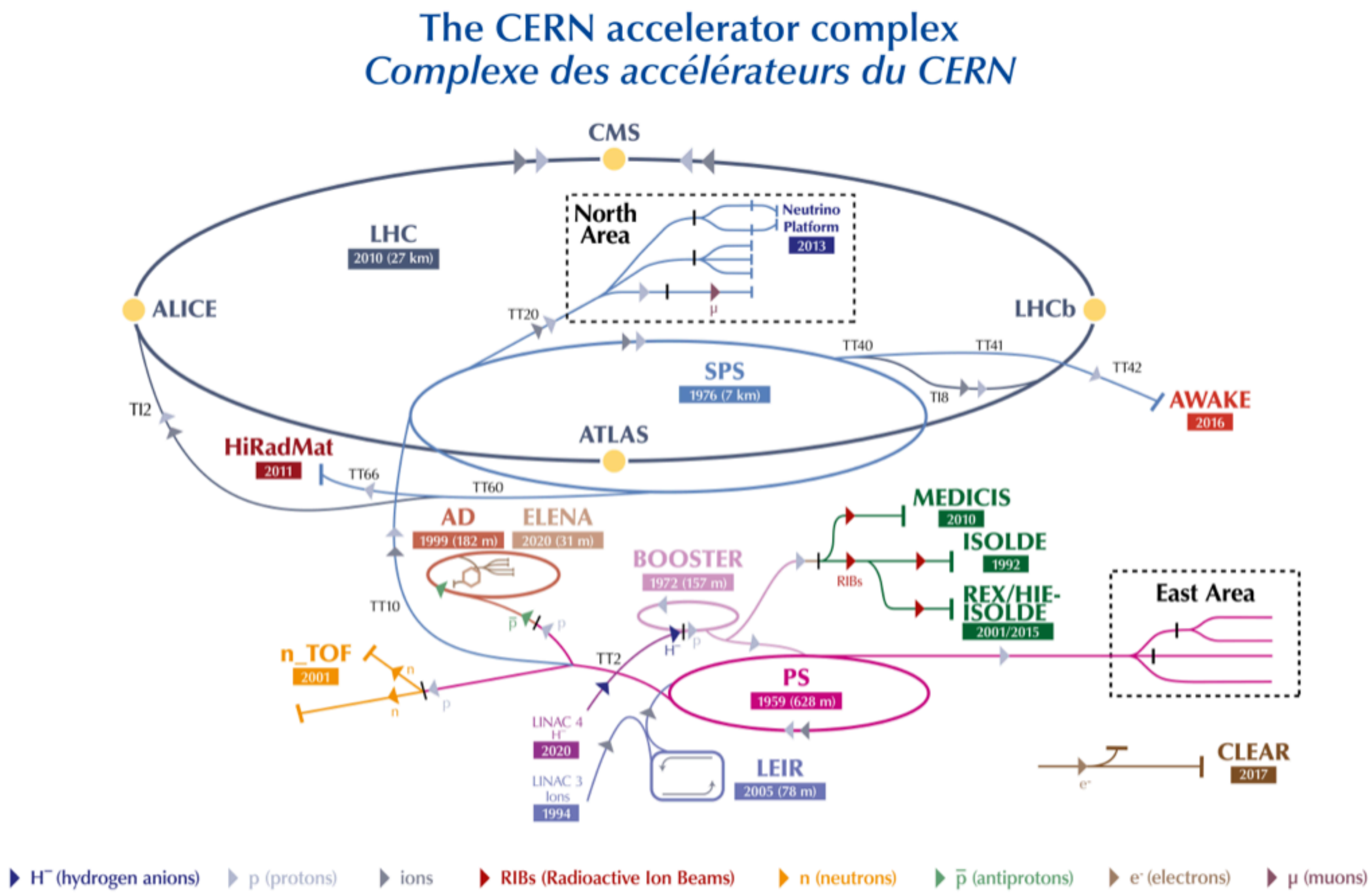
Towards (more) autonomous accelerators -
Status and vision at CERN

V. Kain, A. Huschauer, N. Madysa, C. Roderick, M. Schenk, F. Velotti

Which accelerator is running autonomously?

No accelerator at CERN is autonomous yet.
The most autonomous ones: LINACs, LEIR



Setting the scene

- Automation has long tradition at CERN's accelerators
  - specially enforced by collider operation $Sp\bar{p}S$, LEP, LHC,… potentially because of size
- **Despite of working as chain of accelerators → degree of automation very different for different accelerators**
- → eventual "full" automation is however only possible if all machines play along
  - e.g. energy drifts in one machine will impact next machine
- **Energy crisis** → automation will become one of the accelerator complex goals
  - faster commissioning, faster mode switching, **more physics in less time**

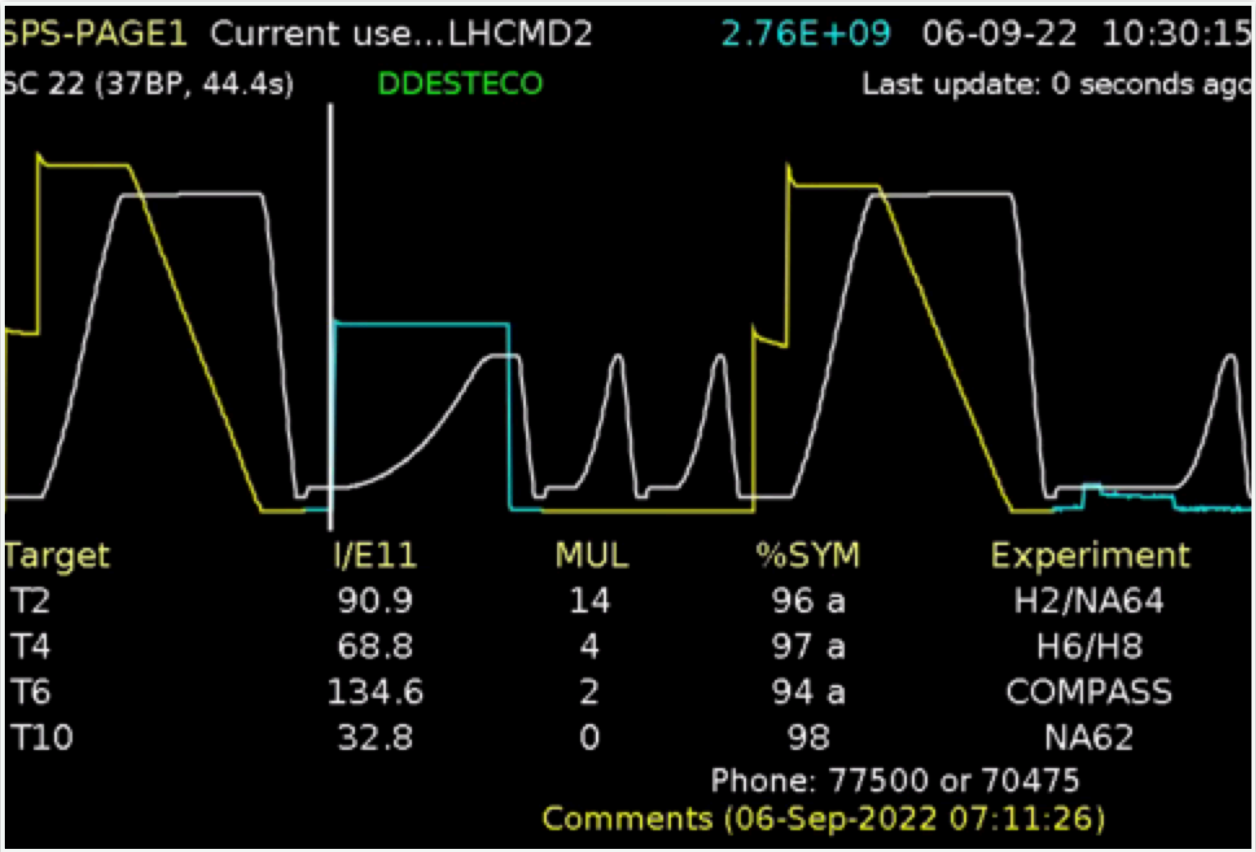
- **Efficiency think tank→ community driven effort instead of individual effort in a corner**

The waves of automation @ CERN

The **LHC** is driven by executing sequencer tasks on demand.

All other machines keep **automatically** playing the programmed **supercycle** over and over again.

- Driven by CERN timing system and multiplexing of settings on equipment frontends



The waves of automation @ CERN

The **current** automation efforts are based on three threads

- **Automation wave 1 (2006 -)**
  - reduce complexity through models **(LSA)**
  - high level parameter control, sequencers, software interlock system, classic control algorithms in feedforward and feedback (SVD, COSE,…)
- **Automation wave 2 (2018 -)**
  - → provide clever solutions if models not available. E.g. Learn them…
  - Python into the control room
  - **Optimisers, ML,… on demand**
- **Automation wave 3 (2021 -)**
  - → close the loop
  - **frameworks** (Generic Optimisation Framework (GeOFF), Machine Learning Platform)
  - **auto**-launch correction, **auto**-resets, **auto**-analysis
  - → auto-pilots

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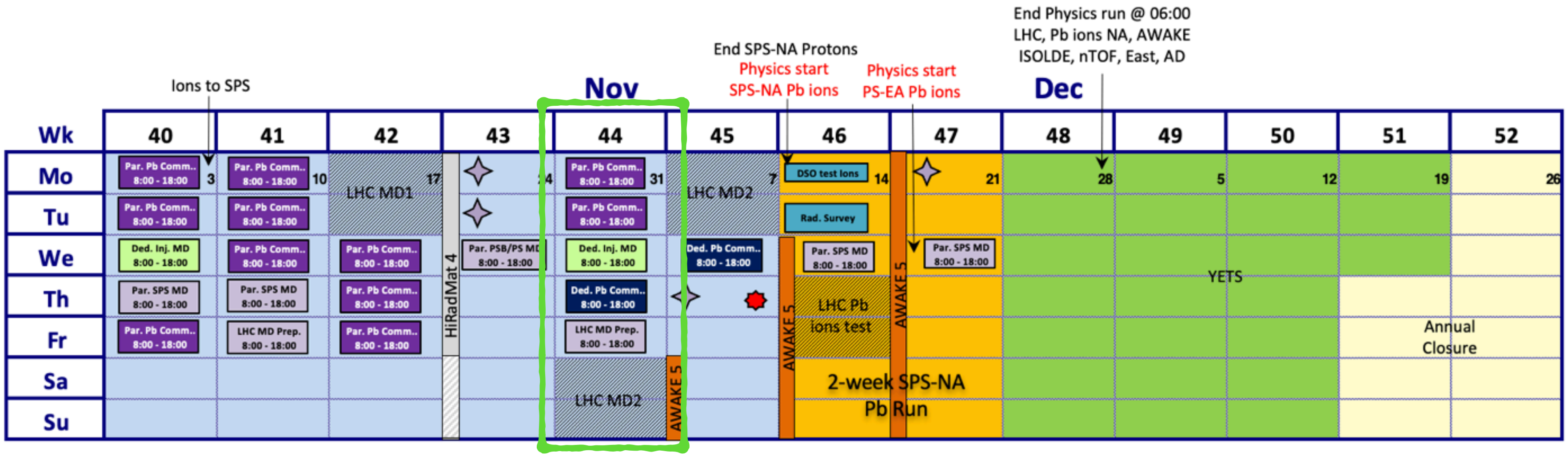
  - ✳ → auto-pilots

→ all building blocks available for autonomous accelerators

Automation: What should we aim for?

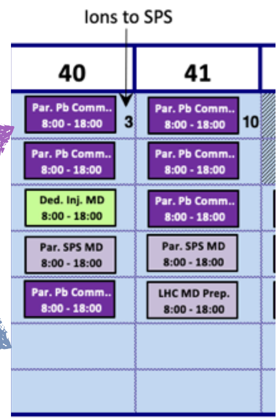
Consider different automation goals for different operational scenarios



★ **Standard Physics operation**

★ **Commissioning, recovery from stops, recovery from major breakdowns**

★ **Machine development, special beams**



Should we automate everything?

Input from **Automation mini workshop** (30/9/2022) at CERN

→ Autonomous (self-driving) accelerators are entirely possible for "routine operation" @ CERN

→ Do not focus on exotic and exceptional running modes (yet)

Which parts/functions can't be FULLY automatized?

- Recovery from events that latch interlocks
- Patrols (a recovery procedure)
- Special beam requirements, new cycles with special settings, …MD

Patrol Box

R. Alemany on the LEIR auto-pilot

Law of diminishing marginal returns

the more automated a process is, the less "return value" by adding more automation. Focus on the next problem

A. Calia on automation of the LHC

What should we aim for?

- **Standard physics operation**
  - ✳ **Aim for 100 % automation**
    - ❖ automatic resets/notifications
    - ❖ automatic timing sequence management + beam requests
    - ❖ contain drifts
  - ✳ Set of “standard" monitoring for all beams/cycles

→ max quality, stability
→ min turn-around

- **Commissioning, recovery from stops, recovery from major breakdowns**

- **Machine development, special beams**

What should we aim for?

- Standard physics operation

- Commissioning, recovery from stops, recovery from major breakdowns
  - Aim for automating all distributed system tests and repetitive tests, scans, parameter optimisation
    - Bach testing (e.g. acc-testing), optimisers, RL, model-based control,…
  - Make complicated measurements simple, repeatable, non-artisanal!
  - **Reduce commissioning time by 50 %**

- Machine development, special beams

→ speed up

→ guaranteed quality (e.g. optimisation for many DoF)

What should we aim for?

- **Standard physics operation**

- **Commissioning, recovery from stops, recovery from major breakdowns**

- **Machine development, special beams**
  - Aim for partial automation (inherited from above)
  - Attention on efficient preparation of “new” cycles: synergy with automation for commissioning;

→ more flexibility
→ less setup time

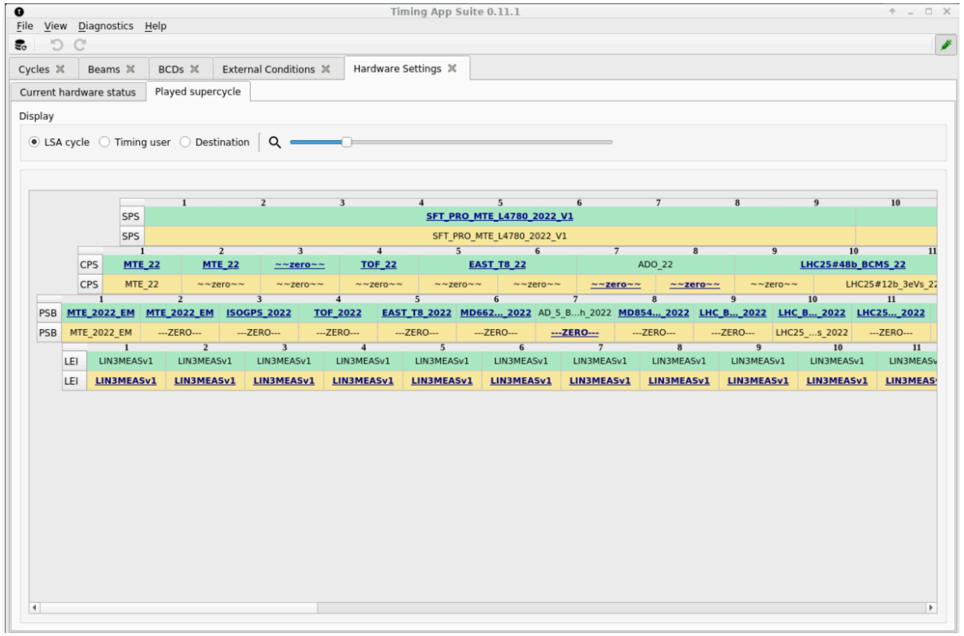
Standard physics operation - tasks

100 % automation?
→ Have solutions or PoC for (almost) all aspects.

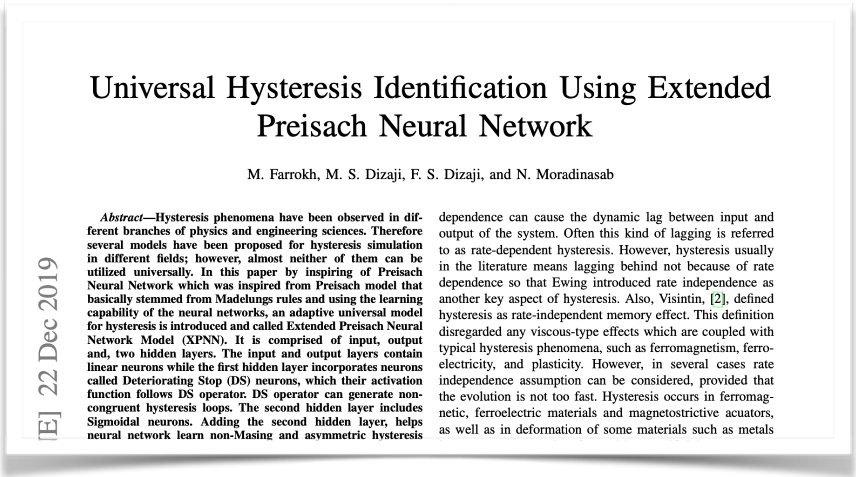
- Adapting **timing sequence** for different cycles to be played (e.g. LHC)
- **Containing drifts**
  - injection oscillations, orbit, injection phase, energy matching, steering to targets, MTE efficiency, stripper foil degradation, $n \times 50$ Hz content in slow extracted spill, RF splitting for LHC beams, ….
- Dealing with effects of **hysteresis** after dynamic economy or supercycle changes
- Dealing with effects of **stray fields**
- Dealing with **intensity dependent effects** and settings
  - tunes, damper, pickup saturation,…
- Dealing with **equipment trips** or states for certain beam conditions
- Launch/set up **on-demand measurements** of certain beam characteristics (e.g. wirescans)

Two game changers

On-the-fly beam requests and automatic cycle scheduling



Magnet modelling: hysteresis & Co



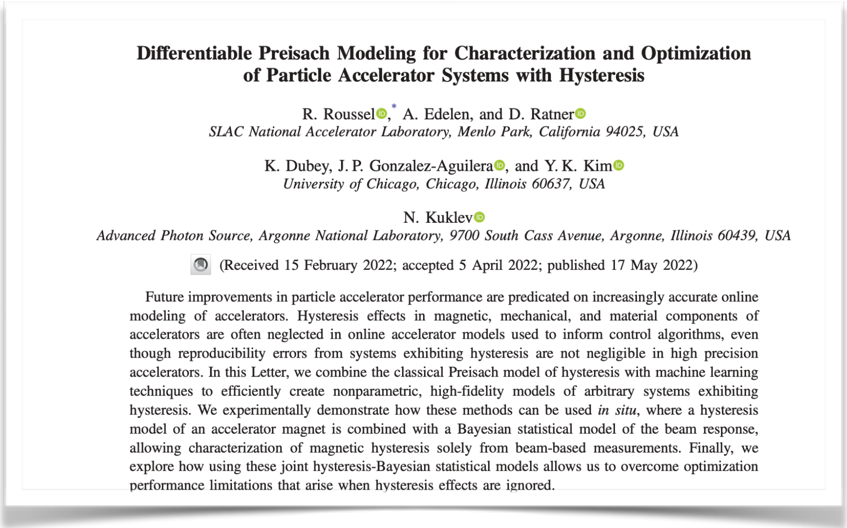
Universal Hysteresis Identification Using Extended Preisach Neural Network

M. Farrokh, M. S. Dizaji, F. S. Dizaji, and N. Moradinasab

[E] 22 Dec 2019

Abstract—Hysteresis phenomena have been observed in different branches of physics and engineering sciences. Therefore several models have been proposed for hysteresis simulation in different fields; however, almost neither of them can be utilized universally. In this paper by inspiring of Preisach Neural Network which was inspired from Preisach model that basically stemmed from Madelungs rules and using the learning capability of the neural networks, an adaptive universal model for hysteresis is introduced and called Extended Preisach Neural Network Model (XPNN). It is comprised of input, output and, two hidden layers. The input and output layers contain linear neurons while the first hidden layer incorporates neurons called Deteriorating Stop (DS) neurons, which their activation function follows DS operator. DS operator can generate non-congruent hysteresis loops. The second hidden layer includes Sigmoidal neurons. Adding the second hidden layer, helps neural network learn non-Masing and asymmetric hysteresis

dependence can cause the dynamic lag between input and output of the system. Often this kind of lagging is referred to as rate-dependent hysteresis. However, hysteresis usually in the literature means lagging behind not because of rate dependence so that Ewing introduced rate independence as another key aspect of hysteresis. Also, Visintin, [2], defined hysteresis as rate-independent memory effect. This definition disregarded any viscous-type effects which are coupled with typical hysteresis phenomena, such as ferromagnetism, ferro-electricity, and plasticity. However, in several cases rate independence assumption can be considered, provided that the evolution is not too fast. Hysteresis occurs in ferromagnetic, ferroelectric materials and magnetostrictive acuators, as well as in deformation of some materials such as metals



Differentiable Preisach Modeling for Characterization and Optimization of Particle Accelerator Systems with Hysteresis

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Future improvements in particle accelerator performance are predicated on increasingly accurate online modeling of accelerators. Hysteresis effects in magnetic, mechanical, and material components of accelerators are often neglected in online accelerator models used to inform control algorithms, even though reproducibility errors from systems exhibiting hysteresis are not negligible in high precision accelerators. In this Letter, we combine the classical Preisach model of hysteresis with machine learning techniques to efficiently create nonparametric, high-fidelity models of arbitrary systems exhibiting hysteresis. We experimentally demonstrate how these methods can be used *in situ*, where a hysteresis model of an accelerator magnet is combined with a Bayesian statistical model of the beam response, allowing characterization of magnetic hysteresis solely from beam-based measurements. Finally, we explore how using these joint hysteresis-Bayesian statistical models allows us to overcome optimization performance limitations that arise when hysteresis effects are ignored.

Kill n birds with one stone... (n>3)

→ Controll hysteresis and eddy currents

PoC for the entire control stack:

PhD between Data Sience section & magnet group

Also including sextupoles and octupoles

Start date 1/1/2023

BE-CSS PhD Project Proposal — Contacts: Verena Kain, Chris Roderick

High precision prediction and control of magnetic fields in synchrotrons

Introduction – motivation

Magnetic hysteresis, eddy currents, and imperfections during magnet manufacturing severely limit classical parameter modelling and settings generation to control today's multi-cycling accelerators. In particular, the dependence of the magnetic field on the cycling history cannot be addressed with our current control room tools and concepts. Various workarounds, such as pre-cycling or magnetic pre-functions, have been implemented to overcome these limitations - all of them are time-consuming, limit flexibility and are not generally applicable.

Main goal

The main goal is to leverage recent advances in computational techniques and machine learning (ML) to model and predict hysteric behaviour based on measurement data. In turn, computation of magnetic cycles can be made and applied in real-time, as supercycles are created, adjusting the magnet electrical supply to compensate for the hysteresis and other non-linearities of the equipment.

Potential benefits

- Improve the field reproducibility of accelerator magnets due to decoupling and modularising operation, improving overall beam performance.
- Increase accelerator physics time by eliminating the magnetic pre-functions employed at present.
- Establish a methodology for training ML magnetic field models and applying the results to accelerator operations.
- Gain understanding of how to decouple additional contributors (such as the power converter ripple and overshoot) in the best manner.
- Optimize for energy saving.

Other Ingredients

- For high energy/intensity machines: comprehensive independent interlock system
- **Automatic interlock analysis** and fault finding for all machines
- **All equipment** state **monitored** according to beam type and accelerator mode

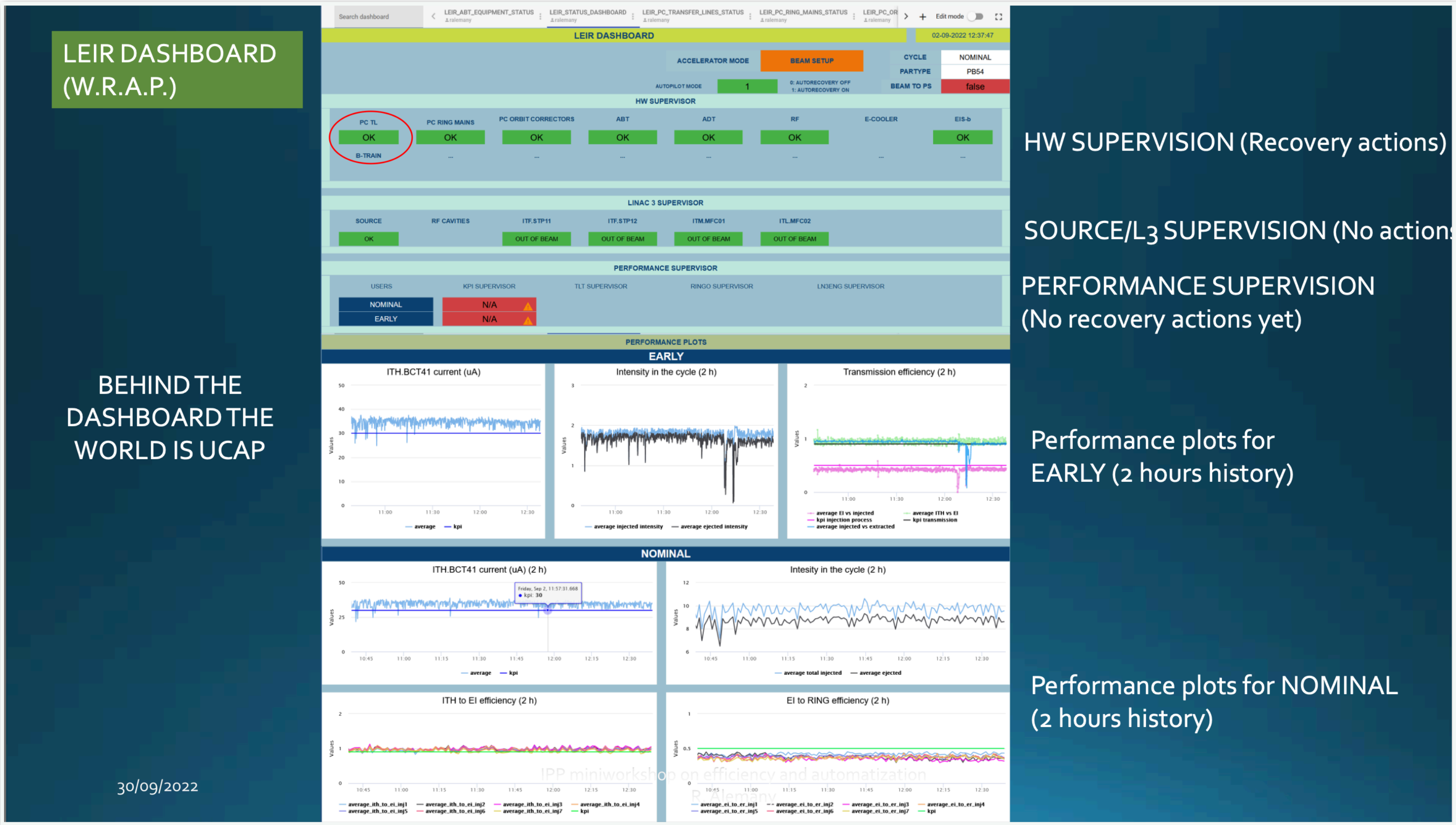
★ Auto-pilots

- **standardised auto-reset**
  - configuration, capture to logbook, define reset strategy (e.g. inform expert after 3 attempts)
- **automatic diagnostics** and analysis
  - instruments measure every cycle for all beams
  - analyse: denoising, computer vision, anomaly detection, forecasting,…
- **controllers on top of continuous diagnostics**
  - → GeOFF on servers: RL, ES, numerical optimisers

Example - LEIR auto-pilot

LEIR auto-pilot in the making

- monitors all equipment; recovery actions
- performance supervision: plan to launch correction algorithms, GeOFF;

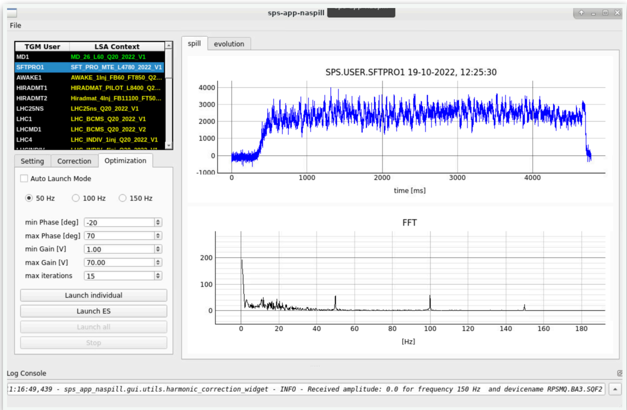


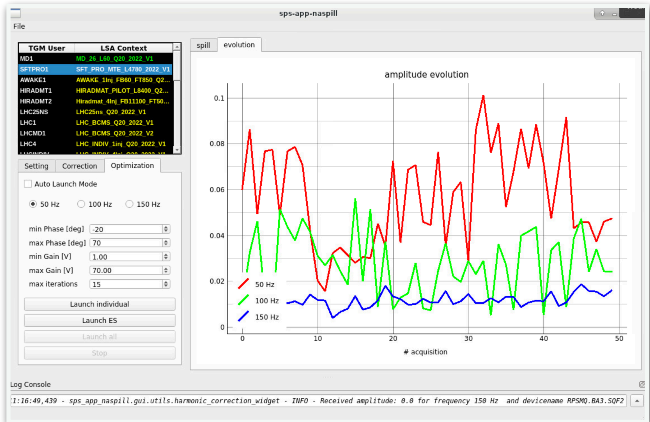
R. Alemany @ mini workshop on Automation

Examples: Containing drifts using GeOFF

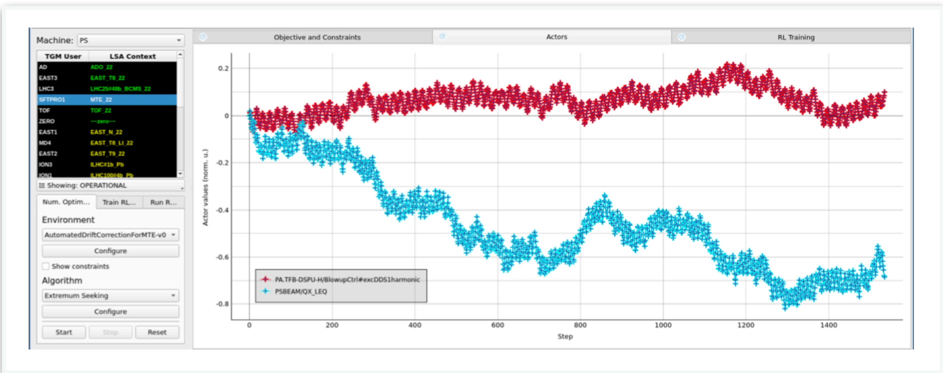
Containing $n \times 50$ **Hz ripple in SPS slow extracted spill**

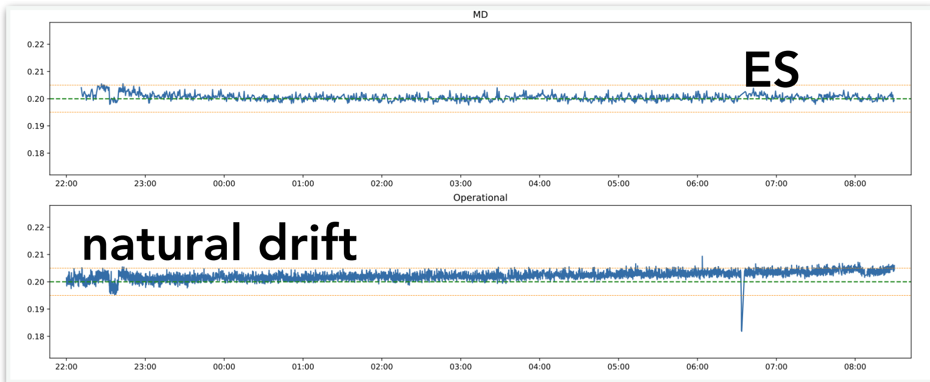
Tracks $n \times 50$ Hz amplitudes and stabilises: either with ES or automatically triggering BOBYQA





ES for **Multi-turn resonant fast extraction** efficiency stabilisation in the **PS** (work in progress)

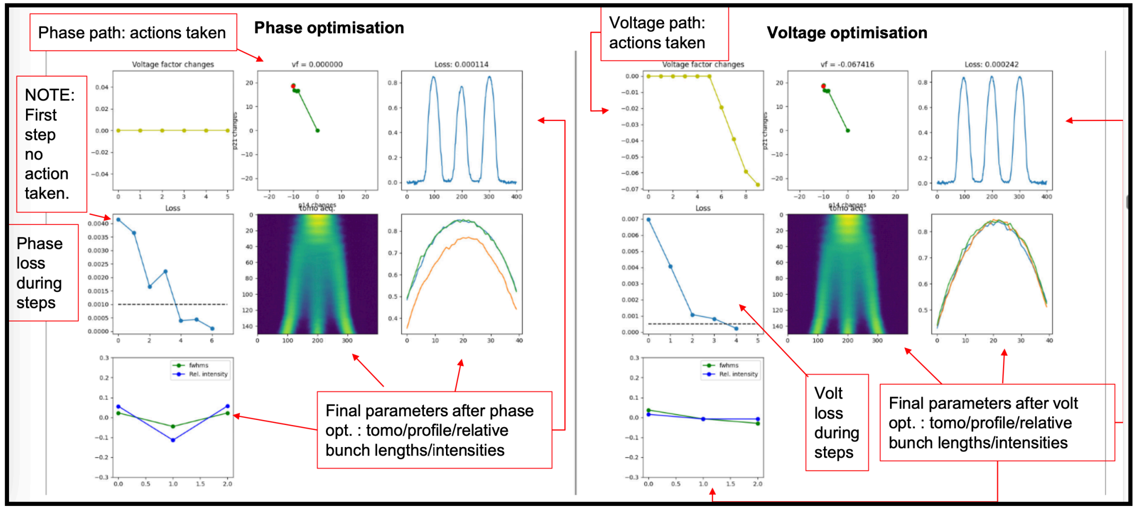


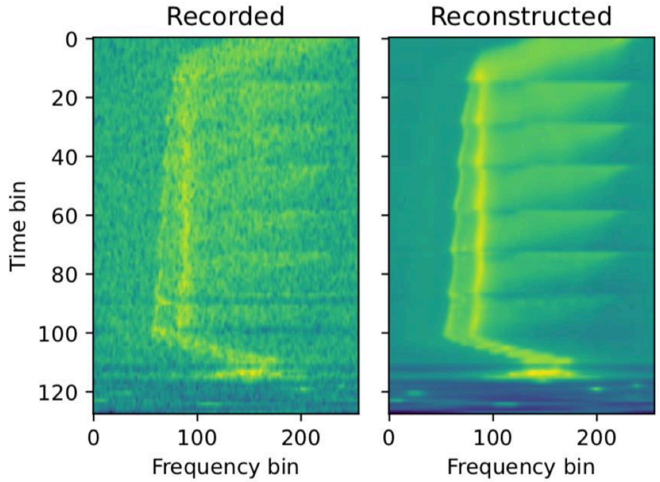


Examples: Containing drifts with ML and RL

RL agent to correct **RF phase and voltage** to produce uniform RF splitting in PS for LHC beams

- ★ Trained in simulation and successfully transferred to control room
- ★ RL algorithm: Soft Actor-Critic (SAC); multi-agent algorithm using CNN to define initial set point



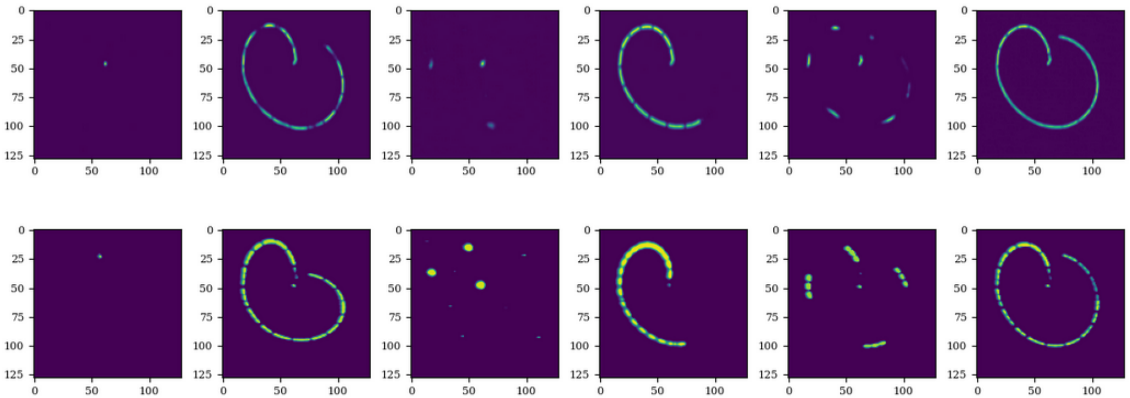


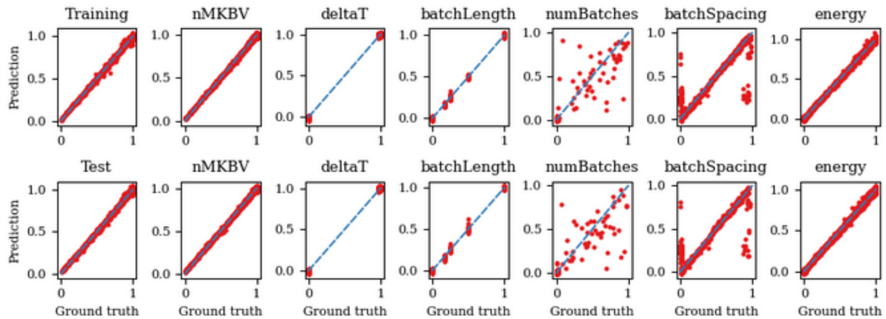
Other example: control r**amping and debunching cavity in LINAC3** for optimal injection efficiency into LEIR, based on **Schottky spectrum**

Containing drifts in a wider sense

Optimising uptime - predictive maintenance

- Example: classify dump kicker failures from the beam dump pattern images: SPS and LHC
- VAE model trained on simulations and applied on real data
- Extract physical information about the system from images through latent space





Logging system on hadoop cluster to be further exploited for prognostics

Ingredients: Commissioning

★ Automatic batch testing: with and without beam

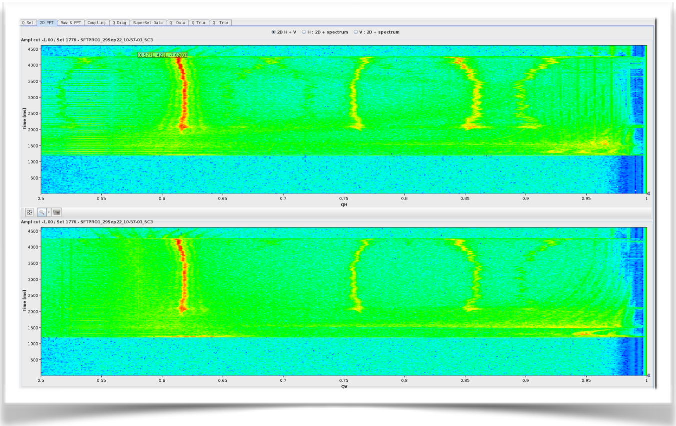
★ Optimisers/RL/model-based control for setting up

★ Consolidate beam instrumentation* → e.g. FIFO for BPMs

* might need big investment in R&D, material,…

★ Simplifications of measurements and correction by using models and ML

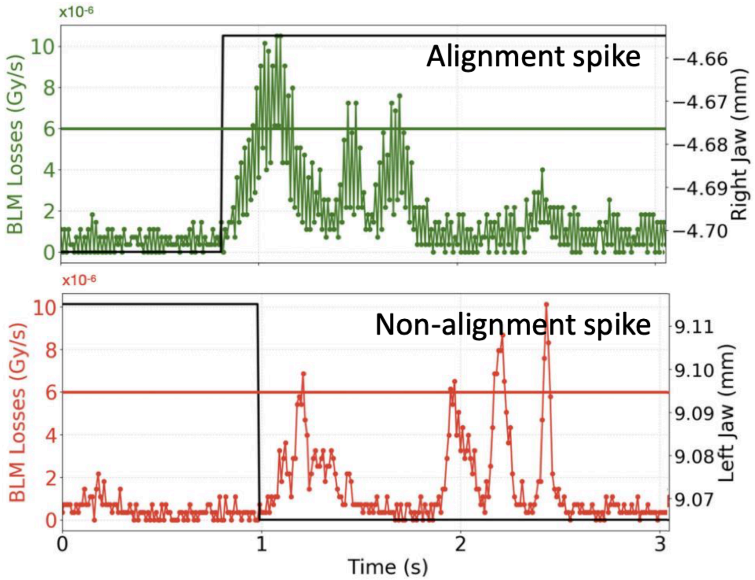
- Example: chromaticity measurement based on trimming parameter $\frac{dp}{p}$ and denoising algorithm for tune measurement

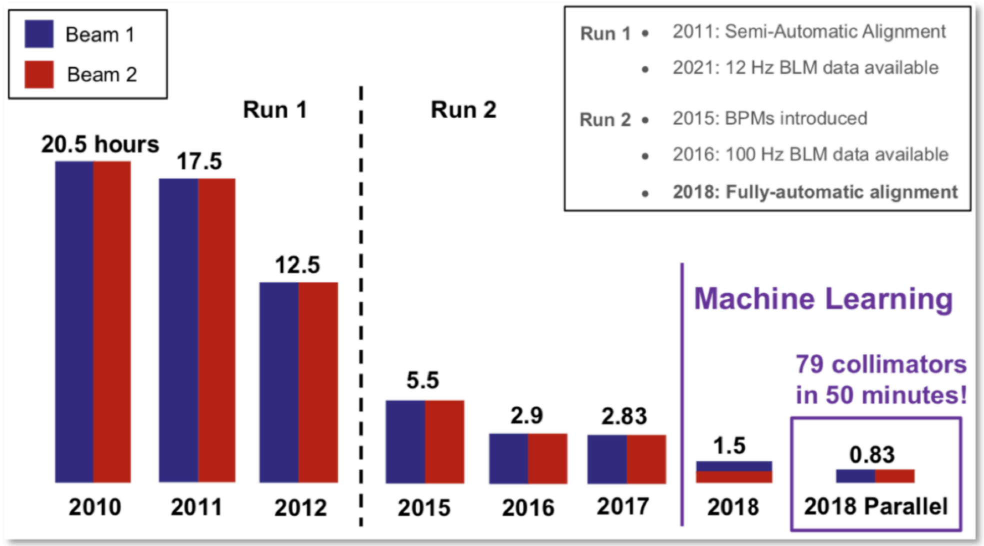


Examples: efficient commissioning

Numerical optimisation and ML used for many setting up tasks:

Alignment with beam for **LHC collimators**, electro-static septum (ZS) in the SPS, bent crystal for shadowing (ZS):

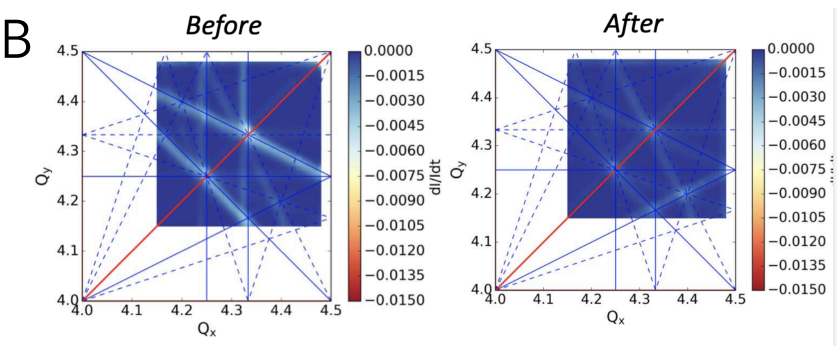




Optimisers with GeOFF:

Used for resonance compensation in PS & PSB loss reduction, transmission optimisation,…

> 20 problems across the complex

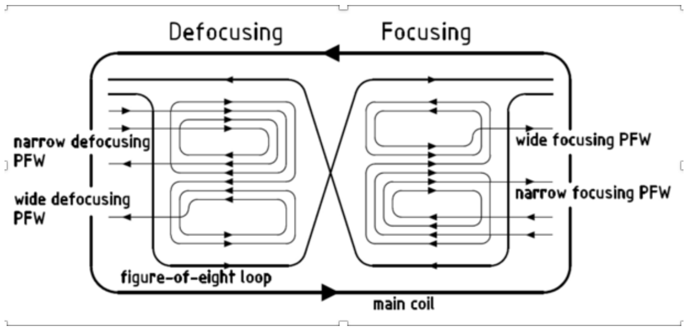


Examples: efficient commissioning

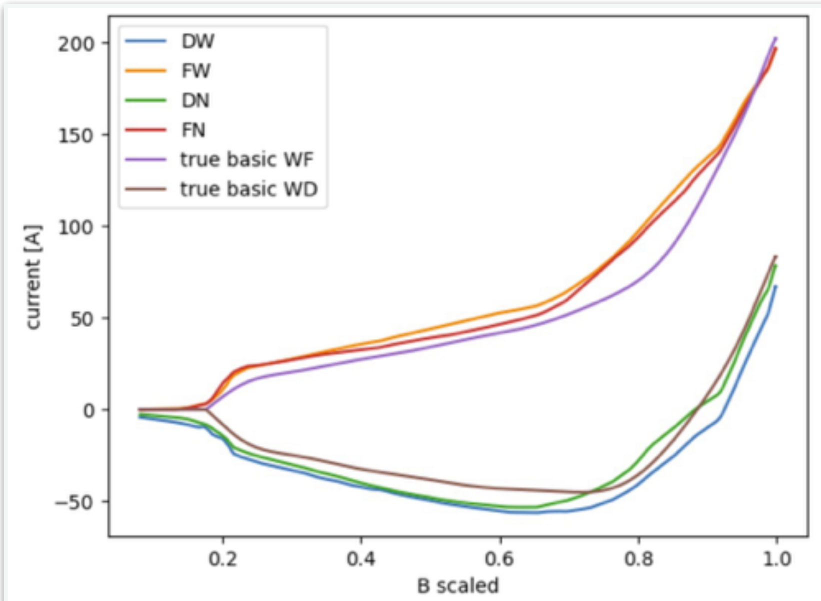
Learning models

Example: **Modelling "Pole Face Windings" control PS**

- Control for $\Delta Q_{h,v}$ and $\Delta Q'_{h,v}$ available from polynomial fits
- From data learn neural network F^* for "generation" of current functions for desired $Q_{h,v}$ and $Q'_{h,v}$ for given B function



$$F^* \begin{pmatrix} Q_x \\ Q_y \\ Q'_x \\ Q'_y \\ B \end{pmatrix} = \begin{pmatrix} I_{DN} \\ I_{FN} \\ I_{DW} \\ I_{FW} \\ I_{8L} \end{pmatrix}$$



When?

R. Alemany at the mini-workshop on Automation: “Give us time…"

When?

→ give us **priority** and we do it faster

- Data science section in Beams Department
- Energy crisis
- Efficiency think tank

→ **Goal:** Test **autonomous injectors + LHC for standard operation during 2025 run : 24 h test**

- use LS3 to consolidate and reach out to experimental facilities, ISOLDE, AD/ELENA

What's needed?

Intermediate milestones (preliminary):

- **LEIR auto-pilot** consolidate in 2023 and **establish what to be generalised** for other machines
  - includes GeOFF on servers (UCAP)
- Make sure **every equipment state is monitored** by end of 2023
  - auto-resets by end of 2024
- **Quality monitoring and control** - decide how by end of 2023
  - Examples: YASP-like auto-pilots for injection oscillations all machines, energy error, Injection phase
- **Batch testing**: first examples after next winter stop
  - Define common strategy during 2023
- Simplify and automate complicated measurements in 2023
- First ideas of **hysteresis compensation tech stack 2023**
  - guinea pig: MBs and MQs in the SPS
- By end of winter stop 2024: **sequencer** for preparing for access, mode changes, hardware commissioning tests

Conclusion

- **Efficient accelerator operation one of new key themes** at CERN
  - energy and resource efficient
  - efficient and flexible operation

- **Data Science section** in the Beams department for AI/ML solutions for efficient beam operation
- **"Efficiency Think Tank"** was put in place to define priorities by end of Q1 2023
  - Need to define priorities, timeline and quantify potential benefit
- (More) **autonomous accelerator operation** has already been identified as **clear priority**
  - Standard physics operation should become 100 % autonomous
  - Commissioning time reduced by 50 %

- CERN controls infrastructure and frameworks are (almost all) mature enough to implement autonomous accelerator operation