

CONSOLIDATION OF THE LHC SUPERCONDUCTING MAGNETS AND CIRCUITS DURING LS1

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Abstract

All the activities necessary to consolidate the LHC superconducting magnets and circuits are presented, especially the consolidation of the main splices, replacement of weak cryomagnets, the consolidation of the DFBA's and the special interventions. For each of them, the baseline strategy is presented, highlighting the reasons that led to these choices and the remaining risk level.

In particular, the progress of the work of the LHC Splices Task Force, the recommendations of the second LHC Splices Review (November 2011) and their analysis are reported. Finally, the work planning, the organization chart and the associated resources are detailed.

MAIN SPLICES

The design and procedures for consolidation of the 13 kA busbar splices of the main dipole and quadrupole circuits were presented and submitted to an international review committee at the second LHC splices review [1]. This review is part of a series of reviews and the next ones have been preliminarily planned, assuming a beginning of the intervention on the interconnections (ICs) in January 2013:

- 3rd Review: September 2012: Production Readiness
- 4th Review: March 2013: Quality Audit

A functional specification [2], formalising the requirements defined in the frame of the splices task force [3], was written. The final design of the consolidated shunt was assessed to meet all the requirements. This is a major achievement. At the time of the review, the electrical insulation was almost finalised except for some details. Now, a final concept, answering positively the remarks of the review committee, is available.

The criteria used to decide if a splice has to be redone were found adequate:

1. $R_{8_excess} > 5 \mu\Omega$ (Resistance of the copper to copper junction)
2. Outlying $R_{splices}$ @ 1.9 K (a maximum of 123 splices) (Resistance of the superconductor to superconductor junction)
3. Geometry not allowing nominal shunt installation
4. Visual defects

Since redoing a splice is not a riskless operation (major intervention on the delicate Rutherford superconducting cables), and it takes time and resources, reworking has to be done only if strictly necessary.

The proposal to install single shunts on the quadrupole circuits, after validation in the splices task force, was endorsed by the international review committee, under the following conditions:

- ✓ Strict application of the production and quality control procedures;
- ✓ The clamp is effective in limiting the deflection and stress on splice, to prevent the future degradation of the copper stabilizer connection;
- ✓ The energy extraction time constant is reduced to less than 20 s. [4];

It was decided to consolidate the DFBA (Electrical feedboxes) superconducting circuits (splices and busbars) to the same standard as the arc ones and the sharing of responsibilities is defined [5]. For the intervention on the splices themselves, the same teams will take this in charge while the procedures, tooling and work to give access to them will be carried out by the responsible equipment group. It has to be noted that in 2 out of the 16 DFBA's, some splices cannot be consolidated in-situ so methods lowering the inherent risk have to be studied.

All the superconducting circuits from current lead to current lead were screened by a pool of experts [6]. 24 practical recommendations were formulated. The high risk issues concern mainly the 13 kA splices, hence the need to work on the arc splices but also on the DFBA ones (see above). Other weaknesses were identified like the spiders (Busbars supporting devices). Procedures to consolidate them are under definition. On one hand, this long shutdown is a possibility for a massive consolidation but on the other hand, the risks generated, the reliability improvement, the time and resources involved have to be taken into account in the decision to do it or not.

SPECIAL INTERVENTIONS

This topic was covered in [7]; an update is given here.

Replacement of magnets

8 dipoles and 1 short straight section will be replaced because of their high inner splice resistance. This amount was estimated last year but is now substantiated by a careful analysis and a massive test programme [8]. It was concluded that leaving these 9 magnets would be too risky due to a possible lack of mechanical strength. On the other hand, some extra 30 magnets present a very small risk. As the approach used is very conservative and as no degradation was noticed in LHC or in SM18 extensive testing, this risk is accepted. The magnets removed during LS1 will be tested and inspected, and this will help to elaborate the strategy for possible replacement of magnets during LS2.

4 dipoles will have to be replaced because of a weakness in the quench heater circuit. One magnet does not presently withstand the voltage of 1.9 kV. A repair in-situ will be tried at the beginning of the LS1. Nevertheless

a spare and the resources will be foreseen for an exchange if the repair is not successful.

14 magnets have wrongly oriented beam screens around the LHC ring. This could increase the heat load because the synchrotron radiation will generate more electrons. Such an effect cannot be measured at 3 TeV, but might become relevant at 7 TeV. In Ref. [9], it is recommended to install one cryodipole with conform beam screens orientation to avoid to have more than one cryodipole with wrong beam screens orientation per cooling loop. So, 2 cryodipoles have to be replaced in half cells 26R3 and 32R3. The actual type of cryodipole to be exchanged is left free and can be used as an optimisation parameter for the global installation strategy.

By replacing the SSS Q23R3 and Q27R3, the RQS circuits will be restored in sector 34. As a second priority but in the baseline, the SSS Q5L8 housing a non-conform corrector circuit (RCBCHS5.L8B1) will be replaced by a SSS with a new corrector. The RO circuit (Q28R3 & Q32R3) will not be restored in LS1 but will be studied for LS2 in case of need.

All known and new leaks will be searched and repaired during LS1. The most critical one on the magnet side is in the vacuum subsector A27L4 [10]. The experience so far is that all localised leaks could be repaired in-situ. No spare magnet is prepared since its exact location, hence its type are not known. If necessary, it could be ready in a few weeks in most of the cases. If it is a complex SSS, this could take several months.

The undulators are having non-conformities but are working satisfactorily. A spare cold mass is available, it will be cryostated and cold tested in 2012. After testing and assessment of its impact on operation, a decision on the need for replacement can be made.

Table 1: Magnets to be replaced

| Reason | Dip | SSS | Total |
|-----------------------------------|------------|------------|--------------|
| High inner splice resistance | 8 | 1 | 9 |
| Electrical integrity | 5 | 0 | 5 |
| Reversed beam screens | 2 | 0 | 0 |
| Beam optics (Q23R3 & Q27R3, Q5L8) | 0 | 3 | 3 |
| Leaks(*) | 0 | 0 | 0 |
| Undulator(**) | 0 | 0 | 0 |
| TOTAL | 15 | 4 | 19 |

(*) Only one critical leak in sector 34 may not be accepted so could require the replacement of a magnet if it cannot be repaired in-situ. Based on the experience so far, it is not likely.

(**) Not planned but to be decided in 2012.

The plan is to have these 19 cryomagnets ready to be lowered before the start of LS1. There are already sufficient number of dipoles, the assignment process by the MEB is running and the planning for work in SMI2 is defined. Up to date info is available at [11]

Consolidation of Connection Cryostats (CC)

A consolidation campaign on the CC was started during the 2008-09 shutdown [12]. To avoid major delays and as tests have proven that the risk was very low, two CC (L1&3) were not consolidated and one was even not

inspected (L8). During LS1, the baseline is to inspect all the CC to check the long term efficiency of the fixing procedure and especially the CC L8 for which no info is available; consolidate it if necessary and also the 2 remaining ones. Note that if the DS collimators had been installed in IR3, the CC in 11L3 would have been replaced by a shorter one, cancelling the need for its consolidation.

Safety pressure relief devices [13]

In the 2008-09 shutdown, three sectors were not warmed up and therefore, it was not possible to install all the DN200 pressure relief devices. Also, the safety pressure relief devices could not be installed in Q6R2 & Q6L8. It is planned to complete the installation of the safety pressure relief devices during the next shutdown. About 600 relief valves have to be installed. Self reclosing "flap" valves will also be installed [14].

Plug-In Modules (PIMs)

The strategy [7,14] is summarised in Table 2. As some bellows are very fragile, new permanent protection shells will be installed before the closure of the ICs [14,15].

Table 2: Replacement of PIMs

| Reason | # | Remark |
|---|-------------|-----------------------------------|
| Preventive replacements at the arc extremities (Q7/MB; MB/Q7) | 18 | Some already re-placed in 2008-09 |
| Heavily damaged | ≈10 | |
| Failure at warm-up | ≈14-18 | Estimate |
| Around exchanged arc cryomagnets (#18) | 72 | 4 per cryomagnet |
| TOTAL | ≈116 | Estimate |

Circuits issues

For various reasons, both the main circuits and also many correctors have not been commissioned up to 7 TeV equivalent current [7, 17, 18, 19]. Some are planned to be treated during LS1, some not, like D2R8 for example. Extensive testing at cold and warm before the opening of the ICs should be done in order to assess the real limitations and support the preparation of the possible interventions. In parallel, actual and realistic requirements for operation towards 7 TeV needs to be devised, using the experience acquired thanks to LHC runs so far. This should be given sufficient resources and time to allow to focus efforts on the priority interventions. In that phase, unknown non-conformities would require interventions that could have major impact on resources and schedule.

Other issues

The helium level gauge of two stand-alone magnets will be consolidated (Q6R2&L8). [7,16]

Two leaking Y-lines (17-19R7 & 19-22R8) will be fixed. [7].

The non-conformity on the passive heaters of the inner triplets [20] will be treated at the end of LS1 for

radioprotection reasons. Points 1 & 5 will be treated in priority.

The 6 kA splices resistance measurements have been completed and no outlier has been revealed. Targeted inspection is foreseeable.

During the assembly of the first sector (78), some 600 A line N connections were found non-conform. Most of them were inspected and redone if necessary. For the non-inspected ones, sampled inspections could be planned.

With respect to last year plan [7,26], it was decided to postpone the installation of DS collimators in IR3. This reduces the workload but, as side effect, gives extrawork for consolidation of the connection cryostat 11L3 and the replacement of Q7R3.

Many local interventions are required to give access for short interventions, like for example BPM cables checks and possibly repairs, recovery of the radioprotection samples for analysis [25] or installation of new ones.

Last but not least, interventions will be required to solve new issues appearing before the shutdown and also to manage non-conformities generated by the other activities during the shutdown. This is difficult to plan but small contingency is foreseen for this. If not sufficient, the options will be:

- To accept a longer shutdown duration allowing to shift experienced resources working on the main splices to the special intervention team
- To reduce the scope of work of the special intervention team

It is not recommended to shift experienced resources planned for the main splices consolidation to the special intervention team because of the criticality of this operation.

It is important to remind that work will take place all around the LHC circumference, making the coordination and follow-up quite demanding in terms of supervision staff.

ORGANISATION AND RESOURCES

The consolidation of the superconducting magnets and circuits during LS1 generates a workload for 220 persons full time equivalent during more than one year. It is 20 more than presented last year [23], mainly due to the decision to consolidate the DFBA circuits. Assuming committed contributions from other groups are validated, 40 persons are missing. Only one third of the involved staff is presently trained and experienced. Training will be a challenge for this year. A simplified organisation chart is given in Fig. 1. This project is part of the global LS1 project led by F Bordry.

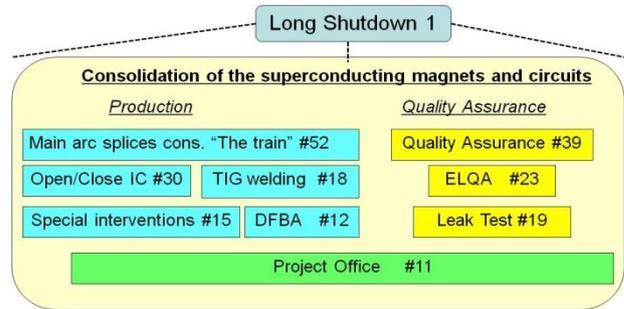


Fig. 1: Simplified Organisation Chart

There are production and quality assurance activities and also a project office, aiming at providing general support and coordinating some interfering activities (transport, logistics, tests on chains of magnets like pressure and leak test, some ELQA) and also activities necessary to prepare the worksite [removal of sensors (Survey, BLM, QPS,...), safety, general logistics,...].

The teams working on the consolidation will start at point 5, going clockwise. Fig. 2 is an overview of the other activities to be carried out on the superconducting magnets. The Special Interventions Team (SIT) will aim at completing its work before the arrival of the “splices train”.

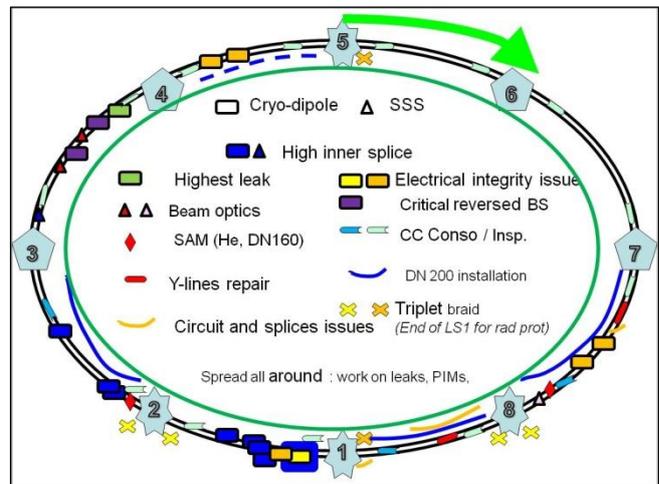


Fig. 2: Overview of the special interventions

The global planning [21] gives the boundary conditions for the consolidation of the magnets. Within the allocated space-time windows, the various teams are defining and managing their own detailed schedule. It is mandatory to reach the ambitious production rate of 53 IC/week. The best rate achieved during the series installation was 30 IC/week. For the 8 sectors, the consolidation of the main splices will last 14 months and the worksite will extend on four sectors (> 13 km). This does not contain any contingency. It has to be noted that the first sector will be power tested only one year after the start of the consolidation, too late to change anything on the work procedures.

A web interface tool, called WISH [22] for Web Interface SHUTDOWN, is under development. It will:

- Ensure real time recording of the work progress, easing coordination
- Trace each single task (operator, tooling)
- Allow fast reaction for NC management
- Support the data transfer to MTF for trace-ability

Tests and debugging of the WISH are foreseen in August 2012. This requires an efficient (3G) internet connection all along LHC tunnel.

220 persons are needed to accomplish this work

OTHER TOPICS

Busbar Spiders

A doubt on the busbar “spiders” was identified by the experts screening the LHC circuits [6]. Work is on-going to possibly define a consolidation procedure [1]. The issue will be reviewed by the LHC Splices task force and a proposal made in 2012.

The diodes

High resistances were measured in the diodes circuits of the LHC during quench propagation tests. A working group (TE-MPE & TE-MSD) has conducted off-line testing of the diodes. Data from series production, spare diodes and diodes recovered from 34 was analysed. Instrumented diodes were tested in SM18.

The diodes behaviour observed in the LHC tunnel has been confirmed as a typical one and, even if not explained yet, is not considered as an issue for LHC operation. It is characteristic of the diode to heat sink contact. Further tests are planned in SM18. This is not a complete guarantee that all diodes can withstand a nominal current decay. There might be a few isolated cases where contact resistance is too large.

No massive intervention is planned on the diodes during LS1. Local tests and/or inspections are possible.

Copper Stabiliser Continuity Measurement (CSCM)

This method has been described and reviewed at several occasions [1,19]. It could be used to qualify the main splices, but also other parts of 13 kA circuits, for operation at 7 TeV. An approval for the continuation of this project is needed. As the goal has changed since the proposal of this method, the necessary conditions have also to be reviewed and updated. A possible planning is:

- January 2013: Type test in one sector at the end of the physics run
- End of LS1: campaign on the LHC to qualify main circuits for operation at 7 TeV. The impact on the schedule would be 4 weeks if the 8 sectors are tested but there could be no impact if the last one(s) are not tested.

This method gives information on the highest segment resistance between voltage taps in a LHC sector. It could be useful information, especially if some splices are extremely difficult to access for consolidation (DFBA for example) and therefore are not treated. It is also validating other parts of the bypass circuits (i.e. diodes)

Safety and radioprotection

These aspects were treated in [1]. The use of lead-containing solder is under assessment with the TE safety officer. This should not be an issue. For the radioprotection, the workplan is:

- Continuous review of detailed estimates of radiation levels
- Verification on samples (both outside and inside IC [25])
- Radioprotection inspector to go with the working team at opening of the ICs
Some interesting points to note:
 - The regulations impose to companies from member states and institutes to follow their own national legislation. For industrial support teams, this will imply wearing two dosimeters: one issued by their home country and one from CERN,
 - Any material removed from the LHC tunnel will have to be traced
 - Use of methods generating dust or small particles should be minimised
 - SMI2, the exit building for removed magnets, should become a supervised workshop due to the low expected activation of the magnets at the time of LS1. Storage of removed magnets will have to obey the RP rules.

New IC thermal shield design

During the 2008-09 shut-down, certain drawbacks of the IC thermal shield design were noted: notably blockage of the shield and risk of MLI fire during welding operation. In view of the heat load margin, a new design of the thermal shield is being studied. It reduces the number of welds (and grindings in case of dismantling). After further modelling and testing, a choice will be made in 2012, and eventually submitted for approval.

CONCLUSIONS

Some decisions have to be taken in 2012:

- DFBA consolidation
- Reinforcement of the spider insulation
- New IC thermal shield design
- Known circuits non-conformities
- Undulator replacement
- CSCM
- Diodes
- ...and all what will appear.

The consolidation of LHC superconducting magnets and circuits has been reviewed by an international committee of experts in the LHC splice review in November 2011. The final design of the consolidated 13 kA busbar splice meets all the requirements and recommendations of the review and is now being prepared for production.

The replacement of magnets and consolidation of the main splices are the two major priorities of LS1, and are estimated to require 14 months each and a combined effort of 220 FTE, of which about 40 have still to be

identified. 2012 will be the key year for the preparation for these activities, especially the training of the new staff joining the experienced teams. The planned production rate of 53 IC/week is very ambitious, with a minimal contingency in resources and schedule.

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