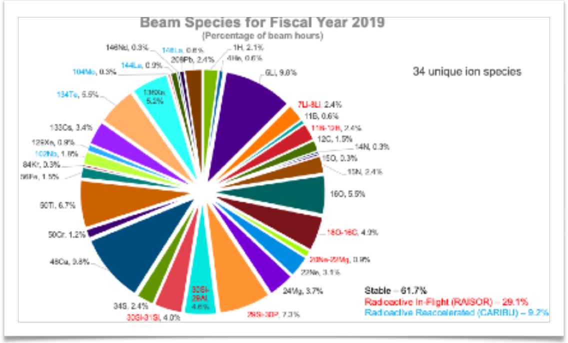
Autonomous Optimization of the Secondary Beam Production and Delivery at the ATLAS In-Flight Facility

DOE NP PI EXCHANGE
November 2022
FOA DE-FOA-0002490

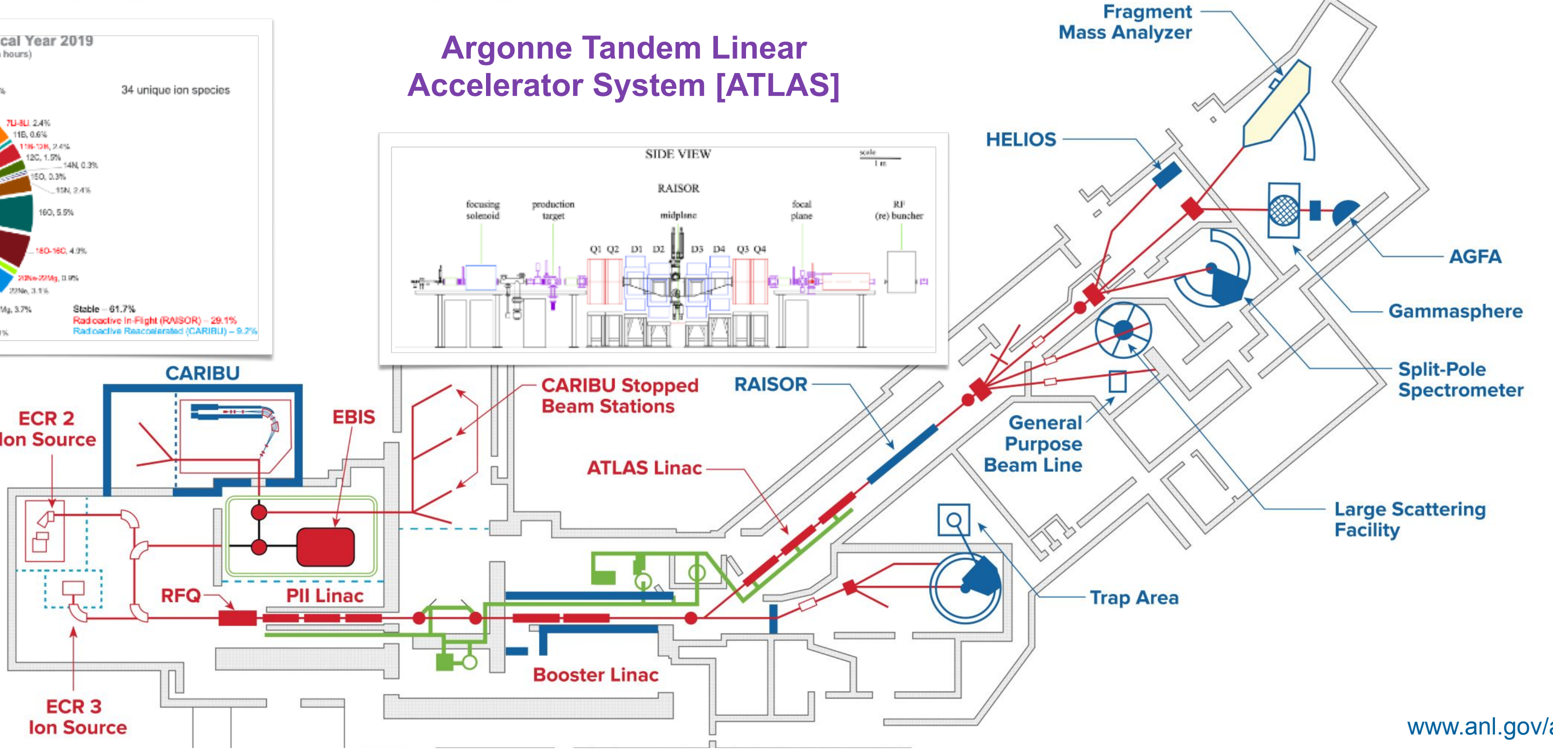
CALEM R. HOFFMAN (PI)
Physicist
Argonne National Laboratory

JEFFREY LARSON (CO-INV.)
Argonne National Laboratory

BACKGROUND ON THE IN-FLIGHT PROGRAM AT ATLAS



Argonne Tandem Linear Accelerator System [ATLAS]



www.anl.gov/atlas

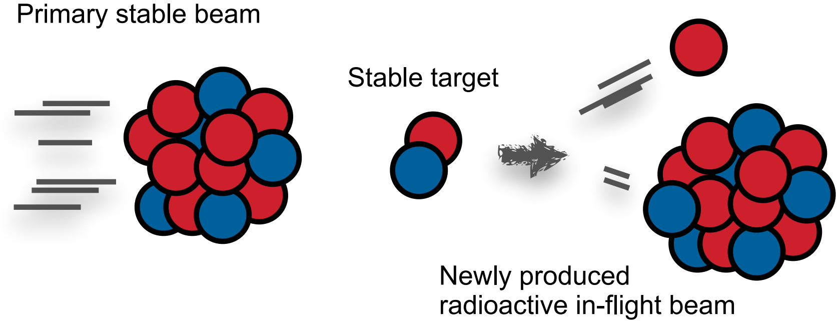
ATLAS ACCELERATOR FACILITY OVERVIEW

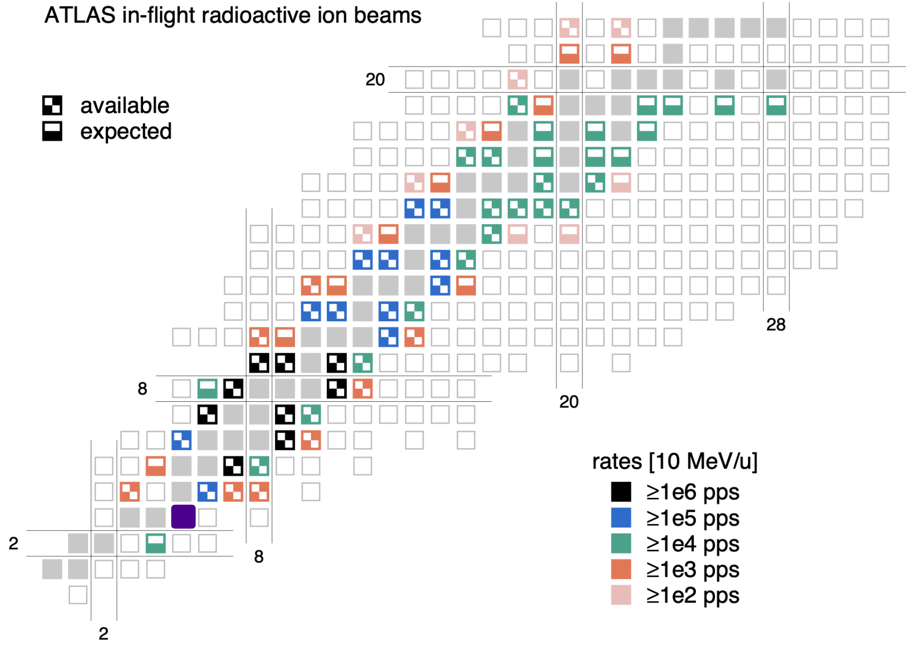
- US DOE National User Facility covering a broad range of nuclear science
- Few hundred Users per year, >6000 Hrs running time, range of experimental equipment
- High intensity stable beams up to ~18 MeV/u [100's of particle nA - uA]
- Radioactive beams [source/re-accelerated - nuCARIBU, in-flight - RAISOR]

Argonne NATIONAL LABORATORY

UTILIZE TRANSFER REACTIONS FOR IN-FLIGHT BEAM PRODUCTION

Highly selective, good kinematics & cross sections, multiple energy / beam+target options

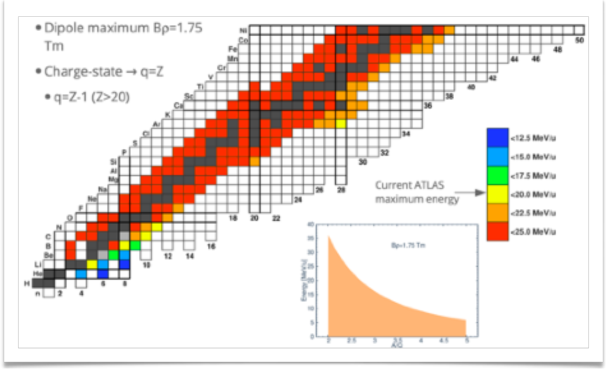




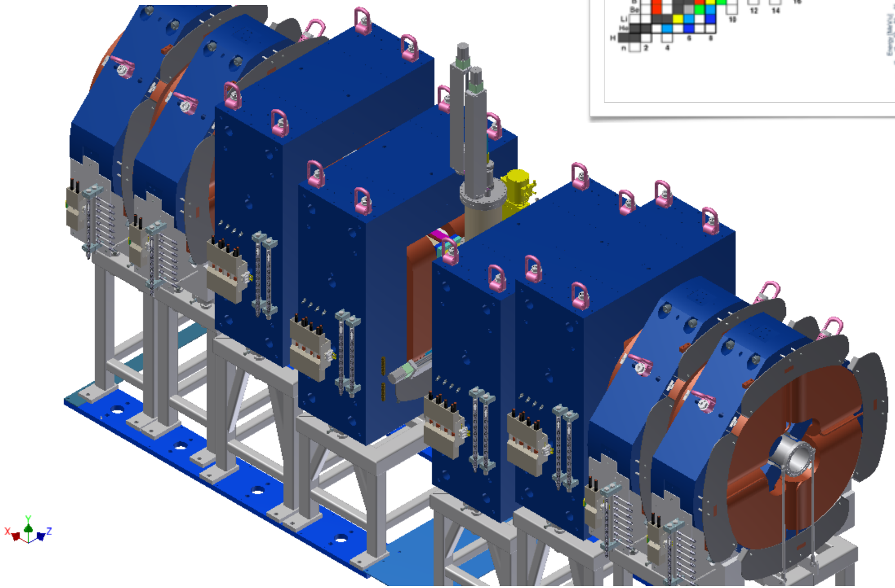
RAISOR DESIGN LAYOUT AND FEATURES

Multiple key design features considered & implemented

- Magnetic chicane w/ quadrupole doublet bookends
  - Momentum selection & stopping of primary beam current

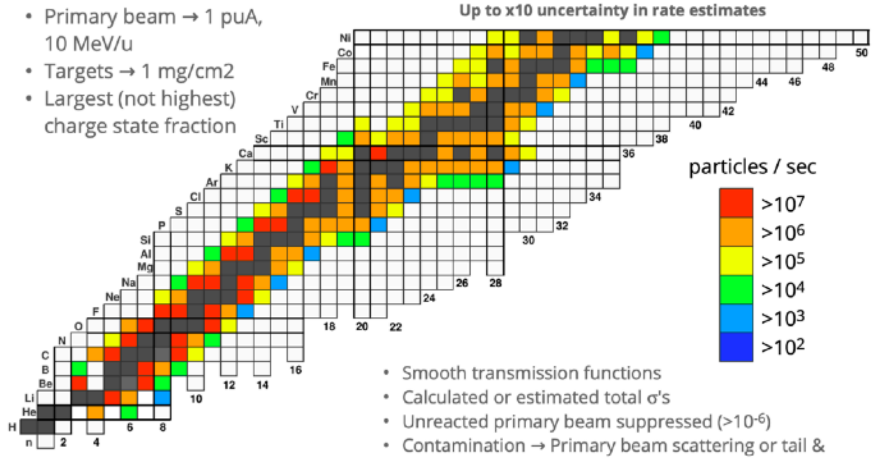


Total length	6.6 m
Angular acceptance	75 mrad
Mid plane dispersion	1.3 mm/%
Max rigidity [-30 cm]	1.75 Tm
Dipole field integral	0.73 Tm
Quadrupole pole tip	1 T
Dipole gap	8 cm
Quadrupole aperture	16 cm
Momentum acceptance	<20%



Argonne NATIONAL LABORATORY

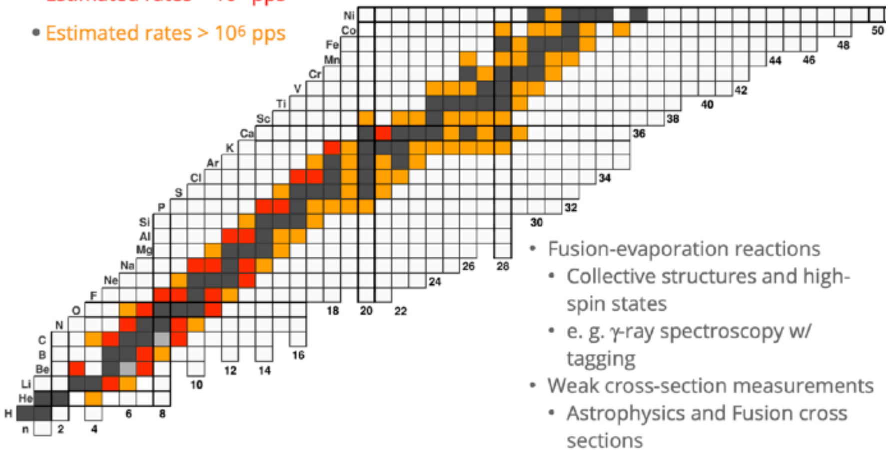
- Primary beam → 1 puA, 10 MeV/u
- Targets → 1 mg/cm2
- Largest (not highest) charge state fraction



- Smooth transmission functions
- Calculated or estimated total σ's
- Unreacted primary beam suppressed (>10^{-6})
- Contamination → Primary beam scattering or tail & other reaction channels
- > 25% transported to experimental areas

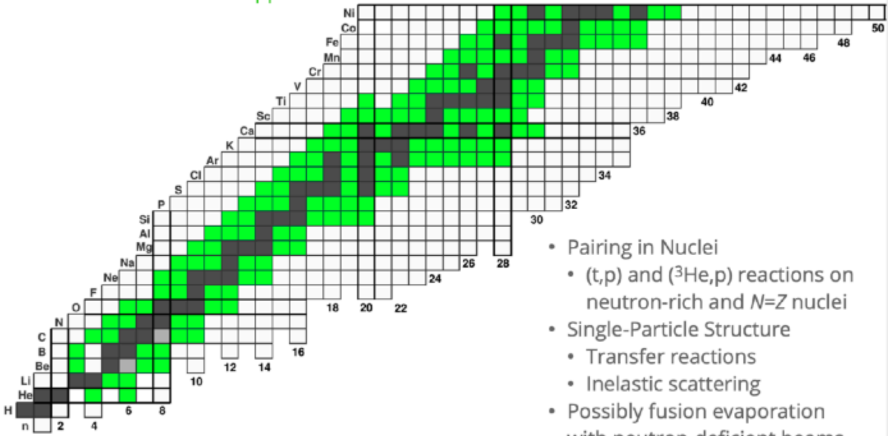
www.phy.anl.gov/airis/rates.html

- Estimated rates > 10^7 pps
- Estimated rates > 10^6 pps



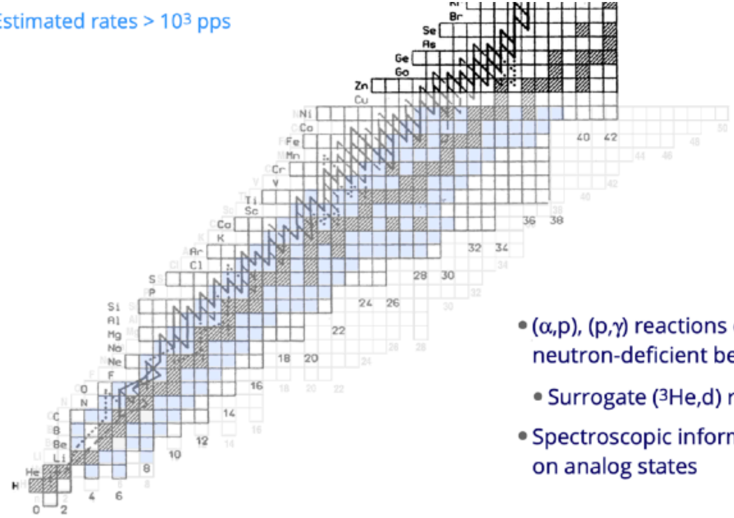
- Fusion-evaporation reactions
  - Collective structures and high-spin states
  - e. g. γ-ray spectroscopy w/ tagging
- Weak cross-section measurements
  - Astrophysics and Fusion cross sections
  - Transfer and fusion reactions

- Estimated rates > 10^4 pps



- Pairing in Nuclei
  - (t,p) and (^{3}He,p) reactions on neutron-rich and $N=Z$ nuclei
- Single-Particle Structure
  - Transfer reactions
  - Inelastic scattering
- Possibly fusion evaporation with neutron-deficient beams
  - ^{38}Ca, ^{42}Ti, ^{56}Ni, (^{60}Zn) etc.

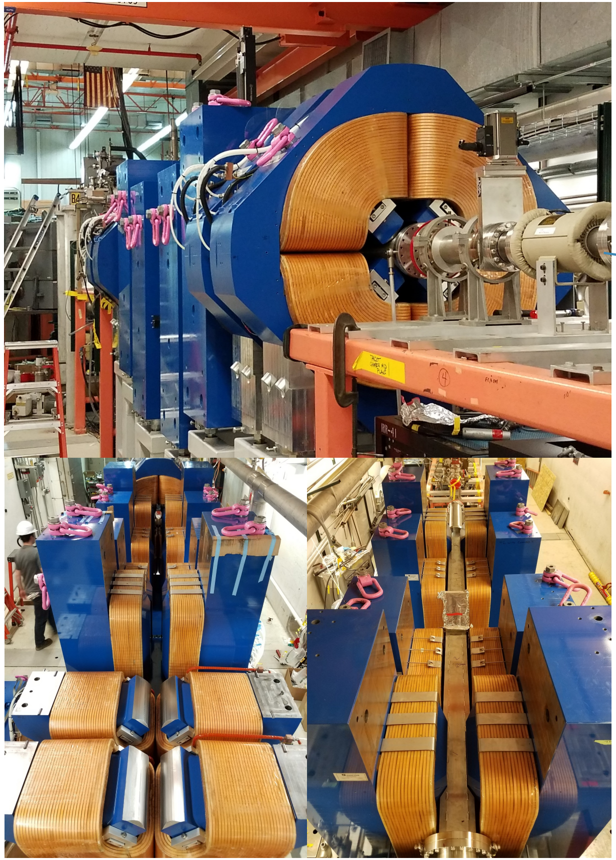
- Estimated rates > 10^3 pps



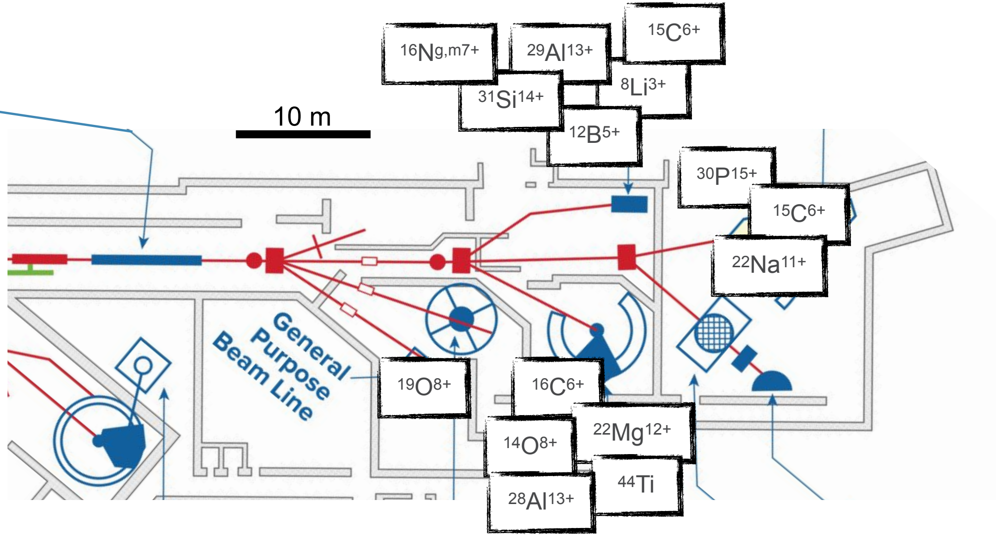
- (α,p), (p,γ) reactions on neutron-deficient beams
- Surrogate (^{3}He,d) reaction
- Spectroscopic information on analog states

RAISOR COMMISSIONING AND OPERATING PRINCIPLES

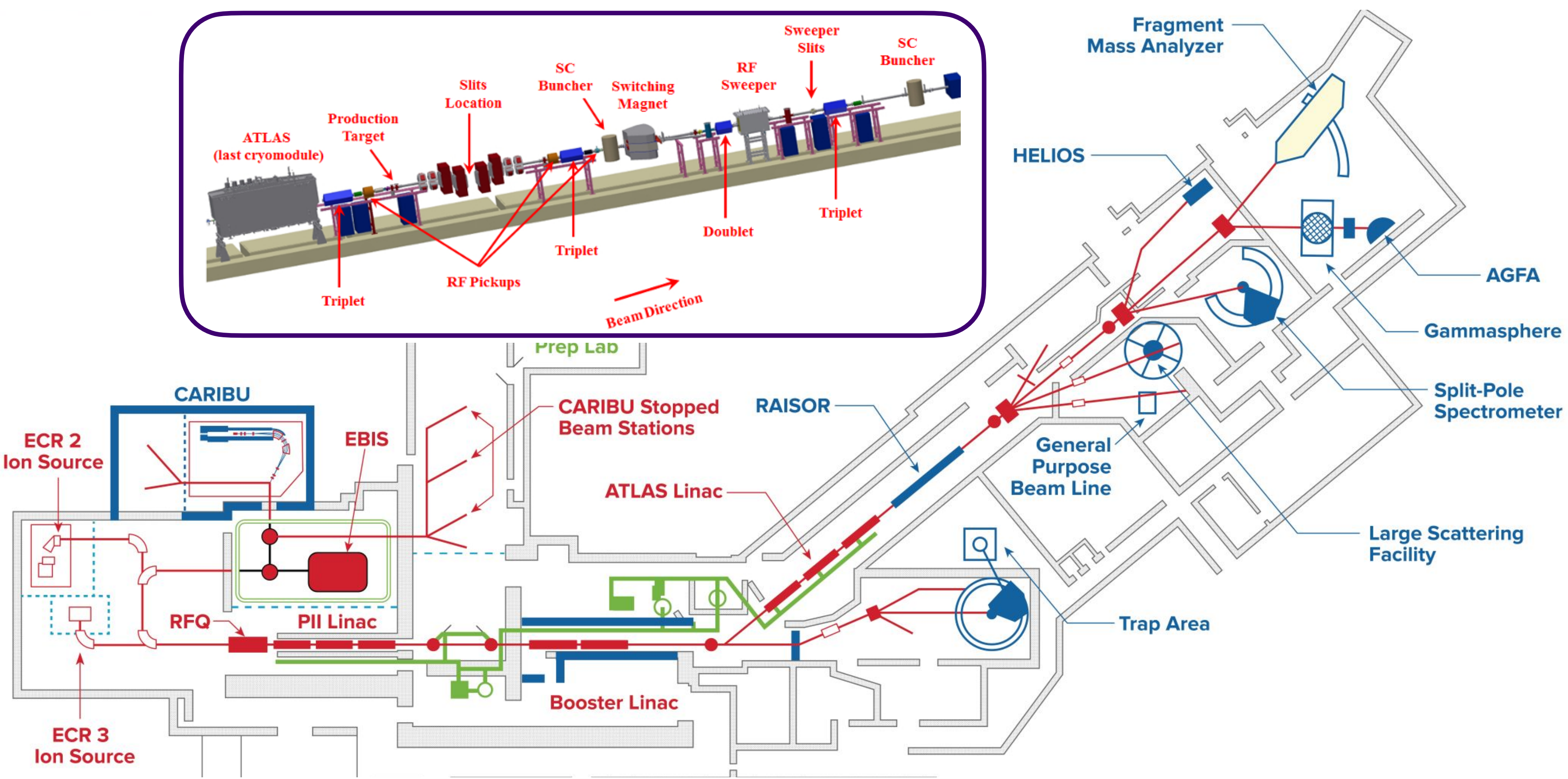
AIRIS project complete fall 2018, RAISOR has been in operation since 2019



>15 radioactive beam measurements at 4 different experimental locations [10's m downstream of RAISOR]

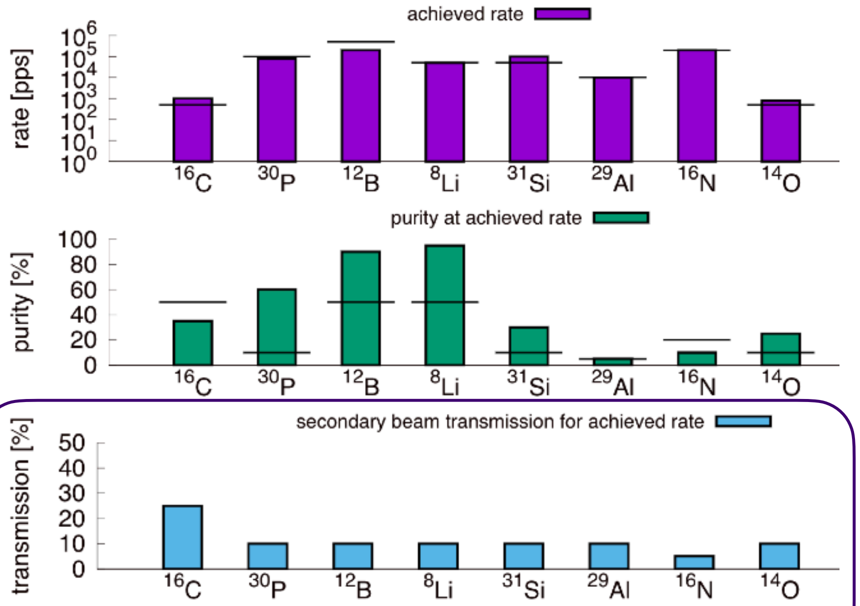


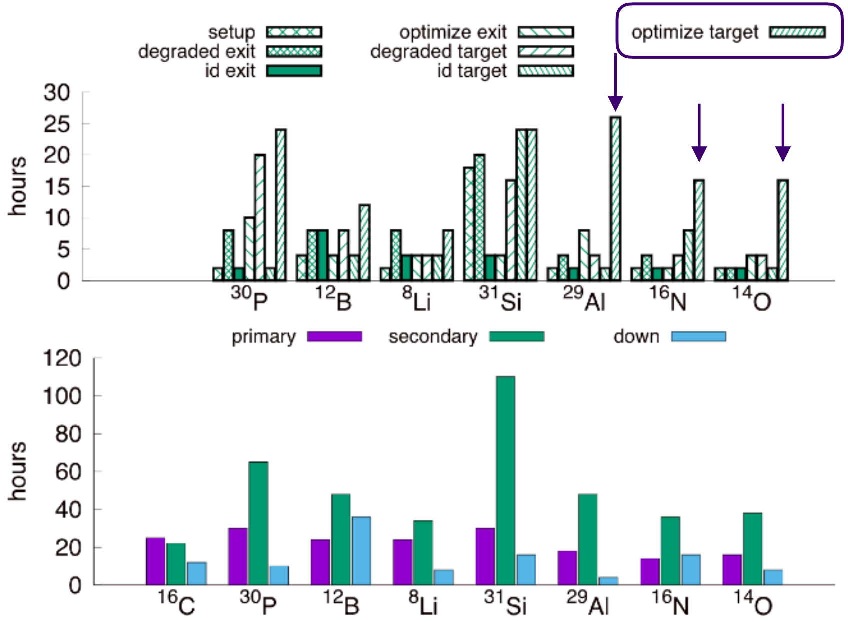
TRANSPORT BEAM LINES FROM RAISOR - TO - TARGET

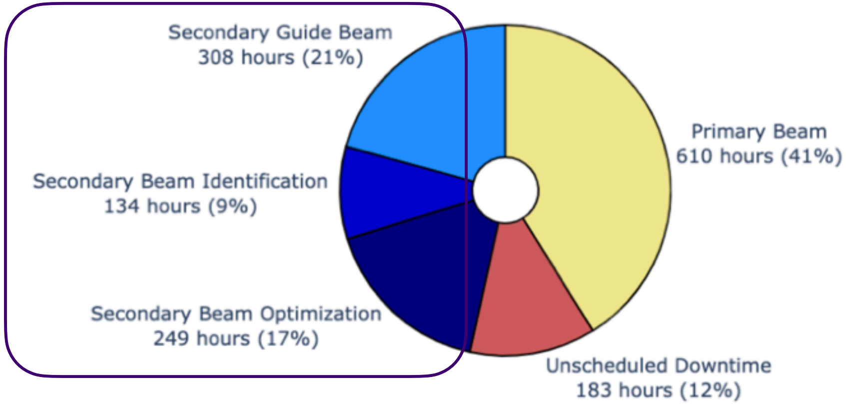


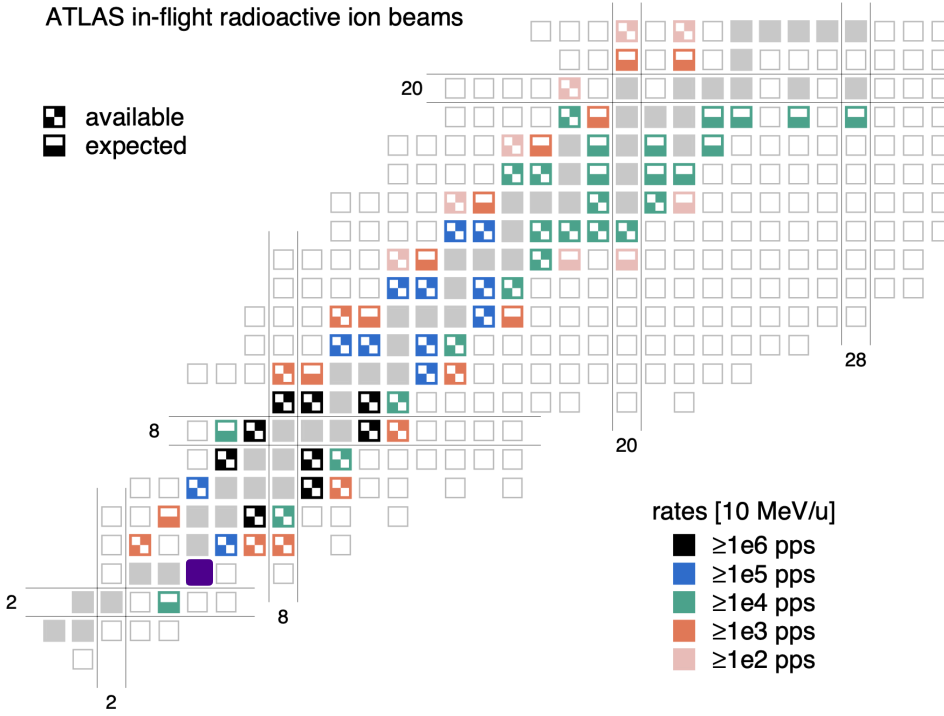
OPPORTUNITIES FOR IMPROVEMENT

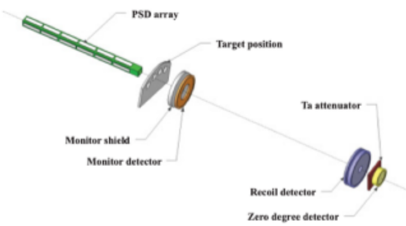
Some in-flight beam & tuning data

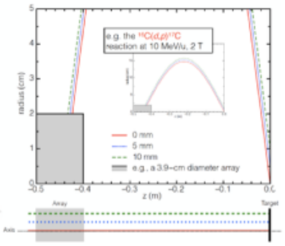


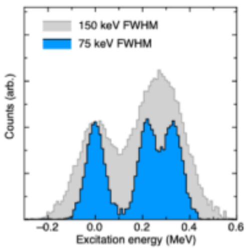












IMPROVE THE IN-FLIGHT BEAM QUALITY, TRANSMISSION, UP-TIME, AND DELIVERY TIMES
ENHANCED SCIENTIFIC POTENTIAL
= RETURN HOURS TO EXPERIMENTAL WORK =
= IMPROVED BEAM QUALITY, RELIABILITY, REPRODUCIBILITY =
= EXTEND THE REACH OF IN-FLIGHT BEAM PRODUCTION =

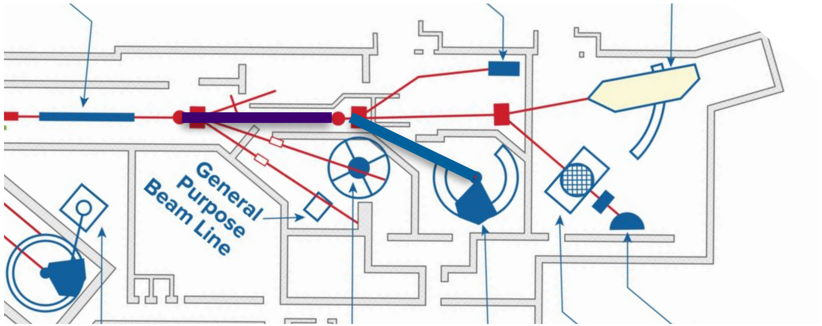
THE OPTSB PROJECT

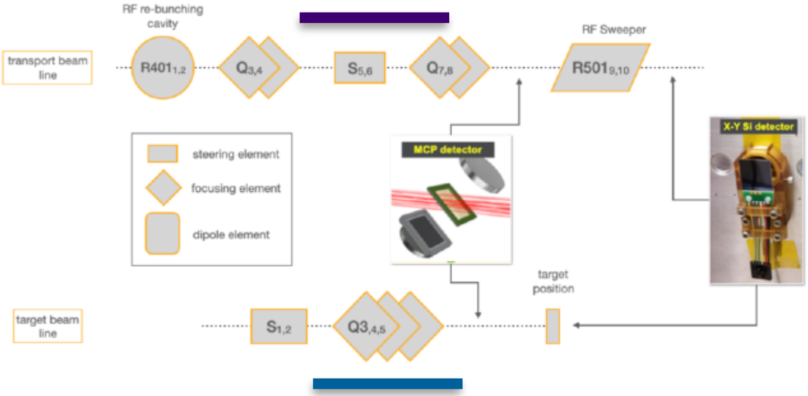
OPTSB: OPTIMIZATION OF SECONDARY BEAMS

Implement an autonomous system for optimizing the transport & delivery of secondary beams produced in-flight at ATLAS

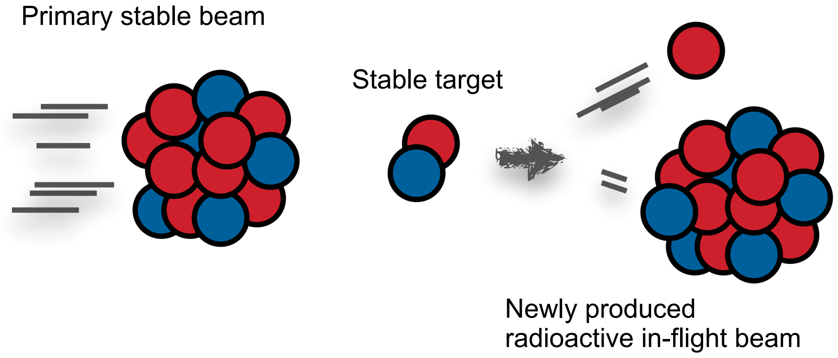
Major Deliverables:

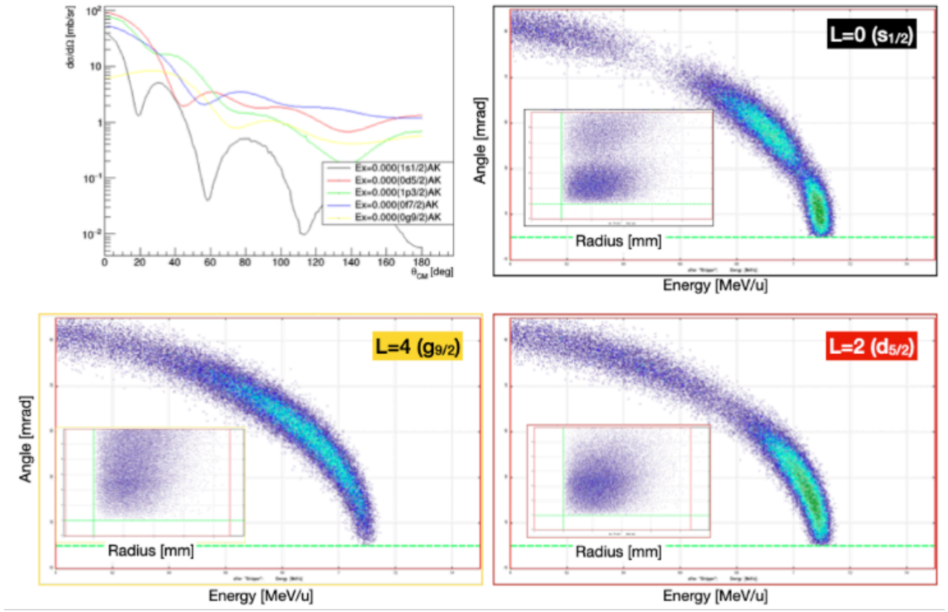
1. The optimization of the secondary beam profile onto an experimental target.
2. The optimization of the secondary beam purity and transport through the ATLAS transport beam line, including the RF components (the RF Sweeper and re-bunching RF cavity).



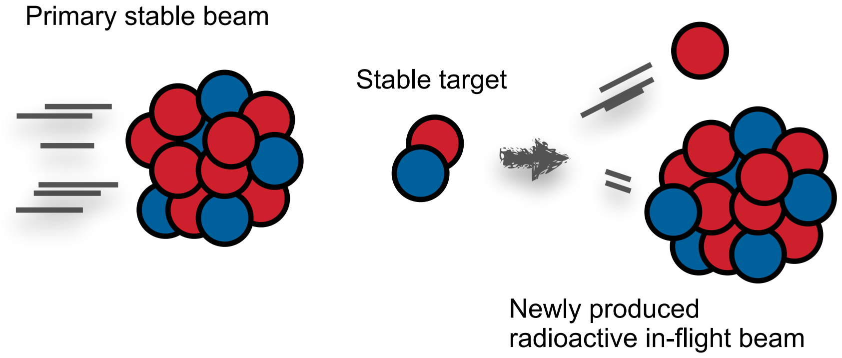


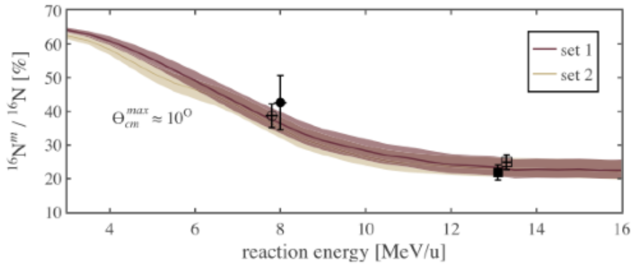
Argonne NATIONAL LABORATORY

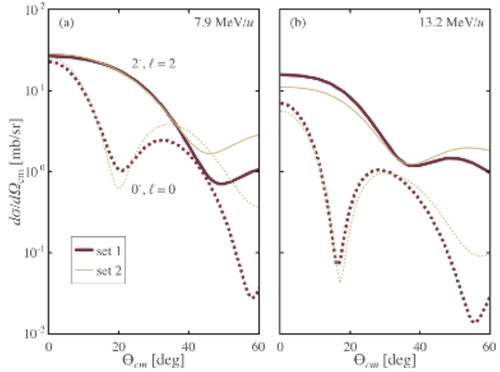




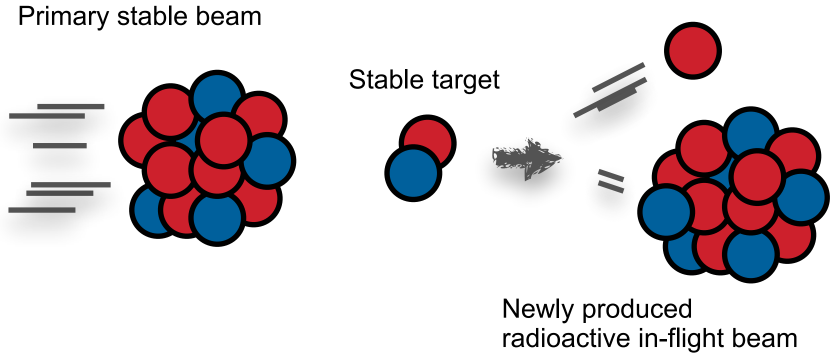
CHALLENGES FOR ATLAS IN-FLIGHT BEAMS
= TRANSFER REACTIONS W/ UNKNOWN ANGULAR DISTRIBUTIONS
= RANGES OF ENERGIES, INTENSITIES, REACTION TYPES REQUIRED
= ATLAS IS DOE U.S. STABLE BEAM USER FACILITY FOR 35+ YEARS

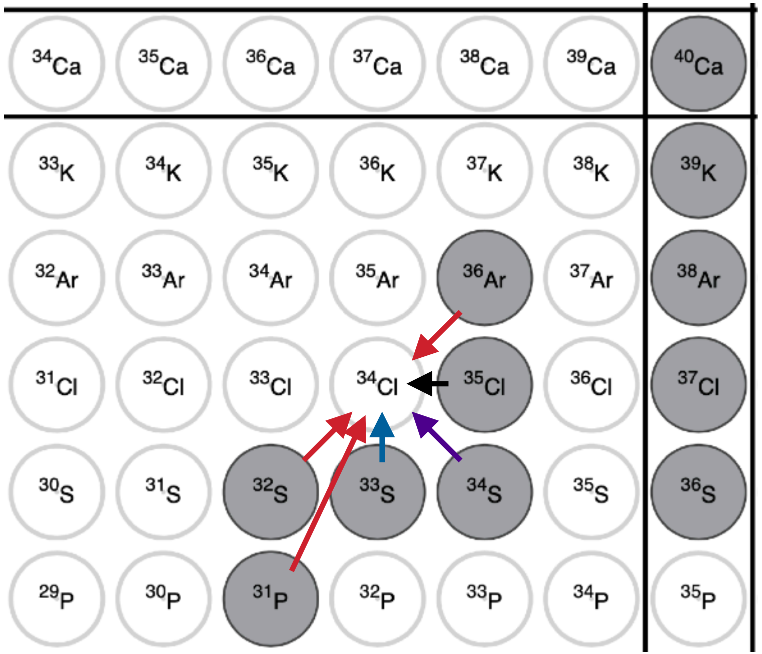






CHALLENGES FOR ATLAS IN-FLIGHT BEAMS
= TRANSFER REACTIONS W/ UNKNOWN ANGULAR DISTRIBUTIONS
= RANGES OF ENERGIES, INTENSITIES, REACTION TYPES REQUIRED
= ATLAS IS DOE U.S. STABLE BEAM USER FACILITY FOR 35+ YEARS





CHALLENGES FOR ATLAS IN-FLIGHT BEAMS

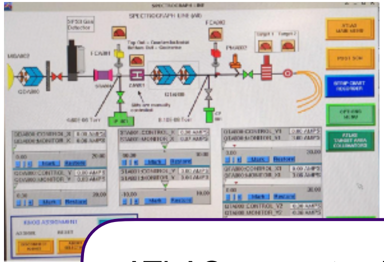
= TRANSFER REACTIONS W/ UNKNOWN ANGULAR DISTRIBUTIONS

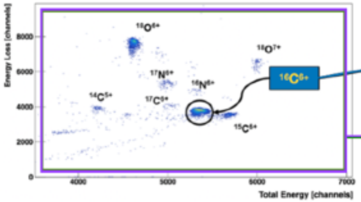
= RANGES OF ENERGIES, INTENSITIES, REACTION TYPES REQUIRED

= ATLAS IS DOE U.S. STABLE BEAM USER FACILITY FOR 35+ YEARS

OPTSB: OPTIMIZATION OF SECONDARY BEAMS

Complete data processing paradigm





A high-performance time series engine

ATLAS magnet values

DataBase [influxDB]

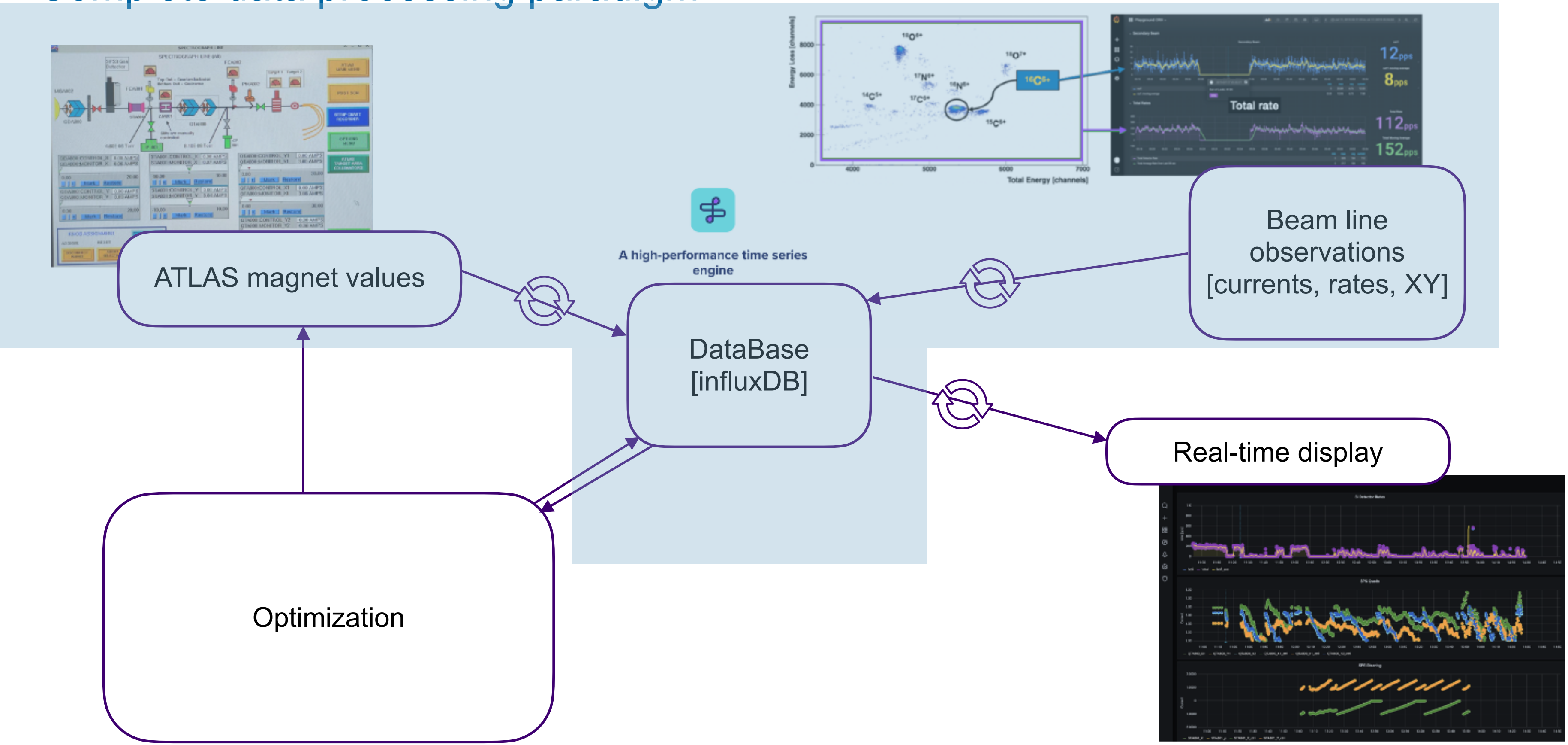
Beam line observations [currents, rates, XY]

Real-time display

Optimization

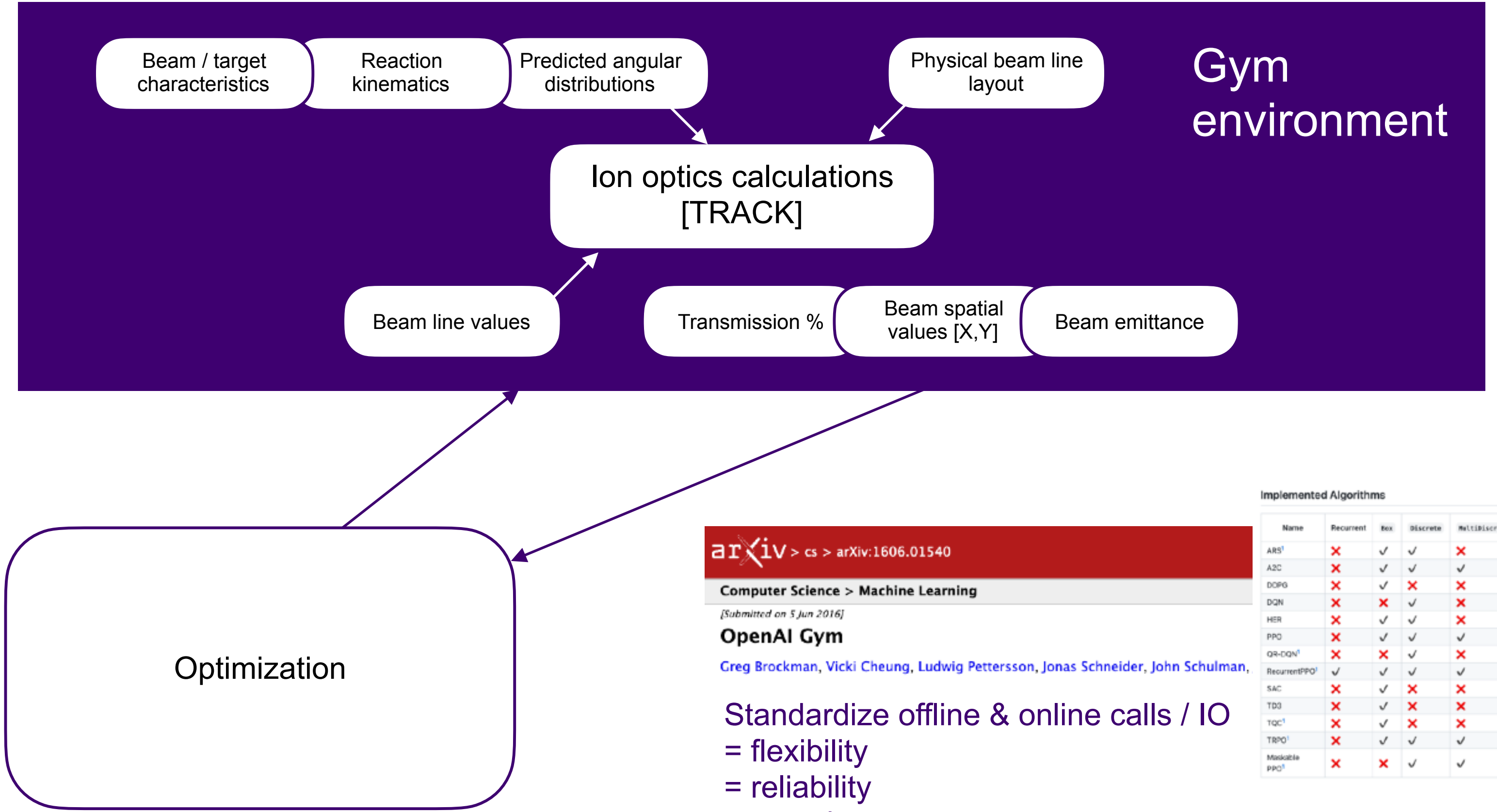
OPTSB: OPTIMIZATION OF SECONDARY BEAMS

Complete data processing paradigm



OPTSB: OPTIMIZATION OF SECONDARY BEAMS

Data processing overview: Offline simulations for checks & training



arXiv > cs > arXiv:1606.01540

Computer Science > Machine Learning

[Submitted on 5 Jun 2016]

OpenAI Gym

Greg Brockman, Vicki Cheung, Ludwig Pettersson, Jonas Schneider, John Schulman,

Standardize offline & online calls / IO
= flexibility
= reliability
= growth

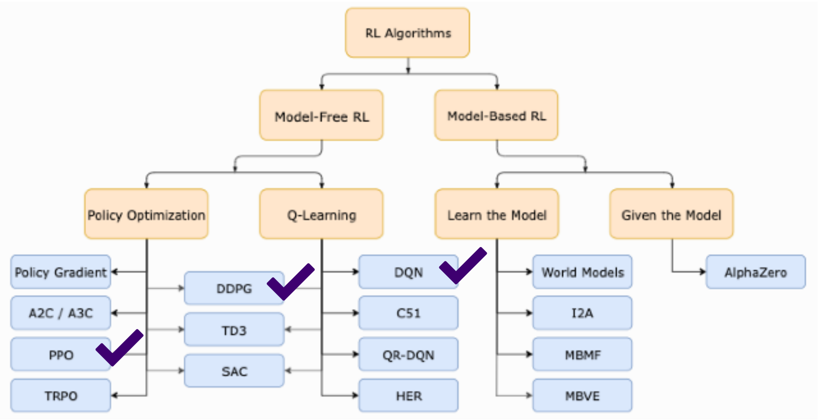
Implemented Algorithms

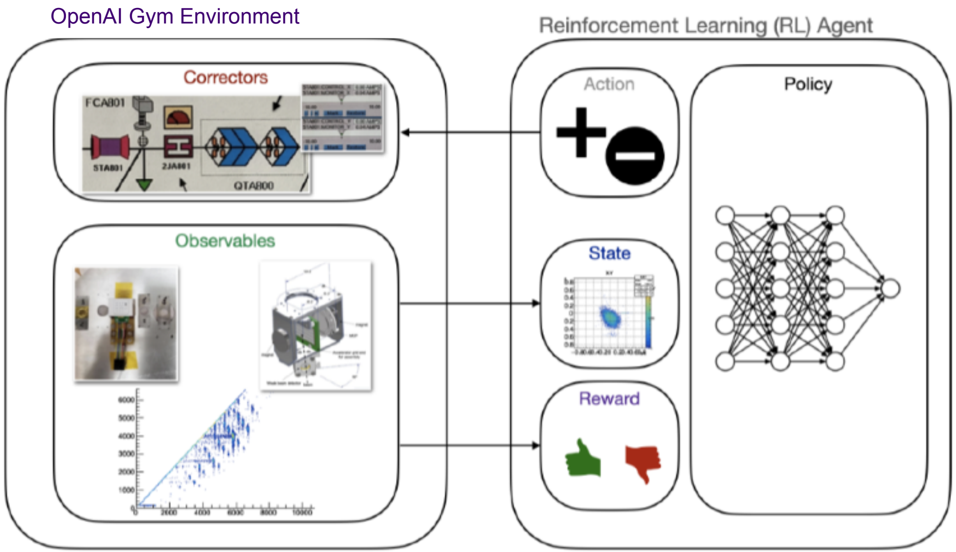
Name	Recurrent	Box	Discrete	MultiDiscrete	MultiBinary	Multi Processing
ARS[1]	✗	✓	✓	✗	✗	✓
A2C	✗	✓	✓	✓	✓	✓
DDPG	✗	✓	✗	✗	✗	✓
DQN	✗	✗	✓	✗	✗	✓
HER	✗	✓	✓	✗	✗	✗
PPO	✗	✓	✓	✓	✓	✓
QR-DQN[1]	✗	✗	✓	✗	✗	✓
RecurrentPPO[1]	✓	✓	✓	✓	✓	✓
SAC	✗	✓	✗	✗	✗	✓
TD3	✗	✓	✗	✗	✗	✓
TQC[1]	✗	✓	✗	✗	✗	✓
TRPO[1]	✗	✓	✓	✓	✓	✓
Maskable PPO[1]	✗	✗	✓	✓	✓	✓

OPTSB: OPTIMIZATION OF SECONDARY BEAMS

Optimization methods: Reinforcement Learning

1. Continuous control preferred
   Magnet field settings, etc…
2. Discrete control is a possible option
   Modify present field by fixed amount
3. Bayesian Optimization not expected to be ideal solution
   Each solution has multiple unknowns / variable numbers, i.e. distributions, initial conditions, etc…



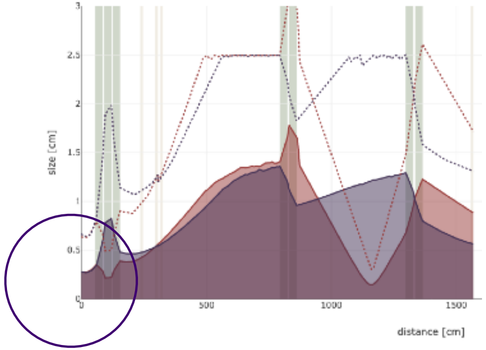


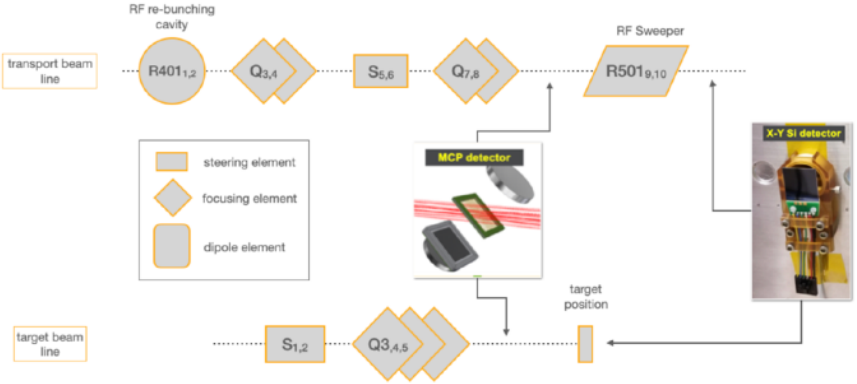
OPTSB: OPTIMIZATION OF SECONDARY BEAMS

Project Plan & On-going Status: Offline simulations & gym environments

Defining reward:
= Transmission +
= Purity +
= Wall time …

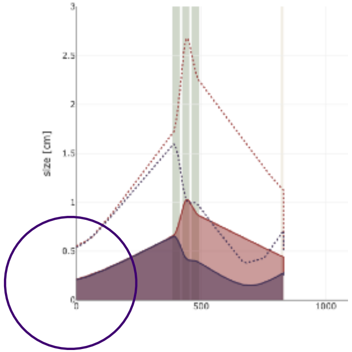
State:
= Rates / Transmission
= Purity
= Beam emittance



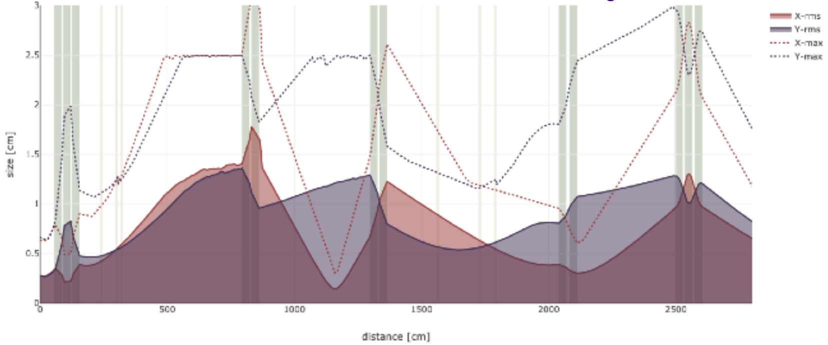


Defining reward:
= Transmission +
= Beam positioning +
= Beam angle / emittance
= Wall time

State:
= Rates / Transmission
= Beam emittance



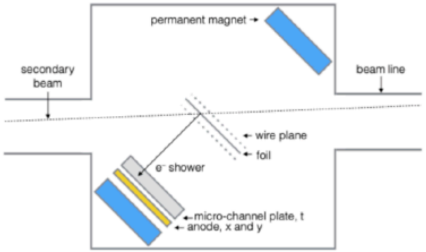
Full beam line simulation: RAISOR exit - to - target

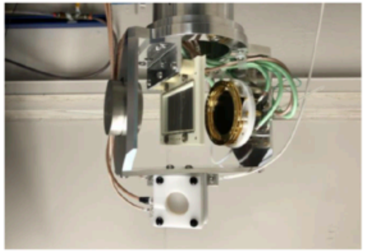


OPTSB: OPTIMIZATION OF SECONDARY BEAMS

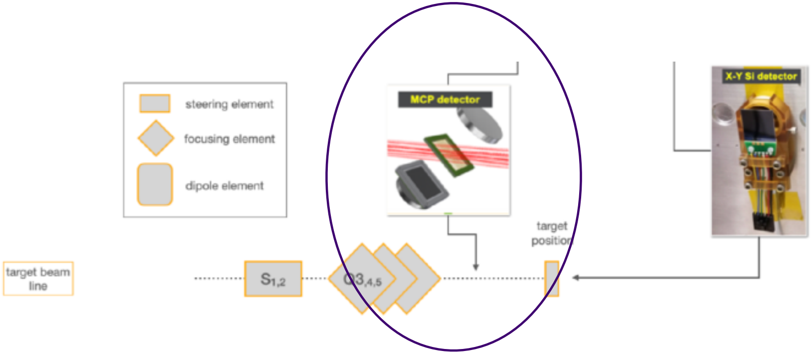
Hardware / sensor upgrades for beam line observations [acquiring the state data]

Secondary electron detection by a Multi-Channel Plate [MCP]





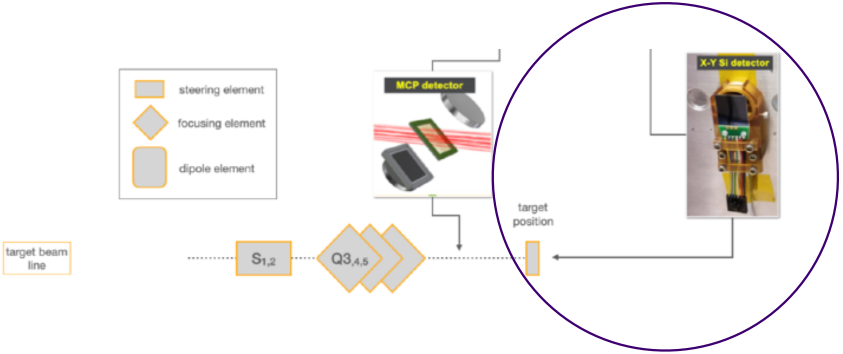
Passive detection of beam positioning [~1 mm] & timing [< 1 ns] event - by - event
= system constructed & tested offline

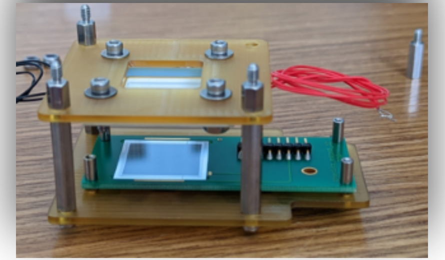


Beam line modifications complete for MCP assembly installation in Jan ‘23

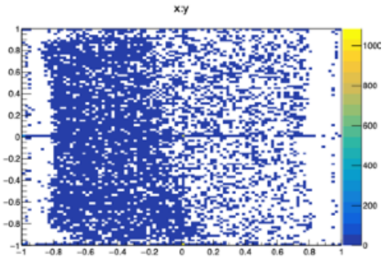
OPTSB: OPTIMIZATION OF SECONDARY BEAMS

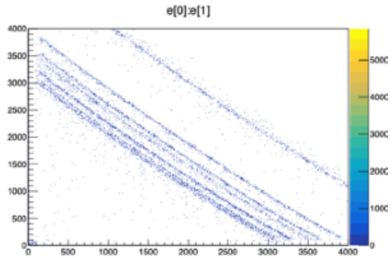
Hardware / sensor upgrades for beam line observations [acquiring the state data]

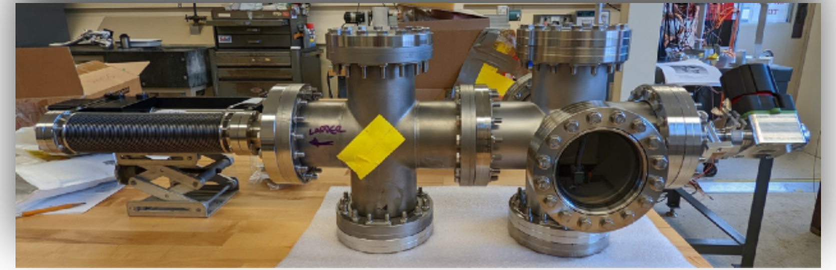




Particle identification + positioning detector system
= Si detector system & readout tested offline



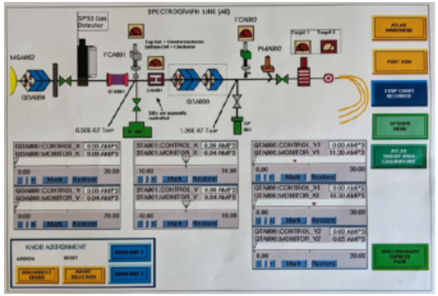




Offline assembly & testing of diagnostic target drive

OPTSB: OPTIMIZATION OF SECONDARY BEAMS

Setting, Reading, & Combining machine / beam monitoring data



Python API / Server

A high-performance time series engine

DataBase [influxDB]

Data for training & characterization of the TRACK simulations

NEXT STEPS IN PROJECT PLAN

Planned hardware installations during ATLAS January shutdown

Enact ML training w/ online + offline data for on to target optimization

Implement first online optimization of target line planned for spring CY23

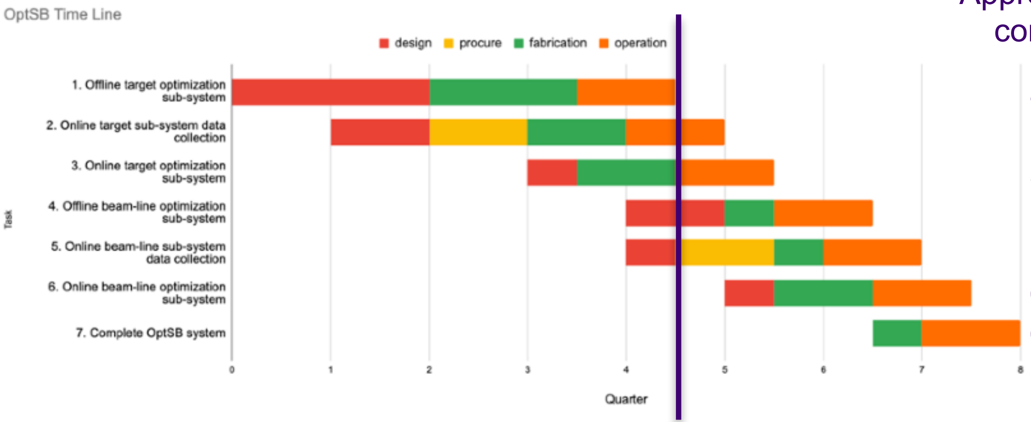
Benchmark ML and mathematical optimization methods / ML on transport line optimization
- Need to build a more encompassing data base of possible reactions, energies, etc…

Now in the process of procuring hardware for the second set of diagnostic stations for transport line

Exploring other beam diagnostic options: Real time imaging with scintillators and high-speed cameras, photo readout of MCPs on tracking stations, etc…

BUDGET, MILESTONES, FUTURE DIRECTIONS

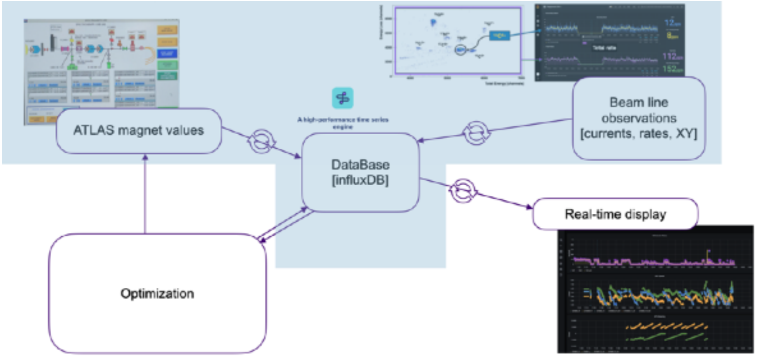
MAJOR PROJECT MILESTONES, COMPLETION %, & COSTING



Approximate % completed

80%
70%
50%
10%
10%
0%
0%

	FY22 ($k)	FY23 ($k)	Totals ($k)
a) Funds allocated	$375	$375	$750
b) Actual costs to date	$145	$45	$190



SUMMARY & CONCLUSIONS

= The transport & delivery of in-flight radioactive beams provides a unique opportunity to apply optimization techniques.

= OptSB project: Implementation of an optimization scheme for in-flight beam transport & delivery at ATLAS from RAISOR - to - target.

= Science enhancement on numerous fronts, including directly via returned beam hours

= Two sub-sections [transport line / target] w/ online & offline (simulated ion transport) components.

= Progress on required hardware developments & installation, offline OpenAI gym developments & preliminary optimization progress, and real-time online data collection.

= Continue along developed path & plan.

ACKNOWLEDGEMENTS

An encompassing project / operation intertwining numerous areas of expertise

Argonne PHY Low Energy: Khushi Bhatt (postdoc on project, started Aug. 2022)
Argonne MCS (optimization / ML): Jeff Larson, Matt Menickelly
Argonne PHY Accelerator Group: Brahim Mustapha, Jose Martinez Marin

RAISOR daq / hardware: Gemma Wilson [LSU], Ryan Tang (postdoc), Jie Chen
ATLAS Operations team
ATLAS Controls System Grop
Low Energy Technical Support

DOE NP: FOA DE-FOA-0002490


END