CHALLENGES OF K-MODULATION MEASUREMENTS IN THE LHC RUN 3

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Abstract

The future upgrade to the High-Luminosity Large Hadron Collider (HL-LHC) will impose tight tolerances on Interaction Point (IP) optics measurements. k-modulation is currently the preferred method in the LHC for IP optics measurements and will play a critical role in the HL-LHC. As such, Run 3 of the LHC provides an ideal test-bench for addressing challenges in k-modulation. In the first commissioning year of Run 3, this method was used to measure and validate optics with β^* ranging from 30 cm to 24 m. However unsatisfactory reproducibility was observed for low β^* measurements. This paper presents the k-modulation results for the start of Run 3 with in depth analyses, and highlights the sensitivity of this method in view of the challenging HL-LHC runs.

INTRODUCTION

The method of k-modulation has been successfully used in many accelerators [1–14], and has been the preferred method for IP optics measurements since Run 2 of the LHC [2, 14–16]. This method played a central role in achieving record low β-beating levels during Run 2 [17]. It also played a key role in successfully commissioning the LHC optics in the first year of Run 3 [18, 19].

While it has been successfully used, its reproducibility has, in some cases, been unsatisfactory at low β^* conditions. This resulted in longer periods of commissioning spent on k-modulation measurements then desired. This paper gives a short overview of the k-modulation method, discusses possible causes for low reproducibility resulting from data quality and timing issues, and finally presents the measured β^* for collision optics.

The Method of K-Modulation

The current implementation of the k-modulation method in the LHC relies on a sinusoidal gradient modulation of the two quadrupoles closest to the IP [2]. By measuring the change in tunes and quadrupole strengths, the average β-functions in the triplets can be accurately measured by numerically fitting Eq. (1),

$$\beta_{\mathrm{AV}_{x,y}}(\Delta Q_{x,y}) = \pm\Big[\cot(2\pi Q_{x,y})(1-\cos(2\pi\Delta Q_{x,y})) + \sin(2\pi\Delta Q_{x,y})\Big]\frac{2}{\Delta K L}\,. \tag{1}$$

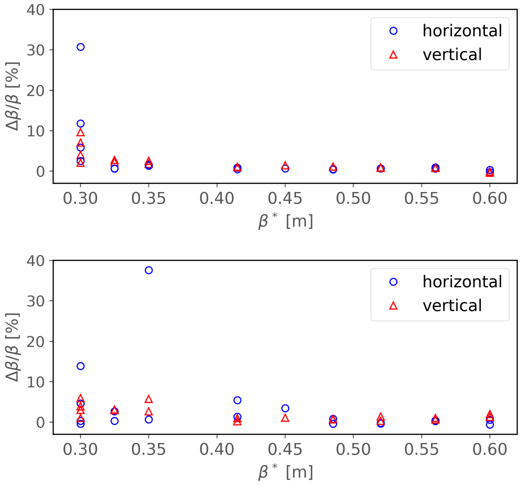

Figure 1: Variation of calculated β^* for consecutive measurements ranging from $\beta^* = 0.60$ m to $\beta^* = 0.30$ m in IP1. The results for Beam 1 are shown in the top plot, while the results for Beam 2 are shown in the bottom plot.

From the measurements of average β in the inner triplets the quadratic betatron equation of a drift is solved numerically to obtain β^* measurements, as well as the location of the waist where the minimum β-function is located [14, 16]. Furthermore, the β-functions at the nearest BPMs are also obtained, and serve as valuable inputs for global optics corrections [17, 18].

REPRODUCIBILITY CHALLENGES IN THE LHC

While k-modulation provides very accurate measurements of IP optics at large β^* values, uncertainties tend to increase through the β^* squeeze. Indeed, the effects of tune noise and waist offsets become increasingly problematic at $\beta^* = 30$ cm [14]. Figure 1 shows the measured β^*-beating for both beams for multiple k-modulation measurements at various settings of β^* on the 11th and 12th of June 2022. While the measurements show good reproducibility at $\beta^* = 60$ cm this deteriorates moving towards $\beta^* = 30$ cm. This reduced reproducibility increases the required commissioning time and needs to be understood. Several sources will be discussed in this paper, such as the BBQ tune data quality and timing offsets between the BBQ data and triplet current measurements.

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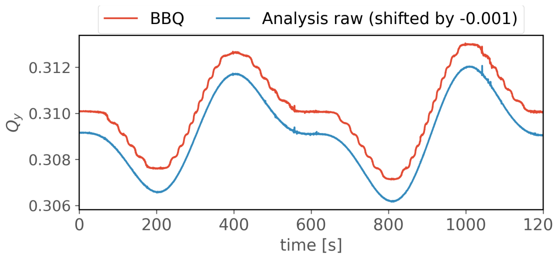

Figure 2: Comparison of tune data received from the BBQ system (in red) and tune obtained from the re-analysis of the BBQ raw data in post-processing (in blue). The step-like behaviour of the tune disappears with the new FFT analysis.

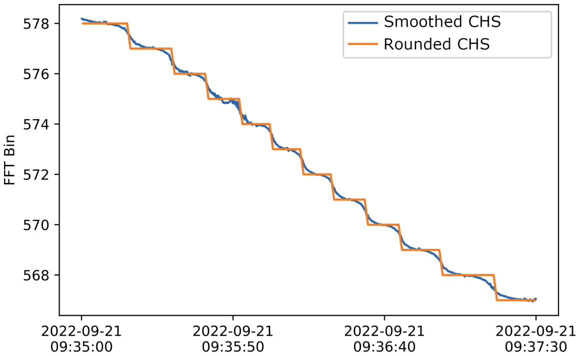

Figure 3: Analysis of the BBQ binning resolution compared to the measured tune data from the Continuous High Sensitivity (CHS) BBQ source.

BBQ Data Quality

The LHC tune measurements are performed by a diode-based base-band-tune (BBQ) technique. This high-sensitivity device records turn-by-turn transverse position data and performs spectral analysis. The current implementation of the k-modulation measurements in the LHC rely on the internal spectral analysis performed by the BBQ. More specifically, the LHC.BQBBQ.CONTINUOUS_HS tune data source is used for k-modulation measurements. During 2022, several k-modulation measurements showed significant perturbations of tune measurements during the modulations, causing a step-like behaviour in the tune response. Figure 2 clearly shows the step-like tune measurements obtained from the BBQ (in red), and serves as an extreme example of such perturbed responses. Such distorted tune measurements can have a significant effect on the quality of k-modulation measurements and can further affect the reproducibility of this method, thus motivating closer inspection of the tune data source.

The steps in the BBQ data come from the frequency resolution of the 2048 point FFT that is used in the BBQ system, as is shown in Fig. 3. A smoothing function is then applied by the BBQ peak-search algorithm, which in some rare cases generates steps in the tune signal.

Since the raw transverse turn-by-turn BBQ data is continuously stored online, the data can be re-analysed using different spectral analysis methods or parameters. In this study the BBQ raw data has been re-analysed using zero padding and a Hamming filter to provide smooth interpolation. The comparison between the default BBQ tune data, and the tune signal from re-analysed raw BBQ data is shown in Fig. 2, where the resulting new analysis is shown in blue and displaced by -0.001 to avoid overlapping data. The new spectral analysis offers a more robust calculation of machine tunes during the modulation of the triplet quadrupoles. This clearly motivates the post-processing of raw BBQ data for future k-modulation measurements.

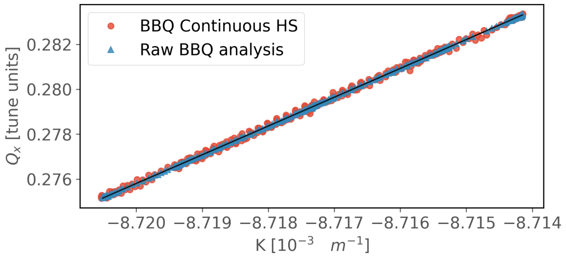

Figure 4: Tune data from the internal BBQ analysis (red) and the re-analysis of the raw BBQ data (blue) versus measured triplet strength. The resulting fit is displayed as in black.

Timing Offset Data

k-modulation measurements rely on accurate phasing between triplet quadrupole strength measurements and tune measurements. During Run 2 of the LHC it has been generally assumed that the timing was accurate. However, analysis performed in 2022 shows that a timing mismatch in the stored data may be affecting the obtained results.

The average β-functions are calculated by fitting Eq. (1) to the measured triplet strengths and tunes. The resulting fit parameters can be compared to the measurement data. Figure 4 compares the measured tune data as a function of quadrupole strength, and the fit of the data. At first sight the fit appears to be very good. However, looking more closely at the difference between the data and the fit a pattern is observed. Figure 5 shows the residual between the measurement data and the fit $r = Q^{\text{meas}} - Q^{\text{fit}}$ as a function of the rate of change of the quadrupole strength. Perfect synchronisation between the tune and quadrupole strength data would result in a flat residual dominated by the noise of the measured tunes. However, a small but clear slope is observed in the residual, indicating a possible mismatch in synchronisation. Figure 5 is representative for all k-modulation measurements performed in 2022 for all IPs and beams.

The re-analysis of the raw BBQ data shows clear improvements in the synchronization of the tune data with the quadrupole current measurements. Figure 5 also shows the residual between the data and the fit obtained from the new analysis. The residual is independent of the rate of change of the quadrupole strength, thus indicating an improved timing. Furthermore, the variance of the residual is improved in the new analysis with respect to the internal BBQ tune analysis.

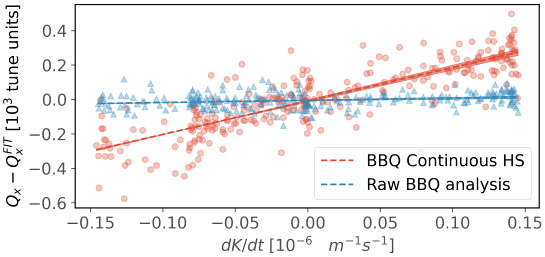

Figure 5: The residual between the tune data of the internal BBQ analysis (red) and the re-analysis of the raw BBQ data (blue) with their respective fit results, versus the rate of change of the triplet strength.

2022 β^* COLLISION OPTICS RESULTS

Final k-modulation measurements were taken on the 17th of June 2022 after all optics corrections were applied. Table 1 shows the results obtained for two consecutive k-modulation measurements at $\beta^* = 0.3$ m in IP1 and IP5 respectively. The results from the online analysis with the Continuous High Sensitivity (CHS) tune data source, and the refined offline analysis with the raw BBQ data (Raw), are compared in the Table 1. While both methods generally agree with each other, differences of up to a few percent are observed, specifically in the second measurement of IP1 Beam 2, where the measured β^*-beating increases significantly with the new analysis. Also, some variation can be observed in the calculated β^* as well as the estimated measurement error between consecutive measurements with the same settings. In some cases the errors appear to be underestimated, and motivate further studies to better estimate the individual measurement errors.

By using the average over the two consecutive k-modulation measurements, an effective β^* can be calculated for each IP, and an estimate of the luminosity imbalance between ATLAS and CMS can be obtained. Table 2 shows the effective β^* for both IP1 and IP5, as well as the calculated luminosity imbalance. The new method, based on the raw BBQ data, now predicts a small imbalance in favor of CMS (IP5) by 1.3%, which is still within the operational tolerances.

CONCLUSIONS

The method of k-modulation forms the basis for IP optics measurements in the LHC and the HL-LHC. The reproducibility of this method is a critical issue for its successful deployment in the HL-LHC, and this will become more important at lower β^*. The current use of k-modulation in the LHC thus provides valuable insights for its use in the HL-LHC.

In 2022, k-modulation measurements played a central role in validating the IP optics for operation and ensuring a low luminosity imbalance between the ATLAS and CMS detectors. However, varying results have been observed for consecutive measurements generating interest in improving the analysis for low β^* values.

Table 1: Comparison of Two Consecutive Measurements of β^*-Beating Between the Online Analysis Using the BBQ CONTINUOUS HS (CHS) Tune Data and the Re-analysed Raw BBQ Data (Raw), for Two Consecutive Measurements, for Both IP1 and IP5

	Analysis	$\frac{\Delta\beta_x}{\beta_x}$ [%]	$\frac{\Delta\beta_y}{\beta_y}$ [%]
IP1 B1	CHS 1	-1.8 ± 0.1	1.7 ± 0.6
	CHS 2	-1.9 ± 0.1	0.4 ± 0.4
	RAW 1	-1.8 ± 0.11	2.9 ± 0.8
	RAW 2	-1.5 ± 0.3	0.7 ± 0.4
IP1 B2	CHS 1	2.4 ± 0.8	4.5 ± 0.9
	CHS 2	1.3 ± 0.7	2.7 ± 0.6
	RAW 1	3.5 ± 0.9	4.5 ± 0.8
	RAW 2	6.4 ± 1.2	7.9 ± 1.2
IP5 B1	CHS 1	2.1 ± 0.8	0.5 ± 0.3
	CHS 2	3.3 ± 0.9	0.8 ± 0.4
	RAW 1	2.0 ± 0.7	0.1 ± 0.12
	RAW 2	1.8 ± 0.6	0.0 ± 0.1
IP5 B2	CHS 1	2.1 ± 1.0	0.9 ± 1.1
	CHS 2	1.5 ± 1.0	-0.6 ± 0.9
	RAW 1	2.3 ± 0.9	1.7 ± 1.1
	RAW 2	1.8 ± 0.9	2.1 ± 1.1

Table 2: Effective β^* Averaged Over the Two Final Measurements, and the Expected Luminosity Imbalance Between ATLAS and CMS

Source	eff. β^*_{IP1}	eff. β^*_{IP5}	IP1/IP5 $\mathcal{L}$
CHS	0.303	0.304	1.002
RAW	0.308	0.304	0.987

The tune data obtained from the BBQ system shows potential issues arising from the internal smoothing algorithms used. Improvements can be made by analysing the raw BBQ signal in post-processing. Observed steps in BBQ tune data, are interpolated much more smoothly with the new method, and better reflect the tune response to the quadrupole gradient modulation.

A potential timing delay between the extracted tune data and the quadrupole strength data has been discovered. The re-analysis of the raw BBQ data also improves the synchronization of the tune and quadrupole strength data sources in the analysis.

A comparison between the calculated IP optics using the new and old analysis has been presented. The new analysis can lead to significant changes in calculated β^*, further highlighting the extreme sensitivity of this method to variations of tune, currents and timing offsets.

The improvements discussed in this paper lead to important refinements of the k-modulation method in the LHC, and help better prepare for the challenging HL-LHC conditions.

REFERENCES

[1] R. Calaga, R. Miyamoto, R. Tomás, and G. Vanbavinckhove, "Beta* Measurement in the LHC Based on K-modulation", CERN, Geneva, Switzerland, Tech. Rep., CERN-ATS-2011-149, 2011. `https://cds.cern.ch/record/1382057`

[2] M. Kuhn *et al.*, "New Tools for K-modulation in the LHC", CERN, Geneva, Switzerland, Tech. Rep., CERN-ACC-2014-0159, 2014. `https://cds.cern.ch/record/1742310`

[3] A. Hofmann and B. Zotter, "Run 641, 13.10.1975, 26 GeV/c, Measurement of the B-functions in the ISR", Note, ISR-TH-AH-BZ-amb, 1975. `http://cds.cern.ch/record/1131122`

[4] J. Borer, A. Hofmann, J. P. Koutchouk, T. Risselada, and B. W. Zotter, "Measurements of betatron phase advance and beta function in the ISR", *IEEE Trans. Nucl. Sci.*, vol. 30, p. 2406, 1983. `https://cds.cern.ch/record/143606`

[5] J. E. Poole, "Proceedings of the third LEP performance workshop", CERN, Geneva, Switzerland, CERN-SL-Div-Rep-93-019-DI, 1993. `http://cds.cern.ch/record/90748`

[6] I. Barnett, *et al.*, "Dynamic beam based calibration of orbit monitors at LEP; rev. version", CERN, Geneva, Switzerland, Tech. Rep., CERN-SL-95-97-BI, 1995. `https://cds.cern.ch/record/293401`

[7] G. H. Hoffstätter, "HERA accelerator studies", DESY, Germany, Tech. Rep., DESY-HERA-2000-07, 2000. `http://cds.cern.ch/record/486208`

[8] A. Jansson, P. Lebrun, and J. T. Volk, "Beta Function Measurement in the Tevatron Using Quadrupole Gradient Modulation", in *Proc. PAC'05*, Knoxville, TN, USA, May 2005, paper RPAT033.

[9] Z. Martí, J. Campmany, J. Marcos, V. Massana, and X. N. Gavaldà, "Detailed Characterization of ALBA Quadrupoles for Beta Function Determination", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 338–340. `doi:10.18429/JACoW-IPAC2015-MOPJE028`

[10] G. Goddere, J. Kewisch, S. Peggs, T. Satogata, S. Tepikian, and D. Trbojevic, "Measurements of the Betatron Functions and Phases in RHIC", in *Proc. EPAC'98*, Stockholm, Sweden, Jun. 1998, paper WEP06G.

[11] M, Hofer and R. Tomás, "Effect of local linear coupling on linear and nonlinear observables in circular accelerators", *Phys. Rev. Accel. Beams*, vol. 23, p. 094001, Sep. 2020. `doi:10.1103/PhysRevAccelBeams.23.094001`

[12] P, Thrane, R. Tomás, A. Koval, K. Ohmi, Y. Ohnishi, and A. Wegscheider, "Measuring β^* in SuperKEKB with K modulation", *Phys. Rev. Accel. Beams*, vol. 23, p. 012803, Jan. 2020. `doi:10.1103/PhysRevAccelBeams.23.012803`

[13] D. Trbojevic, L. A. Ahrens, M. Bai, V. I. Ptitsyn, T. Satogata, and J. van Zeijts, "Measurements of the Betatron Functions in RHIC", in *Proc. PAC'01*, Chicago, IL, USA, Jun. 2001, paper RPAH123, pp. 3135–3137.

[14] F. Carlier and R. Tomás, "Accuracy and feasibility of the β^* measurement for LHC and High Luminosity LHC using k modulation", *Phys. Rev. Accel. Beams*, vol. 20, p. 011005, Jan. 2017. `doi:10.1103/PhysRevAccelBeams.20.011005`

[15] H. Garcia-Morales, M. Hofer, E. H. Maclean, L. van Riesen-Haupt, and R. Tomás, "Phase advance constraint in K modulation for precise β-function determination", *Phys. Rev. Accel. Beams*, vol. 25, p. 041002, Apr. 2022. `doi:10.1103/PhysRevAccelBeams.25.041002`

[16] M. Hofer, F. S. Carlier, and R. Tomás, "K-Modulation in Future High Energy Colliders", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 476–479. `doi:10.18429/JACoW-IPAC2019-MOPMP022`

[17] T. Persson *et al.*, "LHC optics commissioning: A journey towards 1% optics control", *Phys. Rev. Accel. Beams*, vol. 20, p. 061002, Jun. 2017. `doi:10.1103/PhysRevAccelBeams.20.061002`

[18] T. H. B. Persson *et al.*, "Optics Correction Strategy for Run 3 of the LHC", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 1687–1690. `doi:10.18429/JACoW-IPAC2022-WEPOST008`

[19] F. Carlier *et al.*, "LHC Run 3 Optics corrections", presented at IPAC'23, Vencie, Italy, May. 2023, paper MOPL015, this conference.