

LSS LAYOUT OPTIMIZATIONS FOR LOW-BETA OPTICS FOR THE HL-LHC*

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Abstract

The High Luminosity LHC (HL-LHC) project aims to upgrade the existing LHC to a peak luminosity of the order $10^{35} \text{ cm}^{-2}\text{s}^{-1}$, while retaining as much of the nominal layout and hardware as possible. The current baseline for this upgrade is the use of the Achromatic Telescopic Squeeze (ATS) concept, which allows mini-Beta squeeze in IRs 1 and 5 (ATLAS and CMS respectively) far below that possible with nominal optics. However it is useful to both explore the parameter space of the ATS scheme while also attempting to push the boundaries of the nominal layout. This paper presents a study into maximising optical flexibility of the nominal LHC Long Straight Sections (LSSs) around IPs 1 and 5. This involves replacing, moving or adding magnets within the LSS to investigate feasibility of exploiting a more conventional optical scheme than the ATS scheme. In particular the option of replacing single LSS quadrupoles with doublets is explored. The study also looks at making similar changes to the LSS while also implementing the ATS scheme, to further explore the ATS parameter space with the benefit of experience gained into flexibility of a modified nominal LHC optical scheme.

INTRODUCTION

The HL-LHC project aims to upgrade luminosity of the LHC. For this an understanding of the nominal LHC optics is required to fully exploit its potential with a minimum of costly changes. The achromatic telescopic squeeze (ATS) [1] scheme, designed to overcome LHC limitations, is the current solution to this. This paper presents an exploratory study of the flexibility of the nominal LHC LSS optics to aid understanding both of the nominal LHC and the ATS scheme.

The nominal LHC optics has various identified limitations on how low β^* can be squeezed. Primarily, these are mechanical aperture of the inner triplet (IT) quadrupoles, matching quadrupoles and separator dipoles, correction of first- and second-order chromaticity, and minimum/maximum matching quadrupole strengths.

The dominating limit is chromaticity, giving a limit of $\beta^* > 30 \text{ cm}$. Aperture limitations give $\beta^* > 26 \text{ cm}$. This study focuses however on the flexibility of the matching quadrupoles and their strength limitations. The nominal LHC optics give a hard limit of $\beta^* > 15 \text{ cm}$ [2]. Technically feasible solutions are above this. Understanding of LSS limitations for the benefit of the ATS scheme is the

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goal, but a conventional non-ATS HL-LHC optics would require these limitations to be addressed separately.

The LSS matching section includes four quadrupoles, Q4 through Q7. Q1 through Q3 are the IT quadrupoles. When decreasing β^* to near 15 cm, Q5 and Q6 both tend to their minimum strengths, while Q7 tends to its maximum. Table 1 shows strengths of matching quadrupoles on the left side of IP5. The quadrupole gradient g is related to the normalised strength k by $g = kp/e$.

Table 1: Selection of LSS and IR Quadrupoles Around IP5 in the Nominal LHC for Beam 1, Matched for $\beta^* = 15 \text{ cm}$. Q5 and Q6 Approach Minimum, Q7 Approaches Maximum

s [m]	Name	k1	g [Tm ⁻¹]	Strength [%]
-264	QB7.L	-0.00852	-199	99.5
-261	QA7.L	-0.00852	-199	99.5
-226	Q6.L	0.000338	7.88	4.92
-194	Q5.L	-0.000395	-9.22	5.76
-168	Q4.L	0.00261	60.9	38.0
-47.0	Q3.L	-0.00871	-203	88.6
-38.6	QB2.L	0.00871	203	88.6
-32.1	QA2.L	0.00871	203	88.6
-23.0	Q1.L	-0.00871	-203	88.6

To investigate the optical limitations of the nominal layout, two modifications are studied. Firstly, the replacement of the Q5 and Q6 quadrupoles with doublets to avoid hitting minimum strengths. Secondly, the removal of the Q7 upper strength limit, with a view to possibly implementing a second Q7 to realise this. The triplets are not modified (they would reduce the optics flexibility and increase the chromatic aberrations while offering the aperture required for the beam), in to directly compare the proposed modifications with the optics developed on the standard LHC.

The optics is rematched iteratively using a derivative of the nominal LHC matching scripts for MADX [3]. The target β^* is incrementally lowered after every successful match. The iterative match provides a strength profile for each magnet to perform a squeeze from injection to collision optics. Study of the profiles produced can give insight into the limitations along the match, allowing changes to be made accordingly.

Q5 Q6 DOUBLET OPTICS

Quadrupoles are not allowed to fall below 3% of their maximum strength; power supplies become subject to unacceptable noise at this level, creating substantial field er-

rors. Also if Q5 and Q6 fall to zero, they do not contribute to the match and greater strain is placed on the other quadrupoles. Q5 and Q6 are therefore replaced with quadrupole doublets. In the case of the left Q5 focusing (F) quadrupole, for instance, this adds a defocusing (D) quadrupole upstream. The original Q5 is now known as Q5b, and the second as Q5a¹. This allows the match to increase the strength of Q5b, and counter the increase by increasing the strength of Q5a.

The converse is true of the left Q6. Q6 becomes Q6a and Q6b, an F quad, is placed upstream. This total addition of one F quadrupole and one D quadrupole preserves the pseudo-FODO alternating layout. Figure 1 shows the new layout. The LSS is nearly anti-symmetric, so on the right side all these changes are mirrored and polarities are reversed. This soft anti-symmetry is not constrained in these matches and some results show strong asymmetry.

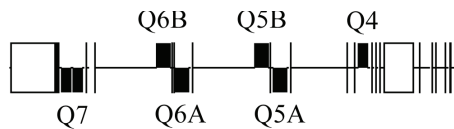


Figure 1: Layout for the left IP5 Q7, Q6 and Q5 matching quadrupoles. Q6 and Q5 are replaced with doublets.

The matching scripts are modified to account for the new quadrupoles, and giving them the same maximum and minimum limits as their originals. The nominal phase advance across the entire IP is maintained, but the phase advance of $\pi/2$ from the IP to the arc sextupoles is not; without the ATS β -wave the effects on chromatic correction strength are negligible. The Q5 Q6 doublets have not been found to add sufficient flexibility to include this constraint.

Results

The Q5 Q6 doublet yields increase optical flexibility, and a β^* of 10 cm is achieved. Below $\beta^* \approx 40$ cm, Q7 as before tends strongly toward its maximum strength. At $\beta^* = 10$ cm Q7 is the limiting factor and cannot be made stronger. The Q5 Q6 doublet, in allowing Q5 and Q6 to have increased strength, allow Q5 and Q6 to participate in the match. Their effective exclusion from the nominal match left Q7 to deal with β growth over a long apparent drift space rather than a well-controlled envelope. The Q5 Q6 doublet therefore brings the required strength of Q7 down for any given β^* , allowing the match to continue further before hitting the Q7 limit. Figure 2 shows the evolution of key quadrupole strengths during the match. Figure 3 shows the optics with β on square root scale. Peak β is ~ 26 km.

Below $\beta^* \approx 40$ cm Q7 strength is still seen to run out of strength, but with sufficient headroom to achieve $\beta^* = 10$ cm. The profiles show non-monotonic behaviour which may cause problems in machine operation. Before $\beta^* \approx$

¹Naming conventions are simplified for clarity in this paper. These names do not represent the actual LHC conventions

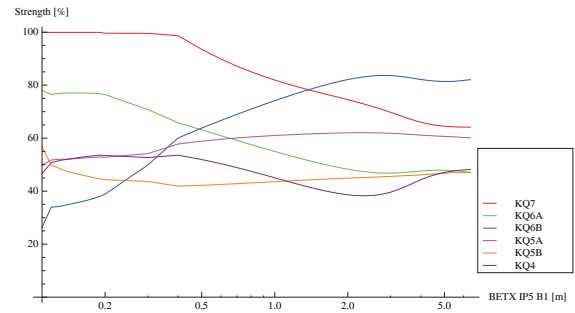


Figure 2: Evolution of selected quadrupole strengths in the Q5 Q6 doublet match during β^* squeeze. β^* is on log scale.

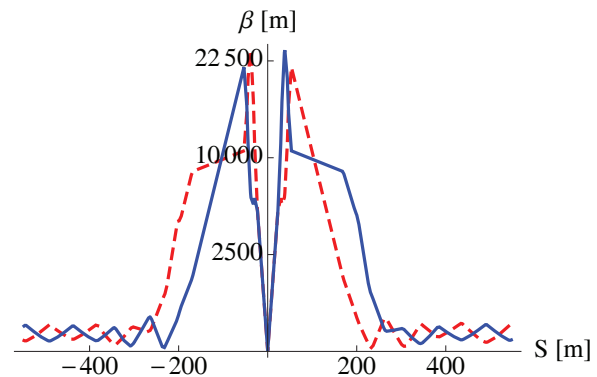


Figure 3: Optics around IP5 for the Q5 Q6 doublets case, with β on square root scale. β_x is red, β_y is blue.

40 cm the strengths vary smoothly so this may not be a problem. Beyond this, as Q7 strength approaches the limit, the strengths of the other quadrupoles vary unevenly to take the additional strain. Asymmetry is seen between left and right quadrupoles, but usually within the limit of a factor of 2. Q5 however shows a factor of 4 asymmetry. This may be fixable with specific optimisation.

Chromatic β -beating is large with this layout. Q' is corrected to +2 units using the sextupole families, but little to no strength is left to correct Q'' . Figure 4 shows the horizontal chromatic β -beating around the ring with $\Delta p/p = 1 \times 10^{-4}$. Without ATS phase advance constraints and β -wave, beating of up to $\sim 115\%$ is seen.

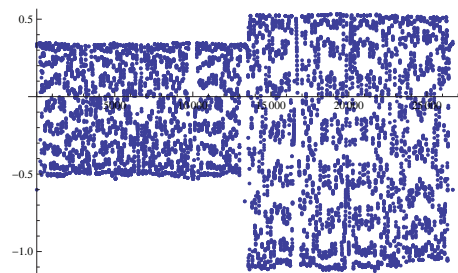


Figure 4: Horizontal off-momentum β -beat around LHC ring for Q5 Q6 doublets optics with $\Delta p/p = 1 \times 10^{-4}$.

Aperture issues using nominal quadrupoles are worsened, with minimum $n_1 = 3.08$, compared to 3.61 in the 15 cm optics. This may be solved by the new HL-LHC large aperture quadrupoles.

UNLIMITED Q7

To investigate the impact of increased available strength of Q7, the upper limit on Q7 strength is removed. The Q5 Q6 doublet match is run from the beginning without limits on Q7. As above, sextupole phase constraints are ignored.

Results

Matching is achieved down to $\beta^* = 6$ cm. As seen in Fig. 5 the removal of Q7 limits changes the squeeze significantly. Q7 strength is $\sim 165\%$, but this increase allows all quadrupoles to vary smoothly to the end of the squeeze, showing how severely optically limiting the Q7 strength is. Q5 asymmetry is brought within normal bounds. Figure 6 shows the optics with β on square root scale. Peak β is ~ 40 km, a large increase over the $\beta^* = 10$ cm case.

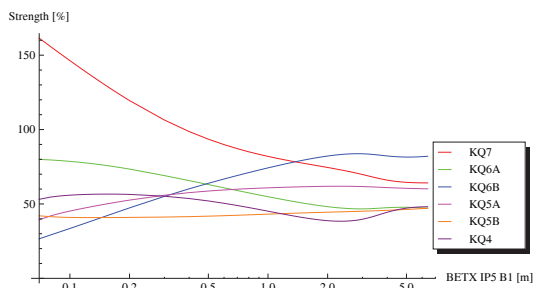


Figure 5: Evolution of a selection of quadrupole strengths in unlimited Q7 match during β^* squeeze. β^* is on log scale.

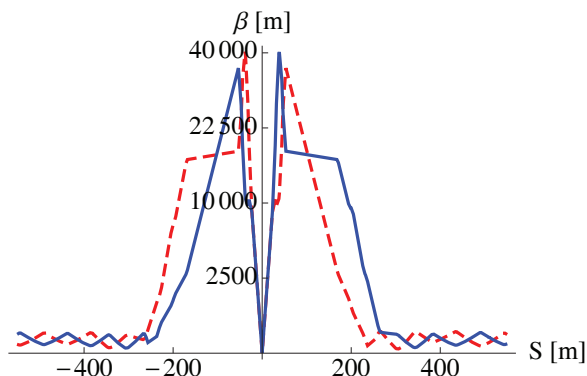


Figure 6: Optics around IP5 for the unlimited Q7 case, with β on square root scale. β_x is red, β_y is blue.

Chromatic effects are increased above those in the Q5 Q6 doublet match. Figure 7 shows the off-momentum horizontal β -beat with $\Delta p/p = 1 \times 10^{-4}$. Beating of up to

$\sim 350\%$ is seen without the ATS scheme, and Q' cannot be corrected below $\beta^* = 10$ cm.

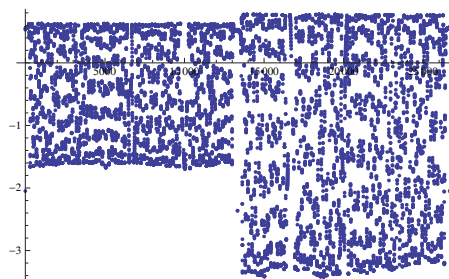


Figure 7: Horizontal off-momentum β -beat around the LHC for unlimited Q7 optics with $\Delta p/p = 1 \times 10^{-4}$.

Aperture is also worse than in the Q5 Q6 doublet case, with a minimum n_1 of 1.86 for nominal quadrupoles. This may be too extreme to be solved with the new HL-LHC large aperture magnets.

SUMMARY

Significant optical flexibility may be gained by replacing Q5 and Q6 with doublets and increasing the strength limit on Q7, perhaps by addition of a second Q7 quadrupole. The Q5 Q6 doublet scheme allows reduction of β^* from 15 cm to 10 cm. Large aperture magnets are required for this solution, although the large aperture IT quadrupoles would likely further increase chromatic effects.

Increasing the strength of Q7 to $\sim 165\%$ allows a further reduction to 6 cm. Q7 is a severe limiting factor as can be seen from the changed behaviour of the β^* squeeze. Aperture is a severe concern here, but an unlimited Q7 has major benefits even at $\beta^* = 10$ cm in smoothing the squeeze and allowing flexibility.

At the limit of $\beta^* = 6$ cm, all quadrupoles appear within safe limits. The matching routine is unable to minimise the penalty function further, suggesting a hard limit on the nominal LHC optics. To improve upon this, a radically different layout may be needed. In both cases chromatic effects are extreme and significant modification would be needed for the nominal LHC to achieve any β^* below ~ 30 cm.

The modifications here do not add the required flexibility to mitigate chromatic limitations. While it is unlikely that these modifications could form an alternative “conventional” optics to ATS, they could be integrated in the ATS scheme to significantly increase flexibility, by demonstrating that the IP-to-sextupole phase advance constraints can be sustained for a wide range of β^* .

REFERENCES

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- [2] S. Fartoukh, private communication.
- [3] CERN, “MADX”, <http://mad.web.cern.ch/mad>