APERTURE LIMITATIONS FOR 2ND GENERATION NB$_3$SN LHC IR QUADRUPOLES[1]

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Abstract

One of the straightforward ways towards the higher luminosity in the LHC is a replacement of the present 70-mm NbTi quadrupoles with Nb$_3$Sn quadrupoles which would provide the same field gradient but in a larger aperture. Conceptual designs of such magnets with 90 mm aperture have been developed and studied. This paper discusses the possibilities and limitations of further increasing the aperture of Nb$_3$Sn low-beta quadrupoles , and shows that an aperture up to 110 mm is possible.

INTRODUCTION

Present optics of two LHC interaction regions (IR) is based on single-bore inner triplets consisting 70-mm NbTi quadrupoles with a nominal field gradient of 205 T/m operating at T=1.9 K. These magnets were designed to provide β*=50 cm for a nominal LHC luminosity of 10^{34} cm^{-2}s^{-1} [1]. Replacing them with higher performance magnets will be a major component of the LHC luminosity upgrades.

The future LHC luminosity upgrade plans being discussed at present time require new low-beta quadrupoles with higher field gradient, larger operation margin and larger magnet aperture [2,3]. Preliminary analysis shows that large-aperture quadrupoles based on Nb$_3$Sn superconductor meet these basic requirements [4,5]. This paper continues the studies with the goal to determine the aperture limitations for Nb$_3$Sn IR quadrupoles.

MAGNET DESIGN

The conceptual design of 90-mm Nb$_3$Sn quadrupole magnets based on 2-layer shell-type designs has been recently developed and analyzed [6,7]. The 90-mm aperture is close to the limit for a 2-layer design due to the large cable aspect ratio. Therefore 4-layer designs were considered for quadrupoles with 100-mm and 110-mm aperture. Both magnets consist of two double-layer shell-type coils and cold iron yoke. The goal was to achieve a nominal field gradient of 205 T/m with a 20% margin and the best field quality with one wedge in the innermost layer. The current density in the coil layers was graded, providing a noticeable contribution to the field gradients. The circular iron yoke was set 15 mm beyond the coil to provide space for the collars. The magnetic permeability of the iron was constant and equal to 1000. The 4-layer 100 and 110 mm coil cross-sections as well as 2-layer 90 mm quadrupole coil optimized with ROXIE code are shown in Figure 1.
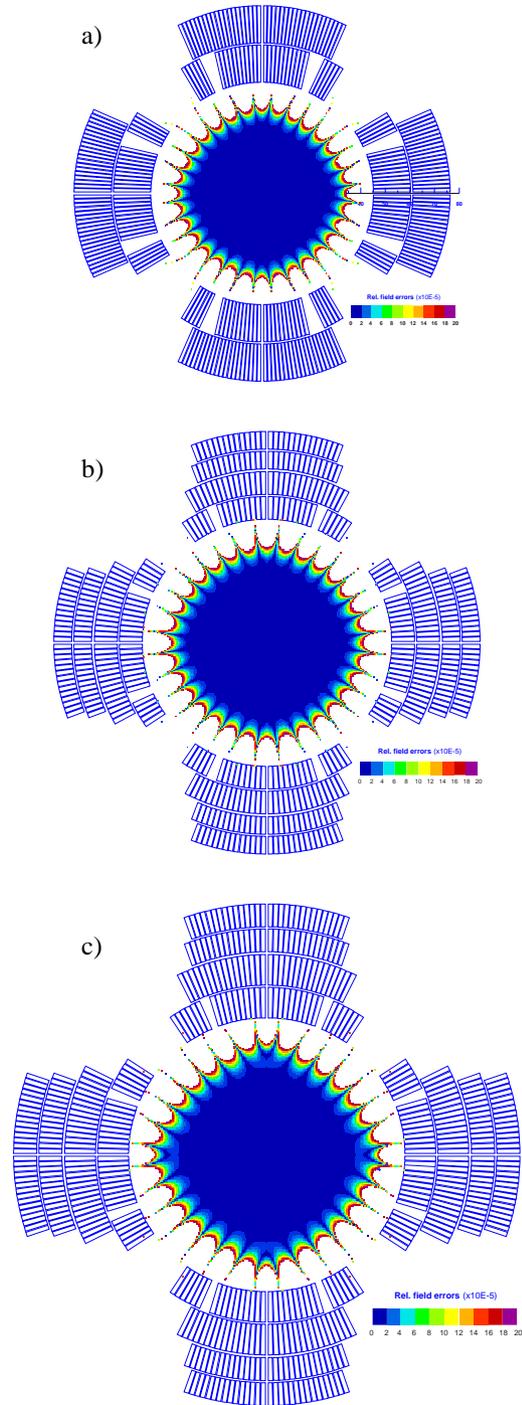

Figure 1: Quadrupole coil cross-sections with 90-mm (a), 100-mm (b) and 110-mm (c) apertures.

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The coil parameters for all the three quadrupole designs are summarized in Table 1. The coil width and volume required to reach the target field gradient increase dramatically in the 110-mm aperture quadrupole design.

Table 1: Coil parameters.

Parameter	Aperture		
	110 mm	100 mm	90 mm
Number of layers	4		2
Number of turns	248	228	144
Coil width, mm	45.5	34.5	31.5
Coil area, cm^2	84.9	59.3	48.1

Table 2 summarizes the final cable parameters for the all three designs. Two different cables are used in each 4-layer quadrupoles in order to increase the efficiency of magnet design. The cables are based on the same 1-mm Nb_3Sn strand. The cable dimensions including insulation were determined in an iterative optimization process in order to achieve maximum gradients with minimum coil areas. The cable keystone angle was set to ensure the radial position of each turn in the coil. The 2-layer 90-mm quadrupole uses one cable based on the 0.7 mm Nb_3Sn strand in both layers.

All the cables have the same packing factor of 89% and Cu:nonCu ratio of 1.2. Practical experience shows that the cables used in the 4-layer designs are simpler for manufacturing and have better mechanical and electrical properties than the cable used in the 2-layer design due to the smaller aspect ratio.

Table 2: Cable parameters.

Parameter	Aperture				
	110 mm		100 mm		90 mm
Coil layer	1-2	3-4	1-2	3-4	1-2
Number of strands	24	18	18	14	42
Strand D, mm	1.0				0.7
Cable width, mm	12.33	9.23	9.23	7.17	15.14
Inner edge, mm	1.59	1.66	1.61	1.67	1.08
Outer edge, mm	1.94	1.87	1.92	1.86	1.39
Keystone angle, deg	1.7	1.3	1.9	1.5	1.18
Aspect ratio	7	5	5	4	12

MAGNET PARAMETERS

Field quality

Table 3 presents the systematic geometrical harmonics at the reference radius equals to the half of the coil bore radius for the 100-mm and 110-mm designs and also for the 2-layer 90-mm quadrupole. For comparison the field harmonics of present 70-mm NbTi LHC IR quadrupoles (MQXB) at the reference radius of 17 mm (which as well corresponds to the half bore radius for this magnet) are also presented.

The first allowed geometrical harmonics, b_6 at $R_{ref}=R_{bore}/2$ is almost the same for 90, 100 and 110 mm

designs and it is noticeably better than the b_6 in present 70-mm design. The higher order geometrical harmonics, b_{10} and b_{14}, are almost the same in 90, 100 and 110 mm designs and slightly higher than in MQXB. If required, the geometrical harmonics can be further optimized by introducing additional wedges in the coil.

Table 3: Systematic field harmonics b_n @$R_{ref}=R_{bore}/2$.

n	Aperture			
	110 mm	100 mm	90 mm	70 mm
6	0.0002	0.0005	0.0006	-0.013
10	0.0033	0.0029	0.0045	-0.001
14	0.0118	0.0046	0.0069	-0.0011

Short sample limit

Figure 2 shows the calculated quench gradient for 110, 100 and 90 mm quadrupoles as a function of the critical current density in the non-copper area of the superconducting cable. The Nb_3Sn strands with $J_c(12T,4.2K)$ more than 3 kA/mm^2 allow a quench gradient above 250 T/m to be reached in all the designs. An R&D program in the U.S., aimed at the development of high J_c Nb_3Sn strands for a new generation of SC accelerator magnets, has been launched few years ago. Based on the results achieved in the framework of this program, strands with the critical current density >3 kA/mm^2 will be available in 2-3 years. The $J_c(12T,4.2K)$ of 2.9 kA/mm^2 has been reached in short samples. However, more work has to be done on reduction of strand magnetization and improvement of their stability.

The data presented in Figure 2 and Table 1 confirm that the efficiency of the magnet design decreases with aperture increasing. In order to reach the same field gradient wider coils with higher critical current density are required.

The maximum quench field in the coil of the 110, 100 and 90 mm quadrupoles reaches 15.3, 14.5 and 13.5 T respectively with cable critical current density of 3 kA/mm^2 at 12 T and 4.2 K. The maximum field in the 110 mm quadrupole exceeds the maximum field achieved in the Nb_3Sn high field accelerator magnets at present time.
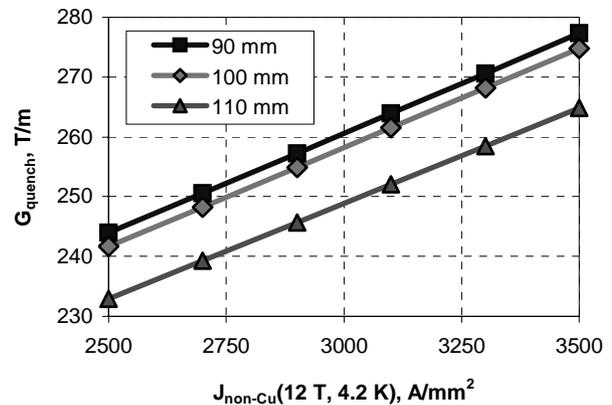

Figure 2: Quench gradients at 4.2 K as functions of the critical current density in the coil.

Lorentz forces and coil stress

Table 4 presents the calculated horizontal and vertical components of the Lorentz force applied to one octant of the coil at the nominal field gradient of 205 T/m, and the maximum stress in the coil associated with these forces. Analysis shows that the level of Lorentz forces in the 90-mm quadrupole reaches the same level as in the LHC arc dipoles. In the quadrupole with 110 mm aperture the expected Lorentz forces are higher than the forces in the Nb_3Sn high field dipole models being developed at the present time for different applications.

The level of mechanical stresses in the coil of the 110 mm quadrupole approaches to 100 MPa. To provide the coil pre-stress of this level at operating temperature, the coil prestress during fabrication increases to the level at which significant irreversible Nb_3Sn strand degradation may occur. Clearly, the robust mechanical structure capable of providing an adequate coil support during operation and avoiding coil over-compression during fabrication is a key element for these quadrupole designs.

Table 4: Lorentz forces and maximum coil stress.

Parameter	Aperture		
	110 mm	100 mm	90 mm
Fx(205T/m), MN/m	3.44	2.38	1.5
Fy(205T/m), MN/m	-3.42	-2.39	-1.92
Maximum coil stress, MPa	99	90	73

Quench protection

All superconducting accelerator magnets have large stored energy and require a special quench protection system in case of quench. Magnet inductance and stored energy at the nominal field gradient of 205 T/m for the 110, 100 and 90 mm quadrupoles are presented in Table 5. Quench protection of these magnets can be provided using the traditional approach based on internal quench protection heaters, which distribute the stored energy in the coil, thereby preventing coil overheating and reducing the voltages between the coil and ground as well as mechanical shock in the coil during quench. The acceptable coil maximum temperature for accelerator magnets is 300-400 K. The results of calculation of the maximum coil hot spot temperature, T_{hs}, in the region where the quench occurred and the maximum temperature under the quench heaters, T_{blk}, are reported in Table 5 for the fractions of coil volume quenched by the heaters, F_{qh}, of 50% and 25%.

Table 5: Quench protection parameters.

Parameter		Aperture		
		110 mm	100 mm	90 mm
L, mH/m		17.46	14.71	4.86
W(205 T/m), kJ/m		1181	703	468
T_{hs}, K	F_{qh}=50%	230	225	230
	F_{qh}=25%	335	320	315
T_{blk}, K	F_{qh}=50%	150	140	127
	F_{qh}=25%	220	200	180

For the redundancy of quench protection system the parameter F_{qh} that provides safe coil protection, should be less than 50%. In this case two parallel sets of heaters could be installed in the magnet. Calculations show that even for F_{qh}=25% the coil maximum temperature in all the quadrupole designs is within 315-335 K. With F_{qh}=50% the maximum temperature does not exceed 250 K which is more comfortable for brittle Nb_3Sn coils.

CONCLUSION

The studies presented here show that a 110-mm aperture quadrupole magnet using Nb_3Sn strand can provide a maximum field gradient of 250 T/m (20% above the present nominal gradient of 205 T/m) with acceptable field quality. Quench protection of these magnets can be provided using the traditional approach based on internal quench heaters.

Single-aperture inner triplets with these magnets can reduce β* by a factor of 3, from 50 cm to 17 cm leading to a potential luminosity increase by a factor of 3.

However, the following parameters make the 110 mm quadrupoles quite challenging:
- the critical current margin of 20% requires high-performance Nb_3Sn strands with the critical current density Jc(12T,4.2K)>3 kA/mm^2;
- the peak field in the coil at quench exceeds the state-of-the-art level of 15 T for Nb_3Sn accelerator magnets;
- the maximum stress in the coil, induced by Lorentz forces, reaches 100 MPa approaching the level of stress which may cause significant degradation or even damage of brittle Nb_3Sn coils.

The risks associated with the above factors have to be analyzed and taken into account while choosing the final quadrupole aperture.

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