Technical Meeting on the Quench Protection Heaters and Electrical Tests of the 11T Dipole

(held on 11th January 2019 at CERN)

REPORT

Panel:

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1. Foreword

The Panel acknowledges the efforts carried out by the speakers and the WP11 Team to collect all the documentation and the data presented during the Meeting. In particular, the Panel appreciates the major advancements over the last months in the understanding of the discussed issues and in the large variety of tests performed in such a short lapse of time.

The presented material allows to provide a coherent overall view of the present situation with respect to the quench heater manufacturing, the integration of the quench heaters in the coils and the related electrical tests.

The Panel appreciates the big effort deployed to compile all the information due to the vast amount of performed tests and generated data, and encourages the tracking of those data.

The Panel thanks the speakers and the organisers for the clear and open discussions, the transparency of the process, and the professional level of the presentations.

2. Introduction

Following several failures of the insulation between quench heaters and coils within the 11 Tesla Dipole Prototype (which is part of the development programme that CERN carries out for the HL-LHC Project), the MSC Group of the TE Department called for a Technical Meeting to discuss the relevant aspects of the quench protection heaters and the electrical tests.

As a summary, the main goals of the Meeting were to assess on:

- the quench protection heater (QH) design, manufacturing, Quality Assurance (QA) and Quality Control (QC);

- the integration of the quench heaters within the coil insulation system, considering as well the relevant aspects related to manufacturing of the collared coils;

- the electrical tests conducted to qualify the coils and ancillary equipment (quench heaters, instrumentation, etc);

- the risks of electrical failures in the present quench heater design, comparing those risks for other options;

- the strategy to follow taking into consideration the boundary conditions given by the LS2 schedule milestones.

3. Recollection of comments and findings during the talks. Recommendations.

In the following, a short summary of each talk is given that includes a recollection of comments and relevant findings as well as the specific recommendations that were agreed among the members of the Panel during the closed session.

Talk #1: Boundary conditions, coils insulation system design and issues identification - F. Savary

The dipole insulation system was described in this talk, including the 0.1 mm thick quench heater which is impregnated together with the coils. The nominal outer radius of coil is 60.8 mm. The supplies that are to be delivered by the GE contract include coils and collared coils for three (3) 11T dipole full assemblies, i.e. four (4) cold masses plus two (2) spare cold masses. The sequence for the production of coils was part of this presentation, including some details for each of the different steps from winding to yoking and welding.

The services provided by the industrial contract with GE were presented, covering the supply of 30 coils (NB. A coil corresponds to one pole of one aperture of a 5.5m 11T Dipole). The schedule for deliveries was explained. Some delays occurred on the first coils due to initial training of the contractors' personnel, the optimization of the manufacturing procedures and of the collaring process. Currently, the work is ongoing for coil GE-C09. GE-C07 coil is finished with the QH embedded. GE-C08 is reacted. GE-C04 was declared as non-conform.

Any modification on the QH layout could only be implemented as from coil GE-C10, with a decision to be made before the end of January. The scope of production of 30 coils includes 6 more coils than nominally needed. In addition to this, the MSC Group communicated to the Panel that there is a provision for strands equivalent to 5 additional coils. No decision is taken yet to produce cable using those 5 unit lengths (ULs). Contractually, the coils production should be finished by June 2020. Target delivery dates are anticipated with respect to the contractual delivery dates.

The QA holding points on the production were presented and are well identified. Following the issue of the quench performance of the 11 MBH prototype aperture 02, and the issue of quench heater insulation degradation during hi-pot tests, the aperture 01 of the prototype was assembled with the first collared coils assembly of the series production made by GE. In this "hybrid" prototype, only the new collared coils assembly will be powered. The cold tests should start around the middle of February 2019.

With respect to the LHC LS2 Planning, the first assembly unit is due to be installed from November 2019.

The training results of the 11T dipole prototype were shown.

Findings:

- The nominal turn insulation was changed from November 2017 and applied as from SP107 model. The insulation thickness reference was updated at 105 um under 5 MPa with some increase of the mica width. For the previous models, up to SP106, including the two-in-one models DP101 and DP102, and for the prototype, the insulation thickness was 130 micrometers under 5 MPa.
- Following the low performance of the MBH 11T prototype, after its reconfiguration in the hybrid assembly, the HV QC tests revealed at 2.1kV and room temperature an issue of degradation of the QH-to-coil insulation, obtaining a resistance in the order of MOhm.
- A total of 8 series coils are already equipped with impregnated (internal) QH but none of them was tested at cold yet.
- Cold testing of the first series collared coils is foreseen in February 2019 (LMBHP001)
- Coil #10 of the series is the first coil of the third cold mass, and the first one where a change could be made for QH implementation provided decision is made before the deadline of end of January.

Recommendations:

R1- A curve showing the actual production rate is needed to be compared with the presented baseline.

R2- The Panel recommends to manufacture eight additional coils for spare collared coils packs (see details of this recommendation under Talk #8 by F. Savary, R18).

Talk #2: Quench protection studies on 11T dipole and comparison with test results - S. Izquierdo

The protection scheme for the 11T dipole and the required efficiency were discussed in this talk. Each pole of an aperture is protected with four quench heaters strips, connected into two circuits, making a total of four heater circuits per aperture. High field and low field heater strips are in series, and dissipate different power density (HF and LF don't have same width).

Insulation schemes with impregnated heaters (baseline since 2016, similar to inner triplet's QXF magnets) and non-impregnated heaters (option) were shown. In the past, some magnets had non-impregnated QH (including the past 11T models made at Fermilab in the USA). For those, a 0.1mm thick S-glass layer was applied prior to impregnation in order to have a smooth surface on the external radius of the coil on which the QH were glued. This layer of glue had uneven thickness. It has been shown that this glue did not have any impact onto heater delay.

The non-impregnated QH is not as mature as the impregnated one in terms of QA-QC procedures.

Findings:

- The assumptions for QH firing presented were: 5 ms for detection time , 10 ms for validation and 5 ms for thyristor firing delay.
- The worst case scenario is based on 2 circuits failure which leads to a maximum voltage to ground up to 950 V.
- Several coils equipped with non-impregnated, and glued, QH had an additional layer of fiber S-glass of 0.1 mm thickness between the coil and the QH. Benchmark for an externally glued QH (glue thickness estimated to 25 microns but not considered for calculations) and internal impregnated QHs gave a difference in delay of 10 ms.
- Either internally or externally installed, a 0.1mm thick S-glass will produce an additional delay of 10 ms at high current. Similar polyimide thickness has 3 times more impact on delay than the fiber glass.
- QH efficiency was studied to assess the hot spot temperature vs MIITs.
- In case of non-impregnated QH, the possibility of inspection of the coil surface is present.
- The influence of QH current on delay is minimal as pushing current up to 200 A would only gain 2 ms (with 3 times more deposit power).
- The limits in MIITs were investigated on SP106 showing conductor degradation of 2% after 17.5 MIITs (475 K). In addition, some initial degradation was found in this conductor which doesn't allow to consider this value as a hard limit.
- The glass transition of resin is estimated at 440K and could be considered as an upper bound not to exceed (considering safety margin).

Recommendations:

R3- The panel recommends to perform more high-MIITs tests on models and the hybrid prototype up to 400 K hotspot limit.

R4- It is recommended to check the present assumptions and the impact of changes in tunnel conditions as to what regards the detection time, the validation time, and the threshold values, as we are in the steep region of MIITs vs temperature and therefore any additional delay may imply a large temperature variation.

Talk #3: Heater design, manufacture and QC - Ch. Scheuerlein

The design of quench heaters was presented in this talk. The initial laminate polyimide-epoxy glue-stainless steel is supplied by the company GTS. Only visual QC is performed at this stage. The copper layer is applied at CERN by an electroplating process. The final etching to create the strips, the holes and final cutting to shape are performed at company Trackwise. The perforated holes are 4 mm apart from active strip to avoid surface discharge in air. Values of copper and stainless steel thicknesses have been under control and within specifications. The production of the series QH for the 11T dipole is complete.

The standard QC hi-pot test on finalized QH was presented. Seven out of 32 heaters had to be repaired due to local discharges through the insulation (due to pinholes or defects) and are planned to be used in production. Some improvement on hi-pot test was implemented with applied load which increased reproducibility and reduced leakage current.

Contrary to LHC quench heaters, the ones manufactured for the 11T dipoles do not have a coverlay due to the constraint given by the size of the mold cavity.

Findings:

- No particular QC tests (other than visual inspection) have been performed on the GTS laminate. It would have been better to test electrically the laminate before etching. Statistics from polyimide films show a small amount of pin holes, so the question of rejection the faulty QH should be considered (out of 32 units)
- The QH are perforated to ease the impregnation with 4 mm minimum distance between strip and holes. No design requirement for the choice of this parameter is available apart to fulfill the in-air breakdown value.
- Hi-pot tests using roller under pressure according to LHC past QC procedure were not followed. Some alternative HV test with the roller are investigated showing unstable leakage current down to 1.4 uA.
- The Hi-pot test of a new encapsulated QH prototype with overlay shows good results of breakdown up to 6.5kV.
- One of the original reasons to use traces impregnated in coils was also to allow connection of voltage taps using printed tracks onto the quench heater. These voltage taps are not part of the series (baseline) dipoles.
- Copper deposition and control of the related parameters has given very good results.

Recommendations:

R5 - The Panel recommends not to use repaired QH.

R6 - The Panel recommends to use a coverlay to be applied in external position, to study a design which allows using the coverlay facing the coil with openings for wire connections. The coverlay should be treated with strict QA/QC procedures.

R7 - The Panel recommends to use a high voltage test roller (following the experience of LHC) to qualify electrically the quench heaters.

R8 - Strict cleanliness should be preserved during handling, storage and installation of the quench heaters.

Talk #4: Heater implementation in coils (baseline) - F. Savary

The main manufacturing steps in the process to obtain collared coils were presented in this talk with special accent on the impregnation phase and related tooling. An analysis of the thicknesses of coil, insulation layers and mould was presented. Successive refitting of radii using Teflon layer was discussed.

The QH polyimide substrate is facing the reacted, turn-insulated coil surface. The ground insulation consists of 5 layers of polyimide each of 125 um thickness. The impregnation uses a seal foil with Teflon paint. The radius of the impregnation cavity is 60.953 mm, and that of the mandrel 29.885 mm. The manufacturing steps related to the insertion of QH before impregnation was shown.

Findings:

- Cracking and delamination of the impregnated fiber on the ID of the coil was often observed on the short models after cold testing. Delamination of QH was also observed. The quality of the impregnation (voids, cracks) cannot be assured at this point (we do not know any NDT process for this). In case of external QH, a possibility opens for inspection the coils. How to confirm there are no holes in the resin pack has not been addressed. Collaring does not seem to be the cause as CR01 and CR02 hi-pot tests results show high breakdown voltage value.
- The external surface of turn insulation (fiber glass or mica tape) does not seem reliable in some areas, hence the insulation relies on the integrity of the (thin) QH polyimide substrate.
- The question was raised about the estimate of the differential thermal stress developing in operation between QH layers and coils, which is related to the state of interface surfaces.

Recommendations:

None.

Talk #5: Electrical tests baseline - Tiago da Rosa

This talk presented the electrical test values that have been set at the HL-LHC Project level for the electrical qualification at the end of manufacturing, at reception and during qualification tests at warm and cold at the test stations and later while installed in the tunnel. The presentation's contents are detailed in an updated version of the document describing the 11T dipole electrical design criteria. The document is under approval.

The methodology to calculate the voltage withstand levels values at warm and at cold was explained. Triggered by the findings during hi-pot tests on the 11T dipole prototype, the document now includes a proposal for a test at an intermediate temperature.

Findings:

- A new test is proposed to cover characterization of coils after the cold tests by hi-potting them (to ground, to quench heaters) in a 1 bar He gas atmosphere at a temperature in the range of 150 K - 200K, at the expected worst case voltage (3.3 kV, 3.2 kV respectively). The proposed range of temperatures is estimated as the one expected in the cold masses after a quench.
- With the exception of the newly proposed test at an intermediate temperature, the test voltages and strategy presented are fully consistent with the ones applied to all LHC magnets.

Recommendations:

R9 - The test strategy and criteria are consistent with LHC ones, however as the insulation of quench heaters is weaker the Panel supports the proposal to add an intermediate Hi-pot test before the last warm up, at the above He gas temperature/pressure, including for series magnets.

Talk #6: Electrical tests and root cause analyses of faults – J. Petrik

The acceptance tests performed on the 11T MBH series production were presented in this talk, with the standard categories of HV tests done at various manufacturing steps. The issue of insulation resistance which occurred on the 11T prototype was discussed as well as the investigations in an extended test program on the short and long models. The insulation under quench heaters shows variation of thicknesses of both fiber glass and mica due to wrinkles or corrugation due to external shape of conductors surface.

Findings:

- It appears that the hi-pot repeatability of tests is an important factor, and is influenced by test duration, levels and dwell time.
- All short models are tested at 1kV at RT during manufacture, tested after cold test, not revealing large defects.
- The test of impregnated QH insulation system in coils is done at 3.3 kV for the series coils before cold testing.
- The QH insulation failure happened on the 11T prototype during hi pot tests carried out after cold testing, during the final reception tests of the modified prototype, at around 2.1 kV.
- An extended test program was set to provoke direct shorts in order to localize them by provoking HV arcing. All shorts were revealed to appear in the low field strips both short and long coils. The appearance of weaknesses in the low field strip suggests that the effect is reduction of polyimide thickness, but the reasons are not clear.
- All coils which have been cold tested and hi-pot tested have shown breakdown voltage around 2.1 kV, unlike for the SP107 representative of the new insulation system which exhibited 2.8 kV. In any case, SP107 has undergone 2 thermal cycles, and shown lower breakdown value afterwards.
- Any coil which has not been cold tested (up to 5) has shown breakdown voltage greater than 4kV.
- Several regions are observed in shown micrographic sections with thickness of polyimide reduced to half of the nominal value.

- After reaction, both mica and fiber glass get damaged in some edge locations, hence the quality of the impregnated resin insulation between coil and quench heater can not be guaranteed.
- The support grid of the mica tape has not been fully identified (type of fiberglass, size), this should be clarified as well as the residual thickness of the mica after reaction.
- There are observed thickness variations due to uneven surface of conductors. It appears that there is no clear control of the thickness of both the S-glass fiber and the mica layers under the QH polyimide as shown in micrographic views.
- Even if the original Mica tape thickness is 80 um after reaction, it could be porous, this remains to be checked.
- An extended, on-going hi-pot test campaign was presented which includes mechanical tests to determine the mechanism of failure, Paschen test, partial discharge tests, thermal cycles at 77K, and further hi-pot tests in gas helium atmosphere. The results of these tests were not yet available at the time of the Meeting.

Recommendations:

R10- The multiple processes of the insulation system should keep integrity of polyimide layer intact, as the epoxy-fiberglass and mica thicknesses can not be guaranteed (see micrographs). Local deformations of active parts should be avoided. The Panel observed that in some views the stainless steel strip of the QH was very close to the coil turns.

R11- The Panel recommends to perform several (not less than three) thermal cycles of the long, prototype coils (maybe in a dedicated test stand) to understand the effects of the cycles. In this direction, the Panel supports the ongoing initiative to thermal cycle a collared, short coil-pack in LN2 in a test stand and to check intermediate insulation resistance levels in order to observe possible degradation (see also R13).

R12- The Panel recommends the characterization of the short model QH insulation after cold test at similar voltage levels to long coils.

<u>**Talk #7: SP109 endurance test results, investigation of HV test station limits - G. Willering**</u>

The leakage currents at different voltage levels have been characterized for the test stations in SM18. This talk presented the corresponding results. The horizontal test benches can withstand up to 3.4 kV. The vertical test beds will be limited to about 1kV in gas environment.

A summary of the outcome from the endurance quench heater test and cycling tests carried out on various models was presented. During hi-pot testing of model SP109 in gas helium at an intermediate temperature, some breakdown appeared as limits seem from the station. No degradation was observed following the breakdown.

Findings:

- Variations of insulation resistance as function of humidity were measured in test stations.
- Hi-pot tests in gas He atmosphere can be done during warm up on a vertical test station, with control of the (non-uniform) temperature better than 20K in gradient.
- SP109 has undergone gas He test and breakdown at 1.1 kV was observed but there were no indications where it occurred (magnet or insert).
- No noticeable damage on 11T models QH after cold test, but test levels were rather low.

- Tests performed so far on the magnets show that there is no issue coming from neither the QH nor the magnet powering cycles.

Recommendations:

R13- The Panel recommends at least three thermal cycles with the next hybrid prototype before the shutdown of SM18 cryogenics. This recommendation relates to R11.

Talk #8: Possible scenarios for 11 T dipole production - F. Savary

An alternative solution of non-impregnated, external QH was presented during this talk, with an overall view onto the different implications in case of change. The feasibility of an external QH has been proven and therefore the MSC group is seriously considering this option. In order to make the outer surface of the impregnated coils smooth, the insertion of a 60 um fiberglass layer at the external radius of the coil is proposed. An option for 90 um thick fiberglass is also presented.

The radius of the impregnation cavity can be adapted to the new diameter of the coil, and the ground insulation scheme shall be modified to accommodate for the change.

The addition of the 60um layer of insulation will make the hot spot temperature to increase in case of 2 QH circuits failing up to 363 K in the case of nominal current and 386 K for ultimate current. An assessment of no-degradation of the magnet performance when exceeding the nominal 350 K limit is required (see R3).

The coverlay of 50+25 um additional thickness will provide additional rigidity and is considered in the case of external heaters.

It is recalled that the first two magnets (coils GE-C01 to GE-C09) have impregnated heaters, and that the implementation of changes in the QH position requires a decision before end of January 2019.

There is provision for 5 unit lengths of conductor in the plan (i.e. enough for one spare magnet).

It is also confirmed within this presentation that analysis of various micrographs from the prototype show that the quality of the final product can not guarantee an uniform thickness of insulation.

Findings:

- Several alternatives to improve the electrical integrity between QH and coil have been presented. Different options are proposed including adding a 60um fiberglass wrap under the impregnated QH.
- If an additional layer of fiberglass of 60 microns is added, the heater delay at nominal current will increase to 18.5 ms for the high field strip.
- There is the plan to further test SP109 with high MIITs, but in this case one can not guarantee where the quench starts (unlike with SP106, which had an interlayer QH).
- The external QH installation was tested and proven on a few short models only. Two samples of long QHs with coverlay have been produced.
- The maximum dielectric strength will depend on the total thickness of insulating material and its actual level of degradation. The table of breakdown voltages presented corresponds to the nominal expected values.
- With regard to the findings on the weakness of the impregnated QH option, the question was raised if the already produced (two) series magnets that incorporate the internal option could be used for LHC. The Panel emitted a proposal to keep them as spares if time allows for

manufacturing new magnets with external heaters to install. According to the schedule presented, the foreseen time to installation in the tunnel does not allow for manufacturing the complete amount of collared coils that would permit to keep the first two magnets as spares. See R18.

- At present, without further tests, one can not define the expected lifetime of the current design.
- Frédéric showed additional micrographs of CR006 cut sections from prototype showing voids in the interlayers.

Recommendations:

R14- The Panel strongly recommends positioning the QH outside of the impregnated coil.

R15- The Panel recommends the use of a polyimide coverlay of 50 um with glue thickness of 25 um. Compensation of the layers in the ground insulation is foreseen with a reduction of total thickness to 4 x 125 microns.

R16- The Panel recommends to match the radius of the impregnation cavity to the outer radius of the coil.

R17- The Panel supports the use of a glass layer to smoothen the external surface. The preference goes for the 60um thick option, as the 90 um thick fiberglass option doesn't seem to be really advantageous in terms of dielectric. One shall ensure that the new proposal does not add more than 60 microns of insulation by adjusting the radius of the impregnation cavity.

R18- The Panel would support that the already made coils with impregnated heaters be installed in the LHC tunnel in order to meet the LS2 schedule, provided that an equivalent number of additional spare, collared coils are manufactured with external heaters. To this end, the existing coils with internal heaters should be qualified from an electrical point of view including the intermediate temperature test in gas helium at 1 bar, 150-200 K. The influence of (and possible degradation due to) several thermal cycles to the coils with impregnated QH has to be assessed upon as well (see R13). NB.- The implications in terms of budget to the HL-LHC Project were not discussed.

R19- The Panel recommends that the table comparing the different options (slide 9) include realistic dielectric strength voltages for the baseline, as it was known that the theoretical values for this option are out of reach.

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