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The First Long Shutdown (LS1) for the LHC

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The paper describes the preparation phase with the prioritisation of the activities, the building of the teams and the planning of the shutdown. Then, it gives an overview of the injector activities and the main projects in the LHC. The decision to restart at 6.5 TeV after the LS1 is recalled.

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Abstract

The LHC has been delivering data to the physics experiments since the first collisions in 2009. The first long shutdown (LS1), which started on 14 February 2013, was triggered by the need to consolidate the magnet interconnections to allow the LHC to operate at the design energy of 14 TeV in the centre-of-mass. It has now become a major shutdown, which, in addition, includes other repairs, consolidation, upgrades and cabling across the whole accelerator complex and the associated experimental facilities. A detailed CERN-wide resource-loaded schedule was prepared aiming at resuming LHC physics in early 2015, while the rest of the CERN complex will gradually start up again in the second half of 2014.

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INTRODUCTION

Following the incident in one of the main dipole circuits of the LHC on September 19th 2008, a detailed analysis was carried out [1]. Thanks to the availability of spare magnets, Sector 3-4 could be repaired in 6 months. In addition, a global consolidation of the magnet protection system and important re-engineering of several systems took place so that such an incident would be avoided in the future.

An upgraded quench protection system was designed and installed to protect all bus-bar joints of the arc main dipole and main quadrupole circuits [2]. In parallel an improved pressure relief system for the insulation vacuum was installed on the magnet cryostats. But in order to restart quickly the LHC (November 2009) and to provide data to the experiments, it was decided to warm-up only four LHC sectors, therefore the 200 mm diameter valves for the improvement of the pressure relief system were only installed on these four sectors.

The interconnections between the LHC main magnets are made of soldered joints (splices) of two superconducting cables stabilized by a copper bus bar. The measurements performed in 2009 in the four warm sectors demonstrated that there are defective copper bus bar joints in the machine (10-15% of the high current interconnections). Based on these measurements, it was decided to restart the LHC operation at 3.5 TeV and to consolidate the LHC during the LS1 in 2012. With the respectable integrated luminosity in 2011, the CERN management decide to run the LHC through 2012 to give to the experiments the data needed to fully explore this energy range before moving up to higher energy. To enhance the discovery potential, after two years of operation and an operational experience with stored beams exceeding 100 MJ, the beam energy was increased to 4 TeV in 2012.

Thanks to the fantastic LHC performance [3], this staged strategy proved successful and culminated, with the announcement of the discovery of a Higgs-like boson on 4th July 2012.

LS1 STRATEGY AND RESSOURCES

As described above, the LS1 was triggered by the need to consolidate the magnet interconnections to allow the LHC to operate at the design energy of 14 TeV in the centre-of-mass. It became rapidly a major shutdown, which, in addition, includes other repairs, consolidations, upgrades and cabling across the whole accelerator complex and the associated experimental facilities. LS1 will see a massive programme of maintenance for the LHC and its injectors in the wake of more than three years of operation without the long winter shutdowns that were the norm in the past.

The LS1 preparation started just after the decision to resume the LHC operation at 3.5 TeV, i.e. more than three years ago. The strategy was to define the duration of key activities needed for safe and reliable operation of the CERN accelerator complex (LHC and its injectors) to run the LHC at 7 TeV at the nominal luminosity. After several iterations with the technical coordination of the LHC experiments, the LHC machine and its injectors, the minimum time needed from “beam off” to “beam on” in the LHC was determined to be 20 months. Rapidly it became clear that it would be necessary to prioritize all the activities requested by equipment groups and the projects; this to ensure that the 20 month time frame would be sufficient to perform all the consolidation and upgrades needed to achieve the goals of LS1 (as well as carry out the full maintenance of the different systems),. Often these interventions are planned and organized in terms of the resources in the groups, therefore it was vital to gather all the information on the support needed from other groups, to check the coactivity conflicts and to define the required manpower. Regular and dedicated meetings were held with the different stakeholders to obtain a clear and complete picture of the activities related to the accelerator complex and the LHC experiments. All the information was compiled in a database and a special software tool (PLAN) was developed as a decision support tool.

The five following levels were set to prioritize all the activities:

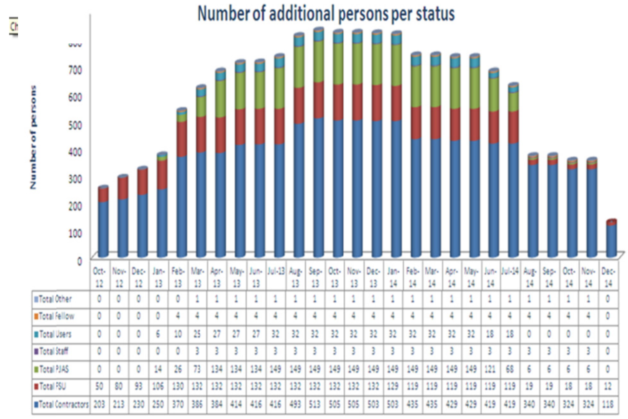
Table1: LS1 Priorities

Priority	Activity
P0	Safety
P1	LHC operation at 7 TeV with nominal performance
P2	Reliable operation up to LS2
P3	CERN approved projects
P4	Non-CERN approved projects

All activities classified as P0 to P2 were integrated in the LS1 schedule. The activities with priority P3 and P4 were only retained if they were compatible with the CERN-wide resource-loaded planning allowing a beam injection in the LHC machine by January 2015. Activities not retained are postponed for the winter technical stops (12-13 weeks) after 2015 or for the next long shutdown LS2 (currently planned in 2018).

The availability of human resources is decisive for the success and in defining the length of LS1. Major efforts were made to redirect CERN internal resources towards LS1 activities, to initiate or strengthen collaborations with international institutes and to establish or reinforce industrial service contracts. Figure 1 shows the evolution of these external resources during the LS1 with a peak above 850 persons during the summer 2013.

A massive and solid preparation has taken place in the last two years: detailed and documented procedures, safety analysis, ALARA plans, integration, Engineering Change Request (ECR), logistics, etc. With all the co-activities and the large numbers of persons intervening in the accelerators (up to 1600 persons), the safety was confirmed as THE priority of the LS1.



	Oct-12	Nov-12	Dec-12	Jan-13	Feb-13	Mar-13	Apr-13	May-13	Jun-13	Jul-13	Aug-13	Sep-13	Oct-13	Nov-13	Dec-13	Jan-14	Feb-14	Mar-14	Apr-14	May-14	Jun-14	Jul-14	Aug-14	Sep-14	Oct-14	Nov-14	Dec-14
Total Other	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Total Fellow	0	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0
Total Users	0	0	0	6	10	25	27	27	27	32	32	32	32	32	32	32	32	32	32	32	18	18	0	0	0	0	0
Total Staff	0	0	0	0	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0
Total PJAS	0	0	0	14	26	73	134	134	134	149	149	149	149	149	149	149	149	149	149	149	121	68	6	6	6	6	0
Total FSU	50	80	93	106	130	132	132	132	132	132	132	132	132	132	132	129	119	119	119	119	119	119	19	19	18	18	12
Total Contractors	203	213	230	250	370	386	384	414	416	416	493	513	505	505	503	503	435	435	429	429	419	419	340	340	324	324	118

Figure 1: Overall additional number of persons at CERN during LS1.

Several logistics issues, induced by the massive arrival of new personnel, had to be specially addressed: these included registration, training, transport, parking, access, catering, accommodation, etc.

Detailed schedules for the LHC and its injectors were defined, discussed and approved by all the stakeholders. Figure 2 shows, as an example, the schedule for the LHC that is driven by the splice consolidation work (blue blocks).

In the following sections, the main activities for the LHC injectors and the two main projects in the LHC are presented.

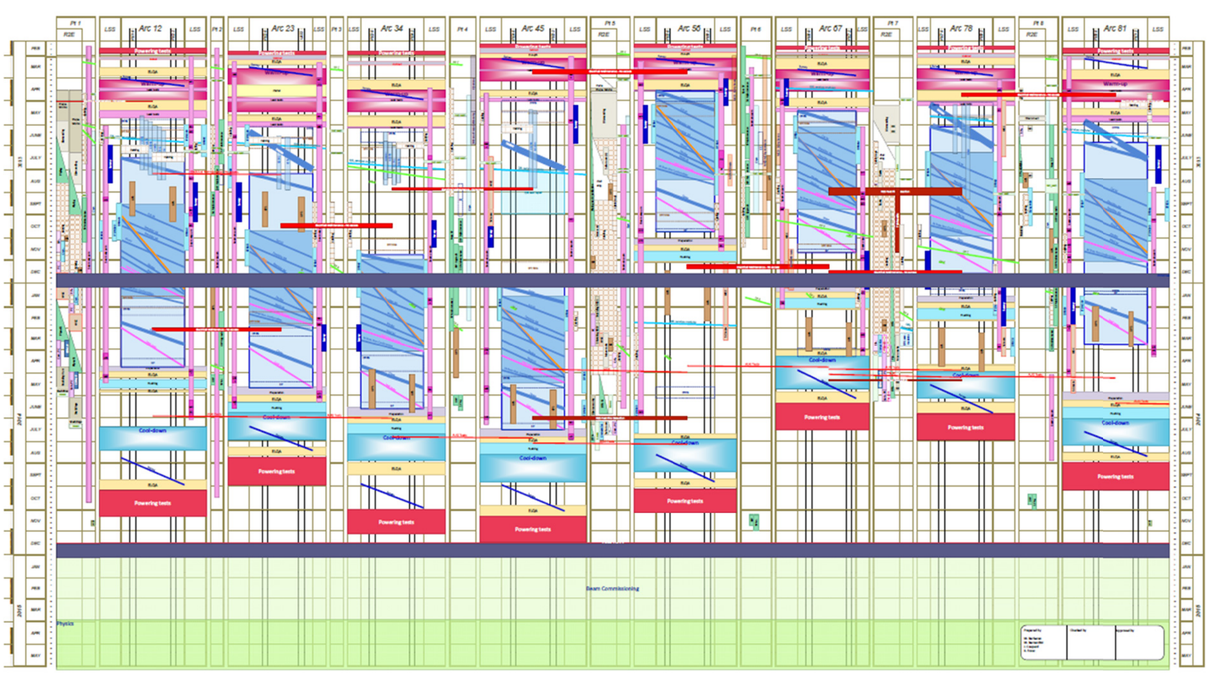


Figure 2: The main LS1 schedule for the LHC machine.

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MAIN ACTIVITIES FOR INJECTORS

After more than three years of operation without the long winter shutdowns that were the norm in the past, the LHC injectors and the associated experimental areas need a full maintenance of all the equipment systems.

Several activities in the framework of the upgrade of the LHC injectors (LIU project [4]) have been planned during LS1 but some LIU activities were postponed to the LS2 largely due to the overload of the cabling supervision teams.

As it is impossible to mention all the activities, only the principal ones are listed below. The main activities in the PS and PS Booster (PSB) are:

- Installation and commissioning of the new access systems
- Replacement of the cooling and ventilation system
- Upgrade of the RF systems
- Improvement of the radiation shielding over the PS
- Renovation of the PS vacuum control system
- Alignment work
- Preparatory works for 2 GeV upgrade during LS2 in the PSB (e.g. new beam bump to handle Linac4 type beams, etc.).

The main activities in the SPS are:

- Vacuum coating of 16 dipoles for e-cloud mitigation test
- Upgrade and reduction of the impedance of the kicker systems
- Major upgrade of RF systems (power increased up to 4 MW)
- Major capacity upgrade for cooling and ventilation to allow the above RF upgrade tests and later operation
- Replacement of 18 kV transformers for the main power converters
- Realignment works
- Replacement of irradiated cables in one sector (sextant 1) and in North experimental area (TCC2)
- Installation of new optical fibre systems in three sectors (BA1, BA5 and BA6)

As an example of the dynamic and continuous management of the shutdown activities, the discovery of a vacuum leak in injection PSB kicker, at the start of the LS1, should be mentioned. The replacement of this kicker by its spare is compulsory and the construction of a new spare should be planned.

The LHC injectors and the respective experimental areas will resume gradually their operation in the second half of 2014: the PSB by mid-June, the PS by mid-July and the SPS by mid-October 2014.

SUPERCONDUCTING MAGNETS AND CIRCUITS CONSOLIDATION (SMACC)

As mentioned in the introduction, following the September 2008 incident, a dedicated task force made a detailed analysis of all the magnet circuits [1].

The *Splices Task Force* was set up to review the status of all superconducting splices in the LHC and to prepare the necessary consolidation actions [5].

Following three reviews by an international committee (October 2010, November 2011 and November 2012), the specification of the consolidated splices, the subsequent design, the detailed consolidation procedures and the quality assurance (QA) were finalised and approved by end 2012.

The central consolidation of the interconnection consists in adding a shunt across the splice interfaces and a new electrical insulation system (see Figs. 3 and 4). The design had to be compatible with the existing splice environment and to meet electrical resistance, mechanical stress, radiation resistance and hydraulic impedance requirements:

- The shunts applied to the present splices (without renewing them) have to ensure the electrical continuity of the copper stabiliser of the bus bars in all conditions.
- The electrical insulation system, in addition to providing sufficient dielectric strength between the circuits and to ground, also has to provide a mechanical restraint that limits stresses and deformations of the bus bars and splices due to Lorentz forces.

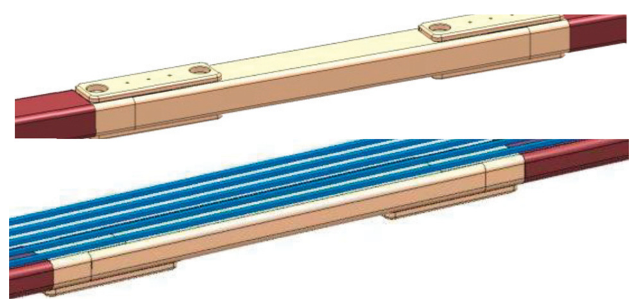

Figure 3: Design of the consolidated dipole (top) and quadrupole magnets bus splice.

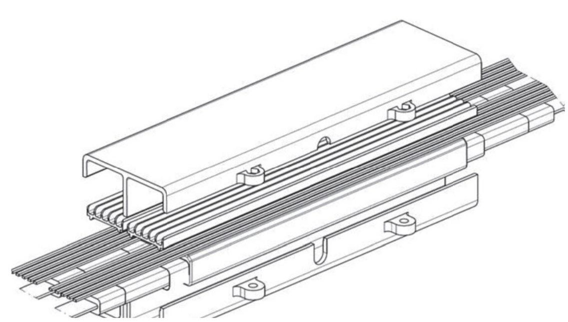

Figure 4: The new electrical insulation and mechanical support box enclosing two parallel bus line splices.

The quality controls will be applied both to existing and consolidated splices. The new shunts and the new insulation boxes will be installed on all 13 kA bus bar splices. In addition, it is expected that about 10-15 % of the splices have to be completely opened and remade.

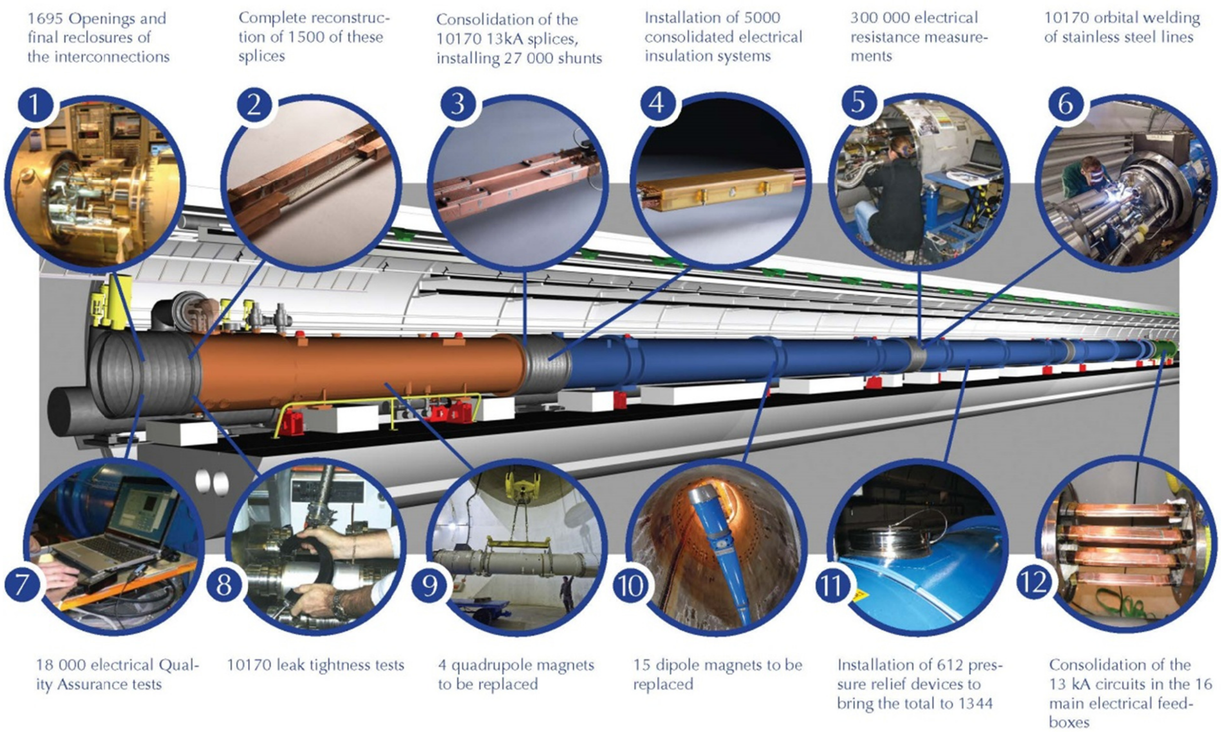

Figure 5: The main SMACC consolidations during the Long Shutdown 1.

That means that 1000–1500 splices will need to be redone and more than 27,000 shunts added to overcome possible problems with poor contacts between the superconducting cable and the copper stabilizer.

The teams will need to open the interconnections between each of the 1695 main magnet cryostats. They will repair and consolidate around 500 interconnections at a time, with a work site that will gradually cover the entire 27-km circumference of the LHC. The planned production rate of 53 interconnections per week will be a constant challenge and is closely monitored.

LS1 is also the opportunity to resolve non-conformities in the magnet circuits, which could be a limitation for operation at 7 TeV per beam. As a result 18 main superconducting magnets will be replaced: 15 dipoles and 3 quadrupoles.

The SMACC project also includes the consolidation of the cryogenic feed boxes and the installation of pressure-relief valves on the sectors that were not equipped in 2009. Figure 5 illustrates, in a very concise form, the main activities of the SMACC project [6].

These activities will require 15 months and a combined effort of about 260 persons.

RADIATION TO ELECTRONICS (R2E)

A Radiation to Electronics (R2E) Task Force was created in 2007 to evaluate the risk of failures due to radiation in the control equipment installed in the underground areas of the LHC.

The level of the flux of hadrons in the multi MeV range from the collimation system (Point 7 of LHC) and from the collisions in Atlas, CMS and LHCb (Points 1,5 and 8) induce Single Event Errors (SEEs) on the standard electronics present in the equipment located around these locations. During 2011 and 2012, the perturbation to the LHC operation was measured (Fig. 6). The improvement (from 12 dumps per fb^{-1} to 3 dumps per fb^{-1}) brought in the 2011-2012 winter stop was obtained by a partial relocation of sensitive equipment and some strategic shielding. During LS1 a reduction by a factor 6 must be achieved to increase the MTBF of the LHC to one week for failures of controls electronics caused by radiation at nominal beam conditions.

A phased strategy was proposed by the R2E project after massive equipment testing campaigns to identify critical components, and a pragmatic list of mitigation actions (relocation or redesign of equipment, shielding, etc.) was established to solve the identified problems

The R2E project team has been working for more than three years, in close collaboration with all of the groups responsible for LHC equipment and services.

During LS1, 15 equipment groups will be working at Points 1, 5, 7 and 8, where more than 100 control and power racks will have to be moved. In addition, the shielding in the service caverns (RR) at Points 1 and 5 will be reinforced. In the LHC tunnel, the electronics that are most vulnerable to single-event effects are those used in power converters, cryogenics and the QPS (Quench Protection System). To make the QPS more robust, more than 1000 circuit cards will be replaced during LS1. The R2E work is expected to take slightly more than 70 weeks and a combined effort of about 150 persons.

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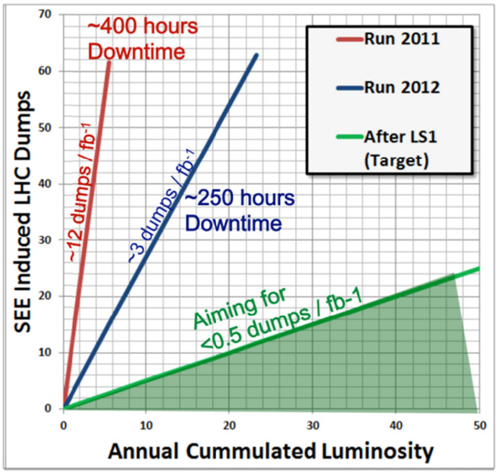

Figure 6: LHC beam dumps due to single-event effects against beam luminosity.

LHC ENERGY AFTER LS1

All the LHC main dipoles were trained to reach 8.5-9 T, i.e. well above 8.3 T or 7 TeV equivalent energy, during individual tests at CERN [7]. Based on this data, the first estimate of ~330 quenches needed to reach nominal was given, i.e. about one quench every four LHC dipoles. In 2008 all the LHC main dipole circuits were trained to 5 TeV, two sectors to 6 TeV, and one sector was pushed up to 6.6 TeV. In the 5-6 TeV range, a few quenches were needed to retrain the LHC dipoles, and none for the quadrupoles. After the 2008 incident, 39 magnets were removed from Sector 3-4 and after minor repairs, not involving the active part of the magnet, 32 of them were tested in SM18. As the LHC was operated at 3.5 TeV and 4 TeV during 2012, no additional quench data was accumulated but additional effort on the modelling side was deployed.

An analysis of all the available estimates show that negligible training is needed to reach 6 TeV, 0-50 quenches for 6.25 TeV and 0-100 quenches to 6.5 TeV (10-15 quenches per sector) (Fig. 7).

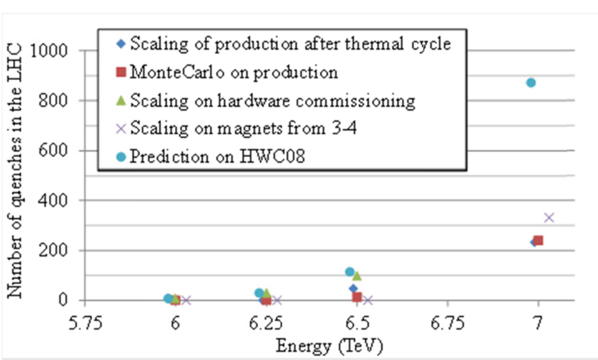

Figure 7: Summary of estimates of needed training in the LHC dipoles to reach 6-7 TeV equivalent energy.

Obviously due to the very limited dataset, the error associated to these estimates is large, but these numbers will be confirmed during the first powering tests starting in June 2014.

Based on these estimates and to limit strong mechanical and thermal stresses in the superconducting coil during a quench, a decision was taken to restart the LHC at 6.5 TeV after the LS1. Based on the operational experience in 2015, it could be decided to push this limit during additional powering tests (e.g. end of run) and whether increase the energy before or after the LS2.

CONCLUSIONS

After a last shift from November 2012 to February 2013 [3], the first long shutdown started on 14th February 2013.

The first activities were the powering tests with the objective to identify possible limitations (other than the splices in the main circuits) on the superconducting circuits of the LHC for the operation at 7 TeV that must be fixed during LS1. These tests were very positive. The warm-up of the 8 sectors of the LHC will be finished by mid-May 2013. The main projects across the accelerator complex have now started, after the powering tests (LHC and in the injectors) and are on schedule after the first 3 months. The progress of the LS1 can be followed with dashboards updated every week [8].

The LS1 is a marathon and will not be all plain sailing but thanks to a solid preparation and to the dedication of many people, crossing the finish line is foreseen for the end of 2014, respecting the LS1 slogan: “Safety first, quality second, schedule third”.

ACKNOWLEDGMENTS

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