Nb_3Sn QUADRUPOLES IN THE LHC IR PHASE I UPGRADE*

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Abstract

After a number of years of operation at nominal parameters, the LHC will be upgraded for higher luminosity. This paper discusses the possibility of using a limited number of Nb_3Sn quadrupoles for hybrid optics layouts for the LHC Phase I luminosity upgrades with both NbTi and Nb_3Sn quadrupoles. Magnet parameters and issues related to using Nb_3Sn quadrupoles including aperture, gradient, magnetic length, field quality, operation margin, et cetera are discussed.

INTRODUCTION

CERN is planning to upgrade two LHC IRs in two phases with a target luminosity for Phase I of ~$2.5 \cdot 10^{34}$ $cm^{-2}s^{-1}$ and up to 10^{35} $cm^{-2}s^{-1}$ for Phase II [1]. In Phase I the baseline 70-mm NbTi low-beta quadrupoles will nominally be replaced with larger aperture NbTi magnets and in Phase II with higher performance Nb_3Sn magnets. U.S.-LARP is working on the development of large aperture high-performance Nb_3Sn quadrupoles for the LHC Phase II upgrade [2]. Recent progress with Nb_3Sn magnets suggests the possibility of using Nb_3Sn quadrupoles in the Phase I upgrade, improving the luminosity through an early demonstration of Nb_3Sn magnet technology in a real accelerator environment.

The final version of Phase I optics and magnet parameters have not been chosen yet. Two preferable optics layouts, Lowbetamax (LBM) and Symmetric (SYM), based on large aperture NbTi quadrupoles are being studied at CERN [3]. LARP is participating in the optimization and study of Phase I upgrade scenarios exploring the advantages and feasibility of using Nb_3Sn quadrupoles to replace either the Q1 or Q3 NbTi quadrupoles. The study includes optics, magnet parameters, operating margins and tracking. The results of LBM and SYM optics and radiation heat deposition analysis are reported in [4]. The main NbTi quadrupole parameters required for these two cases are shown in Table 1. This paper discusses the parameters of Nb_3Sn magnets for hybrid optics layouts for the Phase I upgrade.

Table 1: NbTi quadrupole parameters for LowBetaMax (LBM) and Symmetric (SYM) Phase I optics.

	LBM			SYM		
	Coil ID, mm	L_{mag}, m	G_{nom}, T/m	Coil ID, mm	L_{mag}, m	G_{nom}, T/m
Q1	90	7.060	167.21	130	9.200	121.86
Q2a	130	7.787	-121.37	130	7.800	-121.86
Q2b	130	7.787	-121.37	130	7.800	-121.86
Q3	130	8.711	121.37	130	9.200	121.86

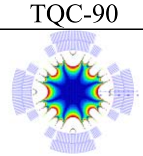
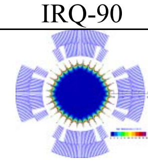
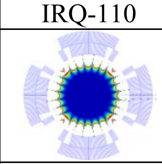
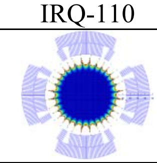
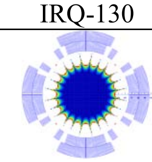
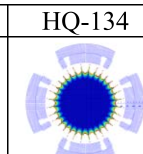
Nb_3Sn QUADRUPOLES FOR PHASE I

To replace NbTi magnets in Phase I optics without impact on the triplet optical functions and other systems, Nb_3Sn magnets should be completely compatible with triplet vacuum, cryogenics, power and quench protection systems. In particular, Nb_3Sn magnets should provide the same focusing strength as the relevant NbTi quadrupoles at the same operation current (~12.5 kA for NbTi quadrupoles based on LHC cables [5]). The operation margin of Nb_3Sn quadrupoles has to be increased with respect to the baseline NbTi quadrupoles to compensate for the earlier state of this new technology.

Magnet Aperture and Parameters

Design studies were performed for Nb_3Sn quadrupoles with apertures ranging from 90 to 134 mm and maximum field gradients at least 20% above the nominal gradient in the NbTi magnets presented in Table 1. Magnet parameters are summarized in Table 2.

Table 2: Basic Parameters of Nb_3Sn IR Quadrupoles for LHC Phase I Upgrade.

	TQC-90	IRQ-90	IRQ-110	IRQ-110	IRQ-130	HQ-134
Coil cross-section						
Coil ID, mm	90		110		130	134
Strand OD, mm	0.7	0.7	0.7	0.8	0.7	0.8
Cable width,mm	10.05	15.14	15.10	15.15	15.10	15.15
B_{max}(1.9K), T	12.9	13.8	14.4	14.5	14.5	15.0
G_{max}(1.9K), T/m	248	268	229	229	193	193
G_{nom}(12.5kA)	208.3	185.6	179.7	168.0	155.9	144.5
G_{max}/Gnom	1.19	1.44	1.28	1.37	1.24	1.34
W(12.5kA),kJ/m	358	384	674	595	923	857
J_{cu}, A/mm^2	2407	1546	1585	1345	1585	1345

* This work was supported by the U.S. Department of Energy.

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Design options were limited by two-layer coils based on a 15-mm wide Nb_3Sn cable (comparable with the LHC NbTi cables). The magnet maximum field and field gradient were calculated for the Nb_3Sn strands with Jc(12T,4.2K)=2.5 kA/mm^2. The parameters in Table 2 characterize the relative complexity of different magnet designs and their operation at the nominal current. The stored energy (and Lorentz forces) increases with magnet aperture, which complicates the magnet mechanical structure and the magnet quench protection.

For comparison, the design parameters of the LARP technology quadrupoles of the TQ series [6]-[7] based on 10-mm wide cable are also presented. Ten 1-m long models of the TQS and TQC series have been fabricated and tested. The maximum field gradient reached in those models was on the level of 200-220 T/m, which is ~15-20% lower that the design values for these magnets at 1.9 K. While the causes of magnet degradation are being investigated, the present level of degradation has to be added to the magnet operation margin. One can see that IRQ-90, IRQ-110 and HQ-134 provide sufficient operation margins required for Nb_3Sn quadrupoles at the present time.

Magnet Length

The Nb_3Sn magnet length is currently limited to 4 meters. This limitation comes from the limited experience with long Nb_3Sn coils which includes two 3.5-m long racetrack coils tested in a common coil configuration [8] and 2-m and 4-m long cos-theta coils tested in a mirror configuration [9]. LARP is working on a 4-m long quadrupole of LQ series to demonstrate the Nb_3Sn technology scale up for large aperture quadrupoles [10]. Thus, the 8-9 m long NbTi Q1 or Q3 quadrupoles in both Phase I optics layouts have to be replaced by two ~4-m long or shorter Nb_3Sn magnets with appropriate gradient.

To study the magnetic coupling between two closely placed coils, the magnet end gradient and field harmonics were calculated for two values of coil-to-coil gap. The gap of 50 mm corresponds to the minimal distance between the coils installed in the same iron yoke. The gap of 250 mm corresponds to the case of two independent cold masses placed in the same cryostat.

Fig. 1 shows the relative coil end position with a coil-to-coil gap of 50 mm. Figs. 2 and 3 show the variation of magnet gradient and b_6 between magnets with coil-to-coil gaps of 50 and 250 mm. As can be seen, in both cases there is no magnetic coupling between the two coils. Thus, they should be considered as independent magnets in optics and tracking analysis.

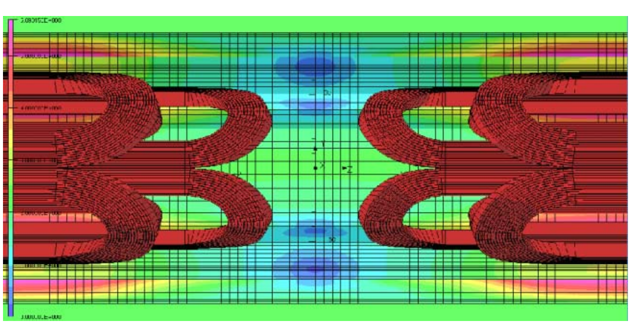

Figure 1: Coil end position with coil-to-coil gap of 50mm.

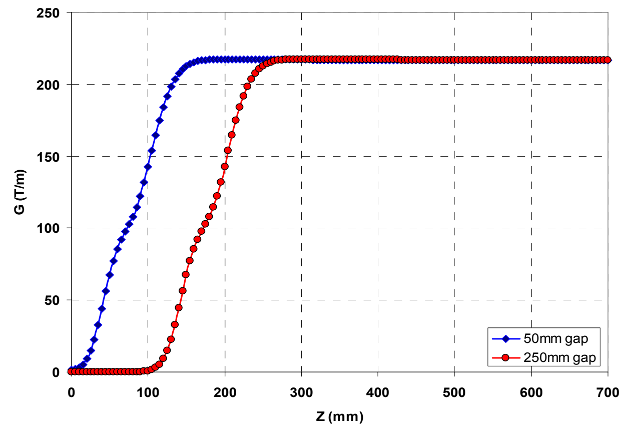

Figure 2: Longitudinal variation of field gradient between magnets.

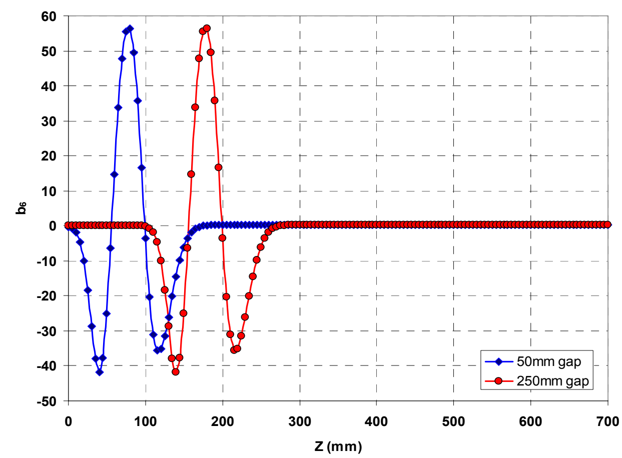

Figure 3: Longitudinal variation of b_6 between magnets.

Field Quality

Field quality and its reproducibility for Nb_3Sn IR quadrupoles was estimated based on magnetic measurements of five LARP TQ short models [11]. The systematic low-order harmonics and their RMS spread at the reference radius equal to half of the coil aperture are reported in Table 3.

Table 3: Systematic Field Harmonics and Their RMS Spread at R_{ref} = 22.5 mm

n	Systematic		RMS	
	b_n	a_n	b_n	a_n
3	-0.40	0.43	1.87	2.46
4	0.51	-1.56	1.10	3.42
5	0.81	3.81	3.55	3.74
6	-6.70	-0.27	0.35	0.70
7	0.02	-0.22	0.12	0.19
8	-0.02	-0.16	0.16	0.32
9	0.07	-0.14	0.11	0.13
10	0.14	0.00	0.08	0.05

The harmonics RMS spread in Nb_3Sn 90-mm TQ models and NbTi 70-mm LHC IR quadrupoles of the HGQ series [12] are plotted in Fig. 4. A comparison of TQ and HGQ data shows that the RMS spread of geometrical harmonics in Nb_3Sn quadrupoles is a factor of 3 larger then the harmonics spread in NbTi quadrupoles. This is also consistent with the observation in Nb_3Sn dipole models [13].

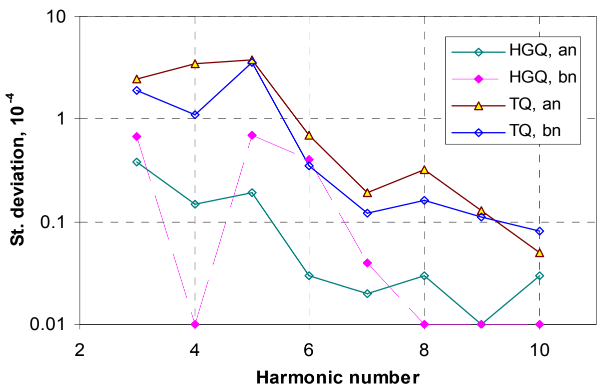

Figure 4: Normal b_n and skew a_n random errors in 5 Nb_3Sn TQ and 8 NbTi HGQ models.

Analysis of field quality in Nb_3Sn model magnets (both dipoles and quadrupoles) shows that they have quite large persistent current effects in low-order allowed harmonics due to the large effective filament size in the state-of-the-art high-Jc Nb_3Sn strands. However, it was shown that this effect can be reduced by reducing the Deff or compensated using relatively simple passive correction [13]. The eddy current effects in present Nb_3Sn models are also quite large and vary from magnet to magnet, which is likely due to inter-strand contact resistance variations in the cable. This effect can be reduced by using a stainless steel core inside the cable. The long-term decay and snap-back effects were not observed in either of the Nb_3Sn TQ models. This is different from the results of NbTi HGQ and MQXB magnets which exhibited prominent decay and snap-back effects. However, it is consistent with the absence of snap-back in other Nb_3Sn magnets made of similar conductors [14].

CONCLUSIONS

Designs and parameters of Nb_3Sn quadrupoles with apertures from 90 mm up to 134 mm were studied. Quadrupoles with 90, 110 and 130 mm with large operation margin of ~40% were used in optics and operation margin studies. The field quality of Nb_3Sn quadrupoles was estimated based on the data for five 90-mm LARP TQ models. Studies of the effects of field quality in Nb_3Sn quadrupoles are in progress.

The experience with TQ models suggests that the 90-mm design is most ready for use in the Phase I upgrade as Q1 in both LBM and SYM optics. Quadrupoles with 110-130 mm aperture can provide a larger aperture margin and could be used as Q1 or Q3 in LBM or SYM optics. The 130-mm quadrupoles are the most complicated magnets with the most challenging performance parameters. It is unlikely that they could be ready for installation in Phase I on time. The 110-mm quadrupoles have sufficient aperture and operation margin, and more realistic operation parameters. They have the greatest flexibility for installation in Phase I and would pave the way toward IR quadrupoles for the Phase II upgrade.

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