LHC IR Upgrade: a Dipole First Option *

Riccardo de Maria, CERN, Geneva, Switzerland

Abstract

A dipole first option, able to reach a β^* of $25\mathrm{cm}$, is proposed for the luminosity upgrade of LHC. Within this option only the triplets, the separation-recombination dipoles and Q5 are been upgraded. The main specifications (length, strength, aperture) for the new magnets are provided. The optical solutions with the crossing schemes for injection, collision and the transitions are found. The chromaticity correction is studied.

INTRODUCTION

The aim of the LHC luminosity upgrade is to increase the luminosity from $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by increasing the number of protons per bunch, increasing the number of bunches, reducing the longitudinal beam size and reducing β^* by upgrading the insertion region [1].

The upgrade of the interaction regions (IR) of the main experiments ATLAS and CMS (IR1 and IR5 respectively) is expected to provide a β^* of $25\mathrm{cm}$ increasing the luminosity by a factor 2.

The present layout, designed for β^* of $55\mathrm{cm}$, is not able to provide a β^* of $25\mathrm{cm}$ because the triplet quadrupoles can not fulfill the required specifications on mechanical aperture. Moreover the lifetime of the triplets is estimated to be limited to 7 years at the nominal luminosity due the radiation [1] coming from the IP. If no relevant change in the design with respect to the radiation protection is performed this time is reduced by an order of magnitude at the upgraded luminosity implying a triplet replacement on a year basis.

In opposition to the present quadrupole first layout, a new one, called dipole first layout, has been proposed [2] which should be able to incorporate an efficient absorber with the separation/recombination dipole assembly and to obtain a β^* of $25\mathrm{cm}$ by taking advantage of new magnet technology. A dipole first layout is expected to ease the radiation protection issues as the first dipole can act as a spectrometer and absorb the charged debris.

In this paper a realistic implementation of the dipole first layout is proposed and studied with respect to its optic properties and integration in the machine. In particular the collision-, injection- and transition-optics, the crossing angle and parallel separation schemes, linear chromaticity correction and specifications of the magnets strengths and apertures are presented.

The motivations for the studies are to test the feasibility of the main assumptions of the layout, the compatibility of the new elements with the rest of the LHC ring elements and to set a reference for comparison with other possible layouts.

* Work supported by CERN and EPFL

LAYOUT

The new layout has been designed to maintain all the LHC parameters, all the elements but the triplets and the separation-recombination dipoles in order to keep the cost of the upgrade as low as possible. It turned out that in addition Q5, which is not a wide aperture magnet, needs to be replaced due to larger mechanical aperture requirements. The new magnets require a new technology, such as magnets based on Nb3Sn superconductor material. The requirements for the aperture are 10σ separation of the two beams in order to keep the beam beam interaction small, and 9σ from the beam pipe to avoid the beam losses like in the present LHC. The radiation heat load and radioactivity issues, though quite important for a realist design, have not been taken into account and will be addressed in further studies.

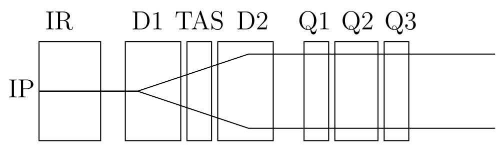

Figure 1: Dipole first layout. IP is the interaction point, IR is the detector region, D1 is the recombination dipole, D2 is the separation dipole, TAS is a place holder for an absorber, Q1,Q2,Q3 the triplet magnets.

One half of the dipole first layout is shown in the Figure 1. The full layout is symmetric with respect to the interaction point (IP), only half is shown. Going from left to right are sketched:

Experiment

IR marks the experimental region where the detectors are placed. In the baseline LHC the distance at which the TAS is placed, is 19.05 meters and is the minimum distance (L^*) from which magnets can be placed. The feasibility of using small magnets even inside the detector region is under study.

D1

The D1 dipole is supposed to split the beams coming from the IP giving to them the deflection needed to achieve the nominal separation of $194\mathrm{mm}$. In order to reduce the distance from the triplets to the IP, the dipole should provide the highest possible field and enough aperture to reserve the space for the splitting. It has been assumed that the Nb3Sn technology will provide a field of $15\mathrm{T}$ and an aperture of $100\mathrm{mm}$. The required aperture at the beginning of D1 can be approximately calculated using [3]:

$$A = 33\sigma + 7\mathrm{mm} \quad (1)$$

$$\sigma = \sqrt{\beta\varepsilon + D\delta} \quad (2)$$

$$\beta = \beta^* + \frac{s^2}{\beta^*} \quad (3)$$

The required aperture at the end can be estimated by adding the separation due to the dipole.

D2

The D2 dipole brings the two beams parallel to their nominal separation. We assume a two-in-one design. The required aperture can be estimated using [3]:

$$A = 22\sigma + 7\mathrm{mm} \quad (4)$$

Figure 2 sketches the D1-D2 assembly showing the beam envelope at 10σ.

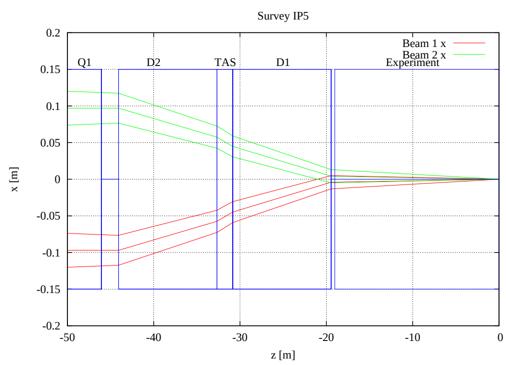

Figure 2: Survey of the D1-D2 assembly showing the beam envelope at 10σ.

TAS

The TAS is a placeholder for an absorber for the radiation coming from the IR. The length is taken from the LHC baseline design. The radiation produced by charged particles should be absorbed by D1 whose field acts as a spectrometer deviating the debris along its sides which can be equipped with absorber. As neutral flux is not bended, it has to be absorbed in the region marked by TAS before encountering the first two-in-one magnets, unless they are designed to have a hole in the middle.

Magnet	d from IP	length	field	aperture
D1	19.450m	11.400m	15.1T	120mm
D2	32.670m	11.400m	15.1T	80mm
Q1	46.050m	4.550m	231T/m	80mm
Q2a	51.870m	4.500m	257T/m	80mm
Q2b	57.690m	4.500m	257T/m	80mm
Q3	57.690m	5.000m	280T/m	80mm

Table 1: Specifications of the upgrade new elements.

Q1-Q3

Q1-Q3 are the triplet quadrupoles with a two-in-one design. The required aperture can be estimated again using equation (4).

Table 1 shows a summary of the specifications for the new elements.

OPTICS

Figures 3 and 4 show the collision optics for Beam 1 and Beam 2. There are several differences with respect to the baseline optics due the new layout.

The increase of the maximum β function, $18\mathrm{km}$ compared to the $4\mathrm{km}$ of the baseline LHC, is due to the decrease of β^* and the increase of the distance from the IP of the quadrupoles (about $46\mathrm{m}$ instead of $23\mathrm{m}$).

In the matching region (Q4-Q7) the dispersion is not zero. This is due to the fact that D1-D2 introduce a dispersion jump that has to be compensated in order to get a zero dispersion at the IP. Dispersion in this region reduces the degrees of freedom of the matching quadrupoles which by them self are no longer able to match the triplet assembly to the arcs. The dispersion suppressor quadrupoles have to be used for the matching purpose. Moreover the dispersion breaks the symmetry between left and right with respect to the IP and the symmetry between Beam 1 and Beam 2, making the optics solution slightly different for each of these regions.

Figure 5 shows the mechanical aperture in term of n1 [4] values of this optics. It shows that Q5, due to the high β values, needs a bigger aperture. The high values of β are unavoidable due the layout. An upgrade of Q5 to a wide aperture quadrupole, like an MQY, is necessary.

Transition to Injection Optics

The existence of a continuous path of the magnet strengths from collision to injection is not obvious because the strengths of the quadrupoles are close to their limits, the beta functions are high and the dispersion in the matching section reduces degrees of freedom.

For this particular layout a solution has been found using a new matching routine in MADX able to cope the complex boundary conditions arising from the broken symmetries and the barely sufficient flexibility of the LHC optics.

Figures 6 and 7 show the strengths of the quadrupole during the transition.

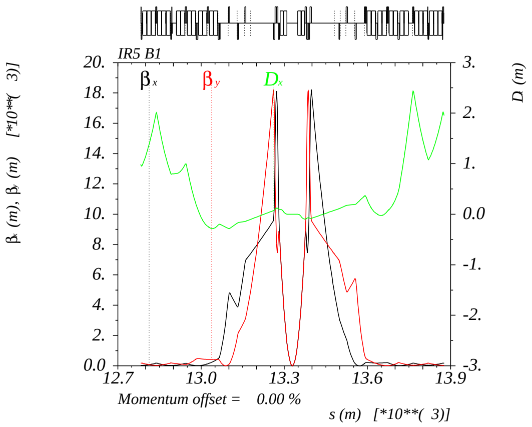

Figure 3: Collision optics of Beam 1 for the dipole first upgrade option.

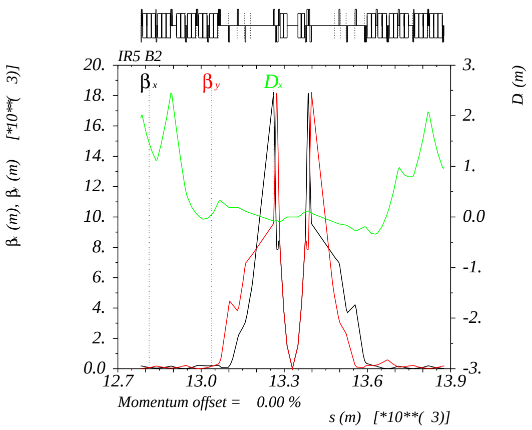

Figure 4: Collision optics of Beam 2 for the dipole first upgrade option.

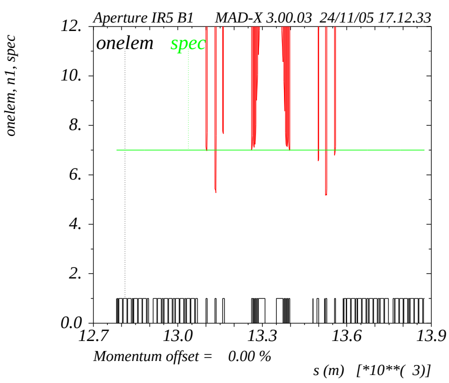

Figure 5: Mechanical aperture at collision expressed in term of n1 for the dipole first upgrade option.

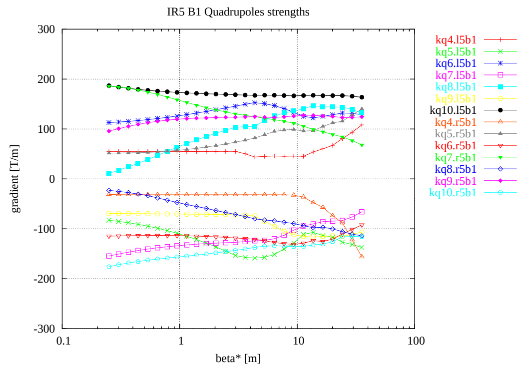

Figure 6: Strengths of the insertion quadrupoles Q4-Q10 during the transition of β^* on from collision to injection for Beam 1

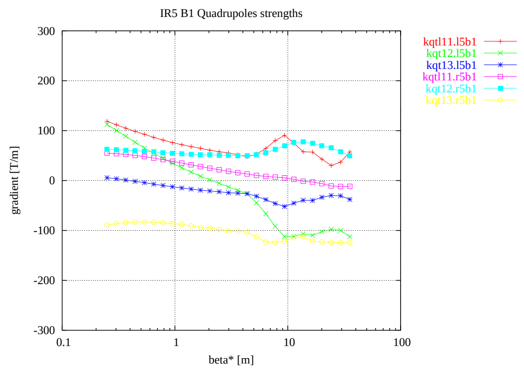

Figure 7: Strengths of the insertion trim quadrupoles Q11-Q13 during the transition of β^* on from collision to injection for Beam 1

The evolution of the quadrupole strengths is smooth but with some inversion of the slope which might be a problem because of hysteresis effect for the multipole errors.

Injection Optics

The injection optics shown in the Figure 8 present no additional issues compared to the present LHC optics and it is confirmed by the aperture calculation shown in Figure 9.

Tunability

In order to evaluate the operational margin of the insertion a phase advance scan of the insertion at collision for Beam 1 and Beam 2 has been performed.

Figure 10 shows the values of the horizontal and vertical phase advance for which a reasonable collision optics solution has been found. It shows that the insertion keeps good tunability ($\frac{\delta\mu_x}{2\pi} = 0.016$, $\frac{\delta\mu_y}{2\pi} = 0.10$) properties.

The horizontal phase is one order of magnitude less flexible due to the horizontal dispersion to be matched. Any-

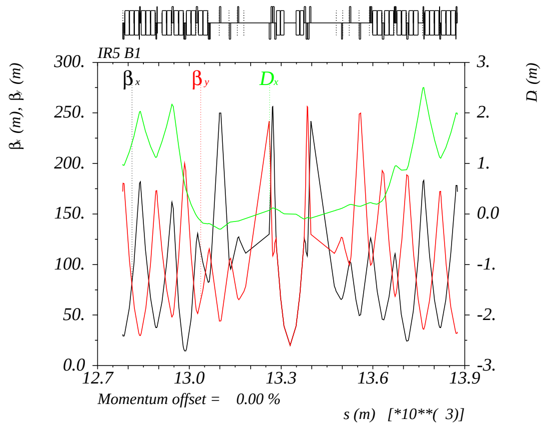

Figure 8: Collision optics of Beam 1 for the dipole first upgrade option.

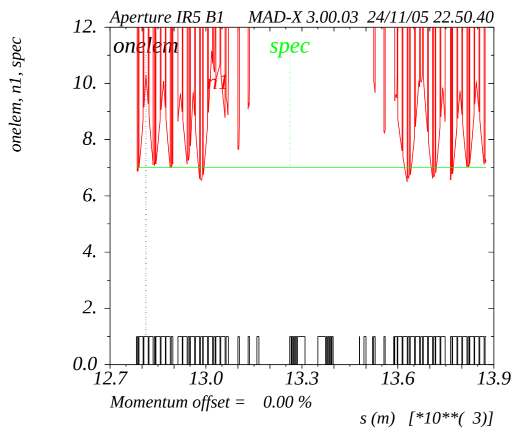

Figure 9: Mechanical aperture at injection expressed in terms of n1 for the dipole first upgrade option.

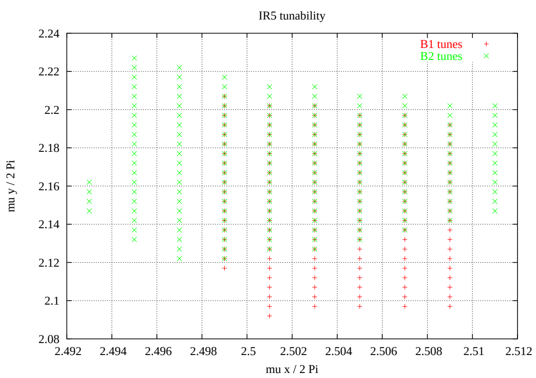

Figure 10: Tunability of the upgraded insertion. For each cross (red for Beam 1 and green for Beam 2) a reasonable collision optics exists.

Data	Unit	LHC	Upg.
Energy	[GeV]	7000	7000
Relativistic gamma		7461	7461
Normalized emmittance	[μm rad]	3.750	3.750
Emmittance (ε)	[nm rad]	0.503	0.503
RMS beam size at IP	[μm]	16.63	11.21
Half crossing angle (ϕ)	[μrad]	142.5	211.4
Half separation (d)	[σ]	4.714	4.714

Table 2: Data used for estimating the required crossing angle for the baseline LHC and dipole first layout.

way the overall flexibility is comparable with the nominal LHC optics [5].

CROSSING ANGLE SCHEME

A crossing angle different from zero is needed for the LHC in order to limit the long range beam-beam interaction between the two beams. The amount of angle depends on the separation needed to reduce the long range beam beam interaction. The minimum required crossing angle can be estimated using

$$\frac{d}{\sigma} = \phi\sqrt{\frac{\beta^*}{\varepsilon}}, \tag{5}$$

where d is the distance between the center of the beams, σ is the RMS beam size and ε is the emittance.

The table 2 shows the values of the crossing angles needed for the baseline LHC and dipole first layout LHC in order to fulfill the required beam separation.

The crossing angle schemes are performed by D1 and D2 and not anymore by orbit corrector magnet before the triplets. This is a great advantage because reduces the aperture needs of the triplet magnets and does not introduce vertical and horizontal spurious dispersion.

Figure 11 and 12 show the crossing angle schemes for the horizontal and vertical plane. The former can be achieved with a slightly different angle for D1 and D2 and the latter by tilting D1 and D2 resulting in a vertical deflection

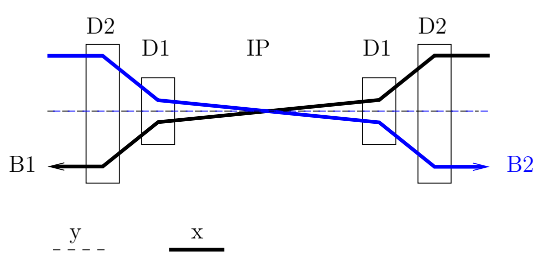

Figure 11: Horizontal crossing angle scheme. The continuous line represent projection in the $z-x$ plane, and the dashed the $z-y$ one.

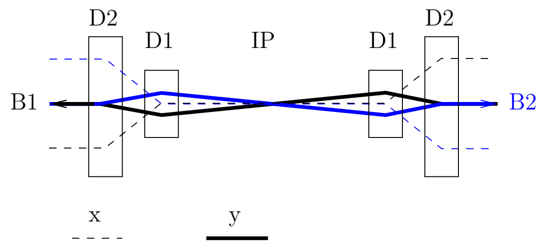

Figure 12: Vertical crossing angle scheme. The continuous line represent projection in the $z - y$ plane, and the dashed the $z - x$ one.

A separation at the IP is also need during the injection and the acceleration of the particles. It can be achieved either using the orbit corrector magnets or dividing D1 and D2 in two parts and powering them differently. Figure 13 shows an example for the last option where is performed a horizontal crossing angle and a vertical separation. Figure 14 shows, on the contrary, a vertical crossing angle and a horizontal separation.

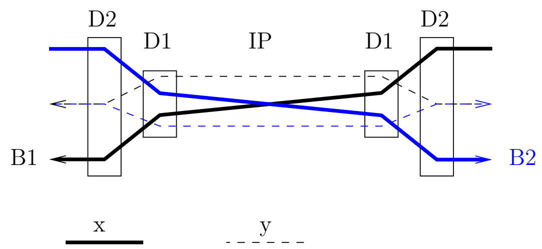

Figure 13: Separation scheme for the vertical crossing angle. The continuous line represents the projection in the $z - y$ plane, and the dashed the $z - x$ one.

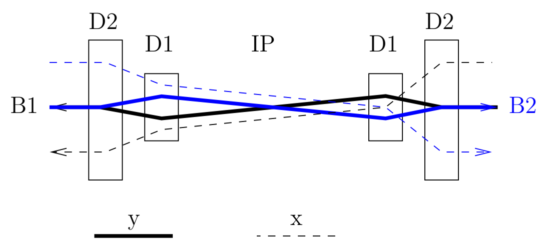

Figure 14: Separation scheme for the vertical crossing angle. The continuous line represents the projection in the $z - y$ plane, and the dashed the $z - x$ one.

Figure 15 shows the dispersion function when the crossing angle scheme is on and shows that there is no mismatch outside the interaction region.

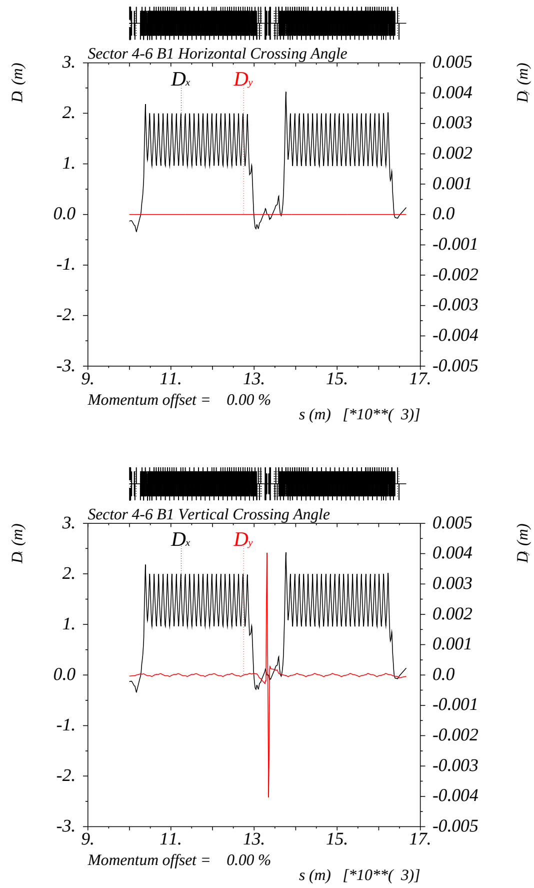

Figure 15: Horizontal and vertical dispersion function between IP4 and IP6 when the respectively the horizontal and the vertical crossing angle are on.

Family	Max Field at 17mm	Max k_2
MSS	$1.280\mathrm{T}$	$0.379\mathrm{m}^{-2}$
MCS	$0.471\mathrm{T}$	$0.139\mathrm{m}^{-2}$

Table 3: Sextupoles families in LHC and their strengths.

CHROMATICITY

The chromaticity is enhanced by high β values. In the LHC there are two families of available corrector magnets, the focusing and defocusing arc sextupoles MSS and the spool piece magnets MCS inside the main dipoles. Table 3 shows their strengths.

The linear chromaticity can be corrected using these families in two different ways, summarized in Table 4.

In the first option only the arc sextupoles are used, using almost all the budget available of the defocusing sextupoles. In the second the spool species are used to balance the required strength of all the sextupoles.

Figures 16 and 17 shows the tune versus δp using the two schemes.

	MSS F	MSS D	MCS
1.	54.1%	92.7%	0%
2.	71.4%	70.0%	70.0%

Table 4: Sextupoles strengths for the linear chromaticity correction.

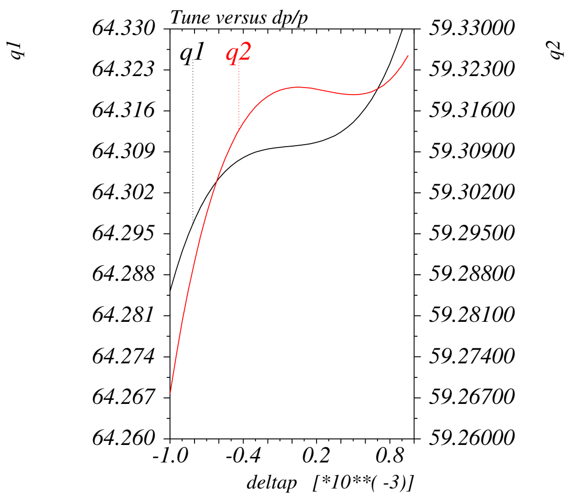

Figure 16: Horizontal (q1) and vertical (q2) tune versus $\frac{\Delta p}{p}$ corrected by the arc sextupoles.

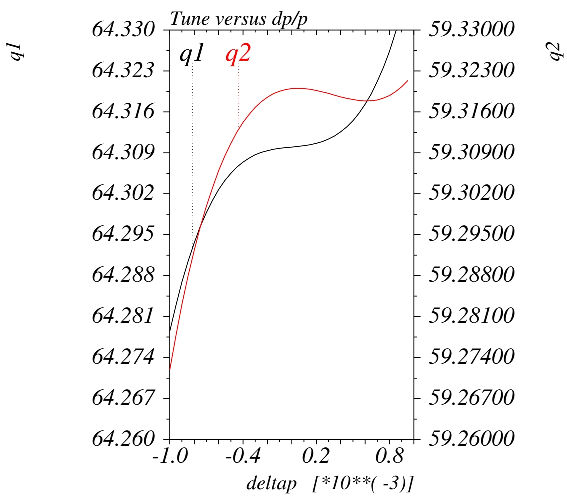

Figure 17: Horizontal (q1) and vertical (q2) tune versus $\frac{\Delta p}{p}$ corrected by the arc and spool sextupoles.

In both cases the non linear terms are quite strong and studies for their correction using local schemes are on going.

CONCLUSION

A dipole first scenario with the relevant optics configuration has been developed. The required aperture is compatible with the specifications for the elements.

In this framework Q5 should be replaced from a MQM type of the baseline to a wider aperture quadrupole like an MQY type.

A transition between injection and collision exists. This was not obvious due the dispersion in the triplets, but it was demonstrated that the insertion region is compatible with the optics of a dipole first layout.

The linear chromaticity can be corrected with the sextupoles in the arcs, but not the non linear terms requiring probably an additional local chromaticity correction.

There are new advantages with respect quadrupole first option:

- The crossing schemes is completely managed by D1 D2 which cancel the dispersion mismatch due the orbit changes.
- The first dipole (D1) can act as an absorber for the charged debris reducing the needs of dedicated devices even if a solution for the neutron flux has to be found.
- The dipole first layout reduces the long range beam-beam interactions due the early separation of the beam.

The drawbacks are the already mentioned protection from the neutral flux. The magnet technology is pushed to the limits and it is not guarantied that the proposed elements will be ready at the upgrade time.

There are several open questions still to be answered for a complete evaluation of this option: the non linear chromaticity correction and its effect on the long term stability of the beam, the radiation protection that is more demanding due than the present LHC due the increase of one order of magnitude of the luminosity, the effects of β^* of 18km on the tolerances for the ground motion, multipole errors and alignments and the integration of a TAS absorber into the D1/D2 assembly.

REFERENCES

[1] Francesco Ruggiero. LHC Accelerator R&D and Upgrade Scenarios. Technical Report LHC-Project-Report-666, CERN, August 2003.

[2] Olivier Sim Bruening, Roberto Cappi, R. Garoby, O. Grbner, W. Herr, T. Linnecar, R. Ostojic, K. Potter, L. Rossi, F. Ruggiero, Karlheinz Schindl, Graham Roger Stevenson, L. Tavian, T. Taylor, Emmanuel Tsesmelis, E. Weisse, and Frank Zimmermann. LHC Luminosity and energy upgrade :

A Feasibility Study. Technical Report LHC-Project-Report-626, CERN, dec 2002.

[3] Oliver Bruening. Possible Dipole First Options and Challenges, sep 2005. LHC LUMI 2005 CARE-HHH-APD Workshop.

[4] J.B. Jeanneret and R.Ostojic. Geometrical acceptance in LHC Version 5.0. LHC Project Note 111, CERN, sep 1997.

[5] Oliver Sim Bruening. Optics Solutions in IR1 and IR5 for Ring-1 and Ring-2 of the LHC Version 6.0. Technical Report LHC-PROJECT-NOTE-187, CERN, apr 1999.