Conceptual Design Study of Nb_3Sn Low-beta Quadrupoles for 2^{nd} Generation LHC IRs

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***Abstract*—Conceptual designs of 90-mm aperture high-gradient quadrupoles based on the Nb_3Sn superconductor, are being developed at Fermilab for possible 2^{nd} generation IRs with the similar optics as in the current low-beta insertions. Magnet designs and results of magnetic, mechanical, thermal and quench protection analysis for these magnets are presented and discussed.**

***Index Terms*—Accelerator magnet, low-beta quadrupole, Nb_3Sn superconductor.**

I. 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 the nominal luminosity in two high-luminosity IRs of 10^{34} $cm^{-2}s^{-1}$. The 1st generation 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 with 70-mm bore coils, and operate at 1.9 K under high radiation in two high-luminosity IRs.

In order to reach the highest possible luminosity a new generation of low-beta quadrupoles is required [3]. The previous studies [4] show that an increase of the magnet aperture from 70 mm to 90 mm or more is one the most attractive ways of IR quadrupole upgrade. These magnets should also 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 superconductors 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 Nb_3Sn is produced on commercial level in the form of multifilament stabilized strands and allows considering it as a real candidate for these magnets.

Based on the radiation dose, an estimate of the low-beta quadrupoles lifetime in the high luminosity IRs is about 6-7 years. The components that restrict the lifetime of present NbTi magnets in hard LHC IR radiation environment are the G11 end parts. Recent progress in magnet technology allows using metallic end parts and epoxy-free insulating materials [5] in new generation LHC IR quadrupoles.

This paper reports the results of study of 2nd generation IR quadrupoles for the high-luminosity LHC IRs with larger aperture and possibly higher field gradient based on the Nb_3Sn superconductor acceptable for reliable LHC operation at highest possible luminosities.

II. DESIGN AND PARAMETERS

A. Magnetic Design

Two 90-mm quadrupole coil cross-sections optimized for the best geometrical field quality using ROXIE code are shown in Fig. 1. Design I (left) consists of 37 turns/octant combined in 4 blocks. Design II (right) has 36 turns/octant grouped in 3 blocks. Both designs utilize Rutherford cables made of 42 Nb_3Sn strands 0.7 mm in diameter and insulated with 0.2 mm thick high-temperature insulation.

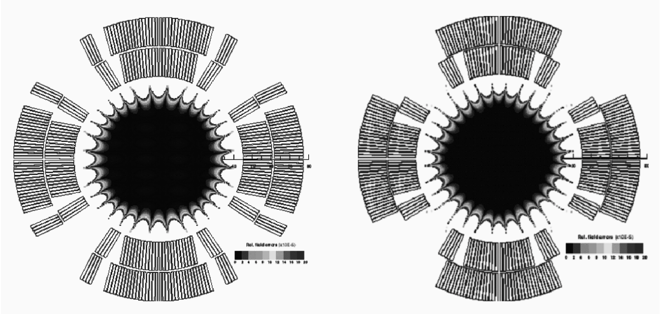

Fig. 1. The quadrupole coil cross-sections.

The iron yoke was optimized using OPERA 2D code. The additional constraints included the yoke outer diameter of 400 mm (as in MQXB) and maximum hole cross-section area, necessary for the longitudinal heat transfer inside the cold mass at the ultimate luminosity and consistent with the field quality requirements. The optimized yoke cross-section for design II is shown in Fig. 2. Eight large holes with total area of 400 cm^2 serve for the heat transfer and four rectangular holes are reserved for electrical buses and instrumentation. The holes occupy significant fraction of the iron cross-section area reducing its radial mechanical rigidity, therefore the coil prestress and radial mechanical support is provided by strong 30 mm thick stand-alone collars.

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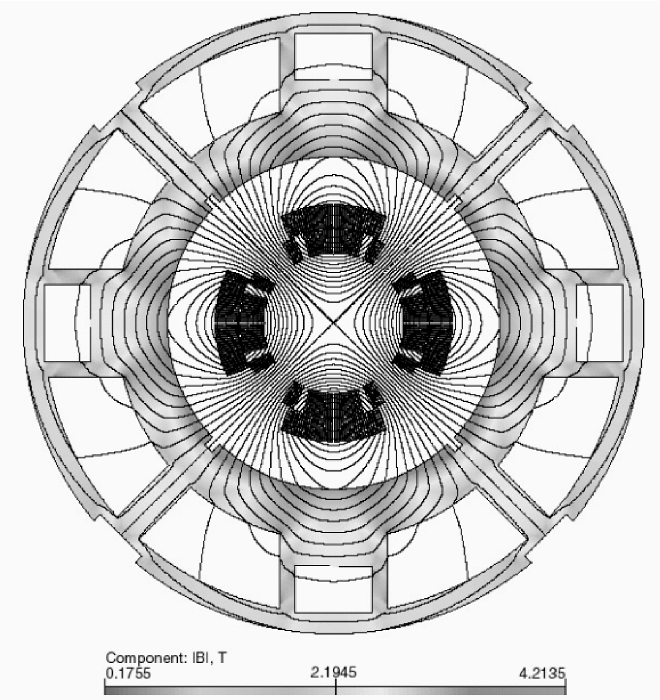

Fig. 2. The optimized iron yoke cross-section.

The geometrical harmonics for design I and II are shown in Table I. Both designs provide systematic harmonics an order of magnitude better than the 70-mm MQXB design.

TABLE I
GEOMETRICAL HARMONICS AT 17 MM RADIUS, 10^{-4}

n	Systematic b_n		
	Design I	Design II	MQXB
6	0.00029	0.00018	-0.013
10	0.00002	0.00048	-0.001

The effects of coil magnetization at low field gradients and iron saturation at high gradients on b_6 are shown in Fig. 3 and Fig. 4. Even with the restriction on the iron OD and cooling channel size it is possible to suppress the iron saturation effect using the holes in the yoke to the level of ~10^{-6}.

In order to correct the large coil magnetization effect in Nb_3Sn magnets with large (~100 μm) effective filament size, simple passive correction based on thin iron strips was developed and successfully tested in Nb_3Sn dipole models [6,7]. In the proposed Nb_3Sn quadrupoles one iron strip placed on top of each inner-layer wedge reduces b_6 at low fields by a factor of four to the level less than in MQXB. The coil magnetization effect could be also reduced using PIT Nb_3Sn strands with the effective filament diameter of 20-30 μm.

Fig. 5 presents the maximum field gradient at 1.95 K and 4.5 K operation temperature versus the critical current density of the Nb_3Sn cable in the coil with Cu/nonCu=1.2. In order to provide the field gradient of 205 T/m with 15-20% critical current margin, the critical current density of Nb_3Sn 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% Ic degradation during cabling).

The nominal field gradient of 205 T/m is reached in the described quadrupoles at a nominal current of 14.1 kA.

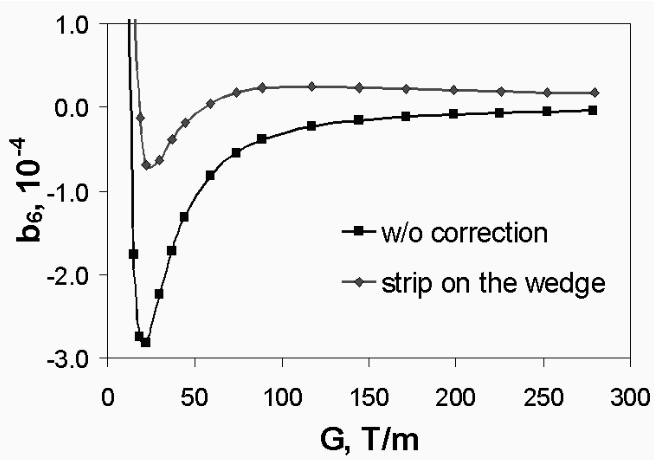

Fig. 3. The coil magnetization effect in b_6 at R_{ref}=17 mm.

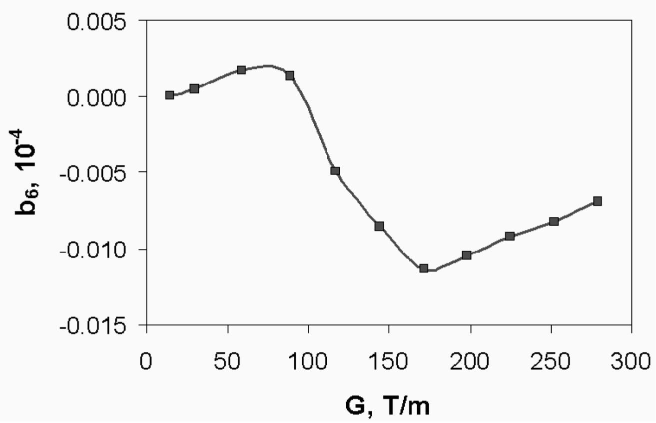

Fig. 4. The iron saturation effect in b_6 at R_{ref}=17 mm.

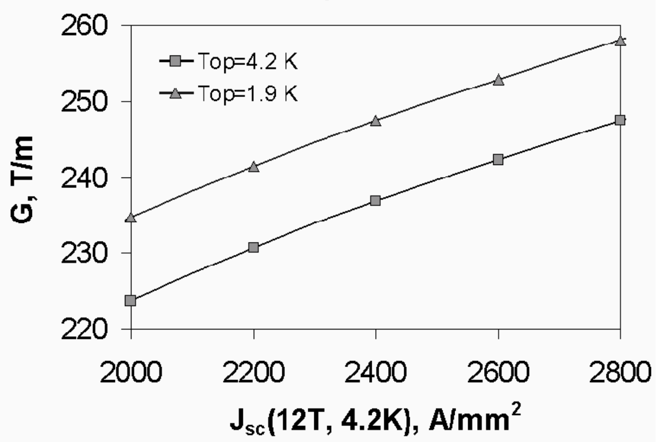

Fig. 5. The maximum field gradient vs. the critical current density of Nb_3Sn cable in the coil.

B. *Mechanical Analysis*

Coil support structure stabilizes field harmonics in operation cycles as well as reduces the probability of spontaneous quenches due to turn motion. There are two options to support the coil for the proposed magnets: a) with rigid stand-alone collars and b) with iron yoke and thick skin. The later is being used in most of the high field accelerator magnets. However, since large cooling holes reduce the radial mechanical rigidity of the iron yoke, the stand-alone collar structure has certain advantages and was chosen for the further analysis.

TABLE II
STRESS IN THE COIL AND IN THE COLLAR

Stages	Azimuthal Stress, MPa				Peak Collar Stress
	Inner Coil		Outer Coil		
	Mid-Plane	Pole	Mid-Plane	Pole	MPa
Before Spring Back	125	98	58	85	361
After Spring Back	50	31	41	38	481
4.2 K, 0 T/m	43	21	21	27	272
4.2 K, 240 T/m	134	0	83	16	800

Two variants of this design were analyzed. The first design is similar to the MQXB design in which the pole area is a part of the collar. The required pre-stress to the coil is delivered through azimuthal coil oversizing. The second design is with round collars in which the pole pieces are a part of the impregnated coil. The required pre-stress in the coil is typically achieved by radial compression of the coils through radial interference of the coil and the collar structure. The later simplifies the fabrication process. However, the first variant provides better stiffness to the collar structure, which helps to maintain the pre-stress in the coil.

The acceptable mechanical criteria are:

- The peak stress in the coil is less than 150 MPa to prevent the irreversible critical current degradation of brittle Nb_3Sn.
- The minimum coil stress is more than 5 MPa at nominal gradient to ensure the coils are under compression.
- The maximum collar stress is less than the yield stress of the collar material.
- Maximum coil displacements under Lorentz forces are less than 0.1 mm to prevent spontaneous quenches and to provide harmonics stability in operation cycles.

Mechanical analysis of the two possible coil support structures shows that the regular collar design meets all the above criteria (see Table II) whereas for the round collar design the coil starts to unload. The assembly procedure for the round collar design is being looked into to reduce the spring-back effect so that the pre-stress in the coil could be higher avoiding the unloading of coil at peak gradient. For both the structures the turn radial and azimuthal motion under the Lorentz force is practically within the required range. The peak equivalent stress in the major elements of coil support structure is less than the yield stress of the materials used.

C. Thermal Analysis

Magnet critical temperature margin dT_c, determined by the inner-layer midplane turns, versus the critical current margin is shown in Fig. 6 for Nb_3Sn quadrupoles and for the NbTi MQXB. At 1.95 K the critical temperature margin of Nb_3Sn quadrupoles is a factor of three higher than dT_c of the NbTi MQXB. Even at 4.5 K the critical temperature margin of Nb_3Sn quadrupoles is still a factor of two higher than the MQXB margin at 1.95 K.

An increase of the luminosity leads to a growth of radiation-induced heat depositions in the magnets [8] increasing the coil local temperatures and the total heat load on magnet cold masses. To determine the quench limits and operation margin of Nb_3Sn quadrupoles a thermal analysis was performed using a 2D 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 1.95 K in the annular channel and on the outer surface of the coil.

Fig. 7 present the calculated quench limits for the inner-layer midplane turns of the Nb_3Sn quadrupole and NbTi MQXB versus the magnet critical current margin at 1.95 K. The calculated energy deposition at nominal LHC luminosity is 3.6 mW/cm^3. Fig. 7 shows that at 1.95 K the Nb_3Sn quadrupoles with G_{nom}=205 T/m can operate at heat load a factor of 10 higher than the nominal one. At 4.5 K the operation margin will be lower due to the lower dT_c but still sufficient for heat load increase by a factor of 5.

Presented above data for the magnet quench limits and operation margins are valid if the He nominal temperature does not change dramatically with the heat load variations. In case of operation at 1.95 K the temperature of superfluid HeII is determined by the heat transfer conditions inside the magnet cold mass. Analysis shows that a radial heat transport out to the yoke holes is important. Radial channels spaced less than 0.5 m, necessary also for quench pressure venting in order to avoid collapse of the beam tube, are very effective.

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 Fig. 8. As it can be seen, the holes in the iron yoke shown in Fig. 2 with total area of 400 cm^2 allow restricting the HeII temperature rise inside the cold mass by 10 mK for heat flux up to 60 W/m.

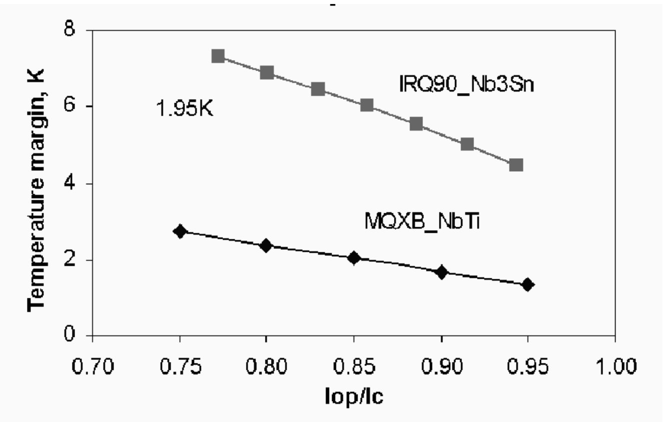

Fig. 6. The critical temperature margin for the Nb_3Sn quadrupole and NbTi MQXB vs. the magnet critical current margin.

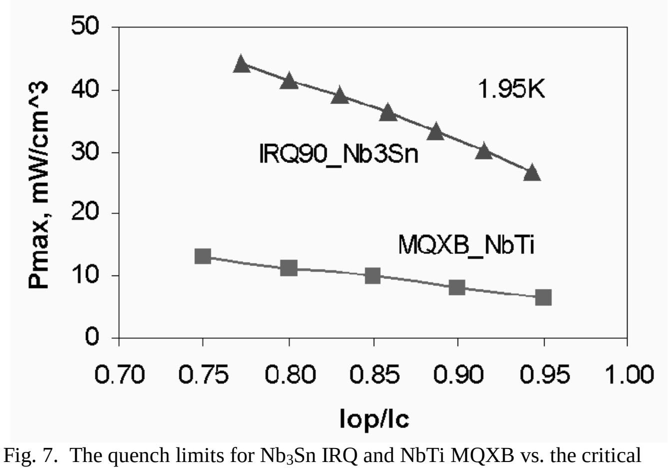

Fig. 7. The quench limits for Nb_3Sn IRQ and NbTi MQXB vs. the critical current margin at T_{op}=1.95 K.

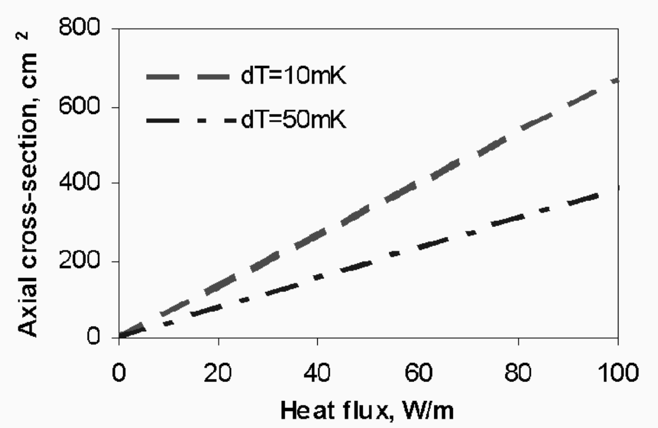

Fig. 8. The cold mass axial heat transport cross-sectional area vs. the cold mass heat flux.

D. *Quench Protection*

Due to a larger aperture, the 90-mm Nb_3Sn quadrupoles have a nominal stored energy by a factor of two higher than the 70-mm MQXB. That certainly complicates their quench protection. The main dangers for the superconducting magnet during a quench are coil overheating and associated with that mechanical overstress as well as high voltages between turns and between coil and ground. The limitations were set to 300 K for the peak coil temperature, 1 kV for the maximum turn to ground voltage and 100 V for the maximum turn to turn voltage. First experiments indicate that the Nb_3Sn coils can be heated up to 420 K after a quench without permanently degrading the brittle superconductor [9]. However, it is reasonable at this stage to set a lower temperature limit since the effect of repeated temperature excursions over the magnet lifetime is not well known. The above voltage limits are in agreement with the data for insulation impregnated with epoxy or polyimid and include a large safety factor [5,10].

A summary of the quench analysis for 6-m long 90-mm Nb_3Sn quadrupole is given in Table 3. The analysis assumes a total heater delay of 30 ms. The voltages and temperatures listed in the table are below or at the limits for a 30% heater coverage. Quench heaters placed on the outer coils provide a 55% heater coverage required for reliable magnet protection.

Another important quench protection parameter is the Cu/nonCu ratio. Given cable dimensions as required by the magnetic design the Cu/nonCu ratio, together with the critical current density in the superconductor, determines the current density in the copper matrix during a quench. Simulations show that the choice of Cu/nonCu=1.2 and a minimum 25% heater coverage are compatible with the temperature and voltage limits.

TABLE III
QUADRUPOLE QUENCH PROTECTION PARAMETERS

Heater coverage (%)	25	50
Max. hot spot temperature (K)	315	230
Max. temperature underneath heaters (K)	180	127
Max. coil-to-ground voltage (V)	420	407
Max. turn-to-turn voltage (V)	65	30

III. CONCLUSION

The results of conceptual design studies show that 90-mm Nb_3Sn low-beta quadrupoles proposed for the LHC high-luminosity IR upgrade are feasible. Their major parameters meet the preliminary requirements for these magnets. The quadrupole magnets based on the two-layer shell-type coils can provide the nominal field gradient of 205 T/m with required critical current and large critical temperature margins using state of the art Nb_3Sn strands. The expected field harmonics are comparable or even better than those reached in MQXB design.

The nominal field gradient of 205 T/m is achieved at nominal currents less than 15 kA making these magnets compatible with present power supply and current leads. The size of the magnet cold mass is the same as the size of MQXB cold mass which in case of operation in superfluid HeII allows using the available quadrupole cryostat and triplet cryogenics system including feed boxes and HeII heat exchanger. For operation at 4.5 K a new cryostat will be required.

The quench protection analysis shows that it is possible to operate the proposed Nb_3Sn quadrupolets with a nominal field gradient of 205 T/m and magnetic length of 6-7 m within the temperature limit of 300 K providing a minimum heater coverage of 25%. A 50% coverage for redundancy can be provided by placing the heaters on the coil outer surface as in MQXB quadrupoles.

The presented magnets have a lot of potential for design optimization and require significant efforts for development of their technologies. Some important parameters such as magnet training, training memory, field quality, reproducibility of main parameters from magnet to magnet, etc., that depend not only on magnet design but also on its technology as well as magnet long-term performance in real operation conditions have to be studied and optimized experimentally.

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