

MEASUREMENT OF LOCAL CHROMATICITY IN THE LHC

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Abstract

Local chromaticity is defined as the local variation of the total betatron phase advance with momentum deviation δ , and it can be interpreted as a measurement of the chromaticity generated over a limited segment of the lattice, rather than for the entire ring. It can be a useful tool to understand various insights of the beam operation, in particular how the phase is locally modulated by beam energy and how the overall chromaticity builds up along the lattice. The local chromaticity was first evaluated in the Large Hadron Collider (LHC) during the Run 3 commissioning in 2025, when a large RF frequency scan was performed, revealing a very large discrepancy with respect to the LHC optics model. This paper presents the methods and the results of the analysis.

INTRODUCTION

Chromaticity is defined as the variation of the betatron tune with energy. In the LHC, it is typically measured by modulating the beam energy while simultaneously acquiring the tune [1]. This approach is robust and widely adopted for characterizing the effect of energy on the betatron phase. However, chromaticity alone provides no information on how the local chromatic betatron phase varies around the ring. Local chromaticity is thus defined as the chromaticity of a limited segment of the lattice,

$$Q'_{x,y}(s) = \frac{1}{2\pi} \left. \frac{\partial \Delta \phi_{x,y}(s, \delta)}{\partial \delta} \right|_{\delta=0} \quad (1)$$

When s is equal to the ring length, the local chromaticity reduces to the conventional chromaticity. The phase advance $\Delta \phi_{x,y}(s, \delta)$ can be expressed as the Taylor expansion around the on-momentum value. The expansion is carried out to second-order, proved to be sufficient (see below). The resulting coefficients define the first- and second-order local chromaticity. To evaluate these coefficients, the total betatron phase advance is measured at each BPM for several momentum deviations. Turn-by-Turn (TbT) data were acquired via forced oscillations induced with an AC dipole [2, 3]. The induced excitation remains coherent over the 6600 turns of the acquisition window, ensuring high-quality spectral analysis. A correction is applied to compensate for the phase error induced by the AC dipole [4]. A zero-padded FFT (HARPY) [5] was subsequently applied to the acquired data to retrieve the frequency spectrum from which the phase advance is computed. The measured phase advances are then fitted with a second-order polynomial function to extract the local chromaticity coefficients, as shown for an arbitrary BPM, in Fig. 1.

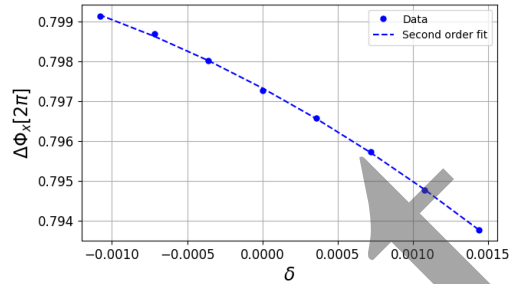


Figure 1: Horizontal phase advance vs δ at BPM.32R3.B1.

MEASUREMENTS – LHC

The local chromaticity was first evaluated in the LHC during Run 3 injection commissioning in 2025. The chromaticity was corrected to approximately 3 units in each plane with the main sextupole magnets (MS). The RF frequency was modulated from -350 Hz to $+350$ Hz in steps of 50 Hz, which corresponds to a relative momentum deviation δ ranging between ± 0.0025 . The original goal of this measurement was the study of chromatic Resonance Driving Terms (RDTs) [6]. Therefore the machine tune feedback system (QFB) [7] was kept on during the measurement to ensure a constant AC dipole frequency offset. The QFB acts on the trim quadrupoles (MQTs) correcting the tunes to their on-momentum values. For the injection optics, these are $Q_x = 62.28$ and $Q_y = 60.31$. With the corrected chromaticity $Q' = 3.0$, the maximum tune shift being compensated is approximately ± 0.0075 , a small fraction of the nominal tune. As described before, the phase advance is evaluated at each BPM from the initial BPM taken as the reference start of the lattice. In Fig. 2, the difference between the measured and the on-momentum model phase advance is shown for LHC Beam 1 (B1), for both planes, for the tested momentum deviations. A localized spread in the horizontal phase advance at different momenta is immediately visible in the vicinity of IP4 and IP8 for B1, around 6000 and 20000 m. Similar results were obtained for LHC Beam 2 (B2). This behavior is most evident in the horizontal plane, while in the vertical plane the phase advance remains coherent along the ring. As described before, the local chromaticity is extracted from the TbT data. The measured linear local chromaticity for both planes is shown in Fig. 3 for B1, and in Fig. 4 for B2, only for the horizontal plane. The vertical plane results for B2 are similar to those for B1. The second-order local chromaticity for B1 is presented in Fig. 5; again similar results were observed for B2. The second-order local chromaticity is small compared to the linear term. At the maximum tested δ , a direct comparison of the two terms in the Taylor expansion reveals that the second-order contribution is on average one order of magnitude smaller than the linear term. In the vertical plane, the linear local chromaticity is locally compensated, exhibiting oscillations around zero. In

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the horizontal plane, however, a clear pattern emerges for both beams: the linear local chromaticity builds up in the non-ATS arcs [8] (across IP1 and IP5) and is subsequently self-compensated in the ATS arcs.

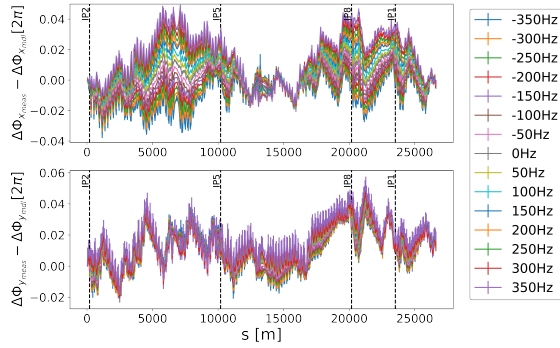


Figure 2: Phase advance for B1.

At the end of the lattice, both model and measured linear local chromaticity converge to the same values, ensuring agreement between the measured and model tunes and chromaticity. This highlights an advantage of local chromaticity measurements: the conventional chromaticity measurement is consistent with expectations, even if the local behavior around the ring differs significantly.

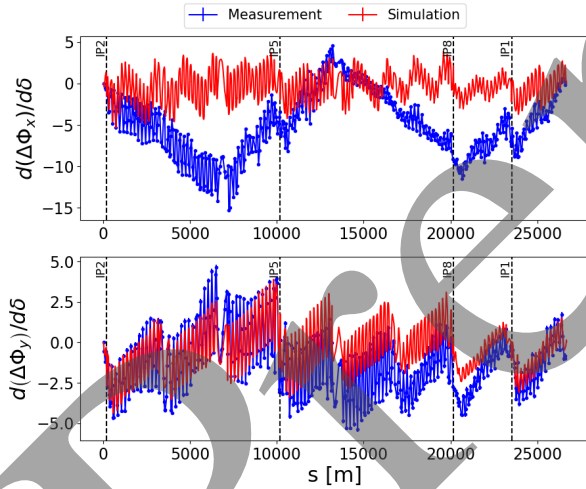


Figure 3: Measured and model local chromaticities, for B1.

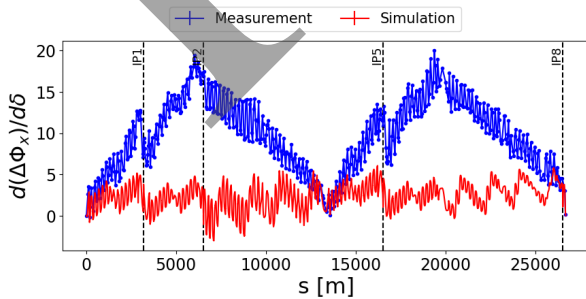


Figure 4: Measured and model horizontal local chromaticity, for B2.

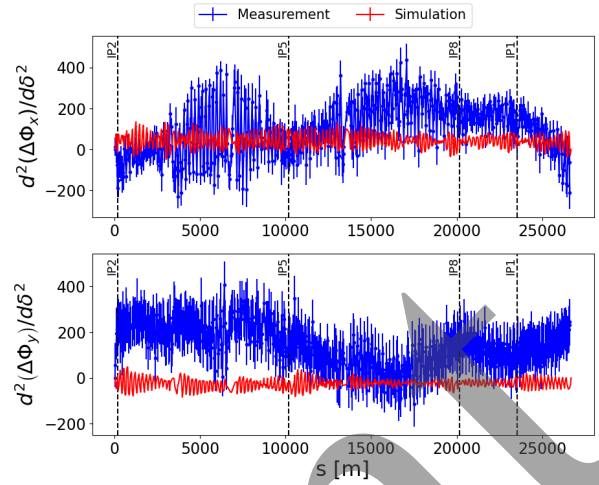


Figure 5: Measured and model second order local chromaticity, for B1.

Simulations

Simulations were carried out to validate the measurements. The effect of the QFB was accounted for by matching the tunes off-momentum to their on-momentum values using MQTs, in the same way as had been done during the measurements. Optics functions are retrieved with off-momentum MAD-X Twiss commands. Several models were considered: the nominal LHC design model, a model using the actual main sextupole settings at the time of the measurement, extracted from the LHC Software Architecture (LSA), a model including random and systematic sextupole errors introduced according to the Field Description for the LHC (FiDel) [9], together with corresponding sextupole correctors (MCS), and a model including the expected b_3 decay at the time of the measurement together with extracted MCS strengths. All of them showed quite similar results, reproducing well the measured chromatic correction pattern in the vertical plane, but showing a clear discrepancy in the horizontal plane. In all simulated and designed LHC scenarios the local chromaticity is expected to be locally compensated around the ring in both planes. Simulation results with the extracted MS strengths are shown in red in Figs. 3, 4, and 5.

Further Studies on the Role of MQTs and MSs

The chromatic beta-beating and the Montague functions [10] were also evaluated for both planes, from both the model and the measurements. The horizontal and vertical Montague functions W are shown in Fig. 6 for B1, analogous results were observed for B2. This shows that the discrepancies observed in the local chromaticity analysis are not reflected in the chromatic beta-beating or related quantities. While isolated spikes are visible in the Montague functions, these appear in both planes, and are actually more pronounced in the vertical plane, whereas the local chromaticity build-up is observed exclusively in the horizontal plane. This is a hint at the possible sources of local chromaticity mismatch. If the error sources are systematically separated by 90° in phase advance, they will affect the phase

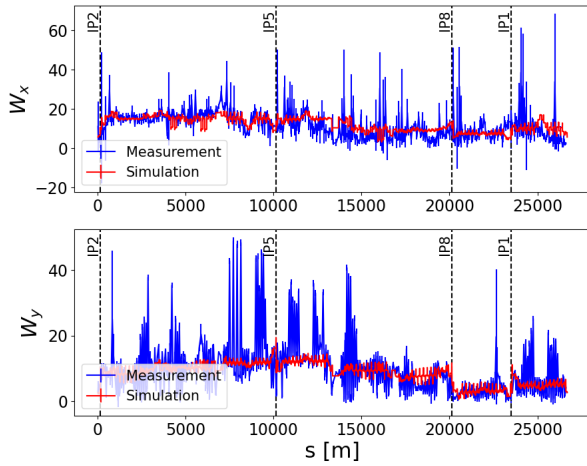


Figure 6: Measured and model Montague functions W .

but the perturbations on beta functions will cancel. Consequently, a chromatic effect observed in the phase advance but not in the beta functions can be attributed to this kind of sources — as is the case for MQT and MS magnets.

Regarding the MS, an attempt was made to reproduce the measured local chromaticity pattern by matching the sextupole settings, but this required an offset of $+0.03 \text{ m}^{-2}$ to the normalized strength of the focusing sextupoles (MSF), corresponding to a 100% offset for some of the magnets, which was considered unlikely. Regarding the MQTs, they could reproduce the observed chromatic phase error, if the powering of all ATS and non-ATS arcs were accidentally swapped in the LHC. However a check of MQT powering currents during the measurement showed variations only in the expected circuits.

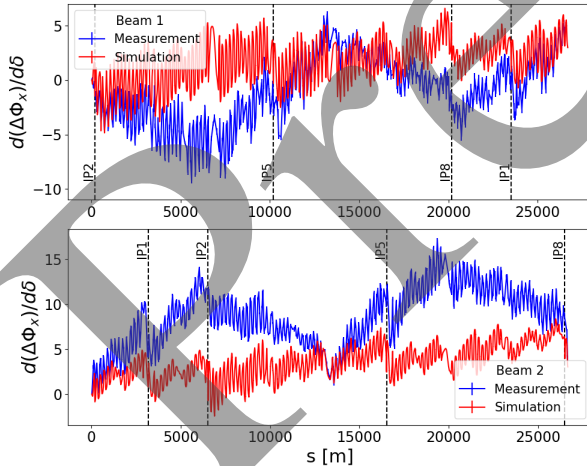


Figure 7: Measured and model horizontal local chromaticity, without QFB.

To test any role of the MQT, additional measurements were carried out during a dedicated Machine Development (MD) session, performing the same RF scan with the tune feedback disabled. The results are shown in Fig. 7. The magnitude of the deviation from the model is lower than in the previous measurement; however, it is difficult to establish whether it is related to the MQTs, as the measurements were

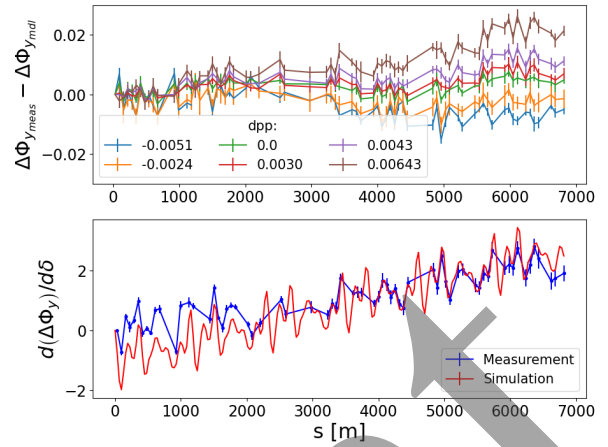


Figure 8: Measurement and vertical local chromaticity.

repeated several months later and the observed reduction could also be attributed to a different dynamic b_3 component. This is further supported by the 2026 commissioning results, where a linear local chromaticity of similar magnitude to the 2025 QFB-off measurement was observed, despite the QFB being kept on. A dedicated MD has therefore been requested to characterize the two effects, performing consecutive measurements, with and without QFB, with the same machine configuration.

MEASUREMENTS – SPS

To further validate the method, a dedicated MD was carried out to perform the same measurement, for the first time, in the CERN Super Proton Synchrotron (SPS), scanning δ values from -0.5% to 0.6% . Single-kick excitations, instead of the AC dipole, were used to excite the beam and acquire the TbT data [11]. Unfortunately, acceptable data were available only in the vertical plane, due to an extremely fast decoherence observed in the horizontal plane. The model has been updated with the sextupole settings extracted from the machine at the measurement time. In Fig. 8, the measurement results (top) are shown alongside the model and measured linear vertical local chromaticity (bottom). For the SPS, the model roughly reproduces the measurements.

CONCLUSIONS

Local chromaticity is a valuable observable for the commissioning and correction of off-momentum optics, providing detailed insight into how the chromatic phase is corrected across the different sections of the machine. The LHC model has been shown not to correctly reproduce the horizontal local chromaticity at injection energy. This is particularly relevant in light of operational experience during 2025, where the optimal phase shift deployed in 2023 [12] had to be increased to mitigate a collimator hierarchy breakage. The required phase shifts are of the same order of magnitude as the chromatic phase errors identified here, for the largest tested δ . This further motivates the importance of identifying the source behind these discrepancies.

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