Progress in the System Design of the Inner Triplet of 70 mm Aperture Quadrupoles for the LHC Low-β Insertions

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Abstract

In order to optimize the design of the LHC low-β insertions, several configurations of the inner quadrupole triplet have been considered. In addition to layout considerations, solutions leading to the most suitable compromise for such system requirements as efficient power extraction in presence of significant particle losses and standardized design and powering of the quadrupoles, have been investigated. The study is based on the 70 mm aperture quadrupole designed for 250 T/m at 1.9 K, a model of which is presently under construction.

1 INTRODUCTION

The Large Hadron Collider (LHC) proposal [1], has been accompanied by a vigorous superconducting magnet development program [2]. As part of this program, a 1 m model of the 250 T/m low-β quadrupole is presently being built by Oxford Instruments [3]. This is a special magnet based on a four layer coil with an aperture of 70 mm, designed specifically to achieve low magnetic field multipole errors required for the LHC low-β, and cleaning and dump insertions. The design principles and the magnetic performance of the quadrupole have been presented in ref.[4].

The quadrupole under consideration is part of the inner triplet located on either side of the LHC experiments. Together with the outer triplet, imbedded in the dispersion suppressor, the inner triplet tunes the low-β insertion for a β^* of 0.5 m at the machine nominal energy of 7 TeV and luminosity of $1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. However, as it is close to the interaction point (20 m), the inner triplet is exposed to a high flux of particle secondaries emanating from the collisions, which produces high power density in the superconductor and considerable cryogenic heat load, which in turn may jeopardize reliable operation of the magnets.

In order to assess various aspects of the inner triplet design, we have undertaken to analyze the operation of the triplet from a systems point of view, exploring solutions for standardized magnet design and powering, flexible magnet trimming, reduced particle loss and efficient heat load extraction, etc. The goal of this study was to find the conditions under which the magnets operate reliably, while improving the machine-experiment integration and minimizing the costs. In this report we present some of our findings which go in the direction of a fully optimized design of the inner triplet.

2 INNER TRIPLET LAYOUT AND MATCHING

2.1 *Standard Layout*

The standard layout of the LHC low-β insertion is described in detail in ref.[1]. For the purposes of this report, we recall that the standard inner triplet, Figure 1, is located 20 m upstream of the interaction point (IP), and is preceded by the separation/recombination dipole D1; an anti-symmetrical arrangement is located on the opposite side of the IP. The triplet comprises two symmetric quadrupole doublets (with 6.1 m and 6.9 m long magnets) placed back to back, where the longer magnets are on the outside, and the inner ones are excited in series. The separation between the magnets is 1.44 m, the minimum space required for connections.

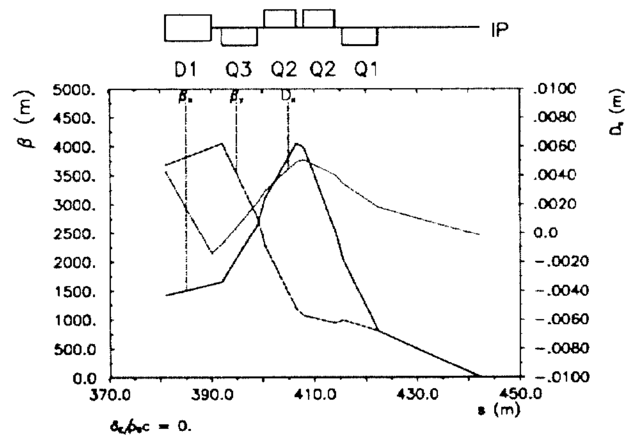

Figure 1: Standard inner triplet layout

2.2 *Alternative Layouts and Matching*

In order to facilitate the tuning of the triplet, various possibilities were considered. Firstly, it was suggested that a copper absorber 1.8 m long, which is located in front of Q1, could be engineered as a warm quadrupole with an aperture of 30 mm and a gradient of 50 T/m. Alternatively, a short (1 m) superconducting quadrupole (Q3') with an aperture of $\simeq$ 100 mm and a gradient of 140 T/m could be placed in between Q3 and D1. Both of these solutions were considered in subsequent matching runs, and it was found that Q3' added much more flexibility to the triplet trimming, and is in general a more effective solution.

An important aspect of the layout is the standardization of the length of the quadrupoles with an obvious engineering and cost gain. Indeed, the optimum quadrupole length corresponding to the LHC main dipole field of 8.65 T is 5.5 – 6 m. Furthermore, for this particular range, solutions for equal magnet excitations were also found, with the trimming of the line performed by Q3'. We have also considered cases where Q2 and Q3 are of equal length and standard design, with the aperture and peak gradient of the low-β model, while Q1 is a special magnet with a considerably higher gradient ($\simeq$ 300 T/m), built in either $NbSn_3$ or NbTi technology (in which case the aperture of the magnet needs to be $\simeq$ 50 mm). At present such ideas are considered to be applicable to an upgrade of the insertion, with the emphasis being put on using similar elements for Q1, Q2 and Q3 in the initial phase of the LHC.

The insertion was matched with the usual constraints for collision optics: anti-symmetry of optical functions, zero dispersion around the IP, and equal phase advances in the transverse planes, while the Q1-Q3 gradients were limited to 235 T/m. These constraints lead to eight simultaneous conditions, while we have ten independent quadrupole strengths (the inner and outer triplet, and the four dispersion suppressor quads). This redundancy is used to constrain the $\hat{\beta}$ values, and to impose $\hat{\beta}_x = \hat{\beta}_y$. The actual value of $\hat{\beta}$ depends then on the distance from the barycentre of Q2-Q3 to the IP. In case of the standard triplet layout and collision parameters, the dependance of $\hat{\beta}$ on the IP-Q1 distance, l_0, is approximately:

$$\hat{\beta}_x = \hat{\beta}_y = 1780 + 66 l_0 + 2.12 l_0^2 \tag{1}$$

so that for an IP-Q1 distance of 23 m, for example, a $\hat{\beta}_{x,y}$ of 4400 m should be expected, compared to 4000 m for the standard layout. On the other hand, because of the deviation of the central orbit in the inner triplet, a matching condition $\hat{\beta}_x = C\hat{\beta}_y$, where C is a scaling factor, was also considered. For C close to 1, the $\hat{\beta}$ values in the two planes, which occur in between the two Q2's ($\hat{\beta}_x$), and immediately upstream of Q3 ($\hat{\beta}_y$), are related by:

$$\hat{\beta}_y = 16460 - 2.7\hat{\beta}_x \tag{2}$$

It is therefore possible to reduce the $\hat{\beta}$ at the point of maximum beam deviation (4 mm), with a corresponding increase of betatron amplitudes at the entrance of Q3, where the deviation is significantly smaller (2 mm). This asymmetry, which may help to reduce the damaging effects of the random field errors, can be accomplished by a small adjustment of Q3', whose aperture can be chosen to minimize its own contribution to the dynamical aperture. An example of the matched insertion with a modified layout featuring Q3', IP-Q1 distance of 23 m, 5.5 m low-β quadrupoles and drift S1 between Q1-Q2 of 2.5 m, is shown in Figure 2.

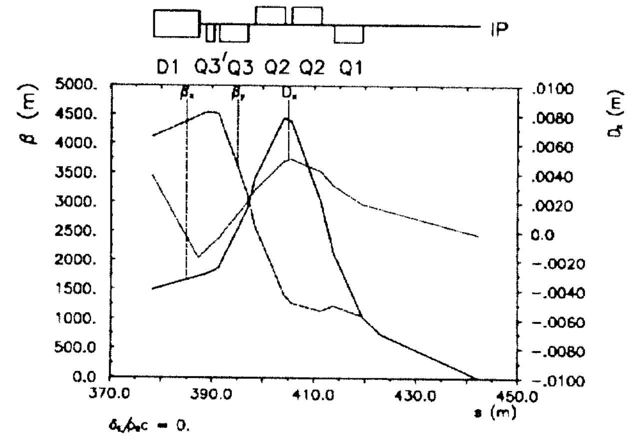

Figure 2: Optical functions in the inner triplet with 5.5 m low-β quadrupoles and Q3' matched along the actual orbit

3 PARTICLE LOSSES IN THE INNER TRIPLET

The particle losses in the LHC interaction region were studied in ref.[5], where it has been found that the two critical locations in the triplet are the outer ends of Q1 and D1, where the power density due to the secondaries is maximum. Furthermore, the power density is higher in the even than in the odd IP because of the finite crossing angle and inversion of the quadrupole sequence, and is strongly peaked in the transverse planes of Q1 with a $\sigma \sim 2$ degrees. It has also been found that it depends on the average magnetic field in the Q1 coil, decreasing by a factor of four between the cases when no field and a nominal field of 8 T are assumed in the coil. The estimated peak power density for the nominal luminosity is 2.7 mW/cm^3, which should be compared to 10 mW/cm^3, believed to be the quench limit in superconductors. Both of these figures bear, however, large model or measurement uncertainties.

In order to study the dependence of beam losses on the inner triplet layout, two additional possibilities were considered:

- a triplet with Q1 of 4.5 m, Q2 and Q3 of 6.0 m, and a drift S1 of 1.44 m, and
- a triplet with all quadrupoles 5.5 m, and a drift S1 of 2.5 m.

These layouts were further examined in cases of 56 mm and 70 mm quadrupole apertures, and IP-Q1 distance in the range of 20 – 25 m. Since the transport of charged secondaries, which contribute about 60% to the total power flux, depends on the exact magnetic field profile along the line, the low-β insertion for each of the above cases was matched as a whole, as illustrated in Figure 2. Together with the standard layout, we therefore obtained a representative number of cases for deducing relevant correlations.

A typical distribution of the beam loss power over the triplet is shown in Figure 3. Note the two-hump structure which arises from the change of focusing planes between the sequences Q1-Q2 and Q2-Q3, so that charged secondaries, which were about to hit the walls of the vacuum chamber in one transverse plane, change direction and are deflected towards the magnet axis, while spreading out in the other. It should be noted that as far as the transport of secondaries is concerned, the drift S1 appears as if it were an integral part of Q1, so that the total power under the entrance peak is very nearly constant for all layouts considered. It is therefore very important for the total heat load of Q1 that its length be decreased on account of longer separation from Q2. This does not modify the total power dissipated over the rest of the triplet, a significant fraction of which can be intercepted by an absorber placed in S1. The added space between Q1 and Q2 makes it possible to envisage placing Q1 in a separate cryostat, which may facilitate its replacement in case of radiation damage or for upgrades.

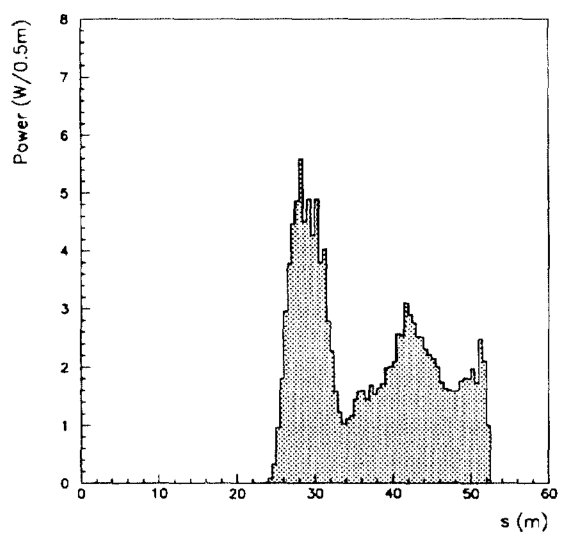

Figure 3: Beam loss power in 0.5 m bins as function of distance along the inner triplet

The total beam loss power in Q1 as function of its length and IP-Q1 distance is shown in Figure 4. A reduction of the length from 6.9 m (standard layout) to 5.5 m implies a decrease of 30% in the cryogenic load. A longer experimental area results in a proportionally higher power in Q1, so that for 23 m, the total power is reduced by 20% with respect to the standard layout. However, the operating margin of Q1 is improved, since the focusing strength decreases also. Unfortunately, no such clear correlation between the power density in Q1 and its length can be derived. On the basis of beam irradiance calculations it may be concluded that the power density does not change significantly in the practical range of Q1 lengths.

4 CONCLUSIONS

In an effort to study the inner triplet of the LHC low-β insertions from the systems point of view, several possibilities concerning triplet tuning, magnet standardization and minimizing particle loss were considered. It has been

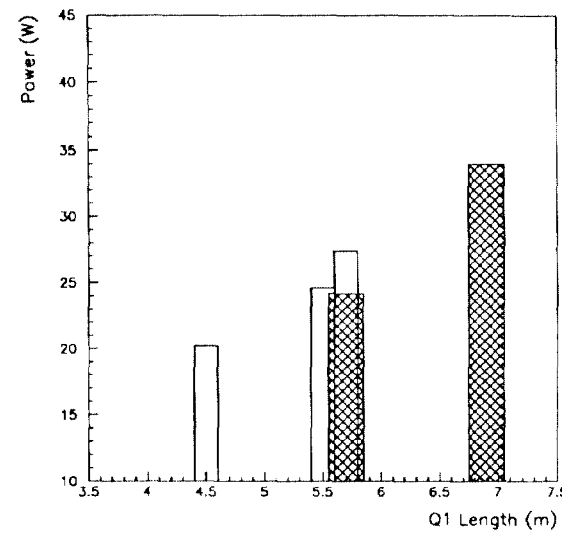

Figure 4: Total power in Q1 vs. length for IP-Q1 distance of 20 m (hatched) and 23 m (white)

concluded that for an optimized layout the gradient of Q1 should be as high as possible and that its length should be reduced to provide a larger separation from Q2. In order to have equal quadrupole length and flexible trimming, a short quadrupole (Q3') needs to be introduced upstream of Q3. For reasons of particle loss, the aperture of Q1 should be greater than 56 mm, so that an equal aperture of 70 mm for all magnets is retained. The magnets in the triplet can be standardized to 5.5 m with a separation of 1.44 m, except between Q1 and Q2, which should be at least 2.5 m. With these modifications, it should be possible to increase the free space on each side of the interaction point by two to three metres without appreciable loss of luminosity. The total power in Q1 is in that case reduced by 20-30%, while an additional 1 m long, 40 mm aperture absorber in between Q1 and Q2 reduces the energy deposit in the other quadrupoles by 30%.

5 REFERENCES

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