THE ZAKOPANE CONFERENCE ON NUCLEAR PHYSICS 2026

A PRACTICAL PATH TO AI/ML BEAM AUTOMATION: DEPLOYMENT LESSONS AND TOOLS FROM ATLAS

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Argonne National Laboratory

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

Argonne NATIONAL LABORATORY
Argonne Tandem Linac Accelerator System

ACKNOWLEDGMENTS

Brahim Mustapha
Calem Hoffman
Adwaith Ravichandran (PD)
Sergio Lopez-Caceres (PD)
Khushi Bhatt (PD)
Anthony Tran (student)
ATLAS operators
ATLAS controls group

FUNDS

DOE LAB-20-2261 [2020]
DOE DE-FOA-0002875 [2023]

FEEL FREE TO REACH OUT IF YOU HAVE QUESTIONS

OUTLINE

Disclaimer: This is NOT a comprehensive list of AI/ML tools for accelerator facilities.

BO for accel review: R. Roussel, et al. Phys. Rev. Accel. Beams 27, 084801 (2024)

Introduction

- What is ATLAS (at Argonne)?
- Ongoing ATLAS AI/ML efforts
- What is CARIBU/nuCARIBU?

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- Challenges and Project Goals
- Our approach to safe radioactive beam tuning automation
- Example of live beam tuning automation

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- Example of live beam tuning automation

Wrapping up

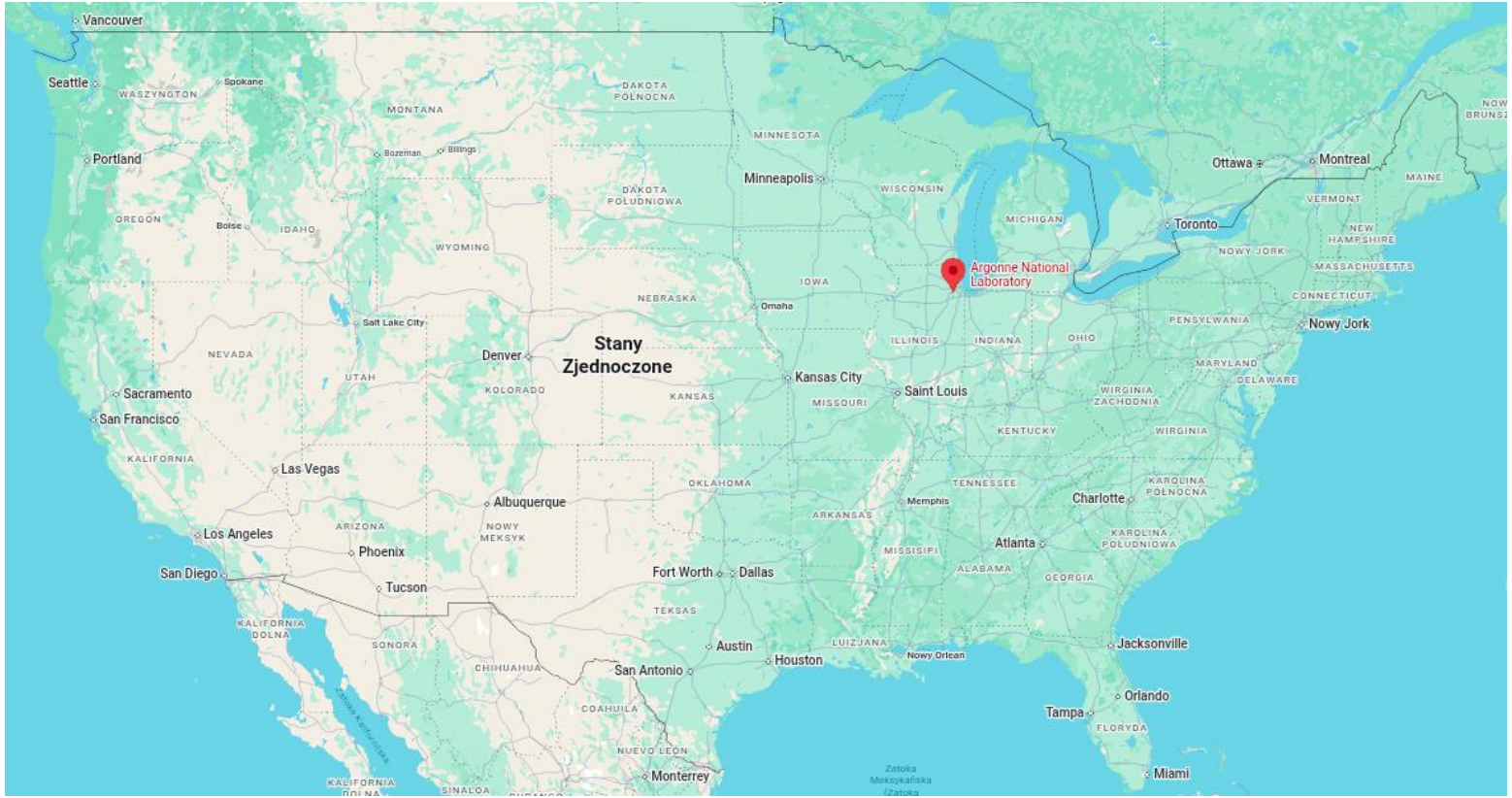
- Some lessons I've learned
- Epilogue

INTRODUCTION

WHAT IS ATLAS?

NOT THE LHC ATLAS

Located in Argonne Nat Lab, about 37 km from Chicago O'Hare Int. Airport




Argonne
NATIONAL LABORATORY
80
1946–2026

ATLAS?
EST. 1985

The Argonne Tandem Linac Accelerator System (ATLAS) is a U.S. **user facility** that supports forefront nuclear physics research with stable and radioactive heavy ion beams

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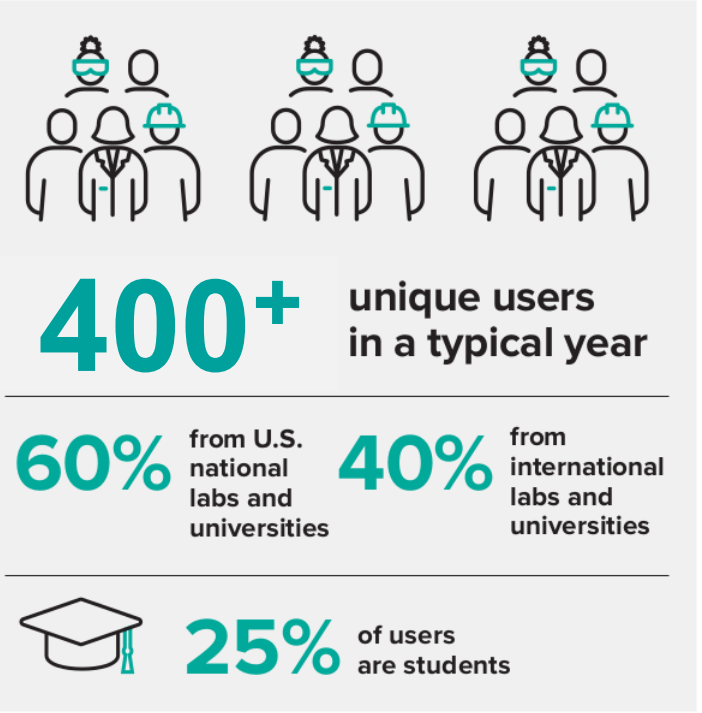
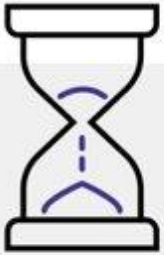


ATLAS?

Primary sponsor: U.S. Dept of Energy (DOE)

The Argonne Tandem Linac Accelerator System (ATLAS) is a U.S. **user facility** that supports forefront nuclear physics research with stable and radioactive heavy ion beams

6,000+ hours of beam time delivered annually



~50 scientific and user support staff

https://www.anl.gov/atlas

INTRODUCTION

AI/ML EFFORTS

ATLAS AI/ML EFFORTS FOR ACCEL OPERATIONS

First project (finished)

- PI B. Mustapha
- DOE Funds LAB-20-2261 [2020]
- Successful proof of concept
- Postdoc
  - Jose Martinez-Marin

ATLAS AI/ML EFFORTS FOR ACCEL OPERATIONS

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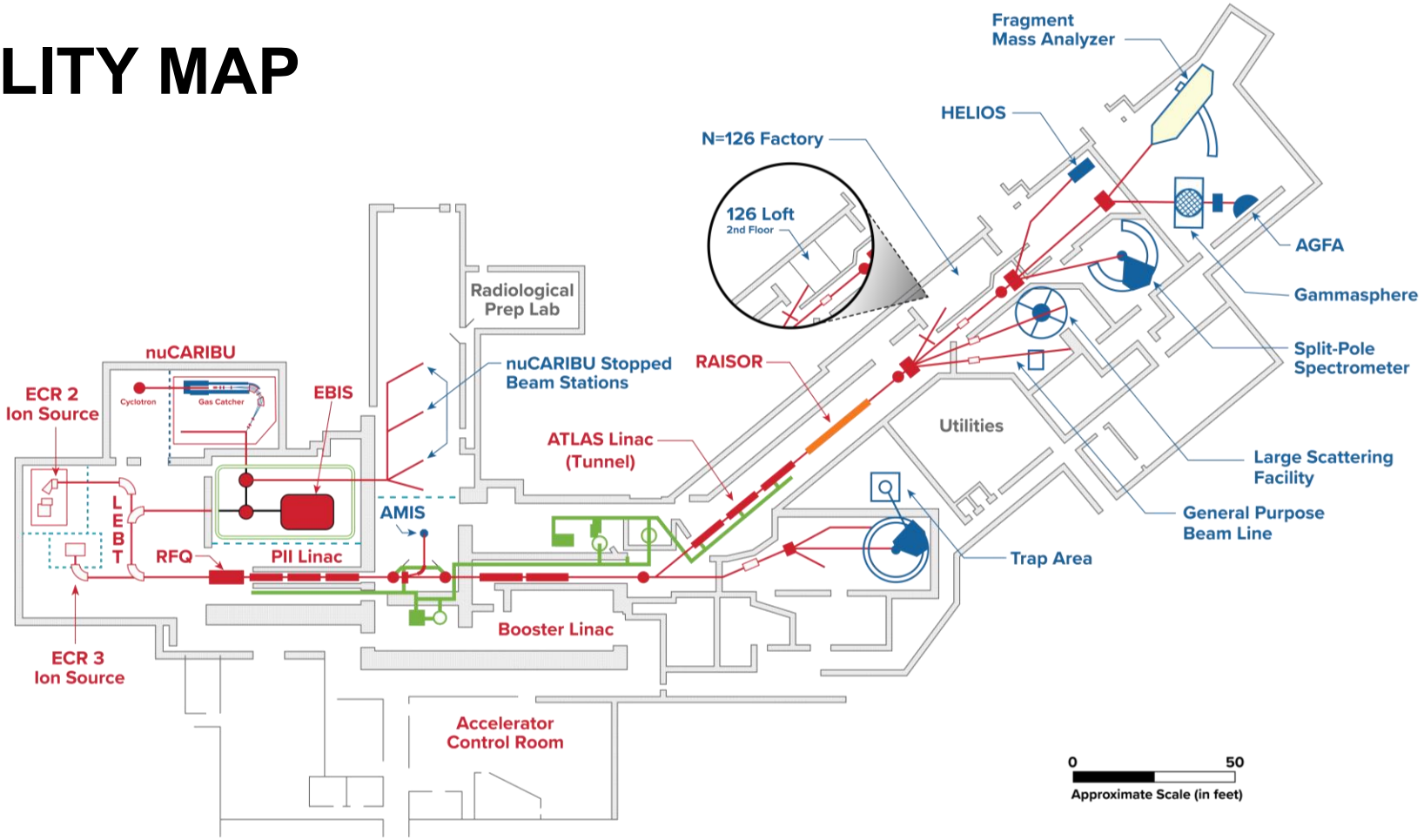
Consolidated project

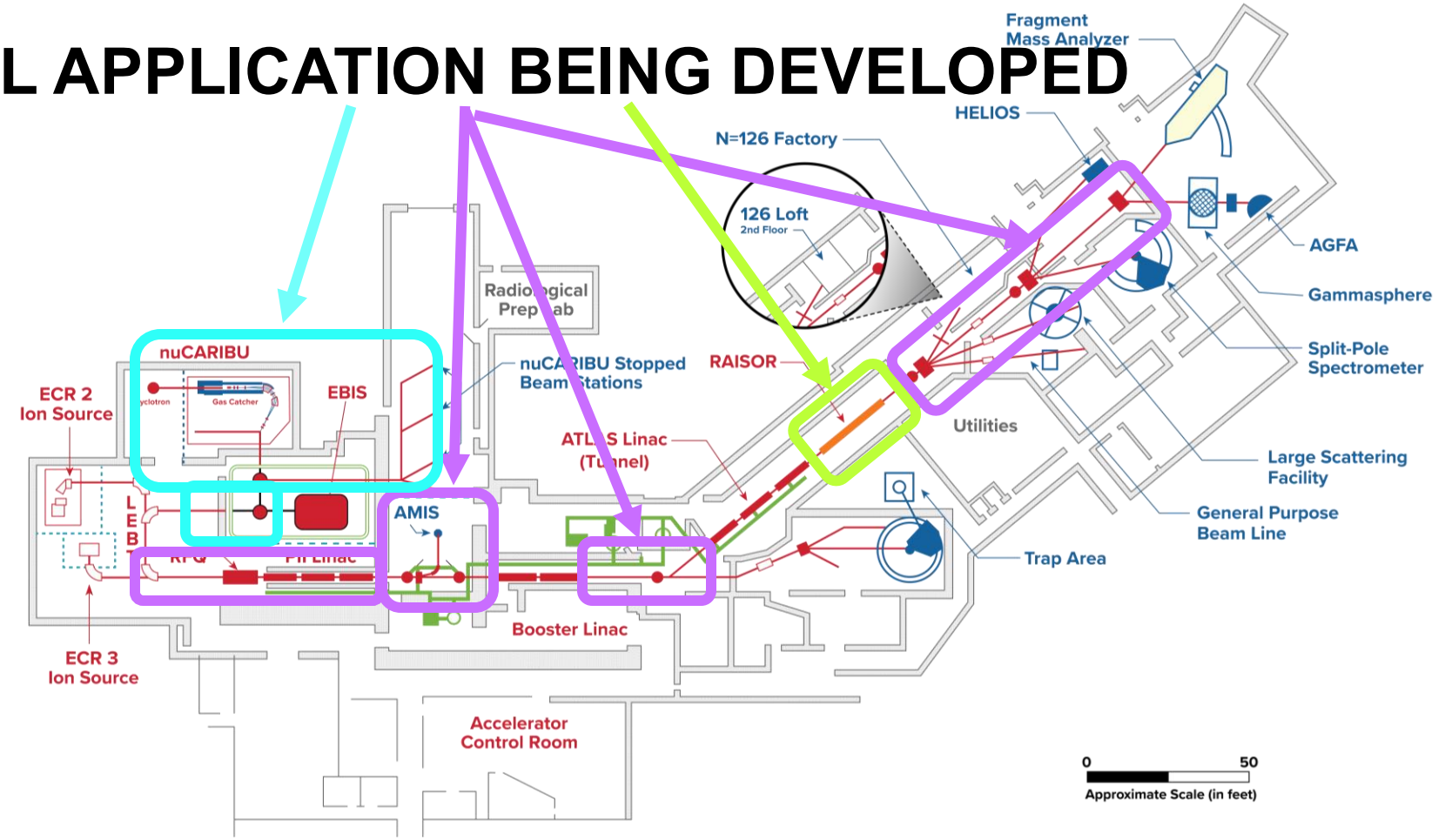
- **PIs: B. Mustapha, C. Hoffman, DSG**
- DOE Funds DE-FOA-0002875 [2023]
- 3 sub-projects:
  - Main accelerator
  - RAISOR (rad. beams)
  - CARIBU/nuCARIBU (rad. beams)
- PDs and students
  - Adwaith Ravichandran
  - Sergio Lopez-Caceres
  - Anthony Tran, et al.

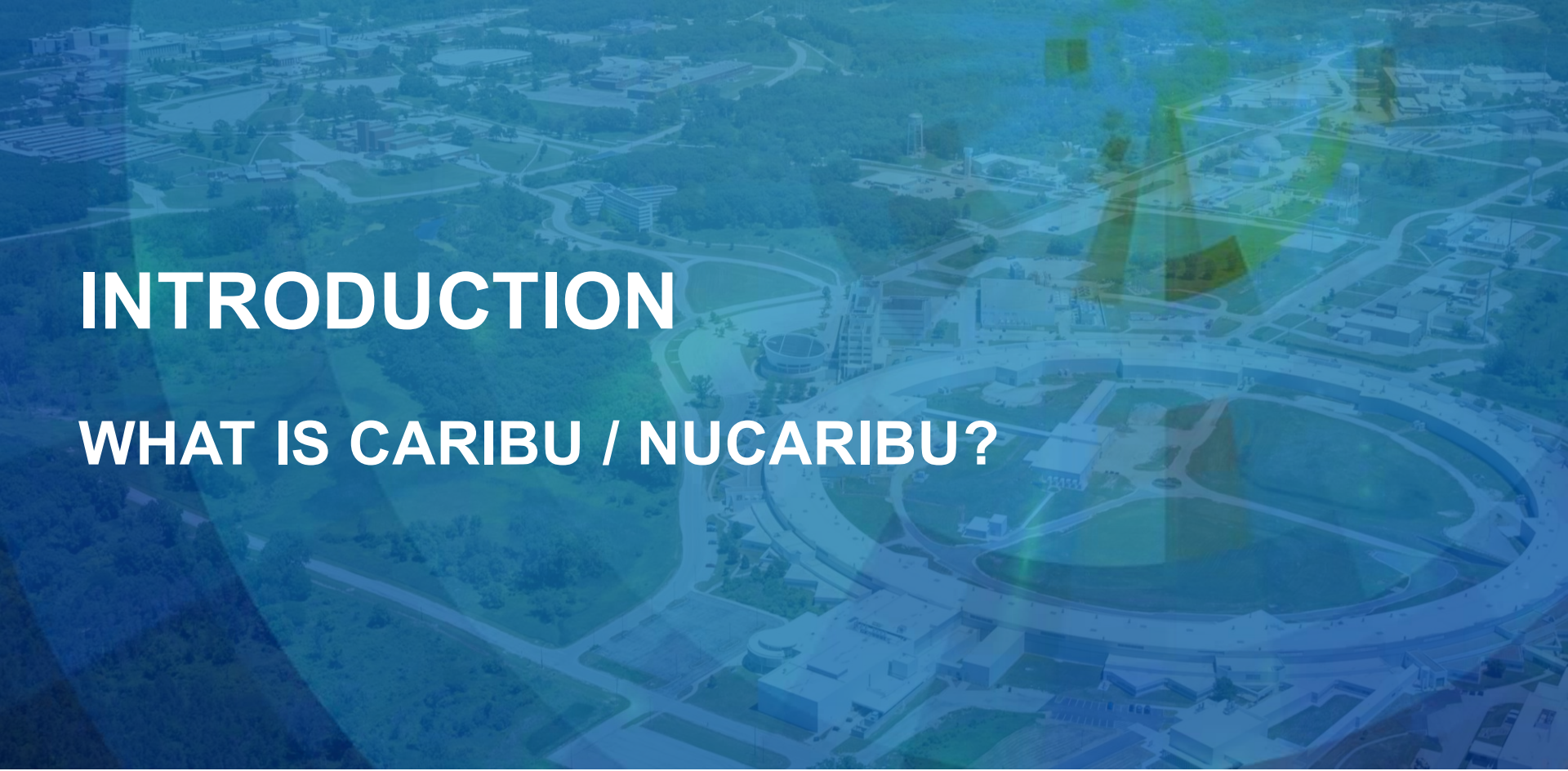
Final phase: Deploy practical AI/ML applications to increase operational efficiency

FACILITY MAP



AI/ML APPLICATION BEING DEVELOPED





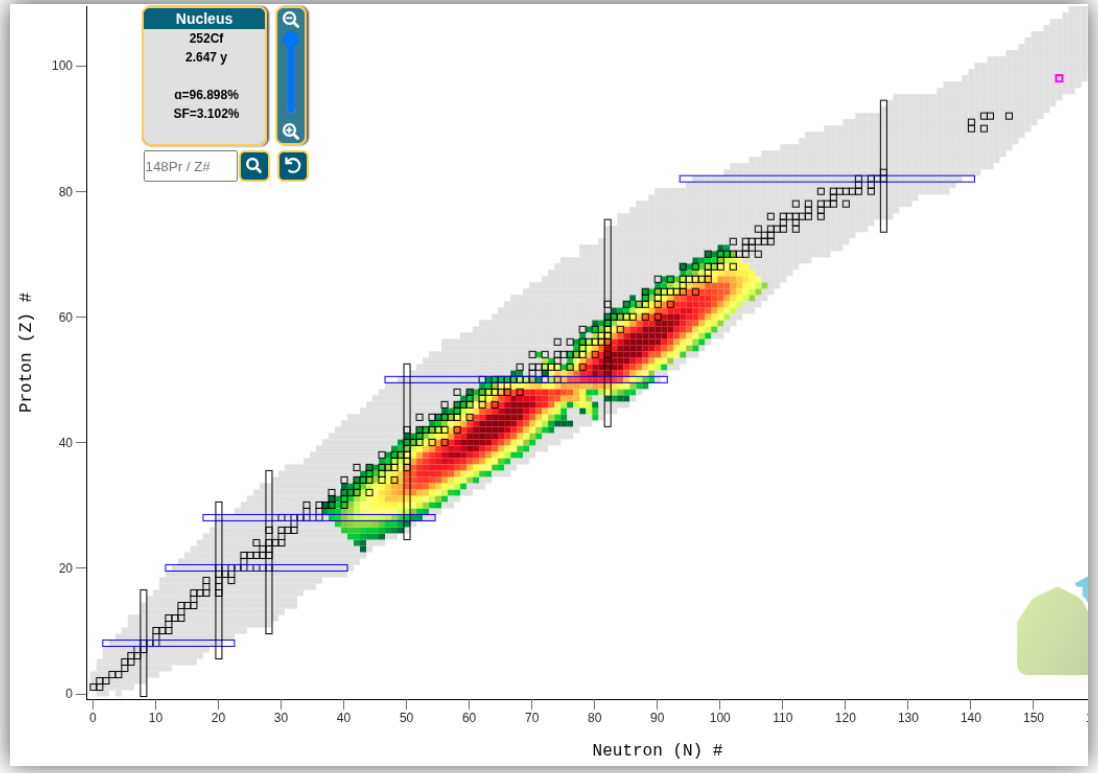
INTRODUCTION

WHAT IS CARIBU / NUCARIBU?

WHAT IS CARIBU/NUCARIBU?

A radioactive ion source part of the ATLAS facility

- **CARIBU** = CAlifornium Rare Isotope Breeder Upgrade
- CARIBU RIP 2024
- CARIBU provided beams of heavy ions made from fission fragments of ^{252}Cf (10^2 – 10^4 pps)



WHAT IS CARIBU/NUCARIBU?

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- **nuCARIBU** - a major upgrade to increase the source intensities by using neutron-induced fission on ^{235}U
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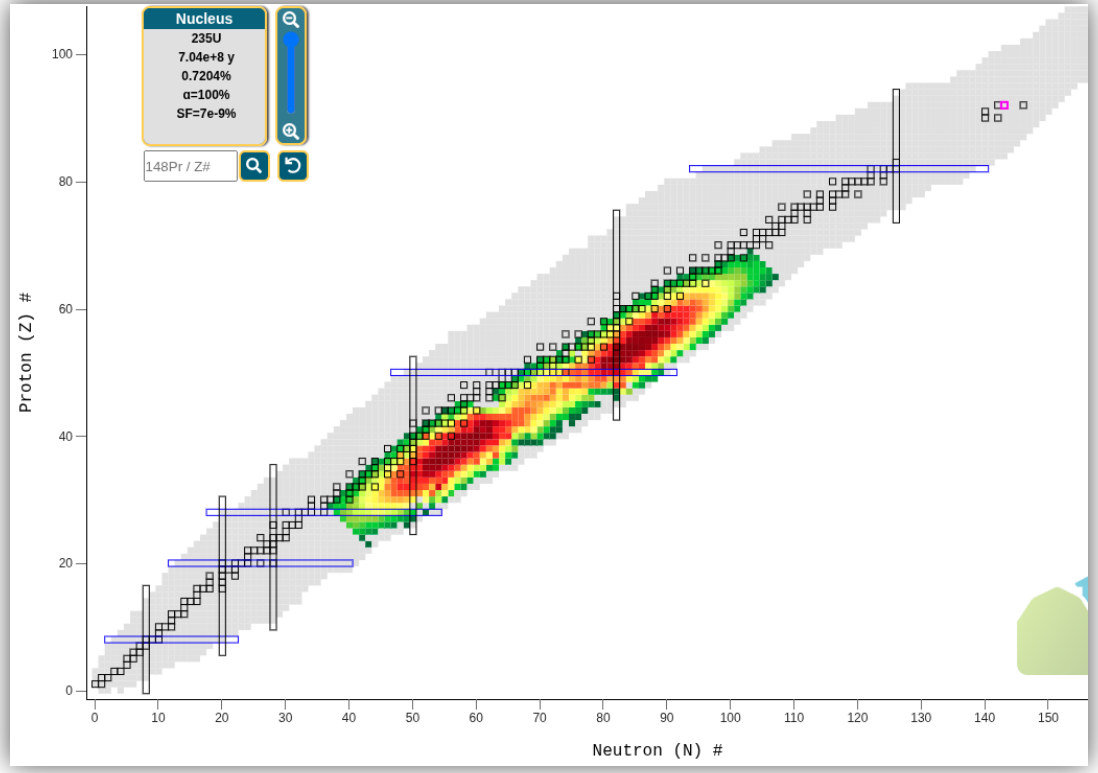

https://www.anl.gov/atlas/nucaribu-beams

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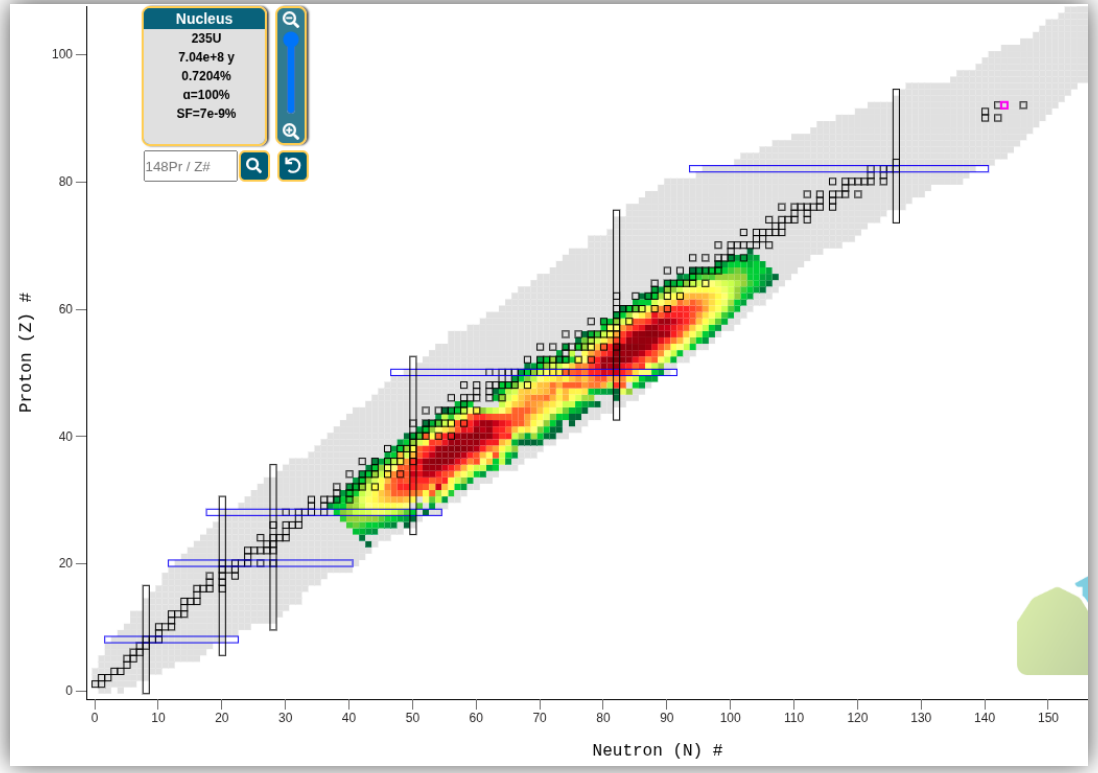
- **nuCARIBU** - a major upgrade to increase the source intensities by using neutron-induced fission on ^{235}U
  (and possibly other fissionable targets)

- Provides slow (keV) beams for:
  - decay studies, laser spectroscopy, ion traps, and
  - charge breeder (EBIS) for post-acceleration

- First experiments ran **Jun/2026**



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DEPLOYMENT EXAMPLE

CHALLENGES AND PROJECT GOALS

NUCARIBU OPERATIONS CHALLENGES

Not an exhaustive list

Workforce shortage

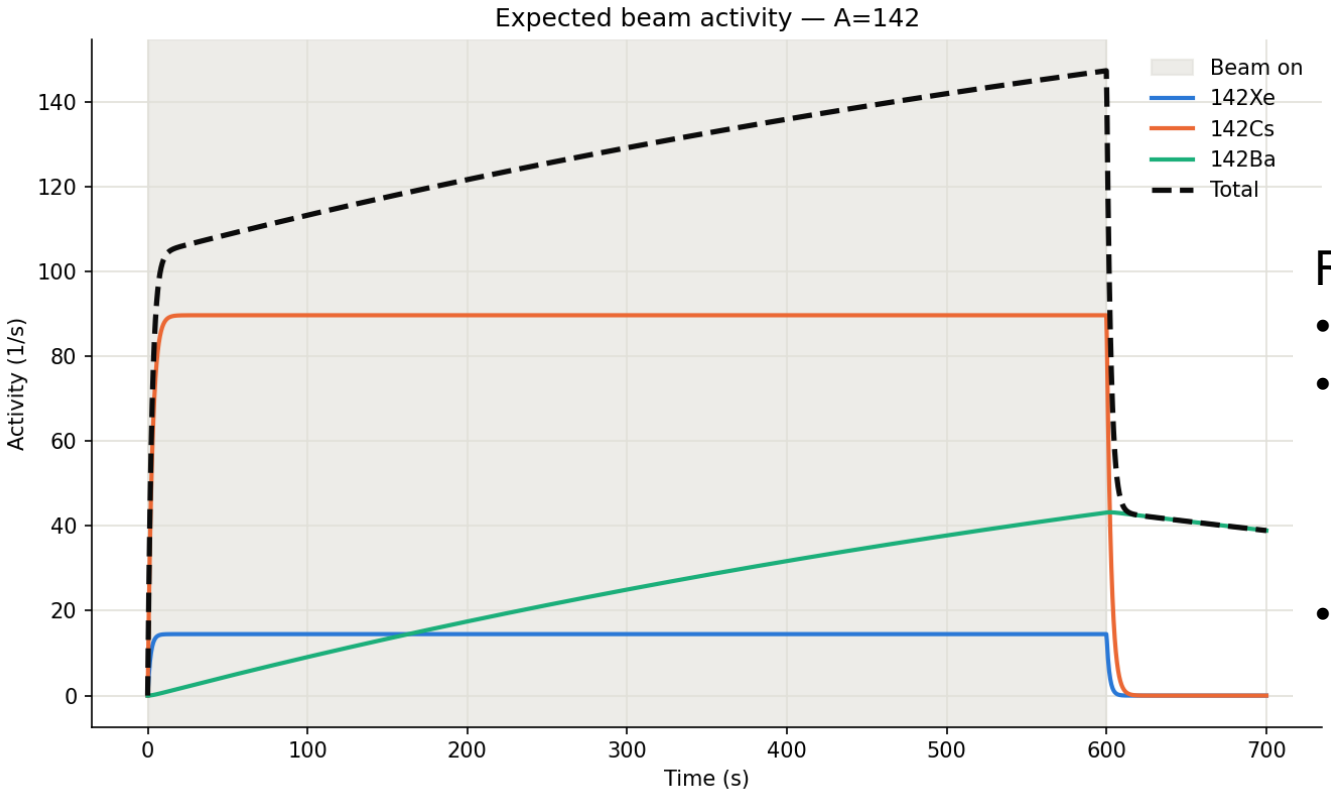
- Presently nuCARIBU is operated as experimental device
- Expert-driven approach
- Beam delivery done by 2-4 staff

Slow beam tuning

- Beam tuning observable is rate from beta decay in Si detectors
- Response wait times similar to half lives

NUCARIBU OPERATIONS CHALLENGES

A/Q=142/+1, an example of a good case: 142Cs -> 142Ba -> 142La



Response depends on:

- Fission yields
- Half-lives
  - 142Cs ~ 1.7 sec
  - 142Ba ~ 11 min
- Helium ionization potential

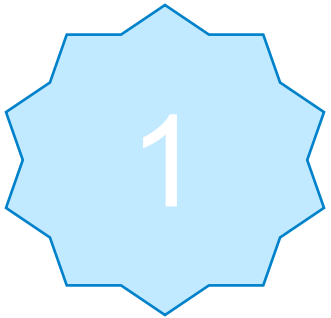
NUCARIBU OPERATIONS CHALLENGE

Automating parts of the beam tuning process could:

- help us with workforce challenges
- reduce effort spent in "mechanical" tasks
- set the stage for optimum delivery of nuCARIBU beams in the era of ATLAS multi-user operations
- accelerate the pace of discovery

OUR HIGH-LEVEL GOALS

To increase nuCARIBU operational efficiency via automation



Automate radioactive beam extraction and transport from source to: a) selected user stations and b) the charge breeder entrance

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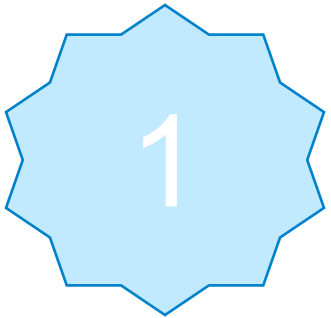

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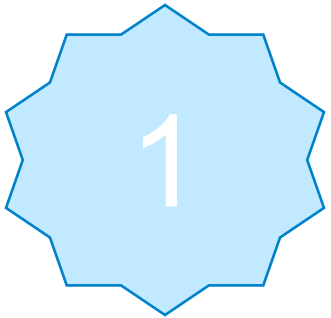

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Expand methods to assist with reaccelerated beams (resonant charge breeding, inj/ext)

Optimize mass separation when using the Multi-Reflection Time-Of-Flight (MRTOF) device

DEPLOYMENT EXAMPLE

OUR APPROACH TO SAFE RADIOACTIVE BEAM TUNING AUTOMATION

U.S. DEPARTMENT of ENERGY

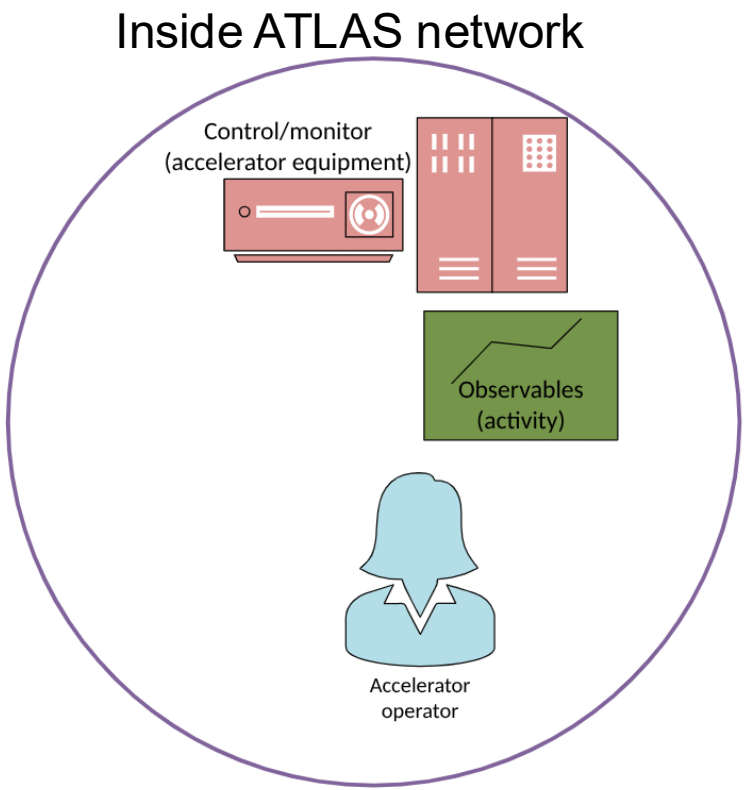
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY

Argonne Tandem Linac Accelerator System

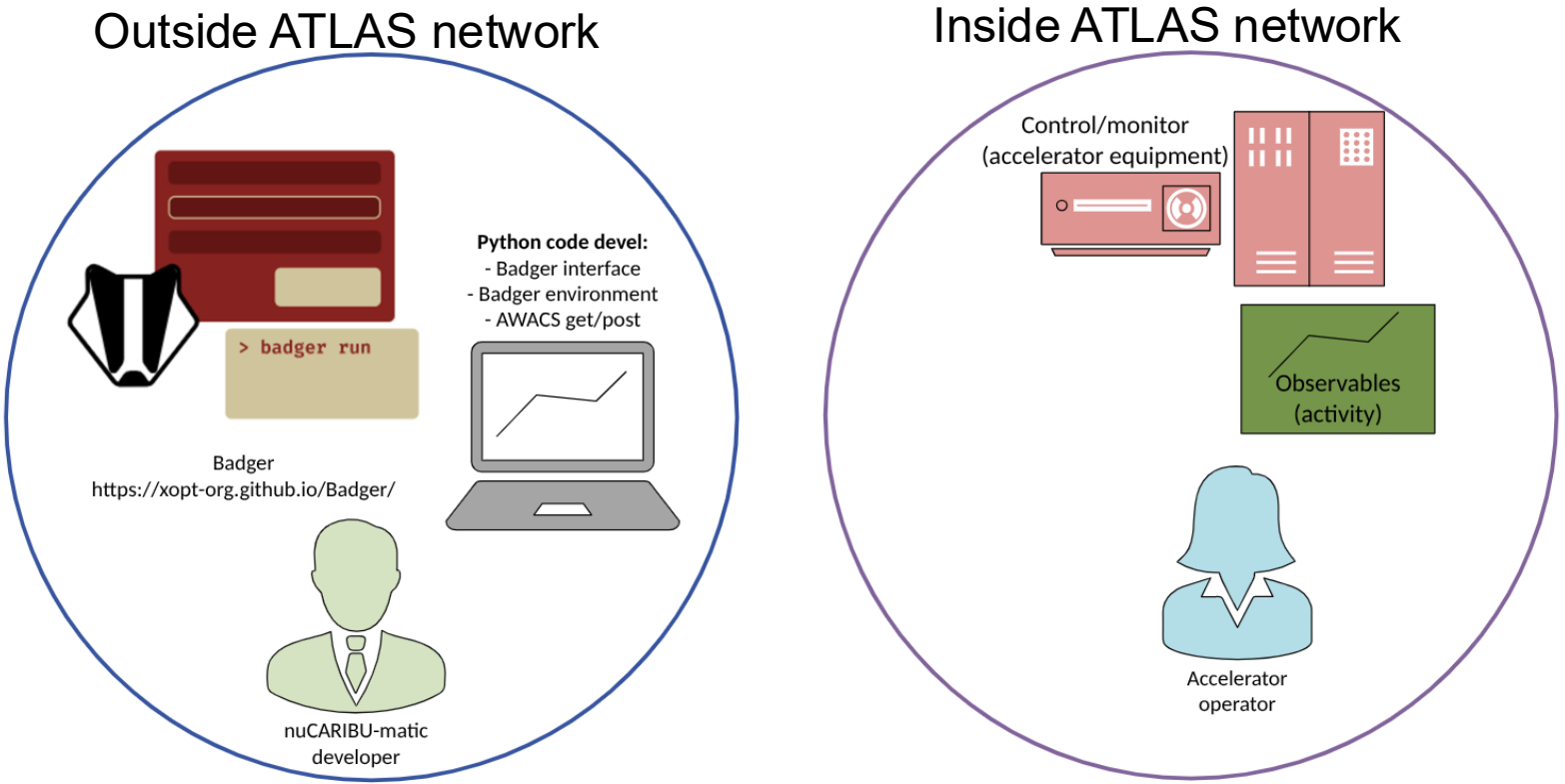
INITIAL CONDITIONS

Accelerator elements can be controlled/monitored by computer



OUR APPROACH

One big obstacle is infrastructure (controls / networking)



References

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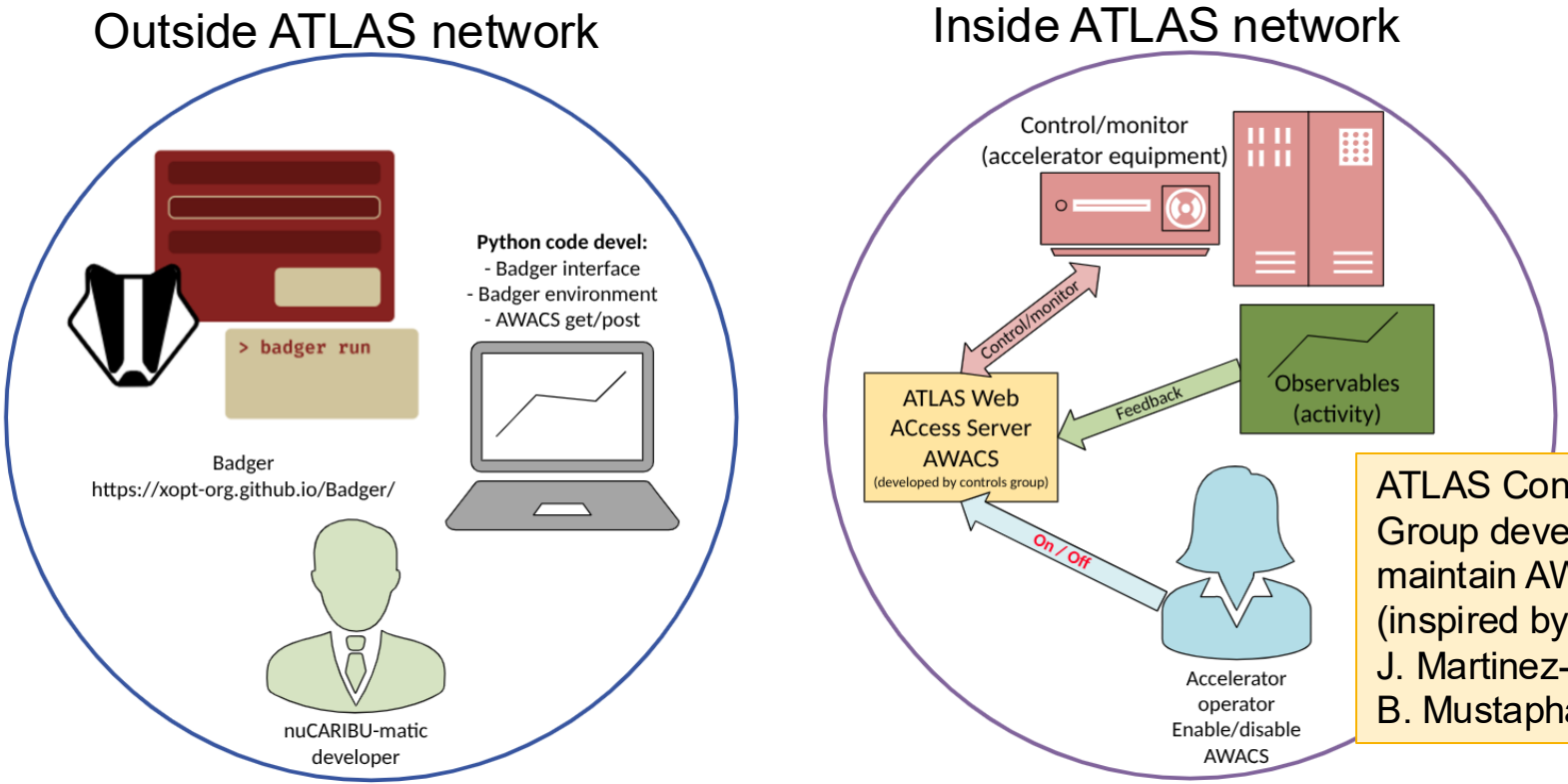

ATLAS Controls Group developed and maintain AWACS (inspired by efforts of J. Martinez-Marin and B. Mustapha)

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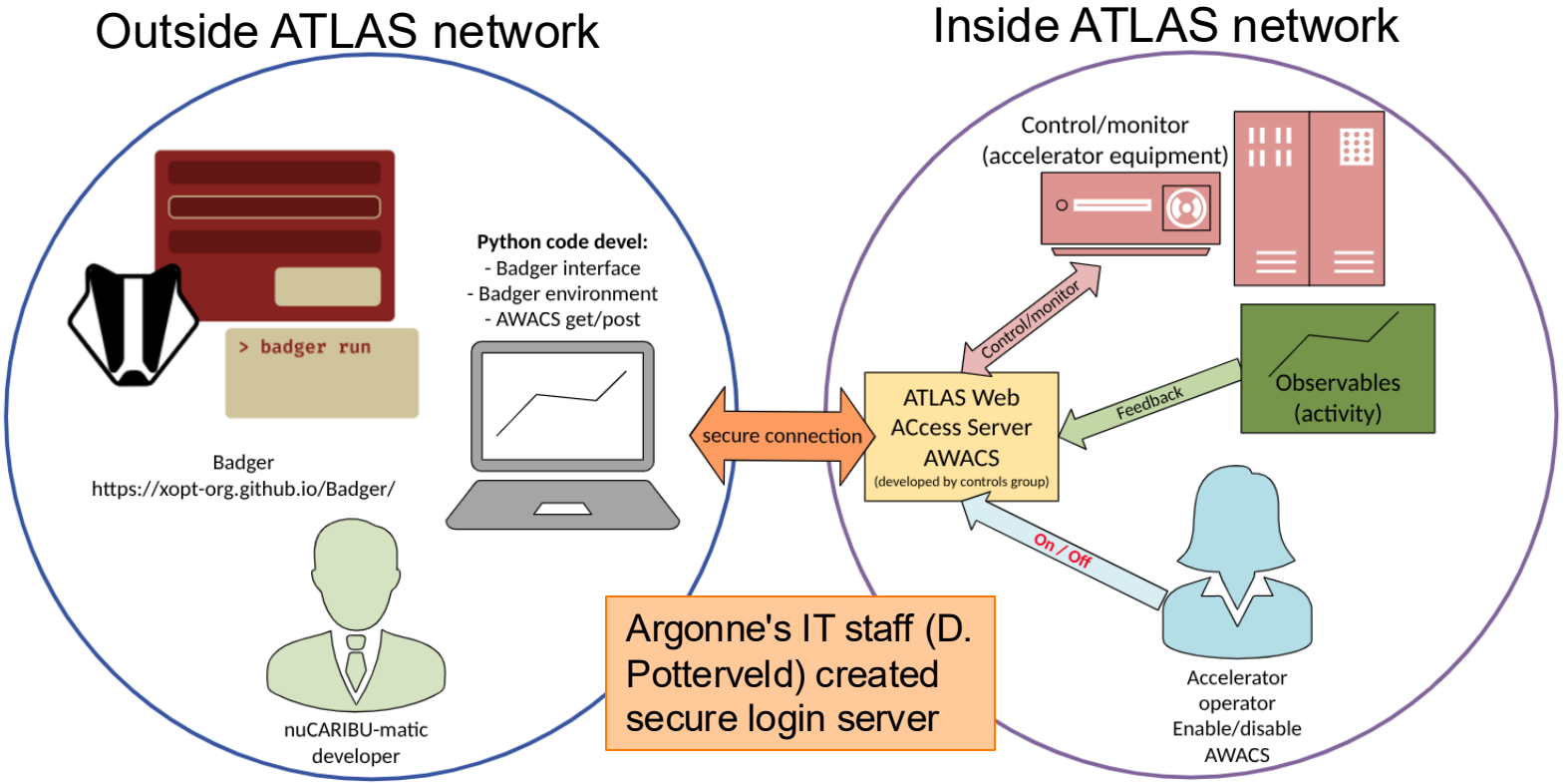

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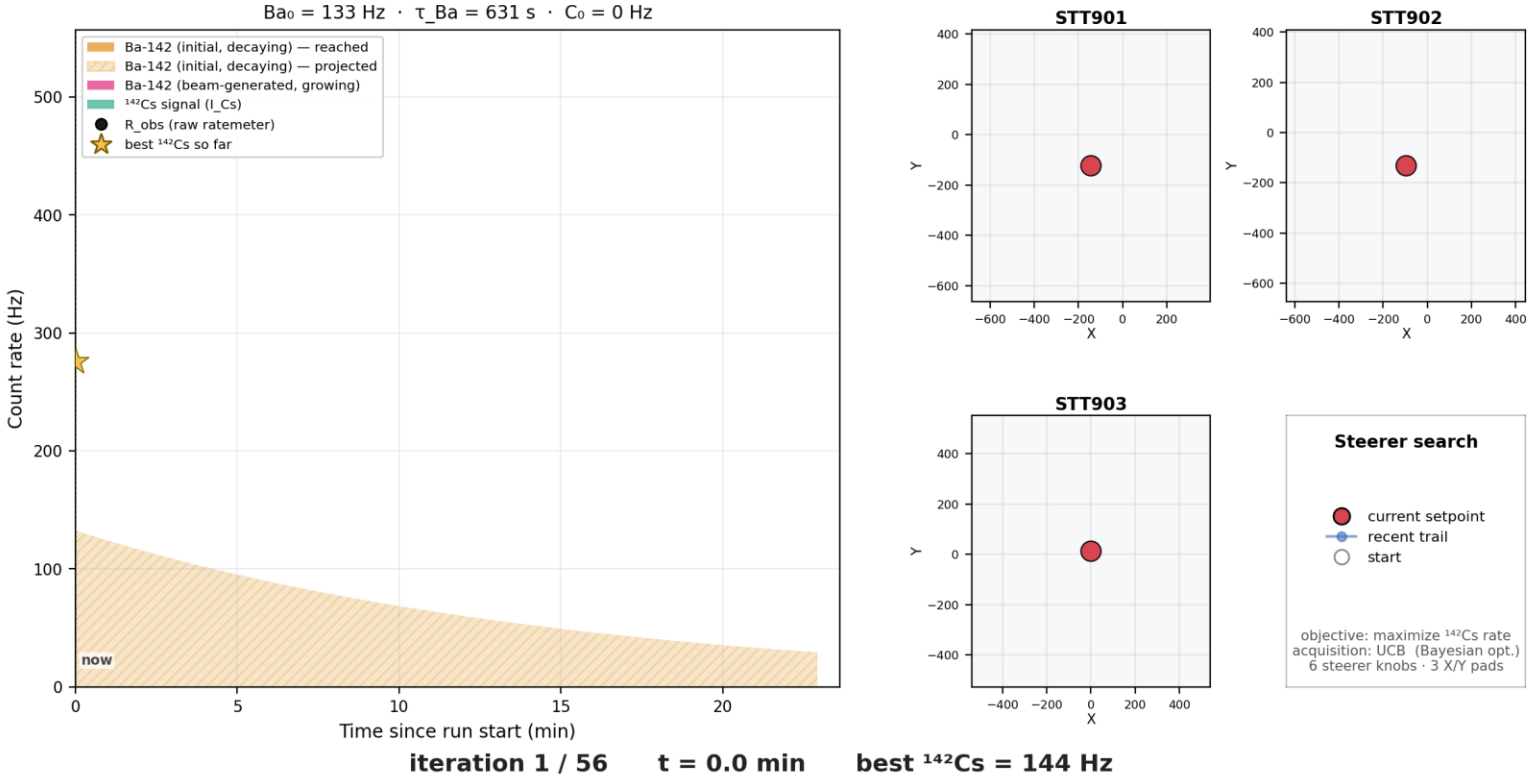
DEPLOYMENT EXAMPLE

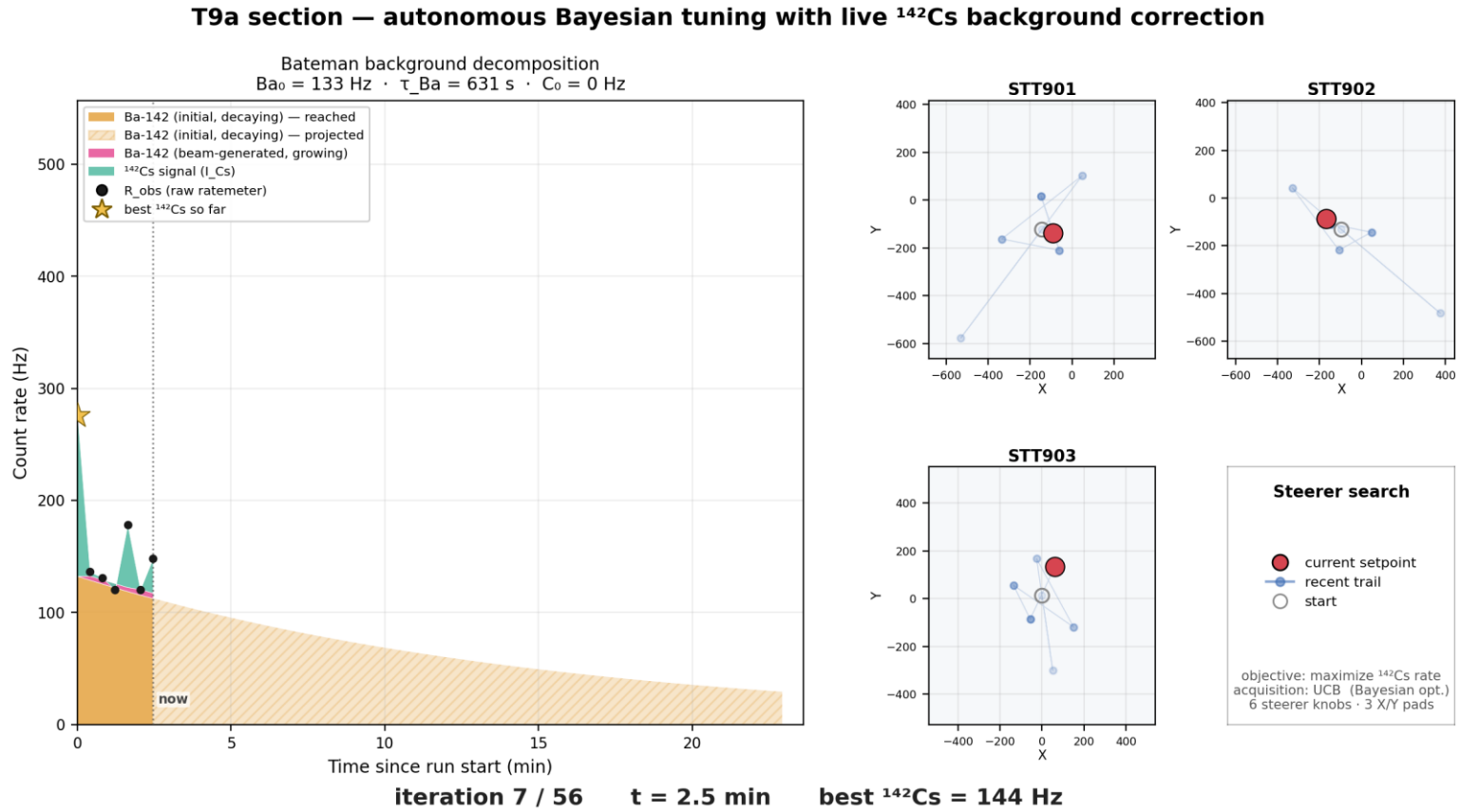
EXAMPLE OF LIVE BEAM TUNING AUTOMATION

USING AI/ML TOOL FOR RAD. BEAM TUNING

Showing only one beam line section (many more not shown here)



USING AI/ML TOOL FOR RAD. BEAM TUNING



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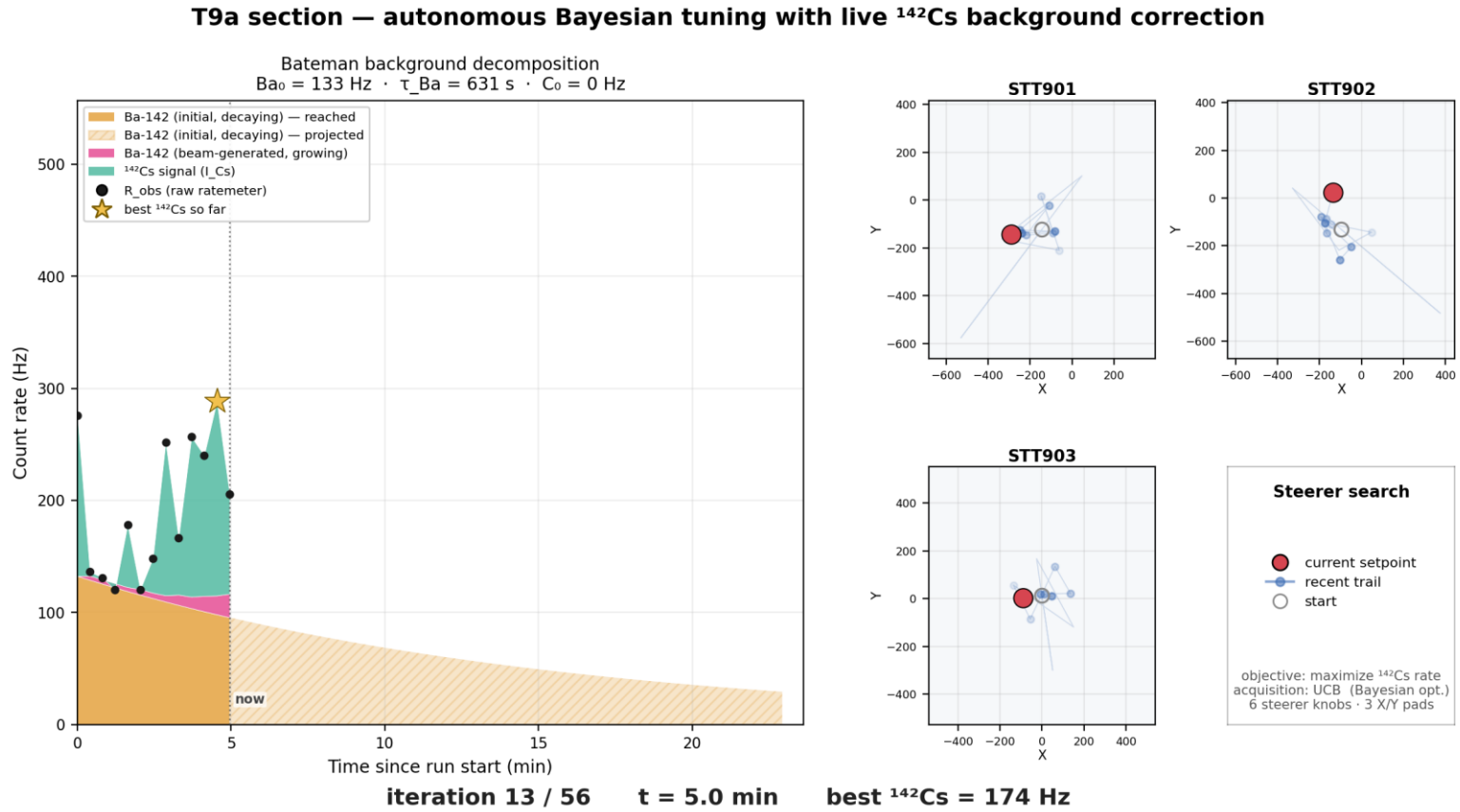

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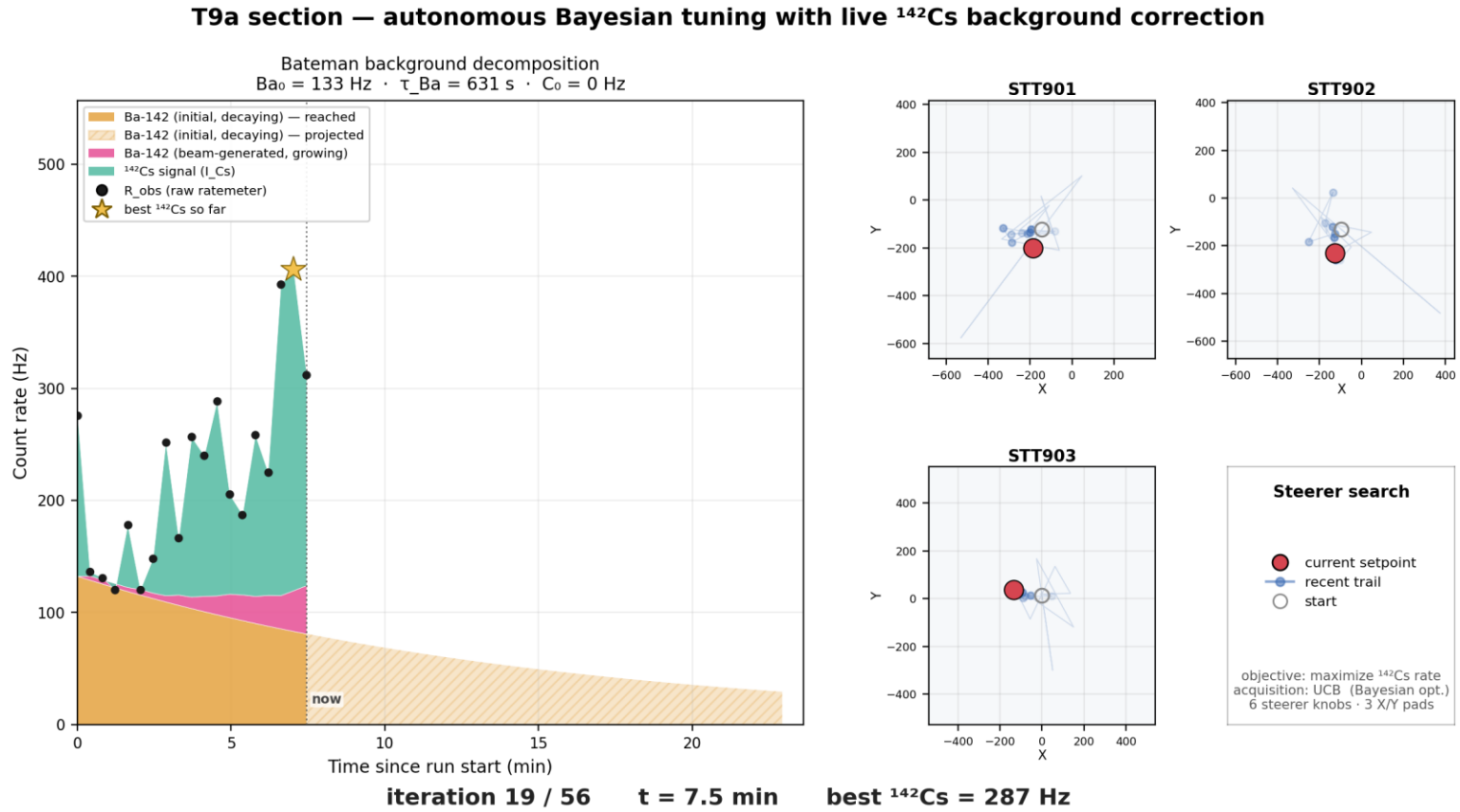

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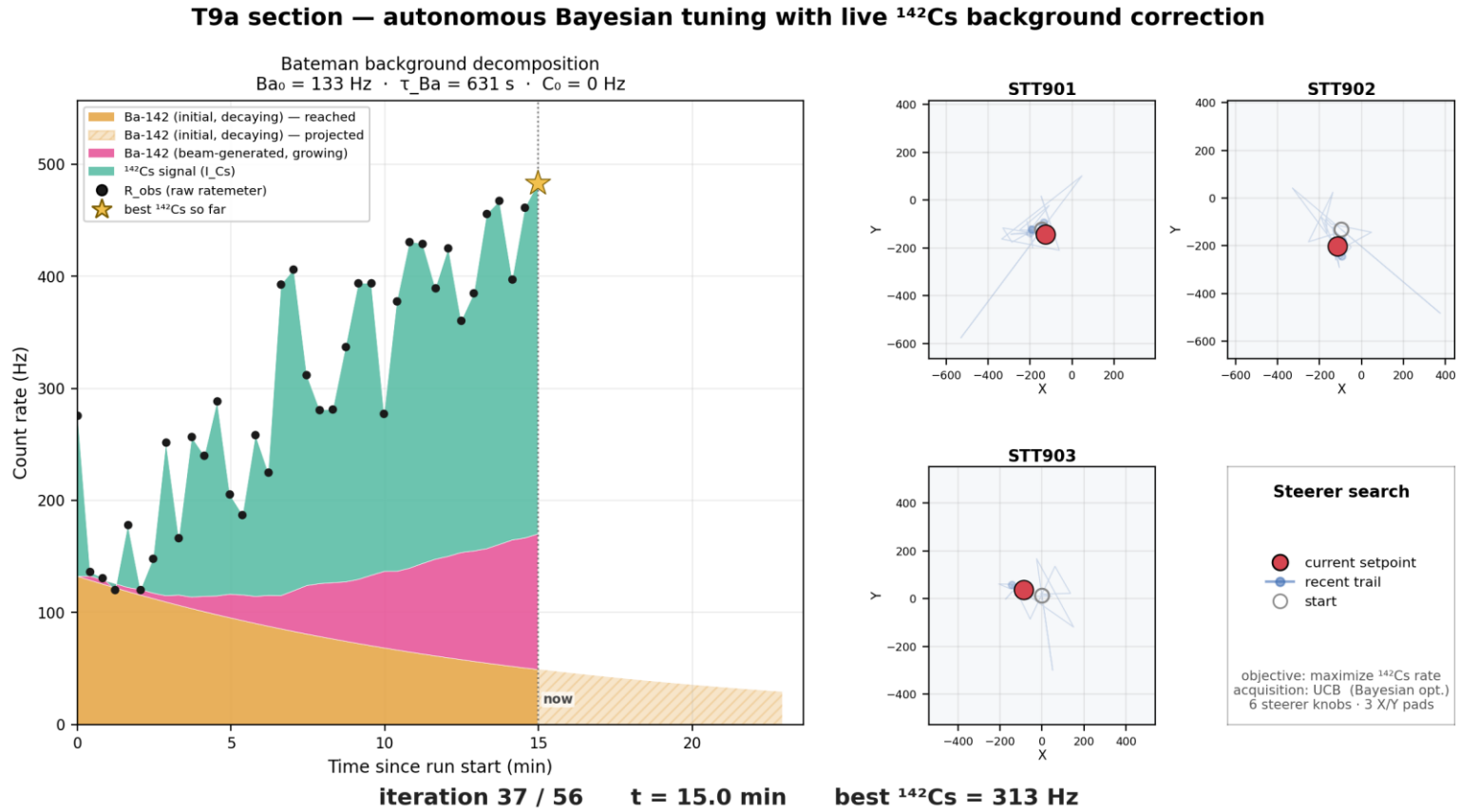

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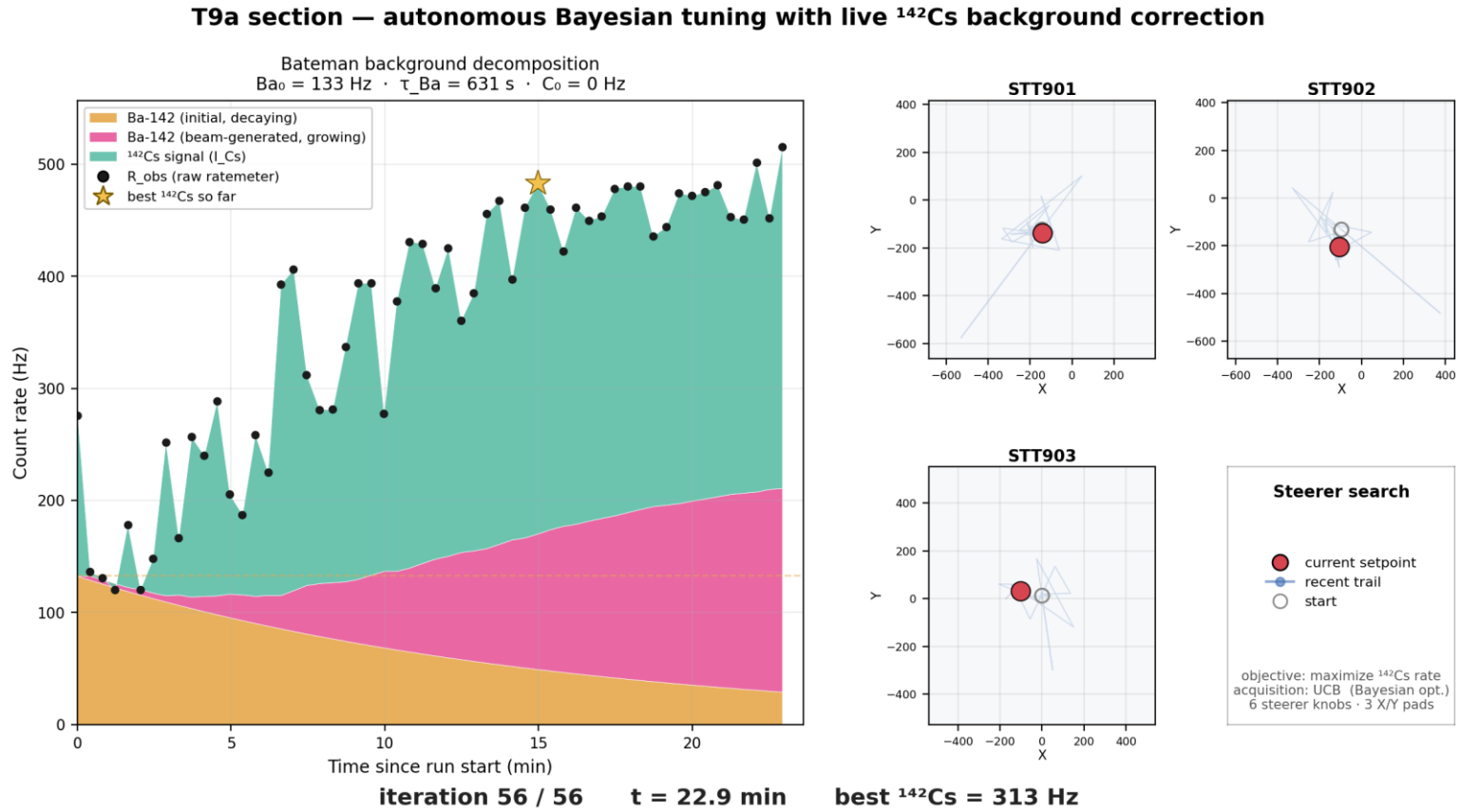

WRAPPING UP

SOME LESSONS I'VE LEARNED

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From this and other AI/ML efforts for accelerator operations

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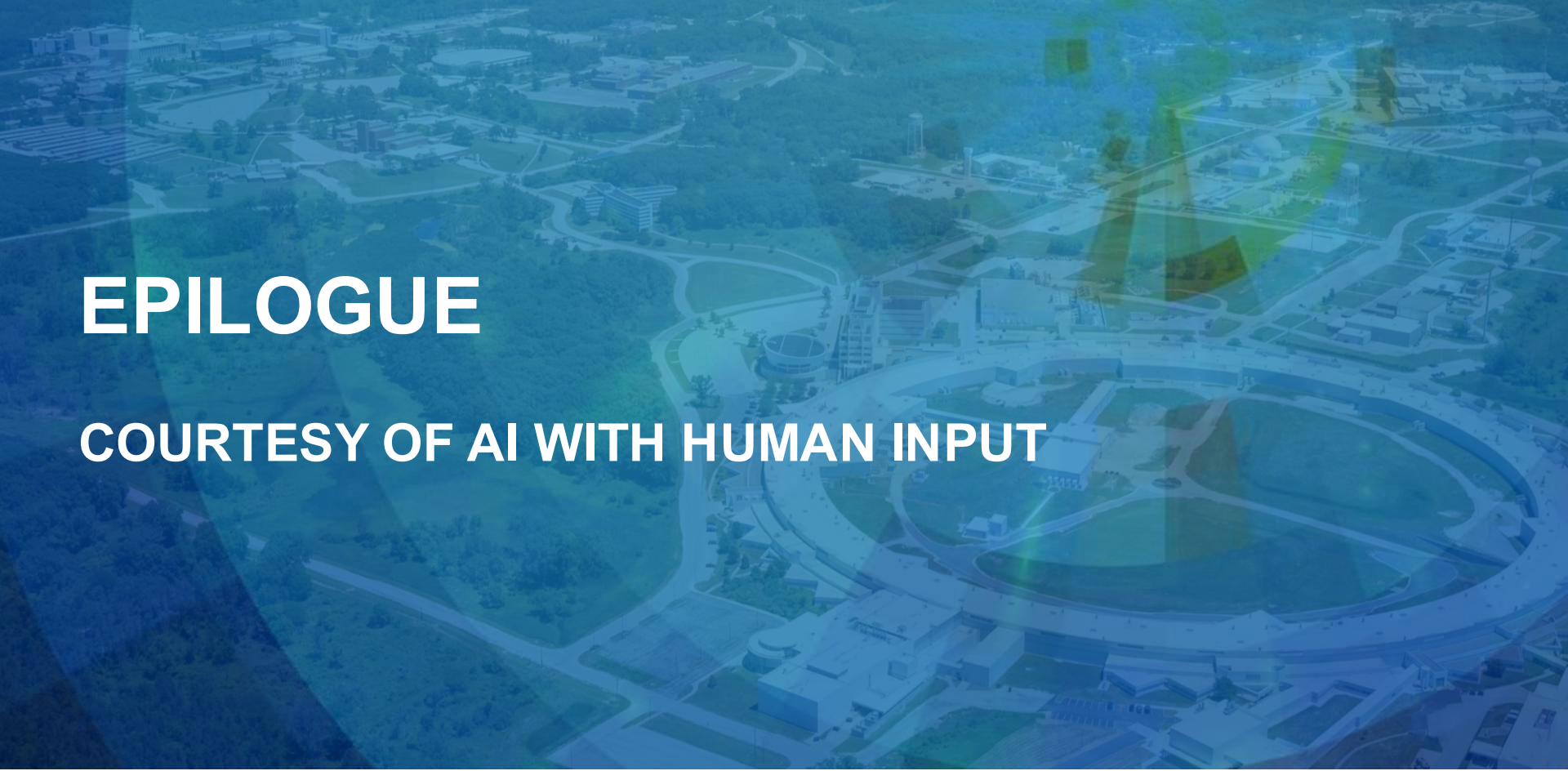
7. Gain momentum from rapid application deployment: quick prototyping and iterative user feedback



EPILOGUE

COURTESY OF AI WITH HUMAN INPUT

BACKUP SLIDES

LIST OF PUBLICATIONS

From our work on AI

Journal papers

"AI-Assisted Transport of Radioactive Ion Beams", S. Lopez-Caceres, D. Santiago-Gonzalez, Phys. Rev. Accel & Beams (2025, under review). Preprint available at: https://arxiv.org/abs/2504.06469

“Bayesian optimization algorithms for accelerator physics”, R. Roussel et al, Phys. Rev. Accel. & Beams 27, 084801 (2024).

“Predicting beam transmission using 2-dimensional phase space projections of hadron Accelerators”, A. Tran et al, Front. Phys. 10:955555 (2022), doi: 10.3389/fphy.2022.955555

Conference papers

“Beam Tomography using MCMC”, A. Tran et al, in Proceedings of IPAC’24 Conference, Nashville, Tennessee, May 2024.

“Real-time Bayesian Optimization with Deep Kernel Learning and NN-Prior Mean for Accelerator Operations”, J. Martinez and B. Mustapha, in Proceedings of IPAC’23 Conference, Venice, Italy, May 2023.

“Beam Tomography with Coupling using Maximum Entropy Technique”, A. Tran and Y. Hao, in Proceedings of IPAC’23 Conference, Venice, Italy, May 2023.

“Machine Learning to support the ATLAS Linac Operations at Argonne”, B. Mustapha et al, 3rd ICFA Workshop on Machine Learning for Accelerators, Chicago, Illinois, November 2022.

“Relating Initial Distribution to Beam Loss on the Front End of a Heavy-Ion Linac using Machine Learning”, A. Tran et al, in Proceedings of NAPAC’22, Albuquerque, New Mexico, August 2022.

“Model-based Calibration of Control Parameters at the Argonne Wakefield Accelerator”, I. Sugrue et al, in Proceedings of NAPAC’22, Albuquerque, New Mexico, August 2022.

“Reinforcement Learning and Bayesian Optimization for Ion Linac Operations”, J. Martinez et al, in Proceedings of HIAT’22 Conference, Darmstadt, Germany, June 2022.

“AI-ML Developments for the ATLAS Ion Linac Facility”, B. Mustapha et al, in Proceedings of IPAC’21 Conference, Campinas, Brazil, May 2021.

IN THE (ARGONNE AND DOE) NEWS

FEATURE STORY | ARGONNE NATIONAL LABORATORY

The next frontier in nuclear physics

How AI is supporting operations and revolutionizing research at ATLAS

News | Media Contacts | Experts Guide | Press Releases | Feature Stories | In the News | Soc

BY AMBER ROSE | MAY 8, 2025

Recent advancements at the ATLAS user facility are enhancing operations and efficiency to help unlock new insights into the universe's fundamental forces.

In the quest to solve fundamental mysteries about the universe, nuclear physics stands at the forefront, probing the very building blocks of matter and the forces that govern their interactions. At the U.S. Department of Energy's (DOE) Argonne National Laboratory, a prominent fixture in this exploration is the Argonne Tandem Linac Accelerator System (ATLAS), a DOE Office of Science user

DOE Office of Science Research News Update

US Department of Energy Office of Science sent this bulletin at 05/27/2025 10:25 AM EDT

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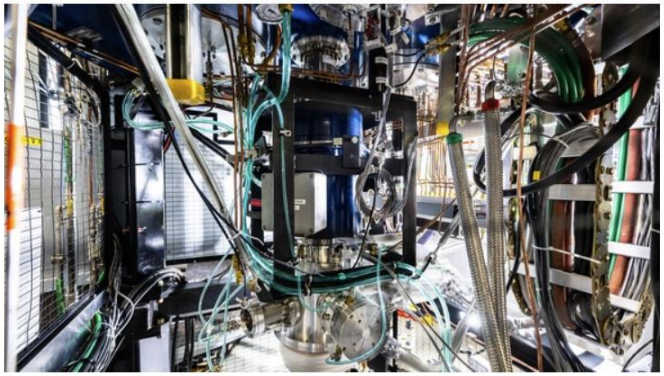
U.S. DEPARTMENT of ENERGY | Office of Science

RESEARCH NEWS UPDATE

27 May 2025

The Next Frontier in Nuclear Physics



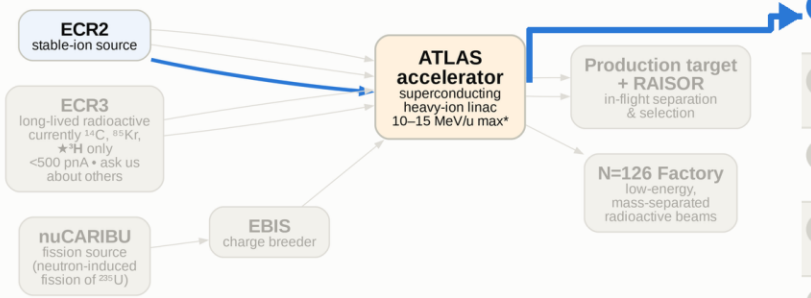
Nuclear physics examines the very building blocks of the matter that makes up everything we can detect. It also studies the fundamental forces of physics. Researchers investigate which forces bind protons and neutrons together in atoms, how these interactions result in elements, and what rare nuclei can show us about the origin of matter. Researchers at DOE's Argonne National Laboratory use the Argonne Tandem Linac Accelerator System (ATLAS), a DOE Office of Science user facility, to explore these issues. The team of researchers is exploring new ways to make ATLAS ever more effective, from using AI to creating a "digital twin" where scientists can test beam settings in a virtual space.

ATLAS BEAM TYPES AND CAPABILITIES

A high-level description

Pathway 1: Stable beams

everyday stable heavy-ion beams from ECR2



	Gamma-ray spectroscopy	Charged-particle spectroscopy	Reaction studies	Laser spectroscopy	Mass measurements	Accelerator Mass Spectrometry (AMS)
1 **Stable beams** *10–15 MeV/u* · 1–1000 pnA*	●	●	●	●		●
2 **Long-lived radioactive** ★ *10–15 MeV/u* · <500 pnA*	●	●	●			●
3 **In-flight radioactive** *10–15 MeV/u*, fast · <10⁶ pps*	●	●	●			
4 **N=126 Factory** *low energy, not accelerated*	◌			◌	●	
5 **nuCARIBU, accelerated** *10–15 MeV/u* · <10⁴ pps*	●	●	●			
6 **nuCARIBU, low-energy** *low energy · <10⁵ pps*	●			●	●	

● now ◌ planned ★ **new capability**

* 10–15 MeV/nucleon nominal max; heavier beams top out lower.

Other pathways are dimmed for clarity — see the full capabilities diagram for all six.

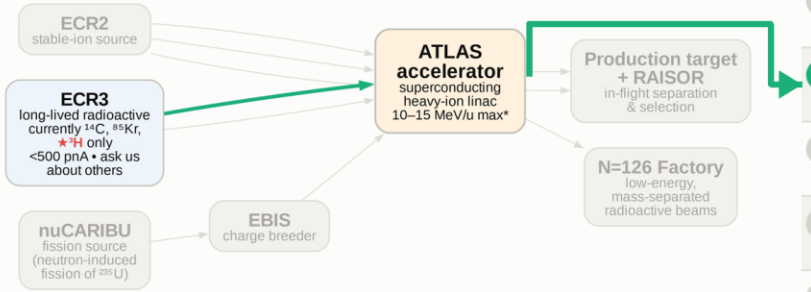
ATLAS BEAM TYPES AND CAPABILITIES

A high-level description

Pathway 2: Long-lived radioactive

the new ^{3}H (tritium) capability, from ECR3

First exp with intense 3H beam done Jul/2026
(4 AMeV, 500 pnA = 3E+12 pps)



	Gamma-ray spectroscopy	Charged-particle spectroscopy	Reaction studies	Laser spectroscopy	Mass measurements	Accelerator Mass Spectrometry (AMS)
1 Stable beams — *10–15 MeV/u* · 1–1000 pnA*	●	●	●	●		●
2 **Long-lived radioactive** ★ — *10–15 MeV/u* · <500 pnA*	●	●	●			●
3 In-flight radioactive — *10–15 MeV/u*, fast · <10^{6} pps*	●	●	●			
4 N=126 Factory — *low energy, not accelerated*	◌			◌	●	
5 nuCARIBU, accelerated — *10–15 MeV/u* · <10^{4} pps*	●	●	●			
6 nuCARIBU, low-energy — *low energy · <10^{5} pps*	●			●	●	

● now ◌ planned ★ **new capability**

* 10–15 MeV/nucleon nominal max; heavier beams top out lower.

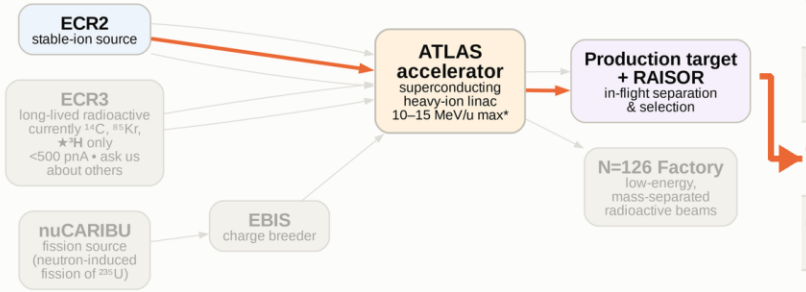
Other pathways are dimmed for clarity — see the full capabilities diagram for all six.

ATLAS BEAM TYPES AND CAPABILITIES

A high-level description

Pathway 3a: In-flight radioactive (RAISOR)

via ECR2 — stable-ion beam through the in-flight separator



	Gamma-ray spectroscopy	Charged-particle spectroscopy	Reaction studies	Laser spectroscopy	Mass measurements	Accelerator Mass Spectrometry (AMS)
1 Stable beams — *10–15 MeV/u* · 1–1000 pnA*	●	●	●	●		●
2 Long-lived radioactive ★ — *10–15 MeV/u* · <500 pnA*	●	●	●			●
3 **In-flight radioactive** — *10–15 MeV/u*, fast · <10⁶ pps*	●	●	●			
4 N=126 Factory — *low energy, not accelerated*	◌			◌	●	
5 nuCARIBU, accelerated — *10–15 MeV/u* · <10⁴ pps*	●	●	●			
6 nuCARIBU, low-energy — *low energy · <10⁵ pps*	●			●	●	

● now ◌ planned ★ **new capability**

* 10–15 MeV/nucleon nominal max; heavier beams top out lower.

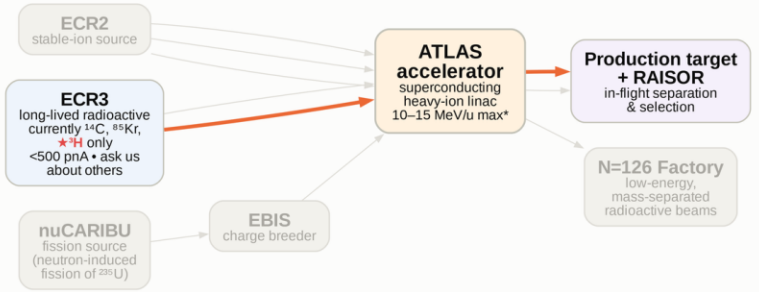
Other pathways are dimmed for clarity — see the full capabilities diagram for all six.

ATLAS BEAM TYPES AND CAPABILITIES

A high-level description

Pathway 3b: In-flight radioactive (RAISOR)

via ECR3 — long-lived radioactive beam through the in-flight separator



	Gamma-ray spectroscopy	Charged-particle spectroscopy	Reaction studies	Laser spectroscopy	Mass measurements	Accelerator Mass Spectrometry (AMS)
1 Stable beams — *10–15 MeV/u* · 1–1000 pnA*	●	●	●	●		●
2 Long-lived radioactive ★ — *10–15 MeV/u* · <500 pnA*	●	●	●			●
3 **In-flight radioactive** — *10–15 MeV/u*, fast · <10⁶ pps*	●	●	●			
4 N=126 Factory — *low energy, not accelerated*	◌			◌	●	
5 nuCARIBU, accelerated — *10–15 MeV/u* · <10⁴ pps*	●	●	●			
6 nuCARIBU, low-energy — *low energy · <10⁵ pps*	●			●	●	

● now ◌ planned ★ **new capability**

* 10–15 MeV/nucleon nominal max; heavier beams top out lower.

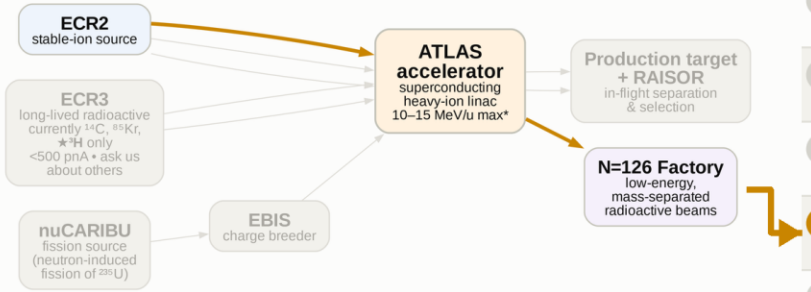
Other pathways are dimmed for clarity — see the full capabilities diagram for all six.

ATLAS BEAM TYPES AND CAPABILITIES

A high-level description

Pathway 4: N=126 Factory

low-energy, mass-separated radioactive beams



	Gamma-ray spectroscopy	Charged-particle spectroscopy	Reaction studies	Laser spectroscopy	Mass measurements	Accelerator Mass Spectrometry (AMS)
1 Stable beams — *10–15 MeV/u* · 1–1000 pnA*	●	●	●	●		●
2 Long-lived radioactive ★ — *10–15 MeV/u* · <500 pnA*	●	●	●			●
3 In-flight radioactive — *10–15 MeV/u*, fast · <10⁶ pps*	●	●	●			
4 **N=126 Factory** — *low energy, not accelerated*	◌			◌	●	
5 nuCARIBU, accelerated — *10–15 MeV/u* · <10⁴ pps*	●	●	●			
6 nuCARIBU, low-energy — *low energy · <10⁵ pps*	●			●	●	

● now ◌ planned ★ **new capability**

* 10–15 MeV/nucleon nominal max; heavier beams top out lower.

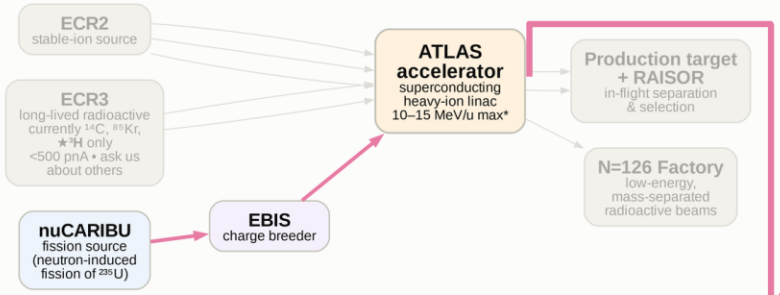
Other pathways are dimmed for clarity — see the full capabilities diagram for all six.

ATLAS BEAM TYPES AND CAPABILITIES

A high-level description

Pathway 5: nuCARIBU, accelerated

fission fragments, charge-bred and accelerated



	Gamma-ray spectroscopy	Charged-particle spectroscopy	Reaction studies	Laser spectroscopy	Mass measurements	Accelerator Mass Spectrometry (AMS)
1 Stable beams — *10–15 MeV/u* · 1–1000 pnA*	●	●	●	●		●
2 Long-lived radioactive ★ — *10–15 MeV/u* · <500 pnA*	●	●	●			●
3 In-flight radioactive — *10–15 MeV/u*, fast · <10⁶ pps*	●	●	●			
4 N=126 Factory — *low energy, not accelerated*	◌			◌	●	
5 **nuCARIBU, accelerated** — *10–15 MeV/u* · <10⁴ pps*	●	●	●			
6 nuCARIBU, low-energy — *low energy · <10⁵ pps*	●			●	●	

● now ◌ planned ★ **new capability**

* 10–15 MeV/nucleon nominal max; heavier beams top out lower.

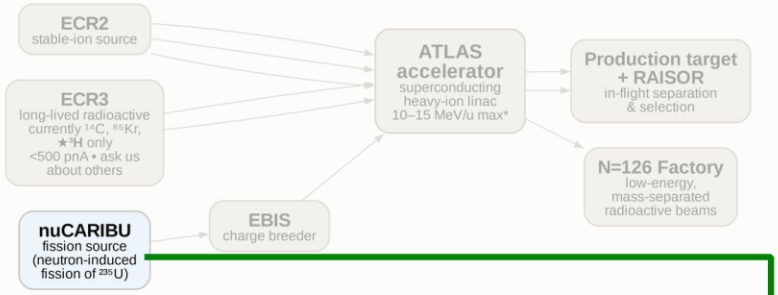
Other pathways are dimmed for clarity — see the full capabilities diagram for all six.

ATLAS BEAM TYPES AND CAPABILITIES

A high-level description

Pathway 6: nuCARIBU, low-energy

fission fragments delivered without acceleration



	Gamma-ray spectroscopy	Charged-particle spectroscopy	Reaction studies	Laser spectroscopy	Mass measurements	Accelerator Mass Spectrometry (AMS)
1 Stable beams — *10–15 MeV/u* · 1–1000 pnA*	●	●	●	●		●
2 Long-lived radioactive ★ — *10–15 MeV/u* · <500 pnA*	●	●	●			●
3 In-flight radioactive — *10–15 MeV/u*, fast · <10⁶ pps*	●	●	●			
4 N=126 Factory — *low energy, not accelerated*	◌			◌	●	
5 nuCARIBU, accelerated — *10–15 MeV/u* · <10⁴ pps*	●	●	●			
6 nuCARIBU, low-energy — *low energy · <10⁵ pps*	**●**			**●**	**●**	

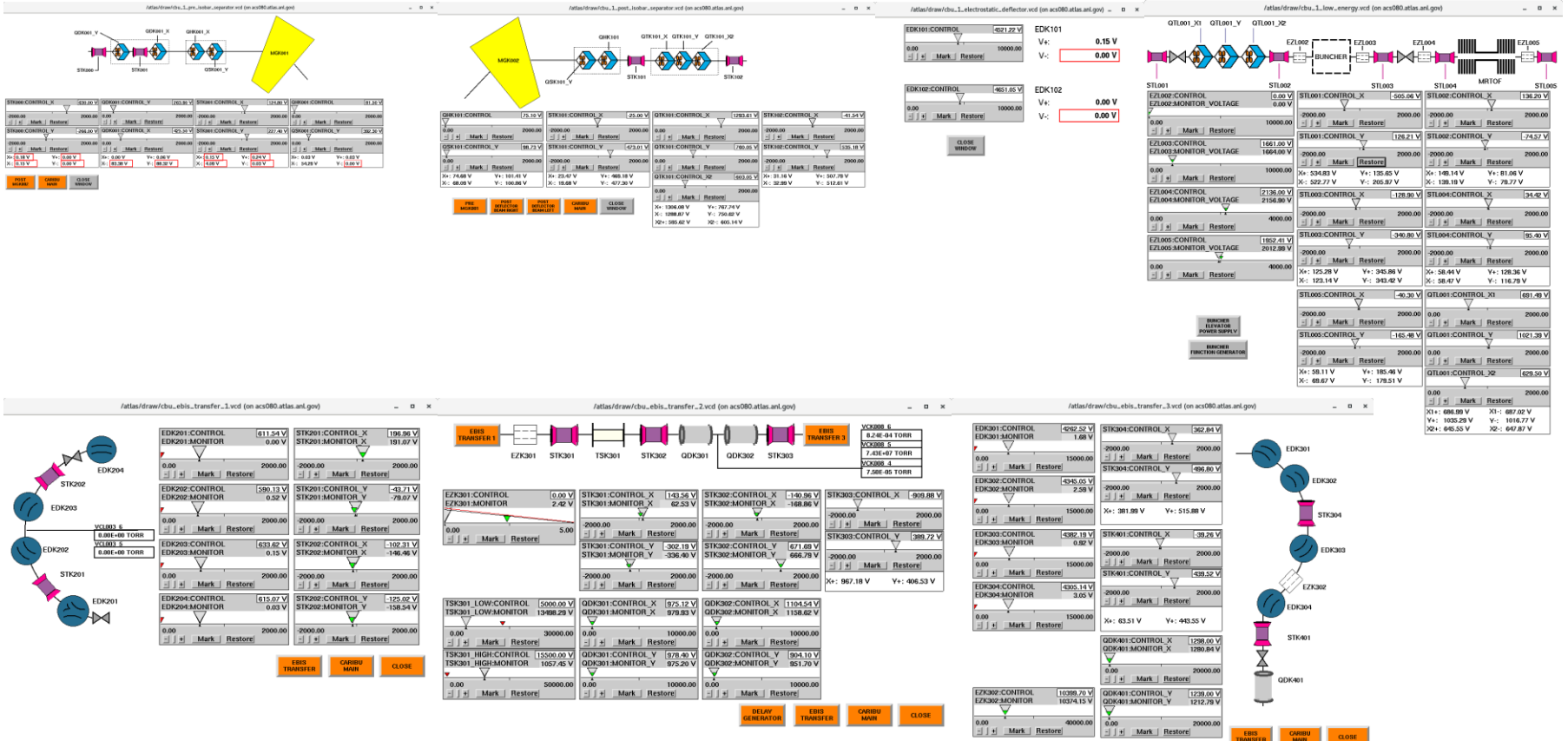
● now ◌ planned **★ new capability**

* 10–15 MeV/nucleon nominal max; heavier beams top out lower.

Other pathways are dimmed for clarity — see the full capabilities diagram for all six.

NUCARIBU CONTROLS

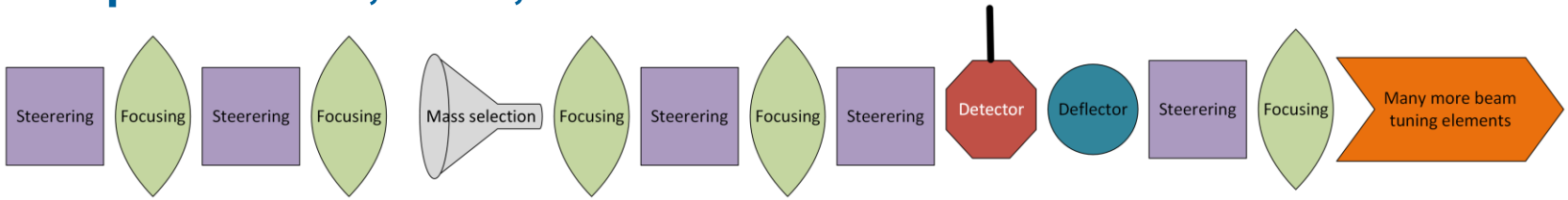
60+ control parameters on this slide (there are more not shown here)



NUCARIBU CONTROLS – SIMPLIFIED VIEW

inactive

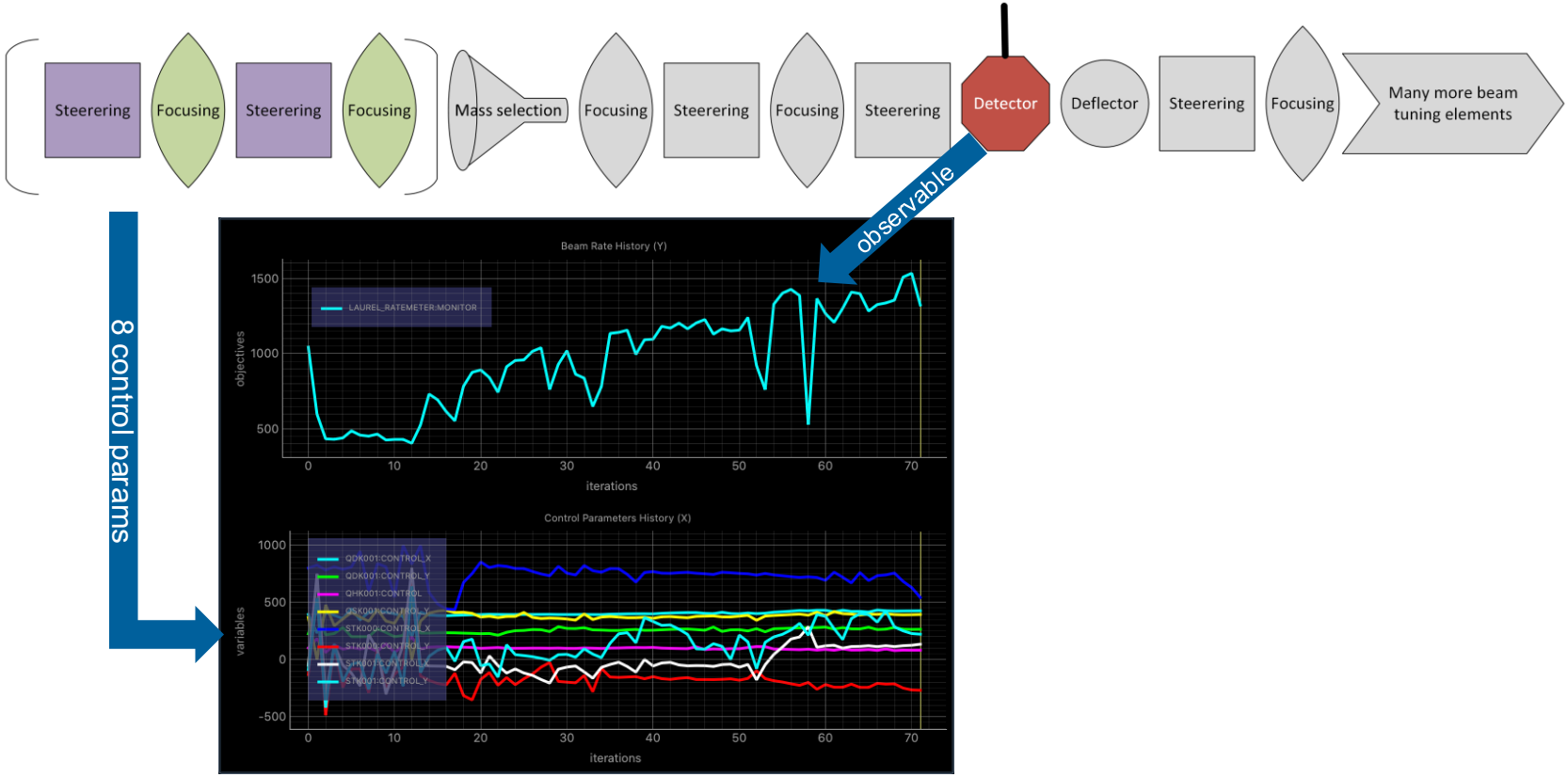
Transport: focus, steer, measure



NUCARIBU CONTROLS – SIMPLIFIED VIEW

Splitting in sections, each with 10 or less control parameters

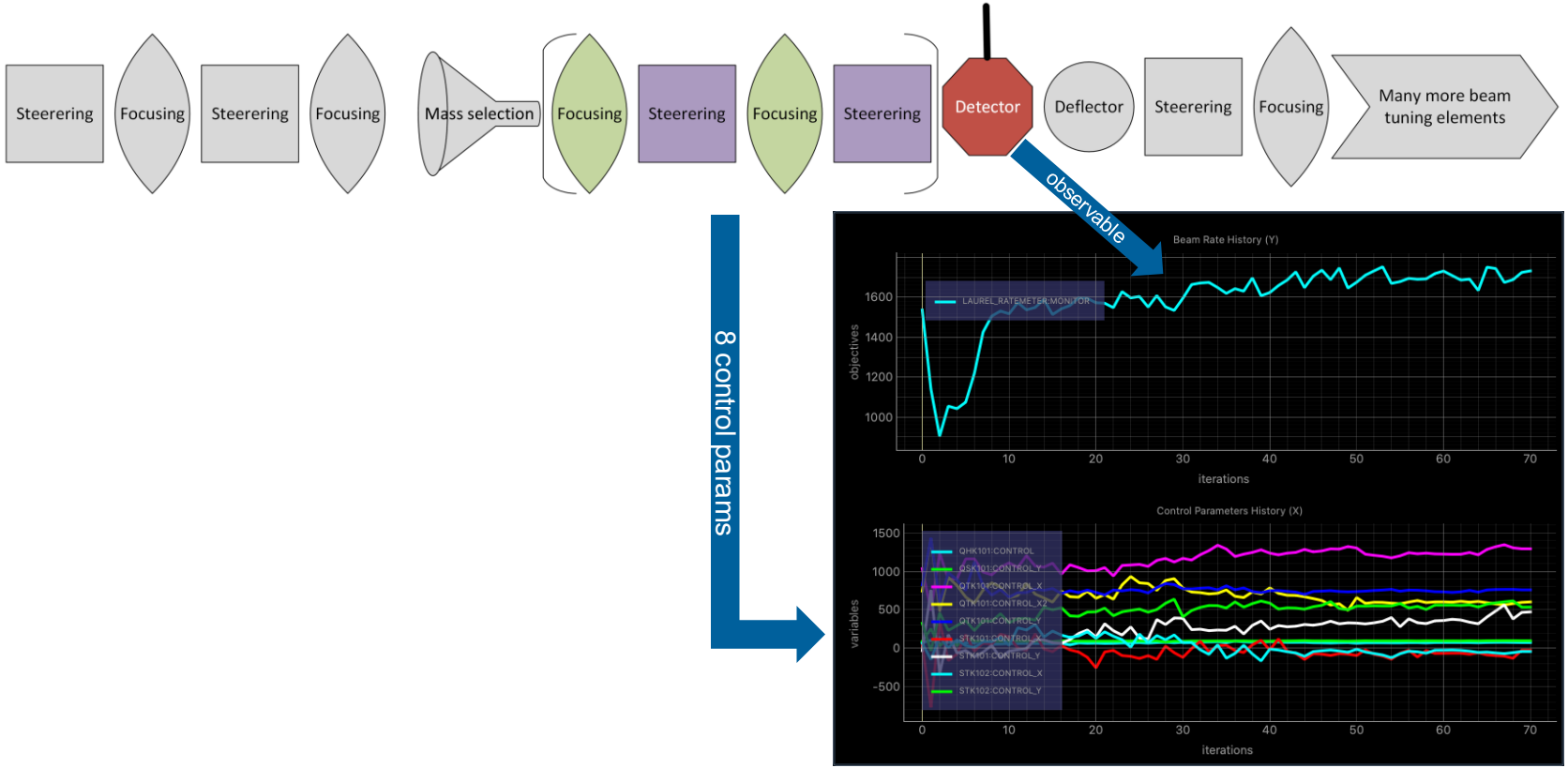
inactive



NUCARIBU CONTROLS – SIMPLIFIED VIEW

Splitting in sections, each with 10 or less control parameters

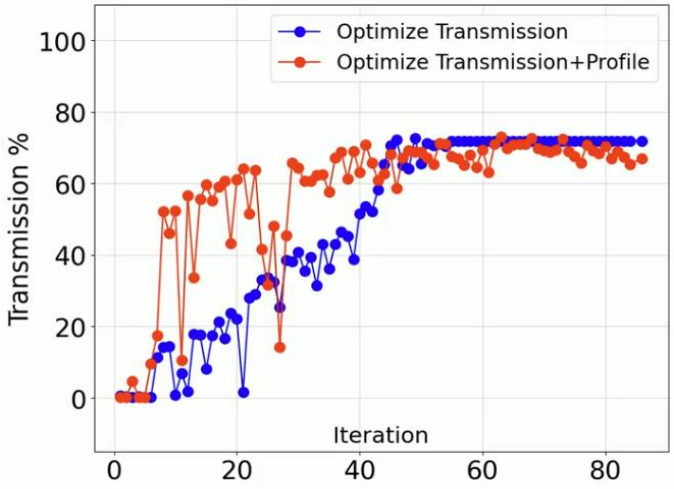
inactive

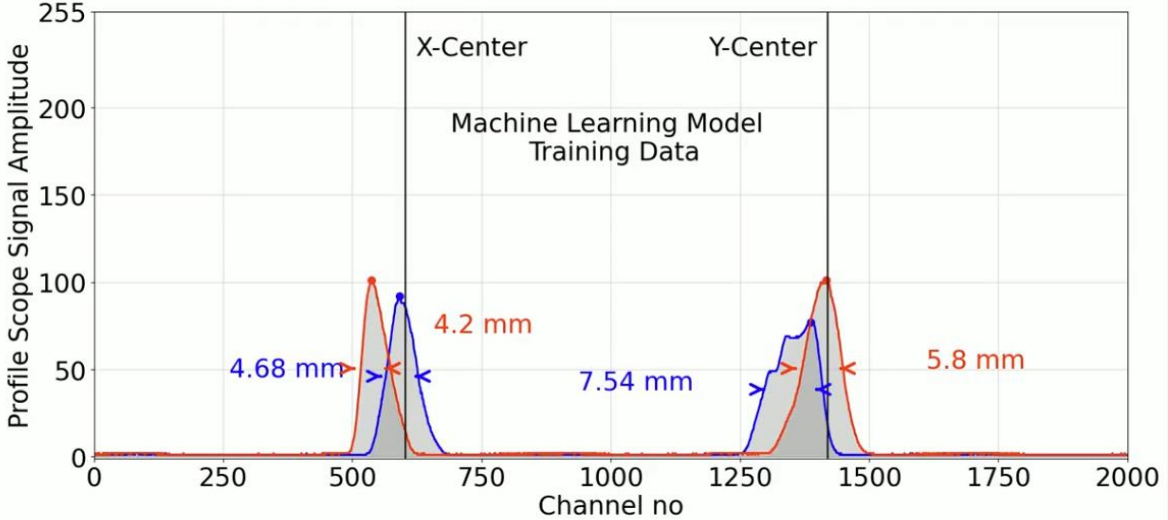


SELECTED RESULTS - REAL BENEFITS

Simultaneous transmission + beam shape optimization

Final configuration





Optimization time: ~7 minutes


Argonne
NATIONAL LABORATORY
Argonne Tandem Linac
Accelerator System
U.S. DEPARTMENT
of ENERGY