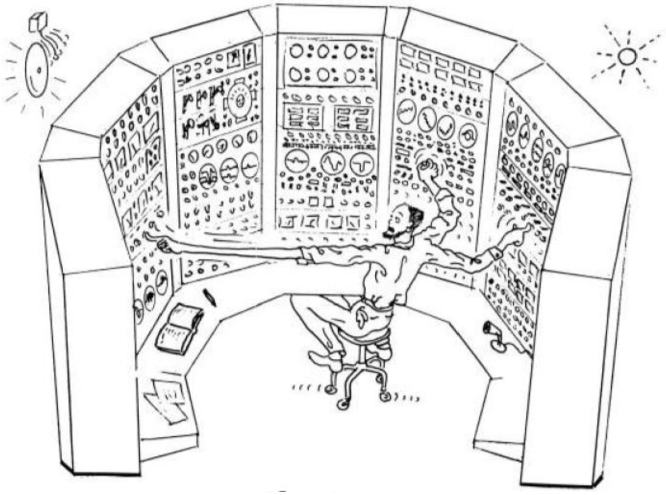
BE-CSS and SY-ABT activities

A. Huschauer, V. Kain, M. Schenk, F. Velotti
on behalf of the extended EPA & accelerator communities

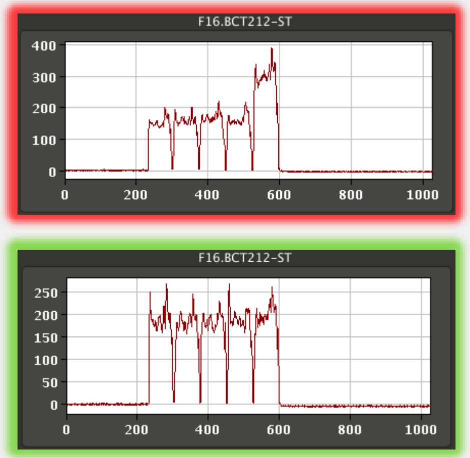
Intro



- **ML & NNs** for applications in **beam operations** and **beam transfer**
- **Dealing with a very diverse landscape of problems & data**
  - **Controllers:** parameter optimisation & drift compensation (on-demand or continuous), feed-backs / feed-forward corrections, scheduling
  - **Monitoring:** forecasting, virtual / enhanced diagnostics, anomaly detection
  - **Other:** project on LLMs (knowledge retrieval)
- **No "one size fits all"**
  - (Meta-)**RL, BO, model-predictive control** (GP-MPC), **physics-informed** methods, **transformers**, numerical **optimisers** (gradient free) & **classical control**
    often in combination with simulations or surrogate models
  - **Anomaly detection:** typically **auto-encoders**, but also **SVMs, isolation forests**, …
  - **Challenges:** no online training (sample efficiency) → sim2real gap, exploitation vs exploration / continual learning, **running safely & reliably 24/7**, lack of beam observation / diagnostics, …
- **Remarks on safety**
  - Above everything, we have an **independent machine protection system**(*)
  - Controllers typically work in **bounded parameter space**
  - Can still have **undesirable consequences** if controllers unsafe: **degraded beam quality, increased particle loss and radio-activation, machine downtime**

(*)ML-free

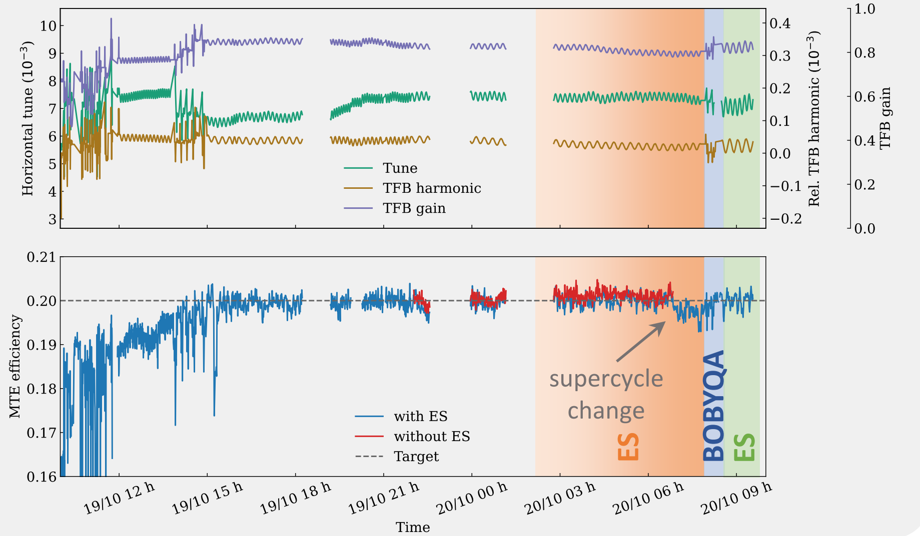
Examples using classical control



PS Multi-Turn Extraction

- **Automatic drift compensation**
- **Successfully tested** and tuned in MDs
- **Hybrid agent:** continuous controller interleaved with optimizer when far off

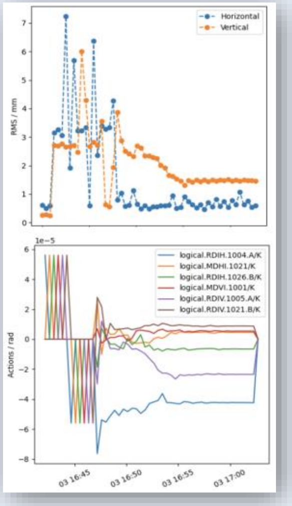
A. Huschauer, M. Schenk, C. Uden



Trajectory steering framework

using acc-geoff4ucap

- **Versatile objective**
  Beam position, beam loss, …
- **Various algorithms**
  incl. Micado / SVD, numerical opt.
- **In 2024:** PS2SPS, SPS2LHC



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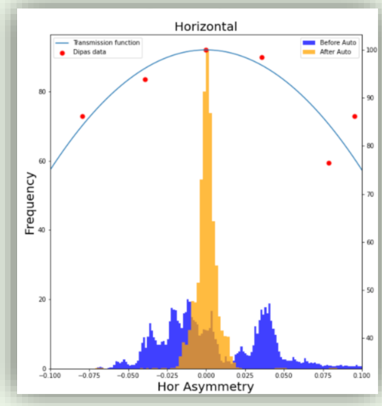
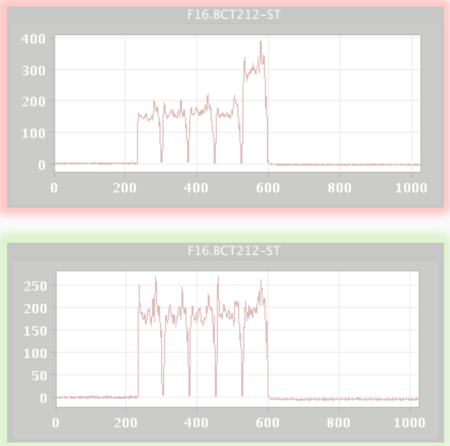
PS EAST: fixed target beam steering

- **PID** regulator on **UCAP**
- **Simple & effective**
- **Similar controller** for TL towards AD



J. McCarthy

Examples using classical control



PS Multi-Turn Extraction

- ➢ **Automatic drift compensation**
- ➢ **Successfully tested** and tuned in MDs

- **Generally easier to validate than ML-based methods**
  - ➢ Bounded parameter spaces
  - ➢ Predictable / deterministic behaviour
  - ➢ Can still run into unforeseen situations over longer time scales

Trajectory steering fra

using acc-geoff4ucap

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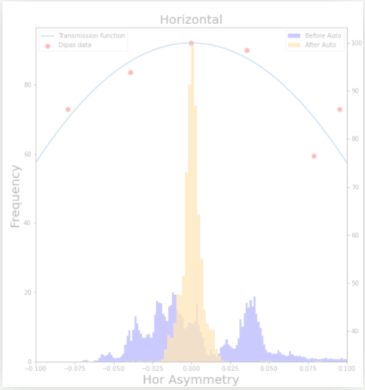
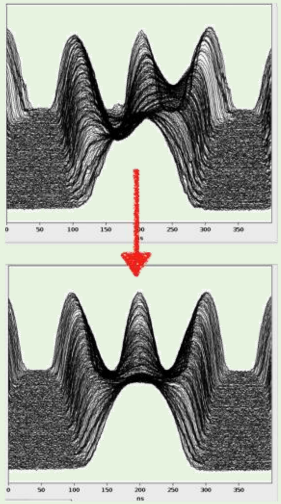


J. McCarthy

Examples using RL



PS

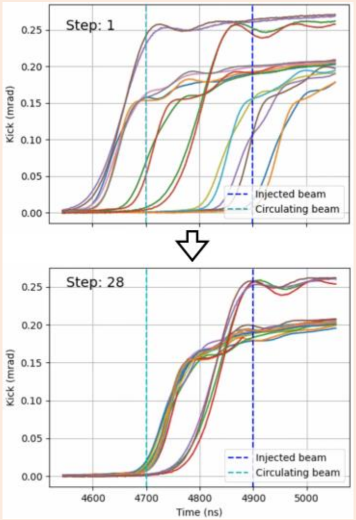
- Correct RF **phase & voltage** for **uniform bunch splitting** (LHC beams)
- **Multi-agent** (SAC) & **CNN** for initial guess
- Successful **sim2real** transfer
- **If things go wrong:** degraded beam

A. Lasheen, J. Wulff

PS to SPS

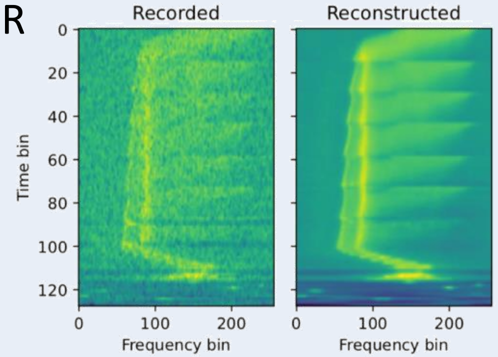
- Adjust **fine delays** of SPS **injection kicker**
- RL agent (PPO) trained on **data-driven dynamics model**
- **If things go wrong:** beam loss, activation

M. Remta, F. Velotti

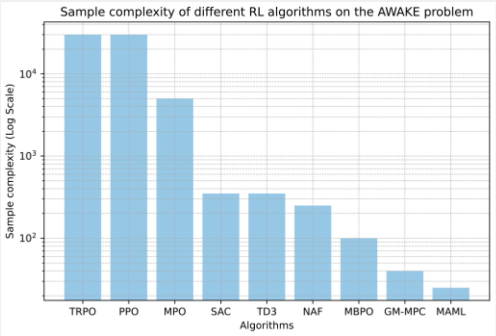


LINAC3 / LEIR

- Achieve **optimal injection** into LEIR
- RL state based on **β-VAE-encoded Schottky** spectra
- Agent trained on **data-driven dynamics model**
- **If things go wrong:** beam loss, activation, equipment trips



V. Kain, N. Madysa, B. Rodriguez



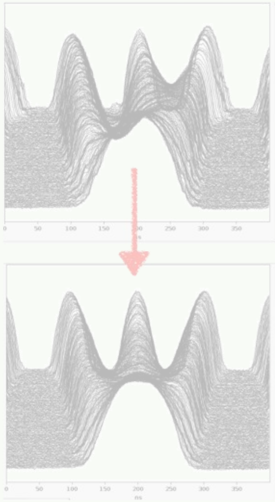
S. Hirlaender, V. Kain

AWAKE

- **Steer electron beam** in AWAKE line
- **Test-bed** for different RL algorithms & sim2real transfer
- Large improvements in **sample efficiency** (Meta RL)
- **If things go wrong:** not critical

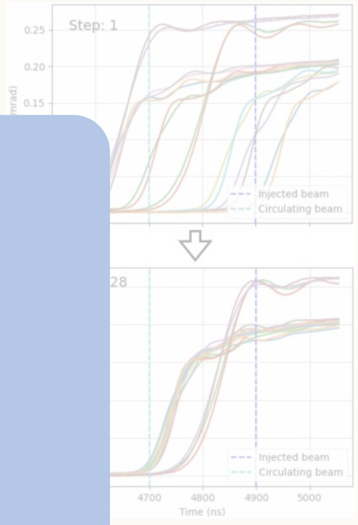
Examples using RL

PS



A. L

PS to SPS



- **RL training "by definition" unsafe** (trial and error learning)
  there are some ways to add safety to RL …
- **RL policies typically hard to validate:** true for all NNs, even if RL policy networks are typically small
  are all actions safe for all possible states?
- **For us**
  - Usually **no online training** possible (safer)
  - Instead **sim2real transfer** either using simulation or data-driven dynamics model (might be safety issue, depending on sim2real gap)
  - **Continuous state-action spaces**

LINAC3 / LEIR

- Achieve **optimal**
- RL state based on **β-VAE-encoded Schottky** spectra
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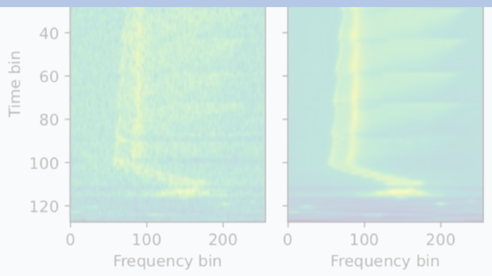
- **If things go wrong:** beam loss, activation, equipment trips



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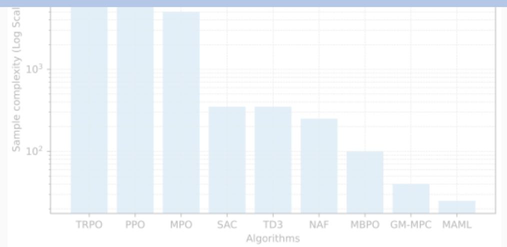


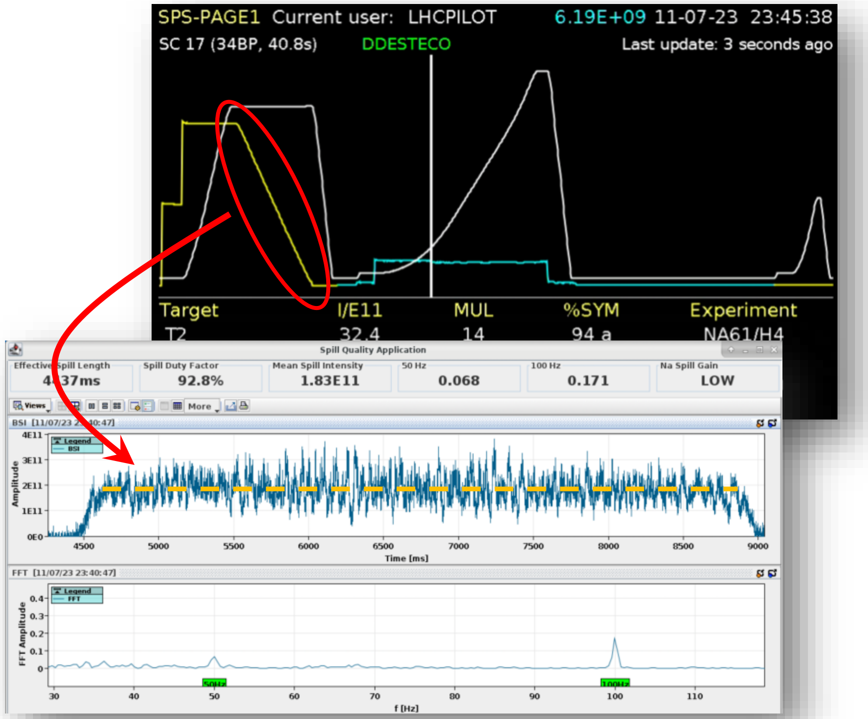
S. Hirlaender, V. Kain

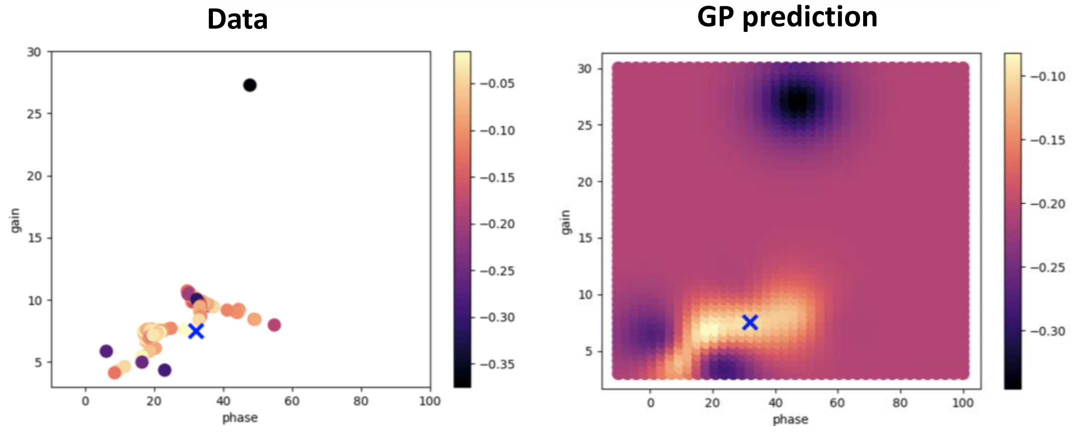
- …**eam** in
- **Test-bed** for different RL algorithms & sim2real transfer
- Large improvements in **sample efficiency** (Meta RL)
- **If things go wrong:** not critical

Example using BO

Spill noise cancellation

- **SPS** slow-extracted beam has **50 Hz & 100 Hz noise** originating from **quadrupole** power converter **ripple**
- **Continuous controller for active noise cancellation**
  - ➢ Adaptive Bayesian optimisation
  - ➢ Spatio-temporal Gaussian Process model
  - ➢ Low dimensional: two spatial parameters + time
- **Challenges**
  - ➢ Exploration vs exploitation
  - ➢ Jumping to bounds occasionally
    under control with proximal biasing
  - ➢ Time dependence: model updates on-the-fly, has sometimes ended up in "degenerate state", but does usually recover
- **If things go wrong:** degraded beam and potentially time lost for physics experiments
- **N.B.:** there is SafeOpt for safety-critical BO

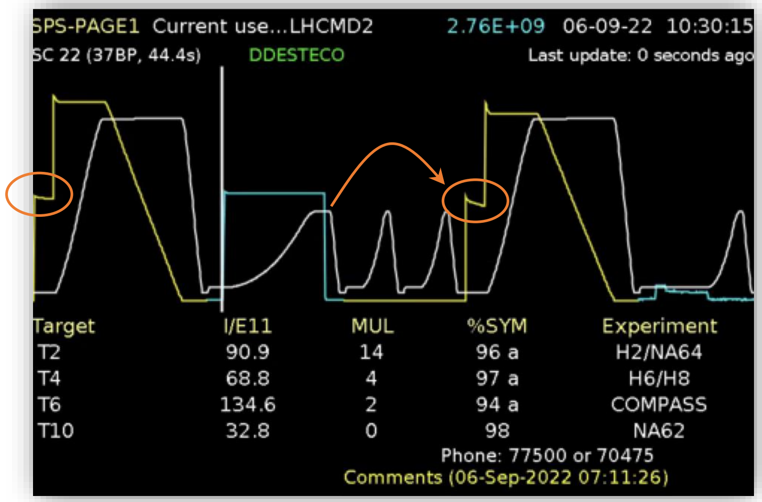


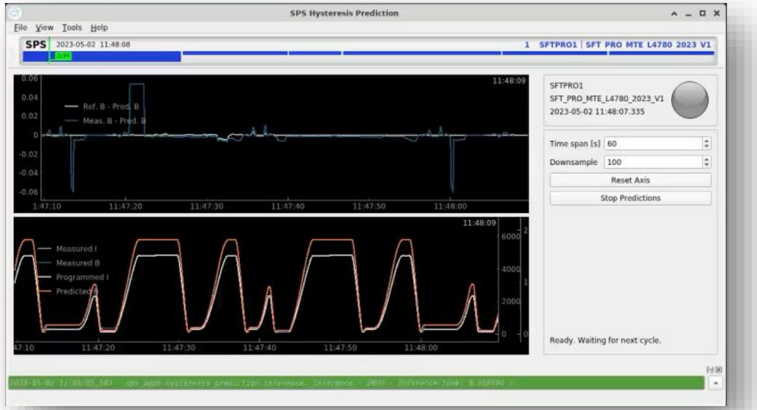


Example using PhyLSTM / transformers

Hysteresis & eddy-current compensation

- **Context**
  - **Multipole magnets** define beam trajectory, size, oscillation, and some aspects of collective beam behaviour
  - Many CERN accelerators are **multi-user machines** each with a **different magnetic cycle**
  - **Magnetic hysteresis** introduces **change in beam dynamics** for identical cycles which is problematic in many ways
- **Method & challenges**
  - **Feed-forward correction on magnetic strength** to provide reproducible fields
  - **PhyLSTM & Transformer models** trained on dipole data
  - **Generalisability & accuracy** of model
- **Safety aspect**
  - **PhyLSTM:** typically well behaved, even when extrapolating
  - **Transformer-based models:** hard to validate ”for all possible inputs” / to some degree unpredictable
  - Add **safeguard at model output** to limit allowed change of magnetic field





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Equipment-related ML

- Define new paradigm of **smart and agile equipment**
  e.g. adding context-awareness: beam parameters, machine state, etc.
  ➡ automate **setup, fault analysis, and recovery**

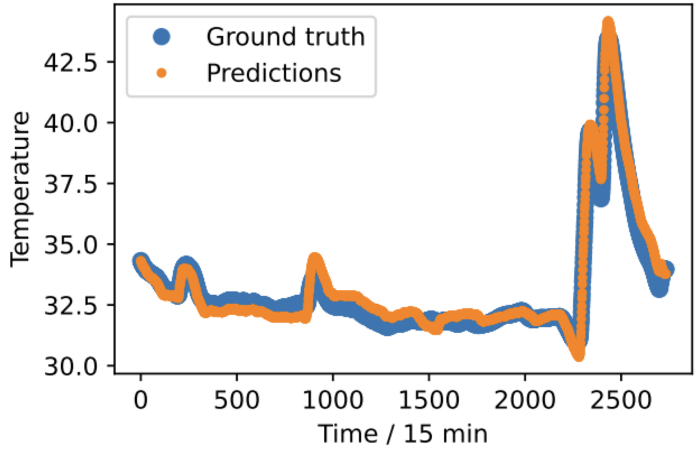
- **Ongoing pilot studies**
  - **Potentially safety-critical:** mix-in ML models to decide whether equipment can be **reset automatically**
    e.g. anomaly detection for vacuum interlock spikes on kicker magnet using VAE
  - **Adding safety:** e.g. Conv AE for SPS beam dump anomaly detection, kicker magnet temperature forecasting

- **Systematic studies in that direction have started relatively recently**
  - Validation / safety could become more relevant in the coming years

Equipment-related ML

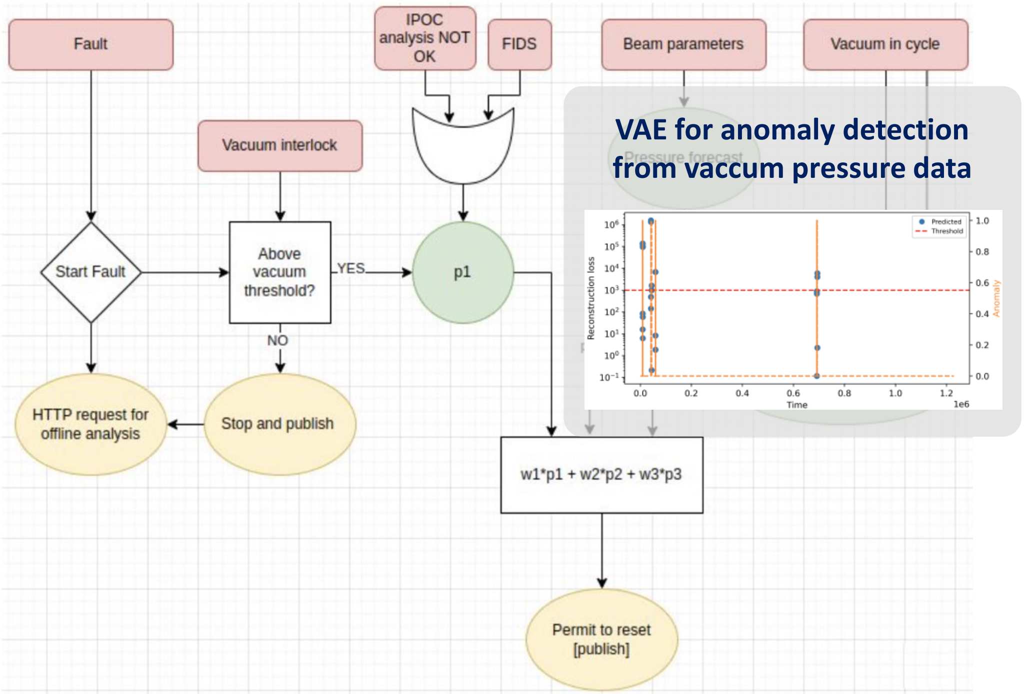
Temperature forecasting & pressure anomalies

- **Example 1**
  Kicker magnet temperature forecasting
  - **Kicker temperatures limit SPS high-intensity operation** (beam-induced heating)
  - **Goal:** create **temperature forecast** using online measurement, current machine operation and future planning
  - **Method:** Light Gradient Boosting Machine and using beam-induced heating equation



F.M. Velotti et al.

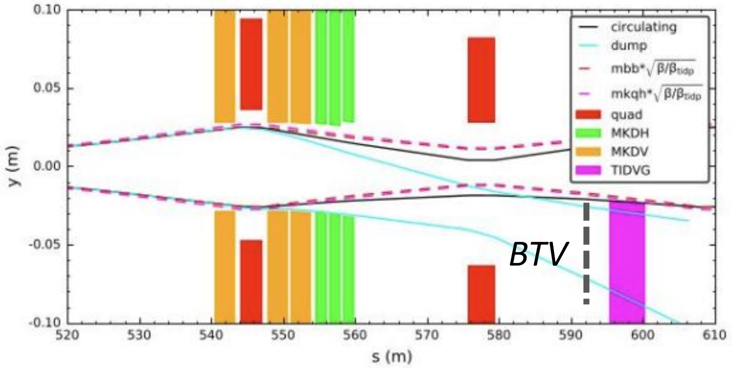
- **Example 2**
  Auto-reset of SPS kicker following vacuum interlock
  - **Goal:** correctly classify vacuum "spikes" to avoid unnecessary downtime
  - **Method:** VAE trained on historical time-series data
  - **Auto-reset and automatic e-mail** with diagnostics plots to experts



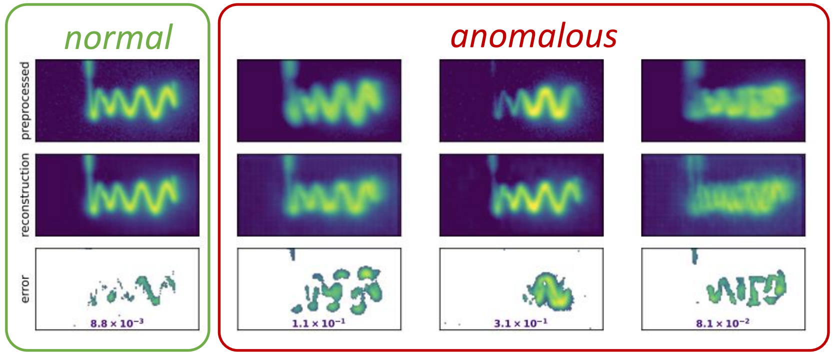
Equipment-related ML

Beam dump system failure

F. Huhn, F.M. Velotti, B. Goddard



- **SPS beam dump system** (SBDS)
  - **Machine-safety critical**
  - Malfunctioning may result in **unwanted activation or damage**
- **Goal:** detect anomalous beam dump patterns from BTV images
  - **Challenges:** unlabelled data, be robust to both seen and unseen anomalies, high variability due to other effects, …
  - **Heavily biased towards "normal"** images: train **convolutional AE** and use **reconstruction loss** to identify anomalies



- **Results**
  - Anomalous SBDS behaviour: **~5 - 20 x higher reconstruction error**
  - Additional info on **localisation of error** (helpful to diagnose)
  - Deployed and **running operationally**
- **Safety aspect**
  - Adds **additional diagnostic and safety check** for the beam dump kickers
  - At the moment **just monitoring**