

SYSTEMS LAYOUT OF THE LOW- β INSERTIONS FOR THE LHC EXPERIMENTS

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Abstract

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 proposed experiments, ALICE and LHC-B, the separation dipoles and matching sections share the available space with the injection equipment. In this report we present the systems layout of the experimental insertions for the LHC, and review the requirements for the superconducting magnets.

1 INTRODUCTION

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 proposed experiments, ALICE and LHC-B, are at points 2 and 8, where beam injection will occur. In these four insertions the two beams are guided onto crossing orbits by a pair of recombination-separation dipoles.

The final focus in the low- β insertions is achieved with an inner triplet together with a matching section of four quadrupoles. In the low- β triplets the beams travel in a single beam tube, and must be sufficiently separated at all times. Besides providing high gradients in a sufficiently wide aperture, the superconducting low- β quadrupoles must sustain considerable heat load from secondary particles generated in the high luminosity collisions. At points 2 and 8, the luminosity is lower but the matching section and separation dipoles share the available space with the injection equipment, creating further constraints.

2 HIGH LUMINOSITY INSERTIONS

The layout of the left half of a LHC high luminosity insertion is shown in Figure 1. The ATLAS and CMS insertions are identical, and are mirror symmetric around the interaction point. The insertion consists of a low- β triplet, a pair of recombination-separation dipoles, D1-D2, and a matching section of four quadrupoles, Q4-Q7. It is designed for a collision β^* of 0.5 m, corresponding to the nominal LHC luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at 7 TeV. At injection energy, the insertion is detuned by adjusting the matching section to a β^* of 12 m. The low- β triplets do not participate in

the tuning, except to keep the phase advance of the insertion constant. The matching section has enough reserve to adjust the β^* of the insertion beyond the nominal range.

2.1 Low- β Triplets

The low- β triplets, shown in Figure 2, consist of four wide aperture superconducting quadrupoles powered by a common power supply. The outer two quadrupoles, Q1 and Q3, are 6.3 m long, while the central one is divided for convenience into two identical units, Q2a and Q2b, 5.5 m each. The low- β triplet is 23 m from the interaction point, and is preceded by a 1.8 m long copper absorber (TAS), located within the front shielding of the experiments.

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 at nominal luminosity. This issue has been studied by several groups [2, 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, sufficient to place a supplementary 1.5 m absorber. Protection of the triplet as a whole may be further improved by increasing the thickness of the quadrupole cold bore.

The space of 1 m between Q2a and Q2b is required for the combined horizontal-vertical orbit corrector. In this location the β -function has a maximum in one plane, while the maximum in the orthogonal plane occurs upstream of Q3, where an additional orbit corrector is envisaged. The space between Q2b and Q3 is used to adjust the optics of the single parameter low- β triplet to that of the matching section. The resulting drift of 3.5 m is slightly longer than otherwise needed for magnet interconnects, a BPM and multipole spool pieces.

The single aperture quadrupoles Q1-Q3 are considered the most demanding magnets in the experimental insertions. Besides accommodating fully separated beams at injection, they must provide a high field gradient and low multipole errors required for the colliding beams, and sustain high power density of the secondary particles. A 70 mm aperture quadrupole with a design gradient of 240 T/m adequately fulfils these requirements. A magnet development program for the low- β quadrupole is in progress in CERN, Fermilab and KEK [4, 5, 6]. The successful test of the first low- β quadrupole model [7], indicates that the chosen operating gradient of the triplet, 200 T/m at 7 TeV, provides an adequate operational margin at full luminosity.

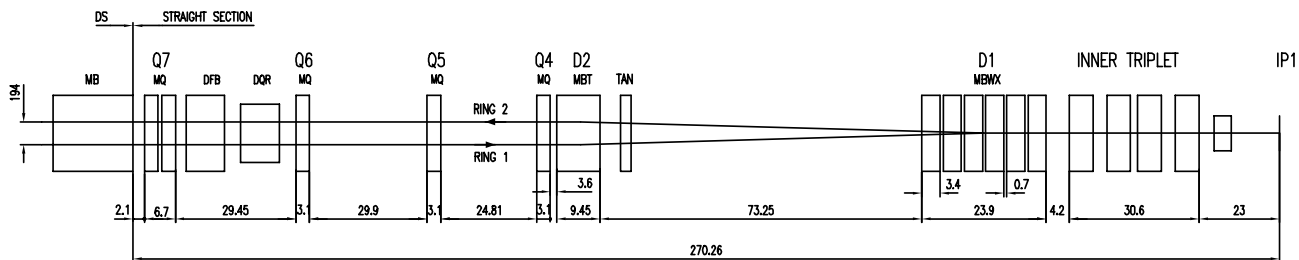


Figure 1: Schematic layout of the left half of the LHC high luminosity insertion. The layout is symmetrical with respect to the IP, and is identical for the ATLAS and CMS experiments.

2.2 Separation Dipoles and the Matching Section

The separation of the beams must be made as close as possible to the interaction point in order to avoid long range parasitic crossings, which occur every 3.75 m in the common vacuum chamber. The separation is accomplished with a pair of bending magnets, D1 and D2. It has been proposed in [1] that both D1 and D2 be superconducting magnets using identical coils. This solution has been a matter of concern since similarly to the low- β triplet, D1 is also submitted to intense irradiation by the secondaries. Its magnetic field deviates the charged particles into its own coil, so that its aperture has to be larger than 80 mm in order to avoid excessive energy deposit [3]. On the other hand, a coil aperture greater than 90 mm seems to be incompatible with a bore separation of 194 mm in the two-in-one D2. An alternative, retained in this proposal, is to use a resistive D1, which is made possible by the larger separation between the dipoles than proposed in [1]. The neutral secondaries are not deviated by D1 and are stopped in a dedicated absorber (TAN) placed a few metres downstream of the two-in-one superconducting D2. D2 has a coil aperture of 80 mm and is located 155 m from the interaction point.

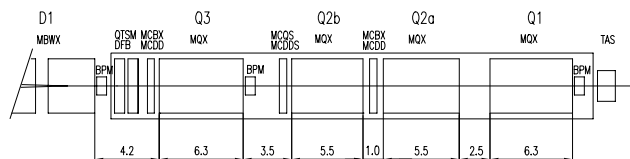


Figure 2: Schematic layout of the LHC low- β triplet.

The matching section of the high luminosity insertion consists of four twin aperture quadrupoles, Q4-Q7. These are standard LHC arc quadrupoles with independent powering of apertures. In the nominal tuning range, the gradients of the matching quadrupoles vary down to 35% of the nominal gradient of 210 T/m.

2.3 Crossing Scheme and Geometrical Acceptance

The nominal LHC luminosity is achieved with the beams colliding at a full crossing angle of 200 μ rad [1]. At injection, and similarly at top energy prior to collision, the beams need to be separated in the common part of the vacuum chamber, typically by 10 σ . The separation scheme consists of imposing a crossing angle at the interaction

point, together with a parallel separation of the beams in the plane orthogonal to the crossing plane. The crossing plane may be additionally rotated around the longitudinal axis in order to limit the effects of the long range interactions [8]. As a result, the beams follow complicated trajectories in the low- β triplets, so that the beam separation and the geometrical acceptance of the triplets depend on all parameters of the scheme.

The method used for calculating the acceptance of LHC magnets is based on fitting the normalised beam halo, which is the result of multi-turn beam cleaning, to the shape of the magnet cold bore [9]. Specific conditions in each magnet, such as β -functions, closed orbit errors, mechanical tolerances and alignment, are taken into account, and the acceptance calculated in terms of the equivalent primary collimator aperture. For the nominal primary collimator at 5.5 σ , an acceptance greater than 7 σ is required everywhere in the insertions. In Figure 3, the beam separation and the acceptance of the low- β triplet are shown for the injection β^* of 12 m and full crossing angle of 400 μ rad. In this particular case, the beam separation is larger than 10 σ , and the acceptance of the triplet is greater than the required primary collimator equivalent of 7 σ . The acceptance minimum occurs in between Q2a and Q2b, as shown in Figure 3, or at the upstream end of Q3 if the crossing plane is rotated by 45 degrees. An analysis of different sets of crossing parameters leads to the conclusion that the 70 mm aperture of the low- β quadrupole is large enough to accommodate crossing angles of up to 450 μ rad, both at injection and collision energies.

These results correspond to the optics studied to date. Recent layout studies indicate that the low- β triplet could be advanced by about 0.5 m towards the IP, without modifications to the experiments. As a result, the acceptance of the triplet would be increased, and $\hat{\beta}$ in Q2-Q3 reduced. For the purpose of operating margin, 10 cm longer low- β quadrupoles should be foreseen.

3 EXPERIMENTAL INSERTIONS COMBINED WITH BEAM INJECTION

The layout of the low- β insertions for the ALICE and LHC - B experiments follows the same general approach of the high luminosity insertions, i.e. a matching section of four quadrupoles is used to tune the low- β triplets. The

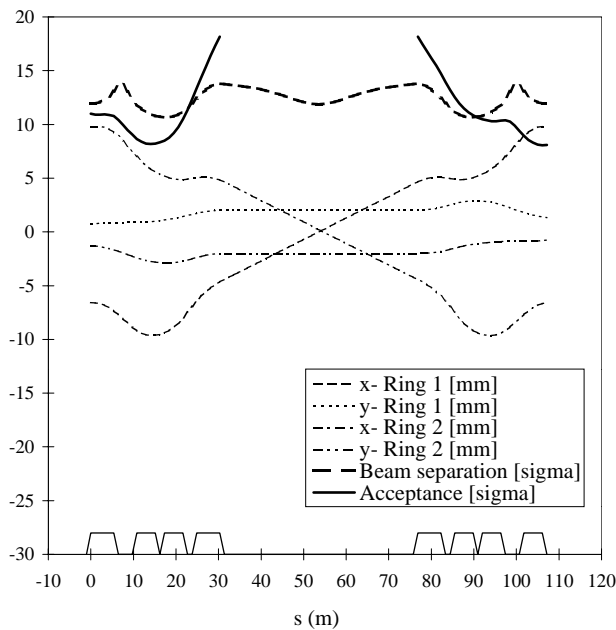


Figure 3: Trajectory of the two beams in the low- β triplets for a horizontal plane at full crossing angle of $400 \mu\text{rad}$ and vertical separation of 4 mm. The separation of the beams and geometrical acceptance of the quadrupoles are also shown for these conditions.

important difference comes from the fact that in both insertions the layout of the matching section must satisfy the severe requirements of the beam injection system. For example, long warm drifts between the quadrupoles must be provided for the injection kicker and septum magnets, whose position is related to the geometry of the beam injection tunnels. Furthermore, strict requirements must be fulfilled in order to protect the low- β triplets and the rest of the machine against badly injected or accidentally kicked circulating beams. Although these requirements substantially limit the flexibility of the insertion, it is nevertheless continuously tunable from the injection β^* of 12 m to a collision value of 0.5 m. To allow ALICE runs with p-p collisions, the β^* can be detuned up to 250 m. The difficulties in fulfilling the injection requirements are partially offset in LHC-B where the interaction point is displaced by 11.25 m from the centre of the insertion, leaving more space between the injection magnets and the matching quadrupoles. The layout then provides a tuning range of 5-50 m for the LHC-B experiment.

The low- β triplets in ALICE and LHC-B insertions are identical to those in the high luminosity insertions, except that the front absorber is not required. Due to the shortage of space, both D1 and D2 are 9.45 m long superconducting dipoles. While the aperture of D1 is determined by the separation scheme, that of D2 must be large enough to allow the passage of miskicked beams. It has been determined that in both cases a coil aperture of 80 mm is sufficient, leading to a proposal where identical coils are used in both the single aperture D1 and two-in-one D2, and the

two dipoles could possibly be powered in series.

The matching section quadrupole Q5 has a particular role as the beam is injected through it at vertical angle of 0.35 mrad. Similarly, Q4 must be big enough to let pass accidentally kicked beams. In both cases, it is proposed to use twin aperture quadrupoles with a coil aperture of 70 mm [10]. These quadrupoles have sufficient acceptance to cope with these situations, but constrain the placement of dipole correctors used for the crossing scheme. The other quadrupoles in the matching section are standard LHC arc quadrupoles, except that the cryostat of Q6 has to be adapted for the passage of injection lines.

4 CONCLUSIONS

The design of the LHC low- β insertion has advanced to the point where the requirements of experiments could be harmonised with the flexibility of the collider operation and superconducting magnet performance. In this report we have reviewed the systems layout of the experimental insertions, and specified the requirements for the superconducting magnets.

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