Large-Aperture Nb_3Sn Quadrupoles for 2nd generation LHC IRs[1]

A.V. Zlobin*, E. Barzi, D. Chichili, Yu. Huang, V.V. Kashikhin, M. Lamm,
P.J. Limon, N. Mokhov, I. Novitski, T. Peterson, J.B. Strait, S. Yadav
Fermilab, P.O. Box 500, Batavia, IL 60510

Abstract

The 1st generation of low-beta quadrupoles for the LHC interaction region (IR) was designed to achieve the nominal LHC luminosity of 10^{34} $cm^{-2}s^{-1}$. Given that the lifetime of the 1st generation IR quadrupoles is limited by ionizing radiation to 6-7 years, the 2nd generation of IR quadrupoles has to be developed with the goal to achieve the ultimate luminosity up to 10^{35} $cm^{-2}s^{-1}$. The IR quadrupole parameters such as nominal gradient, dynamic aperture and physical aperture, operation margins are the main factors limiting the machine performance. Conceptual designs of 90-mm aperture high-gradient quadrupoles, suitable for use in 2nd generation high-luminosity LHC IRs with the similar optics, are presented. The issues related to the field gradient, field quality and operation margins are discussed.

1 INTRODUCTION

The Large Hadron Collider (LHC) is designed for the collision of proton beams in four interaction regions (IRs) with the nominal energy of 7 TeV per beam and nominal luminosity in two high-luminosity IRs of 10^{34} $cm^{-2}s^{-1}$. The 1st generation of low-beta quadrupoles for the LHC IR inner triplets based on NbTi superconductor have been developed and are being fabricated by KEK (MQXA) and Fermilab (MQXB) in collaboration with CERN [1,2]. They provide a nominal field gradient of 205 T/m with a 20% margin at the high luminosity insertions with 70-mm coils, and operate at 1.9K under high radiation in two high-luminosity IRs. Based on the radiation dose, an estimate of the low-beta quadrupoles lifetime in the high luminosity IRs is about 6-7 years.

In order to reach the highest possible luminosity a new generation of low-beta quadrupoles is required. These magnets should utilize superconductors with higher than NbTi critical parameters, and materials and components with higher radiation strength. At the present time there are several classes of superconducting materials that have higher critical temperature to provide the required operation margin, and higher critical field and critical current to reach the same or even higher field gradient in the same or larger aperture. However, only Nb3Sn superconductor is produced on the commercial level at a sufficiently reasonable price and rate in the form of multifilament stabilized strands to be considered as a real candidate for these magnets.

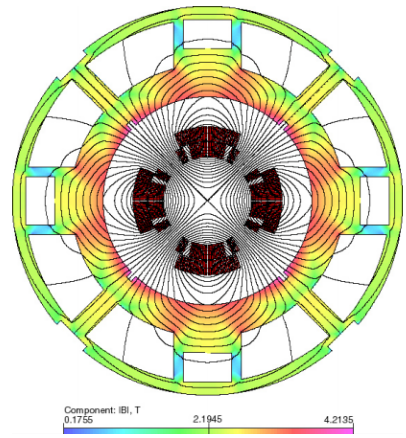

Figure 1: Optimized 90-mm quadrupole cross-section.

This paper present possible 2nd generation IR quadrupoles for the high-luminosity LHC IRs with larger aperture and possibly higher field gradient based on the Nb3Sn superconductor with the lifetime acceptable for reliable LHC operation at highest possible luminosities.

2 QUADRUPOLE DESIGN AND PARAMETERS

The results of previous studies [3] show that the 90-mm Nb3Sn low-beta quadrupoles proposed for the LHC high-luminosity IR upgrade are feasible. Their major parameters meet the preliminary requirements to these magnets allowing a reduction of β* by a factor of two in the interaction point. This increases the luminosity by a factor of two. Further luminosity increase could be reached increasing the beam currents.

The 90-mm quadrupole coil cross-section was further optimized for the best geometrical field quality with minimal number of wedges, thick 30-mm collars and operation current below 15 kA. It has 36 turns per octant grouped in 3 blocks. The coil uses Rutherford cable made of 42 Nb3Sn strands 0.7 mm in diameter and insulated with ~0.18 mm thick high-temperature insulation.

The iron yoke was optimized with additional constraints including the yoke outer diameter of 400 mm (as for MQXB) and maximum hole cross-section area allowed by the field quality requirements necessary for the longitudinal heat transfer inside the cold mass at the ultimate luminosity. The optimized using OPERA 2D code quadrupole coil and yoke cross-sections are shown in Figure 1. Eight large holes with total area of 400 cm^2

[1] Work supported by the U.S. Department of Energy
*E-mail address: zlobin@fnal.gov

serve for the heat transfer and four rectangular holes are reserved for electrical buses and instrumentation. The holes occupies a significant fraction of the iron cross-section reducing its radial mechanical rigidity. It requires using strong 30-mm thick stand-alone collars for coil mechanical support. The nominal field gradient of 205 T/m is reached at the nominal currents of 14.1 kA.

The systematic and random (due to ±50 μm block displacement) geometrical harmonics are shown in Table 1. The design provides systematic geometrical harmonics an order of magnitude better than in present 70-mm MQXB design. For the assumed quite large random block displacements, the calculated harmonics RMS spread is close or better (except few low order harmonics) than for MQXB where block displacement was within ±15 μm. The yoke saturation effect is suppressed to 10^{-4}.

Table 1: Geometrical harmonics at 17 mm radius, 10^{-4}.

n	Systematic b_n		Random (±50 μm block displacement) σ_{an}/σ_{bn},	
	Nb3Sn IRQ	MQXB	Nb3Sn IRQ	MQXB
3	-	-	1.114	0.28/0.26
4	-	-	0.456	0.37/0.08
5	-	-	0.172	0.15/0.07
6	0.0002	-0.013	0.069	0.05/0.17
7	-	-	0.025	0.03/0.03
8	-	-	0.009	0.01/0.00
9	-	-	0.003	0.01/0.00
10	0.0005	-0.001	0.001	0.00/0.01

In order to correct large coil magnetization effect in Nb3Sn magnets, simple passive correction approaches were developed and successfully tested in Nb3Sn dipole models [4,5]. In the case of quadrupole magnet one iron strip placed on top of the wedge in the inner layer reduces b6 at low fields by a factor of four to the level less than in MQXB. If necessary the coil magnetization effect could be also reduced using more expensive PIT Nb3Sn strands with effective filament diameter ~20-30 μm.

Figure 2 presents the maximum field gradient in magnet bore at 1.95 K or 4.5 K operation temperature versus the critical current density of the Nb3Sn cable in

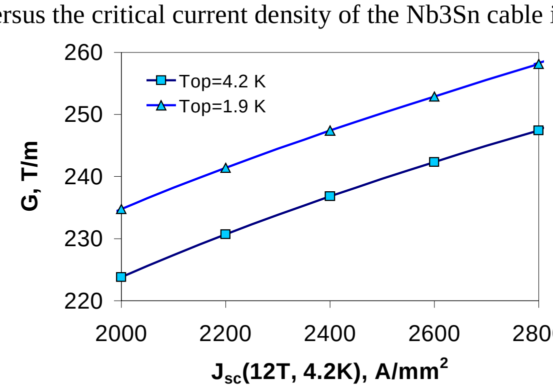

Figure 2: The maximum field gradient versus the critical current density of Nb3Sn cable in the coil.

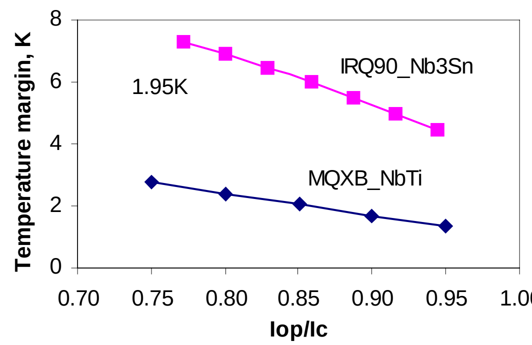

Figure 3: Critical temperature margin for the Nb3Sn quad and MQXB versus the critical current margin.

the coil. In order to provide the nominal field gradient of 205 T/m with 15-20% critical current margin, the critical current density of Nb3Sn strands at 12 T and 4.2 K has to be 2400-2500 A/mm^2 for operation at 1.95 K or 2800-3000 A/mm^2 for operation at 4.5 K (including 10% critical current degradation during cabling).

The magnet critical temperature margin dTc, determined by the inner-layer midplane turns for the Nb3Sn quadrupole and for the NbTi MQXB versus the magnet critical current margin, is shown in Figure 3. At Top=1.95 K the critical temperature margin of Nb3Sn quadrupoles are a factor of three higher than dTc of NbTi MQXB. Even at Top=4.5 K the critical temperature margin of Nb3Sn quadrupoles is still a factor of two higher than the MQXB margin.

The luminosity increase leads to a growth of the radiation-induced heat depositions in the magnets increasing the coil local temperatures and the total heat load on magnet cold masses. To determine the quench limits and operation margin of Nb3Sn quadrupoles a thermal analysis was performed using a 2-D ANSYS thermal model. The model included the inner and outer coil layers, the ground insulation, and the stainless steel collars. Boundary conditions included constant HeII temperature of 1.9 K in the annular channel and on the outer surface of the coil.

Figure 4 present the calculated quench limits for the inner-layer midplane turns of Nb3Sn IRQ and NbTi MQXB versus the critical current margin at Top=1.95 K.

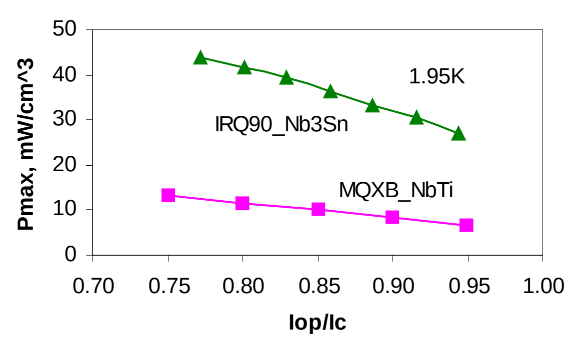

Figure 4: Quench limits for Nb3Sn IRQ and NbTi MQXB (inner-layer midplane turns) versus the critical current margin at Top=1.95 K.

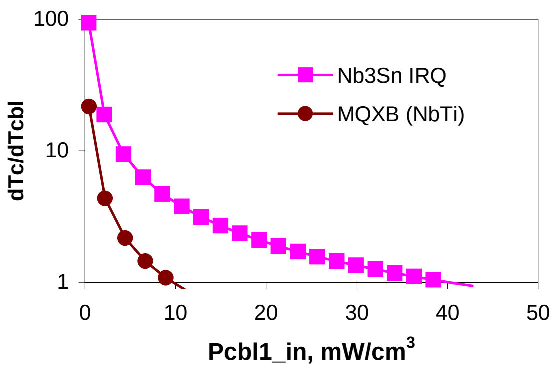

Figure 5: Magnet operation margin versus the maximum energy deposition in the inner-layer mid-plane turn for the Nb3Sn IR quadrupoles and present NbTi MQXB.

The operation margin is defined as a ratio of the turn critical temperature margin dTc to the turn temperature rise dTcbl. Figure 5 shows the dependence of magnet operation margin versus the maximum energy deposition in the inner-layer mid-plane turn for the Nb3Sn IR quadrupoles and for NbTi MQXB. The energy deposition at nominal LHC luminosity is 3.6 mW/cm^3. According to the calculations, the Nb3Sn IR quadrupoles at Gnom=205 T/m and Tnom=1.9 K can operate at heat load level a factor of 10 higher than the nominal one.

Data presented above for the magnet quench limits and operation margins are valid if the He nominal temperature does not increase dramatically with the heat load variations. In case of operation at 1.95 K the temperature of superfluid HeII is determined by heat transfer conditions inside the magnet cold mass. Analysis shows that periodic radial heat transport, about every 0.5 m, out to the yoke holes is necessary for heat transport and also for quench pressure venting in order to avoid collapse of the beam tube. The calculated total cold mass axial heat transport cross-sectional area versus the total cold mass heat flux for 10 mK and 50 mK temperature increase is shown in Figure 6.

Analysis shows that for heat loads up to about 400 W, the present cryogenic system including yoke hole size is adequate. Although the cold mass described here is capable of greater than a 400 W heat load, other factors in

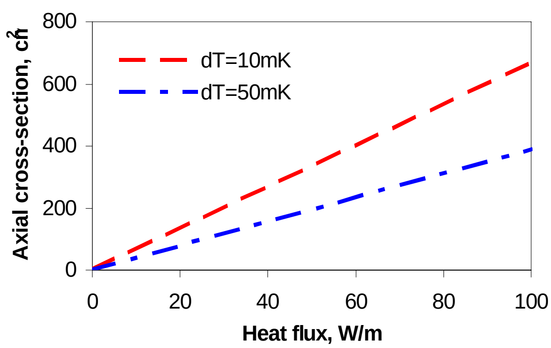

Figure 6: Total cold mass axial heat transport cross-sectional area versus total cold mass heat flux.

the present IR cryogenic system may limit heat removal beyond 400 W. One can consider options for reducing heat deposited to the 1.9 K level, such as a 4-20 K internal liner, a thinner cold mass with warm iron, or a magnet entirely cooled at T=4.5 K.

3 CONCLUSIONS

Analysis shows that the 90-mm quadrupole magnets based on the Nb3Sn two-layer shell-type coils can provide the nominal field gradient of 205 T/m with sufficient critical current and large critical temperature margins using state of the art Nb3Sn strands. The expected systematic and random field harmonics are comparable or even better than reached in MQXB. The nominal field gradient of 205 T/m is achieved at nominal currents less than 16 kA making these magnets compatible with present power system that includes power supply and current leads.

The size of magnet cold mass is the same as the size of MQXB cold mass which allows using the available quadrupole cryostat and triplet cryogenics system including feed boxes and HeII heat exchanger. Above 400 W total heat load, factors other than cold mass heat transport may limit heat removal. Operational experience with the present LHC IR cryogenic system will be important for understanding these other thermal limitations and to what extent modifications to the cryostats and cryogenic system would be required.

4 REFERENCES

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