LHC MAGNETIC MODEL REVISITED: BEAM-BASED MEASUREMENTS AND MACHINE REPRODUCIBILITY AT INJECTION

J. Wańczyk*, J. F. Esteban Müller, L. Fiscarelli, M. Hostettler, D. Jacquet, M. Solfaroli Camillocci,
G. Trad, J. Wenninger, European Organization for Nuclear Research, Geneva, Switzerland

Abstract

The harmonic components of the LHC superconducting magnets exhibit a characteristic decay at low field, primarily caused by current redistribution within the superconducting cables, inducing changes in the beam tune and chromaticity during the injection plateau. A feed-forward compensation system based on the FiDeL magnetic model counteracts these effects using parameterisations of the field harmonics as functions of time, current, and magnet history. In this work, dedicated beam-based measurements from the 2025 LHC run are used to update the FiDeL tune decay model parameters at 450 GeV. The fill-to-fill reproducibility of the machine at injection is assessed through the distribution of residual manual tune and chromaticity corrections, which yield $\sigma_Q = 0.003$–0.004 tune units and $\sigma_{Q'} = 2.0$–2.7 chromaticity units respectively. For fills preceded by a high-energy flat top, the flat-bottom duration is identified as the dominant source of variability ($r > 0.5$), and a parametric correction model $H_{\mathrm{FB}}(t_{\mathrm{FB}})$ is derived and validated, reducing this correlation. A significant correlation between tune corrections and arc helium bath temperature is also reported as a candidate for future model improvement.

INTRODUCTION

In superconducting accelerators, current redistribution and changes in the local magnetization within the Rutherford cables of the main dipoles and quadrupoles cause characteristic drifts of the magnetic-field multipoles during the injection plateau. This field decay affects the allowed multipoles, such as the sextupole component (b3) in the dipoles, which drives chromaticity changes, and the main component (b2) in the quadrupoles, which drives tune changes. The phenomenon has been a known operational challenge since its discovery at the Tevatron in 1987, where chromaticity changes of up to 70 units were observed [1]. A further complication is that the decay amplitude depends on the magnet powering history prior to injection, making it non-reproducible from cycle to cycle. This motivated the development of FiDeL (Field Description for the LHC), a feed-forward prediction system whose mathematical framework is described in [2,3]. A striking discrepancy emerged during early LHC operation: while single-magnet measurements predicted decay time constants of 200–300 s, beam-based measurements revealed time constants of 1000–4000 s and tune decay of ~0.04 units, far exceeding pre-operational expectations [4].

Since 2011, dynamic corrections for tune and chromaticity decay have been applied operationally using beam-based parameters; the most recent update prior to the 2025 run is documented in [3]. Despite these corrections, residual offsets persist fill-to-fill at injection, requiring frequent manual operator trims. This paper reports three related activities carried out on 2025 LHC data and applied in the 2026 run: an update of the FiDeL tune decay model parameters from dedicated beam measurements; a systematic characterisation of the residual manual corrections and their dominant drivers; and the derivation and validation of an improved flat-bottom correction term $H_{\mathrm{FB}}(t_{\mathrm{FB}})$ for the tune. Full details of the analysis are reported in [5].

UPDATED DECAY MODEL PARAMETERS

The FiDeL tune decay model parameters — decay amplitude δ_Q, mixing factor d, and time constant τ — were updated from dedicated beam measurements performed during 2025 commissioning at 450 GeV, for two fill categories: precycle fills (injection after a full precycle to recondition the magnets) and flat-top fills (injection after a high-energy flat top).

A key complication encountered in the measurements is that the observed decay is not fully reproducible across fills even under nominally identical powering conditions, as illustrated in Fig. 1: five PRE fills from early and mid-2025 commissioning span a visible spread, limiting the precision of any single-fill parameter extraction. To mitigate this, fits were performed simultaneously on all available fills.

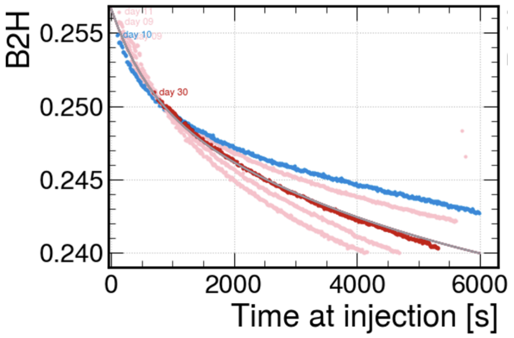

Figure 1: Fill-to-fill non-reproducibility of the tune decay on the injection plateau for five PRE fills. Three commissioning fills (pink) and two April 2025 fills (red, blue); grey line shows the simultaneous fit to all five.

For precycle fills, a free simultaneous fit to all five fills was adopted as the updated model. In the horizontal plane the new correction is larger than the Run 2 baseline by approximately 4–5 × 10^{-3} tune units after 4 h at injection; in the vertical plane it is smaller by 1–3 × 10^{-3}. For flat-top fills, only two dedicated fills were available, as measuring the full decay curve requires many hours at injection and

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[*] joanna.wanczyk@cern.ch

the large parameter space of the powering history makes systematic sampling impractical within a single commissioning period. To guard against a large parameter shift driven by limited statistics, the adopted model is taken as the average of the new free fit and the Run 2 baseline. The horizontal-plane flat-top history scaling $H_{\mathrm{FT}}(t_{\mathrm{FT}})$ was re-evaluated using four combined 2025–2026 commissioning points, with the adopted value again averaged with the Run 2 reference. The updated parameters were further verified with dedicated beam measurements during 2026 commissioning, showing that residual deviations remain, and thus indicating that the model description is still incomplete. The complete parameter set for all beam-planes is reported in [5]. No dedicated chromaticity decay measurements were performed; chromaticity model parameters are carried over from Run 2 unchanged.

MACHINE REPRODUCIBILITY AND CORRELATION ANALYSIS

The width of the manual correction distributions provides a direct measure of fill-to-fill machine reproducibility at injection: a narrower distribution indicates that the FiDeL feed-forward more accurately pre-compensates the field drift, leaving less for operators to correct manually. Table 1 summarises the correction statistics for tune and chromaticity from all the 2025 *pp* nominal physics fills.

For the tune, precycle fills scatter around the per-plane median with $\sigma = 0.003$–0.004 tune units; flat-top fills are systematically shifted by +0.003–+0.005 tune units relative to precycle fills and show a comparable or slightly larger spread. Chromaticity reproducibility is good across all planes ($\sigma = 2.0$–2.7 units), with a flat-top offset whose sign is opposite in the horizontal and vertical planes, consistent with partial but imperfect absorption of the flat-top history in the chromaticity model. A dedicated update of the chromaticity H_{FT} scaling from beam measurements is recommended for a future run.

Table 1: Manual correction statistics per beam-plane from the 2025 *pp* physics run. Tune units (top); chromaticity units (bottom). Shift = $\tilde{x}_{\mathrm{FT}} - \tilde{x}_{\mathrm{PRE}}$.

	PRE		FT		
Plane	median	σ	median	σ	Shift
Tune					
B1H	−0.0156	0.0036	−0.0123	0.0046	+0.0033
B2H	−0.0246	0.0038	−0.0215	0.0044	+0.0031
B1V	+0.0510	0.0031	+0.0539	0.0032	+0.0029
B2V	+0.0869	0.0040	+0.0915	0.0039	+0.0046
Chromaticity					
B1H	−20.5	2.67	−22.3	2.58	−1.8
B2H	−20.0	2.68	−22.3	2.54	−2.3
B1V	−17.7	2.19	−15.5	2.03	+2.2
B2V	−19.2	2.26	−16.5	2.10	+2.7

To identify the dominant sources of fill-to-fill variability, Pearson correlation coefficients between the residual corrections (after subtracting the precycle fill median per plane) and a set of candidate variables were computed separately for precycle and flat-top fill sub-samples. Two variables show statistically significant correlations with the tune correction in flat-top fills.

Flat-bottom duration t_{FB} is the most strongly correlated variable, with $r > 0.5$ in all horizontal planes and $r = 0.44$ in B1V (Fig. 2). This dependence is absent from the current operational FiDeL tune model, where the corresponding term in Δ_{PH} is fixed to unity, motivating the H_{FB} model described in the next section. No analogous t_{FB} correlation is found for chromaticity, where this term is already included in the model.

Arc average helium bath temperature shows a significant correlation in the vertical planes, with individual arcs reaching $r \approx 0.56$ for B2V. The correction spread is also larger at lower bath temperatures. This correlation is identified as a candidate for future model improvement but is not yet incorporated operationally.

For precycle fills, no variable reaches the significance threshold ($|r| > 0.2$) in any plane. The residual scatter in precycle fills therefore reflects contributions not captured by the current model; likely magnet ageing, beam-induced persistent-current changes, or thermal history on timescales longer than one fill, and remains an open problem.

H_{FB} CORRECTION MODEL AND VALIDATION

The strong t_{FB} correlation in flat-top fills motivates reinstating the flat-bottom scaling term in the tune powering-history factor, which had been fixed to unity in the operational model. The correction follows the functional form of Δ_{PH} in [3], normalised at a fixed reference time $t_{\mathrm{FB,ref}} = 600$ s chosen to match the typical flat-bottom duration of precycle fills. However, since the data do not necessarily cross unity at this reference point, an additional scale parameter δ_2 is introduced, so that

$$H_{\mathrm{FB}}(t_{\mathrm{FB}}) = \delta_2 \, \frac{P_0 - P_1 e^{-t_{\mathrm{FB}}/\tau_p}}{P_0 - P_1 e^{-t_{\mathrm{FB,ref}}/\tau_p}}, \qquad (1)$$

where by construction $H_{\mathrm{FB}}(t_{\mathrm{FB,ref}}) = \delta_2$. A value $\delta_2 \neq 1$ absorbs the systematic offset between flat-top and precycle fill correction distributions that is not accounted for by the t_{FB} shape alone. The shape parameters P_0, P_1, τ_p, and δ_2 are fitted from the 2025 flat-top fill correction data using a log-binned median profile of the ratio of total required correction to the improved model baseline, with synthetic anchor points added at short and long t_{FB} to stabilise the extrapolation. Fitted parameters are listed in Table 2.

At the typical flat-top fill flat-bottom duration of ~800 s, the H_{FB} factor is 0.99–1.01 in the horizontal planes and

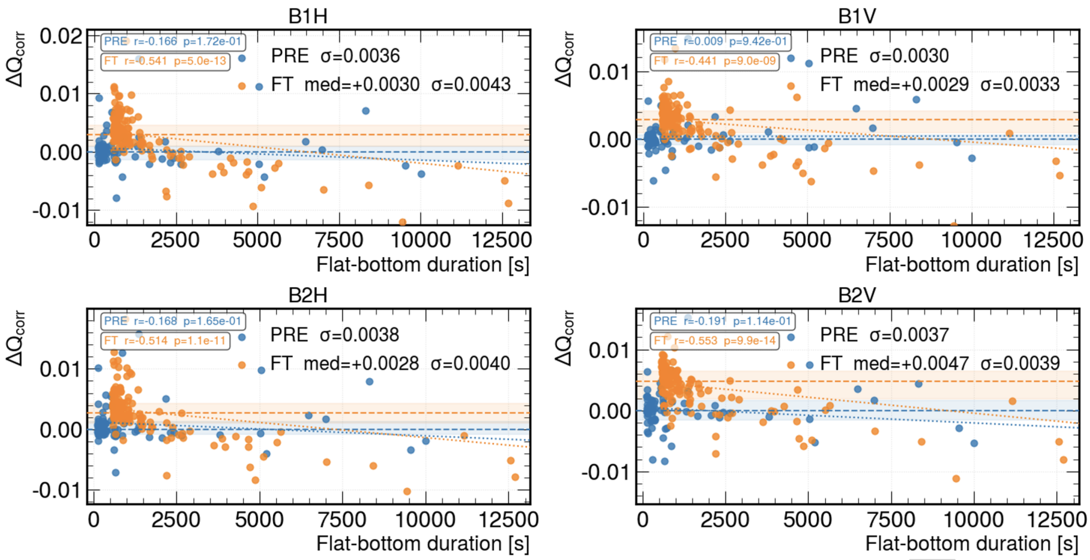

Figure 2: Manual tune corrections of all 2025 nominal physics fills vs. flat-bottom duration t_{FB} for all four beam-planes (precycle fills: blue, flat-top fills: orange). Dashed lines: per-category median with shaded 1σ bands. Pearson r and p annotated per panel.

Table 2: Best-fit H_{FB} parameters (Eq. 1) with fixed reference $t_{\text{FB,ref}} = 600\,\text{s}$. All planes converge to the upper bound $\tau_p = 3000\,\text{s}$ (see text).

Plane	P_0	P_1	τ_p [s]	δ_2
B1H	0.652	−0.316	3000*	1.030
B2H	0.764	−0.281	3000*	1.002
B1V	0.710	−0.290	3000*	1.236
B2V	0.722	−0.388	3000*	1.428

*τ_p at upper bound of fit constraint.

larger in the vertical planes, where the fitted δ_2 reaches 1.24–1.43, corresponding to additional tune corrections of $3\text{–}4 \times 10^{-3}$ and $5\text{–}8 \times 10^{-3}$ tune units respectively relative to the current model. This is comparable in magnitude to the observed systematic offset between flat-top and precycle fills of $3\text{–}5 \times 10^{-3}$ tune units, confirming that t_{FB} accounts for a significant fraction of that shift.

Applying the correction significantly reduces the residual dependence: the Pearson $|r|$ drops below 0.2 for all beam-planes (from > 0.5 before correction). A residual correlation remains, reflecting the limitation of the fixed reference time parametrisation. Importantly, the median of the flat-top fill distribution is brought closer to the precycle fill reference (example shown in Fig. 3), meaning that the systematic offset between the two history categories, which previously required systematic manual corrections by operators at the start of each flat-top fill, is substantially reduced. These parameters have been implemented in FiDeL at the start of the 2026 run.

SUMMARY

The FiDeL tune decay model has been updated from dedicated 2025 beam measurements. Analysis of manual correction distributions from the 2025 physics run quantifies fill-to-fill reproducibility at injection: tune corrections scatter with $\sigma = 0.003\text{–}0.004$ tune units for precycle fills; flat-top fills carry a systematic excess primarily driven by the flat-bottom duration t_{FB}. A parametric $H_{\text{FB}}(t_{\text{FB}})$ correction model has been derived, validated, and deployed at the start of the 2026 run, reducing the t_{FB} correlation and narrowing the flat-top fill correction distribution toward the precycle fill reference. A significant correlation between tune corrections and arc average helium bath temperature (up to $r \approx 0.56$) is identified and recommended for further investigation. For precycle fills the source of residual scatter remains unidentified; one possible explanation is that the precycle, performed at reduced current, does not fully erase the magnet powering history, leaving residual effects not captured by the current model.

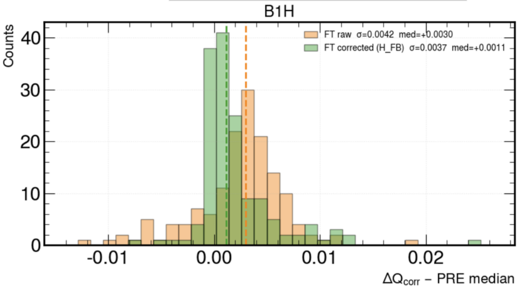

Figure 3: Distributions of manual tune corrections for all nominal physics 2025 fills for the example of B1H. Orange: original FT corrections; green: residuals after applying H_{FB}.

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