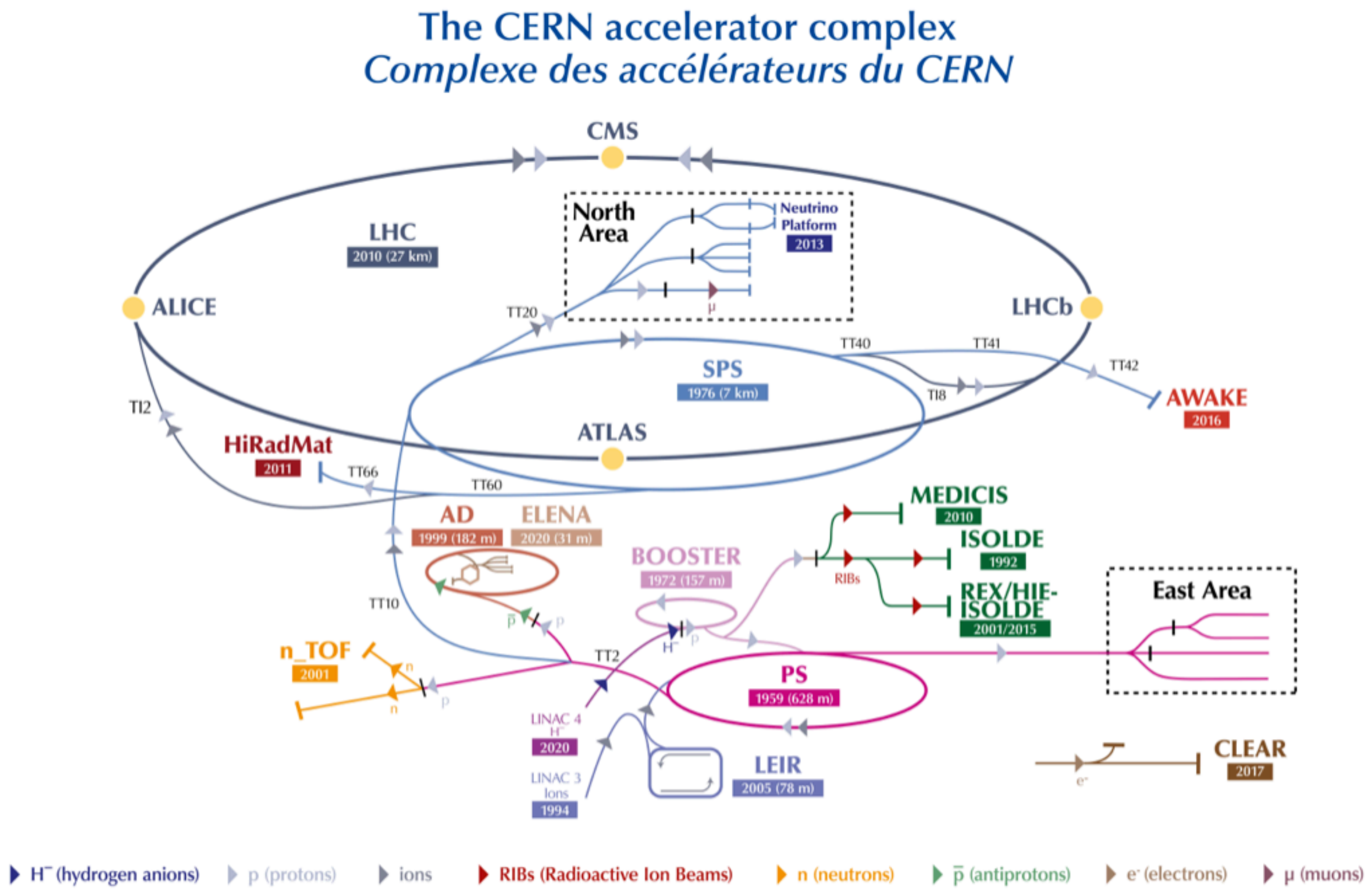
Efficient Particle Accelerators (EPA) Project

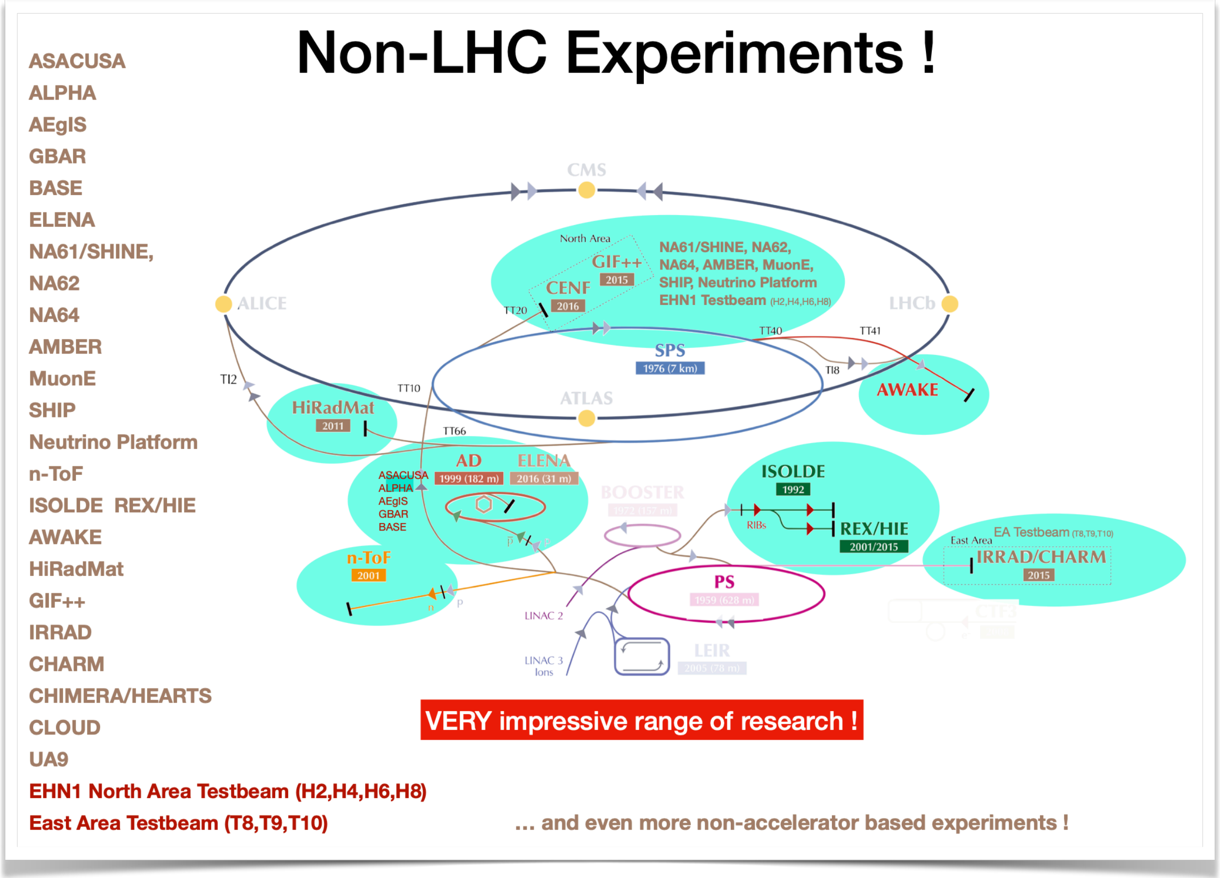
EPA core: V. Kain, A. Calia, L. Felsberger, J.C. Garnier, R. Gorbonosov, M. Hostettler, A. Huschauer, F. Irannejad, D. Jacquet, K. Papastergiou, C. Petrone, M. Schenk, M. Sobieszek, G. Trad, F. Velotti

The CERN accelerator complex



LHC and non-LHC physics

Not only LHC physics! → Many different beam types, production schemes,…



Screenshot from recent Chamonix CERN Accelerator Performance workshop Jan '24

Flexibility comes at a prize. Examples...

Summary talk IEF’21

2. Address reproducibility and availability

- Availability OK, under control of Groups. **Reproducibility** is critical concern with increasing flexibility and multi-destination operation
- Transmission problems and instability in beam delivery in many locations. “Need more time in 2022”→have to ensure this is there (add in schedule?) #A
- Addressing reproducibility relies on many factors including equipment, accelerator modelling and high-level controls approach

Other input from IEF'21

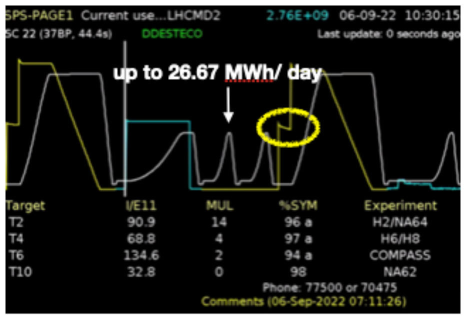
→ Current **beam scheduling** has severe impact on resources needed to run accelerators and on efficiency

- ✳ Statistics: 20-100 clicks to change supercycle = 2-25 min; 40-60 times/24 h

Input from JAPW’22

→ **Hysteresis** is severe limitation for efficiency and flexibility in most machines, current mitigation methods wasting energy

- ✳ ~ 15 % of yearly cost of SPS fixed target cycle for “waste" cycles and quasi-degauss Cycle MD1



Efficiency Think Tank (ETT): Oct ’22 - Mar ‘23

ETT = Body for brainstorming for strategy definition for more efficient CERN accelerator exploitation

Response to IEF’21 concerns with efficiency and reproducibility

- large extended team for community discussions, small core team to synthesise directions

Wide range of efficiency topics touched

- shorter turn-around, more flexibility, energy efficiency,…

Key target areas identified

- 7 high priority recommendations
- Exhaustive lists per machine for potential improvements

Prepared terrain for implementation

- First proposal for resources and timelines for high-priority recommendations
- Post-ETT: defined follow-up project: Efficient Particle Accelerators (EPA) project

ETT conclusion in summary

ETT showed that

reproducibility, energy saving, efficiency, flexibility can be significantly improved by

- **Automating accelerator/experimental facility operation**
  - Immediate benefit, lowest upfront investment, very mature already → lowest hanging fruit, highest priority
- **Improving and automating equipment**
  - Less mature concepts, potentially expensive, longer term → high potential impact, high priority

Cultural aspects:

- Promote Awareness → synergy with RAWG
- Ensure simultaneous evolution across similar equipment/teams
- Sharing and common development - profiting from work already done (CTTB approach)

7 recommendations

CERN
Esplanade des Particules 1
P.O. Box
1211 Geneva 23 Switzerland

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2922514	1.0	RELEASED

REFERENCE
2922514

Date: July 28, 2023

PROJECT REPORT

Efficiency Think Tank Report

1. **Hysteresis compensation**
2. **Automatic and dynamic beam scheduling**
3. **Automatic LHC filling**
4. **Auto-pilots**
5. **Automatic fault analysis, recovery and prevention**
6. **Automatic testing and sequencing**
7. **Automatic parameter optimisation**

Reported in IEFC 1/9/2023, IPP 2/6/2023

Future accelerators? Like FCC...

The ***business-as-usual*** solution: FCC just larger LHC

- Brute force scale-up → using helicopters to reduce intervention times, more people, more sites,...
- (Financially excluded, luckily)

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The ***elegant*** solution: FCC to be run like a space telescope.

- Reinvent exploitation paradigm: hierarchical autonomous systems
- AI is key technology
- Management's preferred option

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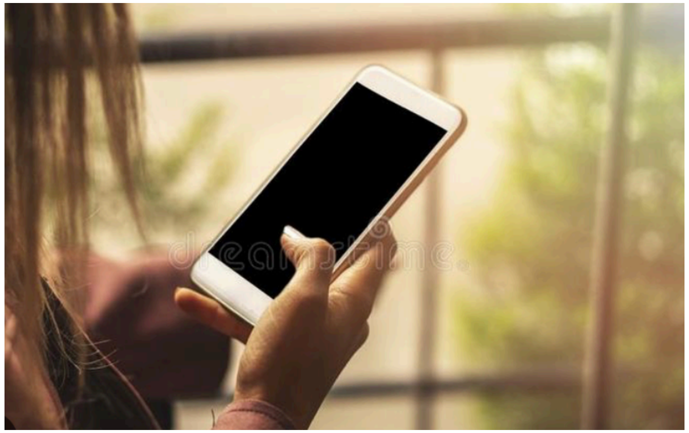
- Management's preferred option

Need to use the next 10 years as test bed to be ready with adequate design choices

The (obvious) new equipment paradigm



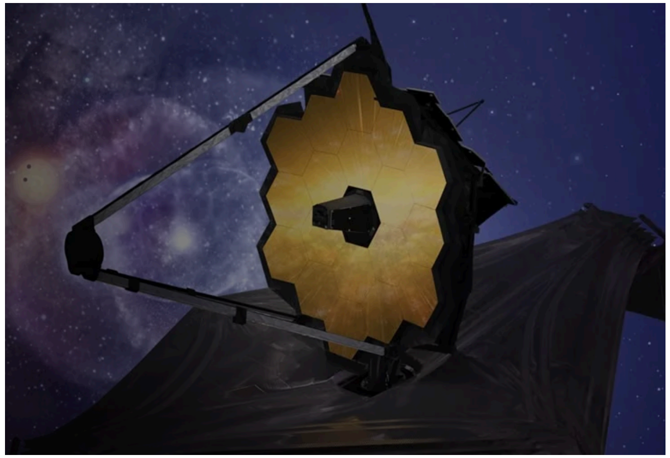
Think banking apps, heating systems,….
All digital, all remote controllable/ analysable

Simulations will be key.
Fast-executing, differentiable.
Digital twins…

Exploit **automation** at every level.

Automation across systems.
Automation within given system.
→ different players to implement automation

All equipment designed with automation in mind:
auto-configure, auto-stabilize, auto-analyse, auto-recover,…



You cannot go there to fix it…
Redundancy, robotics,…

ATSMB launch of Efficient Particle Accelerators (EPA) Project

In October 2023, with mandate to:

- drive implementation of ETT recommendations for Injectors and LHC (p+ and ions)
- create efficiency culture and track improvements with **KPIs**
- identify synergies within ATS and possible collaborations and reduce duplication
- provide meeting place and discussion forum to ensure common approach
- define efficiency roadmap for other facilities (NA, EA, ISOLDE, AD, …) during LS3
- prepare grounds for future exploitation model and evaluate potentials for FCC

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Ambitious in scope!

7 ETT recommendations = 9 EPA work packages

During project preparation identified necessity of controls infrastructure evolution.

Each WP is high-level deliverable.

Project Lead and Coordination: V. Kain
Deputy: A. Huschauer

WP1 Dynamic Beam Scheduling Lead: F. Irannejad	WP2 Automatic LHC Filling Lead: A. Huschauer, G. Trad	WP3 Automatic Parameter Control & Optimisation Lead: M. Schenk
WP4 Hysteresis Compensation Lead: C. Petrone	WP5 Next Generation Sequencer Lead: R. Gorbonosov	WP6 Efficient Settings Management Lead: M. Hostettler
WP7 Automated Equipment Testing Lead: A. Calia, J.C. Garnier	WP8 Automate Equipment Lead: F. Velotti, K. Papastergiou	WP9 Data Processing Framework Lead: M. Sobieszek

Goals

Focus is on automation → increase efficiency, reproducibility, flexibility and margins for Operation

WP1 Dynamic Beam Scheduling:

- Remove fixed supercycle concept; algorithmically and dynamically schedule beams

WP2 Automatic LHC Filling:

- Automate and standardise LHC beam preparation and filling; reduce LHC turn-around time to theoretical value

WP3 Automatic Parameter Control and Optimisation:

- Automate parameter optimisation, automatically contain drifts

WP4 Hysteresis Compensation:

- Deterministic field control, decouple cycles

WP7 Automatic Equipment Testing:

- AccTesting for “all" equipment for injectors and LHC, fully automated HWC and ISTs

WP8 Automate Equipment:

- Automatic equipment setup; automate fault analysis, recovery; input/framework for preventive maintenance

Proposed governance

Core team: WP leaders and L. Felsberger (RAWG), D. Jacquet (SMWG)

- Meet ~ bi-weekly
- EPA indico: https://indico.cern.ch/category/17316/
- Track progress: https://its.cern.ch/jira/projects/EPA/summary

Extended team: equipment and controls experts, machine specialists, EiCs

- Collect feedback max. once per month

EPA to report to CTTB

- Communicate evolution of KPIs to IEFC and LMC
- EPA will define equipment "guidelines". Need CTTB to endorse and push

Timeline

Time bounded project: improvements ready for Run 4

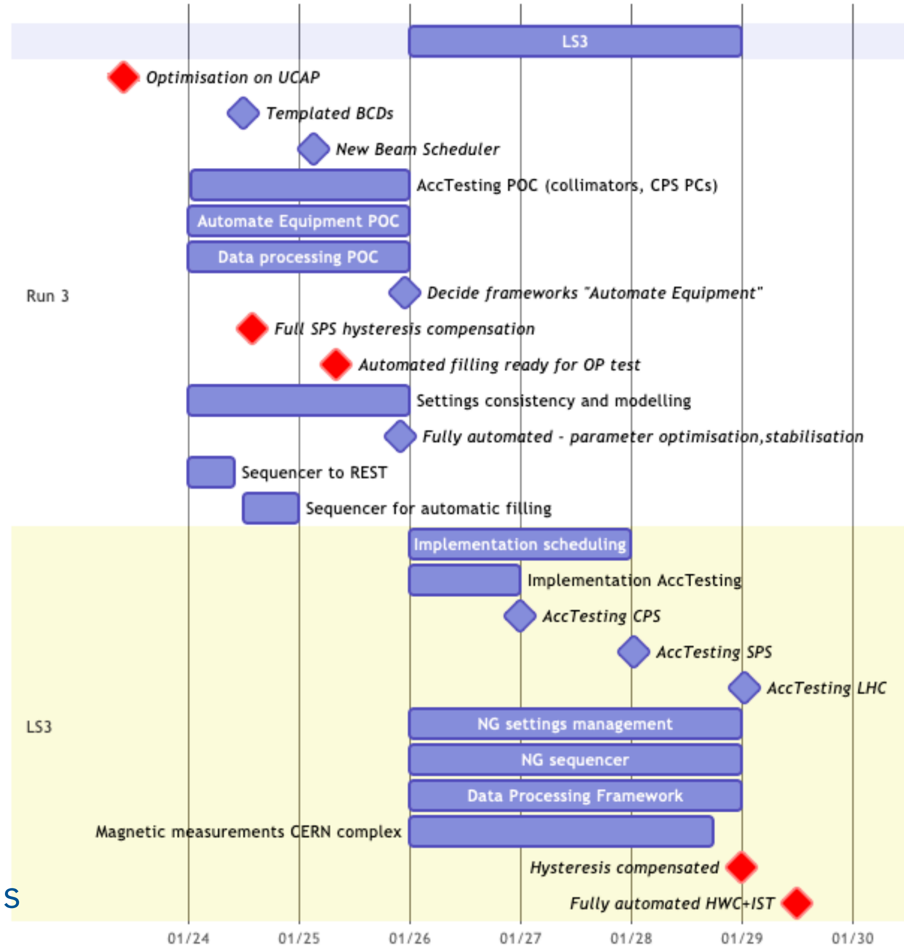
- ✳ Only 50 % of budget allocated during MTP exercise '24

Project has 2 phases:

- ◉ Prototyping and first operational tests in Run 3
  - ✳ To reach milestones: **important to start YETS 23-24**
- ◉ Full implementation during LS3

Propose budget and resource review end 2025.

- ◉ Decision on solutions/options only after study
- ◉ i.e. for **WP1** (Dynamic Beam Scheduling), **WP4** (Hysteresis compensation), **WP8** (Automate Equipment)



Resources: GRAD, TECH

- Investment was needed NOW, to gain in efficiency in medium term (2-5 years).
- Experts and Teams already occupied with Exploitation, Projects and Studies, but all recognise the urgent need for efficiency improvements.
- Only feasible approach: **Graduates**, supervised by expert Staff, with a core team coordinating and providing the central solutions.
  - Nota: no new DOCT foreseen (initially), since essentially implementation.
- Original proposal

	2024		2025		2026		2027		2028	
	TECH	GRAD	TECH	GRAD	TECH	GRAD	TECH	GRAD	TECH	GRAD
head count	4	8	3	12	2	15	2	12	2	9
kCHF	168	840	126	1224	84	1539	84	1224	84	945
total kCHF	**1008**		**1350**		**1623**		**1308**		**1029**	

- 50 % of budget agreed → change of spending profile to spend initially as planned
  - …and reduce in scope later

Resources: Material

Original proposal…

- **WP4** (Hysteresis Compensation) and **8** (Automate Equipment) will require new equipment to be designed/installed.
- EPA needs to foresee deblocking shortage of GPUs in ATS for training and inference of AI solutions
  - Required for **WP3** (Automatic Parameter Control and Optimisation), **4** (Hysteresis Compensation), **8** (Automate Equipment), **9** (Data Processing Framework)

		2024	2025	2026	2027	2028
Tech workshops	[kCHF]	20	20	20	20	20
GPUs	[kCHF]		100	100	50	50
Measurement probes	[kCHF]		30			
IoTs, integration, etc	[kCHF]	10	60	50		
Total	[kCHF]	**30**	**210**	**170**	**70**	**70**

What to be expected from EPA before LS3?

Automation Infrastructure - readiness

Many classical automation concepts came from the LHC → injectors

- Sequencer, high level parameter control
- **EPA WP5 (Next Generation Sequencer) & WP6 (Efficient Settings Management) to ensure evolution for new requirements**

Automation Infrastructure - readiness

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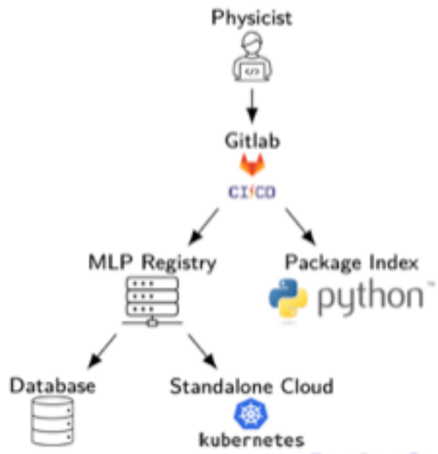
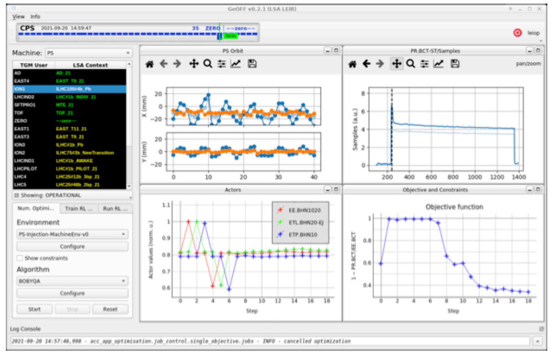
Since LHC: preparing for **automation including AI/ML** - injectors on forefront

- **Acc-Py** (Accelerating Python): unlocked the potential of Python in CERN ATS including control rooms
  - Python distribution, Python Package Index, release of applications to centrally managed deployment location
- **UCAP:** Unified Controls Acquisition and Processing ("Virtual Device Service") → servers on-the-fly in JAVA or Python
  - Provides infrastructure to run "transformations" and event building
  - Expect **evolution with EPA WP9** (Data Processing Framework)
- **MLP** (Machine Learning Platform): store and share AI models between users and applications of different languages

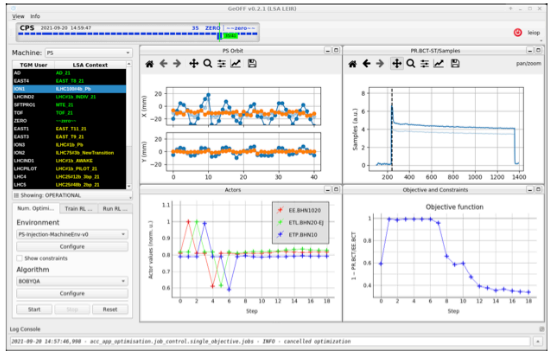


Automation Infrastructure - readiness



- **Generic Optimisation Framework GeOFF**
  - Manual scans and grid scans are inefficient for multi-parameter problems → optimisation algorithms
  - GeOFF = easy and flexible parameter optimisation in the control room
  - To date: > 20 parameter optimisation problems automated across complex

Automation Infrastructure - readiness



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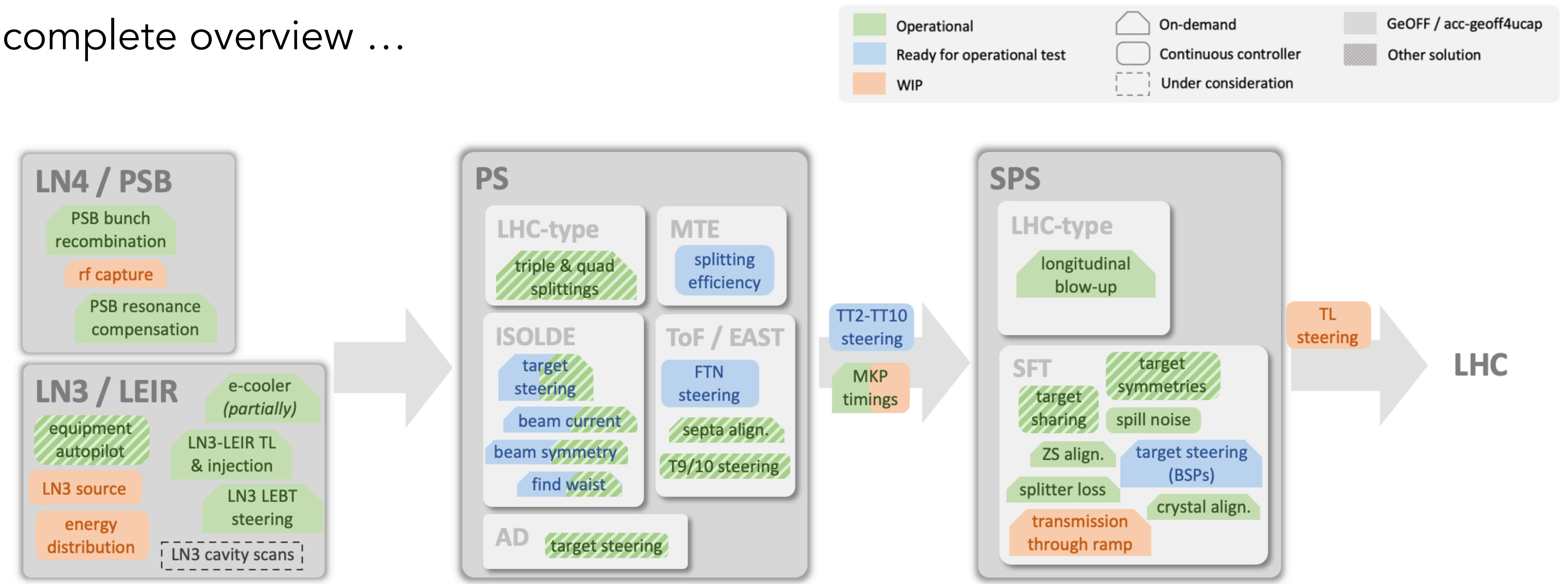
- **Optimisation framework for auto-pilots**
  - GeOFF on UCAP → acc-geoff4ucap
  - Also available: **GPUs on UCAP** for e.g. Adaptive Bayesian Optimisation (ABO)
  - **EPA WP3** (Automated Parameter Control & Optimisation) **in 2024:**
    - automated PS2SPS steering, LINAC3 source control, NA TT20 steering,…
    - MTE efficiency drift stabilisation

WP3 - Auto-pilots, optimisers,...

An incomplete overview …



Courtesy M. Schenk

Status: multiple new auto-pilots / optimisers under development - many used operationally

Trends 2024: on-demand → continuous (UCAP)

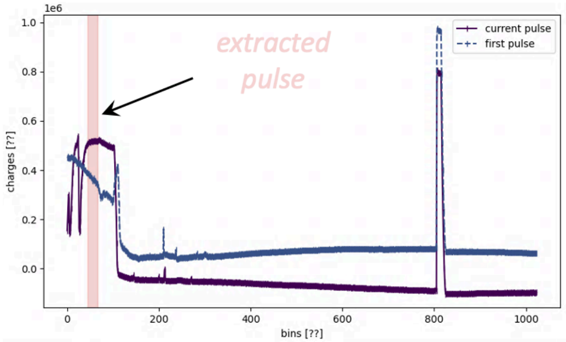
Until end of run 3: automation of all typical optimisation and continuous control problems

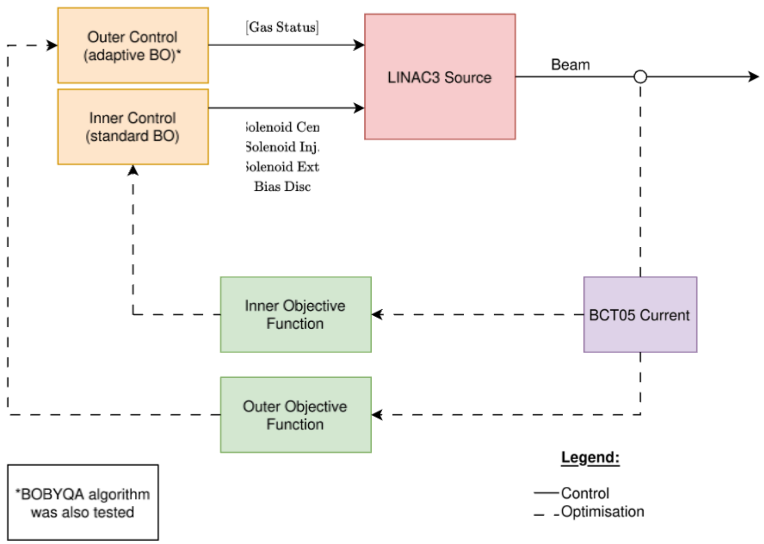
Recent example: LINAC3 source control

Results from tests in December ’24

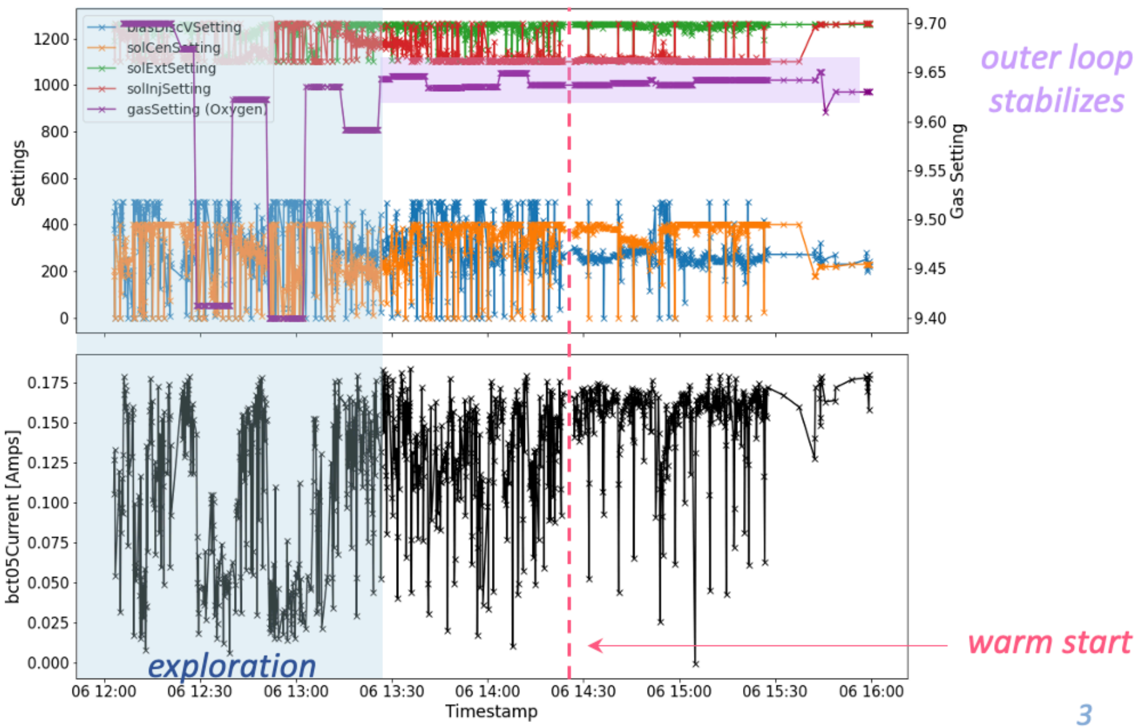
Complex setup with hierarchical controller → nested control loop

Adaptive Bayesian Optimisation as continuous control



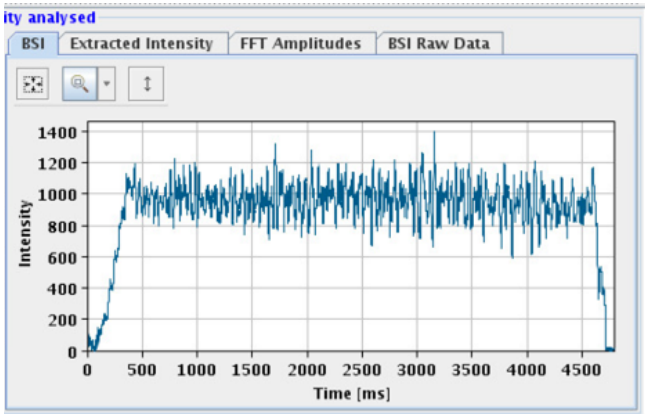


Outer loop with adaptive BO



Another example: SPS mains noise

50 Hz noise on slow extracted spill



Running 24/7 on UCAP with GPU

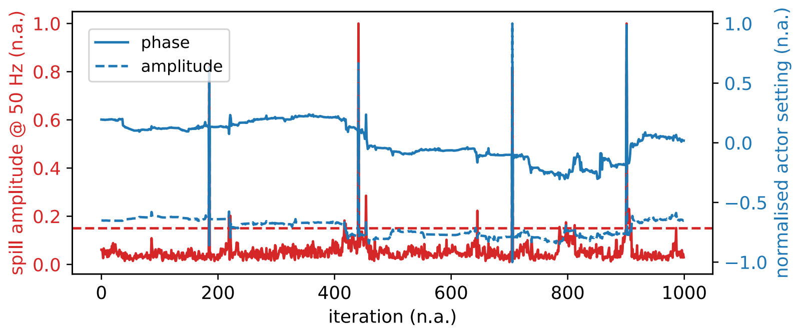
Modulate voltage of main quadrupoles at $\mathbf{n} \times \mathbf{50}$ Hz to compensate.

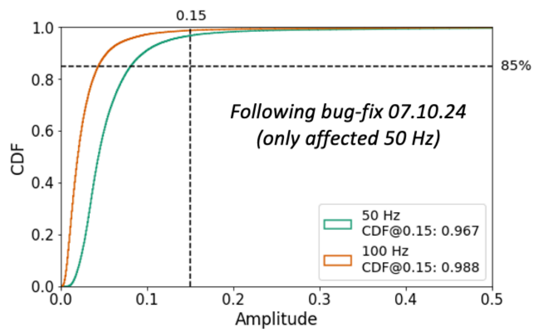
However, spill noise changes over time following the European grid.

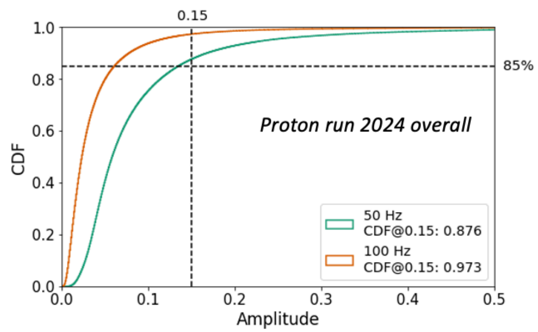
→ adaptive continuous control, **A**daptive **B**ayesian **O**ptimisation

Model objective function f as $f(\mathbf{x}, t)$. Spectral mixture kernel S for t and Matern for control parameters

Kernel: $k([t_1, \mathbf{x_1}], [t_2, \mathbf{x_2}]) = \theta_k \times S(t_1, t_2) \times M(\mathbf{x_1}, \mathbf{x_2})$

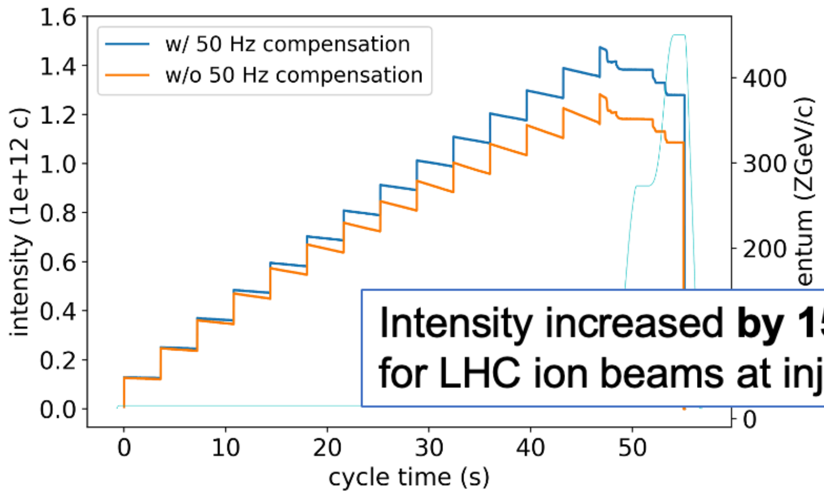






Another example: SPS mains noise

During the ion run used 50 Hz correction on LHC beams in 2024.



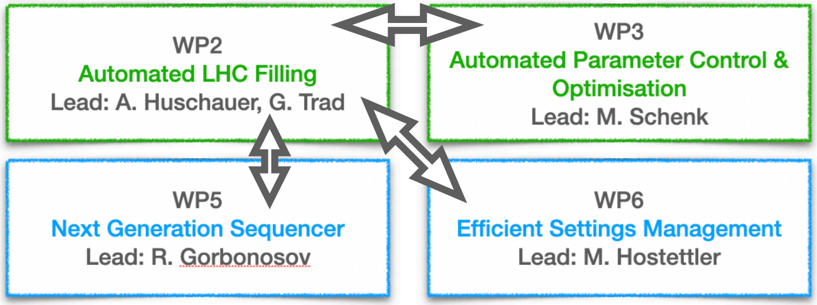
Intensity increased **by 15-20%** for LHC ion beams at injection

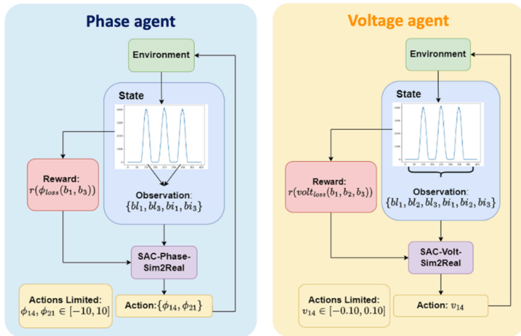
Montoring directly QF/QD DCCT ripple.

WP2 - Automated LHC filling

Key is **automating LHC beam preparation**

- requires next generation sequencer
- improved longitudinal beam observation
- various auto-pilots



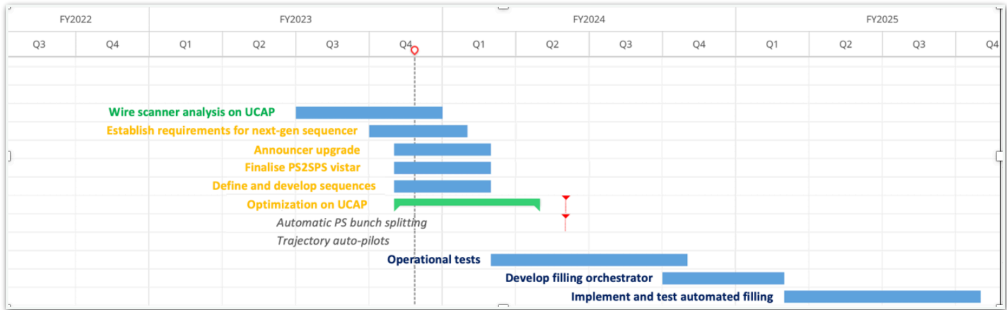


→ 2024: existing PS tripple splitting RL agents to UCAP

→ 2024: new approach for PS double splitting

Automation plans for 2025:

- Trajectory auto-pilots
- Automatic PS bunch splitting optimisatior
- Semi-automated sequencing of tasks using existing tools



Semi-automated filling tests: **2025**

Fully automated filling tests: **2026**

WP4 - Hysteresis Compensation

Goal: generic way of feedforward correction of field changes by predicting hysteresis and eddy current effects with AI

Pilot during run 3 for SPS main dipoles and quadrupoles, sextupoles and octupoles

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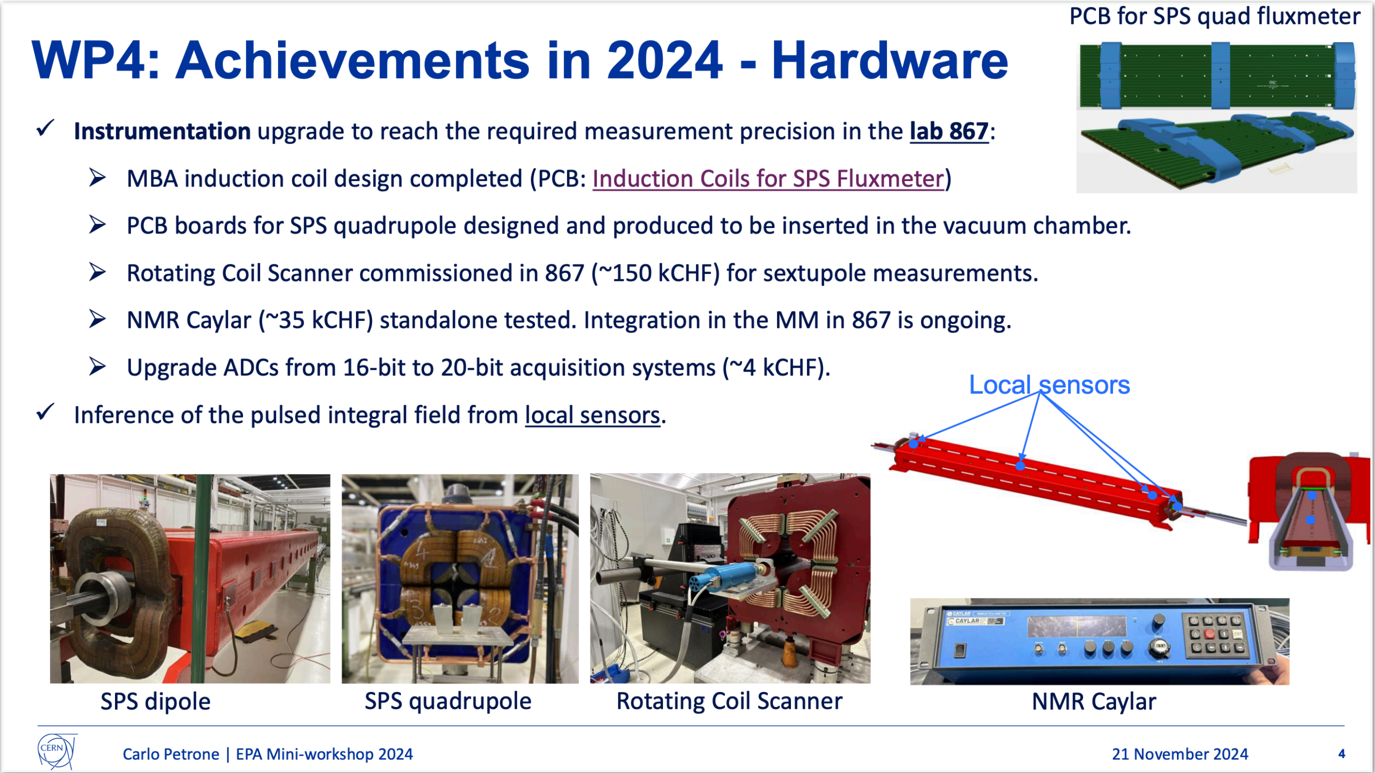
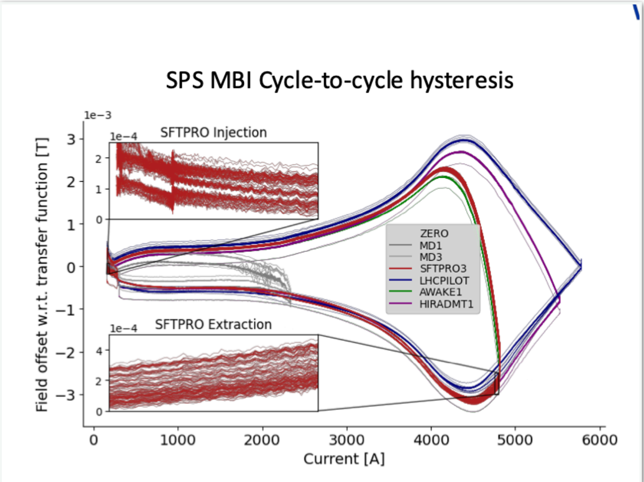


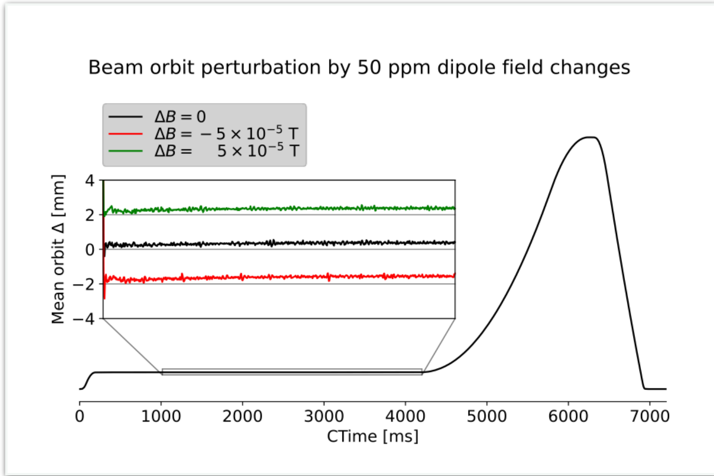
WP4 - Hysteresis Compensation

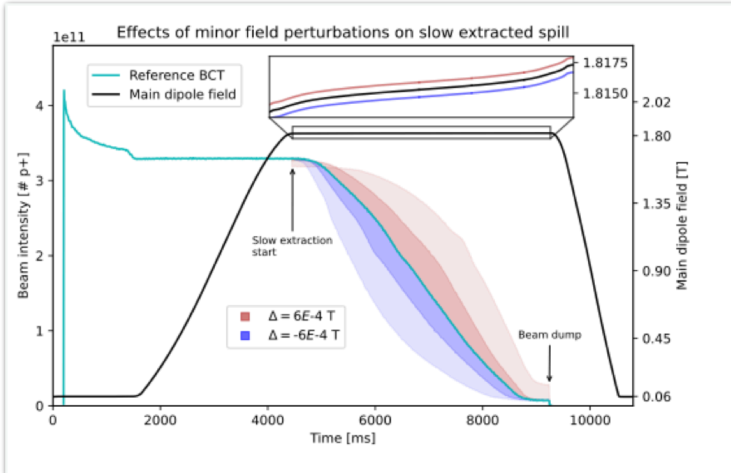
Goal: generic way of feedforward correction of field changes by predicting hysteresis and eddy current effects with AI

Pilot during run 3 for SPS main dipoles and quadrupoles, sextupoles and octupoles

Significant progress in 2024 for the SPS main dipoles (BTRAIN): hysteresis effects ± 1 permil, cycle-by-cycle field changes ± 100 ppm max → significant effect on beam







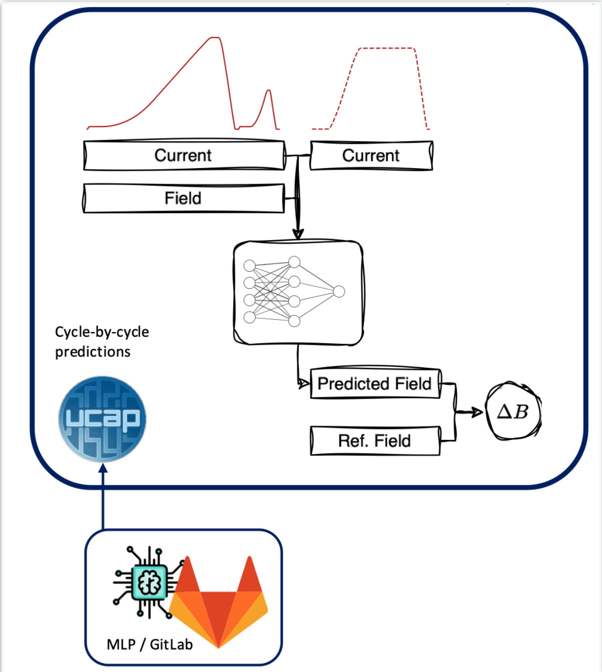
Courtesy Anton Lu

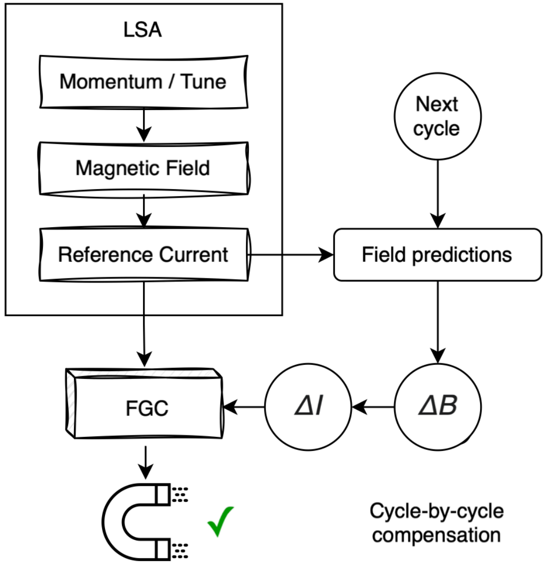
WP4 - Hysteresis Compensation

Goal: generic way of feedforward correction of field changes by predicting hysteresis and eddy current effects with AI

Pilot during run 3 for SPS main dipoles and quadrupoles, sextupoles and octupoles

The solution: Temporal Fusion Transformers ANNs trained on measured field





Courtesy A. Lu, V. Di Capua, C. Petrone

WP4 - Hysteresis Compensation

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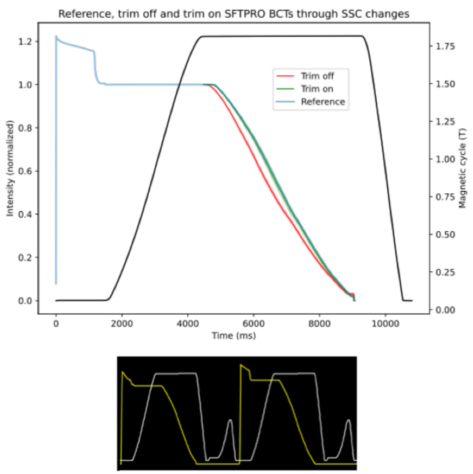
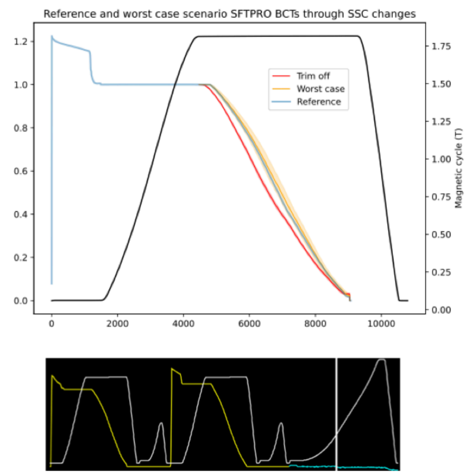
Pilot during run 3 for SPS main dipoles and quadrupoles, sextupoles and octupoles

Promising results:

Slow extraction slope can be stabilised independent of supercycle ($2 - 3 \times 10^{-4}$ T changes)



(Field compensation OFF)
FT + LHC → 2x FT



Field compensation ON – worst case

Courtesy Anton Lu

WP4 - Hysteresis Compensation

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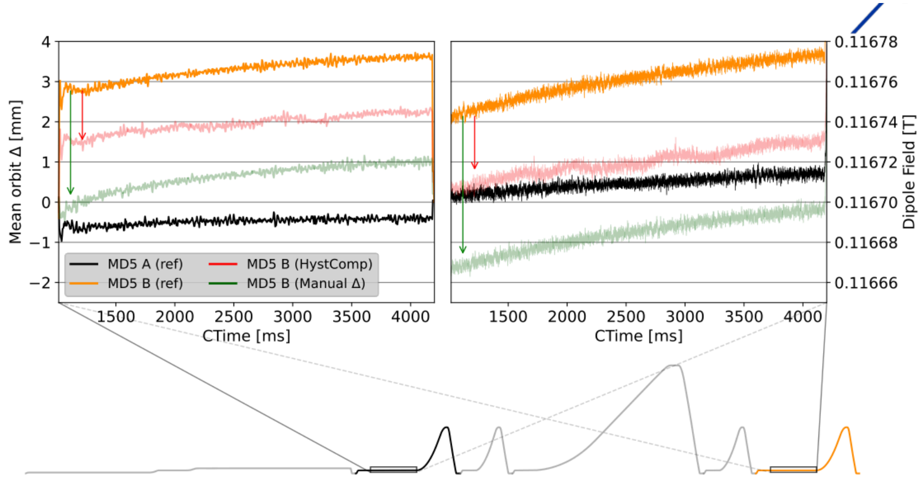
Pilot during run 3 for SPS main dipoles and quadrupoles, sextupoles and octupoles

Status: field prediction satisfies the required accuracy of 10 ppm, but BTRAIN data does not include all dynamic effects. Needs to be learned based on beam data.

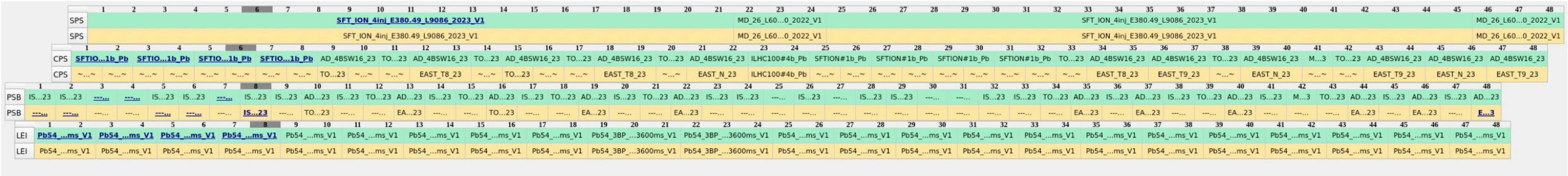
Next: full "eddy current compensation", quadrupoles, sextupoles, octupoles and other machines.



Courtesy Anton Lu

WP1 - Dynamic Beam Scheduling

Beam scheduling = constrained scheduling problem across injectors



IEF'21 workshop analysis→ current **beam scheduling** has severe impact on resources needed to run accelerators and on efficiency

- ✳ Statistics: 20-100 clicks to change supercycle = 2-25 min; 40-60 times/24 h

Status 2024

- ◉ Prepared new scheduler application with template supercycles across complex
  - ✳ Allows to integrate different types of alogrithms. I.e. OR tools constraint programming,…

Plans 2025

- ◉ No supercycles programmed anymore, beams to be scheduled by scheduler

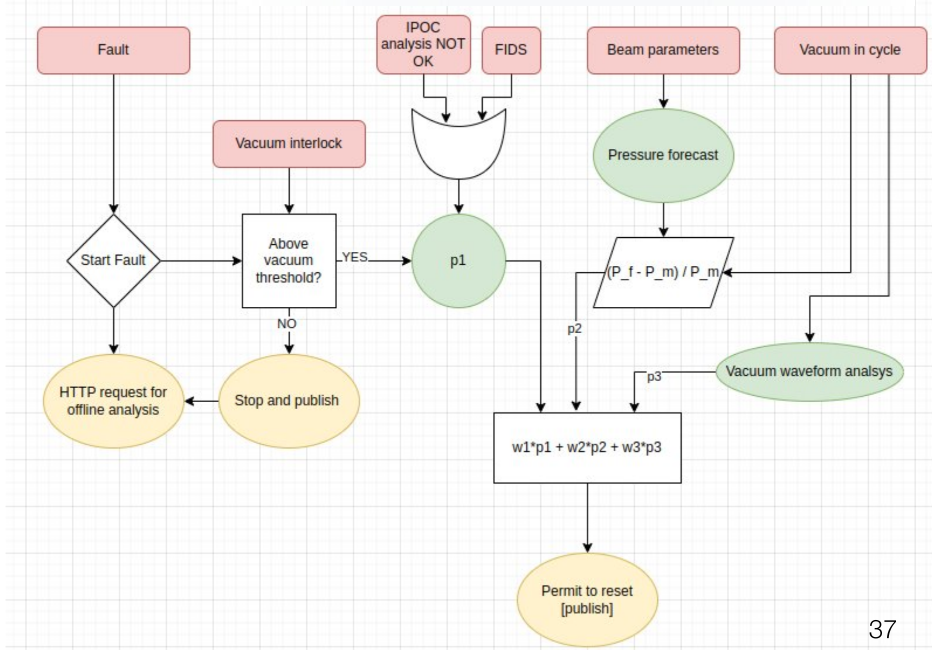
WP8 - Automate Equipment

Goal during run 3: **define new paradigm** of *smart* and *agile* equipment integration and exploitation

- → auto-configure, auto-analyse, auto-recover, → predictive maintenance with AI
- Driven by the equipment groups
- Main implementation during LS3

Expected **efficiency improvements during run 3**:

- → Pilot implementations of parts of framework
- Examples:
  - SY/RF & OP/PS: Controlled auto-resets of PS RF trips and improved fault tracking
  - SY/ABT: Controlled SPS kicker vacuum interlock auto-resets during LHC high intensity tests

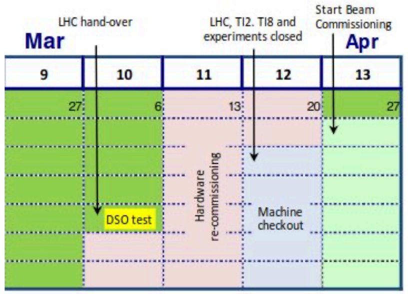


WP7 - Automatic Equipment Testing

From the project definition:

Context and goal

- HW commissioning and ISTs are crucial for smooth machine restart
- Any gain of time → potentially more physics !
- Repeatability and <u>trust</u> → process robustness and traceability
- Automated testing across the complex :
  - Less stress on the operations team
  - Execution and Analysis defined by system experts
  - Automatic reports and checklists



Start a Run with a fully automated HW commissioning campaign and ISTs for LHC and injectors

2023-10-10 WP7 Project Definition 2

Goal for 2025: AccTesting for PS power converters and LHC collimators

- Integrate EPC Picasso (EPC Python platform for testing) in AccTesting

Expected status end of run 3

- Automated beam scheduling based on requests by users
- Automated LHC filling preparation and orchestration
- All standard physics tuning automated
  - Solution for transient trims and BCD dependent trimming
- Hysteresis and other dynamic effects in the SPS compensated
  - First results for modelling based on simulation
- First automated HWC tests in injectors and extended automated HWC in LHC
- Measurable availability improvement from automatic equipment resets and reconfiguration for pilot systems
- Framework for equipment automation partially available

In summary

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→ with EPA CERN is preparing a new accelerator exploitation paradigm

→ blazing the trail for the FCC