COMMISSIONING AND OPERATION AT β^* = 1000 m IN THE LHC

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Abstract

We have developed a special optics with a β^* of 1000 m for two interaction regions (IR1 and IR5) in the LHC, to produce very low divergence beams required for elastic proton-proton scattering. We describe the design, commissioning and operation of this optics in the LHC. The β^* of 1000 m was reached by de-squeezing the beams using 17 intermediate steps beyond the β^* of 90 m, which had been the previous highest β^* value reached in the LHC. The optics was measured and the β beating globally corrected to a level of 10%.

INTRODUCTION

In standard high luminosity operation of the LHC, the beam sizes at the interaction points are reduced using low β^*-optics, using a minimum of $\beta^* = 0.6$ m in 2012. This maximizes the rate of proton collisions as required for rare processes like Higgs production. Squeezing the beams to low β^* however also increases the angular beam divergence, such that proton-proton scattering at small angles cannot be observed.

The standard high-luminosity, low-β operation in the LHC is therefore complemented by a few days of special high-β operation in which the beams are de-squeezed to very high-β^*, which minimises the angular divergence and makes very low angle scattering accessible.

STRATEGY AND CONSTRAINTS

The time to develop, commission and operate the special high-β^* optics is limited in the LHC to a few days. In early 2012, a strategic decision was made to restrict the LHC operation until mid-June exclusively to the high-luminosity operation to maximize chances to obtain first evidence for the Higgs particle for the summer conferences, and to delay the special runs to the second part of 2012.

High-β optics have to respect additional constraints: the phase advances in the vertical plane between interaction point and the roman pots placed 240 m downstream from the interaction points (in case of ATLAS-ALFA at IP1, 220 m for TOTEM at IP5), must be 90° such that the scattering angle at the interaction point directly translates into a position offset at the roman pot detectors [1, 2]. The LHC interaction region quadrupoles in the 2 rings are currently connected using single return cables. This restricts the current ratio for the main insertion quadrupoles to $0.5 < \text{beam1/beam2} < 2$.

The increase in β^* and beam size reduces the available aperture in the interaction regions. It becomes more difficult to keep beams transversely separated during the desqueeze and to provide sufficient orbit corrector strength and aperture to allow for separation scans to find and optimise collisions.

Based on these constraints, we estimated in spring 2012, that an already ambitious goal would be to commission operation at 500 m simultaneously in IP1 and IP5, and to attempt to extend this to a maximum of $\beta^* = 1000$ m if things go extremely well and sufficient time would be available [3].

1000 m OPTICS

The β and dispersion functions of the 1000 m optics are shown in Fig. 1 for IR5.

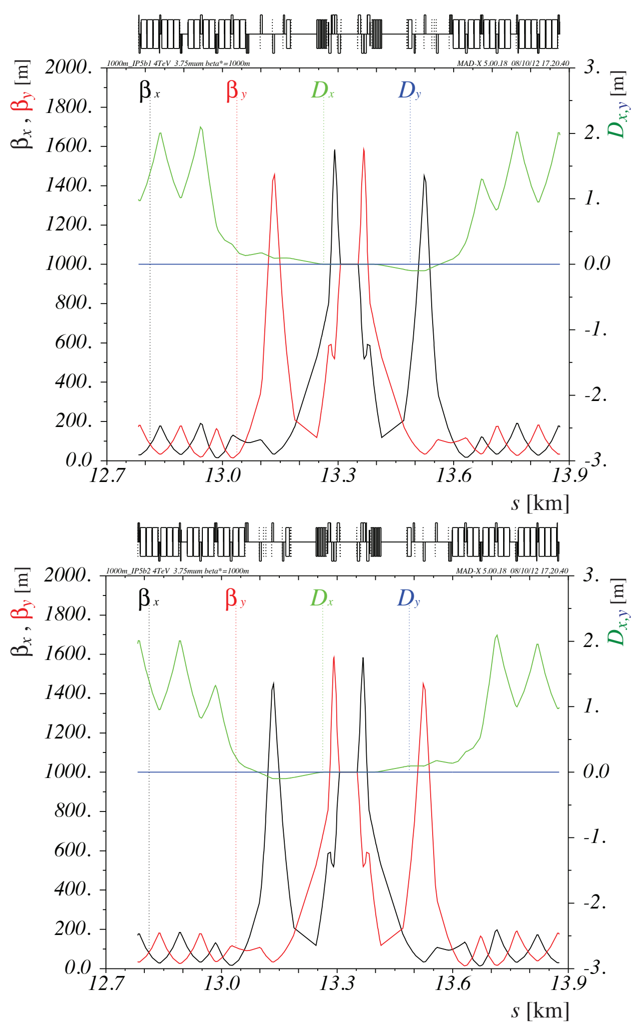

Figure 1: 1000m IP5, B1 (top) and B2 (bottom).

Figure 2 shows the aperture in terms of n_1 ($\sim$number of nominal σ including tolerances) around IR5 for beam 1 of the LHC [4]. Very similar apertures were also calculated for beam 2 and IP1 in the LHC. The minimum value of 6.3 σ is located at 21 m from the IP (TAS region). At 1000 m, this aperture bottleneck is a bit below our usual $n_1 = 7$ specification, shown as green lines.

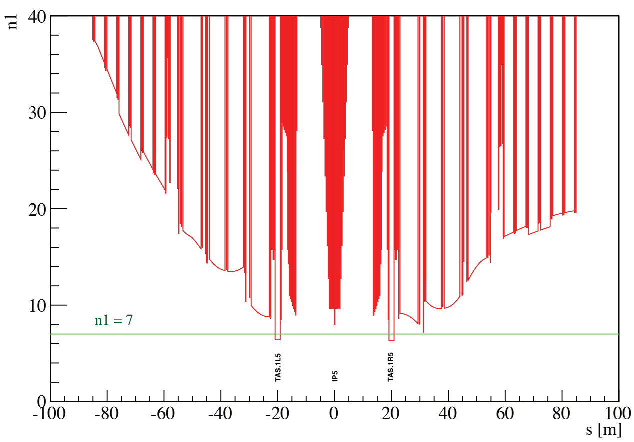

Figure 2: Aperture at 4 TeV, for the design emittance $\epsilon_N = 3.75\,\mu$m at $\beta^* = 1000$ m around IP5 including ± 2 mm parallel separation.

Table 1 shows main optics parameters at the IP and the roman pots. The effective length $L_y = \sqrt{\beta_y^* \beta_{y,\mathrm{RP}}} \sin(\mu_{y,\mathrm{RP}})$ (equivalent to the off-diagonal element R_{34} of the transport matrix) between the IP and the roman pots, and the reduction in contribution to the tune of the high-β insertion compared to standard optics are also given. The optics layout is identical in IP1 and IP5. The roman pot positions instead are different : downstream of quadrupole Q6 at 240 m in IP1 and upstream of Q6 at 220 m from IP5. As a result, the β-functions at the roman pot positions differ significantly between IP1 and IP5.

Table 1: Optics parameters at 1000 m for IP1 and IP5 for the roman pots at 240 m from the IP1, and 220 m from IP5, and the tune reduction compared to the standard optics. Beam sizes are given for a beam energy of 4 TeV and the design emittance $\epsilon_N = 3.75\,\mu$m.

Optics	1000 m, IP1		1000 m, IP5	
Beam	1	2	1	2
$\beta^*_{x,y}$, m	1000	1000	1000	1000
$\sigma^*_{x,y}$, mm	0.934	0.934	0.934	0.934
$\beta_{x,\mathrm{RP}}$, m	270.3	267.0	587.0	585.7
$\beta_{y,\mathrm{RP}}$, m	101.2	101.0	81.5	81.6
L_y, m	165.3	164.2	218.8	218.6
$\mu_{x,\mathrm{RP}}/2\pi$	0.4992	0.49929	0.49051	0.49051
$\mu_{y,\mathrm{RP}}/2\pi$	0.250	0.250	0.250	0.250
ΔQ_x	0.2115	0.2027	0.1772	0.1690
ΔQ_y	0.2440	0.2440	0.2440	0.2440

COMMISSIONING STEPS

High-β values are reached by de-squeezing the optics in the insertions IR1 and IR5 simultaneously at top energy from the injection and ramp value of 11 m in steps. Each step corresponds to an increase in β^* of 10 to 20 per cent and is chosen such, that the optics mismatch from linear extrapolation of magnet strengths between the steps remains at the level of a few per cent. This procedure was first very successfully applied in the LHC last year in the de-squeeze to 90 m [5]. The main arc quadrupoles of the LHC (QD, QF) were used to compensate the major reduction in tune (about 0.4 in x and nearly 0.5 in y during the de-squeeze).

Before any operation with beams in 2012, we performed tests in the control system with magnet powering which demonstrated that a maximum of $\beta^* = 1000$ m is still compatible with the hardware as presently installed. The main commissioning steps with beams were as follows

- at the end of the re-commissioning to 90 m at the beam energy of 4 TeV, de-squeezing successfully in 7 steps (on the 18 June) to a $\beta^* = 500$ m in IR1 and IR5 simultaneously
- two machine studies dedicated to high-β (21-23/6), measuring and correcting the optics at 500 m, first continuation of the de-squeeze in 5 additional steps to $\beta^* = 1000$ m without any significant beam-loss
- measuring and correcting the optics at 1000 m and first collisions (13-14/9)

Before the 1000 m optics could be used for physics, we had to demonstrate that it is possible to operate this optics with very tight collimation and roman pot settings. Details of this step are described in another contribution to this conference [6].

OPTICS MEASUREMENTS

Optics measurements of dispersion, coupling and β-beat were performed with the use of the AC-dipole [7]. The β-beat was between 20% and 30% before the corrections. From the measurement of the uncorrected optics, corrections were calculated and later applied. The corrections were calculated using a response matrix based on the ideal model [8]. The correctors close to IP1 and IP5, as well as the common correctors, were not used in the corrections. After the corrections the β-beat was reduced to $\sim$ 10%. Figure 3 shows the β-beat along the machine before and after correction.

The β^* at IP1 and IP5 were measured after the correction using K-modulation. The quadrupoles right and left of IP1 and IP5 were adjusted separately while the $\Delta Q_{x,y}$ were recorded [9]. The preliminary results, shown in Table 2, are overall in good agreement with the design optics. However, a tendency that the measured β^* is slightly higher then the design is observed.

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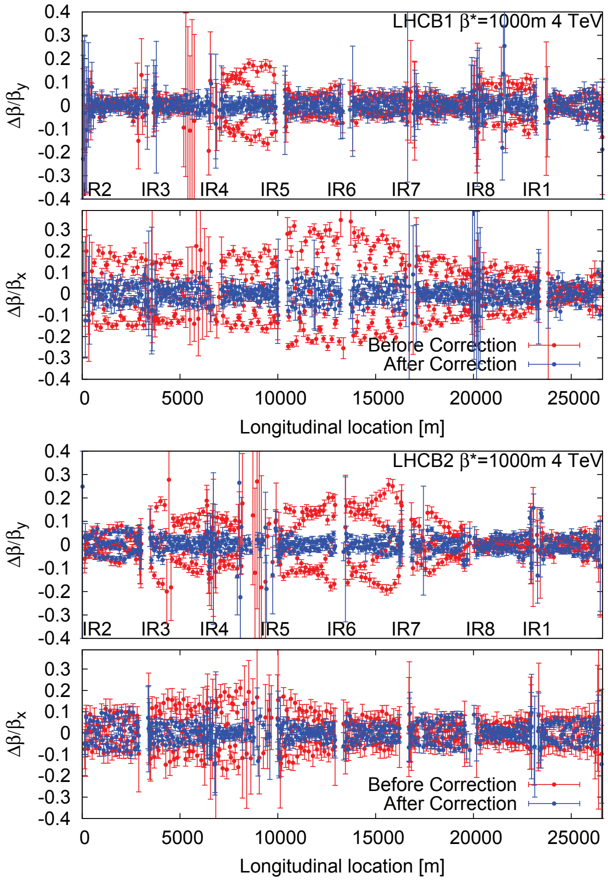

Figure 3: Measured β-beat at $\beta^* = 1000$m. Beam 1 is shown at the top and Beam 2 at the bottom.

Table 2: The $\beta^*_{x,y}$ of IP1 and IP5 measured with K-modulation.

IP	β^*_x [m]	β^*_y [m]
IP1	1112 ± 24	1045 ± 70
IP5	1106 ± 74	1025 ± 8

PHYSICS RUN AT 1000 m

Figure 4 shows an overview of the physics run of the 1000 m optics in the LHC. After losing a first fill at 1000 m (due to a spurious quench protection trigger, not related to high-β operation), collisions at 1000 m were provided for the ATLAS-ALFA and TOTEM experiments over a period of 10 hours in a single fill. The experiments recorded several 100 000 elastic proton-proton scattering events and were for the first time at LHC energies able to reach the Coulomb interference region [10].

CONCLUSION AND OUTLOOK

Even higher β^* values of the order of 2000 m will be required for the LHC run after the current first long shutdown to reach the Coulomb interference region at an increased beam energy of 6.5 TeV. This will require the installation of additional power cables on some of the insertion region quadrupoles, and at the same time provide more flexibility to optimize the phase advances between the interaction points and the roman pots.

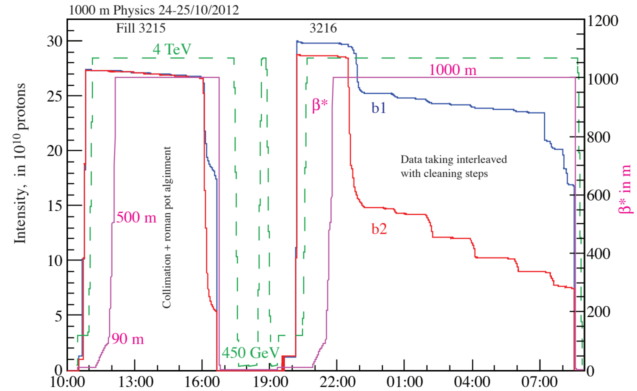

Figure 4: Beam 1, 2 intensities, energy and β^* as a function of time over 23 h for the 1000 m runs on the 24 to 25 October.

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