Report of the Review Committee On the Fermilab HGQ R&D Program (FNAL, 18-19 March 1999)

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Foreword

Enclosed is the report of the committee which met at Fermi National Accelerator Laboratory on 18 and 19 March 1999 to review the Fermilab R&D program on High Gradient Quadrupole magnets for the Large Hadron Collider Insertion Regions. The review committee consisted of Arnaud Devred, CEA/Saclay (Chairman), Mike Anerella, BNL, Daniel Leroy, CERN, Ranko Ostojic, CERN, Bob Schermer, consultant, and Pierre Védrine, CEA/Saclay. It initially included Akira Yamamoto, KEK, who could not attend the review. The review was called up by Jim Strait, US LHC Accelerator Project Manager, with the charge given in Appendix 1.

Prior to the review, the committee was provided through the World Wide Web with a number of relevant documents, including a technical summary of the model magnet program written by Jim Kerby, Fermilab LHC Accelerator Project Manager, enclosed in Appendix 2. The two-day review itself was articulated around presentations by Jim Kerby and Alexander Zlobin, IR Quadrupole Level 3 Project Manager, and included a detailed tour of the coil winding, curing, sizing and collaring facilities located in Industrial Building 3. Copies of the presentations by Kerby and Zlobin are given in Appendix 3. Additional information provided to the committee included a summary table of measured RRR, a summary table for the cable R&D test program, a table of material properties used in the ANSYS computations, a plot of cable short sample training measured at BNL, examples of strain gauge measurements, and various plots of computed electromagnetic forces in the coil ends. Some of these documents are given in Appendix 4. In general, the discussions were very open and the committee was very pleased with the cooperation of the FNAL team.

Executive Summary

The committee is pleased with the results of model magnet HGQ05, whose quench performance is greatly improved with respect to previous model magnets. In particular, the level of the first quench during the initial test at 4.5 K is significantly higher and the magnet reached its short sample limit in a small number of steps. Furthermore, during the subsequent test at 1.9 K, the currents of the first few quenches increase more rapidly than on previous magnets, with only two training quenches below the maximum operating gradient of 215 T/m. The quench current levels off at about 96 % of the estimated short sample limit at 1.9 K, making this magnet the most successful of the series.

The promising results of model magnet HGQ05 constitute a significant step forward and provide a solid basis upon which to base the magnet program. The committee strongly recommends that the test results of this magnet be fully analyzed and compared to those of previous model magnets so as to understand which modifications can explain the improved performance. Furthermore, the committee suggests that FNAL gets as much information as possible from this magnet by re-testing it, for instance, with different end configurations.

Although the quench performance of magnet HGQ05 shows good progress, it is not yet fully satisfactory and can still be improved. The committee recommends that particular attention be paid to the first training quenches at 1.9 K and that more analyses be carried out to find possible correlations between quench start localization and specific mechanical features. In particular, the committee recommends analyzing in detail collar deflection data that seem to indicate that the first training quenches at 1.9 K may have originated in a region of low azimuthal coil pre-compression.

The relative success of magnet HGQ05 and a detailed understanding of the reasons behind it should help focus the magnet program on a limited number of clearly identified issues. The magnet program should be revised immediately to incorporate the lessons learned from magnet HGQ05 and to address the most outstanding issues. The committee, however, strongly recommends that the design variants investigated in the oncoming model magnets be limited to a strict minimum, and that only one major change be implemented in each new magnet. At this stage, the goal of the program should be to duplicate and improve the performance of magnet HGQ05 rather than explore new design features.

Following are some comments the committee wishes to make on a number of technical matters that were discussed during the two-day review. The list is not exhaustive and the recommendations are only meant to help identify critical design issues and to establish priorities.

1 End Part Material

There is clear evidence from the test results of model magnets HGQ02 and HGQ03 that the quench performance of these magnets was impaired by the use of Ultem for the coil end parts. This conclusion is supported by test results from two LHC arc dipole magnet models built at CERN. Magnets HGQ01 and HGQ05 use G10 end parts, while starting with magnet HGQ06, the end parts will be made out of G11.

The committee endorses the change of end part material from Ultem back to impregnated glass fibers and recommends stopping all further R&D effort on Ultem.

2 Thermodynamic Cable Stability

There is a lingering discussion among the accelerator magnet community about the possibility that slow training observed on a number of NbTi model magnets operated at 1.9 K may be a signature of inherent thermodynamic cable stability problems. For example, data were presented at the review from a series of critical current measurements performed at BNL on short samples taken from the cables used in model magnet HGQ06 (at 1.9 K and in a 8.7 T transverse field). These cable short samples trained rather badly. The inner coil cable was especially poor; first quench was slightly above 11500 A and quench current crept up to about 17000 A after 30 to 40 quenches, while the expected critical current (extrapolated from the 4.2 K data) is above 18500 A. In comparison, it was announced that similar measurements performed on a short sample of LHC outer dipole cable exhibited very little training.

It is the committee's strong conviction that thermodynamic stability is only of concern when within a few percent of the short sample limit, and that poor training behavior like that observed on model magnets HGQ01 through HGQ03 is of mechanical origin. The results of model magnet HGQ05, which uses cables very similar to those used in previous model magnets, and yet exhibits much better quench performance, reinforce this conviction. There were some debates among the committee about the degree to which the short sample test results are representative of magnet performance and it is suggested to wait for the test results of model magnet HGQ06 before drawing any conclusions.

3 Cable Annealing, Adhesive for the Insulation, and Curing Temperature

Unlike the cables developed by CERN for the LHC arc dipole and quadrupole magnets, the cables used for the HGQ magnets are not baked and are made from un-annealed strands left over from the SSC program. The cable strands are thus heavily cold-worked, as proven by the low RRR measured on the as received cables (between 34 and 57).

The cable insulation used for the coils of model magnets HGQ02 and HGQ03 relies on a polyimide adhesive, with a softening temperature of 180 to 190 °C. Curing the coils of model magnets HGQ02 and HGQ03 at such temperature resulted in a significant annealing of the copper, as proven by RRR measurements performed on the magnet coils during cold test: the RRR of the inner coil cables went from 45 to 215-225 while the RRR of the outer coil cables went from 35 to 95-105. According to SSC experience, a measured cable RRR of the order of 200, corresponds to a bulk copper RRR of 300, which, for IGC-type wires, is indicative of a fully-annealed state. Such annealing is, of course, accompanied by microstructure reorganizations and internal stress re-distributions within the cable strands that result, typically, in an increase in strand diameter and a reduction in strand length. As a direct effect of this annealing the coils shrink axially when removed from the curing mold, thereby requiring special handling procedures.

The cable insulation used for the coils of model magnets HGQ01 and HGQ05 relies on an epoxy-based adhesive, with a low thermosetting temperature (135 °C for 90 minutes). Compared to model magnets HGQ02 and HGQ03, the low-temperature curing of the coils of model magnets HGQ01 and HGQ05 only resulted in partial annealing of the cable strand copper, as again shown by RRR measurements on the magnet coils (RRR of the inner coil cable used for magnet HGQ01 changed from 43 to 145, while that of the outer coil cable increased from 34 to 57 – The RRR data for magnet HGQ05 were not available at the time of the review). It is likely that this partial annealing causes less microstructure reorganization and less internal stress redistribution. There are some indications that the axial shrinkage measured after curing on the straight sections of the outer coils of model magnets HGQ01 and HGQ05 is somewhat lower than that measured on magnets HGQ02 and HGQ03.

The use of un-annealed strands and cables in the HGQ magnets is a legacy of the SSC program that was becoming a hot issue at the time of SSC cancellation. CERN has a very different approach to the issue, which is to de-couple the annealing step from the curing step. Requirements on coil size reproducibility imply that the curing operation be performed under pressure and in confined space. This is particularly true for the curing of the HGQ magnet coils where the mold is kept closed during the high temperature phase. The worry, then, is that, when curing is performed in a confined volume and accompanied with strong annealing, the internal stresses cannot freely redistribute and may remain frozen at some locations. This creates a potential risk that, upon magnet energization, the application of the Lorentz forces causes stress releases that may lead to premature quenching. The risk of freezing internal stresses can be diminished by maintaining a low pressure during the high temperature phase of the curing cycle as promoted by BNL for all-polyimide coils (but then, a coil sizing step is required during the cool off phase of the curing schedule). The risk can be further reduced (if not altogether eliminated) by performing an annealing step on the strands at final size, and, if needed, a baking of the cable.

The committee wishes to point out that one of the differences between model magnet HGQ05 and its two predecessors (magnets HGQ02 and HGQ03) is that it uses an insulation system with an epoxy-based adhesive and that, therefore, its coils were cured at a lower temperature. (Magnet HGQ01 also uses the same insulation system and its coils were also cured at the same low temperature, and yet its quench performance was as bad as that of magnets HGQ02 and HGQ03. This, however, can be explained by the fact that the outer coils of this magnet were badly oversized, which was corrected by decreasing the thickness of the pole shims in the magnet straight sections, while nothing could be done to the coil ends. As a result, there were steps at the transitions between the coil straight sections and the coil ends where, as it turned out, most of the training quenches originated.) The committee suggests that the low temperature cure may be one of the reasons for the better performance of model magnet HGQ05 and recommends that this issue be investigated further.

The choice of a polyimide adhesive was driven by the fact that the company contracted by Fermilab to apply an epoxy layer on the polyimide tape had trouble controlling the layer thickness. Thus, there is a risk that extra material will flow and thereby occlude the 2-mm-wide cooling channels deliberately left in the outer insulation wrap of the inner cable. The KEK team working on the LHC IR quadrupole magnet program was confronted with a similar problem, and they have found a company in Japan able to produce very thin epoxy layers. The committee recommends that FNAL get information from KEK, and, if required, order material from the Japanese company. If this material is appropriate, the committee suggests using it for magnet production and staying with the low temperature cure.

If FNAL decides to go ahead with the polyimide adhesive and high temperature cure, the committee deems it necessary to seriously address the annealing issue. As it is quite complex and there is not enough time to develop a complete R&D program, the committee suggests that FNAL rely extensively on the experience accumulated at CERN and follow the same procedures for strand annealing and stabrite coating. CERN also employs a cable baking procedure that is mainly designed to ensure a proper and reproducible level of interstrand resistances. The same procedure could also be followed if a control of the interstrand resistance is required.

It must be stressed, however, that the recipes developed by CERN are applied to strands produced according to a specific schedule of cold-work and heat-treatment cycles optimized to fulfil LHC requirements, and it may be that these recipes are not directly applicable to SSC strands. In particular, annealing the strand at final size may result in unwanted critical current density degradation. It is, therefore, necessary to validate these recipes by a complete set of electrical and mechanical measurements on strands and cable short samples. The committee feels that these measurements should be done as quickly as possible and should serve as a basis for the decision on the cables to be used in magnets HGQ08 and HGQ09.

4 Number of inner and outer cable strands

Magnets HGQ01 through HGQ06 use inner cables made up of 38 strands and outer cables made up of 46 strands. Starting with magnet HGQ07, FNAL proposes to reduce the number of strands in the inner cables to 37 for all further magnets and to use a 45-strand cable in the outer coils of magnet HGQ07.

The present 38-strand cable has a high lateral compaction (15.35 mm for a final width of 15.4 mm, yielding 99.7 %), while the lateral compaction of the 46-strand cable is of the order of 96.8 %. A high lateral compaction makes the cable puffy and easily unstable mechanically.

The committee sees no reason to reduce the number of strands in the outer cable and suggests reverting to a 46-strand cable for the outer coils of magnet HGQ07.

The committee does see some good reasons for reducing the number of strands in the inner cable from 38 to 37. However, the quoted packing factor of 87.6% for the 37-strand cable is lower than the present packing factors of the LHC inner and outer cables, which are of the order of 89%. The committee therefore recommends that winding tests be performed as soon as possible on this new cable before using it in a magnet.

5 Cable Lay Pitch and Splice Design

Magnets HGQ01 through HGQ05 use right lay cables for the inner coils and left lay cables for the outer coils. Starting with magnet HGQ06, the inner coils are wound from left-lay cables in order to utilize the stock of right–twisted strands left over from SSC.

The committee thinks that the choice of cable lay direction should be based on technical criteria, such as windability, and not on cost, given that the savings of using leftover SSC strands is probably minimal (for instance, how does it compare to the cost of an additional model magnet?).

The committee wishes also to point out that in the case of the LHC dipole magnets the inner and outer cable lay directions were chosen so as to ensure that the cable with the largest aspect ratio is wound in the favorable direction, and that, when spliced together, the strands of the two cables do not lie parallel but cross at an angle. It is believed that strand crossing in the splice forces the current to redistribute itself more evenly among the strands when transferring from one cable to the other, thereby limiting the risk of highly non-uniform current distribution.

In any case, and especially if the chosen cable lay directions are such that the strands of the two cables are parallel in the splice, the committee recommends to develop and evaluate procedures which ensure low and reproducible splice resistances.

6 Overlapping of Cable Insulation

Starting with magnet HGQ03, the overlap of the inner layer of the inner cable polyimide insulation was increased from 50 to about 55% in an effort to increase coil sizes.

While somewhat successful in achieving the desired coil size goal, the committee feels that the overlap should be restored to 50% at the earliest convenience.

The temptation to revise the insulation overlap is clear: it is a fast way to implement a change in coil size and still use cable which is on hand. However, its use results in areas along the conductor where for about 22% of the width of the polyimide film there are 3 layers, whereas for the other 78%, there are only 2. When closing the curing mold, the 3-layer areas are subjected to higher stresses than the 2-layer areas. It is likely that these higher stresses produce plastic deformations of the polyimide film, which locally reduce its thickness and allow the spacing between conductors to become more or less uniform. To achieve uniform spacing, the film thickness in the 3-layer area must be reduced by about one third. This may degrade the film, leave it vulnerable to long term fatigue and create a risk of electrical shorts. Furthermore, upon coil winding, there can be points in the coil where 3-layer areas of adjacent turns pile up atop of each other, resulting in undesirable non-uniformities in the coil package.

In order to tune up coil sizes, the committee recommends either to increase strand diameter and cable midthickness or to revise the insulation scheme so as to achieve the desired azimuthal sizes while maintaining a 50% overlap, as was done for the LHC arc quadrupole magnet. The first solution is propably more efficient, but depends on whether or not FNAL must rely on the existing inventory of SSC strands at final size or has the freedom to change strand parameters. Note that increasing the conductor volume may also help increase the inner coil Young's modulus (see next section).

7 Matching Coil Mechanical Properties

The Young's moduli of the inner coils assembled in magnets HGQ02 through HGQ04 were of the order of 4 to 5 GPa, while the Young's moduli of the outer coils were of the order of 10 to 11 GPa. In the case of magnet HGQ05, the inner coils were re-cured at a smaller size in order to increase the Young's modulus (up to 8 GPa) and better match the mechanical properties of the outer coils.

The committee considers that matching the Young's moduli of the inner and outer coils is probably a good idea, but thinks that further investigations should be carried out to understand the origin of the low inner coil modulus. It can be, for instance, that the pressure applied during the curing of the inner coils is too low. This can be compensated by increasing the conductor volume as suggested in the previous section.

8 Collar Packs

On model magnets HGQ01 through HGQ03, the 1.5-mm-thick collars, manufactured by stamping, were assembled one by one around the coil assembly. Tests carried out on magnet HGQ04 showed that there could be some benefit in grouping the collars into packs so as to reduce the risks of buckling and increase stability under axial forces. It also facilitates the mounting of the bearing strips at the collar poles while providing a continuous support to the coil pole turns. Starting with model magnet HGQ05, the collars are assembled into 3-inch-long packs before being mounted around the coil assembly.

The committee sees no objection to the use of collar packs but recommends that their engineering be revised to reduce the high frictional forces that need to be overcome to assemble them.

9 Magnetic Design of Coil Ends

Several variants for the design of the coil ends have been developed and are being tried on the model magnets. In particular, starting with magnet HGQ06, the largest conductor block of the inner coils is split into two in order to reduce the size of the inner coil end spacers. This change was mainly driven by mechanical considerations.

The committee suggests pursuing the optimization of the field, forces and winding geometry of the coil ends so as to ensure that the peak field in the ends is significantly smaller than in the straight section, and that, for each winding block, the axial outward force is larger than the inward force coming from the other winding blocks. The committee also recommends studying a split of the largest conductor block in the outer coils.

10 Studying Axial Mechanics

The committee is pleased to see that FNAL has conducted analytic and FEA studies of axial mechanics and recommends that these studies be continued. In particular, it would be very useful to gain a more precise understanding of the effects of collet and end bullet restraint.

11 Axial Pre-Loading by Bullets

The HGQ model magnets include bullets that can be used to apply an axial pre-load to the coil ends. The justifications for this axial pre-loading are as follows: (1) to ensure that the coil ends are compacted and remain in compression so as to limit the risk of conductor motion, and (2) to prevent stick-slip motions between coil and collars and collars and yoke, which may cause premature quenching.

Various tests have been carried out on the early model magnets which have shown that applying or removing axial pre-loading neither improved nor degraded the poor quench performance of these magnets. The ends of the more successful model magnet HQS05 were axially constrained.

The committee wishes to point out that, in the case of the HGQ magnet design, the collars are supposedly free to move within the iron yoke, which should eliminate the risk of stick-slip motions. This is similar to the case of the LHC arc quadrupole magnets designed at CEA/Saclay, where the ends are not constrained. CEA/Saclay has already built and tested two full-length arc quadrupole magnets that exhibited reasonable quench performance. The committee therefore thinks that the necessity of constraining the magnet ends axially has yet to be proven, and recommends that model magnet HGQ05 be re-tested with unscrewed bullets.

12 Aluminum Collets and Coil End Shimming

The return ends of model magnets HGQ01 and HGQ02 and both ends of model magnet HGQ03 were supported by round collars, while the lead ends of magnets HGQ01 and HGQ02 and both ends of magnet HGQ05 were supported by aluminum collets. FNAL proposes to support all magnet ends with collets.

The committee considers that the collets are a reasonable solution to end clamping, with which Fermilab has a lot of experience and feels confident. However, the committee recommends improving the reproducibility of coil end sizes and developing a more production-oriented procedure for coil end shimming.

13 Bolting of Collets to End Plates

On model magnet HGQ05, the collets at both ends of the collared-coil assembly were bolted to the end plates while bullet screws, also mounted on the end plates, applied an axial pre-load to the coil ends. The justification for doing so is as follows. During cooldown, the collared-coil assembly shrinks more in the axial direction than the shell-end-plate assembly. As a result, bolting to the end plates should result, at the end of cooldown, in a tensile axial force. This force is expected to put the straight section of the collared-coil assembly into tension, and, when combined with the axial pre-load applied by the bullets, to ensure that the coil ends are compacted and remain in compression. Maintaining the coil ends under compression is believed to reduce the risk of conductor motions under the axial component of the Lorentz force and, thereby, may help limiting premature quenching in these areas.

Bolting the collets to the end plates is one of the major differences between magnet HGQ05 and its predecessors that could explain the better quench performance of this magnet. The committee, however, thinks that, as already pointed out in recommendation 11, the necessity of constraining the magnet ends axially has yet to be proven and once again recommends to retest model magnet HGQ05 with unbolted collets and unscrewed bullets.

The committee thinks that more efforts should be made to achieve a detailed understanding of the effects of the collet bolting on the overall axial mechanics of the magnet and on how these effects scale with magnet length. These efforts should go into refining the FEA model under development and in trying to verify the simulation results on an actual magnet. In particular, if FNAL decides to keep bolting the collets on the oncoming model magnets, the committee recommends instrumenting the bolts with strain gauges (as is considered for model magnet HGQ06). Also, the long term behavior after thermal cycling and quench performance should be addressed, as the compression of the magnet ends relies on collet friction which may be modified by the loading cycles to which the collets are subjected.

14 Quench Protection and Energy Extraction

At present, power tests of the model magnets are performed with energy extraction (up to 70% of the stored energy is extracted). There is evidence from the test results of at least two of the model magnets (HGQ01 and HGQ03) that the heater tests performed without energy extraction may have resulted in degradation of the quench current.

The committee recommends that systematic tests be carried out to demonstrate that the magnets are protected and that their quench performance is not significantly degraded when the energy is not extracted, as is the case in LHC. However, the committee does not see the need of pursuing studies on different quench heater configurations and suggest choosing the one the most reliable and easy to assemble.

15 R&D Program and Prototype Schedule

The committee suggests that the magnet R&D program be revised to incorporate fully the results of recent and future retest of model magnet HGQ05. The committee also recommends that the model magnet program be carried out at a pace leaving enough time for evaluating each model and allowing a reasonable degree of feedback. In particular, the committee insists that all models be tested thoroughly, both in terms of quench performance and field quality.

The committee recommends that the program focus on a limited number of issues in order to still improve the performance and ensure reproducibility. The committee strongly recommends that the revised program include at least two nominally identical magnets having the final magnetic and mechanical design.

The committee recommends keeping the original schedule for the full-scale prototype, even if FNAL decides to extend the model magnet program, but strongly insists that the prototype be built using the final cable design.

16 Overall Program Priority

From all the issues discussed above, the committee considers that the most critical are those concerning strand annealing and coil curing, and recommends that they be addressed as quickly as possible (in particular, in time for choosing the cables to be used in the full-length prototype).

Appendix 1:
Charge of the Review Committee

Appendix 2:
Technical Summary
of the Model Magnet R&D Program

Appendix 3:
Copies of the Presentations
By Jim Kerby and Alexander Zlobin

Appendix 4:
Selected Additional Informations
Provided During the Review