INTERACTION REGION WITH SLIM QUADRUPOLES

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Abstract

An optical performance's improvement of the interaction region can be obtained with the addition of new quadrupoles in the forward detectors area. Such scenario would allow decreasing the β^* below the nominal value. The basic concept consists in using quadrupoles to break the quadratic behavior of β in the free space between the IP and the IR triplets. In this new configuration we present the performance improvements and the hardware requirements.

INTRODUCTION

A possible scenario for increasing the LHC luminosity would consist in using stronger quadrupoles in the IR triplets to get a lower β^* [1][2]. This however would produce a larger β-peak in the triplet and an increase of magnet aperture would also be required.

The potential increase of field gradient provided by a possible upgrade of the present triplets with Nb_3Sn quadrupoles would be then strongly limited by the need of increasing the aperture. Solutions considering moving the whole triplet closer to the IP may be envisaged, but they would imply a heavy change on the experimental area.

The proposal described in this paper aims at breaking the quadratic behavior of the beta function by implementing a pseudo-β-translation interposing two quadrupoles between the IR triplet and the IP. A further upgrade of the main triplets with Nb_3Sn magnets would then strongly benefit from this scheme. This approach is in principle applicable to both ATLAS and CMS (as an example, we are considering the case of CMS), provided the hardware constraints in the experimental areas can be handled.

One of the advantages of this proposal is that it makes possible the use of very compact and light quadrupoles, because of moderate requirements in gradient and aperture.

We also studied an alternative to this scheme where the triplet is shifted to ~ 13 m from IP. To increase the integrated strengths keeping the gradients unchanged we have increased the Q1, Q2 and Q3 lengths. The apertures, gradients and lengths are evaluated in both solutions and compared.

OPTICS LAYOUT

The nominal layout of LHC in the interaction regions (IR1 and IR5) is based on a triplet that provide the final focusing of the beam (Fig. 1).

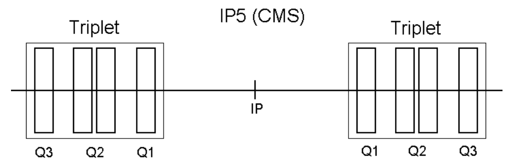

Figure 1: Nominal LHC IR layout.

The distance between IP and Q1 is 22.965 m and this space is, from the optical point of view, a drift without any constraint. This means that the β function is free to increase (from IP to the entrance of Q1) with the law:

$$\beta_{Q1} = \beta^* - 2l_d\alpha^* + l_d^2(\frac{1+\alpha^{*2}}{\beta^*}) \tag{1}$$

where β^* and α^* are, respectively, the values of β and $-\frac{1}{2}\frac{\partial\beta}{\partial s}$ evaluated in IP (nominal values for LHC are $\beta^* = 0.55$ m and $\alpha^* \sim 0$) and l_d is the length of drift.

This law is quadratic in the length of drift l_d and the nominal layout from triplet to IP is shown in Fig. 2.

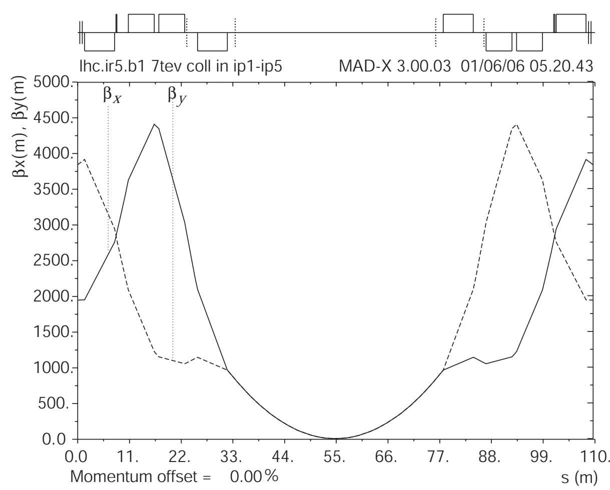

Figure 2: Nominal LHC β function between IP and Q1.

The idea of this study is to introduce two quadrupoles between IP and Q1 in order to modify the parabolic law introducing a shift into β function (Fig. 3).

Following this idea we create the new layout represented in Fig. 4 where two new quadrupoles, SQ1 and SQ2 (Slim Quadrupole 1 and Slim Quadrupole 2) provide the requested shift into β function.

The parameters of these new quadrupoles have been preliminary evaluated with ad-hoc Matlab and C non linear equation solver and then have been introduced into nominal Mad-X (v6.5) optic structure and matched with the existing

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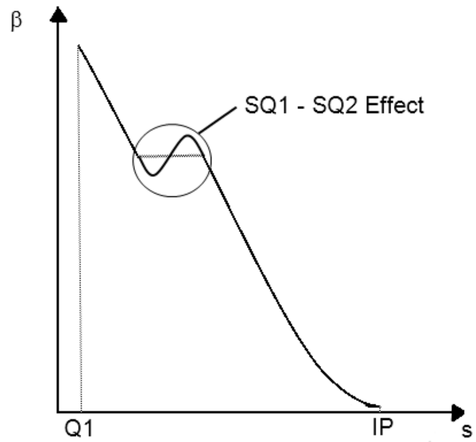

Figure 3: Shift in β function.

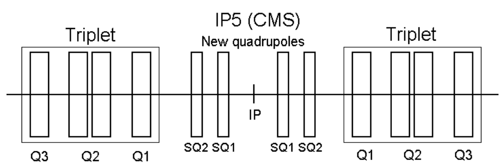

Figure 4: New proposed LHC IR layout.

magnets. The relevant results can be certainly further optimized by acting on distances of new quadrupoles from Q1, the inter-distance between SQ1 and SQ2 and by a better matching evaluated with a more powerful non linear solver which is under development.

The aperture of this magnets has been computed using the formula for D_{min} presented in [1]

$$D_{min} > 1.1 \cdot (7.5 + 2 \cdot 9)\sigma + 2 \cdot (d + 3\text{ mm} + 1.6\text{ mm}) \quad (2)$$

with a beam envelope of $9\ \sigma$, a beam separation of $7.5\ \sigma$, the β-beating of 20%, a peak orbit excursion of 3 mm, and a mechanical tolerance of 1.6 mm. The parameters with a dependence from β are σ and the spurious dispersion orbit d. They could be evaluated as shown in [1]. In SQ1 and SQ2 the β function is, respectively, 916 m and 1108 m (~ 12.5 m from IP) with a $D_{min} > 32$ mm for SQ1 and $D_{min} > 35$ mm for SQ2.

The values of gradients and lengths are summarized in Table 1.

Table 1: New quadrupole lengths.

Magnet	**Length**	**Gradient**	**Min. diameter**
SQ1	~ 3 m	~ 118 T/m	> 32 mm
SQ2	~ 3.5 m	~ 163 T/m	> 35 mm

It is interesting to see that this scheme is not very challenging for the gradients and the apertures and, as discussed later, may be fulfilled by light and compact quadrupoles.

The new shape of β function, with new quadrupoles, is reported in Fig. 5. . This preliminary solution reduce the

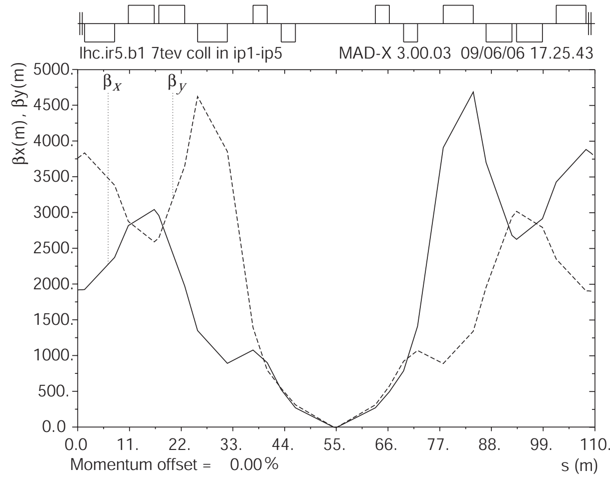

Figure 5: New LHC β function between IP and Q1.

value of β^* from the nominal value of 0.55 m to a new value of 0.22 m.

As anticipated, we have also explored an alternative scenario capable of reducing β^* of a similar value. (Fig. 6)

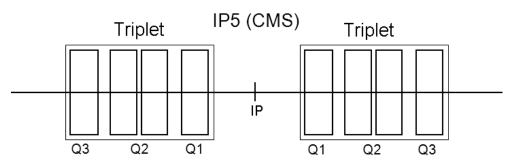

Figure 6: Alternative layout with increased lengths triplet at 13 m from IP.

Here the triplets are positioned at ~ 13 m from the IP with an increasing in the magnets length in order to preserve the value of gradients. The maximum value of β inside the triplet increases to ~ 5800 m so that the magnet aperture has to be increased consequently.

A summary of triplet characteristics in this solution are shown in Table 2: The advantage of triplet at 13 m arise in

Table 2: Solution with triplet at 13 m from IP.

Magnet	**Length**	**Gradient**	**Min. diameter**
Q1	~ 7.5 m	$\sim 203\ T/m$	> 72 mm
Q2	~ 6.3 m	$\sim 203\ T/m$	> 77 mm
Q3	~ 7.4 m	$\sim 203\ T/m$	> 74 mm

the use of four magnets instead of six for final focalization (less power lines and less cryogenic pipes into detectors area), but the drawbacks of bigger apertures, gradients and lengths suggest that the scheme based on SQ1 and SQ2 could be better developed and integrated into experiments.

The gain in luminosity is, in principle, $\propto \frac{1}{\beta^*}$ but a lower β^* increases the beam-beam effect and a higher crossing angle is required with a consequent decrease in luminosity.

The luminosity for the LHC is:

$$L = F\frac{n_b N_b^2 f_{rev}}{4\pi\sigma^*} \tag{3}$$

where n_b is the number of bunches, N_b is the number of protons for each bunch, f_{rev} is the revolution frequency of the bunch, σ^* is the transverse rms beam size and F is the geometric factor expressed by:

$$F \approx \frac{1}{\sqrt{1+(\frac{\theta_c\sigma_z}{2\sigma^*})^2}} \tag{4}$$

where θ_z is the crossing angle and σ_z is the rms bunch length.

A numerical tracking can estimate the dependence of θ_c from bunch charge, bunch length and long range beam-beam effect [4] [5]:

$$\theta_c = \theta_{c0}\sqrt{\frac{\beta_0^*}{\beta^*}}(6.5 + 3\sqrt{\frac{N_b n_b n_{LR}}{N_{b0} n_{b0} n_{LR0}}}) \tag{5}$$

where n_{LR} is the number of long-range beam-beam collisions and the 0 index represents the nominal values.

The crossing angle thus increases with $\frac{1}{\sqrt{\beta^*}}$ decreasing, consequently, the geometric factor F and the luminosity.

This effect is present in any luminosity upgrade based on β^* reduction. Possible solutions are a decreasing in σ_z (decreasing of bunch length), introduction of crab cavities to improve the geometric factor, or the introduction of a new dipole in the very last meters from IP (the so-called D0 [3]) in order to reduce the crossing angle in the IP.

HARDWARE

The SQ1 and SQ2 magnets should have to be integrated in the space presently corresponding to the hadronic forward calorimeter (HF) of the CMS experiment and to the so called “Castor space” of the rotating shielding structure.

Several possibilities may be envisaged, including a modification of the rotating shielding itself to host the new magnets, which in this case shall be small and light enough to fit into the modified, longer structure. In this direction, an option of slim ironless quadrupoles can be considered. Such magnets can be hosted in a 300 mm diameter cryostat and the weight of the whole doublet could be contained within about 3 tons.

Radiation and beam deposited energy estimate for this scheme have not yet been carried out and it is very likely that absorbers have to be introduced. The magnet aperture required by optics in principle may be even smaller that the one of the IR triplets, i.e. 70 mm, due to the lower beta function. In particular for SQ1, the relatively low gradient required would allow increasing the physical aperture to about 100 mm to incorporate a radiation shield.

An additional absorber, if required, may probably be incorporated in the CMS end-cap. Depending on the resulting beam induced heat deposited losses in the SQ1$-$SQ2 superconducting coils, different alternative for the superconducting cables may be envisaged.

An operating heat power transfer of the order of 10 W/m of magnet length is considered a reasonable upper limit for accelerator magnets using Rutherford cable, the use of cable in conduit conductors would allow evacuating about 50 W/m of magnet length.

Superconducting accelerator magnets with internally cooled cables are already in use for the Nuclotron [6] in a superferric configuration and new studies are under way for the development of magnets for SIS100 of the FAIR Project. However in this case the field quality and the gradient level are fully determined by the position of the conductors and by the achievable overall current density : in both cases Rutherford cables provide better results, in addition to possibly easier manufacture and more reliable operation. Finally, a particular attention shall be dedicated to make these magnets radiation resistant. Considering their limited size, one may consider their replacement after $2-3$ years of operation.

Similar considerations would apply for a possible integration of this scheme in ATLAS.

CONCLUSIONS

The presented new layout shows that a luminosity upgrade is possible with optimization in the present LHC configuration with the introduction of additional slim quadruple magnets between the IR triplet and the IP.

From an optical point of view this solution is equivalent to shift triplet forward into detector and increasing the lengths of quadrupoles, but with a lower impact in hardware and integration.

The most interesting result consists in the possibility to locally modify the behavior of β in the IP region translating the function from the nominal parabolic shape to a new one with lower β^*.

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