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EVOLUTION OF SPECIAL LHC OPTICS CONFIGURATIONS RUN 3 UPDATE

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Abstract

The Large Hadron Collider (LHC) employs special optics and configurations, alongside low-β^* collision optics, to address specific experimental requirements. These include calibrating luminosity monitors through dedicated van der Meer (vdM) scans and facilitating forward physics measurements in TOTEM and ALFA experiments (high-β^* runs). The special optics have been in use since Run 1, and for Run 3, they have been updated for compatibility with standard low-beta collision optics to ensure streamlined commissioning and reduced setup time. For vdM optics in Run 3, beam de-squeezing yields β^* values of 19.2 to 24 m, while in high-β^* optics, beams are de-squeezed first to round beams of 120 m β^*, followed by a second step to optics with β^* of 3 km in the horizontal and 6 km in the vertical plane. The 2023 run with high-β^* optics at km range, incorporates tight collimation settings with the use of crystal collimation schemes at top energy, aiming to substantially reduce backgrounds in the experiments. This publication introduces and discusses the updated optics for Run 3, covering their validation, optics measurement results, and operational insights.

INTRODUCTION

For the LHC's nominal operation at high luminosity and maximal proton collision rate, low-β^* optics are employed, achieving β^* values as low as 0.30–0.25 m [1]. Special optics have been developed to address specific requirements, such as absolute calibration of luminosity-sensitive detectors via the vdM method [2], and the study of forward physics in TOTEM and ALFA experiments, which analyze proton-proton scattering products at small angles. Initially developed in Run 1 [3], these optics have been updated for Run 3 to accommodate revised experiment requirements, while remaining compatible with the standard low-β^* collision optics at injection, ensuring streamlined commissioning and reduced setup time.

vdM Optics In the vdM case, the optics involve de-squeezing the beams at the interaction points from an injection β^* of 11 m to β^* values of 19.2 m for IP1, IP2, and IP5, and 24 m for IP8, as specified by the experiments. For example, Fig. 1 illustrates the optics obtained for IP1. While maintaining left-right anti-symmetry, aperture constraints, and phase advance similar to that of the nominal low-β^*, the insertion optics is matched to the regular arcs at both ends

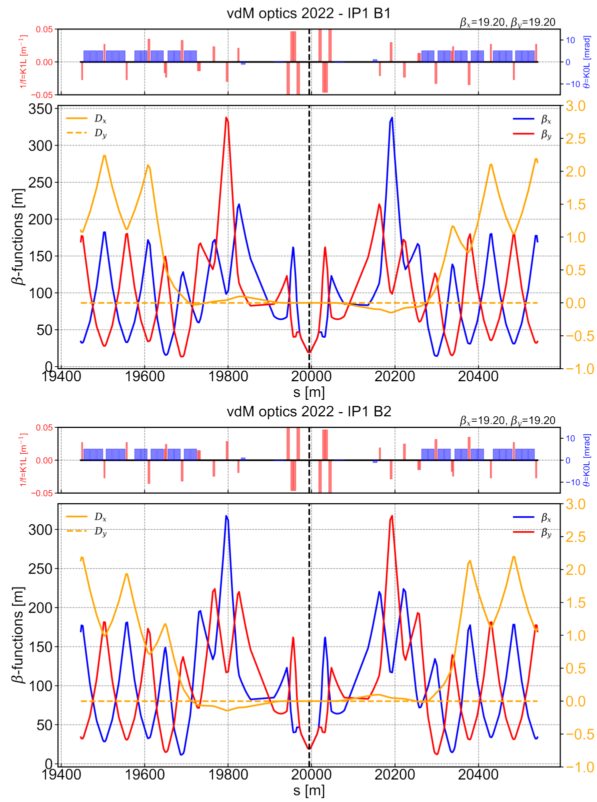

Figure 1: The vdM optics for the insertion around IP1 for B1 (top) and B2 (bottom) at a β^* of 19.2 m.

for both beams for all interaction points. The transition from injection to top energy and β^* de-squeeze values occurred with eight matched points maintaining a beta-beating of less than 2 % between them.

High-β^* Optics The high-β^* optics are designed to provide large β^* values with small beam divergence at the IP, along with parallel to point focusing in the measurement vertical plane at the location of the Roman Pot (RP) detectors of the experiments, located approximately 220 m at either side of the IP. In this setup, the pp scattering products emitted through small four-momentum transfer t at small angles θ_y^* at the IP, typically of few microradians ($-t \sim p^2\theta_y^{*,2}$), can be separated from the circulating beam and detected at a distance y in the RP detectors following $y \sim L_{\mathrm{eff},y} \cdot \theta$, with $L_{\mathrm{eff},y} = \sqrt{\beta_{\mathrm{RP},y}\beta_y^*}\sin(\Delta\mu_y)$. $\beta_{\mathrm{RP},y}$ is the betatron amplitude at the RP location and $\Delta\mu_y$ the phase advance between the IP and the RP location in the vertical plane. The beam

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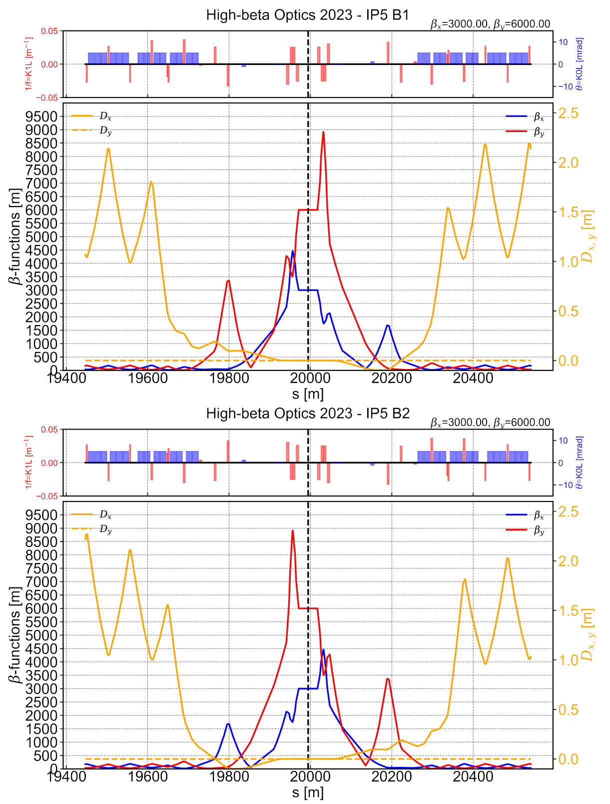

Figure 2: The 3/6 km high-beta optics at IP5 for B1 (top) and B2 (bottom).

size at the IP is large, and the machine is filled with a low number of bunches to prevent parasitic collisions [4].

For Run 3, experiments plan the final set of measurements with a focus on configurations featuring ultimate β^* values. These configurations involve collisions of round beams at a β^* of 120 m, followed by a setup with β^* of 6 km in the vertical plane and 3 km in the horizontal plane to maintain reasonable luminosity. Referred to as the 3/6 km optics, they enable the investigation of very low t values to determine the total cross-section and elastic scattering in the Coulomb-Nuclear Interference (CNI) region, as well as probing the ρ parameter normalization of the total cross-section. Fig. 2 illustrates the optics obtained for the IR5 insertion for the TOTEM experiment. Table 1 summarizes key optics parameters.

Achieving km-β^* values poses challenges, with constraints on β^* and $\beta_{\mathrm{RP},y}$ and phase advances $\Delta\mu_y$ maximizing $L_{\mathrm{eff},y}$. These introduce significant phase advance changes: 62° in horizontal and 79° in vertical compared to nominal low-beta optics, compensated by adjusting the quads in all arcs. Some insertion quadrupoles and power converters are pushed to limits, with aperture constraints around IP mitigated by tight collimation settings. The transition from injection to high-β^* optics utilizes vdM optics up to 17.8 m β^* for compatibility and reduced commissioning time, then extends to 120 m β^* before final de-squeeze to 3/6 km β^* settings. This transition involves 26 matched β^* points, maintaining 3 % beta-beating between successive points.

Table 1: Key parameters for the high-beta optics for B1. B2 has similar parameters. The RP locations refer to the layout point where the optics conditions are applied, in the region of ALFA and TOTEM spectrometers.

		IP1	$\mathrm{RP}_{\mathrm{ALFA}}$	**IP5**	$\mathrm{RP}_{\mathrm{TOTEM}}$
s	[m]	-	241.5	-	220.0
β_x	[m]	3000	317.5	2982	864.1
β_y	[m]	6000	19.4	6000	14.3
α_x		0.0	3.26	0.0	26.98
α_y		0.0	0.41	0.0	-0.28
σ_x	[mm]	1.2	0.37	1.2	0.65
σ_y	[mm]	1.7	0.09	1.7	0.08
$\Delta\mu_x$	[°]	-	181.5	-	178.4
$\Delta\mu_y$	[°]	-	90.9	-	89.9
$L_{\mathbf{eff},x}$	[m]	-	-24.4	-	44.8
$L_{\mathbf{eff},y}$	[m]	-	319.3	-	293.4

OPTICS MEASUREMENTS

The vdM optics were commissioned in May 2022. The transition from injection to final β^* at top energy lasted approximately 21.2 minutes. Beam-based corrections of linear optics, including coupling, were calculated and implemented, with measurements conducted using quadrupole K-modulation and forced oscillations [5–8]. The measured β^* was found to be within 5 % to the nominal values in the optics for all beams and planes. It was not further corrected as the precision in the luminosity calibration using the vdM method does not depend on the exact value of the β^* but only on the error determining it, which was found to be 1.5 % from the K-modulation and phase measurements, to be combined with a 1.5 % error due to fill-to-fill variation estimated from repeated measurements.

The high-beta optics were commissioned in May-June 2023, starting with the segment up to β^* 120 m and the full de-squeeze to β^* 3/6 km in September 2023. The full de-squeeze from injection to the 3/6 km β^* took approximately 72 min, with the last part done at top-energy. Fig. 3 depicts the initial and final beta-beating after linear optics corrections, decreased from 100 % to less than 5 %, with RMS below 2.5 % across the entire ring. Corrections to the inner triplet magnet strength were around 0.3 %. Validation of the corrections was done by examining the phase advance variation, which for the segment IP to RP locations remained below 5 % after all corrections were applied.

PHYSICS RUNS

The vdM optics is used in dedicated LHC fills occurring during the operation year. The machine parameters, along with the optics, are such to minimize sources of uncertainties during the process. Typically, the LHC is filled with 140 isolated bunches in each beam, arranged so as to avoid

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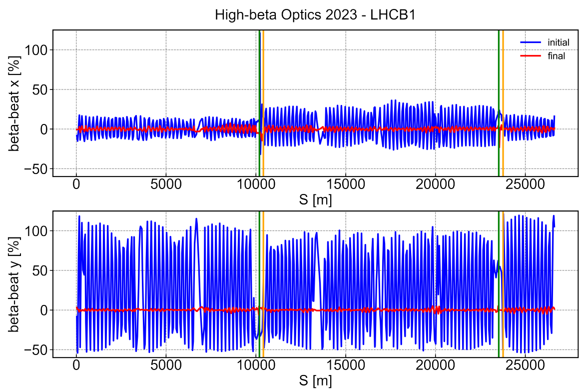

Figure 3: Beta-beating of B1 before and after all corrections for the x (top) and y (bottom) planes for the 3/6 km optics. The green lines indicate the location of the IPs and the orange the RP detectors. Similar performance was observed for B2.

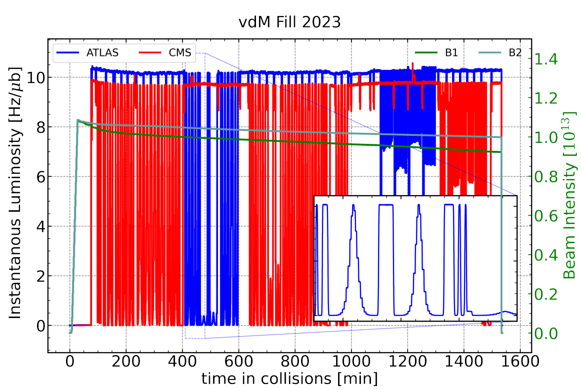

Figure 4: Beam intensity and instantaneous luminosity evolution in ATLAS and CMS experiments during a long vdM fill in June 2023. Inset: zoom in a period with two successive Vernier scans of the beams in x and y planes up to 6 σ.

parasitic long-range encounters between the incoming and outgoing bunches at all interaction points. In this configuration, the beams can collide head-on with zero crossing angle to minimize effects from orbit drifts and beam-beam related uncertainties. The bunch intensity is adjusted to 0.7–0.8×10^{11} protons. The bunches are produced in the injectors with larger normalized emittance than nominal, about 3 µm rad, and with minimized transverse beam tails. The transverse beam size at the IP is about 60 µm.

Figure 4 shows the beam intensity and instantaneous luminosity evolution in ATLAS and CMS during a vdM fill in 2023. Thanks to excellent beam stability, a record fill of 24.06 h in collisions was achieved, in which numerous planar or combined 2D x, y scans were realized.

The high-β^* 3/6 km optics was used in September 2023 for TOTEM and ALFA experiment physics. The machine was filled with only 3 bunches per beam with intensities of 0.5–0.6×10^{11} protons, and a special configuration of the LHC collimation system was setup in order to minimize the background to the RP detectors. Figure 5 shows the beam intensity evolution for an example fill: the beams are scraped in both planes with the primary collimators

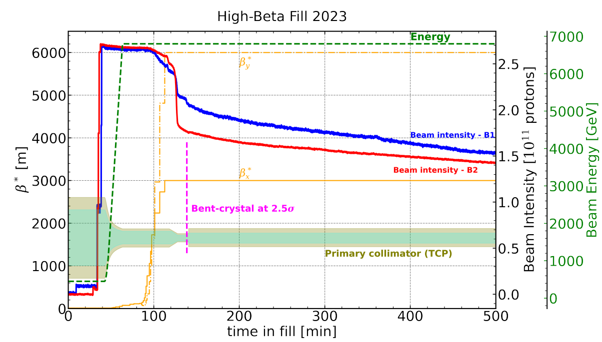

Figure 5: Beam intensity evolution during a high-β^* fill.

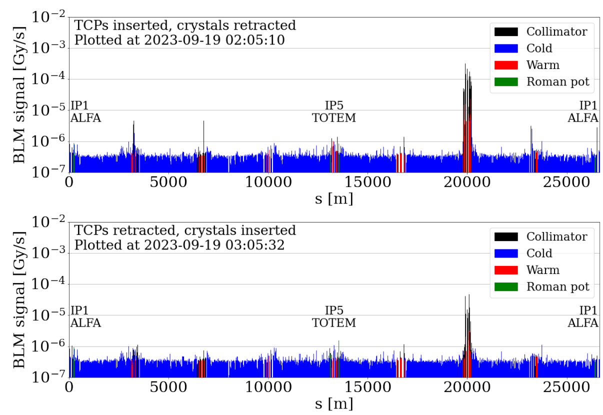

Figure 6: Loss pattern along the LHC ring during the high-β^* 3/6 km fill, using a standard TCP (top) or a bent-crystal (bottom) as primary collimator.

inserted gradually down to 2.3 σ to simultaneously mitigate the aperture limitations around the IPs and facilitate the detection of the pp scattering products within the detector acceptance.

Then, the primary collimators are retracted and the bent-crystal collimators are inserted adiabatically to 2.5 σ, with the process being almost transparent for the beam intensity. The benefit of using the bent-crystals is shown in Fig. 6, where a reduction of the beam losses at the vicinity of the RP detectors by up to an order of magnitude is shown [9–11]. Thanks to the observed low halo re-population speed [11], there was no need to periodically repeat the scraping phase.

In this configuration, the high-β^* fills typically lasted 7–14 hours in collisions, allowing the experiments to collect the planned 300 µb^{-1} of collision data, over a period of 10 days.

CONCLUSION

In LHC Run 3, updated vdM calibration and high-β^* optics were effectively deployed. The vdM optics enabled longer fills, facilitating extensive measurements under consistent conditions for improved precision. The high-β^* 3/6 km optics run, enabled TOTEM and ALFA experiments to probe low momentum transfer regions in pp scattering under optimal conditions using bent crystals as primary collimators, showcasing their potential for background reduction.

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