A detailed ML example: SPS spill quality control

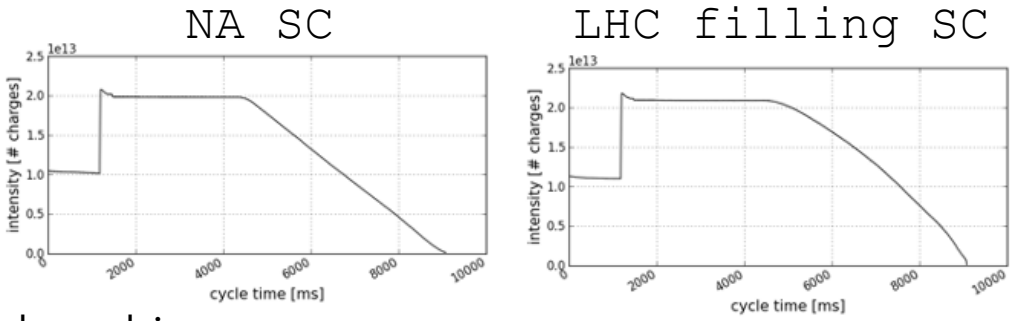
V. Kain, P. Arrutia, F. Follin, A. Lu, G. Papotti, M. Schenk, F. Velotti

Motivation

Spill quality degrades with the slightest perturbation

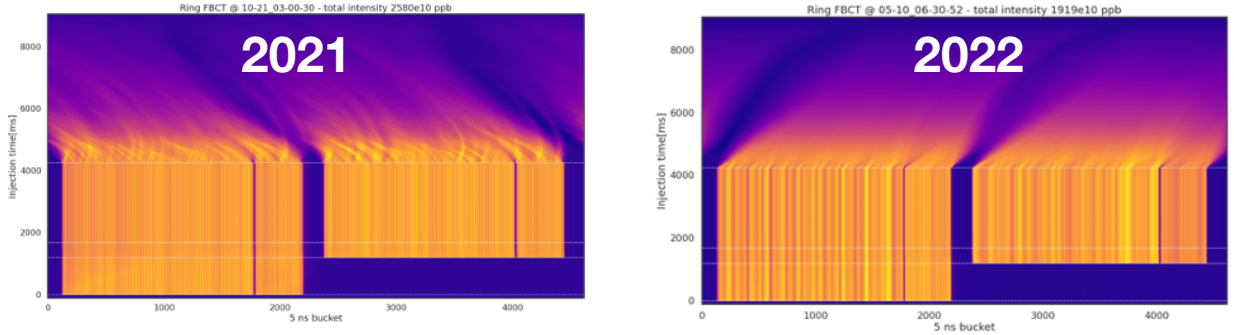
★ Macro-spill shape: Hysteresis

- ✳ Is being addressed as part of PhD
- ✳ Currently: manual adjustments



★ High frequency ripple from “slow” debunching

- ✳ **Solved:** Regulating at 0 V



★ Low frequency ripple from power converters

- ✳ Implemented solution: $n \times 50$ Hz active control + Empty Bucket Channeling with 800 MHz
- ✳ **Goal:** keep modulation amplitudes below 0.15 normalised for $> 85\,\%$ of time

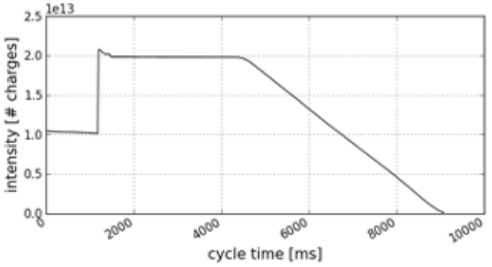
Motivation

Spill quality degrades with the slightest perturbation

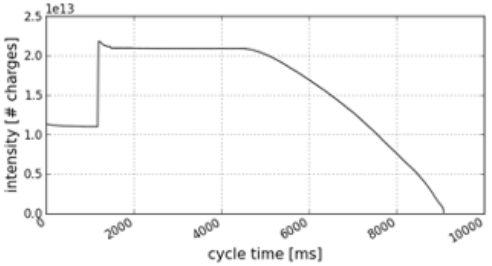
★ Macro-spill shape: Hysteresis

- ✳ Is being addressed as part of PhD
- ✳ Currently: manual adjustments

NA SC

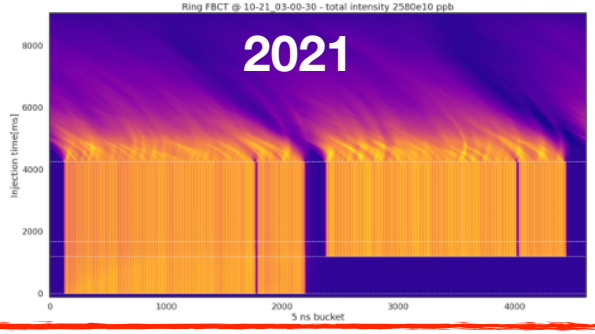


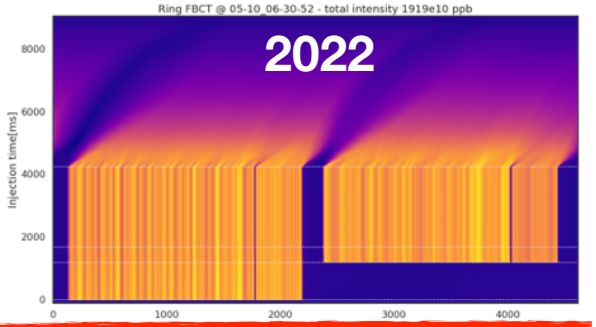
LHC filling SC



★ High frequency ripple from "slow" debunching

- ✳ **Solved:** Regulating at 0 V





★ Low frequency ripple from power converters

- ✳ Implemented solution: $n \times 50$ Hz active control + Empty Bucket Channeling with 800 MHz
- ✳ **Goal:** keep modulation amplitudes below 0.15 normalised for $> 85\,\%$ of time

Status for $n \times 50$ Hz noise for NA spill

Since Long Shutdown 2, 50 and i.e. 100 Hz noise problematic.

Also, larger shot-by-shot fluctuations during day.

Status for $n \times 50$ Hz noise for NA spill

Since Long Shutdown 2, 50 and i.e. 100 Hz noise problematic.

Also, larger shot-by-shot fluctuations during day.

→ auto-launch numerical optimisation in 2022 → 50 Hz OK

Status for $n \times 50$ Hz noise for NA spill

Since Long Shutdown 2, 50 and i.e. 100 Hz noise problematic.

Also, larger shot-by-shot fluctuations during day.

→ auto-launch numerical optimisation in 2022 → 50 Hz OK

→ continuous control in 2023 with Adaptive Bayesian Optimisation and Empty Bucket Channeling → 50 and 100 Hz OK

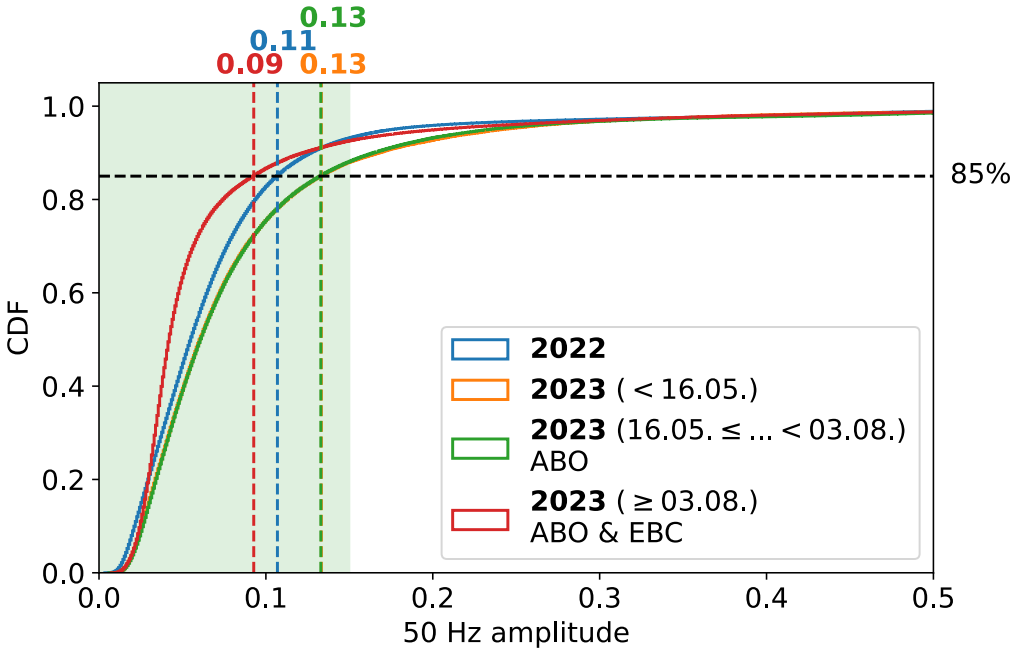
Status for $n \times 50$ Hz noise for NA spill

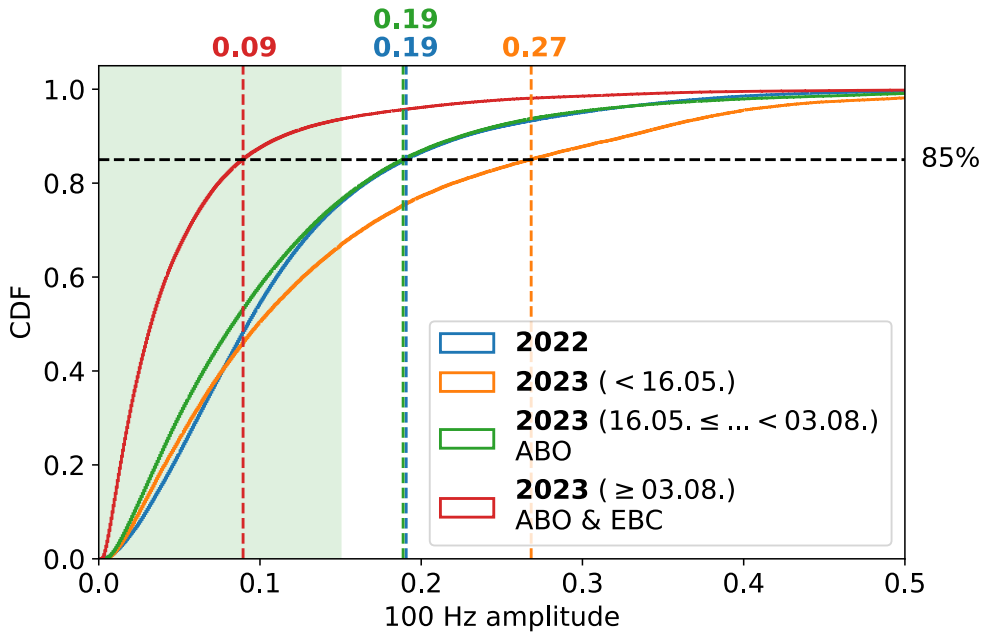
Since Long Shutdown 2, 50 and i.e. 100 Hz noise problematic.

Also, larger shot-by-shot fluctuations during day.

→ auto-launch numerical optimisation in 2022 → 50 Hz OK

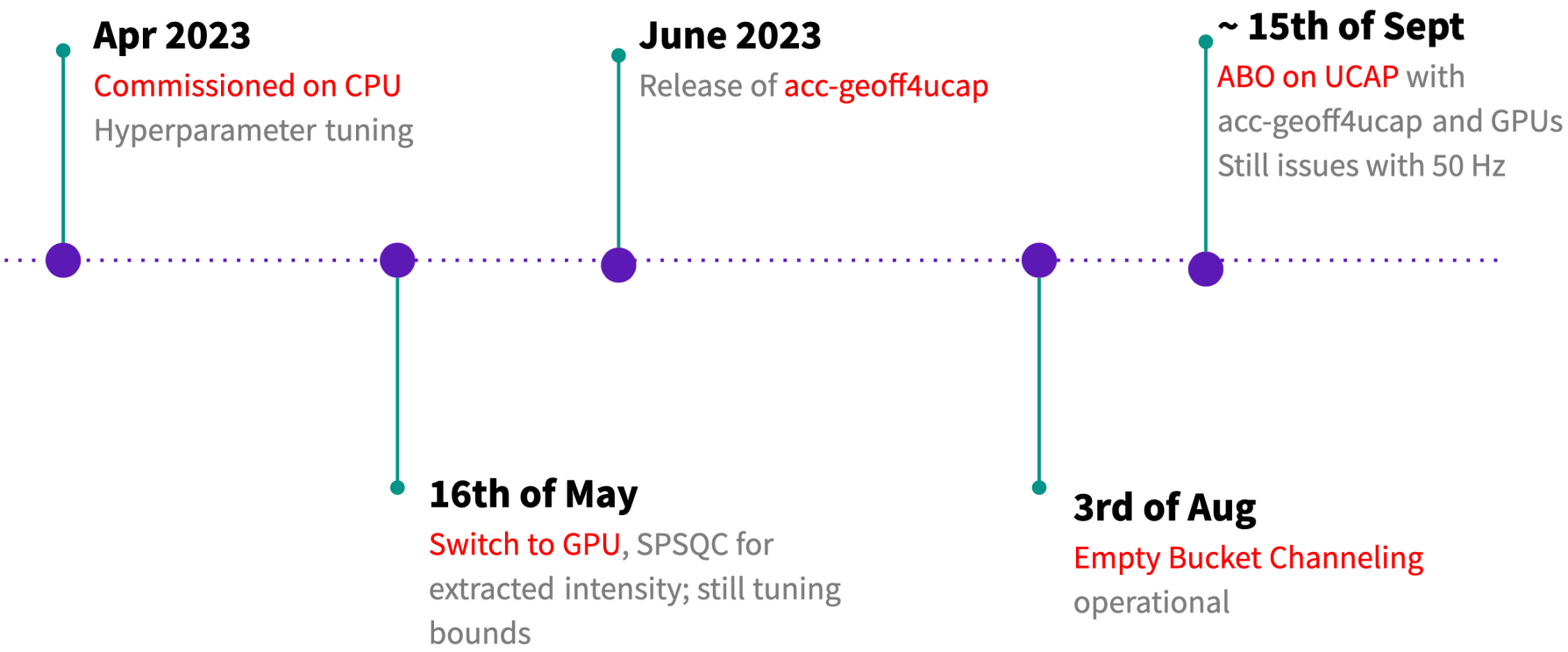
→ continuous control in 2023 with Adaptive Bayesian Optimisation and Empty Bucket Channeling → 50 and 100 Hz OK





Evolution through 2023

ABO 2023



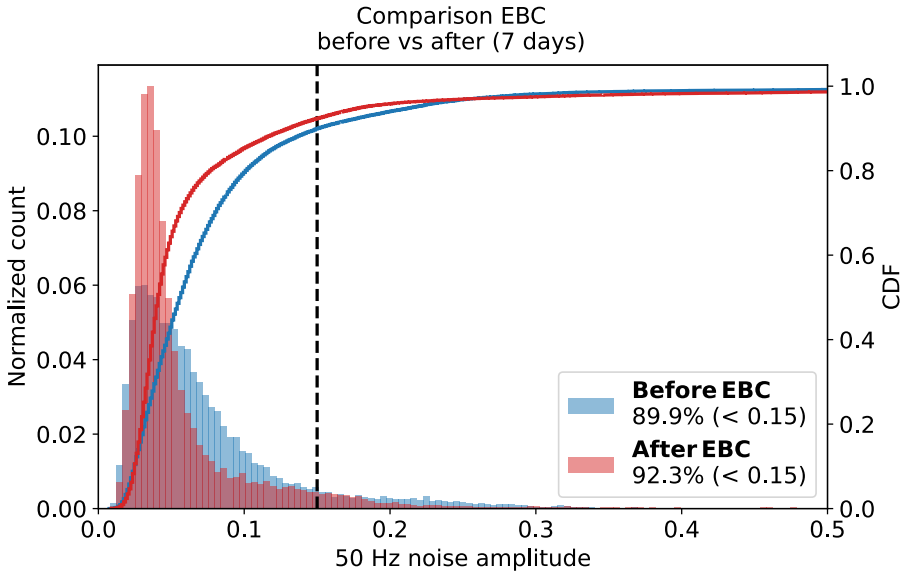
Performance improvements throughout the year!

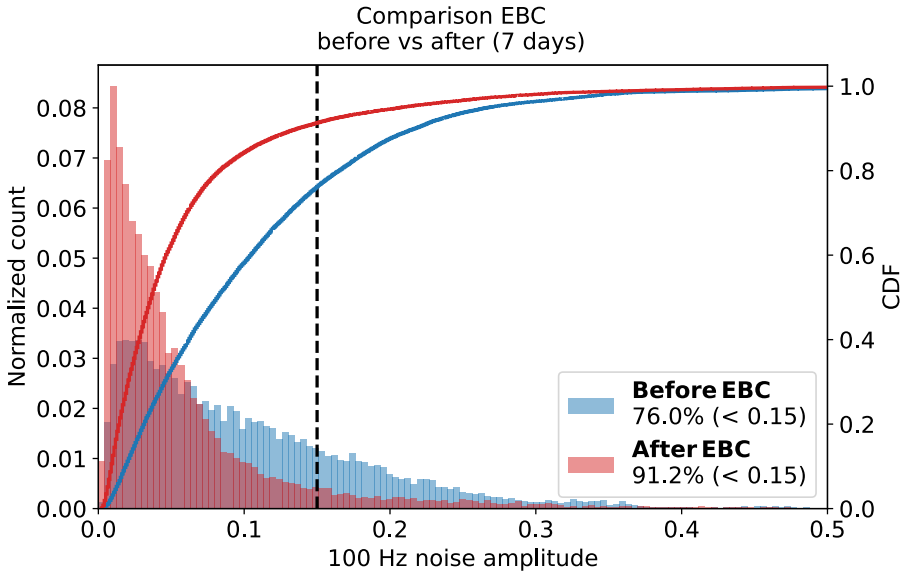
Effect of Empty Bucket Channeling

Comparison ABO+EBC of 7 days before and after switching on EBC.

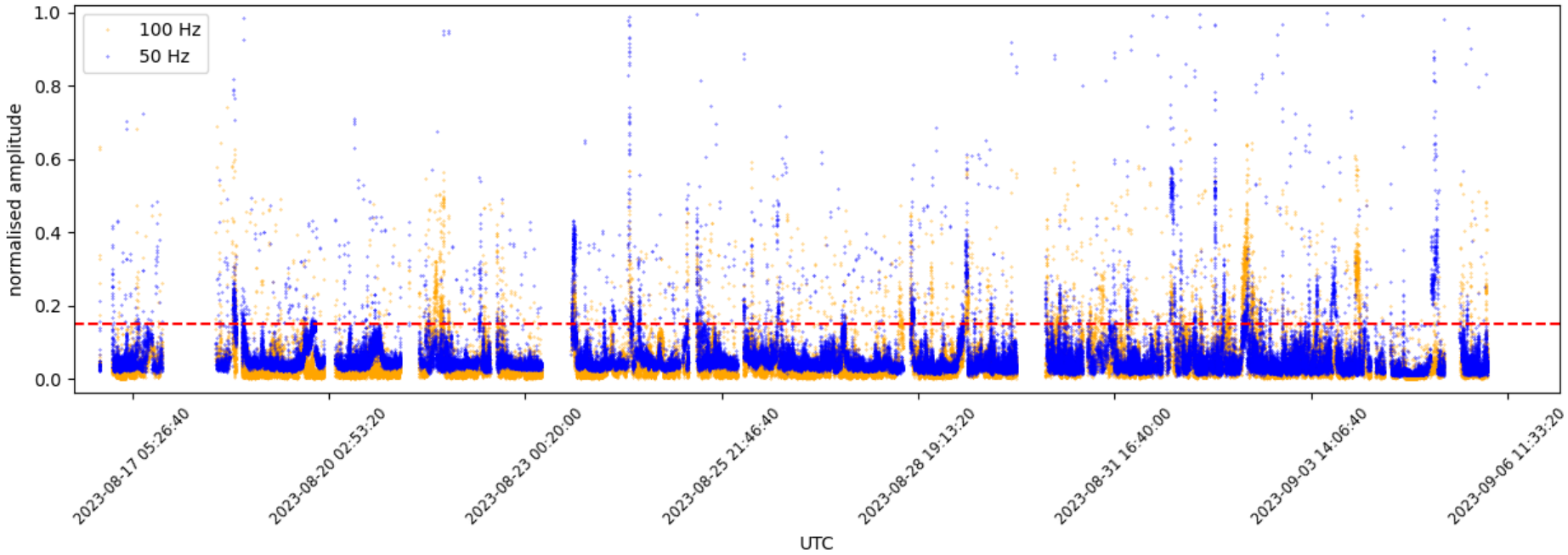
★ Unfortunately EBC alone is not sufficient, ABO needs to do base correction

★ EBC improves the overall result





Impression - some weeks in Aug '23



→ ABO tracks well; recovers after long stops

→ Some issues still in 2023 - all are being addressed

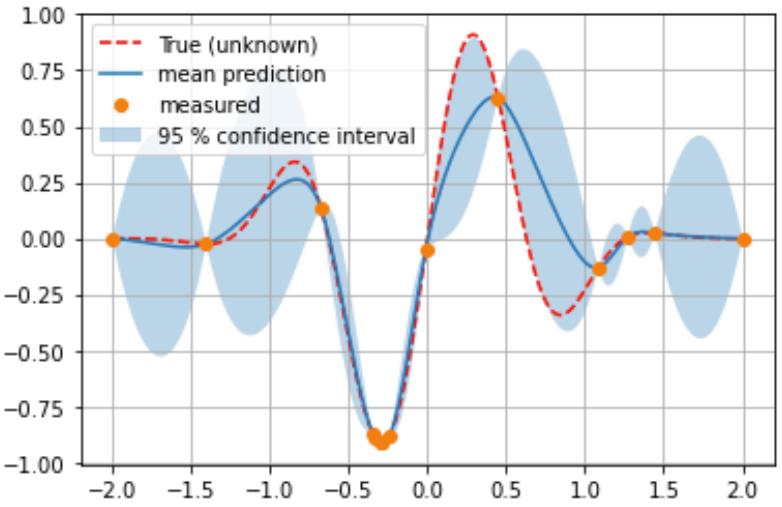
- ✳ exploration and hyperparameters, sharing GPU with other processes (→ controller lock-up), exploration spikes

Bayesian Optimisation - brief intro

★ Regression of objective function with probabilistic model:
Gaussian process described by mean function $\mu(x)$ and covariance function $k(x, x') \rightarrow$ *kernel* function

★ GP is **conditioned** (no fit) with new data assuming prior and using Bayesian rule → posterior

★ Optimisation: will not only use $\mu(x)$, but utilise also $\sigma(x) \rightarrow$ not optimising objective function directly, but ***acquisition function*** e.g. $\alpha(x) = \alpha(\mu(x), \sigma(x))$. Suitable for non-convex optimisation.



Example of 1D optimisation problem.

Can embed physics knowledge into kernel.
Kernel can also be tuned (fit) on historic data to increase sample-efficiency

Adaptive Bayesian Optimisation

Idea: build Gaussian Process for timeseries prediction with *SpectralMixtureKernel* $S(t, t')$

Gaussian Process Kernels for Pattern Discovery and Extrapolation

Andrew Gordon Wilson AGW38@CAM.AC.UK
Department of Engineering, University of Cambridge, Cambridge, UK

Ryan Prescott Adams RPA@SEAS.HARVARD.EDU
School of Engineering and Applied Sciences, Harvard University, Cambridge, USA

→ add one dimension in problem space: t to predict $t + 1$ into future; optimise x at $t + 1$ → **continuous control**

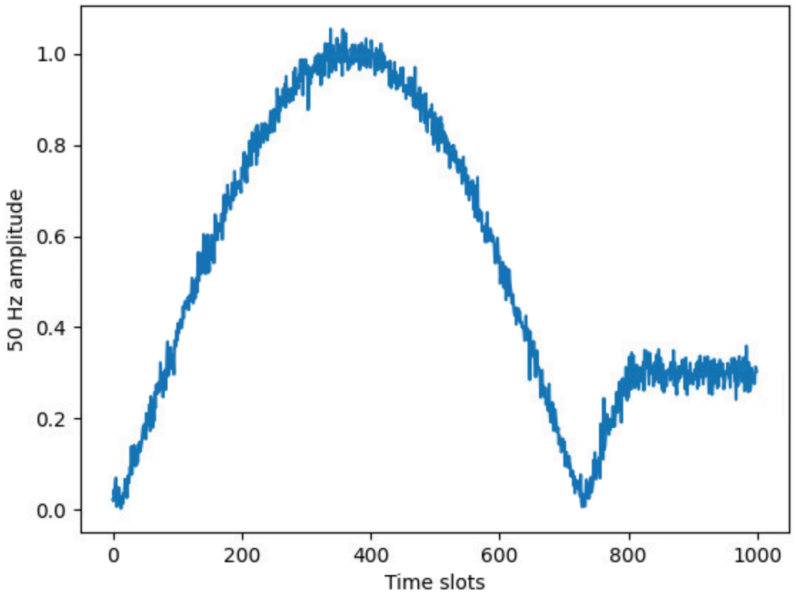
→ GP with composite kernel: the kernel that is currently used:

$$\sigma^2 \times S(t, t') \times RBF(x, x')$$

Tuning ABO - introduction

Simulation: simplified $n \times 50$ Hz control of slow extracted spill

- ★ Only 50 Hz
- ★ Only 1 D: find correct phase
- ★ phase of spill is linearly changing over time
- ★ the spill measurement is noisy



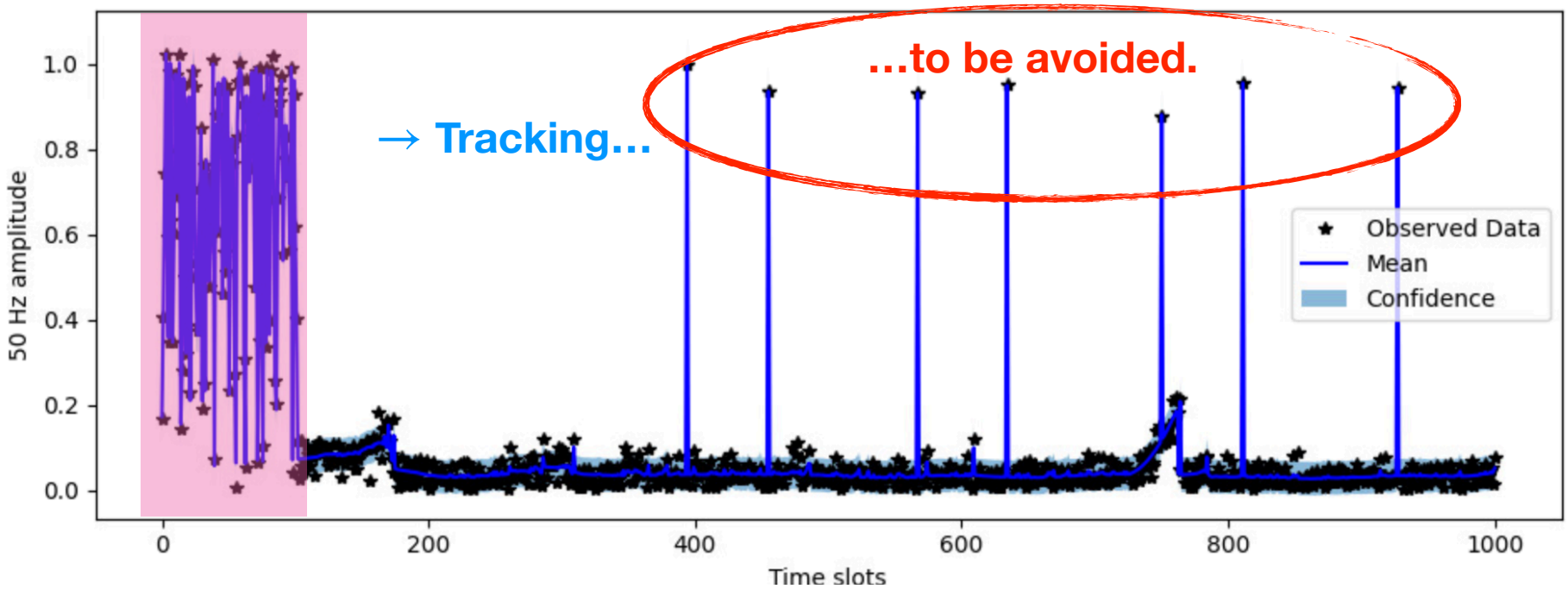
Evolution of 50 Hz amplitude with constant correction

Tuning ABO - introduction

Using *Upper Confidence Bound* acquisition function:

★ hyperparameter β guides exploration, optimal: reactive, but sufficiently conservative

100 random training samples



★ for continuous controller more hyperparameters: e.g. buffer length

✳ key for forecasting accuracy; optimum buffer length to be tuned again for UCAP with GPU.

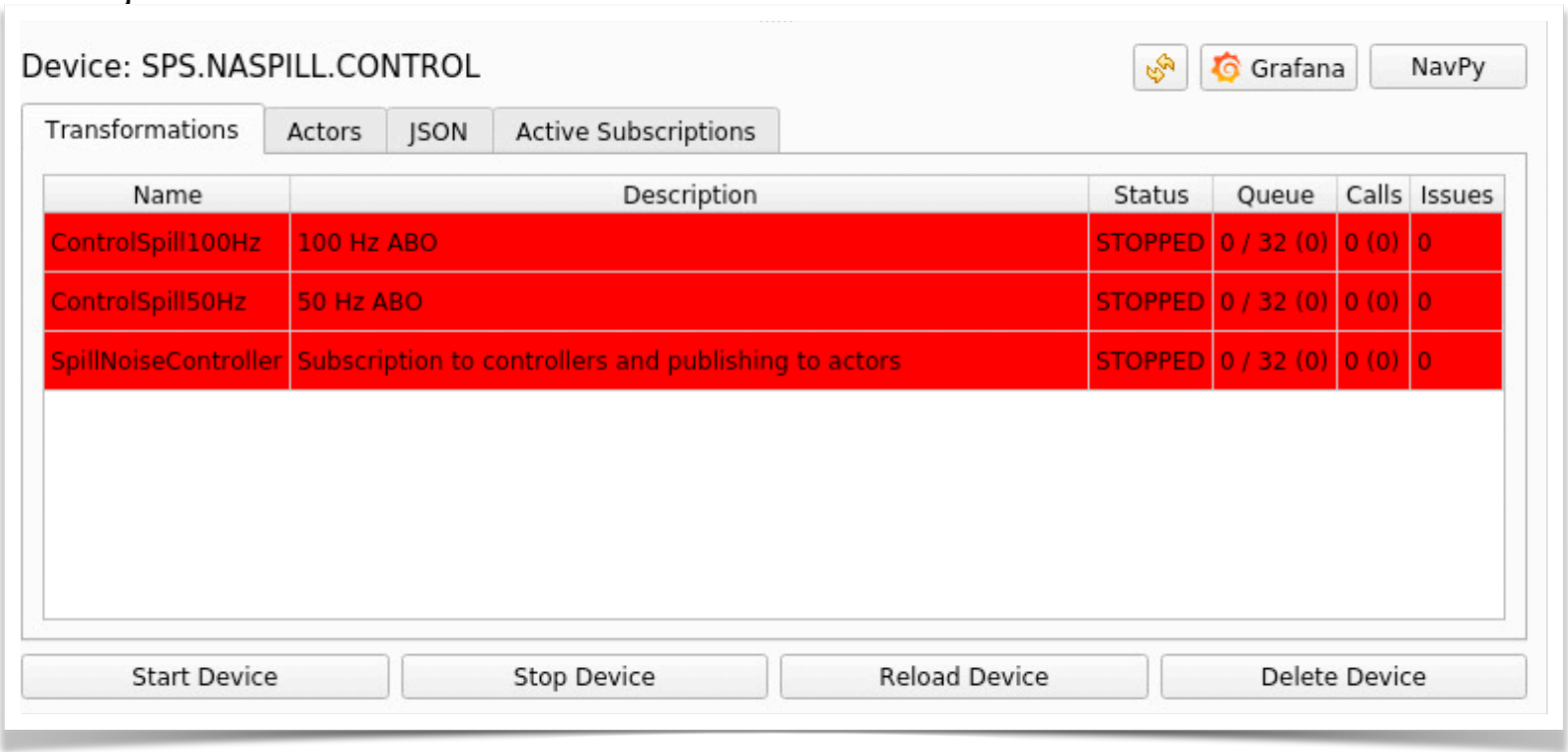
Implementation

★ ABO custom made algorithm based on BoTorch and cernml-coi-optimizers package → GPU accelerated

★ 2 acc-geoff4ucap controllers: 50 Hz, 100 Hz

★ UCAP node with GPU: “Y" implementation

✴ `SpillNoiseController` sets QF phase and amplitude for $n \times 50$ Hz noise injection



Avoiding exploration spikes - Proximal biasing

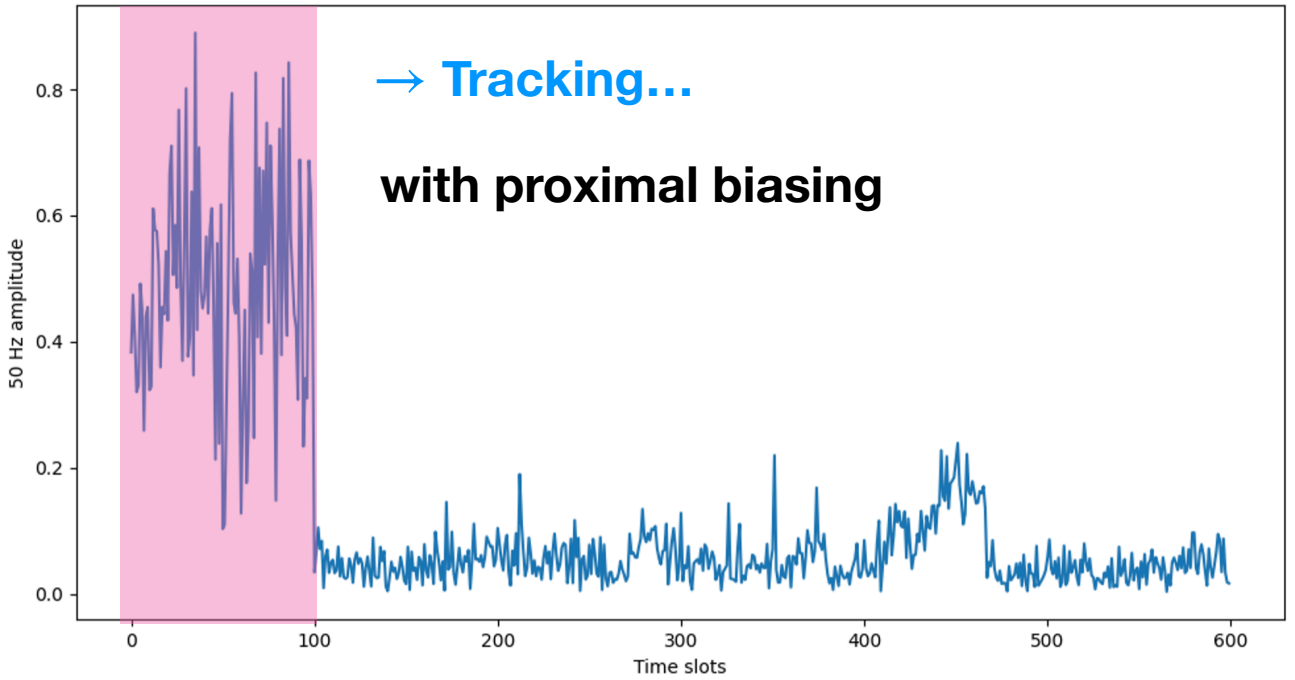
By wrapping the acquisition function $\tilde{\alpha}(x) = \alpha(x) \cdot \exp(-\frac{(x - x_0)^2}{2l^2})$,

x_0 is last observed location in parameter space. l is an additional hyperparameter

→ no exploration spikes, but slightly less reactive. To be tuned with beam.

Below: simulation with 2 DOF (phase, amplitude) → no (big) spikes!

100 random training samples



Conclusion and next steps

Adaptive Bayesian Optimisation and Empty Bucket Channeling can sufficiently stabilise $n \times 50$ Hz ripples of NA spill.

2023 = first operational experience with all controls components for EBC+ABO; improvements throughout the year

2024 = full exploitation!

Next steps:

- ★ dedicated GPU?
- ★ tune 50 Hz buffer length for UCAP controller
- ★ tune proximal biasing
- ★ ensure to be able to switch to spare power supply (QS) during run
  - ✳ Current controls only for nominal power supply QF