Advancements in Accelerator Operation

Automation and AI integration

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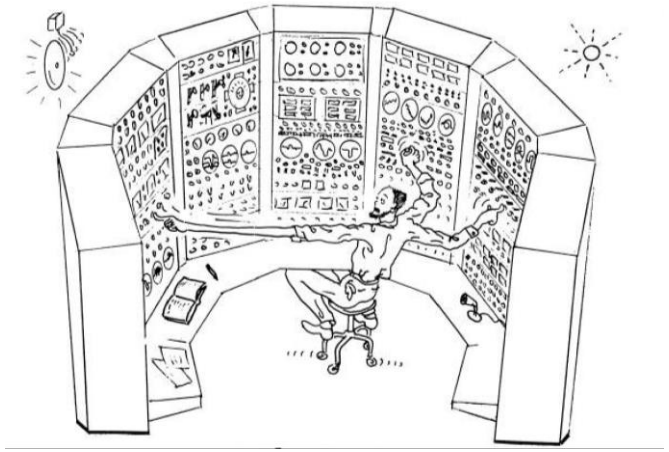
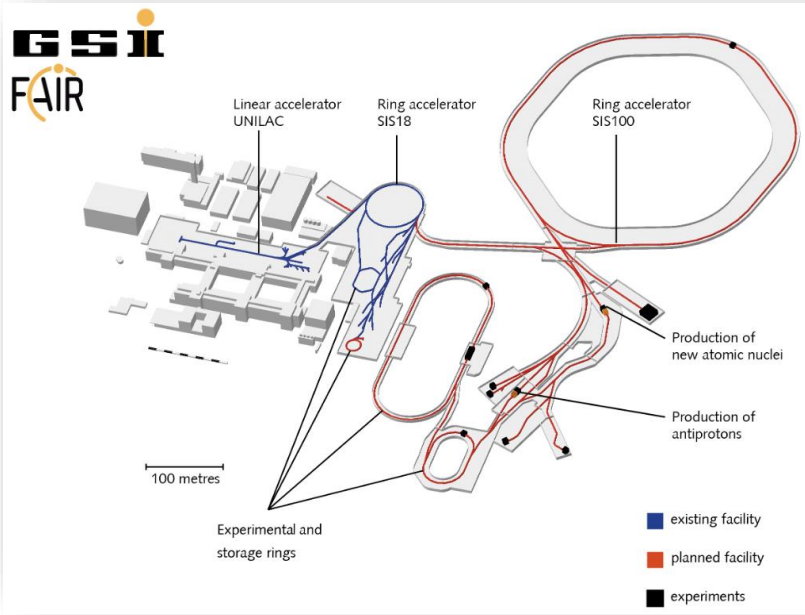
Beam operation challenges

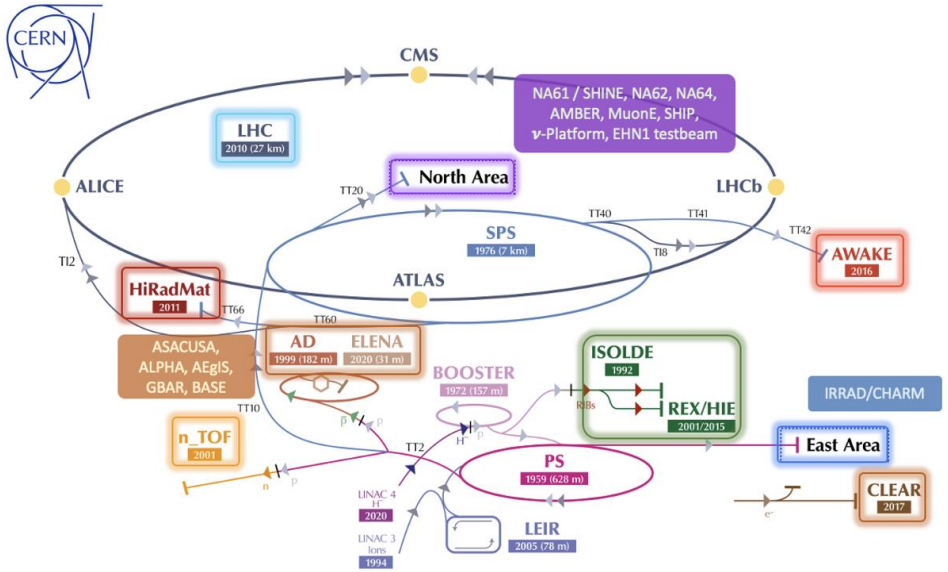
Motivation

- **Machine availability** & **beam quality** are essential to reach **physics objectives**
  parameter drifts, fault recovery & prediction, testing, …
- Broad spectrum of **machine & beam types** with **multi-destination** operation
  beam commissioning & preparation, hysteresis & eddy-currents, scheduling, …

➡ **Exploit automation & technological advances (ML / AI) where possible**



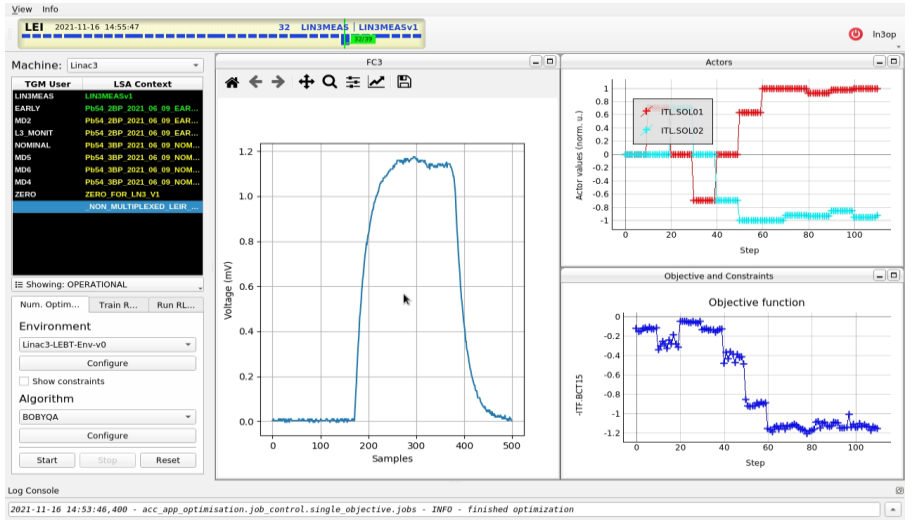




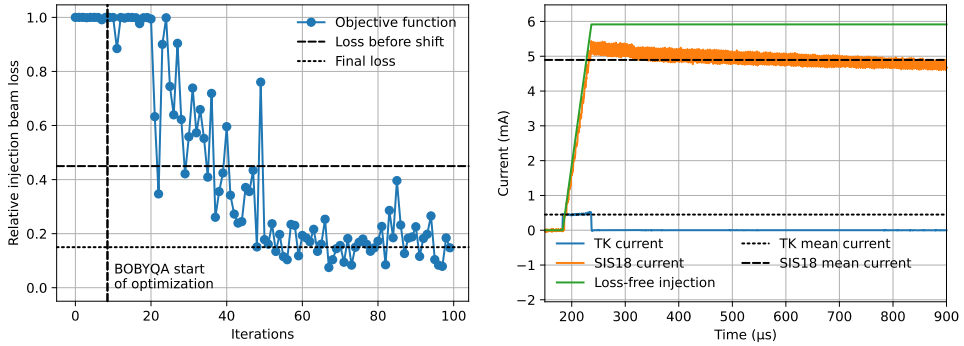
GeOFF Collaboration

History & scope

- Focus on **parameter optimization & drift compensation** here
- Address in **generic & flexible manner** ➡ framework
- **Generic Optimization Framework & Frontend** (GeOFF)
  - **Python framework** to unify **different optimization approaches**
    Classical Black-Box & Bayesian Optimization, Reinforcement Learning, Continuous Optimal Control
  - **Standardized interfaces**, **tools** for developers & **docs**
  - **GUI application** that wraps everything together
  - *"Facilitate implementation of parameter optimization task with primary focus on problem itself"*
- **Initiated and originally developed at CERN**
- **Since 2022 informal, yet effective collaboration with GSI**
  focus on AI, optimization algorithm & tools development, knowledge sharing



Example: *CERN Linac3*



Example: *GSI SIS18*

GeOFF: status & plans

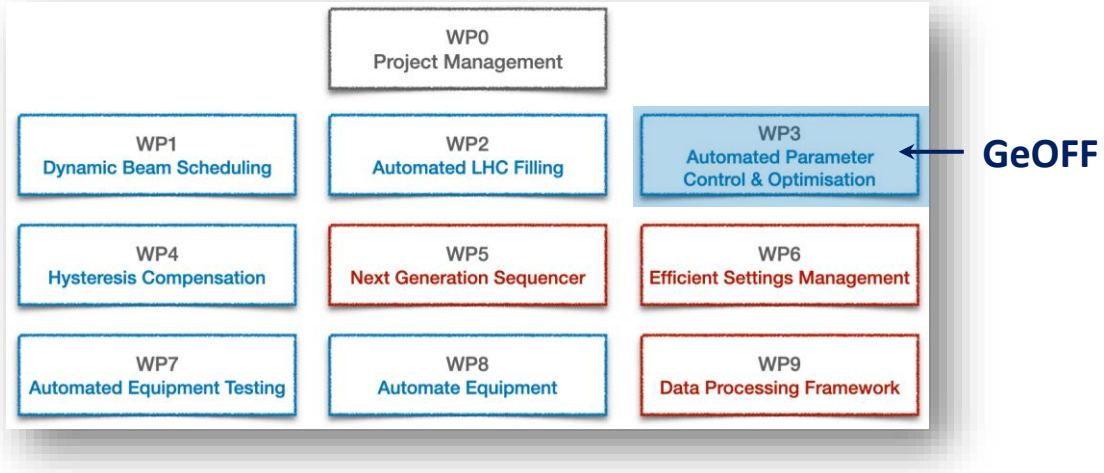
… at CERN & GSI/FAIR

GSI/FAIR

- **EURO-LABS** finances a scientific staff member for three years in the Accelerator Physics Group
- **Maintenance and co-development of GeOFF**
- Participation of several **Master / PhD students** from TU Darmstadt

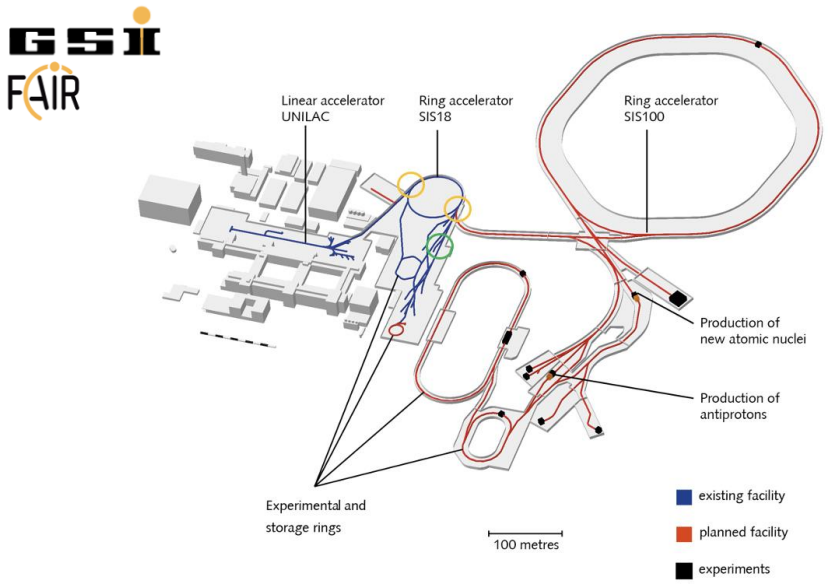
CERN

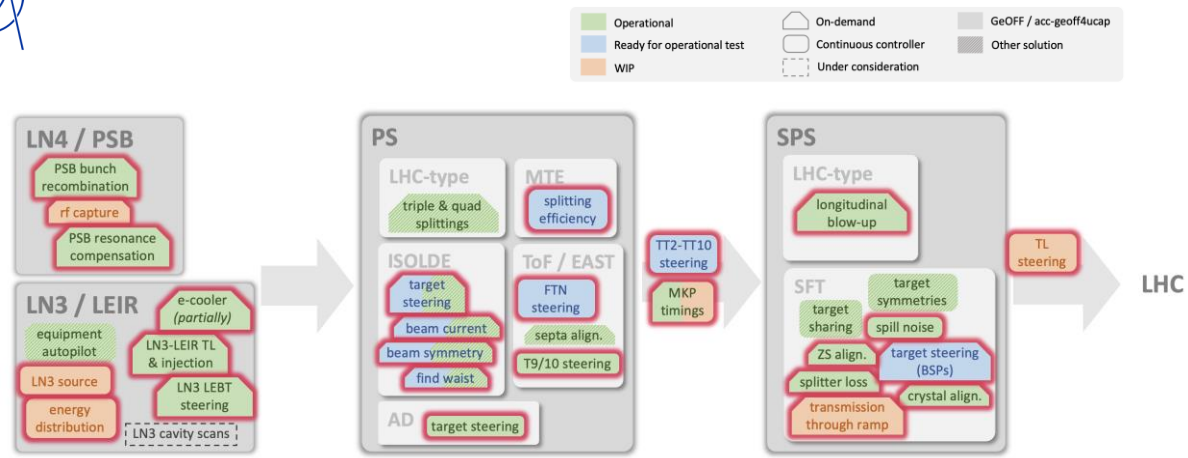
- **GeOFF one of core products** of DSB section in BE-CSS
  - Two staff part time for maintenance, improvements, and evolution
- **Efficient Particle Accelerators project** (EPA)
  - **Goal:** explore and exploit **automation & ML/AI** systematically **across complex**
  - **Approved** in autumn 2023 for a **5-year period**



GeOFF: status & plans

… at CERN & GSI/FAIR





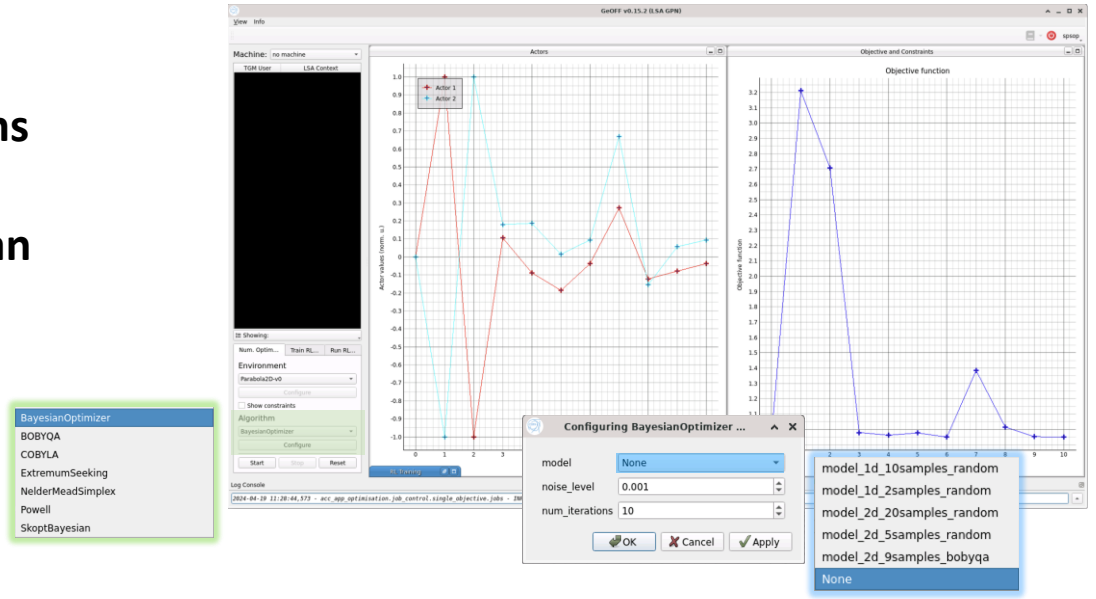
- November 2023: **successful optimization** runs using GeOFF at **TK**, **SIS18** & **FRS**
- Introduction of **Python Bridge** to access LSA & FESA via Python
- Investigation of safe deployment of **Python applications** in control room
  topic for the FAIR Mini-MAC controls review

- **GeOFF** since LS2 **main optimization framework** in use
  beam commissioning & day-to-day operation, further auto-pilots under development
- **Trend from on-demand to continuous control**
  Ported GeOFF concept to server: **UCAP*** infrastructure with **Python & GPU** support is key

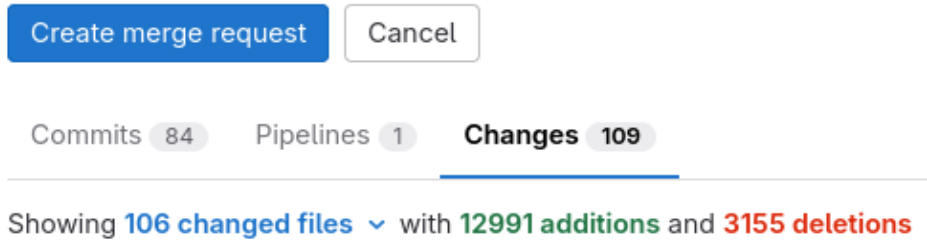
* *Unified Controls Acquisition and Processing: data processing pipelines on server*

GeOFF: recent developments
Custom algorithms, upgrades, and maintenance

- **Features & algorithms**
  - Optimization tasks can have **custom configurable algorithms**
    e.g.: model-based controller with prior knowledge
  - **GSI:** preparing proof-of-concept of **Multi-Objective Bayesian Optimization** (BO)
  - **CERN:** resonance compensation with **pre-conditioned BO**
    ongoing tests at PSB



- **Upgrades and maintenance**
  - Repayment of technical debt by **upgrading** dependencies, adjusting all interfaces and **fixing bugs**
    - GeOFF is heavily based on **OpenAI Gym**
    - OpenAI ceased development:
      Farama Foundation took it over as **Gymnasium**
    - Many backwards-incompatible changes since then
  - Update documentation



GeOFF: next steps

Highest priority items and common interests

- Improve **Bayesian Optimization** (BO) support
  - CERN: Adaptive BO, BO with non-constant prior
  - GSI: Multi-Objective BO
- Improve **integration of Reinforcement Learning**
- Evolution of **GUI application**
  - CERN: distribute maintenance work between accelerators
  - GSI: use outside CERN is EURO-LABS requirement

Conclusions

- **GSI-CERN collaboration on GeOFF has been highly successful and will continue**
  - Labs are in **direct collaboration** and through **EU-projects**
  - **CERN** has a lot of experience in **automation and AI**
  - **GSI** is making progress in the field, and **offers valuable contributions in terms of algorithms**
    e.g.: Multi-Objective Bayesian Optimization
  - Both labs are facing **similar control problems**
    e.g.: resonance compensation, spill noise cancellation, drift compensation in general
- **GeOFF is a great example where GSI & CERN profit from common infrastructure and share expertise**
- **Strengthening collaboration** further is goal of the *Artificial Intelligence for Accelerators, User Communities and Associated Technologies project (ARTIFACT)**

**pending approval*

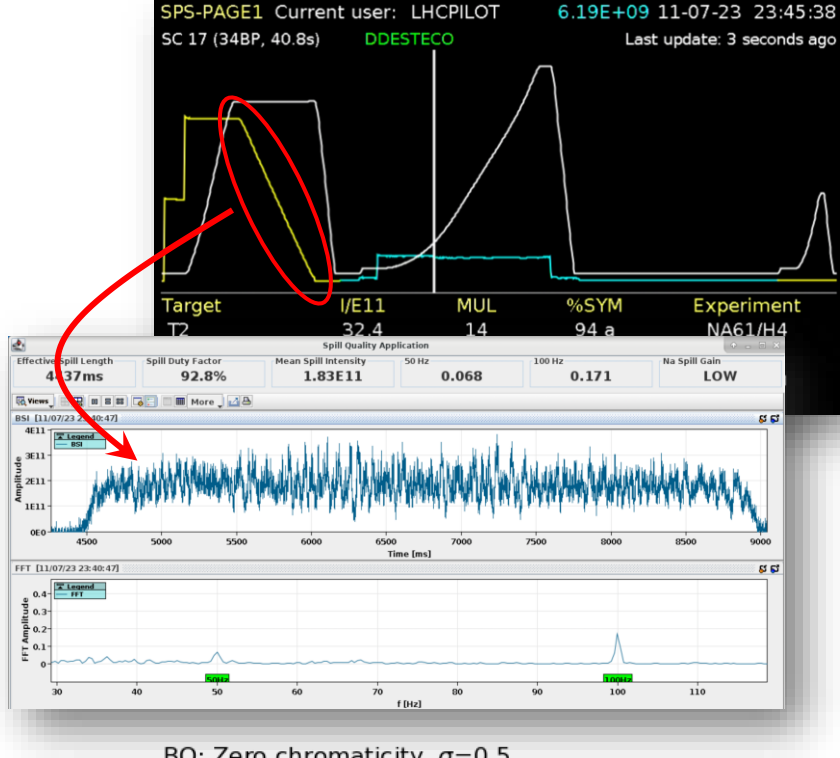
Thank you

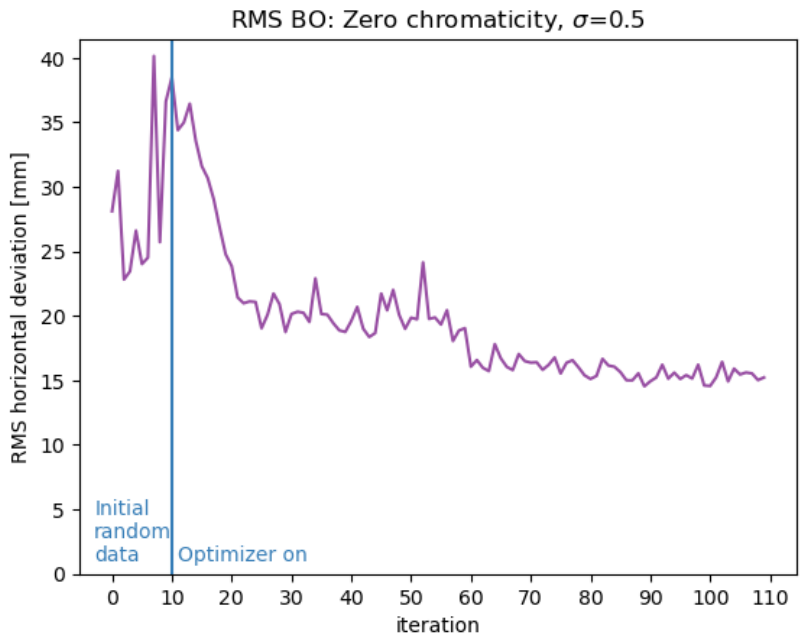
Backup

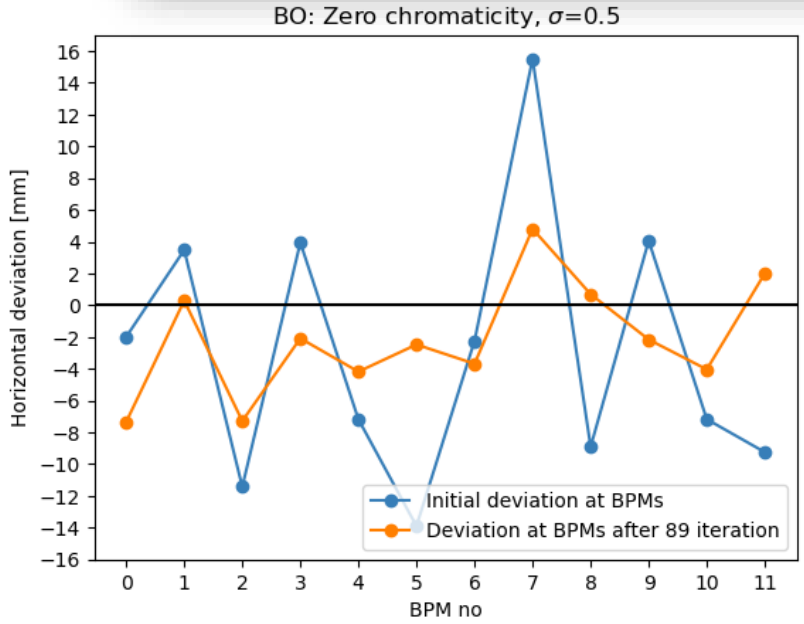
Next Steps in GeOFF

Highest Priority Items and Common Interests

- Improve **Bayesian Optimization** support
  - CERN: Adaptive Bayesian Control
  - GSI: Multi-Objective Bayesian Optimization
- Improve **integration of RL**
- Evolution of **GUI application**
  - CERN: distribute maintenance work between accelerators
  - GSI: use outside CERN is EURO-LABS requirement



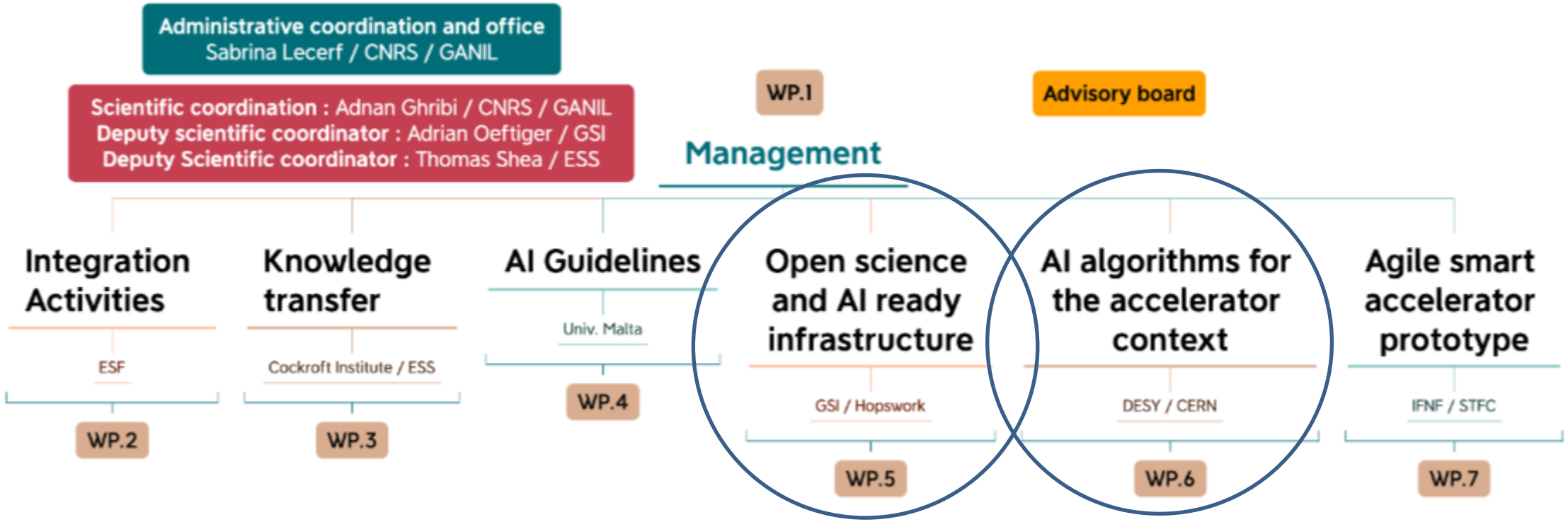




V. Isensee (TU Darmstadt), C. Caliari (TU Darmstadt), A. Oeftiger (GSI)

ARTIFACT

Artificial Intelligence for Accelerators, User Communities and Associated Technologies



- 15 research infrastructures
- 10 M€ overall
- Time period: Jan 2025 – Dec 2028
- WP5/WP6 offer more opportunity for collaboration between CERN and GSI

WP5 Package Leader:
A. Mistry (GSI)

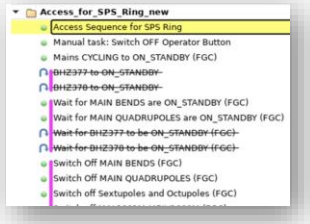
WP6 Deputy Leader:
V. Kain (CERN)

Subtask 6.4.4:
S. Appel (GSI)

Infrastructure
Frameworks & building blocks

Classical automation concepts

- **Sequencer:** programmatic execution of tasks
- High-level parameter models
- **AccTesting**



➡ **EPA:** sequencer 2.0, equipment testing, efficient settings management

Acc-Py
"accelerating Python"

- **Full integration of Python with control system**
- Online data acquisition, equipment access (set / get), app development, …
- Python package index

UCAP
Unified Controls Acquisition & Processing

- **Virtual device service**
- Event-based, online **data transformations**

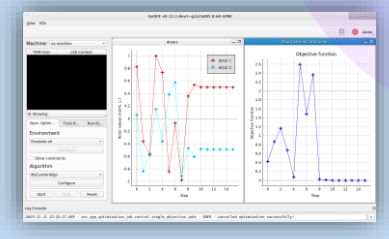
➡ **Further evolution with EPA**

Enabling automation with AI / ML

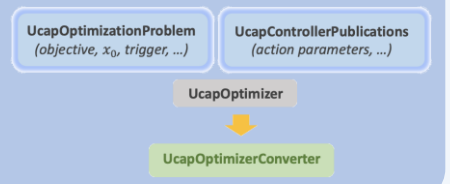
Auto-pilots & optimizers

- **Facilitate** implementation of control problems
- **Exploit & expose features** of control architecture
- Maintain **uniformity** across complex

GeOFF
Generic Optimization Framework and Frontend

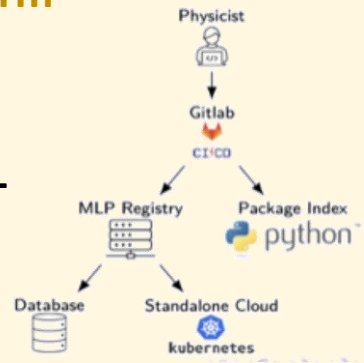


acc-geoff4ucap
Framework for optimization & control via UCAP



Machine Learning Platform
Deployment & inference of (ML) models

- **Train, store & share ML models with VC**
- Language agnostic
- Available in control room



Infrastructure

UCAP & acc-geoff4ucap

UCAP

Framework & service to implement & run **online data processing pipelines**

Acquire

- *Subscribe to data sources*
- *Group data via EventBuilder*

Transform

- *Process incoming data*
- *Java or **Python***
- ***GPU support***

Publish

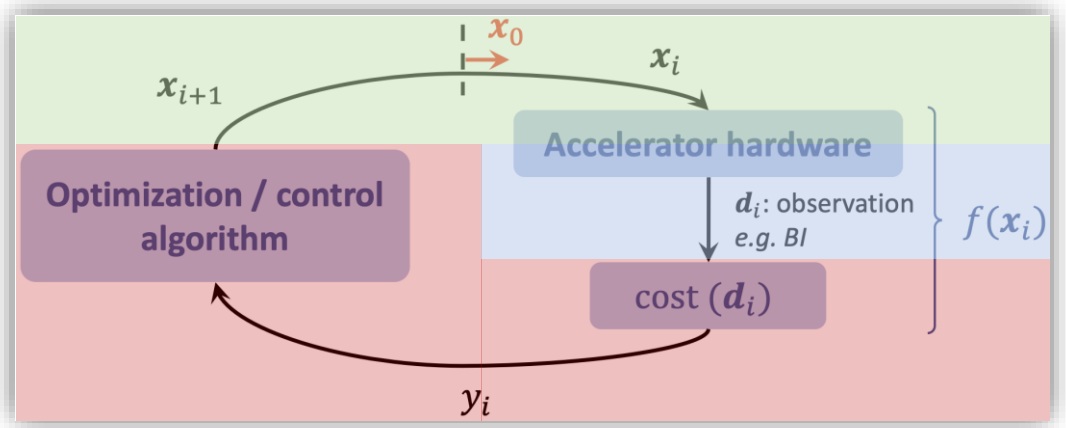
- *Publish results*
- *Can be **hardware "sets"***

- UCAP pipelines can be **chained** and built into **hierarchies**
- Conceptually simple, and very **powerful**

acc-geoff4ucap

NEW

Use UCAP to implement the **optimization / control loop on server**

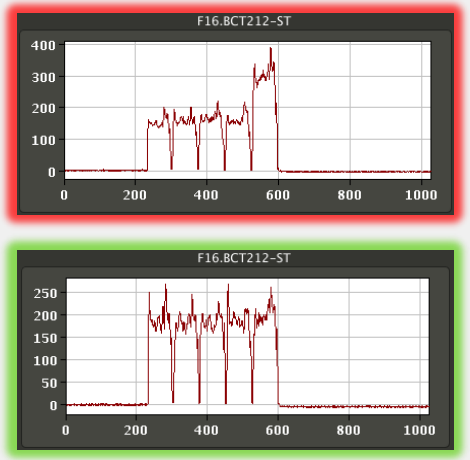


Great infrastructure to run auto-pilots

continuous controllers or auto-launching optimizers

Status & results

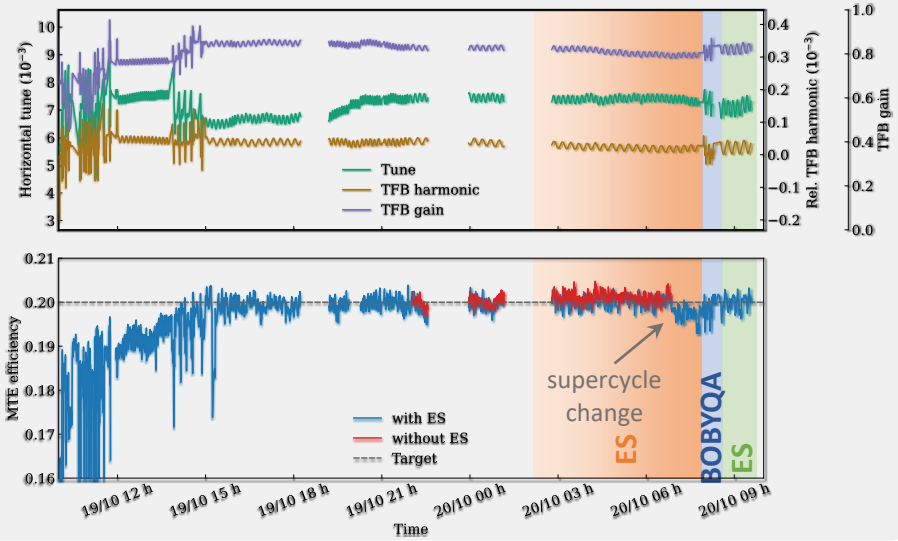
Auto-pilots: a selection



PS Multi-Turn Extraction

- **Automatic drift compensation**
- **Successfully tested** and tuned in MDs with controllers on **UCAP**
- **Hybrid agent:** continuous controller interleaved with optimizer when far off
- **Upcoming operational test**

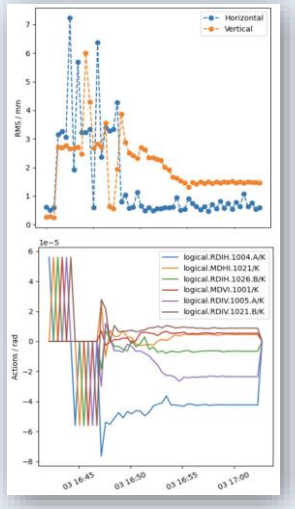
A. Huschauer, M. Schenk, C. Uden



Trajectory steering framework

using acc-geoff4ucap

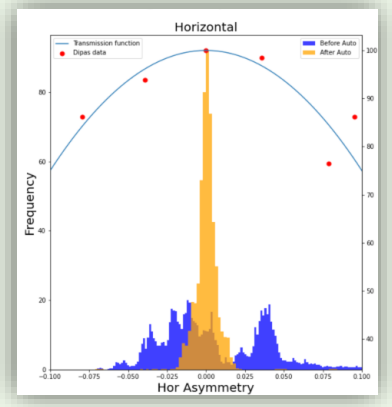
- **Versatile objective**
  Beam position, beam loss, …
- **Generic settings & actors**
- **Various algorithms**
  incl. Micado / SVD
- **In 2024:** PS2SPS, SPS2LHC



G. Trad, F. Velotti

PS EAST: fixed target beam steering

- **PID** regulator on **UCAP**
- **Simple & effective**
- **2024:** integrate with acc-geoff4ucap
- **Similar controller** for TL towards AD

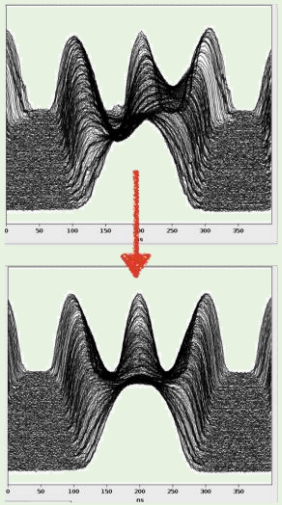


J. McCarthy

Status & results

Reinforcement learning: a selection

WP3
Automated Parameter Control & Optimisation



PS

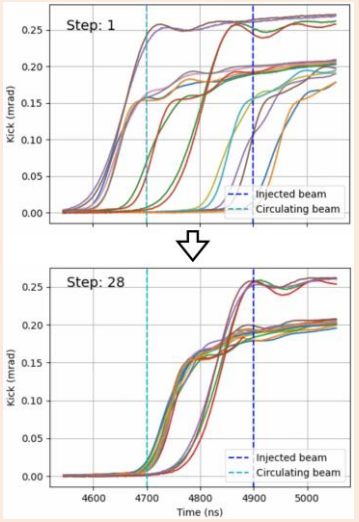
- Correct RF **phase & voltage** for **uniform bunch splitting** (LHC beams)
- Successful **sim2real** & fully **operational**
- **Multi-agent** (SAC) & **CNN** for initial guess
- **Next: continuous** controller (UCAP)

A. Lasheen, J. Wulff

PS to SPS

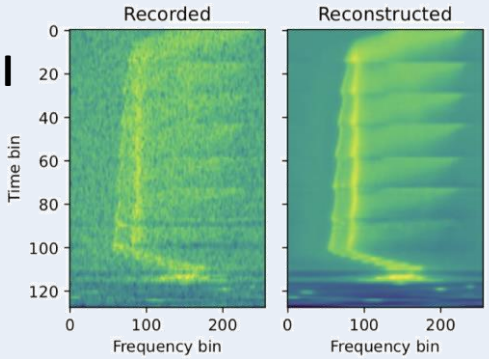
- Adjust **fine delays** of SPS **injection kicker**
- RL agent (PPO) trained on **data-driven dynamics model**
- Ready for **sim2real test**

M. Remta, F. Velotti

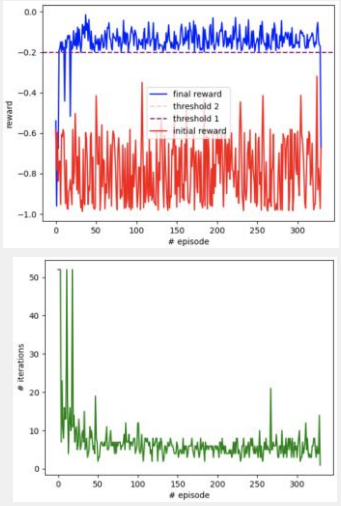


LINAC3 / LEIR

- **PhD project** *(B. Rodriguez)*: control LINAC3 cavities for **optimal injection efficiency** into LEIR
- RL state based on **VAE-encoded Schottky** spectra
- Agent trained on **data-driven dynamics model**



V. Kain, N. Madysa



SPS

- **Steer DC beams** in TT20 TL using **split-foil** secondary emission **monitors**
- Works well in simulations, **with noise and varying emittances**
- Ready for **sim2real test**

N. Bruchon, V. Kain