Overview of LHC Low-β Triplets and Correction Scheme Issues

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1. Introduction

The LHC experimental insertions consist of a low-β triplet, a pair of separation dipoles, and a matching section of four quadrupoles. The superconducting low-β quadrupoles must accommodate separated beams at injection, provide high field gradients and low multipole errors for colliding beams, and sustain considerable heat load from secondary particles generated in the high luminosity ATLAS and CMS experiments. In the other two experiments, ALICE and LHC-b, the separation dipoles and matching sections share the available space with the injection equipment, which implies less flexibility for beam separation. In this report we give an overview of the layout and required performance of the LHC experimental insertions, and discuss issues related to the triplet correction scheme that should be discussed during this Workshop.

2. LHC Experimental Insertions

The layout of the Large Hadron Collider comprises eight straight sections available for experiments and major machine systems [1]. The two high luminosity p-p experiments, ATLAS and CMS, are located on the symmetry axis of the machine, at interaction points 1 and 5. The other two experiments, ALICE and LHC-b, are at points 2 and 8, where the counter rotating beams are injected in Ring 1 and Ring 2, respectively. In these four insertions, a pair of recombination-separation dipoles guides the two beams onto crossing orbits. In points 1 and 5, the first separation dipole D1 is a conventional resistive magnet, while D2 is a superconducting magnet. In points 2 and 8, where space is tight and luminosity lower, both separation dipoles are superconducting magnets.

Table 1. Nominal collision parameters for LHC experimental insertions

Insertion	p-p				Heavy-ion			
	β* (m)	ξ (µrad)	Δ (mm)	L ($cm^{-2}s^{-1}$)	β* (m)	ξ (µrad)	Δ (mm)	L ($cm^{-2}s^{-1}$)
IR1	0.5	±150 (V)	0	10^{34}				
IR2	10	±100 (V)	±0.5	10^{30}	0.5 50	±75 (V)	0	10^{28}
IR5	0.5	±150 (H)	0	10^{34}	0.5	±75 (H)	0	10^{28}
IR8	1 50	±150 (V) ±50 (V)	0	10^{32}				

The nominal collision parameters of the LHC experimental insertions are summarised in Table 1. For p-p runs, the high luminosity insertions will operate at the highest luminosity of

10^{34} $cm^{-2}s^{-1}$, which correspond to a β* of 0.5 m. In order to minimise the effects of long range beam-beam interactions the beams will collide with a crossing angle of ±150 μrad, in the vertical plane in IR1 and horizontal in IR5. The other two insertions will also observe p-p collisions. They will, however, operate in a detuned mode, corresponding to the injection optics with a β* of 10 m. Furthermore, in order to reduce the luminosity in IR2 to the level of acceptable for the ALICE experiment (10^{30} $cm^{-2}s^{-1}$), halo-type collisions with parallel beam separation Δ of ±0.5 mm are envisaged. For heavy-ion runs, it is presently foreseen that two experiments will collect physics data: the dedicated heavy-ion experiment ALICE in IR2, and the CMS experiment in IR5. Luminosity of 10^{28} $cm^{-2}s^{-1}$ is expected for a β* of 0.5 m. Due to the heavy-ion bunch spacing of 125 ns, the crossing angle can be reduced in this mode to ±75 μrad with a still satisfactory beam lifetime.

3. Baseline Layout and Performance of the Low-β Triplet

The low-β triplets, Fig.1, consist of four wide aperture superconducting quadrupoles [2]. The outer two quadrupoles, Q1 and Q3, are 6.3 m long, while the central one is divided for engineering reasons into two identical units, Q2a and Q2b, 5.5 m each. The triplets are identical in all insertions, and are at 23 m from the interaction points. In the high luminosity insertions, a 1.8 m copper absorber (TAS), located within the front shielding of the experiments, ensures the protection of the triplets. The main parameters of the low-β quadrupoles are given in Table 2.

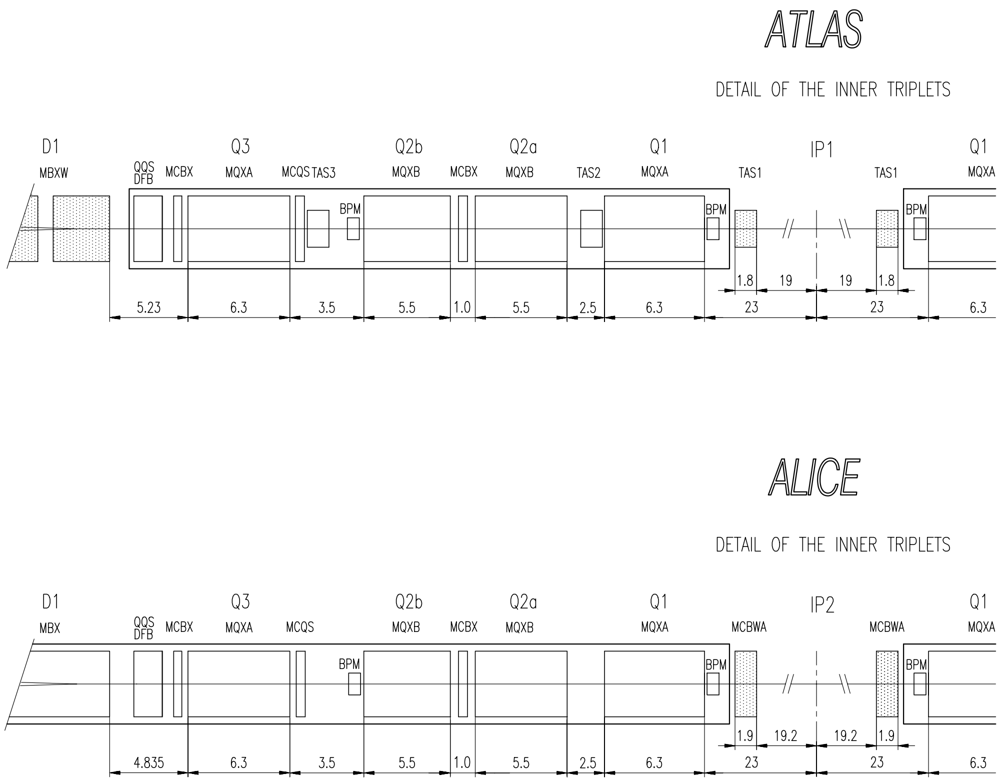

Fig.1. Baseline layout of the LHC low-β triplets in IR1 and IR2

One of the most important issues in the design of the low-β triplets is the protection of the superconducting quadrupoles against the high flux of secondary particles emanating from the p-p collisions. This issue has been thoroughly studied [3] and it has been found that the Q2a quadrupole, where the power density due to the secondaries is the highest, can be better protected by optimising its distance from Q1. Based on these studies, the separation between Q1-Q2a has been set to 2.5 m. This is sufficient place for a supplementary absorber (TAS2). The protection of the triplets is further improved by increasing the wall thickness of the cold bore by reducing its inner diameter to 60 mm, Table 2, and by including an absorber TAS3 in between Q2 and Q3. In IR2 and IR8, these absorbers are not needed, and the inner diameter of the cold bore is set to its nominal value of 63 mm for the purpose of increasing the geometrical acceptance of the triplets.

Table 2. Nominal parameters of the LHC low-β quadrupoles

Aperture		
Coil aperture		70 mm
Cold bore ID	IR2/8	63 mm
	IR1/5	60 mm
Operating Gradient		205 T/m
Alignment		
Initial radial		0.3 mm rms
Initial tilt		0.3 mrad rms
Twist		0.3 mrad/m
Longitudinal		1 mm rms

The space of 1 m between Q2a and Q2b is reserved for the combined horizontal-vertical orbit corrector (MCBX). In this location the β-function is maximum in one plane (x or y, depending on the polarity of Q2), while the maximum in the orthogonal plane occurs upstream of Q3, where an additional orbit corrector is envisaged. These correctors are capable of compensating individual misalignment of the quadrupoles by an initial amount given in Table 2. Experience in operating the machine and the development of beam-based techniques should result in considerable improvement of quadrupole alignment. The triplet is also equipped with a skew quadrupole corrector in between Q2b and Q3 (MCQS), and two directional beam position monitors, one in front of Q1 and the other between Q2b and Q3.

Decision has been recently taken in the sense that the Q1 and Q3 quadrupoles (MQXA) will be supplied by KEK as part of the Japanese contribution to the LHC, while Q2a and Q2b (MQXB), as well as the superconducting D1 in IR2 and IR8, will be part of the US contribution. The corrector packages and BPMs will be supplied by CERN. The cold-mass integration and cryostating will be done by Fermilab as part of the US-LHC project.

The operational parameters of the LHC, in particular the crossing angle and β* in collision, imply that the two beams are offset by as much as 8 mm from the quadrupole axis. As a result, the low-β quadrupoles must satisfy stringent field quality requirements. Several recent discussions on field quality issues [4] have resulted in reference error tables for the two quadrupole types. The latest version of the tables contains important systematic and random errors, as well as uncertainties expected in production magnets.

The performance for the LHC low-β triplets is defined in terms of the target dynamic aperture, calculated on the basis of tracking over 10^5 turns. Having in mind the collision parameters given in Table 1, the target performance of the LHC for p-p collisions is 12 σ for the average and 10 σ for the minimum dynamic aperture, Table 3. With the rms beam size of 1.5 mm, this corresponds to a good field region of the quadrupoles of 26 mm. A similar target dynamic aperture is required for heavy-ion collisions.

Table 3. Nominal tunes and target dynamic aperture of the LHC

Betatron tunes (H/V)	63.31/59.32
Synchrotron tune	0.00212
Chromaticity (H/V)	2/2
Target performance	
p-p high luminosity	
Average DA	12 σ
Min DA	10 σ
Heavy-ions	
Average DA	< 12 σ

On the basis of the present version of the MQXA and MQXB error tables, it is clear that the target performance will be difficult to achieve without higher-order multipole correctors [5]. The layout of the triplet provides three locations for these correctors, nested within the dipole and skew quadrupole correctors. The basic assumptions for defining these correctors are:

- Magnetic length of 500 mm, as for MCBX and MCQS
- Operating margin of about 50% which takes into account the background field of the main linear correctors (3 T, H/V for the MCBX, and 30 T/m for the MCQS)
- Normal field correctors located preferentially within MCBX, skew within MCQS
- Number of nested multipole layers limited to 2 for normal correctors, and 3 for skew correctors.

The expected strength of the multipole correctors, Table 4, based on using the LHC sextupole corrector wire (rated at 600 A) and satisfying the above guidelines [6], gives an indication of the expected correction range.

Table 4. Expected strength of multipole correctors

Multipole Corrector	Field (T) @ 17 mm	
b3, a3	0.100	0.150
b4, a4	0.066	0.086
b5, a5	0.037	0.044
b6, a6	0.020	0.020
b10	0.003	

4. Correction Scheme Issues

The present Workshop is an outstanding opportunity to review a number of issues related to the low-β triplet layout and correction scheme, in particular the definition of the multipolar corrector location, strength and technology. Below is a list, necessarily incomplete, of questions we should discuss during the Workshop:

Inner triplet layout

- The present orientation of the quadrupole lead ends was determined on the basis of compensation of lead end b6 errors. With better knowledge of the field errors, can we consider that the orientation of the quadrupoles is still optimal?
- The positions of corrector packages were determined in the early stages of the triplet design. Is there reason to consider alternative layouts, in particular could we envisage that the first MCBX dipole is moved to the Q3 end of Q2?
- In order to minimise the number of corrector leads, could we envisage only a vertical dipole corrector at Q3 (MCBX.Q3)?
- Should the corrector packages in IR2 and IR8 triplets be identical to, or could they be a subset of those installed in high luminosity insertions IR1 and IR5?

Corrector strength and technology

- Is the strength of linear correctors MCBX and MCQS adequate?
- What is the minimal set of multipole correctors and what are the positions that minimise their strength? In particular is there a need for more than two correctors in any package?
- What are the criteria for setting the multipole corrector strengths? In particular:
    a) What version of the quadrupole error table should be used (presently available, or updated with the latest results of R&D models)?
    b) What accuracy of field measurements should be assumed?
    c) Should the strength be determined as the maximum value over the set of N random machines, or rather as Avg + n SD? What are the choices of N and n which give statistically relevant results?
    d) Should sorting strategies be included when selecting N random machines?
- What is the interplay between corrector alignment and their strength and position? Is the corrector alignment of 0.5 mm rms appropriate?
- The nominal corrector current should match one of the standard LHC bi-polar power supplies (±60, ±120, or ±600 A). Is there a clear preference for one of these ranges?

I hope the lively discussions we all expect and look forward to during the Workshop will result in clear statements as to these and other issues related to the layout and compensation scheme of the LHC low-β triplets.

References

[1] The LHC Study Group, *The Large Hadron Collider,* Conceptual Design, CERN/AC/95-05.

[2] R. Ostojic, T.M. Taylor and S. Weisz, “Systems Layout of the Low-β Insertions for the LHC Experiments”, PAC’97, Vancouver, LHC Project Report 129

[3] J. Strait and N. M. Mokhov, “Optimisation of the LHC Interaction Region With Respect to Beam-Induced Energy Deposition”, EPAC’96, Barcelona, LHC Project Report 43.

[4] LHC Accelerator Physics Workshop, Fermilab, Oct. 19-20, 1998

[5] J. Wei et al, “Insertion Region Local Correction for the LHC”, PAC’99

[6] M. Karppinen, private communication