60° PHASE ADVANCE OPTICS MEASUREMENTS IN THE LARGE HADRON COLLIDER AT CERN

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Abstract

The Large Hadron Collider (LHC) arcs have been designed for a FODO optics with roughly 90° betatron phase advance per arc cell, but not necessarily with exactly the same optics in the eight sectors of the ring. Measuring an optics with a significantly different arc cell phase advance, e.g. 60° which is at the limit for aperture at LHC injection, offers the possibility of understanding the LHC in an unprecedented depth. Furthermore, this optics would allow focusing higher energy beams, since the required quadrupole settings are lower than for the standard 90° optics for the same beam energy. Such an optics has therefore been designed, respecting all constraints for one low intensity pilot bunch per beam, and tested during commissioning of LHC Run 3 in 2022. First measurements, performed only for one beam at injection, are presented and compared to results obtained for the nominal 90° optics.

MOTIVATION

With approximately 27 km circumference, the Large Hadron Collider (LHC) [1] at CERN presently collides two counter-rotating proton beams, each with 6.8 TeV beam energy, and holds the luminosity record for hadrons of about $2 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$. Its upgrade, the High Luminosity LHC (HL-LHC) [2], aims at increasing this value to at least $5 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$, which demands an improved understanding of the existing lattice [3]. Previous studies [4] aiming to measure the momentum compaction factor, α_C, from Turn-by-Turn (TbT) data suggest an average arc Beam Position Monitor (BPM) calibration error. While all analyzed optics with roughly 90° arc cell phase advance feature an α_C between 3.2×10^{-4} and 3.5×10^{-4}, this parameter is about a factor 2 larger (6.9×10^{-4}) in the here presented 60° optics. Hence, measuring α_C for this 60° optics helps concluding on possible calibration errors. The most fundamental difference between 90° and 60° arc cell phase advance optics is that the latter requires about 30% lower main quadrupole gradients at the same beam energy and could, therefore, be used for possible energy upgrades of the HL-LHC; or also for the hadron Future Circular Collider [5–7]. Furthermore, the betatron integer tune split is reduced from 2 to 1, and, thus, magnetic multipole errors and misalignments are probed differently, allowing for an improved understanding of the lattice. A 60° optics has therefore been designed and first measurements performed for Beam 1 with one low-intensity ($\approx 10^{10}$ protons) bunch at 450 GeV. More information is given in Ref. [8].

DESIGN CONSIDERATIONS

The optics design has been carried out using MAD-X [9] and is based on the 2021 injection optics [10]. Reducing the phase advance to 60° in the arc FODO cells increases the β-functions and the dispersion. The LHC has 8 arcs, each with 23 FODO cells, connecting 8 Interaction Regions (IRs) with various functionalities. The main experiments are located in IR1 and IR5. IR2 and IR8 host specialised experimental detectors and are where Beam 1 and Beam 2 are injected, respectively. Momentum and betatron collimation is located in IR3 and IR7 respectively, whilst IR4 hosts the accelerating RF-cavities, with the beam dumps in IR6. Each FODO cell, shown in Fig. 1, consists of 6 main dipoles (MBs), each with one sextupole corrector (MCS). After every second MB is an octupole (MCO) and decapole (MCD) corrector. The short straight section is equipped with a main quadrupole (MQ), a trim quadrupole (MQT), an orbit corrector (MCB), a main sextupole (MS) and a BPM.

In addition to the arcs, the optics in all IRs and dispersion suppressors is also modified. Dispersion peaks are limited to about 4.5 m, while the Beam Stay Clear, evaluated in MAD-X [11] using parameters in Ref. [12], is more than 13 σ in the arcs for 90° and 60° optics. Local bottlenecks of about 8 σ arise in the latter and stem from large local β-functions. These minima are sufficient for measurements with one pilot bunch at 450 GeV. The nominal fractional tune working points at injection of 0.28 (horizontal), 0.31 (vertical) are kept. No crossing angles or beam separations are included, resulting in a flat optics and zero vertical dispersion. Tune and chromaticity knobs are generated using all arc MQT and MS circuits, respectively. Skew quadrupoles are used for coupling control.

With 60° phase advance, the MQs are powered with roughly 500 A current at 450 GeV, compared to about 750 A

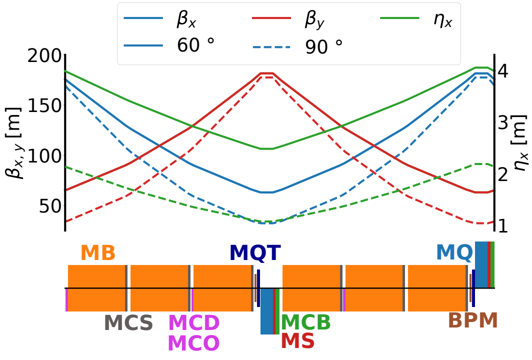

Figure 1: 60° and 90° FODO cell optics. Focusing (defocusing) elements are shown above (below) the horizontal axis.

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for 90° optics. The impact of MQ transfer function errors at 500 A, given in Ref. [13], are simulated by applying them via a random Gaussian distribution for 100 different seeds. Tune shifts are corrected using MQTs and a maximum horizontal and vertical β-beating (relative error of the β-function with respect to the error-free model) of 5.2 % is found. Systematic quadrupole errors (b_2, see also [14]) in the MBs are, amongst others, summarized in the WISE tables [15, 16] for 60 different seeds and are applied to the 60° optics. The generated phase shift is corrected using arc MQTs. The required strength is roughly 10 and 25 % larger for focusing and defocusing MQTs, respectively, in the 60° optics compared to 90° optics. Combining quadrupolar errors in MQ and MB elements, and correcting using MQTs yields an rms β-beating below 6.5 % for both beams and planes.

MEASUREMENTS

A 60° optics was measured for the first time in the LHC during commissioning of Run 3 in 2022 [17]. We note, that only Beam 1 was measured, with the results presented here. Commissioning of a completely new optics requires beam threading, performed with one bunch of $\approx 5 \times 10^9$ protons. During this procedure for the 60°optics, the Beam 1 bunch was lost in the cold section before IR7 due to a large vertical orbit, leading to a magnet quench. However, stable conditions were quickly recovered and the threading completed successfully. Once a circulating beam was established, orbit, linear coupling and tune corrections were performed.

Optics

Optics measurements are performed using the same techniques as for the 90° optics, see [18, 19], using an AC-dipole with $\Delta Q_x = 0.012$ and $\Delta Q_y = -0.01$ with respect to the nominal tune. Both on- and off-momentum measurements are acquired. Comparing the 60° with the 90° injection optics, a respective rms β-beating of 15 and 9 % is measured horizontally with 10 and 13 % measured vertically. However, large horizontal β-beating peaks up to 40 % between IR5 and IR7 are found in the 60° optics, as seen in Fig. 2.

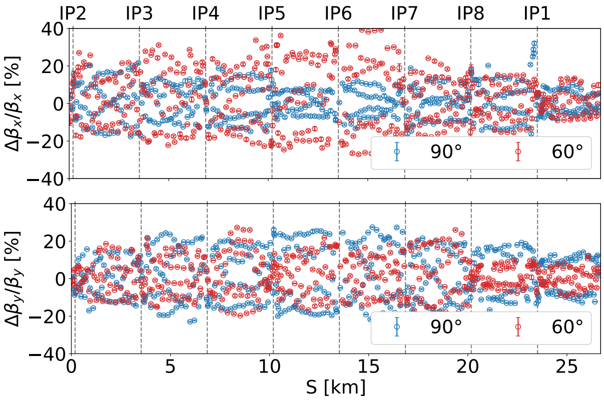

Figure 2: Measured horizontal (top) and vertical (bottom) β-beating for 60° and 90° optics.

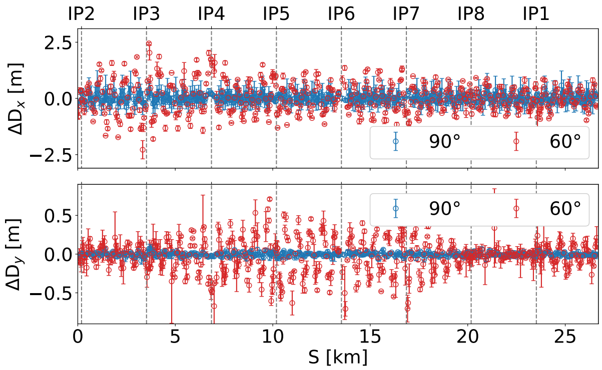

Figure 3: Horizontal (top) and vertical (bottom) absolute error of dispersion measurements for 60° and 90° optics.

Although linear coupling has the same qualitative pattern for the two optics, the measured C^-, however, is about a factor 2 larger for the 60° optics, namely $(1.858 \pm 0.002) \times 10^{-3}$, compared to $(0.906 \pm 0.001) \times 10^{-3}$.

A relative momentum offset δ of approximately ±0.003 is obtained using $\delta = \langle D_{x,i}\, CO_{x,i} \rangle / \langle D_{x,i} \rangle$ with the model horizontal dispersion D_x and the measured closed orbit CO_x at arc BPM i. The absolute horizontal rms dispersion error, shown in Fig. 3, is about a factor 3 larger for 60° optics, which stems partially from a factor 2 larger arc dispersion. Vertically, however, a factor 9 larger rms dispersion is found, the origin of which is presently being investigated. Since the optics is only measured at three distinct δ values, higher-order dispersion [20] cannot be estimated.

Global corrections for the 60° optics are calculated using a response matrix approach, reducing the β-beating, the phase advance shift and normalized horizontal dispersion [21] with all available quadrupolar circuits in the arcs and IRs. Vertical dispersion is not corrected. The relative change of quadrupole strength is up to $\Delta K = \pm 3 \times 10^{-4}$ in IR1 and IR8. The measured rms horizontal and vertical β-beating of 15 and 10 % is reduced to approximately 6 % in both planes. However local β-beating peaks of up to 40% are generated horizontally by the significant quadrupole strength adjustments, as shown in Fig. 4. Calculated and applied

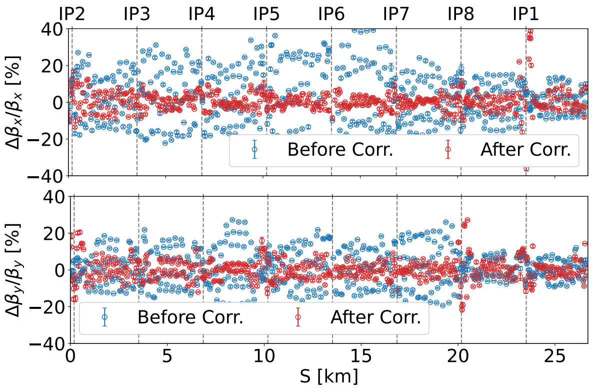

Figure 4: Measured horizontal (top) and vertical (bottom) β-beating before and after global optics corrections.

corrections were sufficient for this beam test, but further corrections are envisaged in future measurements.

Chromaticity Scan

Chromaticity describes the tune shift with δ. In the presence of chromaticity, the tune is given by the Taylor expansion

$$Q_{x,y}(\delta) = \sum_{n=0}^{\infty} \frac{1}{n!} Q_{x,y}^{(n)} \delta^n \ . \qquad (1)$$

A chromaticity measurement was performed for the first time for the 60° optics, by varying the RF-frequency [22]. The induced δ ranges from -2.3×10^{-3} to 1.1×10^{-3} with the tune measured via the Base-Band Tune system (BBQ) [23] at each step. The chromaticity function was fitted according to Eq. (1) up to $n = 5$, as shown in Fig. 5. Simulations were performed with MADX-PTC including normal and skew multipole errors from octupoles to hexadecapoles [14] and compared to measurements. For reference, the ratio between measurements and simulations is also given for the 90° optics. Contrary to the 90° injection optics, where only up to $Q_{x,y}^{(3)}$ is found [22], up to $Q_{x,y}^{(5)}$ is observed in the 60° optics. It can be observed that model and measurements agree quite poorly for most terms, something requiring further studies to understand the discrepancy. A summary of the results is given in Table 1.

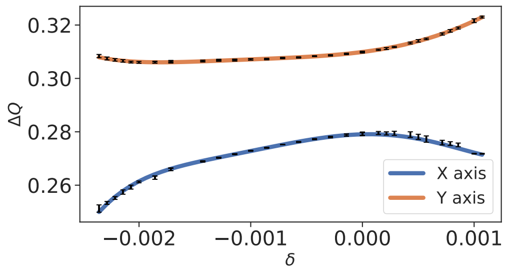

Figure 5: Measurement of chromaticity with unpowered correctors, including a fit up to $n = 5$ (see Eq. (1)).

Table 1: Measured (Meas.) and model (Sim.) higher-order chromaticity for 60° optics including the ratio (Meas./Sim.). The ratio is also given for virgin 90° injection optics.

	Sim.	**Meas.**	**Ratio**	
			60°	**90°**
$Q_x^{(2)}$ [10^3]	1.7 ± 0.1	-16.6 ± 0.5	-9.6	-4.1
$Q_x^{(3)}$ [10^6]	61.5 ± 0.2	-13.2 ± 1.2	-0.2	0.43
$Q_x^{(4)}$ [10^9]	-1.7 ± 0.1	41.1 ± 5.8	-24.0	-
$Q_x^{(5)}$ [10^{12}]	22.7 ± 0.1	102.7 ± 8.5	4.5	-
$Q_y^{(2)}$ [10^3]	-1.1 ± 0.1	9.0 ± 0.1	-8.0	-0.6
$Q_y^{(3)}$ [10^6]	-50.1 ± 0.1	12.0 ± 0.4	-0.2	0.42
$Q_y^{(4)}$ [10^9]	0.4 ± 0.1	-1.3 ± 1.8	-3.0	-
$Q_y^{(5)}$ [10^{12}]	-15.7 ± 0.1	-22.6 ± 2.8	1.4	-

BPM Calibration

Similar to [4] α_C is measured from TbT data by fitting the relative momentum offset obtained using the measured closed orbit over the RF-frequency shift $\Delta f/f$, namely $\delta = -(\gamma_{\text{rel}}^{-2} + \alpha_C)^{-1}(\Delta f/f)$. At 450 GeV with the relativistic Lorentz-factor, γ_{rel}, γ_{rel}^{-2} is 4.33×10^{-6}. For the 60° optics a 4.63 % lower α_C with respect to the model is measured. Over various measurements obtained for 90° optics in Run 2 and Run 3, together with the 60° optics measurements a systematic lower α_C by 3.02 ± 0.003 % is found, with the error bar obtained from the linear fit shown in Fig. 6. Since the observed offset is consistent between various optics, it is presently assumed that this discrepancy arises from an average horizontal arc BPM calibration error of +3 %.

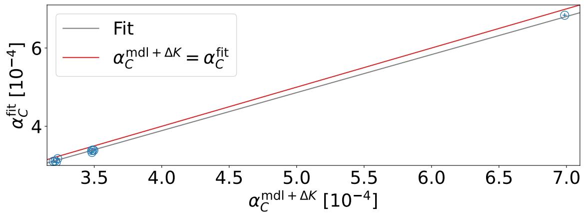

Figure 6: Measured momentum compaction factor from TbT data compared to that of the model for 90° and 60° optics.

SUMMARY AND OUTLOOK

For the first time in the LHC, a new optics with a reduced phase advance of 60° in the arc FODO cells has been designed and successfully deployed for a test on Beam 1 during Run 3 commissioning at 450 GeV. After beam threading and orbit corrections, the optics was successfully measured and global corrections calculated and applied. Compared to the 90° injection optics, a drastically larger vertical dispersion was found, the origin of which is being presently being investigated. Comparing the data from 60° and 90° optics measurements opens the possibility to better localize error sources. Chromaticity up to fifth order was measured, suggesting severe non-linear contributions that are being further investigated. Using on- and off-momentum closed-orbit measurements the momentum compaction factor is measured to be 4.63 % lower than the model. The average over various optics measurements yields roughly −3 %, which is attributed to an average arc BPM calibration error of +3 %, which could, consequently, demand a re-evaluation of IR BPM calibration [24]. It should be noted that this only applies to the horizontal plane and no conclusion can be drawn for the vertical one. Measurements for Beam 2 remain to be and are foreseen to be done during LHC Run 3.

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