OASIS WS ON MACHINE LEARNING

Bayesian Optimization Applied to Radioactive Beam Transport for the AGATA-EXOTIC Campaign at LNL

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M. Mazzocco, A. Goasduff, P. Figuera, D. Torresi,
S. Bottoni, F. Galtarossa, A. Gottardo,
and the AGATA-EXOTIC Collaboration.

INFN EXOTIC Radioactive Nuclear Beams

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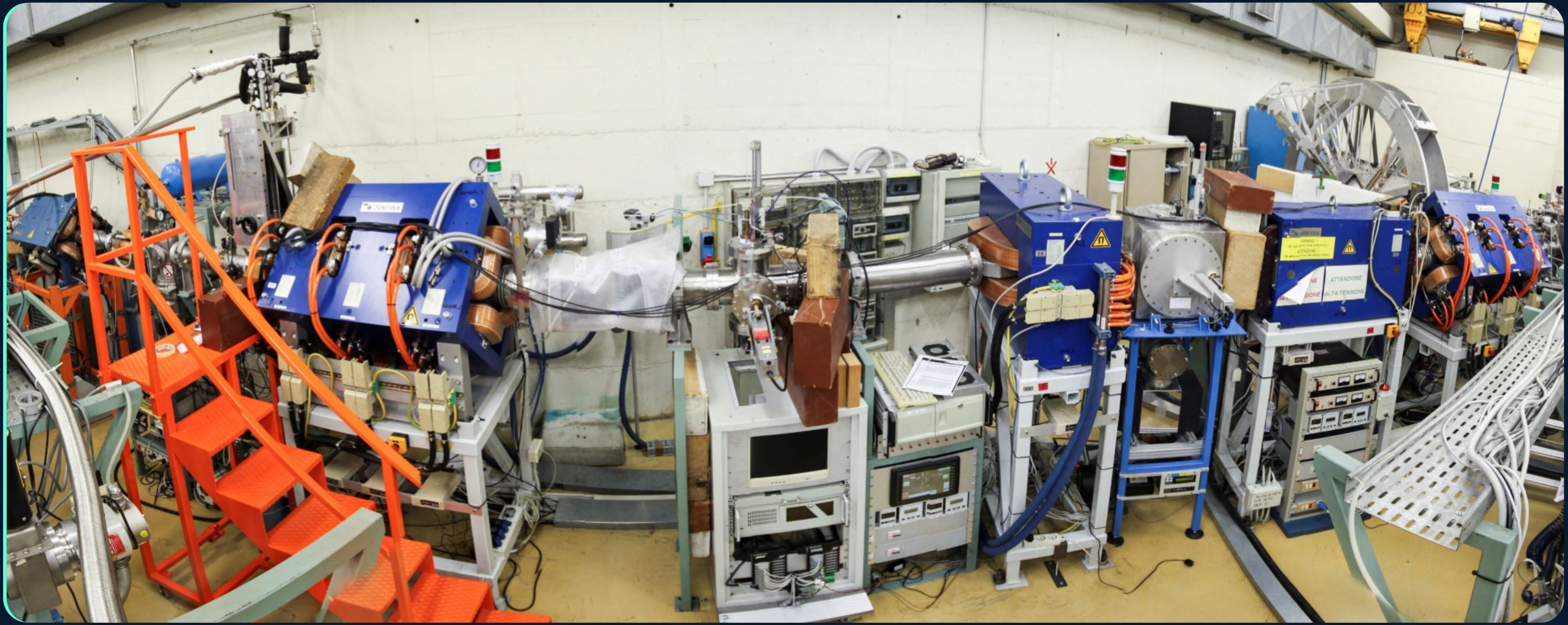
The EXOTIC Facility at LNL

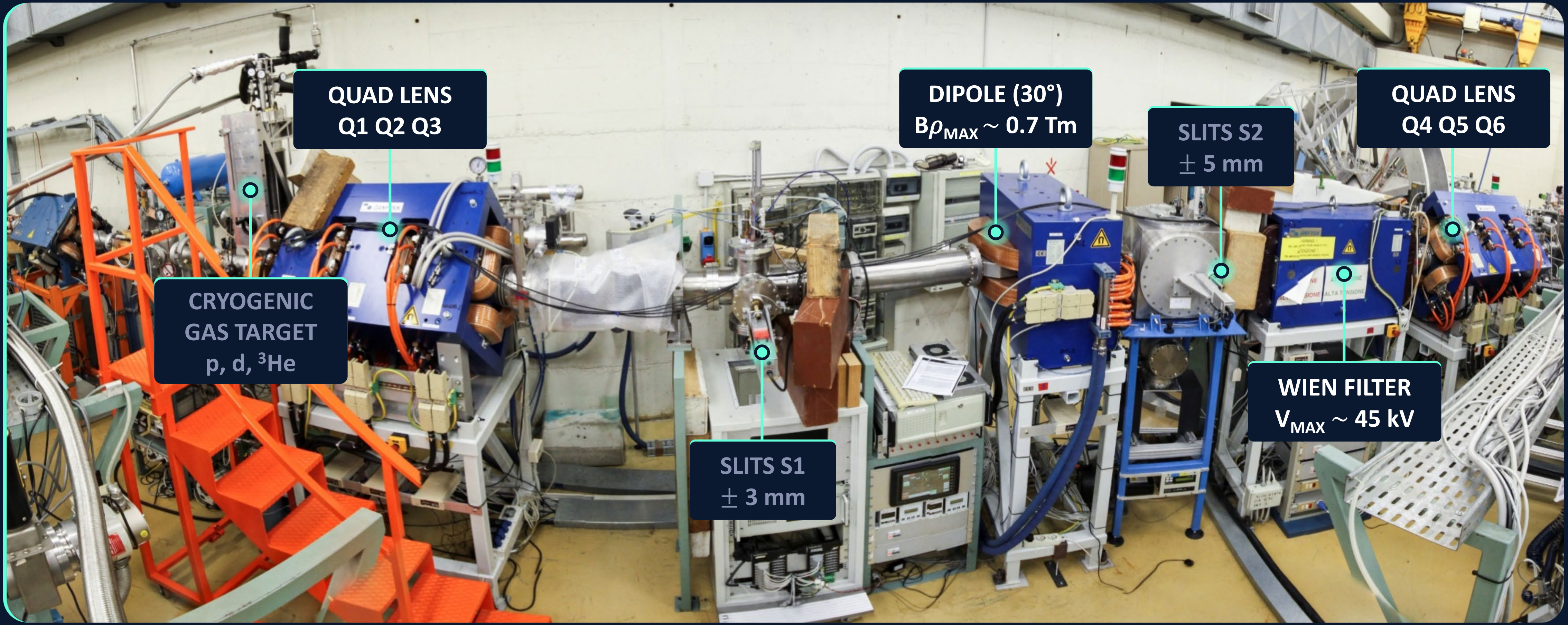
Low energy Radioactive Ion Beams (RIBs) via two-body inverse kinematics reactions induced by LNL-XTU tandem accelerator heavy-ion beams



SECTION 01

The EXOTIC Facility at LNL

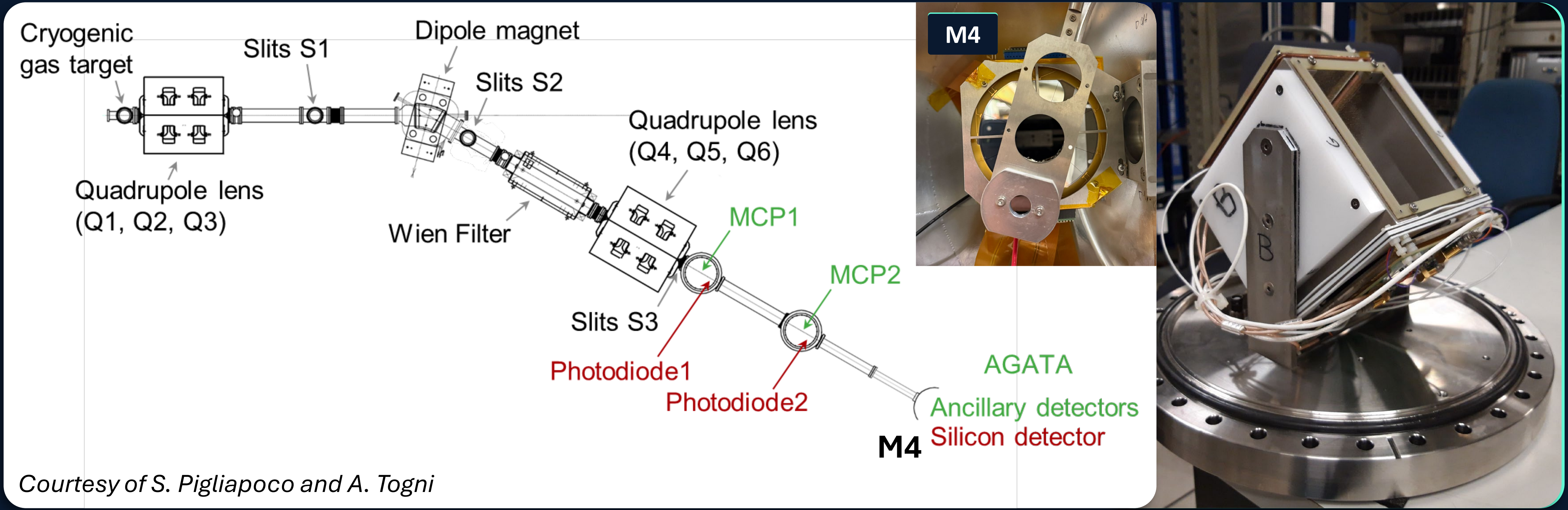
Low energy Radioactive Ion Beams (RIBs) via two-body inverse kinematics reactions induced by LNL-XTU tandem accelerator heavy-ion beams



SECTION 01

The EXOTIC Facility at LNL

Upgrade and refurbishment + new diagnostic and tracking system



Courtesy of S. Pigliapoco and A. Togni

Beam diagnostic by photodiodes and M4 silicon monitor at AGATA target position

First AGATA-EXOTIC coupling in 2025!

Beam tracking by Micro-Channel Plate detectors (MCP1, MCP2) with:

- Diameter: 104 mm
- Position resolution: ~2 mm
- Intrinsic time resolution: 400 ps

SECTION 02

RIBs Campaign

Physics cases using ^{8}Li, ^{7}Be and ^{11}C radioactive ion beams

Solving the puzzle of quadrupole strength in ^{8}Li to benchmark ab initio predictions

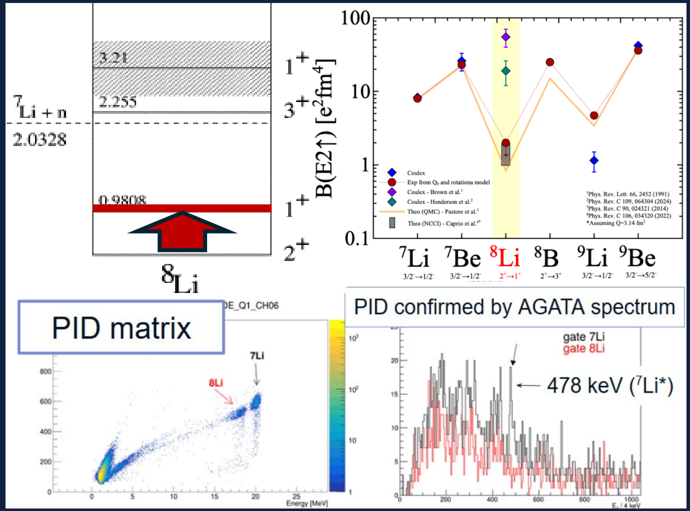
SPOKESPERSONS

S. Bottoni, F. Galtarossa, M. Rocchini

RIB: ^{8}Li at 20 MeV ($5\cdot10^{4}$ pps)

Secondary target: ^{109}Ag 2.5 mg/cm²

Setup: AGATA + Si Detectors



Particle-γ Correlation Studies for the System ^{7}Be + ^{208}Pb at near-barrier Energies

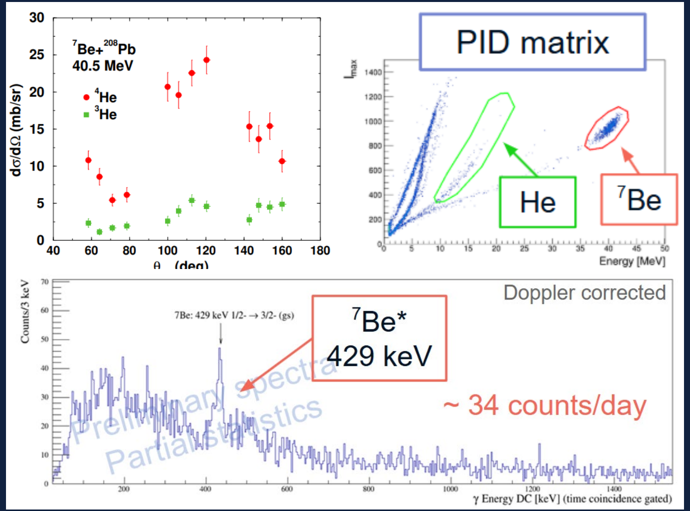
SPOKESPERSONS

M. Mazzocco, G. Zhang, S. Pigliapoco

RIB: ^{7}Be at 40.5 MeV ($1.6\cdot10^{5}$ pps)

Secondary target: ^{208}Pb 2 mg/cm²

Setup: AGATA + Si Detectors



Isospin Mixing and Cluster Configurations in ^{12}C

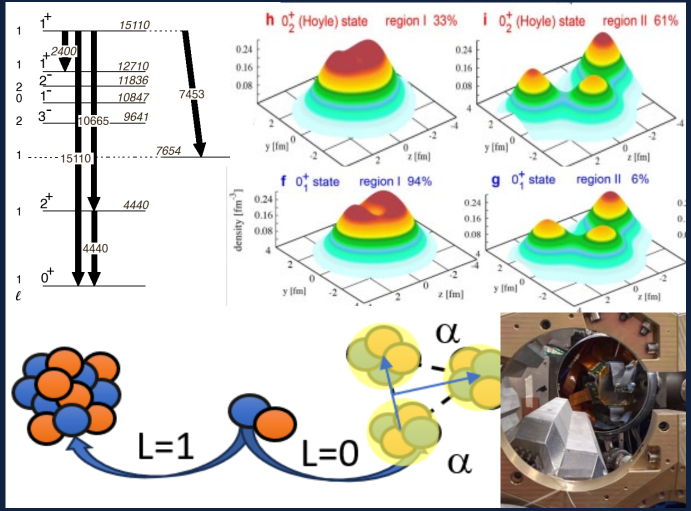
SPOKESPERSONS

L. Zago, A. Gottardo

RIB: ^{11}C at 54 MeV (10^{5} pps)

Secondary target: CD_2 2 mg/cm²

Setup: AGATA + Si Detectors



SECTION 02

RIBs Campaign

Physics cases using ^{8}Li, ^{7}Be and ^{11}C radioactive ion beams

Solving the puzzle of quadrupole strength in ^{8}Li to benchmark ab initio predictions

SPOKESPERSONS

S. Bottoni, F. Galtarossa, M. Rocchini

RIB: ^{8}Li at 20 MeV ($5 \cdot 10^{4}$ pps)

Secondary target: ^{109}Ag 2.5 mg/cm²

Setup: AGATA + Si Detectors

d(^{7}Li,^{8}Li)p at 28 MeV

Primary beam: ^{7}Li

Particle-γ Correlation Studies for the System ^{7}Be + ^{208}Pb at near-barrier Energies

SPOKESPERSONS

M. Mazzocco, G. Zhang, S. Pigliapoco

RIB: ^{7}Be at 40.5 MeV ($1.6 \cdot 10^{5}$ pps)

Secondary target: ^{208}Pb 2 mg/cm²

Setup: AGATA + Si Detectors

p(^{7}Li,^{7}Be)n at 49 MeV

Primary beam: ^{7}Li

Isospin Mixing and Cluster Configurations in ^{12}C

SPOKESPERSONS

L. Zago, A. Gottardo

RIB: ^{11}C at 54 MeV (10^{5} pps)

Secondary target: CD_2 2 mg/cm²

Setup: AGATA + Si Detectors

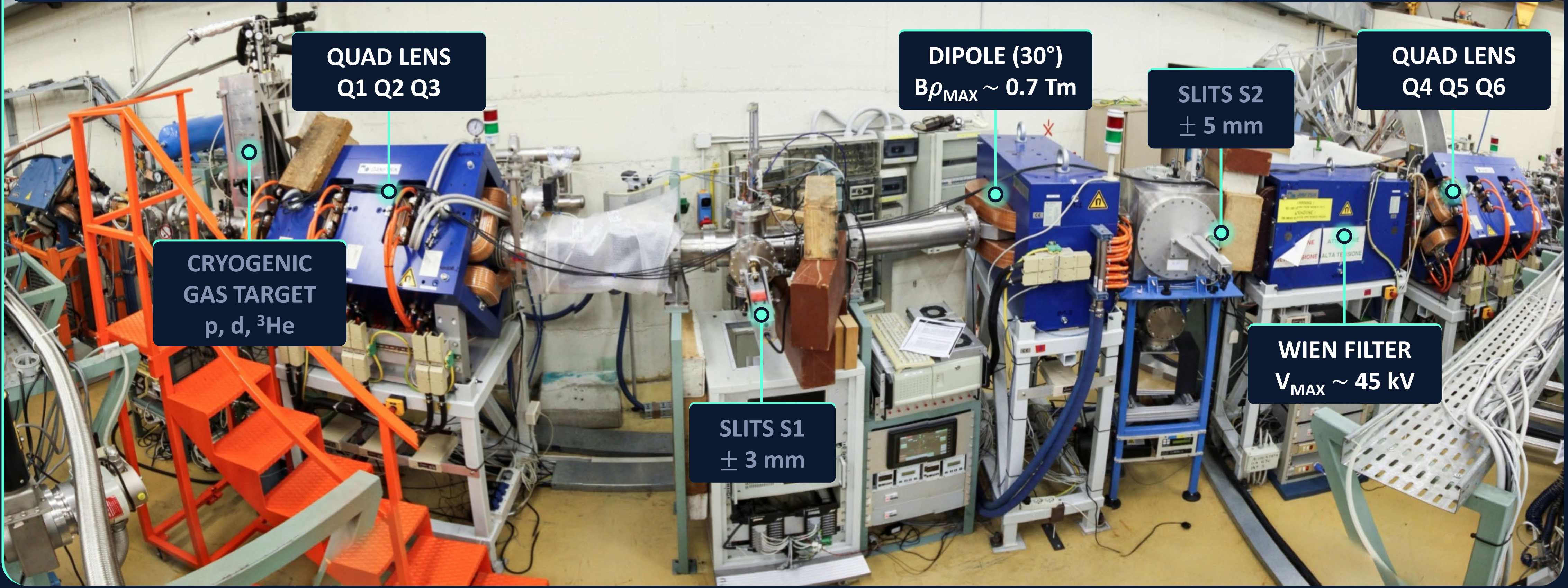
p(^{11}B,^{11}C)n at 70 MeV

Primary beam: ^{11}B

Bayesian Optimization

Sequential Model-Based Optimization and tunable parameters

Objective: Maximize the beam current at AGATA target position using as few observations as possible
Parameters: Q1, Q2, Q3, DM, WF, Q4, Q5, Q6 (current-controlled electromagnets by EPICS platform)



SECTION 03

Bayesian Optimization

Sequential Model-Based Optimization and tunable parameters

Objective: Maximize the beam current at AGATA target position using as few observations as possible
Parameters: Q1, Q2, Q3, DM, WF, Q4, Q5, Q6 (current-controlled electromagnets by EPICS platform)

SURROGATE STATISTICAL MODEL

Gaussian Process (GP)

$$f(\boldsymbol{x}) \sim GP(\mu(\boldsymbol{x}), k(\boldsymbol{x}, \boldsymbol{x}'))$$

Target function — Mean — Covariance

Set of observations (x_i, y_i) with $y_i = f(x_i) + \epsilon_i$

GP regression to calculate predicted mean and variance anywhere in input space

As the number of observations grows, the posterior distribution improves

ACQUISITION FUNCTION

Upper Confidence Bound (UCB)

$$\alpha_{UCB}(\boldsymbol{x}) = \mu(\boldsymbol{x}) + \kappa\, \sigma(\boldsymbol{x})$$

Mean — Covariance

Based on GP posterior, criterion to assess if a test point is a good potential candidate point to evaluate

Sets the exploration policy of the algorithm given a certain value of trade-off hyperparameter κ

If $\kappa \ll 1$, UCB prioritizes exploitation; if $\kappa \gg 1$, UCB prioritizes exploration.

SECTION 03

Bayesian Optimization

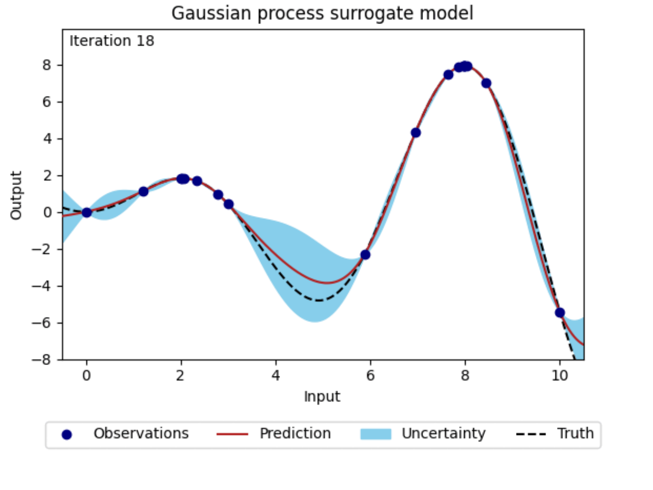
Sequential Model-Based Optimization and tunable parameters

Objective: Maximize the beam current at AGATA target position using as few observations as possible
Parameters: Q1, Q2, Q3, DM, WF, Q4, Q5, Q6 (current-controlled electromagnets by EPICS platform)

SURROGATE STATISTICAL MODEL

Gaussian Process (GP)

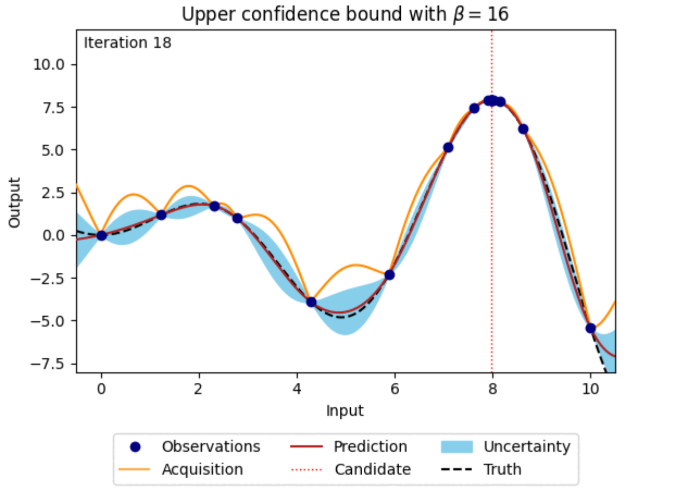
$$f(x) \sim GP(\mu(x), k(x, x'))$$



ACQUISITION FUNCTION

Upper Confidence Bound (UCB)

$$\alpha_{UCB}(x) = \mu(x) + \kappa\,\sigma(x)$$



SECTION 03

Bayesian Optimization

Optimization algorithm

OPTIMIZER

Suggest-Evaluate-Register Paradigm

1. Define the prior for the GP (initial dataset's mean).
2. Define the parameters hypervolume X.
3. Define the acquisition function (UCB, EI, EPI…).
4. Observe target function f on n_0 random initial points, inside the hypervolume X (initial dataset D_0).
5. for i = 1, 2, …, n_{BO} do
   I. Build a GP using available data D_{i-1}.
   II. Find the next evaluation point x_i based on acquisition.
   III. Observe $y_i = f(x_i) + \epsilon_i$.
   IV. Augment the dataset $D_i = D_{i-1} \cup (x_i, y_i)$.

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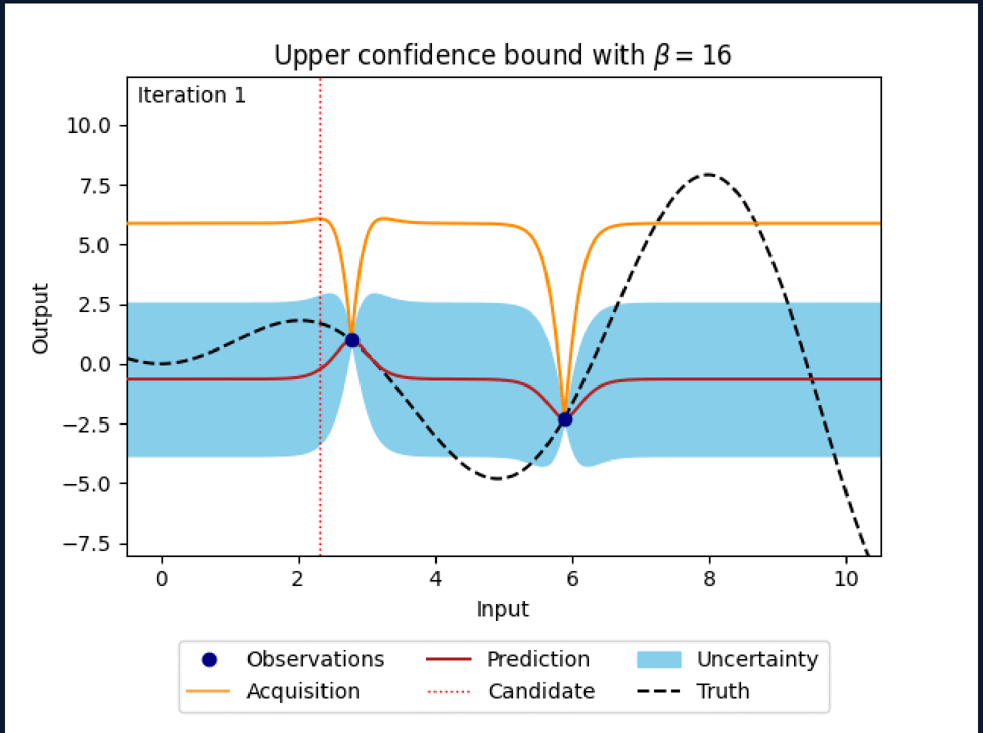
n_0 random initial points → n_{BO} Bayesian iterations



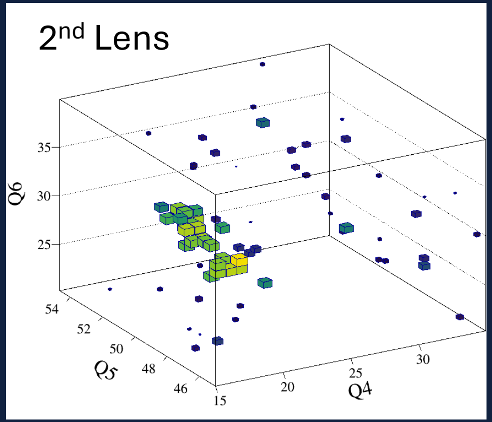
From https://nubopy.com

Results

^{11}C and algorithm perfomances

^{11}C – BO search

Initial random search + BO (n_0 = 40, n_{BO} = 60)



- Fast convergence: 0.5–1 h
- Easy and automatic procedure
- All parameters optimized simultaneously

Total current:

$1.4 \cdot 10^5$ pps

(Expected: $1 \cdot 10^5$ pps)

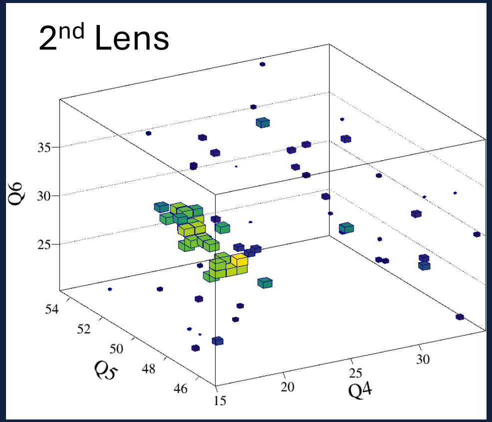
SECTION 04

Results

^{11}C and algorithm perfomances

^{11}C – BO search

Initial random search + BO (n_0 = 40, n_{BO} = 60)



- Fast convergence: 0.5–1 h
- Easy and automatic procedure
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Total current:

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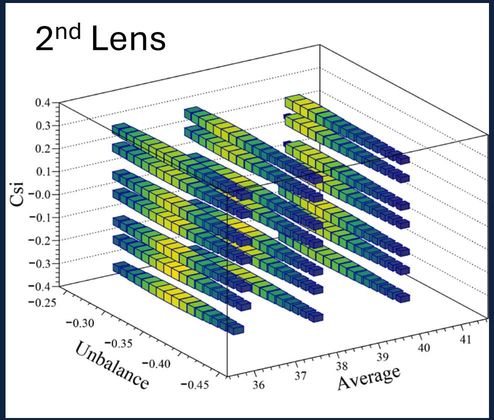
^{11}C – Grid search

GS + Domain pan & zoom for each lens and DM/BWF



- Long and difficult procedure: 8–12 h
- Most iterations are redundant
- Rate depends more on one parameter (Unbalance)

Total current:

$1.1 \cdot 10^5$ pps

(Expected: $1 \cdot 10^5$ pps)

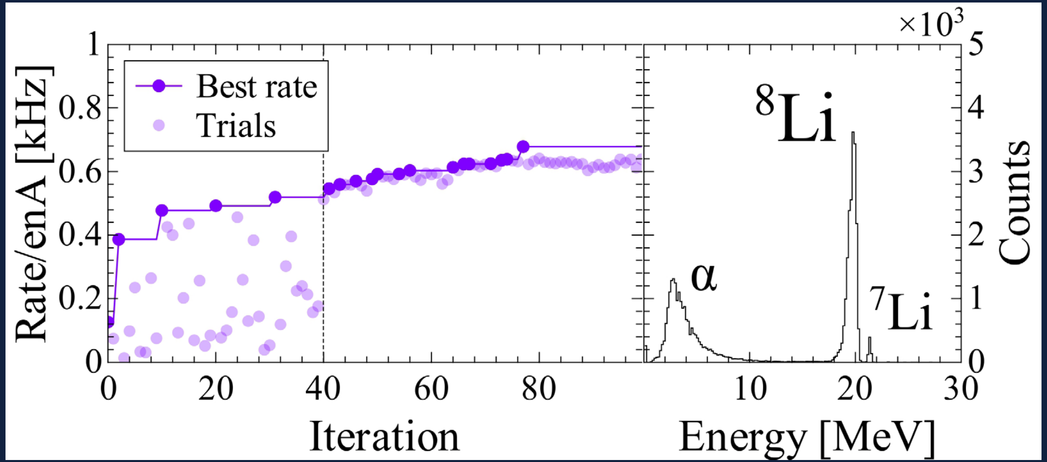
Results

^{8}Li and ^{7}Be radioactive ion beams

^{8}Li

Target function: Rate on M4 at AGATA target position
Parameters: Q1, Q2, Q3, Q4, Q5, Q6
Starting point: TRACEWIN* simulations, UCB κ = 0.1
Iterations: n_0 = 40, n_{BO} = 60 (10 s runs)

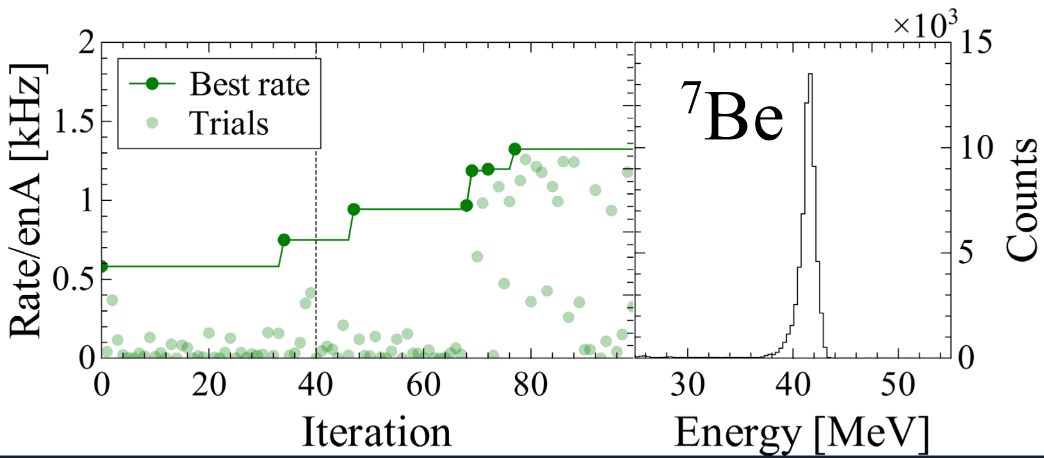
Fixed DM & WF + limited initial quadrupoles bounds to avoid ^{7}Li scattered beam contaminants



^{7}Be

Target function: Rate on M4 at AGATA target position
Parameters: Q1, Q2, Q3, DM, WF, Q4, Q5, Q6
Starting point: TRACEWIN* simulations, UCB κ = 2.576
Iterations: n_0 = 40, n_{BO} = 60 (10 s runs)

2nd quadrupole lens increased by 10% with respect to simulated values, Q2 and Q3 decreased a bit



*https://www.dacm-logiciels.fr/tracewin

SECTION 04

Results

^{8}Li and ^{7}Be radioactive ion beams

^{8}Li

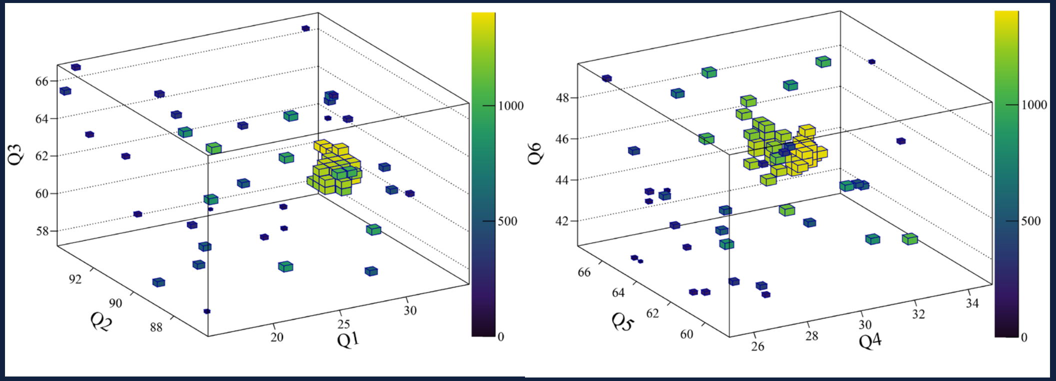
Total current:

$1.6 \cdot 10^5$ pps

(Expected: $5 \cdot 10^4$ pps)

Optimization time:

0.5–1 h



^{7}Be

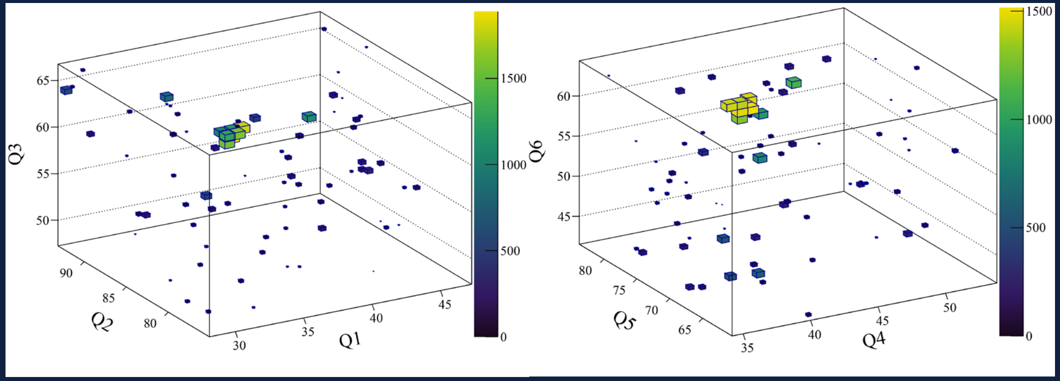
Total current:

$3.2 \cdot 10^5$ pps

(Expected: $2.5 \cdot 10^5$ pps)

Optimization time:

0.5–1 h



SECTION 05

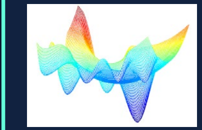
Conclusions

- Bayesian Optimization (BO) was applied to improve the transport and focusing of RIBs, produced with the EXOTIC facility (LNL).
- ^{8}Li, ^{7}Be and ^{11}C secondary beams were successfully transported, reaching the requested intensities at the AGATA target position.
- Optimization time was cut by 90% (from 8-12 h to 0.5-1h), compared to grid search and manual tuning (tested for ^{11}C).

Future perspectives:

Refine BO hyperparameters and apply Multi-Objective Bayesian optimization to minimize contaminants and beam energy straggling, potentially opening the possibility to explore additional EXOTIC RIBs.

Acknowledgements:



ALGORITHM IMPLEMENTATION

Bayesian Optimization (bayes_opt)

bayesian-optimization.github.io

Thank you!

SECTION 03

Bayesian Optimization

Optimization algorithm

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   - III. Observe $y_i = f(x_i) + \epsilon_i$.
   - IV. Augment the dataset $D_i = D_{i-1} \cup (x_i, y_i)$.

GP specifics:

- Matern 2.5 kernel k
  Stationary (depends only on distance $d(\boldsymbol{x}, \boldsymbol{x}')$)

$$k(x_i, x_j) = \left(1 + \frac{\sqrt{5}}{l} d(x_i, x_j) + \frac{5}{3l} d(x_i, x_j)^2\right) \exp\left(-\frac{\sqrt{5}}{l} d(x_i, x_j)\right)$$

  l = 1 initial, $l \in (10^{-5}, 10^{5})$ optimized when fitting the GP
  ν = 2.5 fixed

- $\alpha = 10^{-6}$, to be increased if noisy data
- Restart = 5 (to prevent local minima stagnation)
- Save and load optimizer state