LOW-β QUADRUPOLE DESIGNS FOR THE LHC LUMINOSITY* UPGRADE

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Abstract

Several scenarios are considered for the upgrade of the LHC insertions in view of increasing the luminosity beyond 10^{34} $cm^{-2}s^{-1}$. In the case of "quadrupole first" option, superconducting low-β quadrupoles with apertures in the range of 90-110 mm are required in view of increased heat loads and beam crossing angles. We present possible low-β quadrupole designs based on existing Nb_3Sn and LHC NbTi superconductors, present scaling laws for the magnet parameters and discuss relative advantages of the underlying triplet layouts.

INTRODUCTION

Several possible scenarios are considered in view of upgrading the LHC nominal luminosity to several times 10^{34} $cm^{-2}s^{-1}$ [1]. In the case of the "quadrupole first" option, the present LHC low-β triplet would be replaced with magnets with an aperture in the range of 90-110 mm, compatible with a β* of 0.25 m or less, increased beam crossing angles and higher heat loads associated with increased luminosity. Achieving field gradients of the present triplet (205 T/m) in such large apertures is beyond the reach of NbTi magnet technology. The superconductor of predilection for the new generation of high-field magnets is Nb_3Sn, and several studies have confirmed the potential of this technology for the LHC upgrade [2].

A recent study [3] has examined an alternative where the aperture and length of the quadrupoles are optimised according to their position in the triplet. This approach is well suited to NbTi technology, which is sufficiently mastered that several magnet designs (apertures and lengths) can be readily extrapolated from the LHC experience. Although inherently less performing than Nb_3Sn magnets, this approach deserves further investigation should a change of low-β quadrupoles be necessary sooner than it is possible to complete the Nb_3Sn magnet R&D. In this study we take this approach a step further and consider several possible designs for large aperture quadrupoles with moderate gradient based on the superconducting cables developed for the LHC. We also consider a possible design of a 60 mm Nb_3Sn quadrupole, and discuss relative advantages of the underlying triplet layouts.

MAGNET DESIGN

NbTi Quadrupoles

The conceptual designs of the low-β quadrupoles considered here are based on the superconducting cables used in the LHC magnets: the inner layer of the LHC main dipole (MB), the main quadrupole (MQ) and the 70 mm insertion quadrupole (MQY) [4]. Their respective parameters are summarised in Table 1. Apart from the clear technical and cost advantage, the use of existing cables with well established parameters sets a basis for comparison with future NbTi cables that could be further optimised for this particular application.

Table 1: Main parameters of the superconducting cables

	MQY	MQ	MB
Width [mm]	8.3	15.10	15.10
Mid-thickness [mm]	0.84/1.28	1.48	1.90
Critical current, Ic [A] @ 9 T, 1.9K	5070/ 9110	12960	13750
dIc/dB [A/T]	1350/ 2550	3650	4800

Several coil cross-sections with apertures varying from 90 to 110 mm were examined, either in two layer or four layer configurations. In all cases, the coil cross-section was optimised by modifying the number of turns and the block layout until the allowed field multipoles b_6 and b_{10} were below 0.01 units. The reference radius was taken as 17/70 of the coil inner diameter, where 17 mm is the reference radius of the present 70 mm LHC low-β quadrupoles. The inner radius of the iron yoke was assumed to be at 30 mm from the outer radius of the coil. No attempt was made at this time to include constructional features of the iron yoke. All quadrupoles are considered to operate at 1.9 K. The coil cross-sections of the three main designs are shown in Fig. 1.

The operating gradient and other design parameters were extracted at 80% of the magnet load line in order to respect operational margins required in conditions of high beam induced heat load. This is a "soft" criterion which does not take into account probable improvements in the critical current density of the NbTi cables for a small scale production. Furthermore, experience gained in operating the present LHC triplet with beam will certainly influence refining the criterion for the operating current.

With the above conditions, the operating gradients of the quadrupoles as function of coil aperture are shown in Fig. 2. In the case of the design using the MQYcable, the operating gradient of a 70 mm aperture quadrupole, which corresponds to the as-built LHC insertion quadrupole MQY, is also given. Due to the lower engineering current density, the magnets with MB/MQ and MB cables have lower gradients by 10% and 15% compared to the design with the MQY cable. The increase of aperture from 90 to 110 mm results in a decrease of operating gradient by about 18% in all cases. The operating current decreases in all cases by about 10%.

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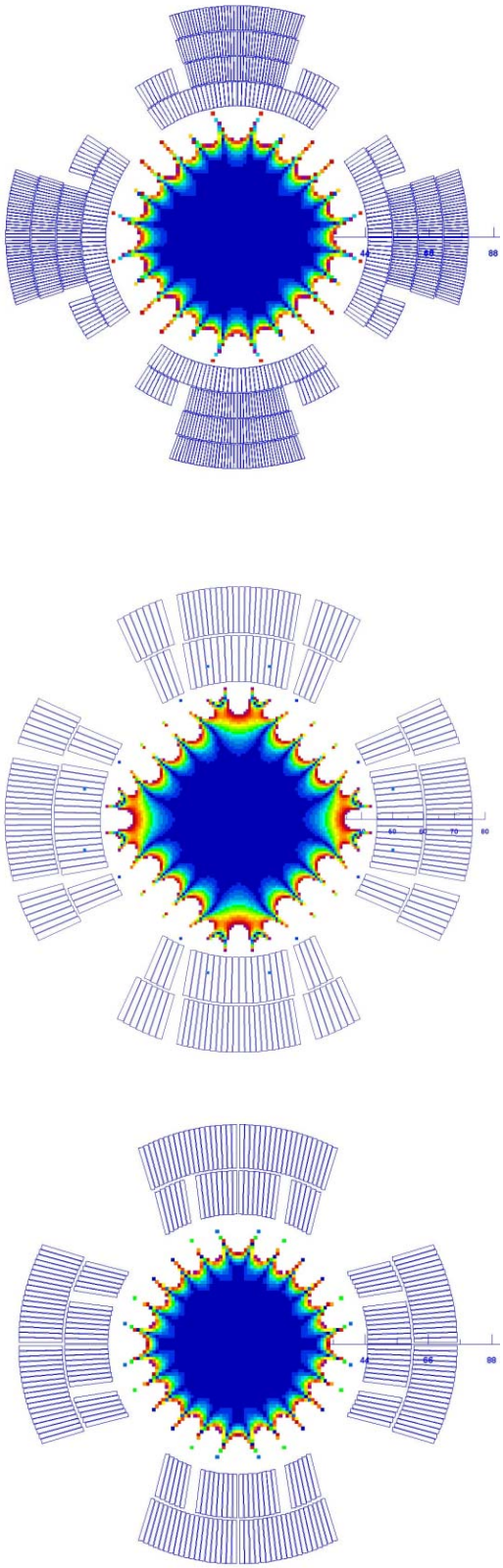

Figure 1. Coil cross-sections for three quadrupole designs. Top: four-layer quadrupole using MQY cable. Middle: two-layer quadrupole using MB and MQ cables. Bottom: two-layer quadrupole using MQ cable. Coil aperture is 90 mm in all cases. The core indicates the good field region with a relative field error below 2 10^{-4}.

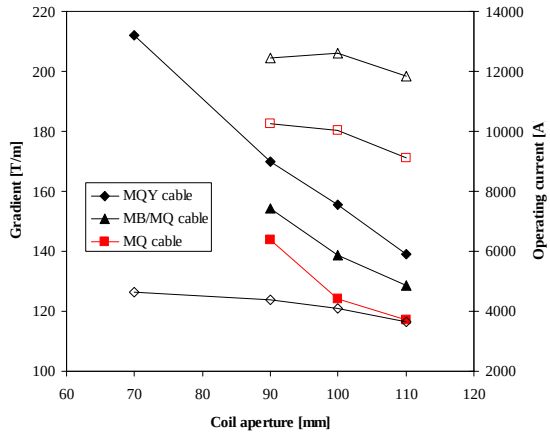

Figure 2. Quadrupole operating gradient (full symbols) and current (empty symbols) as function of coil aperture.

As expected, the stored energy increases with aperture, as shown in Fig. 3. The forces in the magnets also increase and reach 1.3 MN/m for the 110 mm quadrupole using MQY cable. The magnets must be actively protected, and we assume full-length quench heaters with similar coil coverage and activation time as in the LHC magnets. Under these conditions, due to larger conductor volume and decreasing current, the hot-spot temperature, Fig. 3, falls off for larger apertures. All these parameters are similar to the LHC superconducting magnets.

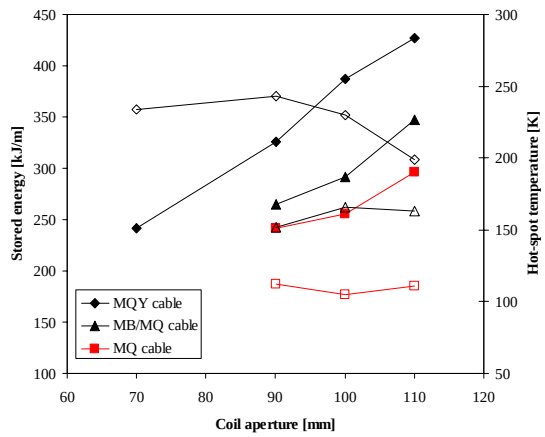

Figure 3. Stored energy (full symbols) and hot-spot temperature (empty symbols) as function of coil aperture.

We have also considered other coil configurations including those with an open mid-plane, where several turns of the inner layer are removed to improve the cooling of the coil. In all cases, however, the additional reduction of the operating gradient was about 10%.

Nb_3Sn Quadrupole

Conceptual designs of Nb_3Sn quadrupoles with apertures in the range of 90 mm were studied by the Fermilab and LBNL teams [2], [5]. Here we examine a 60 mm aperture Nb_3Sn quadrupole using as an example the cable developed by University of Twente in collaboration with CERN [6]. This 16.4 mm wide cable contains 35 strands (0.9 mm diameter) made by the

powder-in-tube (PIT) process, and has a non-copper critical current of 2230 A/mm^2 at 12 T and 4.5 K. A quadrupole optimised under the same conditions as the NbTi quadrupoles is shown in Fig. 4. Its operating gradient is 310 T/m with a peak field in the coil of 10.5 T at 20 kA. The fact that the peak field is below that achieved in recent Nb_3Sn dipole models indicates that further cable and coil optimization is possible.

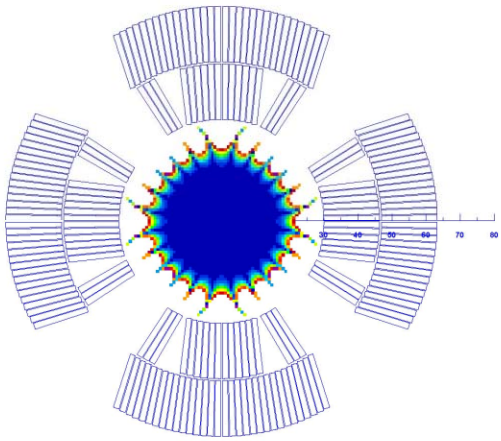

Figure 4. Coil cross-section of a 60 mm aperture quadrupole using 16.4 mm Nb_3Sn cable.

TRIPLET LAYOUTS

The present LHC low-β triplet consists of four quadrupoles with a coil aperture of 70 mm operated at 1.9 K [4]. For the purpose of this study we consider a triplet consisting of two inner (Q2A, Q2B) and two outer quadrupoles (Q1, Q3) with a spacing of 2 m between all magnets. The Q1 quadrupole is at 23 m from the IP, as for the LHC low-β triplet. This arrangement slightly differs from that considered in [3], where the quadrupole spacing was 0.3 m and L* equal to 22 m.

The coil aperture of the low-β quadrupoles is estimated from:

$$D_{\min} \geq 1.1*(7.5+2*9)\sigma + 2*(d_s + 3\text{mm} + 1.6\text{mm}) + 10\text{mm}$$

which takes into account the beam envelope (9σ), beam separation (7.5σ), β-beating (20%), peak orbit excursion (3 mm) and mechanical tolerances (1.6 mm). The term d_s is the spurious dispersion orbit introduced in [3], which depends on the crossing angle θ_c. The additional 10 mm account for the beam tube and the beam screen. For the nominal LHC optics, β* is 0.5 m and maximum beam size 1.54 mm, giving a D_{min} of 68 mm.

A fully symmetric triplet with 8 m long quadrupoles, when matched to the present LHC experimental insertion, requires a gradient of 150 T/m at 7 TeV. The required apertures are given in Table 2, and the magnets could use NbTi cable. If the length of Q3 is increased to 10 m, the required gradients decrease to about 140 T/m. Alternatively, the length of Q1 could be reduced. It is interesting to note that a 4 m long Nb_3Sn quadrupole as Q1, similar to the one shown in Fig. 4, would result in the same ratio of β_{peak}/β^* as in the present LHC triplet.

Table 2: Main parameters of the quadrupoles at 7 TeV in different arrangements of the low-β triplet. The spacing between the quadrupoles is 2 m and L* is 23 m.

	LHC triplet		Symmetric triplet		Long Q3		Short Q1	
	Q2, Q3	**Q1**	**Q2, Q3**	**Q1**	**Q2, Q3**	**Q1**	**Q2, Q3**	**Q1**
β* [m]	0.50	0.50	0.25	0.25	0.25	0.25	0.25	0.25
β_{peak} [m]	4750	1265	11520	5400	11840	5440	9500	3600
θ_c [μrad]	315	315	445	445	445	445	445	445
σ [mm]	1.5	0.8	2.4	1.6	2.4	1.6	2.2	1.3
d(s)	2.8	1.4	4.2	2.9	4.3	2.9	3.9	2.4
D_{min} [mm]	67.6	44.2	94.5	70.8	95.5	70.9	87.6	61.3
g [T/m]	198.5	198.5	151.8	151.8	137.8	161.1	151.8	338.6
L [m]	5.5/6.3	6.3	8.0	8.0	8.0/10.0	8.0	8.0	4.0

A comparison of requirements in Table 2 and operating gradients in Fig. 2 shows that several possibilities exist if moderate gradient quadrupoles with an aperture of 90-110 mm were to be used for the upgrade of the LHC low-β triplets. The most promising, a four layer quadrupole based on the MQY cable, could in principle provide an aperture of 100 mm, larger than necessary for a β* of 0.25 m. In all cases, the lengths of the NbTi quadrupoles are well within the reach of the present technology. The option with a short Q1 using Nb_3Sn cable seems particularly interesting as it reduces the costs and risks inherent to this developing technology.

CONCLUSIONS

Several possible low-β quadrupole designs were considered in the perspective of the "quadrupole first" scenario of the LHC luminosity upgrade. We show that field gradients of 150 T/m may be achieved with coil apertures of 90-110 mm using existing LHC cables. An upgraded triplet requires in this case 8-10 m long quadrupoles, built as an extension of existing technology. A hybrid triplet, including a 60 mm aperture Nb_3Sn quadrupole, is proposed as an attractive intermediate step towards a triplet with all quadrupoles built using Nb_3Sn cable.

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