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Project Report

High-Beta Optics and Running Prospects

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Received: 9 October 2018; Accepted: 11 March 2019; Published: 18 March 2019

Abstract: Dedicated high-beta optics are used to make forward proton scattering measurements possible at the LHC. Following a short general introduction and history of special high-beta optics and running conditions, we describe the two types of special high-beta runs planned for 2018. A run at top energy at $\beta^*_y = 90\,\mathrm{m}$ for elastic and diffractive scattering, and a low energy run to measure the rho-parameter in the Coulomb interference region.

Keywords: optics for forward physics; machine induced backgrounds; rho-parameter

1. Introduction and Short History

Measurements of low angle scattering processes at high energy colliders require special efforts, both on the machine and detector side. On the machine side, special optics with high β^* are used to obtain at the interaction points beams with small angular beam divergence, and on the detector side special movable "Roman Pot" detectors are used to record the scattered particles very close to the beam. These techniques were pioneered at the ISR and used at hadron colliders like the Sp$\bar{\text{p}}$S and TEVATRON proton–antiproton colliders [1,2]. Optics with high $\beta^* \approx 4000\,\mathrm{m}$ were also considered for the SSC [3]. An early version of a high-β^* optics for the LHC was described in [4].

The general evolution of β-functions and beam sizes around an LHC interaction region are illustrated in Figure 1.

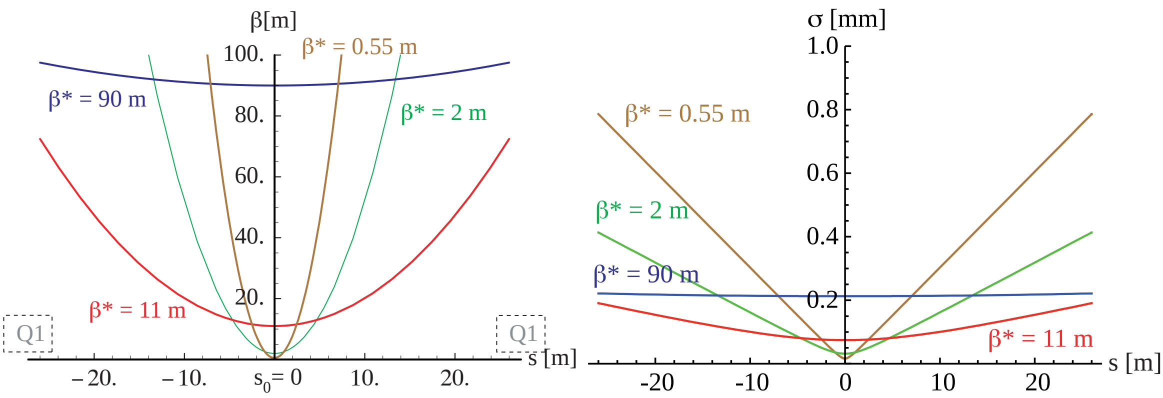

Figure 1. β-functions and beam sizes σ at distance s from the interaction point at $s_0 = 0$, for $\beta^* = 0.55, 2, 11$ and $90\,\mathrm{m}$ up to $L^* = \pm 26\,\mathrm{m}$, for the LHC design beam energy $E_b = 7\,\mathrm{TeV}$ and normalized emittance $\epsilon_N = 3.75\,\mu\mathrm{m}$.

The β-function near a waist (and more generally any field free region) has the form of a parabola

$$\beta(s) = \beta^* + \frac{(s - s_0)^2}{\beta^*}, \tag{1}$$

where β^* is the β-function at the waist position s_0.

The r.m.s. beam size σ and the angular beam divergence σ' (in a region with negligible dispersion as relevant for interaction regions) depend on the beam emittance ϵ and β-function as

$$\sigma = \sqrt{\epsilon\,\beta} \qquad \sigma' = \sqrt{\epsilon/\beta}\,. \tag{2}$$

The distance from the interaction point to the (centre of) the first quadrupole (Q1) is $L^* = 26\,\text{m}$ in the LHC.

Small values of $\beta^* \ll L^*$ are used in standard operation to obtain small beam sizes and high luminosities.

High $\beta^* > L^*$ are used in special runs to reduce the beam divergence and make small scattering angles observable. The beam size at the interaction region is increased and approximately constant throughout the interaction region up to the first quadrupoles. The cross sections for forward proton scattering are large, such that millions of elastic scattering events can typically be recorded in few days of special runs in spite of the reduced luminosity. The time required to set up and commission special optics in the LHC is typically also few days, comparable to the time required to record the data.

The (real space, geometrical) emittance decreases with energy according to

$$\epsilon = \frac{\epsilon_N}{\beta_l \gamma}, \tag{3}$$

where $\beta_l \gamma$ are the Lorentz-parameters of the beams.

At high energy, the negative four momentum squared Mandelstam variable $-t$ increases in very good approximation with beam momentum p (and c.m.s. energy $E_{\text{cms}} = 2E_b \approx 2p$) and scattering angle θ squared according to

$$-\,t = p^2\,\theta^2. \tag{4}$$

Of particular interest in elastic proton scattering is the determination of the ρ-parameter, the real to imaginary ratio of the nuclear elastic scattering amplitude at $t = 0$ [5,6]. Measurements of the ρ-parameter in the Coulomb interference (CI) region require very low $|t|$ values of the order of $|t| = 10^{-3}\,\text{GeV}^2$. Reaching a fixed t requires that the beam divergence squared

$$(\sigma')^2 = \frac{\epsilon}{\beta^*} = \frac{\epsilon_N}{\beta_l \gamma\, \beta^*} \tag{5}$$

decreases with energy squared. With the linear decrease of emittance with energy, this can be achieved by a linear scaling of β^* with energy.

Numerical values from injection to design top energy are given in Table 1, taking as reference the $\beta^* = 2500\,\text{m}$ used to measure the ρ-parameter at a c.m.s. energy of 13 TeV. In practice, the larger beam sizes at low energy also result in reduced detector margins for the same Roman Pot (RP) approach in terms of beam sizes, such that a smaller value of $\beta^* = 100\,\text{m}$ is sufficient to get to the CI interference at LHC interaction energy.

Table 1. Energy scaling of the scattering angle θ and β^* at fixed $|t| = 10^{-3}\,\text{GeV}^2$ as relevant for measurements of the ρ-parameter in the CI-interference region.

p TeV	E_{cms} TeV	θ µrad	β^* m
0.45	0.9	70	170
1	2	32	380
2	4	16	770
4	8	7.9	1540
6.5	13	4.9	2500
7	14	4.5	2690

Now, a short overview year by year of the main activities related to special high-β^* runs in the LHC. For LHC RUN1:

2011 developing the de-squeeze from the injection $\beta^* = 11$ m to 90 m using 17 intermediate steps. Measuring and correcting the major tune change (of nearly 0.5 per interaction region) by global compensation using the whole ring [7]—done at the 2011 physics energy of a 3.5 TeV/beam.

2012 $\beta^* = 90$ m run using up to 112 bunches/beam without crossing angle, and de-squeezing to $\beta^* = 1000$ m to measure in the CI region at 8 TeV c.m.s. (using a single physics fill), with vertical Roman Pots at 3 σ and repeated cleaning with primary collimators at 2 σ at time intervals of about one hour [8–11].

For the present RUN2, which has a top c.m.s. energy of 13 TeV:

2015 $\beta^* = 90$ m run with 671 bunches and 100 ns bunch spacing, using a ± 50 µrad crossing angle, full machine protection verification, delivering 0.74 pb^{-1} per experiment, limiting pile-up to $\mu \approx 0.05$, with Roman Pots at 10 σ.

2016 ρ measurement in the CI region at $\beta^* = 2500$ m, with vertical Roman Pots at 3 σ, a maximum of 3×10^{11} protons per beam, normalized emittances as low as ~ 1 µrad, delivering $\gtrsim 0.4\,\text{nb}^{-1}$ per experiment.

2017 production year concentrating mostly on low β^* operation. First tests at $\beta^*_y = 100$ m to get to the CI region at injection energy get postponed towards the end of the year by vacuum issues in LHC (air trapped in LHC cell "16L2").

2018 $\beta^* = 90$ m run to collect significantly more luminosity than in 2015, carried out in summer 2018 using an optics with lower $\beta^*_x = 45$ m in IP5, and plans to measure the ρ parameter at low energy ($\sqrt{s} = 0.9 - 1.8$ TeV) and intensity of $< 5 \times 10^{11}$ per beam if sufficiently low background conditions can be obtained, later in the year.

The insertion magnet powering requirements for high-β^* optics are rather different and in some respects more demanding than what is needed for standard operation: some quadrupoles (typically Q4, Q7) will be operated at rather low currents. The trim power converters RTQX1 and RTQX2 that allow for different currents in the triplet quadrupoles Q1–Q3 are essential for high-β^* runs. The RTQX1 maximum current used in operation of usually 550 A was extended this year to allow for the 564 A of the 45/90 m optics. In view of the requests to run with high-β^* at low energy, the minimum currents accessible in operation of the insertion quadrupoles were reduced in the beginning of 2017 from roughly 3% to 2% of the maximum current, to 80 A for Q4 and 120 A for Q5–Q10. Extra cables were installed at Q4 (during long shutdown 1 in IP5 and the winter stop 2015/2016 in IP1) to allow for independent powering of Q4 for both beams (without factor two ratio constraints [12]), as required by the $\beta^* = 2500$ m optics used in 2016. This turned out to be also very important to optimize the 45/90 m optics this year, which requires very different currents for the two beams at IP5, 2070 A in Q4 for the outgoing beam 1 and -145 A for the incoming beam 2.

2. High-β^* Optics for Low Energy

Following the very successful $\beta^* = 2500$ m run in 2016 which provided evidence for a rather small ρ-parameter at top LHC energy [13] with interesting physics consequences, we were asked by the experiments to see if it would be possible to develop special optics and obtain adequate running conditions to measure the ρ-parameter at low energy in the LHC to similar precision as at top energy. This would fill the large gap in energies between the ISR and top LHC energies and allow a more direct comparison with p$\bar{\text{p}}$ data from Sp$\bar{\text{p}}$S and TEVATRON. These ideas were discussed in a combined LPC–LPCC workshop in October 2016. We pointed out that a run at low energy (6.5 TeV/0.45 TeV $= 14.4\times$ lower than standard than the usual energy for physics operation) would have additional challenges like in particular much faster horizontal emittance and bunch length growth by Intrabeam Scattering (IBS) [14]. Physics runs would be, if at all possible, rather short. Since the

LHC turnaround time (from physics back to physics after cycling, injection, ramp) is of the order of three hours, an attractive option would be to perform the measurement directly at the injection energy. After a series of academic studies involving several trial optics and taking into account the feedback from both the ALFA and TOTEM experiments, as well as from the machine side on aperture, power converters, injection and machine, the optics versions "v4" for IP1 and "v3b" for IP5 were selected for tests with beam. They are shown for beam 1 in Figure 2.

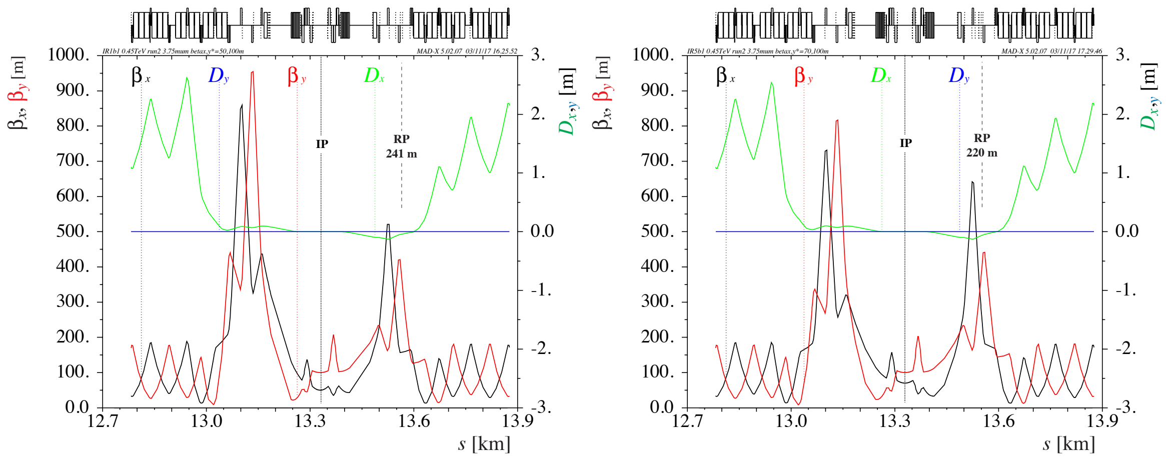

Figure 2. 50/100 m and 70/100 m optics, first successfully tested in the LHC on 26 October 2017.

They feature for both experiments $\beta_y^* = 100$ m and a phase advance of 90° between IP and the nominal Roman Pot positions (241 m from IP1, 220 m at IP5) in the vertical plane. A lower $\beta_x^* = 50$ m for IP1 and $\beta_x^* = 70$ m for IP5 was chosen in the horizontal plane to improve the t_{max} acceptance. The phase advance in the horizontal plane was matched to be close to 180° (but not exactly 180°, as important for ALFA). They were successfully commissioned with beam on 26 October 2017. The β functions were measured and corrected (to a β-beating level below 10% [15]). The aperture was found to be tight but still sufficient for direct injection, and no abnormal losses were observed. These optics were subsequently used in three study sessions for ALFA and TOTEM with tight collimation and Roman Pots very close to the beam. Backgrounds were found to be very high, but manageable for TOTEM, as reported at this conference [16]. Significant horizontal and longitudinal blow up were observed at the time scales expected from IBS. Figure 3 shows the LHC status screen towards the end of the third test, which demonstrated a fast turnaround (measurements, dump, injection, back to measurements) in only 20 min.

It is believed that the backgrounds observed very close to the beam are caused by beam halo particles which hit the Roman Pots, directly or more often after scattering off from general aperture restrictions or collimators. The expected main halo drivers and their dependence on energy E and brightness (proton density) are

- IBS/Touschek, proportional to brightness, scaling roughly as $1/E$, in addition at top energy to some extent compensated by synchrotron radiation damping [17]
- beam–beam interaction, proportional to brightness, for constant normalized emittance to first order independent of energy, but possibly enhanced at low energy in combination with the other halo drivers
- vibration and noise, depending on the sources which may be constant with energy or scaling with $1/E$

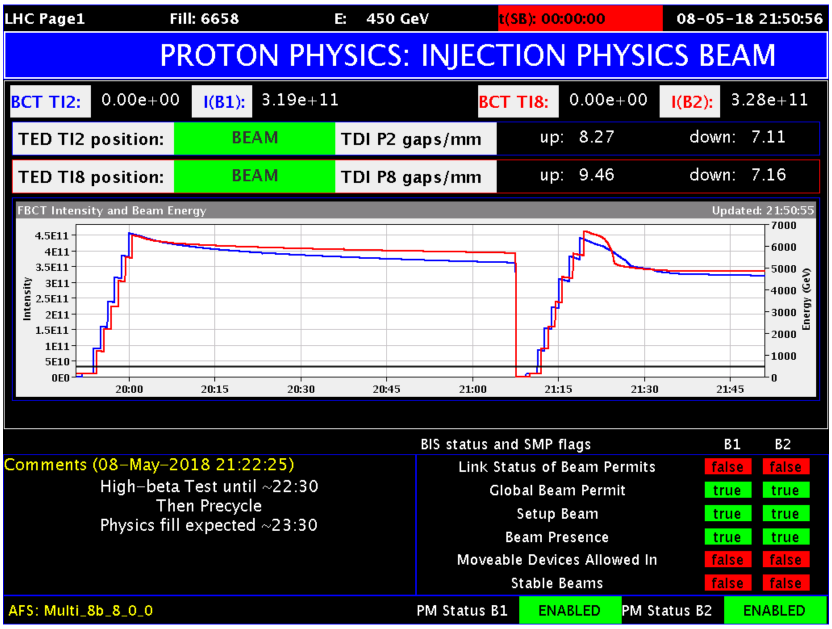

Figure 3. 8 May 2018, immediate refill.

Halo re-population at high energy was rather slow, such that halo collimation at 2 σ and retraction to 2.5 σ could be followed by data taking at acceptable background levels for time intervals of the order of one hour, with Roman Pots at 3 σ. Halo re-population at low energies appears to be much faster, roughly increased by $1/E$.

ALFA reported that backgrounds were too high to perform meaningful measurements at injection energy and proposed a doubling of energy and β^*. This would require a major study and setup time. A de-squeeze of large beams at low energy in the presence of major IBS has never been attempted before, and may turn out to be "rather dirty". The advantage of a fast turnaround would be lost, and it is not likely that a doubling of energy would bring a break-through in backgrounds due to the expected slow scaling of halo-drivers with energy.

Mitigations currently favoured and studied focus on

- the optimization of the collimation hierarchy for the specific needs of high-β^* at low energy guided by simulations, to reduce backgrounds at Roman Pots [18]
- migitation of halo generation by an optimization of machine parameters (RF-voltage, bunch length, brightness versus luminosity, chromaticity, octupole settings)

to obtain adequate background conditions at both IP1 and IP5.

3. $\beta^* = 90$ m at Top Energy

TOTEM was recently upgraded with fast timing detectors to manage higher pile-up rates, and requested together with CMS a physics run at a $\beta^* = 90$ m at top energy, aiming for a tenfold increase in statistics compared to the previous $\beta^* = 90$ m run in 2015. On the optics and beam dynamics side, a significant increase in luminosity compared to the already rather well optimized $\beta^* = 90$ m run in 2015 with peak luminosities reaching 1.3×10^{31} cm^{-2} s^{-1} is challenging. It is attempted by a combination of

1. allowing for a smaller $\beta^*_x = 45$ m in the horizontal plane, increasing the luminosity by 40% ($\sqrt{2}$), but also beam–beam effects by $\sim 17\%$.
2. increasing the brilliance (number of protons per bunch divided by the emittance) and beam–beam tune shifts $\xi_{x,y}$ which were not pushed to the limits in 2015 ($\xi_{x,y} \lesssim 0.004$) to keep a low pile-up, and profiting from lower emittances available from the injectors in 2018

3. doubling the number of bunches, by reducing the bunch spacing from 100 ns to 50 ns combined with an increased crossing angle compared to ±50 ns used in 2015 to limit parasitic beam–beam effects
4. moving to a new tune working point closer to half integer tunes to allow for higher beam–beam tune shifts $\xi > 0.01$ per crossing [19,20].

The last point had soon to be dropped: the $\beta^* = 90\,\text{m}$ was scheduled for summer 2018 with rather limited preparation time and the time allocated for other machine-studies was over-committed.

Further changes compared to 2015 were: general optics changes motivated by HL-LHC, and the different ATLAS-ALFA request for the same $\beta^* = 90\,\text{m}$ in both planes. This required a complete re-match of the de-squeeze. The eleven intermediate steps up to $\beta^* = 43\,\text{m}$ have the same β^* in both planes and are used at both IPs. For ATLAS-ALFA in IP1, the de-squeeze to $\beta^* = 90\,\text{m}$ is continued in both planes. For CMS-TOTEM in IP5, β^*_x is kept constant at a value of $\beta^* = 45\,\text{m}$ while the de-squeeze is continued in the vertical plan to $\beta^*_y = 90\,\text{m}$ using seven intermediate steps. First tests in the LHC control system (before any tests with beam) revealed that the de-squeeze time was limited by changes in the triplet trim RTQX1. This was taken into account in a further iteration: while the triplet trim is important to meet all constraints at the final point with $\beta^*_{x,y} = 45, 90\,\text{m}$, it was possible to keep the trim at zero until $\beta^*_y = 60\,\text{m}$ and to gain time by performing a combined ramp and de-squeeze up to $\beta^*_y = 67\,\text{m}$. The synchronous ramp-down of quadrupoles with circulating beams that is required in the de-squeeze to high-β^* is typically slower than the ramp up in the LHC: the combined ramp and de-squeeze from the injection value $\beta^* = 11\,\text{m}$ at 450 GeV to $\beta^*_y = 67\,\text{m}$ at 6.5 TeV beam energy is done in 21 min. The remaining de-squeeze to the physics optics at $\beta^*_y = 90\,\text{m}$ requires 45 min.

The $\beta^* = 90\,\text{m}$ optics used in 2018 are shown for beam 1 in Figure 4, where it can be seen that the $\beta^*_{x,y} = 90/90\,\text{m}$ optics shown on the left side is more (anti-) symmetric with respect to the IP than the 45/90 optics.

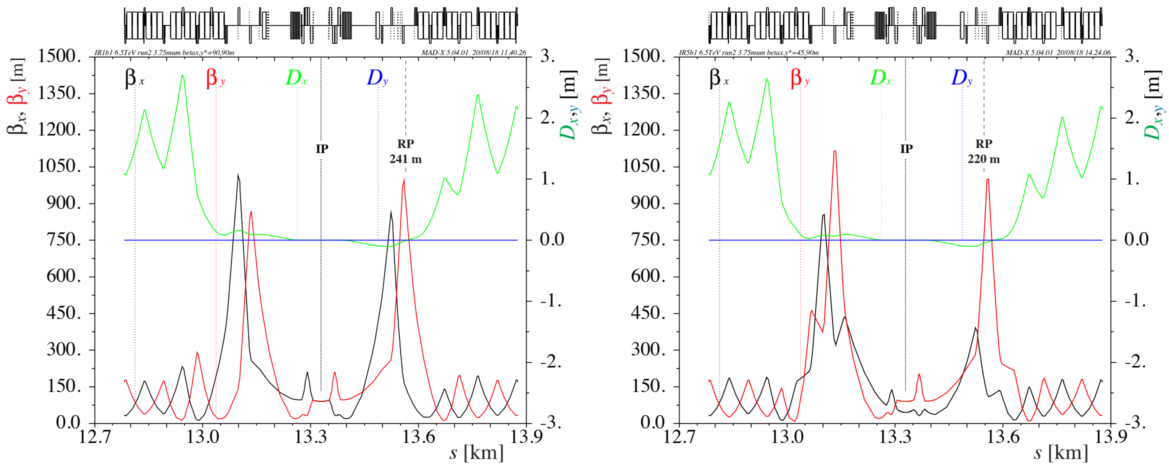

Figure 4. 90/90 m optics for ATLAS-ALFA (**left**) and 45/90 m optics for TOTEM (**right**).

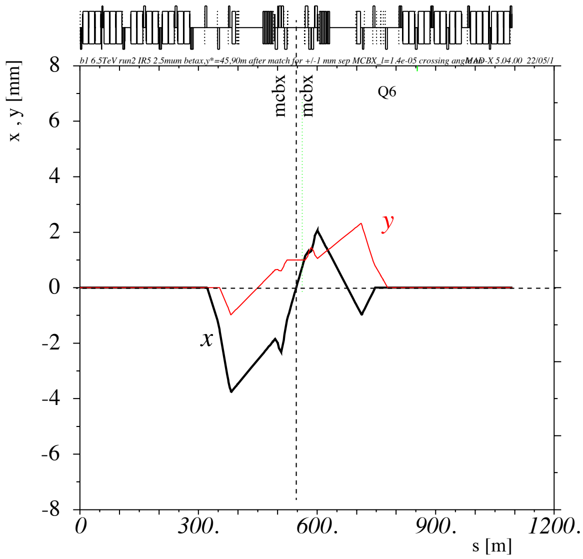

Figure 5. Magnet strength optimized separation and crossing bump, 45/90 m optics, IP5, beam 1.

Aperture at top energy at $\beta^*_y = 90$ m is not critical. Instead, separation and crossing angle bumps are limited by the maximum strength available from corrector magnets. The separation and crossing angle bumps were optimized to minimize the maximum magnet strength needed (Figure 5). The crossing angle could be increased by 20% compared to 2015 to ±60 µrad, providing a separation of $\pm 4.2\,\sigma$ for the first parasitic encounter at 50 ns bunch spacing in IP5, at a normalized emittance of 1.6 µm, leaving sufficient margins to adjust collisions.

The de-squeeze was successfully commissioned with beam by the time of this workshop (end of May 2018). At the time of writing (August 2018), we know that the 90 m run was successfully performed a month later in week 27 (2–7 July). Peak luminosities reached $6 \times 10^{31}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which turned out to be more than sufficient for both experiments, who actually asked for leveling to lower luminosity at the beginning of fills. A bunch spacing of 100 ns with 732 colliding bunches was used during the first two days as requested by ALFA, followed by 50 ns operation with 1450 colliding bunches. Integrated luminosities delivered to the experiments reached $4.5\,\mathrm{pb}^{-1}$ for ATLAS-ALFA at IP1 and $5.8\,\mathrm{pb}^{-1}$ for CMS-TOTEM at IP5.

4. Conclusions

Two types of special high-β^* runs are planned in 2018, which is the final year of operation of the LHC at RUN2. First, the 90 m run for low-mass diffraction studies (glue-balls, missing mass) at top energy ($E_{cms} = 13$ TeV). Secondly, a low energy run to record elastic proton–proton scattering at very small angles in the Coulomb interference region, to determine the ρ-parameter and total cross section in the large energy gap between ISR and maximum LHC energies and to provide for more direct comparison with $p\bar{p}$ results from $Sp\bar{p}S$ and TEVATRON.

For the machine, these are both challenging runs that push some beam and equipment parameters into previously un-explored territory.

The optics with direct injection into high-β^* for the low energy run has been successfully commissioned, and the background conditions were reported by the TOTEM experiment to be fully manageable to perform the requested measurements. Further efforts are required to reduce backgrounds for ALFA at IP1.

By the time of writing (summer 2018), the $\beta^* = 90$ m run has very successfully been terminated for both experiments.

Acknowledgments: Getting the optics described here into operation is a major effort for the LHC teams, relying in particular on the support of : the LHC operation team Jörg Wenninger, Matteo Solfaroli et al., my ABP (accelerator physics) colleagues that include the collimation team Roderik Bruce, Hector Garcia Morales, Stefano Redaelli et al., the optics measurement and correction team Rogelio Thomas et al., Riccardo de Maria and Massimo Giovannozzi for fruitful discussions on optics and aperture, the collective effects and machine protection teams, the TOTEM and ATLAS-ALFA teams, and the LHC program coordinators J. Boyd, C. Schwick and B. Petersen for their efforts to organize and schedule the special runs including the preparatory study and commissioning sessions.

Conflicts of Interest: The author declare no conflict of interest.

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