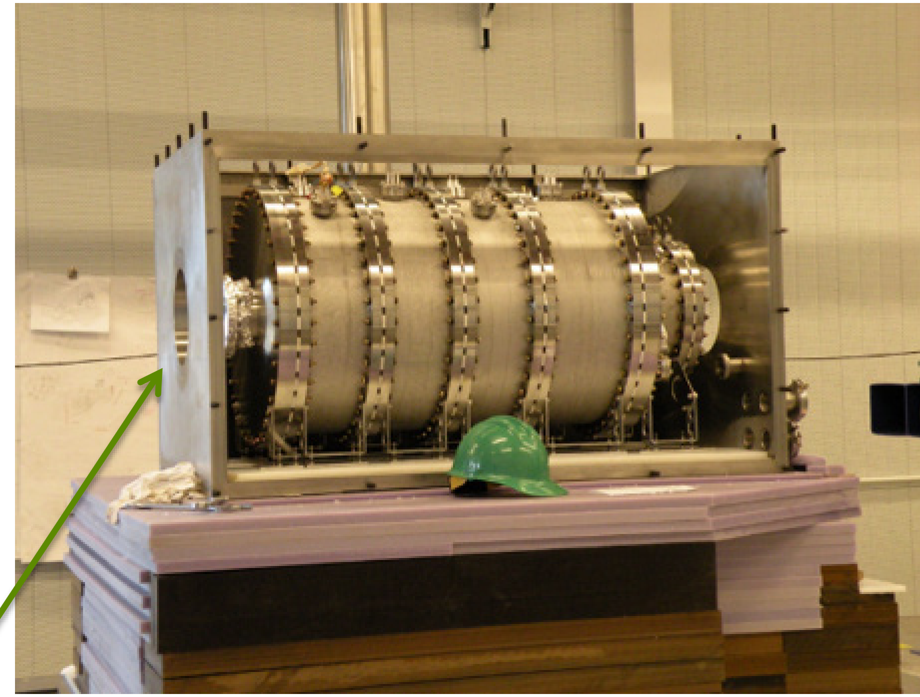
- *Cyclotron passed factory acceptance test*
- *Has been delivered to Argonne on Jan 31 2022*

- *Beam transport system design completed*
- *Solicitation period for triplet and magnetic chicane closed on Feb 14 2022*
- *Scheduled Nov 2022 delivery*

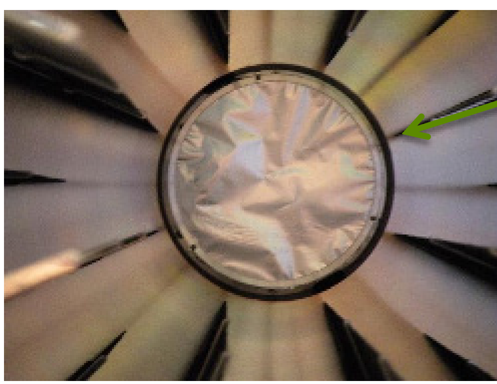
- *Concept developed for high power heat removal*
- *Prototype built and being tested*

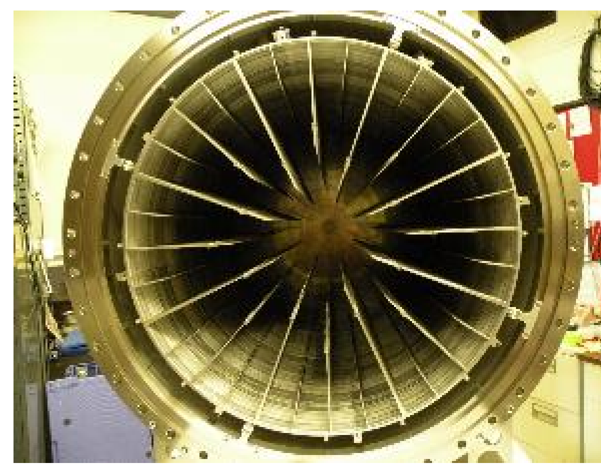
GAS CATCHER MODS





- Enlarge opening in gas catcher box
- Replace endplate to one with large thin window and foil support

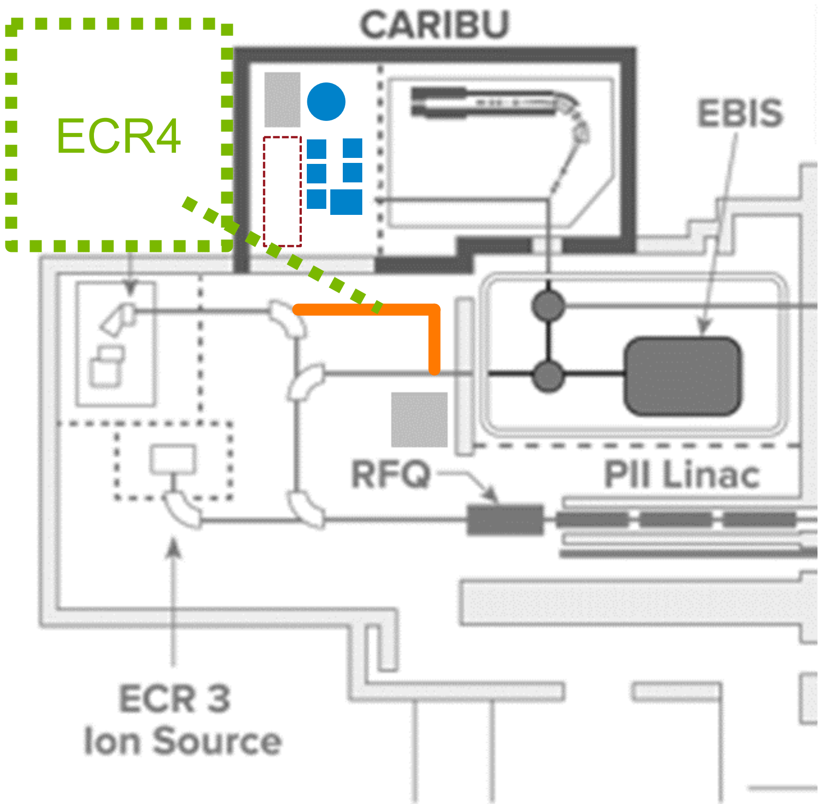




COORDINATION WITH OTHER ACTIVITIES

Space shared with multiple projects

- Canadian Penning Trap (CPT) relocation
- nuCARIBU cyclotron and support equipment
- ATLAS Multi-User Upgrade PII LEBT construction
- ECR4 (possible future high current ECR source) site planning



Scheduling constraints

- Minimize disruption to running CARIBU program
- Allow completion of some unique high-profile experiments that require the ^{252}Cf source

WHAT DO WE GAIN WITH NUCARIBU?

- CARIBU was a revolutionary project: the first RIB facility based on a gas catcher system
- The project pushed many technical boundaries and had some weaknesses that were resolved over time through hard and innovative work. One weakness remains, the actual ^{252}Cf source, whose production has shown to be non-reproducible and to yield too thick a source even in the best cases.
- nuCARIBU resolve this final issue. It provides:
  - a reproducible and controllable source of fission
  - higher total yield
  - the ability to focus on different regions by choosing the best suited fissionable material
  - an approach where the main source of radiation can be turned off, greatly simplifying safety and maintenance at CARIBU
  - an easier and cheaper to operate in the long run CARIBU that relies on less resources that might disappear at ANL
  - access to the neutron-induced fission process which is in itself of interest
- Should start operation in March 2023 after a 3-4 months shutdown of CARIBU program

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
  - Follows a coherent upgrade program to add accelerator and experimental capabilities to better address the community's evolving science goals

- CARIBU itself provides ~3000-4000 hrs/yr of beamtime to users. Most of its beams are unique and in high demand. It is a critical component of the research program and future facility upgrades such as the ATLAS Multi-User Upgrade.

- The facility needs to make CARIBU as powerful and reliable as possible … while minimizing downtime to the running programs
  - Small remaining issues have been addressed
  - The main large issue remains developing a better way to obtain the fission fragments than the ^{252}Cf source

nuCARIBU should allow us to address this last hurdle.