Introduction

The LHC Inner Triplet System - Overview

The inner triplet system provides the final focusing of the proton beams before collision at four locations in the machine, the high luminosity interaction regions located at IRs 1 and 5 (figure 1), and the low luminosity interaction regions located at IRs 2 and 8 (figure 2). The primary hardware difference between the high and low luminosity interaction regions is the use of conventional D1 magnets (LBXW) at the high luminosity interaction regions, and superconducting D1 magnets (LBX) at the low luminosity interaction region, necessitated by the energy deposition to the D1 at the high luminosity IRs.

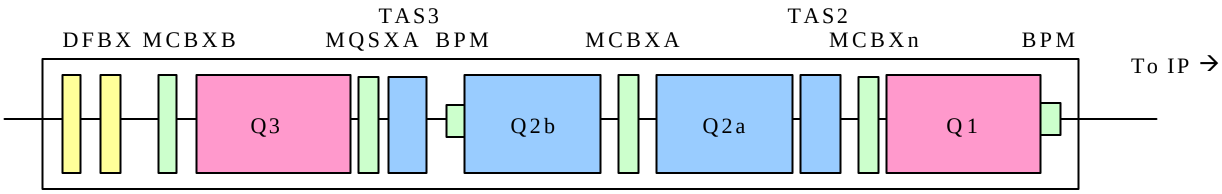

Figure 1. Inner Triplet System Schematic, IR1/5

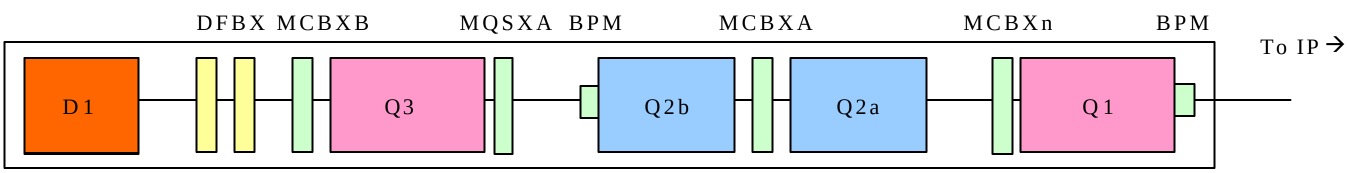

Figure 2. Inner Triplet System Schematic, IR2/8

Each inner triplet consists of 3 quadrupole optical elements, Q1, Q2 and Q3, 4 multipole corrector assemblies, MCBXn (where n in this case is determined by the exact location in LHC), MCBXA, MQSX, and MCBXB, and a D1, as shown in v6.1 optics. The quadrupoles operate at a gradient of 215 T/m in IRs 2 and 8, and 205 T/m in IRs 1 and 5, at LHC nominal energy of 7TeV per beam and luminosity of 10^{34} $cm^{-2}s^{-1}$.

The quadrupoles of the inner triplet focus the beams to small spot sizes, about 0.016 mm at the IPs in IR1 and IR5. At the entrance face of Q1, the beam size increases to more than 0.7 mm and reaches a maximum of 1.5 mm in the triplets. Due to the large beam size and the crossing angle, the beams are subject to non-linear fields of these magnets. The dynamic aperture under collision conditions is largely determined by the field errors in these quadrupoles. Non-linear multipole windings in corrector packages placed in the IRs are needed to compensate the errors in the triplets. The required dynamic aperture is specified to be 12 sigma, as determined by 100,000 turns tracking calculations.

Component Responsibilities

The LHC inner triplets are comprised of components designed and developed at five laboratories world-wide. The responsibilities of each of the laboratories for components in the system is briefly described here, starting with the magnetic components of the inner triplet and working outwards.

KEK is responsible for the design, manufacture, acceptance testing, and delivery of the MQXA (Q1 and Q3) cold masses to Fermilab. Fermilab is responsible for the design, manufacture, and acceptance testing of the MQXB (Q2a and Q2b) cold masses. CERN is responsible for the design, manufacture, acceptance testing, and delivery of the MCBX and MQSX corrector elements to Fermilab.

Fermilab is responsible for the design and assembly of a 1.9K vessel which includes the above magnetic components, and for the design, manufacture and assembly of a cryostat to contain the 1.9K assemblies. Fermilab is responsible for the design, manufacture and insertion of the main bus for all quadrupoles, and for the cold bore within each cryostat. Fermilab is responsible for providing an interconnect kit to CERN, including components for the assembly of the TAS2/3 absorbers and components for connection of all piping excluding the beam tube. Fermilab is responsible for producing the data relating the magnetic axis of the components to fiducials on the external surface of the cryostat. Fermilab is responsible for the delivery of the completed, cryostatted assemblies to CERN.

CERN is responsible for the Beam Position Monitors, Beam Tube RF connection, and any absorber or liner which may be inserted in the cold bore of the quadrupoles. CERN is responsible for the assembly of these devices on the delivered cryostatted assemblies.

LBNL is responsible for the design, manufacture, acceptance testing and delivery of the DFBX Inner Triplet Feedboxes to CERN.

BNL is responsible for the design, manufacture, acceptance testing and delivery of the LBX beam separation dipole to CERN.

CERN is responsible for the jacks on which all assemblies are placed, and is responsible for the installation of all components in the LHC tunnel.

Scope of This Report

The scope of this document and review is the Fermilab built MQXB prototype cold mass, including the end plates, but not specifics of the end domes, bus bar, or beam tube design. The cryostat design, and final assembly of the components by Fermilab are also outside the scope.

MQXB Design Overview

The Fermilab built MQXB quadrupole base design has been previously described in detail in the Technical Design Handbook. A short overview of the magnet design follows. The basic cross section of the magnet is shown in Figure 3. The magnet consists of a graded 2 layer coil, each made from SSC style conductor, with a 70mm bore. The coils are made of keystoned Rutherford type NbTi cables based on SSC type strand, with different cable being used in the inner and outer layers. Both cables are 15.4mm wide, but have different mid-thicknesses, 1.465mm for the inner and 1.146mm for the outer. The inner coil consists of 14 turns, with a single wedge between turns 11 and 12, while the outer coil consists of 16 turns, with a single wedge located between turns 15 and 16. The coils are insulated turn to turn, coil to coil, and coil to ground by layers of Kapton insulation, and coated with QIX adhesive when appropriate. Protection is provided by a heater located in the insulation between the outer coil and the collar laminations.

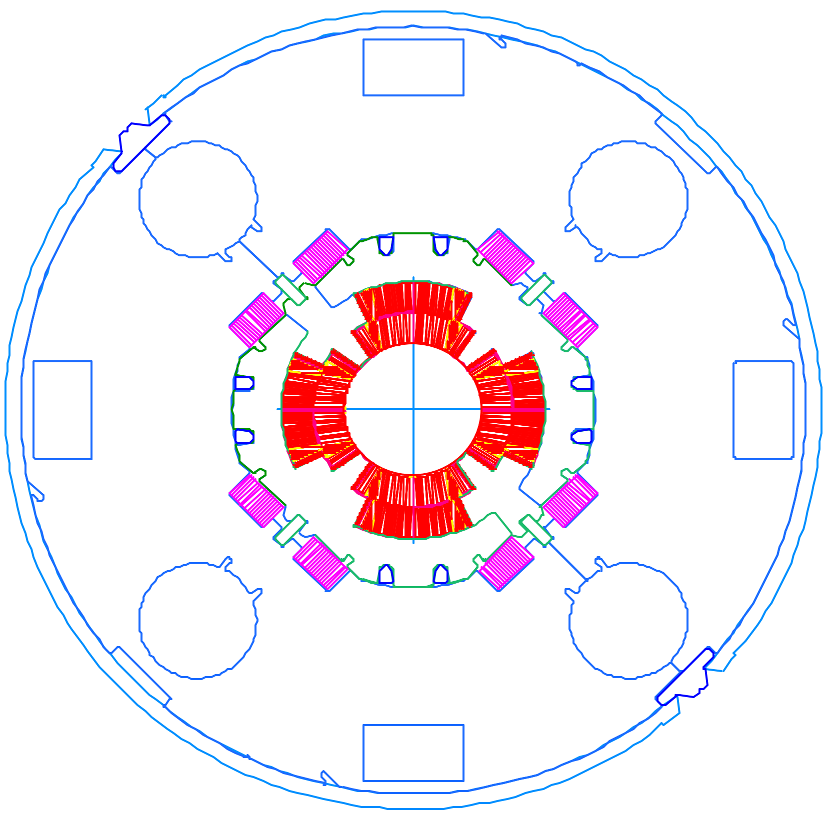

Figure 3. HGQ Cross Section

The end parts are made of G11CR, which provides for minimal differential thermal contraction between the part and the coil, and satisfactory radiation hardness. The inner coil is split into three blocks around the end, one split in the same location as the wedge, and another which separates the 11 turns near the midplane into 2 blocks of 5 and 6 turns. The outer coil ends have two blocks, with the split in the same location as the wedge.

The coils are supported in the body by standalone Nitronic 40 stainless steel collars, which are keyed with 2 keys in each quadrant for locking. The collars are preassembled into welded 'packs' before final assembly, with small filler laminations providing support in the collar pole region. The coils are collared in a stepwise fashion along the length in a vertical collaring press. Over the ends, G11 spacers surrounded by an aluminum collet provide support which closely matches the body support in both preload and deflection under all conditions. A picture of a completed collared coil assembly is shown in Figure 4. At this point in the construction, all the mechanical support mechanisms for the coil are in place.

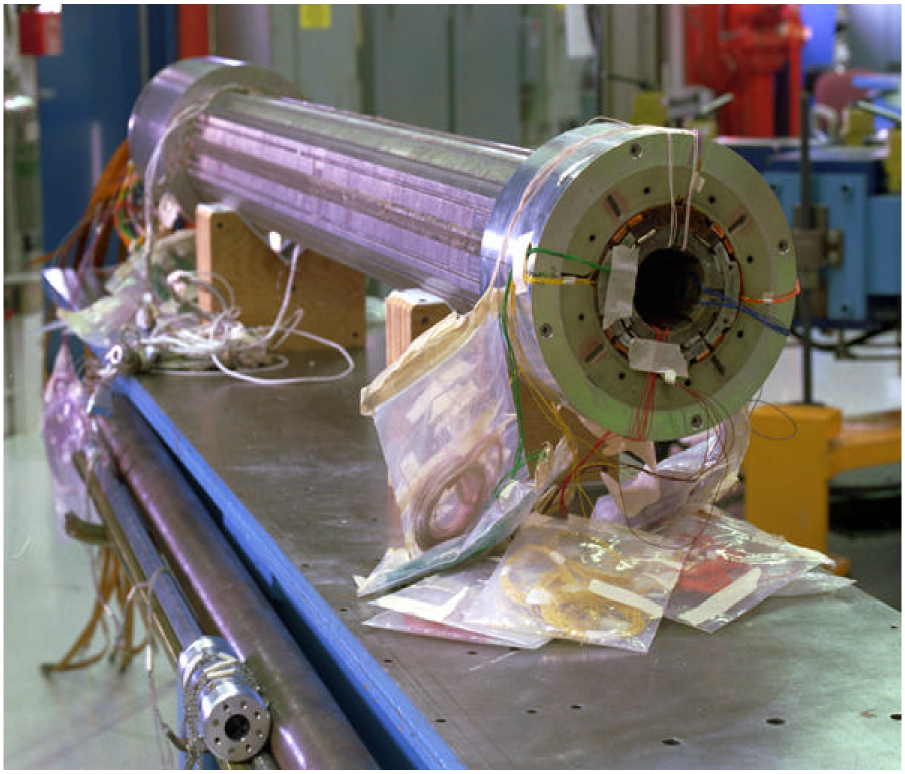

Figure 4. Collared Coil Assembly

Around the collared coil assembly is placed a set of iron yoke laminations. Over the body iron laminations are used, while over the end modified stainless steel laminations are placed which allow clearance for the collets but reduce the end field and support the skin to the end plate. The yokes registered to the collared coil by collar yoke alignment keys at each pole. The skin surrounds the yoke, and through the skin alignment key and the welding process, determines the final straightness of the assembly. In the production magnets this also serves as the helium containment vessel. Note the skin and yoke do not provide any mechanical support to the collared coil as is typical in many current magnet designs, the skin only must hold the yoke halves together for magnetic field purposes.

The assembly is closed by end plates, which are welded circumferentially to the skins after they are cut to length. The support of the end collets and coil ends is applied through tension bolts and bullets which thread into the end plate.

Design Goals

The MQXB design have a series of design criteria for acceptance into the LHC machine, and the Fermilab model magnet program was initiated to prove the satisfactory performance of the design to these criteria. They are:

- Quench Performance -- the MQXB operates at 215 T/m in IPs 2/8, and 205T/m in IPs 1/5, under high energy deposition conditions. To show that the magnets meet these criteria with good training memory, the goal is that each magnet will be trained to 230T/m in the first thermal cycle, and then show performance at or above 220T/m in the second thermal cycle.
- Field Quality – based on the magnet conceptual design and AP studies, a series of target harmonics for the MQXB magnets has been created in Reference Table 2.0 (see below). The goal is that the design be consistent or better than that listed.
- Quench Protection -- the target temperature for the magnet after a quench has been 400K or less, and electrical voltages to ground of less than 1kV.
- Thermal Margin -- the inner and outer coils should have an appropriate temperature margin and need to be cooled sufficiently such that even under the strenuous deposition conditions at the high luminosity interaction points, the quench performance of the magnet is not degraded.
- Alignment -- the target average twist for a cold mass before cryostatting is 0.2 mrad/m or less.

Table 1. MQXB Reference Harmonics (v2.0)

Reference Table 2.0 (@17mm)																
	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10
Uncert.	0.30	0.30	0.20	0.20	0.20	0.20	0.60	0.05	0.05	0.04	0.03	0.03	0.02	0.02	0.02	0.02
Random	0.80	0.80	0.80	0.80	0.30	0.30	0.60	0.10	0.06	0.06	0.05	0.04	0.03	0.02	0.03	0.03

Model Magnet Program Results

The model magnet program has demonstrated adequate magnet performance in all of the required areas, and magnet HGQ09 achieves or surpasses every performance requirement. A synopsis of the program results as compared to the requirements is as follows:

- Quench Performance -- over the past year, all magnets, HGQ05 through HGQ09, have met the operational requirements. The last two models tested, HGQ08 and HGQ09, have been tested in accordance with the planned production magnet quench test cycle, and achieve the 230T/m goal after a few quenches, with second thermal cycle quenches above 220T/m.
- Field Quality --field quality has been well understood from the start of the program, including magnets HGQ01 through HGQ03 after the measured harmonics in these magnets is corrected for known shims which were added to achieve the desired preload. In magnets HGQ05 through HGQ09, the coil size is well understood, no correction is required, and the magnets agree with the reference table well enough that a new version 3.0 of the error table has just been produced which may allow for a reduction in the corrector strengths specified for the inner triplet. Dynamic effects

seen in magnets HGQ06 through HGQ08 have been solved by introduction of a two stage cure cycle, demonstrated in HGQ09.

- Quench Protection --has been shown to be adequate in all models. A CERN type heater, covering the outer coil, sufficiently protects the magnet under all circumstances.
- Thermal Margin -- the use of stabrite coated cable in HGQ08 allowed for direct measurements of the thermal margin of the magnet by measuring quench current as a function of AC losses. The results showed that although the inner coil is not irrigated in the manner expected, the margin is still sufficient for LHC operation.
- Alignment -- the twist built into the early models was large. Since HGQ05, it has come progressively down, such that in HGQ08 and HGQ09 it is on the order of less than 0.15mrad/m (in HGQ09 the average is actually zero to three decimals). The random twist about the average is 0.1mrad. The cold masses are straight to less than 0.001" by measurement. These values are considerably better than currently expected by our AP colleagues as being necessary, and since the long magnets will use the same yoke/skin welding press, we can expect similar success.

Through HGQ09, the model magnet program has demonstrated the robustness of the design, and it's adequacy to meet the LHC requirements.

<u>Model Magnet Program Technical Summary</u>

This document summarizes in detail the findings and conclusions of the HGQ model magnet program. After the series of model magnets, and with the variations introduced first to cure the poor quench performance seen in early model magnets, then to prepare for long magnet production, the data can be analyzed to draw some conclusions from the program. Grouped by topic, these include:

1. Changing the strand count in the inner coil from 38 to 37 has had no impact on quench performance. In short sample tests the cable tests very similarly, suggesting the removal of a strand has been offset by less degradation during cabling.
2. Inner coils made with left lay cable (wound in the unfavorable direction) resulted in a much higher production rejection rate, ~25%, as compared to coils made with right lay cable, <5%. Once good coils are assembled in a magnet, no difference in quench performance is seen.
3. Stabrite coated cable is qualitatively harder to handle and wind than non-coated cable.
4. G10/G11 end parts improve quench performance, due to better matching of the differential contraction of the cable and end part.
5. There is no difference seen in quench performance between 4 block or 5 block end designs.
6. Since HGQ05 we have better matched the inner and outer coil properties. Although this continues to be our practice, we have not run a reverse experiment to prove this.
7. Coils cured at 135 C and high or low pressure show no interstrand resistance effects. Coils cured at 190 C and low pressure show no interstrand resistance effects. Coils cured at 190 C and high pressure show low, and for non-stabrite

coated cable, variable interstrand resistance. Cable made from bare copper, cured in a two step process, first at 190C and low pressure, then at 135 C and high pressure, show no interstrand resistance effects.

8. In HGQ05 and HGQ07 three thermal cycles were run, to investigate the effect of end restraint of the collared coil vs. leaving the ends free. No correlation is seen.
9. As a corollary to (7), thinning the end plate from 50mm to 35mm shows no effect on performance.
10. The use of collets over both ends of the magnet is easier to assembly, and allows for the addition of tension bolts with little design modifications.
11. Individual collars (0.060" thick in this magnet) without filler collars can twist in the pole region during assembly. Collar packs address this problem and are easier to handle during final assembly.
12. Leaving a filler collar out intermittently to allow for cooling has no effect on quench performance.
13. Using a bearing strip across the pole surface, or having the collar contact the insulation directly, has no effect on quench performance.
14. Aligning the keys with the end of the collar packs, or across collar packs, has no effect on quench performance.
15. Leaving the end regions uncollared for up to a few days after the body has been collared has no effect on quench performance.
16. Coil prestresses in the range 60 to 95 MPa all result in adequate quench performance for this design.

Report Structure

The next chapters of this report detail the investigations, findings, and conclusions of R&D efforts in and associated with the HGQ model magnet program. Some of the findings are obvious, some are subtle, and some have been blind alleys, but they have resulted in a useful body of knowledge, and a highly successful magnet design.

The program now proceeds to the full scale prototype stage, which includes the first prototype cryostat to be assembled. The MQXB magnet is about 5.8m long, as compared to the 1.8m long HGQ model magnets. The prototype MQXB will follow the best design, components, and procedures developed in models HGQ05-HGQ09. Details of this design can be found in the chapter on the prototype design and plans. To test the full length magnet, a cryostat is required, and an outline of the status of that design is also included.