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for the LHC Interaction Regions**

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Development of a High Gradient Quadrupole for the LHC Interaction Regions

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Abstract - A collaboration of Fermilab, Lawrence Berkeley National Laboratory and Brookhaven National Laboratory is engaged in the design of a high gradient quadrupole suitable for use in the LHC interaction regions. The cold iron design incorporates a two-layer, $\cos(2\theta)$ coil geometry with a 70 mm aperture operating in superfluid helium. This paper summarizes the progress on a magnetic, mechanical and thermal design that meets the requirements of maximum gradient above 250 T/m, high field quality and provision for adequate cooling in a high radiation environment.

I. INTRODUCTION

Fermilab, Lawrence Berkeley National Laboratory (LBNL) and Brookhaven National Laboratory (BNL), have formed a consortium to provide components for the Large Hadron Collider (LHC) [1] to be built at CERN in Geneva, Switzerland. A proposed U.S. contribution is the high gradient quadrupoles (HGQ) for the interaction regions. These magnets have to provide a nominal field gradient of 235 T/m and high field quality in the large aperture of 70 mm at magnet length of 5.5 m. They also must operate in superfluid helium with a beam induced heat load of up to 40 Watts per magnet. This paper describes the status of the project as of this date.

II. MAGNET DESIGN

2.1 Design Description

The current design of the HGQ consists of four, two layer shell-type coils connected in series. A two-layer geometry was chosen based on quench protection, thermal and mechanical considerations, because it provides lower inductance as well as better coil cooling and support as compared to a four-layer design concept [2]. Moreover, this approach rests solidly on our past experience, and allows the use of existing tooling.

Figure 1 shows the conductor distribution for one octant of the magnet. Two keystoneed Rutherford-type NbTi cables based on the SSC type strands are used, one for each layer. Both cables have the same width of 15.4 mm but different

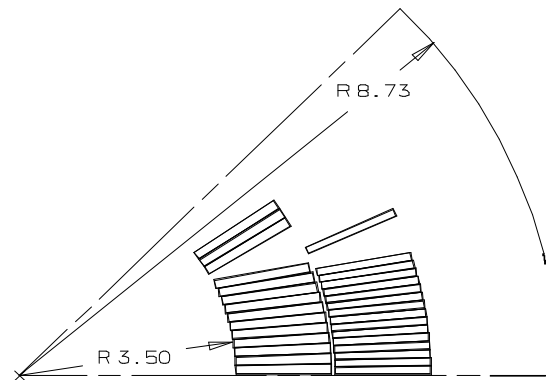


Figure 1. Two layer HGQ coil cross-section.

mid-thickness of 1.457 mm for the inner layer cable and 1.146 mm for the outer one. The cables are insulated with a multilayer Kapton insulation having 75 μm azimuthal and 100 μm radial thickness. Each of the four coils consists of 14 turns in the inner layer, and 16 turns in the outer layer. The interlayer insulation thickness is 0.483 mm and the half-thickness of the mid-plane insulation is 0.202 mm for both layers. Each octant has two spacers, one for each layer, which allow a fine adjustment of the field quality. The coil ends have the same blockwise layout of turns as in the magnet body. The turn positions at the ends were optimized to reduce the maximum field and to improve field quality.

The iron yoke has an inner radius of 8.73 cm and an outer radius of 20 cm. Calculations have shown that a 20 cm outer radius allows one to incorporate all holes for electrical bus and heat exchanger without a significant degradation of the field quality. The final optimization of the iron yoke cross-section, however, will take place at a later stage. In order to provide a good operating margin in the coil ends, the iron yoke is terminated at a distance of 10 cm from the end of coil straight section. For this configuration, the peak magnetic field will occur in the straight section of the magnet.

The design low-order harmonics for the quadrupole central field, calculated with ROXIE [3] assuming an iron yoke of infinite permeability, are shown in Table I.

TABLE I
DESIGN HARMONIC COEFFICIENTS IN 10^{-4} UNITS
OF THE MAIN QUADRUPOLE FIELD

N	b_n @ 1cm	b_n @ 2.5cm
6	0.0046	0.17
10	-0.000013	-0.02
14	-0.000018	-1.06

The effect of iron saturation on the field quality has been evaluated using POISOPT [4,5]. The range of variation for b_6 is within 0.025 units at 1 cm reference radius and the effect on higher order harmonics is very small.

2.2 Conductor Development

The parameters of the inner (cable 1) and outer (cable 2) layer cables are listed in Table II.

TABLE II
HGQ CABLE PARAMETERS

Parameter	Unit	Cable 1	Cable 2
Radial width, bare	mm	15.4	15.4
Minor edge, bare	mm	1.326	1.054
Major edge, bare	mm	1.587	1.238
Number of strands		38	46
Strand diameter	mm	0.808	0.648

Since the two-layer design requires cables with large aspect ratio, the mechanical stability of the cable during winding is a critical issue. Samples for both the inner and the outer cable have been produced by LBNL and winding studies have been carried out at Fermilab with successful results [6].

The superconducting cables which are currently being produced for HGQ model magnets use SSC strands, with a nominal $J_c(5T,4.2K)$ of 2.75 kA/mm^2 . The SSC conductor will eventually be replaced with improved conductor that is now under development. The goal of the program is to produce strands with a critical current density $J_c(5T,4.2K)$ of 3.4 kA/mm^2 at a filament diameter of $10 \mu\text{m}$ or less [7].

Table III summarizes the short sample limits for the bore field gradient as well as field and current in each layer for both the existing and the improved conductors. This analysis has been carried out with POISOPT taking into account the nonlinear characteristic of the iron. A 5% cable degradation factor with respect to the nominal current density has been assumed.

As can be seen, for the present SSC conductor the current limit in the outer layer is 0.3 kA smaller than the corresponding limit for the inner layer, although the opposite situation would be more desirable. However, for the improved conductor the lower limit is found in the inner layer.

TABLE III
HGQ SHORT SAMPLE LIMITS

J_c 5T,4.2K kA/mm^2	Field gradient T/m	Inner layer		Outer layer	
		B_{SS} T	I_{SS} kA	B_{SS} T	I_{SS} kA
2.75	250.2	9.8	14.1	8.1	13.8
3.4	268.1	10.3	14.8	8.7	14.9

To provide additional margin, a reduction of the Cu:SC ratio from 1.3 to 1.1 in the inner cable and from 1.8 to 1.6 in the outer one is also envisaged. This will allow one to increase the maximum quadrupole gradient and to provide better temperature margin and higher coil stability against heat pulses in nominal operating conditions.

2.3 Coil Support Structure

The coils are mechanically supported by means of the collar laminations, cold iron yoke and helium vessel skin. Thick end plates are used to restrict the longitudinal coil motion under Lorentz forces.

Aluminum collars, 20 mm wide, provide the initial coil preload to define the coil geometry at room temperature so as to allow warm magnetic measurements to be made. Final coil prestress, necessary to reduce the radial and azimuthal motion of turns under Lorentz force action, is created with the help of a two-piece iron yoke and a welded 8 mm thick stainless steel helium vessel skin. The collar-yoke contact is provided at all temperatures at the 4 mid-plane points. It is ensured by the larger collar than yoke diameter and the collar deflections due to coil preload. After welding, a prestress of 200 MPa is created in the skin at room temperature. Following cooldown skin prestress increases to 400 MPa and the compressive force between iron halves can reach up to $6.5 \cdot 10^6 \text{ N/m}$. This is slightly less than the Lorentz force of $7.4 \cdot 10^6 \text{ N/m}$ at current of 14 kA. To keep the yoke gap closed at this current level, Lorentz force is distributed appropriately between collars and skin. The required distribution is provided by the appropriate collar-yoke interference at helium temperature. At the same time the collar-yoke interference also affects the value of the coil azimuthal prestress at room and helium temperatures.

Finite element analysis using ANSYS has been performed [8] to optimize the azimuthal coil prestress at room temperature and the collar-yoke interference. The lower prestress bound is set by the requirement that the coil stress at a gradient of 250 T/m be $\geq 15 \text{ MPa}$. The upper bound corresponds to the case when the gap between yoke pieces begins to open at room temperature. Additional bounds are set by limits on the peak stress in collar material in the collared coil state and on the maximum stress applied to the insulation. The range of acceptable preload is between the above mentioned limits.

Table IV shows azimuthal compressive stress on the coils during assembly, cooldown, and excitation to 14 kA

for the lower and upper bound cases having the warm undeflected collar-yoke interference of 50 μm .

TABLE IV
AZIMUTHAL COIL PRESTRESS IN THE POLE

Coil mechanical stage	Coil stress, MPa			
	Inner layer		Outer layer	
	Min	Max	Min	Max
Collaring	37	60	25	48
Yoking	60	91	43	71
Cooldown	50	85	36	69
Excitation	14	48	14	48

For the chosen collar-yoke interference of 50 μm , there is a range of acceptable collared coil preload of ± 10 MPa for both layers.

2.4 Magnet Cooling

The HGQ coil is designed to be bath cooled by pressurized superfluid helium at nominal temperature 1.9 K. All heat will be removed from the magnet into the cryogenic system by saturated superfluid helium maintained at 1.8 K. There will be He II heat exchanger in the magnet.

The quadrupole coils in the LHC interaction regions are subject to a steady heat load up to 40 Watts per magnet and a peak energy density as large as 1.2 mW/g at the coil inner-layer mid-planes due to secondary particles from beam-beam collisions at the nominal luminosity. To decrease the radiation induced heat deposition in the coil, the use of a thick (~ 10 mm) beam absorber placed inside the beam pipe has been proposed [9].

The coil temperature rise is determined by the heat deposition and coil cooling conditions and it must be below the coil critical temperature margin. Table V shows the computed temperature rise in the mid-plane turns of the coil inner and outer layers, which are exposed to the maximal heat load. It is assumed that the inner layer cable is cooled through the small cable edge into the annular helium channel and the outer layer cable is cooled through the coil inner layer and collars. Heat depositions given in Table V have been averaged through the cable width.

TABLE V
HEAT LOAD AND CABLE TEMPERATURE RISE
FOR THE MID-PLANE COIL TURNS

Coil layer	Mean heating power, W/m		Cable temperature rise, K	
	without absorber	with absorber	without absorber	with absorber
Inner	0.090	0.038	1.29	0.54
Outer	0.014	0.005	1.17	0.42

For both cases (without or with absorber) coil temperature rise is below its critical temperature margin which is 1.7 K for the mid-plane inner-layer turn and 3.1 K for the outer-layer one. Nevertheless the cable insulation is further optimized in such a way as to provide the best cooling conditions for coil inner layer, as well as required electrical strength and mechanical properties. The goal is to keep the cable temperature below T_λ and to take advantages of the possible penetration of superfluid helium under the cable insulation. Required cable cooling perimeter in this case has to be at least 25% of the inner cable perimeter for the case without absorber and 10% with absorber. To achieve this goal special interturn channels in the coil inner layer are formed by the cable insulation.

The calculated temperature profile within 2 mm wide and 16 mm long He II channel for varying channel height is shown in Fig. 2. As can be seen, a minimum gap of 14 μm is required to keep the superfluid helium temperature inside the channels below 1.95 K [10].

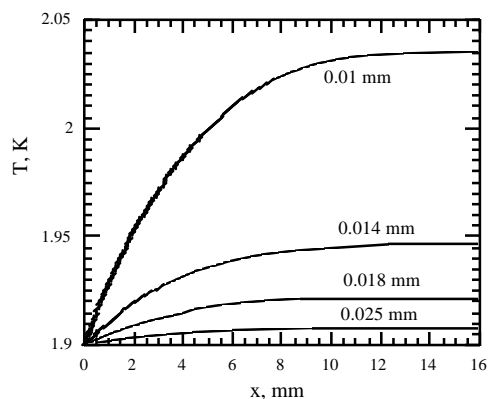


Figure 2. Temperature profile in He II channel for varying channel height for the maximum heat load case.

Based on the above study a two wrap cable insulation scheme is planned. The cables are wrapped with 25 μm thick Kapton tape with a 50% overlap for electrical insulation purposes and one layer of spiral wrapped 50 μm thick Kapton tape for mechanical protection and to provide required He II cooling channels in the coil inner layer.

2.5 Quench Protection

The energy stored in the magnet is 294 kJ/m at nominal current of 13 kA. To protect the magnet during a quench, quench heaters will be used. A two layer design allows one to put the heaters in between the inner and outer layers to increase their efficiency. Each interlayer heater is 2×5.5 m long and can quench one side of 10 inner layer and 15 outer

layer turns in two neighboring coils. The number of heaters in the magnet is 4 (2 of them are operating and 2 are spare).

The computed relationship between T_{\max} and quench integral for the inner and outer cables is presented in Figure 3. To keep the cable maximum temperature after quench below 400 K as in the LHC arc dipoles [1], the quench integral has to be less than $25 \cdot 10^6 \text{A}^2\text{s}$ for the inner layer cable and $17 \cdot 10^6 \text{A}^2\text{s}$ for the outer layer cable.

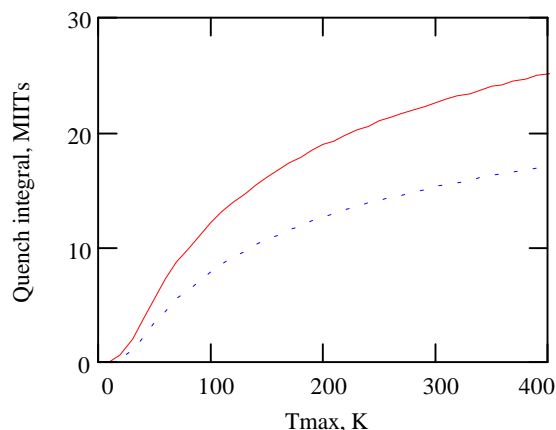


Figure 3. Relationship between the cable maximum temperature and quench integral:
 — - inner layer cable; - outer layer cable.

The maximum value of a quench integral depends on the operating current, quench detection and circuit operation time as well as current decay after heater induced quench. Heater induced quench integral is the same for all turns in the magnet quenched by the heaters and it equals to $11 \cdot 10^6 \text{A}^2\text{s}$ at nominal current 13 kA. The outer layer cable, quenched by heaters, is heated to the maximum temperature of 155 K and the inner layer one to 85 K. The additional integral value for the point where quench is originated is limited by $14 \cdot 10^6 \text{A}^2\text{s}$ for the inner cable and $7 \cdot 10^6 \text{A}^2\text{s}$ for the outer one. Corresponding values for the quench detection and circuit operation time are 85 ms for the inner cable and 40 ms for the outer one. The maximum turn-to-turn voltage in the inner layer is 25 V and in the outer one is 10 V. Coil-ground voltage for interlayer heaters does not exceed 200 V. All above mentioned quench parameters for the HGQ are close to those for the arc LHC dipoles [1].

As can be seen, the chosen quench protection scheme for the HGQ with two interlayer heaters provides reliable magnet protection from the viewpoint of both maximum coil temperature and voltage drop in the magnet [11].

III. CONCLUSIONS

The HGQ design for the LHC interaction regions, developed by the Fermilab/LBNL/BNL collaboration, meets the requirements imposed for such magnets by the LHC specification. The described above quadrupole design concept as well as the basic solutions of the mechanical, thermal and quench protection problems will be tested experimentally on a series of short models. The develop-

ment of tooling for magnet assembling and special test facility with HeII vertical cryostat are in progress. Tests of the first short model are planned for the Spring of 1997.

IV. ACKNOWLEDGMENTS

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