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90M OPTICS STUDIES AND OPERATION IN THE LHC

H. Burkhardt, G. Müller, S. Redaelli, R. Tomas, G. Vanbavinckhove, J. Wenninger, CERN, Geneva, Switzerland, S. Cavalier, LAL,Université Paris Sud 11, S. White, BNL, Upton, New York

Abstract

A high $\beta^* = 90\,\mathrm{m}$ optics was commissioned and used for first very forward physics operation in the LHC in 2011. The experience gained from working with this optics in 5 studies and operation periods in 2011 was very positive. The target $\beta^* = 90\,\mathrm{m}$ was reached by a de-squeeze from the standard 11 m injection and ramp optics on the first attempt and collisions and first physics results obtained in the second study. The optics was measured and corrected with good precision. The running conditions were rather clean and allowed for measurements with roman pots very close to the beam.

INTRODUCTION

High β^* optics have been requested by the ATLAS-ALFA and TOTEM experiment to be used in special physic runs for low angle precision measurements of the proton-proton scattering in the LHC using roman pot detectors installed in the very forward region around the LHC interaction points IP1 and IP5 [1, 2].

The experience with the 90 m optics, has been very positive in 2011. We had 5 short special running periods dedicated to the operation at 90 m adding up to a total 4.2 days of running time [3]. We succeeded to reach 90 m using a de-squeeze from the standard 11 m injection optics and ramp in a single fill [4] using the main quadrupoles of all LHC arcs for the external tune compensation and to commission the new 90 m optics with parallel separation bumps in the second special run. This allowed to bring beams into collisions at the end of the second special run dedicated to 90 m, see Fig. 1 [5], and to leave beams into collisions for about an hour which was used by the TOTEM experiment to obtain a first measurement of the total proton-proton cross section at LHC energies to a precision of 3% [6].

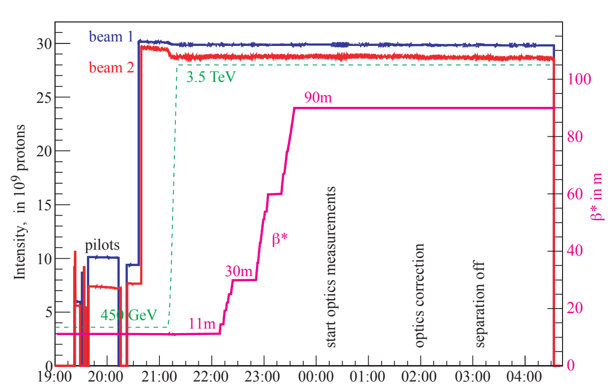

Figure 1: Intensities, energy and β^* as a function of time during the 2nd study dedicated to 90 m.

The following three dedicated 90 m sessions were used to re-measure the optics, adjust collimators and roman pots closely around the beam and for data taking for the TOTEM and ALFA experiments.

The beam intensity in the special 90 m runs is much reduced (nearly 1000 times) compared to standard high luminosity operation. This allows for much tighter collimator and roman pot settings at 90 m than in standard physics. The crossing angle is turned off for high-β operation. The minimal bunch spacing to avoid parasitic crossings without crossing angle is 524 ns, which limits the maximum number of bunches to 156, see also Table 1. For the special 90 m runs described here, we used typically 3 bunches, two with an intensity of 7×10^{10} protons and a third very low intensity probe bunch.

Table 1: Comparison of the main intensity related beam parameters for the 90 m runs, compared to standard 2011 high luminosity operation and LHC design parameters.

	90 m	standard 2011	LHC design
bunch spacing	≥ 524 ns	50 ns	25 ns
#bunches	$\sim 3, \leq 156$	1380	2808
total intensity	2.5×10^{11}	2×10^{14}	3.2×10^{14}

In this paper, we summarize the experience with the 90 m optics commissioning and operation in 2011. Future plans and prospects are described in [7]. Precise local measurements of optics parameters performed with the TOTEM detector are described in [8].

GETTING TO 90 M

The 90 m optics have been designed to use as much as possible the standard LHC injection and energy ramp. The aim is to minimize the extra set-up time required in special running conditions. The injection optics is the standard optics, with $\beta^* = 11, 10, 11, 10\,\mathrm{m}$ in the LHC interaction points IP 1, 2, 5, 8 which uses crossing angles in all interaction points. The procedure for the ramping up to the physics energy in 2011, $E_b = 3.5\,\mathrm{GeV}$, is the same as for standard operation with one exception : the parallel separation is kept always at a constant $\pm 2\,\mathrm{mm}$ in IPs 1 and 5. The crossing angles in IP1 and IP5 are turned off at top energy before the de-squeeze to 90 m.

The target value of $\beta^* = 90\,\mathrm{m}$ is reached by a de-squeeze from the injection $\beta^* = 11\,\mathrm{m}$ using 17 intermediate steps. A major challenge in the simultaneous de-squeeze of IP1 and IP5 from $\beta^* = 11\,\mathrm{m}$ to $\beta^* = 90\,\mathrm{m}$ is a significant tune reduction of up to 0.45. It is compensated by an increase of the strength of the main LHC quadrupoles (QD, QF) during the de-squeeze, which mod-

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ifies the optics all around the LHC and induces a few per cent of β-beating [9]. Orbit and tune feedbacks were used during the de-squeeze, and the required corrections incorporated as feed-forward for the following de-squeeze [4], which allowed to reduce the number of stops during the de-squeeze in the subsequent 90 m runs.

OPTICS MEASUREMENTS

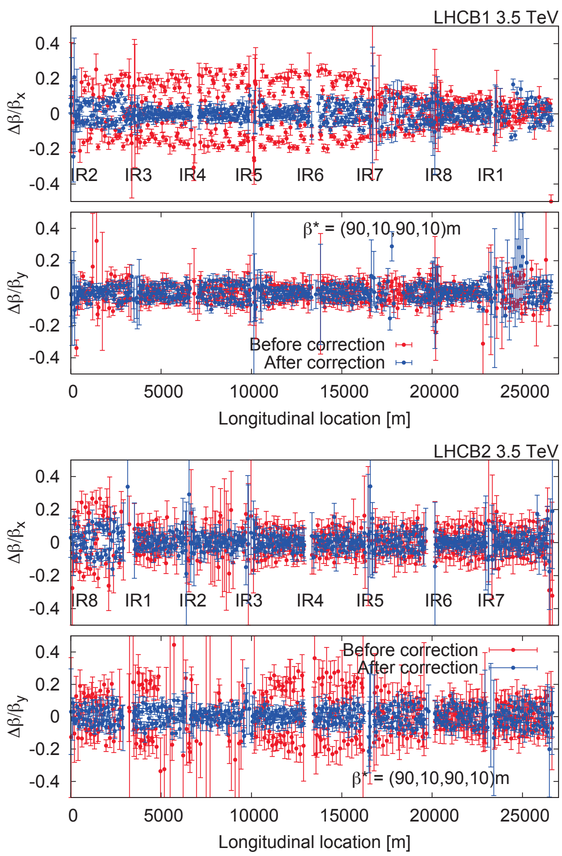

Figure 2: Measured β-beat at, 90 m, for beam 1 x,y (top) and beam 2 x,y (bottom).

Global optics measurements of β, coupling and dispersion were performed using the LHC AC-dipoles, which induce transverse oscillations [10]. In addition, the β^* and waist were measured locally at IP1 and IP5 using K-modulation [11]. The initial β-beating (which is the normalized difference between measured and model β) in the first 90 m study was found to be between 20 and 30% [4]. Based on these measurements, corrections were calculated and applied for the subsequent 90 m runs. The global corrections were calculated using a response matrix approach. No common correctors were used for these corrections. Fig. 2 shows the measured β-beat and Fig. 3 the dispersion measured at 90 m before and after correction. The β-beat after the corrections was reduced to $10 - 15\%$.

The experiments require an accurate knowledge of the effective length

$$L^y = \sqrt{\beta^* \beta^{rp}} \sin \mu \,, \tag{1}$$

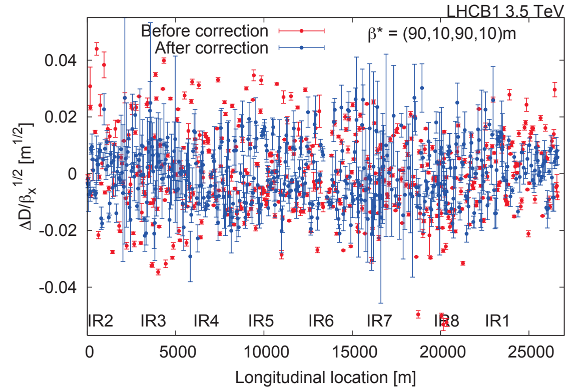

Figure 3: The normalized horizontal dispersion for beam 1, before corrections (red) and after corrections (blue).

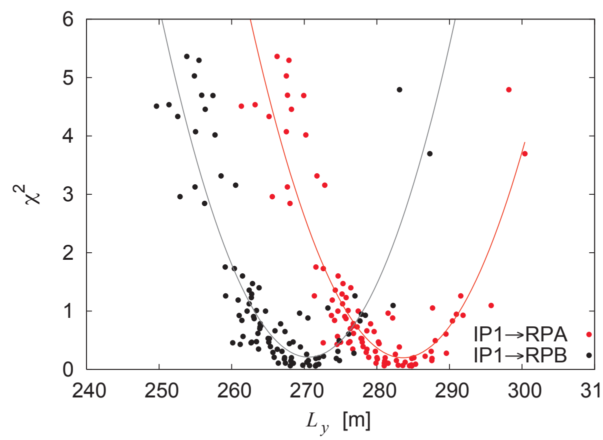

Figure 4: χ^2 versus measured L^y, using different optics models generated by Monte-Carlo simulation.

where β^* and β^{rp} are the β-function at the IP and roman pot, respectively; μ is the phase advance between the roman pot and the IP. L^y translates an angular kick at the IP to an offset at the roman pot (equivalent to the transfer matrix element R_{34}). Two different techniques were used to determine the effective length L^y from the optics measurements. The first is a segment-by-segment technique, referred to as SBS [12], in which the measured optical functions at the nearest available BPMs are used to obtain the values of the right hand side of Eq. 1. This approach assumes an ideal model between the BPMs, the IP and the roman pots. Table 2 shows the most precise values obtained by SBS for the TOTEM roman pots. The accuracy is 3% on L^y.

The second method is based on Monte-Carlo simulation and does not require to assume an ideal optics. Instead, 100 machine models are generated using different random sets of quadrupole errors and compared to the AC-dipole measurements. Fig. 4 shows the χ^2 versus the corresponding L^y for the different models. Table 3 lists the L^y values obtained by both techniques which agree within the error bars. The L^y values obtained at the minimum χ^2 from

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Monte-Carlo modeling are expected to be less affected by systematic errors and are slightly higher than the values obtained from SBS.

Table 2: Measured vertical β functions at the TOTEM roman pots and the IP, phase advance and effective length.

RP	β^{rp} [m]	β^* [m]	$\mu/2\pi$	L^y [m]
A	871 ± 3	89.7 ± 5.6	0.26 ± 0.01	277 ± 9
B	793 ± 7	89.7 ± 5.6	0.27 ± 0.01	264 ± 8

Table 3: L^y values obtained using the Segment-By-Segment technique (SBS) and Monte-Carlo (MC) modeling for the TOTEM roman pots.

Roman pot	Approach	$L^y[m]$
A	SBS	277 ± 9
A	MC	283 ± 8
B	SBS	264 ± 8
B	MC	270 ± 8

ROMAN POTS AND COLLIMATION

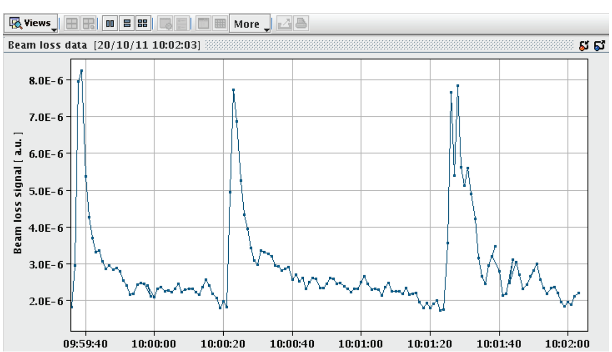

Figure 5: Closing the primary collimators to $5\,\sigma$. Loss rates recorded as a function of time for three $10\,\mu$m (or 0.036σ) steps, in 90 m operation at the 20 October 2011 at 10:02.

Collimators and roman pots are set from the LHC control room using the same motorization and procedures. They are centered around the beams based on the observation of the local beam loss rates using a semi-automatic beam-based alignment procedure [13]. This is illustrated in Fig. 5. The loss rate can be seen to increase sharply at each step and to decay within seconds to the previous level, showing that halo particles were removed. Using this procedure, the primary vertical collimators were closed down to $4.6\,\sigma$, in the last 90 m special run at a total intensity of 2×10^{11} protons / beam, mostly on two bunches of each 7×10^{10} protons (with σ calculated for a nominal $3.5\,\mu m$ normalized emittance). Towards the end of the final study, the vertical roman pots were closed to a minimum of $4.8\,\sigma$, remaining just within the shadow of the primary collimators, but receiving already increased background rates by intercepting some of the secondary halo. This showed, that it is in principle possible to bring roman pots very close to the beam for small beam intensities. It also showed, that it would be desirable to further reduce the emittances (here we had on average $2.2\,\mu$m) and to leave more margin between primary collimators, secondary collimators and roman pots.

SUMMARY

The initial experience with operation at higher β^* in the LHC has been very positive and allowed to achieve all our goals for this special running mode in 2011 in just four days of dedicated operation. The simultaneous de-squeeze to 90 m in IP1 and IP5 worked on the first attempt in-spite of the major tune changes. Collisions were reached in the second dedicated 90 m session and allowed for a first total proton-proton cross section measurement at the LHC. The optics was well measured and corrected. Data was recorded by the ALFA and TOTEM collaborations over $\sim$ 10 hours in stable conditions at 90 m with roman pots very close to the beam, down to $4.6\,\sigma$ for primary collimators and $4.8\,\sigma$ for the vertical roman pots in the final 90 m session in 2011.

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