European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 315

A beam separation and collision scheme for IP1 and IP5 at the LHC for optics version 6.1

O. Brüning and W. Herr, SL Division,
R. Ostojic, LHC Division, CERN, 1211-Geneva 23

Abstract

In this report we describe the proposed beam separation and collision schemes for interaction points 1 and 5 in the LHC for optics version 6. The original proposal for optics version 5 was redesigned to be compatible with new requirements and the existing hardware. Contrary to the original scheme, in our scenario some magnets in the common part of the two rings are used to establish part of the crossing angle. However, individual control of the two beams remains fully possible. The necessary corrector strengths are significantly smaller and the aperture requirements less severe. Furthermore, this new scheme would allow to further increase the crossing angle, if required.

Administrative Secretariat
LHC Division
CERN
CH-1211 Geneva 23
Switzerland

Geneva, 10 November 1999

1 Introduction

The CERN Large Hadron Collider (LHC) is designed for highest luminosity and therefore requires an operation with high bunch intensities and a large number of bunches [1]. The main limit on the bunch intensity will eventually come from beam-beam effects. To allow a maximum number of bunches, they are closely spaced (25 ns) and in order to avoid unwanted collisions in the part where the two beams share a common vacuum chamber, the beams must collide at a small crossing angle in all experimental interaction regions [2]. Since the common part is much longer than the bunch spacing, parasitic collisions, so-called long range interactions, of the separated beams cannot be avoided. The crossing angle has to provide a sufficient separation at all parasitic encounters to keep the effects from long range beam-beam interactions small and should allow a quasi head-on collision at the central interaction point. This is true in particular for the two low β^* interaction regions IR1 and IR5 where the long range effects are strongest [2]. Before the two beams are brought into collision, i.e. for injection and the energy ramp, the central head on collision must also be avoided. This is done with a parallel separation bump in the plane orthogonal to the crossing plane. This bump must also serve as a handle to push the beams into collision and to adjust the collision point in this plane, if necessary.

A scheme for beam separation was developed for the previous version of the LHC optics (Version 5.0) but suffered from insufficient strength of the available correctors [3]. For the new version of the optics (Version 6.0 and later [4]) this separation scheme can not be applied as it was foreseen and a new scheme was designed. The requirements for the separation scheme arise from beam dynamics considerations as well as from hardware requirements. It should also allow a flexible operation of the machine.

2 Boundary conditions

From beam dynamics considerations, the separation scheme has to fulfill certain requirements:

– Sufficient separation at the parasitic encounters.
– Independent control of the two beams.
– Possibility to further increase the separation, i.e. the crossing angle, if required.
– Fine adjustment of the collisions.
– Separation of the head-on collision at injection and during the ramp.
– Crossing in horizontal and vertical plane.

The last point deserves some explanation. It is a particular feature of long range interactions that the focussing in the plane of separation has the opposite sign with respect to the other plane when the beams are separated more than a few times the transverse beam size. The unwanted effects of long range interactions can therefore be largely compensated when the crossing plane is alternating horizontal and vertical [2].

Another special feature of LHC beam-beam effects arises from the structure of the bunch trains, leading to so-called PACMAN bunches. A consequence of the different collision schedule of PACMAN bunches, each of these bunches has a slightly different closed orbit which requires a fine adjustment of the collision point to a fraction of a σ [2, 5]. The separation scheme must allow such an adjustment in both planes, independent for the two beams.

Although it is desirable to have a crossing angle as large as possible to minimize the beam-beam effects, its maximum value is limited by other considerations:

– Luminosity is reduced for large crossing angles.
– Requirements for the field quality in the triplet quadrupoles are stronger.

– Large physical aperture is needed.
– Available corrector strength to provide the separation.
– Compatibility with other equipment, e.g. for injection.

The compensation effects are most important where β^* is small, i.e. the high luminosity regions 1 and 5 [2]. It was decided to cross in the vertical plane in interaction region 1 (ATLAS experiment) and in the horizontal plane in region 5 (CMS experiment). The crossing planes in region 2 (ALICE) and 8 (LHCB) are vertical for compatibility with the injection equipment and the experimental layout. Furthermore, both experiments have dipole spectrometers that disturb the closed orbit and require local compensation. The compensation schemes and possible operational procedures for the spectrometer magnets have to be included in the design of the separation scheme and are presently under study. Therefore, the separation scheme for regions 2 and 8 will be treated in a separate note.

2.1 Separation requirements

The requirements on the separation are determined by evaluating the effects of long range interactions on the beam stability. Tune footprints and weak-strong simulations (see contributions in [6, 7]) have been studied and a minimum separation was determined. Except in collision, this separation is a combination of the crossing angle and the parallel orbit bump. Important for the strength of beam-beam effects is the normalized separation, i.e. the separation in units of the transverse beam size. For low β^* insertions this separation is constant in the drift space between the left and right focussing triplets, but it can vary slightly inside the triplet quadrupoles [2] up to the D1 separation dipoles which separate the beams. The basic parameters taking into account the above boundary conditions are summarized in Tab. 1 for the main phases of operation, i.e. injection, ramp, pre-collision and collision. The parallel separation refers to the separation of the central head-

State	$\beta^*_{x,y}$ (m)	half crossing angle (μrad)	half parallel separation (mm)	d_{ip} (σ)	d_{drift} (σ)	d_{min} (σ)
Injection	18.0	± 160.0	± 2.50	13.3	13.5	9.4
End of ramp	18.0	± 40.0	± 0.75	15.8	15.5	10.0
Pre-collision	0.5	± 150.0	± 0.50	63.0	9.5	7.0
Collision	0.5	± 150.0	0.0	0.0	9.5	7.0

Table 1: *Required separation conditions in IP1 and IP5. The corresponding separation in units of the beam size are given for the interaction point (d_{ip}), in the driftspace (d_{drift}) and the minimum separation (d_{min}) in the whole region between the D1 separation dipoles left and right. All separation bumps are designed to be symmetric between the two beams and provide half of the crossing angle and parallel separation.*

on collision point. The studies [6] also indicate that it could be desirable to have the option to further increase the crossing angle for very high beam intensities, should this become necessary.

2.2 Available corrector parameters

In Tab.2 the properties of the available corrector magnets are shown. The separa-

Type	Maximum field (T)	Mag. length (m)	Max. $\int Bdl$ (Tm)	Max. angle at 7 TeV (μrad)
MBXW	1.38	3.43	4.690	$\pm$ 200.0
MCB	3.0	0.84	2.520	$\pm$ 108.0
MCBL	3.0	1.25	3.750	$\pm$ 160.7
MCBY	3.0	0.84	2.520	$\pm$ 108.0
MCBX (h)	3.3	0.50	1.650	$\pm$ 70.7
MCBX (v)	3.3	0.50	1.650	$\pm$ 70.7

Table 2: *Properties of available correction magnets.*

tion dipoles (D1) are of the type MBXW and are the first stage to separate the beams into individual vacuum chambers. The standard orbit correction is done using correctors of type MCB or MCBL and the correctors MCBY are dedicated wide aperture dipole correctors previously used to establish the separation and crossing angle [3]. The inner triplet correctors MCBX each have a vertical (v) and a horizontal (h) unit.

3 Separation scheme in collision

During collision, the separation of the unwanted parasitic collisions is mainly accomplished with the crossing angle. However, it is important to have the possibility to adjust both the crossing angle and offsets of the collision point. All presented schemes are symmetric between the two beams, i.e. half of the crossing angle or parallel separation are provided by equivalent orbit bumps in each of the two beams of the separate rings.

3.1 Previous separation scheme

For the original separation scheme designed for version 5.0 of the optics [3] dedicated correctors of the type MCBY were foreseen near the Q4 and Q5 magnets at each interaction point. This allowed the individual steering of the two beams since none of the corrector magnets is in the common part [3]. It further avoided large orbit amplitudes in the magnets Q5 and beyond. Near Q4 two dedicated correctors, one in each plane, were foreseen (DVQ4, DHQ4). Next to Q5 two dedicated correctors in the crossing plane and one in the other plane were required, (e.g. DVQ5A, DVQ5B, DHQ5, for IP1). In total, 5 correctors on each side for each beam were required, i.e. 20 for each interaction region. The standard orbit correctors near Q4 and Q5 were reserved for orbit corrections. The phase advance between the correctors was not ideal to establish a crossing angle and the doubling of the correctors near Q5 became necessary to get sufficient strength. For the present optics version, the solution presented in [3] suffers from an even more unfavourable phase advance between the correctors (≈1°) and from the correctors to the interaction point (≈90°), leading to too large corrector strengths required. Due to the large initial deflection, the orbit offsets in the Q4 quadrupole and D2 separation magnet were very significant, i.e. ± 4.5 mm, therefore reducing the available aperture. Furthermore, to avoid collective effects such as electron cloud effects, it may be required to keep this offset small. Possible extensions to this scheme such as providing part of the crossing angle by the D2 separation dipole, would only work for horizontal crossing angles, therefore making the separation schemes in IP1 and IP5 very different, which is not desirable for compensation of beam-beam effects.

3.2 Separation strategies

3.2.1 Crossing angle

Different strategies are possible to achieve the necessary crossing angle and separation. All considerations are valid for IP1 as well as for IP5, except that the horizontal and vertical planes are exchanged. All studies presented here are therefore only for IP1 and can easily be generalized for IP5. The condition to have individual control of the two beams can be fulfilled if only correctors outside the common part are used. In the simplest case a corrector at a phase distance of nπ (n $\geq$ 1) to the interaction point can easily produce the desired crossing angle. Such a separation bump producing an angle of 150 μrad

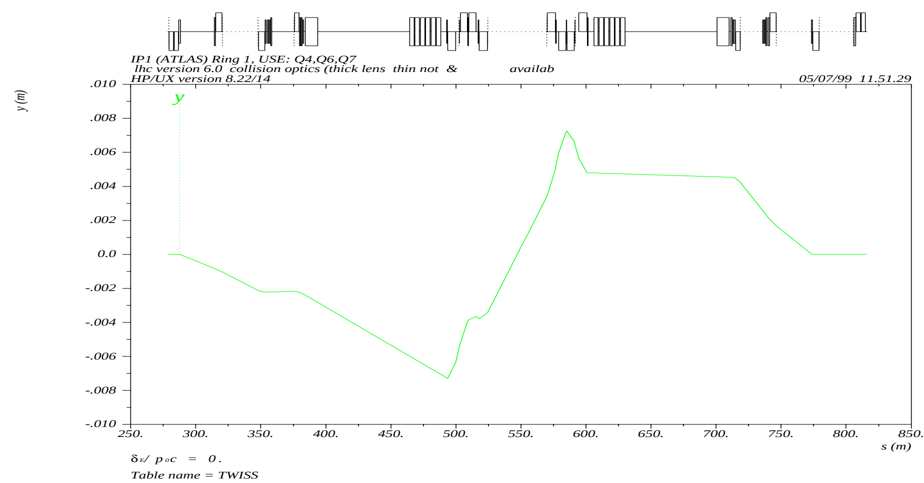

Figure 1: Crossing angle orbit bump with outside magnets only (Scheme A, for strengths see Tab. 4).

is shown in Fig.1 (scheme A). The necessary corrector strengths are given in Tab.3. However, this solution requires an extended bump about 490 m long and a phase advance of almost exactly 2π between the outmost correctors. This bump is limited by the available aperture in the insertion, in particular in quadrupole Q4 and separation magnet D2 (≈ 4.5 mm offset). Dipole correctors in the common part can significantly help to produce a crossing angle, and ensure a separation of minimum extension. Such corrector magnets exist at the triplet quadrupoles Q2 and Q3 and are of type MCBX. However, they do not permit independent control of the beams. Furthermore, most of their available strengths is required to correct possible misalignment of the triplet [8]. To avoid this problem, we

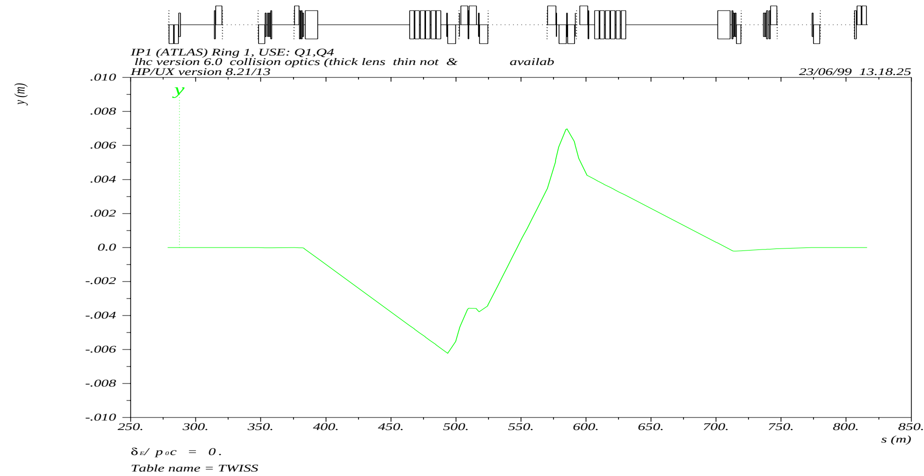

Figure 2: Crossing angle orbit bump with two magnets common to both beams (Scheme B, for strengths see Tab. 5).

propose to add another corrector of type MCBX to the quadrupoles Q1 on both sides of the interaction point. The correctors CXQ1 are mounted on the Q1 quadrupoles of the focussing triplet on their far side from the interaction point. Since they are common to both beams, the correctors left and right are assumed to have the same strength but opposite sign for the crossing angle orbit bump. The quadrupoles Q1 are then similar to the Q3 quadrupoles which simplifies the triplet hardware significantly. In Fig.2 these additional correctors CXQ1 were used for the separation together with the dedicated dipoles near Q4 (DVQ4). The orbit correctors near Q4 are reserved for orbit corrections and are not used for the separation scheme. A small remaining non-closure of the bump was corrected with orbit correctors further away (scheme B). The necessary corrector strengths are given in Tab.4. It can be seen that only 50% of the available strength of the additional correctors is used for the bump, leaving the remaining strength for orbit corrections and therefore increasing the correction power in the triplet significantly. This scheme allows to keep the longitudinal extension of the bump and therefore the space requirements small, but the individual control of the beams is almost impossible. Furthermore, although the deflection angles are relatively small, due to the large β-function at the Q1 magnet, this bump becomes rather sensitive to optics errors. The total length of this bump is around 430 m. Both types of bumps (Figs. 1 and 2) allow to establish the full crossing angle of 300 μrad independently. A natural extension is to combine the two bumps, thus avoiding the large kicks and aperture problems, while maintaining separate beam control since the bumps are linearly superimposed. The two bumps can be used as independent 'knobs' to minimize the required strengths and aperture requirements and to reduce the sensitivity to errors. This is the proposed scenario and Fig.3 shows the crossing angle when part of the separation is provided by each scheme. The sharing for Fig.3 is 30 % scheme A and 70 % scheme B, but that can be adjusted as required. The crossing angle bump appears significantly smoother and the individual control of the beams is fully maintained over the full range of $\pm$ 150 μrad. Figs.1-3 were done for the collision optics at 7 TeV to ensure the corrector strength is sufficient. The available corrector strengths would allow to double the crossing angle since both schemes can provide the full angle separately. However, the

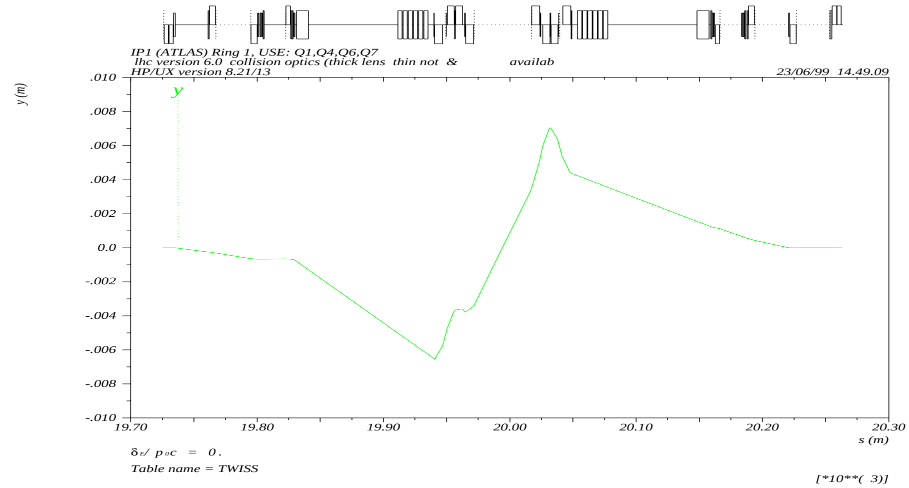

Figure 3: Crossing angle orbit bump in collision, ±150 μrad, shared by scheme A (30%) and B (70%).

available strength for orbit corrections would be reduced while for the proposed scenario at most 17% of the available strength of orbit correctors are used for the bumps at 7 TeV. The maximum possible crossing angle is only limited by the available aperture. The orbit offset in the D2 separation magnet is now approximately ± 1 mm.

3.2.2 Horizontal and vertical parallel separation

A parallel separation in the plane orthogonal to the crossing plane is required during injection and ramping to separate the beams at the central collision point (Tab.1). An

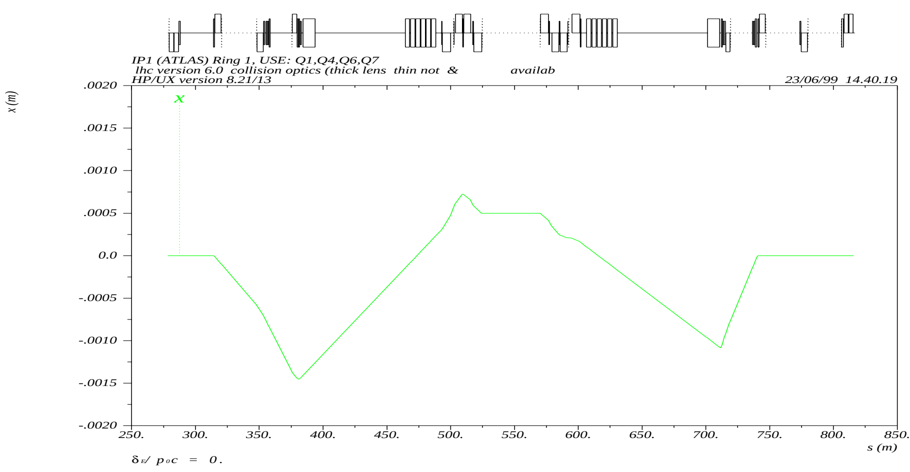

Figure 4: Parallel horizontal separation of ± 0.5 mm in IP1 before collision (Scheme A, for strengths see Tab. 5).

example of such a parallel separation orbit bump is shown in Fig.4 for the collision optics at 7 TeV, i.e. before the beams are brought into collision. Only correctors outside the common part are used and the corrector strengths used for this separation bump are

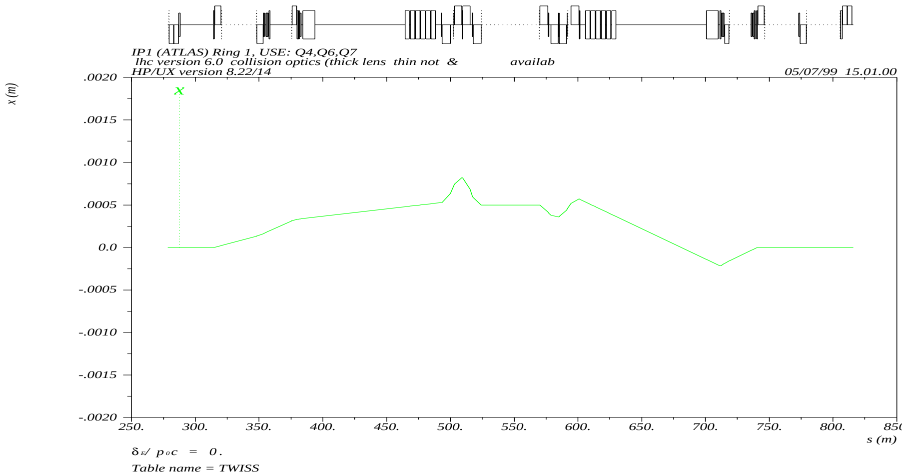

Figure 5: Parallel horizontal separation of $\pm$ 0.5 mm in IP1 before collision (Scheme B, for strengths see Tab. 6).

summarized in Tab.5. The aperture requirements outside the head on collision region are rather large and the orbit offset in the Q4 quadrupole is three times larger than the separation at the central collision point. Although this may be acceptable in collision, for injection the required separation is five times larger and the required aperture can become too large. It is therefore desirable to apply the same procedure as used above for the crossing angle also for the parallel separation bump. The additional correctors near Q1 have a horizontal unit that can be used to create a short parallel bump. Such a short bump is shown in Fig.5. The strengths for the correctors are given in Tab.6. Contrary to the crossing angle bump, the two correctors CXQ1 left and right have now the same strength and the same sign. A linear combination of the two bumps, providing individual control of the two beams, is shown in Fig.6. The required aperture is significantly reduced.

It is further desirable to adjust the beams with symmetric bumps in the plane of the crossing angle. Such a bump, displacing the beam in IP1 by 1 mm, is shown in Fig.7 and the corresponding strengths are given in Tab.7. This type of bump needs individual control of the two beams and is therefore established with corrector magnets acting only on one beam.

None of the proposed orbit bumps for interaction regions 1 and 5 require any of the dedicated correctors previously installed near Q5 (DVQ5, DHQ5 etc.) for the original separation scheme [3]. As a consequence, 12 corrector magnets of type MCBY become unnecessary. Although the same scenario for the separation is foreseen for interaction regions 2 and 8, it remains to be studied whether additional constraints due to the injection allow to economize on all these magnets as well. Some of the additional correctors used are standard orbit correctors, but the required strengths are small and their use in the separation scheme does not compromise the orbit correction.

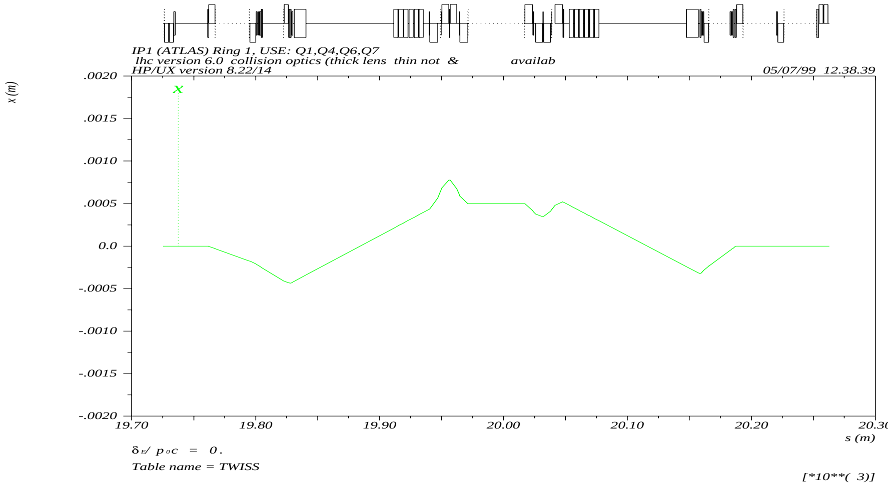

Figure 6: Parallel horizontal separation of ± 0.5 mm in IP1 before collision, shared between scheme A and B.

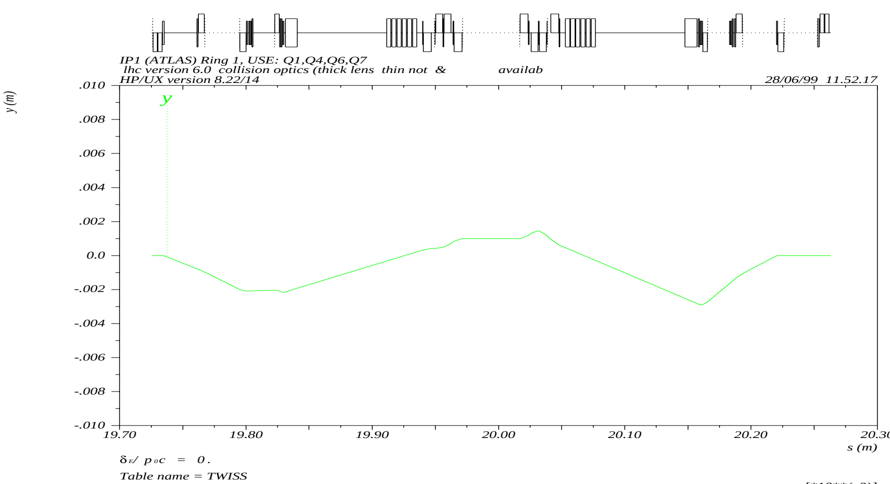

Figure 7: Parallel vertical displacement of ± 1 mm separation in IP1, for strengths see Tab. 7

3.3 Aperture requirements

The aperture requirements for the separation bumps have to be calculated taking into account the available aperture, the actual optics, beam parameters and possible orbit errors. The aperture is quoted in terms of n_1, the maximum allowed position of the primary collimator which provides sufficient protection of the magnets. This value should not become smaller than ≈ 7 in Fig.8. The values n_1 are calculated with the aperture program apl [9], using a peak closed orbit distortion of 4 mm, a momentum error of 0.1%, a β-beating of 20% and standard mechanical tolerances [9]. The horizontal

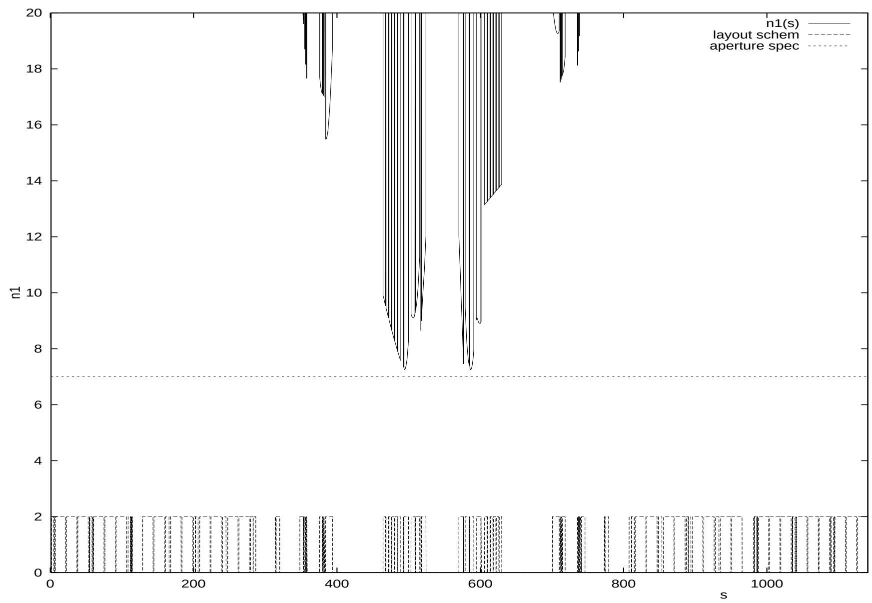

Figure 8: Maximum allowed position in σ of primary collimator which provides protection of magnets.For collision optics at 7 TeV.

scale includes the interaction region and the dispersion suppressors on both sides. Taking the conditions defined above, a maximum crossing angle of $\pm$ 180 μrad can presently be envisaged compatible with the hardware limits and assumed tolerances. It can also be hoped that the assumed orbit distortion will become smaller when the machine is better understood and requires larger crossing angles for higher bunch intensities.

4 Separation scheme for injection and ramping

At injection and during the ramp, the beams must be sufficiently separated all the time in both planes. The injection optics is maintained during the entire ramp and therefore only one optics must be considered. Since the injection will take place in IP2 and IP8, no provision for injection equipment is necessary for IP1 and IP5. The separation requirements at injection and at the end of the energy ramp are given in Tab.1. Using the same separation scheme as in collision, the crossing angle as well as the parallel separation bumps are shown in Figs. 9 and 10. A larger parallel bump is required at injection ($\pm$ 2.5 mm). The required corrector strengths for the bumps in Figs. 9 and 10 are given in Tabs. 8 and 9. The crossing angle at the end of the ramp was designed to be ± 40 μrad to maintain a constant relative separation. However, this is not a limit and the crossing angle could easily be increased.

Due to the larger transverse beam size at injection the available aperture requires

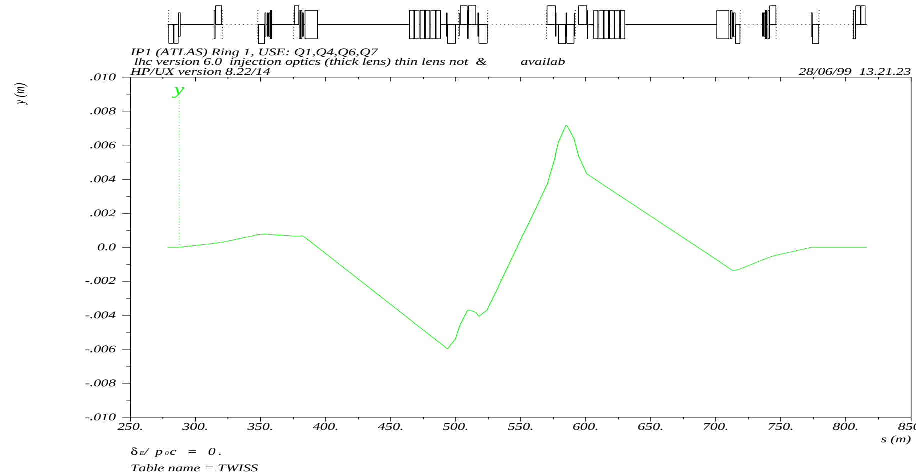

Figure 9: Crossing angle orbit bump at injection, ± 160 μrad, shared by scheme A (30%) and B (70%), for strengths see Tab. 8.

attention. Assuming the same conditions as above, the maximum allowed position of the collimator, n_1, are shown in Fig. 11.

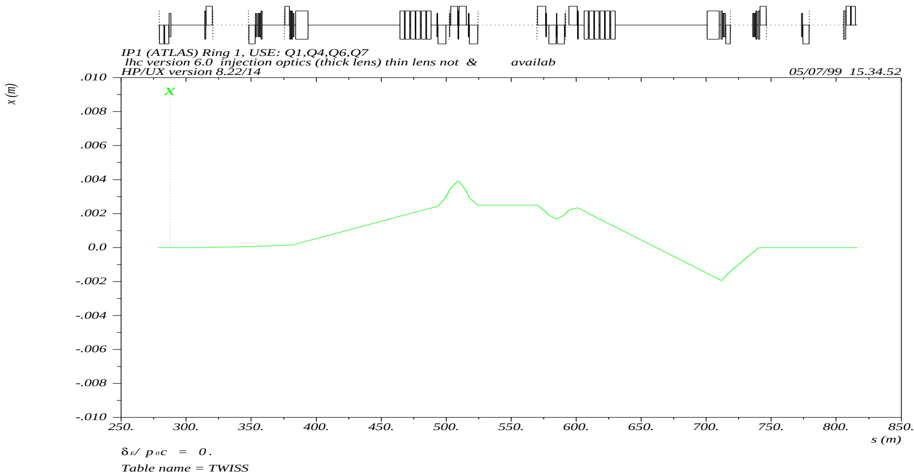

Figure 10: Horizontal parallel separation (± 2.5 mm) at injection, for strengths see Tab. 9.

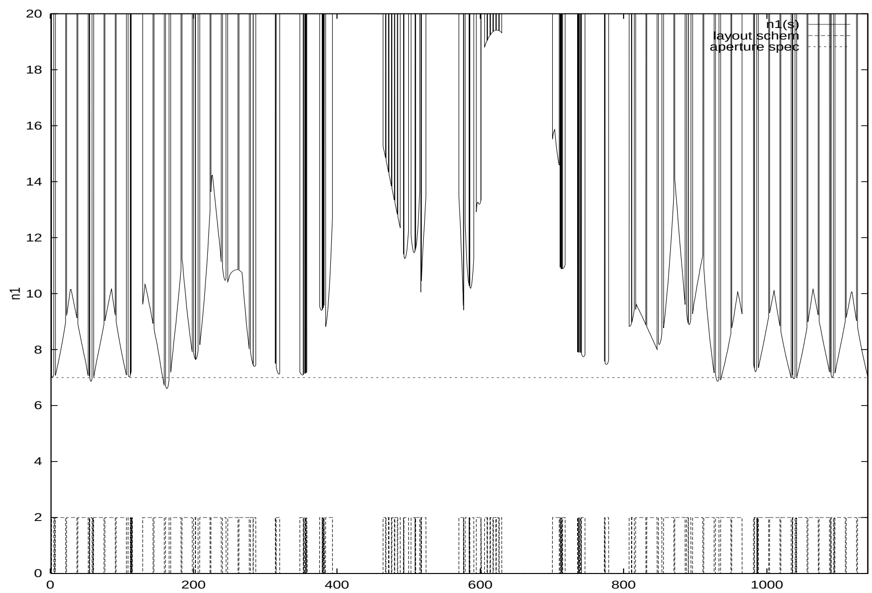

Figure 11: Maximum allowed position in σ of primary collimator which provides protection of magnets. Calculated for injection optics at 450 GeV.

5 Conclusion

We have presented a proposal for a beam separation scheme for interaction regions 1 and 5 for the LHC for optics version 6.0. It complies with requirements from beam dynamics as well as hardware considerations. In particular it does not suffer from insufficient corrector strength or marginal physical aperture. Although correctors common to both beams are used, individual control of the two beams is fully ensured with the presented mixture of two types of separation bumps. Additional corrector magnets mounted on the 4 triplet quadrupoles Q1 are proposed while 12 correctors of type MCBY can be economized.

References

[1] LHC Conceptual Design, CERN/AC/95-05, (1995).

[2] W. Herr; *Beam-beam effects in the LHC*, Part. Acc. **50** (1995) 69.

[3] J. Miles; *A Baseline Beam Separation Scheme for the LHC*, LHC Project Note 136 (1998).

[4] O. Brüning; *Optics Solutions in IR1 and IR5 for Ring-1 and Ring-2 of the LHC Version 6.0*, LHC Project Note 187 (1998).

[5] W. Herr; *Effect of PACMAN bunches in the LHC*, LHC Project Report 39 (1996).

[6] J. Poole, F. Zimmermann (eds); *Proceedings of the Workshop on Beam-beam Effects in Large Hadron Colliders*, CERN/SL/99-039 (AP) (1999).

[7] M. Böge et al; Proc. 1997 Part. Acc. Conf., Vancouver (1997), 1356.

[8] J.-P. Koutchouk; Private communication.

[9] J.B. Jeanneret and R. Ostojic; *Geometrical aperture in the LHC Version 5.0*, LHC Project Note 111 (1997).

Appendix

Name	Type	Location	Angle (μrad)	$\int Bdl$ (Tm)
KV1.L1	MCBY	4.85 m from Q4.L1	-13.550	-0.3162
KV1.R1	MCBY	-3.65 m from Q4.R1	-26.659	-0.6220
KCV6.R1	MCB	Q6.R1 orbit corrector	61.122	1.4262
KCV7.L1	MCBL	Q7.L1 orbit corrector	-31.016	-0.7237

Table 3: *Required corrector strengths in IP1 collision optics at 7 TeV (Scheme A, ± 150 μrad).*

Name	Type	Location	Angle (μrad)	$\int Bdl$ (Tm)
KV1.L1	MCBY	4.85 m from Q4.L1	-55.736	-1.3005
KV1.R1	MCBY	-3.65 m from Q4.R1	40.985	0.9563
KCVQ1.L1	MCBX	-3.709 m from Q1.L1	34.405	0.8028
KCVQ1.R1	MCBX	3.709 m from Q1.R1	-34.405	-0.8028
KCV6.R1	MCB	Q6.R1 orbit corrector	-2.846	-0.0664
KCV7.L1	MCBL	Q7.L1 orbit corrector	-0.165	-0.0038

Table 4: *Required corrector strengths in IP1 collision optics at 7 TeV (Scheme B, ± 150 μrad).*

Name	Type	Location	Angle (μrad)	$\int Bdl$ (Tm)
KH1.L1	MCBY	3.65 m from Q4.L1	23.676	0.5524
KH1.R1	MCBY	-4.85 m from Q4.R1	60.216	1.4050
KCH5.R1	MCB	Q5.R1 orbit corrector	-35.739	-0.8339
KCH6.L1	MCB	Q6.L1 orbit corrector	-17.921	-0.4182

Table 5: *Required corrector strengths in IP1 collision optics at 7 TeV (For 0.5 mm horizontal, parallel separation, scheme A).*

Name	Type	Location	Angle (μrad)	$\int Bdl$ (Tm)
KH1.L1	MCBY	3.65 m from Q4.L1	-0.072	0.002
KH1.R1	MCBY	-4.85 m from Q4.R1	16.894	0.394
KCHQ1.L1	MCBX	-3.709 m from Q1.L1	13.000	0.303
KCHQ1.R1	MCBX	3.709 m from Q1.R1	13.000	0.303
KCH5.R1	MCB	Q5.R1 orbit corrector	-7.154	-0.167
KCH6.L1	MCB	Q6.L1 orbit corrector	4.116	-0.096

Table 6: *Required corrector strengths in IP1 collision optics at 7 TeV (For 0.5 mm horizontal, parallel separation, scheme B).*

Name	Type	Location	Angle (μrad)	$\int Bdl$ (Tm)
KV1.L1	MCBY	4.85 m from Q4.L1	51.963	1.2125
KV1.R1	MCBY	-3.65 m from Q4.R1	50.298	1.1736
KCV6.R1	MCB	Q6.R1 orbit corrector	-39.311	-0.9173
KCV7.L1	MCBL	Q7.L1 orbit corrector	-29.149	-0.6801

Table 7: *Required corrector strengths in IP1 collision optics at 7 TeV (For 1 mm vertical displacement).*

Name	Type	Location	Angle (μrad)	$\int Bdl$ (Tm)
KV1.L1	MCBY	4.85 m from Q4.L1	-65.152	-0.0977
KV1.R1	MCBY	-3.65 m from Q4.R1	61.081	0.0916
KCVQ1.L1	MCBX	-3.709 m from Q1.L1	62.471	0.0937
KCVQ1.R1	MCBX	3.709 m from Q1.R1	-62.471	-0.0937
KCV6.R1	MCB	Q6.R1 orbit corrector	-16.888	-0.0253
KCV7.L1	MCBL	Q7.L1 orbit corrector	8.700	0.0131

Table 8: *Required corrector strengths in IP1 injection optics at 450 GeV (Scheme A+B, ± 160 μrad).*

Name	Type	Location	Angle (μrad)	$\int Bdl$ (Tm)
KH1.L1	MCBY	3.65 m from Q4.L1	19.298	0.0289
KH1.R1	MCBY	-4.85 m from Q4.R1	126.337	0.1895
KCHQ1.L1	MCBX	-3.709 m from Q1.L1	45.000	0.0675
KCHQ1.R1	MCBX	3.709 m from Q1.R1	45.000	0.0675
KCH5.R1	MCB	Q5.R1 orbit corrector	-63.951	-0.0959
KCH6.L1	MCB	Q6.L1 orbit corrector	1.760	0.0026

Table 9: *Required corrector strengths in IP1 injection optics at 450 GeV (For 2.5 mm horizontal, parallel separation).*