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

DOE NP PI EXCHANGE
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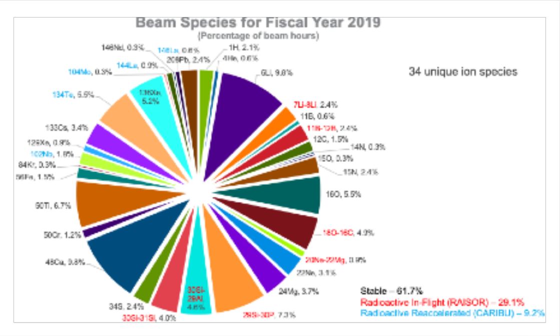
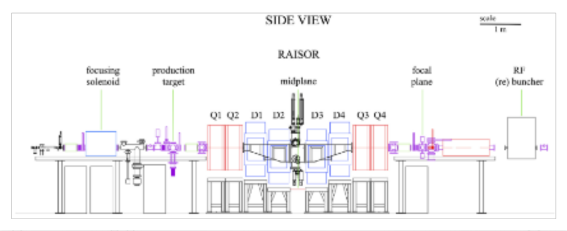
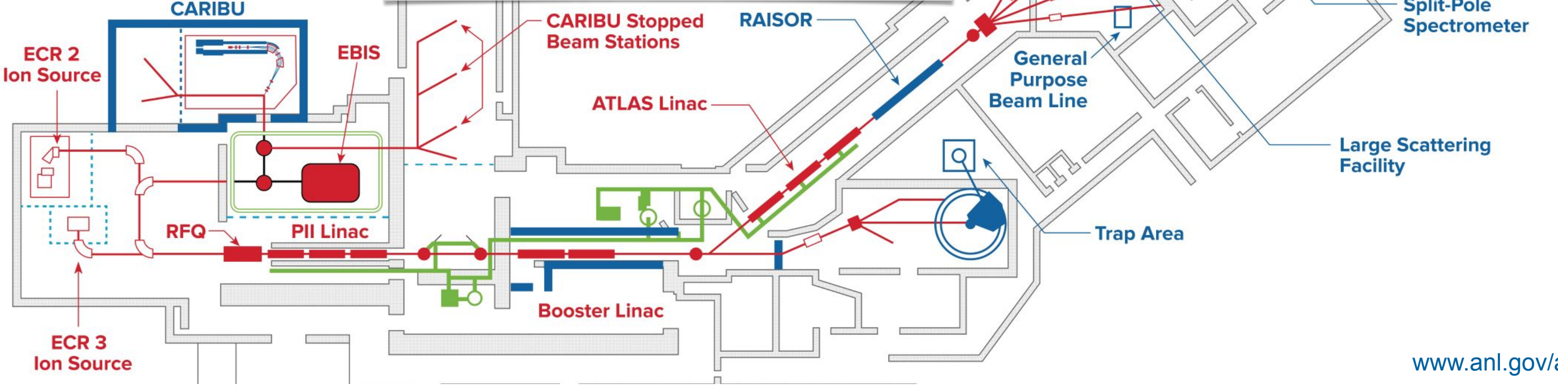
Argonne National Laboratory

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]

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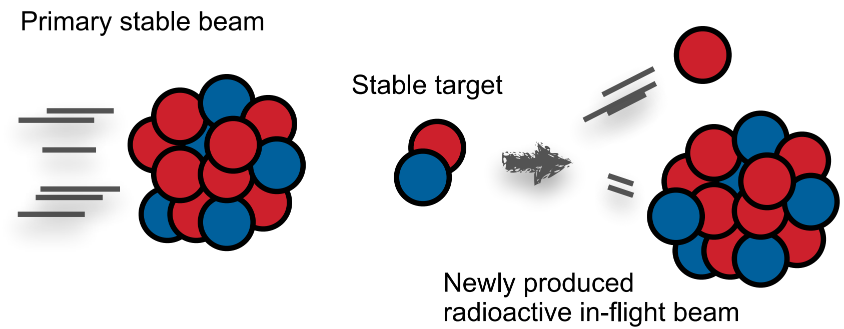
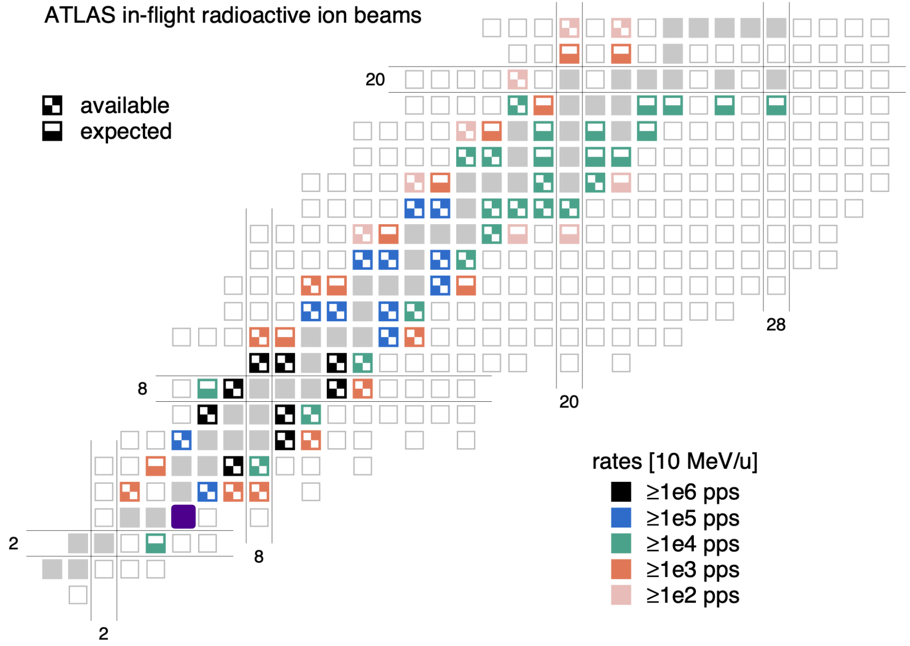
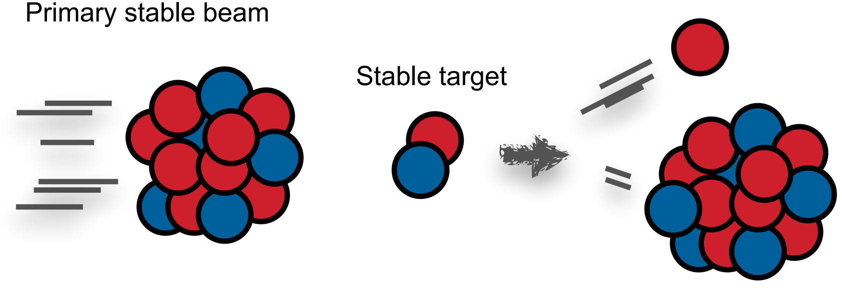
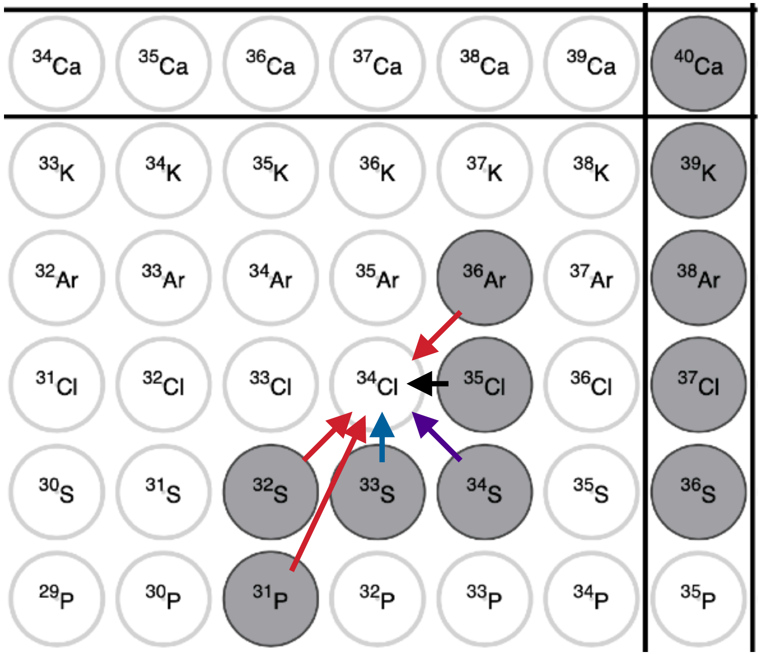
UTILIZE TRANSFER REACTIONS FOR IN-FLIGHT BEAM PRODUCTION

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

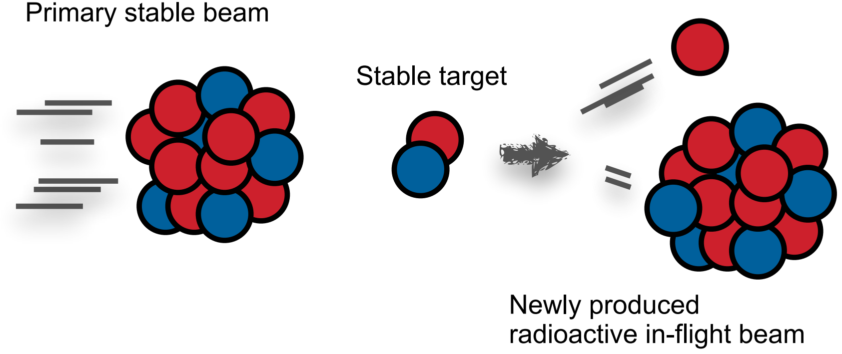


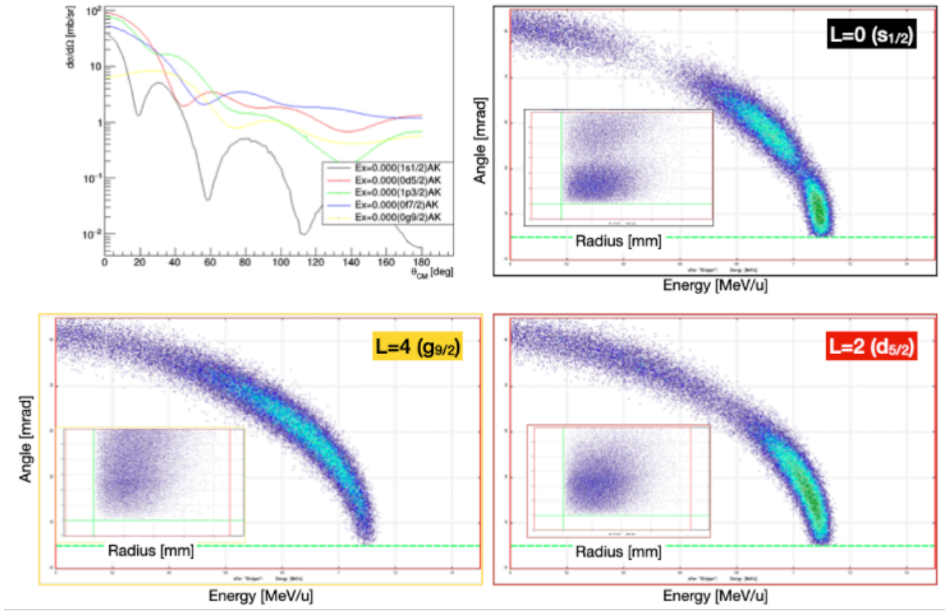






OPERATIONAL CHALLENGES FOR ATLAS IN-FLIGHT BEAMS
= TRANSFER REACTIONS W/ UNKNOWN ANGULAR DISTRIBUTIONS
= RANGE OF ENERGIES, INTENSITIES, REACTION TYPES REQUIRED
= UNIQUE EXPERIENCE FOR EACH PRODUCTION / TUNE





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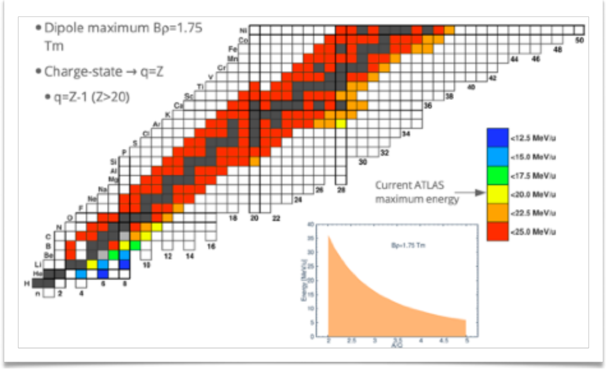
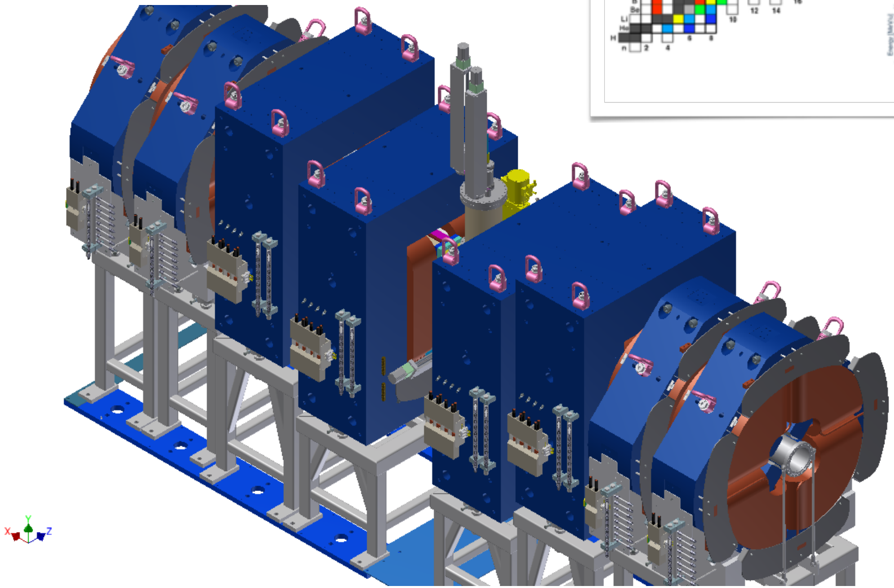
RAISOR DESIGN LAYOUT AND FEATURES

Multiple key design features considered & implemented

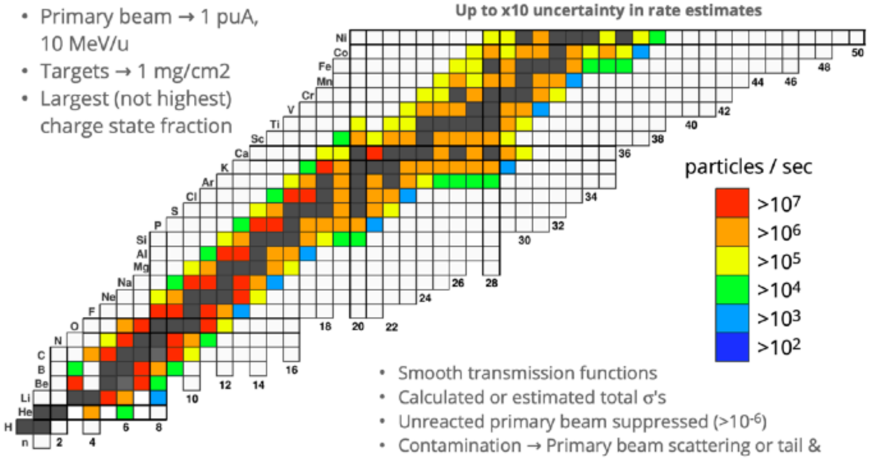
- Magnetic chicane w/ quadrupole doublet bookends
  - Momentum selection & stopping of primary beam current



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%



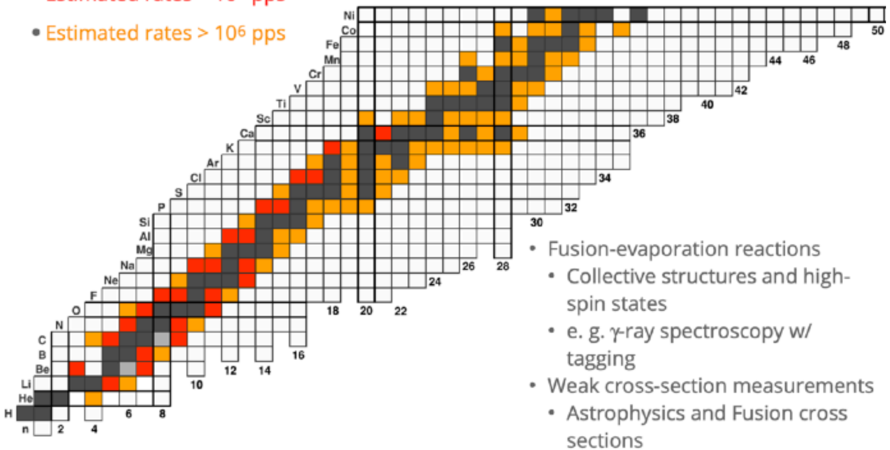
- Primary beam → 1 puA, 10 MeV/u
- Targets → 1 mg/cm2
- Largest (not highest) charge state fraction



- 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

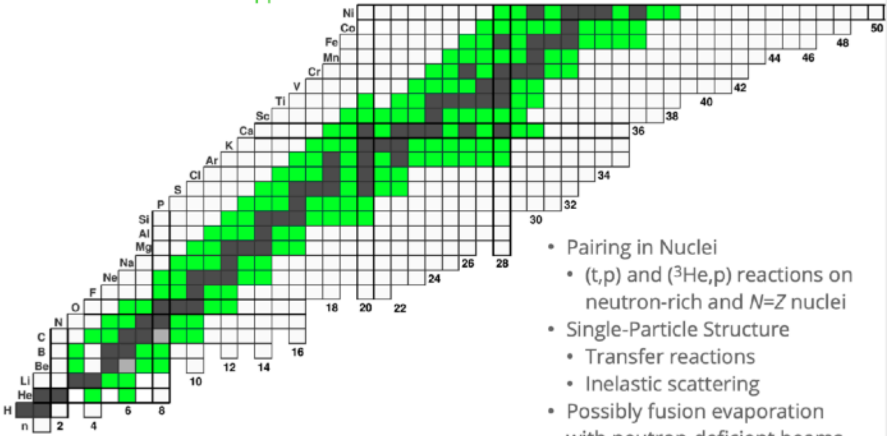
www.phy.anl.gov/airis/rates.html

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



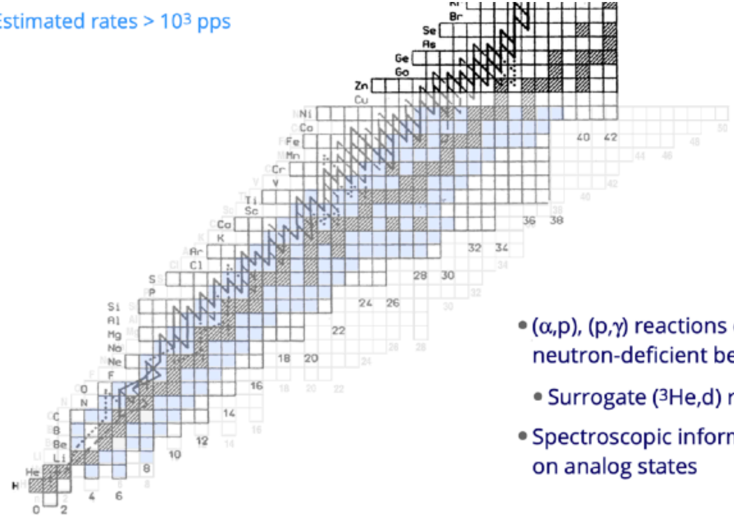
- Fusion-evaporation reactions
  - Collective structures and high-spin states
  - e. g. γ-ray spectroscopy w/ tagging
- Weak cross-section measurements
  - Astrophysics and Fusion cross sections
  - Transfer and fusion reactions

- 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.

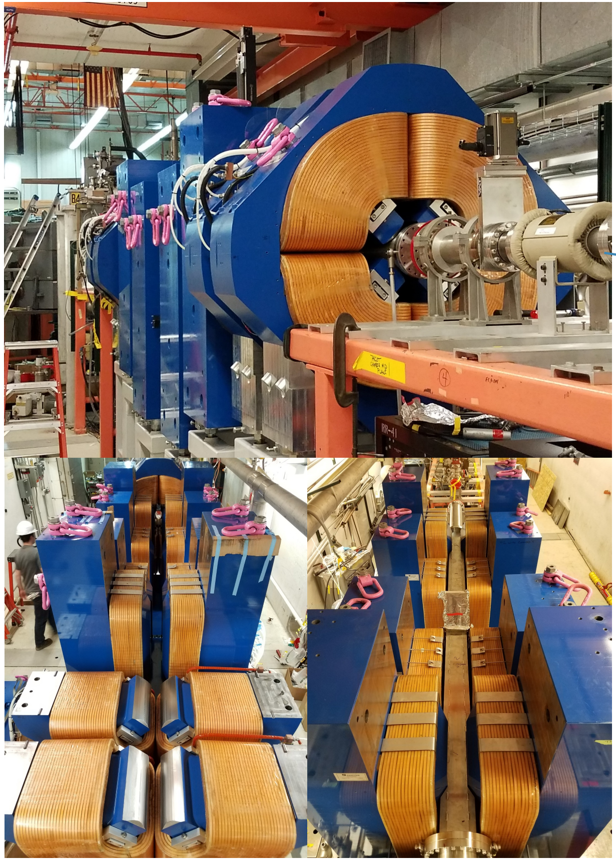
- Estimated rates > 10^3 pps



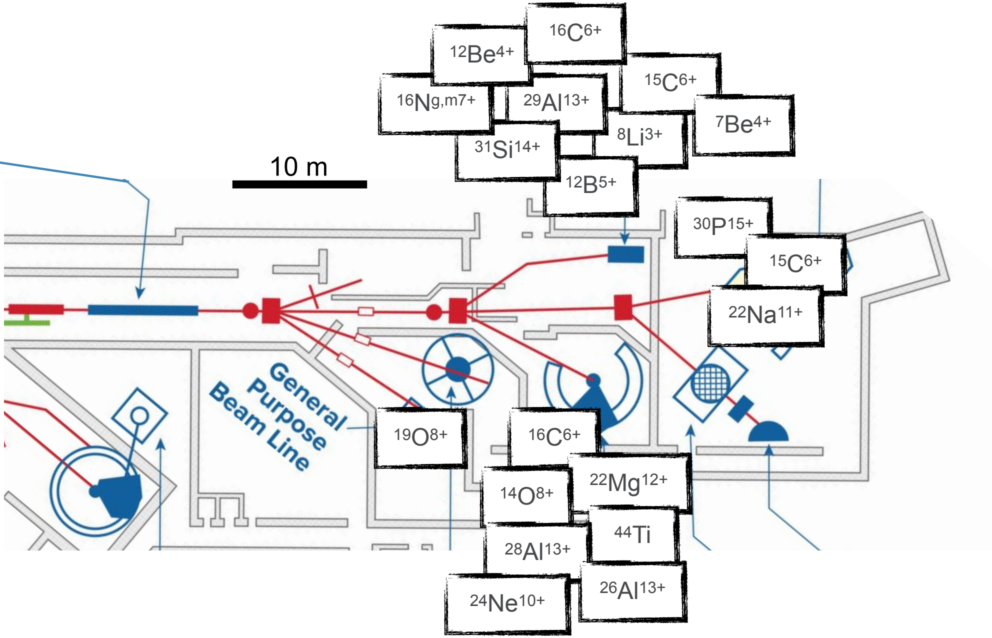
- (α,p), (p,γ) reactions on neutron-deficient beams
- Surrogate (^{3}He,d) reaction
- Spectroscopic information on analog states

RAISOR COMMISSIONING AND OPERATING PRINCIPLES

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



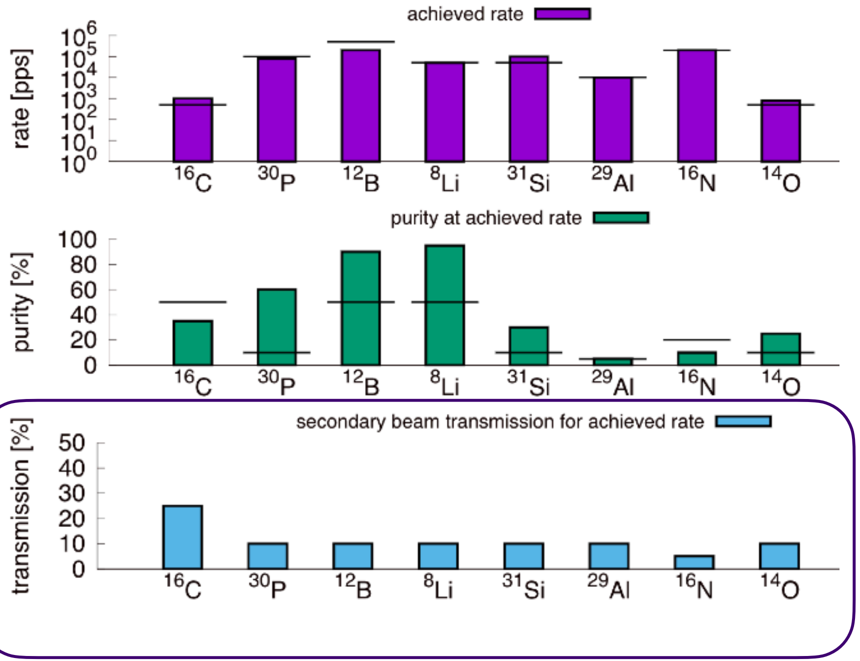
>20 radioactive beam measurements at 4 different experimental locations [+10's m downstream of RAISOR]

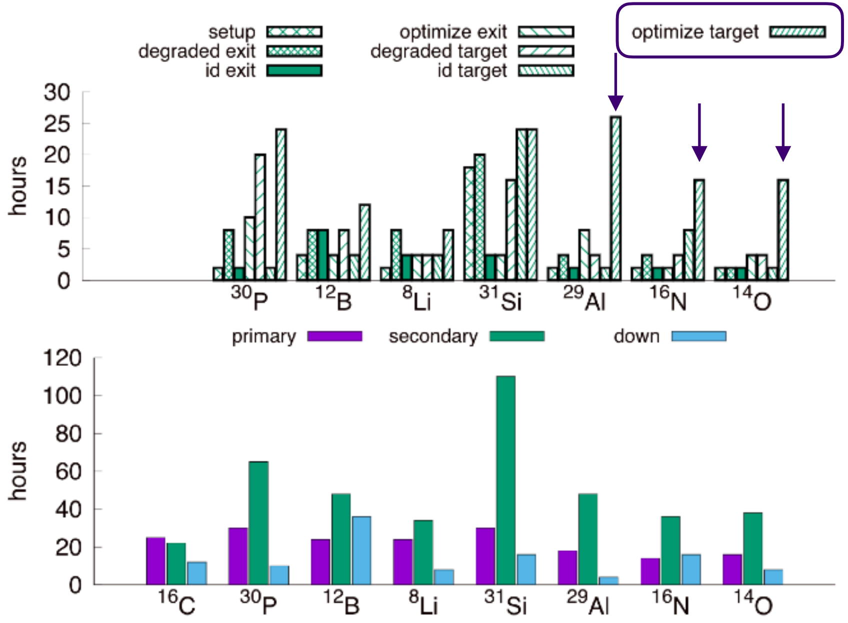


Tang et al., PRC 2022
Hoffman et al., NIMA 2022
Chen et al., PRC 2022
Jayatissa et al., PRL 2023

OPPORTUNITIES FOR IMPROVEMENT

Some in-flight beam & tuning data





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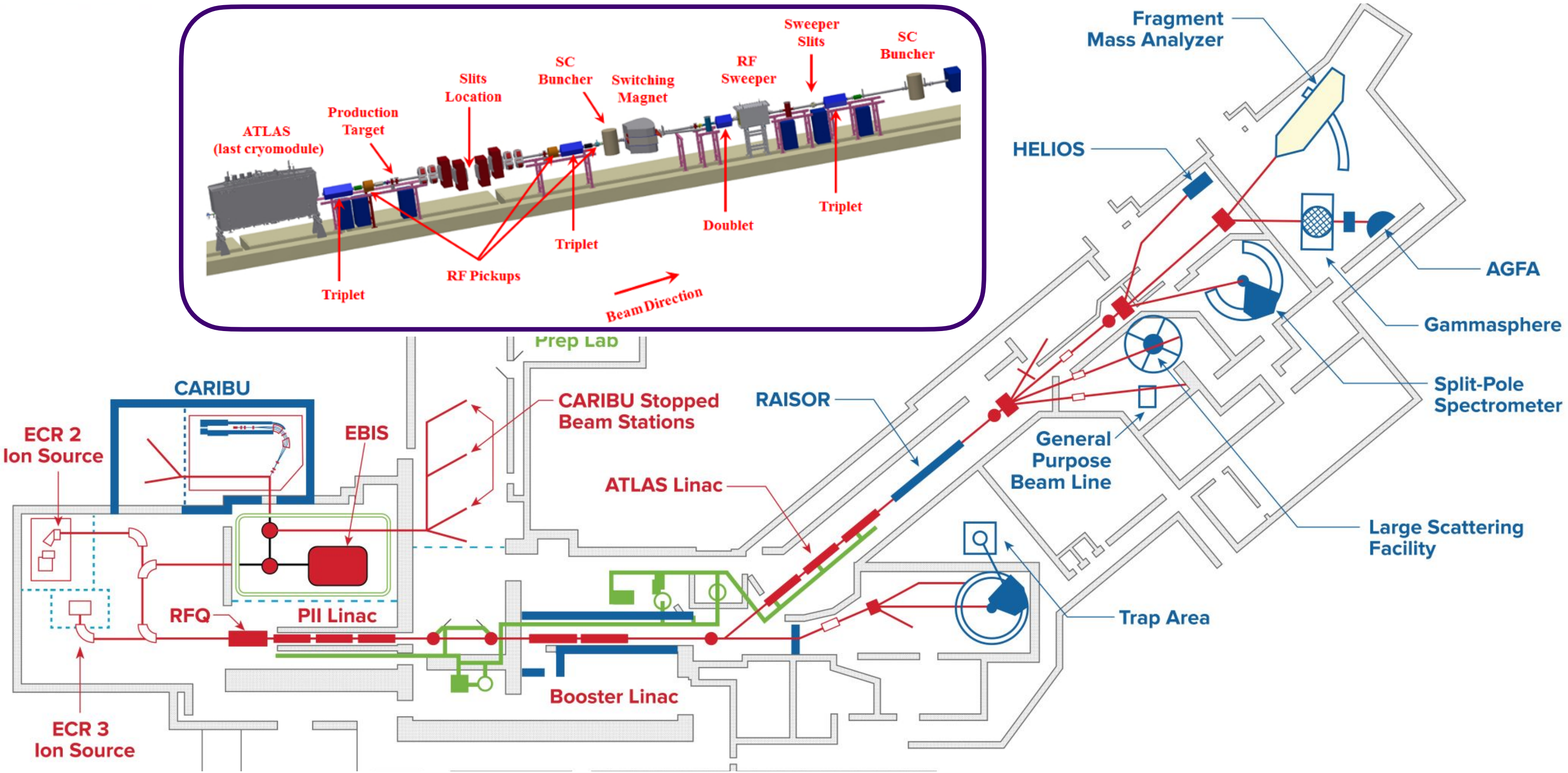
TRANSPORT BEAM LINES FROM RAISOR - TO - TARGET



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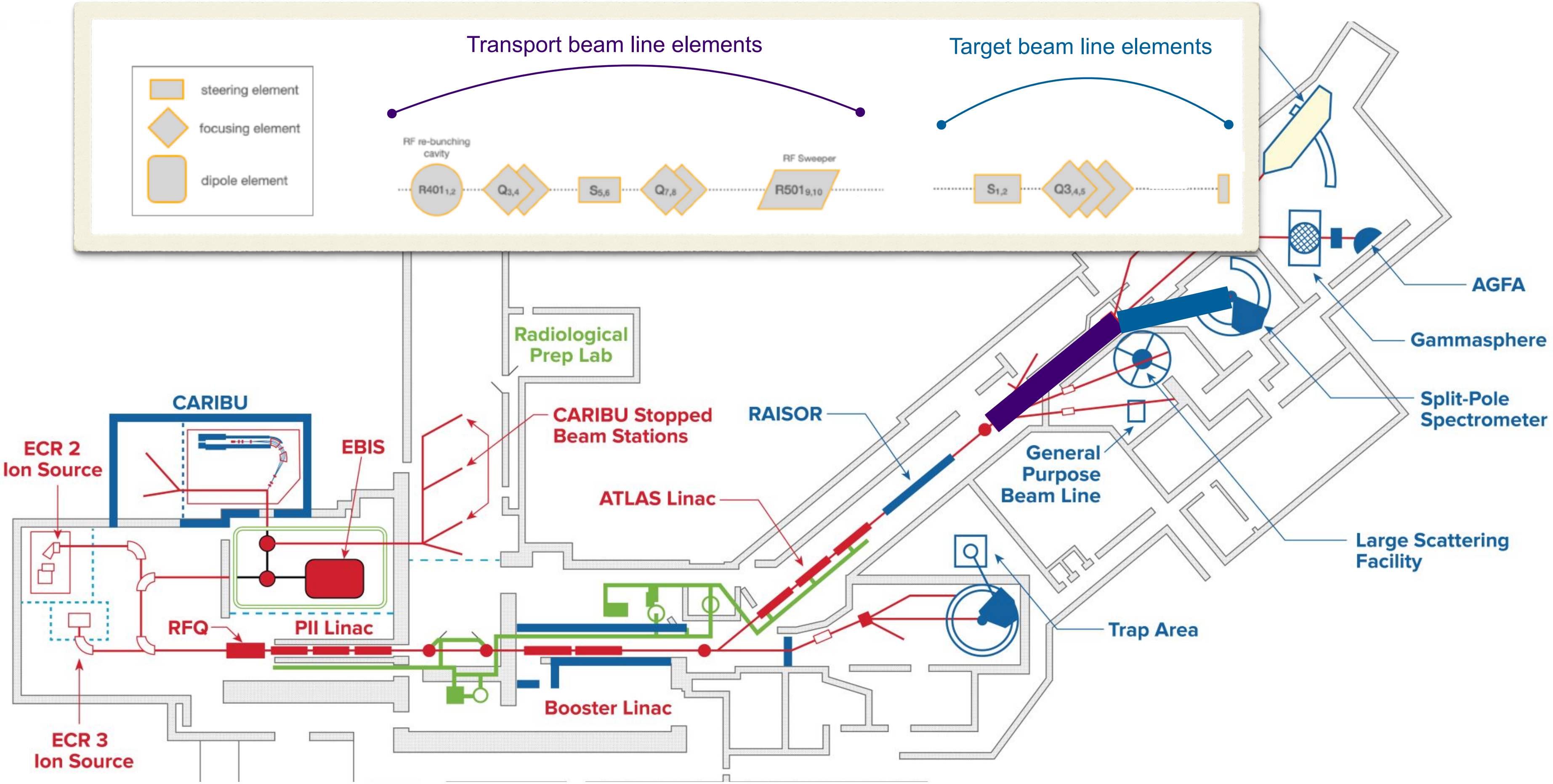
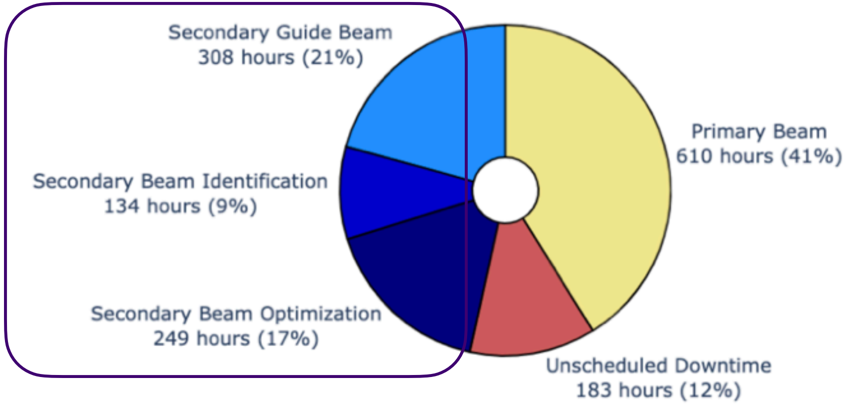
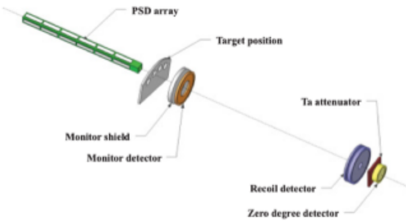
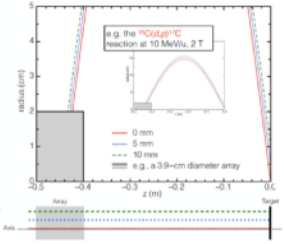
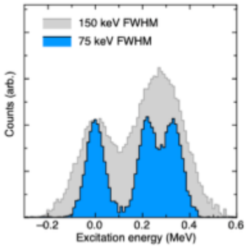
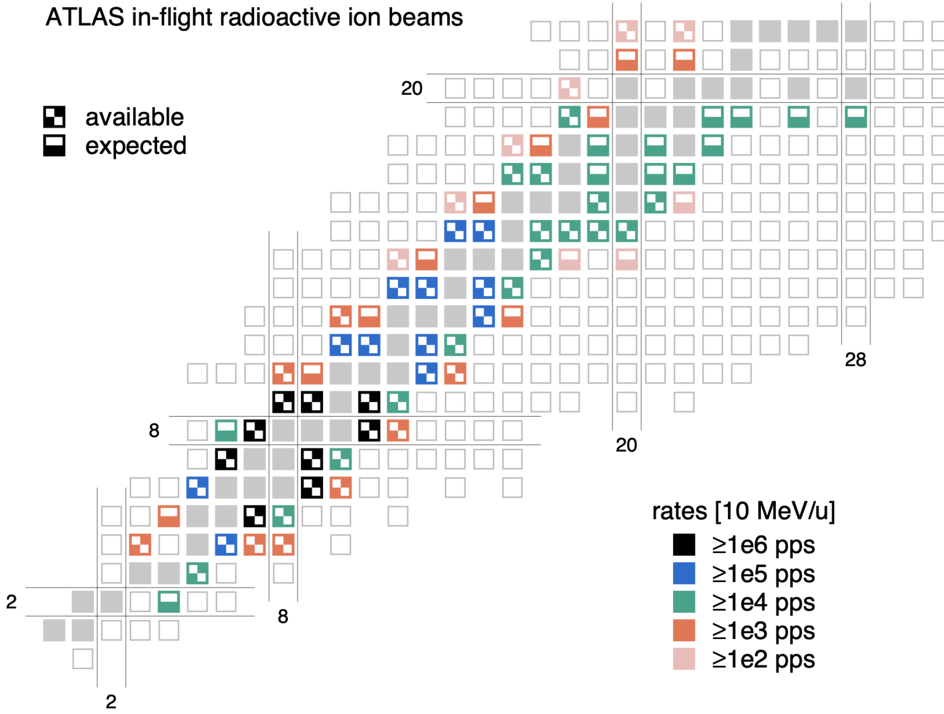












IMPROVE THE IN-FLIGHT BEAM QUALITY, TRANSMISSION, UP-TIME, AND DELIVERY TIMES
ENHANCED SCIENTIFIC POTENTIAL
= RETURN HOURS TO EXPERIMENTAL WORK =
= IMPROVED BEAM QUALITY, RELIABILITY, REPRODUCIBILITY =
= EXTEND THE REACH OF IN-FLIGHT BEAM PRODUCTION =

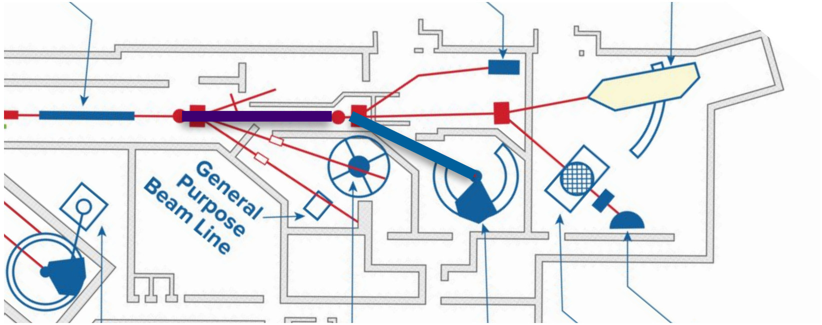
THE OPTSB PROJECT

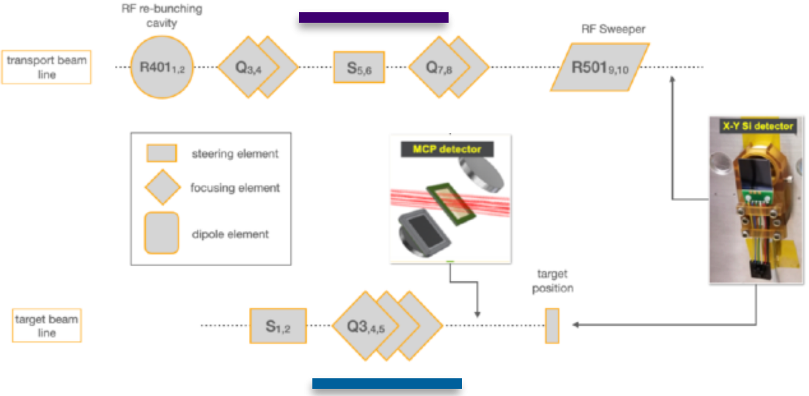
OPTSB: OPTIMIZATION OF SECONDARY BEAMS

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).





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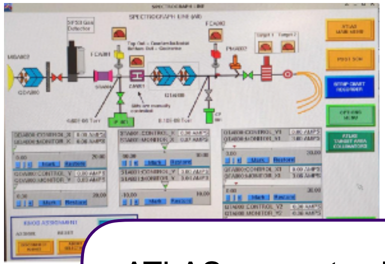
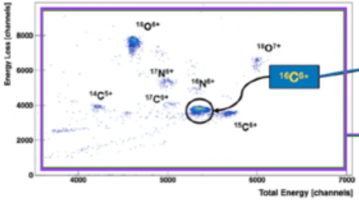


ATLAS magnet values



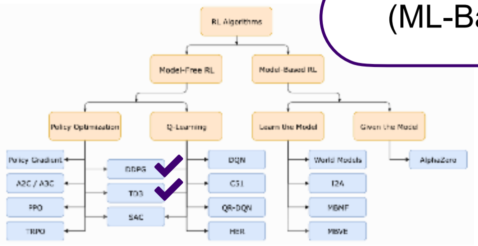
A high-performance time series engine

DataBase [influxDB]

Beam line observations [currents, rates, XY]

Real-time display

(ML-Based) Optimization



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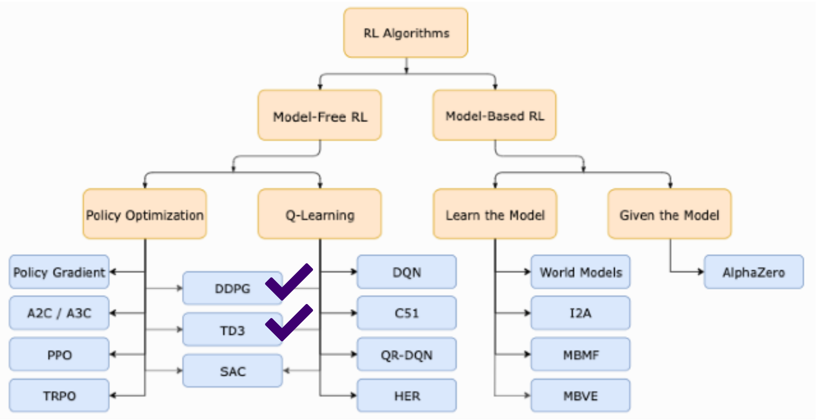
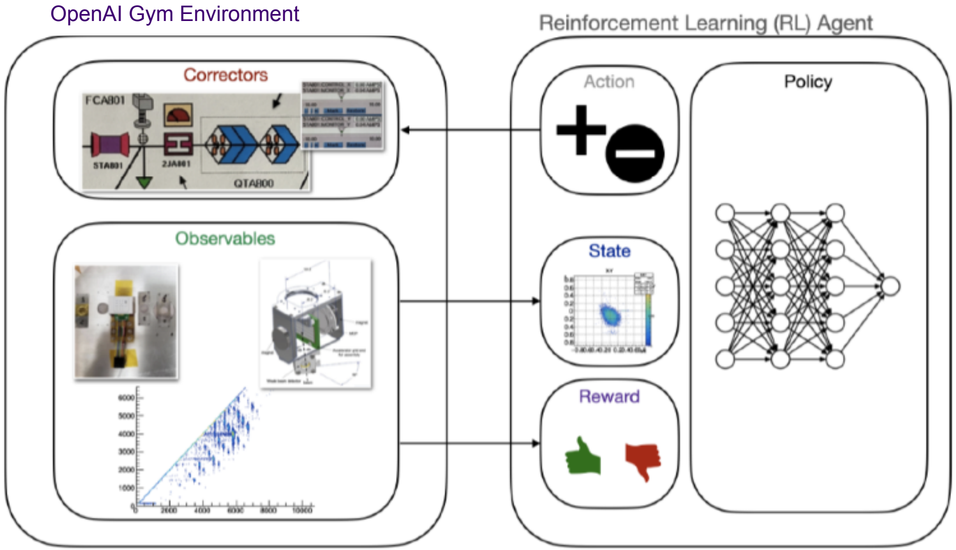
OPTSB: OPTIMIZATION OF SECONDARY BEAMS

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…



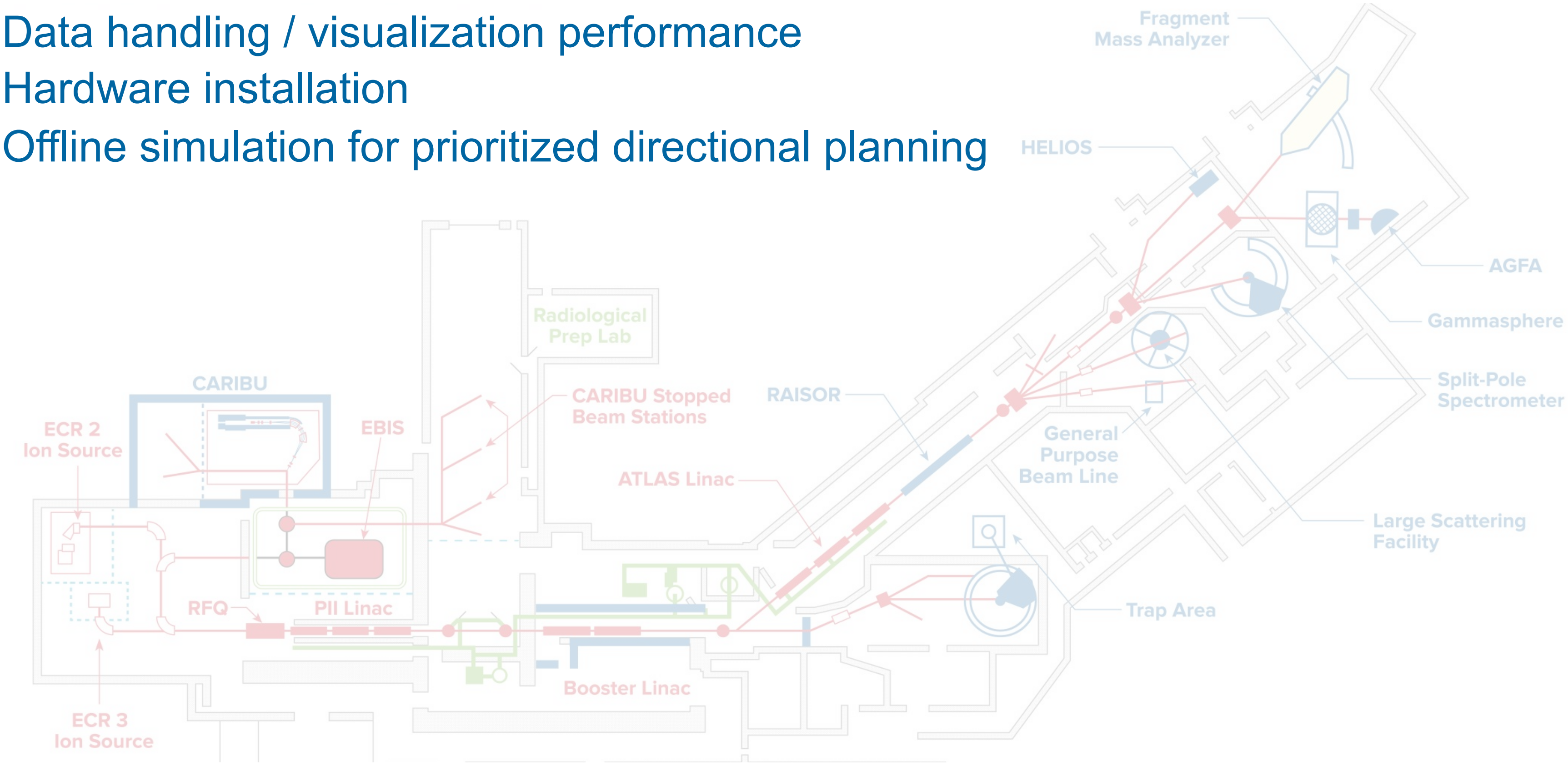


PROGRESS & UPDATES: PRIMARILY OFFLINE

Data handling / visualization performance

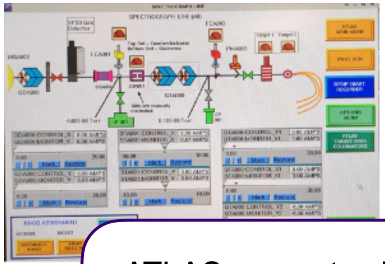
Hardware installation

Offline simulation for prioritized directional planning



IMPROVING EFFICIENCY OF DATA-FLOW

Explored reliability, boundary checks, & timing improvements



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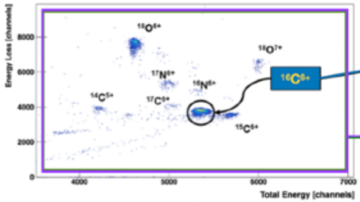

Beam line observations [currents, rates, XY]

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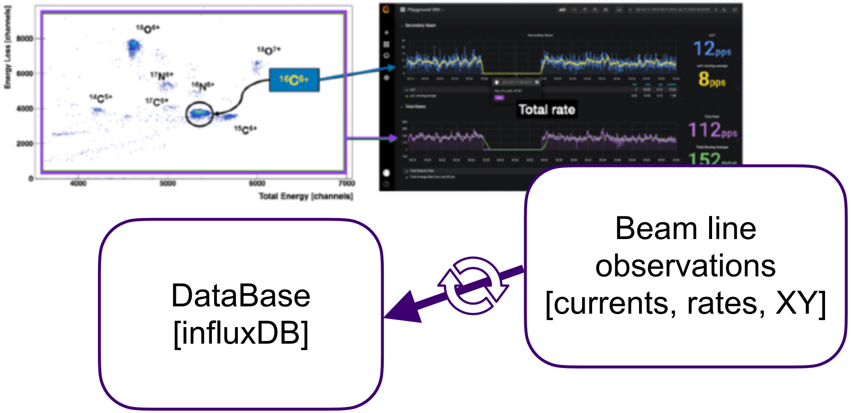
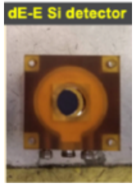
Beam-line data collection & handling

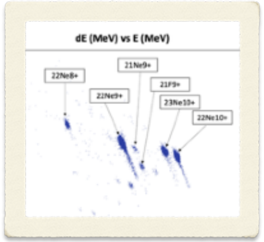
+100 - 500 Hz, 30 channels, 10 - 12 reduction/manipulation processes
+ Benchmarked systems offline with signal emulator(s)

+Exploring newly developed daq software (FSU daq) [T. L. Tang et al.,]
+Exploring informative histogram settings / filling solutions,
i.e. bin dependence upon rates or info required
+Explore 2-D image generation / saving for future CNN work

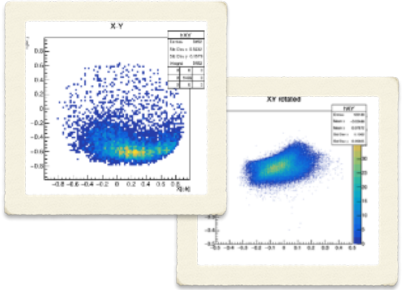


+ Total & individual rates [~1 sec period]





+ Multi positional info [~2 - 4 secs]
+ Rate dependence on uncertainty
(FHWM, Gauss. Fit for positional info)



+ Event-by-event vector reconstruction [3 - 5 sec]
+ Similar rate dependence for uncertainties
/ stats

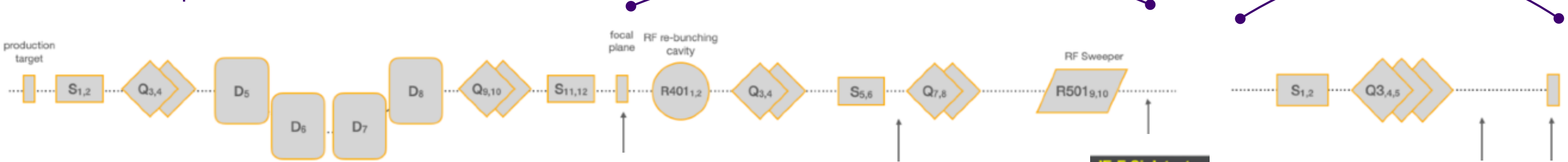
COMPLETED ALL REQUIRED HARDWARE INSTALLS

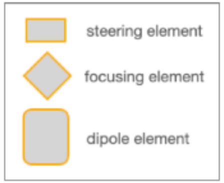
Full suite of diagnostics at the desired ‘target’ & ‘transport’ beam-line positions

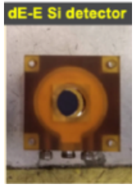
RAISOR: achromatic in-flight beam separator

Transport beam line elements

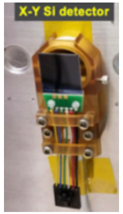
Target beam line elements



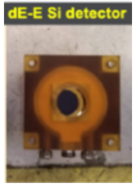




Particle identification & rates



Particle identification, beam positioning, & rates



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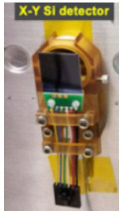
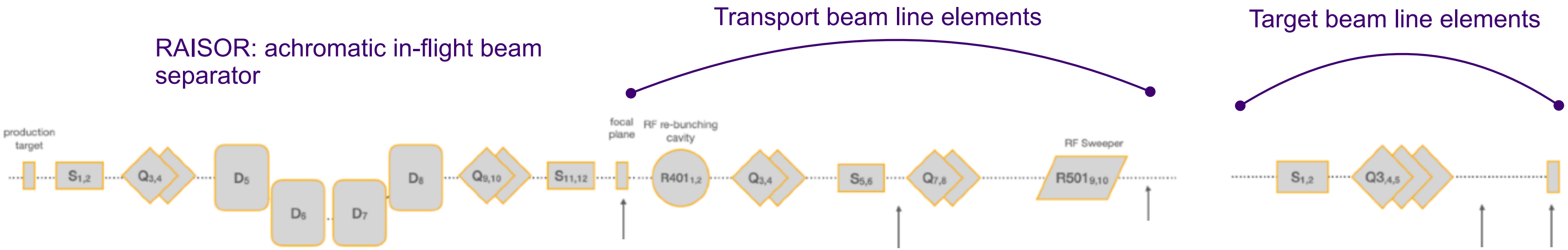


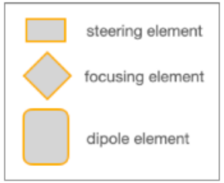
Particle identification, time-of-flight, combined beam positioning (beam vector) & particle rates

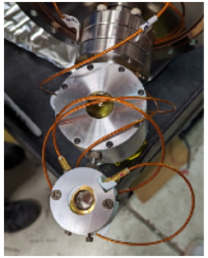
+ Newly constructed & installed particle ID + beam-profile stations (x2)
+ target station coupled to newly constructed passive PS (tof) MCP station
+ Integrated available particle ID detector systems
+ Det. placements guided by TRACK simulations (& physical parameters)
+ All integrated into digital DAQ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

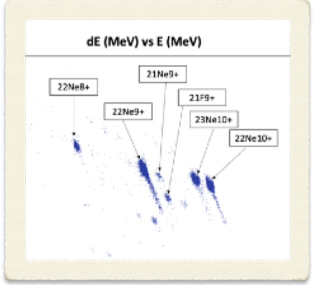
COMPLETED ALL REQUIRED HARDWARE INSTALLS

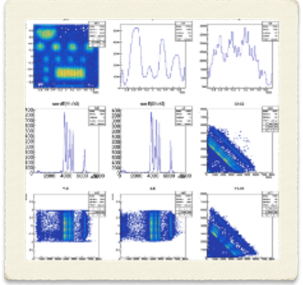
Full suite of diagnostics at the desired ‘target’ & ‘transport’ beam-line positions











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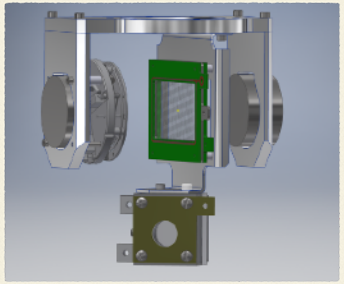
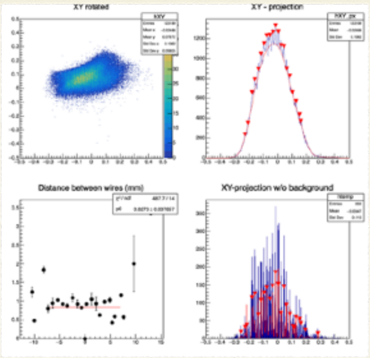
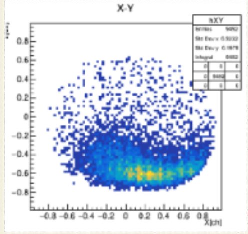


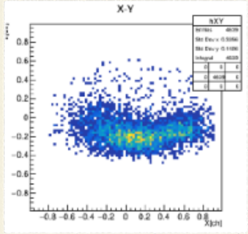


Operation of position sensitive MCP with ATLAS beam

Target beam line elements

~2 m flight path





Operation of position sensitive Si detector with an ATLAS beam

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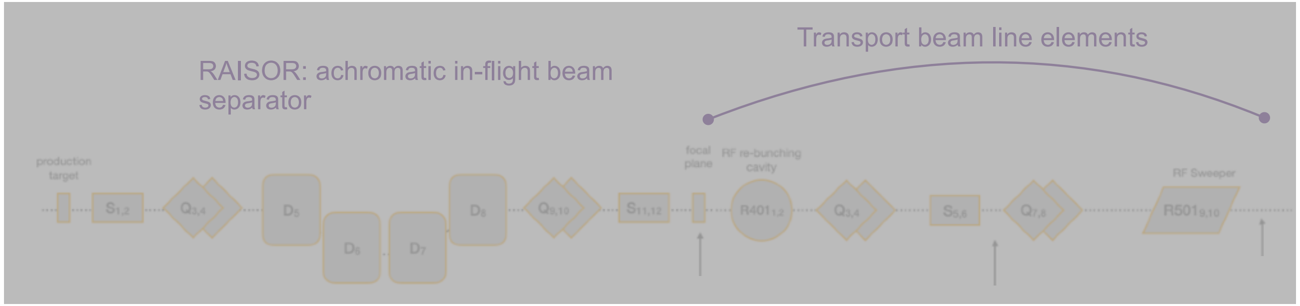
UTILIZATION OF ION-OPTICS SIMULATION [TRACK]

Characterization of hardware to inform simulations & RL parameters



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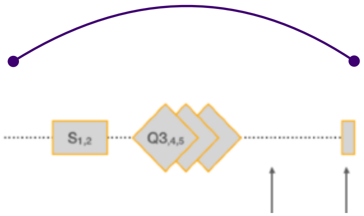


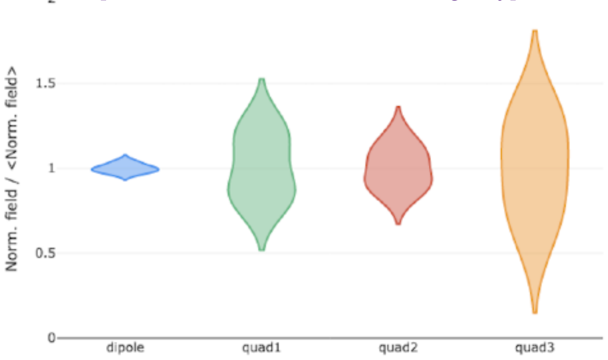
Historical Data:
- Contributes insight into action limits, correlations and hyper-parameter tuning [10 sets on target line, 25 sets on transport line]

Completed magnetic field scans with Hall probe for each element

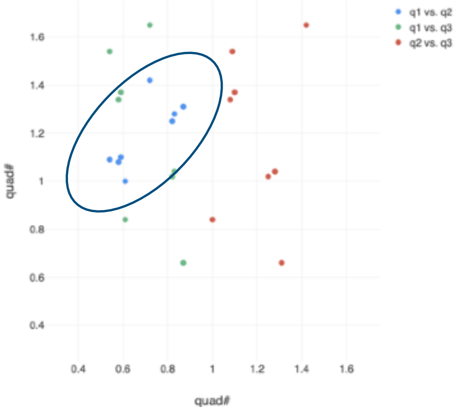
Developed inputs for 12 independent data sets [A,q,E,**emittance parameters**]

Basic comparisons between limited data collected to simulation show qualitative agreement

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

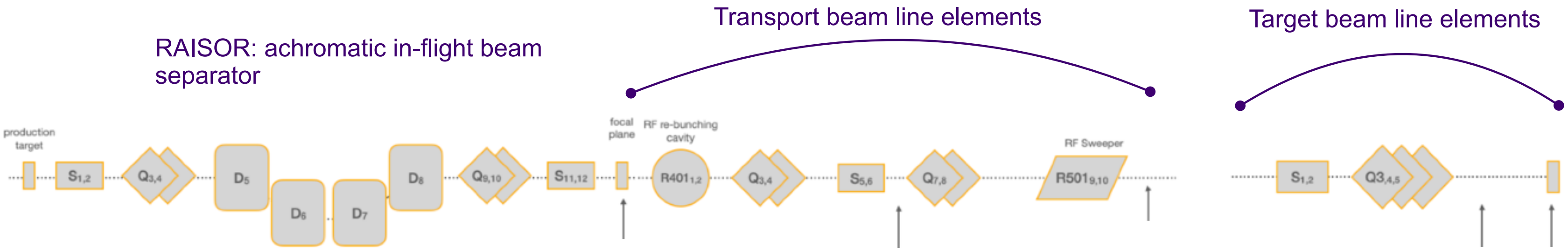


Quadrupole 1 vs. Quadrupole 2



UTILIZATION OF ION-OPTICS SIMULATION [TRACK]

Built-in assumptions for the input distributions to the simulations [angle vs. energy]

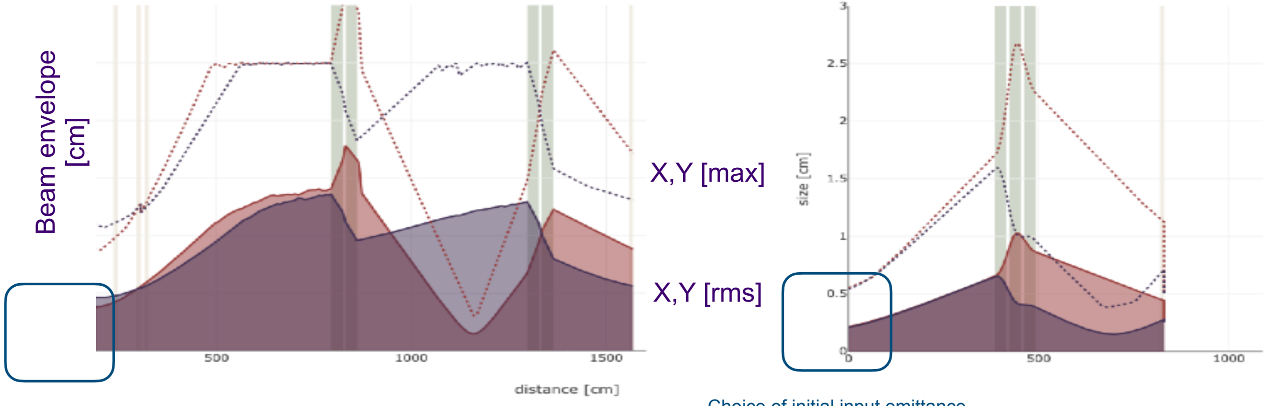


Historical Data:
- Contributes insight into action limits, correlations and hyper-parameter tuning [10 sets on target line, 25 sets on transport line]

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



Choice of initial input emittance

DEVELOPMENTS & CHECKS THROUGH OFFLINE SIMULATIONS

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?

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

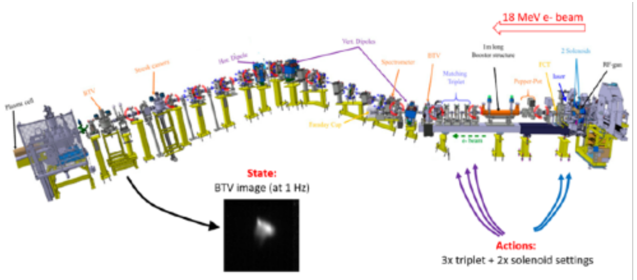


Figure 1. AWAKE beamline showing location of the matching devices (actions) and the observation BTV.

Two main goals could be incorporated into reward values

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

Beam transmission / intensity

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

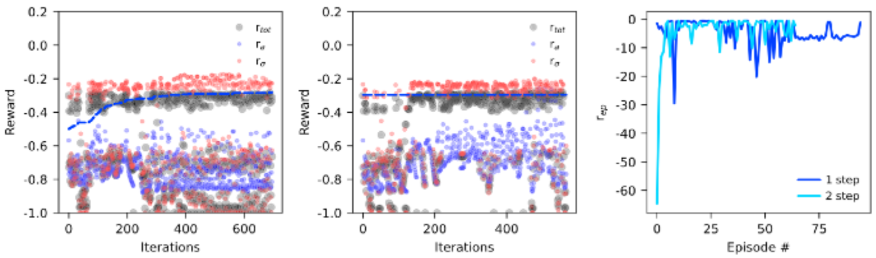
Ratio of # of beam particles generated vs. observed

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



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DEVELOPMENTS & CHECKS THROUGH OFFLINE SIMULATIONS

Demonstrated success of RL-based optimization for transmission & focussing

Simulation (offline) Results [target optimization]:
- Implemented the TD3 RL scheme:
    - 3 actions (quadrupoles), state defined by transmission, spatial info, calculated angles
- TRACK provides radial and transmission state info
- Explore various emittance parameters
    - Primary beam like: smaller
    - Secondary beam like: larger
    - Asymmetric input beam parameters
- Emphasis to keep total steps below ~600 -> in practice expect less 1 hour wall-clock time
- Explored reward dangling, other obvious tools and tricks

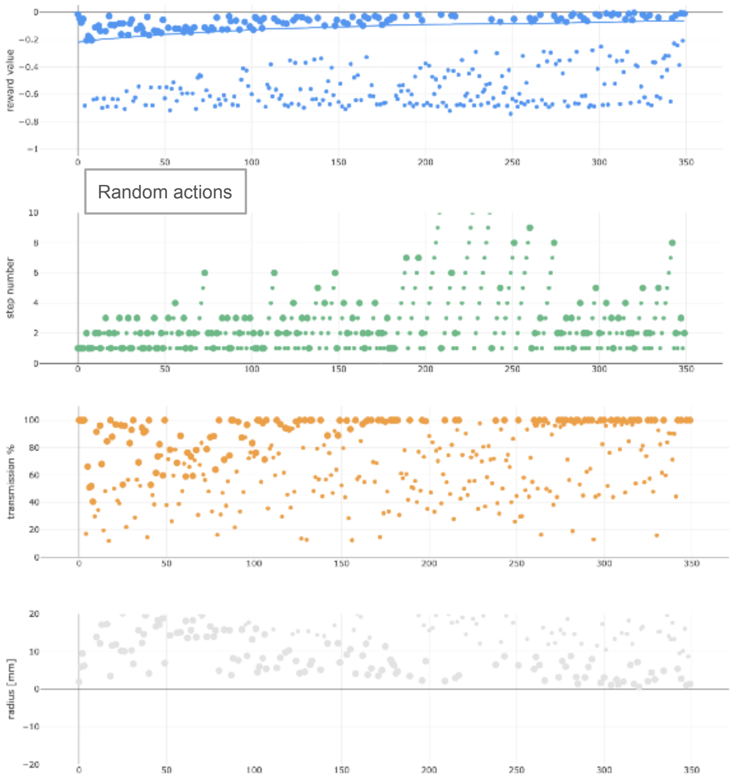
Results:
- Key hyper-parameters:
    1. Reward goal / type
    2. Random upfront training amount vs. TD3 noise (searching)
- Various successful trainings demonstrated [as low as 200 steps]
- Training on radius most promising, optimal transmission

Reward / step

Step count / episode

Transmission %

Radius at target Position



Step #

DEVELOPMENTS & CHECKS THROUGH OFFLINE SIMULATIONS

Demonstrated success of RL-based optimization for transmission & focussing

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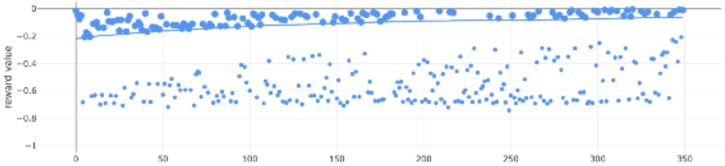
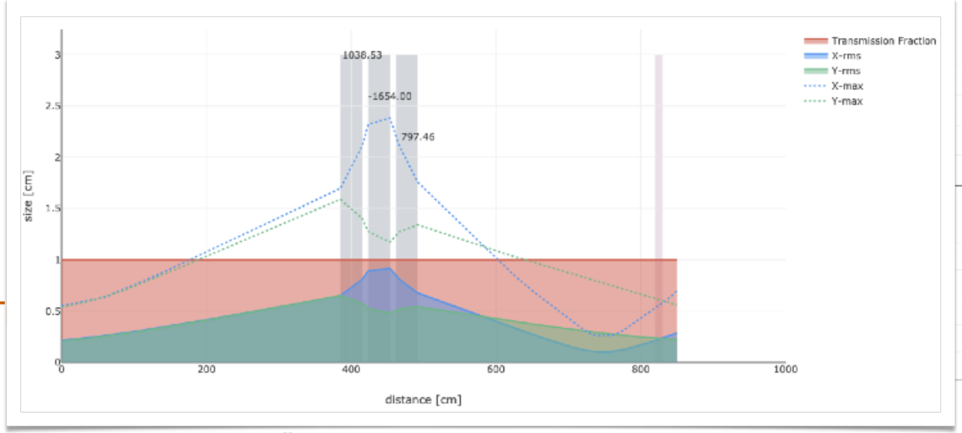
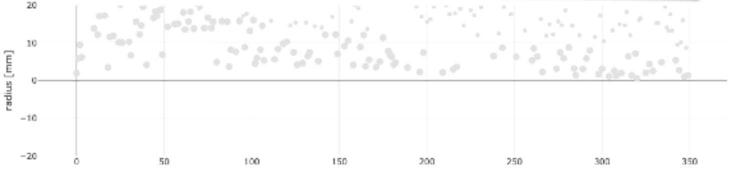




Radius at target Position



Step #

DEVELOPMENTS & CHECKS THROUGH OFFLINE SIMULATIONS

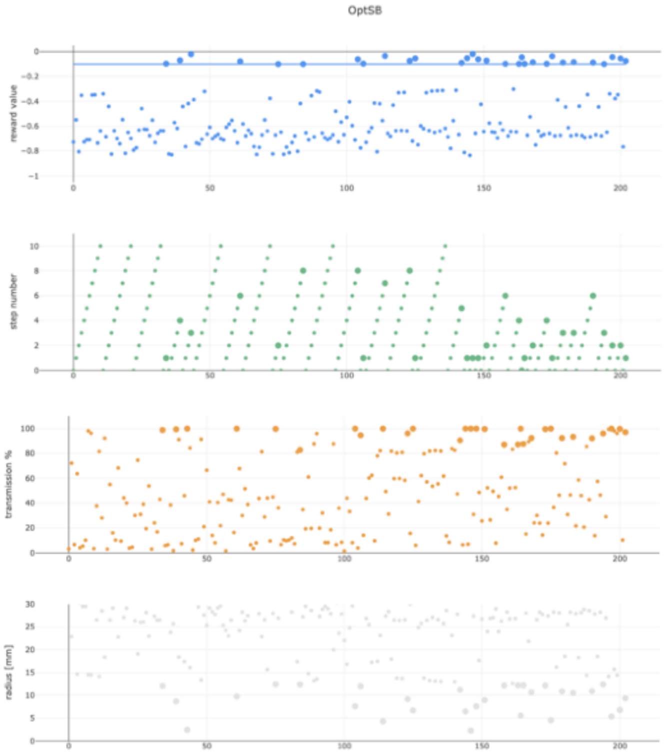
Demonstrated success of RL-based optimization for transmission & focussing

Reward / step

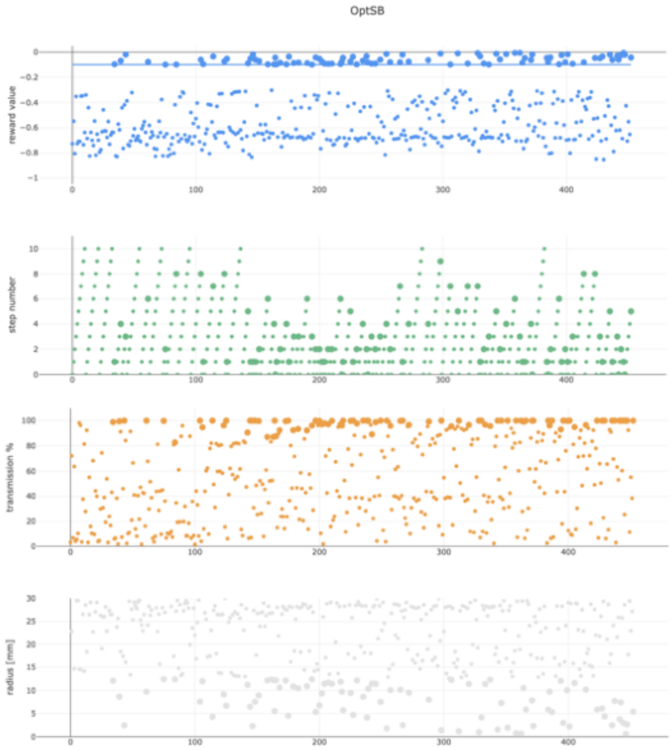
Step count / episode

Transmission %

Radius at target Position



Step #



Step #

Fixed max reward: radius
Good after 200 steps
Better after 400+

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DEVELOPMENTS & CHECKS THROUGH OFFLINE SIMULATIONS

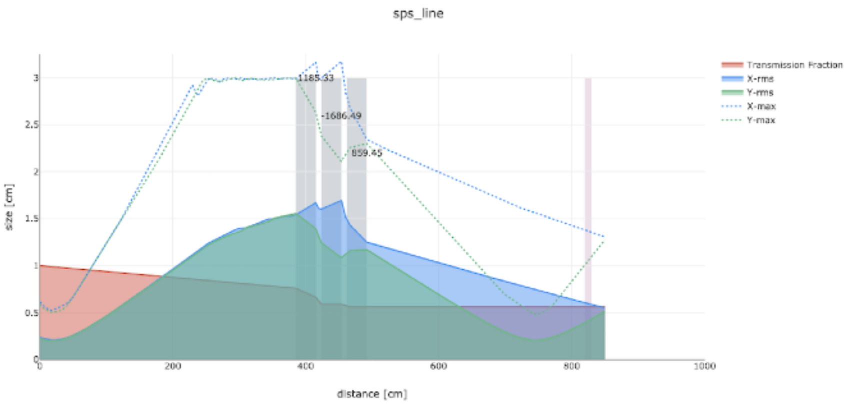
Demonstrated success of RL-based optimization for transmission & focussing

Reward / step

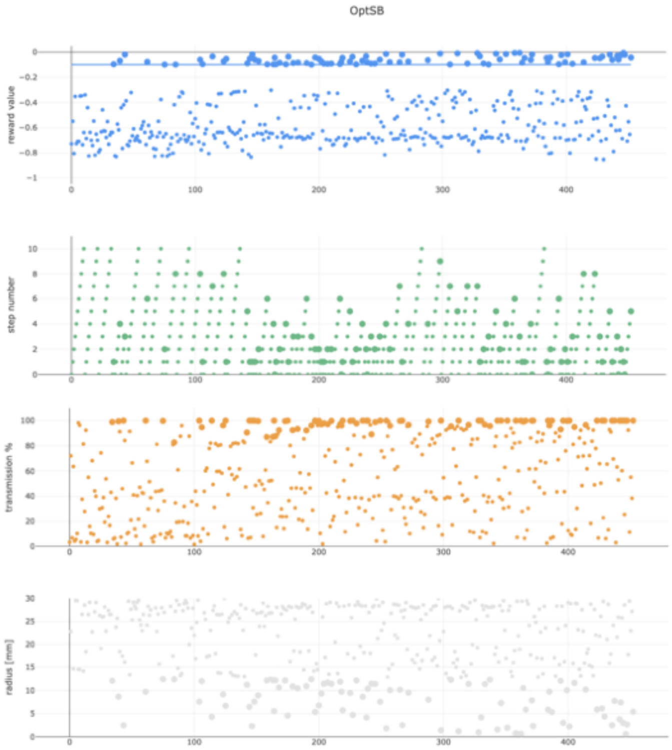
Step count / episode

Transmission %

Radius at target Position



Step #



Step #

Fixed max reward: radius
Larger input emittance (left)
Smaller (right)

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DEVELOPMENTS & CHECKS THROUGH OFFLINE SIMULATIONS

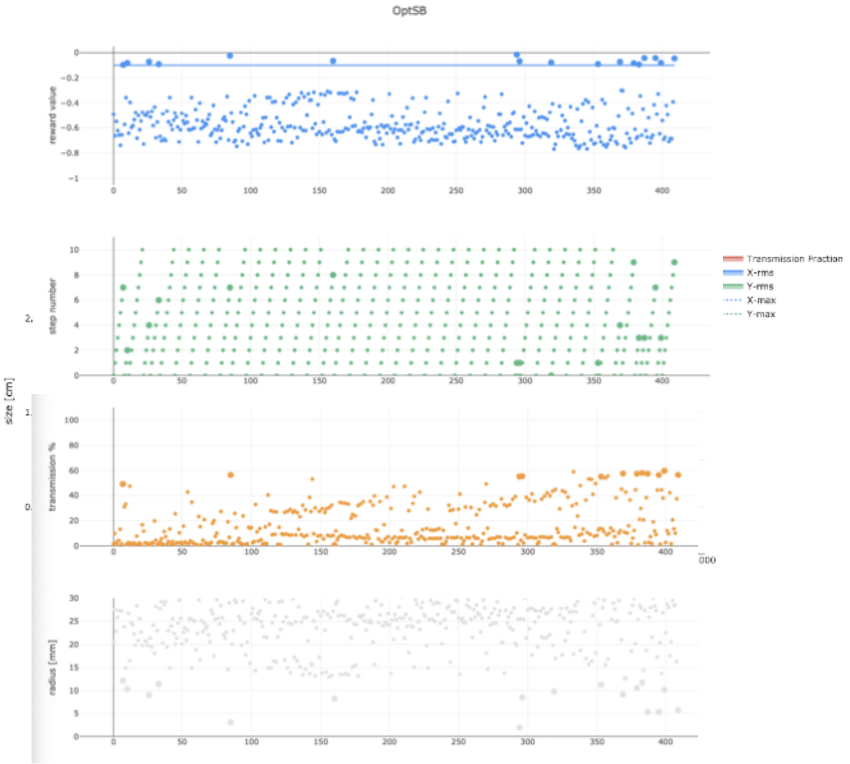
Demonstrated success of RL-based optimization for transmission & focussing

Reward / step

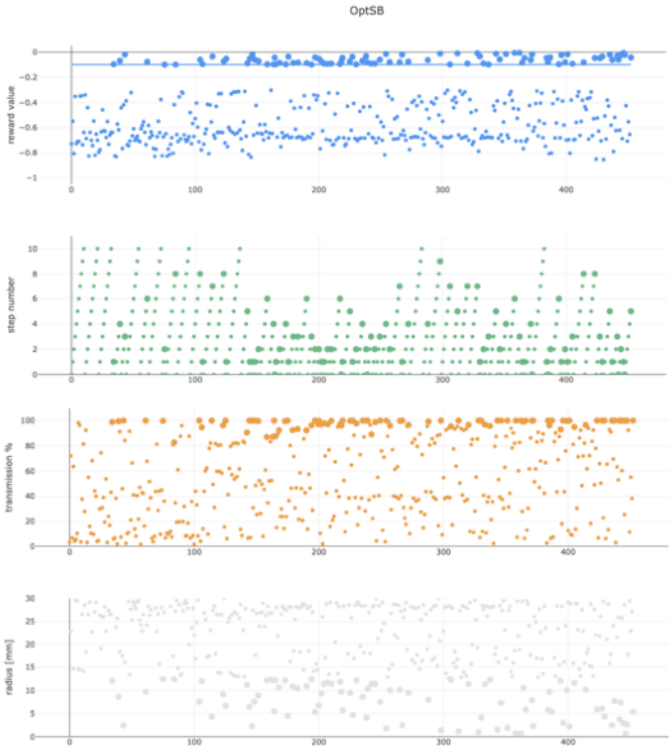
Step count / episode

Transmission %

Radius at target Position



Step #



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Fixed max reward: radius
Larger input emittance (left)
Smaller (right)

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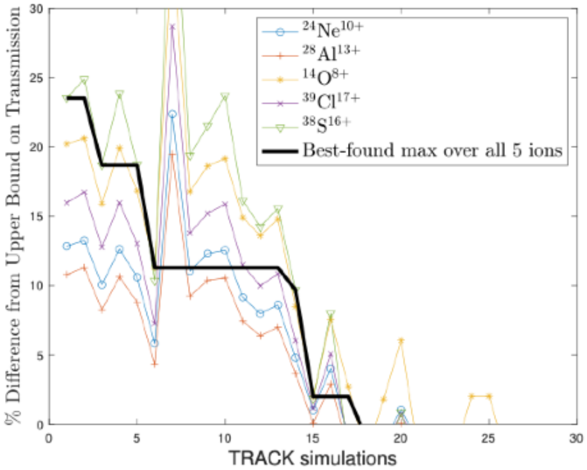
ONGOING & FUTURE OFFLINE DEVELOPMENTS

Developments / Comparisons with other optimization methods
Growth towards full transport + target beam-line optimization framework

Employ in-house optimization solver (manifold sampling) to solve

$$\min_{x} \max_{i=1,2,\ldots,\#ions} \ell(x, \theta_i)$$

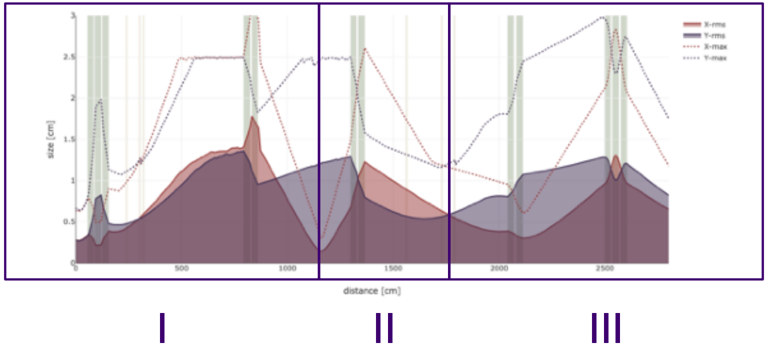
where x denotes quadrupole magnet settings, θ_i denotes an ion species, and $\ell(x, \theta_i)$ denotes the number of particles lost in transmission.



Joining of the beam transport line & target line:

+ At present no practical success for optimizing more than 3 - 5 beam-line elements simultaneously
+ Instead utilized a segmented / series approach (analogous to a more true operations mode)
+ Still looking to explore the possibility to freeze / unfreeze elements either during or after initial segmented optimization
+ Correlations within the action space

Full beam line simulation: RAISOR exit - to - target

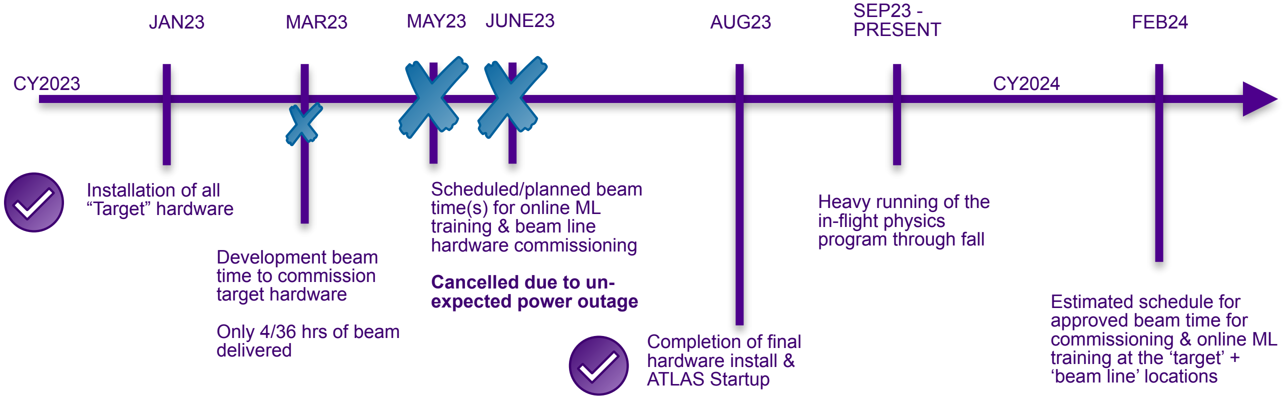


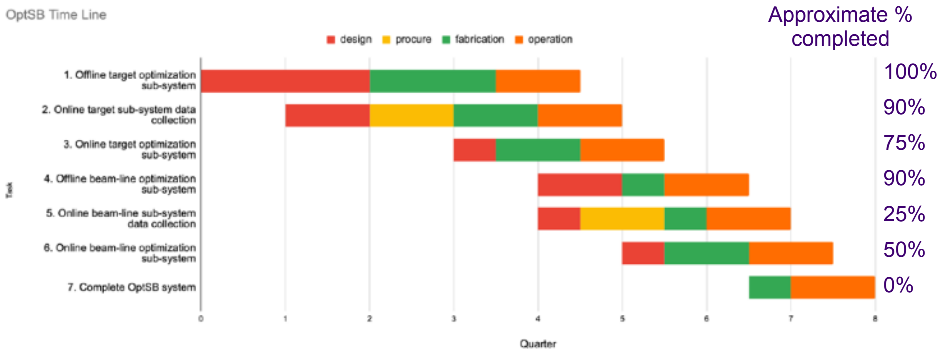
Explore other optimization schemes based on more visual information

+ 2D based images from diagnostics [video]
+ May require less data (reduce collection times)
+ Larger resource task for offline simulations to validate

BUDGET, MILESTONES, FUTURE DIRECTIONS

MAJOR PROJECT MILESTONES, COMPLETION %, & COSTING





	FY22 ($k)	FY23 ($k)	Totals ($k)
a) Funds allocated	$375	$375	$750
b) Actual costs to date	$270	$255	$525

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NEXT STEPS TO DEMONSTRATE PROJECT GOALS

Final preparations for beam time in Feb./March 2024

Enact ML training w/ online data for target optimization to SPS
- explore three different beam types (primary, degraded, secondary)
- two different primary beam species

Benchmark data to other mathematical optimization methods

Second beam-time run in early summer ’24 to apply procedures to full beam line transport optimization

Develop an implementation plan for regular use [narrow down hyper-parameter search list, folding into operations beam-delivery documentation, estimates of future support effort, etc…]

Explore other 2-D image beam diagnostic options (hardware & ML training):
- Real time imaging with scintillators and high-speed cameras
- Photo readout of MCPs on tracking stations
- 2-D contour of target distributions vs. rms / FWHM / averages

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.

= Completed required hardware developments & installation, offline developments & demonstrated optimization progress

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

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END