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INVESTIGATIONS ON A Q0 DOUBLET OPTICS FOR THE LHC LUMINOSITY UPGRADE*

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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 m from the IP. We present here the doublet optics and the magnets layout such as gradients, lengths, positions and apertures. In this scheme we show the gain in luminosity and chromaticity, with respect to a nominal layout with β* = 0.25 m (i.e. LHC phase 1 upgrade) and β* = 0.15 m, due to a smaller beta-max. We show the alignment tolerance and the energy deposition issues, in Q0A-Q0B. We also consider shielding the magnets with liners. The capability of Q0 optics to limit the β function could be exploited after the LHC Phase 1 upgrade in order to reduce the β* below 0.25 m, leaving the upgraded triplet unchanged

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The Q0 scheme of the LHC insertion region is based on the introduction of a doublet of quadrupoles at 13 m from the IP. We present here the doublet optics and the magnets layout such as gradients, lengths, positions and apertures. In this scheme we show the gain in luminosity and chromaticity, with respect to a nominal layout with $\beta^* = 0.25\,\mathrm{m}$ (i.e. LHC phase 1 upgrade) and $\beta^* = 0.15\,\mathrm{m}$, due to a smaller beta-max. We show the alignment tolerance and the energy deposition issues, in Q0A-Q0B. We also consider shielding the magnets with liners. The capability of Q0 optics to limit the β function could be exploited after the LHC Phase 1 upgrade in order to reduce the β^* below 0.25 m, leaving the upgraded triplet unchanged.

THE OPTICS

One option for the LHC IR Phase 2 upgrade [1] is based on the introduction of two new quadrupoles inside the experimental devices, at 13 meters from IP. The scenario was presented in [2] and [3] and it is summarized in Fig. 1 and Table 1.

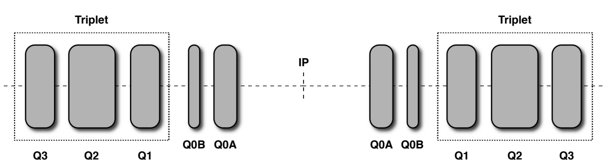

Figure 1: Q0 Layout.

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

This layout is based on a triplet (Q1-Q3) as close as possible to the LHC nominal triplet and a doublet (Q0A-Q0B) that starts at 13 meters from IP.

Here Q0A is a challenging magnet in term of gradient, but the required aperture at 13 meters is smaller than at 23 meters because the β function increases quadratically with the distance from IP.

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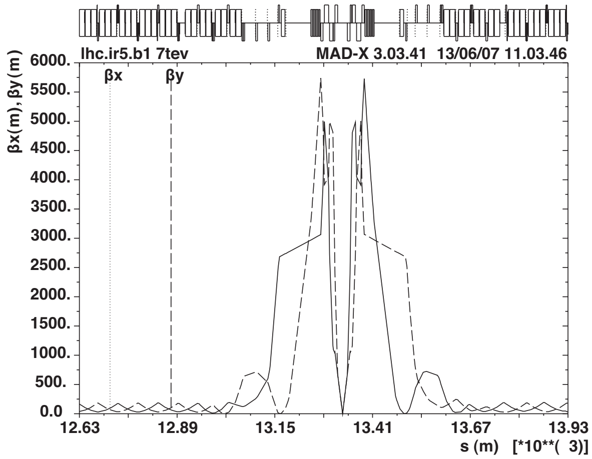

Figure 2: β function with Q0 and with $\beta^* = 0.25$ m.

Aperture

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

$$D_{\min} > 1.1(10 + 2 \times 9)\sigma + 2(d + 3\ \mathrm{mm} + 1.6\ \mathrm{mm}) \quad (1)$$

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 spurious dispersion orbit d is a function of the crossing angle, so in general it depends on the β function, but for this estimation the crossing angle is assumed constant to the $285\ \mu\mathrm{rad}$ and $d = 8.84\ \mathrm{mm}$. The parameter depending on β is the rms beam radius σ. The values for beta function and the apertures (at $\beta^* = 0.25\mathrm{m}$) are summarized in Table 2.

Table 2: Magnet apertures at $\beta^* = 0.25$ m.

Magnet	β Max [m]	$\mathrm{D_{min}}$ [mm]
Q0A	2300	60.0
Q0B	4300	72.1
Q1	5780	79.3
Q2	5820	79.5
Q3	5770	79.2

Comparision with nominal triplet

This optics can keep under control the β max with an advantage in the aperture and chromaticity with respect to layouts with triplet at 23 m from IP.

The comparison between the Q0 solution and the triplet with $\mathrm{l}^* = 23$ m with $\beta^* = 0.25$ m and $\beta^* = 0.15$ m is shown Table 3 and 4. In particular we take into account the maximum value of the β function in the final focusing interaction region, the largest aperture required in the magnets (in general Q2) and the chromaticity contribution from IP to Q3.

Table 3: Q0 vs. Nominal with β^*=0.25 m.

	Q0	**Nominal**
Max β [m]	5820	9673
Max Aperture [mm]	79.5	88
IR Chromaticity	-22.76	-28.12

Table 4: Q0 vs. Nominal with β^*=0.15 m.

	Q0	**Nominal**
Max β [m]	9696	16120
Max Aperture [mm]	89	100
IR Chromaticity	-37.93	-46.87

MISALIGNMENTS

Following the arguments in [4] 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 the structure is 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:

$$\delta_x(s) = \xi\left[\sum_i \left(\theta\sqrt{\beta_x}\right)_i \cos\left(\pi Q_x - |\Delta\mu_i|\right)\right] \quad (2)$$

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, $\Delta\mu_i = \mu_x(s) - \mu_x(s_i)$ 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 with respect to a misalignment in the not-shared sector. On the other hand, if the Q0A and Q0B magnets move in phase, the kicks of the quadrupoles tend to compensate since the positive dipolar component for the focusing magnet corresponds to a negative dipolar component for the defocusing magnet.

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 $\delta_x(s) \approx 0.825\sqrt{\beta_x(s)}\Delta X_{Q_x}$, i.e. 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 is given by a misalignment of 50μm.

If the Q0 doublet is mounted in a rigid structure, the closed orbit error induced by a misalignment of the structure itself is almost compensated and the required alignment precision (according to [4]) becomes of hundreds of μm.

ENERGY DEPOSITION

The scattered particles that come from the IP and collide on the magnets are an important issue to consider in the Q0 layout . These particles increase the temperature on the superconducting coils of the magnets with a possible risk of quench.

To evaluate the energy deposition a fully integrated particle physics MonteCarlo simulation package (FLUKA) is used. The simulations are performed with the optic v6.5, a full crossing angle of 285 μrad and a luminosity of $10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, this parameter is assumed just as a scaling factor for the energy deposition in a scenario of a luminosity upgrade of a factor 10; a crossing angle of 285 μrad and a luminosity of $10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ are in general incompatible without a beam-beam compensation scheme. The geometry of the magnets used in FLUKA is schematized in Fig. 3.

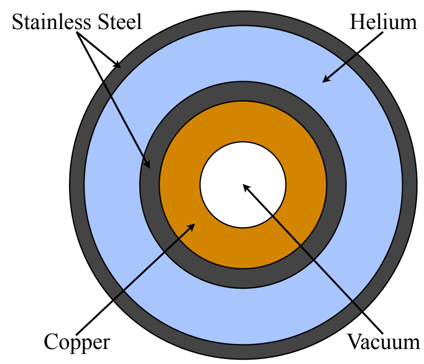

Figure 3: Magnet schematization for FLUKA.

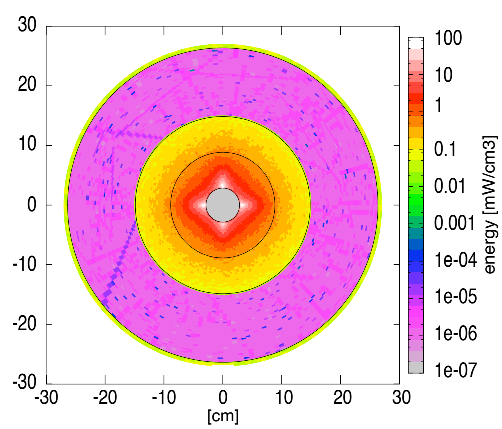

Figure 4: Energy deposition in Q0A.

The first estimation of energy deposition on Q0A is shown in Fig. 4. The energy peak on the coils is around $100\ \mathrm{mW/cm^3}$ that is unacceptable for Nb-Ti (with a limit of $\sim 4.3\ \mathrm{mW/cm^3}$) but also for $\mathrm{Nb_3Sn}$ (with a limit of

$\sim 12\ \mathrm{mW/cm^3}$) [5].

A possible way to reduce the energy deposition on coils is to apply a liner of $1\ \mathrm{cm}$ of thickness into the beam pipe to shield the coils, as proposed in [6].

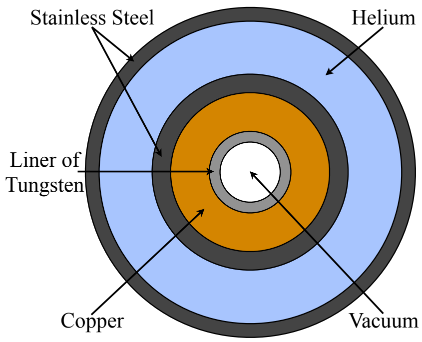

Figure 5: Magnet schematization for FLUKA with liner.

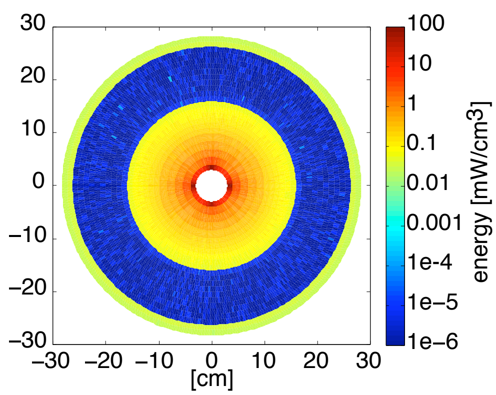

Figure 6: Energy deposition in Q0A with liner.

Figure 6 shows the action of the liner: the peak of power is inside the tungsten and the coils are protected. This can be verified looking at the peak power along the length of the cable as shown in Fig. 7. The peak in the first cable of Q0A which is the most irradiated cable, is $11.6\ \mathrm{mW/cm^3}$, that can be compatible with $\mathrm{Nb_3Sn}$. For Q0B the situation is better because the radiation is partially absorbed by the liner of Q0A; the power's peak in the first coil of Q0B is $8.1\ \mathrm{mW/cm^3}$ and the behavior is shown in fig 8.

CONCLUSIONS

A doublet in front of the inner triplet, i.e. the so-called Q0 option, together with a device for beam-beam effect compensation (with a 285 μrad of crossing angle and a β^* below $0.25\ \mathrm{m}$ only electron lens can compensate the beam-beam effect), can be a route for the LHC Phase 2 luminosity upgrade ($10^{35}\ \mathrm{cm^{-2}s^{-1}}$) since it gives rise to smaller β functions.

The misalignment tolerances required for Q0A and Q0B are similar to those required for the inner triplet: dipolar correctors are required in order to recover relative misalignments.

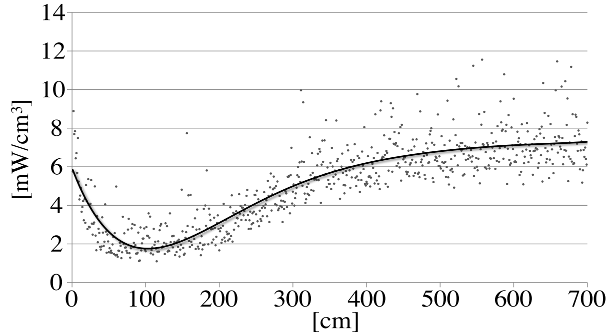

Figure 7: Peak of energy deposition in the first cable of Q0A with liner.

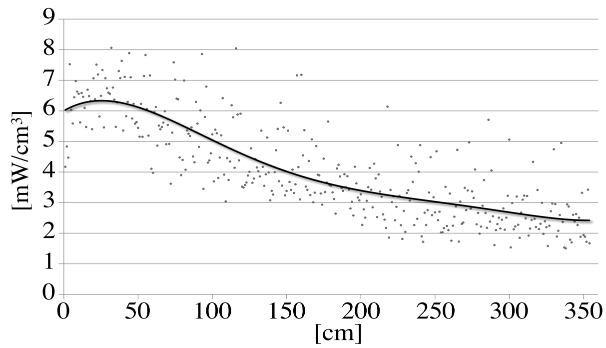

Figure 8: Peak of energy deposition in the first cable of Q0B with liner.

The issue of energy deposition is of strong relevance: an optimized shielding scheme based upon liners is mandatory to reduce the power on the coils of a factor 10 with respect to the non-shilded magnets, thus bring this layout compatible with the $\mathrm{Nb_3Sn}$ shielded.

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