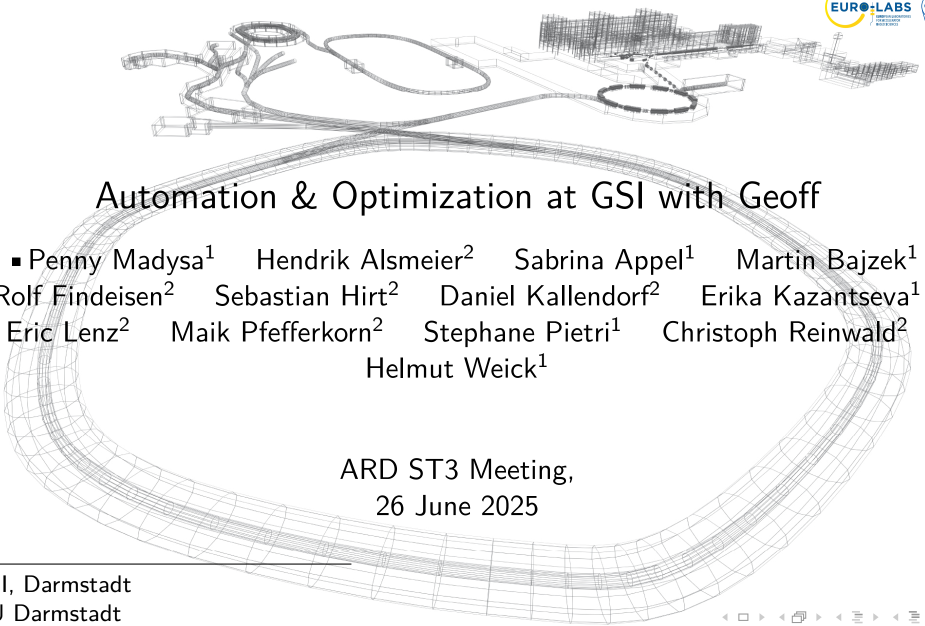

Automation & Optimization at GSI with Geoff

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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]

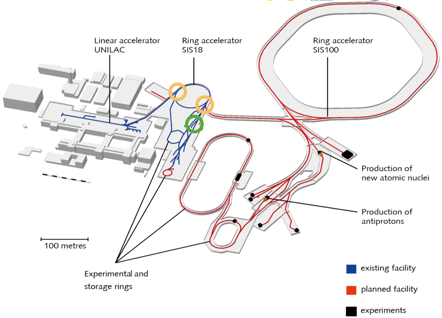
ARD ST3 Meeting,
26 June 2025

[1]GSI, Darmstadt
[2]TU Darmstadt

GSI/FAIR Overview

Automation & Optimization with Python

- beam steering and focusing (TK, X2)
- multi-turn injection loss minimization (SIS18)
- closed-orbit correction for non-standard optics (SIS18)
- beam-based magnetic field errors identification (SIS18)
- slow extraction loss minimization (SIS18)
- beam steering and focusing (FRS)



Methods of Interest

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

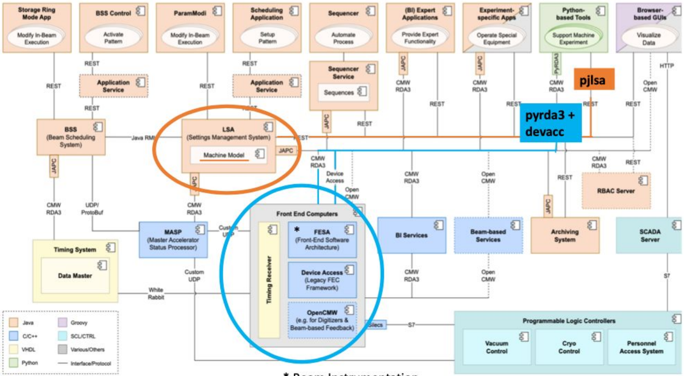
Work power

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

Python Bridge

Key ingredient: Python bridge to GSI Control System

Python bridge to control system



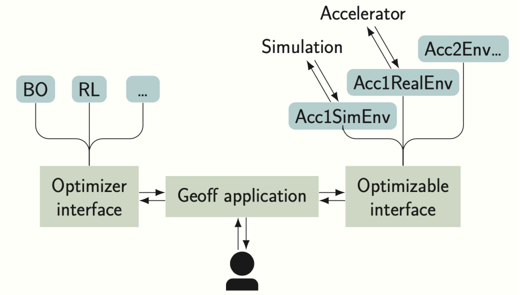
* Beam Instrumentation

H. Hüther. Controls Architecture. FAIR MAC Review on Controls. 2024

- FESA: retrieve data from beam diagnostic devices
- LSA: log, calculate & verify settings for beam control

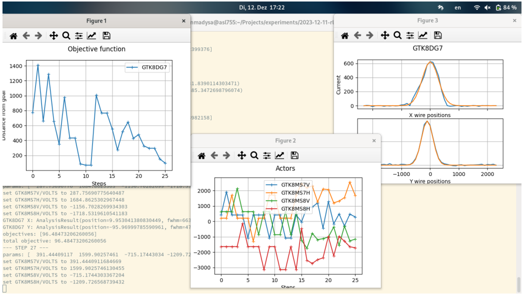
Geoff

- https://gitlab.cern.ch/geoff/
- collaboration between CERN and GSI
- Python-based framework to harmonize libraries for optimization, optimal control and RL
- standardized interfaces and adapters for third-party packages
- optimization problems are packaged classes: allows optimization of very complex problems
- supports live plotting, data logging, and is agnostic of the controls system
- flexible, extensible, maintainable

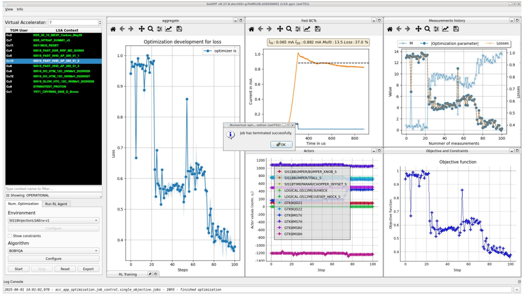


Preprint: arxiv:2506.03796
Paper submitted to *SoftwareX*

Geoff



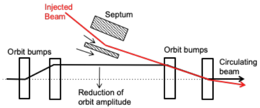
runs in the terminal ...

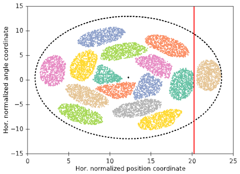


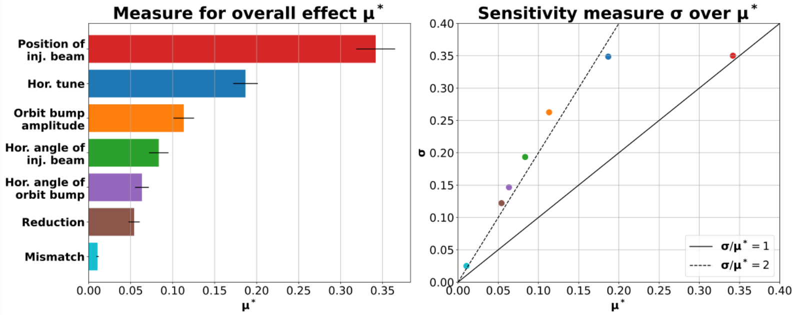
... and in a GUI!

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^*)

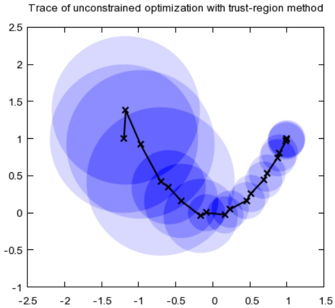
(C. Reinwald, master's thesis)

Numerical Optimization

- example: BOBYQA
- deterministic, derivative-free black-box optimizer
- sequential trust-region algorithm with quadratic approximations to the objective function

+ easy to use, more time for problem formulation, system interaction, data analysis
+ few hyperparameters to tune
+ low computational cost
+ resistant to noise and measurement errors

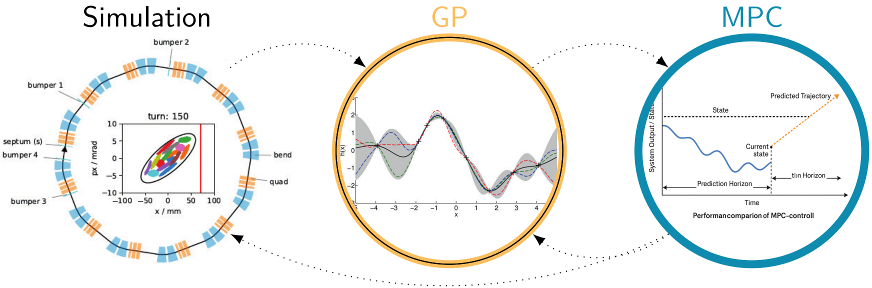
– starts from scratch each time
– less reliable with non-convex problems



1 C. Cartis, arXiv:1804.00154 (2018), https://pypi.org/project/Py-BOBYQA

- M. J. D. Powell, Tech. Rep. DAMTP 2009/NA06, Cambridge (2009)

GP-MPC at SIS18

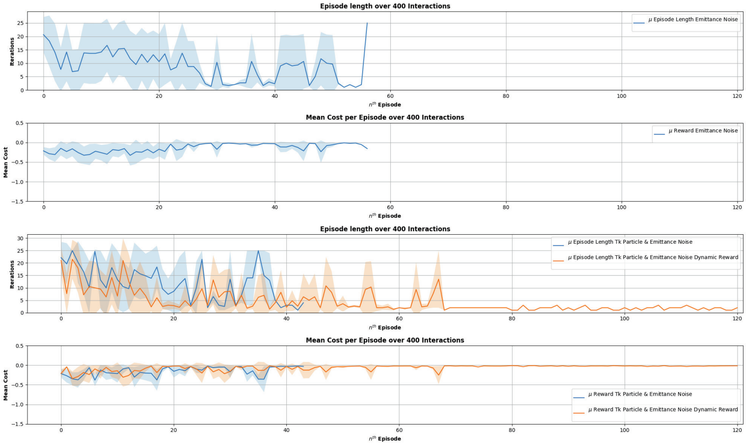


(S. Appel, B. Halilovic)

- combines Gaussian Processes with Model Predictive Control
- GP trained on real measurements or simulations
- controller predicts next action based on GP model
- data-effcient, noise-robust

GP-MPC at SIS18

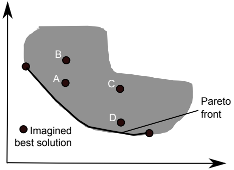
Training results on simulation based on XSuite:



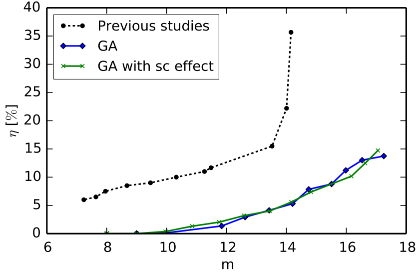
(S. Appel, B. Halilovic)

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)

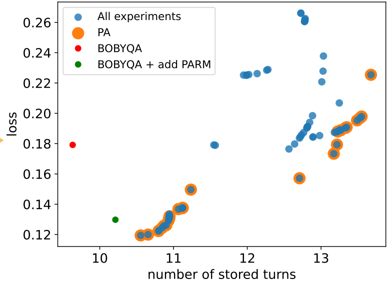


Simulation with Genetic Algorithms



Optimization of injector beam line is missing

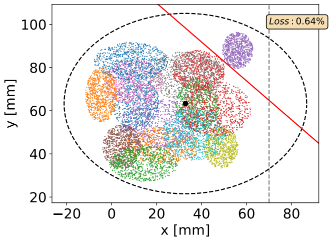
Measurements

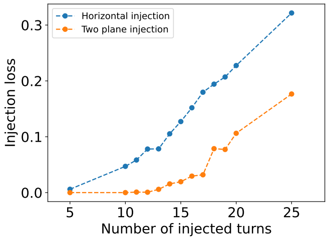


Possible upgrade for SIS18 injection

- 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

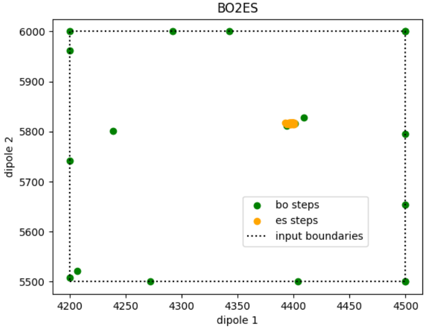
(S.Appel)

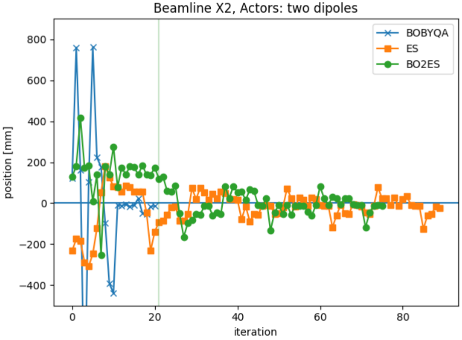




Exploration of Novel Optimizers at the X2 Beamline

- 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)



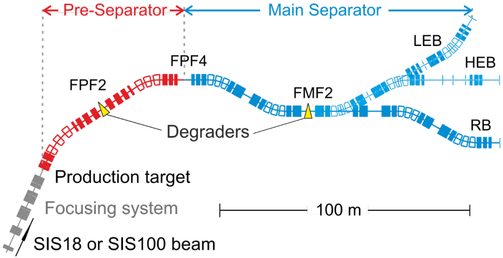


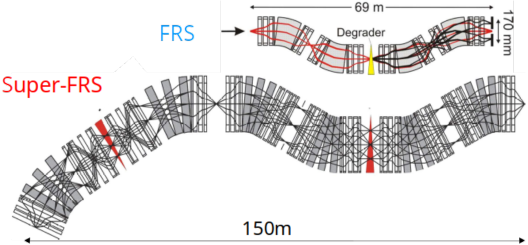
(H. Alsmeier, R. Findeisen, S. Hirt, E. Lenz, M. Pfefferkorn)

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× 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

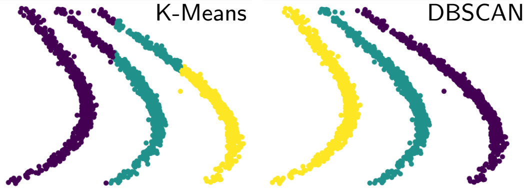
Machine Interface

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

Optimization Goals

0th order: center the beam (vertical steerers, main dipoles)
1st order: set focus, dispersion (quadrupoles)
2nd order: minimize aberrations (sextupoles)
3rd 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:

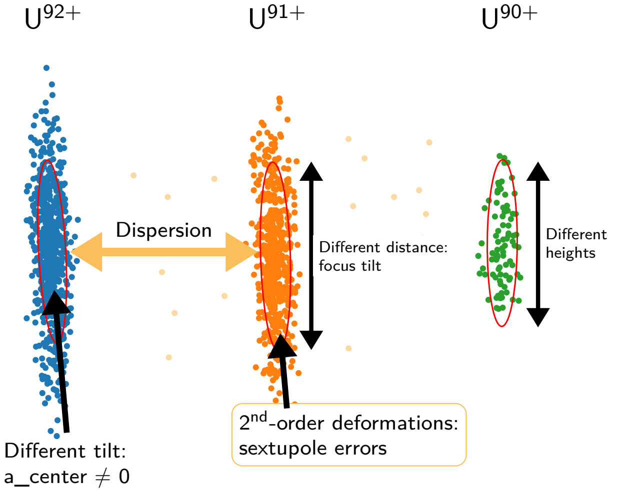
- Twiss parameters
- Non-dispersive 1st-order transfer matrix

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

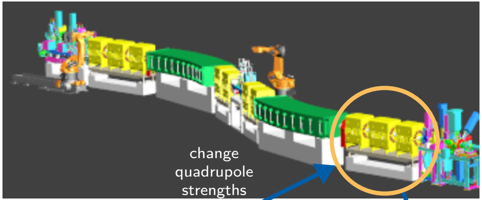
Proof of principle:

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

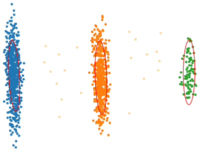
- use other observables
- tune entire 1st-order optics
- include dispersion

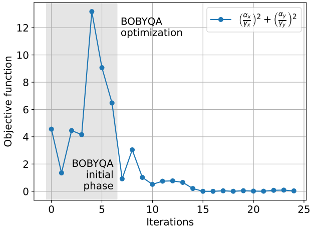
Illustration of FRS Dispersive Area



TPC Data Dnalysis

evaluation of beam spot slope





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

Summary and Outlook

Summary

- Python framework to facilitate transition from numerical optimization to RL
- only requirement: Python interface to the controls system
- widespread use at CERN, proof of concept at GSI

Outlook

- ecosystem keeps shifting: Gymnasium $\rightarrow$ 1.0, NumPy $\rightarrow$ 2.0
- further development of the GUI app
- more experiments at GSI and CEA Paris-Saclay