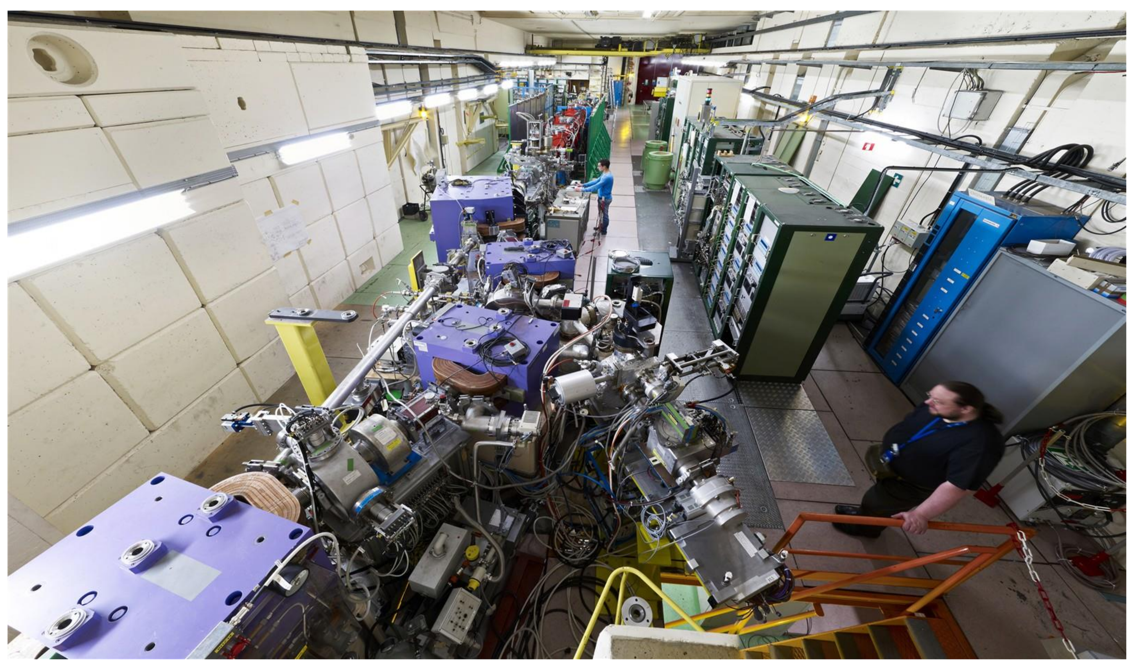
Developments towards autonomous optimisation and stabilisation of the GTS-LHC ION SOURCE at CERN

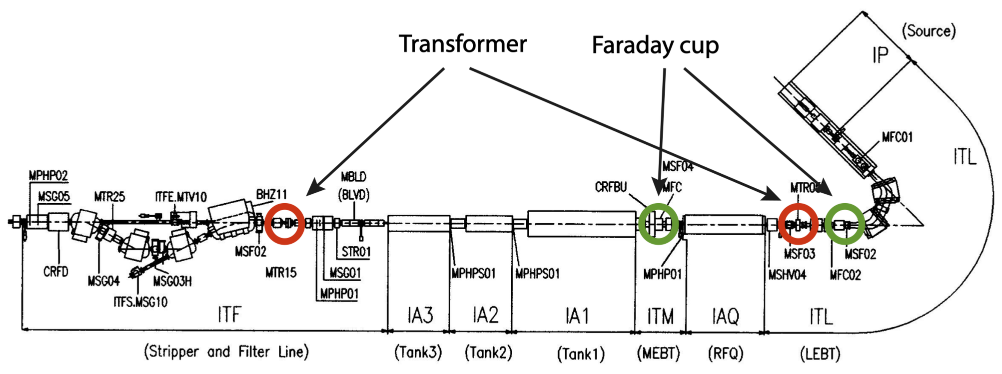
D. Küchler, L. Foldesi, V. Kain, A. Menor de Onate, B. Rodriguez Mateos, M. Schenk, CERN, Geneva, Switzerland.

GTS-LHC 14.5 GHz Electron Cyclotron Resonance Ion Source at CERN LINAC3

The GTS-LHC ECR ion source at CERN LINAC3 provides different heavy ion beams for the LHC as well as the PS and SPS fixed target experiments.

Building on first experience with state-of-the-art model-based adaptive stabilisation algorithms, this contribution presents the results obtained at the LINAC3 ion source after introducing a hierarchical control architecture to better deal with the different response times after control parameter changes.

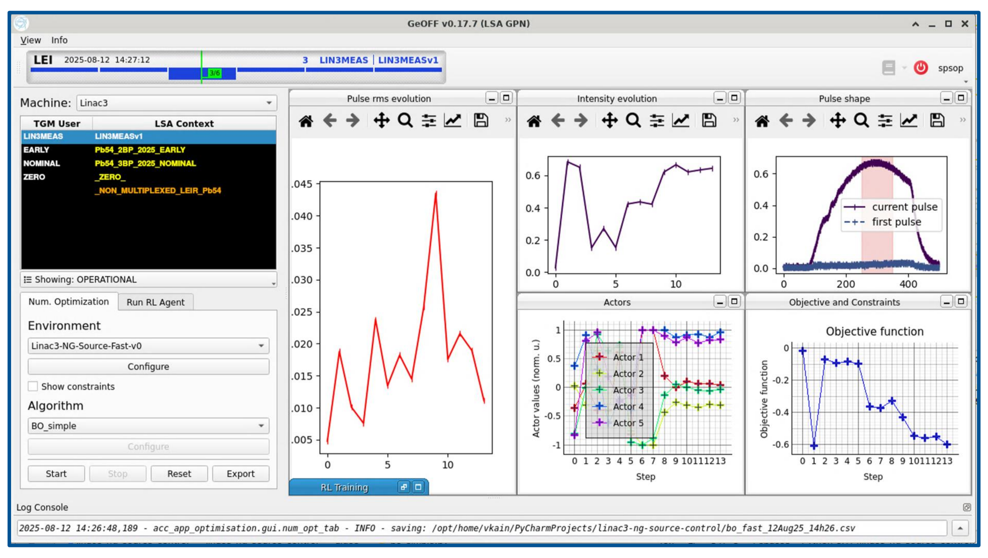




Tailor-made algorithms were necessary to limit exploration during periods of change of the overall system. The most promising architecture relies however on determining settling times dynamically, which then significantly simplifies the control architecture. It was only tested in August 2025.

The remaining challenges and steps towards full operational deployment will be summarised.

Ingredients: autonomous LINAC3 Source Control



Integration in control system

- Optimization task implemented as "environment" within CERN Generic optimisation framework (GeOFF) [1]
- Choice of optimization algorithms: most promising Bayesian Optimization (BO) with or without historical Gaussian Process posterior (virgin model)
- Objective: maximize intensity out of source, minimize rms within pulse and rms between consecutive pulses. Measured by: beam current transformer or faraday cup
- Objective function: $y = (-1)\cdot \bar{I} + 1.5\cdot \sigma_{intra} + 2.5\cdot \sigma_{inter}$
- Up to 6 degrees of freedom: 3 solenoid currents, voltage of bias disc, microwave power, oxygen gas injection regulation voltage

Main challenge

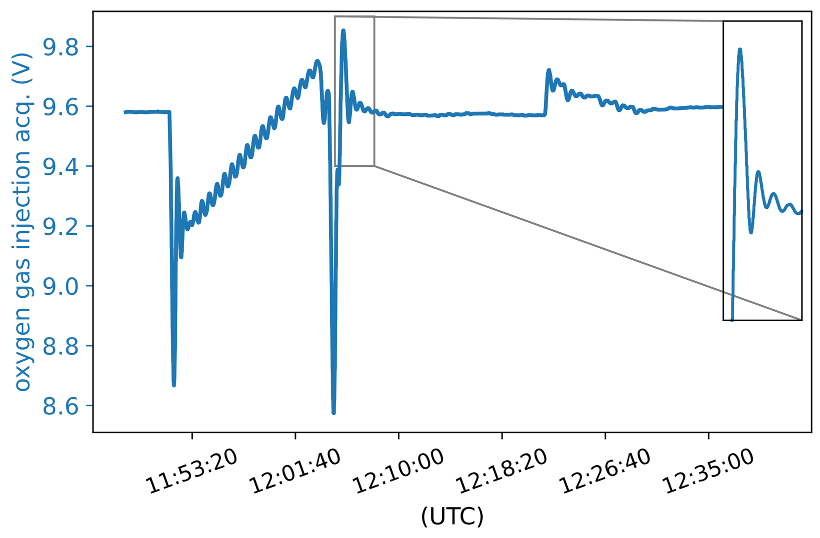
Effects of solenoids and bias disc mostly immediate.

Changes to the gas injection system only stabilize after several minutes → waiting time to be applied before evaluating the objective.

See figure below for evolution and the "ringing" of gas injection measured voltage during one of the optimization runs.

→ Different latencies: Original implementation: 2 optimization tasks running in parallel and independently with same objective function. Sub-optimal [2].

Waiting times were used (30 s or 120 s) for slower loop.

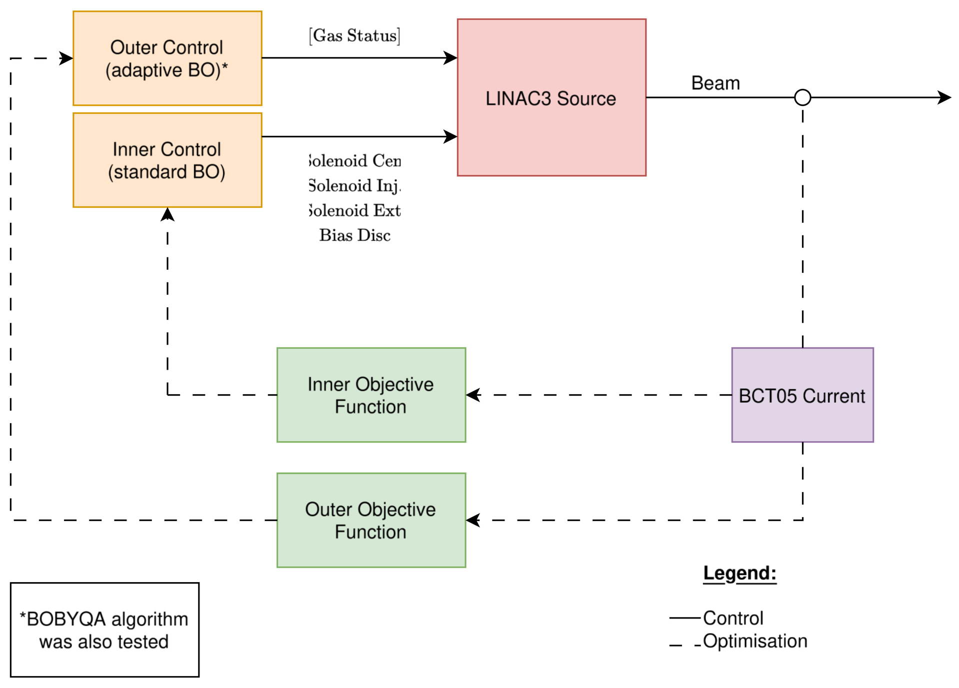


1st improvement: Hierarchical Controller

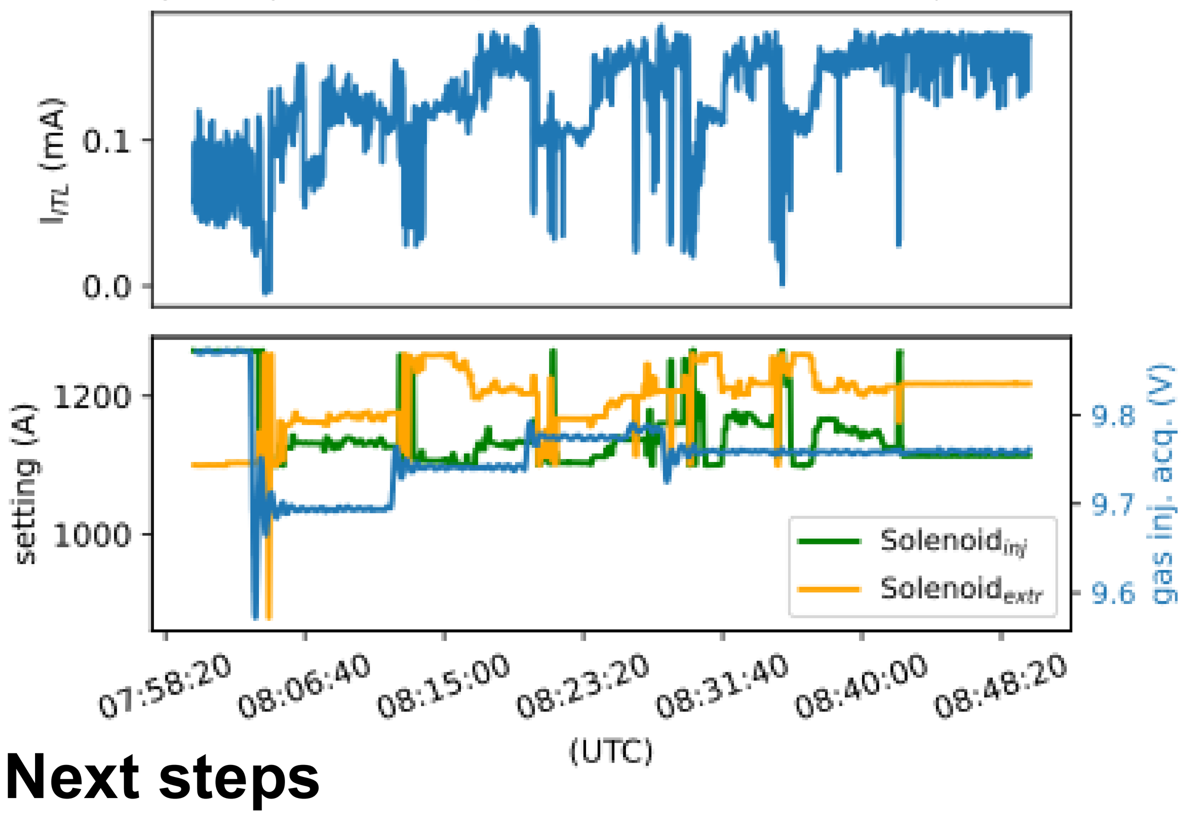
GeOFF allows to build arbitrarily complex control architectures with for example several nested and synchronized optimization/control loops.

In December 2024 another test series for automating LINAC3 source control took place for testing a nested setup which led to improved performance wrt the first implementation.

Inter-pulse reproducibility was not part the objective yet. Avoiding unnecessary exploration when triggering the inner loop (fast actors) was non-trivial, but not a showstopper (use historical data, adaptive BO). Plot below: BOBYQA for outer loop (slow actor, i.e. gas), BO for inner loop (fast actors).



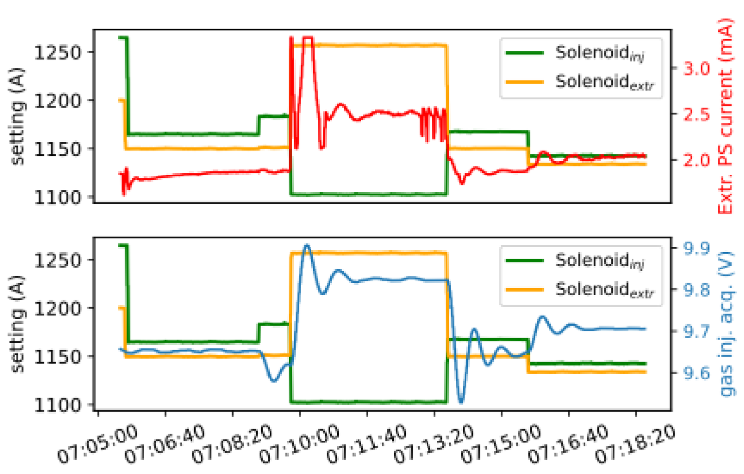
Hierarchical controller: only 2 fast actors and gas injection acquisition shown for clarity.

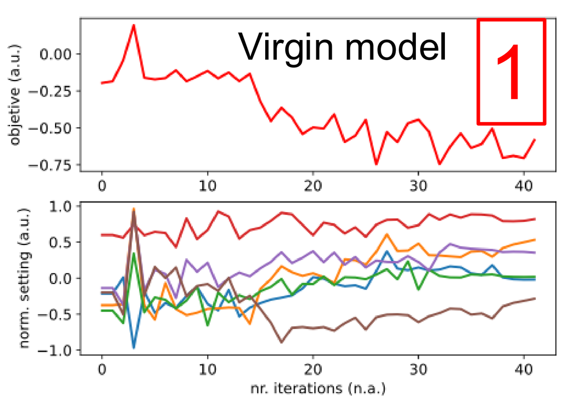


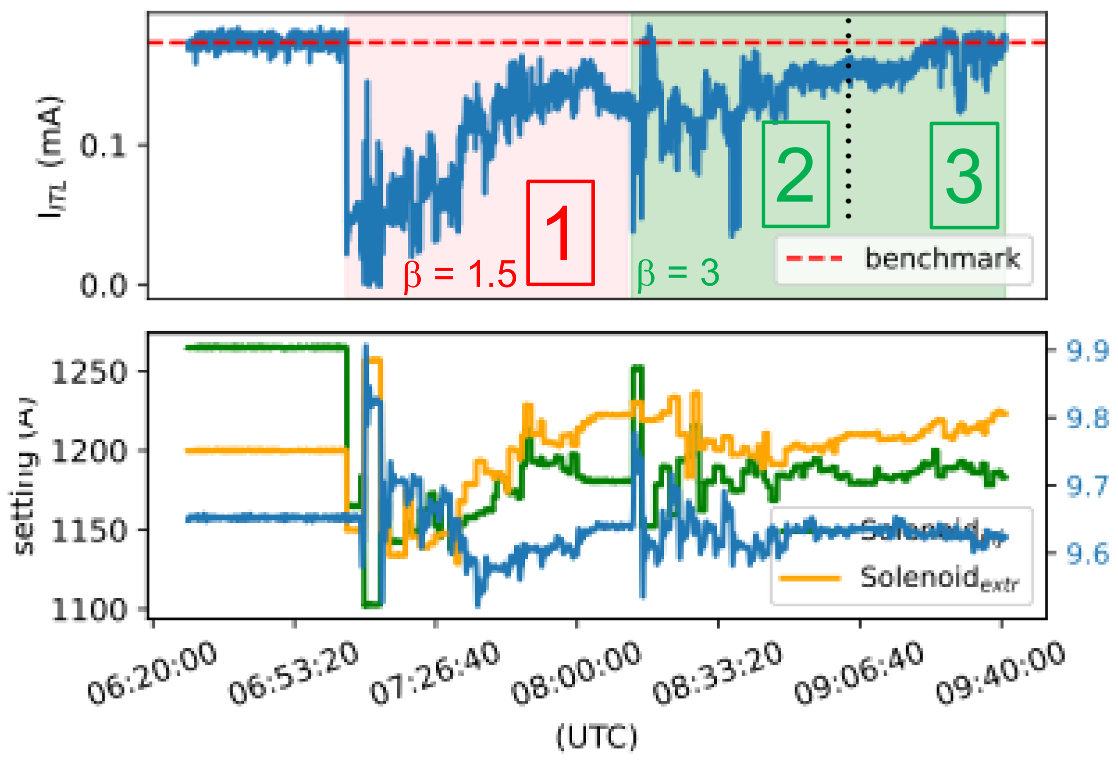
Most promising architecture for autonomous LINAC3 source control

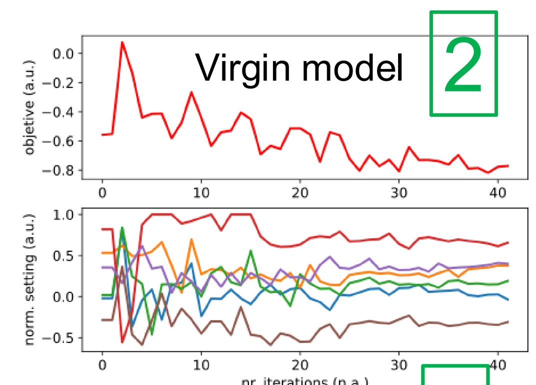
The test series in August 2025 was to address shortcomings in previous tests: optimize inter-pulse reproducibility while maximizing intensity, improving pulse baseline correction taking slope into account, stopping sending corrections after reaching threshold to avoid unnecessary extrapolation **and dynamically revealing settling times**.

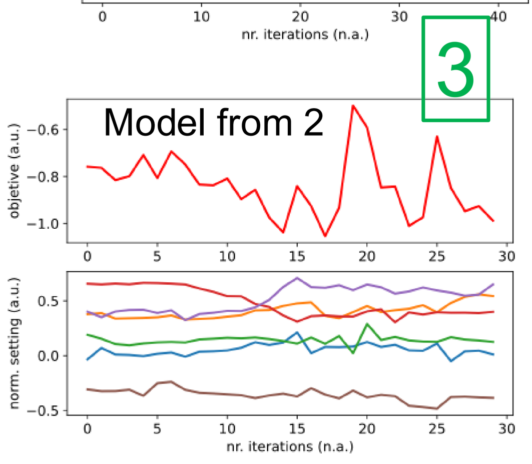
The stability of the total current measured at the extraction power supply serves as a proxy observable to determine settling times of the source after settings changes (i.e. also the fast actors require waiting time after big changes). Observing it and waiting for it to become stable within certain adjustable criteria allowed to run **all actors in a single loop**, including gas injection.











Results of successful recovery test from detuned source. BO with different exploration settings (β).

Next steps

The next tests are foreseen for the fixed target ion run in 2026. The goal will be to build on the promising 2025 architecture and demonstrate long-term stabilisation with the idea to only act if necessary. The mechanism was already tested in 2025. The long-term validity of the collected data and learned model still needs to be assessed. Instead of using already collected data, only the mean from the last model for a non-constant mean prior could be a solution.

References:

[1] N. Madysa et al, "Generic Optimization Framework and Frontend", https://doi.org/10.5281/zenodo.8434512 .

[2] D. Kuchler et al, "Continuous Data-driven control of the GTS-LHC Ion Source" , ECRIS2024, 2024.