CRYOGENICS EXPERIENCE DURING RUN2 AND IMPACT OF LS2 ON NEXT RUN

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Abstract

The first part of the presentation will summarize the overall cryogenic performance and availability for Run2. Main evolutions and effects on the cryogenic system during Run2 will be presented. The second part will focus on the LS2, in particular the main maintenance and evolutions engaged. We will present their expected effects on the global availability on one hand and their expected influence on the cryogenic limitations with respect to the required cooling power during Run3 on the other hand. Finally, we re-formulate the expected cooling power limitations taking into account the balance between 1.9 K cooling power used for Inner Triplet and 4.5-20 K non-isothermal cooling power used for Beam Screens.

CRYOGENIC PERFORMANCE AND AVAILABILITY FOR RUN2

The LHC Run2 lasted 4.5 years . The LHC physics Run2 ended in December 2018 but the Cryo system will be locked only after full accelerator warming-up to room temperature (May 2019). Figure 1 shows the temperature evolution of cold masses during the whole Run2.

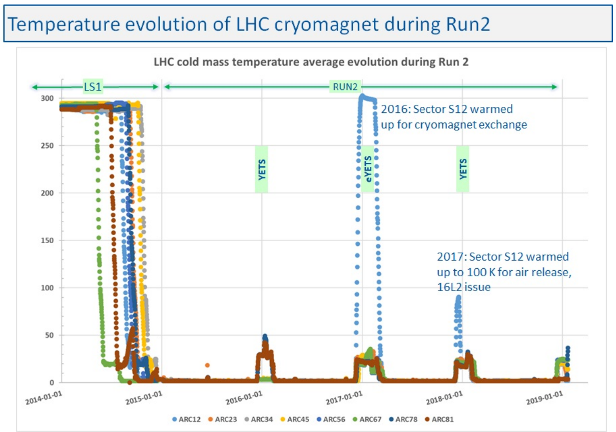


Figure 1: Temperature evolution of LHC during Run2

LHC Cryo availability from Run1 to Run2

The LHC overall cryogenic availability has evolved positively over time. During Run1, single event upset (SEU) problems and utility issues had a direct impact on availability. Multiple upgrades and interventions during LS1 had solved a majority of the issues found during Run1. Figure 2 shows the LHC Cryogenic availability since the beginning of Run1.

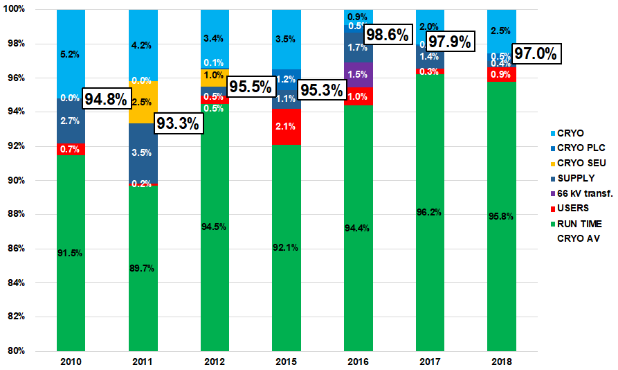


Figure 2: LHC-availability-overall Run1-2

Run2 operational time distribution vs availability

Since Run2, the running time distribution all along the year shows in average 15 days allocated for maintenance, 118 days allocated for cold stand by and beam commissioning. The remaining 232 days (5500 hours) are assigned to LHC physics production. LHC Cryogenic availability refers to this period. Whereas Cryogenic facilities must be operational during 8400 hours. Figure 3 shows the allocated time distribution for Cryogenic equipment.

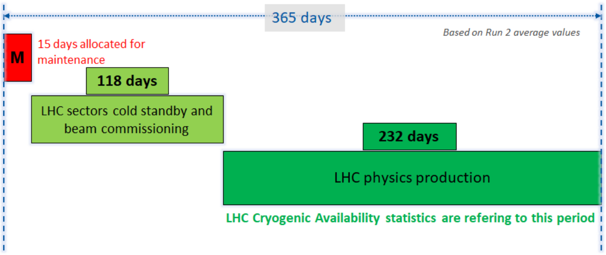


Figure 3: LHC Run2 allocated time

During YETS period, every Cryo island must keep the two associated sectors in cold standby. For this purpose, only one cryoplant is stopped during 15 days for maintenance and the second one is taking care of the two sectors. Then the two installations are swapped for a new 15 days period. We must note than no major intervention is possible on the components remaining cold.

From cryogenic equipment point of view, Run2 duration of 4.5 years is in the limit range of 40000 running hours for equipment. This long period is in the high range of the Mean Time Between Maintenance (MTBM) of the equipment. To summarize, the Run2 duration is the maximum acceptable limit for current equipment compatible with an overall availability in the range 97 to 98%.

A more detailed analysis shows, undermentioned, the major issues during Run2.

During the year 2015, a major helium leak in the insulation vacuum of a P8 cryoplant has generated a poor quality of supercritical helium. The direct consequence was more than 60 CryoMaintain losses mostly linked to DFB liquid helium level stabilization.

In parallel, our equipment had to face multiple issues on the electrical hardware, 24 VDC and instrumentation used for the Cold Compressors units. These problems has been mainly solved during the 2015 YETS.

Weasel issue (1.5% of availability), PLCs and utilities issues have dominated year 2016 issues. These issues were partially solved during eYETS but it was technically not possible to exchange all PLCs. Remaining former PLCs will finally be exchanged during the LS2.

The year 2017 was the best year of the run with very good cryo availability (98.6%).

During the year 2018, several problems of software communication, electromagnetic sensitivity and instrumentation coupled with recurrent clogging of Cold compressor inlet filter have decreased the cryo availability. CRYO team faced also one cold compressor major fault that required the exchange of the faulty cartridge for repair in the manufacturer premises, however without major impact as the second available unit came in operation.

All these issues not yet solved will be addressed and will drive priorities definition for action in the LS2 consolidations.

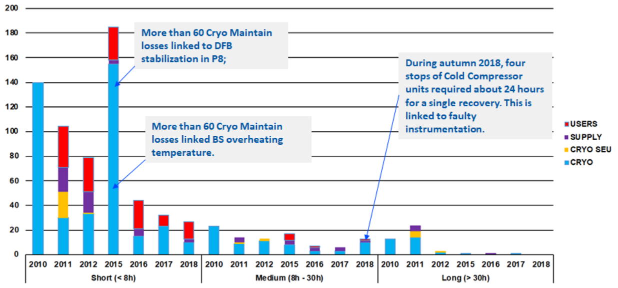
Figure 4 shows the statistical distribution of the duration of stops during Run1 & Run2. We can note, for year 2015, more than 120 stops related either to poor quality of supercritical helium or Beam screen overheating. Beam screen overheating has generated short losses of CryoMaintain, about minutes. However, this triggers a complete pre-cycle with a duration of interruption of the order of one hour. During autumn 2018, four stops of Cold Compressor units required about 24 hours for a single recovery. Excessive recovery duration (12 hours) is mainly linked to drifting or faulty instrumentation. An aging effect linked to the impossibility to exchange/calibrate instruments during entire run 2 explain the problem.

LHC cryogenic helium balance

Figure 5 shows helium consumption overview from Run1 to Run2. We should expect losses in the order of 10% of the helium inventory per year. This must be considered as a floor value, difficult to improve despite a permanent follow-up and close investigations for leaking circuits.

Main control logic evolutions during Run2

Throughout Run2, Beam Induced Heat Load (BIHL) increased in parallel with the increase of beam intensity. This heat load is mostly deposited on the Beam Screens. A new process control method has been deployed and tuned all along Run2. This method use the Feedforward (FF) control concept based on the real time calculation of the BIHL according to the beam parameters.



More than 60 Cryo Maintain losses linked to DFB stabilization in P8;

More than 60 Cryo Maintain losses linked BS overheating temperature.

During autumn 2018, four stops of Cold Compressor units required about 24 hours for a single recovery. This is linked to faulty instrumentation.

Figure 4: Statistical distribution according to the duration of the stops

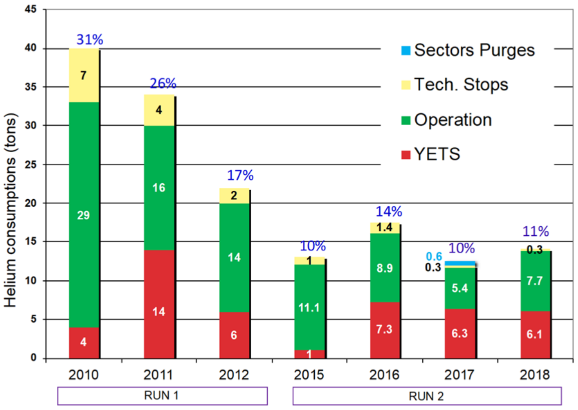


Figure 5: Helium balance overview over Run1 & 2

At first, during 2015, the FF control parameters was set using common parameters for Beam Screen (BS) valves of arc & IT.

Then during eYETS 2016, FF common control loops has been installed for BS heaters of arc & IT. In parallel, FF individually adjustable were deployed on heaters and valves of BS circuits used for standalone magnets. Results were good enough to trig the use of the same concept for all BS control loop. The updated software has been deployed during YETS 2017. This has been concomitant with the increase of the BIHL during year 2018. This final deployment is considered as highly successful and will be maintained for the Run3. Table 1 shows evolution, all along Run2, of the control parameters from traditional Feedback control to the individualisation of the FeedForward.

In parallel, the control team has implemented a double action on High Load (HL) Inner Triplet temperatures when collisions start (loss of CS/CM) thus avoiding important transients. These actions consists to thermally pre-load inner triplets using electrical heaters when collisions are not yet present (200 W / IT) and on the other hand to apply a Feedforward control loop, based on ATLAS/CMS luminosity

Table 1: Main beam screen control logic evolutions

	Run 1 (2008-2012)	**Run2 (2015)**	**Run2 (2016/2017)**	**Run2 (2018)**
ARC + IT Valves	FB	FB+Common FF	FB + Common FF	FB + Indiv FF
ARC + IT Heaters	FB	FB	FB + Common FF	FB + Indiv FF
SAM Valves	FB	FB	FB + Indiv FF	FB + Indiv FF
SAM Heaters	FB	FB	FB + Indiv FF	FB + Indiv FF

FB = Feedback Control / FF = Feed-Forward Control / Common FF = same QBS estimation for all half-cells

signals, to drive the cooling valves. The combined answer is efficient and is validated up to a luminosity of $2^{34} cm^{-2} s^{-1}$.

The support control and electricity team conducted SVC immunity investigations. The aim was to understand the ghost spike that appear randomly on the P2 cold compressor unit. A solution will be deployed during LS2. With the same approach, a new CERN designed process control prototype for Linde Cold Compressors unit has been successful validated at the end of the Run2.

Finally, a complete review of the interlocks and safety chains used on cryo refrigerators has been done during year 2017 to solve recurrent issues and optimize interlocks vs availability. The aim was to avoid unnecessary cryoplant stops linked to over specified safety chains. Prototype software has been updated during YETS-2018 and validated in 2018 at P4 & P6 (one prototype per cryoplant generation).

MAINTENANCE & CONSOLIDATIONS PLANNED DURING LS2

Major overhauling & refurbishing

A long stop type LS is always shared in several phases. Some of these phases, such as warming-up and cooling-down of the sectors, are not compressible. In facts, every Cryoplant is stopped for major maintenance during less than 10 months. During this period, around sixty warm Helium compressors and as many 3.3 kV electrical motor will be sent to manufacturer premises in Europe, for major overhauling. In parallel around eight cold compressors cartridges will also be sent mainly in Japan for major maintenance.

The electrical cabinets used on the former four LEP Cryoplant Helium compressors stations reached their obsolescence and are causing many stops. Their rebuilt is foreseen during LS2 with the present state of the art equipment.

A major upgrade with new hardware models for Active Magnetic Bearing Controller and Variable Frequency Drive is foreseen. In parallel, the original local PLC delivered by the Cold Compressors supplier will be replaced with new PLC (CERN model). The SVC immunity will be reinforced on all Cold compressors systems.

More globally, the “standard” maintenance plan, constituted of 4000 preventive and 500 corrective work orders, will take place during this period.

Control logic upgrade & optimisation

The feed-forward action for the Beam Screen and Inner is now stable. Only fine re-tuning will be necessary at the beginning of Run3.

Taking into account the tests performed at the end Run2, an upgraded revision of the Cold Compressor CERN designed software will be deployed. The aim is to minimize duration and increase the reproducibility of the 1.9 K pumping sequences.

During Run2, some full stop of Cryoplants occurred, linked to a poorly calibrated interlocks and inappropriate safety chains. After deep analysis, some of them appears inadequate in LHC configuration. An upgrade has been validated on 2 cryoplants in 2018 and will be deployed on the 6 other cryoplants during LS2.

The mass flow distribution over the sectors during 1.9 K pumping phase is not optimised. Some new scripts are under development and will be deployed to automatically optimise the mass flow distribution.

Many operation sequences are manually driven. The purpose of this upgrade is to automatize selected sequences such as the warming-up of former LEP cryoplants, the full warm-up/cool-down of LHC sector. It is also foreseen to partially automatize the Quench recovery sequence to help operator during the 500 training quench recovery sequences foreseen at the end of LS2.

LHC Cryo data analysis foreseen for Run3

The Cryogenic Operation team has developed in 2018 an automatic scan (“Ronde”). This bot drives 320 jobs analyses among thousands signals over the LHC cryogenics every night. All potential problems are automatically published on the `http://CryoDataAnalytics.web.cern.ch` with corresponding trends.

The same scheme is applied to analyse the beam screen heat load profiles in instrumented half-cells after every beam dump.

Figure 6 shows abnormal heat load detected in 11R2 during Ion Run, Nov. 2018.

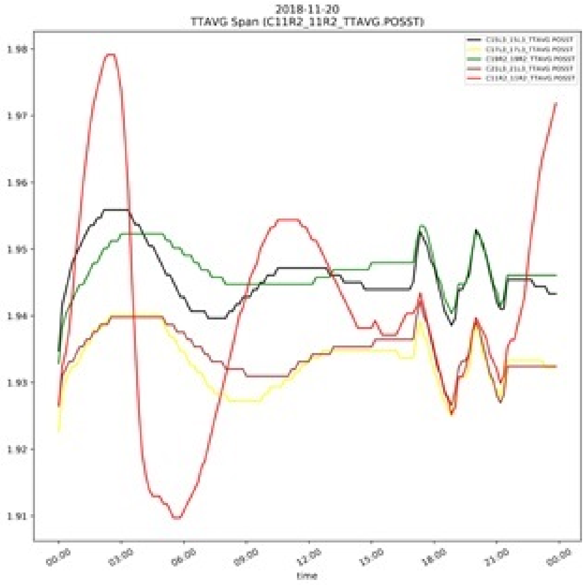


Figure 6: Abnormal heat load detected in 11R2

RUN 3 EXPECTED COOLING POWER LIMITATIONS

Beam induced heat load on Beam Screen @ 4.6-20K

From the beginning of run 2, it quickly became obvious that the beam induced heat loads would exceed the installed capacity of 7600 W for low load sectors and of 7700 W for high load sectors. This overload problem has been addressed by modifying the LHC filling scheme to cope with this maximum acceptable thermal load. On the other hand, CRG team has worked to re-allocate available thermal power recovered thanks to low thermal load at the level 1.9K to the non-isothermal level 4.6-20 K.

Figure 7 shows the Beam Induced Heat Load [BIHL] according to the LHC design report and highlights Run2-2016 extra load over the maximum limits.

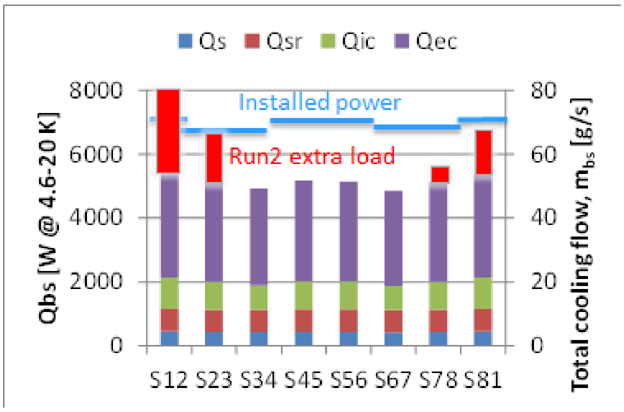


Figure 7: Beam Induced Heat Load according to LHC design report

Figure 8 shows the BIHL distribution for two typical sectors (low & high load sector) versus time during Run2-2016. It appears clearly, than BIHL are higher than values, defined in design report for non-isothermal level 4.6-20 K.

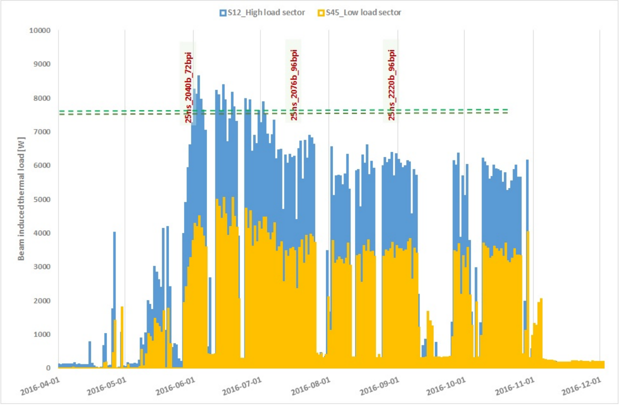


Figure 8: BIHL for two typical sectors

Beam induced heat load on Inner Triplet @ 1.9K

The second major limitation of the cryogenic system is the extraction of the dynamic heat load deposited by the experiments on the triplets (debris of colliding particles). Following the initial pressure test failure, the decreased diameter installed heat exchanger is able to extract 270 W of dynamic load to which we must add the equivalent of 40 W of static thermal load.

Figure 9 shows the cooling principle of the Inner Triplet [IT].

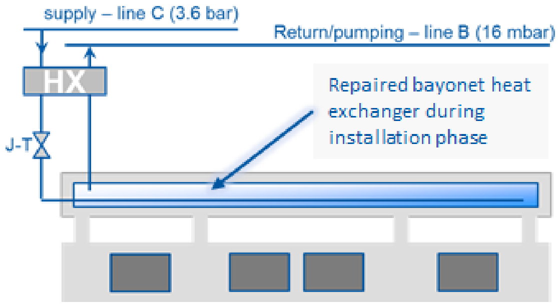


Figure 9: cooling principle of the Inner Triplet

Recent tests demonstrates that there is no operating margins by storing energy (Helium Temperature increase in the triplet). The origin is the saturation of the HX with bi-stable behaviour.

Figure 10 shows measurements performed during Run2 to quantify the maximum dynamic thermal load that it is possible to extract on high load IT (P1 & P5). An anomaly has been observed for ITR5 due to a valve non-conformity: This will be addressed during LS2.

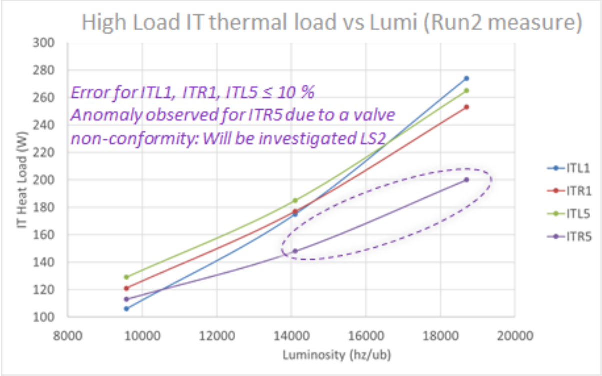


Figure 10: High load Inner triplet extracted power

Combined global cooling power of Beam Screen and Inner Triplet

Thanks to the build-in interplant connections, an adapted configuration makes it possible to transfer the 1.9 K cooling power refrigeration margin to the non-isothermal refrigeration level of 4.6-20 K.

Figure 11 shows the configuration adopted during the Run2 (2017/2018). This configuration is considered as the master configuration for the Run3.

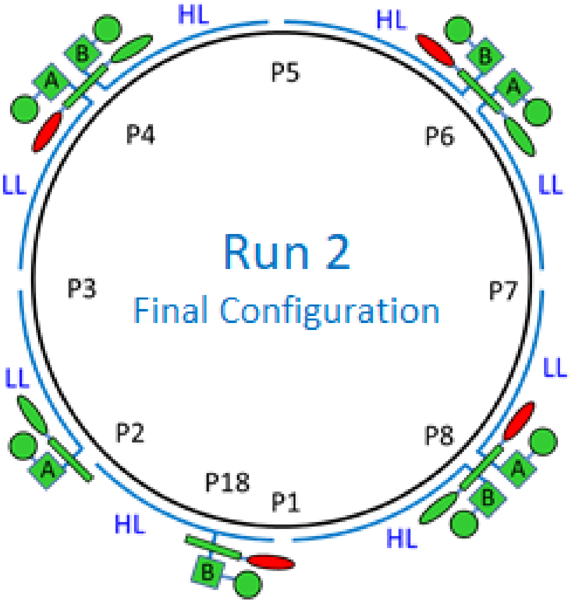


Figure 11: Cryogenic configuration during Run2-2018

Combined global cooling power of Beam Screen and Inner Triplet

For the following chapter, as the two levels of refrigeration are mixed in the cryoplant, we will synthetize by using the combined global cooling power data of Beam Screen and Inner Triplet.

The maximum guaranteed capacity for s1-2 BS cooling was measured as 200 W/half cell. The measurements done in configuration of physics run 2017, for fill 5979 (configuration applied for 2018 operation identical to configuration 2017). In case of ITR1 operation with 270 W for 1.9 K cooling loop (maximum guaranteed cooling capacity at 1.9 K) the related guaranteed capacity for BS cooling will be 195 W/half cell.

Table 2 summarize the combined global refrigeration power available for the cooling of beam screen half-cell together with the 1.9 k cooling power required for Inner Triplet. Sectors 4-5, 5-6 and 6-7 has been measured after Evian 2019 workshop and are updated according to these measurements. This summary is valid for the end of Run2 and for Run3. The capacity values are depending on beam operation scenario. These capacity values will have to be reviewed for Run4 and later.

Table 2: Combined global refrigeration power

Sector	**Capacity [W/hc]**	**conf 2017 [W/hc]**	**Global ref. [W/IT];[W/hc]**
S1-2	180*	200	270;195
S2-3	195	205*	
S3-4	125	145*	
S4-5	180	200*	270;195
S5-6	240	260*	270;255
S6-7	175	195*	
S7-8	175	195*	
S8-1	230	250*	270;245

* *Recalculated value, contingency of 10 W/hc*

CONCLUSIONS & PERSPECTIVES

Cryogenic capacity for ITs at P1 and P5 is limited. The guaranteed value for dynamic heat load compensation was measured and is equal to 270 W (306 W for total heat load). With such capacity, based on a simplify scaling law, the luminosity could be increased up to an equivalent Lpeak=2.2e34 Hz/cm2 for 6.5 TeV and Lpeak=2.05e34 Hz/cm2 for 7 TeV.

Five sectors over eight were measured. Sector 3-4 shows the capacity of 125 W/half cell while sector 8-1 has 230 W/half cell (design configuration). Developed Feed-Forward control logic allows for BS heat compensation in local cooling loops for any applied beam parameters injected up to now to the machine (for physics).

The experience gained during Run1 and Run2 was used to optimize the non-isothermal refrigeration capacity @ 4.6-20 K that is well beyond the Design Report. In particular the refrigeration capacity transfer from the 1.9 K level to 4.6-20 K has been developed and put into service while maintaining an overall availability definitively superior to Run 1. This configuration has demonstrated its ability to adapt to the current maximum thermal load and will be used during Run3.

The global combined refrigeration capacity shall be considered as the limit for future runs of the machine. However the overall situation will be updated by the HL-LHC cryogenic upgrade at P4 (LS2) and the implementation of two new cryogenic plants at P1 and P5 in LS3.