LHC CRYOGENICS – PERSPECTIVES FOR RUN2 OPERATION

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Abstract

The first period of LHC cryogenic operation between 2008 and 2013 allowed gaining practical knowledge about the machine operational behaviour. The cryogenic system operation scenario for Run1 was defined and set regarding minimization of potential failures and energy consumption. Tuning of the cooling power in local cooling loops was adjusted according to the requirements for the heat extraction.

The Long Shutdown 1 (LS1), started on the beginning of 2013, allowed for maintenance, upgrade and necessary repairs on the LHC cryogenic installation focusing on preparation for post LS1 accelerator run.

In order to provide required cooling power, configuration of the cryoplants for Run2 will be set differently than for Run1, the available margins will change. The constraints imposed by beam-induced heating during scrubbing run or normal Run2 have been analyzed.

In case of installation failures, the critical spare components management will allow for direct replacement of faulty elements of the installation in most adapted time. The mitigation of failures can be also done by cryogenic plants reconfiguration, in some cases with impact on LHC beam operation scenarios.

INTRODUCTION

The cryogenic infrastructure built around LHC ring is composed of 8 cryogenic plants supplying 8 related LHC sectors. Four of the plants were upgraded from LEP cryogenic system and are supplying low load sectors, and four of them have been installed as new for LHC and are supplying high load sectors [1] (see Fig 1).

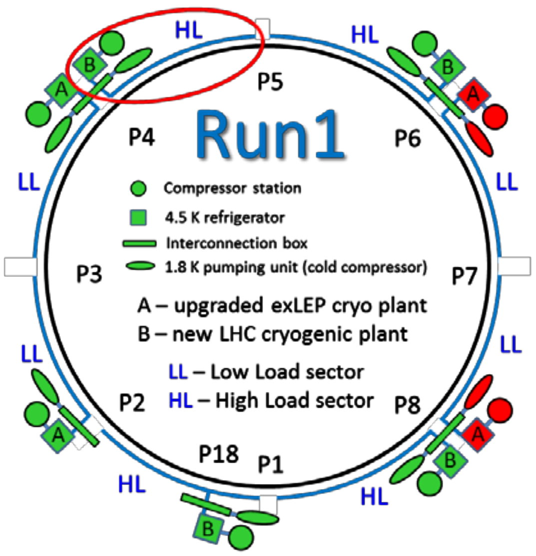

Figure 1: LHC cryogenic infrastructure.

The helium refrigeration process is ensured by considerable number of rotary machines (64 screw compressors, 74 expansion turbines and 28 cold compressors). The system provides cooling power for the magnets, RF cavities and DFBs with their 1258 current leads. The related control system drives ~4000 PID loops and consists of nearly 60000 I/O signals.

LHC RUN1 SUMMARY

The LHC Run1 allowed gaining operational knowledge about performance and requirements related to the cryogenic system. The Run1, with beam parameters lower than nominal, allowed for LHC operation with disabled cryoplants A at P6 and P8 (see Fig.1). The cooling power for both related sectors was provided by plants B. This configuration allowed for electrical power savings over all 3 years of operation between 10 and 20% with relation to the installed power (see Fig.2). The negative aspect of the configuration was longer recovery time at P6 and P8 after the failures. Such configuration was not applied nor at P4 because of additional heat load coming from RF modules neither at P18 because of non-standard configuration of the plants.

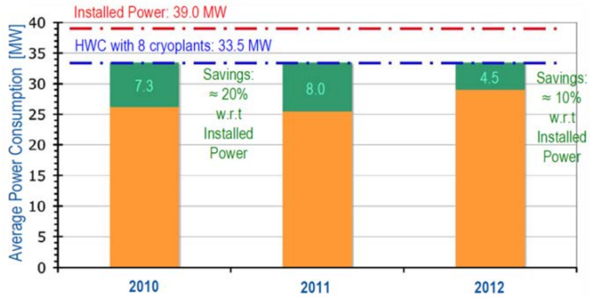

Figure 2: Power consumption and savings during Run1.

Thanks to collective effort in the cryogenic team the helium loses were reduced by factor of ~2 during 3 years of operation (see Fig. 3).

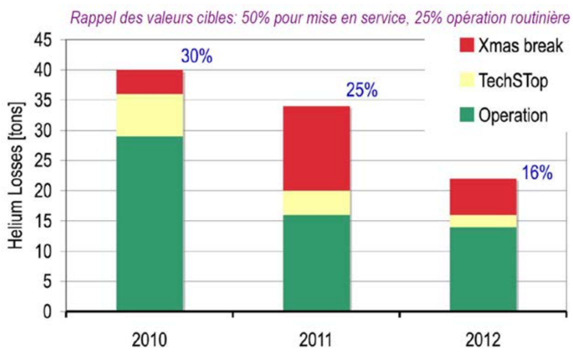

Figure 3: Helium losses reduction during Run1.

The cryogenic global availability for first 2 years of Run1 was equal to about 90% (see Fig 4). The significant impact of single event upset (SEU) was noted during increase of beam parameters in 2011. The problem of SEU and utilitiy failures were treated for last year of Run1 alowing to raise up the global availability to ~95%.

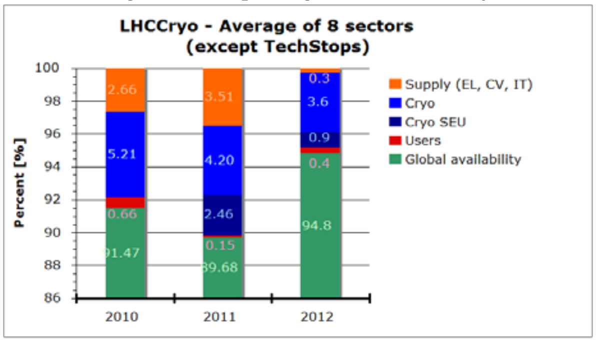

Figure 4: Cryogenic availability – Run1 summary.

MAIN LS1 ACTIVITIES

During LS1 multiple activities were performed on the cryogenic system. The main of them are listed below (see Fig. 5):

- The maintenance work was done on all helium compressor stations (major overhaul of the compressors and electrical motors),
- 4 leaks were repaired on 4.5 K refrigerators, the leaks have been declared during Run1 and warm up before LS1,
- 16 leaky QRL bellows were replaced, the leaks have been declared during the warm up before LS1,
- 2 DFB's gimbal bellows were replaced, the bellows were found deformed during the LS1 inspection,
- R2E campaign was performed in 4 LHC places to avoid excessive radiation to electronics during future LHC runs.

Also many other smaller activities, not visible on the large scale, were performed during LS1 with aim to higher the machine reliability.

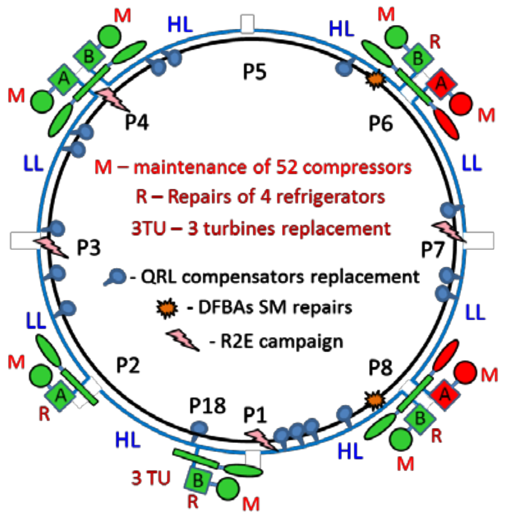

Figure 5: Main activities on cryogenic system during LS1.

RUN2 OPERATION SCENARIOS AND POSSIBLE REDUNDANCY

In order to guarantee required heat extraction from LHC during Run2 the baseline for cryogenic system operation scenario is to run all cryogenic plants (see Fig. 6).

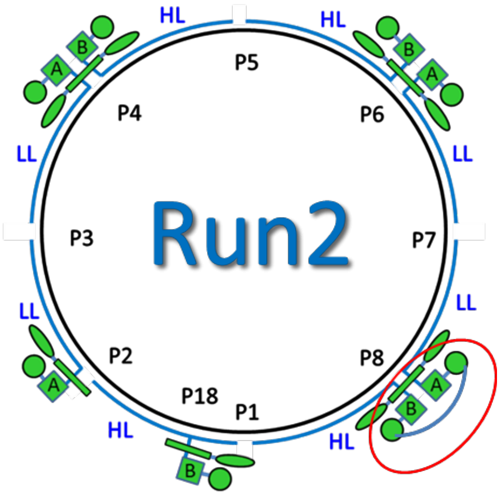

Figure 6: Baseline for LHC Run2 operation scenario.

Compressor station possible redundancy

Thanks to installed inter-piping connections between the cryogenic plants, the compressor stations A and B at P4, 6 and 8 can be linked together to profit from the existing helium flow global margin in case of any compressor failure (see P8 on Fig. 6 and Fig 7).

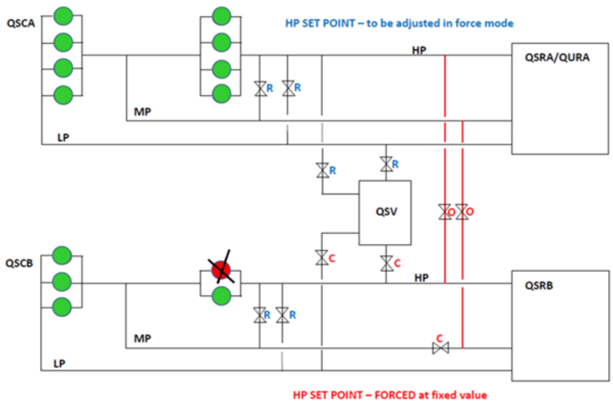

Figure 7: Configuration of linked compressor stations.

More difficult situation is at P18 and P2 where replacement of the faulty compressor has to be considered (except P2 low pressure stage). The available flow margins on low pressure stage (LP) and high pressure stage (HP), considering the biggest compressor lost, are presented in Fig. 8 (the analysis is done for the case of nominal cold box refrigeration capacity). The spares for each type of the compressors and related electrical motors are available at CERN storage and are ready to replace the faulty machines when needed.

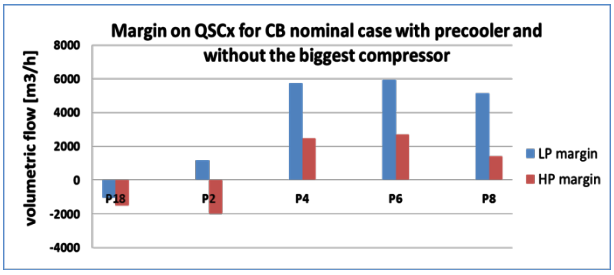

Figure 8: Helium flow margins for compressor stations.

Main LHC 4.5K refrigerators

The most fragile parts in the main LHC cryogenic refrigerators are the rotary machines – turbines. The analysis of possible redundancy and spare parts management lead to identify 3 categories of the turbines regarding associated criticality in case of failure. An example of the analysis for AirLiquide refrigerator is presented in Fig. 9.

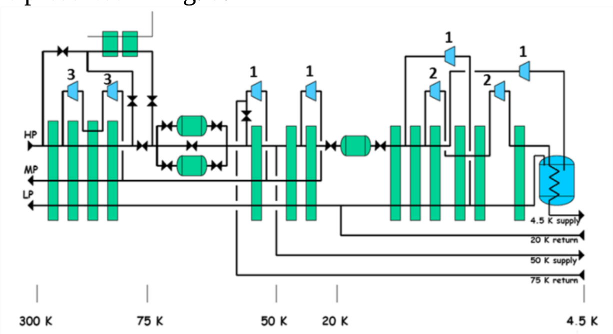

Figure 9: Air Liquide QSRB – turbines criticality.

- Category 1 (high criticality): Operation without the turbine results in a considerable loss in refrigeration power. All types of this turbines category are covered with available spares in CERN storage.
- Category 2 (moderate criticality): Operation without the turbine is possible with a moderate loss in refrigeration power. All types of this turbine category are covered with available spares in CERN storage.
- Category 3 (low criticality): Operation without this turbine is possible with nearly no loss in refrigeration power as the refrigeration power loss can be compensated with LN2. The special contracts signed with the suppliers allow for this turbine category repairs within 4 weeks while normal repair delay can take up to a few months.

Cold compressors – 1.8K pumping units

There are two types of 1.8 K pumping units installed on LHC. One of them is equipped with 3 and other with 4 cold compressors. The cold compressor is the most fragile part of the unit. The run of the unit without even one compressor is not possible, so in case of failure the faulty compressor has to be replaced to allow further operation. All types of the compressors are covered by a spare available in CERN storage.

However, behaviour of the LHC machine shows lower than expected thermal load at 1.8 K. This fact let to presume that operation of two sectors with one pumping unit running together with two 4.5 K refrigerators should be possible during Run2 (see Fig. 10). The proposed scenario was never set up for operation and is to be tested before Run2. The operation in such configuration will require longer recovery times in case of failures but could be considered as a redundancy if needed.

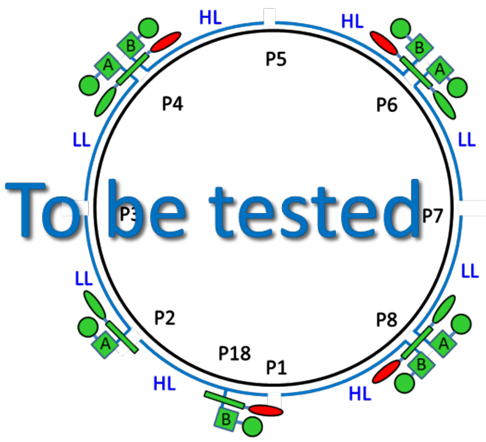

Figure 10: Run2 optional scenario with one pumping unit for 2 sectors.

Cryogenic plant major failure

In case of the major failure of a cryogenic plant at P6 or P8 the operation of the LHC will be possible with reduced beam parameters setting configuration from Run1 (see Fig. 11). Loss of cryoplant A has less impact on the cryogenic power than loss of cryoplant B.

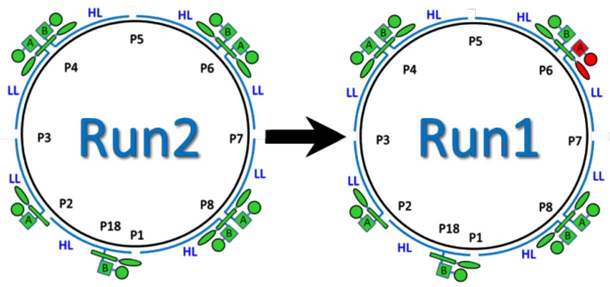

Figure 11: Example of operation scenario in case of cryoplant A loss at P6.

NON CONFORMITIES

There are currently two known non conformities present in the cryogenic system. Both concerns helium leaks specified below:

- Sector 8-1, internal leak on QRL header D, rate of 1.6 E-6 mbarl/s @ 10 bar, 1.4 E-7 mbarl/s @ 1 bar, localization at Q24R8 at dcum 24455 m,
- Sector 1-2, internal leak on QRL header C, rate of 1.7 E-5 mbarl/s @ 10 bara, pre-localized at ~Q13L2

QUENCHES AND RECOVERY

Until now experience for quenches recovery with current above 6.5 kA comes from before Run1 quench training campaign (already 5-6 years ago). The LHC Run1 experienced some "easy quenches" without opening of the quench valves (QV), with pressure rise in the cold mass below 15 bars. The analysis of the recovery after quenches was presented during Chamonix Workshop in 2009. The updated analysis combined with presented in Chamonix graph is shown in Fig. 12.

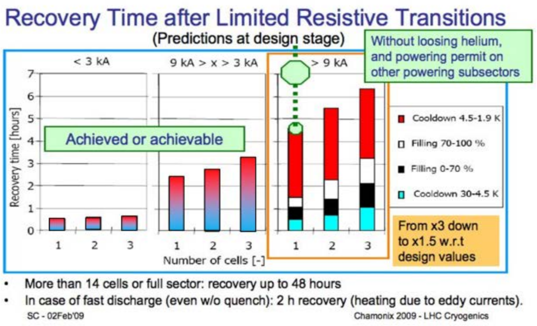

Figure 12: Recovery after quenches

Any quench occurred up to now on the LHC installation did not cause helium loss from the cryogenic installation. In case of opening of the QVs (quenches above 6.5 kA) the helium lost from the cold mass volume was recovered as foreseen in the system. New learning with quenches and recovery will be the subject of future experience for Run2 during the magnets training.

RUN2 BEAM PARAMETERS – CRYOGENIC MARGINS AND LIMITS

The detailed analysis of the beam induced heating was presented during Evian Workshop in December 2012 [2]. This chapter will summarize the work done during LS1 to upgrade the system and will present key values for margins and limits for the refrigeration power.

ARC, SAMs and ITs beam screen circuit

The analysis of scrubbing runs (December 2012) shown e-cloud heat deposition measured on beam screen circuits (BS). The curves in Fig. 13 show topology of the heat deposition with existed before LS1 limitations on specific BS cooling loops.

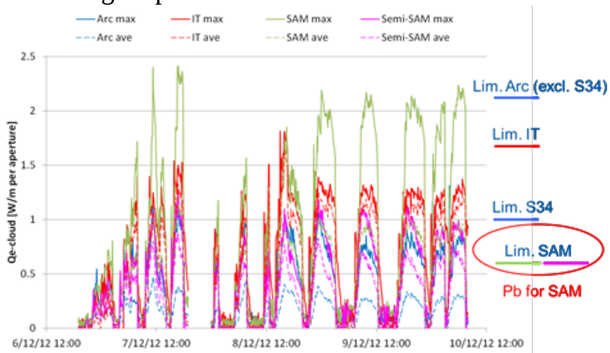

Figure 13: Scrubbing run heat deposition.

The hydraulic limitations on local cooling loops of the beam screen had to be upgraded on SAM and semi-SAM magnets over the accelerator length (38 valve poppets were replaced during LS1). The upgrade was applied also on arc section in sector 3-4 where the cryogenic valve poppets were replaced to go back to the level of cooling capacity equal to the other sectors. The present local limitation for beam scrubbing on all BS cooling loops is about 2 W/m per aperture (see Table 1).

Table 1: Old and new local limitation on BS circuits.

Inventory		Length [m]	Local limitation (BS cooling loop and valve): CV kvmax [m3/h] Old	CV kvmax [m3/h] New	Qbs max [W/m per aperture] Old	Qbs max [W/m per aperture] New	Qbs 25 ns 2015 [W/m per aperture]	Remaining for beam scrubbing [W/m per aperture] Old	Remaining for beam scrubbing [W/m per aperture] New
SAM Type 1	Q5R1 Q6R1 Q6L5 Q5L5 Q6R5 Q6R5 Q6L1 Q5L1	8.2	0.02	0.06	1.0	2.4	0.4	0.6	2.1
SAM Type 2	Q6L4 Q6R4 Q5L6 Q4L6 Q4R6 Q5R6	6.9	0.03	0.06	2.3	3.9	0.5	1.8	3.4
	D3L4 D3R4	11.2	0.03	0.06	1.5	2.4	0.3	1.1	2.1
	Q6L2 Q6R2 Q6L3 Q6R3 Q6L7 Q6R7 Q6L8 Q6R8	12.0	0.03	0.06	1.4	2.3	0.3	1.1	2.0
	Q5L2 Q5R2 Q5L8 Q5R8	13.0	0.03	0.06	1.3	2.1	0.3	1.0	1.8
Semi-SAM	Q5D4L4 D4Q5R4	16.7	0.05	0.1	1.6	3.2	0.5	1.1	2.8
	D2Q4R1 Q4D2L5 D2Q4R5 Q4D2L1	19.4	0.05	0.1	1.4	2.8	0.4	1.0	2.4
	Q4D2L2 D2Q4R2 Q4D2L8 D2Q4R8	22.8	0.05	0.1	1.2	2.4	0.4	0.8	2.0
IT	ITL1 ITR1 ITL5 ITR5	35.0	0.26		5.7		3.3	2.4	
	ITL2 ITR2 ITL8 ITR8	45.0	0.26		4.4		2.5	1.9	
Arc halfcell	S12 S23 S45 S56 S67 S78 S81	53.5	0.39		2.4		0.3	2.1	
	S34	53.5	0.22	0.39	1.3	2.4	0.3	1.0	2.1

The upgrade allows for full distribution of available refrigeration power moving the limits from local cooling loops to the limit on global refrigeration power. Taking into account equal distribution of the available refrigeration power the new limitation for beam scrubbing will be 1.6 W/m per aperture (see Table 2).

Table 2: Old and new local limitation on BS circuits.

	Global limitation (Cryoplant) 25ns 2015: Qbs max	Qbs 25 ns 2015	Remaining for beam scrubbing
kW per sector	14.8	5.3	9.5
Average W/m per aperture	2.4	0.9	1.6

The distribution of the heat load on the BS and available cooling power for all sectors is presented in Fig. 14 (Qs – static heat load, Qsr – synchrotron radiation, Qic – image current, Qec – electron cloud).

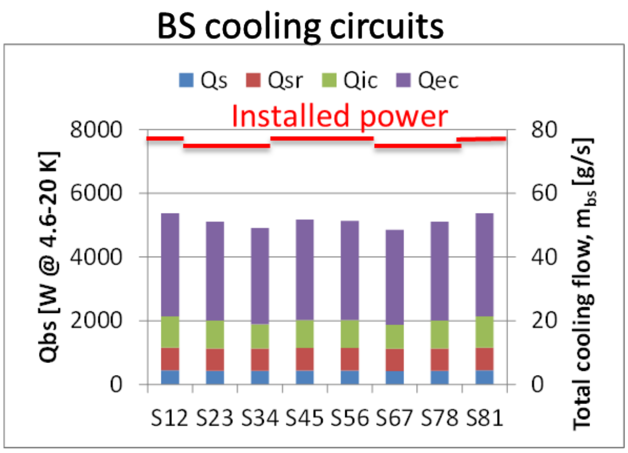

Figure 14: BS heat load and available cooling power.

Heat deposition on the cold mass

The LS1 allowed also for relocation of the braids on all concerned ITs which were wrongly installed before Run1. The local margin on refrigeration power with relation to the luminosity of 1.00E+34 is equal to 1.75 (for details see Table 3).

Table 3: Limitations on ITs cold masses.

	Run 3134					25 ns 2015	50 ns 2015			
Nb [p per bunch]	1.52E+11					1.15E+11	1.60E+11			
nb [-]	1374					2760	1380			
E [TeV]	4					6.5	6.5			
L [Hz/cm2]	6.70E+33					1.00E+34	1.00E+34			
	Qs [W]	Qrh [W]	Qbgs [W]	Qsec [W]	Total [W]	Total scaled [W]	Total scaled [W]	Locally installed [W]	Local margin [W] 25 ns 2015	Local margin [W] 50 ns 2015
Arc cell	18	2.3	2	0.0	23	27	26	90 (1)	63	64
DS cell	25	1.9	2	0.0	29	33	32	140 (1)	107	108
ITL1	60	0.6	0.6	60	121	208	208	320 (2)	112*	112*
ITR1	52	0.6	0.6	60	113	200	200	320 (2)	120	120
ITL2	110	0.6	0.8	0.0	111	113	113	140 (1)	27*	27*
ITR2	50	0.6	0.8	0.0	51	53	53	140 (1)	87*	87*
ITL5	50	0.6	0.6	60	111	198	198	320 (2)	122	122
ITR5	47	0.6	0.6	60	108	195	195	320 (2)	125*	125*
ITL8	80	0.6	0.8	3.6	85	86	86	140 (1)	54*	54*
ITR8	46	0.6	0.8	3.6	51	52	52	140 (1)	88*	88*

Lmax compatible with local margin: 1.75E34

(1): limited by sub-cooling heat exchanger
(2): limited by bayonet heat exchanger (IT)
*: could be jeopardized by NC braid

The distribution of the heat load on the whole sector cold mass and available cooling power for all sectors is presented in Fig. 15 (Qs – static heat load, Qrh – resistive heating, Qbgs – beam gas scattering, Qsec – secondary particles).

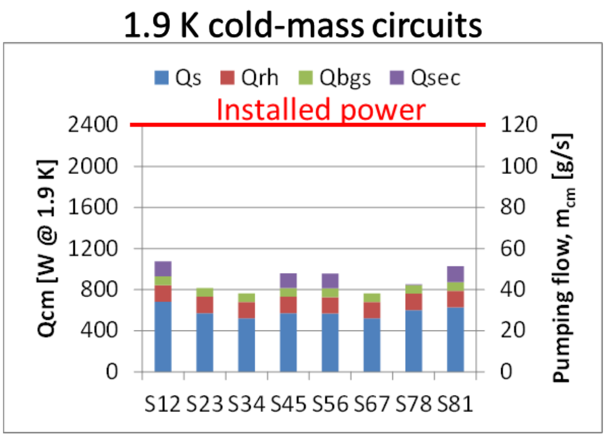

Figure 15: cold mass heat load and available cooling power.

Regarding global heat load coming from the BS circuit and cold mass circuit the available margin is either 1800 W for additional cold mass cooling or 9000 W for additional BS heat load. The representation of global margin for each sector is shown in Fig. 16 combining loads coming from BS and cold mass presented in Figs. 14 and 15.

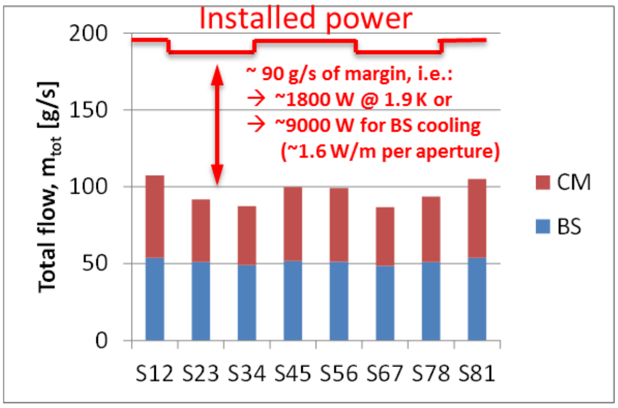

Figure 16: Global cooling margin

CONCLUSIONS

Gained great experience during Run1 allowed operating cryogenic system nearly to 95% of availability during last year of operation. The helium losses were reduced by factor of 2, down to ~22 tons/year. Large LS1 campaign is underway for maintenance, upgrade, repairs and consolidation of different subsystems and components of the LHC cryogenics. Applied study on spare parts and possible redundancies gives good sense of efficient machines operation during Run2 minimizing potential down time. The introduced upgrades on the BS local cooling loops allows for full and more flexible distribution of available global refrigeration power. The existing margin on installed cooling capacity can be used to cover excessive heat load on the LHC cooling loops.

ACKNOWLEDGMENT

Many thanks to all support teams for planned and urgent interventions during Run1 as well as their effort for preparation of Run2 operation.

REFERENCES

[1] O. Bruning et al., “LHC Design Report,” Geneva, 2004.
[2] L. Tavian, “Performance limitations of the LHC cryogenics: 2013 review and 2015 outlook,” LHC Beam Operation workshop – Evian 2012.