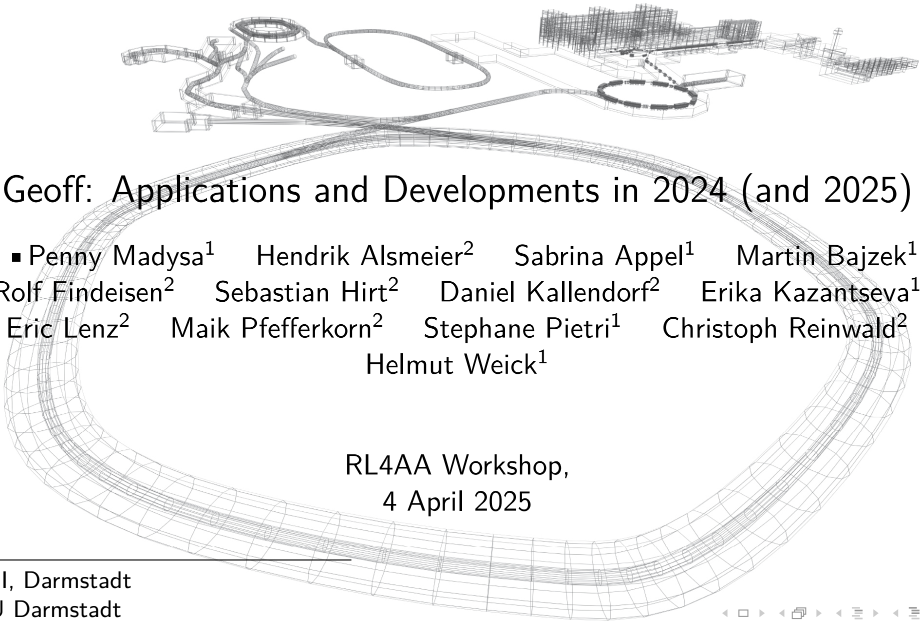


Geoff: Applications and Developments in 2024 (and 2025)

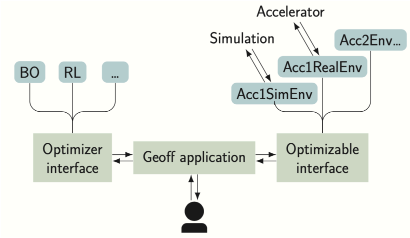
▪ Penny Madysa[1] Hendrik Alsmeier[2] Sabrina Appel[1] Martin Bajzek[1]
Rolf Findeisen[2] Sebastian Hirt[2] Daniel Kallendorf[2] Erika Kazantseva[1]
Eric Lenz[2] Maik Pfefferkorn[2] Stephane Pietri[1] Christoph Reinwald[2]
Helmut Weick[1]

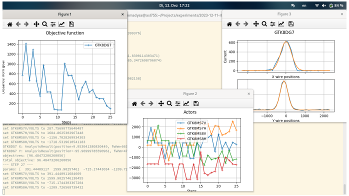
RL4AA Workshop,
4 April 2025

[1]GSI, Darmstadt
[2]TU Darmstadt

Geoff

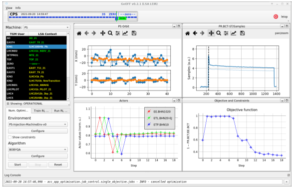
- https://gitlab.cern.ch/geoff/
- Python-based framework to harmonize libraries for optimization, optimal control and RL
- configures and runs agents and environments
- supports plotting, data logging, and is agnostic of the controls system
- flexible, extensible, maintainable





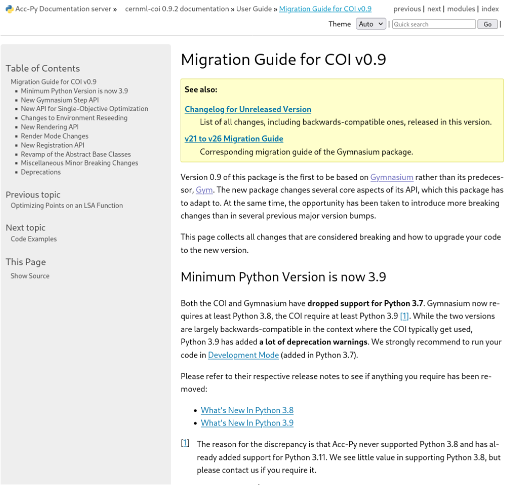
← runs in the terminal ...

... and in a GUI! →



Geoff Status

- migrated from *Gym* to *Gymnasium*
- extensive rewrite, lots of docs
- core packages & GUI app updated
- environments updated by machine experts via migration guide ⟶
- API for Bayesian optimization (`CustomOptimizerProvider`)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Optimizing Points on an LSA Function

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Code Examples

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Migration Guide for COI v0.9

See also:

Changelog for Unreleased Version
List of all changes, including backwards-compatible ones, released in this version.

v21 to v26 Migration Guide
Corresponding migration guide of the Gymnasium package.

Version 0.9 of this package is the first to be based on Gymnasium rather than its predecessor, Gym. The new package changes several core aspects of its API, which this package has to adapt to. At the same time, the opportunity has been taken to introduce more breaking changes than in several previous major version bumps.

This page collects all changes that are considered breaking and how to upgrade your code to the new version.

Minimum Python Version is now 3.9

Both the COI and Gymnasium have **dropped support for Python 3.7**. Gymnasium now requires at least Python 3.8, the COI require at least Python 3.9 [1]. While the two versions are largely backwards-compatible in the context where the COI typically get used, Python 3.9 has added **a lot of deprecation warnings**. We strongly recommend to run your code in Development Mode (added in Python 3.7).

Please refer to their respective release notes to see if anything you require has been removed:

- What's New In Python 3.8
- What's New In Python 3.9

[1] The reason for the discrepancy is that Acc-Py never supported Python 3.8 and has already added support for Python 3.11. We see little value in supporting Python 3.8, but please contact us if you require it.

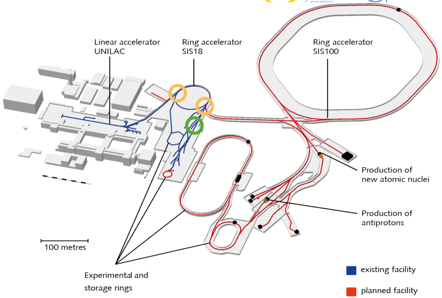
Next Steps:

- update to Gymnasium 1.0, NumPy 2
- PoC use at CEA Saclay, which doesn't have a unified controls system

GSI/FAIR Overview

Automation & Optimization with Python

- injection loss minimization (SIS18)
- beam steering (TK, X2)
- closed-orbit correction for non-standard optics (SIS18)
- slow extraction loss minimization (SIS18)
- beam steering and focusing (FRS)



Methods of Interest

- BOBYQA, Bayesian optimization (BO)
- physics-informed BO
- multi-objective Bayesian optimization (MOBO)
- mixed-method BO + extremum seeking
- data-driven model predictive control (MPC)
- reinforcement learning (RL)

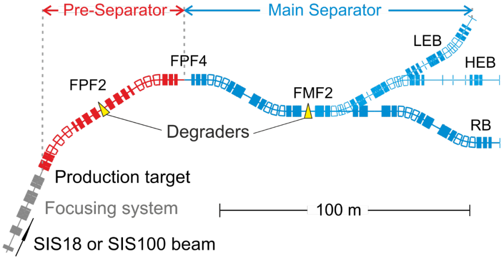
Work power

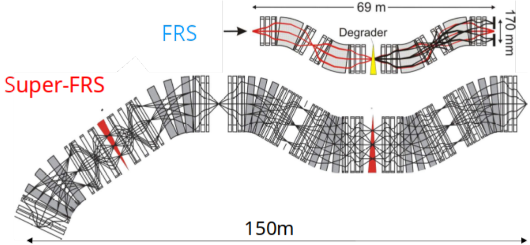
- one scientific staff financed by EURO-LABS
- one master student from PLUS (Salzburg)
- several master/PhD students from TUDa (Darmstadt)

Fragment Separator (FRS) and Super-FRS

- investigates nuclear structure of exotic nuclei
- produces, separates and identifies exotic nuclei
- sends them to downstream experiments or storage ring
- Super-FRS: higher acceptance, more complex ($4\times$ more magnets), gain factors between 1000 (^{12}C) and 7500 (^{132}Sn)
- automation of operational tasks essential

	$B\rho_{max}$	$\Delta p/p$	$\Delta\Phi_x$, $\Delta\Phi_y$	resolving power	gain factor ^{12}C	gain factor ^{132}Sn
FRS	18 Tm	1.0 %	±13, ±13 mrad	1500	1	1
Super-FRS	20 Tm	2.5 %	±40, ±20 mrad	1500	5	10
				including primary rate	250	20 000





FRS and Super-FRS: Goals

Motivation

- scale: manual setup too time consuming
- complexity: different optical modes per user
- accuracy: scaling for same optics but different $B\rho$ not accurate enough

Observables

- profile grid histograms
- phase space spectra from tracking detectors

Machine Interface

- LSA database (trim steerers, magnets)
- FESA (SIS18 monitoring)
- Go4 (experiment-side TPC, current grids)

Optimization Goals

0^{th} order: center the beam (vertical steerers, main dipoles)
1^{st} order: set focus, dispersion (quadrupoles)
2^{nd} order: minimize aberrations (sextupoles)
3^{rd} order: minimize aberrations (octupoles, S-FRS only)

Figure: Track classification (simulation with disabled sextupoles)

(D. Kallendorf, master's thesis)

FRS and Super-FRS: Observables

Central spot:

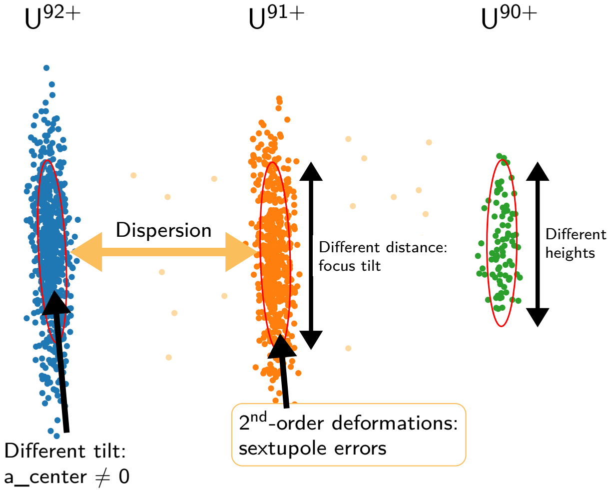
- Twiss parameters
- Non-dispersive 1st-order transfer matrix

Outer spots:

- 1st-/2nd-order dispersive transfer matrix elements

Goal: Bring the spectra as close as possible to desired 1st order parameters

⇒ optimize direct observables, not individual matrix elements!



FRS and Super-FRS: Results

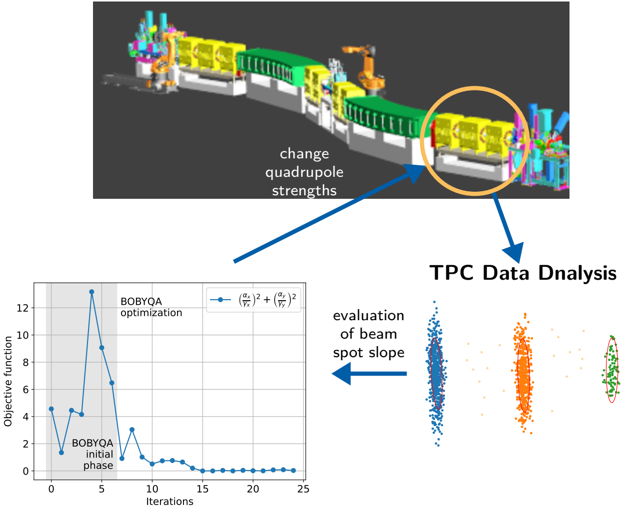
Proof of principle:

1. **steer beams** at target
2. **tune quadrupoles** to focus beam (central spot upright)
3. **tune sextupoles** to remove focal-plane tilt and "banana" deformation

Next step

- use other observables
- tune entire 1st-order optics
- include dispersion

Illustration of FRS Dispersive Area



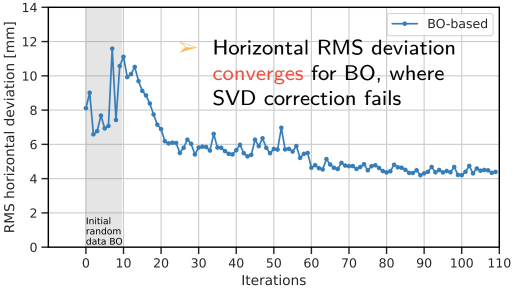
(M. Bajzek, E. Kazantseva, S. Pietri, H. Weick)

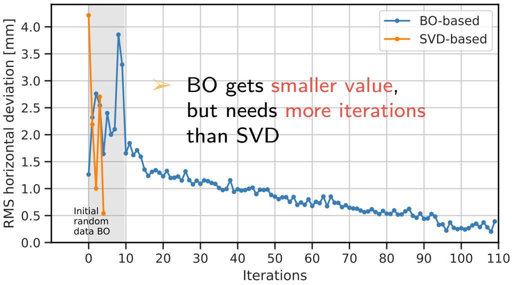
SIS18 Closed-Orbit Correction

- broken-symmetry high-transition-energy SIS18 optics: standard technique fails
- BO provides complementary approach
- additionally handles BPM noise better

Current work:

physics-informed covariance kernels for orbit model between BPMs

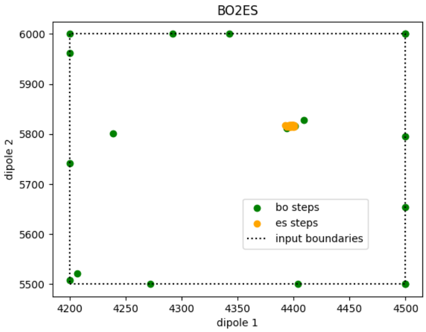


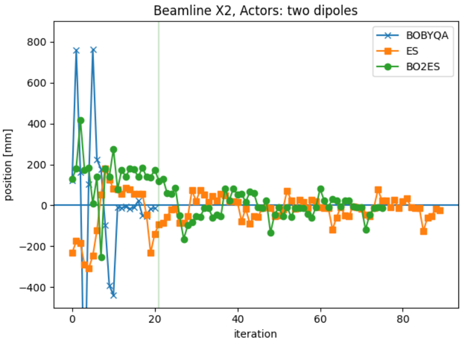


(V. Isensee, master's thesis)

Exploration of Novel Optimizers at the X2 Beamline

- goal: combine gradient-free global + gradient-based local optimization
- BO2ES: two phases of optimization
  1. Bayesian Optimization (efficient global exploration)
  2. Extremum Seeking (finetuning of best candidate)

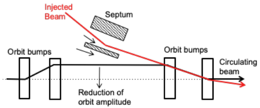


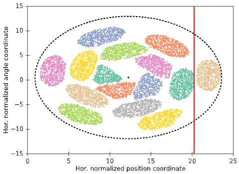


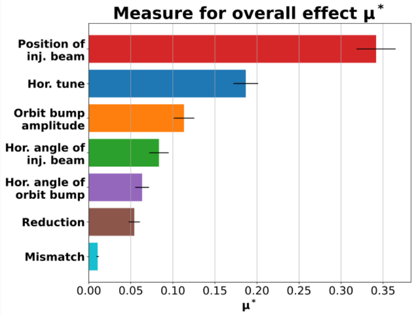
(H. Alsmeier, R. Findeisen, S. Hirt, E. Lenz, M. Pfefferkorn)

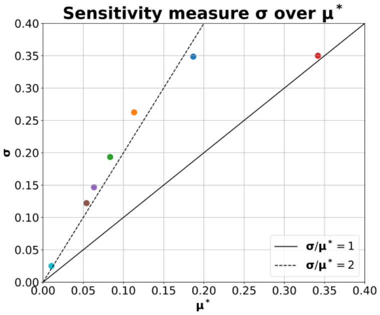
SIS18 Multi-Turn Injection

- Liouville's theorem: beam can only go into free phase space
- Competing goals:
  - maximize gain factor factor (reach space charge limit)
  - minimize losses at septum (cause vacuum degradation)
- MTI model implemented in Xsuite for fast tracking







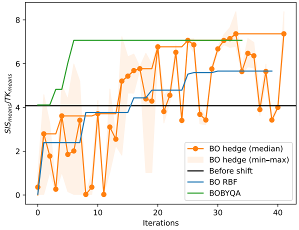


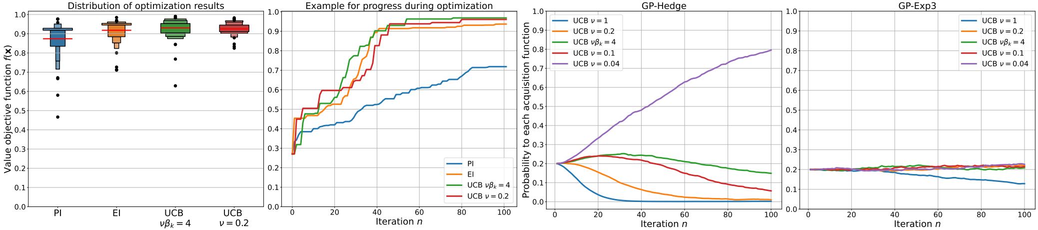
- beam position + tune most important
- all parameters have higher order dynamics (shown by σ/μ^*)

(C. Reinwald, master's thesis)

SIS18 Multi-Turn Injection

- various BO kernels and acquisition functions studied
- combine multiple answers to make BO more general
- *Hedging* algorithm prefers most exploitative answer





(C. Reinwald, master's thesis)

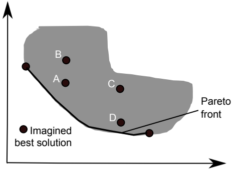
GP-MPC at SIS18

- explore sample-efficient control algorithms
- based on XSuite simulation of SIS18 MTI
- for more information, see poster by Benjamin Halilovic!

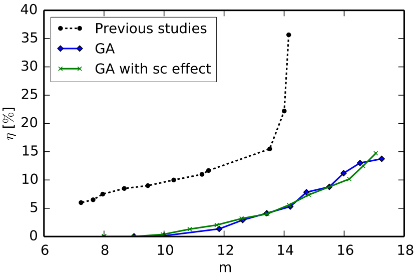
(S. Appel, B. Halilovic)

Multi-Objective Bayesian Optimization

- competing goals: maximize number of injections, minimize loss
- Pareto front: set of solutions strictly better than others
- prior art: simulation with genetic algorithms (S. Appel)

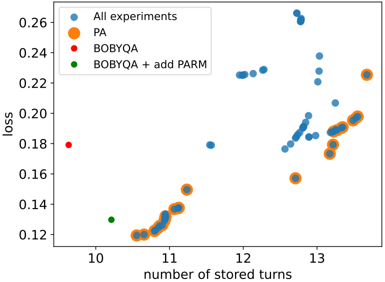


Simulation with Genetic Algorithms



Optimization of injector beam line is missing

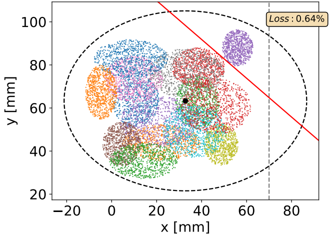
Measurements

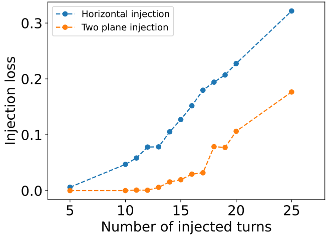


Possible upgrade for SIS18 injection

- SIS18 uses wide range of ions (from protons to uranium)
  - ⇒ injection via charge exchange is impractical
- possible upgrade: two-plane injection
  - tilt injection septum
  - ⇒ use vertical phase space
  - ⇒ overlap beamlets without violating Liouville's theorem
- Drawbacks:
  - requires replacement of injection line and area
  - doubles number of injection parameters

(S.Appel)





Summary and Outlook

Summary

- successful proof of concept at GSI, endorsement from leadership
- Gymnasium migration completed!
- widespread use at CERN

Outlook

- ecosystem keeps shifting: Gymnasium → 1.0, NumPy → 2.0
- make dynamic loading of environments more convenient
- GSI contributions to GUI app development
- more experiments at GSI and CEA Paris-Saclay