IR Upgrade with Quadrupoles First and Dipoles First

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Abstract

We review recent work on the LHC IR upgrades by the US-LARP collaboration. There are several optics designs under consideration – each design differs in the potential luminosity reach, accelerator physics, operational and technical challenges etc. Here we consider two main issues: (i) the likely benefits of moving the IR magnets closer to the IP for both quadrupole first and dipole first designs and (ii) the impact of beam-beam interactions in the two designs. We conclude with a summary of accelerator physics parameters for the two designs.

INTRODUCTION

The baseline quadrupole first design and two flavors of the dipole first design studied by the US-LARP collaboration were discussed at the luminosity 2005 workshop [1]. The two dipole first designs under study feature: (1) triplet focusing with anti-symmetric optics and (2) doublet focusing with symmetric optics in the inner IR magnets. Doublet optics leads to a larger luminosity at the cost of producing elliptical beams at the IP and enhanced chromaticities. Table 1 shows the required aperture and peak fields in the inner IR magnets at collision optics for the three designs.

Table 1: Maximum pole tip field and apertures required in the IR magnets at collision optics

	Pole-tip field [T]	Aperture [mm]
Quads 1st	10	101
Dipoles 1st: triplets	11	107
Dipoles 1st: doublets	10	104

The requirements on the aperture are about the same in all designs (within 10%) even though the beta functions are about three times larger in the dipole first designs. Both beams are accommodated within a single aperture in the quadrupole first designs while the beams are separated into different apertures in the dipole first designs. The optics and layout will be discussed in the following sections. The optics of the insertions has been matched into the complete LHC ring by R. Tomas-Garcia. The MADX files of the complete lattices are available on the LHC upgrade repository [2].

A complete IR design requires study of accelerator physics issues including but not necessarily limited to: optically matched designs at all stages of the operational cycle, correction of linear and non-linear chromaticity of the insertions, correction of the non-linear fields of the IR magnets, the impact of beam-beam interactions, energy deposition in the magnets from the collisions at the IP, correction of dispersion within the IR, susceptibility to alignment errors, power supply noise, ground motion etc.

A critical parameter that affects all these issues is the distance of the first magnet from the IP. At the Luminosity 2005 workshop there was some discussion with experimenters from Atlas and CMS about the feasibility of placing magnets inside the detectors. In the following sections we explore how moving magnets closer to the IP might improve the IR performance. We also take a first look at the impact of beam-beam interactions in the different designs.

QUADS FIRST

The optics functions through an insertion with β^*=0.25 m is shown in Fig. 1. The layout is unchanged with L* (distance to the first quadrupole) = 23 m as in the baseline design. The vertical dispersion at IP5 is created by the vertical crossing angle at IP1. The maximum β is about 9 km, about twice the baseline value.

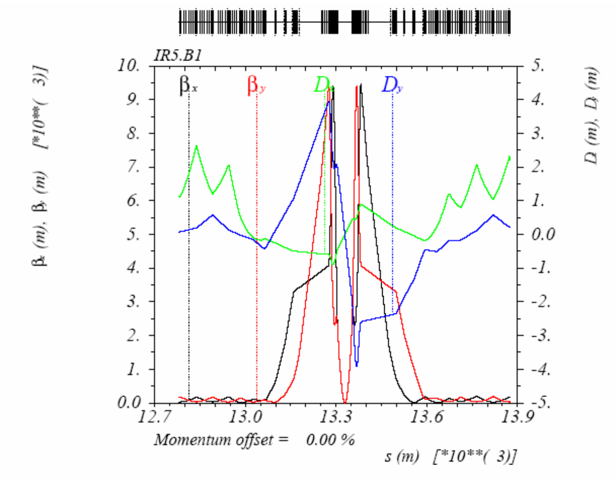

Figure 1: Optics for baseline insertion with β^* = 0.25 m.

*Variation with L**

Moving the magnets closer to the IP reduces the β^{max} for the same value of β^*. Conversely, keeping β^{max} constant allows us to reduce β^* for a potential gain in luminosity at lower L*. For this exercise we adopted a shorter version of the insertion extending from Q4 on the left to Q4 on the right. The optics at these quadrupoles was matched to nearly the same values as in the complete insertion at β^* = 0.2 5 m. The gradients are kept the same but the quadrupole lengths are changed to reduce β^* to the lowest possible value keeping β^{max} constant at each value of L*.

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The luminosity depends directly on β* as 1/ β* and indirectly through the crossing angle. For the beam separation to stay constant as β* is decreased, the crossing angle must increase as $1/\sqrt{\beta^*}$ which reduces the luminosity. If L* decreases by more than half the bunch spacing, the number of parasitic interactions also falls. In such cases we can take advantage of an empirical scaling by Papaphilippou and Zimmerman [3] which suggests that the crossing angle scales as $\sqrt{N_{LR}}$ where N_{LR} is the number of parasitic interactions.

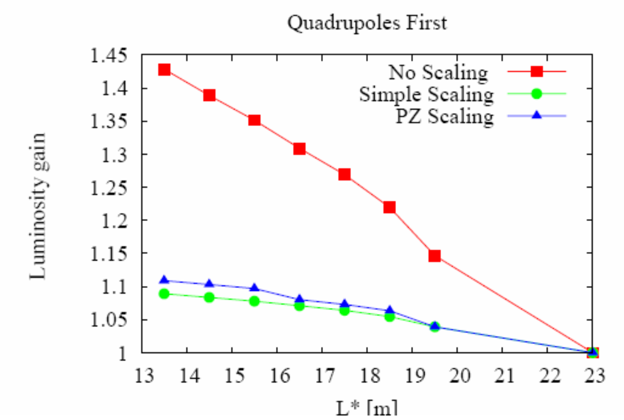

Figure 2: Luminosity vs. L*; with quads first.

The luminosity at each L* can be calculated after β* is found from optical matching. The dependence of the luminosity on L* is shown in Fig. 2 for three cases. The case "No scaling" does not take into account the dependence on crossing angle. This might be appropriate if some means of beam-beam compensation is found that allows the crossing angle to stay constant. The difference between simple scaling (only the crossing angle but not dependence on N_{LR}) and PZ scaling [3] is not significant. The luminosity gain by reducing L* to 13 m is about 11% if the crossing angle dependence is included while the gain is nearly 45% if the crossing angle can be allowed to stay constant. This result clearly shows that reducing the L* in itself will not significantly increase the luminosity unless parasitic beam-beam interactions are compensated to allow for the same or smaller crossing angle.

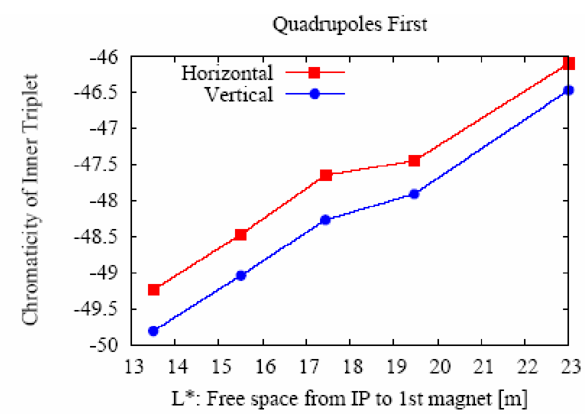

Figure 3: Chromaticity vs. L*; quads first.

As the quadrupoles are moved closer to the IP, their focusing strengths increase; therefore the chromaticity of the inner triplet also increases with shorter L*. Fig. 3 shows the change in chromaticity – about 4 units per IR per plane as L* is reduced from 23 m to 13 m.

Beam-beam effects

We now analyse the beam-beam interactions with L* = 23 m and β* = 0.50 m (baseline) and β* = 0.25 m (upgrade). At β* = 0.25 m, the crossing angle is increased to 400μrad from the baseline value of 285 μrad. Fig. 4 shows the tune footprint (calculated analytically) up to 6σ when the head-on interactions and 30 long-range interactions each at IP1 and IP5 are included. The footprints are nearly the same since the beam separations (in units of σ) are almost the same.

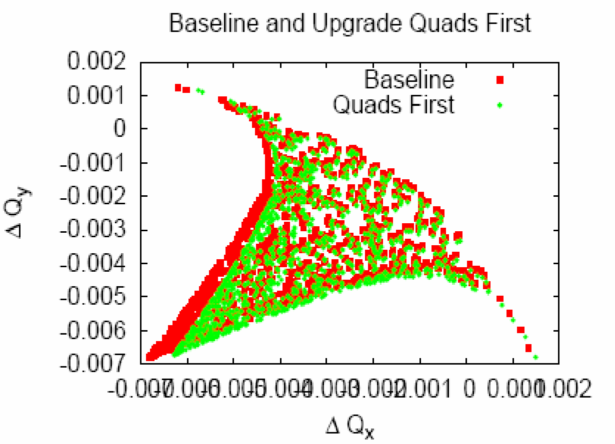

Figure 4: Beam-beam tune footprints to 6σ.

Resonance driving terms can also be used to characterize the strength of the non-linearity. With the LHC working point at (0.31, 0.32), the nearby low-order resonances are the 3rd and 10th. Figs. 5 and 6 show the strongest 3rd and 10th order resonance driving terms magnitude at each of the parasitics in IR5, evaluated at amplitude of 6σ. The analytical expressions may be found in Reference [4]. Perhaps due to differences in matching, the beam separations (in units of σ) in the drift space are slightly different in the two lattices. Since higher order resonances are more sensitive to beam separations, the differences in separation are amplified for the 10th order resonances. The strongest resonance terms are contributed by the parasitics at smallest separations (~7σ) in the IR quadrupoles. When all the parasitics are included, the beam-beam resonance driving terms in the baseline and the upgrade lattice are not significantly different at amplitude of 6σ.

Simulations can also probe the impact of the beam-beam interactions. We have used the code BBSIM developed at FNAL [5] to calculate diffusion coefficients at different amplitudes. Fig. 6 shows the horizontal diffusion coefficient Dx as a function of the radial amplitude Ar for the two lattices, and similarly Fig. 7 shows the dependence of Dy on Ar.

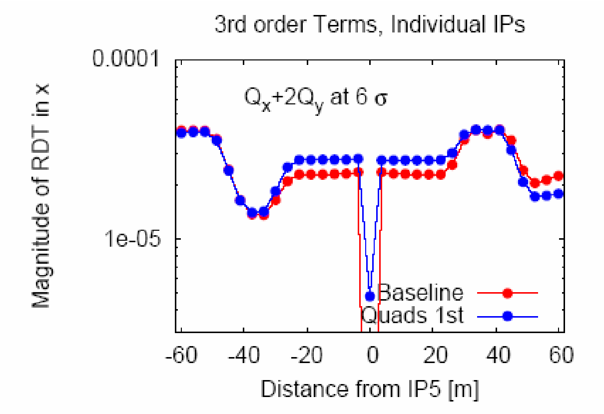

Figure 4: Beam-beam Qx+2Qy resonance driving term magnitude in the baseline and upgrade at each parasitic interaction in IR5.

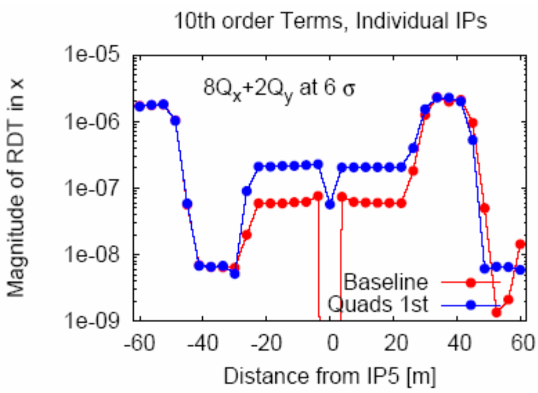

Figure 5: Beam-beam 8Qx+2Qy resonance driving term magnitude in the baseline and upgrade at each parasitic interaction in IR5.

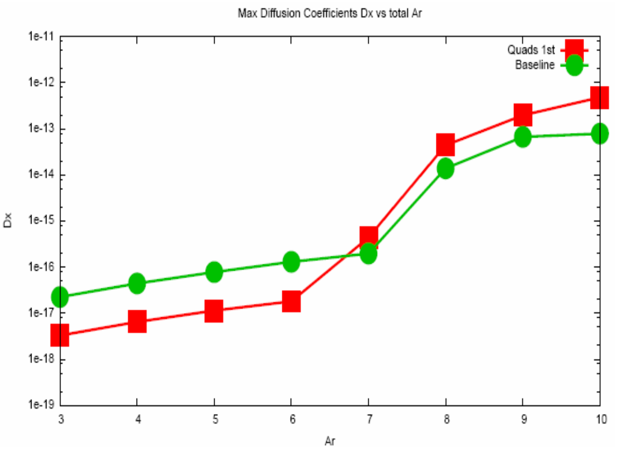

Figure 6: Diffusion coefficient Dx in the horizontal plane vs. amplitude for the baseline and upgrade optics.

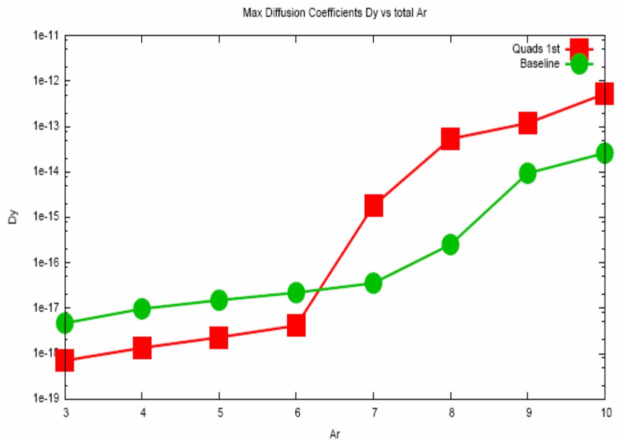

Figure 7: Diffusion coefficient Dy in the vertical plane vs. amplitude for the baseline and upgrade optics.

Vertical diffusion appears to be stronger in the upgrade optics at amplitudes larger than 6σ. We observe that the diffusion jumps at 8-9σ in the baseline lattice but the jump occurs at 7σ in the upgrade lattice. This suggests that the beam-beam interactions will further limit the dynamic aperture in the upgrade. This makes the need for beam-beam compensation stronger.

DIPOLES FIRST

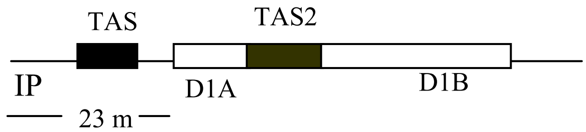

Figure 8: Layout of the TAS absorbers with dipoles first. Sketch is not to scale.

We will mainly use the dipole first triplet focusing layout to compare with the quadrupoles first layout. The special design required for the D1 dipole magnet to cope with the energy deposition was discussed in [1]. An integrated field of 20 Tm is required to deflect the charged particle debris into a second absorber TAS2 to protect dipole D1. Fig. 9 shows the layout. The 10 m long D1 dipole is split into two with D1A of 1.5 m length (strength 20 Tm) and D1B of 8.5 m length. A 5m long neutral absorber TAN is placed after the second separation dipole TAN. As a consequence the first quadrupole Q1 is moved back to 55.5 m from the IP compared to 23 m in the quadrupole first layout. This increases the beta functions at the quadrupoles. The twiss functions through the insertion are shown in Fig. 9. The maximum beta function increases to about 27 km.

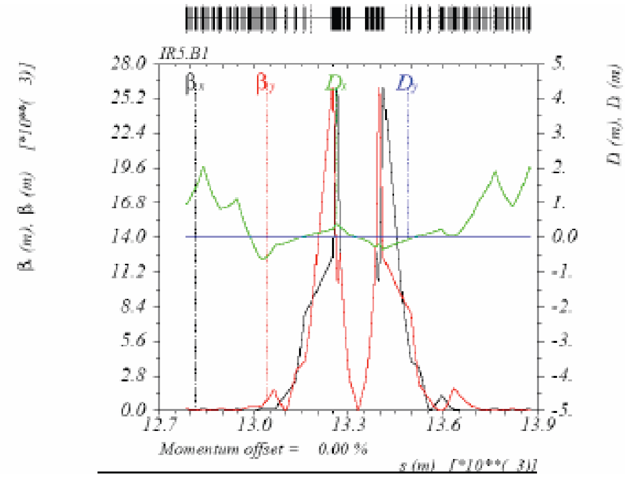

Figure 9: Twiss functions through IR5 at collision with dipoles first, triplet focusing.

*Variation with L**

The potential luminosity reach of the dipoles first optics with smaller L* was studied similarly as for the quadrupole first optics. The part of the insertion between the Q4s was used; β^{max} was kept constant while matching to the lowest β* at each value of L*. Since the quadrupoles are much further back in this optics, β* values are higher for the same shift towards the IP.

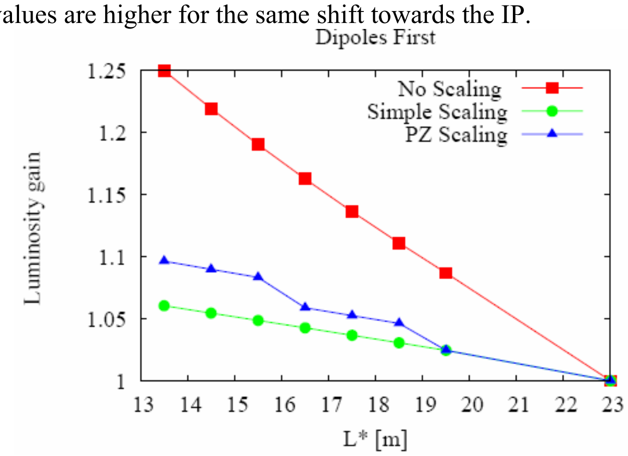

Figure 10: Luminosity as D1 is moved from 23m to 13m from the IP; dipole first optics, triplet focusing.

Fig. 10 shows the gain in luminosity as the magnets are moved closer to the IP. In this figure the horizontal axis is the distance of D1 from the IP. For the case of "no scaling", i.e. no change in crossing angle with distance, the gain in luminosity is about 25% at 13 m. The gain in luminosity in the other two cases when the crossing angle is increased at smaller L* is limited to 10% at 13m. There is at least one caveat in comparing these results with the quadrupole-first layout. Due to the smaller number of parasitic interactions with dipoles first, a smaller crossing angle might suffice, which would increase the luminosity beyond the values shown in Fig. 10.

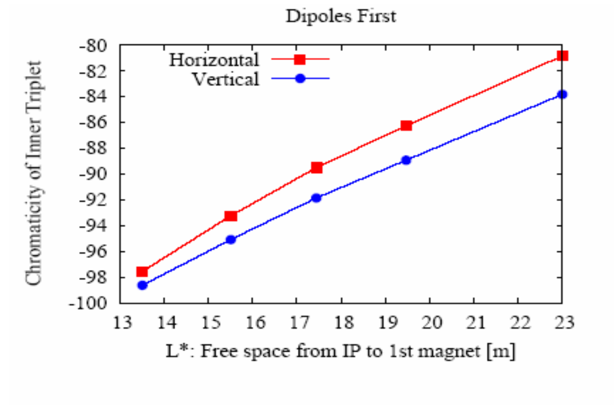

Figure 11: Change in chromaticity with L*; dipoles first, triplet focusing.

The chromaticity is higher in the dipoles first layout because of the higher β functions. Fig. 11 shows that as the D1 dipole is moved from 23 m to 13 m the chromaticity increases by about 20 units per IR per plane. Reducing L* in this fashion (keeping β^{max} constant) keeps apertures constant, thus it can be physically realized without changing the quadrupoles. However this strategy would significantly increase the sextupole strengths. Other strategies can be envisaged, e.g. keeping the chromaticity constant while reducing L*. The aperture requirements would change with L*.

Beam-beam calculations

The chief advantage of the dipoles first layout is the smaller number of parasitic beam-beam interactions. The beams are in separate beam pipes when they enter the quadrupoles. Fig. 12 shows the beam separation in the baseline layout and in the dipoles first layout. In the latter, the beam separation stays constant at 9.4σ (crossing angle 400 μrad at β* = 0.25 m) at all the parasitics.

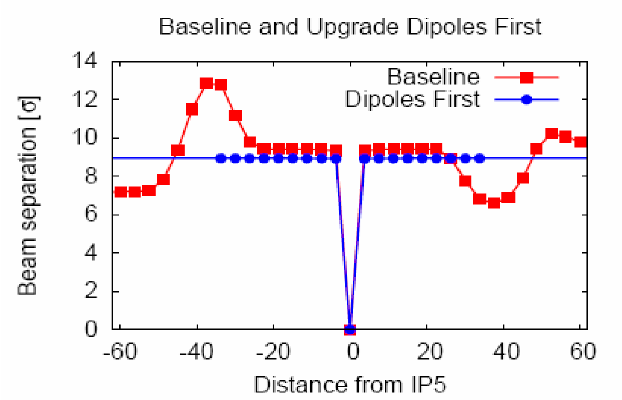

Figure 12: Beam separation at the parasitic interactions in the baseline and the upgrade.

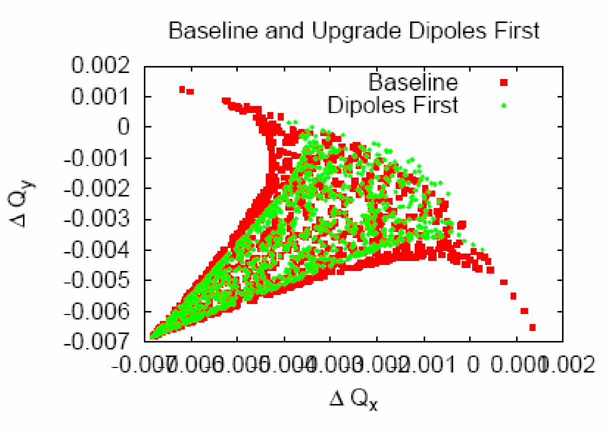

Figure 13: Beam-beam tune footprint in the baseline and dipole first layout, triplet focusing.

As expected the beam-beam tune footprint, seen in Fig. 13, is smaller especially at amplitudes greater than 3σ. The largest 3rd and 10th order resonance driving terms are shown in Figs. 14 and 15. Summed over all the interactions, the resonances are weaker in the dipoles first layout because of the fewer parasitics but mainly because, unlike as in the baseline, there are no parasitics at the smallest separations of about 7σ.

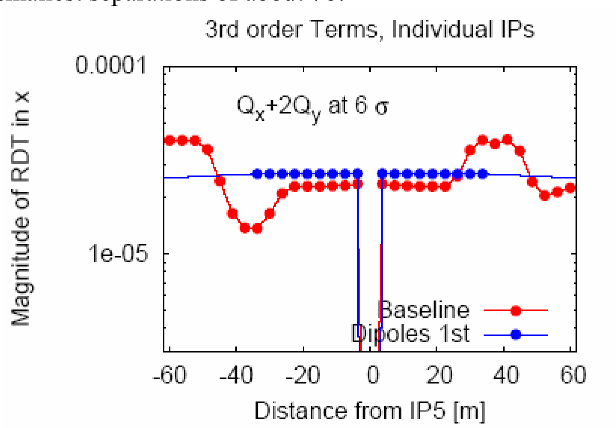

Figure 14: Largest 3rd order resonance driving terms in the baseline and the dipole-first layouts.

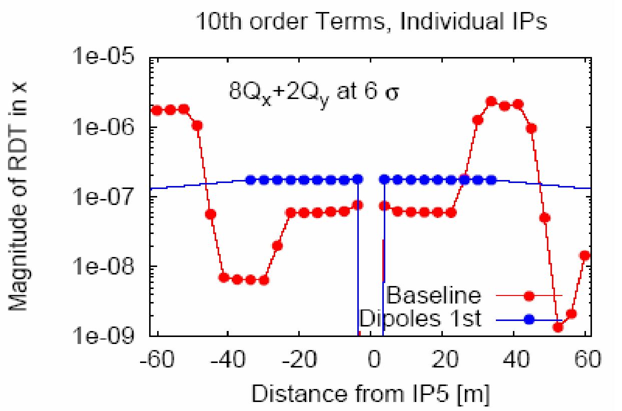

Figure 15: Largest 10th order resonance driving terms in the baseline and the dipole first layouts.

Simulations with BBSIM of the diffusion due to the beam-beam interactions also show the improvement in the dipoles first layout compared with the baseline. Figure 16 and 17 show the horizontal and vertical diffusion coefficients respectively for all three layouts. At amplitude up to 7σ, the diffusion coefficients in the dipoles first case are smaller by about two orders of magnitude. There is a jump in the diffusion at 8σ in both the baseline and dipoles first cases. Diffusion is largest in the quadrupoles first upgrade optics at amplitudes larger than 7σ.

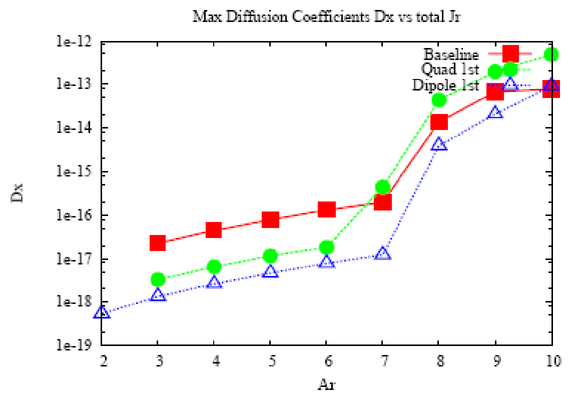

Figure 16: Horizontal diffusion coefficient Dx vs. the radial amplitude Ar for all three layouts.

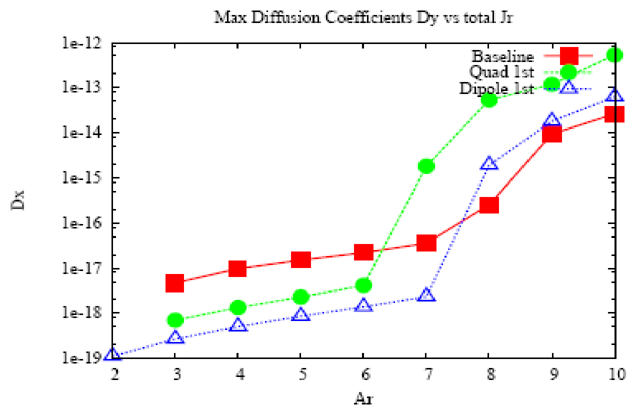

Figure 17: Vertical diffusion coefficient Dy vs. Ar for all three layouts.

Doublet focusing vs. Triplet focusing

Doublets create optics with $\beta_x^* \neq \beta_y^*$. This can be used to advantage by having $\beta_x^* > \beta_y^*$ when the crossing plane is horizontal and benefit from the larger luminosity compared to the situation with $\beta_x^* = \beta_y^*$. However the parasitic interactions are stronger in this optics, e.g. the tune footprint is larger [1]. A separate strong-strong simulation by J. Qiang (LBL) shows that the emittance growth from head-on collisions is higher with elliptical beams (doublets) than with round beams (triplets). IRs with doublet optics also has higher chromaticities than with triplets. Thus the higher luminosity with the doublets exacts a steep price in terms of other beam phenomena.

SUMMARY

We have compared several aspects of the quadrupoles first and dipoles first layouts. The apertures and pole tip field requirements are about the same in all layouts: apertures ~ 110 mm, pole tip field ~ 11 T. Chromaticities are higher with dipoles first. Beam-beam interactions are weaker with dipoles first, as expected; diffusion is about two orders of magnitude smaller at amplitudes up to 7σ.

Table 2: Comparison of the main features in the quadrupoles first and dipoles first layouts design

	Quads 1st	**Dipoles 1st**
Lowest β* at L* = 19 m	0.22	0.23
Luminosity gain at L* = 19 m vs. L* = 23 m	1.04 – 1.15	1.02 – 1.09
L* = 23 m		
β^{Max} [m] at β* = 0.25 m	9484	26092
Max aperture [mm]	101	107
Max pole tip field [T]	10.1	10.7
Q' of inner quads	-48	-99
Max 3rd order bb resonance	0.9×10^{-3}	0.5×10^{-3}
Max 10th order bb resonance	0.16×10^{-3}	0.3×10^{-5}
Beam-beam diffusion	Jump at 7σ	Jump at 8σ
Max Energy Deposition in quads [mW/g]	1.0	0.6

Recent energy deposition simulations with the two layouts show that energy deposition in the inner triplet quadrupoles is less with dipoles first and can be mitigated at luminosities of 10^{35} cm^2sec^{-1} [6]. This presumes however that the challenging open mid-plane magnet proposed for D1 is feasible. Table 2 summarizes the key parameters of the comparison between the layouts.

We also compared the luminosity gain by reducing L* in both layouts. While β* can be reduced to 0.17 m with quadrupoles first and 0.20 m with dipoles first at L* = 13 m, the gain in luminosity is limited due to the need for increasing the crossing angle as 1/√β*. Active beam-beam compensation of the parasitic interactions would improve the performance and the luminosity gain.

REFERENCES

[1] T. Sen et al. "US-LARP Progress on LHC IR upgrades", Proceedings of the Lumi 05 workshop, Arcidosso, 2005.
[2] LHC IR Upgrade Lattice Repository: http://care-hhh.web.cern.ch/care-hhh/SuperLHC_IRoptics/ IRoptics.html
[3] Y. Papaphilippou and F. Zimmerman, Phys. Rev. ST AB, 5 (2002) 074001.
[4] T. Sen et al., Phys. Rev. ST AB, 7 (2004) 041001.
[5] BBSIM web site: http://www-ap.fnal.gov/~tsen/BBCODE/public/
[6] N. Mokhov et al., presented at this workshop.