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LHC cryogenics – new experience of run with increased beam energy and intensity

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Abstract. After the LHC first long shut down (LS1), when necessary consolidation and maintenance activities were performed on different technical systems, the Large Hadron Collider was progressively cooled down from ambient to operation temperatures from May of 2014. Prior to physics run with increased beam energy to 6.5 TeV/beam, increased beam intensity and modified beam injection scheme, several qualifications and tests affecting cryogenic system have been performed to ensure stable run of the accelerator. New beam parameters were gradually applied to the accelerator, reducing operational margins of cryogenic capacity from previous run. The process optimization and related updates in the control system were applied. This paper will briefly recall the main consolidations performed on the cryogenic system during LS1. The cool down process and behaviour of the cryogenic system during qualifications and tests will be presented. Difficulties and applied solutions during the run will be discussed. The availability and helium losses statistics for full year operation of 2015 will be given.

1. Introduction

The LHC [1] started its operation with beam on 10th September 2008. After 9 days of operation, designed to run at 7 TeV/beam machine experienced a major incident in sector 3-4 stopping the accelerator for one year. The origin of failure was found in the magnet's interconnection, where the electrical resistance of the superconductor exceeded admissible values. After performing the necessary repairs, a measurement method was developed which confirmed the presence of similar but less severe nonconformities in other places of the machine. In order to operate safely, the first LHC run between 2009 and 2013 was performed with reduced beam energy, initially to 3.5 TeV/beam and then to 4 TeV/beam. The first long shut down (LS1) was mainly dedicated to the consolidation of the magnet interconnections to allow for increase of the accelerator energy to nominal value. The second LHC operation period started successfully on 4th May 2015 with beam operation at 6.5 TeV/beam with potential for the energy increase to 7 TeV/beam.

The cryogenic system took advantage from this progressive increase of the beam operation parameters to learn and optimize the system with increasing heat load coming from beam energy and intensity. Figure 1 summarizes the LHC operation periods with temperature profiles over the years from 2007 to 2016.



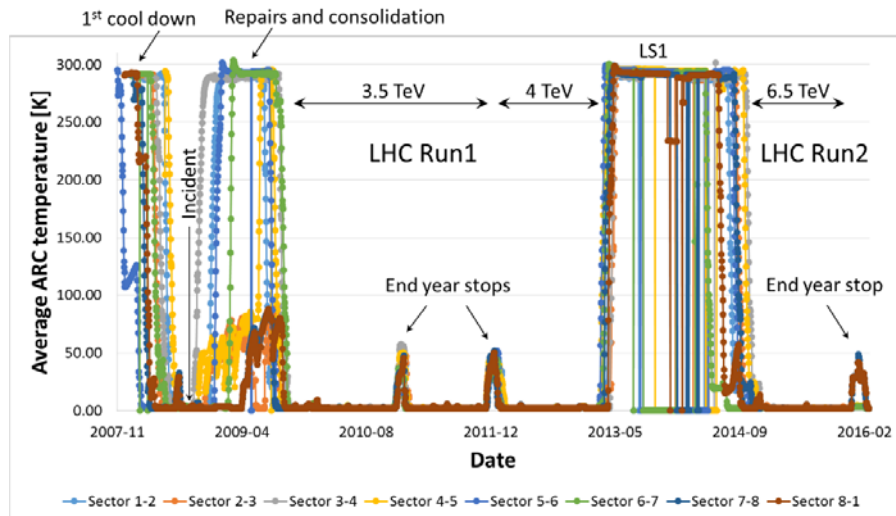


Figure 1. LHC main magnets average temperature evolution (2007–2016).

2. LS1, cool down and preparation for 6.5 TeV run

2.1. LS1 main cryogenic activities

Several activities were performed during the long shut down on the cryogenic system, the main ones are listed below (location of work shown in Figure 2):

- major overhaul of helium screw compressors (after 40000 h of operation) was the most complex activity which required precise logistics with contractor to respect global planning,
- radiation to electronics (R2E) project allowed for displacement of sensitive part of the electrical and control systems in the safe area to avoid further damage by radiation from which equipment suffered during Run1,
- mechanical intervention to repair helium leaks on main refrigerators,
- replacement of deformed compensation bellows on Electrical Distribution Feed Boxes (DFBs) and Cryogenic Distribution Line (QRL) [2].

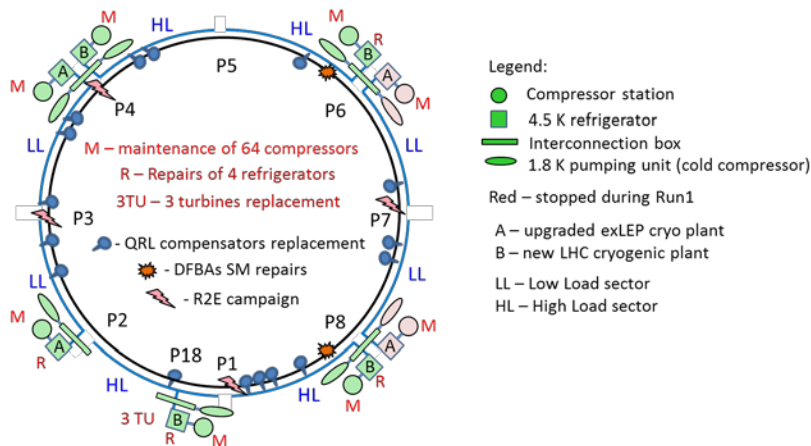


Figure 2. LS1 activities on the LHC cryogenic system.

All nonconformities have been treated in the machine. It is worth mentioning that no Single Event Upset (SEU) was declared during 2015 run after LS1 R2E project.

2.2. *Copper Stabiliser Continuity Measurement (CSCM) test prior to the energy increase*

The LHC superconductors are embedded in copper stabilizer forming the bus-bar. The copper part of the bus-bar takes over the function of the current conductor during a resistive transition. For this reason it is important to ensure that the stabilizer in the LHC electrical circuits has the correct continuity, especially for high current corresponding to run at an increased beam energy of 6.5 TeV. An example of identified non-conformity is presented in Figure 3.

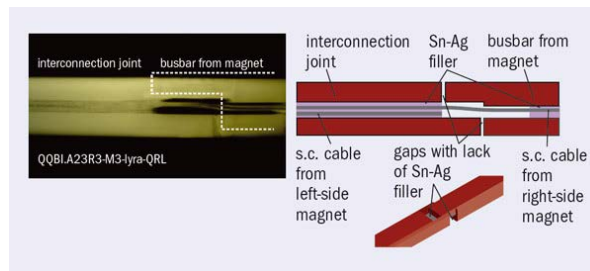


Figure 3. An example of identified electrical interconnection non-conformity.

After LS1, when all non-conformities on the magnet interconnections were treated, the main bus-bars temperature was stabilized at 20 K, and the surrounding helium pressure increased to 4.5 bar. At such condition, out of superconductivity state for NbTi superconductor, the current conduction in energized electrically bus-bar flowed via the copper stabilizer part and investigation on the continuity of the stabilizer was performed.

During the CSCM test cryogenic refrigeration system run at reduced capacity. The main magnet supply line was conditioned at normal operation parameters with supercritical helium. The magnets temperature was adjusted using a standard cold mass cooling loop regulated at an increased temperature level. Some of the cold mass heaters were used to homogenize the temperature of all main LHC magnets.

The CSCM test was performed on all LHC dipole circuits up to the current of 11 kA (corresponding to beam energy of 6.5 TeV) and confirmed correct continuity of the copper stabilizer.

2.3. *Magnets training for beam energy increase*

The increase of the beam energy from 4 TeV (Run1) to 6.5 TeV (Run2) required the magnets to be trained. Prior to the physics run the magnet’s current was progressively increased in all LHC sectors causing several resistive transitions (so-called quenches) of different LHC dipoles. The circuits were considered as qualified when no resistive transition appeared during the current rump and for 2 hours of energization at a level corresponding to 6.55 TeV. Figure 4 presents a global view of the number of resistive transitions that occurred during the training. The increased number of resistive transitions in sector 4-5 was studied but is still unexplained.

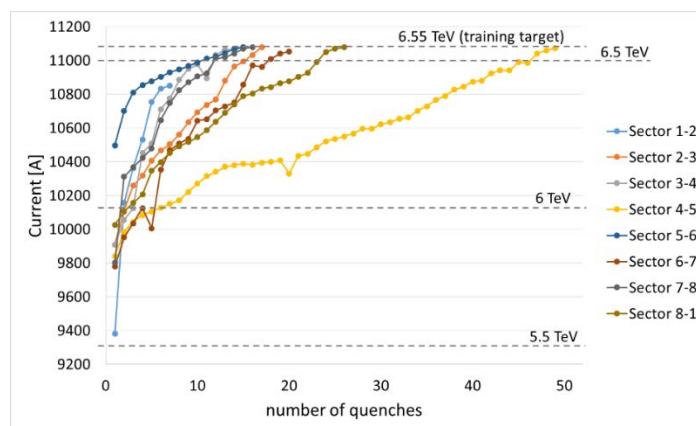


Figure 4. Number of resistive transitions for LHC sectors in function of current (training for 6.5 TeV).

During resistive transitions, the cryogenic system had to cope with abrupt changes of the thermodynamic conditions related to heat deposition to the cold mass superfluid helium bath. In order to protect the magnets from over pressurization, safety valves handled the quench condition by relieving into the return header, preventing the helium pressure in the magnets from exceeding 17 bar. The nearly 3-km long return header acted as a buffer volume for recovered helium. The exit pressure from the header was controlled at 1.35 bar for smooth depressurization, preventing the warm compressor station from stopping, due to a high suction pressure. Figure 5 shows main thermodynamic parameters in the helium volumes of one LHC cryogenic cell for chosen resistive transition and recovery.

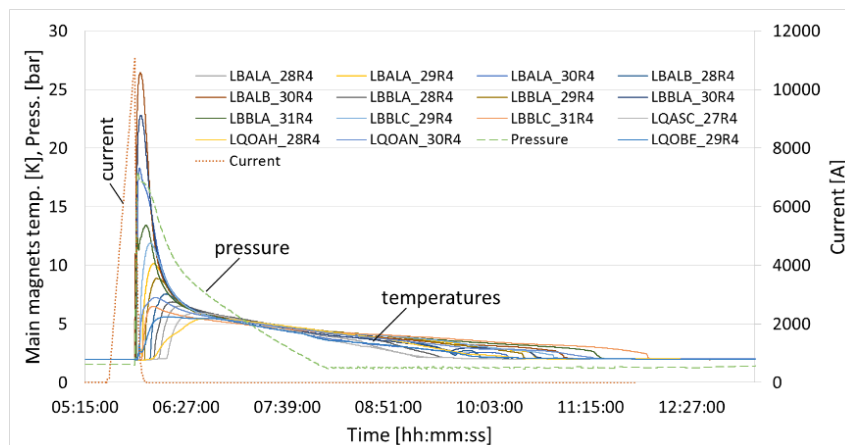


Figure 5. Quench and recovery in sector 4-5 at 11060 A.

3. Operation at 6.5 TeV

The beam induced heat load is deposited on two cryogenically cooled circuits: 1.9 K superfluid helium bath and on 4.5 K – 20 K beam screen circuit. This heat load varies strongly with energy, beam intensity, length of the beam bunches and luminosity in collisions [1].

3.1. Thermal load on the magnet cold mass at 1.9 K

According to the design, nominal cryogenic capacity requirements for heat load evacuation at 1.9 K is 1460 W (for high load sector in steady state operating mode) and installed capacity is 2400 W. The dynamic heat load at 1.9 K comes from contribution of resistive heating in the bus-bar splices and as a beam induced heating [1].

The total cold mass heat load at 1.9 K was recalculated for Run1 and Run2 on sector 1-2 using enthalpy balance method for chosen reference fills 3134 and 4569. The total heat load was equal to 717 W and 878 W respectively and can be expressed as:

$$Q_{HL} = \Delta h \cdot m_{1.8KPU} - Q_{EH} \quad (1)$$

where Δh is helium enthalpy difference upstream J-T valve and downstream the cold mass heat exchanger, $m_{1.8KPU}$ is the flow treated by cold pumping unit and Q_{EH} is electrical power applied on 1.9 K circuit.

The existing capacity margin allowed for optimization of the cryogenic plants operation scenario and use of a part of saved capacity for heat compensation at 4.5 K – 20 K cooling level (see Figures 7, 8 and section 3.3).

3.2. Thermal load on the beam screen circuit 4.5 - 20 K

Increase of the beam energy and intensity with change of operation mode from 50 ns to 25 ns of the inter-bunches spacing had a major impact on the heat load growth.

According to measurements performed during Run2 the photo-electron cloud was not homogeneously distributed in the machine and in some cases it pushed cryogenic plants up to their capacity limits. Applied “scrubbing” (run with beam at injection energy of 450 GeV with the objective to condition the beam pipe for safe acceleration without danger of dump caused by high beam losses or exceeded heat load) was not giving expected cleaning results and it was decided to let clean the machine progressively during the physics run. The cleaning process showed an interesting behavior. Thermally low loaded sectors had tendency to clean faster than high loaded, initial expectation for the cleaning process was inverted. Global view on the beam screen heat load evolution in function of beam parameters is presented in Figure 6 [3].

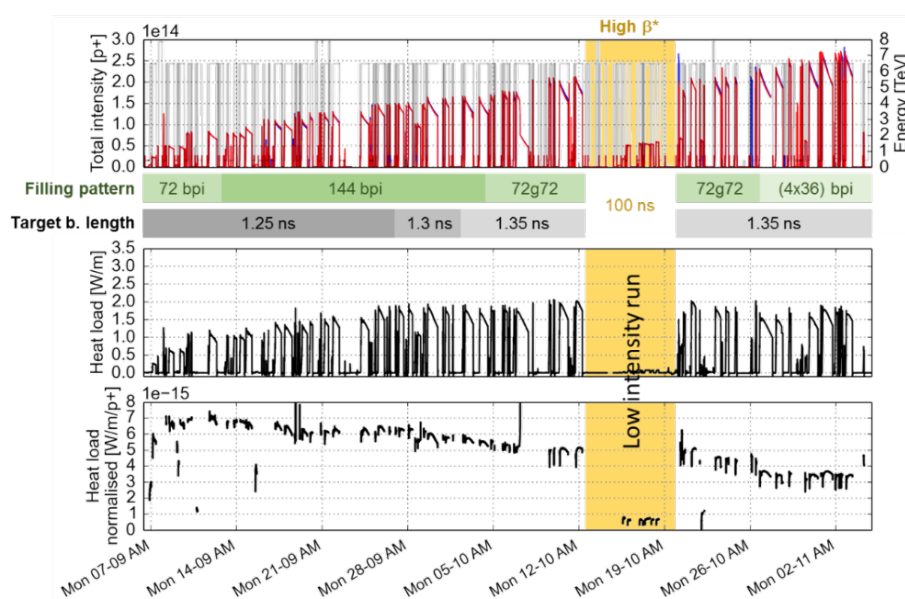


Figure 6. Run2 2015 beam parameters and heat load at beam screen circuit [3].

During the physics run, the thermal effect required from cryogenics fast dynamic response to compensate for increasing beam injection heat load and then large continues requirement for capacity during stable beam operation [4]. To manage the request of fast cooling capacity increase, prior to injection of the beam, a dedicated capacity buffer was prepared in each cold box. Electrical heaters in the phase separators were adjusted at about 1.5 kW to force the cold box to work at high capacity level. While injecting the beam, implemented feed-forward logic increased the flow in local BS loops, the phase separator heaters were gradually ramped down allowing to compensate for dynamic change in global capacity requirements. Then the standard cold box capacity regulation was acting on the system.

Figure 7 summarizes the heat load distribution over the sectors in function of progressively increased beam intensity (units W/hc corresponds to W/LHC half-cell of 53 m long). In some cases, the installed capacity dedicated to beam screen cooling was exceeded. Continuation of the run was possible by recovery of the cold box capacity initially foreseen to be allocated for 1.9 K cooling loop where real heat load was lower than design value (as described in section 3.1). The cleaning effect of high loaded and low loaded sectors is visualized in Figure 7.

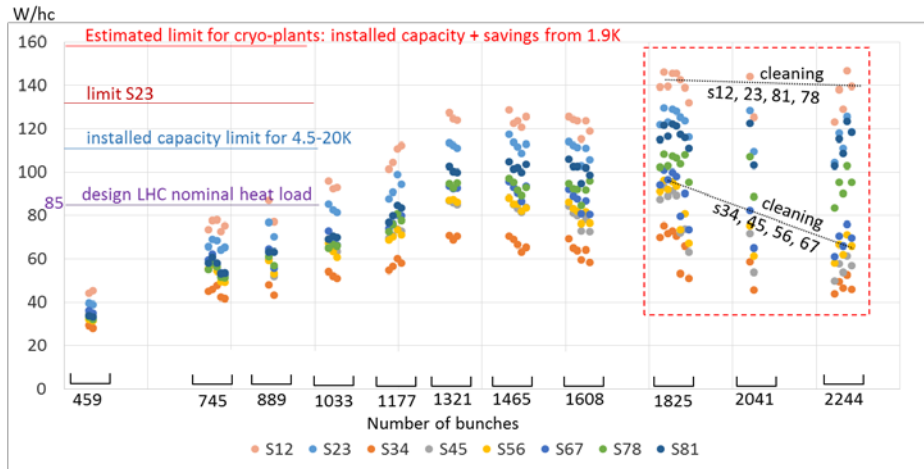


Figure 7. Heat load distribution in LHC sectors vs injected number of bunches.

3.3. Cryogenic operation scenario for Run1 and Run2

First phase of the LHC Run1 allowed gaining of operational knowledge about performance and requirements related to the cryogenic system. The Run1, with beam parameters lower than nominal, allowed LHC operation with disabled cryo-plants A at P6 and P8 (see Figure 8). Thanks to in-built interplants piping the cooling power for both related sectors was provided by plants B. Such configuration allowed to minimize number of operated rotating machines with lowering effect on consumed energy and increasing global availability of the system.

LS1 testing period allowed to validate a new operation scenario for Run2 2015. All 4.5 K refrigerators were in operation to compensate for significantly increased heat load at 4.5 -20 K but 3 of cold pumping units could be kept off.

The next tested operation scenario foresees to stop P18 cold pumping unit for Run2 2016. One of the main motivation for such configuration is that P2 cryogenic plant, which was a limiting plant for global capacity in 2015, will work as an economizer and will be boosted to increase its capacity. All three operation scenarios are presented in Figure 8.

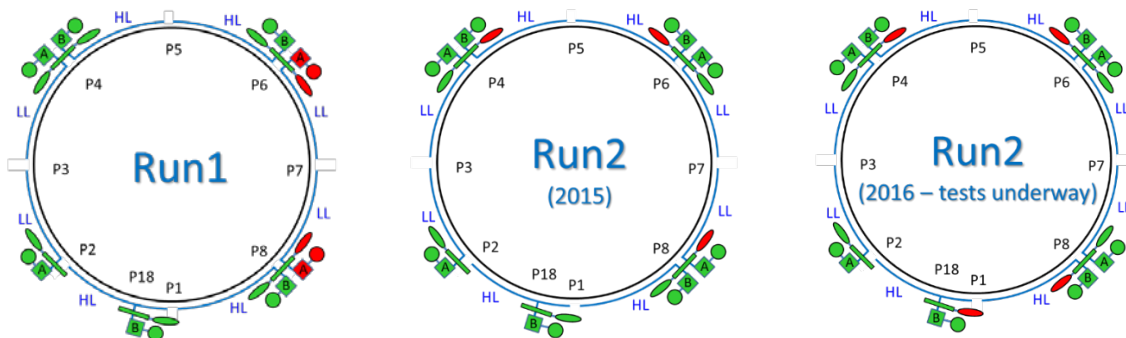


Figure 8. Cryogenic operation scenarios – optimization for Run1 and Run2.

3.4. Availability

Similarly to LHC Run1, presented availability is based on cryogenic interlock signal for maintaining electrical powering in the machine circuits (CM).

Figures 8a and 8b present availability evolution of 1.8 K cold pumping units and 4.5 K refrigerators during Run1 and Run2 for chosen operation scenarios.

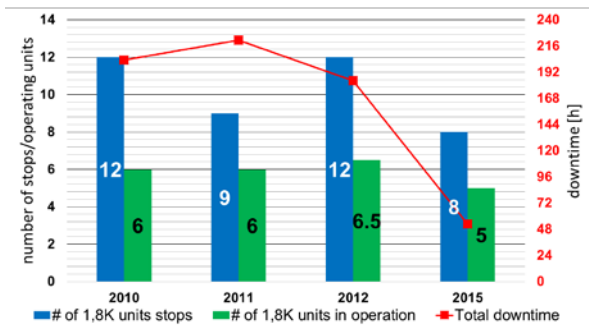


Figure 8a. 1.8 K pumping units reliability.

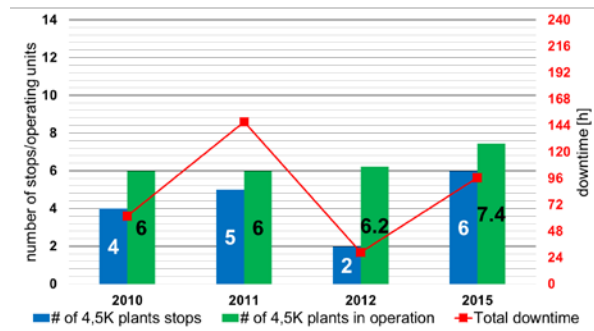


Figure 8b. LHC 4.5 K cold box reliability.

The global availability calculated for 2015 run (from 5th April to 14th December) on the basis of CM signal was equal to 92.1 %. The layout and main contributors for downtime are presented in Figure 9. Comparison with results from Run1 is provided in Figure 10.

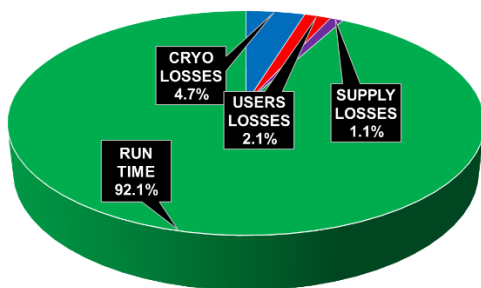


Figure 9. Cryogenic availability 2015.

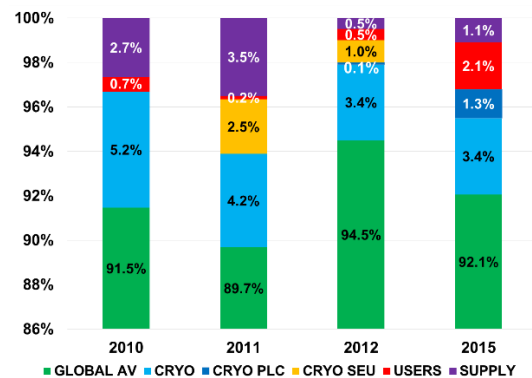


Figure 10. Cryogenic availability 2010 – 2015.

The most time consuming losses were caused by 4 following top contributors covering: PLC failures, cold compressor failures, human factor and electrical/instrumentation failures. The above mentioned 4 types of failures cover 75% of total cryogenic downtime (see Figure 11). The most frequent losses are attributed to Distribution Electrical Feedboxes (DFBs) liquid helium level perturbations caused by degraded quality of supercritical helium as consequence of the failure on refrigerator at P8 as well as to losses of CM signal on DFB(AF) where liquid helium volume is small and CM limits and related regulation should be studied and optimized. The global view on number of CM losses is presented in Figure 12. The most time consuming and most frequent losses are the main subject of study for improvement.

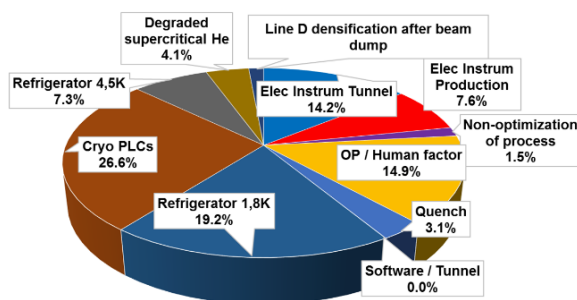


Figure 11. Contribution in down time (2015).

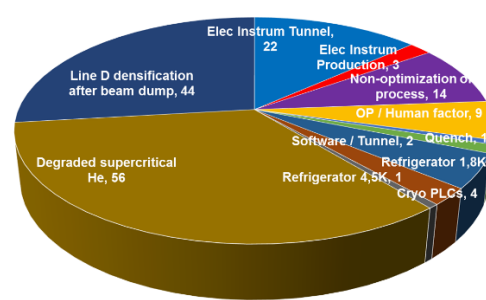


Figure 12. Number of failures (2015).

3.5. Helium inventory and losses

Thanks to collective effort in the cryogenic team during Run1, LS1 and Run2 the helium losses were significantly reduced reaching level of 13% with respect to overall inventory for 2015 run. Figure 13 presents evolution of the helium losses for Run1 and Run2.

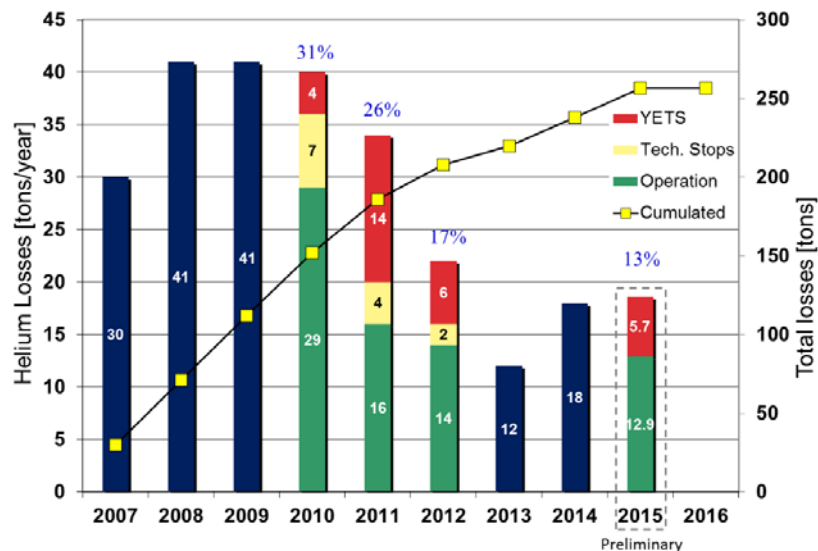


Figure 13. Evolution of helium losses for LHC Run1 and Run2.

4. Conclusions and perspectives

The LHC Run1 with reduced operational parameters allowed for learning and tuning of different technical systems. Main weak points of the accelerator were consolidated during first long shutdown giving confidence for further operation. Dedicated tests and qualifications were performed on the machine prior to Run2 and allowed safe increase of beam energy and intensity with 25 ns operation mode. The heat load on different refrigeration levels was assessed versus beam operation parameters. It confirmed considerably large cooling capacity margin on 1.9 K loop (878 W of the heat load at 6.5 TeV vs 1460 W of nominal heat load and vs 2400 W of installed capacity) as well as no operational margin for beam screen cooling. Such situation was caused by unexpectedly high contribution from photo-electron cloud. For high loaded sectors, the heat load at 4.5 – 20 K exceeded during Run2 the nominal value by nearly factor of 2. Cryogenic plants were pushed to the capacity limits and further process optimization is undertaken for the next operation periods to continue keeping availability on high performance level.

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