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

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Presenter: Brahim Mustapha

OVERVIEW OF THE ATLAS FACILITY IN-FLIGHT SYSTEM

U.S. DEPARTMENT OF ENERGY
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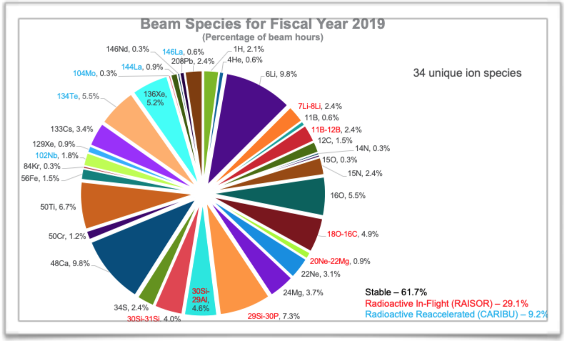
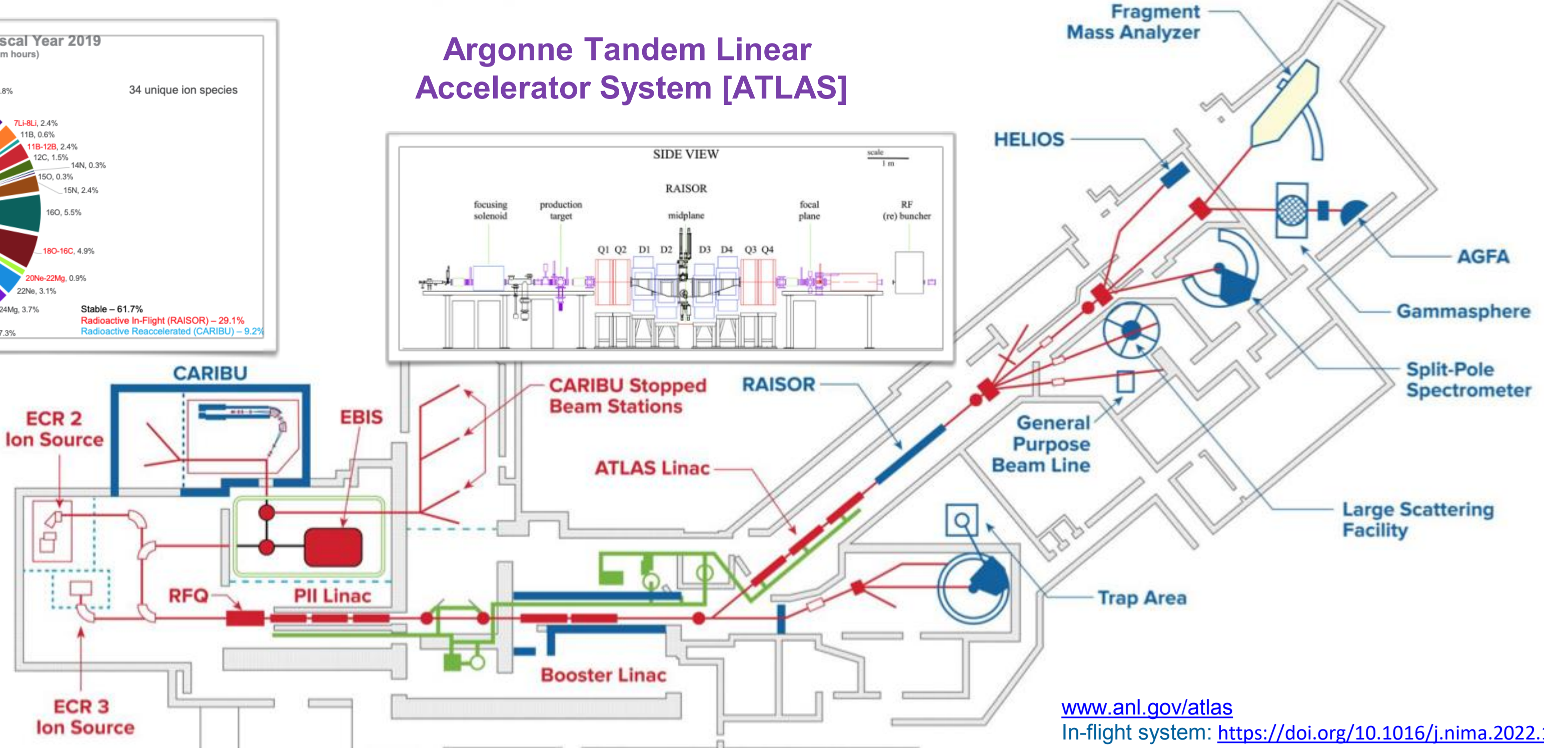


Argonne Tandem Linear Accelerator System [ATLAS]



www.anl.gov/atlas

In-flight system: https://doi.org/10.1016/j.nima.2022.166612

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]
- In-flight beams account for ~20 – 30% of the yearly hourly usage [CY2019 – CY2024]

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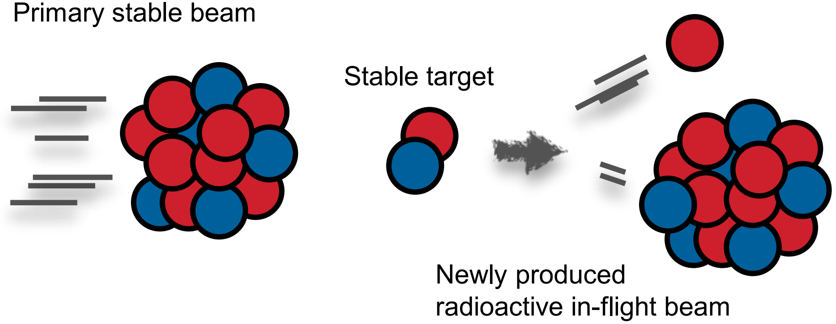
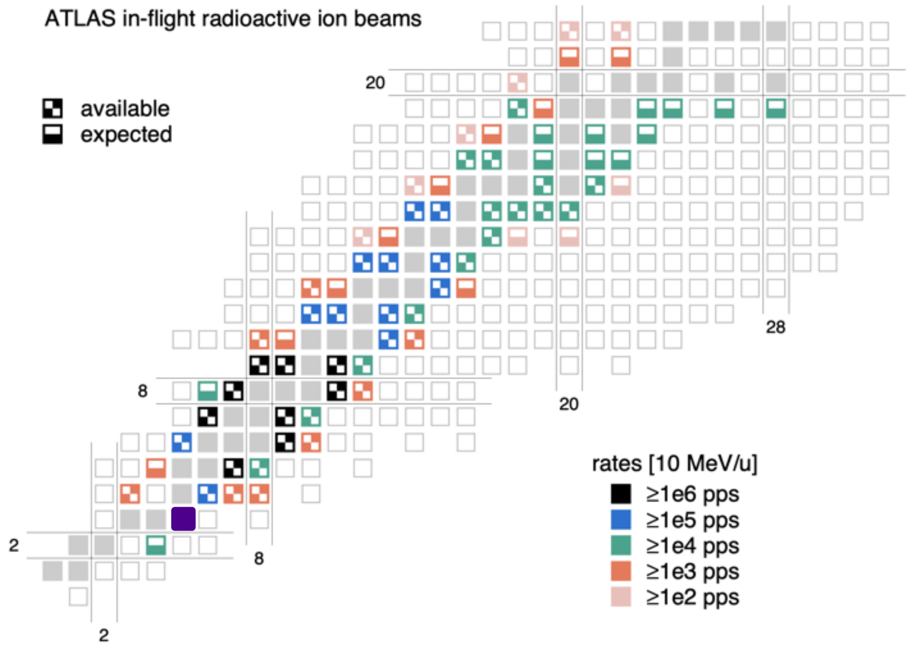
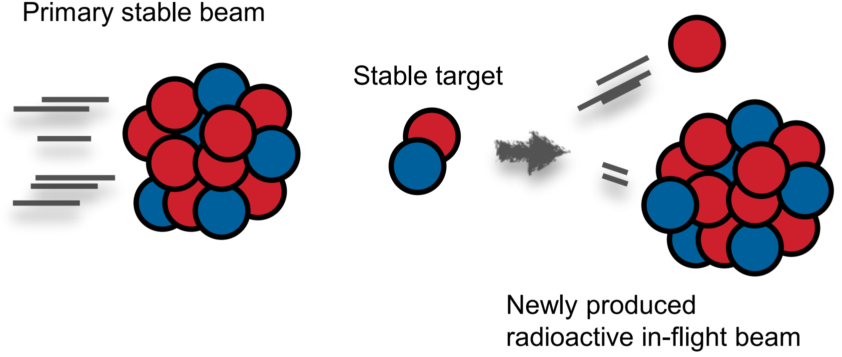
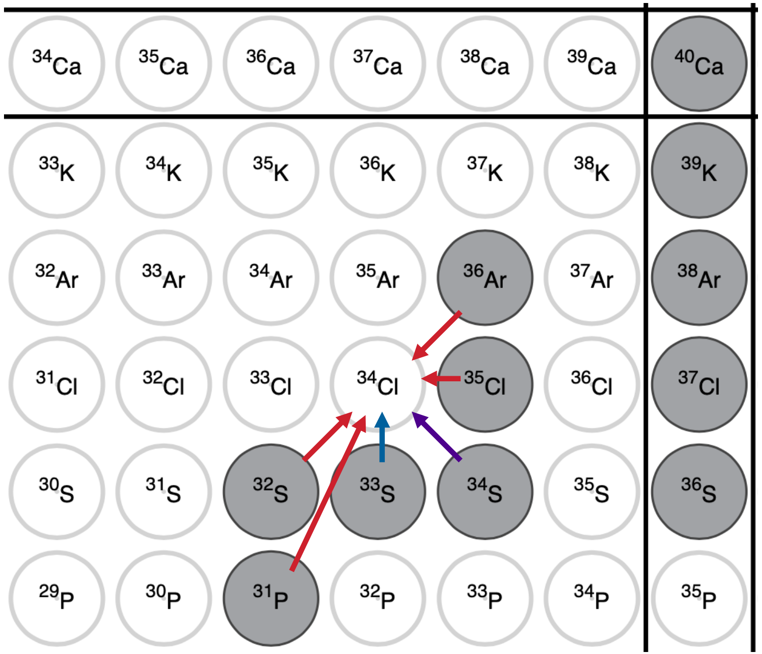
PRIMARILY UTILIZING TRANSFER REACTIONS FOR IN-FLIGHT BEAM PRODUCTION

Highly selective reactions, provide good kinematics & sizeable cross sections
-> Allow for multiple energy / beam+target options to produce a single beam type





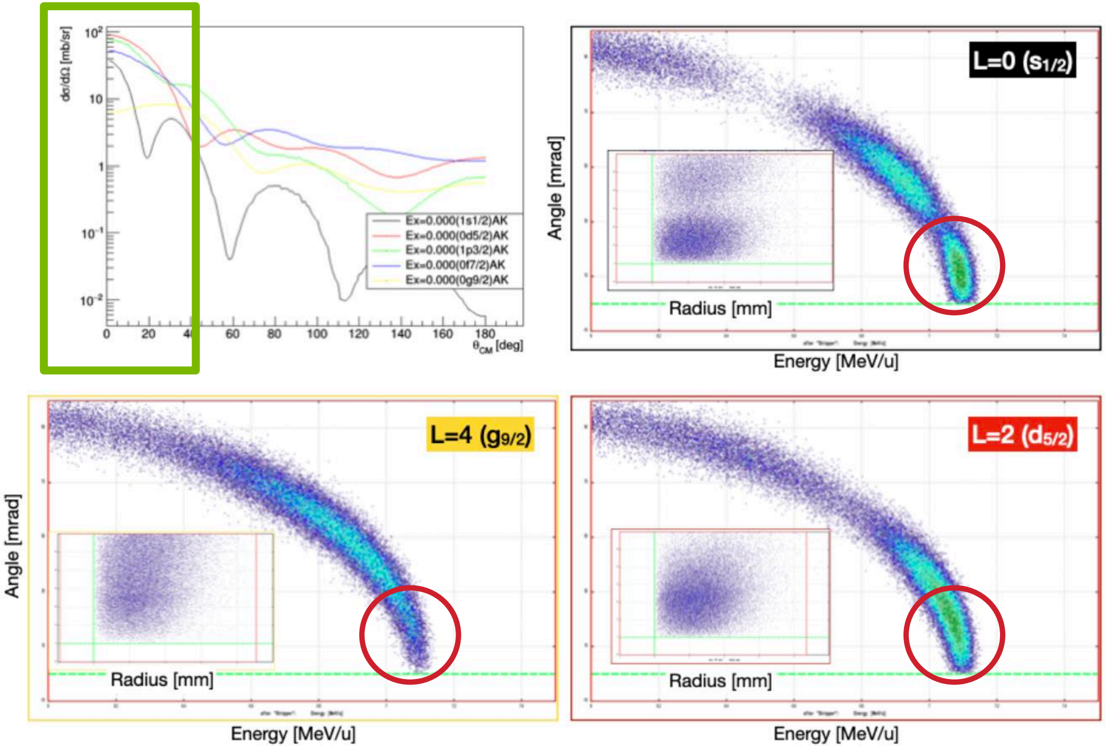




Both ^{33}S(d,n) and ^{34}S(p,n) reactions were used in CY24 at ATLAS to produce beams of ^{34}Cl:

^{33}S(d,n) -> ^{34}Cl beam with **60%** isomer content
^{34}S(p,n) -> ^{34}Cl beam with only **30%** in isomer state

OPERATIONAL CHALLENGES FOR ATLAS IN-FLIGHT BEAMS
= TRANSFER REACTIONS W/ UNKNOWN ANGULAR DISTRIBUTIONS
= RANGE OF ENERGIES, INTENSITIES, REACTION TYPES REQUIRED
= UNIQUE EXPERIENCE FOR EACH PRODUCTION / TUNE



OPERATIONAL CHALLENGES FOR ATLAS IN-FLIGHT BEAMS

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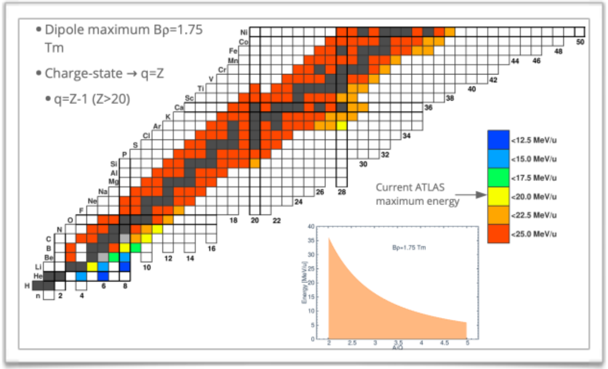
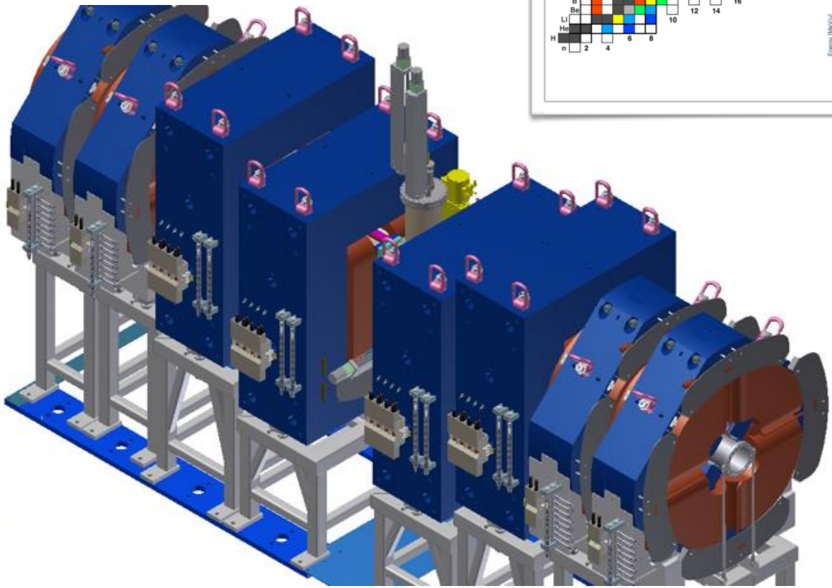
RAISOR DESIGN LAYOUT AND FEATURES

Multiple key design features considered & implemented

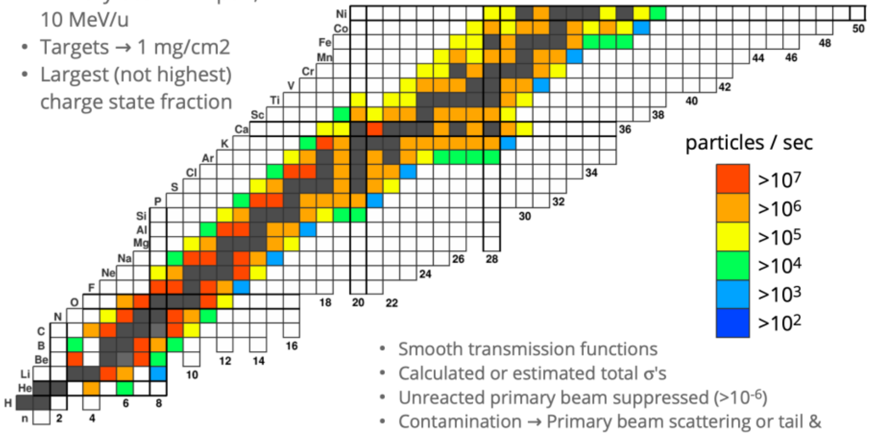
- Magnetic chicane w/ quadrupole doublet bookends
  - Momentum selection & stopping of primary beam current



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%



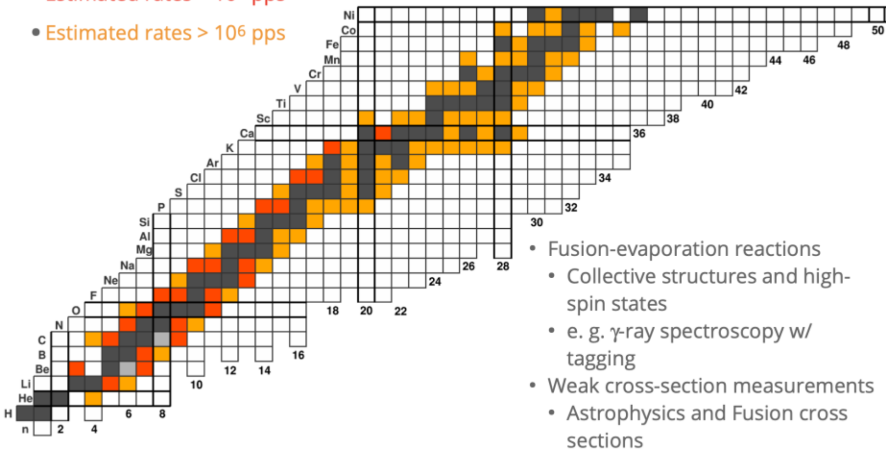
- Primary beam → 1 puA, 10 MeV/u
- Targets → 1 mg/cm2
- Largest (not highest) charge state fraction



- 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

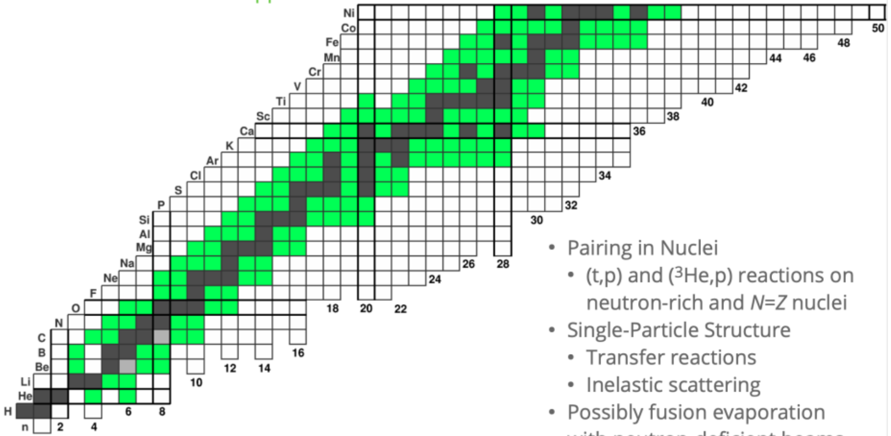
www.phy.anl.gov/airis/rates.html

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



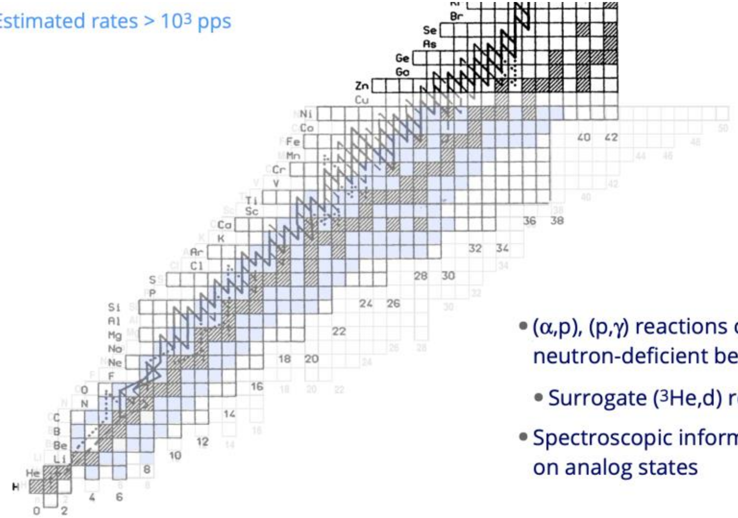
- Fusion-evaporation reactions
  - Collective structures and high-spin states
  - e. g. γ-ray spectroscopy w/ tagging
- Weak cross-section measurements
  - Astrophysics and Fusion cross sections
  - Transfer and fusion reactions

- 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.

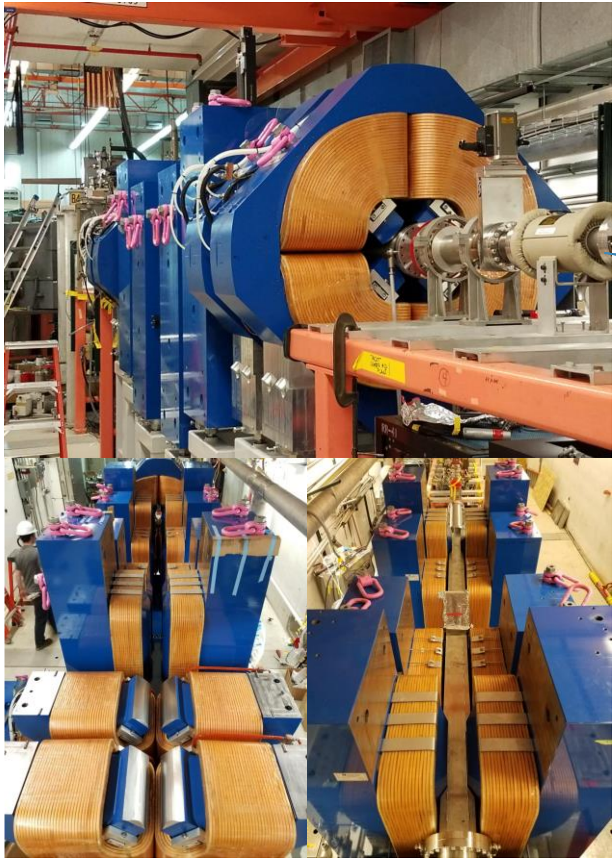
- Estimated rates > 10^3 pps



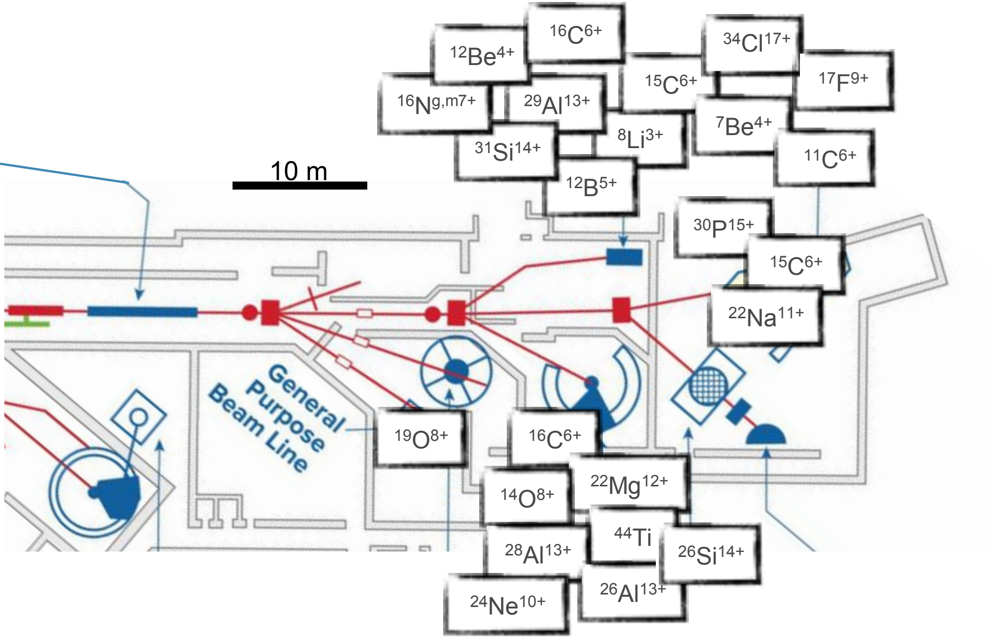
- (α,p), (p,γ) reactions on neutron-deficient beams
- Surrogate (^{3}He,d) reaction
- Spectroscopic information on analog states

RAISOR COMMISSIONING AND OPERATING PRINCIPLES

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



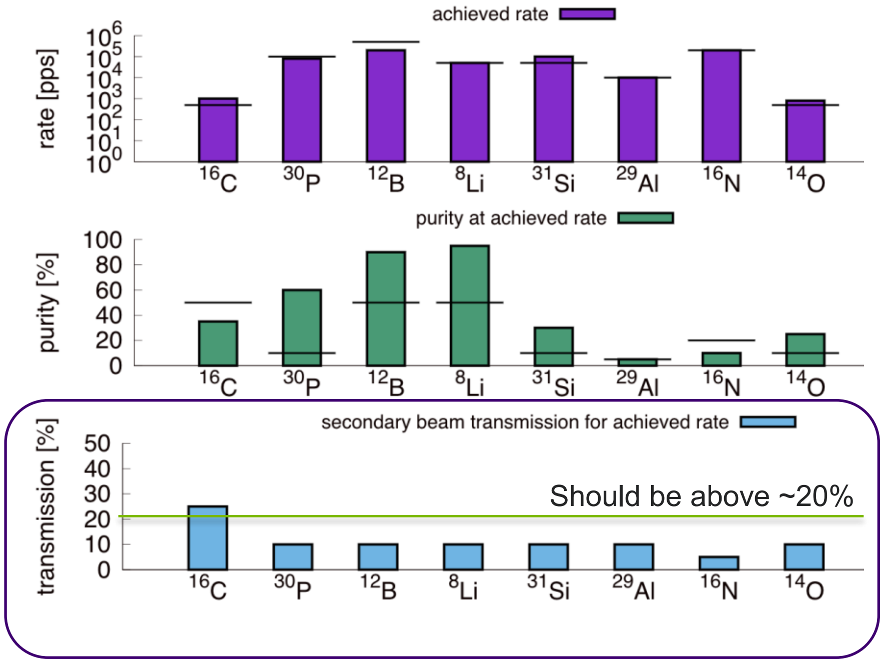
>25 radioactive beam measurements at 4 different experimental locations [+10’s m downstream of RAISOR]

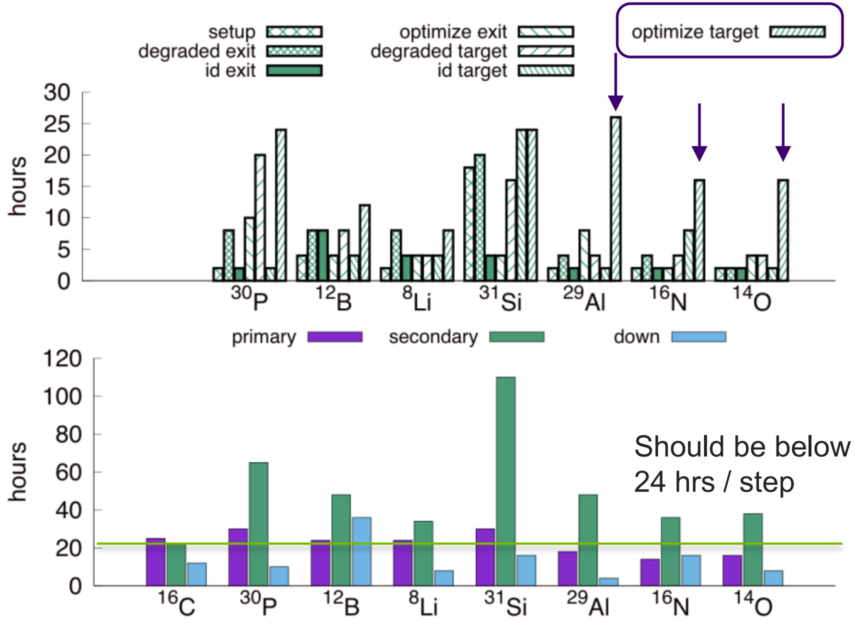


Tang et al., PRC 2022
Hoffman et al., NIMA 2022
Chen et al., PRC 2022
Jayatissa et al., PRL 2023

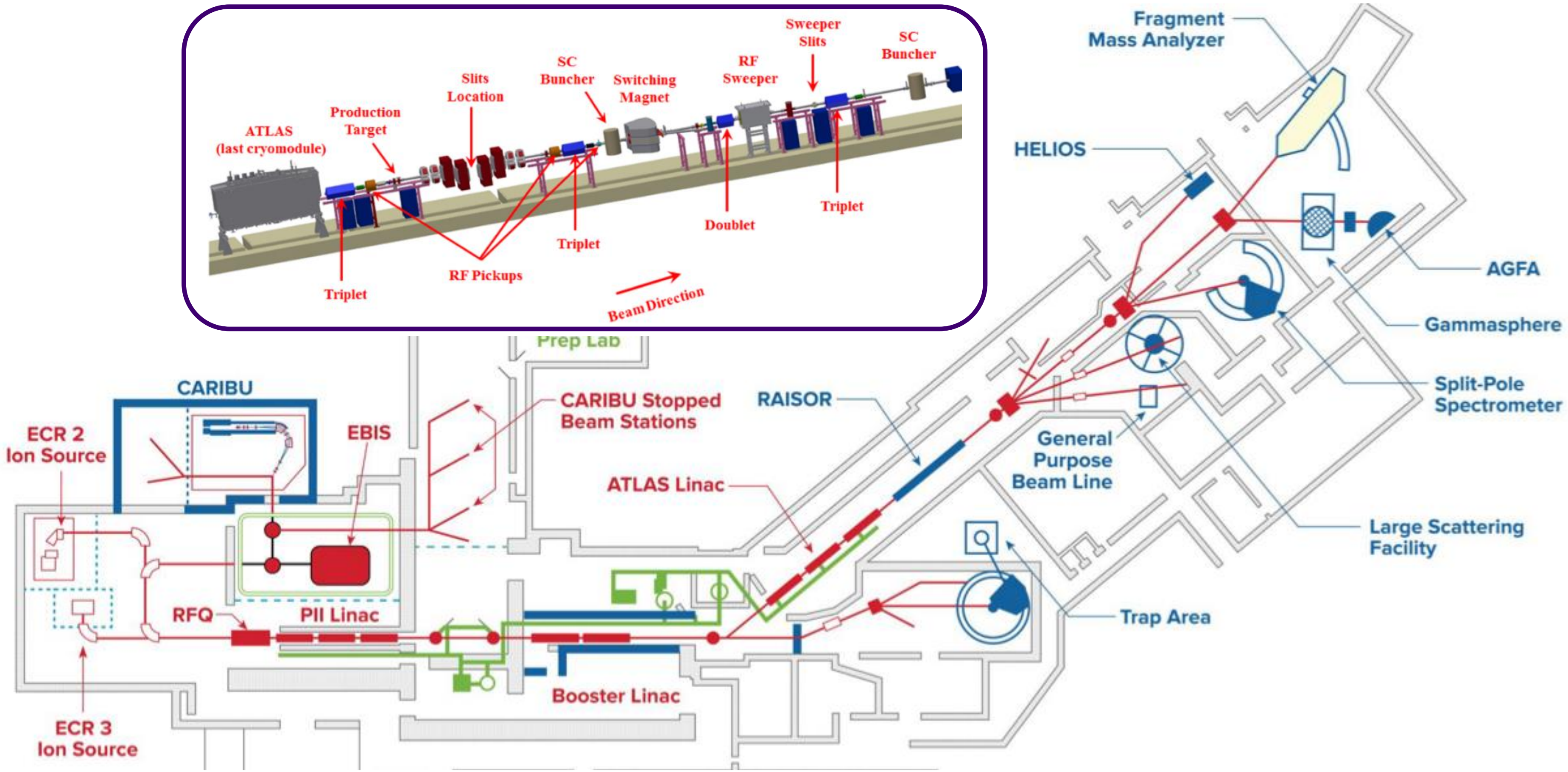
OPPORTUNITIES FOR IMPROVEMENT

Initial data break down of beam delivery performance & tuning hours spent on each of the key tasks required for beam delivery





TRANSPORT BEAM LINES FROM RAISOR - TO - TARGET



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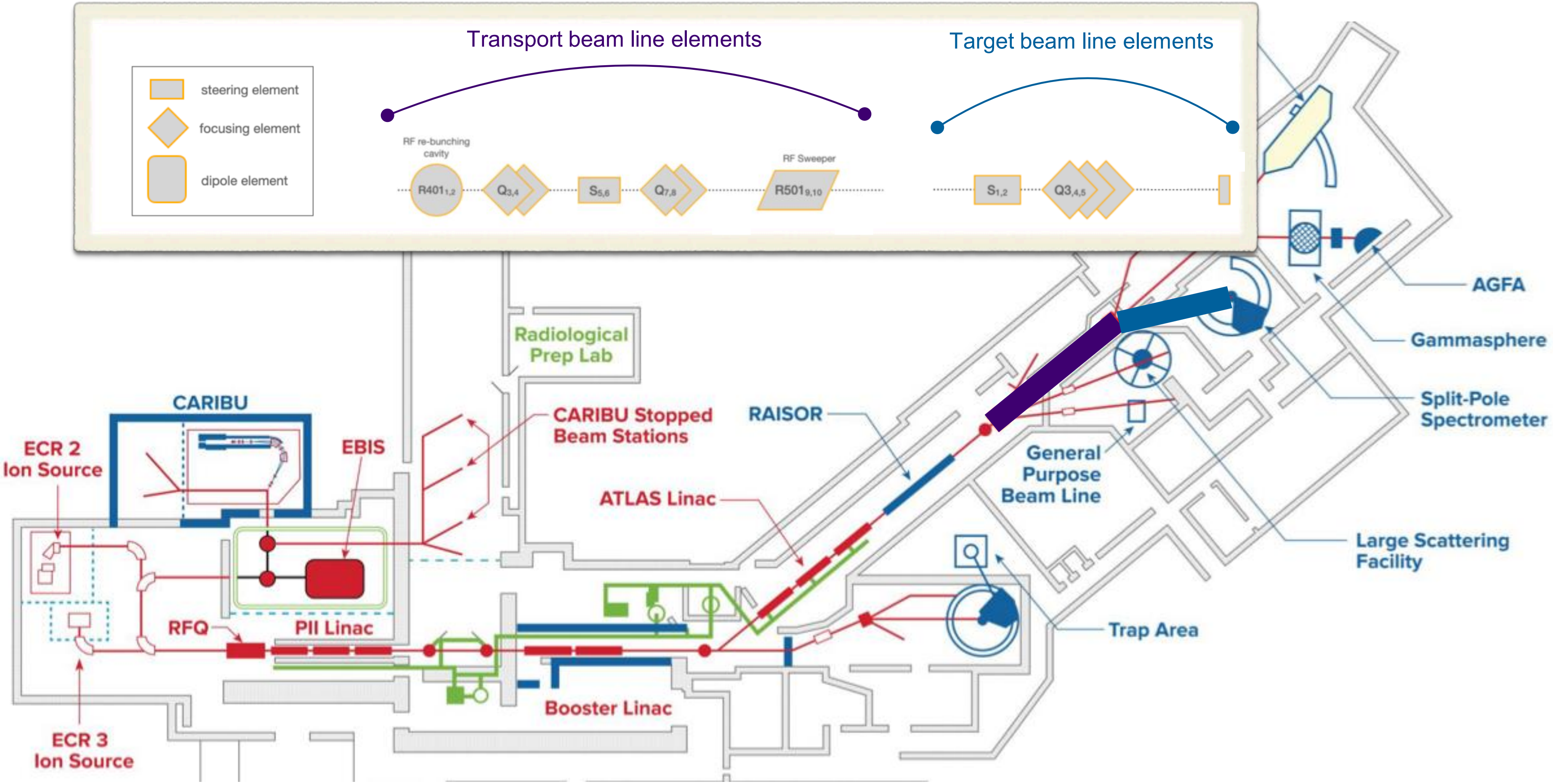
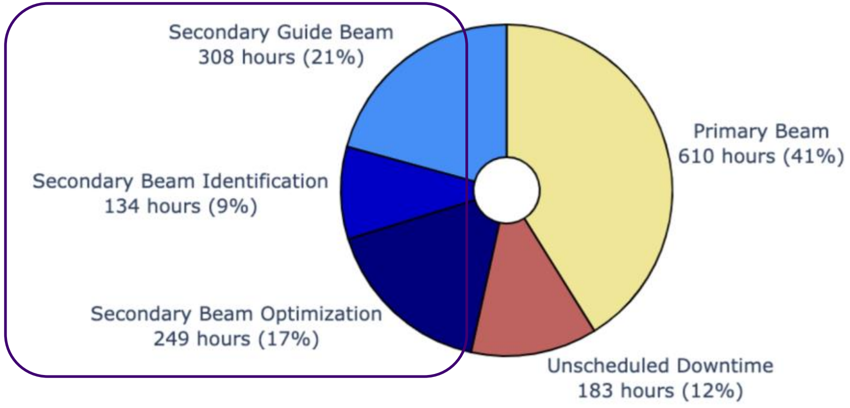
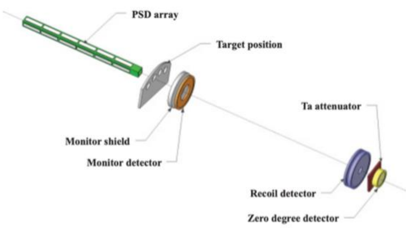
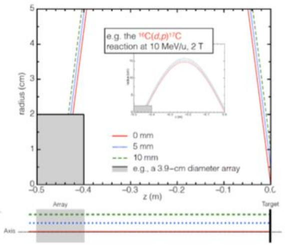
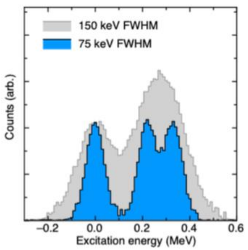
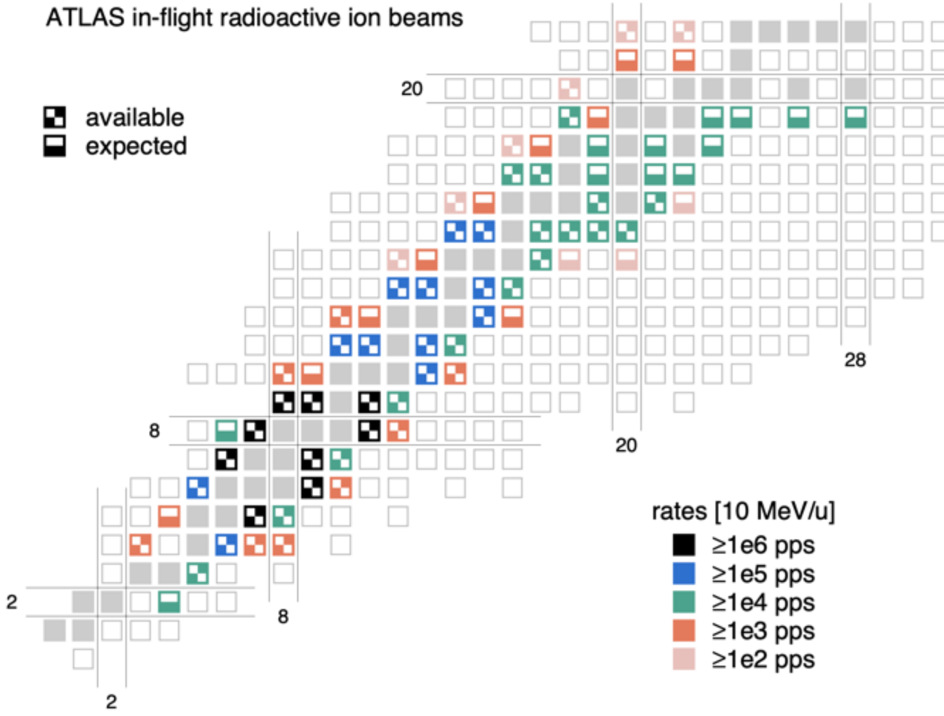












IMPROVE THE IN-FLIGHT BEAM QUALITY, TRANSMISSION, UP-TIME, AND DELIVERY TIMES
ENHANCED SCIENTIFIC POTENTIAL
= RETURN HOURS TO EXPERIMENTAL WORK =
= IMPROVED BEAM QUALITY, RELIABILITY, REPRODUCIBILITY =
= EXTEND THE REACH OF IN-FLIGHT BEAM PRODUCTION =

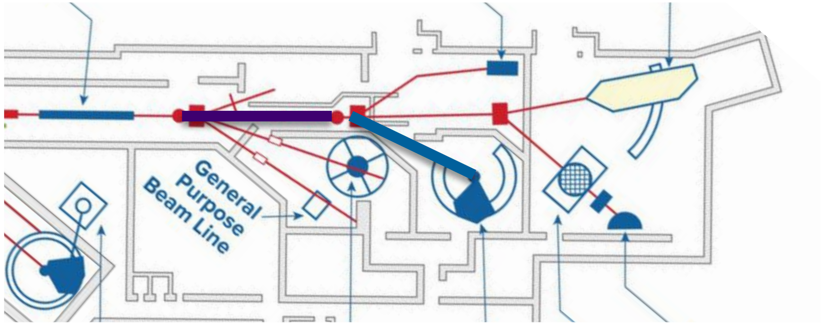
DESCRIPTION OF THE OPTSB PROJECT

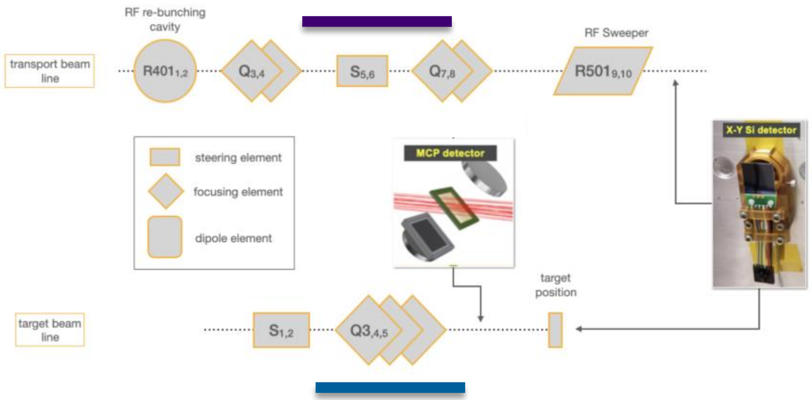
OPTSB: OPTIMIZATION OF SECONDARY BEAMS

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

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).

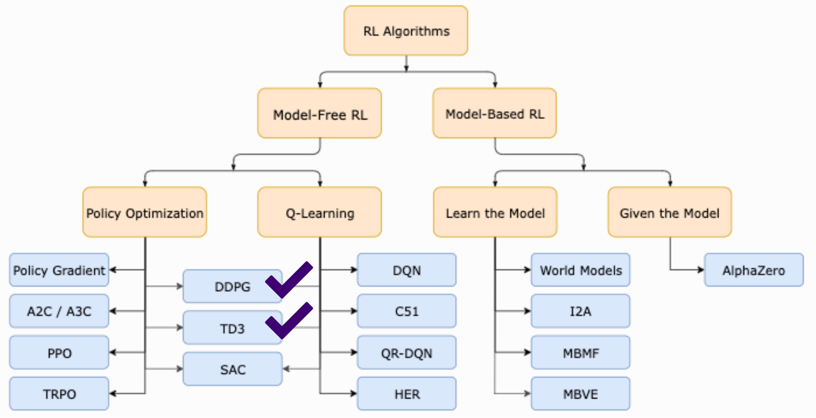


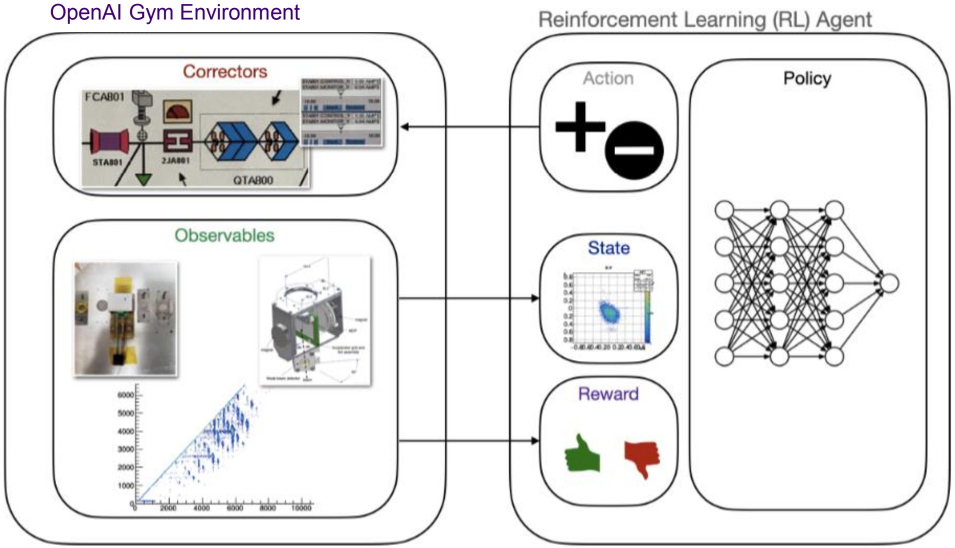


OPTSB: OPTIMIZATION OF SECONDARY BEAMS

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…





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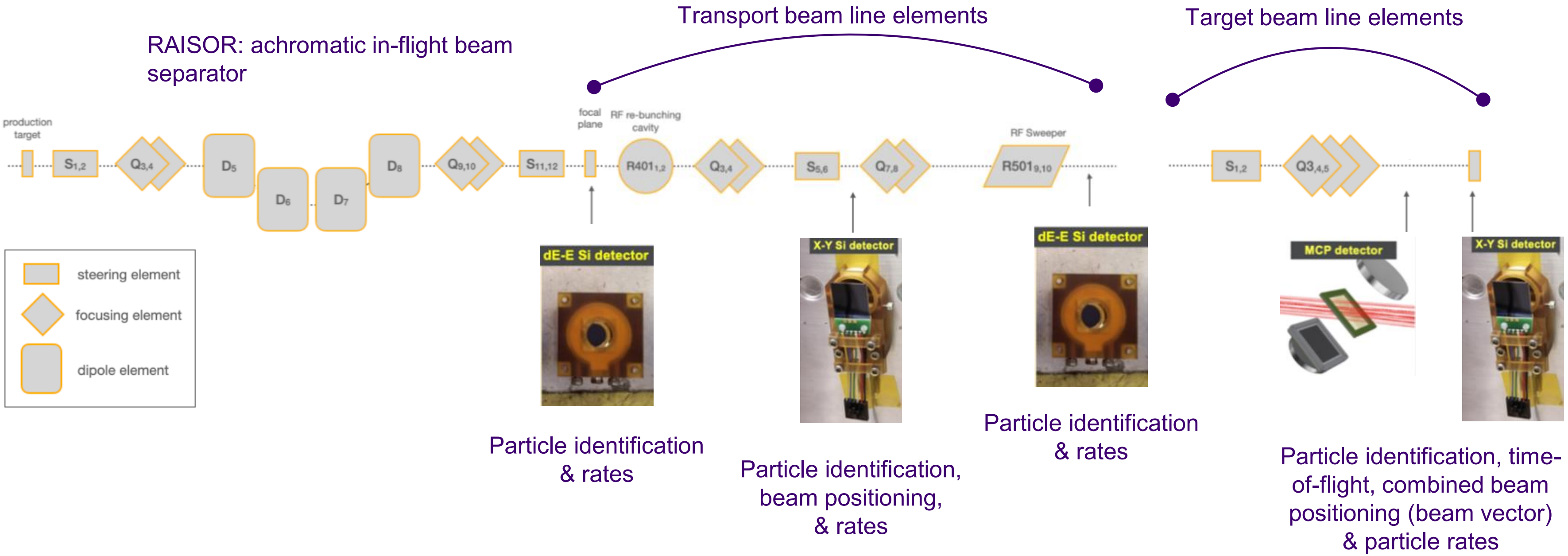
PROJECT IMPLEMENTATION & RESULTS

COMPLETED ALL HARDWARE INSTALLS

Full suite of diagnostics at the desired ‘target’ & ‘transport’ beam-line positions



+ Newly constructed & installed particle ID + beam-profile stations (x2)
+ target station coupled to newly constructed passive PS (tof) MCP station
+ Integrated available particle ID detector systems
+ Det. placements guided by TRACK simulations (& physical parameters)
+ All integrated into digital DAQ w/ real-time [seconds] event processing

+ Khushi Bhatt & Ivan Tolstukhin

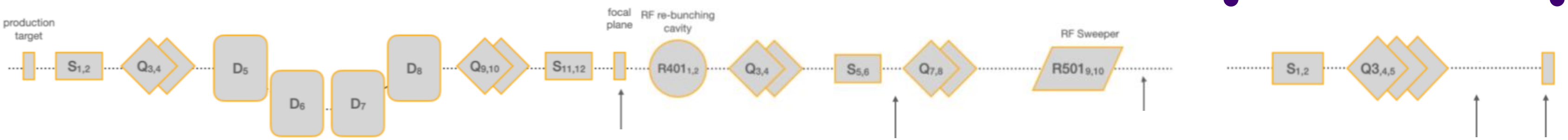
COMPLETED ALL HARDWARE INSTALLS

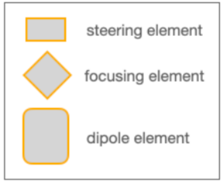
Full suite of diagnostics at the desired ‘target’ & ‘transport’ beam-line positions

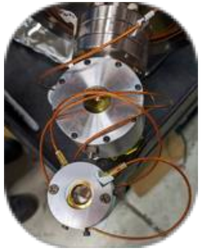
RAISOR: achromatic in-flight beam separator

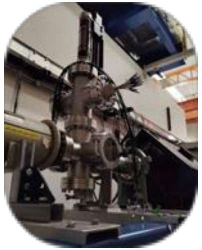
Transport beam line elements

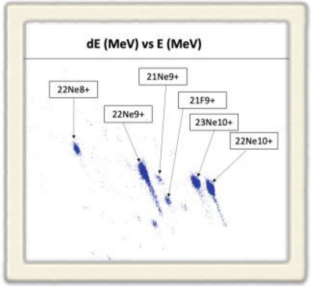
Target beam line elements

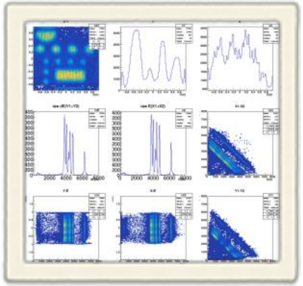












+ Khushi Bhatt & Ivan Tolstukhin

IMPROVED UPON EFFICIENCY OF DATA-FLOW

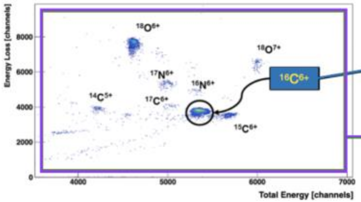
Explored reliability, boundary checks, & timing improvements

Beam-line data collection & handling

+100 - 500 Hz, 30 channels, 10 - 12 reduction/manipulation processes
+ Benchmarked systems offline with signal emulator(s)

+ Developed / Commissioned custom readout and visualization daq software in collaboration with FSU daq [T. L. Tang et al., NIMA 2024]

+Developed 3-D particle-by-particle ray-tracing of the online data at the target station



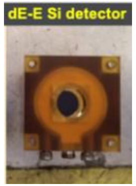
DataBase [influxDB]

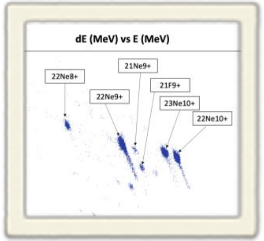
Beam line observations [currents, rates, XY]

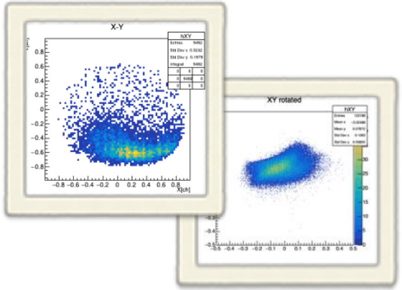
+ Total & individual rates [~1 sec period]

+ Multi positional info [~1-2 sec]
+ Rate dependence on uncertainty (FHWM, Gauss. Fit for positional info)

+ Event-by-event vector reconstruction [<3]
+ Similar rate dependence for uncertainties / stats







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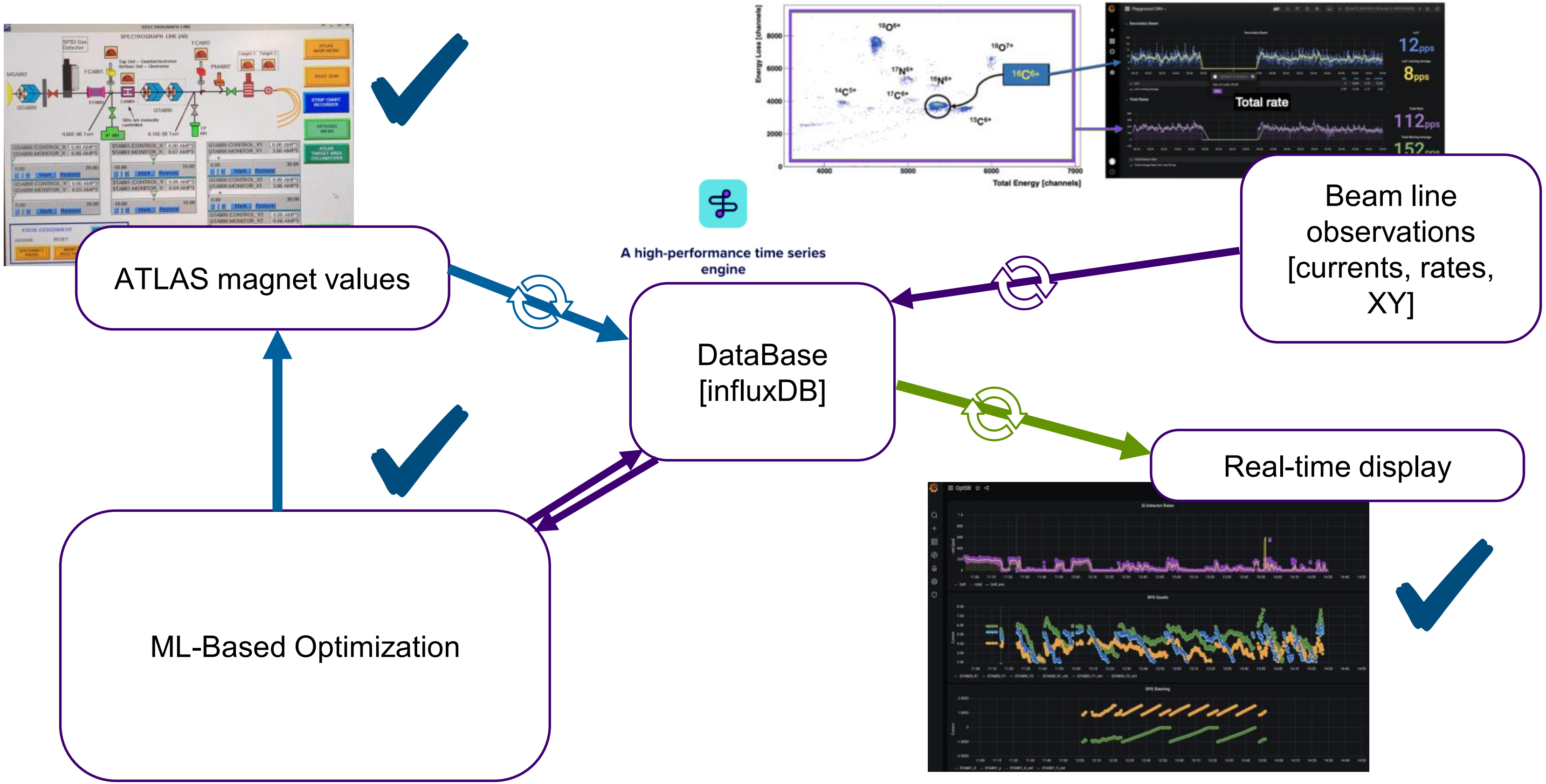
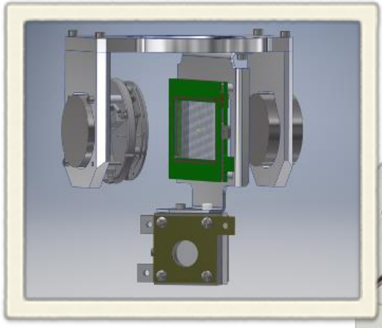
IMPROVING EFFICIENCY OF DATA-FLOW

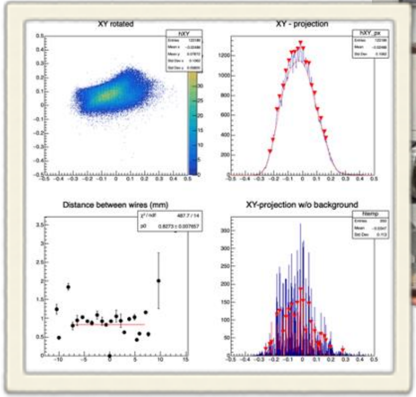
Explored reliability, boundary checks, & timing improvements



OPERATIONAL SYSTEM FOR ONLINE DATA COLLECTION

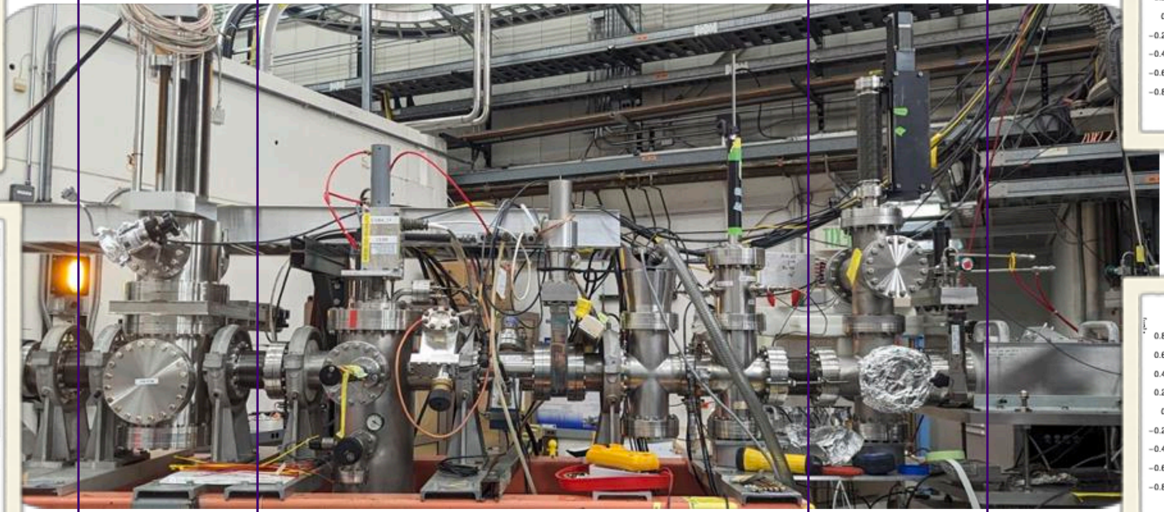
Examples of data collected from the target optimization detector systems



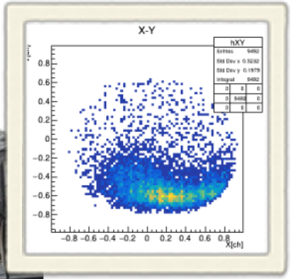


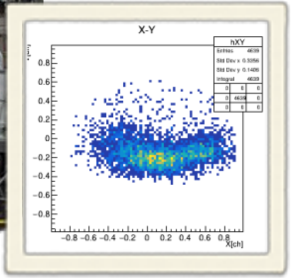
Operation of position sensitive MCP with ATLAS beam

Target beam line elements



~2 m flight path





Operation of position sensitive Si detector with an ATLAS beam

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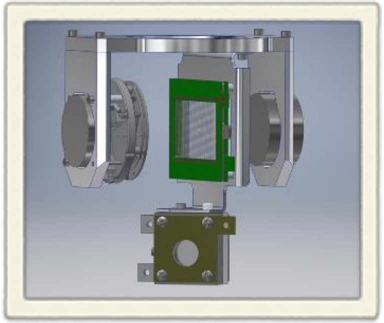
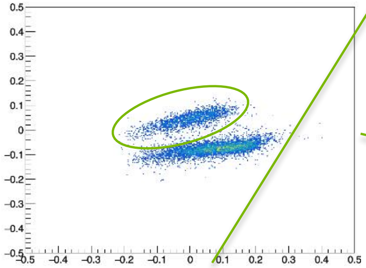
DATA COLLECTION & PROCESSING

Real-time determination of particle trajectories

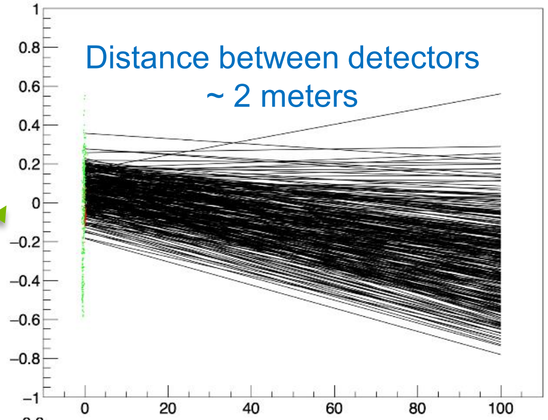
Join the two detectors in time to create event-by-event ion trajectory vectors

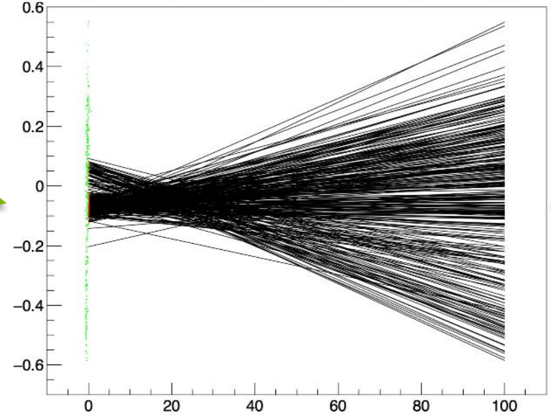


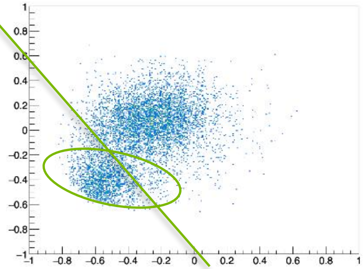


Y position 1

X position 1







Y position 2

X position 2

+used in first optimization with degraded primary beam
+randomized data collection for in-flight beam [^{21}F]

FIRST ONLINE RESULTS & FUTURE DIRECTIONS

ONLINE TARGET OPTIMIZATION APPROACH

Demonstrated success of RL-based optimization for transmission & focussing

Framework constructed is parallel to that used at CERN / AWAKE
- Analogous optimization problem & similar action/state scope
- Proven results with RL-based optimization (TD3) [3 -5 actions]
    - TD3 - updated actor-critic method
- Better performance through an iterative process?
- Focus + transmission in parallel or series?

Two main goals could be incorporated into reward values

$$r_o = -1[r_\sigma \alpha_s + r_i(1-\alpha_s)]$$

Beam transmission / intensity

$$r_i = \frac{1}{i_0}\sum_{j,k} a_{jk} - i_0$$

Ratio of # of beam particles generated vs. observed

Target transverse emittance

$$r_\sigma = r_0 - \frac{1}{r_{\max}}\sqrt{(\sigma_x - \sigma_x^*)^2 + (\sigma_y - \sigma_y^*)^2}$$

Gaussian fit to beam distributions (x,y)

* / r0 based on input particle distribution

Machine Learning: Science and Technology

Towards automatic setup of 18 MeV electron beamline using machine learning

To cite this article: Francesco Maria Velotti *et al* 2023 *Mach. Learn.: Sci. Technol.* 4 025016

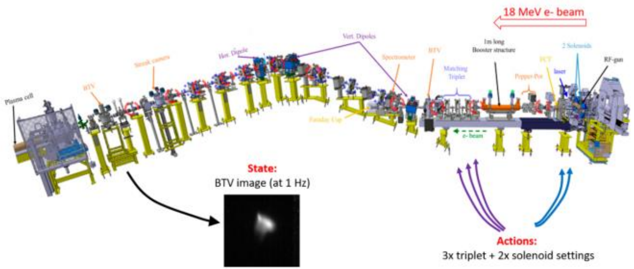
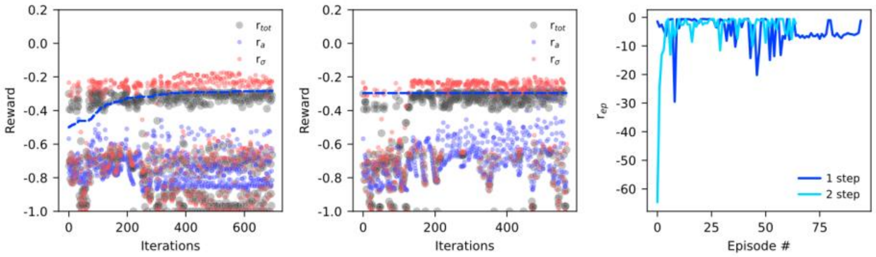
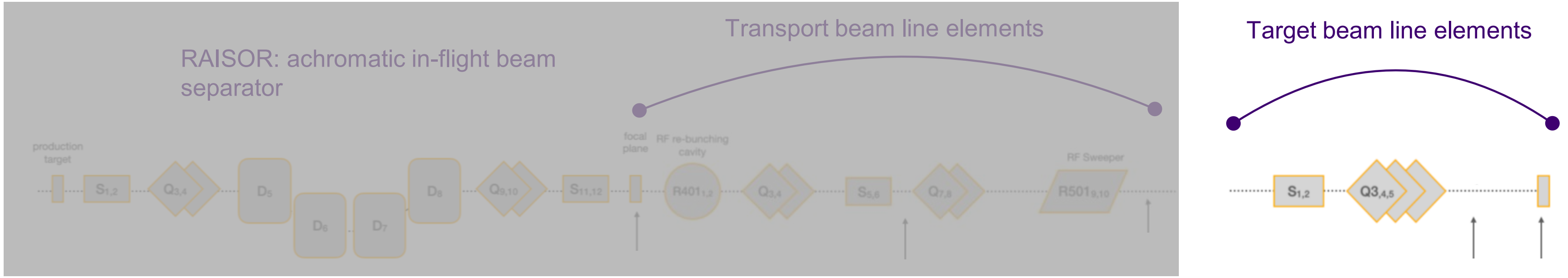


Figure 1. AWAKE beamline showing location of the matching devices (actions) and the observation BTV.



CONSTRAINTS FROM HISTORICAL TUNE DATA & SIMULATION

Characterization of hardware to inform simulations & RL parameters



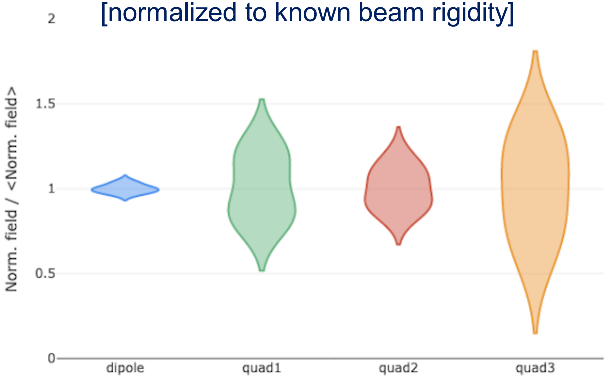
Historical Data:
- Contributes insight into action limits, correlations and hyper-parameter tuning [10 sets on target line, 25 sets on transport line]

Completed magnetic field scans with Hall probe for each element

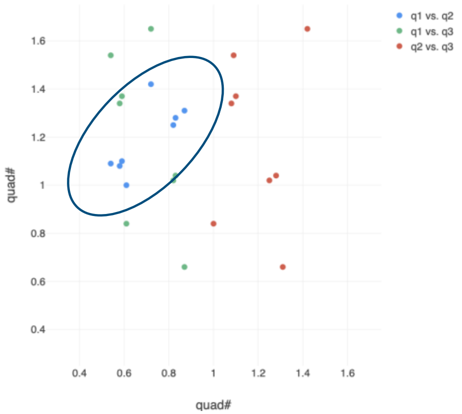
Developed inputs for 12 independent data sets [A, q, E, **emittance parameters**]

Basic comparisons between limited data collected to simulation show qualitative agreement

Distributions based on historical tune data [normalized to known beam rigidity]



Quadrupole 1 vs. Quadrupole 2

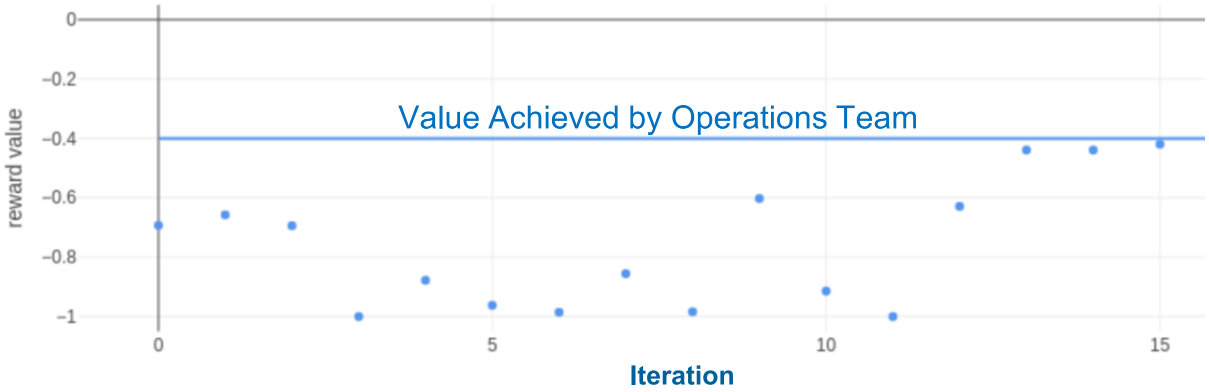


FIRST ONLINE OPTIMIZATION TESTS

Limited-scope execution of TD3 ML Optimization was promising

Optimization of the downstream quadrupole triplet (+ two steering magnets) onto the final target position
$^{22}Ne^{10+}$ primary beam after going through a Be foil

Reward value = transmission only



RANDOM SAMPLING / TRAINING [iteration 1 – 10]

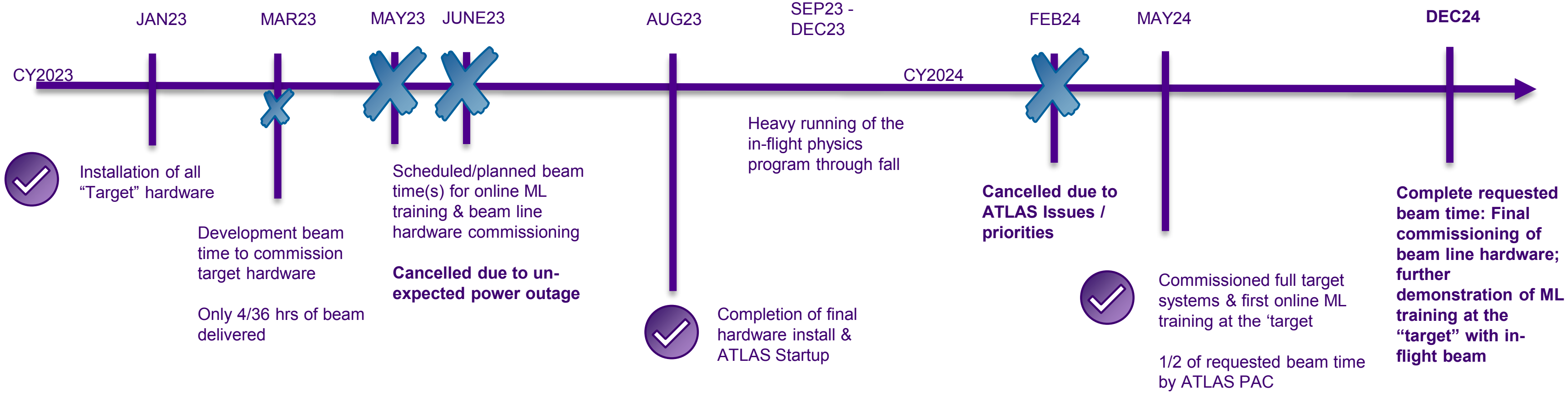
MODEL Predictions [iterations 11 – 15]

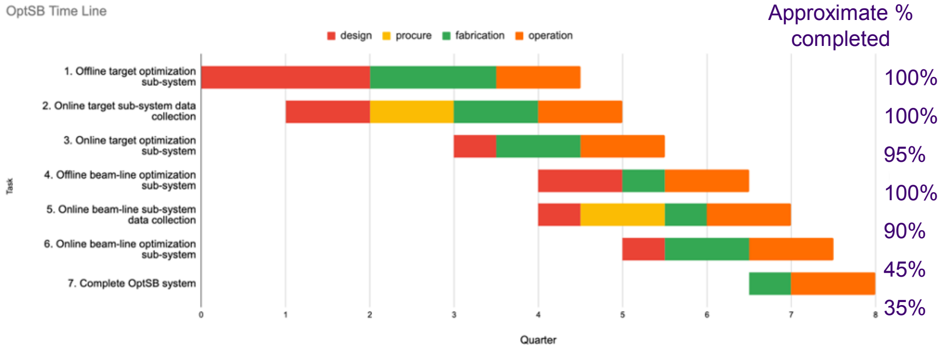
About 10 – 15 seconds per iteration: < 5 mins to achieve operator results

- Data collected from faraday cups
- Quad fields constrained to limited range ~10-15% beyond starting values based on historical data
- Sample weighting will be implemented based on historical data for future runs

UPDATED BUDGET & MILESTONES

MAJOR PROJECT MILESTONES, COMPLETION %, & COSTING





	FY22 ($k)	FY23 ($k)	Totals ($k)
a) Funds allocated	$375	$375	$750
b) Actual costs to date	$375	$335	$710

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OPTSB PROJECT SUMMARY

- Target & beam line beam diagnostic hardware is fully functional
- A complete online data processing loop has been demonstrated including data collection, optimization processing, & accelerator element feedback / adjustment
- First rudimentary online beam optimization achieved for target transmission w/ TD3 ML numerical method
- Full beam-line transport application is planned but requires additional beam times
- Solutions are still being explored for full-transport optimization schemes, e.g., adoption of Bayesian optimization schemes
- Progress has built nicely into project extension of beam optimization & identification at the RAISOR focal plane (discussed in an earlier talk)

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An encompassing project / operation intertwining numerous areas of expertise

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Argonne MCS (optimization / ML): Jeff Larson, Matt Menickelly
Argonne PHY Accelerator Group: **Brahim Mustapha**, Adwaith, Jose Martinez Marin

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

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END