

# DESIGN 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 currently engaged in the design of a high gradient quadrupole suitable for use in the LHC interaction regions. The cold iron design incorporates a two-shell,  $\cos 2\theta$  coil geometry with a 70 mm aperture. This paper summarizes the progress on a magnetic and mechanical design that meets the requirements of maximum gradient  $\geq 250$  T/m, operation at 1.8K, high field quality and provision for adequate cooling in a high radiation environment.

## 1 INTRODUCTION

Fermilab, Lawrence Berkeley National Laboratory (LBNL) and Brookhaven National Laboratory (BNL), have formed a consortium to provide components for the Large Hadron Collider[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 present some formidable challenges. In addition to the large aperture and high gradient, they must operate at superfluid helium temperature with a beam induced heat load of up to 40 W per magnet. The design effort has been underway for less than a year and is far from complete. This paper describes the status of the project as of this date.

## 2 DESIGN

### 2.1 Magnetic Design

The HGQ has a two-layer, graded,  $\cos 2\theta$  coil with a 70 mm diameter bore, magnetic length of 5.5 m and a maximum gradient  $G_{\max} \geq 250$  T/m. The two-layer design was chosen in preference to a 4-layer geometry[2]. Relative to a 4-layer design, quench protection is simplified because the inductance is low and the geometry allows for uniformly heating both coils during a quench. This design also rests solidly on our past experience and makes use of existing tooling. The cable uses existing SSC strand, which has a nominal  $J_c$  of 2,750 A/mm<sup>2</sup>. The SSC conductor will be used for model magnets and

will eventually be replaced with improved conductor that is now under development. The goal of the program is to produce strand with a current density of 3,400 A/mm<sup>2</sup>. Figure 1 shows the expected short sample (ss) performance using the existing conductor, and Table 1 summarizes the expected magnet performance with existing and improved strand, calculated here for  $J_c = 3,300$  A/mm<sup>2</sup>. Table 2 lists the values for the design allowed harmonic coefficients.

Table 1. Short sample (ss) performance parameters.

$J_c$ @ 5T, 4.2K	$G_{ss}$ (T/m)	$I_{ss}$ (A)	$B_{ss}$ (T)
2,750 A/mm <sup>2</sup>	251.6	13,874	10.01
3,300 A/mm <sup>2</sup>	260.7	14,517	10.39

Table 2. Allowed harmonic coefficients (units 10<sup>-4</sup>).

Component	Collision	Injection
b6	0.006	0.01
b10	0.002	0.0015
b14	0.0015	0.001

The two-layer design requires large aspect ratio cables. Samples of both the inner and outer cables have been produced by LBNL and winding trials with the new cables have been successful. Parameters of the improved conductor and cable are given in Tables 3 and 4.

Table 3. Strand parameters for the improved conductor.

Alloy	NbTi
Inner Strand Diameter	0.808 mm
Outer Strand Diameter	0.648 mm
Filament Diameter	9 $\mu$ m
Cu/SC Inner	1.3:1 / 1.1:1
Cu/SC Outer	1.8:1
Twist Pitch	10 mm
Critical Field @ T = 4.2K	10.4 T
Critical Field @ T = 1.8K	13.2 T
Critical Current Density	
T = 4.2 K & B = 5/8 T	3,400/1,500 A/mm <sup>2</sup>
T = 1.8 K & B = 8/11 T	3,700/1,800 A/mm <sup>2</sup>

Table 4. Cable Parameters

	Cable 1 (Inner)	Cable 2 (Outer)
Number of Strands	38	46
Cable Width	15.4 mm	15.4 mm
Keystone Angle	0.99 degrees	0.68 degrees
Mid Thickness	1.457 mm	1.146 mm

The load lines for each coil layer are shown in Fig. 1, indicating the operating margin for a nominal gradient of 235 T/m for the SSC conductor performance parameters. The improved conductor will increase the margin to approximately 11%.

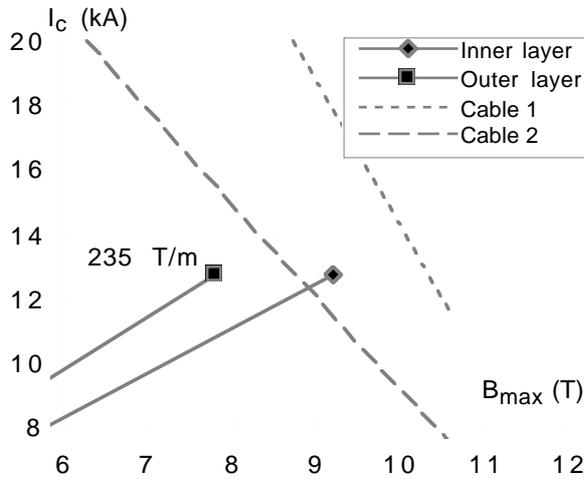


Figure 1. Load lines and critical surfaces for existing strand.

### 2.2 Mechanical Analysis

The HGQ design incorporates the following mechanical features. A strong 20 mm wide aluminum collar provides significant preload and defines the coil geometry so as to allow warm magnetic measurements to be made. A 2-piece iron yoke surrounds the collared coil and is closed both warm and cold. There is collar-yoke contact under all conditions at the 4 coil mid-planes to reduce coil motion under excitation. Contact is ensured by the larger collar than yoke diameter and the collar deflections due to coil preload. The use of yoke-collar shims is planned to adjust for manufacturing tolerances. A welded stainless steel shell, prestressed to about 200 MPa, provides helium containment and compressive load to maintain yoke closure. Following cooldown the compressive force between iron halves reaches at least  $2 \times 10^6$  N/m. This is larger than the radial Lorentz force of  $1.14 \times 10^6$  N/m, so the yoke gap remains closed.

Finite element analysis of this design has been performed[3] using ANSYS to determine limits on the initial collared coil preload and collar-to-yoke spacing. Figure 2 shows azimuthal compressive stress on the coils

during assembly, cooldown to 1.8 K, and excitation to maximum gradient for the lower and upper bound cases having a collar-to-yoke interference (warm, undeflected) of 25  $\mu$ m. Figure 3 shows lower and upper bounds for the coil prestress as a function of the yoke-collar spacing. For a given spacing, the lower bound is set by the requirement that the coil stress at  $G_{max} = 250$  T/m be  $\geq 14$  MPa; the upper bound corresponds to the case when the yoke

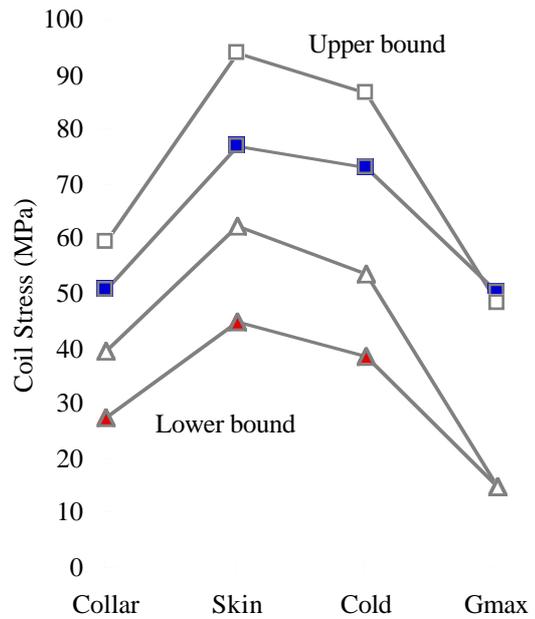


Figure 2. Azimuthal compressive stress on coils during assembly (collaring), cooldown and excitation. Inner (outer) coil stress is shown by open (filled) symbols.

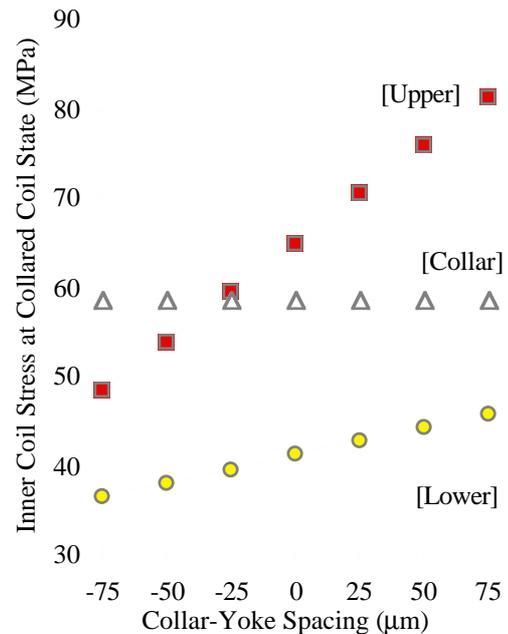


Figure 3. Upper and lower bounds for various collar-yoke spacing and collar stress limit.

mating surface begins to open at  $G_{\max}$ . The final bound is set by the limit on the peak stress in collar material in the initial collared coil state; it is independent of collar-to-yoke spacing. The range of acceptable preload is between the 3 limits. For the design value of 25  $\mu\text{m}$  yoke-collar interference, the range of acceptable collared coil preload is about  $\pm 10$  Mpa. For a given preload, as the collar-yoke spacing increases the collar to yoke force decreases which increases the compressive force between iron halves. The upper bound is a function of that force, so the larger the collar-to-yoke spacing, the larger the upper bound point. Also, all lower bound cases have collar-iron contact cold.

### 2.3 Beam Induced Heat Load

The quadrupole coils in the LHC low- $\beta$  insertions are subject to a constant heat load up to 40 Watts per magnet and a peak energy density as large as 1.2 mW/g at the coil mid-plane due to secondary particles from beam-beam collisions at the nominal luminosity[4]. The HGQ cables are wrapped with 25 micron thick Kapton tape with a 50% overlap for electrical insulation purposes and one layer of spiral wrapped Kapton for mechanical protection

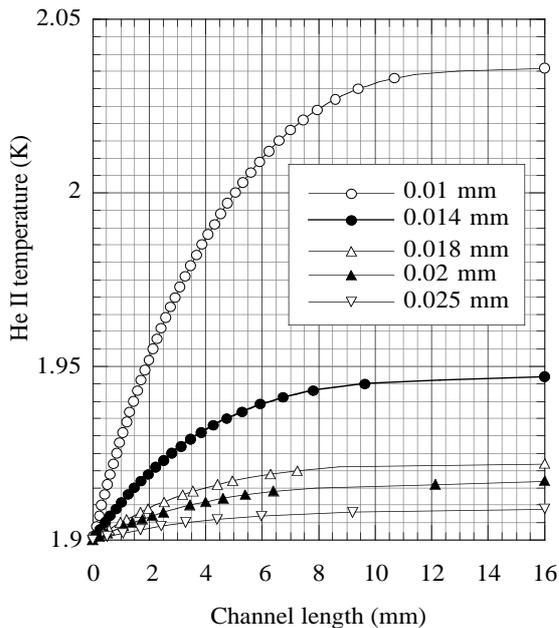


Figure 4. Temperature profile in He II with 2 mm wide cooling channels and varying channel length and height with a surface heat flux of 4.5 mW/cm<sup>2</sup>.

and to provide He II cooling channels. The maximum heat load is at the coil mid-plane and the surface heat flux can be calculated based on the surface area in contact with the He II. The cooling channel formed by the second layer of Kapton insulation film will be deformed during the curing process. The temperature profile within the He II cooling chamber for varying channel gap and length is shown in Fig. 4. A minimum gap of 14 microns is required to keep the He II temperature below 1.95 K.

## 3 CONCLUSIONS

The project is still within its first year and much progress has been made. Several design issues remain to be considered. Tests of the first model are planned for the Spring of 1997.

## 4 ACKNOWLEDGMENTS

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