Karlsruhe Institute of Technology

# 02-2 Bayesian Optimization Demo

## Application for Beam Injection Optimization at KARA Storage Ring

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# KARA Storage Ring Injection Optimization

Karlsruhe Institute of Technology

**Goal:** Improve the injection rate from the booster to the storage ring KARA automatically

**Motivation:**

**Manual trial-and-error**
- Time consuming
- Easily stuck in local optima

**Tool:**

**Bayesian optimization**
- Global optimization
- Fast tuning

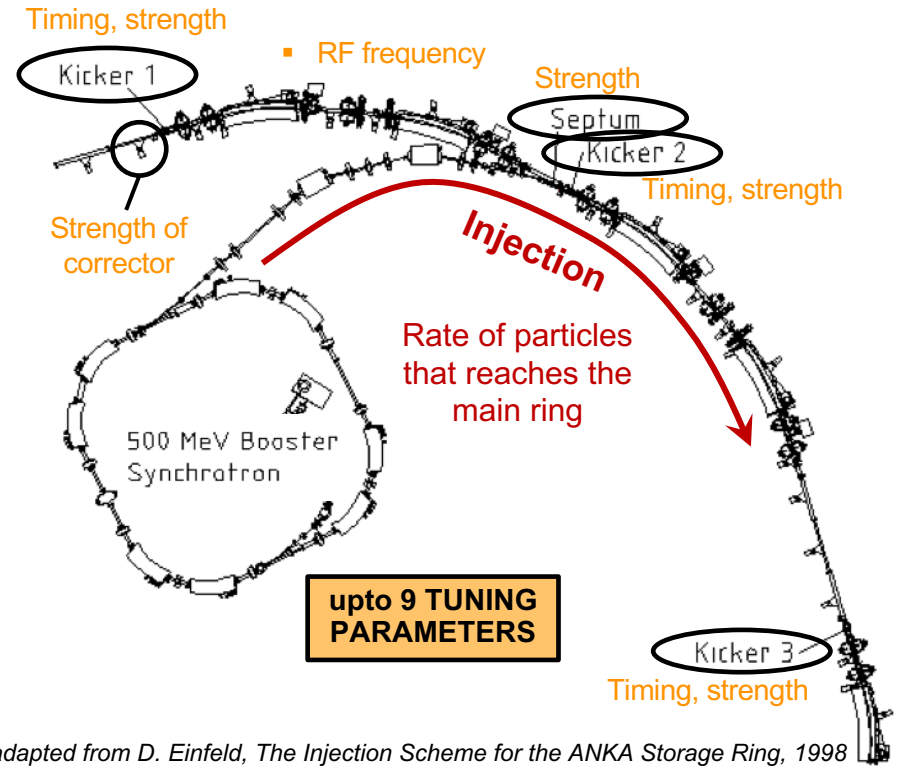



*Figure adapted from D. Einfeld, The Injection Scheme for the ANKA Storage Ring, 1998*

# KARA Storage Ring Injection Optimization

- Circumference: 110.4 m
- Energy: 0.5 GeV (injection) → 2.5 GeV (radiation mode)
- Injection repetition rate 1 Hz
- Injection bump with 3 kicker magnets

Maximize the **objective function**

$$\text{Injection Efficiency} := \frac{\text{net injected current in SR}}{\text{booster extraction current}}$$

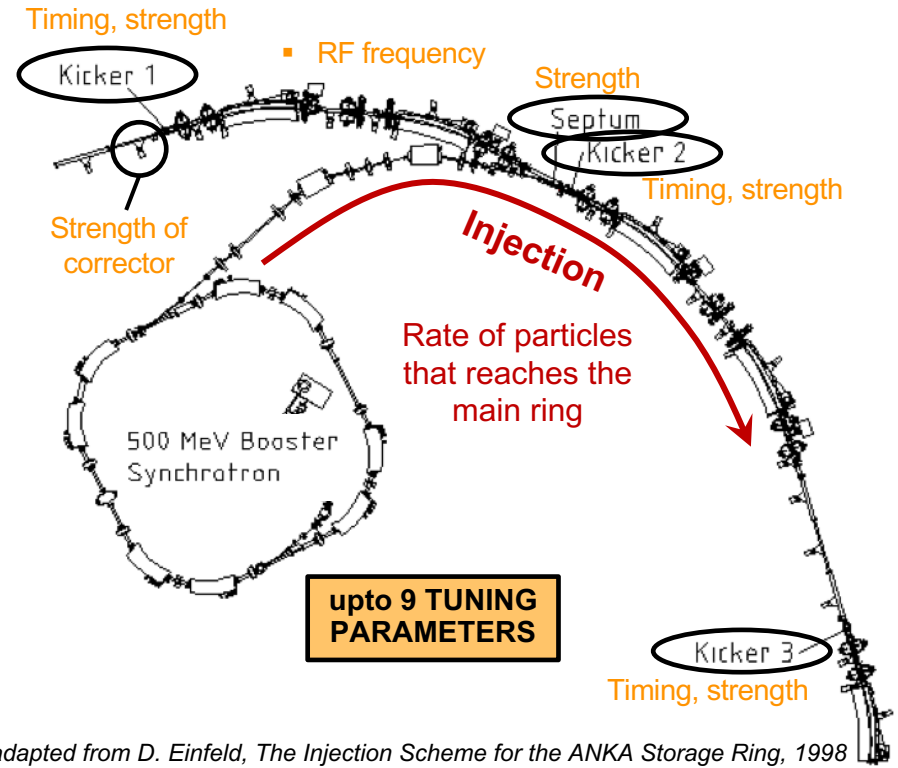
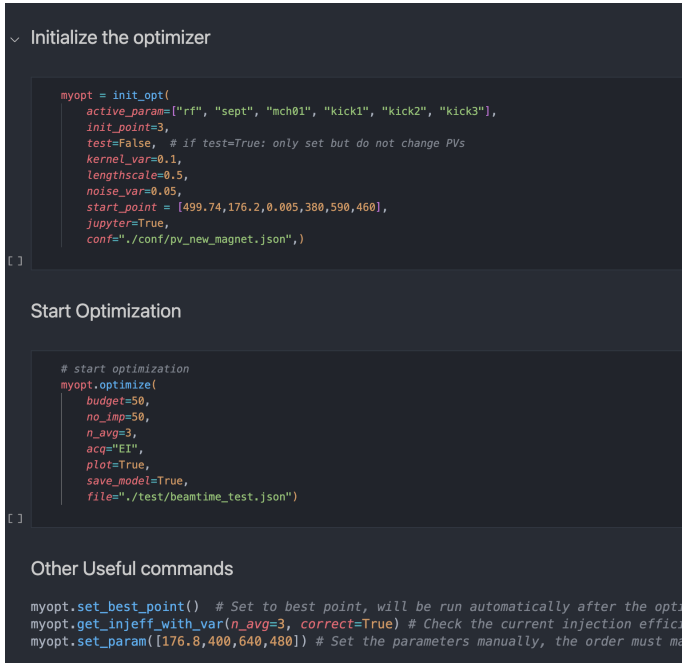



*Figure adapted from D. Einfeld, The Injection Scheme for the ANKA Storage Ring, 1998*

# Implementation Details

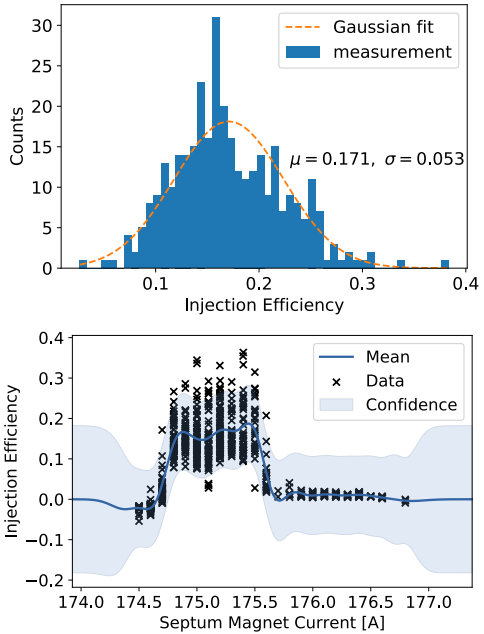
- In-house developed python packages (*GPy* for building the GP model)
- ***Pyepics / (caproto)*** for interaction with machine
- Containerized using **singularity/docker** (stable environment not affected by updates of control room PCs)
- Ready-to-use **Jupyter notebooks**
  - Choose parameter config file (range, PV names...)
  - Choose input parameters, kernel definition, etc.
  - Choose acquisition, optimization steps
  - Start optimization

- (Ongoing) build as **softIOC** and integrate into the control system → easier usage for operators



# GP Hyperparameters

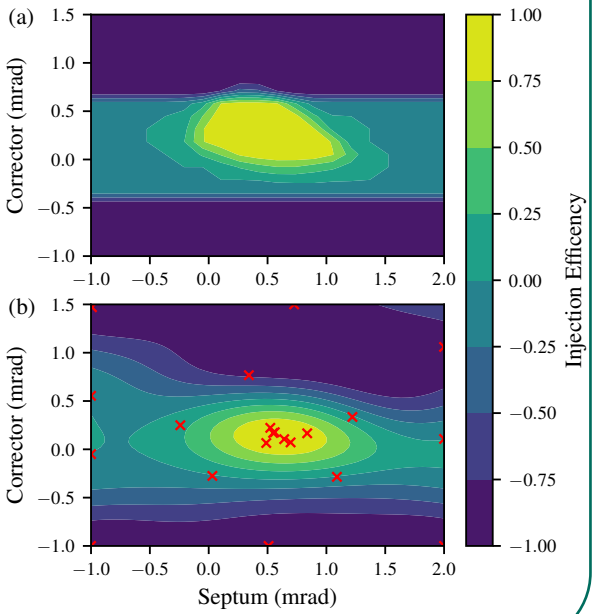
- Signal variance
- Length-scales
- Noise variance
- Parameter Bounds




# GP Posterior Space in Simulation

Grid scan
~ 1h

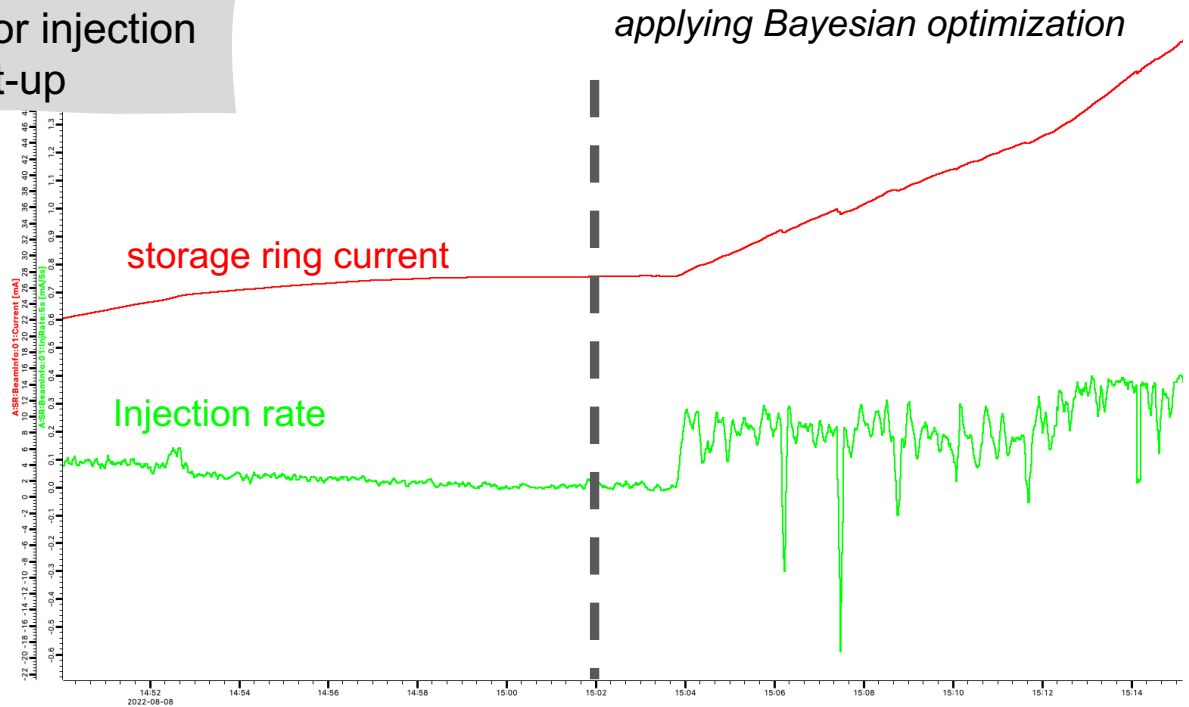
BO after 20 steps
~ 5 min



# BO Demonstration

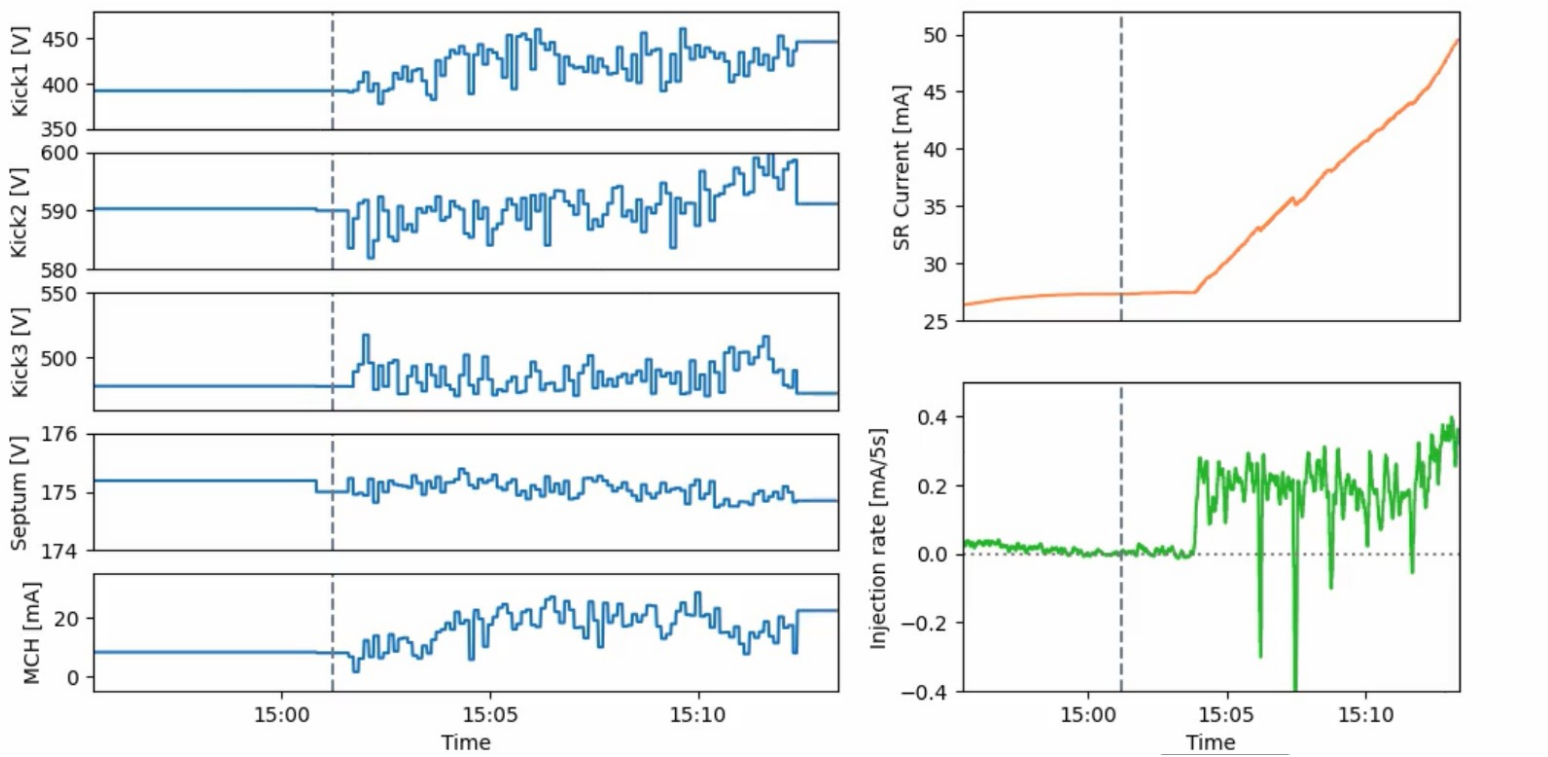
Snapshot of using BO for injection optimization during start-up

Aug. 2022



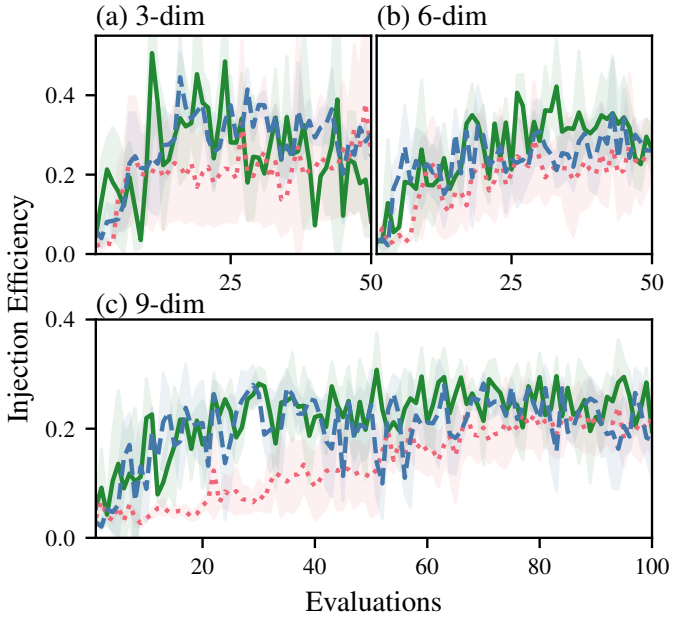
# BO Demonstration

Variation of machine parameters by BO



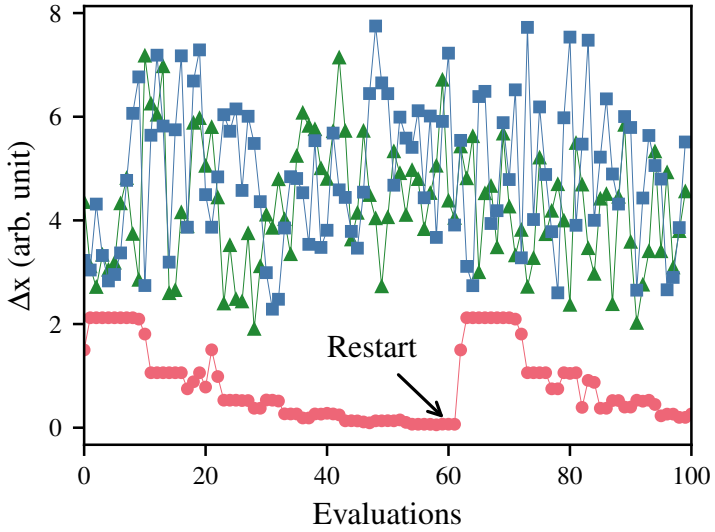
# Comparison with Nelder-Mead *(simplex method)*

BO with **UCB** and **EI** acquisition compared with **N-M**

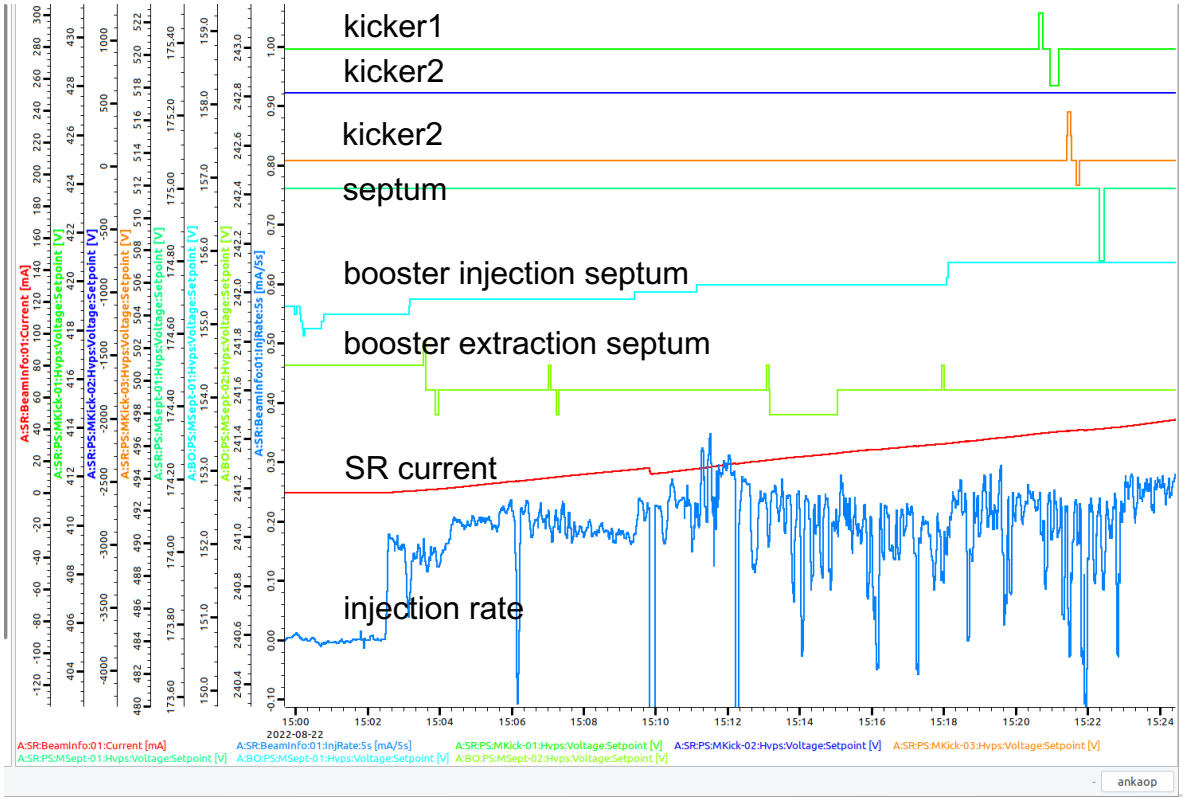


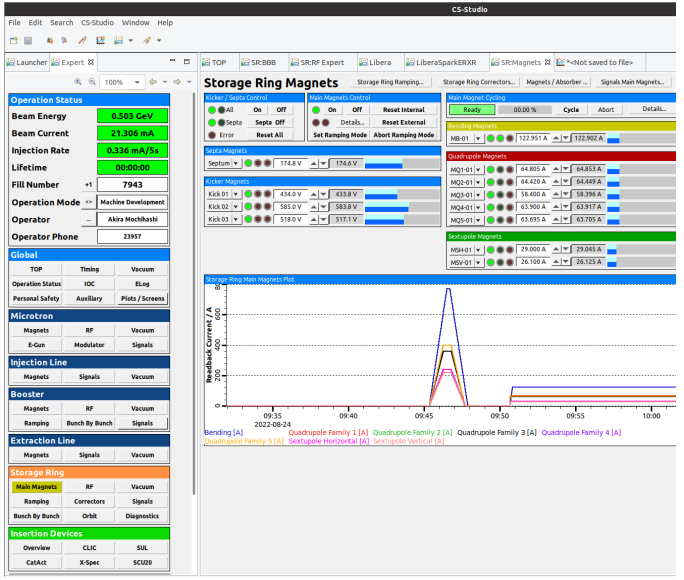

Exploration / convergence behaviour

N-M sometimes gets stuck in local optima and needs to be restarted



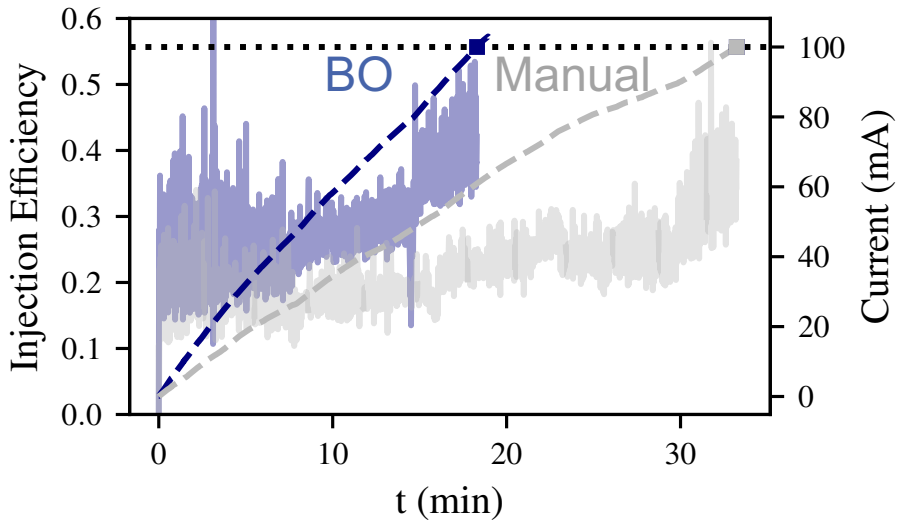
# Manual Tuning



# Manual Tuning

Optimizations with comparable machine condition.
Reduced injection time for 100 mA from 30 min to 18 min.



# Caveat... *in real world application*

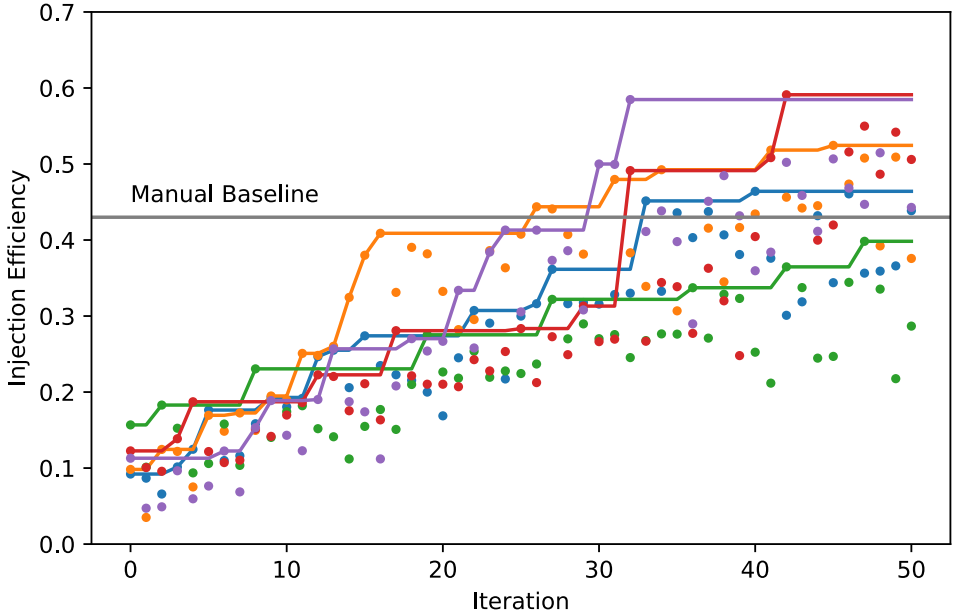
- BO best for **stationary problem,** need additional techniques to include time-varying process (magnet heating up etc.)
- **Exploration / large steps** can lead to undesired conditions (beam loss, machine protection)...
  - Used currently more as *"**optimize and set**"* rather than continuously tracking the optimum setting
- Convergence to global optimum not guaranteed, still affected by **noisy readback values**; sometimes multiple runs required

Mitigations require modifications of the "normal" BO

- Contextual optimization
- Including safety constraints
- Dynamic adapting exploration-exploitation trade-off
- Preference on smaller parameter changes
- ...

# Backup

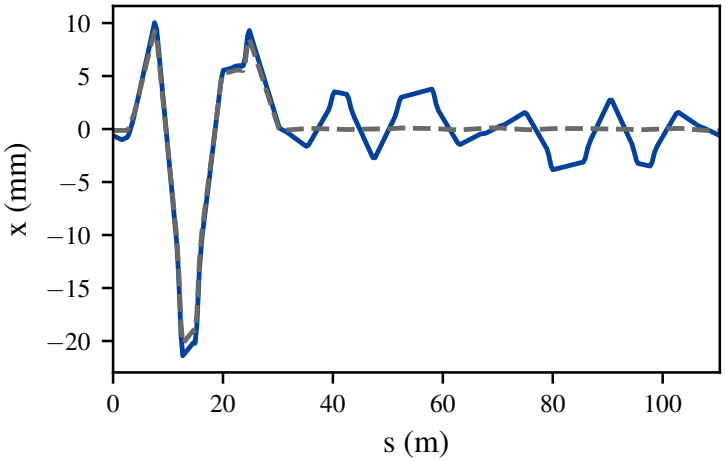
BO runs for commissioning when switching to new magnets power supplies




Manual baseline outperformed in most cases

# Backup

Example of an injection bump orbit found by BO (blue line) compared to reference orbit (grey dashed)



# Backup