CERN

Opération Cryogénique LHC

Synthèse des principaux résultats obtenus

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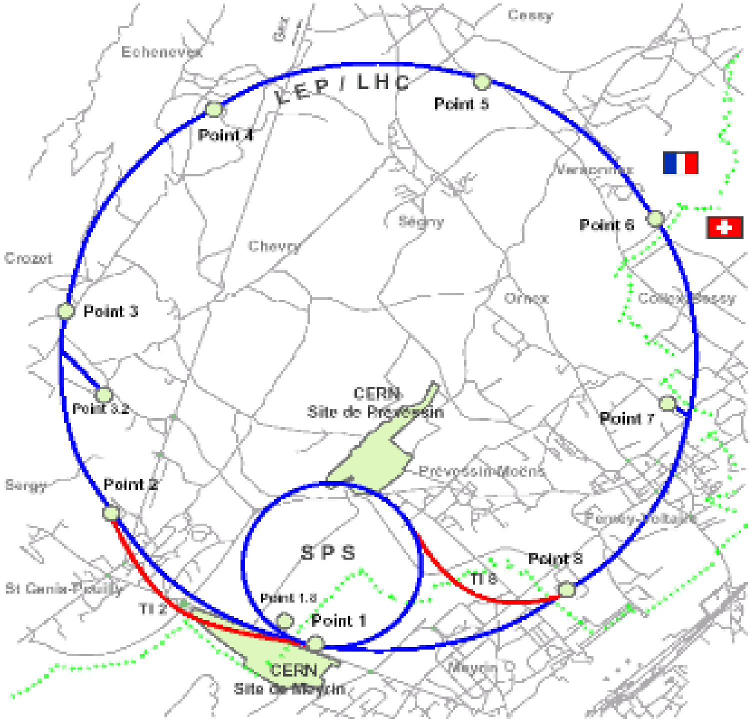
Agenda

- Recall on LHC cryogenics
- Evolution of the global LHC cryogenic system
- Operational adaptation to LHC present behavior
- Benefits of adjustments and remaining issues during Run 2
- Conclusions & Perspectives for Run3

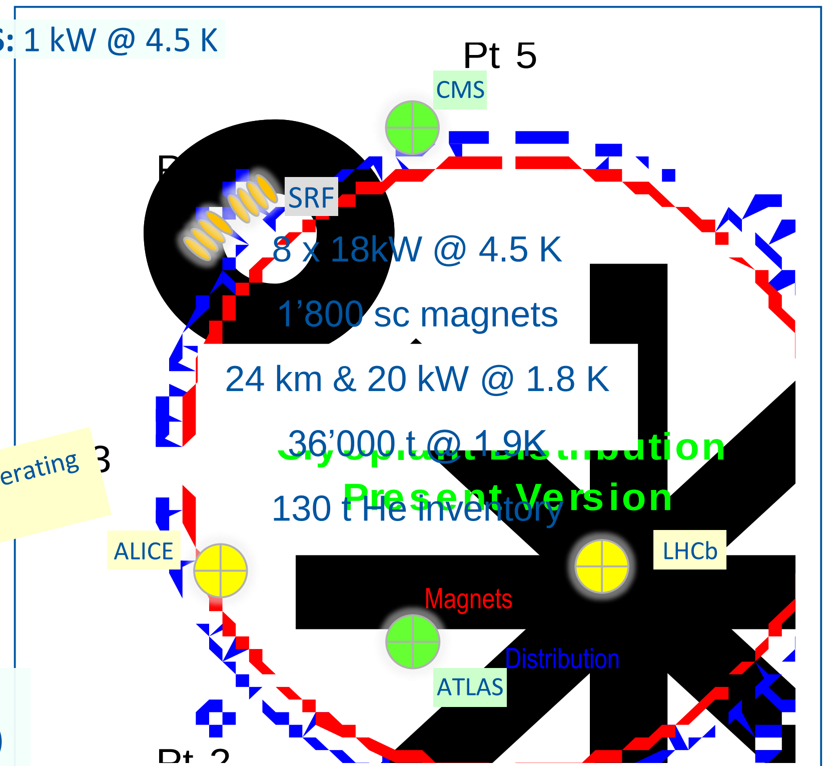
Layout of LHC/Experiments cryogenics



LHC cryogenics is constituted with:

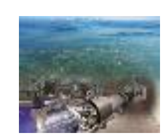
- 24 km of high-field superconducting magnets operating in superfluid helium at 1.9 K or 4.5 K
- SRF cavities operating in helium at 4.5 K
- LHC experiments ATLAS & CMS with magnets operating at 4.5 K

CMS: 1 kW @ 4.5 K



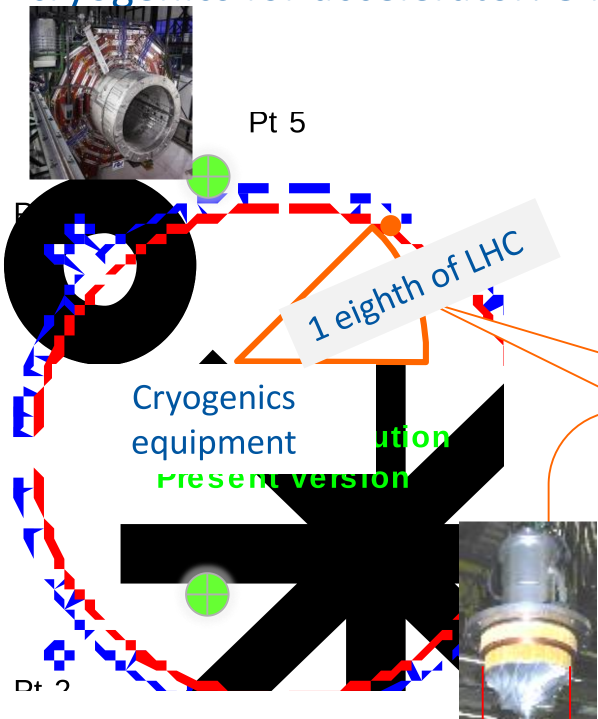
Two LHC experiments ALICE & LHCB operating at room temperature

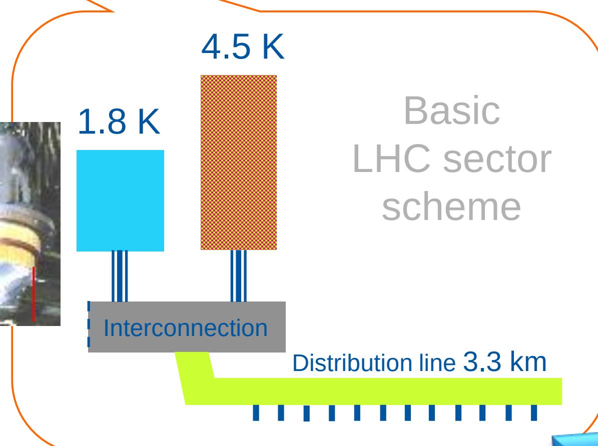
ATLAS:
6 kW @ 4.5 K (magnets)
12 kW @ 40/60 K (shield)

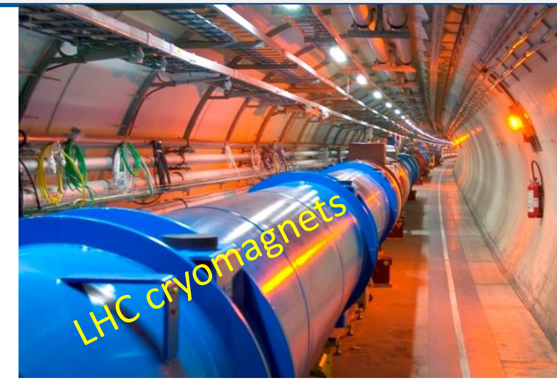


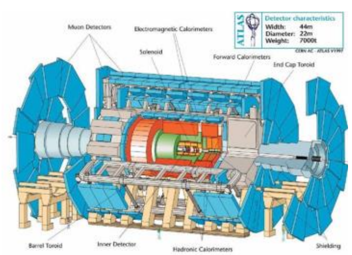
Layout of LHC cooling system

LHC cryogenics for accelerator: 8 independents sectors





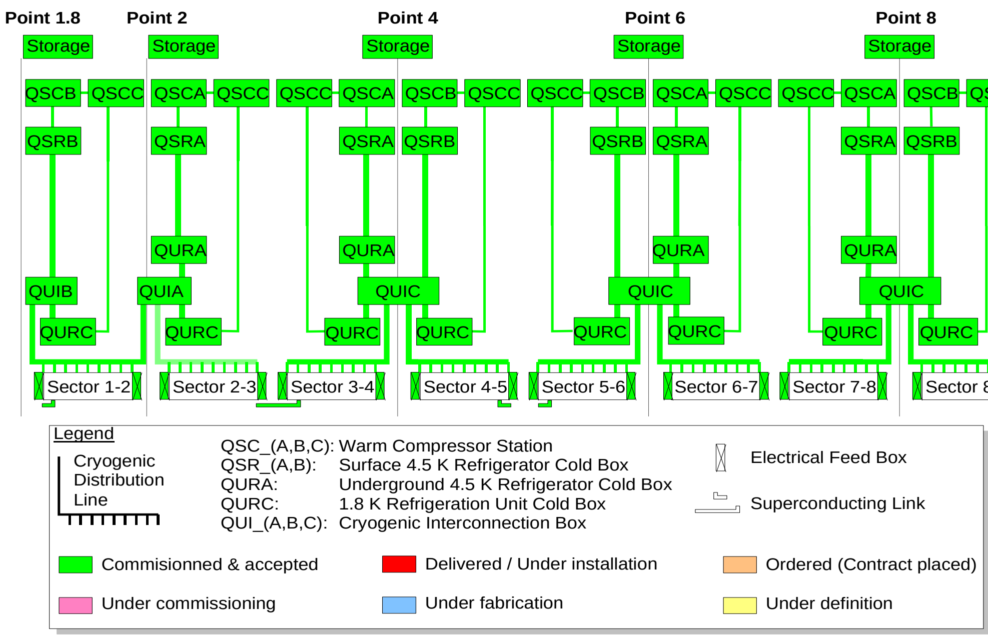




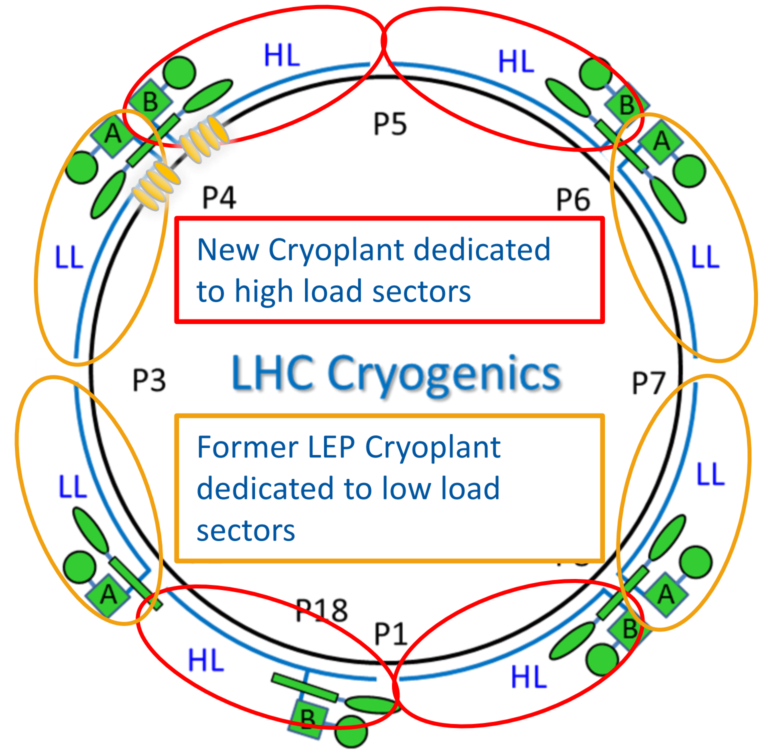
LHC is a complex cryo system with 7 Cryo islands (5 for accelerator and 2 for experiments)

LHC cryogenics for experiments: 2 experiments with cryogenic system

LHC cryogenic hardware configuration

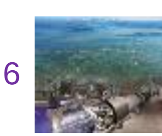


LHC Cryogenics architecture

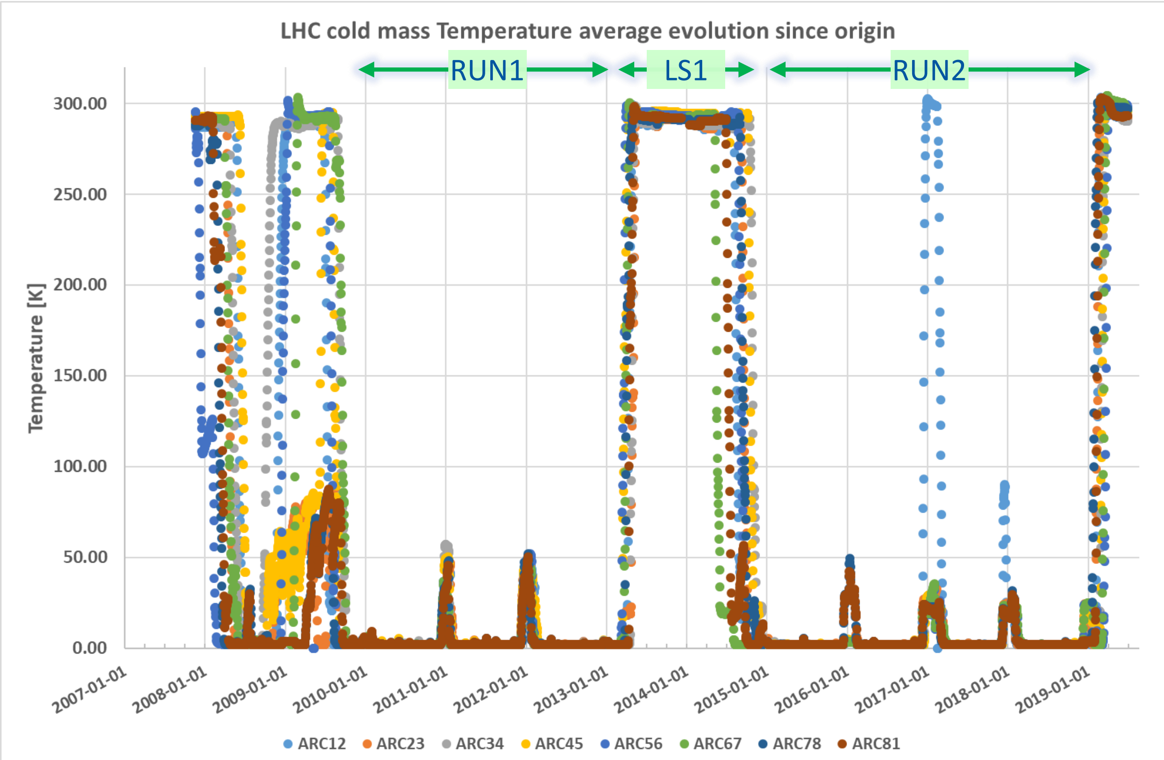


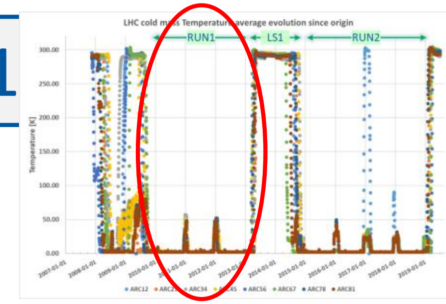
LHC Cryoplants initial distribution

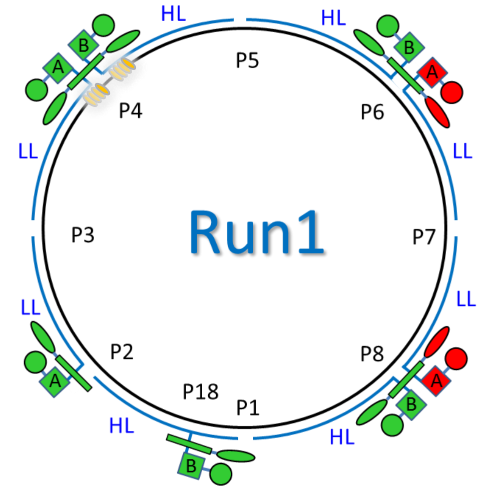
At design level, the cooling capacity of cryoplant were adapted to cover nominal and ultimate LHC operation with equal margins on LL and HL sectors.
Thanks to build-in interplant connections some special configurations are possible for hardware issue mitigations, lower power consumption and availability optimization.



Operational adaptation of configuration Run 1



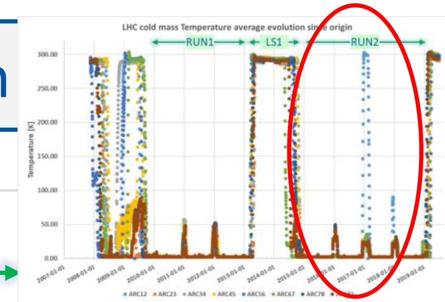


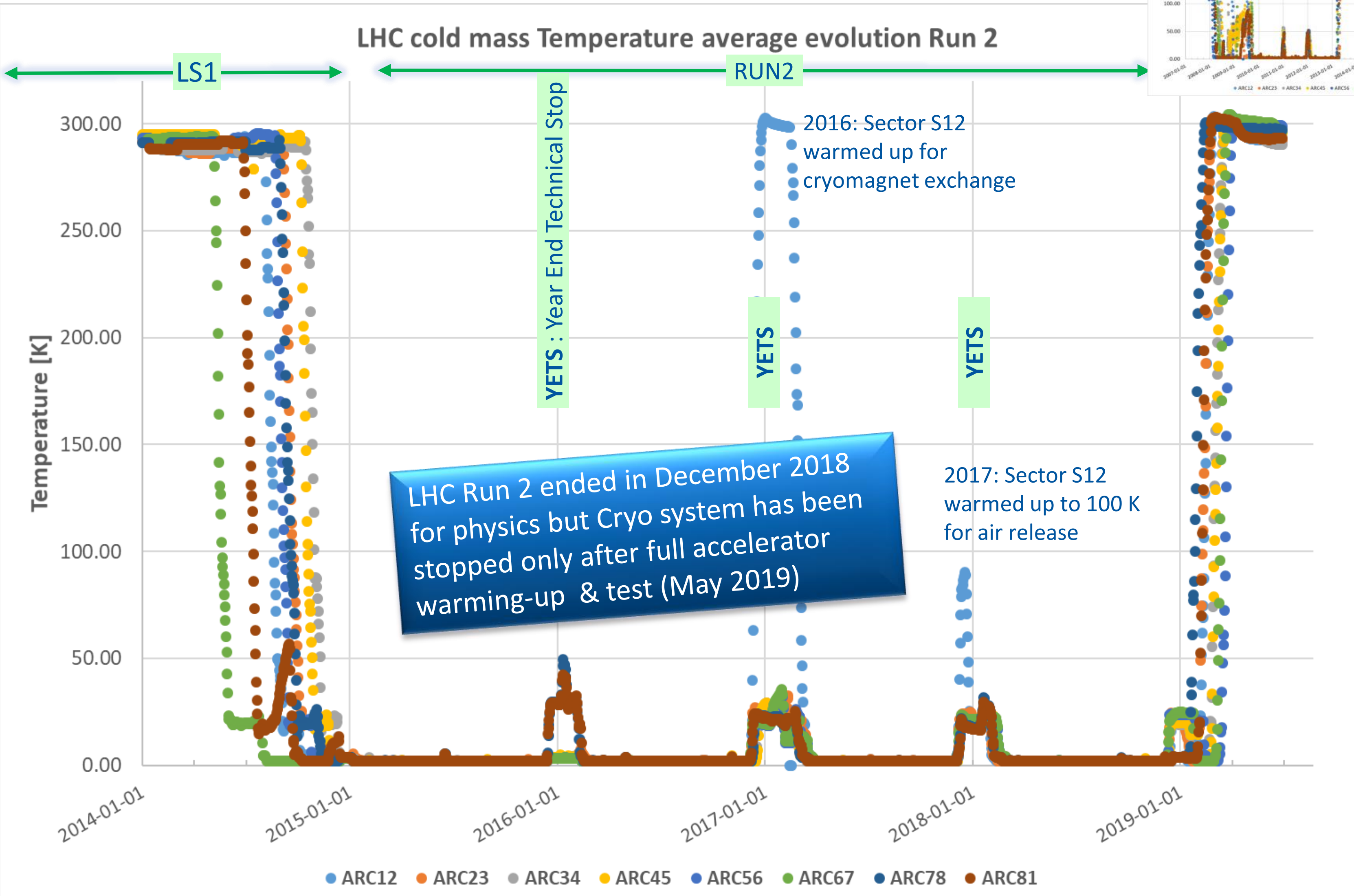


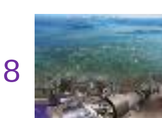
During Run 1 (2010/2013) thanks to the low beam intensity mode, the total heat load deposited on the non-isothermal 4.6-20K level was low enough to allow the stop of two 4.5K-refrigerators. The same model could be applied for the 1.9K level and consequently two 1.8K-units were stopped.

Run 1 has been used to the first operational adaptation of the Cryo cooling configuration

Temperature evolution of cryomagnet during LHC run



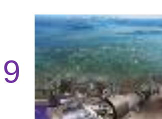




Evolution of the LHC thermal load during Run 2

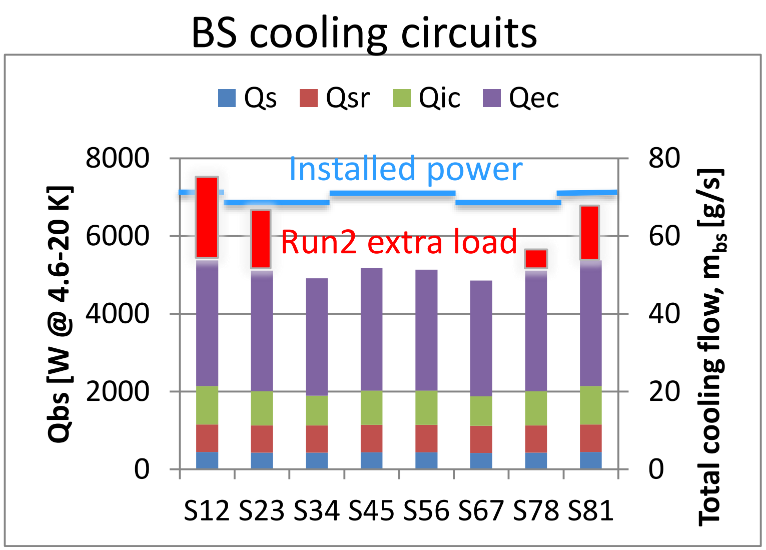
- Run 2 is characterized by the increase of beam energy from 4 to 6.5 TeV.
- Seen from Cryogenic point of view, more thermal energy will be deposited on Inner-Triplets, Arc Cryomagnets and Beam Screen cooling circuits.

Beam induced heat load scaling law				
Beam Parameter	Energy	Bunch current	Bunch number	Bunch length
	E	I_{bunch}	N_{bunch}	s_Z [r.m.s]
Synchrotron radiation	E^4	I_{bunch}	N_{bunch}	-
Image current	-	I_{bunch}^{2}	N_{bunch}	$s_Z^{-3/2}$
Photo-electron cloud	-	I_{bunch}^{3}	N_{bunch}	-
Beam gas scattering	-	I_{bunch}	N_{bunch}	-
Random particle losses	-	I_{bunch}	N_{bunch}	-



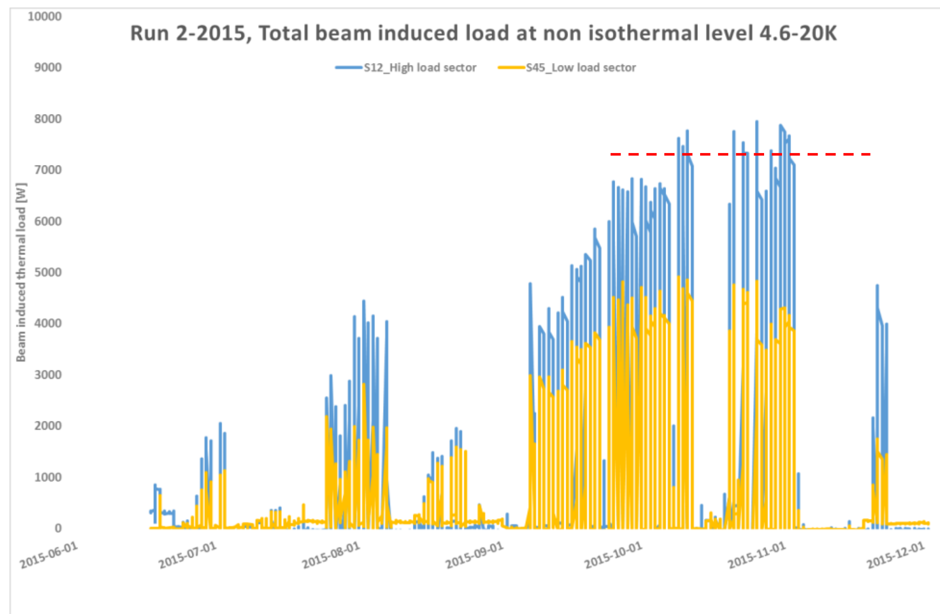
Beam induced heat load on Beam Screen @ 4.6-20K

- Major part of Beam Induced Heat Load (BIHL) is deposited, trough several processes, on the Beam Screen at the temperature level of 4.6-20K.



Main beam induced heat load according to LHC design report

From the beginning of run 2, it quickly became obvious that the beam induced heat loads would exceed the installed powers on the Beam Screen cooling circuit of high load sectors.



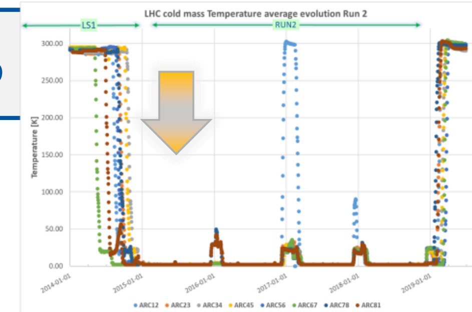
Evolution of the LHC thermal load during Run 2

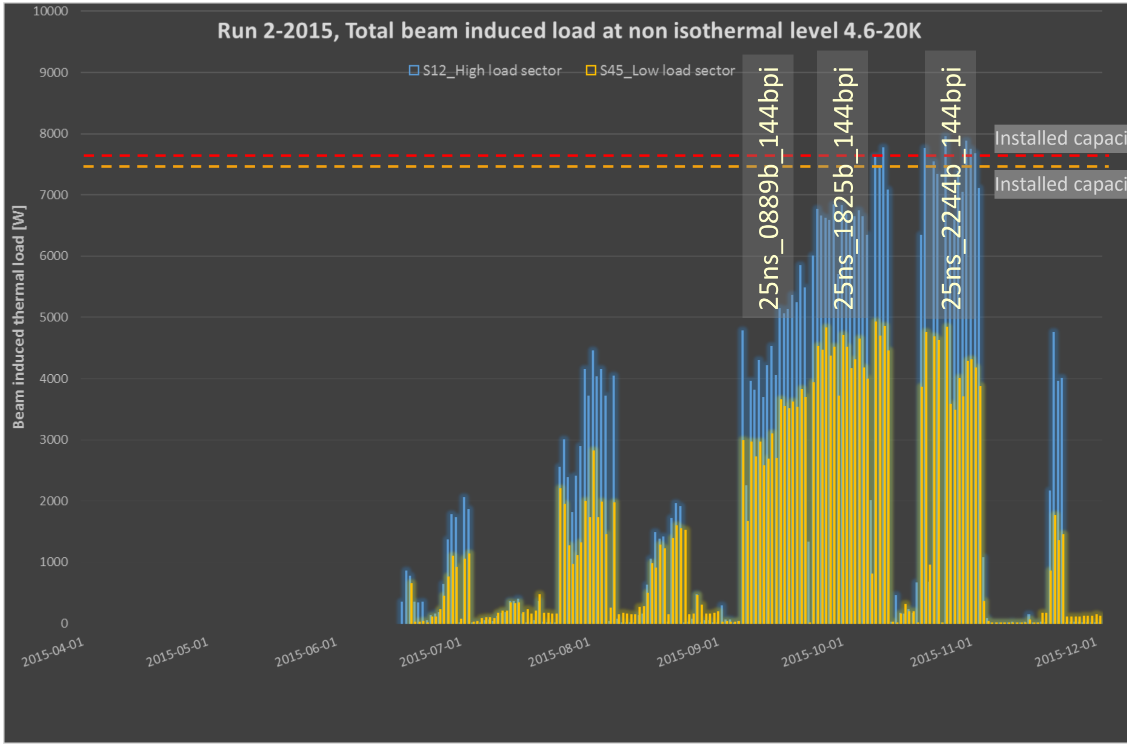
- To cope with the available non-isothermal cooling capacity @ 4.6-20 K there is 2 possibilities:
  - Modify the beam filling scheme in order to keep the same overall luminosity delivered for LHC experiments
  - Re-arrange the 4.5 K helium refrigerators configuration in order to optimize the available cooling power in steady-state mode.

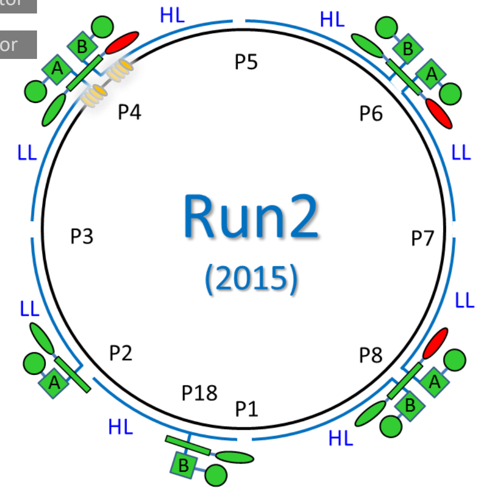
  & Adapt, tune and optimize the control system of the cooling circuits to cope with the transient modes generated by discontinuous presence of beam

These adaptations were put in place progressively throughout the run2

Operational adaptation of configuration Run 2_2015

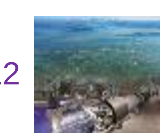






Design Report (DR) defines the total beam induced load at non isothermal level 4.6-20K , respectively 7.7 KW for high load sectors and 7.6 KW for low load sector. During year 2015, the beam induced load generated by the 6.5 TeV beam was measured higher than expected on high load sectors.

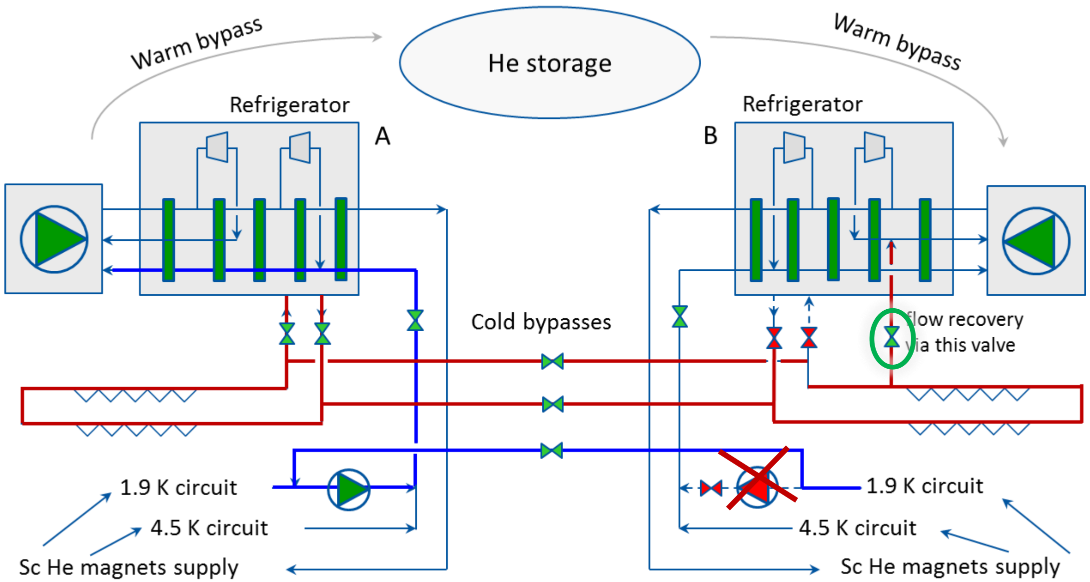
In contrast, w/r to DR at nominal operating mode, static and resistive losses at 1.9 K are lowers then expected (~300 W of margin / sector). A configuration of two 4.5K units & one 1.8K unit was successfully tested and deployed during the 1st year of Run 2.



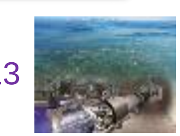
Optimization of cryogenic capacity during Run2 in 2016

- The cooling power requested by the Beam induced heat load @ 4.6/20K was exceeding significantly the design value.
- Oppositely, the dynamic heat load @ 1.9K was lower than the design value.

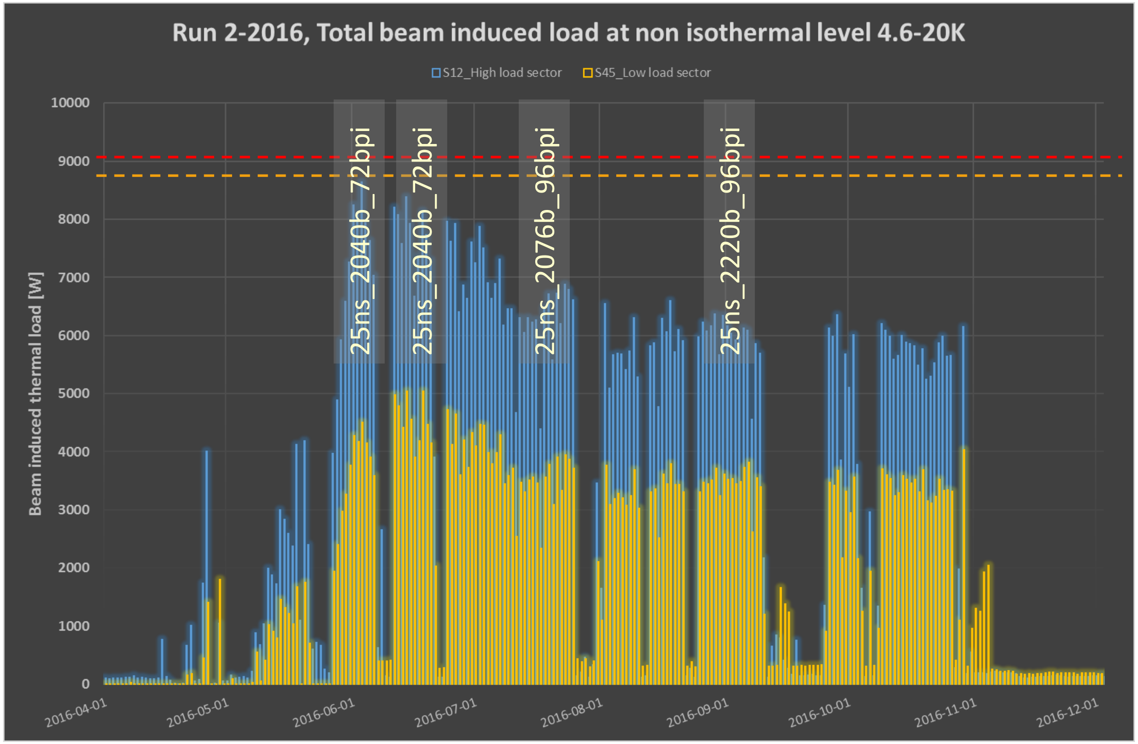
To re-attribute cooling power to the 4.6-20K level, a deactivation of four units @ 1.9K was successfully tested. This requires equilibration of the return flow, using the thermal shielding return circuit (~70 K). The estimated gain of this solution is in the range 1500 W per sector. To be compared to the design value of 7700 W @ 4.6-20 K / sector.

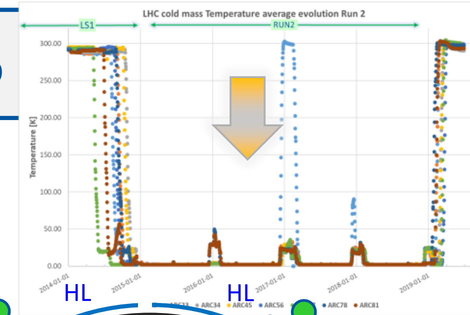


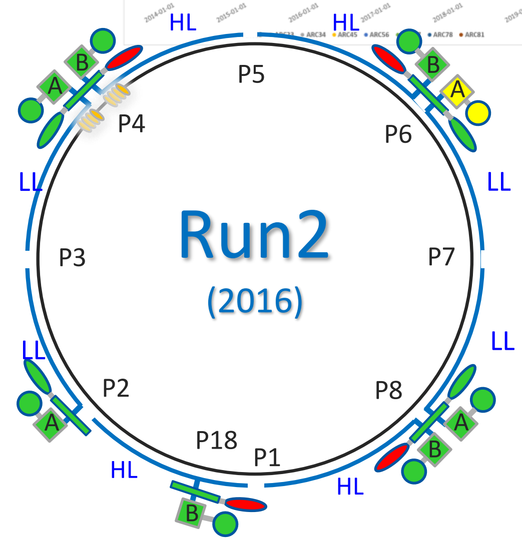
Transfer of 1.9K cooling power toward 4.6-20K level put in service in 2016 and used until now



Operational adaptation of configuration Run 2_2016





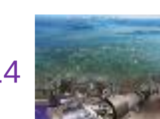


In parallel with the optimization of the cryogenic capacities, the LHC filling scheme progress constantly to reach nominal luminosity for the experiments.

A new filling scheme, so called BCMS (*Batch Compression Merging and Splitting*), has been introduced in 2016 to keep under control the beam induced heat load.

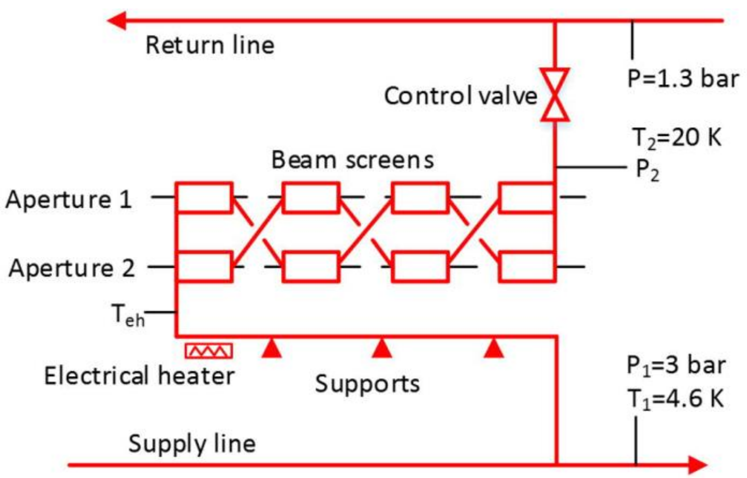
The other important parameter is the beam intensity moving from $9*10^{13}$ up to $3*10^{14}$ p+

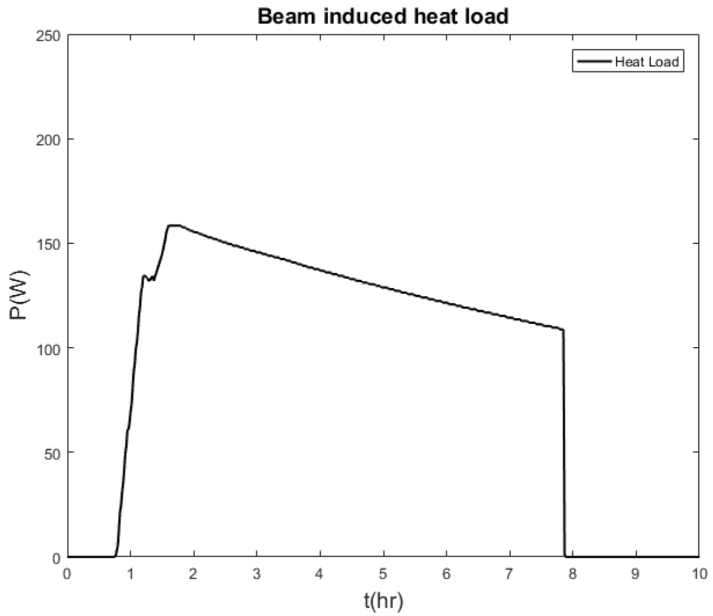
Thanks to the cooling power optimization and to new beam parameters, the run 2_2016 has been successful.



Adapt, tune and optimize the control system used for beam screen cooling 1/3

The classical control loop with regulation of the outlet temperature by the control valve was first implemented during Run 1. Using this method, the LHC struggled with unacceptable temperature oscillations and refrigeration capacity limitation. This method is not compatible in terms of reactivity with the heat load transients generated by the beam injection, current ramp-up and beam dump.



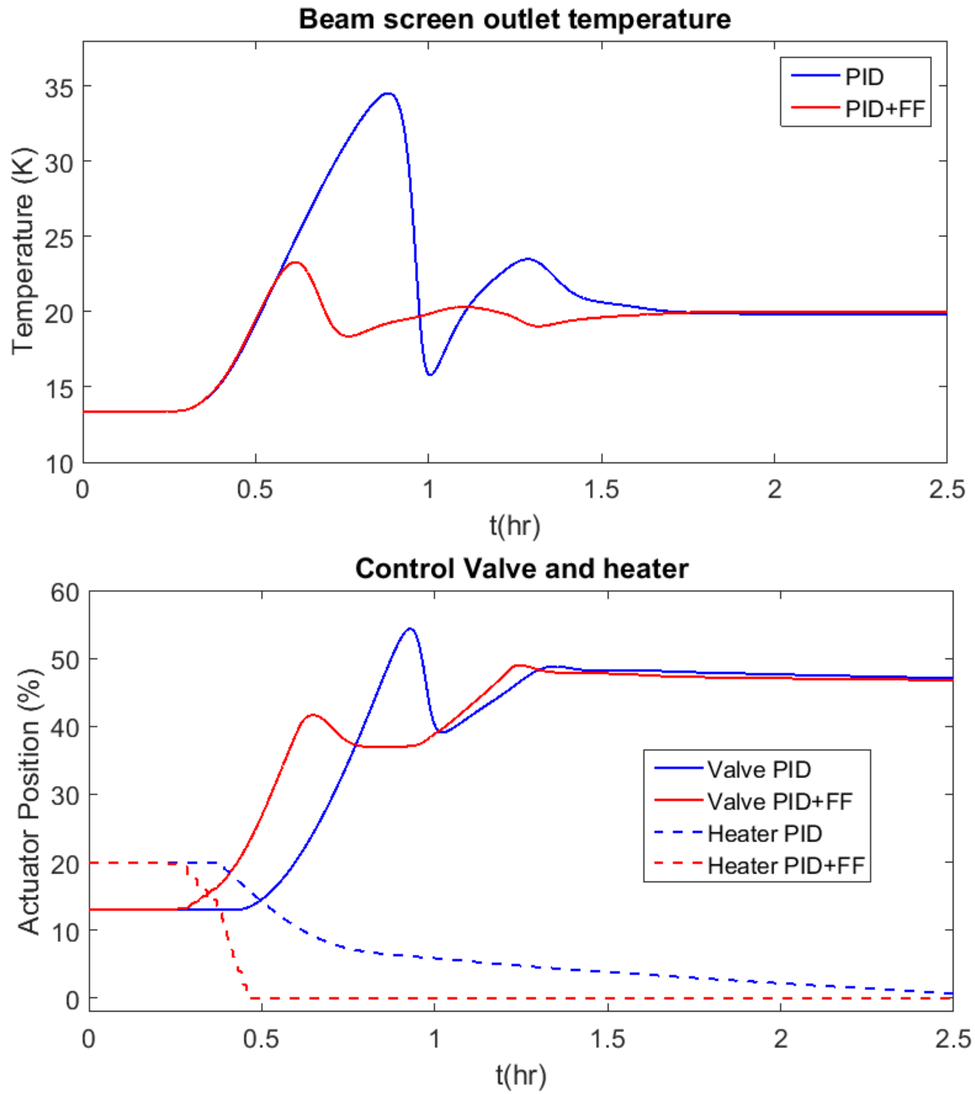


Adapt, tune and optimize the control system used for beam screen cooling 2/3

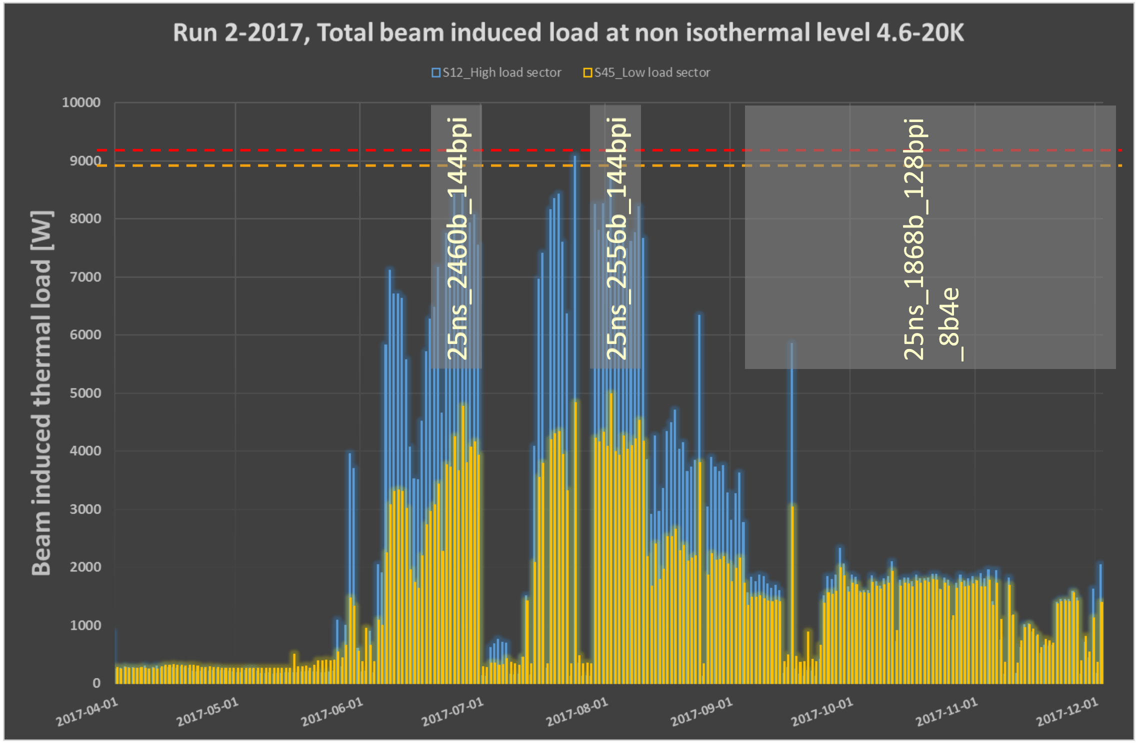
CERN has developed a more efficient control system using FeedForward (FF) action. The FF calculation utilize beam parameters to calculate the average power deposited on the Beam screen and drive, in a parallel way, the outlet control valves & inlet heaters.

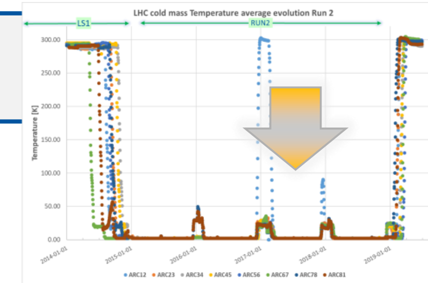
This FF method allows a smooth cold gas return to the cryoplant, necessary guarantee for a smooth evolution of the refrigerator cooling capacity.

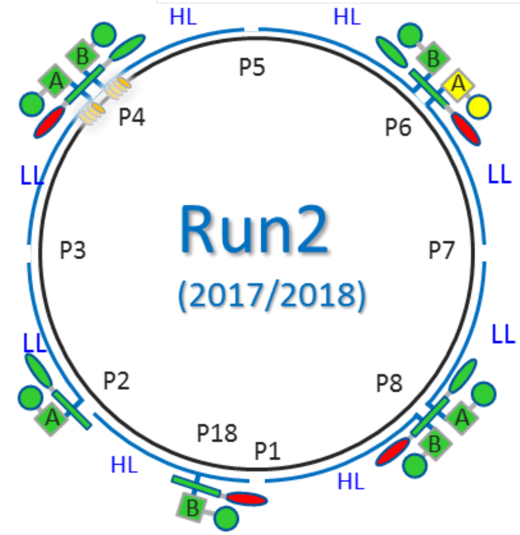
This method was progressively put in service in Run2-2016 and fully deployed in Run2-2017



Operational adaptation of configuration Run 2_2017

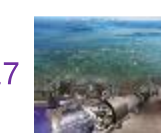






Operational scheme of Run 2_2017 & 2018 is mainly the same than the operational scheme of 2016. The only adaptation is the individualization of the Feed-Forward control to every beam-screen single control loops.

During the second semester 2017, the LHC filling scheme was modified to adapt LHC beam to a local air pollution. The chosen filling scheme so called 8b4e generate a low thermal load ,best for cryogenic point of view, but not optimized on luminosity point of view.



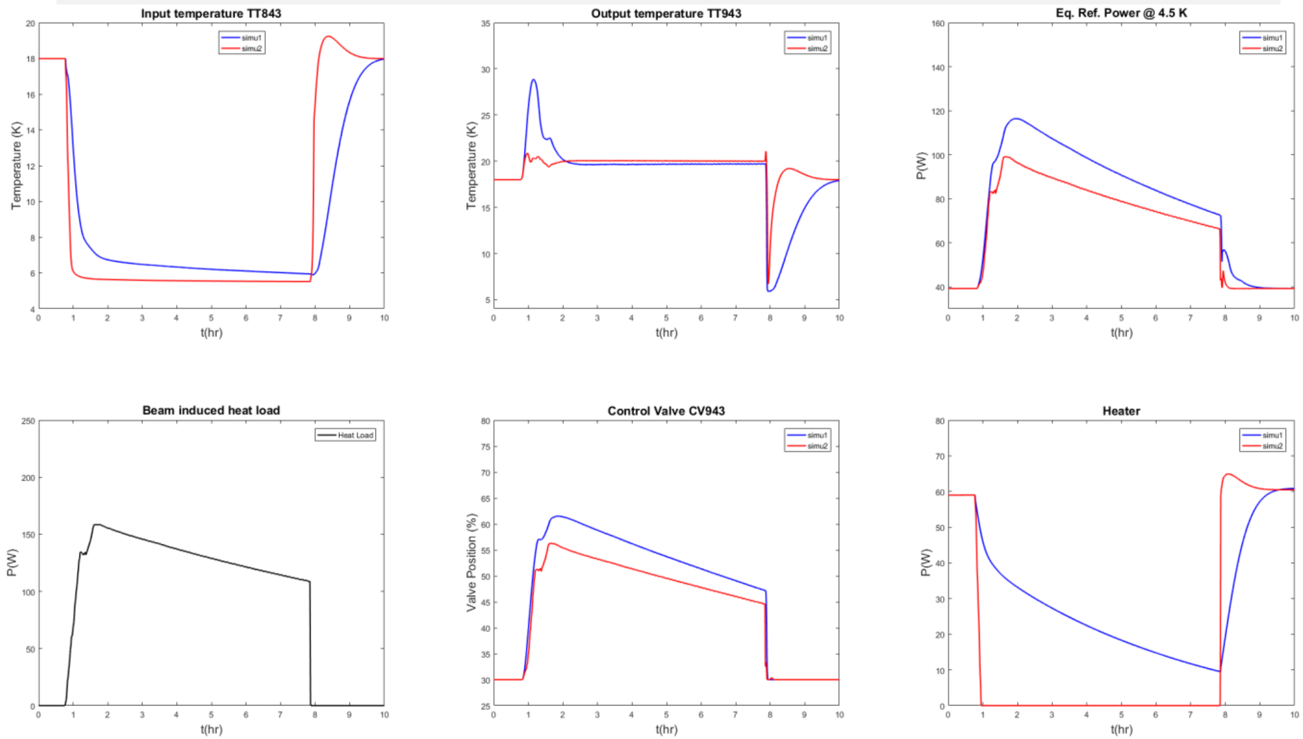
Adapt, tune and optimize the control system used for beam screen cooling 3/3

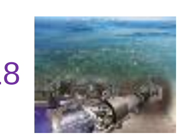
The FF method used as **average** to drive all the cooling valves of a sector was much better than the classical PID controller was. However, linked to the massive parallel controlled valves & heaters (53 circuits), some inconstancy appears with some subcooled circuits and some overheated circuit. This is mainly due to the spread of beam induced heat load not linearly distributed in the sector neither between sectors.

As final step, FF control has been **individually** applied on every singular circuit. This method is currently deployed on all LHC cooling circuits (53 / sector) for RUN2-2018. The equivalent cooling power recovered is in the range 250-300W / sector.

Typical high load sector

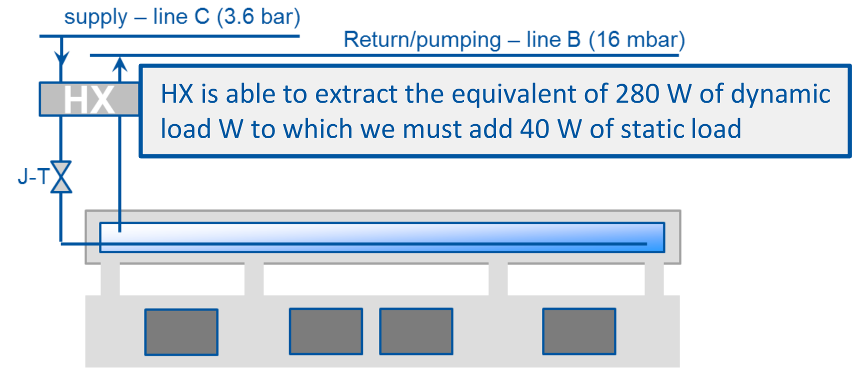
Simu 1: PID controller, Simu 2: FF controller





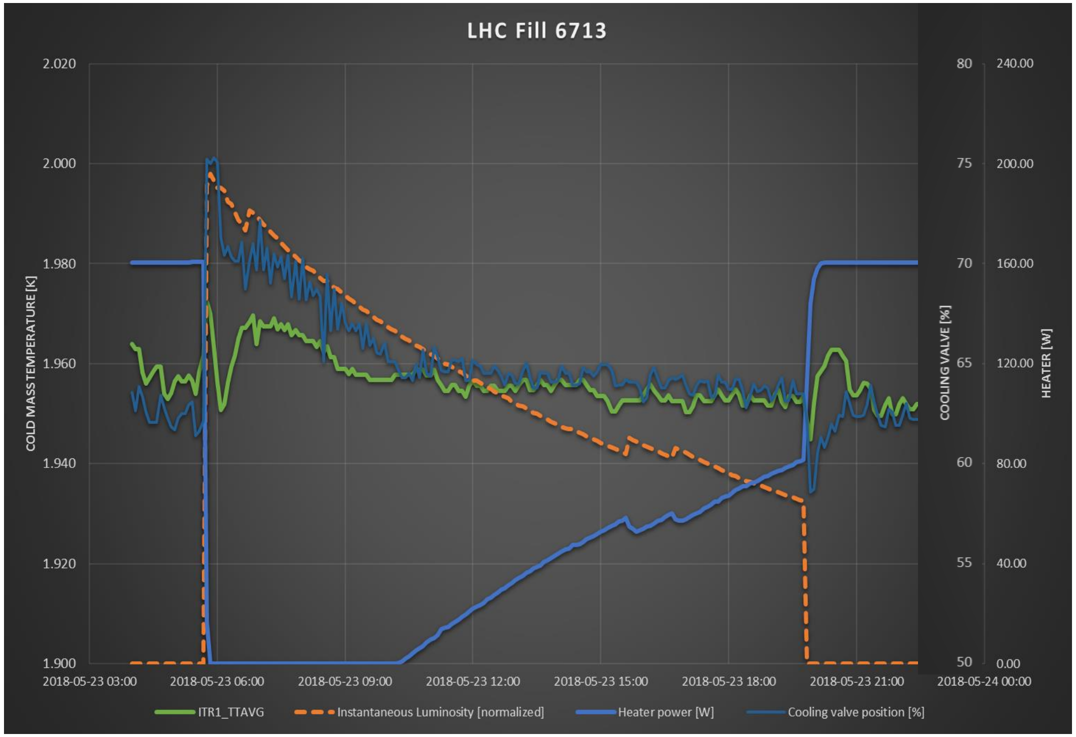
Beam induced heat load on Inner Triplet @ 1.9K

Beam induced dynamic heat load on Inner Triplet (IT) comes mainly from shower of secondary particles ejected from experiments. The energy deposited is proportional with :

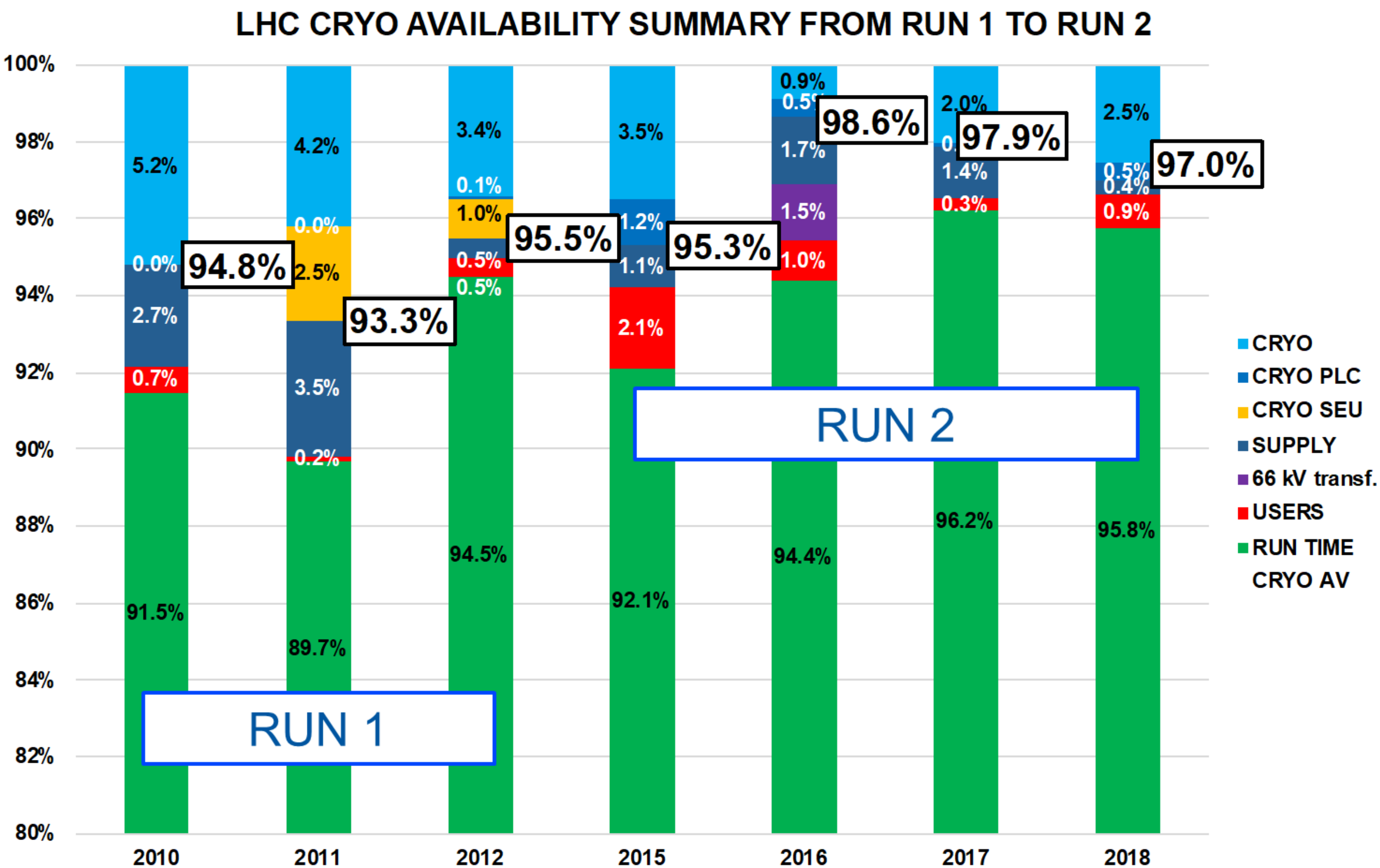


where L_{nom}= 1.0e^34 Hz/cm^2 , $Q_{sec,nom}$= 152 W

A dedicated FF control loop has been developed to comply with the specific beam induced load of the Inner Triplets.



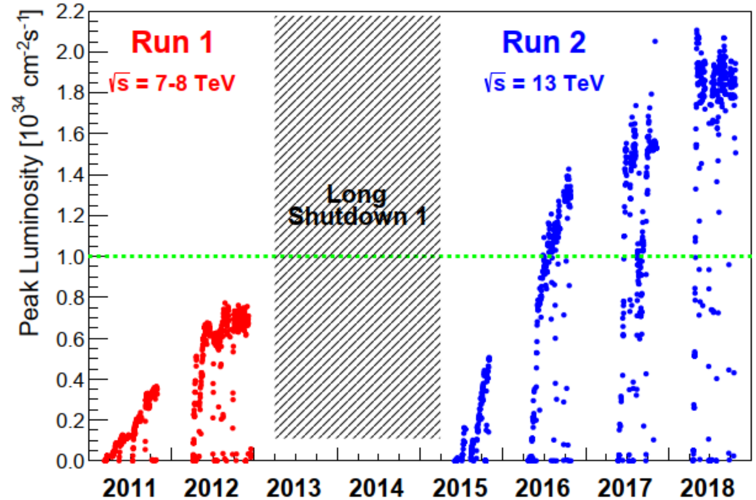
Overall LHC Cryo Availability



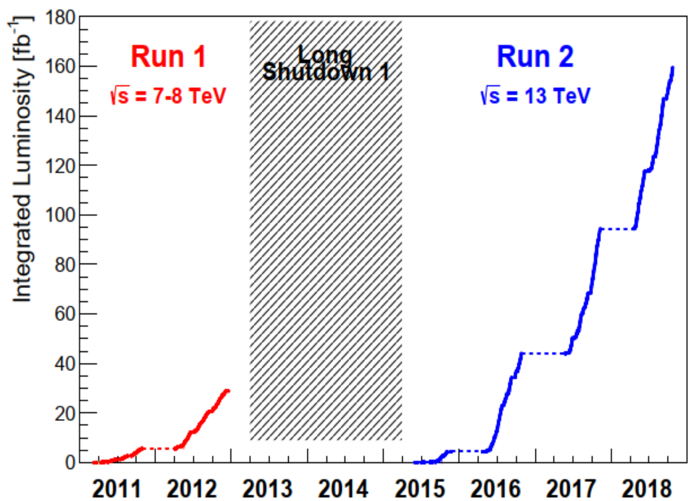
Cryo availability of 97.0% for 8 independent sectors ⇔ 99.6% for each cryoplant !!!

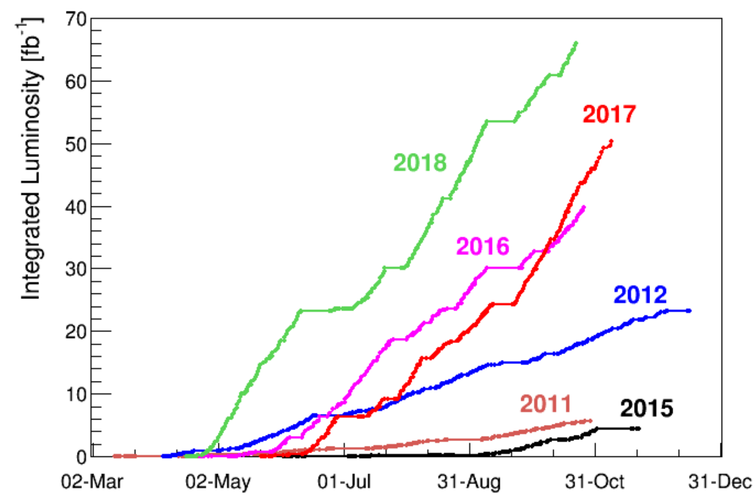
Overall LHC luminosity

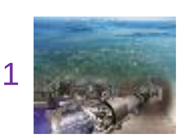
LHC is able operating well above design peak luminosity 2*10 34 cm-2s-1. Levelling has been put in place to cap peak luminosity.



Since the start of LHC, the expected integrated luminosity was 150 fb-1 for the end of Run2. Today, the total integrated luminosity is beyond 160 fb-1.

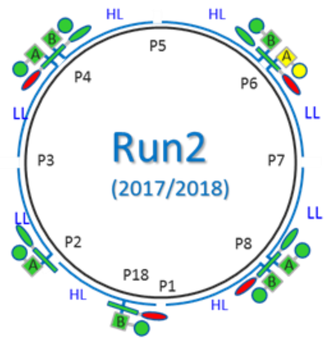




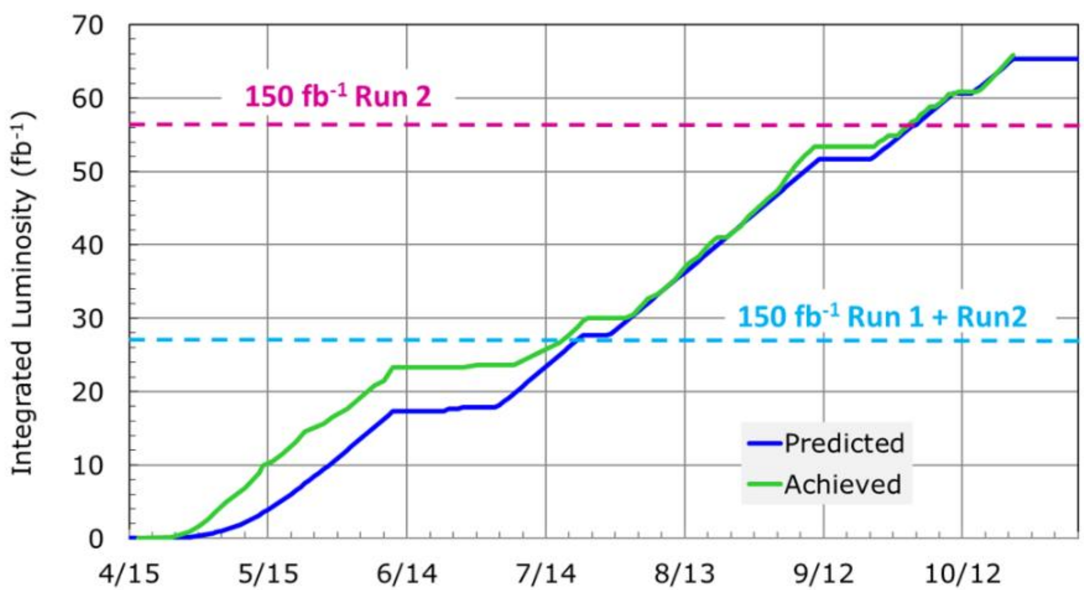


Operation results for 2018 and beyond

The 2018 operation scenario was based on the most optimized operation configuration using existing hardware.
During this period, LHC has produced 60 fb^{-1} to rise the integrated luminosity of 160 fb^{-1}



Luminosity production 2018 for Atlas & CMS



At the end of Year 2018, Run 2 has ended. After warming up, the period of 1.5 years will be used for maintenance & Upgrade tasks.
Next cooling down is foreseen in Spring 2020

Remaining topics on which a constant effort is requested

- Oil Removing System of cryoplants is still a potential issue. A permanent monitoring is mandatory to prevent any massive pollution of the cold boxes. Concerning LHC cryoplants, 8 refrigerators 18 kW @ 4.5K are continuously running during 5 years with a annual stop of 2 to 3 weeks. A rough estimation gives 40000 running hours between maintenance. Some oil pollution pre-alerts are pending.
- In order to maintain good availability, anticipating potential problems is essential. Thanks to the huge amount of data available, we try by constant effort to detect the accumulation of weak signals in order to turn them into pre-alarm information.
- The aging effect on PLC, electronic components and cables insulation could be an issue in the coming years. This will imply a major overhaul of the concerned equipment during the coming maintenance periods.
- Linked to CERN general policy for staff, a permanent turn-over of cryogenic operators generate a knowledge uncertainty. A dedicated training scheme is now on track with more than 25 sequences of training and with use of in-house simulator developed for this need.

Conclusions and perspectives

- The experience gained during Run1 and early Run2 was used to optimize the non-isothermal refrigeration capacity @ 4.6-20 K that is 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 equivalent to Run 1.

- Our cryogenic team uses its analysis, process-calculation and simulation capabilities to develop and optimize the Feed Forward advanced control. On the other hand, these capabilities are widely exploited for the simulator tool used to train operators. The next step, already well advanced, will be to generate early warnings based on data mining.

- No solution described above would be possible without the complete control of the daily operation of multiple cryoplants. This must also include to permanently repeat unexciting but essential tasks such as helium and oil leak check, vibrations monitoring, visual and remote inspection. This list is non-exhaustive!

Merci

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