OPTICS OPTIONS FOR THE 2012 PROTON RUN

M. Giovannozzi, CERN, Geneva, Switzerland
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Abstract

The experience from the past LHC proton run has provided plenty of information and can be used to define possible scenarios for the 2012 physics run. The key parameters such as β* and crossing angle will be reviewed assuming a 4 TeV beam energy and considering options for 25 ns and 50 ns. Possible scenarios for the high-beta optics configuration during the 2012 run will be presented.

INTRODUCTION

The analysis presented in this paper is based on a number of results obtained during the 2011 run, either based on the analysis of the LHC performance during the physics run [1,2] or of dedicated MDs performed to probe specific phenomena, such as beam-beam and impedance effects [3-7]. The definition of optics configurations requires criteria to determine the minimum β* compatible with aperture, the collimators settings, and the required beam-beam separation. The key parameters used throughout this paper are:

- Energy: the beam energy at collision has been assumed to be 4 TeV.
- Transverse emittance: it is assumed, based on the measured performance during the 2011 proton physics run, that at top energy an emittance of $\gamma\varepsilon$=2.5 μm is realistic in case of 50 ns bunch spacing. On the other hand, an emittance of $\gamma\varepsilon$=3.5 μm is realistic in case of 25 ns.
- Beam-beam separation: it is assumed that the required separation should be 9.3 σ for the case of 50 ns bunch spacing, while is should be around 12 σ for 25 ns bunch spacing [2-4].
- Collimator settings: the details of the possible configurations of the collimator system for the 2012 physics run can be found in Refs. [1, 8]. The alternatives are between relaxed or tight settings. Furthermore, it has been recently shown that tolerances might be added in quadrature as they are due to uncorrelated effects. This, in turns, generates two additional sub-cases.
- Impedance effects: according to the results presented in Refs. [5-7], strong octupoles will be needed to counteract impedance effects. For this reason, hardware commissioning of the Landau octupoles up to the nominal current of 550 A has been requested.

In the next section a recap of the optics configurations in 2011 is presented. In the other sections the proposed options for the 2012 proton run will be discussed in details, including the performance reach and some special configurations required by the experiments for CMS and LHCb, as well as high-beta optics for forward physics9.

RECAP OF 2011 BEAM OPTICS CONFIGURATIONS

Injection

The list of β*, half crossing angle, and half parallel separation is reported in Table 1.

Table 1: Main optical parameters at injection used during the 2011 physics run. The crossing angles and the parallel separations are half values and only the absolute value is quoted here. For the case of Alice and LHCb the external angles are reported in this table.

	ATLAS	Alice	CMS	LHCb
β* (m)	11	10	11	10
Crossing angle (μrad)	170	170	170	170
Parallel separation (mm)	2	2	2	2

These values are similar to those quoted in the LHC Design Report [9] and are those listed in an earlier document concerning the physics run parameters for 2010 [10]. It is worth noting here that these values are compatible for both 50 ns and 25 ns bunch spacing.

Top energy

The 2011 physics run was performed at 3.5 TeV/beam. The beam parameters for the second part of the proton run are reported in Table 2.

Table 2: Main optical parameters at top energy used for the second part of the 2011 proton physics run. The crossing angles and the parallel separations are half values and only the absolute value is quoted here. For the case of Alice and LHCb the external angles are reported in this table.

	ATLAS	Alice	CMS	LHCb
β* (m)	1	10	1	3
Crossing angle (μrad)	120	80	120	250
Parallel separation (mm)	0.7	0.7	0.7	0.7

It is worth recalling here that these parameters were put in operation after carefully measuring the available aperture in IR1 and 5 [11] and this required a re-commissioning of the last part of the squeeze [12].

2012 OPTICS OPTIONS: INJECTION

For efficiency reasons no changes will be made to the optics settings at injection for the 2012 run. This would enable maximising the physics time by reducing, as much as possible, the re-commissioning time. Few changes, however, could have been implemented, which could have provided some improvements of the running conditions.

Collision tunes at injection

The successful test of collision tunes applied since beam injection [13] has shown that this approach could bring and advantage in terms of beam lifetime (see Fig. 1).

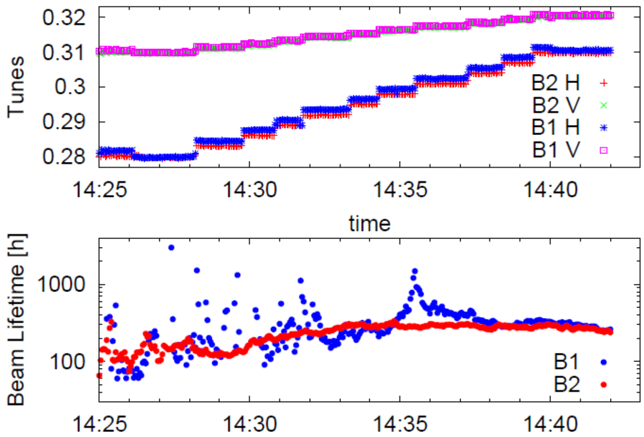

Figure 1: Tune evolution (top) and beam lifetime (bottom) at injection energy from Ref. [13]. The improvement in beam lifetime is clearly seen.

The lifetime appears to increase when the tunes are moved towards the collision values. This could have also shortened the time required to prepare beams for collisions at top energy, thus improving the overall efficiency by maximising the time for physics.

Lower β^* in ATLAS and CMS

Injecting the beams using a smaller value of β^* for ATLAS and CMS would have been an advantage in terms of time required to perform the complete squeeze. The new value of β^* should have been determined on the basis of aperture considerations, but a reduction by a couple of metres seems to be feasible.

The squeeze time is clearly foreseen to increase in 2012 due to the reduced value of β^* proposed for the run and any speed up of the various beam processes would be beneficial for the total time spent in physics. It is also clear, that such a change would have been particularly useful if coupled with the proposed combined ramp and squeeze [14]. Indeed, the lower-than-nominal energy makes it hardly possible to perform the whole squeeze during the ramp. Therefore, starting from a lower value of β at the interaction point would have made more effective the proposed manipulation during the ramp. This proposal will be certainly considered for future runs.

New optics for IR6

Recently, a proposal for a new optics in IR6 has been made [15]. The aim is to improve the phase advance between the dump kicker and the TCSG. This configuration would have an impact on the collimators' settings, either in the sense of allowing a lower β^* or by providing more operational margin for the currently proposed value of β^*. While some aspects require still further investigations [16], it is clear that efforts in this direction will be useful in the future.

2012 OPTICS OPTIONS: TOP ENERGY

The proposed configurations for top energy envisage a half parallel separation of 0.65 mm, which is obtained by rescaling the 2011 value with $\sqrt{\gamma}$.

The crossing angles and the values of β^* are then derived from other considerations. Two sets of parameters can be obtained, depending on the bunch spacing. In Table 3 the parameters for 50 ns as well as 25 ns are reported.

These parameters' sets have been already presented and discussed in [17, 18] following the discussion at the Evian 2011 Workshop. A sizeable reduction in β^* is indeed possible, thus allowing to boost the 2011 performance. The various scenarios can be used to derive the performance reach expected for 2012, which is summarised in Table 4. For simplicity, only the high-luminosity experiments are reported. The beam parameters have been assumed based on the 2011 performance for the 50 ns case (transverse emittance, bunch intensity, and bunch length). For the 25 ns case, the latest results of the MDs in the SPS have been taken into account. It is also worth stressing that, in spite that impedance-related effects might produce an increase in the bunch length for the 25 ns case, this fact as not been taken into account in the numerical estimates reported in Table 4. Such an effect will reduce even further the peak luminosity, thus making even less interesting the 25 ns case (a detailed discussion of the pros and cons of the 50 vs. the 25 ns case can be found in Ref. [19]).

Apart from the striking performance of the 50 ns configurations, which is due to the excellent performance of the injectors' chain and of the LHC machine, the high pile-up is also clearly seen, even if this does not seem to be a source of performance limitation for the experiments. It is also worth stressing the impact of the crossing angle on the value of the peak luminosity: the reduction of the geometric factor is rather sizeable and the benefit for a β^* reduction below 0.70 m in terms of increase of peak luminosity should be carefully considered against the pushed situation in terms of aperture requirements, collimation settings, and impedance effects. These aspects will need to be considered when defining the commissioning strategy for 2012.

It is also clear that there is much more to define and to study than proposing a β^* value. The additional points will be considered in the next section.

Table 3: Main optical parameters at top energy proposed for the 2012 proton physics run and the case of 50 ns and 25 ns bunch spacing. The crossing angles and the parallel separations are half values and only the absolute value is quoted here. For the case of Alice and LHCb the external angles are reported in this table. In all the cases the half parallel separation is 0.65 mm.

Bunch spacing	Collimators settings	Key assumption		ATLAS	Alice	CMS	LHCb
50 ns	Tight	Quadratic sum of tolerances	β* (m)	0.60	3	0.60	3
			Crossing angle (μrad)	145	90	145	230-250
		Linear sum of tolerances	β* (m)	0.70	3	0.70	3
			Crossing angle (μrad)	134	90	134	230-250
	Relaxed		β* (m)	0.90	3	0.90	3
			Crossing angle (μrad)	118	90	118	230-250
25 ns	Tight	Quadratic sum of tolerances	β* (m)	0.80	3	0.80	3
			Crossing angle (μrad)	192	90	192	230-250
		Linear sum of tolerances	β* (m)	0.90	3	0.90	3
			Crossing angle (μrad)	181	90	181	230-250
	Relaxed		β* (m)	1.10	3	1.10	3
			Crossing angle (μrad)	163	90	163	230-250

SOME CONSIDERATIONS OF THE SQUEEZE AT 4 TEV

A number of points should be considered for assessing the feasibility of a squeeze sequence.

Optics files

The optics database under *afs* is already available for generating the settings required for the 2012 physics run. Already in 2011 the squeeze sequence for IR1 and 5 has been optimised to reduce the beta-beating observed for Beam 2 around 1 m [20]. These improved optics solutions have been already in operation in the second part of the 2011 physics run. It is worth noting that below 1 m β*, matched optics are available in steps of β* of 10 cm. It is also worthwhile mentioning that the squeeze sequence for IR2 has been polished in 2011 [21]. During the ion run period it was decided not to use such an improved configuration, but it might be useful to review the situation in 2012 and verify whether the optimised sequence should be implemented in operation.

Magnets and power converters

One of the features of the IR1/5 squeeze sequence is that some of the magnets are decreasing their strength when β* is reduced. This has two main potential drawbacks: i) the power converter might be forced to operate in a regime in which its performance is not optimal; ii) the decrease in strength brings the magnet on the other side of the hysteresis curve, thus introducing magnetic errors unless special care is paid. In Fig. 2 the evolution of the current in the independently powered quadrupoles as a function of β* is shown.

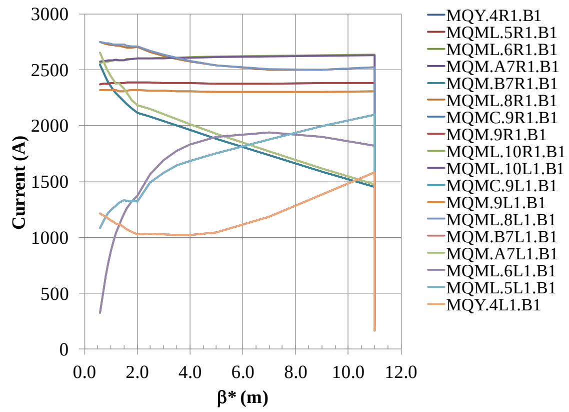

Figure 2: Evolution of the current of the independently powered quadrupoles in IR1 for Beam 1. The decrease of the current for some quadrupoles is clearly visible as well as the very low value achieved by the Q6 magnet.

The sudden jump that occurs for β*=11 m is due to the fact that the optics is kept constant between injection and the arrival at flat top. Then, the reduction of current for some quadrupoles is clearly seen and Q6 reaches the lowest value at the end of the squeeze sequence. Of course, this potential issue would be mitigated by running at higher energy. For the proposed squeeze sequence the current can be as low as 239 A for Beam 2, corresponding to about 4 % of the maximum current rating of the power

Table 4: Summary of performance reach for the high-luminosity experiments in 2012, based on the parameters reported in Table 3. The number of events/crossing has been evaluated assuming a total cross section of 76 mbarn,

Parameter	**Unit**		**50 ns**			**25 ns**	
β*	m	0.90	0.70	0.60	1.10	0.90	0.80
Crossing angle	μrad	118	134	145	163	181	192
Total nuber of bunches			1380			2760	
Bunch intensity	10^{11}		1.50			1.15	
γ ε	μm		2.50			3.50	
Protons per beam	10^{14}		2.1			3.2	
Current per beam	mA		372.4			571.1	
Stored energy per beam	MJ		132.7			203.5	
RMS bunch length	cm		9.40			9.40	
Beam size	mm	0.023	0.020	0.019	0.030	0.027	0.026
Geometric factor		0.901	0.849	0.809	0.891	0.848	0.818
Number of colliding pairs			1331			2662	
Luminosity (10^{33})	$cm^{-2} s^{-1}$	4.6	5.5	6.2	3.1	3.6	3.9
Events per crossing		23.2	28.2	31.3	7.9	9.2	10.0

converter. The risk is that the performance of the power converter is degraded, in particular the ripple stability. Tests were performed [22], indicating that indeed the device is performing well and the ripple is not worse than at higher current, as it can be seen in Fig. 3, where the power converter performance as FFT of its output is shown for high current (top) as well as low current (bottom). No sizeable difference can be seen.

More detailed tests will be performed during the forthcoming hardware commissioning period, but these results are certainly encouraging.

The issue with the wrong branch of the hysteresis curve has been considered already long ago in the framework of the activities of the FiDeL Working Group [23]. At that time the analysis showed that the impact of the transfer function error due to the magnet being controlled using the wrong branch of the hysteresis curve was negligible. Nevertheless, it was decided to implement in LSA a mechanism to take into account the sign of the current derivative to compute the settings [24]. Unfortunately, this was shown to generate steps in the current functions and hence it was removed. Such a mechanism could be replaced by a deterministic knob to be applied at the end of the squeeze sequence to compensate for the wrong settings. It is worth noting that the analysis made was based on a slightly different squeeze sequence and it is therefore planned to check once more the situation in terms of beta-beating and the need to implement a correction using the up-to-date squeeze.

Non-linear correctors in the triplets

As it was stated in the past and then re-checked recently

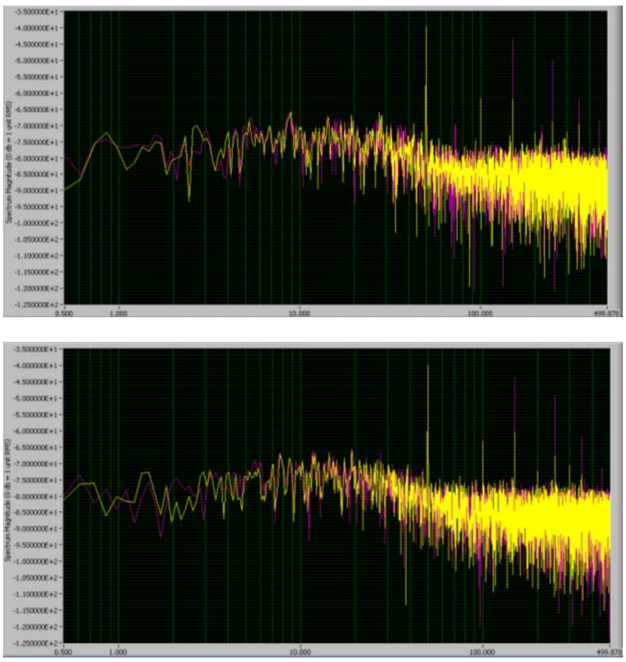

Figure 3: FFT of power convert output at 2000 A (top) and 200 A (bottom). No relevant difference can be found.

[25], the non-linear correctors in the triplets should not be used unless β* is lower than 1 m. In principle, the collimators' settings are such that there should be no particles at relatively large amplitude such that they can experience the non-linear fields generated by triplet quadrupoles. For these reasons, and also taking into account the difficulties in controlling the temperature of

the higher-order correctors, it has been decided to ask for a complete hardware commissioning of the normal sextupolar correctors only, as it was done for the 2011 run. Octupolar correctors should be tested such that they could be used during dedicated machine experiments. It is also worth recalling that during recent aperture measurements parasitic data-taking was performed to collect information concerning the tune and coupling variation as a function of the various bumps used for probing the location of the cold aperture (see Refs. [26, 27] for more details). The data analysis is in progress, but these data might give some insight on the actual triplets' field quality and the need for correction.

Chromatic beta-beating

Another aspect that should not be neglected is the chromatic beta-beating that is generated by the squeezed insertions and degrades inversely proportional with the value of β^*. In Fig. 4 a plot of the beta-beating for off-momentum particles is reported. In the upper part of the plot the chromatic beta-beating is shown for both the horizontal and the vertical planes. The situation corresponding to the 2011 proton physics run is compared with the proposed one for 2012. The increase in chromatic beta-beating is clearly visible and it corresponds to about a factor of two with respect to the 2011 configuration.

Even if the optical conditions for the ion run in 2012 are not covered by this paper (see Ref. [28] for more details), it is interesting to see the impact of a third insertion squeezed to $\beta^* = 0.6$ m. Indeed, in Fig. 4 (bottom) IR1, 2, and 5 are all squeezed to the minimum value and once more the degradation with respect to 2011 running conditions is approximately a factor of two.

The chromatic beta-beating could affect the performance of the collimation system, which relies on phase advance relationships and these are different between the on-momentum and off-momentum particles. In Refs. [29, 30] a detailed analysis of these chromatic effects was performed and the conclusion was that no particular issue was to be expected. Still, it is important to highlight that this year the optical conditions will be really demanding and a completely new regime will be explored.

SPECIAL CONFIGURATIONS FOR CMS AND LHCB

In addition to the overall optical configuration that will be changed with respect to the one used in 2011, there will be a couple of details that might be changed also in the way beams are brought in collision in IR5 and 8.

Vertical IP shift for CMS

Recently it has been announced that the CMS PIXEL detector has been found misaligned with respect to the nominal position as well as the centre of the experimental vacuum pipe. Assuming that the reference system used at the IP coincides with the one that is used to express the position of the LHC magnets, then the inner tracker is displaced by -4 mm in the vertical plane (and also by -2.5 mm in the horizontal plane), while the experimental vacuum pipe is displaced by about -2 mm in the same plane [30]. The first displacement might have a negative impact on the data-taking and a request was made whether the IP could be moved in the vertical plane to compensate for about half of the observed hardware off-set. A preliminary analysis was presented in Ref. [30], while a complete solution was given in [31] and then presented in [32]. In Fig. 5 the proposed bumps are shown (top) together with the aperture in triplets as a function of the vertical IP shift (bottom).

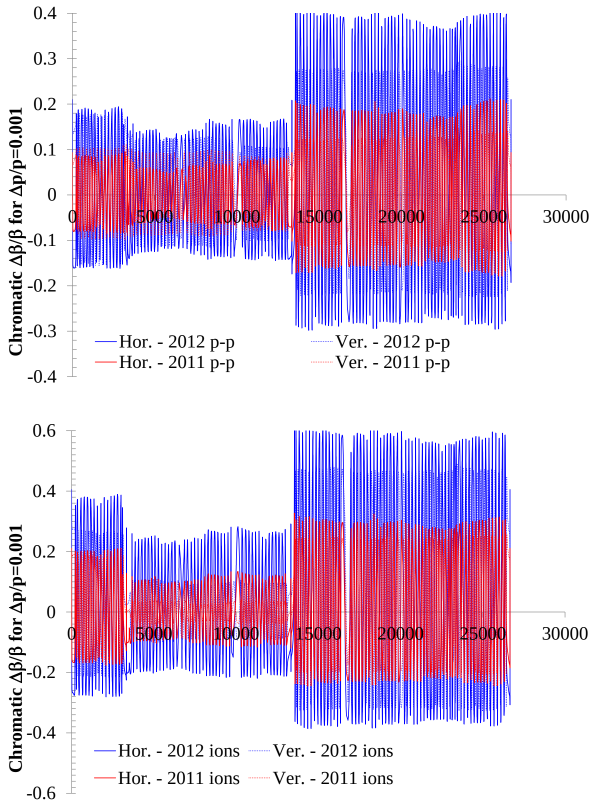

Figure 4: Off-momentum beta-beating for Beam 1 (top) for proton physics configuration, and for the ions physics configuration (bottom). In both cases the origin of the horizontal axis is IP1. In the bottom plot the effect of the squeezed IR2 is clearly visible.

The strength of the dipole correctors used to generate the special bumps does not exceed 63 % of the available strength at 4 TeV and it is fully acceptable.

Of course, the available triplets' aperture is reduced from 10.4 σ to 9.8 σ whenever the IP shift is applied (detailed computations to evaluate the aperture loss in case of luminosity scans should be carried out). In the lower part of Fig. 5 it is clearly seen that up to -1.2 mm of vertical IP shift the limitation is still in the crossing plane and therefore, the triplets' aperture remains constant. Then, if the IP shift is further increased, the aperture starts to decrease as the limitation flips to the separation plane.

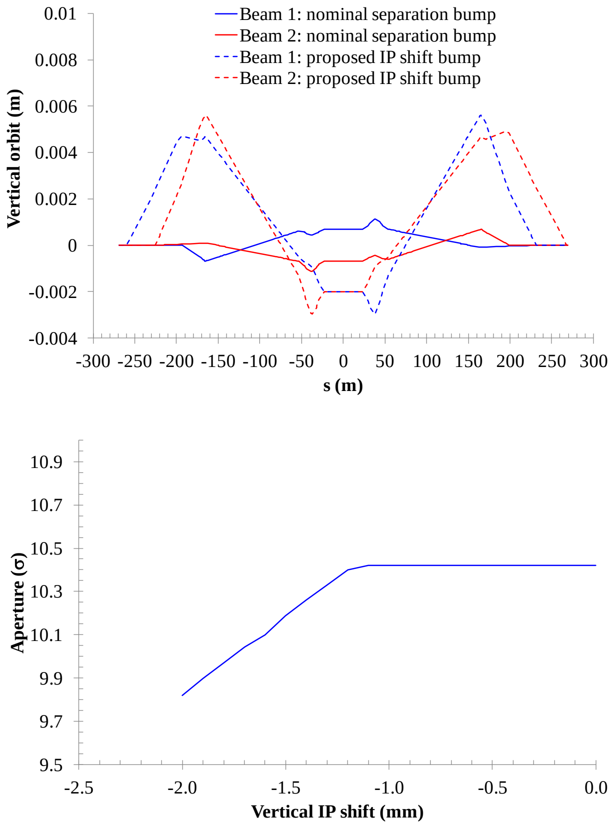

Figure 5: Proposed vertical bumps to shift the IP position (top). The standard separation bumps are also shown for reference. The available triplets' aperture vs. vertical IP shift (bottom) shows a change in its behaviour, as the limiting plane flips from the crossing to the separation one.

It is worth mentioning that the reduced aperture in the triplets could be accounted for by re-adjusting the position of the vertical TCTs without affecting the β* reach. Of course, such a proposal should be approved by the competent machine protection bodies before being put in operation.

Additional vertical crossing angle for LHCb

Since quite some time, the crossing scheme for IR8 was studied in order to propose alternative solutions to the current horizontal crossing [34]. Recently, this topic has been raised once more in view of providing a crossing scheme for which the net crossing angle, i.e., the sum of the spectrometer angle and the external angle, does not depend on the polarity of the spectrometer magnet. In this respect a vertical crossing angle would be the best solution, but is not compatible with the orientation of the beam screens in the triplet magnets. Therefore, while it seems hard to propose an alternative scheme to the nominal one at injection energy, it seems possible to improve the situation at top energy where the aperture is larger [35]. The idea would be add a vertical crossing angle of 90 μrad that should provide enough beam-beam separation (this is the same situation as in IR2). Therefore, the key point is the definition of the operational procedure that should bring from separated beams in the vertical plane and a crossing angle in the horizontal one to colliding beams with a crossing angle in the vertical plane. In addition, it is worth emphasising that the procedure should envisage a strategy to perform the luminosity levelling that is essential for the LHCb data-taking. The situation is being reviewed and the procedure will be defined shortly.

2012 OPTICS OPTIONS: HIGH-BETA

After the very successful commissioning of the high-beta optics [36] during the MD periods in 2011 [37] and a successful data-taking period for TOTEM, the performance reach in 2012 becomes a key point. Indeed, this question is not only relevant for defining the conditions of the 2012 physics run, but also to gather enough information in view of taking decisions for the hardware activities during LS1. In fact, one should recall that the so-called three-lead powering scheme for the independently powered quadrupoles introduces strong coupling between the two beams. Not all possible combinations of gradients for the two beams can be achieved. In order to overcome this difficulty it was proposed to add cables to some pre-defined quadrupoles. The exact details of these hardware changes should be determined via theoretical analysis of the matching flexibility, but also via dedicated beam measurements. For this reason a detailed list of MD studies has been submitted [38] in order to clarify the situation by mid-2012 in view of defining the in advance activities for LS1.

As far as possible optics configurations for the 2012 physics run are concerned, in addition to the "classical" 90 m β* solution, it seems feasible to reach values of 400-500 m with the current hardware and with typical beam parameters, i.e., few bunches of 3×10^{10} p each and a transverse emittance γε of about 2 μm. The matched optics for the un-squeeze sequence are being studied and prepared for settings generation in the coming weeks.

CONCLUSIONS

During the 2012 LHC physics run the machine performance will be pushed, aiming at very low β* values, comparable with the nominal ones [9] even if the energy will be only 57 % of the nominal one. A review of the possible optical configurations at hand has been made together with a discussion of the potential issues that might be encountered during the beam commissioning.

Some hardware issues (hysteresis effect and power converter performance) that are linked with the squeeze to very low β* and at reduced energy, can be anticipated not to be show stoppers. On the other hand a number of beam physics issues might not be at all excluded. As far as single-particle effects are concerned, the optics performance, such as the correction of beta-beating, is assumed to be as good as in the previous year, but only beam will tell whether this assumption is realistic. Other effects might become more and more relevant, such as the longitudinal displacement of the triplet quadrupoles, for which a solution is known, but also chromatic effects, for which a proper solution is known only if the nominal optics is changed to the proposed ATS for HL-LHC as discussed in Ref. [39]. As far as the collective effects are concerned, clearly beam-beam and instabilities will become harder to control. Last but not least, the impact of the strong octupoles required to stabilise the beams in the presence to the tight collimators' settings on the overall beam dynamics will need to be assessed carefully during the beam commissioning period.

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