Nb-Ti SYMMETRIC TRIPLETS FOR THE LHC LUMINOSITY UPGRADE

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Abstract

We study a Nb-Ti lay-out for the triplet in the low-beta interaction regions of the Large Hadron Collider, based on a stretched version of the present baseline. The triplet length is increased from the present value of 32 m up to about 60 m. The quadrupoles are based on a two layer coil made with the LHC main dipole cable. A parametric analysis of the dependence of the optics and magnet performances on the triplet length and aperture is carried out.

INTRODUCTION

The possibility of increasing the focusing in the interaction point of the Large Hadron Collider using a wider and longer Nb-Ti triplet has been considered in several studies [1,2,3]. In this paper we update the results of a parametric analysis developed according to the approach proposed in [4], and presented in [5] and [6]. The triplet lay-out is a stretched version of the today baseline, with quadrupoles of equal gradient and aperture, and different lengths ("symmetric option"). We extend the analysis up to triplet lengths that are ~25 m longer than the baseline, and we consider quadrupoles made up of two layers of the LHC main dipole cable. Moreover, we improved our analysis in a few points, namely i) we correct an overestimate of the LHC cable performance as given in [6], ii) we use a stronger focusing to have smaller beam size in Q4, iii) we increase the distance between Q2a and Q2b to take into account of the interconnection space needed for magnets in separate cryostats, and iv) we include a scaling of the cold bore thickness with the magnet aperture. The paper presents plots giving the main magnetic and optic properties as a function of the length of the triplet, which is taken as the free parameter.

OPTICS CONSTRAINTS

Triplet structure

We consider a triplet whose structure is similar to the LHC baseline [7], i.e., is made up of two focusing quadrupoles Q1, Q3 of equal length l_1, and with two defocusing quadrupoles Q2a and Q2b, each of length l_2, in between. We use the nominal distance l^*=23 m of Q1 from the interaction point (see Fig. 1). With respect to the calculations presented in [5] and [6] we increase the distance between Q2a and Q2b from 1 to 1.6 m to take into account the fact that the two magnets will have a separate cryostat, and not a common one as it is today in the baseline.

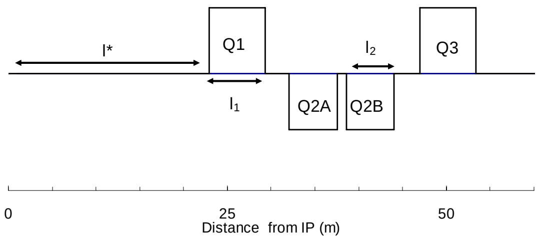

Fig. 1: Lay-out of the triplet close to the IP, nominal case of the LHC.

As in the previous work, we assume that

- all the quadrupoles have the same operational gradient;
- the gap between Q1-Q2 and Q2-Q3 is set to the actual values for the nominal LHC baseline (2.7 m between Q1 and Q2A, and 2.9 m between Q2B and Q3), i.e., we assume that the same structure and length of corrector magnets and instrumentation is kept.

The parametric analysis is carried out using the triplet length as the free parameter. All the following plots will be given in terms of the total quadrupole length, i.e. the length of the triplet minus the length of the gaps (2.7+1.6+2.9=7.2 m).

Approximated matching conditions

With respect to previous work, [5,6] we impose a larger focusing (up to 5%) to have smaller values of the beta functions in Q4 to avoid aperture bottlenecks in these magnets [8]. The obtained approximated matching has β functions in Q4 smaller than 1000 m for β^*=0.25 m. We keep the condition of approximately equal maxima of the β functions in the x and y planes (within a few percent) to determine the relative lengths of Q1-Q3 and Q2. Results are shown in Fig. 2, as a function of the total quadrupole length.

We use a quadratic fit for the inverse of the gradient G as a function of the total quadrupole length as proposed in [6] (see Fig. 3)

$$G = \frac{1}{f l_q^2 + h l_q} \qquad (7)$$

with f=2.33×10^{-6} [T^{-1} m^{-1}] and h=1.51×10^{-4} [T^{-1}] and we extended the fit analysis to total quadrupole lengths up to 55 m. The fit is very precise over the selected range. The obtained gradients are 3-4% larger with respect to the previous analysis [5,6].

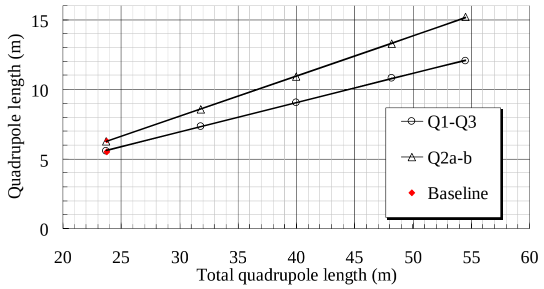

Fig. 2: Length of Q1-Q3 and Q2a-b versus total quadrupole length.

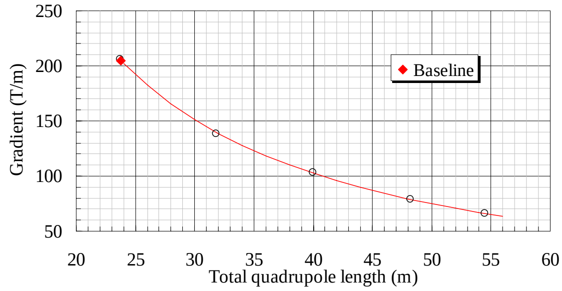

Fig. 3: Inverse of the quadrupole gradient versus total quadrupole length.

MAGNET CONSTRAINTS

Quadrupole aperture versus gradient

We considered two-layer quadrupole lay-outs having the inner and outer layer cable of the main LHC dipole for the inner and for the outer layer respectively, as presented in [6,9]. We used a revised estimate of the parameters of the critical surface of the superconductor

$$j_{sc}(B) = c(B^*_{c2} - B), \quad (1)$$

i.e., c=575 A/mm^2 and B^*_{c2}=13.0 T. These values give a critical current density of 2300 A/mm^2 at 9 T and 1.9 K, which is an average of the measured values in FRESCA test station of 2200-2400 A/mm^2 for the outer layer cables [10]. We use the outer layer values since due to the strong grading the magnet performance is limited by the outer layer [9].

We calculated the critical gradient for quadrupole lay-outs with a aperture ranging from 100 to 220 mm. Results are shown in Fig. 4, where they are compared to the scaling law [11] using that values of c and B^*_{c2}. As in the previous works, we assume that the quadrupoles operational current is set at 80% of the loadline, i.e. a 20% operational margin. A parabolic fit is valid in this range (see Fig. 4). For the same aperture, the gradients are ~10% lower than what presented in [6,9].

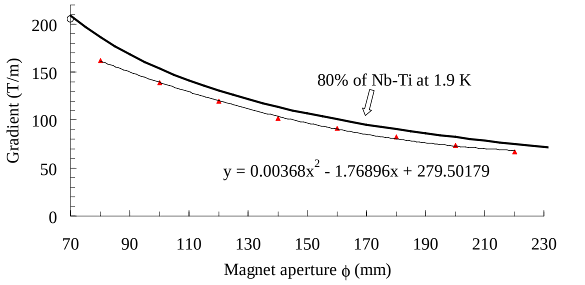

Fig. 4: Quadrupole gradient versus aperture: semi-analytical approach (solid line) and two-layer quadrupoles made with MB cable (markers).

Quadrupole aperture versus triplet length

Putting together Fig. 1 and Fig 4 we obtain in Fig. 7 the largest aperture reachable versus the total quadrupole length. With respect to the previous analysis [6] one obtains, for the same aperture, a ~10% longer total quadrupole length.

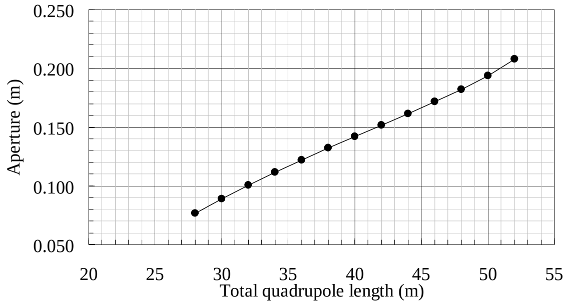

Fig. 7: Aperture of the quadrupole reachable for a matched triplet in Nb-Ti with LHC main dipole cable, two layers, versus triplet length.

Constraints due to the length of the MB cable

Using the estimate of the aperture required for a given triplet length given in Fig. 7, one can compute the cable needed to wind one pole for the longer quadrupoles Q1-Q3. In case of a total quadrupole length of ~41 m, corresponding to an aperture of ~150 mm, one needs a cable length equal to the unit length for the dipoles (see Fig. 8). Beyond these values one has to split each magnet in two cold masses, i.e., go for a modular option [12].

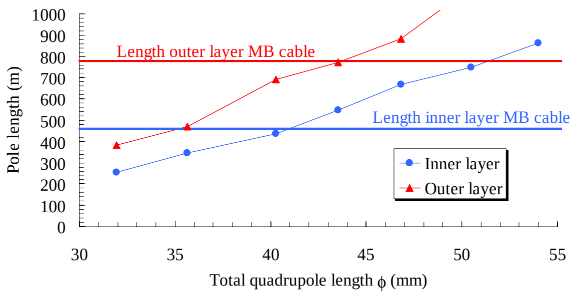

Fig. 8: Needed pole length to wind one pole of the Q1-Q3 magnets, versus triplet length.

Operational current versus triplet length

The operational current is a relevant parameter of the lay-out. Here we present its dependence on the triplet length It ranges between 11 and 9 kA, and decreases with larger apertures and longer triplets.

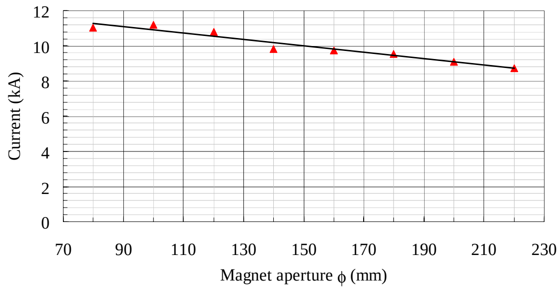

Fig. 9: Operational current in the triplet versus triplet length.

APERTURE CONSTRAINTS

β function

The fit of the maximum beta function in the triplet versus the triplet length is shown in Fig. 9. We use the linear function

$$\beta_{\max} = \frac{l^{*2} + a l_q}{\beta^*} . \tag{4}$$

which holds well on the rather large domain of quadrupole lengths, with a=81 m. Due to the longer gap between Q2a and Q2b the increase of the beta function with respect to [6] is about 5%.

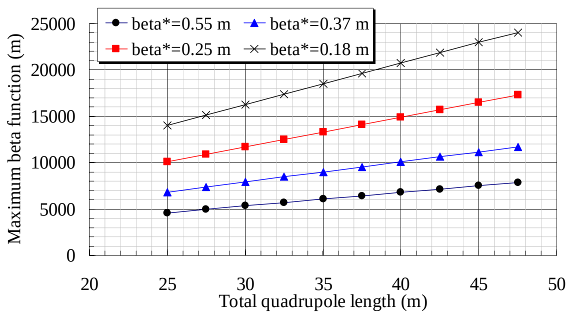

Fig. 10: Maximum beta function versus triplet length.

Aperture requirements

We assume a beam size of 10 sigma and the empirical scaling for the crossing angle with β^* [13], to work out the aperture requirements. In order to have a β^* =0.25 m one needs a total quadrupole length of 34.5 and an aperture of 115 mm (see Fig. 10). An aperture margin of 3 additional σ, which could ease the collimation, can be obtained with a total quadrupole length of 40 m and an aperture of 142 mm (see Fig. 10). This second option is very close to the solution that allows to reach the stronger possible focusing compatible with the chromaticity correction system β^* =0.18 m without margin on the aperture (total quadrupole length of 39.5 m and aperture of 140 mm, see Fig. 11).

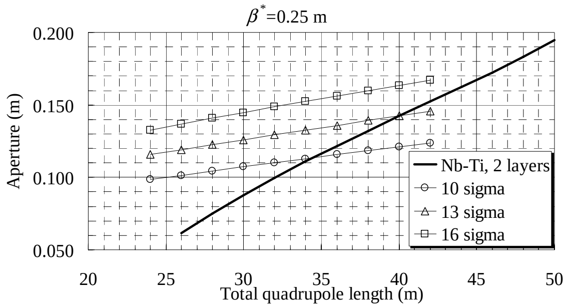

Fig. 11: Aperture requirements for 10, 13 and 16 sigma versus total quadrupole length, β^*=0.25 m.

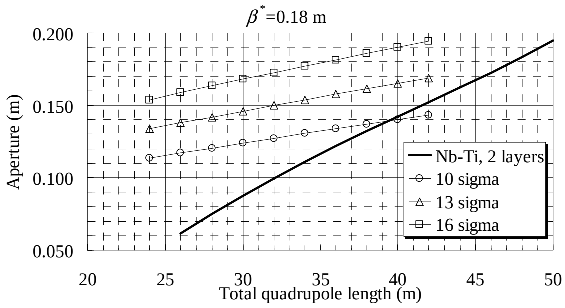

Fig. 12: Aperture requirements for 10, 13 and 16 sigma versus total quadrupole length, β^*=0.18 m.

DISCUSSION

One has two extreme cases: i) a first solution aiming at β^*=0.25 m and no aperture margin, with a total quadrupole length of 34.5 m and aperture of 115 mm, and ii) a second case giving either the largest possible focusing β^*=0.18 m without margin, or the β^*=0.25 m with ~3σ of margin. This second option, with a total quadrupole length of 40 m and aperture of 140 mm, is at the limit of the cable length of the dipoles, i.e. a lay-out with longer quadrupoles should be modular and at least double the number of cold masses. Results are summarized in Table I.

Table I: Quadrupole length, aperture, gradients and maximum beta function at β^*=0.25 m in 2 extreme cases.

l_t	l_1 (m)	l_2 (m)	ϕ (mm)	G (T/m)	β_{max} (Km)
34.6	7.9	9.4	115	125	13.0
40.0	9.0	11.0	140	103	15.0

Margin in aperture is welcome not only for the collimation issues but also to recover performance in case of impossibility of reaching nominal parameters. For example, an emittance blow-up would need a larger aperture with respect to the nominal one to reach the foreseen beam focusing in the IP.

CONCLUSIONS

We updated the parametric analysis carried out in the last years [4,5,6] to find out the solutions for a Nb-Ti triplet made of two layers quadrupole with the LHC main dipole cable. A revised estimate of the cable performances, of the matching conditions, of the gaps in the triplet, and of the aperture clearance needed for the cold bore has been presented. The solution giving the possibility of reaching β^*=0.25 m with here additional sigma for collimation has an aperture of ~140 mm and a quadrupole length of 9/11 m, with respect to previous values of 130 mm, and 8/9 m given in [6].

For the present lay-out, an aperture of ~140 mm appears as a maximum value since i) it corresponds to the maximal length of the available dipole cable and ii) it corresponds to the maximum focusing of 0.18 m without having additional space for collimation. An aperture of ~135 mm would allow to keep basically the same level of performance and would have the advantage of being fully compatible with the large aperture Nb_3Sn quadrupoles foreseen for the LHC Accelerator Research Program [14]. This would keep open the possibility of having a mixed option Nb-Ti and Nb_3Sn for the phase I upgrade, as recently proposed [15].

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