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REPORT OF THE REVIEW COMMITTEE ON THE FERMILAB HGQ R&D PROGRAM

(FNAL, 16 March 2000)

DAPNIA

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MQXB EDR Report

16 March 2000

Foreword

Enclosed is the report of the committee which met at Fermi National Accelerator Laboratory on 16 March 2000 to review the design and test results of the Fermilab High Gradient Quadrupole magnet for the Large Hadron Collider Insertion Regions. The review committee consisted of Mike Anerella, BNL, Arnaud Devred, CEA/Saclay (Chairman), Daniel Leroy, CERN, Ranko Ostojic, CERN, Phil Pfund, Fermilab (secretary), Bob Schermer, consultant, Tom Taylor, CERN, Pierre Védrine, CEA/Saclay, and Akira Yamamoto, KEK. The review was called by Jim Strait, US LHC Accelerator Project Manager, with the charge given in Appendix 1 and the agenda in Appendix 2. It was meant to be a follow up to a review held on 18 and 19 March 1999 on the same topic with pretty much the same review committee (see Report DAPNIA/STCM 99–02).

Prior to the review, the committee was provided through the World Wide Web with a number of relevant documents, including a functional specification, several conference papers summarizing the performance of the model magnets, and a few quench plots. The one-day review was articulated around presentations by Jim Kerby, Fermilab LHC Accelerator Project Manager, Fred Nobrega, Alexander Zlobin, IR Quadrupole Level 3 Project Manager, and Mike Lamm. It included a short tour of the long magnet production facility located in the Industrial Center Building, which enabled the review committee to look at the first 5.5-m-long cured coil. Copies of all the presentations are given in Appendices 3 to 9. Similarly to last year's review, the discussions were very open and the committee was very pleased with the cooperation of the FNAL team.

Executive Summary

The committee is very pleased with the results of model magnets HGQ05 through HGQ09, which meet the specifications on quench performance (save for one, high-level retraining quench of magnet model HGQ06), and which appear to exhibit good field quality. The committee feels that a great deal has been learned from the magnet model program and that it is now a suitable time to move to the next phase and start building full-length prototypes.

Following up on last year's review, the committee thinks that most major technical issues have been properly dealt with and has only minor concerns to raise. It nevertheless recommends pursuing in-depth analyses of the magnet model test results and wishes to identify a few areas of potential problems when moving from short to long magnets.

1. *The design is ready to move on to the full-length prototype*

The R&D program has completed the last of the nine planned 2-m-long magnet models. The next phase of the program is to build and test the first of two planned prototypes. The first prototype (Q2P1) has one MQXB cold mass and the second (Q2P2) has two cold masses (one of them will be new and the other one will that of Q2P1). The cold masses are to be identical to the anticipated final design in length and cross section with the exception of the inclusion of instrumentation.

The committee feels that a great deal has been learned in the last year about quench performance, quench protection and field quality and that the magnet design has reached a mature state. It agrees that it is now time to move on and to start the fabrication of the full-length prototypes.

The committee strongly recommends that the two prototype cold masses be made as similar to each other as possible. While the committee recognizes that unanticipated outcomes may force changes in the design or fabrication, changes should not be planned from the onset.

The committee was provided with a table showing the design features of the Q2P1 cold mass compared with the preceding nine model magnets. The committee concluded that some of the features were not yet fully specified and recommends this be done prior to starting fabrication. As a first example, the parameters of the cure cycle were not clearly presented. Fermilab needs to ensure that they are well defined. There was a consensus among the committee members that FNAL should once again consult with BNL before finalizing its decision. As a second example, it was unclear when and at what level hi-pot tests were to be conducted. FNAL should consult with CERN and KEK regarding the levels of such tests. As a third example, when going from short magnet models to long prototypes, some components may have to be broken up into several parts. These components have to be identified and their lengths have to be determined.

2. *Minimize design changes between the models and prototypes*

The committee was presented with examples of design changes that were planned between the last magnet model and Q2P1. One example is the cable insulation scheme where, previously, the system for the inner cable consisted of one layer of polyimide wrap with 58% overlap covered by one layer with 2 mm gaps. Some consideration is being made to reduce the overlap to 50% and compensate for this by eliminating the 2 mm gap. The committee recommends against this in the absence of any overwhelming need. Changes such as this, although they may be, potentially, improvements, should not be introduced at this late juncture unless validated in advance of their incorporation in the prototype.

3. *Long tooling will need to be thoroughly proofed.*

Much of the long tooling will be used for the first time on the prototypes. The committee understands that much work and careful planning has gone into the set-up and trial runs of this tooling. However, the committee wishes to re-emphasize the importance of thoughtfully checking out this equipment for its impact on the quality of the magnet. One example is the curing press, where a temperature profile through the press can affect the quality of the coil. This occurred in the model length curing press and needed to be corrected. The importance of the full-length tooling to produce coils, collars, cold masses, etc. of mechanical uniformity is recognized. The committee wishes to re-enforce the importance of carefully considering these variables in the plans for proofing of the full-length tooling.

4. *Cables made from different strands*

It is the committee's understanding that the present magnets use cables made from IGC strands left over from SSC, but that an order has been placed to buy Alstom strands to cover the remaining needs of magnet production.

The committee wishes to stress the importance of not underestimating the variability that a second strand manufacturer can introduce. Even if the strands are made according to the same specifications, the changes in raw material suppliers and in production processes can lead to different mechanical behavior that affect axial coil spring-back after curing as well as azimuthal coil sizes. Also, the SSC experience has shown that cables made from bare, un-annealed strands coming from different manufacturers can end-up, especially after a high-temperature cure, with different values and distributions of interstrand resistances, leading to very different ramp-rate behavior.

To prevent any surprise when first using Alstom strands, the committee recommends performing interstrand resistance measurements at BNL and winding short practice coils as soon as such cable is available.

5. *Perceived weakness of the proposed mid-plane insulation scheme*

The committee expresses concern about the proposed solution for the mid-plane insulation of Q2P1, in which there appears to be an unusually short creep distance between adjacent quadrupole coils. In this coil region, the insulation between the coils relies only on the dielectric strength of the turn-to-turn insulation (one dry polyimide wrap of 25 μm, overlapped by 58%). This geometry, with flaps over the inner layer of the inner coil, was chosen to alleviate problems expected during insertion of the beam tube in

the magnet. The Committee suggests that the ground insulation scheme of the Q2P1 prototype in the coil mid-plane region be made fully compatible with the beam tube insertion and further validated on test coils.

6. *Beam tube design and insulation*

The beam tube was explicitly excluded from the scope of the review. For that reason, there was no presentation of the beam tube design, insulation scheme, nor the technique for its insertion and centering. There is evidence from the CERN LHC dipole magnet program that the beam tube insulation may tear due to high pressure waves that occur during magnet quenching in superfluid helium, subsequently causing insulation breakdown and pollution of the cryogenic system. The committee recommends that the beam tube insulation be carefully studied. A possible technique could be to cure the insulation, made of several wraps of XCI-type polyimide tapes, similar to what has been done in RHIC. These studies should be done in time for the Q2P1 prototype assembly.

The committee recommends that the beam tube design, including its insulation system, and insertion and centering technique be included in some future review.

7. *Thermal analysis of the heat transfer in the coil needs more work.*

A two-dimensional, finite element, thermal model was presented during the review. The principal conclusion was that the magnets would have sufficient thermal margin, in conditions of high heat load corresponding to nominal LHC luminosity, even if the cooling channels in the cable insulation are assumed to be closed. (In addition, photomicrographs were shown that indicated that the cooling channels probably are, in fact, closed.)

This is an important point, as it constitutes the only evidence that the magnets will operate with the specified heat loads. The committee was not presented with enough details to be able to assess the validity of the computation. The committee recommends that the technical aspects of the computation be reviewed in detail. It also recommends that the model be validated using the experimental data on AC effects in magnet model HGQ08. Recent measurements of AC losses in the KEK low-β quadrupole model for the LHC might also be used to validate the model.

8. *Pursuit of mechanical data analysis*

The committee was very pleased by the work that has been carried out to analyze the mechanical data recorded during short magnet model production and cold test. Although

the azimuthal coil sizes required to achieve suitable levels of pre-compression, and, subsequently, proper conductor positioning for field quality, are somewhat larger than in the original design, there seems to be good empirical understanding on how to adjust them. Furthermore, the measured deflections of the collared-coil assemblies appear to be well correlated with the expected azimuthal coil pre-compressions, which implies that the collaring process is well in hand. However, the strain-gauge and capacitive-gauge data are far less convincing and exhibit some erratic behavior, especially during cooldown.

Comparisons between measured values of room-temperature pre-compression and computed values using local azimuthal coil sizes were not presented. The committee recommends pursuing the analyses of the mechanical data to assess the reliability of strain-gauge and capacitive-gauge measurements.

9. *Quench start localization*

The quench performance of magnet models HGQ05 through HGQ09 meet the specifications (save for one, high-level retraining quench of magnet model HGQ06). The committee was provided with a summary table of quench start locations that shows that a large number of quenches originated in the magnet body in the turn right below the inner-coil wedge. Detailed analyses on the axial locations of these quenches along the magnet body were not presented. The committee recommends further investigation of the quench area, e.g. using cookies of the magnet cross-section or axial coil plots of quench locations. This may lead to the discovery of problems external to, but in the location of, the incriminated wedge.

10. *Effects of interstrand coupling currents and snap-back of multipole coefficients*

Magnet coils wound from cables with low interstrand resistances can be the source of large interstrand coupling currents while ramping, which produce distortions of the multipole field coefficients. These interstrand coupling currents usually have short time constants. They decay fairly quickly when the magnet ramp is stopped and regenerate as soon as the magnet ramp is resumed. As a result, during a current cycle representative of machine operation, the field distortions produced during magnet ramping are expected to die out while remaining at the injection current, but they reappear almost instantaneously when starting the ramp corresponding to the acceleration phase. The amplitude of the change that the multipole field coefficients undergo upon starting the acceleration ramp at the end of the injection phase is referred to as *snap-back.*

The snap-back of a magnet with large interstrand coupling currents is expected to be larger than that of a magnet with small interstrand coupling currents. Among the various short magnet models that have been tested, magnet HGQ08, which uses staybrite-coated

strands, is known to have low interstrand resistances and large interstrand coupling currents. It is, therefore, puzzling that the quoted snap-back value for the normal dodecapole coefficient (b_6) of this magnet does not appear to be significantly different from that of other magnet models. In addition, HGQ08 exhibits, at injection, an extremely large eddy-current component of the non-allowed normal sextupole coefficient (b_3), a fact that was not pointed out at the review. This indicates a large asymmetry in the interstrand resistance, and might be a significant effect.

The committee is fully aware that this question may not be an issue for the series production magnets, which, it is hoped, will use cables with higher interstrand resistances. Nevertheless, the committee recommends that some further analyses be carried out to determine if the data were correctly interpreted. It also recommends collecting and reviewing the ramp rate sensitivity data from RHIC magnets and comparing them with those of HGQ magnets. Finally, CERN and Fermilab must agree on specifications for tolerable values for eddy current multipoles.

11. Origin of non-allowed normal sextupole coefficient (b_3)

The summary table of multipole coefficients provided to the committee seems to indicate a statistically significant non-zero mean value for the geometric component of b_3. The committee recommends that detailed analyses be carried out to determine the type of symmetry violations that can produce such a non-allowed multipole coefficient in a quadrupole magnet and if anything in either the magnet design or the assembly procedures could lead to such symmetry violations.

Beyond the specific problem of b_3, the committee recommends pursuing systematic analyses of the geometric multipole coefficients in relation to mechanical data and mechanical design.

12. Coordinate the Production Readiness Review with Q2P2

The next major review of the MQXB is a Production Readiness Review (PRR). In general, a PRR is expected to occur after final proof-of-design is complete, *i.e.*, after prototypes are delivered and tested successfully. It is also expected to occur before final production of the deliverables for the LHC. In the case of the MQXB, the PRR is being scheduled to occur after assembly of Q2P2, but before cold testing. The stated reasoning for this is that the assembly of the two cold masses which make up Q2P2 has not been attempted before whereas the cold mass magnetic performance will have been verified in the testing of Q2P1. The committee agrees with this approach but wishes to emphasize the importance of making the cold test results of Q2P1 and the complete assembly results of Q2P2 available to the PRR. Furthermore, if cold testing of Q2P1 leads to significant redesign, then the PRR should be scheduled after completion of the cold testing of Q2P2.

Appendices

1. Charge
2. Agenda
3. Introduction / Overview – presentation by J. Kerby
4. Prototype Magnet Design – presentation by F. Nobrega
5. Short Model Test Results, Mechanical – presentation by A. Zlobin
6. Quench Performance – presentation by M. Lamm
7. Short Model Test Results, Thermal – presentation by A. Zlobin
8. Quench Protection – presentation by M. Lamm
9. Short Model Test Results, Magnetic – presentation by A. Zlobin

Appendix 1

Engineering Design Review – Charge
Quadrupole Cold Mass – MQXB

Background:

The US LHC Accelerator Project is responsible for providing CERN with integrated inner triplet magnet systems for the four interactions regions at points 1, 2, 5, and 8. Each inner triplet consists of four quadrupole magnets, half of which (Q2a and Q2b) are designed and built by Fermilab and half (Q1 and Q3) by KEK, correction coils provided by CERN, and absorbers to protect the magnets from secondary particles from the p-p collisions at the IP. These elements are assembed into three cryostats – Q1 plus correctors; Q2a, Q2b plus correctors; and Q3 plus correctors – by Fermilab. The subject of this review is the design of the Fermilab inner triplet quadrupole cold mass, end plate to end plate. The cryostat design, including the assembly of the several magnetic elements into complete helium vessels ready to insert into the cryostat, will be the subject of a separate review later this year.

The inner triplet quadrupole program includes:

- The design, construction and testing of a series of short (2 m) model magnets in order to develop the design features required to meet the functional requirements.
- The design, construction and testing of two full-scale prototype magnets a prototype cryostats.
- The design, construction and testing of 18 quadrupole magnets, including spares, and the assembly of them and the KEK-provided quadrupoles, together with the CERN-provided correction coils, into complete magnets in cryostats ready for installation in the LHC.

The model magnet program is, by the time of the review, expected to be complete, and the prototype construction is about to start. The intent is that the two prototype quadrupole cold masses are of the same design as will be used for the production series, with the exception of additional instrumentation.

Planned Design Reviews:

An EDR is to be conducted when most of the R&D is complete and the engineering design has been finalized. For a system to pass the EDR, it must be demonstrated that all of the technical and engineering challenges have been adequately addressed.

This Engineering Design Review (EDR) covers the Q2a and Q2b cold masses. It follows a Conceptual Design Review (CDR) that was held in October 1996 and an R&D review on 18-19 March 1999.

The EDR of the inner triplet cryostat, including the procedures for assembling several magnetic elements into a complete liquid helium cold mass, will be conducted at a later date. One or more Production Readiness Reviews (PRRs) will follow the EDRs and before final production begins.

Appendix 1

Engineering Design Review – Charge
Quadrupole Cold Mass – MQXB

Design Team:

The design is represented by:

- Jim Kerby, FNAL Project Manager
- Sasha Zlobin, FNAL
- Mike Lamm, FNAL
- Fred Nobrega, FNAL

Design Review Committee:

The design review committee members are as follows:

- Arnaud Devred, Saclay, Chair
- Phil Pfund, FNAL, Secretary
- Pierre Vedrine, Saclay
- Ranko Ostojic, CERN
- Tom Taylor, CERN
- Mike Anerella, BNL
- Akira Yamamoto, KEK
- Bob Schermer, consultant

Scope of the Review:

The review will cover the design of the Fermilab LHC inner triplet quadrupole magnet, which is, in principle, the same as the design to be used for the production magnet that will be installed in LHC. The review will cover the quadrupole magnet itself, from end-plate to end plate and will address the following items in particular:

- Superconducting cable
- Magnetic design
- Cold mass mechanical design
- Quench protection
- Magnet bus
- Cold bore tube
- Cryogenic/cooling design
- Instrumentation
- Response of the designers to findings from the March 1999 R&D review.
- Extent to which the results from the R&D program supports the critical design choices
- Prototype program plan

Appendix 1

Engineering Design Review – Charge
Quadrupole Cold Mass – MQXB

The design review committee has the usual freedom to investigate other areas of the design that present a risk to the successful completion of the project, installation, and operation in the LHC.

The review committee is asked to evaluate the design presented and recommend whether or not it is ready to be used in the construction of the prototype quadrupoles. The committee is asked also to comment on the extent to which the presented design is adequate to meet the requirements for installation and successful operation in the LHC.

Date of the Review Committee Meeting:

The review is scheduled for Thursday 16 March 2000 at Fermilab. It is anticipated to take one day, but the following morning is explicitly left open for followup activities, if required.

Results of the Review:

This review is a Level-3 project milestone, scheduled for completion 1 April 2000. The review will be complete with the issuing of a report summarizing the technical designs reviewed, committee recommendations, and action items. The forecast date for completion is 7 April 2000.

Appendix 1

Engineering Design Review – Charge
Quadrupole Cold Mass – MQXB

Schedule for the Review:

EDR Schedule – MQXB Cold Mass

18 Feb 2000	Contents of preview package selected by the FNAL Project Manager and approved by the US LHC Project Manager.
22 Feb 2000	Preview package posted on FNAL web site. Reviewers will be notified of the URL and given a list of material posted. Reviewers will be given subsequent notification when additional documents are posted or existing documents are modified.
6 Mar 2000	Reviewers provide preliminary comments to the Chairman. The comments will ensure that issues of specific interest to the reviewers will be adequately addressed during the review meeting. The comments are based on the material provided in the preview package and on each reviewer's previous knowledge of the project and technology.
9 Mar 2000	Agenda revised by the chairman based on preliminary comments from reviewers and discussions with the FNAL Project Manager.
16 Mar 2000	Design Review meeting conducted.
24 Mar 2000	Draft report of the review sent to reviewers by the Chairman.
31 Mar 2000	Reviewers return comments on the draft report to the Chairman.
7 Apr 2000	Final report of review approved by the US LHC Project Manager and issued by the Chairman.

Appendix 1

Engineering Design Review – Charge
Quadrupole Cold Mass – MQXB

Agenda for the Review Meeting

EDR Agenda – MQXB Cold Mass
16 March 2000
FNAL

Thurs. 16 March	
8:45 am	Design Review Committee Planning Session
9:00 am	Presentation and Discussion of Design
12:30 pm	Lunch
1:30 pm	Presentation and Discussion of Design (cont.)
3:30 pm	Design Review Committee Working Session
5:00 pm	Design Review Wrap-up with Designers
7:00 pm	Dinner
Fri. 17 March	
morning	Tours, followup discussion if required.

Appendix 2

MQXB Engineering Design Review *March 16, 2000*

Industrial Center Building, 2nd Floor East Conference Room

Agenda

8:45 AM	Committee Closed Session	
9:00 AM	Overview - Scope of Review - Design Requirements - Model Magnet Program Goals - Baseline Design / Model Magnet Variants - Outline of Talks	J. Kerby
10:00 AM	Prototype Magnet Design - Strand / Cable - Coils / Cure Cycle / Targets - Collars / Prestress Target - Yoke / Skin / End Plate	F. Nobrega
10:30 AM	American Coffee Break	(short, awful, make up time)
11:00 AM	Model Program Results / Conclusions - Mechanical Studies (AZ) - Quench Performance (ML) - Thermal Margin (AZ)	A. Zlobin / M. Lamm
12:30 PM	Lunch (provided)	
1:30 PM	Model Program Results / Conclusions - Quench Protection (ML) - Field Quality (AZ)	A. Zlobin / M. Lamm
2:30 PM	Prototype Plans / Status / Summary	J. Kerby
3:30 PM	Committee Working Session	
5:00 PM	Committee Wrap Up with Designers	
7:00 PM	No host dinner at Chez Leon	

Appendix 3

Introduction / Overview

Jim Kerby

US LHC ACCELERATOR PROJECT

*brookhaven - **fermilab** - berkeley*

Introduction / Overview

Jim Kerby

MQXB Engineering Design Review

16 March 2000

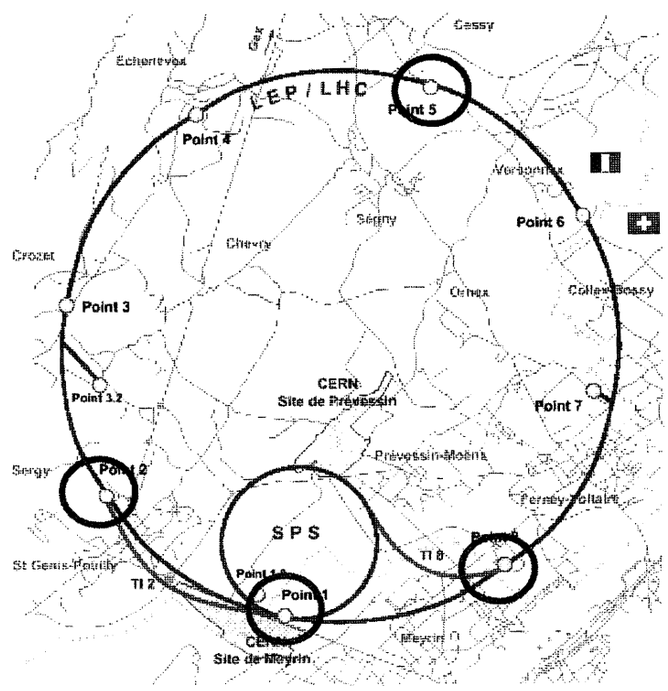
- LHC Inner Triplet Design
- MQXB Design Requirements
- HGQ Model Magnet Program Goals
- Baseline Design / Model Variants
- Outline of Upcoming Talks

US LHC ACCELERATOR PROJECT

*brookhaven - **fermilab** - berkeley*

Fermilab's role in the US-LHC Accelerator Project

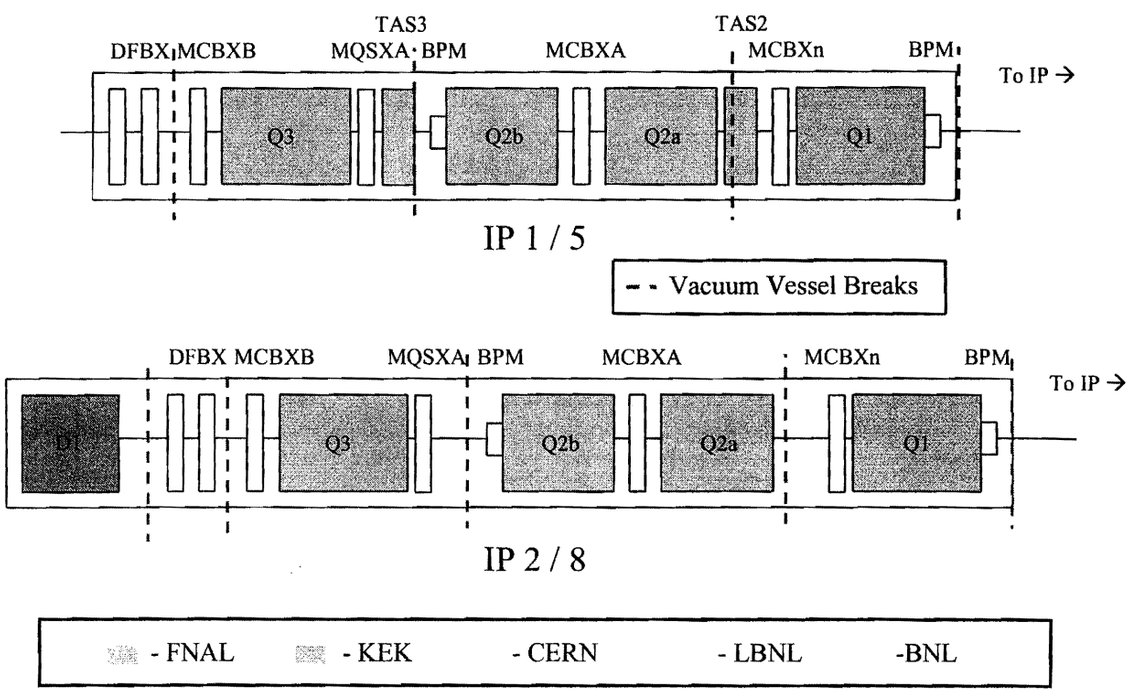
- To provide project management for the 3 involved laboratories,
- To provide support in areas of cryogenics, electrical systems, energy deposition, and beam physics calculations
- To design, build, test and deliver half the final focus quadrupoles
- To design, build, test and deliver cryostats and final assembly for all the final focus quadrupoles, including:
  - U.S.- and Japanese-built quadrupoles
  - CERN-provided correctors



The LHC Inner Triplet

In hardware, Fermilab is designing, developing, and producing

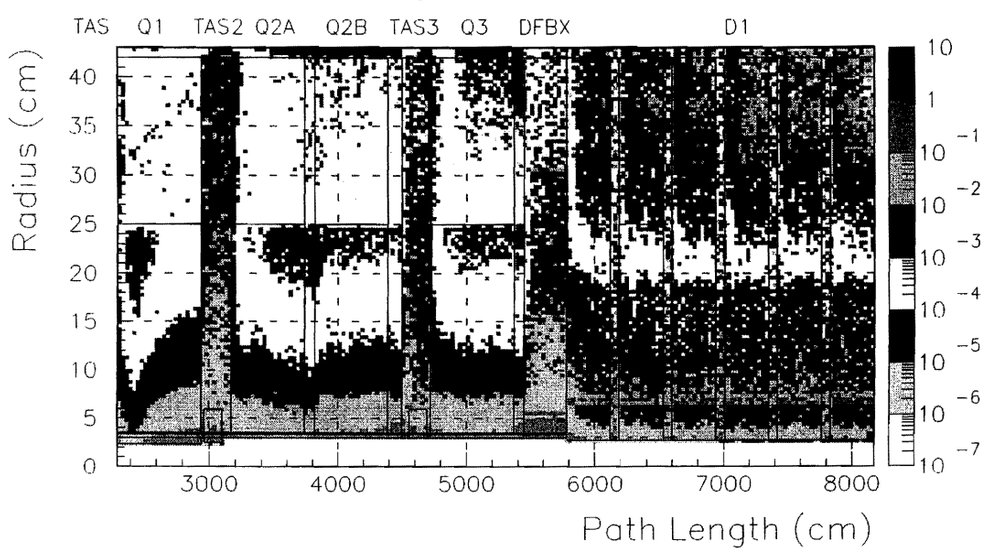
- The Q2a and Q2b cold masses (18 total)
- Cryostats for all the inner triplet magnets, including those made at KEK (27 total)
- Integration and assembly of all components



The LHC Inner Triplet

Apart from providing the gradient to achieve final focus in LHC, the inner triplet quadrupoles are subjected to very high energy deposition in the high luminosity IPs, on the order of 180W per side of an interaction point at IP1 or IP5. Providing adequate coil and magnet cooling margin is critical to maintaining quench performance under operating conditions.

The calculations of N. Mokhov (Feb 2000) for IP5 predict the level of energy deposited for the current inner triplet design, resulting in the following output...

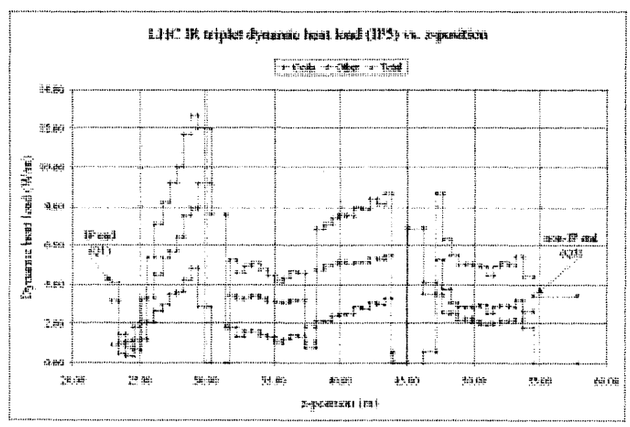


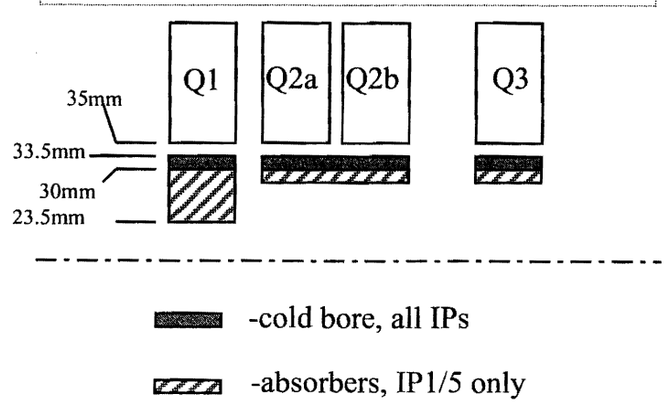
LHC IP5 Inner Triplet MARS ϕ-averaged power density (mW/g)

The LHC Inner Triplet

With a little interpretation, the previous slide can be turned into the following plot, which shows the azimuthally summed deposition into the coils and the remainder of the magnet as a function of length in the inner triplet at IP5.

The predictions result in an operating boundary condition where at nominal luminosity of $10^{-34}cm^{-2}s^{-1}$ a peak load of just over 8W/m needs to be extracted from a Q2, and the coils of Q2 must be cooled such that a peak deposition of 0.4mW/g to the inner coil does not degrade quench performance. A series of absorbers is required inside the beam tube to shield the coils, and reduces the peak deposition by 30%.





MQXB Design Parameters

Operating Gradient (IP1/5)	205 T/m
Operating Gradient (IP2/8)	215 T/m
Coil Inner Diameter	70mm
Magnetic Length	5.5 m
Mechanical Length	5.5m + ε
Harmonics	consistent w/ AP studies
Cooling	sufficient for peak heat loads at IP1/5

Scope of this Review

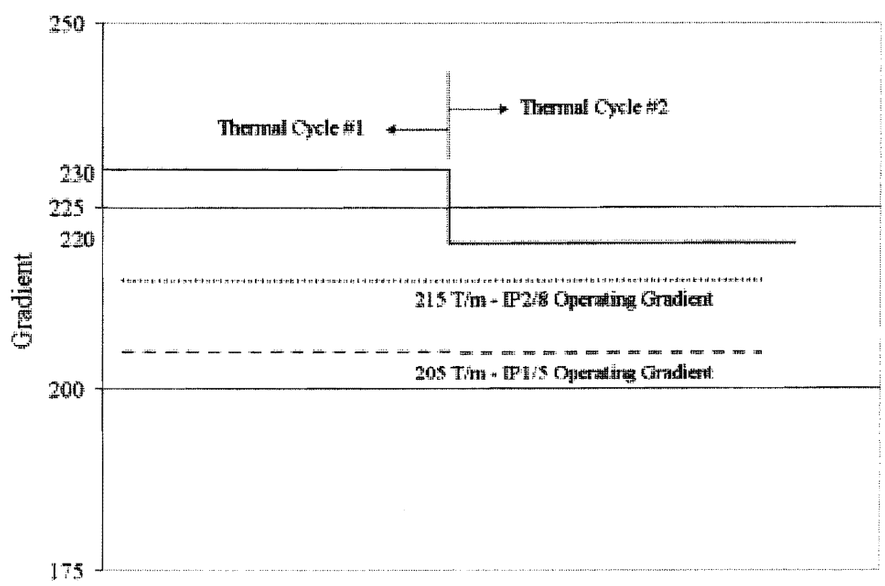
The review covers the MQXB Prototype Design, which includes the cold mass up to and including the end plates and quadrant lead splice block of the magnet.

Not included is the cryostat design, the design of end domes and extension pieces outside the end plates, i.e. bus bar expansion loops, the beam tube, interfaces to correctors and instrumentation, and other components which will be inserted or assembled at the final assembly stage except in manners which they impact the cold mass design--like having enough room in the bus bar slots for the bus bars.

MQXB Design Requirements

Quench Performance training goals for the first and second thermal cycles of each magnet have been set to show that the magnet will meet the operating quench performance requirements, and show sufficient memory such that no retraining is seen in LHC.

Sufficient Thermal Margin is required such that the quench performance remains sufficient when installed at either of the high luminosity interaction points.



MQXB Design Requirements

Harmonics targets have been generated 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. The goal is that the design be consistent with that listed.

MQXB AP Reference Table 2.0 (collision)						
n	$\langle b_n \rangle$	$d(b_n)$	$s(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$s(a_n)$
Body						
3	0	0.3	0.8	0	0.3	0.8
4	0	0.2	0.8	0	0.2	0.8
5	0	0.2	0.3	0	0.2	0.3
6	0	0.6	0.6	0	0.05	0.1
7	0	0.05	0.06	0	0.04	0.06
8	0	0.03	0.05	0	0.03	0.04
9	0	0.02	0.03	0	0.02	0.02
10	0	0.02	0.03	0	0.02	0.03
Lead end (magnetic length ~0.41m)						
2	-	-	-	40	-	-
6	2	2	0.8	0	0.5	0.2
10	-0.2	0.2	0.1	0	0.1	0.1
Return end (magnetic length ~0.33m)						
6	0	1.2	1	-	-	-
10	-0.25	0.25	0.1	-	-	-

MQXB Design Requirements

Alignment Reference Table v1.0

The cold mass alignment target is that the average twist for a cold mass before cryostatting be 0.2mrad/m or less.

	AP Requirements	Mechanical Tolerances	Measurement and Survey Accuracy	
1a) Single MQX cold mass	**Not limiting as long as <>=0. Needs further study**		**Mechanical meas. Not limiting**	
Straightness H and V		100 µm/meter		
Twist		1mrad/5 meter		
1b) Single multilayer corrector field	Moved to 2b			
2a) Relative alignment of MQX magnets in composite Q2		**Mechanical tests scheduled starting in 2000**	*Mech. and stretch wire with survey equip.*	
Q2a/Q2b transverse alignment	500 µm			100 µm
Q2a/Q2b relative roll	1 mrad (rms)			100 µrad (rms)
Q2a/Q2b relative pitch and yaw	100 µrad			130 µrad
2b) Relative alignment of corrector in a composite Q2 and Q3			Should be able to do with mech measurements	
Corrector displacment	500 µm			
Corrector roll	5 mrad			
3) Placement of composite coldmass into cryostat and relating magnetic axis to external fiducial		*Within limits, correctable if adjustments made to cryostat jacks*		
Q1 Displacement transverse	300 µm			180 µm
Displacement longitudinal				
Sag	?	?		?
Roll angle	200 µrad (rms)			100 µrad (rms)
Pitch/Yaw				130 µrad
Q2 Displacement transverse	300 µm			180 µm
Displacement longitudinal				
Sag	?	?		?
Roll angle	100 µrad (rms)			100 µrad (rms)
Pitch/Yaw				130 µrad
Q3 Displacement transverse	300 µm			180 µm
Displacement longitudinal				

MQXB Design Requirements

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.

The electrical system limits have to be consistent with the LHC quench protection system, the 'mixed' mode of assembly of the inner triplets, and the LHC machine system of specifications.

HGQ Model Magnet Program Goals

To demonstrate that the Fermilab quadupole meets the design criteria just described.

When appropriate, to develop improved values for use by accelerator physics colleagues in beam physics simulations

To develop initial production criteria such that reasonable ranges exist as target limits in prototype fabrication (ie, coil size range)

To develop travelers consistent with the fabrication of acceptable magnets by production technicians

HGQ Model Magnet Program Goals

We believe the program achieved each of the goals.

Magnets HGQ05 through HGQ09 show consistently good quench performance.

Steady State harmonics are such that a revision of the AP reference table has been published.

Transient harmonics in HGQ05 and HGQ09 are acceptable.

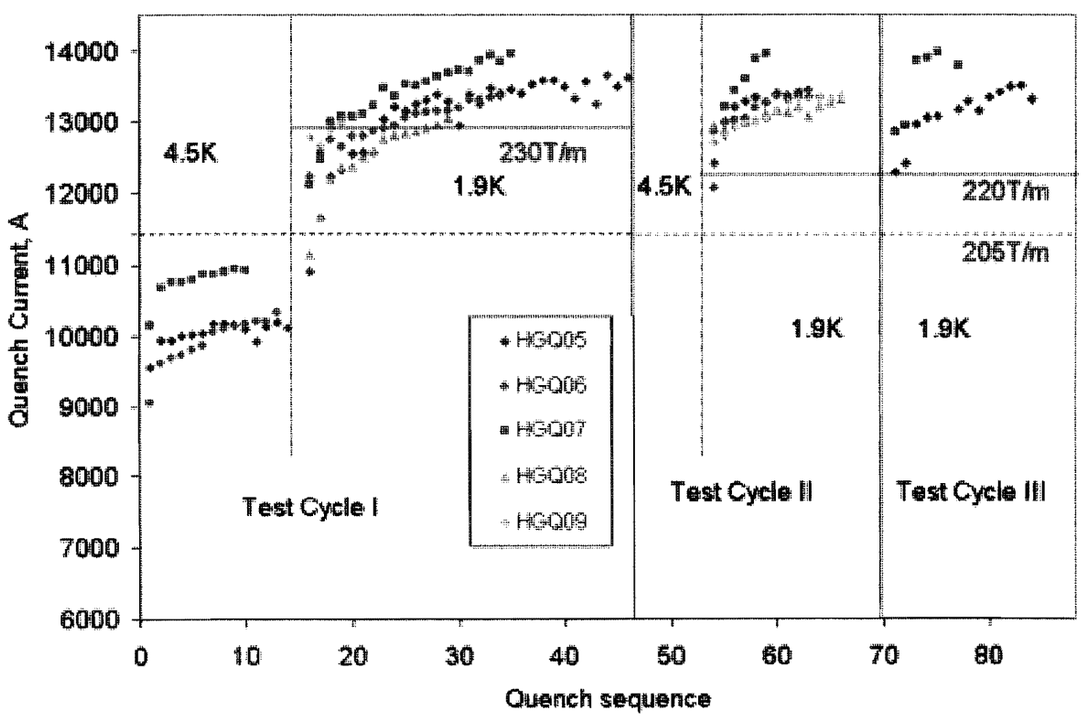
Cold mass straightness and twist are within the targets.

Quench Protection is adequate.

Production ranges on coil size, properties, and prestress have been developed.

Travelers have been developed during the model program, and will be extended during the prototype program.

A Brief Preview of Model Program Results

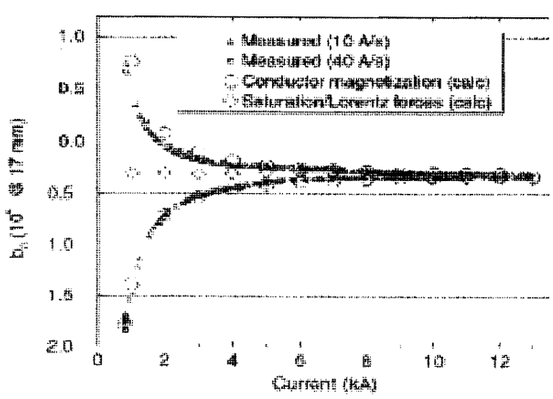


Model Program Results

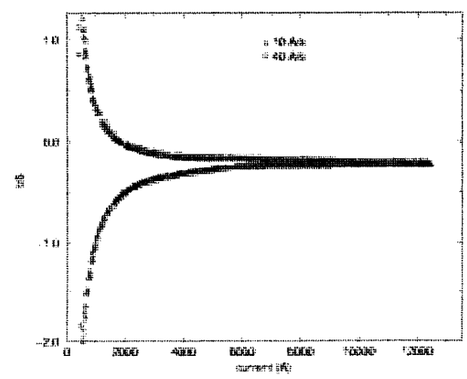
Harmonics...have been understood from HGQ01. However, since HGQ05 has the coil size been close enough to targets such that uncorrected data can be compared directly with the error tables.

A recent issue has been transient harmonics associated with low and varying interstrand resistance. This was addressed in HGQ09 with a modified cure cycle.

Comparison of b6 as a function of current in HGQ05 and HGQ09



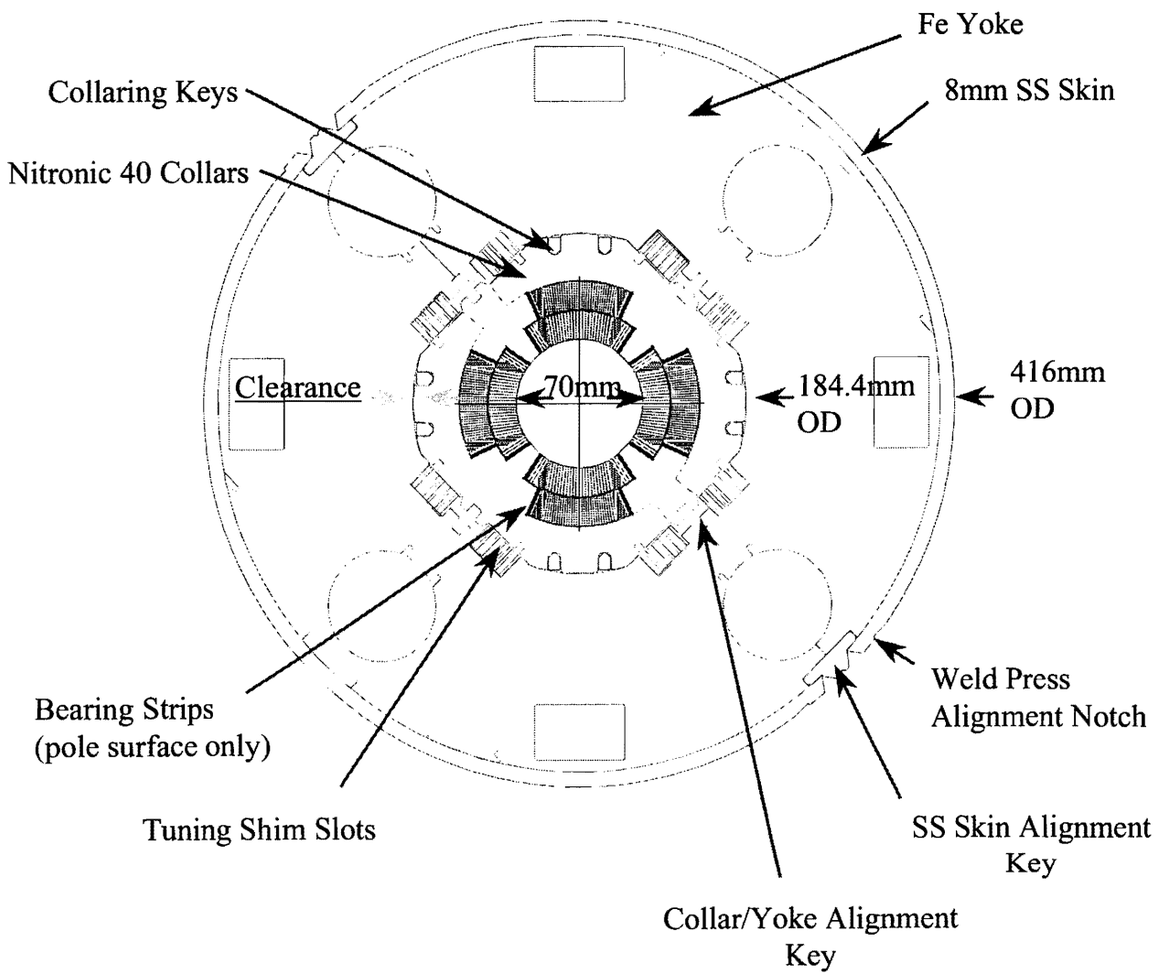
HGQ05



HGQ09

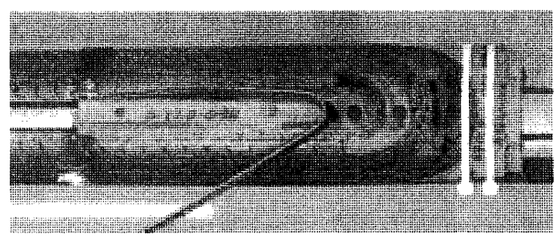
Baseline Design / Model Magnet Variants

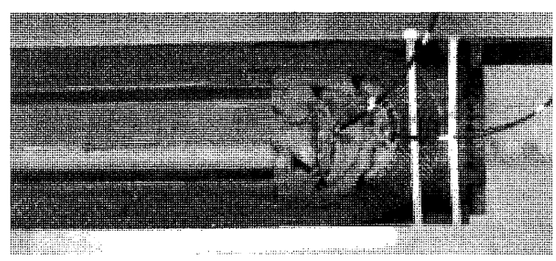
Design Short Sample ~250 T/m

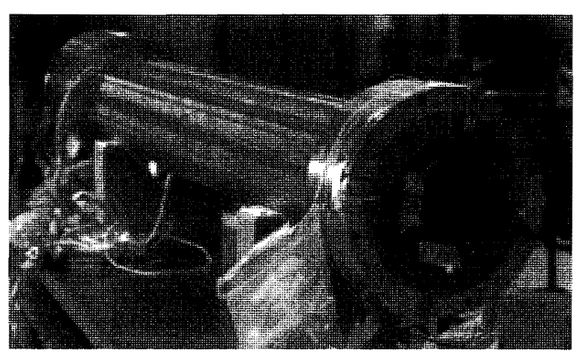


Baseline Design / Model Magnet Variants

Impregnated glass fibers have been used as the end part material in magnets HGQ05-09.
A '5-block' end design was introduced with HGQ06.
The internal splice design has been used since HGQ03.
Coil ends are shimmed for prestress consistent with the body, tapering off towards the end.
Mechanical support is provided by G11 spacers each quadrant, surrounded by an aluminum end can.
End restraint is provided through bullet gauges on the coil ends, and tension bolts to the end can.







Baseline Design / Model Magnet Variants

Strand Parameters*

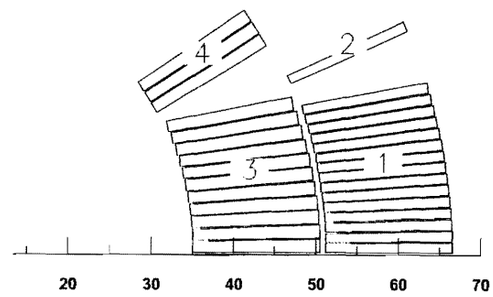
Parameter	Inner cable	Outer cable
Strand diameter [mm]	0.808	0.648/0.651
Filament diameter [μm]	6	6
Cu:SC ratio	1.3:1	1.8:1
RRR	70/100	70/100
Twist pitch [mm]	13	13
Twist direction	left/right	right
I_c(7T,4.2K) [A]	378	185
Strand Condition	bare, unannealed / stabrite, annealed	

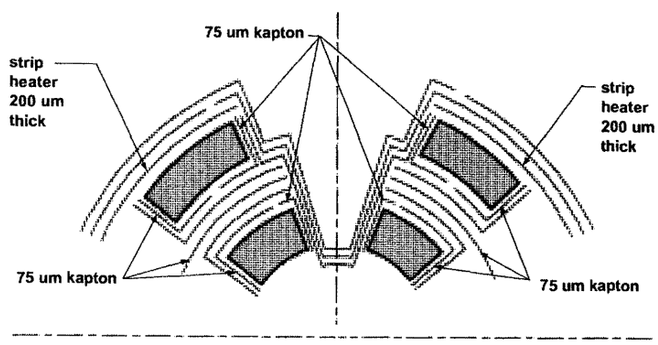
Cable Parameters

Parameter	Inner cable	Outer cable
Radial width [mm]	15.40	15.40
Minor edge [mm]	1.326/1.320	1.054/1.051
Major edge [mm]	1.587/1.610	1.238/1.241
Keystone angle [deg]	0.990/1.079	0.690/0.707
Mean thickness [mm]	1.456	1.146
Packing factor	0.89/0.91	0.91
Number of strands	37/38	46
Cable Lay	right/left	left

Baseline Design / Model Magnet Variants

Magnetic Design gives inner coil of 14 turns, 1 wedge, and outer coil of 16 turns, 1 wedge. Cable is insulated in 2 wraps, an 'electrical' layer of Kapton HA, and a 'mechanical' layer of Kapton LT. ZQIX is used as adhesive on the outer surface of the mechanical wrap.

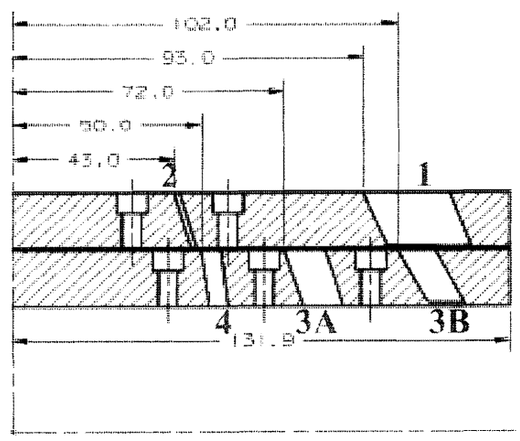


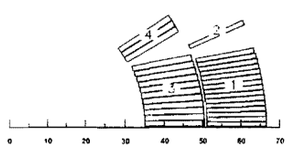


Coil to Coil and Coil to Ground insulation is provided by multiple layers of precreased Kapton sheets. Models have been assembled with strip heaters over the outer coils and between the inner and outer coils.

Baseline Design / Model Magnet Variants

The '5-block' end design splits the large inner coil conductor block into 2 smaller groups, as compared to the '4 block' design. All parts are G11CR.

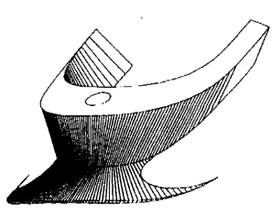


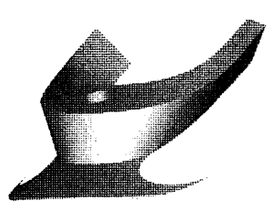


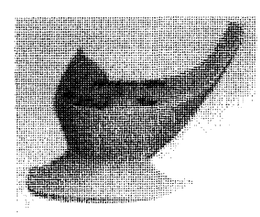
XY plane cut in body

YZ plane cut in end

"Grouped" ends are designed using BEND, minimizing the strain of the cable as it circumvents the end part. Shelves are used to fill voids created by the non-radial lay of the cable over the end. Parts are machined on a 5-axis machine

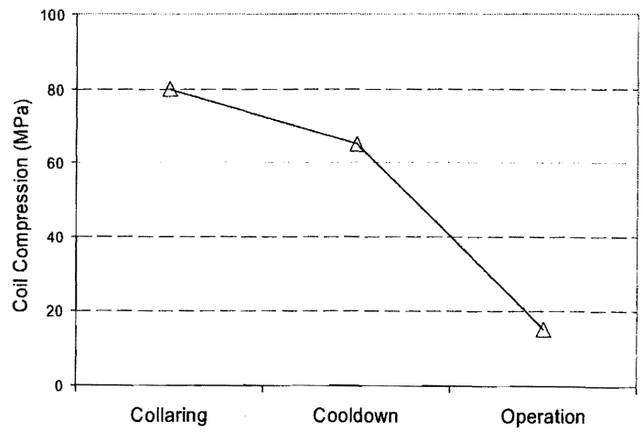


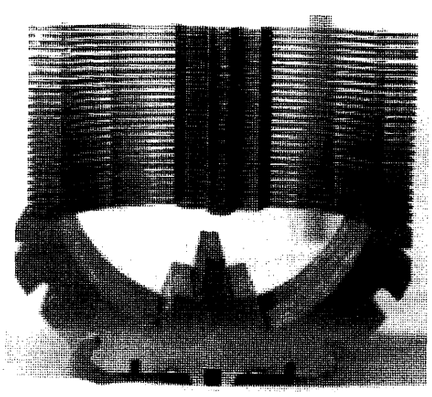




Baseline Design / Model Magnet Variants

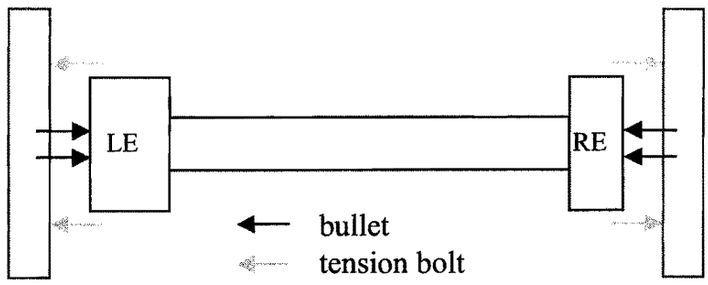
The target prestress is such that even at full excitation, we expect the coils have ~15MPa compressive load at the pole.
Model magnets have been made with preloads ranging from 55 to 100 MPa





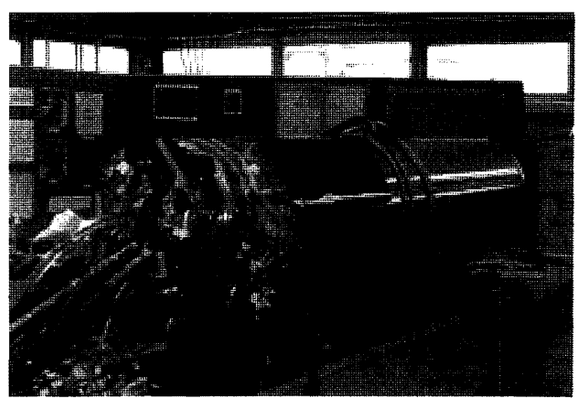
Preload is provided by standalone Nitronic 40 collars in the body, and the aluminum end cans over the ends. The designs are matched for preload and deflection.
Collar packs were introduced to reduce longitudinal collar pole deflection.
Bearing strips were deleted with HGQ08.

Baseline Design / Model Magnet Variants



End restraint is supplied through bullets, which load each quadrant of coil ends, and tension bolts, which tie the end can to the end plate.
Tests in HGQ05 and HGQ07 show quench performance is insensitive to the restraint applied.

End plate thickness has been reduced from 50mm to 35mm in HGQ09.

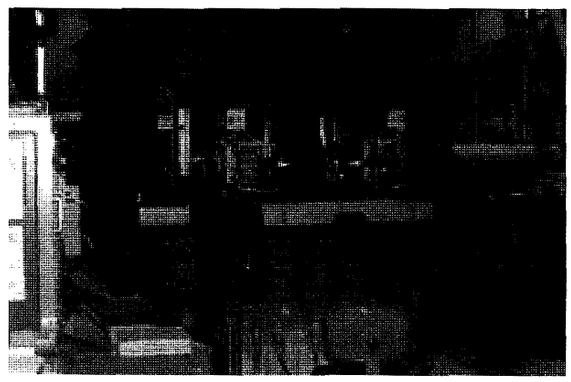


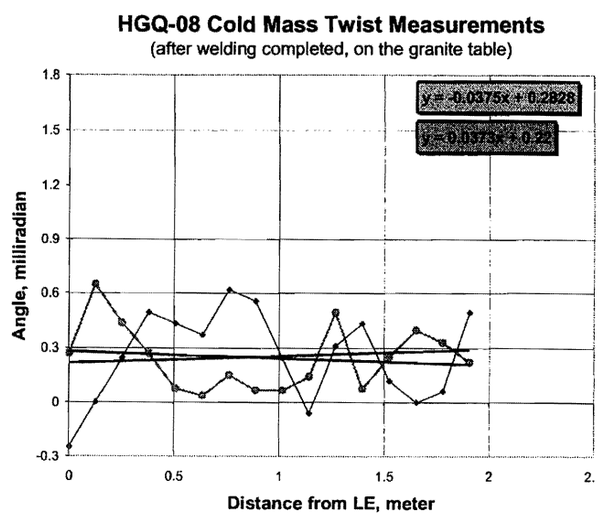
Baseline Design / Model Magnet Variants

Cold Mass alignment is ultimately determined by the TIG welding of the SS skins and the SS yoke/skin alignment key.

The major factor in achieving the alignment twist target in HGQ07 on was control of the relative speeds of the weld heads in the automatic press.

This is the same press to be used on the full length magnets.





Baseline Design / Model Magnet Variants

A detailed list of changes through all model magnets was provided on the web page, and there is another copy as an attachment to this talk.

From HGQ05 on, quench performance of the models improved dramatically, and through HGQ09 all components of the program were demonstrated.

Major factors in achieving the performance goals were:

- Matching the relative differential contraction of the coil ends and end parts. Switching back to G11CR, in our case.
- Introducing a two step cure cycle, which raised the interstrand resistance to acceptable levels.

And lessons for prototype production:

- Winding the inner coil in the favorable direction. The coil rejection rate for left lay inner cable was 25%. Once good coils were made and accepted, there was no difference in performance.
- Locally shimming the curing mold give noticeable improvements in reducing the coil size variation along the length.

Baseline Design / Model Magnet Variants

Other changes which were introduced, but whose direct impact was not seen:

- Matching the inner and outer coil properties.
- Restraint of the ends. Though no effect is seen on quench performance, this ensures the leads are not loaded, and provides a direct means of controlling length.
- Collar packs and end collets.
- Slightly lowering the prestress targets from 80MPa to 75MPa on both the inner and outer coils. Magnets have been made ranging from 55MPa to 100MPa with good results.
- Splitting the large inner coil conductor block into 2 smaller blocks in the end region.
- Reducing the inner cable from 38 to 37 strands.
- Using collaring keys which bridge across collar packs

Baseline Design / Model Magnet Variants

Finally, changes in the program that we don't care to see again:

- Annealed and Stabrite coated cable. The annealing did reduce longitudinal shrinkage of the coils after curing, but this was not such a production issue from the start. The stabrite coated cable was qualitatively less stable and more difficult to wind (though the manufacturer comes into play here as well...). And we still had a ways to go on the transient harmonics.
- ULTEM end parts. In this magnet, not a good thing.

Overview of Upcoming Talks

Upon completion of HGQ09, the goals of the model magnet program have been met. The emphasis now shifts to production of the first long prototype, preparations for which are now underway.

The structure of the remainder of the day focuses on details of the magnet design, and the lessons from the model magnet program which influenced the design. The upcoming agenda and description:

Magnet Design (Fred)

Model Program Results / Conclusions

- Mechanical Studies (Sasha)
- Quench Performance (Mike)
- Thermal Studies (Sasha)
- Quench Protection (Mike)
- Field Quality (Sasha)

Prototype Plans / Status / Summary (me again)

Appendix 4

Prototype Magnet Design

Fred Nobrega

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Prototype Magnet Design

Fred Nobrega

MQXB Engineering Design Review

16 March 2000

- Cable
- Coils
- Collar-Coil Assembly
- Cold Mass Final Assembly

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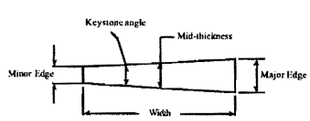
Cable Parameters



Parameter	Unit	Inner cable Value	Inner cable Tolerance	Outer cable Value	Outer cable Tolerance
Number of strands	----	37	-	46	-
Cable width	mm	15.40	±0.025	15.40	±0.025
Minor edge	mm	1.320		1.051	
Cable Mid-thickness	mm	1.465	±0.006	1.146	±0.006
Major edge	mm	1.610		1.241	
Keystone angle	Degree	1.079	±0.05	0.707	±0.05
Transposition length	mm	114	±5	102	±5
Lay direction	----	Right	-	Left	-
Minimum critical current	KA	14.0	-	8.5	-
Minimum unit length	m	180	-	200	-
Minimum collapse tension	Kg	50	-	50	-
Residual twist	Degree	0 - 90		0 - 90	
Minimum bending radius	mm	7		15	

- Inner cable size changed 6, 8, 12 μm respectively
- Keystone angle changed from 0.9771°
- # of inner strands decreased to 37
- Inner left lay cable was unstable with a coil rejection rate of ~25% due to popped strands causing turn – turn shorts.

→ Bought billet w/ left twist strand.

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Cable Insulation

- Insulation design optimized over the course of the model magnet program.
- Inner cable: 25 µm x 9.5mm Kapton w/ 58% overlap surrounded by 50 µm x 9.5mm w/2mm gaps using QIX → Kapton w/ a polyimide-epoxy adhesive.
- Outer cable: 25 µm x 9.5mm Kapton w/ 48% overlap surrounded by 25 µm x 9.5mm w/46% overlap using QIX → Kapton w/ a polyimide-epoxy adhesive.

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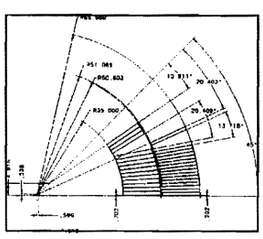
Cable Insulation Summary

Model #	Inner Cable	Outer Cable	Strand Surface	Wire/ Cable HT	Inner Cable Insulation	Outer Cable Insulation	Adhe-sive
HGQ01	38, Right Lay	46, Left Lay	Natural copper	None/ None	25µm x 9.5mm, 48% overlap; 50µm x 4.75mm 2mm gaps	25µm x 9.5mm, 48% overlap; 25µm x 9.5mm 48% overlap	Epoxy
HGQ02	38, Right Lay	46, Left Lay	Natural copper	None/ None	25µM x 9.5mm, 48% overlap; 50µm x 9.5mm 2mm gaps	25µm x 9.5mm, 48% overlap; 50µm x 9.5mm butt lapped	QI
HGQ03	38, Right Lay	46, Left Lay	Natural copper	None/ None	25µm x 9.5mm, 58% overlap; 50µm x 9.5mm 2mm gaps	25µm x 9.5mm, 48% overlap; 50µm x 9.5mm butt lapped	QI
HGQ04	38, Right Lay	46, Left Lay	Natural copper	None/ None	25µm x 9.5mm, 58% overlap; 50µm x 9.5mm 2mm gaps	25µm x 9.5mm, 48% overlap; 50µm x 9.5mm butt lapped	QI

Cable Insulation Summary (continued)

Model #	Inner Cable	Outer Cable	Strand Surface	Wire/ Cable HT	Inner Cable Insulation	Outer Cable Insulation	Adhe-sive
HGQ05	38, Right Lay	46, Left Lay	Natural copper	None/ None	25µm x9.5mm, 55% overlap; 50µm x9.5mm, 2mm gaps	25µm x9.5mm, 48% overlap; 25µm x9.5mm, 43% overlap	Epoxy
HGQ06	38, Left Lay	46, Left Lay	Natural copper	None/ None	25µm x9.5mm, 55% overlap; 50µm x9.5mm, 2mm gaps	25µm x9.5mm, 48% overlap; 25µm x9.5mm, 41% overlap	QI
HGQ07	37, Left Lay	46, Left Lay	Natural copper	None/ None	25µm x9.5mm, 58% overlap; 50µm x9.5mm, 2mm gaps	25µm x9.5mm, 48% overlap; 25µm x9.5mm, 41% overlap	QI
HGQ08	37, Left Lay	46, Left Lay	Stabrite	190C, 1h/ None	25µm x9.5mm, 61% overlap; 50µm x9.5mm, 2mm gaps	25µm x9.5mm, 48% overlap; 25µm x9.5mm, 46% overlap	QIX
HGQ09	37, Left Lay	46, Left Lay	Natural copper	None/ None	25µm x9.5mm, 58% overlap; 50µm x9.5mm, 2mm gaps	25µm x9.5mm, 48% overlap; 25µm x9.5mm, 46% overlap	QIX

Coils



MQXB Coil Cross Section

- Coil size & MOE progression in the model magnet program
- Coil size variation along the length
- Curing parameters
- Coil end design
- Prototype and MQXB coil size parameters
- Prototype and MQXB coil lengths

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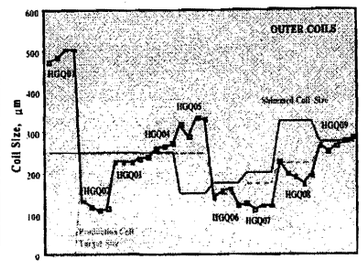
Coil Size Progression



- Average coil size measured at an azimuthal pressure of 83 MPa.
- Kapton shim was added to coils to achieve the desired coil prestress after collaring & keying.
- Dashed lines (orange) set coil target size based on previous magnet
- Solid line (green) set shimmed coil size by strain gauges, MOE and by collar deflection measurements
- HGQ08 used to determine upper limit of prestress range

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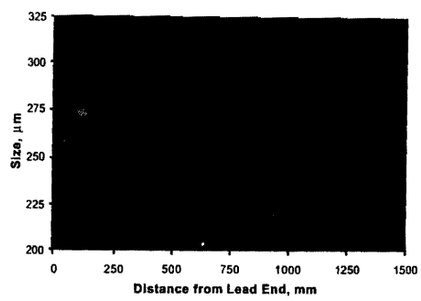
Coil MOE Progression

- MOE measured between 65 & 95 MPA.
- The peak to peak variations within coils is typically less than 1 GPa with typical standard deviations of about 0.4 GPa.
- Based on the model magnet program test results, target coil size and MOE are set to 275 µm and 9 GPA for both the inner and outer coils.

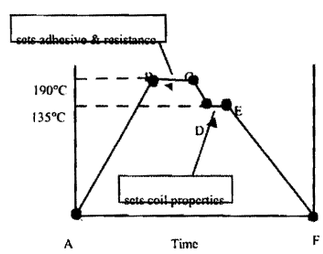
Coil Size Variation Along the Straight Section



Starting with HGQ07, Kapton shimming was added along the length of the coil before curing to reduce variation along the straight section. This variation was as much as 100 µm. Shims were placed azimuthally in the mold cavity and removed after curing. The plot shows the typical shape of the coils along the length of the straight section using this system.

Note that the shimming system might be different for prototype coils as we will be using new tooling for coil winding and curing. Practice coils will be made such that a similar system for the long coils can be used.

Coil Curing Parameters



The two step cycle used in HGQ09 combines the parameters used in HGQ03 and HGQ05. The coils were first cured at 190°C (for better adhesion) with low pressure and then the temperature is reduced to 135°C simultaneously increasing the curing pressure (for higher coil MOE). This process gave coils with acceptable interstrand resistance without significantly decreasing the coil rigidity. HGQ08 had the lowest interstrand resistance due to stabrite coated strands.

Model #	Curing Temperature	Curing pressure
HGQ01	135C	Low
HGQ02	190C	High
HGQ03	190C	High
HGQ04	190C	High
HGQ05	135C	Low
HGQ06	190C	High
HGQ07	190C	High
HGQ08	190C	High
HGQ09	190C/135C	Low/High

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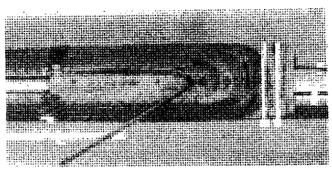
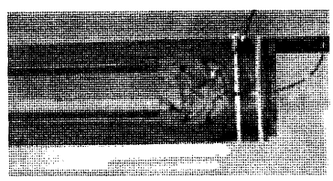
Coil End Design



Cured Lead End Inner Coil

- Ends optimized to minimize physical length, peak field and integrated harmonics
- Internal Splice
- G-11CR end part material- structural and radiation resistance
- 5 block end design for improved mechanical support



Cured Lead End Outer Coil

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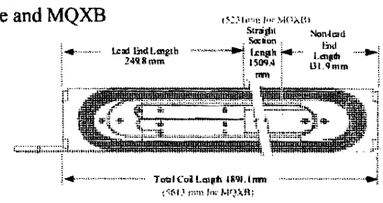
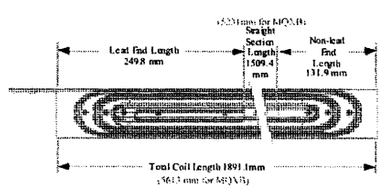
Coil Size and Length Specifications for Prototype and MQXB

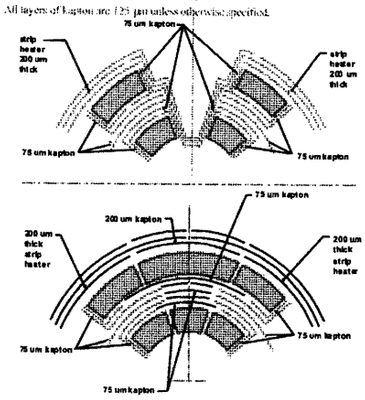
Coil Size Specifications
Inner coil size: 275 um +/- 50um Inner coil MOE: 9Gpa +/- 1GPa Outer coil size: 275um +/- 50um. Outer coil MOE: 9Gpa +/- 1 GPa





Collar-Coil Ground Wrap Insulation

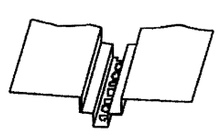
All layers of kapton are 125 μm unless otherwise specified.



The figures show the coil insulation system for the first long prototype. It is not identical to any of the short models. It is closest to the systems used for HGQ08 and HGQ09. The differences between the prototype and HGQ08/9 are:

- The HGQ09 system is identical to this one, except that the "flaps", on the inner layer of the inner coil, were not removed on HGQ09, and are on the prototype.
- On HGQ08, the flaps were removed, but the strip heater, instead of being 200 μm thick, was only 125 μm thick, with a 75 μm layer of Kapton between the strip heater and the outer coils. It is identical in all other respects.

Collar-Coil Ground Wrap Insulation (continued)



Three layers of Kapton, each 125μm, cross each pole, covering the inside surface of the collar laminations. To allow heat flow between the beam tube and the openings between the collars, slots are provided in the Kapton.

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Collar-Coil, Quench Heaters

- Eac[illegible] consists of 4 strip heaters packa[illegible]es as shown.
- [illegible] packag[illegible]ists of two heater strips cov[illegible]ring approximately 12 turns of two [illegible]imuthally adjace[illegible]s.
- Each element is 25 µm thick x 15mm wide sta[illegible]less steel intermittently coated with a thin (4µm) layer of copper on one side. The coated [illegible]reas are 210mm long, alternating with 105mm long areas of bare stainless steel.
- The stainless steel length corresponds to one transposition pitch.
- The two strips will be connected in series at the return end of the magnet.
- The two elements are sandwiched between 100 µm layers of polyimide film and adhesive.
- Heater assemblies are being supplied by CERN.

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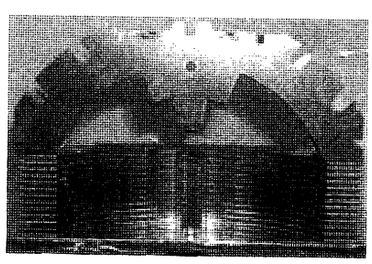
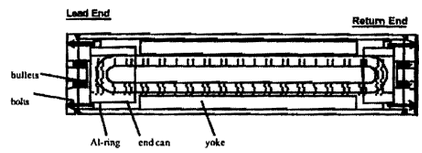
Collar-Coil Assembly, Collar Packs



- The collars are stamped and provide a repeatability from part to part of +/- 15 µm.
- Large and small laminations are alternated, with the small laminations filling the gaps at the pole. The small laminations strengthen the collar structure longitudinally, and provide continuous azimuthal support for the coil.
- The introduction of the small lamination allowed the bearing strips, used on earlier short models, to be eliminated. Magnets HGQ08/9 were built without bearing strips and performed well.

Cold Mass Final Assembly, End Restraint

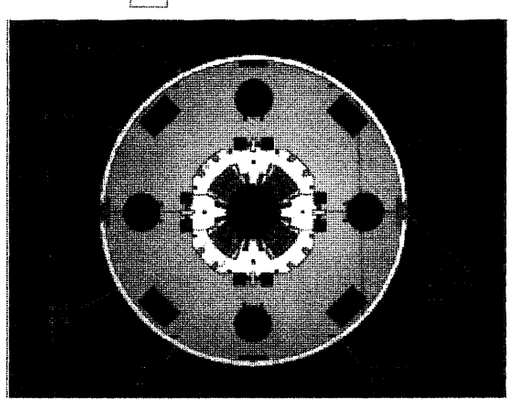


Starting from magnet HGQ-05, the collared coil assembly was secured axially to the end plate using load bolts. Calculations and experiments were conducted in order to verify that the end cans do not slip off the ends of the coils during the axial loading of the collared coil assembly. The figure above shows the axial loading mechanism used to load the collared coil assembly.

An aluminum ring is bolted to the aluminum end can at both the lead and non-lead ends. Load bolts are used to axially tie the collared coil assembly to the end plate through the aluminum ring. Gaps between coil end-saddles and pusher plate are filled with "green putty" to provide a uniform transfer of load to the coils from the end bullets.

A force of 9.8 kN (2,200 lbs.) is applied to each bullet at both the lead and non-lead end of the magnet.

Cold Mass Final Assembly, Yoke Redesign

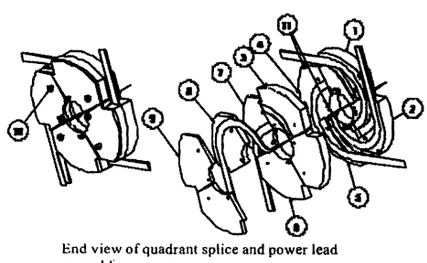


- Yoke redesigned:
  - 50mm cooling holes
  - Tuning shims replaced with iron from yoke

Cold Mass Final Assembly, End Plate

An end plate thickness of 50mm was selected for the initial baseline design based on the assumption that the total longitudinal force on the coils is transferred to the end plate. Bullet end load data from the model magnets show about 20-25% of the axial Lorentz load reacting against the end plate. Strain gauges placed on the skin of the cold mass indicate no additional load transfer to the skin from, for example, any possible collar-yoke interference. Based on analysis and test results of HGQ09, a 35mm end plate will be used.

Cold Mass Final Assembly, Quadrant Splice



End view of quadrant splice and power lead assembly:

1, 2, 3, 4 – splice blocks;

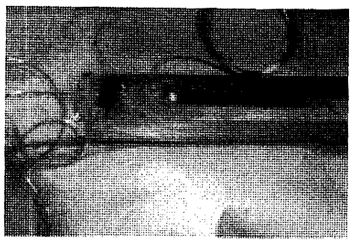
5, 6, 7, 8 – intermediate blocks;

9 – support block cover;

10, 11 – screws.

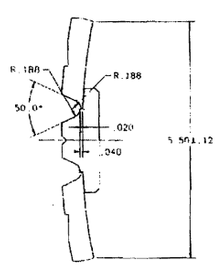
Four coil pairs (quadrants) are connected in series. There are three splices, with the remaining two inner coil leads extending out of the end. The quadrant splice and power lead assembly is mounted on the outer surface of the lead end plate. Cables are routed to ensure four quadrants are powered with proper polarity. Assembly geometry is chosen to maintain quadrupole symmetry to the greatest extent possible. Only the last 120 mm of the cables are straight and are soldered together.

Cold Mass Final Assembly, Copper Stabilizing Lead



Each coil lead has an extra length of specially made "copper only" cable soldered to it. The extra cable begins 25mm inside the end of the saddle and extends to the end of the lead. The picture shows an inner coil with the extra lead attached. The extra copper acts as a quench "stabilizer" making the coil more likely to recover from localized disturbances which can result in a quench. If a quench does occur in the stabilized lead cable, the lower cable resistance and increased heat capacity will greatly reduce the maximum peak coil temperature.

Cold Mass Final Assembly, Skin & Alignment Keys



The weld prep for the skin and alignment key went through several iterations before the correct recipe for welding was found. The width of the key was increased from the original design width of 19mm to 26.5mm to account for the large weld shrinkage. The skin is a helium vessel used to keep the yoke halves in contact at all times and since there is no collar-yoke interference the only load to the skin is due to weld shrinkage. The final weld prep design is a modified J-groove with a 0.5mm sharp corner at the bottom of the groove. The J-groove weld prep in conjunction with the sharp corner forces the arc weld to same location during the fusion pass.

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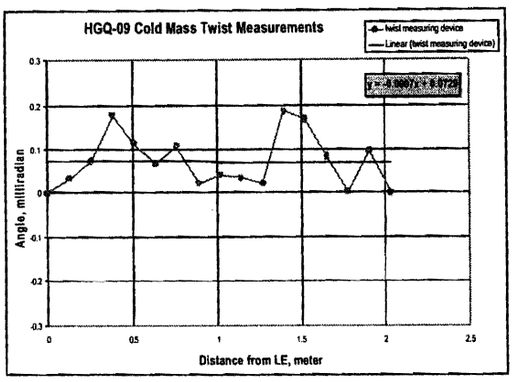
Cold Mass Final Assembly, Cold Mass Twist



Cold mass twist ranged from 0.6 to 4.67 mRad/meter in magnets HGQ01-06. The requirement calls for a twist of less than 0.2 mRad/meter. After numerous studies and upgrades to the weld press the primary culprit was discovered to be the relative weld carriage speed to one another. One weld carriage was moving faster than the other causing a weld shrinkage differential and locking in a twist. Once discovered and corrected, magnets HGQ08 & 09 had a twist less than 0.1 mRad/m!

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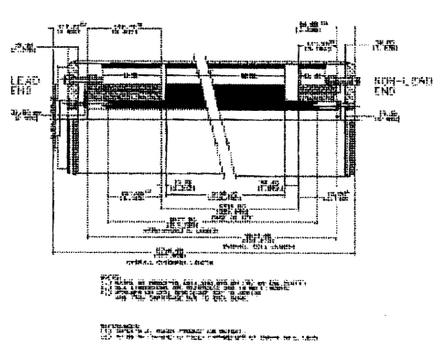
Cold Mass Final Assembly, Prototype Mechanical Layout



Appendix 5

HQG Short Model Test Results: Mechanical Studies

A. Zlobin

HGQ Short Model Test Results:
Mechanical Studies

Outlines

- objectives
- instrumentation
- azimuthal prestress study
- harmonics stability
- longitudinal support study
- skin strain measurements
- summary

Objectives

In order to provide stability of field harmonics over the operational field range and reduce the probability of spontaneous quenches caused by conductor motion, the coil turns must be mechanically constrained by applying stress to the coil during magnet fabrication.

The azimuthal mechanical support and prestress of the HGQ coil is completely provided by the stainless collars and Al end cans.

Thick steel end plates are used to restrict the longitudinal coil motion under Lorentz forces.

The prestress applied to the magnet coils at room temperature which will compensate the prestress decrease resulting from collar spring back, coil creep, difference in the coil and collar thermal contraction and Lorentz forces, was chosen based on results of finite element analysis.

Objectives:

- **azimuthal coil prestress measurement at room and operation temperature**
- **azimuthal prestress and harmonics change at nominal current**
- **longitudinal coil prestress control at room and operation temperature**
- **longitudinal Lorentz force measurement**
- **skin strain**

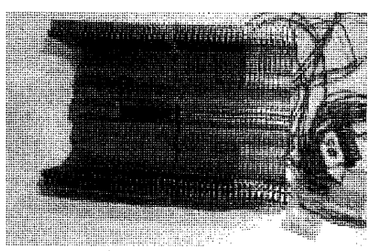
Instrumentation

Instrumentation used for the mechanical studies includes:

- strain gauges (resistive and capacitative) installed in the magnet straight section in order to measure azimuthal stress
- bullet gauges/load screws installed in the end plates to provide longitudinal prestress and monitor longitudinal Lorentz force
- skin gauges to measure strain in the cold mass skin (helium vessel)

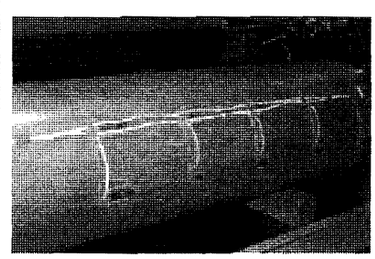
In addition to direct measurements of mechanical parameters, field harmonics measurements taken over the operational cycle were also used to investigate and quantify azimuthal and radial turn motion under the influence of Lorentz forces.

Strain Gauges



Collar pack assembly with inner beam gauge (L) and capacitance gauge (R)

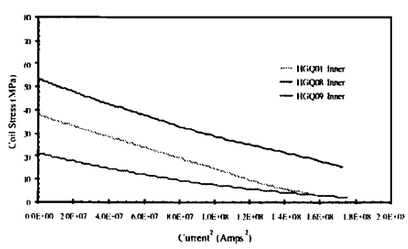
Position and orientation of strain gauges on the cold mass skin as used in magnets HGQ07-09



Azimuthal Prestress Summary

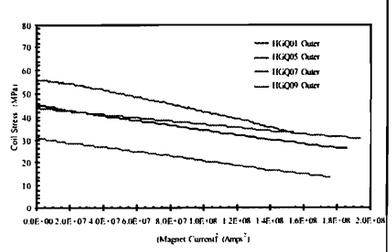
Model Number	Azimuthal prestress @300K Inner layer, MPa	Azimuthal prestress @300K Outer layer, MPa	Azimuthal prestress @1.9K Inner layer, MPa	Azimuthal prestress @1.9K Outer layer, MPa
Design	81	81	74	66
HGQ01	67	72	38	58
HGQ02	73	94	76	84
HGQ03	187	97	173	102
HGQ05	99	55	-	49
HGQ06	59C	61C/139B	-	169B
HGQ07	65C	74C/58B	-	45B
HGQ08	86C/94B	92C/96B	66B	105B
HGQ09	68C/48B	77C/58B	33B	42B

Effect of Azimuthal Lorentz Forces



Average azimuthal stress for the inner coils of magnets HGQ01, HGQ08, and HGQ09

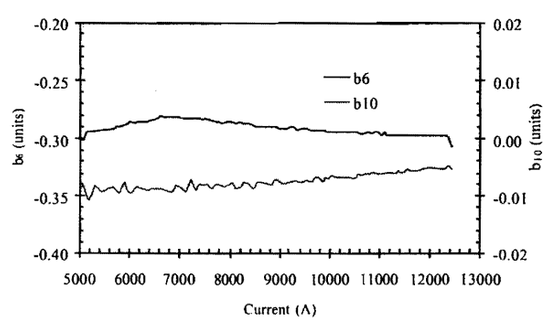
Average outer coil azimuthal stress for magnets HGQ01, 05, 07, and 09



Azimuthal Lorentz Force Summary

Model Number	Azimuthal prestress @300		Azimuthal Lorentz force	
	Inner layer, MPa	Outer layer, MPa	Inner layer, MPa/kA^2	Outer layer, MPa/kA^2
Design	81	81	-0.28	-0.20
HGQ01	67	72	-0.28	-0.13
HGQ02	73	94	-0.31	-0.15
HGQ03	187	97	-0.29	-0.13
HGQ05	99	55	-0.24C	-0.13
HGQ06	59C	61C/139B	-0.41C	-0.26B
HGQ07	65C	74C/58B	-0.16C	-0.11B
HGQ08	86C/94B	92C/96B	-0.20C/-0.28B	-0.16B
HGQ09	68C/48B	77C/58B	-0.26C/-0.16B	-0.11B

Harmonics Stability in Operation Field Range

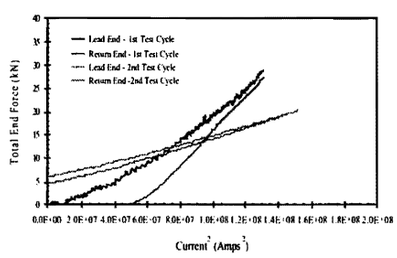


Average value (up/down ramp) of b_6 and b_{10} during a current ramp cycle for HGQ09

Longitudinal Prestress Summary

Model number	Longitudinal end prestress @300K		Longitudinal end prestress @1.9K	
	Lead end, kN	Return end, kN	Lead end, kN	Return end, kN
Design	>0	>0	>0	>0
HGQ01	0.8/14.3	0.8/22.4	0/0.9	0/3.2
HGQ02	7.5	11.4	0	0
HGQ03A	8.2	8.3	0	0
HGQ05	10.5	10.2	5.1	4.1
HGQ06	9.4	9.4	4.7/6.2	3.0/3.0
HGQ07	11*	8*	10.5	7.5*
HGQ08	8.4/8.5	9.0/9.3	10.7/11.3	8.0/9.0
HGQ09	11	9	11.5	7.5

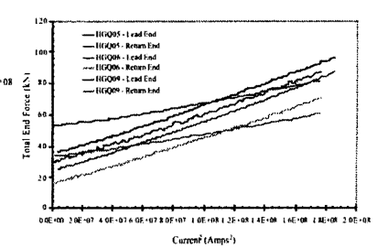
End Lorentz Force Measurement



Total end force on HGQ01 during the first and second test cycles.

The RE end force was increased between test cycles.

Total coil end loads for HGQ05, HGQ06 and HGQ09



Longitudinal Lorentz Force

Model number	End plate thickness, mm	Longitudinal Lorentz force	
		Lead end, kN/kA^2	Return end, kN/kA^2
Design	50	0.36	0.36
HGQ01	50	0.09	0.09
HGQ02	50	0.08	0.07
HGQ03A	50	0.06	0.06
HGQ05	50	0.089	0.091
HGQ06	50	0.088	0.083
HGQ07	50	0.085	0.094
HGQ08	50	0.077/0.082	0.089/0.089
HGQ09	35	0.046	0.043

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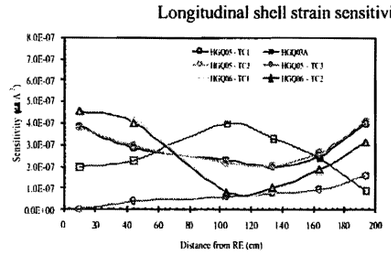
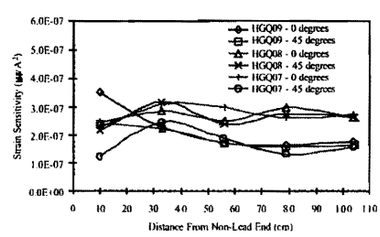
Skin Strain Measurements

Longitudinal shell strain sensitivity along the cold mass length





Mechanical Performance Summary

The Fermilab HGQ mechanical design offers satisfactory coil mechanical support. The mechanical design has been refined and improved through a combination of analytical, computational, and empirical studies.

Radial coil support in magnet body is provided by the welded SS collar packs.

The range of coil prestresses that provides adequate coil precompression and restraint is reasonably large (80±20 MPa), allowing for a coil size deviation in production of ±30 μm, without degradation to quench performance and effect on harmonics stability.

End plates and Al end-cans, attached to the end plates, were chosen to constrain the ends radially and longitudinally. This feature substantially reduced the longitudinal motion resulting from thermal contraction, and allowed positive contact to the end plates to be maintained with much lower initial room temperature end loads.

Since less than 25% of the calculated longitudinal Lorentz force has been measured by the bullet gauges during operation at the design gradient, the end plate thickness has been reduced from 50 mm to 35 mm. This is sufficient to adequately support the measured coil longitudinal loads and reduces the cold mass overall length.

Appendix 6

Quench Performance

Michael Lamm

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Quench Performance

Michael Lamm

MQXB Engineering Design Review

16 March 2000

- Performance Goals
- Training History
- Ramp Rate Dependence
- Temperature Dependence
- Conclusion

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Training Goals for MQX Magnets

-Training at 1.9K to 230 T/m in a small number of quenches.

~10-20 Quenches with energy extraction

....to reduce the cost of qualifying cold mass

-On second thermal cycle, should exceed 220 T/m on first quench

....no re-training quenches in the tunnel

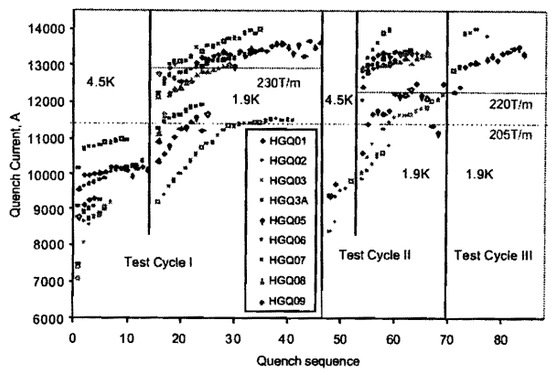
-No degradation of quench performance on the 220 T/m level after full energy deposition quenches

....since there is no energy extraction in the inner triplet

-Mild ramp rate dependence to quench current

.....ramp rate is low but could effect field harmonics

Overview of Quench Performance



Design Improvements Post HGQ03

- Use of G10/G11 as end part material (radiation hardness deemed acceptable)
- Cure of inner coil at higher pressure, resulting in a higher inner layer elasticity modulus and more uniform inner/outer coil mechanical properties
- A continuous body/end transition, including elimination of key extension
- Welded collar packs with pole filler pieces
- Aluminum end can assemblies over both ends
- Attachment of the end cans to the end plate, which ensures contact between the coil ends and end plates as well as stretches the coil straight section after cool-down
- New inner cable (37 strand) and new end design starting from HGQ06

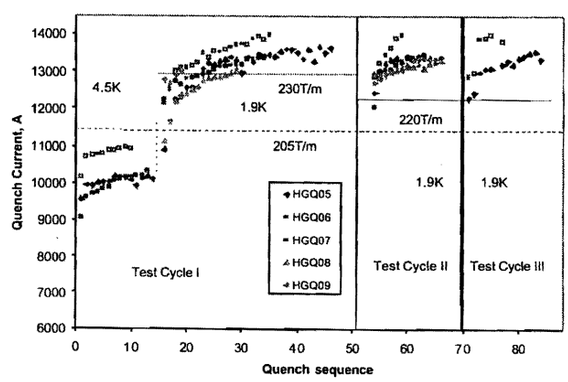
  Stabrite on HGQ08

Quench Summary

Model Number	Iq1(4.5K), A	Iq1(1.9K), A	N(<205T/m)
HGO01	8776	10327	8
HGO02	7365	9191	23
HGO03	7057	10019	7
HGO03A	7438	11228	1

Model Number	Iq1(4.5K), A	Iq1(1.9K), A		N(<205 T/m)	N(<230 T/m)
		TCI	TCII		
HGO05	9553	10896	12417	1	7
HGO06	9056	12224	12044	0	8
HGO07	10155	12101	12855	0	2
HGO08	-	11145	12939	1	12
HGO09	-	12760	12688	0	3

Quench Training of "Later" Magnets



Quench Location for Low Ramp Rate Quenches

	HGQ05		HGQ06		HGQ07		HGQ08		HGQ09	
	pole	wedge	pole	wedge	pole	wedge	pole	wedge	pole	wedge
Inner body	2	13	9	19	1	11	4	10	3	7
Inner end	2	1	5	0	5	5	1	0	1	0
Outer body	4	14	0	0	2	0	1	8	1	2
Outer end	0	16	0	0	0	0	0	0	0	1

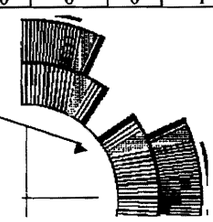
General comments:

-Predominance of quenches in turns near inner wedge (turn 11) correlated to slow training

-No apparent benefit to training at 4.5 K

-Thermal cycle memory is good

-No correlation of prestress to quench performance



Azimuthal Prestress Summary

Model Number	Azimuthal prestress @300K Inner layer, MPa	Azimuthal prestress @300K Outer layer, MPa	Azimuthal prestress @1.9K Inner layer, MPa	Azimuthal prestress @1.9K Outer layer, MPa
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HGQ02	73	94	76	84
HGQ03	187	97	173	102
HGQ05	99	55	-	49
HGQ06	59C	61C/139B	-	169B
HGQ07	65C	74C/58B	-	45B
HGQ08	86C/94B	92C/96B	66B	105B
HGQ09	68C/48B	77C/58B	33B	42B

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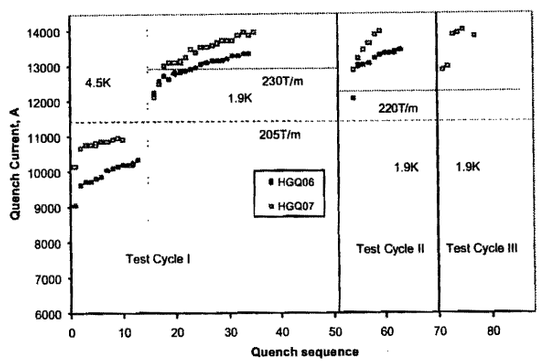
Longitudinal Preload



HGQ05,HGQ06, HGQ08-9 and third TC of HGQ07: longitudinal preload

HGQ07 TC 1&2: no preload

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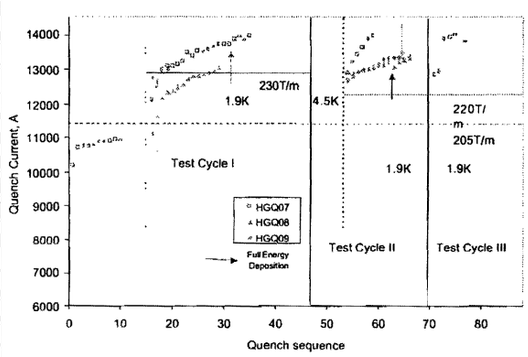
Full Energy Deposition with Spot Heater Induced Quench



Quench training is performed with extraction circuit to minimize recovery as well as for redundant magnet protection.

Verify that full energy deposition does not degrade magnet quench performance

Ramp Rate Dependence

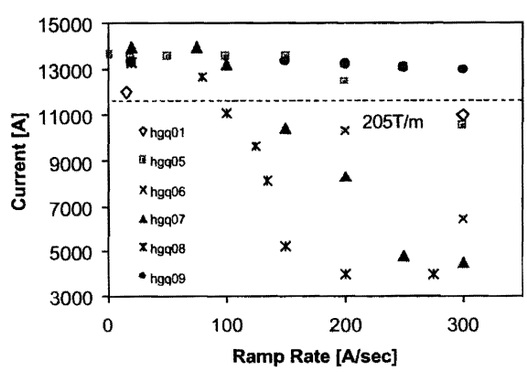
Ramp rate dependence to quench ==>Eddy Current Coupling

Undesirable even at low ramp rates due to effects on field quality

Coupling reduced by (lack of) strand coating and cure cycle

Model Number	Inner coil curing		Strand coating	AC loss @100A/s J/cycle	Ic(300 A/s), A
	Temperature, ^{0}C	Pressure, MPa			
HGQ01	135	20	No	-	10965
HGQ02	190	20	No	210	11335
HGQ03	195	20	No	234	11298
HGQ05	130	80	No	177	10519
HGQ06	190	80	No	1000	6433
HGQ07	190	80	No	589	4487
HGQ08	190	80	Stabrite	4538	3941
HGQ09	190/135	20/80	No		12946

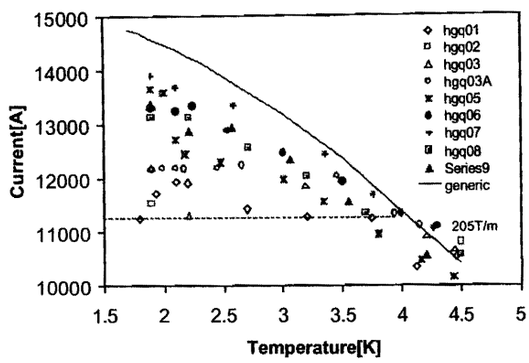
Ramp Rate Sensitivity



For HGQ06-8 high ramp rate quenches occur in "inner midplane"

For HGQ01, HGQ05, & HGQ09 high ramp rate quenches occur near in-outer ramp splice

Temperature Dependence



Generic curve matches data (when not mechanically limited)

At 205 T/m thermal margin in outer pole turn ~1.8K(higher in midplane)

Quench Performance Summary

-Several changes were made to mechanical design after magnet HGQ03

-Subsequent magnets HGQ05-9 exhibited training performance (i.e. peak gradient, number of quenches to reach gradient, performance after thermal cycle) that meet the LHC goals.

-Performance is insensitive to azimuthal prestress within our chosen range. Longitudinal preloading is also not a significant factor

-Quench current appears to be mechanically limited (but well above operating gradient)

-From temperature dependence to quench current, there appears to be a temperature margin for outer pole turn of 1.8K at 205 T/m. Midplane margin will be higher

-Ramp rate dependence to quench has been solved using the the two step cure cycle

Appendix 7

HQG Short Model Test Results: Thermal Studies

A. Zlobin

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HGQ Short Model Test Results:
Thermal Studies

Outlines

- objectives
- radiation heat deposition update
- study of coil cooling conditions
- operation margin calculation
- heat transfer inside magnet

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Thermal Analysis Summary (1998)

Coolin Cond.	Pmax mW/	Pin, W/m	Pout, W/m	Inner layer, ΔT_{cbl}, K	Inner layer, $\Delta Tc:\Delta T_{cbl}$	Outer layer, ΔT_{cbl}, K	Outer layer, $\Delta Tc:\Delta T_{cbl}$
nominal	0.6	0.087	0.028	0.12	20.0	1.4	2.64
poor	0.6	0.087	0.028	1.09	2.17	2.8	1.32

The magnet workability was described in term of an operational margin defined as follows:

operational margin=$\Delta Tc:\Delta T_{cbl}$,

where $\Delta Tc = Tc - Tb$ – cable critical temperature margin,

$\Delta T_{cbl} = T_{cbl} - Tb$ – turn temperature rise,

Tc and T_{cbl} – cable critical and operation temperatures,

Tb – HeII temperature.

ΔTc=2.4/3.7 K inner/outer layer midplane turns,

Nominal cooling conditions: inter-turn cooling channels in the magnet inner layer.

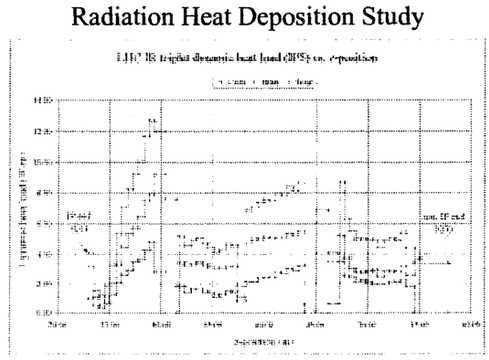
Poor cooling conditions: inter-turn channels do not work (are closed).

Based on these data it was concluded that the developed magnet design provides a sufficient operational margin under expected LHC operational conditions.

Thermal Study Objectives

- update of radiation heat deposition
- coil cooling conditions
- magnet operation margin
- heat transfer in the magnet

Radiation Heat Deposition Study



Pmax=0.4 mW/g (Q2b)

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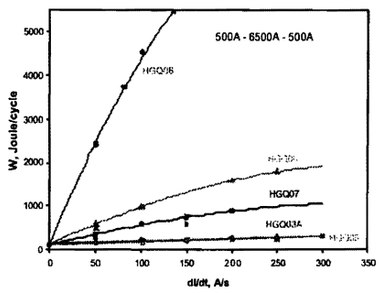
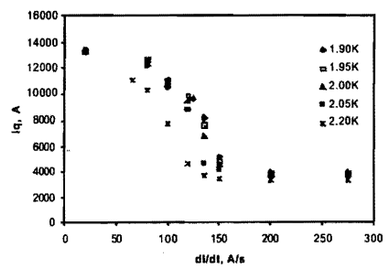
Coil Cooling Condition Study



←AC losses in the triangular cycle with current amplitude change within 500-6500 A range vs the current ramp rate.



Quench current vs current ramp rate measured at different helium temperature→

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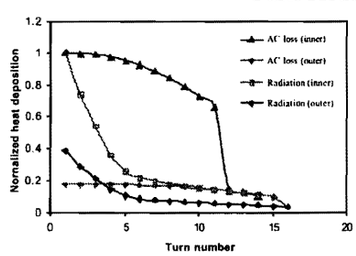
Turn Heating Power

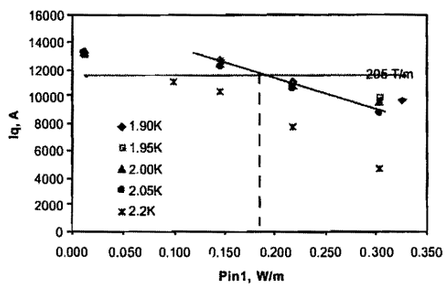


← Distribution of AC Losses and radiation heat deposition in the HGQ coil (dI/dt=100 A/s)

↓ Measured and calculated total AC loss power AC loss power in the HGQ08 coil and AC loss power in the midplane turns at different current ramp rates.

dI/dt, A/s	Pmeas, W/m	Pcalc, W/m	Ra, 10^{-9} Ohm*m	Ra, mcOhm	Pin1/Ptot	Pin1, W/m
50	5.82	5.8	5.3	1.46	0.01	0.0582
60	**8.16**	**8.15**	**5.4**	**1.49**	**0.01**	**0.0816**
70	10.83	10.84	5.5	1.52	0.01	0.1083
80	13.8	13.87	5.6	1.54	0.01	0.1380

Inner-layer Margin and Cooling Conditions



Dependance of the midplane turn quench current vs the heating power. Pmax=0.18-0.19 W/m @ T=1.90-2.05K

Operational margin (OM) of the inner-layer midplane turns could be defined as

$$OM=\Delta Tc:\Delta T_{cbl}=Pmax/Prad,$$

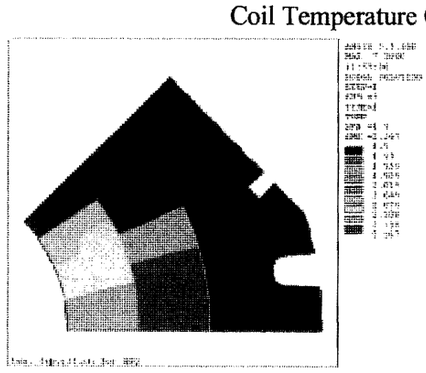
OM(meas)=0.18/0.087=2.07.

OM(calc)=2.17 for the case of poor cooling conditions!

MM:

inner-layer cooling channels are closed!

Coil Temperature Calculation

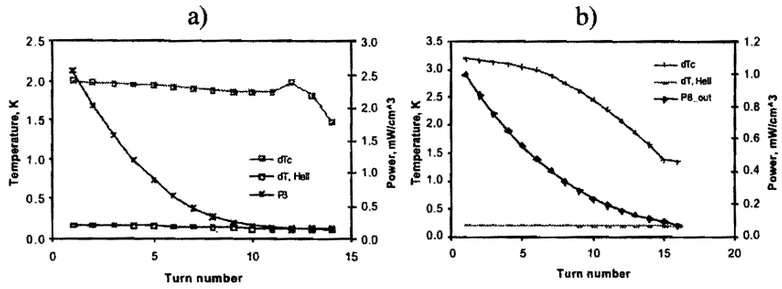


Temperature distribution in the HGQ coil at nominal LHC radiation heat deposition.

Radial and azimuthal temperature gradients are small in spite of strong radial and azimuthal dependences of radiation heat deposition in the coil:

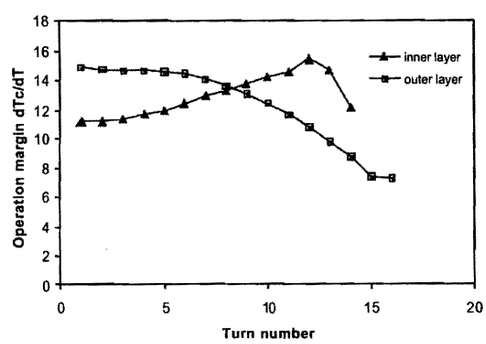
- Inner layer temperature changes from maximum value of 2.134 K in the midplane turn to 2.072 K in the pole turn.
- Outer layer temperature changes from 2.167 K in the midplane to 2.134 K in pole region.
- Radial gradient in both layers less than 5 K.

a) b)



Distribution of radiation heat deposition and temperature, and temperature margin in the HGQ coil: a) inner layer; b) outer layer.

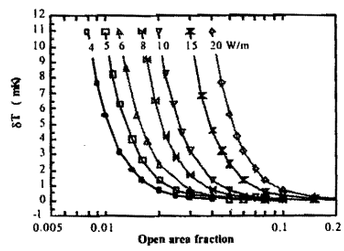
Operational Margin



←Operational margin for inner and outer turns at nominal field gradient of 205 T/m.

- Inner layer margin is ~11 and determined by the midplane turns.
- Outer layer margin is ~7 and determined by the pole turns.
- Magnet operation margin is ~7 for nominal LHC luminosity

Heat Transfer Inside Magnet

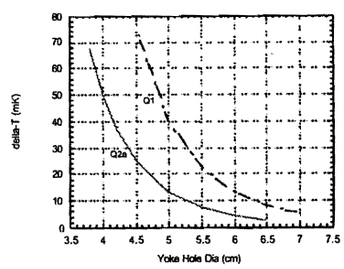


↑ Delta-T through the collar pole tip region versus fraction of pole tip area open for heat transport

•dT(@15W/m)=5 mK →0.04 open → 1.5 mm gaps (missing collar lamination) every 38 mm in each quadrant.

↓ Delta-T axially through the yoke holes in Q1 and Q2a versus hole size assuming four holes and the ultimate heat load.

• dT for 5 cm holes is less than 14 mK



Thermal Study Summary

- Recent analysis shows that maximum heat depositions in Q2 coil at nominal LHC luminosity could be reduced to 0.4 mW/g (or 30% less than expected in 1998)
- Thermal study shows that coil cooling conditions corresponds to the case when channels in the inner-layer insulation are closed and thus do not work. This was visually checked and confirmed in mechanical model.
- Measurements show that the heat flux density from the coil (at coil surface) at nominal and ultimate luminosities is well below its critical value.
- For the heat deposition in the midplane inner-coil turns of 0.08 W/m generated by AC losses the measured operation margin for inner layer is 2.07 that is in a good agreement with calculated value of 2.17. It practically does not depend on helium temperature for T<2.05 K because it is determined mainly by the thermal resistance of coil insulation.
- For the nominal LHC luminosity and updated heat depositions in the coil the magnet operation margin is determined by the outer layer and is ~7. This magnet design does have enough margin to work at the expected ultimate luminosity too.

Appendix 8

Quench Protection

Michael Lamm

US LHC ACCELERATOR PROJECT
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Quench Protection

Michael Lamm

MQXB Engineering Design Review
16 March 2000

- LHC Inner Triplet Electrical Design
- Heater Optimization/Performance
- Hipot Specifications
- Buswork
- Conclusions

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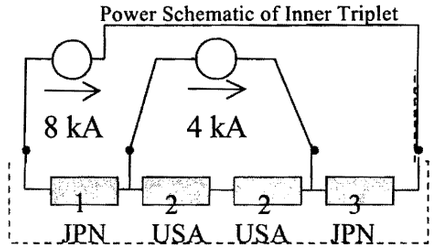
Power Schematic of Inner Triplet



-Connections inside "blue dashed box" are made with superconducting bus bars, connections made through DFBX connected to magnet "3".

- " USA" Q2 consists of two 5.5m magnets connected in series

-Use of diodes or similar device across USA magnet effectively decouples USA/KEK magnet protection

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Quench Protection Parameters

1) CERN quench protection System

2) Bus bar and magnet on same circuit. Detection level 300-500 mV

3) 10 ms of integration time for the inductance-subtracted voltage signals.

4) Magnet protection redundancy.

5) Heater Power Supplies: 7 mF capacitance and 900 V voltage.

6) Heater Circuits RC~100mS, Peak Power >20 W/cm2

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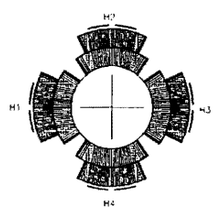
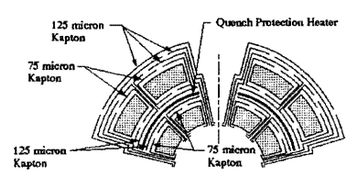
Strip Heater are the Primary Means of Quench Protection





Heater Parameters
-Heater Location
-Heater Insulation
-Heater Width
-Resistance Distribution

Magnet Protection Requirements:

Peak Temperature <400K
Peak Voltage to Ground <1000 V

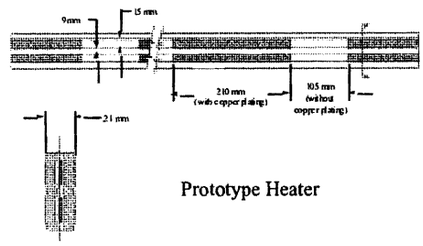
Protection Heaters for HGQ Model Program

Magnet	Position	Element (all 25 μm thick)	Insulation
HGQ01	Inter	Stainless steel 15.9mm wide	325μM
	Outer	None	N/A
HGQ02	Inter	Stainless steel 15.9mm wide	325μM
	Outer	Stainless steel 15.9mm wide	350μM
HGQ03 & HGQ05	Inter	Stainless steel 15.9mm wide	325μM
	Outer	15.9 mm wide with copper plating 38 mm etched areas at 114 mm intervals.	350μM
HGQ06	Inter	None	N/A
	Outer	12.7 mm wide with copper plating 610 mm etched areas at 1930 mm intervals	250μM
HGQ07	Inter	None	N/A
	Outer	22.2 mm wide with copper plating 610 mm etched areas at 1930 mm intervals	250μM
HGQ08	Inter	None	N/A
	Outer	15 mm wide with copper plating 120 mm etched areas at 360 mm intervals.	250μM
HGQ09	Inter	None	N/A
	Outer	15 mm wide with copper plating 102 mm etched areas at 204 mm intervals.	225μM

HGQ08-9 made by CERN

From: HGQ01 with Inter layer, stainless heaters

To: HGQ05-9 with Outer layer distributed resistance



Prototype Heater

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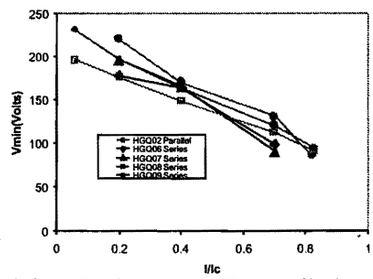
Test Program

-Vertical Magnet Test Facility
- Vertical Dewar, 1.7K-4.5 K Helium
- 18kA 40 V Supply
- Heater Power Supply 450 V 19 mF adjustable

-Heater: Adjust RC time constant and power to simulate LHC conditions
- i.e. 5.5 m long magnet and CERN heater power supply
- Note: Larger SS fraction means larger coil area coverage
  - Smaller SS fraction means smaller RC and higher peak density

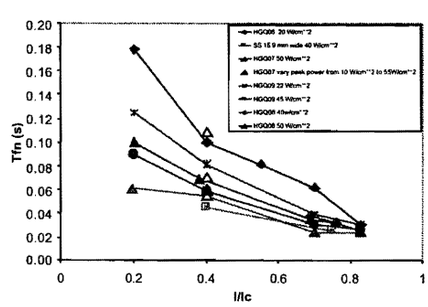
-Spot Heaters Location
- Pole turn inner coil
- Pole turn outer coil
- Midplane outer coil

Minimum Voltage Across Heater to Initiate Quench



Scaled to 5.5 M long magnet, Heaters effective at injection currents with acceptable power supply voltage

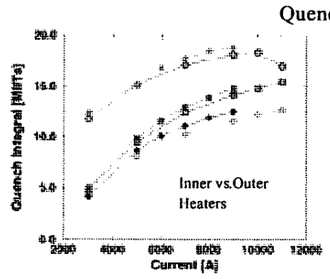
Heater time Delay

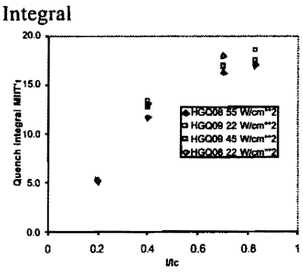


Trends of tfn:

1) Decreases with excitation current
2) Converges to 20-30 mS at excitation current
3) Wider strips, smaller tfn
4) Higher power density, smaller tfn

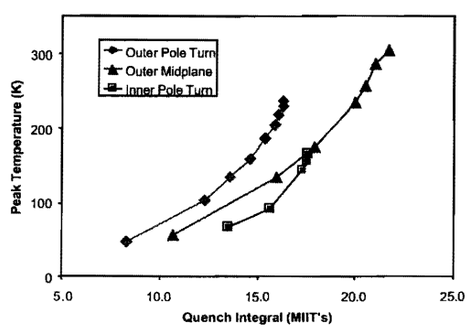
Quench Integral





Outer heaters just as effective as inner
Quench detection times significant part of quench integral
Power more important than longitudinal resistance distribution

MITTS vs. Temperature



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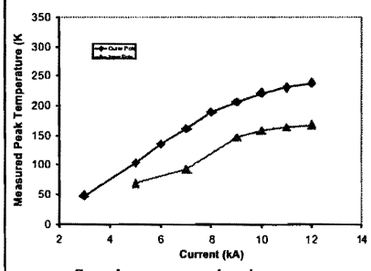
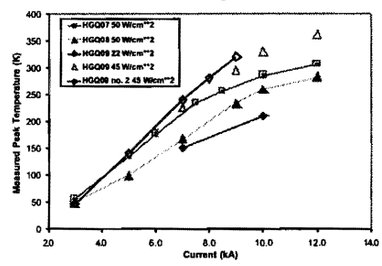
Peak Temperature



Spot heater quenches in pole turn

Most pessimistic quench location tested with spot heater.



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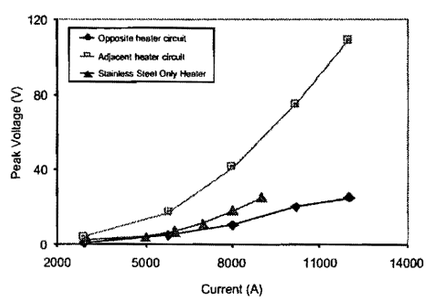
Voltage to Ground



Voltage to ground will be low, less than 200 Volts for full scale magnets

For series connection of two 5.5M magnets, voltage to ground should be less than 600 V (with x2 variation in resistance growth)

Magnet Exceeds Hipot Requirements

CERN Hipot requirements
-Unit should be able to withstand Umax*2 + 500 v
-Cold test at 1.2 Umax
-De-rating of room temperature tests by 0.2 Umax

	Estimated Umax	Required Cold Test	Actual Cold Test
Coil to ground:	<600 V	720 V	1000 V
Heater to ground:	450 V	540 V	1000 V

Measured room temperature Hipot (dry air)

Coil to Ground	>5000 V	Turn to turn	>1000 V
Heater to Ground	>5000 V	Coil to heater	>4500 V
Turn to wedge	>2000 V		

Bus Bar Studies

Bus Bar Goals

I. maximum stability against quenching during normal operation;
II. minimum temperature rise in the bus-bar after a quench (Tpeak< 300 K);
III. maximum quench propagation velocity to accelerate detection of quench;

Bus bar samples consist of US HGQ Inner cable in parallel with

a) 1 US HGQ inner cable
b) 2 US HGQ inner cables
c) 1 copper cable same cross section as HGQ inner cable
d) 2 copper cables same cross section as HGQ inner cable

Cable soldered along length

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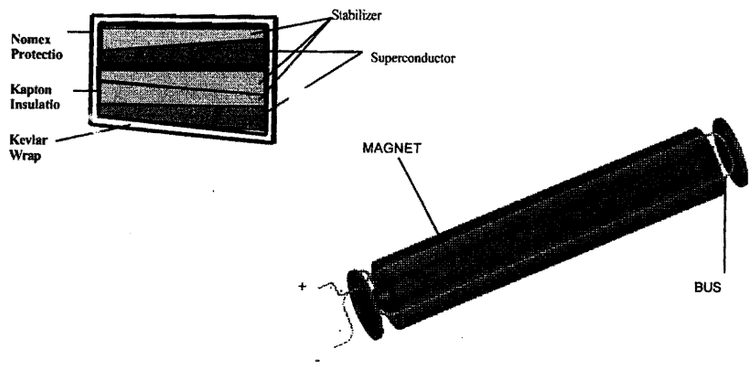
Bus Test in HQG Magnet



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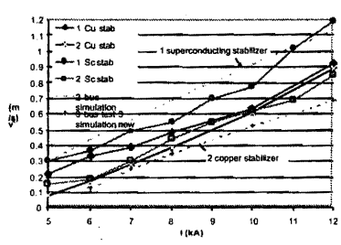
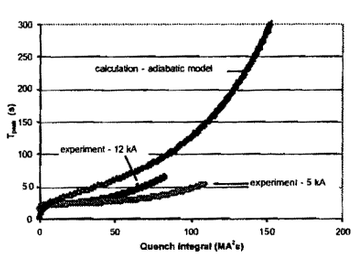
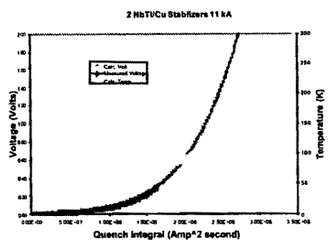
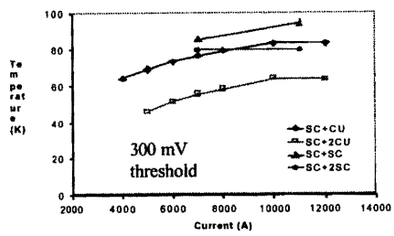
Quench Velocity and Peak Temperature





Extrapolation to Higher Detection Thresholds





$$V_q = I_t \rho_{Cu}(MIIts_{max}) * L_{MPZ}(I_t)\frac{1}{A_{Cu}} + 2\cdot 10^6 \frac{v_q}{I_t A_{Cu}} \int_0^{MIIts_{max}} \rho_{Cu}(MIIts)d(MIIts)$$

Conclusions

Heaters

- -Heaters adequately protection magnet from excessive peak temperatures and peak voltage to ground
- -Outer layer heaters are just as effective as interlayer heater. Outer layer heaters chosen for ease of installation
- -Reducing insulation doesn't seem to have much effect (or small compared to other variables
- -Increasing peak power is more important than longitudinal resistance: use HGQ08 style heater

Hi pot

- -Magnet exceeds requirements

Bus Work

- -Parameterize temperature and velocity
- -Single layer stabilizer is adequate. Opt for 1 layer of copper

Appendix 9

HQG Short Model Test Results: Magnetic Measurements

A. Zlobin

HGQ Short Model Test Results:
Magnetic Measurements

Outlines

- objectives
- transfer function
- magnetic length
- field angle
- body field quality
- end field quality
- summary

Magnetic Measurements Objectives

- magnet transfer function measurement, G/I
- magnetic length measurement
- magnet twist control
- field harmonics measurement in the magnet body
- field harmonics measurement in the end regions
- reproducibility of magnetic field parameters

Definitions of Field Parameters

The coordinate system for magnetic measurement is defined with the **z**-axis at the center of the magnet aperture and pointing from return to lead end with the origin at the boundary between return end and straight section. The **x**-axis is horizontal and pointing right, and the **y**-axis, vertical and pointing up to the observer who faces the magnet lead end.

Magnet transfer function, magnetic length and magnet twist were determined according the following definitions:

- Transfer function: $G/I = B_2^{body}/R_{ref}/I$, $A_2 \equiv 0$,
  where B_2^{body} and A_2 are the "normal" and "skew" quadrupole field strength in magnet body at the reference radius, R_{ref} is reference radius and I is current in the coil.
- Magnetic length: $L_{mag} \equiv \int B_2 dl / B_2^{body}$.
- Magnet twist: $\Delta\Phi_2/\Delta z$ in the magnet body,
  where Φ_2 is the quadrupole phase relative to an angular encoder (arbitrary zero) and z is the longitudinal coordinate.
- Field harmonics:

$$B_y(x,y) + iB_x(x,y) = 10^{-4} B_2 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

where $B_y(x,y)$ and $B_x(x,y)$ are the transverse field components, B_2 is the quadrupole field strength, b_n and a_n are the "normal" and "skew" harmonic coefficients ($b_2 \equiv 10^4$) at a reference radius R_{ref} of 17 mm.

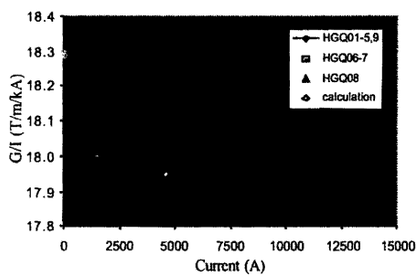
Magnetic Measurement System

Magnetic measurements were performed using a vertical drive, rotating coil system. Probes used have a tangential winding for measurement of higher order harmonics as well as specific dipole and quadrupole windings for measurement of the lowest order components of the field. These windings also allow for bucking the large dipole and quadrupole components in the main coil signal. Most measurements presented were made with a coil of 40.6 mm nominal diameter and length 82 cm. A short probe with 25 mm nominal diameter and 4.3 cm length was used for longitudinal scans of the magnet ends.

Coil winding voltages were read using HP3458 DVMs. An additional DVM was used to monitor magnet current. DVMs were triggered simultaneously by an angular encoder on the probe shaft, synchronizing measurements of field and current. Feed down of the quadrupole signal to the dipole was used to center the probe in the magnet.

Transfer Function

Current, A	G/I, T/m/kA							
	HGQ01	HGQ02	HGQ03	HGQ05	HGQ06	HGQ07	HGQ08	HGQ09
750	18.375	18.338	18.361	18.381	18.139	18.147	18.043	18.391
5750	18.231	18.221	18.229	18.270	18.101	18.076	18.075	18.303
10750	18.011	18.023	18.007	18.051	17.960	17.931	17.929	18.092



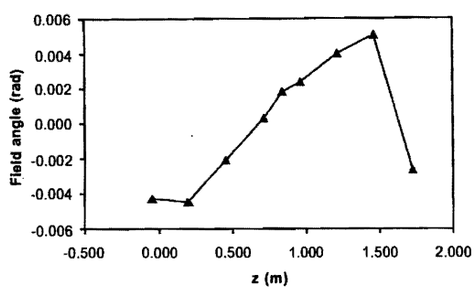
- G/I at low current is 18.35 T/m/kA
- iron saturation effect reduces the transfer function by 2% at nominal current
- good reproducibility from magnet to magnet at all current levels
- good reproducibility in different thermal cycles

Magnetic Length

Model	Probe	I (kA)	T=300 K		T=1.9 K		Lm/Lg
			Lmag (m)	Lgeom (m)	Lmag (m)	Lgeom (m)	
HGQ05	SSW	0.01	1.786±0.003	1.866			0.9571
		0.01	1.781±0.001	1.851			0.9622
HGQ09	long	12			1.779±0.003	1.847	0.9632
		6			1.775±0.003	1.847	0.9610
	short	6			1.776±0.001	1.847	0.9616

- thermal contraction included
- Lmag smaller than Lgeom by ~4%
- effect of longitudinal Lorentz force is small

Field Angle



Field angle measurements in HGQ01

Model number	Mechanical twist, mrad/m	Magnetic twist, mrad/m
HGQ01	4.7	8
HGQ02	0.6	
HGQ03	1.0	
HGQ05	0.9	
HGQ06	1.0	<1
HGQ07	0.2	
HGQ08	0.1	
HGQ09	0.1	

Twist reduction below the goal of 0.2mrad/m was achieved in HGQ07 and subsequent magnets.

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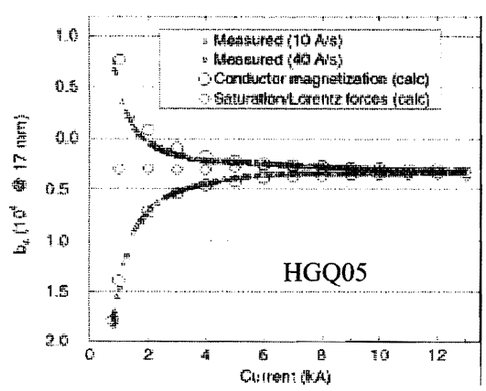
Field Harmonics



- Iron saturation and Lorentz force effects on b_6 at high currents are small
- Coil magnetization effect on b_6 at low currents is in a good agreement with calculations based on SSC strand parameters
- There is no noticeable effect of coil magnetization, iron saturation and Lorentz force on b_{10}

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Eddy Current Effects

Model #	Coil curing cycle Temperature, °C	Pressure	Ic(300A/s), A	Δb_6(40 A/s) @6kA, 10^{-4}
HGQ01	135	low	10965	0.02
HGQ02	190	low	11335	0.21
HGQ03	195	low	11298	0.16
HGQ05	130	low	10519	0.12
HGQ06	190	high	6433	-1.04
HGQ07	190	high	4487	-0.55
HGQ08	190	high	3941	-0.72
HGQ09	190/135	low/high	12946	0.13

Δt (s)		HGQ 01	02	03	05	06	07	08	09	Average	St.dev.
b_6	0	-1.1	-0.9	-0.6	-1.7	-1.5	-1.5	-1.3	-1.2	-1.2	0.4
Δb_6	900	< 0.1	0.9	0.7	0.4	0.6	0.2	0.2	0.3	0.4	0.3
Δb_6	1773	< 0.1	1.0	0.7	0.4	0.7	0.2	0.3	0.3	0.4	0.3

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Field Harmonics at 6 kA (Rref=17 mm).

	HGQ01	HGQ02	HGQ03	HGQ05	HGQ06	HGQ07	HGQ08	HGQ09
b3	0.36	-0.70	1.04	0.72	0.25	0.18	0.61	0.71
a3	0.27	0.55	-0.30	0.12	-0.27	0.41	-0.01	0.35
b4	0.26	0.18	0.14	0.00	0.09	0.01	-0.12	-0.05
a4	2.00	0.53	0.32	0.19	-0.31	-0.50	-0.44	0.31
b5	-0.29	0.09	-0.34	-0.04	-0.11	-0.04	-0.01	0.08
a5	0.02	-0.17	0.26	0.05	-0.07	-0.24	0.12	-0.14
b6	-3.91	-1.54	-1.02	-0.30	-0.05	-0.45	-0.06	-0.28
a6	-0.02	0.03	0.07	-0.03	-0.05	-0.10	-0.03	0.04
b7	-0.08	-0.01	-0.06	0.01	-0.03	0.02	-0.01	0.06
a7	-0.05	0.00	-0.03	0.01	0.00	0.08	0.00	0.02
b8	0.06	0.01	0.00	0.00	0.00	0.00	0.00	-0.01
a8	0.02	0.02	0.03	0.00	0.00	0.01	-0.01	0.01
b9	0.04	0.00	0.00	0.00	0.00	-0.01	0.00	0.00
a9	0.01	-0.01	0.01	0.00	0.00	0.01	0.01	0.00
b10	-0.10	-0.10	-0.04	0.01	0.00	-0.02	-0.01	-0.01
a10	0.02	0.00	-0.01	0.00	0.00	0.00	0.00	0.00

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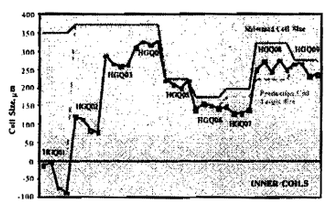
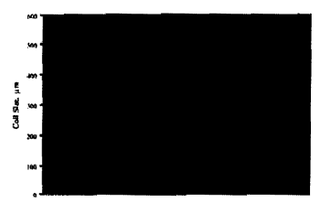
As-built Harmonics

Field harmonics	HGQ 01	02	03	05	06	07	08	09
b^6, calc.	-4.74	-2.86	-1.39	-0.08	-	-	-	-
b^6, meas.	-3.91	-1.54	-1.02	-0.30	-0.05	-0.45	-0.06	-0.28
b^{10}, calc.	-0.14	-0.09	-0.04	0.01	-	-	-	-
b^{10}, meas.	-0.10	-0.10	-0.04	0.01	0.00	-0.02	-0.01	-0.01
a^4, calc.	1.27	0.94	0.00	0.00	-		-	-
a^4, meas.	2.00	0.53	0.32	0.19	-0.31	-0.50	-0.44	0.31
a^8, calc.	0.02	0.00	0.00	0.00	-	-	-	-
a^8, meas.	0.02	0.02	0.03	0.00	0.00	0.01	-0.01	0.01





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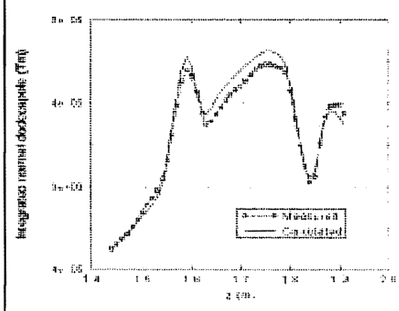
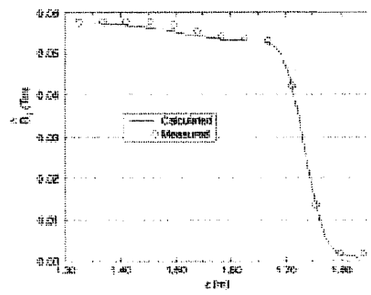
Comparison With IRQ Error Table

bn, an	HGQ01-03 Corrected Mean	RMS	HGQ05-09 Measured Mean	RMS	HGQ01-09 Corrected Mean	RMS	Error table v.2.0 Systematic	Uncertainty	RMS
b3	0.23	0.88	0.49	0.26	0.35	0.55	0.0	0.30	0.80
a3	0.17	0.43	0.12	0.28	0.11	0.33	0.0	0.30	0.80
b4	0.19	0.06	-0.01	0.08	0.08	0.13	0.0	0.20	0.80
a4	0.21	0.58	-0.15	0.37	-0.06	0.48	0.0	0.20	0.80
b5	-0.18	0.24	-0.02	0.07	-0.10	0.16	0.0	0.20	0.30
a5	0.04	0.22	-0.06	0.15	0.00	0.17	0.0	0.20	0.30
b6	0.67	0.56	-0.23	0.17	0.17	0.59	0.0	0.60	0.60
a6	0.03	0.04	-0.03	0.05	-0.02	0.06	0.0	0.05	0.10
b7	-0.05	0.04	0.01	0.03	-0.02	0.04	0.0	0.05	0.06
a7	-0.03	0.03	0.02	0.03	0.00	0.04	0.0	0.04	0.06
b8	0.02	0.03	0.00	0.01	0.01	0.02	0.0	0.03	0.05
a8	0.02	0.02	0.00	0.01	0.01	0.01	0.0	0.03	0.04
b9	0.01	0.02	0.00	0.00	0.00	0.02	0.0	0.02	0.03
a9	0.00	0.01	0.00	0.01	0.00	0.01	0.0	0.02	0.02
b10	0.01	0.03	0.00	0.01	0.00	0.02	0.0	0.02	0.03
a10	0.00	0.02	0.00	0.00	0.00	0.01	0.0	0.02	0.03

End Field Measurement





Lead End Harmonics

Field harmonics	HGQ 01	02	03	05	06	07	08	09
b_6, calc.	3.1	5.5	5.4	5.4	3.5			
b_6, meas.	2.9	4.2	3.8	8.0	3.1	3.1	3.1	3.0
b_{10}, calc.	-0.3	-0.3	-0.4	-0.4	-0.1			
b_{10}, meas.	-0.3	-0.2	-0.4	-0.2	-0.1	-0.1	-0.0	-0.1
a_6, calc.	0.5	0.4	-0.1	-0.1	-0.7			
a_6, meas.	0.1	0.2	-0.3	-0.6	-0.4	-0.3	-0.4	-0.4
a_{10}, calc.	-0.1	0.0	0.0	0.0	0.0			
a_{10}, meas.	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Field harmonic	Lead end (Lm=0.41 m) mean	uncertanty	sigma	Return end (Lm=0.33 m) mean	uncertanty	sigma
b_6	2.0	2.0	0.75	0.0	1.0	0.75
b_{10}	-0.2	0.2	0.1	-0.2	0.2	0.1
a_6	0.0	0.5	0.15	-	-	-
a_{10}	0.0	0.1	0.1	-	-	-

Field Quality Summary

- Magnetic measurements for all magnets are in a good agreement with calculations.
- Magnetic measurements show that required field quality (systematic values and RMS spread) in the magnet body can be achieved within specified uncertainty.
- To simplify magnet design magnetic shims have been eliminated.
- Large eddy current effect observed in some magnets was minimized by using special coil curing cycle
- End field quality is well understood. Systematic field errors in the magnet ends have been reduced with a new end design.
- Based on the data presented in field error tables a field quality specification for magnet production will be formulated