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A Solution for Phase-one Upgrade of the LHC Low-beta Quadrupoles Based on Nb-Ti

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Abstract

We discuss the possibilities of upgrading the LHC triplet quadrupoles by significantly increasing their aperture (and length), using the Nb-Ti cable of the main dipoles. The goal of this first phase in upgrading the triplet is to allow a rapid improvement of the luminosity mostly by removing limitations related to the triplet aperture. Neither the experimental area, including the TAS, nor the basic optics are modified. By the same token, steps are made to allow a moderate increase of the luminosity within the capabilities of the existing detectors. The triplet aperture is sized to decrease the collimator impedance below significance, allow a potential increase of the luminosity by some 50% or up to a factor of 2 with an external ancillary system acting on the geometrical loss factor. Some extra aperture is foreseen to lower the power deposition, to improve field quality and/or to allow a stronger focusing in the event some baseline beam parameters would not be reached. In this way, the proposed phase-one upgrade is versatile and should allow improved performance in a large range of situations.

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1. CONCEPTS AND GOALS FOR A PHASE-ONE UPGRADE

In this paper we study the possibility of developing a first upgrade of the LHC insertion quadrupoles with the main goal of facilitating the rate of increase of the machine performance. To fulfil this goal, the required quadrupole aperture is re-assessed in the light of the present knowledge and largely increased. The same goal defines a set of boundary conditions:

- no modifications of the detectors nor of the detector regions, including the TAS,
- minimum changes in the separation-recombination section (no modification to the D2 magnet)
- use of the well-established Nb-Ti technology and recycling a fraction of the spare LHC dipole superconducting cables.
- no increased complexity of beam optics or dynamics: Q' and Q'' shall be correctable and the geometric aberrations comparable to the baseline, except in extreme cases.

Additional requirements for this second generation quadrupoles are taken into account to maximize its yield: the ultimate limit to this phase-one upgrade is the maximum luminosity that can be tolerated by the present detectors, which can be estimated to be around a factor two above the nominal one [1], i.e., the so-called ultimate luminosity [2]. Enough flexibility should be provided to face not reaching some nominal beam parameters.

A second phase of the upgrade distinct from this study aims at a large luminosity increase by a factor ~ 10 with respect to nominal, an upgrade of the detectors, and the possible use of Nb₃Sn technology that according to the present studies [3] would be able to better withstand the increased energy deposition.

The possibility of increasing the luminosity reach of the existing low-beta triplet quadrupoles using the Nb-Ti technology has been first proposed in Ref. [4], and further developed in [5], with insertion optics using quadrupole apertures ranging from 60 mm to 95 mm. Solutions with extremely large aperture quadrupoles (up to 250 mm) and a reduced peak field have been proposed in [6]. In order to provide a global view of the design options, parametric studies were carried out for the full LHC luminosity upgrade [7,8]. Three important outcomes allow revisiting a phase-one upgrade based on the same Nb-Ti quadrupole technology: i) the quadrupole aperture is the most sensitive parameter for luminosity improvement [7] and calls for significantly larger apertures, ii) these very large apertures with high peak field appear technically possible and with acceptable mechanical forces [8], and iii) the lengthening of the triplet required to keep the required focusing does not give major drawbacks [8].

Recently it has been pointed out [9] that a larger aperture triplet with a constant beam size would reduce the collimator impedance, which presently limits the beam intensity to 40% of the nominal one [10]. Since then, a quantitative estimate of the required collimator gap increase has been carried out [11], showing that it is not outrageous: it amounts to a clearance of ~ 3 additional σ of the beam size (radius) to be provided in the triplet. This clearance would solve one of the important limitations of the collimation phase 1. In addition to these 6 σ aperture increase for collimation, the basic aperture criterion used in [4] was reviewed to better fit the present knowledge of requirements with an additional increase of 4 σ , giving altogether an increase by 10 σ .

The strategy followed to derive an optimal quadrupole aperture stems from the following goals:

- Satisfy the updated aperture requirements, including collimation.
- Combine them with the requirement to have a stronger focusing in the interaction point (IP) up to $\beta^*=0.25$ m to increase the luminosity by $\sim 50\%$ without increasing the beam current. Stronger focusing options become less and less effective due to the increase of the crossing angle; moreover we will show that a focusing below $\beta^*=0.20$ m goes beyond the capabilities of correcting the linear chromaticity with the present hardware (see Section 4.6 and Appendix D). In case of an available ancillary system minimizing the adverse consequence of the crossing angle, such as crab cavities, $\beta^*=0.25$ m would give up to a factor 2.5 in luminosity (see Section 4.8), reaching the maximum tolerable for the detectors.
- Offer a versatile solution to recover from situations where the nominal beam parameters cannot be met, such as
 - recovery from an emittance blow up by 30% during injection and ramp;
 - partial recovery from a bunch current limitation to 75% of nominal;
 - reduction of the power deposition in the triplet quadrupoles if necessary;
 - reduction of the geometric aberrations if necessary.

A novel aspect of this study is the estimate of the expected aberrations. In Ref. [6] it has been pointed out that large beta functions in the quadrupoles can give an insufficient dynamic aperture. Using the concepts developed in [8,12], we show that the presented solution has at $\beta^*=0.25$ m the same level of first-order aberrations as the nominal lay-out at $\beta^*=0.55$ m. This is possible since the quadrupole aperture is not totally filled by the beam, but some space is left for collimation.

While there can be unexpected limitations, it may turn out as well that the bunch current can be increased moderately above nominal with a corresponding increase in luminosity. The increased aperture allows then a reduction of the power deposition to close to its present value.

In the following sections, we first identify an aperture that should fulfill the goals (section 2), propose quadrupole parameters based on a detailed evaluation of the technology (section 3) and finally present the method that may be used to further evaluate the chosen solution or possibly identify alternate ones (section 4). Technical details such as insertion lay-out, superconductor performances, quadrupole design, chromaticity correction and impact on nonlinearities are given in the Appendix.

2. AN OVERVIEW OF THE PARAMETER SPACE

Table 1 shows the demand on quadrupole aperture with the above-mentioned goals. In all cases, the first and second-order chromaticity can be corrected without constraints on the betatron phase distribution around the rings. The scenarios are taken from the former section. Scenarios 2 and 3 give the aperture increase to reduce the impedance ($+3\sigma$, without/with a safety margin) in the present baseline. Scenarios 4 to 6 aim at using the aperture to improve performance, with an optional reduction of the power deposition. It should be noted that scenario 4 yields twice the nominal luminosity if a crab crossing would be provided in addition. Scenarios 7 and 8 show the possible recovery in case of blow-up or current limitation. Scenario 9 gives the luminosity allowed by increasing of the beam current according to the present estimates of the SPS limits.

Table I: Scenarios for upgrade.

Scenario	Collimator clearance	Luminosity	Quad. aperture	Quad. length (average)	Peak power deposition	β^*
	[σ]	10^{34} [$\text{cm}^{-2} \text{s}^{-1}$]	[mm]	[m]	[adim]	[m]
1. Baseline	0	1.00	70	5.9	1.00	0.55
2. Collimation clearance	3	1.00	80	6.3	0.88	0.55
3. Collimation clearance+safety	6	1.00	90	7	0.77	0.55
4. Lower β^*	4	1.35	115	8.2	1.70	0.32
5. Reduce energy deposition with aperture	6	1.35	125	8.9	1.50	0.32
6. Further reduce energy deposition	8	1.24	125	8.9	1.20	0.38
7. If beam blow up by 15%	4	1.00	125	8.9	1.30	0.35
8. If bunch charge limited to 75%	3	0.87	125	8.9	1.25	0.24
9. If current increased to max SPS	3	1.86	125	8.9	2.75	0.25

3 PROPOSAL FOR A NEW TRIPLET

We propose to build a triplet of ~ 34 m magnetic length (~ 40 m with gaps) with 130 mm aperture and 123 T/m operational gradient (80% of the quench level), based on the Nb-Ti cables used in the LHC dipoles [13]. The length of Q1 and Q3 is 9.2 m and Q2 is made up of two 7.8 m long modules. This corresponds to increase the triplet length of the present baseline by 10 m, and involves an upgrade of D1 (see Appendix A). This proposal would allow reaching $\beta^*=0.25$ m (+50% in luminosity), with 3 σ for the collimator gap, and a $\beta_{\text{max}}\sim 13000$ m. The ultimate limit to the beam focusing in the IP would be $\beta^*=0.20$ m (+60% in luminosity), i.e. the minimal allowed for the linear chromaticity correction of two strongly focused IP, with a $\beta_{\text{max}}\sim 16000$ m. Please note that in this extreme case the second order chromaticity correction with lattice sextupoles would not be possible, and should be made via a phasing of the IP [12]. Moreover, one would only have one additional σ for the collimation. In the following section we present the methodology used to make this proposal, based on an extension of the work given in [7,8].

A second option would be to build quadrupoles of the same length, and different operational gradients. Keeping the same goals of the previous paragraph, one would need a triplet of four 9.5 m long quadrupoles, i.e. a 4 m longer triplet, and similar aperture (see Appendix E). A detailed analysis of costs will allow to choose between these options.

In both cases, these very large aperture quadrupoles have a beneficial effect on the beam dynamics. In Appendix F we show that a 130 mm aperture would allow to keep the nonlinearities in case of a $\beta^*=0.25$ m very close (within 30%) to the baseline values at $\beta^*=0.55$ m. On the other hand, a 90 mm aperture triplet at $\beta^*=0.25$ m would have significantly higher nonlinearities. A tracking of the optics with the expected field errors is needed to confirm the results of these scaling laws.

4 FLOWCHART FOR DETERMINING INSERTION PARAMETERS

4.1 Triplet lay-out

We consider a triplet whose structure is similar to the LHC baseline [2] (see Fig. 1). The total length l_q of the quadrupoles is taken as a free parameter. Using this choice, one can derive analytically or semi-analytically all the relevant quantities (length of each quadrupole, beta functions, quadrupole aperture, gradients, chromaticity) as a function l_q , that will be varied

from its nominal value of 24 m to ~40 m. The additional space for the longer triplet can be recovered by moving D1 further away from the IP (see Appendix A). Both l_1 (the length of Q1 and Q3), and l_2 (the length of Q2) will be varied in our analysis. We assume that Q1, Q2 and Q3 have the same gradient. The total length of the quadrupoles l_q and the triplet length l_t are given by

$$l_q = 2(l_1 + l_2) \quad l_t = l_q + g \quad (1)$$

where g is the gap between the quadrupoles, fixed to the actual values for the LHC baseline $g=6.6$ m. We fix the distance l^* of the triplet to the IP to the baseline value of 23 m. In the nominal LHC lay-out one has $l_1=6.37$ m, $l_2=5.50$ m, $l_q=23.74$ m and $l_t=30.34$ m.

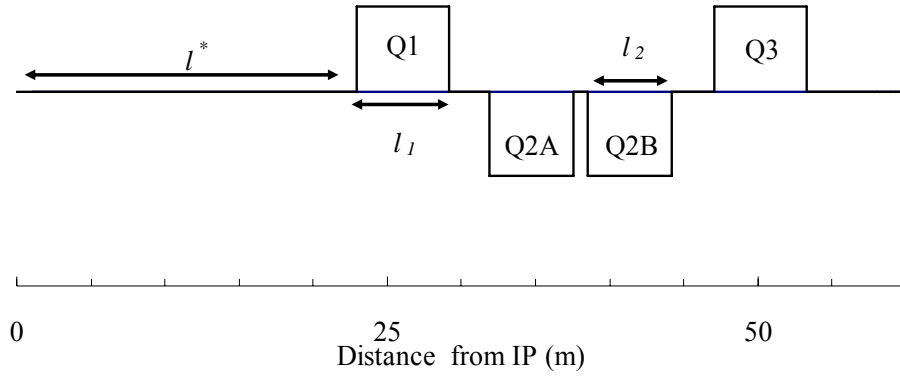


Fig. 1: Lay-out of the triplet close to the IP, nominal case of the LHC.

4.2 Relative length of Q1-Q3 and Q2

Given a total quadrupole length l_q , the relative length of Q1-Q3 and Q2 is obtained by imposing equal values for the beta functions in the transverse planes x and y . Results based on numerical simulations of the thick lens optics are given in Fig. 2 [8].

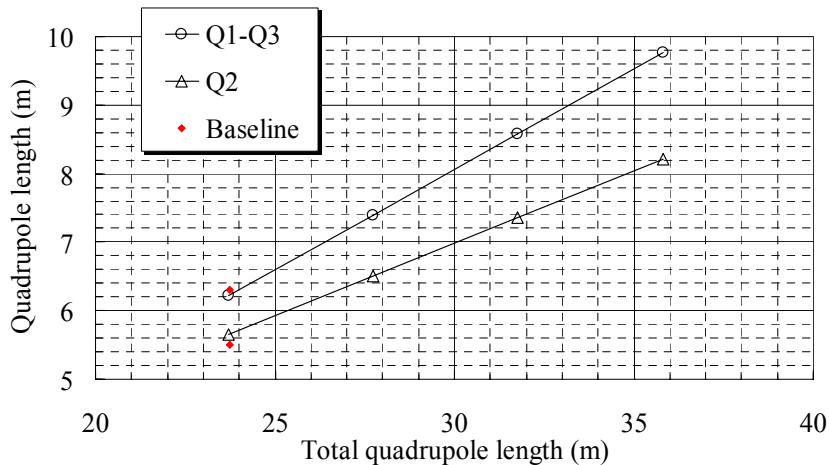


Fig. 2: Length of Q1-Q3 and Q2 versus total quadrupole length.

4.3 Quadrupole gradient

Given a total quadrupole length l_q , and having fixed the lengths of Q1-Q3 and Q2 according to the previous rule, the quadrupole gradient is determined by requiring that the beta

functions (their values and their derivatives) in Q4 are close to the baseline values. We carried out simulations for a β^* of 25 cm. The dependence of the gradient on β^* is weak and is neglected in this analysis. Based on the evaluation of four cases, we propose the following fit (see Fig. 3)

$$G = \frac{1}{fl_q^2 + hl_q} \quad (2)$$

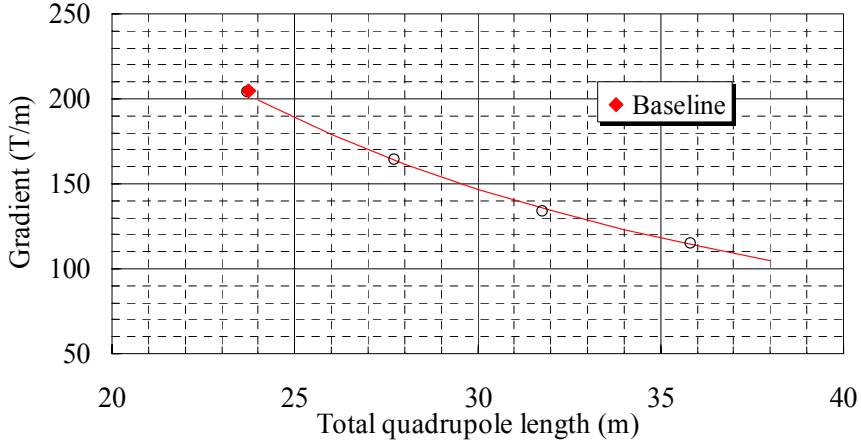


Fig. 3: Gradient versus total quadrupole length.

with $f=2.98 \times 10^{-6}$ ($T^{-1}m^{-1}$) and $h=1.38 \times 10^{-4}$ (T^{-1}). The integrated gradient modulus $|G/l_q$ decreases for increasing quadrupole length (see Fig. 4), since the triplet barycentre is moving away from the IP.

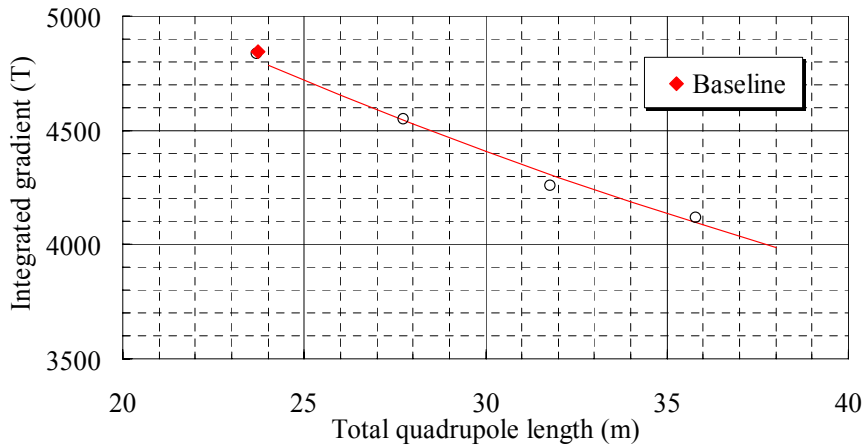


Fig. 4: Integrated gradient versus total quadrupole length.

4.4 Quadrupole aperture

The requirements on the gradient determine the quadrupole aperture for a given superconducting material. Using the Nb-Ti cable of the LHC dipole (cable01 for the inner layer and cable02 for the outer layer) we draw coil cross-sections of quadrupoles with 100, 120 and 140 mm aperture (two layers lay-out). With respect to [5], we extended the analysis to apertures larger than 110 mm, and we used the measured values of the cable critical currents

[13] during the LHC production (see Appendix B). The quadrupole lay-outs are presented in Appendix C. The data relative to 80% of the loadline are presented in Fig. 5. They can be fit with a quadratic form

$$G_c \approx \lambda_0 + \lambda_1\phi + \lambda_2\phi^2 \quad (3)$$

The values of the coefficients for the two layer case are given in Table II. The fit is valid for apertures between 100 and 140 mm. Please note that the aperture is expressed in meters.

Putting together (2) and (3), one can give the maximal aperture obtainable for a given total quadrupole length (see Fig. 6). An aperture of 100 mm can be reached with a total quadrupole length of 28 m, or a 130 mm aperture with a length of 34 m (two layers quadrupoles). The same aperture can be obtained with a one layer quadrupole (i.e., half of the cable) with about 15% longer lengths.

Table II: Coefficients of Eq. (3) for the gradient as a function of the aperture for Nb-Ti and Nb₃Sn, for apertures between 100 and 140 mm, two-layer lay-out.

λ_0	λ_1	λ_2
(T/m)	(T/m ²)	(T/m ³)
351	-2480	5500

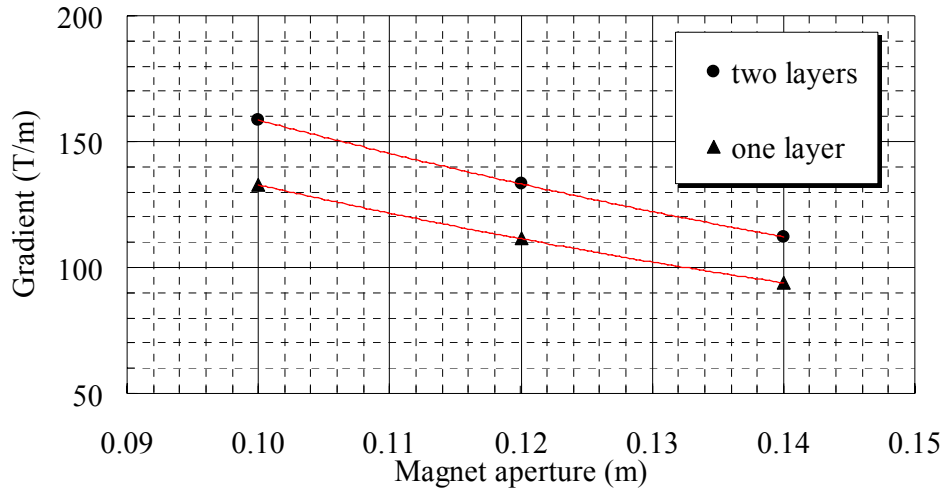


Fig. 5: Gradient versus magnet aperture (80% of the loadline) for two-layer and one-layer quadrupoles made with LHC dipole cables (markers) and parabolic fit for the two-layers (solid line).

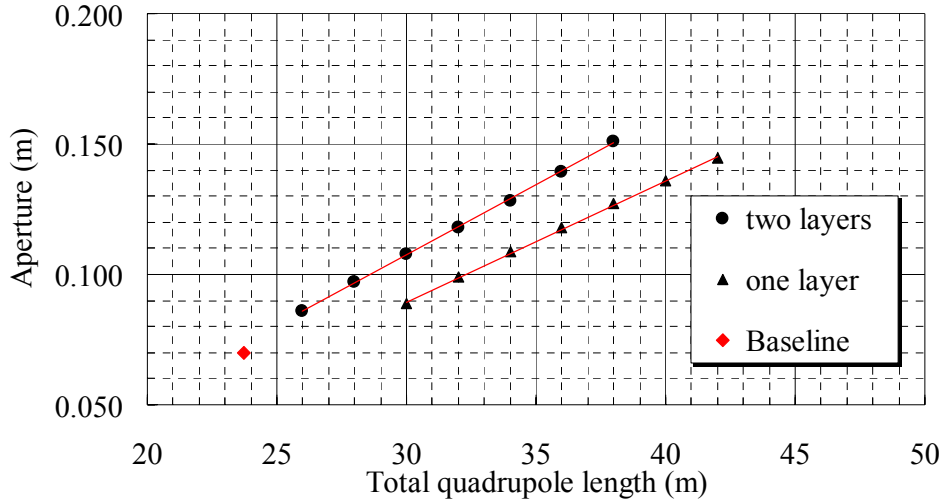


Fig. 6: Maximum aperture obtainable in a Nb-Ti triplet versus total quadrupole length.

4.5 Maximum β functions in the triplet

The total quadrupole length and the β function in the IP determine the β function in the triplet. Simulations [8] show that for the analysed lay-out the maximum β function can be fit by

$$\beta_{\max} = \frac{l^{*2} + al_q}{\beta^*} \quad (4)$$

where the constant $a \sim 77.5$ m. This is valid for quadrupole lengths between 25 and 40 m, and ratios between quadrupole lengths fixed according to the rules described in the previous section. The dependence of the maximum β function on the total quadrupole length and on the β function in the IP is shown in Fig. 7.

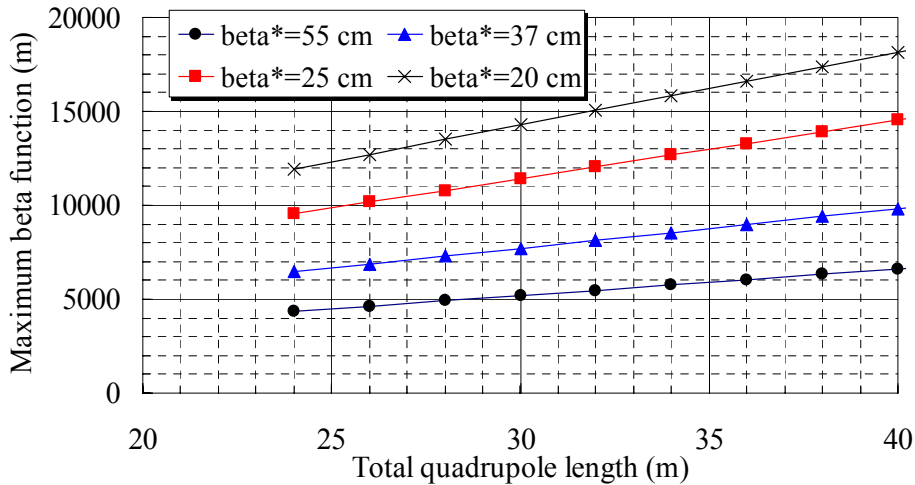


Fig. 7: Maximum β function in the triplet versus triplet length and β^* .

4.6 Linear chromaticity correction

The total quadrupole length and the β function in the IP determine the linear chromaticity given by the triplet. The linear chromaticity is proportional to the inverse of β^* . Numerical

simulations show that it weakly depends on the total length of the quadrupoles (see Fig. 8). The budget for the chromaticity correction is limited by the strength of the lattice sextupoles [14]. In the case of collision, with one insertion at $\beta^*=0.5$ m and one at $\beta^*=1$ m, a budget of $Q'=180$ is left for the two low- β insertions of IP1 and IP5, i.e. $Q'=90$ per insertion (see Appendix D). The linear chromaticity correction is possible up to a β^* of ~ 0.18 - 0.20 m for the analysed quadrupole lengths. This lower limit cannot be reached if one corrects the second order chromaticity Q'' with lattice sextupoles, as in the baseline. An alternative scheme is based on acting on the phase between the interaction points [14]. This correction corresponds to using only two families to push the correction of Q' to its maximum, and leaving the correction of Q'' to a careful phasing of the IP.

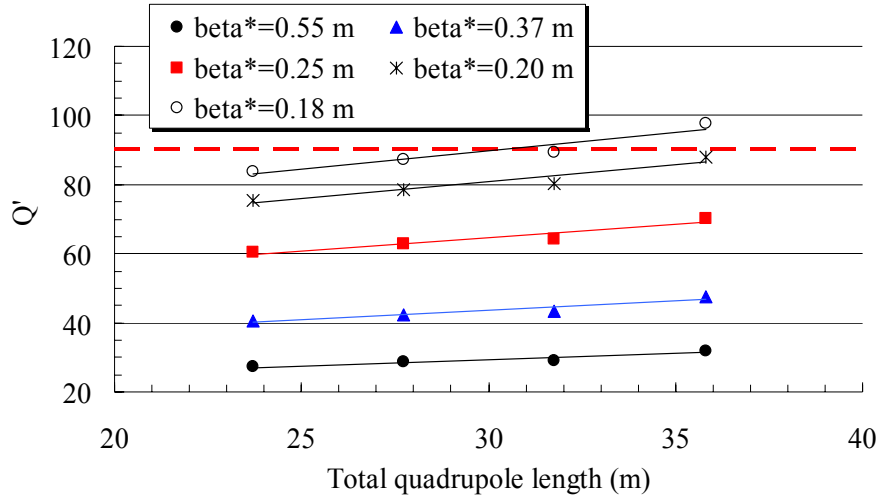


Fig. 8: Linear chromaticity per IP versus total quadrupole length and β^* (markers), and budget for correction (dashed line).

4.7 Minimum β in the interaction point

The quadrupole aperture and lengths determine the minimum β^* that can be reached in the IP. The requirement for the triplet aperture is

$$\phi = \kappa_\beta(d + 2\rho) + 2(A + B + C + D) \quad (5)$$

where d is the separation between the beams, ρ is the radius of the beam, κ_β the beta beating, and the last four terms are given by alignment tolerances (A), beam screen clearance (B), closed orbit (C), and dispersion (D).

All distances are given in meters. The beam radius is taken at 10 sigma

$$\rho = 10\chi\sigma = 10\chi\sqrt{\frac{\varepsilon_n\beta_{\max}}{\gamma}} \quad (6)$$

where ε_n is the normalized beam emittance ($\varepsilon_n=3.75$ m μ rad), γ is the relativistic factor ($\gamma=7461$ at 7 TeV), and $\chi=1$. Taking $\chi=1.3$ or $\chi=1.6$, i.e. 13 or 16 sigmas for the beam size, one can prove that the limits induced by the impedance of the collimation system can be removed [10,11]. The expression for the aperture can be rewritten to explicit the dependence on the beta functions

$$\phi = \phi_0 + \chi\phi_1\sqrt{\beta_{\max}} + \phi_2 \frac{l^* + l_t}{\sqrt{\beta^*}} + \phi_3 \frac{(l^* + l_t)^{3/2}}{\sqrt{\beta^*}} \sqrt{N_b k_b} . \quad (7)$$

We recall that the triplet length l_t is the quadrupole length l_q plus the gap g (see Eq. 1). The values of the coefficients are given in Table III. All lengths are given in meters. Please note that the dependence on the beam current is very small: doubling the beam current requires only 2 mm more of quadrupole aperture in the present baseline. The intersection of the aperture requirements with the performances of the Nb-Ti quadrupoles are shown in Figs. 9-12 for decreasing values of β^* . To reach $\beta^*=0.25$ m one can have 100 mm aperture quadrupoles of 29 m total length (without additional space for improving collimation), or 130 mm aperture quadrupoles of 34 m total length (with three additional sigma for collimation).

Table III: Coefficients of Eq. (7) for the quadrupole aperture, and contributions in the nominal case.

Coefficient		Contribution	
		(mm)	(%)
ϕ_0	0.018	17.8	25
ϕ_1	0.00054	36.1	51
ϕ_2	1.59E-04	11.9	17
ϕ_3	5.49E-13	5.5	8
Total		71.3	100

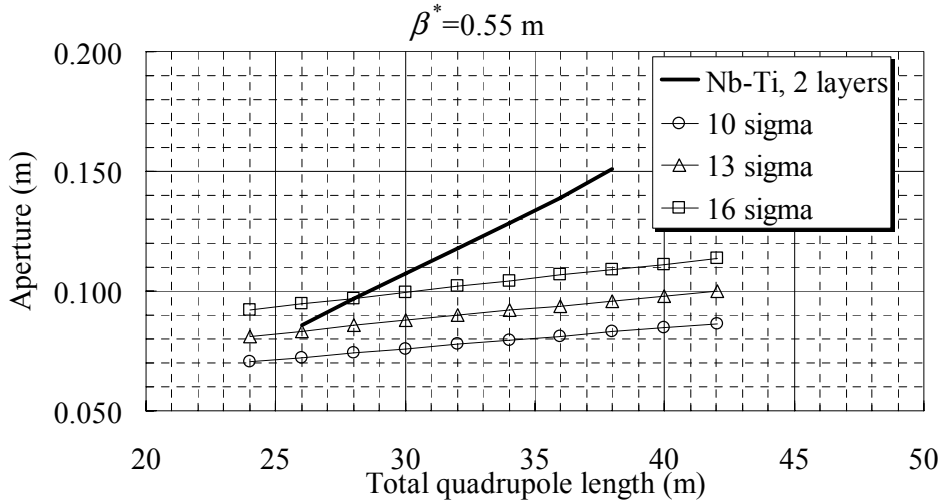


Fig. 9: Aperture requirements for $\beta^*=0.55$ m with different collimation factors and aperture provided by two-layers Nb-Ti quadrupoles versus total quadrupole length.

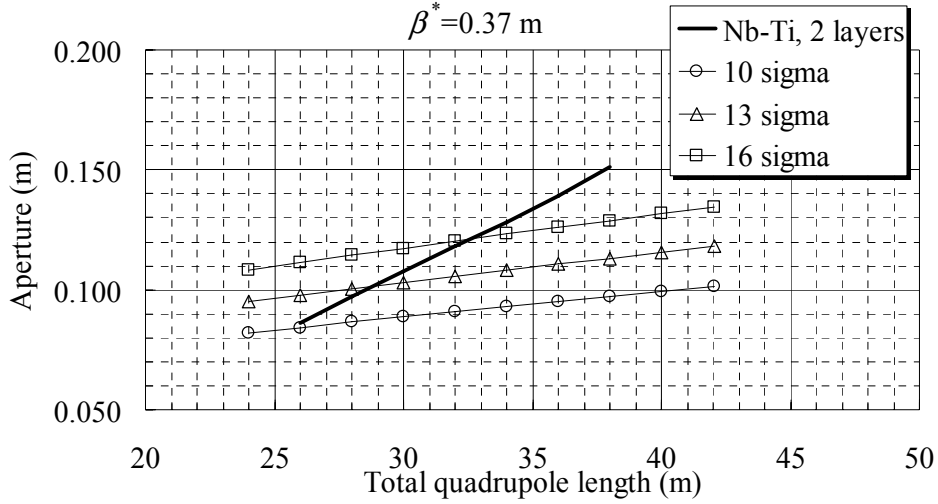


Fig. 10: Aperture requirements for $\beta^*=0.37$ m with different collimation factors and aperture provided by two-layers Nb-Ti quadrupoles versus total quadrupole length.

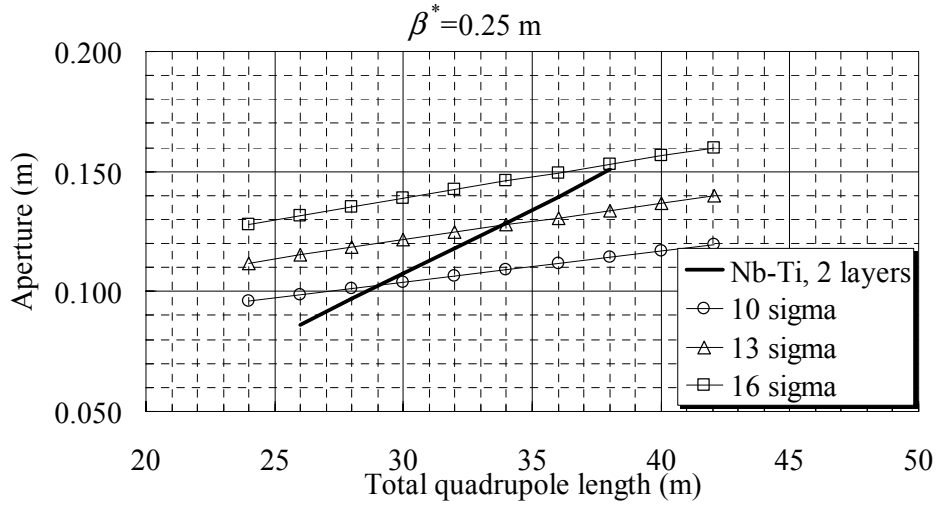


Fig. 11: Aperture requirements for $\beta^*=0.25$ m with different collimation factors and aperture provided by two-layers Nb-Ti quadrupoles versus total quadrupole length.

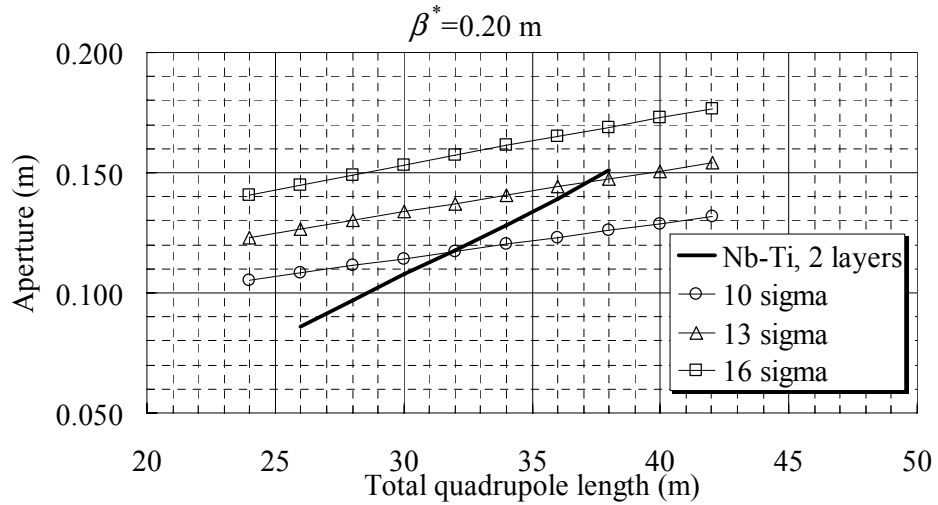


Fig. 12: Aperture requirements for $\beta^*=0.20$ m with different collimation factors and aperture provided by two-layers Nb-Ti quadrupoles versus total quadrupole length.

4.8 Relation between β^* and luminosity

The dependence of the luminosity on β^* is given by the following equation

$$L \propto \frac{F(\beta^*)}{\beta^*} = \frac{1}{\beta^*} \frac{1}{\sqrt{1 + \left(\frac{\theta(\beta^*)\sigma_s}{\sigma(\beta^*)} \right)^2}} \quad (8)$$

where θ is the crossing angle, σ_s is the longitudinal beam size, and $\sigma(\beta^*)$ is the transverse beam size in the IP. Here we do not consider the hourglass effect that is negligible in this range of parameters. The geometric reduction factor F contains a dependence on β^* in the crossing angle and in the beam size. The first one is estimated according to the scaling derived in [15], with $\delta=0.65$

$$\theta = \theta_0 \sqrt{\frac{\beta_0^*}{\beta^*}} \left[\delta + (1-\delta) \sqrt{\frac{l^* + l_t}{l_0^* + l_{t0}}} \sqrt{\frac{N_b k_b}{N_{b0} k_{b0}}} \right], \quad (9)$$

where one finds a dependence on the triplet length. The dependence on the transverse beam size at IP is simple

$$\sigma = \sqrt{\frac{\varepsilon_n \beta^*}{\gamma}} \quad (10)$$

The improvement of luminosity versus β^* is shown in Fig. 13. Setting β^* to 0.25 m (with the same triplet length) gives an improvement of 51% with respect to the baseline. The dependence on the triplet length is small: the same $\beta^*=0.25$ m with a 15 m longer triplet would give a 47% improvement.

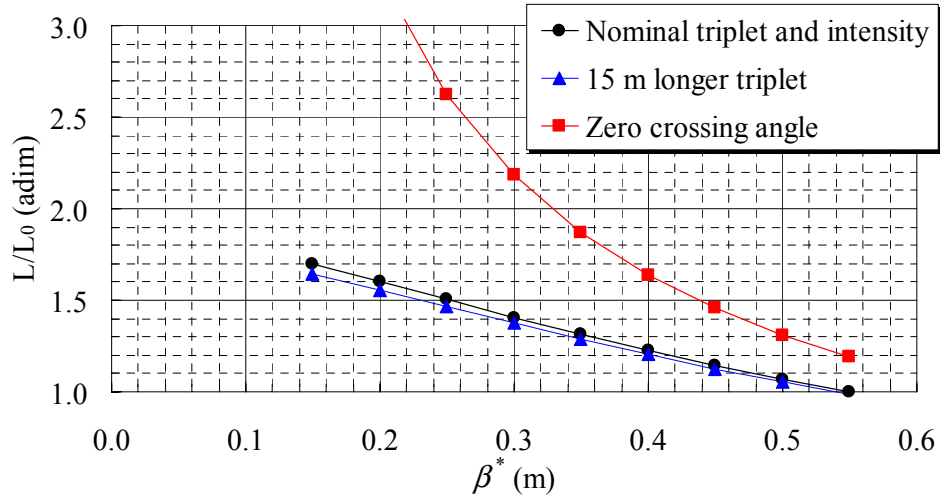


Fig. 13: Gain in luminosity versus β^* for the nominal case, for a triplet 15 m longer and for a half beam intensity.

7. CONCLUSIONS

A versatile Nb-Ti insertion using the dipole superconducting cable can be designed for a phase-one upgrade. The aperture (around 130 mm) is significantly increased with respect to

former proposals. It allows facing the present challenges with a provision for a moderate luminosity increase and most likely a significantly simplified machine operation. It does not seem a priori to raise technological issues. The longer triplet (+10 m) implies some upgrade of the D1 magnets, leaving the rest of the matching section possibly unchanged. We gave explicit equations for the semi-analytical model of the calculation and we produced plots to easily investigate variants or trends. This parametric study points to a solution that shall deserve a detailed analysis.

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APPENDIX A: TRIPLET LENGTH CONSTRAINTS

In the present baseline (see Fig. 14), the triplet is between 23.0 m and 53.3 m from the IP. Between 59.6 m and 84.4 m one has the module of the six separation warm dipoles D1, each providing up to 1.28 T over a length of 3.4 m. The space between Q3 and D1 is around 6 m, covered by 3 m of collimator, plus some correctors and kickers. Therefore, a longer triplet

implies a shift of the D1 position. D2 is a superconducting double aperture magnet providing up to 3.8 T over 9.45 m length.

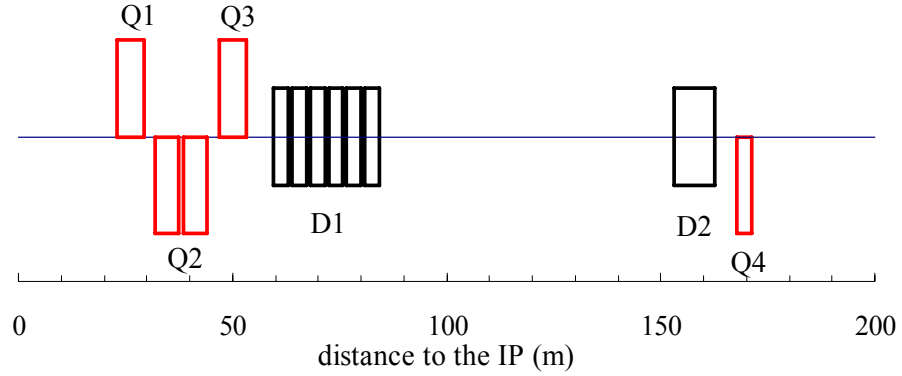


Fig. 14: Nominal lay-out of the separation dipoles

We estimate the D1 or D2 dipole kick as ~ 1.1 mrad (194 mm separation over the distance between D1 and D2 baricentre of ~ 86 m), i.e. 26 Tm at 7 TeV. This corresponds to having D1 powered at the nominal value of 1.28 T. The warm magnets have a margin of 18%. On the other hand, the maximal force of D2 is ~ 36 Tm; using this margin one could reduce distance between D2 and D1 baricentre to 63 m, thus adding ~ 23 m of space for the triplet. This would imply upgrading the D1 dipoles to get the corresponding kick. An increase of the D1 kick to 36 Tm is within the reach of both warm and cold magnets technology.

The aperture issue should be further analyzed. If the D1 aperture is proved to be sufficient at $\beta^* \sim 0.20-0.25$ m, one could envisage to simply shift the D1 of the maximum allowed by their maximal force, i.e. 18% of 86 m, thus giving 15 additional meters available for the triplet.

If needed, stronger magnets could be used to further increase the space available for the triplet. Using a 10 m separation dipole of 8 T, the space needed between the beginning of D1 and the end of D2 would be of 40 m, i.e. one would save 60 m with respect to the present baseline. Therefore, even a 90 m long triplet would find space with an appropriate upgrade of D1 and D2. In all cases, the separation kick would be kept at levels that are anyway much lower than what provided by a single dipole in the arcs (120 Tm). Using this option, it should be verified if the replacement of D1 with a superconducting magnet is compatible with the energy deposition.

APPENDIX B. CABLE PROPERTIES

The critical current of the cable is fit by the following equation

$$I_c = (C_1 + C_2 B) \left(1 - \frac{T}{9.2} \left(1 - \frac{B}{14.5} \right)^{-0.59} \right). \quad (11)$$

The constants C_1 and C_2 specified for the LHC cables [13] are given in Table IV.

Table IV: Specified coefficients of Eq. (11) for the critical current, and features of the LHC main dipole cables.

Cable	C1 (A)	C2 (A/T)	strand diam. (mm)	n strands (adim)	Cu/sc (adim)
01	92074	-6865	1.025	28	1.65
02	65822	-5043	0.825	36	1.95

Codes for evaluating the magnet design are usually based on a linear fit of the critical surface of the current density in the superconductor.

$$j_c = c(B - B_{c2}^*) \quad (12)$$

The agreement between the fit (11) and (12) for the specified values of the cables is given in Fig. 15.

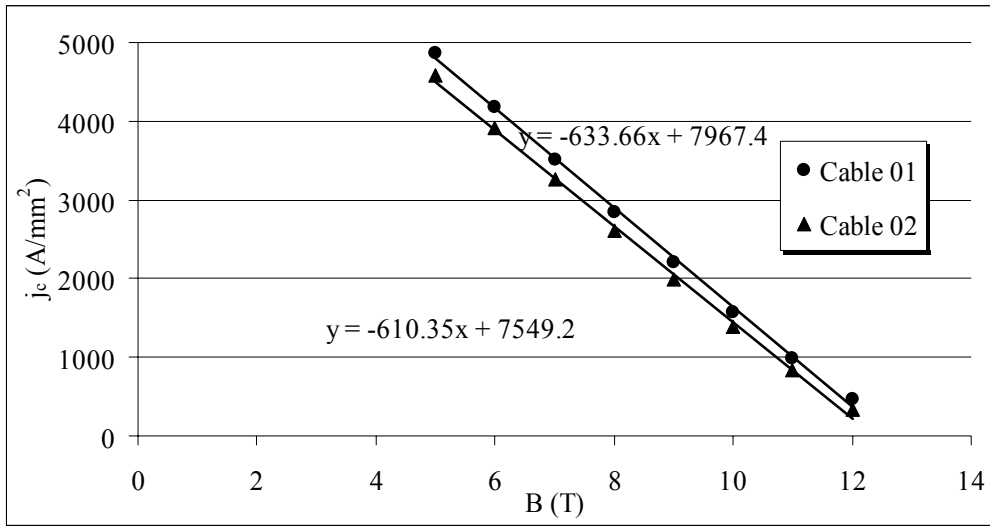


Fig. 15: Critical surface of Nb-Ti cables: specified values according Eq. (11) and linear fit (12).

Critical current measurements are carried out at 4.22 K, and at 7 T for the cable01, and 6 T for the cable 02. The values of the critical current corresponding to the specifications are given in Table V. The actual production of the cables managed to obtain 5% to 10% higher values for the critical current (see Ref. [13]). We assume values of 15000 A for the cable 01, and 14500 A for the cable 02 (see Fig. 16 and 17). The corresponding values for the linear fit of the critical surface are given in Table VI. One obtains for the slope c values of 670 A mm²/T, i.e., around 10% larger than the value of 600 which is commonly used. The B_{c2}^* values are around 13.5 T, 4% larger than the standard value of 13 T.

Table V: Measured versus specified values for the cable critical current

Cable	I (A)		
	Specified	Measured	Gain
01	14214	15000	1.06
02	13198	14500	1.10

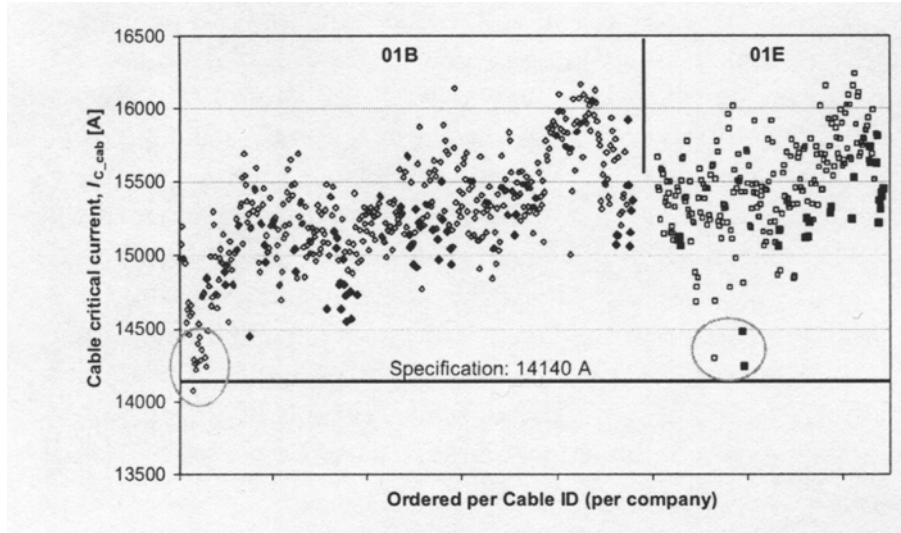


Fig. 16: Measured values of critical current in Cable01, from Ref. [13].

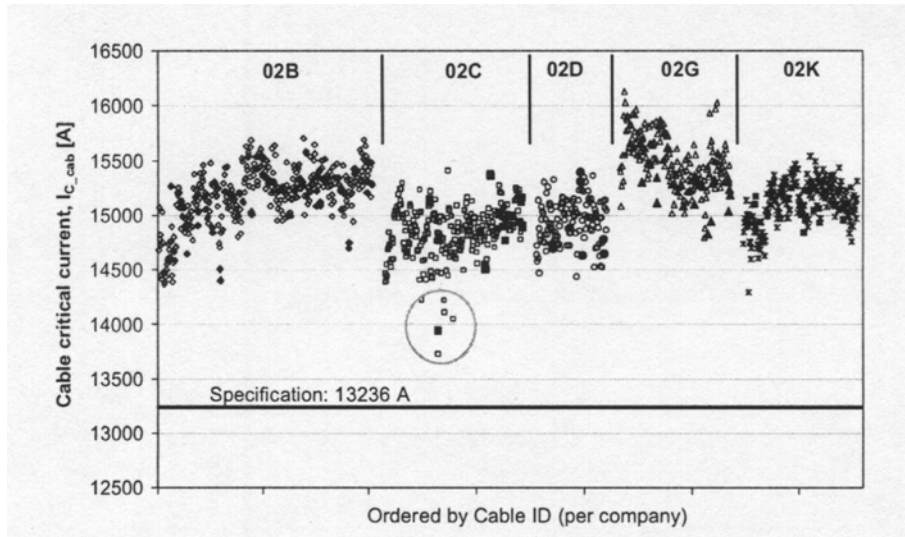


Fig. 17: Measured values of critical current in Cable02, from Ref. [13].

Table VI: Estimate of the coefficients of the linear fit (12) of the Nb-Ti critical surface based on specifications and measurements

Cable	c (A mm ² /T)		B _{c2} [*] (T)	
	Specified	Measured	Specified	Measured
01	634	669	12.6	13.3
02	610	671	12.4	13.6

APPENDIX C. QUADRUPOLE LAY-OUTS

C.1 Maximal gradient

In Ref. [16] we gave an estimate of the critical gradient that can be obtained in a sector quadrupole using a superconductor with a linear critical surface characterized by c and B_{c2}^* (see Eq. 12)

$$G_c = \frac{B_{c2}^* \kappa \gamma_0 \log\left(1 + \frac{2w_{eq}}{\phi}\right)}{1 + \kappa \gamma_0 \left(a_{-1} \frac{2w_{eq}}{\phi} + 1 + a_1 \frac{\phi}{2w_{eq}} \right) \frac{\phi}{2} \log\left(1 + \frac{2w_{eq}}{\phi}\right)} \quad (13)$$

Here ϕ is the aperture diameter (m), w_{eq} the equivalent coil width (m) defined as

$$w_{eq} \equiv \left(\sqrt{1 + \frac{3A}{2\pi r^2}} - 1 \right) \frac{\phi}{2} \quad (14)$$

where A is the coil surface (m²). The filling ratio is defined as

$$\kappa = \kappa_{w-c} \kappa_{c-i} \frac{1}{1 + \nu_{Cu-sc}} \quad (15)$$

where κ_{w-c} is the ratio between the area of the strands in the conductor and the area of the bare conductor, and κ_{c-i} is the ratio between the area of the bare conductor and of the insulated conductor. One has $\gamma_0 = 0.663 \times 10^{-6}$ [Tm/A], and $a_{-1} = 0.042$, $a_1 = 0.113$. This equation gives the critical gradient as a function of the aperture for a lay-out without grading, and no iron. The maximal gradient is reached for values of the coil width close to the aperture radius $w_{eq} \sim \phi/2$.

C.2 Lay-outs with LHC main dipole cable

We considered three quadrupole apertures of 100, 120 and 140 mm. In each case, we designed a cross-section lay-out with two layers, the inner one with the cable01 and the outer one with the cable02. This gives a grading in the coil. The iron has been placed at 25 mm from the outer layer. The coil width of 30 mm gives gradients which are rather close to the maximum value that can be obtained by a coil with an ideal width (i.e., 50 to 70 mm). Results are given in Fig. 18, where the 80% of the gradients are given as operational values. Please note that, due to the strong grading, in all cases the quench limit is reached on the outer layer.

We also give the results relative to cases with one layer: in this case only half of the conductor is used, and the gradient is about 18-19% lower. A third layer would not significantly increase the gradient: for the 140 mm case, one would get 3% more, and for smaller apertures case the gain is smaller. For comparison we also plot the values of Ref. [5] obtained with MQY and MB cables in 90, 100 and 110 mm apertures. All the two-layer lay-outs have been optimized for having b_6 and b_{10} smaller than 1 unit at a reference radius of 1/3 of the aperture. Please note that the same reference radius of 17 mm as used for the LHC arc is less significant due to the larger aperture. The coil lay-outs are given in Figs. 19-21.

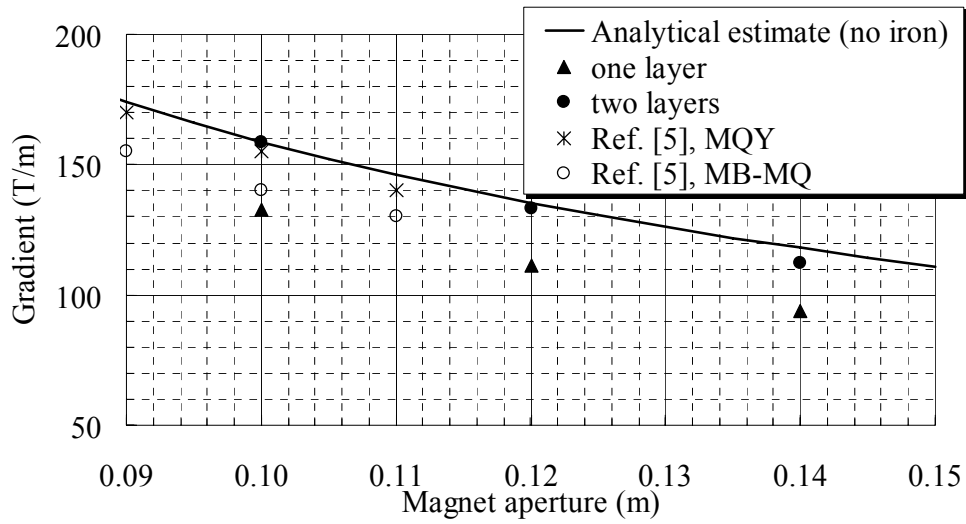


Fig. 18: Quadrupole gradient versus aperture obtained with one and two layers design with cable01 and cable 02 (markers), at 80% of the loadline, analytical estimate of the maximum gradient, and data of Ref. [5].

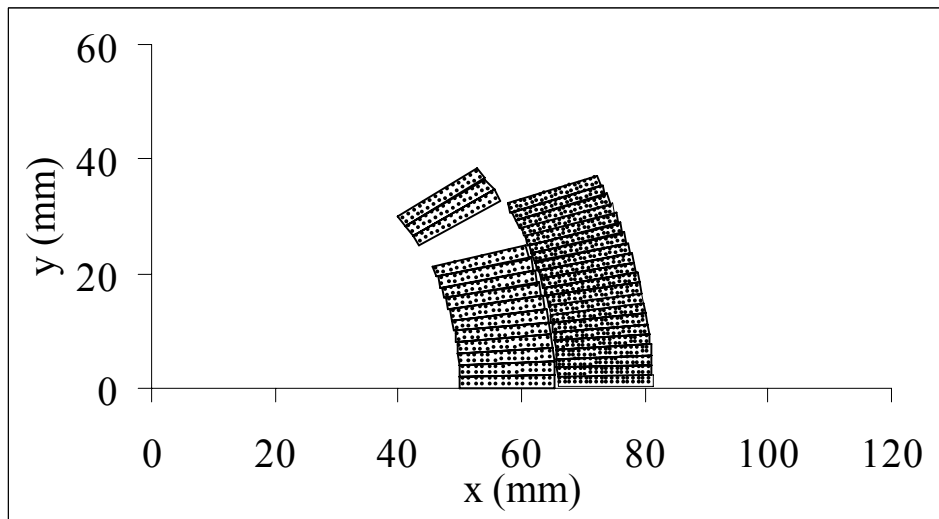


Fig. 19: Two-layers quadrupole of 100 mm aperture.

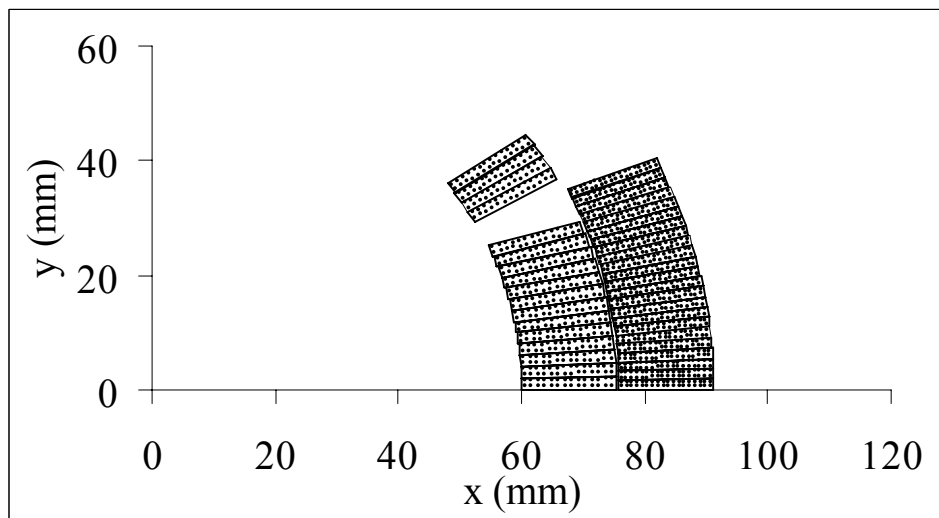


Fig. 20: Two-layers quadrupole of 120 mm aperture.

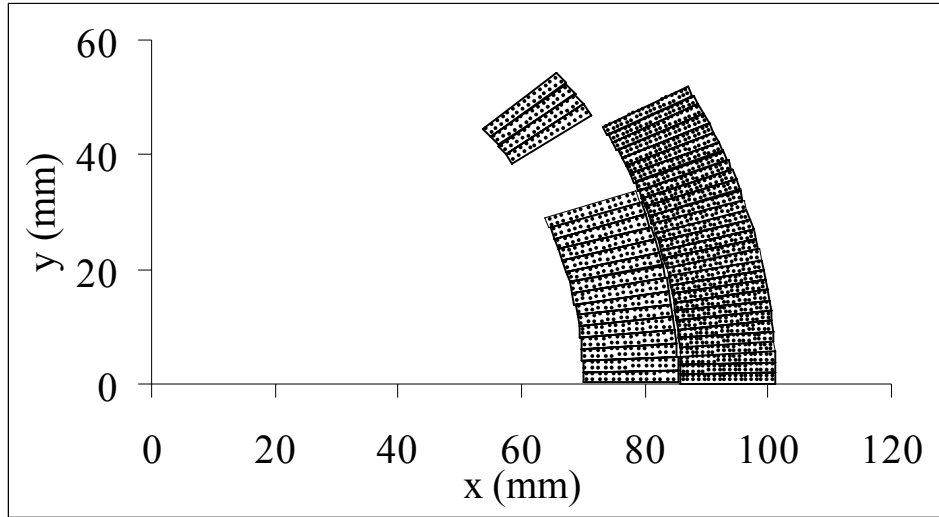


Fig. 21: Two-layers quadrupole of 140 mm aperture.

C.3 Design for a 130 mm aperture quadrupole

A lay-out for the 130 mm aperture quadrupole based on the LHC main dipole inner and outer layer is given in Fig. 22. It is a simple three block layer, based on the 36° sector with a wedge between 24° and 30° for the inner layer (canceling b_6 and b_{10}) and on a 30° sector for the outer layer. The number of turns in the inner layer is $14+4=18$, and in the outer layer is 26. The needed length of inner and outer cable is given in Table VII. Both lengths are smaller than the unit lengths of the dipoles (460 m and 780 m respectively). For the upgrade of IP1 and IP5, 8 Q1-Q3 and 8 Q2 would be needed, corresponding to 64 unit lengths of the cable01 and 64 unit lengths of the cable02.

The critical gradient in this lay-out with the cable data estimated according to Appendix B is 152 T/m with an iron yoke at 120 mm, i.e. leaving a 25 mm space for the collars. The contribution of the iron yoke to the field gradient is 22%. The quench current is 14200 A. At 80% of the loadline this gives an operational current of 11400 A and a gradient of 122 T/m as expected from the fit given in the previous section. Multipoles up to order 10 have been optimized to be within one unit at a reference radius of 44 mm. The stored energy for the 9.2 m long quadrupole is ~ 5 MJ, i.e. closer to the values of the cell dipole (7 MJ for two apertures) than to the values of the MQXA and MQXB (2.3 MJ and 1.4 MJ respectively). Stresses induced by Lorentz forces in operational conditions can be estimated to be ~ 120 MPa.

Table VII: Cable length needed for the 130 mm aperture quadrupole (coil heads excluded).

	Inner layer			Outer layer	
	length (m)	n turns (per octant)	pole length (m)	n turns (per octant)	length (m)
Q1-Q3	9.4	18	338	26	489
Q2	7.8	18	281	26	406

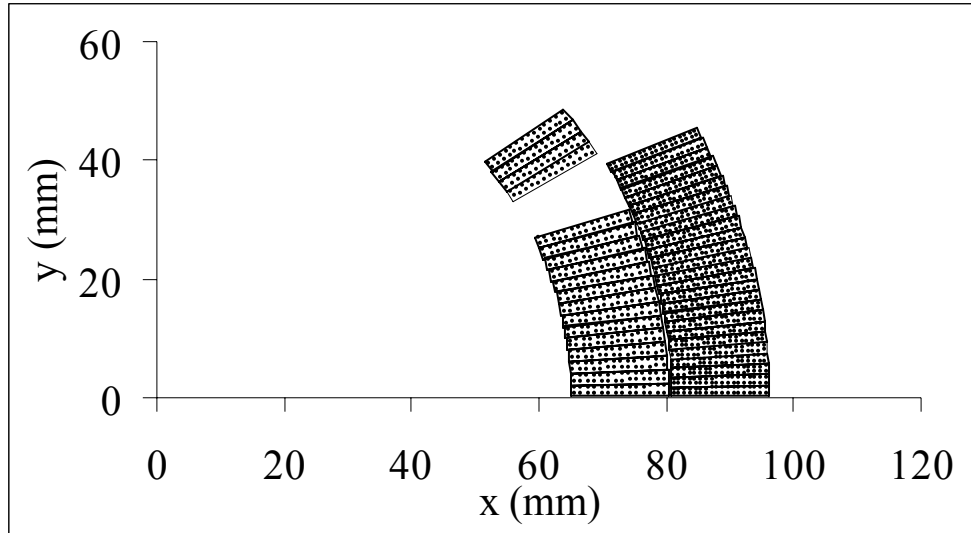


Fig. 22: Two-layers quadrupole of 130 mm aperture.

APPENDIX D: BUDGET FOR LINEAR CHROMATICITY CORRECTION

The regular part of the LHC lattice is made of 23*8 cells with 90° phase advance. The contribution of a single cell in the thin lens approximation is $1/\pi$ and therefore the regular part of the arcs gives a contribution of ~ 60 . At injection the 8 insertions give a contribution of ~ 25 , (i.e. ~ 3 per insertion) for a total chromaticity of the machine of -85 .

From [14], the chromaticity correction at injection is made by setting the cell sextupoles at $k_t=0.07 \text{ m}^{-3}$ and $k_d=-0.11 \text{ m}^{-3}$, i.e. 18% and 28% respectively of their maximum powering value of 0.386 m^{-3} . This implies that the maximum chromaticity that can be corrected by cell sextupoles is $-85/0.28 \sim 300$. Assuming one insertion squeezed at 0.5 m and one at 1 m ($Q'=30+15=45$), plus the four service insertions ($Q'=4*3=12$), one has a budget of $300-60-45-12=183$, i.e. around $Q' \sim 90$ for each low-beta insertion. The previous estimates do not consider the additional linear chromaticity that could be corrected by the main dipole spool pieces. Assuming four IPs squeezed with the same beta functions, as in the ion run, one obtains a maximum $Q' \sim 60$.

APPENDIX E: TRIPLET WITH EQUAL LENGTH QUADRUPOLES

We consider a triplet where the quadrupoles have the same lengths, i.e. $l_1=l_2$. We assume that all quadrupoles have the same aperture; the condition of equal beta functions and the matching are met through a tuning of each quadrupole force. This gives a difference in the quadrupole gradients of 10-20%. The maximum of the absolute value of the gradient in Q1, Q2 and Q3 is fit by (see Fig. 23)

$$G = \frac{1}{fl_q^2 + hl_q} \quad (16)$$

with $f=1.86 \times 10^{-6} \text{ (T}^{-1}\text{m}^{-1}\text{)}$ and $h=1.50 \times 10^{-4} \text{ (T}^{-1}\text{)}$. One has to use a gradient which is around 7-10% larger with respect to the case $l_1 \neq l_2$.

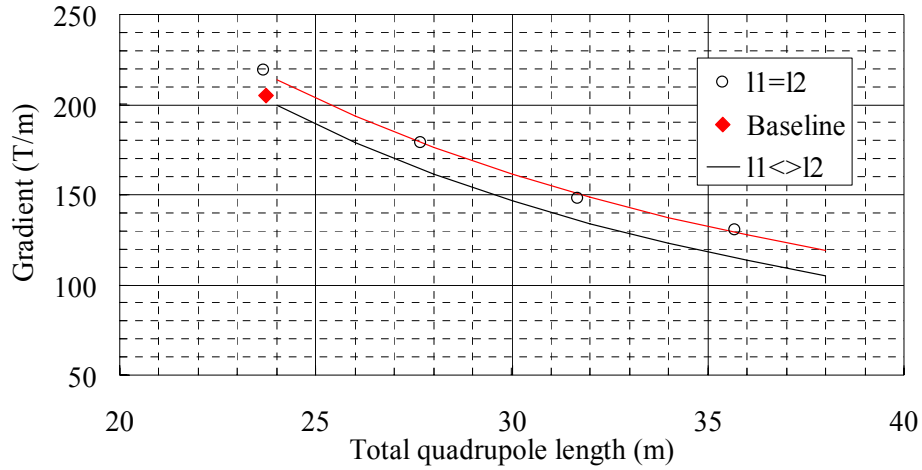


Fig. 23: Gradient versus total quadrupole length.

The aperture versus the quadrupole length is given in Fig. 24. With respect to the case with different lengths, one needs $\sim 10\%$ longer triplet to get the same aperture.

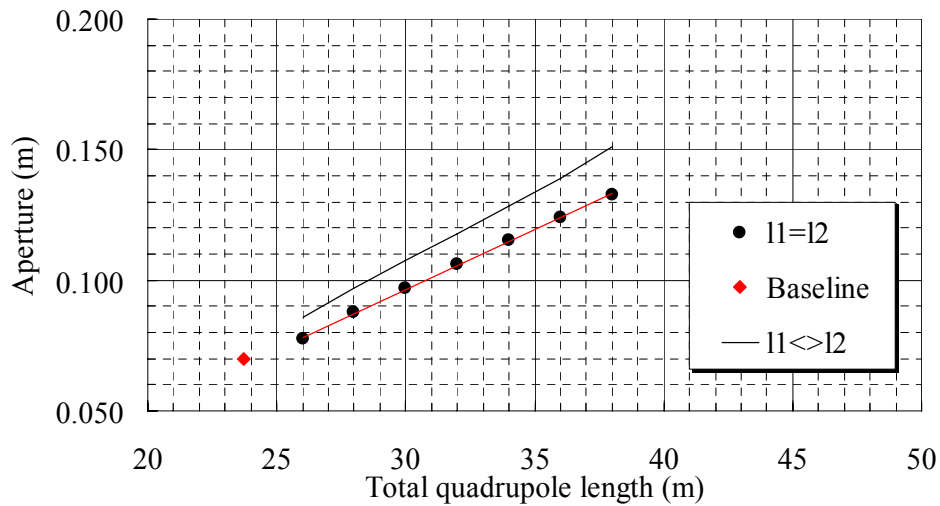


Fig. 24: Maximum aperture obtainable in a Nb-Ti triplet versus total quadrupole length.

The maximum β function in the triplet is the same as in the case of different lengths within 1%. The chromaticity versus quadrupole length and β^* is similar to the case of different lengths (see Fig. 25).

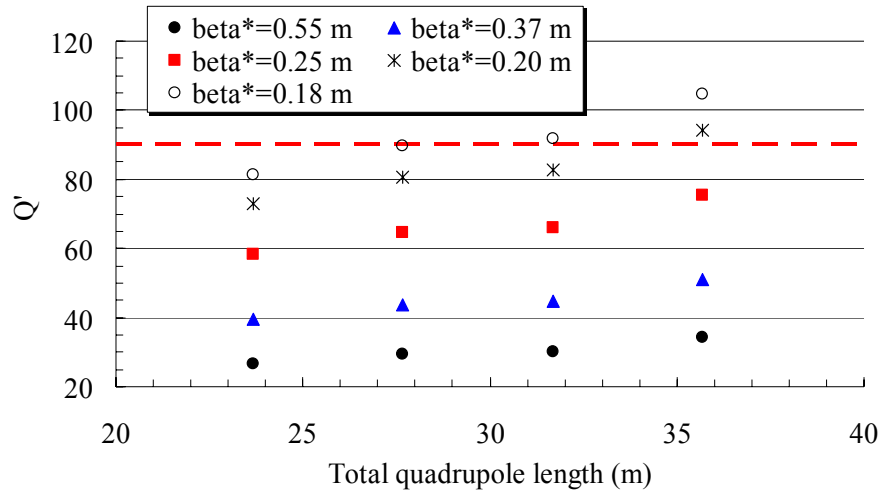


Fig. 25: Linear chromaticity versus total quadrupole length and β^* (markers), and budget for correction (dashed line).

In order to have the aperture needed for a $\beta^* = 0.25$ m and a clearance of 3σ for collimation, one needs a 135 mm aperture triplet with a total length of 38 m, i.e. 13% longer quadrupoles and practically the same aperture (see Fig. 26). With this lay-out, one can reach $\beta^* = 0.20$ m with 1σ for collimation as in the other case (see Fig. 27). This would correspond to having four 9.5 m long quadrupoles. Also in this case, one unit length of the main dipoles would be enough to wind a pole of the quadrupole.

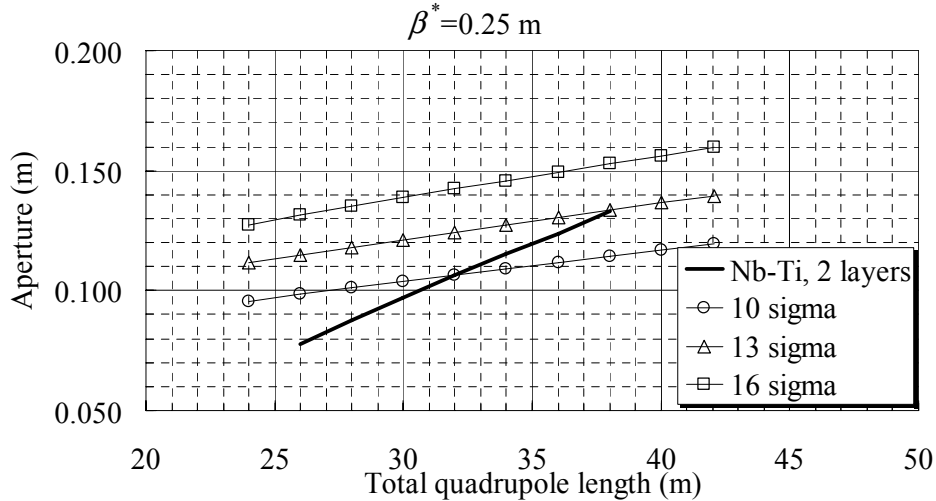


Fig. 26: Aperture requirements for $\beta^* = 0.20$ m with different collimation factors and aperture provided by two-layers Nb-Ti quadrupoles versus total quadrupole length. Case with the same length for all quadrupoles.

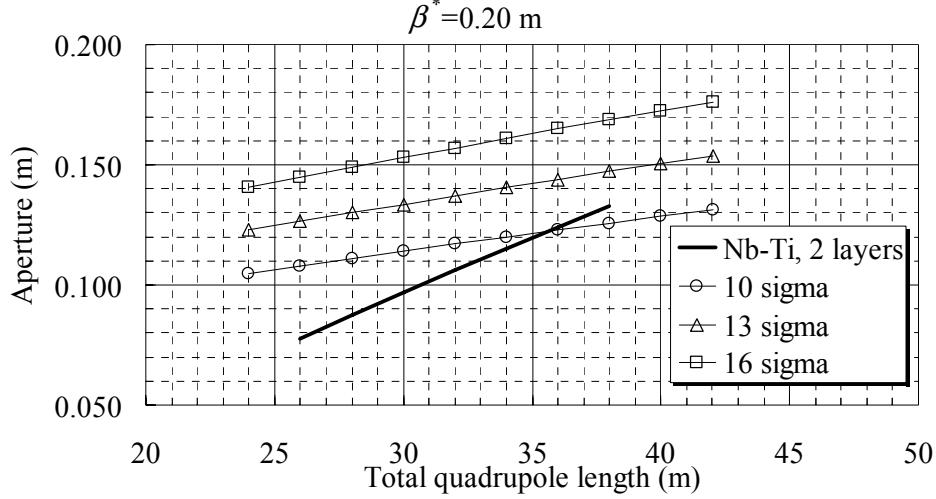


Fig. 27: Aperture requirements for $\beta^*=0.20$ m with different collimation factors and aperture provided by two-layers Nb-Ti quadrupoles versus total quadrupole length. Case with the same length for all quadrupoles.

APPENDIX F: SCALING LAWS FOR FIELD QUALITY AND NONLINEARITIES

Larger beta functions in the triplet induce stronger nonlinearities, and may result in a limited dynamic aperture at collision energy [6]. On the other hand, larger aperture quadrupoles feature an improved field quality. Here we use the approach developed in [12] to estimate the influence of the magnet aperture on the nonlinear terms and a possible compensation to the detrimental effect of a large beta function. The comparison is made with respect to the present baseline, i.e. the 70mm aperture triplet with a $\beta^*=0.55$ m.

We first consider the detuning term due to the octupoles

$$\Delta Q \propto \int K_3 \beta^2 ds, \quad (17)$$

where the coefficient K_3 is related to the multipole b_4

$$K_3 \equiv \frac{1}{B\rho} \frac{\partial^3 B_y}{\partial x^3} \propto \frac{G}{B\rho} \frac{b_4}{R_{ref}^2} \quad (18)$$

thus giving

$$\Delta Q \propto \frac{1}{R_{ref}^2} \int G b_4 \beta^2 ds. \quad (19)$$

We approximate the integral by

$$\int G b_4 \beta^2 ds \approx \bar{b}_4 G_I \beta_{\max}^2 \quad \Delta Q \propto \frac{\bar{b}_4 G_I \beta_{\max}^2}{R_{ref}^2} \quad (20)$$

where G_I is the integrated gradient, the beta function is replaced by its maximum in the triplet and the multipole by its average value along the magnet. According to the analysis carried out in [12], using a reference radius equal to 1/3 of the aperture, multipoles scale with the aperture ϕ according to

$$b_n \propto \frac{1}{\phi}. \quad (21)$$

This scaling is given by the hypothesis, confirmed by experimental data, that the precision in the coil positioning is independent of the magnet aperture. In our case, we have

- The aperture is increased from the baseline of 70 mm to 130 mm by a factor $\kappa=1.86$.
- The integrated gradient decreases of a factor $\lambda=0.87$ from the baseline of a 24 m triplet length to 34 m (see Fig. 4).
- The beta function in the triplet increases from 4400 m ($\beta^*=0.55$ m) to 13000 m ($\beta^*=0.25$ m), i.e. a factor $\mu=2.96$.

The resulting increase of the detuning term in the 34 m proposal is $\lambda\mu^2/\kappa^3=1.18$, i.e. only 18% more than nominal. Please note that for a 90 mm aperture quadrupole one would have $\kappa=1.29$ and $\lambda\mu^2/\kappa^3=3.56$, i.e. a factor 3-4 larger.

We carry out the same analysis for terms which are proportional to the first power of any multipole; they are proportional to the following quantity

$$T_n \propto \frac{\bar{b}_n G_l \beta_{\max}^{n/2}}{R_{ref}^{n-2}} \quad (22)$$

and therefore scale according to

$$T_n \propto \lambda \mu^{n/2} \kappa^{1-n}. \quad (23)$$

The term proportional to second order in b_3 , as for instance the detuning with amplitude due to sextupole, scales with

$$T_3^{(2)} \propto \frac{(\bar{b}_3 G_l)^2 \beta_{\max}^3}{R_{ref}^2} \propto \lambda^2 \mu^3 \kappa^{-4} \quad (24)$$

In Fig. 28 we plot the increase of these terms for a triplet of variable length aiming at having $\beta^*=0.25$ m, with respect to the baseline with $\beta^*=0.55$ m. Results show that the nominal situation is recovered within 50%-30% for apertures larger than 120 mm, and completely for apertures larger than 150 mm.

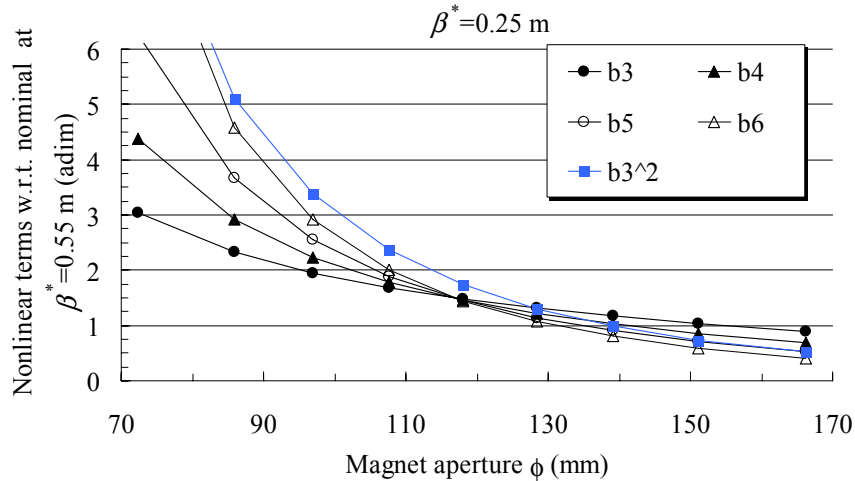


Fig. 28: Increase of nonlinear terms proportional to the first power and second of multipoles for a triplet aiming at $\beta^*=0.25$ m, as a function of the triplet length. The terms are normalized with respect to the baseline $\beta^*=0.55$ m.