Q0 Status *

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Abstract

The Q0 scheme of the LHC insertion region is based on the introduction of a doublet of quadrupoles at 13 meters from IP. In this scenario the value of β^* can be reduced to 0.25 m with a moderate increase of the β function inside the inner triplet. We present here an optical layout, with the required magnets parameters such as gradients, lengths, positions and apertures. We also discuss in some details the tolerance on alignment and the energy deposition.

INTRODUCTION

One possible option for the LHC IR upgrade [1] is based on the introduction of two new quadrupoles inside the experimental devices, at 13 meters from IP.

The potential of this scenario, discussed in [2], is to reduce the quadratic growth of the β function, since the two new quadrupoles should introduce an oscillation of β between the IR triplet and the IP. Ideally, the modified shape of the β function should allow to interconnect the optics with $\beta^* = 0.25$ m in the IP-side to the optics with $\beta^* = 0.55$ m in the inner triplet side, as shown in Fig. 1.

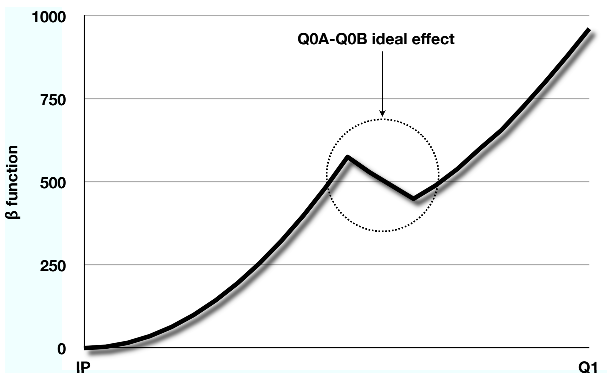

Figure 1: β shift with Q0.

This ideal behavior is the starting point for a new optimization of the interaction region based on five magnets, in which the two Q0s should reduce the quadratic increase of the β function and the inner triplet should provide the final focusing at the interaction point.

In this paper we present an IR layout compatible with LHC optics, in which $\beta^* = 0.25$ m, while the maximum β value is limited to 5820 m (Fig. 3).

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OPTICS LAYOUT

Geometry

The proposed configuration of the interaction region is represented in Fig. 2 and summarized in Table 1. The optical functions are shown in Fig. 3 for the first 70 meters from IP and in Fig. 4 for the whole interaction region.

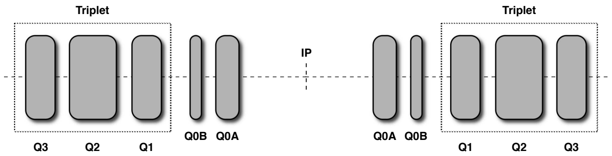

Figure 2: Q0 Layout.

Table 1: IR Layout.

Magnet	**L*** [m]	**Length** [m]	**Gradient** [T/m]
Q0A	13.0	7.2	240
Q0B	20.8	3.6	196
Q1	25.8	8.6	200
Q2	37.1	11.5	172
Q3	52.0	6.0	160

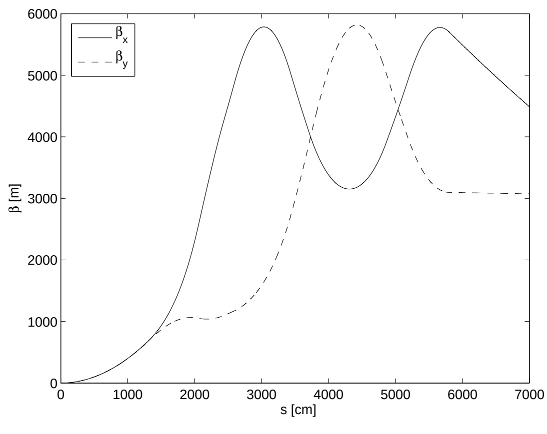

Figure 3: β function in the Q0-Triplet region when $\beta^* = 0.25$ m.

With the nominal LHC IR layout and with $\beta^* = 0.25$ m, the maximum value of β is of about 9700 m (Fig. 5 and Fig. 6).

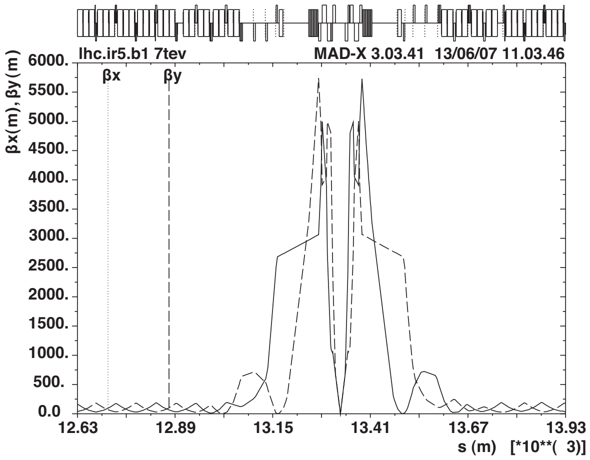

Figure 4: β function with Q0 layout and $\beta^* = 0.25$ m.

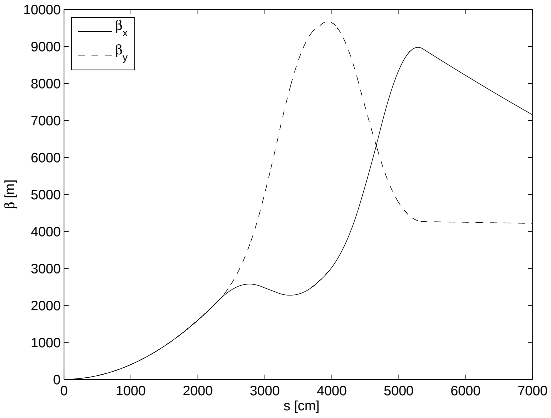

Figure 5: β function in the nominal layout when $\beta^* = 0.25$ m.

By using the Q0 doublet, the maximum value of β decreases to 5820 m. The increase of the initial luminosity is of a factor 2 with respect to the LHC optic at $\beta^* = 0.50$ either in a zero-crossing angle scheme [3] or when compensating the far beam-beam effect. Otherwise it is mandatory to increase the crossing angle according to [4] and [5]:

$$\theta_{\rm c} = \theta_{\rm c0}\sqrt{\frac{\beta_0{}^*}{\beta^*}}(6.5 + 3\sqrt{\frac{\rm N_b n_b n_{LR}}{\rm N_{b0} n_{b0} n_{LR0}}}) \qquad (1)$$

where $\rm n_b$ is the number of bunches, $\rm N_b$ is the number of protons for each bunch, $\rm n_{LR}$ is the number of long-range beam-beam collisions and the 0 index represents the nominal values. The crossing angle affects the luminosity, through the geometric factor, expressed by:

$$F \approx \frac{1}{\sqrt{1 + (\frac{\theta_{\rm c}\sigma_{\rm z}}{2\sigma^*})^2}} \qquad (2)$$

(where $\sigma_{\rm z}$ is the rms bunch length and σ^* is the transverse

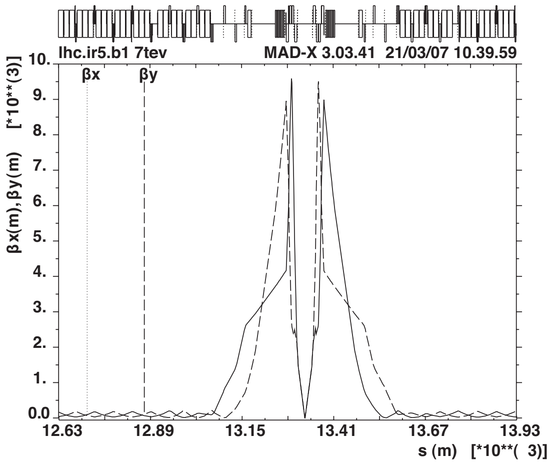

Figure 6: Nominal layout at $\beta^* = 0.25$ m.

rms beam size). The luminosity is given by:

$$L = F\frac{n_{\rm b}{\rm N_b}^2{\rm f_{rev}}}{4\pi{\sigma^*}^2} \qquad (3)$$

where $\rm f_{rev}$ is the revolution frequency of the bunch. If the crossing angle is of 403 μrad, then the gain of the initial luminosity is of 1.75.

Aperture

The minimum value of the quadrupole aperture $\rm D_{min}$ is estimated by means of the formula [6]:

$$\rm D_{min} > 1.1 \cdot (10 + 2 \cdot 9)\sigma + 2 \cdot (d + 3\ mm + 1.6\ mm) \qquad (4)$$

with a beam envelope of 9 σ, a beam separation of 10 σ, a β-beating of 20%, a peak orbit excursion of 3 mm, and a mechanical tolerance of 1.6 mm. The parameters depending on β are the rms beam radius σ and the spurious dispersion orbit $\rm d$. The values for beta function, the apertures and the peak field are summarized in Table 2.

Table 2: Magnet apertures and peak field.

Magnet	β Max [m]	$\rm D_{min}$ [mm]	Peak field [T]
Q0A	2300	60	7.2
Q0B	4300	72	7.1
Q1	5780	80	8.0
Q2	5820	80	6.9
Q3	5770	80	6.4

The required integrated gradients may be reached using $\rm NbTi$ superconductor technology or with $\rm Nb_3Sn$ but with an higher margin for the energy deposition. In an further optimized solution should be possible to decrease the gradient of Q1 increasing the Q3 with minor changes into the β function. It should also be possible to have the same gradients for the five magnets (Q0A-Q3) saving the number of power supply.

Detuning

The injection optics corresponds to a β^* of 5 m. The corresponding β function along the IR is shown in Fig. 7.

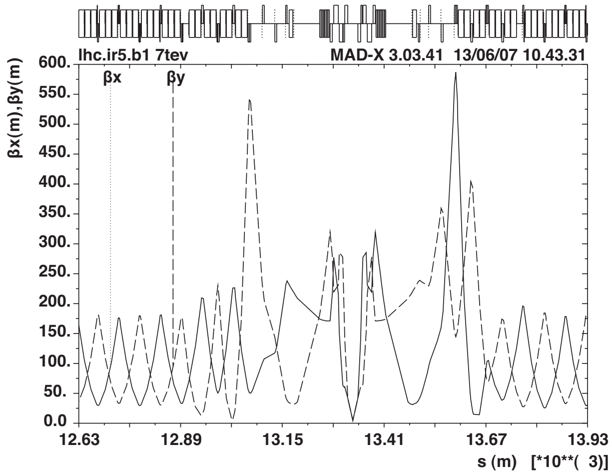

Figure 7: β function at injection.

The transition between injection and collision is performed by varying the gradients of Q4-Q11 as shown in Fig. 8. In a more careful optimization, polarity changes should be prevented. Note that, during the detuning, the gradients of Q0-Q3 remain unchanged.

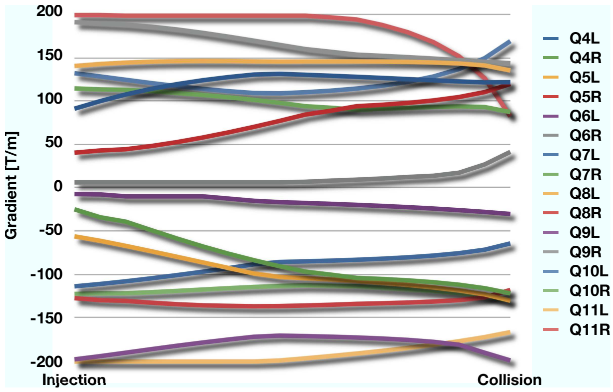

Figure 8: Q4-Q11 gradients from injection to collision.

MISALIGNMENTS

Following the arguments in [7] and [8] it is possible to estimate the misalignment tolerance of Q0A and Q0B. We have to consider two cases, one in which there is a relative misalignment in between Q0A and Q0B, the other in which Q0A-Q0B are in a rigid structure and misaligned with respect to the inner triplet.

In thin lens approximation, the shift $\delta_x(s)$ of the closed orbit, resulting from quadrupole displacements ΔX_{Q_i}, is given by:

$$\delta_x(s) = \xi \left[\sum_i \left(\theta \sqrt{\beta_x} \right)_i \cos\left(\pi Q_x - |\Delta\mu_i| \right) \right] \tag{5}$$

where $\theta_i = K_i l_i \Delta X_{Q_i}$ is the deflection angle of the dipolar component of the misaligned magnet Q_i, $\Delta\mu_i = \mu_x(s) - \mu_x(s_i)$, Q_x is the tune, and the ξ parameter is $\frac{\sqrt{\beta_x(s)}}{2\sin(\pi Q_x)}$.

Note that the sign of $\delta_x(s)$ depends on two factor: the beam and the quadrupole. A positive dipolar component for beam 1 corresponds to a negative one for beam 2. An alignment error in the shared region creates a different effect respect to a misalignment in the not-shared sequence. On the other hand, if the Q0A and Q0B magnets move in phase, the kicks of the quadrupoles tend to be compensate since the positive dipolar component for the focusing magnet corresponds to a negative dipolar component for the defocusing magnet. This is why, quadrupoles with opposite gradients in a rigid structure, tend to compensate the misalignment error of the structure itself.

A numerical estimation of $\delta_x(s)$ induced by Q0A misalignment can be performed using $Q_x = 64.31$, $K = 0.01027\ \mathrm{m}^{-2}$, $l = 7.2$ m, $\beta_x = 2300$ m and $|\mu_x(s) - \mu_x(s_i)| = \frac{\pi}{2}$. In this case $\delta_x(s) \approx 0.825\sqrt{\beta_x(s)}\Delta X_{Q_x}$ that means a closed orbit error of 1.5 mm for a displacement of 50μm.

For Q0B one should use $K = -0.0084\,\mathrm{m}^{-2}$, $l = 3.6$ m, $\beta_x = 4300$ m, $Q_x = 64.31$ and $|\mu_x(s) - \mu_x(s_i)| = \frac{\pi}{2}$. Then one has $\delta_x(s) \approx -0.459\sqrt{\beta_x(s)}\Delta X_{Q_x}$ and a closed orbit error of 0.8 mm for a misalignment of 50μm.

This displacements of the orbits is disruptive for the luminosity: a 7.5μm of counter-phase misalignment decrease the luminosity of 10%. It's evident that a system of correctors is mandatory to compensate this kind of effects.

If the Q0 doublet is mounted in a rigid structure, the closed orbit error induced by a misalignment of the structure itself is compensated to a large extent and the alignment tolerance becomes of some hundreds of μm.

ENERGY DEPOSITION

A preliminary evaluation of the energy deposition in Q0A and Q0B magnet is performed using the design of Fig. 9

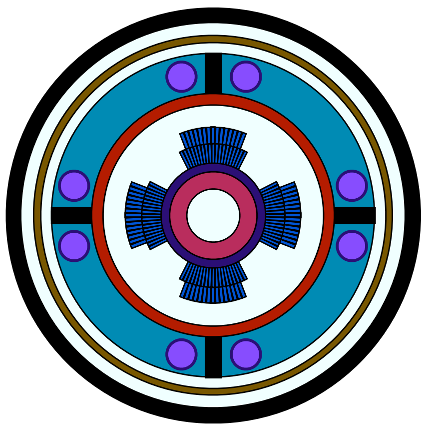

Figure 9: Q0 design.

and the regions inside the magnet are schematized as illustrated in Fig. 10.

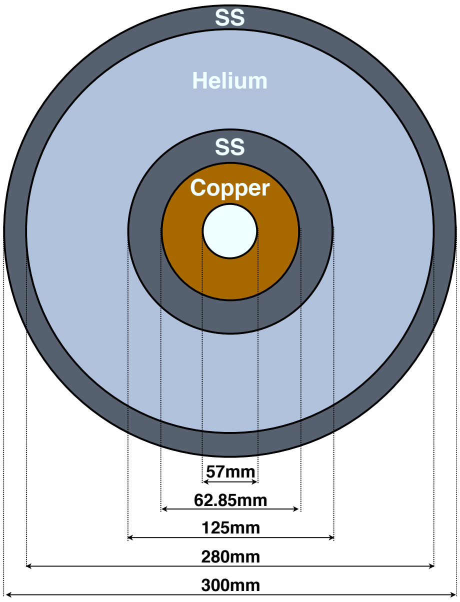

Figure 10: Q0 structure for the FLUKA model.

Here the aperture of the magnet is 57mm because is based on a preliminary model of Q0A magnet. The magnetic field map is obtained from a 2D ROXIE model and the total energy absorbed by this geometry is evaluated in a simulation with the FLUKA code. The results of the simulation is in Fig. 11 for the Q0A and in Fig. 12 for the Q0B.

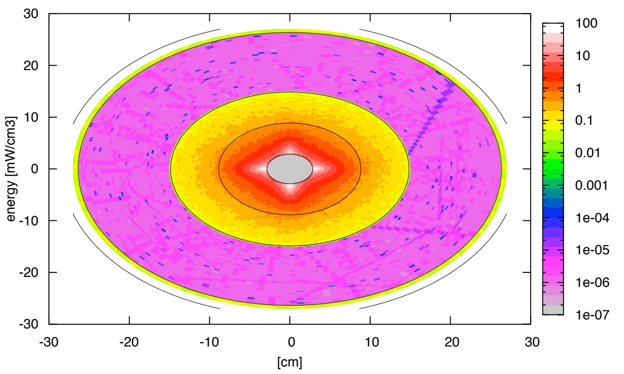

Figure 11: Total energy absorbed by Q0A.

For this simulation was used a luminosity of 10^{35} events per second per cm^2 and a 1 meter long TAS in front of Q0A.

The power on the magnets is 106 W (14.7 W/m) for Q0A and 42.5 W (11 W/m) for Q0B. These powers exceeds the capabilities of the cryogenic system that can extract at most ~ 10 W/m in ideal conditions. Some solutions can be evaluated to reduce the energy deposition as proposed in [9].

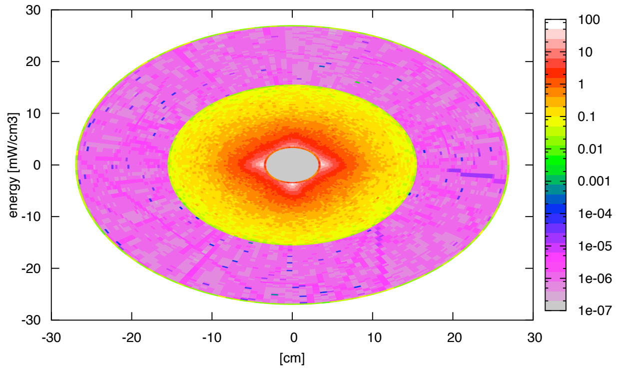

Figure 12: Total energy absorbed by Q0B.

CONCLUSIONS

The Q0 layout is rapidly evolving from the original idea proposed in [2] towards a full integration into the LHC nominal optic (v6.5). The optics proposed in this paper requires a Q0A quadrupole with a gradient of 240 T/m, just compatible with NbTi technology.

Misalignment tolerances for Q0A and Q0B are similar to those required for the inner triplet; it's reasonable to think that the same system of correctors used in the triplet can be applied for Q0A-Q0B.

The energy deposition is an issue that must be fully explore to propose reasonable solutions compatibles with a system of energy extraction in a limited volume such as inside the detector.

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