TD-03-003
January 10, 2003

4-layer Nb_3Sn IR Quadrupoles for the LHC Luminosity Upgrade

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Abstract - Four-layer shell-type quadrupole magnet designs with 100 mm and 110 mm aperture based on the Nb_3Sn superconductor are described. Based on the results obtained the aperture limitations for these magnets are discussed.

Introduction

The future LHC luminosity upgrade plans being discussed at present time [1] in case of similar IR optics require new low-beta quadrupoles with higher operation margin and larger magnet aperture. Preliminary analysis shows that large-aperture quadrupoles based on the Nb_3Sn superconductor meet these two basic requirements.

The conceptual design of 90-mm Nb_3Sn quadrupole magnets based on 2-layer shell-type designs have been recently developed and analyzed [2]. This note continues the studies with the goal to determine the aperture limitations for the Nb_3Sn IR quadrupoles. Since the 90-mm aperture is close to the limit for 2-layer design approach due to large cable aspect ratio, 4-layer designs were considered in this study for quadrupoles with 100-mm and 110-mm aperture. It also allows grading the current density in magnet layers, providing a noticeable contribution to the field gradients.

Coil cross-section and cable parameters

Two 4-layer shell-type quadrupole magnet designs with 100-mm and 110-mm apertures based on Nb_3Sn superconductor were studied. Both magnets consist of two double-layer shell-type coils and cold iron yoke. The design goal was to achieve the nominal field gradient of 205 T/m with 20% margin and the best field quality with one wedge in the innermost layer. The iron yoke was distanced from the coil by 15 mm providing the space for the collars. The magnetic permeability of the iron yoke during the optimization was constant and equal to 1000. The optimized 100-mm and 110-mm coil cross-sections with the field quality diagrams are shown in Figure 1.

Two different cables are used in each magnet in order to increase the efficiency of magnet design. All the cables consist of the same 1-mm Nb_3Sn strand with the copper to non-copper ratio of 1.2. The cable dimensions including insulation were determined in iterative optimization process in order to achieve maximum gradients with minimum coil areas. The cable keystone angle was chosen such that it ensures the radial position of each turn in the coil. Table 1 summarizes the final cable parameters for both designs.

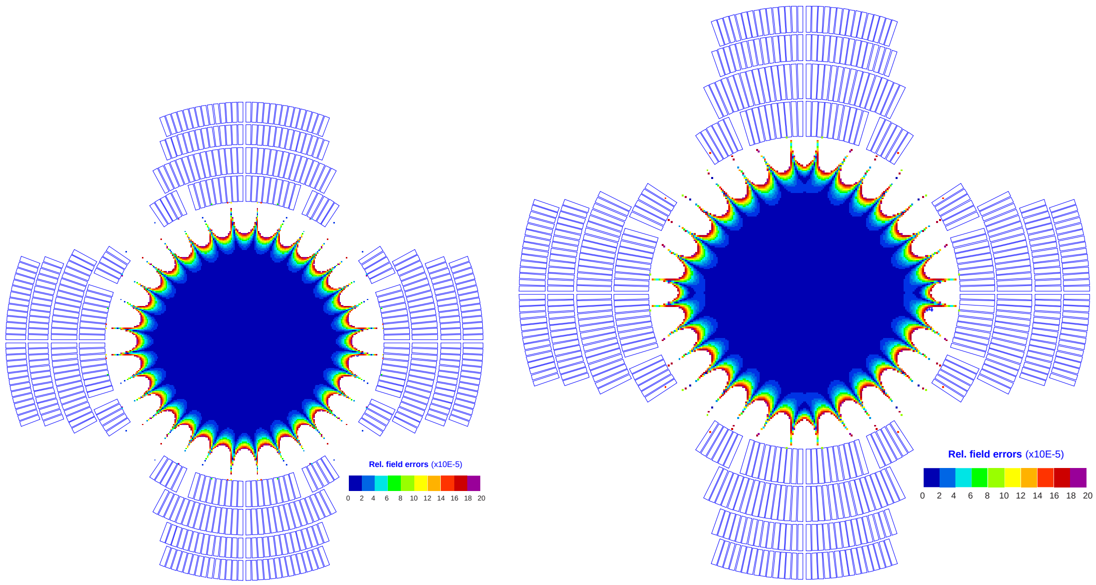

Figure 1. Quadrupole coil cross-sections with 100-mm (left) and 110-mm (right) apertures.

Table 1. Cable parameters.

Parameter	Unit	100 mm design		110 mm design	
		Inner	Outer	Inner	Outer
Number of strands	-	18	14	24	18
Strand diameter	mm	1.000	1.000	1.000	1.000
Cable bare width	mm	9.230	7.165	12.329	9.230
Bare inner edge thickness	mm	1.612	1.671	1.587	1.662
Bare outer edge thickness	mm	1.917	1.858	1.943	1.867
Cabling angle	deg.	14.5	14.5	14.5	14.5
Keystone angle	deg.	1.893	1.495	1.655	1.273
Average packing factor	%	89.0	89.0	89.0	89.0
Inner edge compression	%	19.4	16.4	20.6	16.9
Outer edge compression	%	4.1	7.1	2.8	6.6
Width compression	%	0.0	0.0	0.0	0.0
Radial insulation thickness	mm	0.18	0.18	0.18	0.18
Azimuthal insulation thickness	mm	0.18	0.18	0.18	0.18
Copper to non-copper ratio	-	1.2	1.2	1.2	1.2

Field quality

Table 2 presents the systematic geometrical harmonics at the reference radius of 17 mm and at the reference radius equal to the half of the coil bore radius for 100-mm and 110-mm designs and also for the previously analyzed 2-layer 90-mm quadrupole. For comparison the field harmonics of present 70-mm NbTi MQXB at the reference radius of 17 mm (which as well corresponds to the half bore radius for this magnet) are also presented. As it can be seen, b_6 at R_{ref}=R_{bore}/2 is almost the same for 90-mm quad and 100-mm and 110-mm designs and is noticeably better than in present 70-mm design. b_{10} and b_{14} are almost the same in 90-110 mm designs and slightly higher than in MQXB. The analysis of the random harmonics, collar and coil magnetization and iron saturation effects as well as final optimization of geometrical harmonics will be performed later after the first iteration on the mechanical design.

Table 2. Systematic field harmonics.

n	b_n @ 17 mm			b_n @ R_{bore}/2			b_n @ 17 mm
	110 mm	100 mm	90 mm	110 mm	100 mm	90 mm	70 mm*
6	0.00003	0.00011	0.00018	0.00022	0.00053	0.00056	-0.013
10	0.00007	0.00013	0.00048	0.00333	0.00286	0.00451	-0.001
14	0.00004	0.00004	0.00024	0.01179	0.00456	0.00691	-0.0011

* MQXB

Field distribution and short sample limit

Figure 2 shows the field distribution in the coils at the maximum field gradient in the aperture for each design. The values of maximum field in the coil blocks at quench are reported in Table 3. Although the peak field points belong to the innermost pole turns, the 1st and 3rd layers have nearly the same quench margins due to the current density grading.

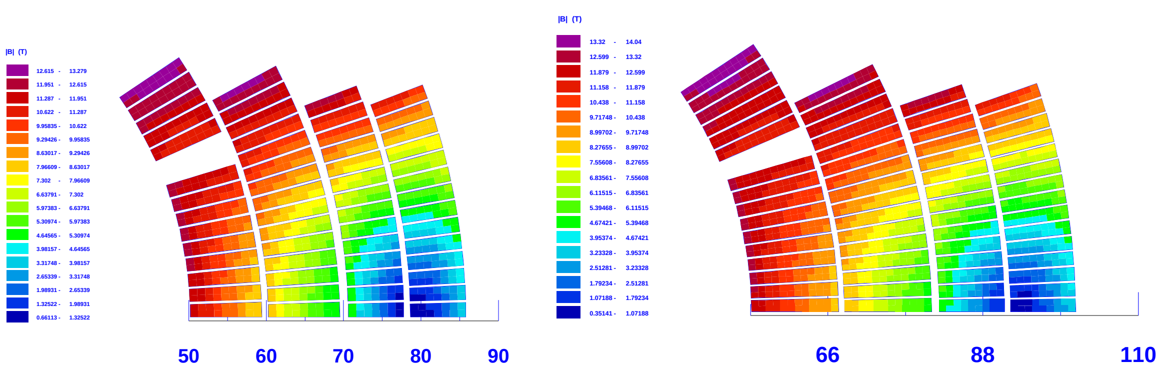

Figure 2. Field distribution inside the coils.

Table 3. Peak field in IR quadrupole blocks.

*Block #	Peak field, T		
	90 mm	100 mm	110 mm
1	11.06	11.06	11.59
2	11.07	12.22	12.83
3	12.36	12.91	13.51
4	-	12.12	12.76
5	-	13.28	14.04
Current, kA	16.155	11.284	12.938

*Block numbering starts from the outermost layer.

Figure 3 presents the quench gradients as functions of the critical current density in superconductor in the coil. The Nb_3Sn strands with Jc(12T, 4.2K) > 3 kA/mm^2 allow reaching the quench gradients above 240 T/m in all the designs.

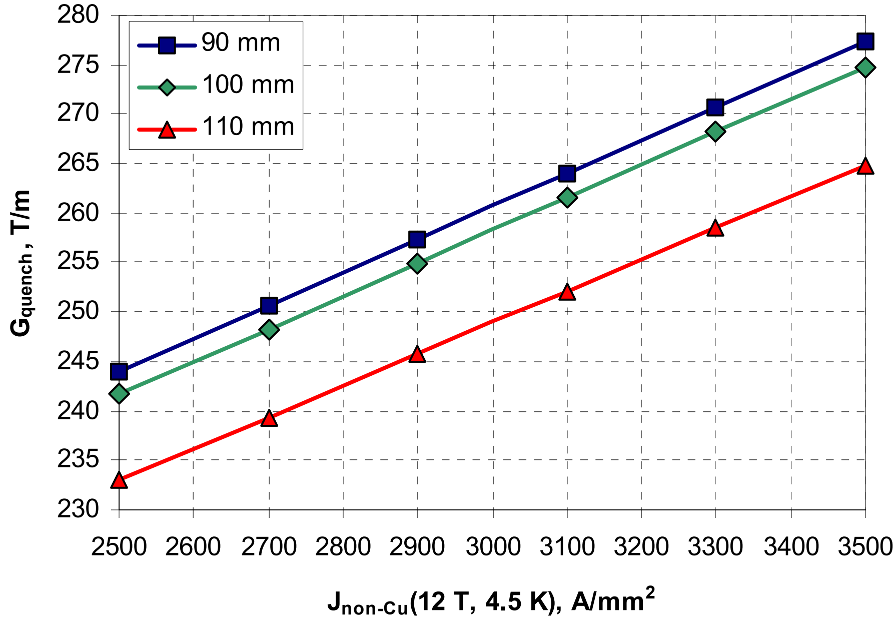

Figure 3. Quench gradients at 4.5 K as functions of the critical current density in the coil.

Magnet parameters

Table 4 summarizes the main magnet parameters of 110-mm and 100-mm 4-layer quadrupoles. For comparison the parameters of 90-mm 2-layer quadrupole are also presented. The quench gradients are reportted for the critical current density in Nb_3Sn coil of 3000 A/mm^2 at 12 T and 4.5 K. The stored energy and Lorentz forces were calculated for the nominal gradient of 205 T/m.

Table 4. Magnet parameters

Parameter		Unit	Aperture size		
			110 mm	100 mm	90 mm
N of layers			4	4	2
N of turns			248	228	144
Coil area (Cu + nonCu)		cm^2	84.88	59.31	48.09
NonCu Jc at 12 T, 4.5 K		A/mm^2	3000	3000	3000
Quench gradient		T/m	248.9	258.2	260.6
Quench current		kA	14.13	12.31	17.64
Peak field in the coil at quench		T	15.28	14.51	13.50
Inductance		mH/m	17.46	14.71	4.86
Stored energy at 205 T/m		kJ/m	1181.4	702.9	468.2
Lorentz forces in the first octant at Gnom=205 T/m	Fx	MN/m	3.44	2.38	1.50
	Fy	MN/m	-3.42	-2.39	-1.92
Maximum coil stress		MPa	99	90	73

Conclusions

As it can be concluded from the presented data, the 110-mm aperture quadrupole magnet can provide the maximum field gradient of 240 T/m (20% above the nominal gradient) with acceptable field quality using the Nb_3Sn strands having Jc(12T, 4.2K) > 3 kA/mm^2. The peak field in the coil at quench exceeds 15 T for this design. The Lorentz forces in the coils are large so that the maximum coil stress approaches to the level of 100 MPa. The stored energies and inductances of 4-layer quadrupoles are significantly larger than the stored energy and inductance of MQXB and the 2-layer 90-mm design. All the above parameters push this design to its technological and operation limits.

References

1. T. Taylor, "Superconducting Magnets for a Super LHC", paper MOYGB002, EPAC2002, Paris (France), June 2002.
2. A.V. Zlobin, G. Ambrosio, N. Andreev, P. Bauer, D. Chichili, Y. Huang, L. Imbasciati, V.V. Kashikhin, M. Lamm, P. Limon, I. Novitski, T. Peterson, J.B. Strait, S. Yadav, R. Yamada, "Conceptual design study of Nb_3Sn low-beta quadrupoles for 2nd generation LHC IRs", Proceedings of 2002 Applied Superconductivity Conference, Houston (USA), August 2002.