

# ADAPTATION OF THE CYOGENIC SYSTEM CAPACITY FOR THE LHC DYNAMIC HEAT LOAD – OPERATIONAL EXPERIENCE

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## Abstract

During the second LHC physics operation period (Run2), between 2015 and 2018, the accelerator operation modes and beam parameters have been adapted thus allowing significantly improved integrated luminosity production. Increased energy, intensity and adapted beam operation schemes with 25 ns of inter-bunches spacing have an essential influence on the dynamic heat load generation with direct impact on the cryogenic cooling system. In order to cope with significantly higher than expected beam induced thermal load, the cryogenic system was tuned and optimized to adapt the required refrigeration capacity to the beam operational requirements. The most challenging part of tuning was focused on the dynamic heat load compensation on the beam screens circuits. The paper will provide the overview on the main differences between the theoretical heat load values considered for initial design and the on-line measurements performed on cryogenic LHC sectors. Finally, the paper will summarize the methodology and tools implemented in the cryogenic process control system allowing the highly efficient on-line adaptation of the refrigeration power with respect to the beam induced heat load distribution.

## INTRODUCTION

The cryogenic system of the Large Hadron Collider (LHC) constructed at CERN (European Organization for Nuclear Research) is composed of eight large cryogenic plants supplying LHC magnets, electrical feed boxes and RF cavities. One cryogenic plant consists warm compressor station, 4.5 K refrigerator, 1.8 K pumping unit and interconnection box as well as related piping and transfer lines allowing for distribution of helium in related LHC sector [1]. The general LHC cryogenic architecture is presented in Fig. 1.

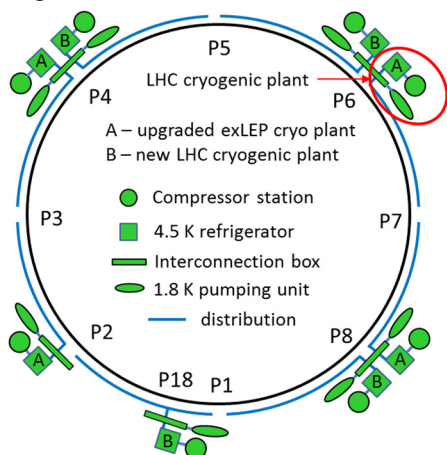


Figure 1: LHC cryogenic architecture.

The operational experience and measured heat load values shows considerable savings related to main magnets refrigeration consumption at 1.9 K. On the other hand, circulating beam with 25 ns of the inter-bunches spacing generates much higher heat load on the beam screen circuit than values considered for design of the system. Thanks to installed bypasses between the cryogenic plants, the cooling power consumption could be optimized and obtained capacity savings re-allocated for compensation of dynamic beam thermal effect.

## LHC 1.9 K COOLING VS. BEAM SCREEN COOLING

In focus on power optimization, each 1.9 K local cooling loop is equipped with a heat exchanger allowing to sub cool the supply stream of supercritical helium using cold return flow coming from the magnets cooling system. Comparing design thermodynamic parameters of supply and return flows at point 1 and point 2 – see Fig. 2 and Eq. (1), we can calculate that increase of enthalpy between these two points is in range of 20 J/g, what corresponds to heat extraction from the magnets.

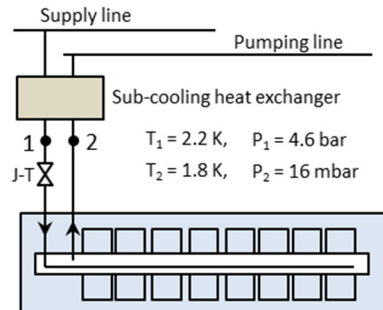


Figure 2: 1.9 K LHC main magnets cooling loop.

$$\Delta h = h_2 - h_1 \quad (1)$$

The beam screen local cooling loop is equipped with several instruments: a heater for flow stabilization, two thermometers on inlet and outlet of the loop and regulation valve as shown in Fig. 3 (one LHC sector contains in arc standard section 52 local cooling loops of 53 m each).

Processing a similar approach as for 1.9 K cooling loop, the corresponding enthalpy increase in the beam screen circuit is in the range of 100 J/g.

Concluding, in terms of consumption of distributed supercritical helium flow, the beam screen refrigeration is five times less costly than refrigeration at 1.9 K. Therefore, any saving from 1.9 K refrigeration is very attractive to be applied for the beam screen cooling.

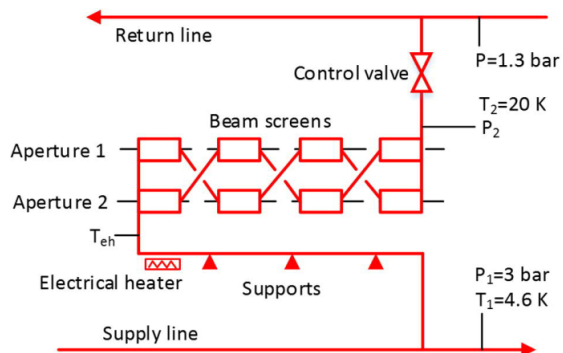


Figure 3: The LHC beam screen local cooling loop.

### BEAM SCREEN DYNAMIC HEAT LOAD

The function of the LHC beam screen is to protect the 1.9 K cold mass circuit from excessive dynamic heating generated by circulating beams as well as allowing keeping ultra-high vacuum in the beam pipes. The dynamic heat load deposited on the beam screen is coming from three contributors: synchrotron radiation, image current and photo-electron effect so-called electron cloud. Depending on beam parameters such as: energy and intensity, the first two components can be precisely calculated [2, 3]. However, analysis of thermal effect coming from electron cloud is much more complex, depending mainly on surface condition, beam intensity, and inter-bunches spacing.

During Run2, the LHC was operated with 6.5 TeV/beam of energy and intensity in the range of  $2 \cdot 10^{34}$ , running with 25 ns of the inter-bunches spacing. Such operation scheme generated particularly high values of dynamic heat load in four LHC sectors, exceeding significantly the design values.

The evolution of dynamic heat load deposition on the beam screen circuit for a representative LHC beam fill (#5979) is presented in Fig. 4 (the average values, given for one beam screen local cooling loop called half-cell).

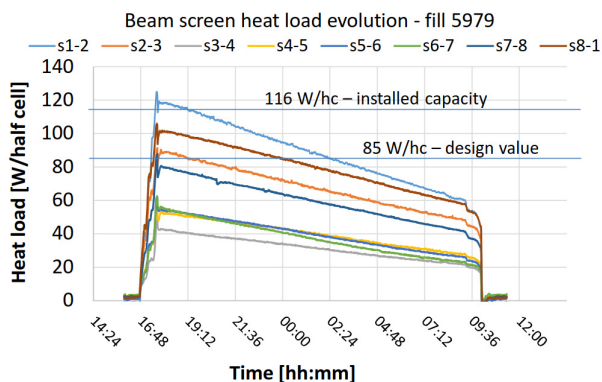


Figure 4: Beam screen dynamic heat load for fill 5979 (June 2017).

The spread of heat deposition between the sectors is not fully understood and is still under investigation.

### RUN2 MEASURED HEAT LOAD AT 1.9 K

Differently to observations on the beam screen, the dynamic heat load generation at 1.9 K measured during Run2 (reference fill #5979) was lower than design values. This fact is related mainly to low electrical resistance measured on magnets interconnection splices. The design and installed values of refrigeration power at 1.9 K as well as the measurement related to sector 1-2 are summarized in Table 1.

Table 1: LHC 1.9 K Refrigeration Values (sector 1-2)

Design [W]	Installed [W]	Measured [W]
1460	2400	1066

Following values presented in Table 1 we can conclude that measured heat load corresponds to less than half of installed capacity of one cold pumping unit.

### OPTIMIZATION OF CRYOGENIC CAPACITY

#### Cryogenic plants operation scenario

In order to deal with high beam screen dynamic heat load, the cryogenic system was subject to serious studies and test program and tests for optimization of the refrigeration capacity provided by related cryogenic plants. The most important gain was obtained by deactivation of four cold pumping units. Thanks to installed interplants bypasses, one cold pumping unit can pump on two LHC sectors – see Fig 5. Such operation scenario was applied for LHC in 2016, 2017 and 2018 runs.

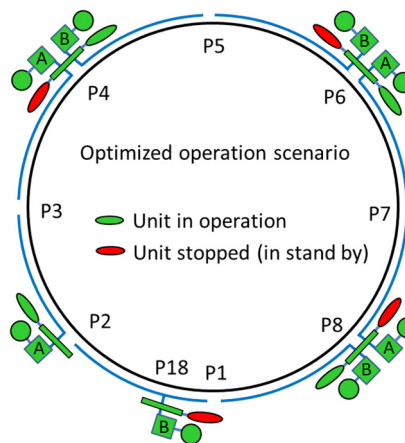


Figure 5: Run2 optimised operation scenario.

However, this solution requires re-equilibration of the helium return flows and by consequence the capacity between two adjacent cryogenic plants. The equilibrium of flows was done on thermal screen circuit, using interplant bypasses. The circulating helium flow diagram is presented in Fig. 6.

The estimated gain of applied solution allows to spare ~1500 W for the beam screen cooling for each LHC sector i.e. to increase the cooling capacity of one half-cell by nearly 30 W.

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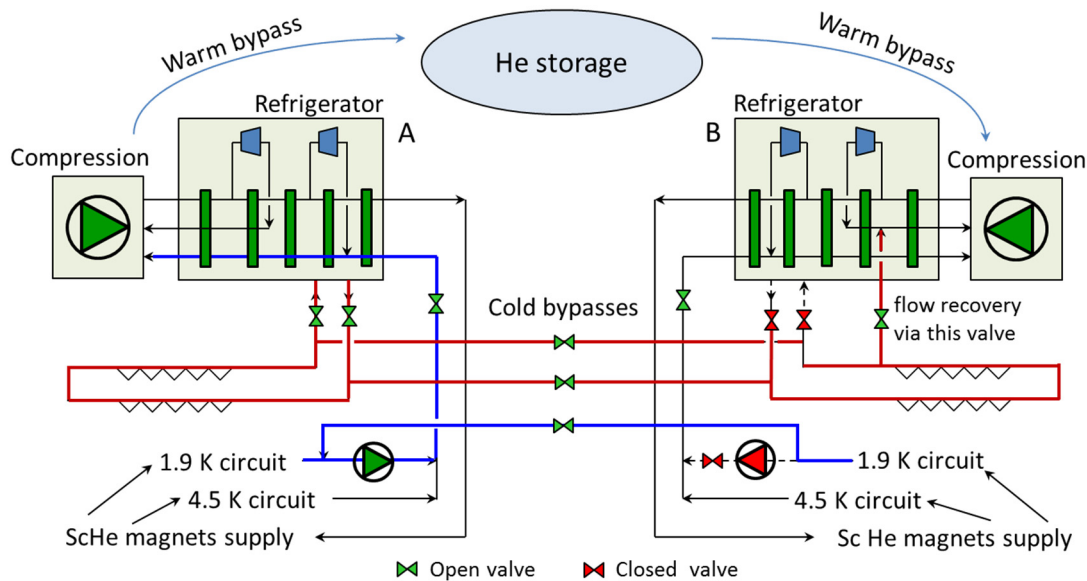


Figure 6: Flow diagram for operation of two adjacent cryogenic plants – production scenario of 2018.

### Beam screen control system optimization

The most challenging part of the process optimization was applied on consumption of global refrigeration power by the beam screen local cooling loops [3, 4]. The optimization was related to development of highly efficient on-line adaptation of the control system acting individually on each local cooling circuit. The most challenging part of the process control concerned transients during the beam injection, current rump and dump of the beam. For such transients, the classical control loop with regulation of the outlet temperature by the control valve (see Fig. 3) was not sufficient in terms of reactivity to compensate the deposited heat load. Using such simple regulation with increased beam parameters, the LHC struggled with unacceptable temperature oscillations, cryogenic condition losses, refrigeration capacity limitation and by consequence periodic unavailability for physics.

The new control system was built using a Feed-Forward (FF) action applied on the beam screen heater and the control valve. Control of both objects is performed by using beam parameters in such a way to keep the beam screen temperature out from oscillations during thermal transients and optimizing for necessary refrigeration capacity consumption. The main principle is to keep the heater in working mode during out of beam period and intensify the cooling flow via the control valve for beam injection and current rump period. A comparison between classic regulation and Feed-Forward action was simulated on selected individual beam screen cooling loop and is presented in Fig. 7. The tuning of the system was applied on each singular cooling circuit depending on the heat load deposition. For entire LHC it required offline computing of 2500 parameters deployed into the control system. Such solution allows to homogenize the beam screen temperature profile over a sector and spare about 250 - 300 W/sector of refrigeration capacity.

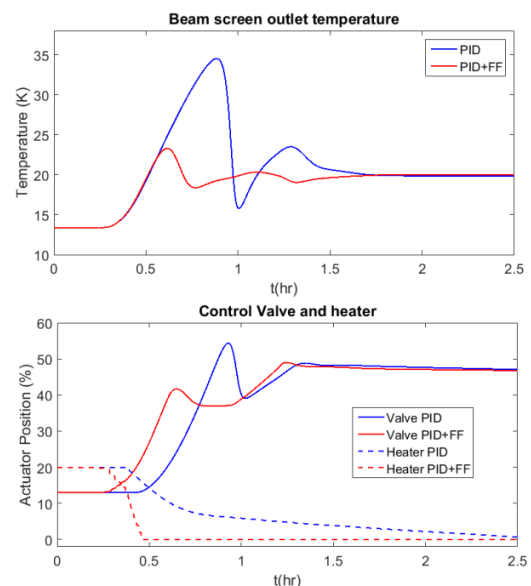


Figure 7: Simulation of response of individual beam screen cooling loop with and without Feed-Forward action [3].

### CONCLUSIONS

Nearly 10 years' experience of the LHC run with different beam parameters shown that heat load inventory of such a complex installation may present considerable divergences from values assumed for design. The operational flexibility in optimizing the global refrigeration power of the LHC was possible using warm and cold bypasses originally installed between adjacent cryogenic plants. The local control loops with large thermal response time required application of Feed-Forward control solution allowing capacity optimization during transients as well as homogenizing the temperature profile over the LHC accelerator.

## REFERENCES

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