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Main improvements of LHC Cryogenics Operation during Run 2 (2015-2018)

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Abstract. After the successful Run 1 (2010-2012), the LHC entered its first Long Shutdown period (LS1, 2013-2014). During LS1 the LHC cryogenic system went under a complete maintenance and consolidation program. The LHC resumed operation in 2015 with an increased beam energy from 4 TeV to 6.5 TeV. Prior to the new physics Run 2 (2015-2018), the LHC was progressively cooled down from ambient to the 1.9 K operation temperature. The LHC has resumed operation with beams in April 2015. Operational margins on the cryogenic capacity were reduced compared to Run 1, mainly due to the observed higher than expected electron-cloud heat load coming from increased beam energy and intensity. Maintaining and improving the cryogenic availability level required the implementation of a series of actions in order to deal with the observed heat loads. This paper describes the results from the process optimization and update of the control system, thus allowing the adjustment of the non-isothermal heat load at 4.5 – 20 K and the optimized dynamic behaviour of the cryogenic system versus the electron-cloud thermal load. Effects from the new regulation settings applied for operation on the electrical distribution feed-boxes and inner triplets will be discussed. The efficiency of the preventive and corrective maintenance, as well as the benefits and issues of the present cryogenic system configuration for Run 2 operational scenario will be described. Finally, the overall availability results and helium management of the LHC cryogenic system during the 2015-2016 operational period will be presented.

1. Introduction

Run 1 operation period from 2009 to 2013 was unique occasion for LHC cryogenics to learn from operation at lower than designed beam energies – initially at 3.5 TeV/beam, then at 4 TeV/beam.
Thanks to the consolidations activities performed during the LHC first long shut-down (LS1) in 2013 and 2014, mainly dedicated to magnets interconnections splices, it was possible to increase the accelerator energy. For Run 2 LHC [1] was then able to operate beams at 6.5 TeV, with potential for energy increase up to 7 TeV, starting from the post-LS1 successful restart in 2015 and up to present day. But increased beam energy and intensity as well as modified beam injection scheme reduced significantly the operational margins of the cryogenic capacity compared to previous run, and required to optimize the process and re-think the overall cryogenic system operational configuration, to cope with the increased thermal load on the beam screen circuit. Figure 1 shows temperature profiles over the years from post-LS1 restart in 2015 to 2017, taking into account the Year-End Technical Stop (YETS) in 2015 (3-month duration) and the Extended Year-End Technical Stop (EYETS) in 2016 (4-month duration).

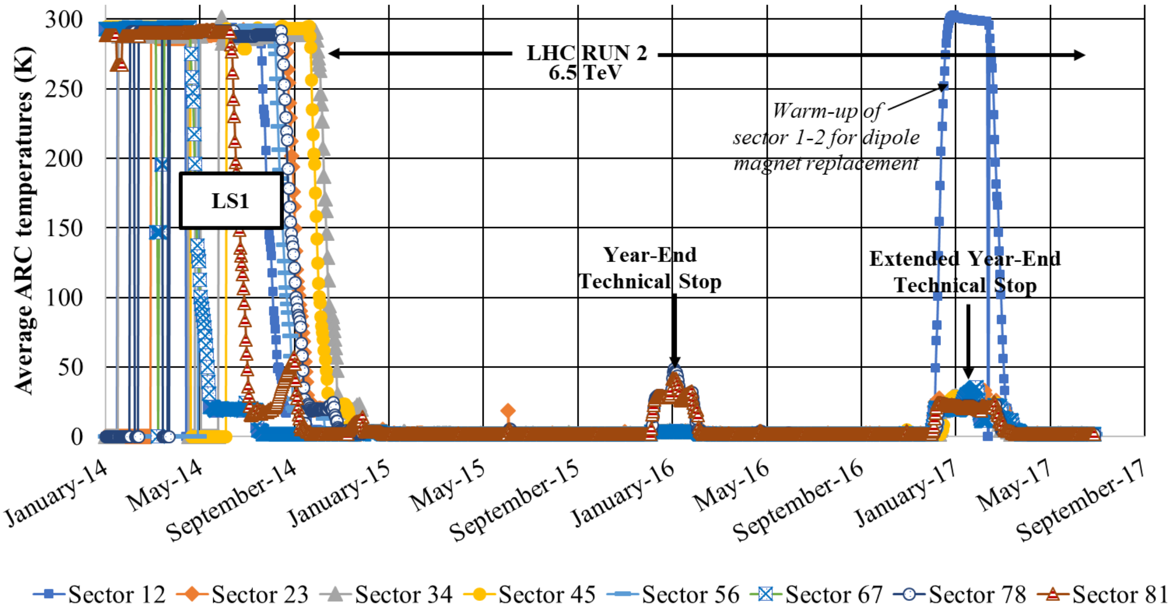

Figure 1. LHC main magnets average temperature evolution (2015–2017).

2. Process optimization and update of the control system

Increased beam-screen heat loads originated from the Run 2 period beams required careful management of the cryogenic cooling capacity in order to maintain the overall system availability.

As the beam induced heat load is deposited on the 1.9 K superfluid helium circuit and on the 4.5 – 20 K beam screen circuit, prerequisites to Run 2 cryogenic operation with these increased beam parameters were to check thermal loads both on magnet cold masses and beam screens [3], before verifying refrigerators which were considered to have the lowest capacity margins [4].

2.1. Beam-induced heat loads

2.1.1. Thermal load on the 4.5 – 20 K circuit and upgrade of the control system. Dealing with the beam-screen heat load (where LHC Design Report required 85 W/half-cell as design capacity and 116 W/half-cell as installed capacity – “half-cell” referring to a LHC cryogenic half-cell of 53 m housing among others one local beam screen cooling loop) originated from the synchrotron radiation, the image current and the electron-cloud effects [2] during the physics run imposed to have a large and continuous global refrigeration capacity with adapted dynamics for heat load increase and decrease during injection and beam dump. This was made possible by preparing a dedicated capacity buffer of 1.5 kW of electrical heating power in the phase separators of the refrigerators, to force them to work at high capacity level [3]. Additionally, new beam parameters required a fast dynamic response that could not be obtained by simple PID regulation loops: two feed-forward actions were added on the electrical heaters and on the valves of each local beam screen cooling loops in the ARCs (the ARC is the region of a LHC sector which contains the main bending and focusing magnets), based on the estimation of the deposited beam screen heat load. This adapted algorithm allowed to use at the best and optimized way the available cryogenic capacity: while injecting the beam, feed-forward logic increased the flow and shut quickly off the electrical heating power in local beam screen loops [4]. The combination of these actions allowed to compensate related dynamic changes in cooling capacity requirements, to stay within the operational boundaries set by the “cryo maintain” interlock temperature of 40 K at the outlet of beam screen loops, and to optimize the refrigeration cycle as the average outlet temperature of beam screen loops respected the nominal setpoint of 20 K. Figure 2 shows the results obtained with the feed-forward logic applied on three LHC sectors and the successful regulation of outlet temperature around 20 K [4].

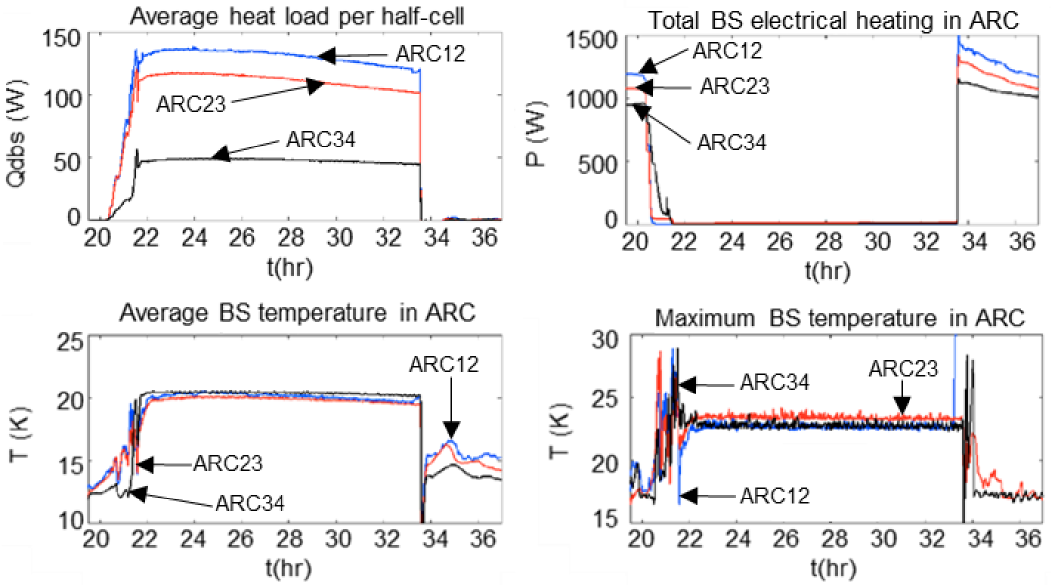

Figure 2. Measurements of LHC beam screen temperatures and heaters using the improved control scheme in November 2015 [4].

The latest improvement performed on the beam screen control system concerns long duration fills, during which feed-forward logic was overcooling the beam screens due to an inaccurate modelling of the heat load, which was not taking into account the existence of an intensity threshold for the electron-cloud formation [7]. In these cases, beam screen heat loads were significantly over-estimated because of intensity decrease due to luminosity burn-off. Introducing this intensity threshold parameter within the feed-forward logic allowed for a better modelling of the heat load decrease during long fills, and an optimized reaction of the cryogenic process.

2.1.2. Thermal load on the 1.9 K circuit. Compared to the design values of cryogenic capacity requirements for high load sectors at such temperature level (namely 1460 W in steady state operation mode and 2400 W as installed capacity), measured heat loads proved to be much lower than anticipated: reference fills for Run 1 and Run 2 gave 717 W (respectively 878 W) in steady state operation [3], thus allowing for the optimization of the cryoplants configuration (see section 2.2.2) and for the partial use of the saved capacity to cope with the increased non-isothermal load at 4.5 – 20 K level.

As the cooling circuits for cold masses and beam screens are both seen by the refrigerators as non-isothermal refrigeration circuits between 4.5 K and 20 K, some capacity re-allocation was possible [2]. Therefore, capacity checks of LHC refrigerators were performed during last extended year-end technical stop (EYETS) in 2017, allowing to assess the cooling capacity that could be transferred from the 1.9 K circuit to the beam screen circuit. Results obtained are still under analysis.

In order to cope with dynamic effect of the heat load deposition on the cold mass originating from particles collisions, feed-forward logic was successfully implemented on 1.9 K regulation loop of inner triplets at interaction points 1 and 5 [6], acting in a similar way to the feed-forward logic of the beam screen circuits cooling loops: at the beginning of collisions, it shut quickly off the electrical heating power of the inner triplets cold mass cooling loops while opening the valves to increase the flow.

2.2. Process optimization and cryogenic system configuration applied for Run 2

2.2.1. Process optimization. As ex-LEP (Large Electron-Positron collider) refrigerators at LHC points 2 and 8 were identified during 2015 operation to have the lowest capacity margins regarding beam-induced heat loads (where LHC Design Report required 7700 W at 4.5 – 20 K as installed capacity for high load sectors and 7600 W at 4.5 – 20 K for low load sectors), preparing the Run 2 imposed to check their capacity and to optimize their process. Cryogenic systems at LHC points 2 and 8 were then optimized with fine tuning at the end of the YETS in March 2016, to cope with the increased beam induced heat loads. This allowed for pushing both refrigerators to their limits: both were aligned with the remaining LHC cold boxes and were able to compensate for 160 W/half-cell of beam-induced heat load, with even small margin kept for sectors stability [6]. Figure 3 depicts the evolution of process parameters during a capacity test performed on former LEP refrigerator at point 8, highlighting a total measured capacity of even 175 W/half-cell, which is slightly above the 160 W/half-cell considered as the installed capacity limit for the 4.5 – 20 K heat load including margin recovered from lower heat-load on the 1.9 K circuit [6], and well above the 85 W/half-cell of design capacity and 116 W/half-cell of installed capacity as stated in the LHC Design Report.

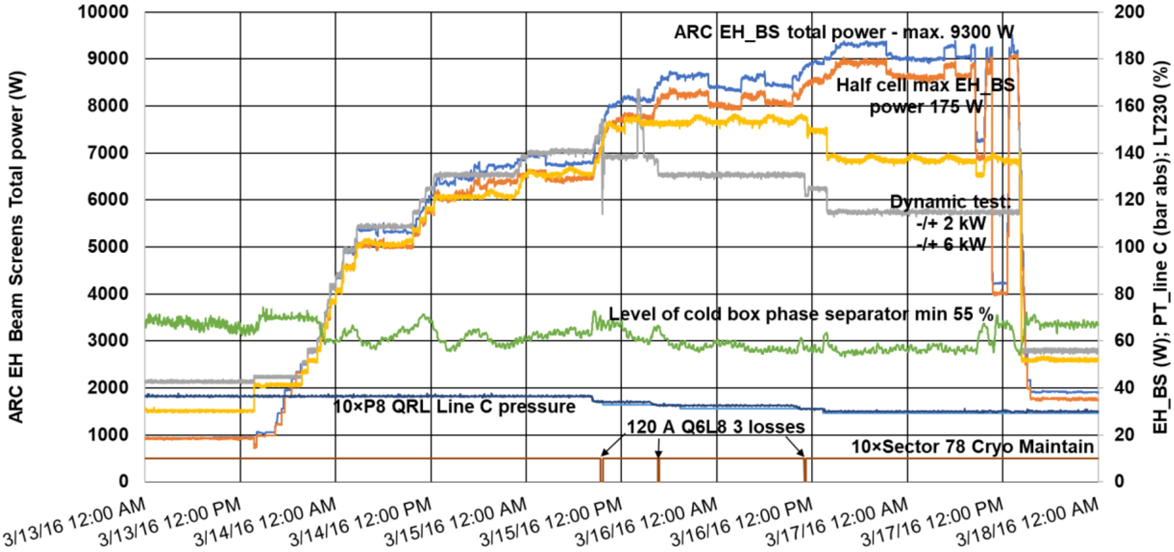

Figure 3. Evolution of process parameters during the capacity test performed on ex-LEP refrigerator at LHC point 8 in March 2016 [6].

2.2.2. Cryogenic system configuration applied for Run 2. While Run 1 allowed for LHC operation with stopped cryoplants thanks to lower than nominal beam parameters, Run 2 increased heat load at 4.5 – 20 K required all 4.5 K cryoplants to be running. However, as heat load on the 1.9 K circuit was lower than anticipated in the design report (see section 2.1.2.), part of the cold pumping units could be kept off, as one of them could cope with the heat load deposited by the beam on the 1.9 K circuit (i.e. on the cold masses) of two sectors, still with some margin left for transients' management (e.g. quenches) [3]. Considering this, Run 2 cryoplants configuration was applied in two steps. First involved the stop of 3 cold pumping units for the 2015 run (in LHC points 4, 6 and 8). Second involved the stop of P18 cold compressor. This allowed for the 4.5 K refrigerator in LHC point 2 to work in economizer mode and have its capacity boosted by unbalanced flow coming back from two sectors. This was made possible by setting up a complex warm gas transfer system to allow both 4.5 K cryoplants of LHC points 2 and 18 to work together despite their different geographical locations. Cryoplant configuration validated in 2016 and currently in operation for the 2017 run is the most optimized one, considering existing and installed hardware. Figure 4 summarizes the different operation scenarios adopted from Run 1 to Run 2 [3].

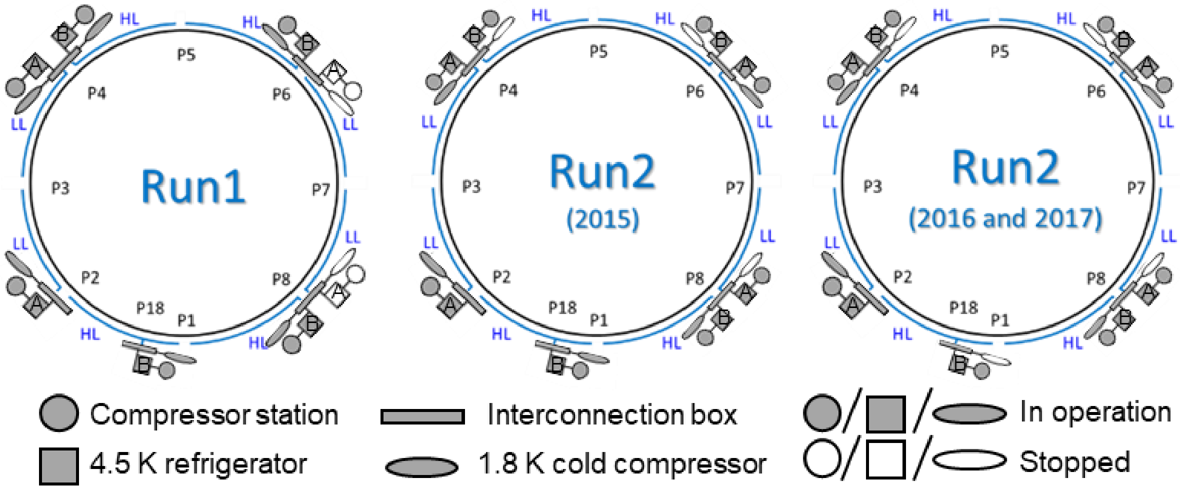

Figure 4. Cryogenic operation scenarios from Run1 to Run2 [3].

3. Results of two consecutive years of operation at 6.5 TeV

Thanks to collective efforts of both cryogenic maintenance and operation teams, 2015 and 2016 showed high availability levels during operation time, those being calculated on the basis of the cryogenic interlock allowing for keeping superconducting magnets electrically powered – the Cryo Maintain (CM).

3.1. Overall cryogenic availability results of Run 2

Run 2 started on April 5th 2015, for an average due operation time to allow for physics with beam of 5800 hours for each year. As 2015 was experienced as a restart year right after the LS1, cryo operation went through a series of failures that were corrected during the technical stops to allow for even better results in 2016. As a direct consequence, reliability of 4.5 K refrigerators and 1.8 K cold pumping units significantly increased from 2015 to 2016. Failure rate for 4.5 K refrigerators decreased from 0.81 to 0.39 per year, with the eight independent cryoplants running. Failure rate for 1.8 K cold pumping units decreased from 1.6 to 0.5 per year, five of them being in operation in 2015 and only four in 2016.

These figures were achieved through systematic analysis and treatment of cryoplant failures thanks to close cooperation between support and operation teams [5].

In addition to cryoplant failures treatment, systematic recording of most time consuming and most frequent losses was done.

For 2015, most time-consuming losses revealed 4 major contributors: PLCs, cold compressors, human factor and electrical/instrumentation failures. They accounted for 75% of the total cryogenic downtime, and were treated accordingly during technical stops. Most frequent losses (60 losses out of 164 in total) were attributed to the cryogenic electrical distribution feedboxes (DFBs) liquid helium level perturbations caused by degraded quality of supercritical helium as a direct consequence of the degradation of the insulation vacuum of one 4.5 K refrigerator at LHC point 8, as well as by oscillations of one DFB liquid helium level beyond Cryo Maintain (CM) thresholds. They were treated by repairing the refrigerator at point 8, as well as by refining CM thresholds and related level regulation of impacted DFB to increase the control loop reactivity and anticipate the DFB level increase after beam dumps.

For 2016, most time-consuming losses revealed 3 major contributors identical to 2015: PLCs, cold compressors and human factor. They accounted for 82.5% of the total cryogenic downtime, and were treated accordingly during technical stops. Focusing on most frequent losses did not reveal any major contributor, as the sharing between them was quite regular for this year.

This approach allowed for producing an accurate statistics which was used to treat most of the cryogenic downtime from 2015 to 2016, as depicted in Figure 5: total cryogenic losses number was reduced by a factor 10 while their related duration was reduced by a factor 4.

CRYO LOSSES		USERS LOSSES		SUPPLY LOSSES		TOTAL LOSSES	
Number	Downtime (h)	Number	Downtime (h)	Number	Downtime (h)	Number	Downtime (h)
164	273.5	**32**	122.3	**7**	61.7	**203**	457.5

2015

2016

CRYO LOSSES		USERS LOSSES		SUPPLY LOSSES		TOTAL LOSSES	
Number	Downtime (h)	Number	Downtime (h)	Number	Downtime (h)	Number	Downtime (h)
16	73.3	**22**	55.5	**7**	163.5	**45**	292.3

Figure 5. Overview of cryo maintain losses origin from 2015 to 2016.

Figure 6 presents the achieved cryogenic availability over the years from Run 1 to Run 2, with preliminary results for the 2017 run. Cryogenic downtime stays in line with previous years. With respect to Run 1, the SEU (single event upset) category was treated during first Long Shutdown of LHC in 2013 thanks to the R2E campaign (radiation to electronics) which allowed for improving overall availability.

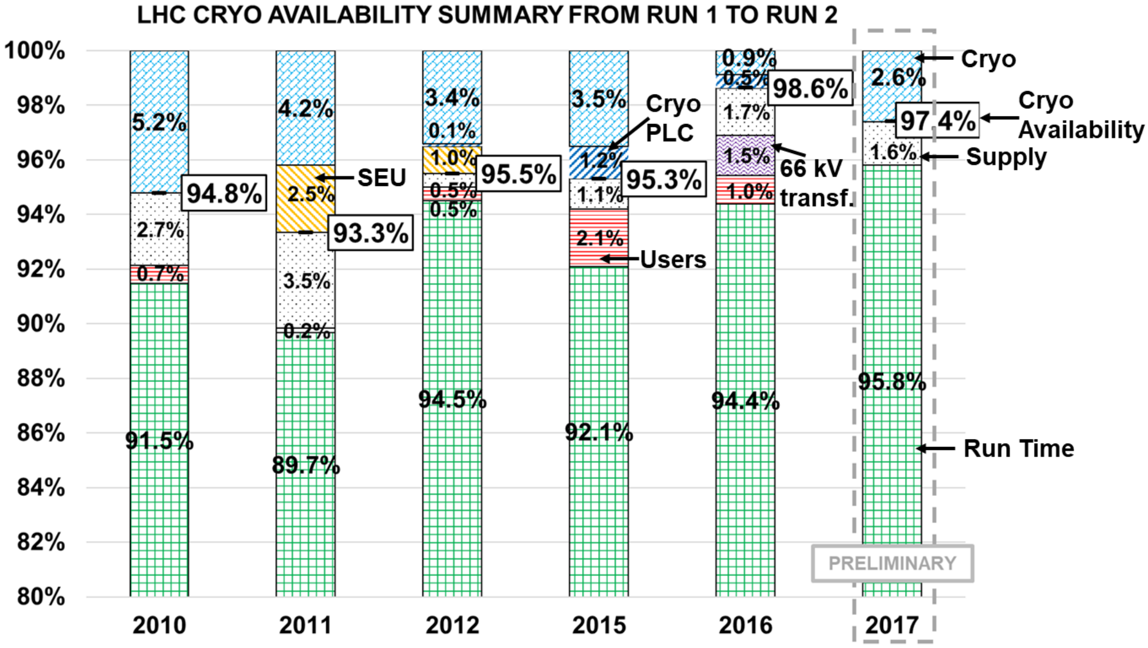

Figure 6. Cryogenic availability over the years from 2010 to 2017.

3.2. Operational management of helium inventory and helium consumptions

During 2015 year-end technical stop, two sectors of the machine (sectors 7-8 and 8-1) were emptied and kept at 20 K while using associated liquid helium storage facility. During 2016 extended year-end technical stop, all sectors were emptied and kept at 20 K, with the exception of sector 1-2 that had to be warmed up to 300 K, because of one dipole magnet replacement in arc cell 31L2. It required the use of external storage: 4 transportable iso-containers of liquid helium were sent to back to industry for external storage for 4 months, for a total of 18 tons. This approach permitted to reduce the format of the needed operation and support teams during this period, and to allocate more time to maintenance. As well, helium losses were even lower in 2016 than in 2015. In addition to the average recurrent losses rate of 900 kg of helium per month, 700 kg of helium were lost per month during the three months of the YETS in 2015, whereas only 600 kg of helium were lost per month during the four months of the EYETS in 2016.

Figure 7 summarizes how the LHC helium inventory is managed by adopting two different helium configurations, considering either operation or extended year-end technical stops.

130 t + **15 t** + **5 t** = **Operation Configuration**

120 t in sectors
10 t in cryoplants
+ storage

Strategic stock

Rotating stock

84 t + **46 t** + **External** = **Year-End Configuration**

LHe (6 dewars at 14 t each)

GHe (all 75 m^3 and 250 m^3 tanks at 18 bar abs)

≥ 18 tons (at least 4 LHe trucks)

Figure 7. LHC helium inventory management

Experience gained by cryogenic operation team from Run 1 allowed for significant reduction of helium losses, thanks to collective effort.

In addition to constant on-line helium inventory follow-up, systematic checks of calculation accuracy were done, allowing for implementing some modification within the calculation model for better estimation of the helium stored in liquid dewars.

As well, systematic checks of gaseous storage facilities and search for helium losses in the ventilation of surface buildings were actions undertaken to reduce these losses. Figure 8 presents LHC helium losses over the past ten years. From Run 1 to Run 2, average annual helium losses rate decreased from 25 % of the total inventory of 130 tons down to 12 %.

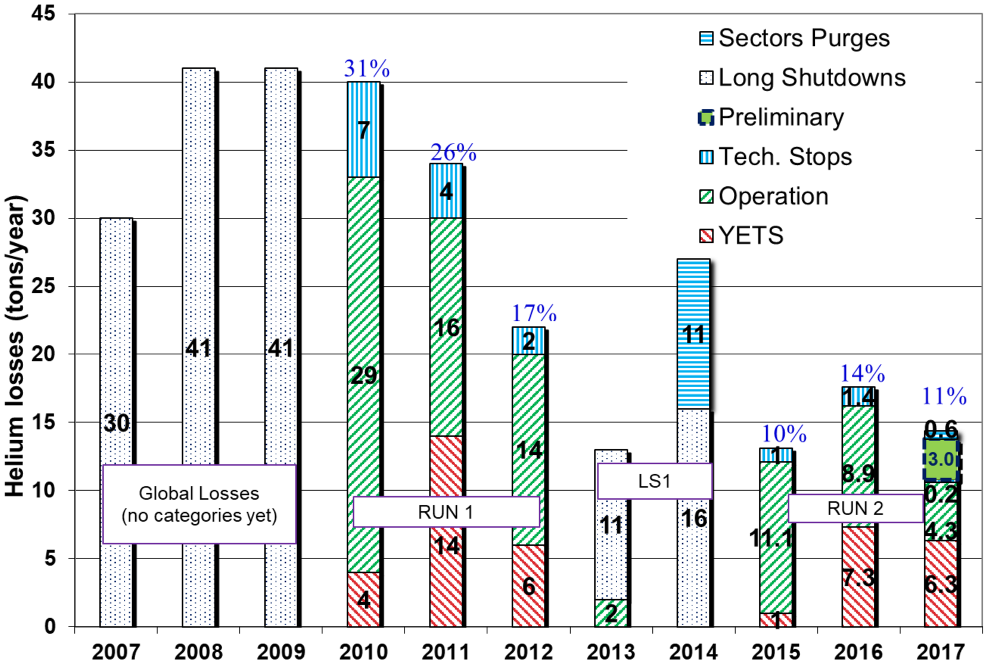

Figure 8. Evolution of helium losses over the ten years of LHC operation.

From the end of Run 1 to Run 2, total recurrent helium losses, which are not accounting for operational consumptions (e.g. sectors purges and conditioning of installations), were even lowered by a factor 2, to reach the average rate of around 3 kg per day of helium for one running cryoplant, as depicted in Figure 9.

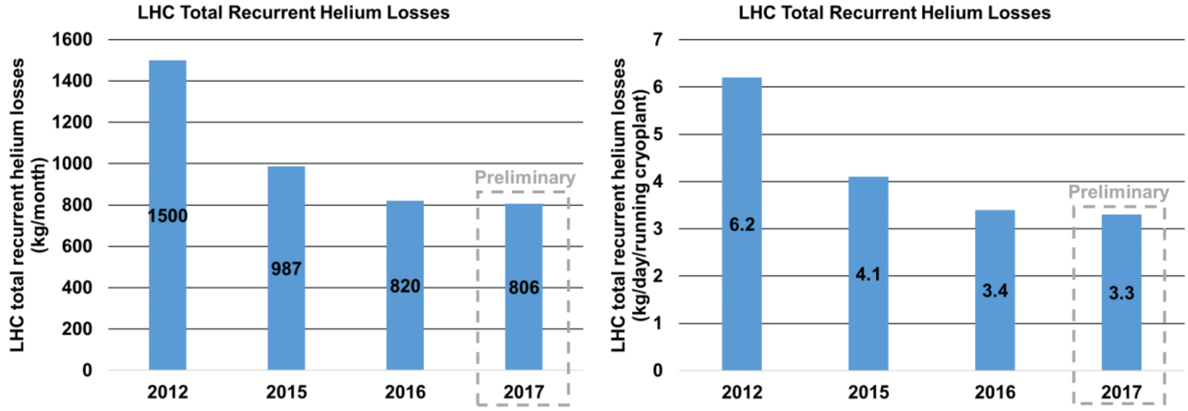

Figure 9. LHC total recurrent helium losses from Run 1 to Run 2.

4. Conclusions and perspectives

Experience gained from Run 1 operation and consolidations performed during LHC first Long Shutdown (LS1) allowed for safe operation with increased beam energy and intensity during Run 2. Large margin of the cooling capacity was confirmed on the 1.9 K circuit [3], where 1582 W of isothermal cooling capacity at 1.9 K could be saved on the cold box level and used for cooling of the beam screen circuit. To cope with excessive beam screen heating, cryoplants were successfully pushed to their limits, while the control system was upgraded with feed-forward action implemented on 1.9 K and non-isothermal 4.5 – 20 K cooling loops to compensate for dynamic heat load coming from new beam parameters.

In order to maintain the high availability level of the cryogenic system during the 2017 and 2018 runs two improvements are being undertaken. Results of the capacity optimization test checks are still under analysis to evaluate the existing margin in the overall beam screen cooling capacity. This approach shall allow for practical evaluation of the existing global margins on the refrigerators. In the meantime, upgrade of the feed-forward action on beam screen individual cooling loops will be tested to act individually on each of them. This shall allow a better distribution of the global cooling capacity to the local cooling loops and by consequence an optimization of the cryogenic process.

5. References

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