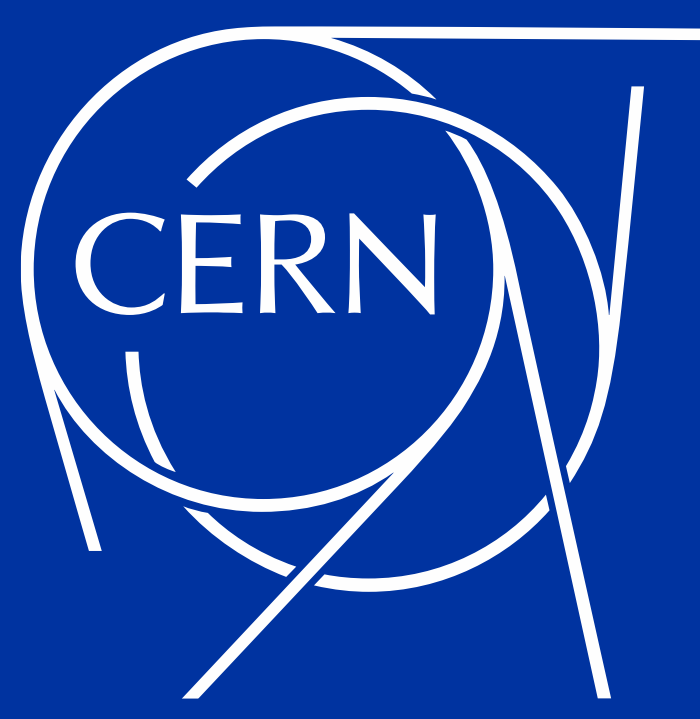




Minimizing the RF power requirements at injection in the Large Hadron Collider

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Motivation

The LLRF system of the Large Hadron Collider (LHC) at CERN was designed to handle strong beam-loading effects. Each superconducting cavity (eight per beam, for two beams) is driven independently by a 300 kW klystron. Several operational mechanisms help to reduce the required RF power:

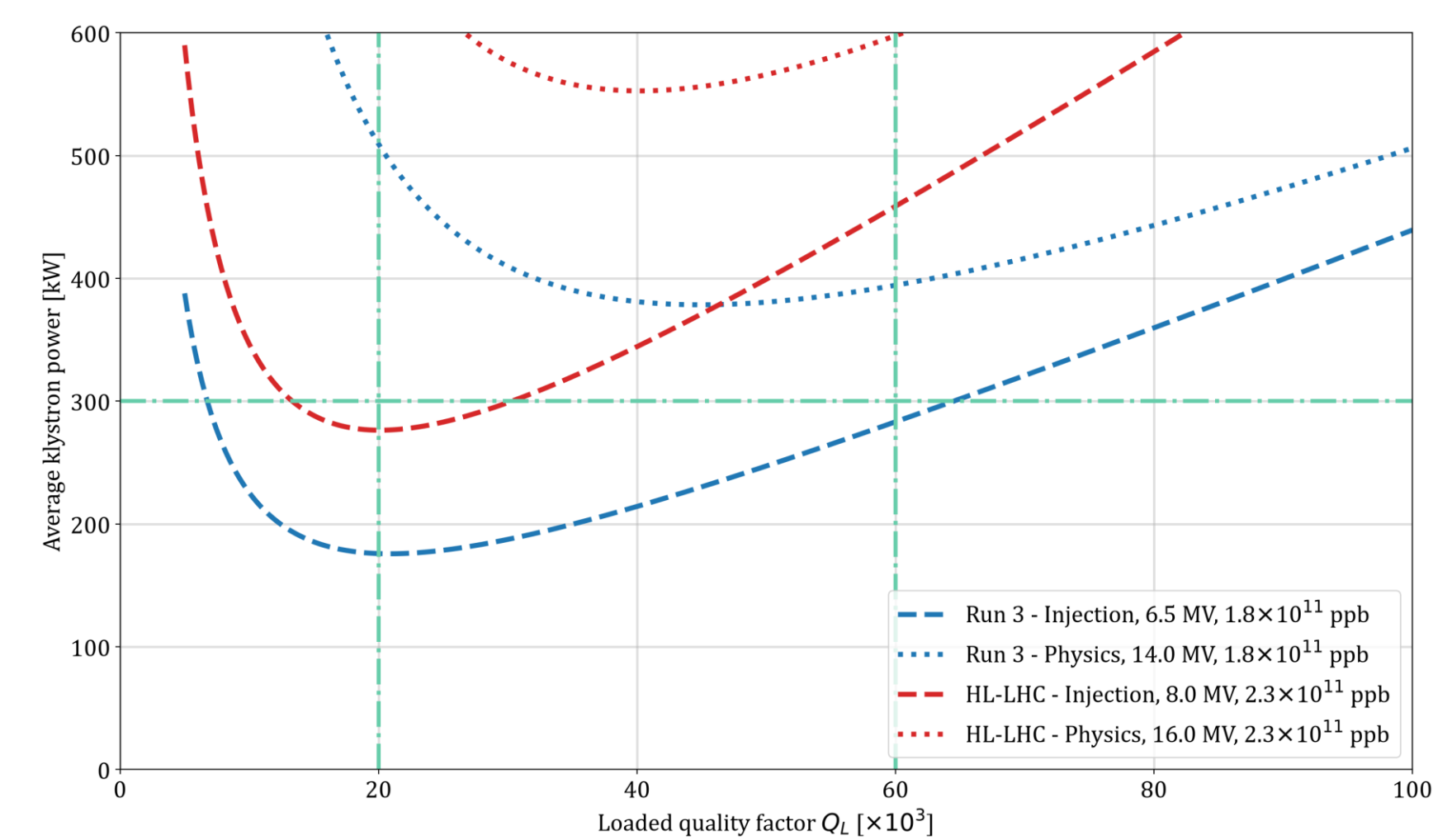


Figure 1 – Theoretical klystron power versus loaded Q with half-detuning only (2760 bunches). The current klystron power limit is 300 kW. Q_L is 20k at injection and 60k during physics operation.

- Movable coupler: The Q_L of the cavity is raised from 20k at injection to 60k during physics operation, matching the minimum required power for each beam energy.
- Half-detuning [1]: The cavities are detuned so that the klystron power stays constant between beam and no-beam segments. This lowers the required average power.
- Full-detuning [2]: After injection, each bunch is phase-modulated to minimize the klystron peak power.

In the High-Luminosity LHC (HL-LHC) era, beam intensities up to 2.3×10^{11} protons per bunch will require additional measures [3]. At injection, one of the main challenges is to match the high-intensity injected beam to the bunches already

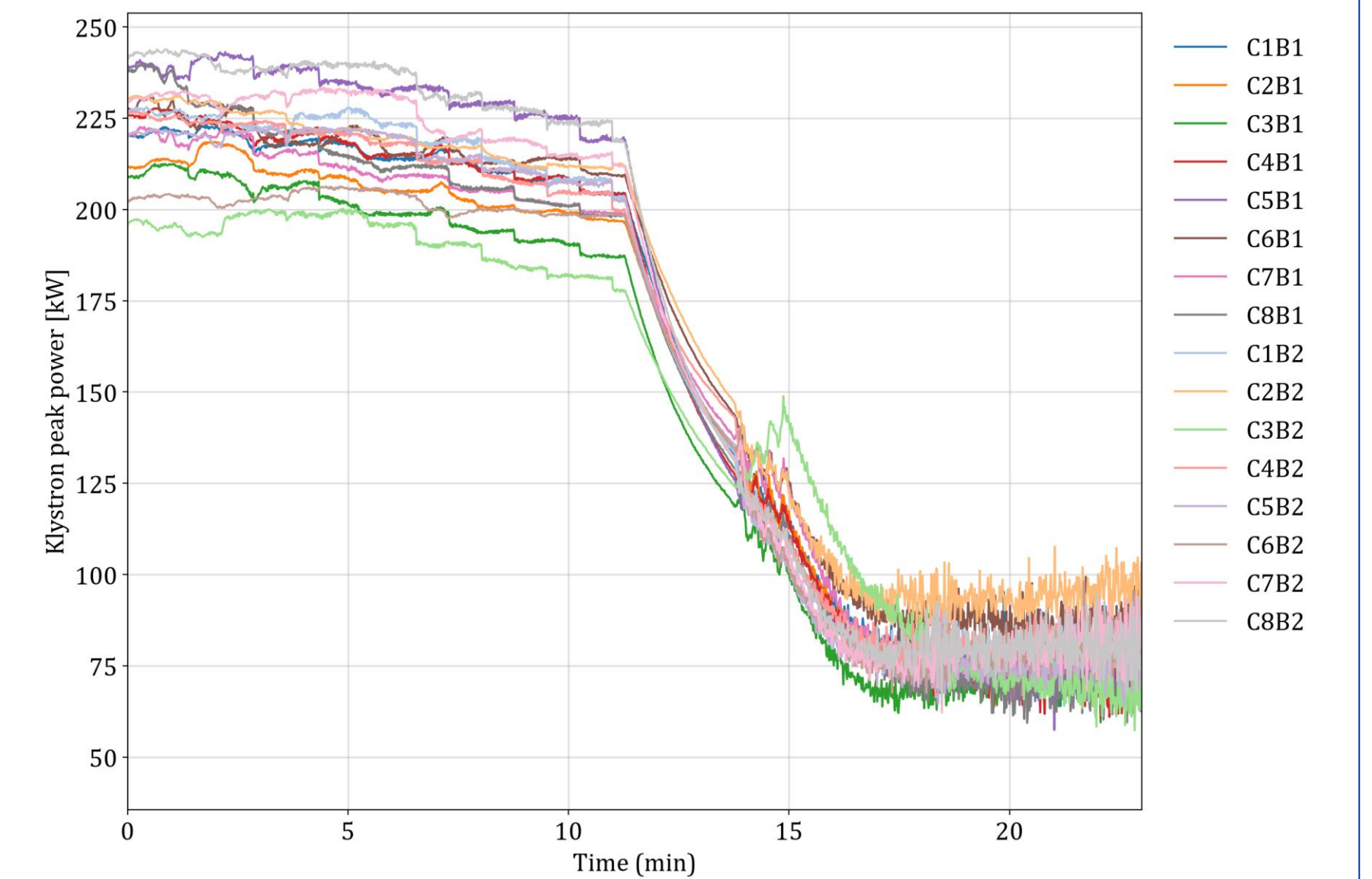


Figure 2 – Full-detuning algorithm in operation after injection.

circulating while keeping power transients small enough that the cavity voltage can be raised for better beam capture [4]. The proposed solution is to inject the bunches with the optimal phase that minimizes the required peak power, in addition to the optimum half-detuning angle [5] for the selected filling pattern.

Implementation

To apply a phase modulation at the individual bunches injected into the LHC, the bunches in the Super Proton Synchrotron (SPS) must also be phase modulated bunch-by-bunch before their extraction.

Both LHC and SPS LLRF systems can be divided in two main sub-systems: Beam Control (phase, radial and synchronization loops) and Cavity Controllers (amplitude and phase regulation in the RF cavities).

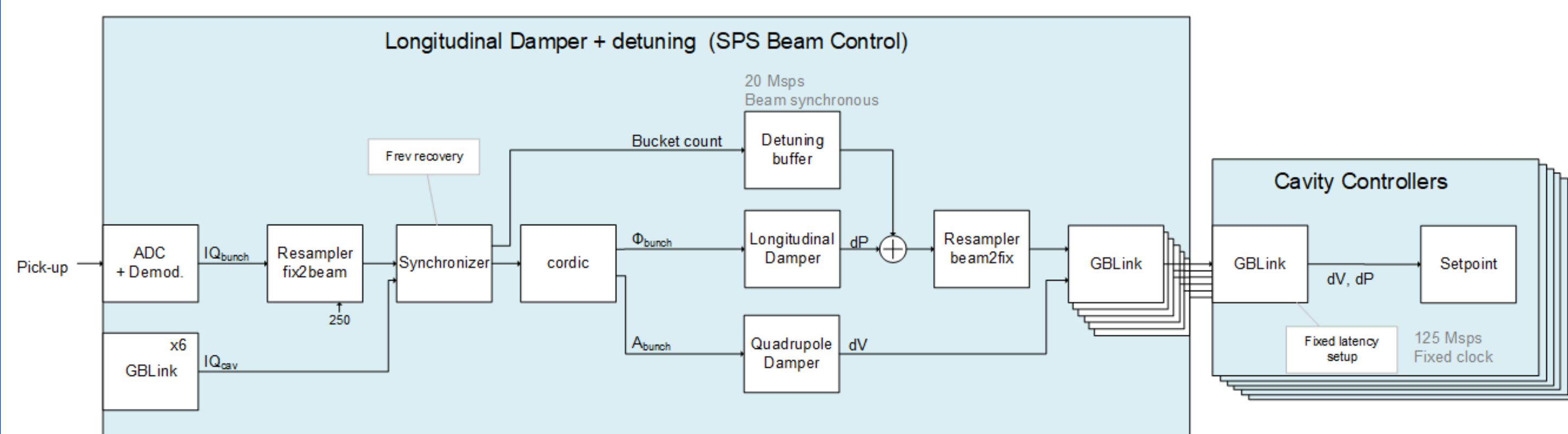


Figure 3 – Block diagram of the SPS Beam Control, focusing on the damper corrections.

In the SPS Beam Control, a pre-computed phase offset is added for each bunch, matching the phases required at LHC injection. This offset is added to the damper corrections and sent to all cavity controllers over dedicated high-speed serial links.

In the LHC, the pre-computed per-bunch phase offsets are added in the Setpoint module of the Cavity Controllers through the longitudinal damper interface, which is currently unused. All Cavity Controllers receive the same 3564 dV/dp values to be injected at 40 MSPS. A dedicated parameter synchronizes the corrections with the bunches so that the first offset lines up with the first bunch. The full-detuning algorithm can still be run independently. If the pre-computed phase offsets are set up correctly, its contribution is minimal.

Setpoint Generation and RF Feedback

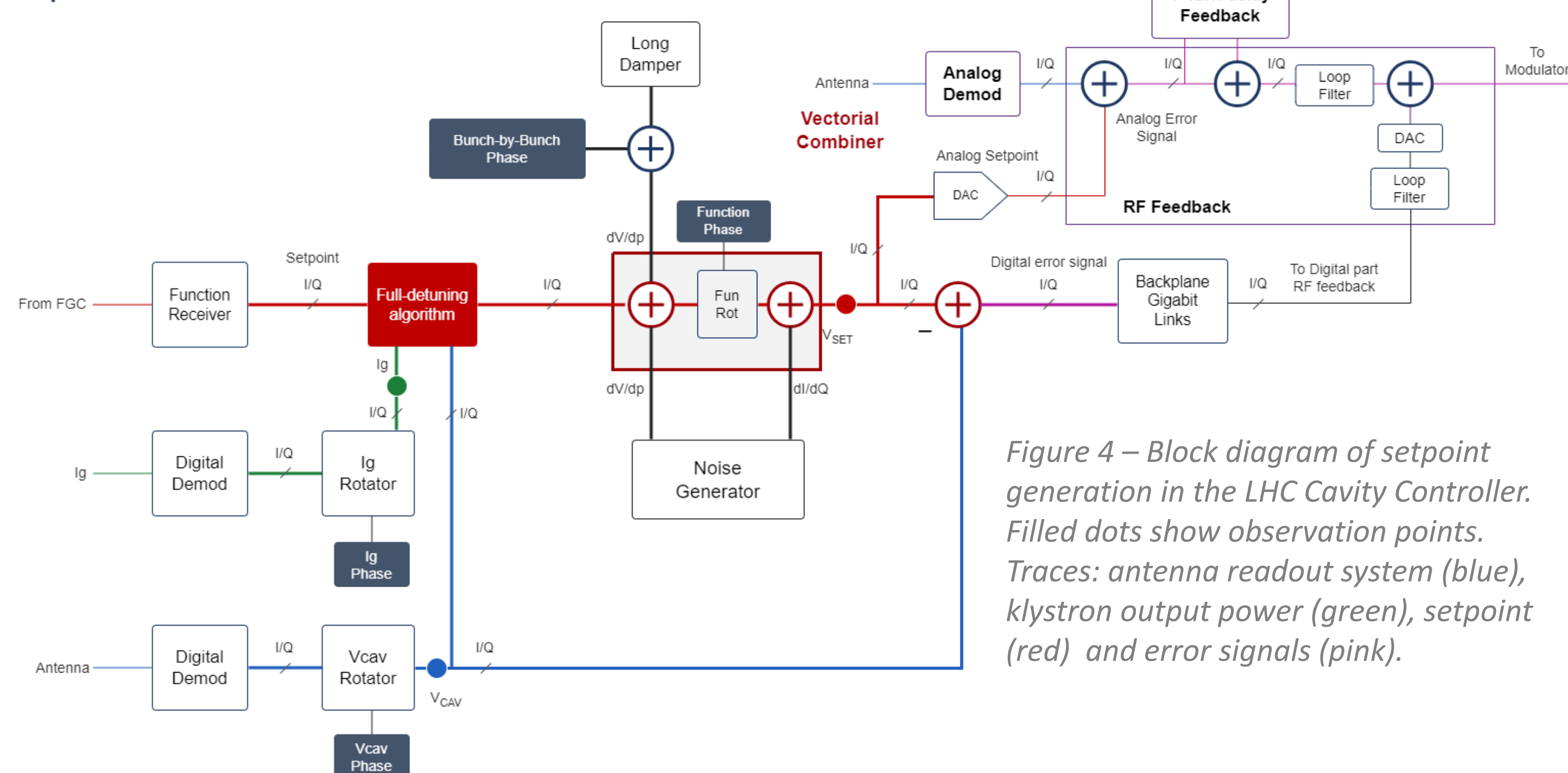


Figure 4 – Block diagram of setpoint generation in the LHC Cavity Controller. Filled dots show observation points. Traces: antenna readout system (blue), klystron output power (green), setpoint (red) and error signals (pink).

Tests and commissioning

Machine Development (MD) tests were carried out to validate the implementation of the bunch-by-bunch modulation principle in both the SPS and LHC machines.

In the SPS, the phase modulation is applied at flat-top. Within about 1000 turns, the bunches of the different trains are shifted in phase to match the phase required at LHC injection.

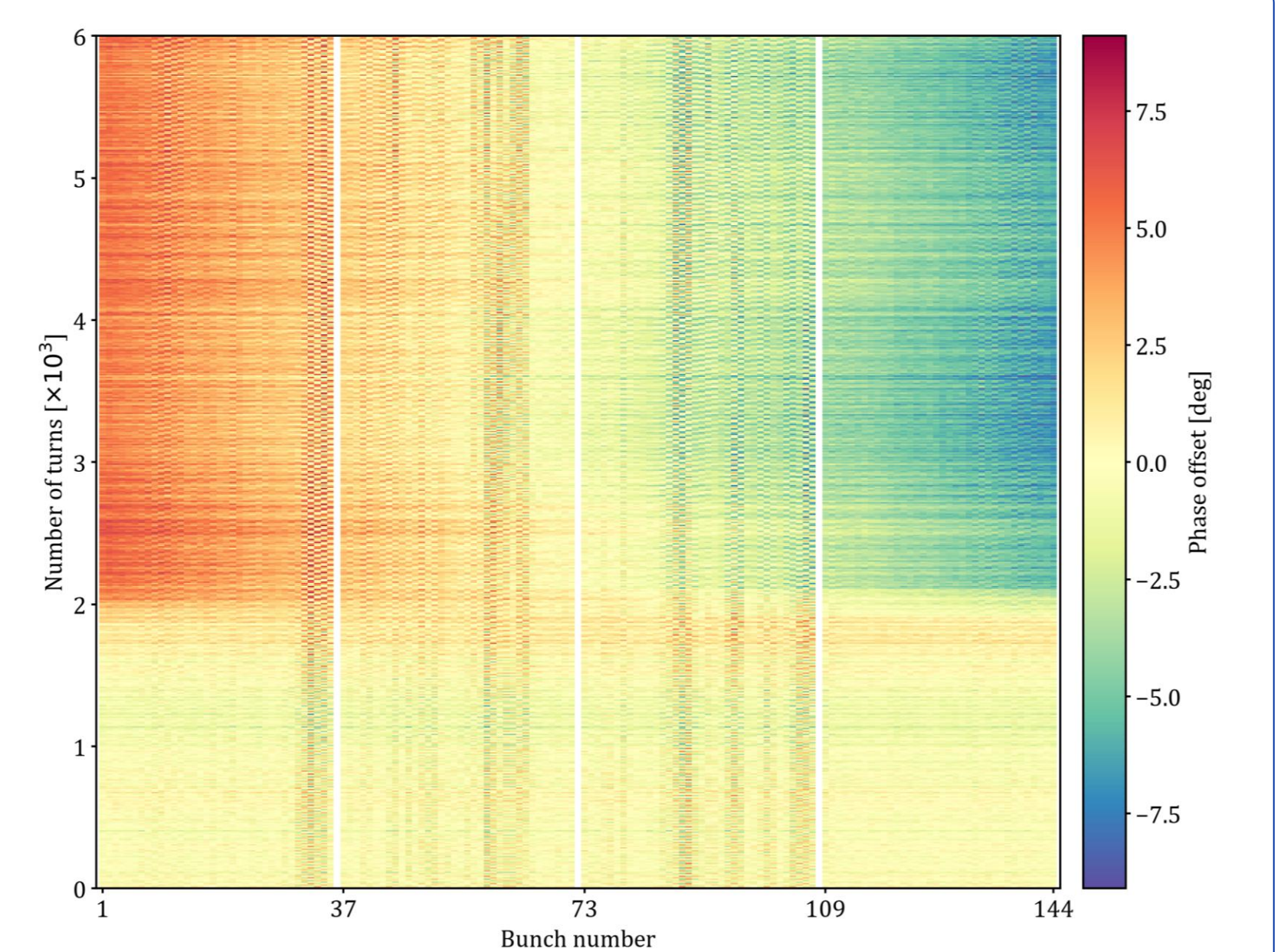


Figure 5 – Phase modulation tests in SPS at flat-top with 4 trains of 36 bunches. The phase offset is computed from an average of the phase of each bunch during the first 100 turns.

In the LHC, the first commissioning step was to align the phase offset in the Setpoint modules with the first injected bunch.

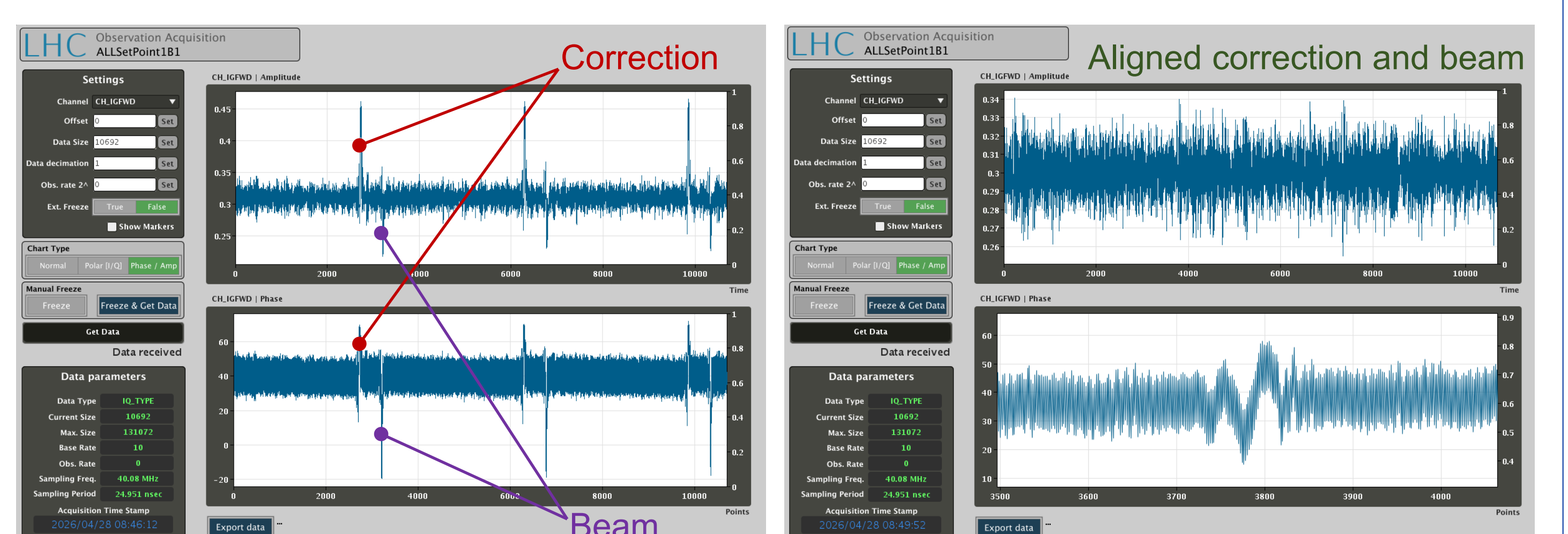


Figure 6 – First bunches injected into the LHC. Left: Unaligned correction and first injected bunches. Right: After correction alignment.

After alignment, a script computed the required corrections from the voltage, filling-pattern, intensity and other parameters.

The peak RF power then fell as beam was injected into the machine. This scheme was also confirmed to work together with the existing full-detuning algorithm.

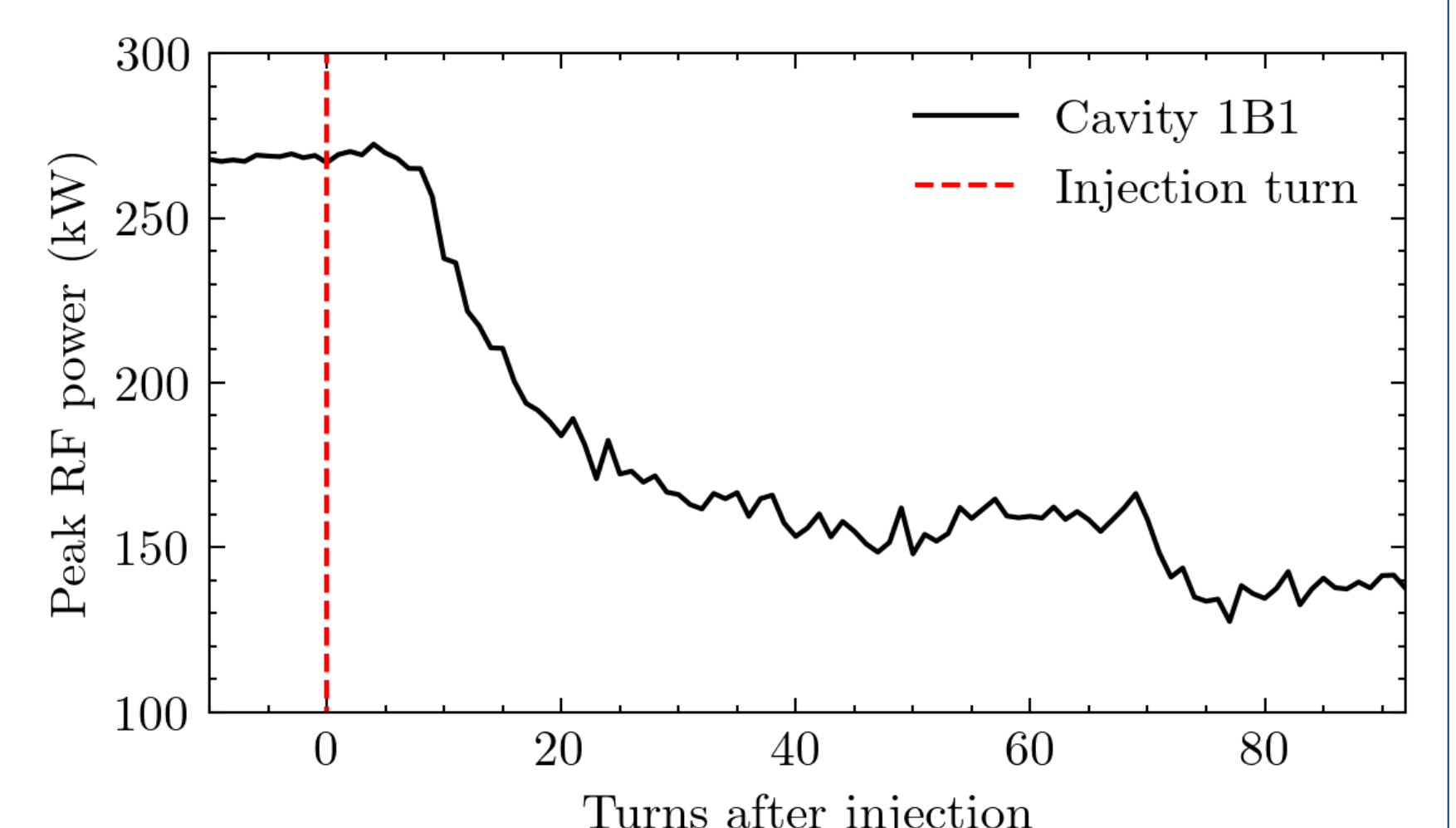


Figure 7 – Peak RF power for cavity 1B1 with the new scheme. Although the klystron saturates before injection, the peak power when the beam circulates is largely reduced.

After the initial commissioning, the computation and loading of the phase offsets is fully automated for operation and was used in subsequent high-intensity tests before the start of Long Shutdown 3.



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