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Abstract. During the LHC (Large Hadron Collider) Run 2 between 2015 and 2018 inclusive, significant dynamic heat loads have been generated and successfully managed by the LHC cryogenic system. These dynamic heat loads are generated by several physical phenomena occurring at two temperature levels and with different time constants. On the magnet cold-mass maintained at 1.9 K, dynamic heat loads are coming from eddy currents generated during the magnet transients, resistive heating in welds of superconducting electrical circuits, beam gas scattering, beam losses, and secondary particles escaping from collisions (debris). On the beam screens, actively cooled between 4.6 K and 20 K, the circulating beams produce also dynamic heat loads due to synchrotron radiations, image current and photo-electron clouds. This paper presents the measurements inventory performed during the Run 2 to assess these dynamic heat loads as a function of the different accelerator parameters (beam energy, beam intensity, injection scheme, etc.). Then, the related compensation measures and adapted cryogenic operation modes applied to manage the induced transients at the different time scales will be presented.

1. Introduction

The second run of the LHC (Large Hadron Collider) at CERN occurred between April 2015 and December 2018. The nominal beam intensities were achieved during this period ($I = 3.2 \cdot 10^{14}$ protons per beam) and the luminosity reached the double of the nominal value ($L = 2.1 \cdot 10^{34}\ cm^{-2} \cdot s^{-1}$) with respect to the LHC design report[1], inducing significant dynamic heat loads on the LHC cryogenic system. Several optimizations and noticeable control modifications were necessary to handle properly these excessive dynamic heat loads in order to continue to smoothly operate the LHC without any limitation coming from the cryogenics.

In the first part, this paper describes the dynamic heat load inventory and measurements performed during the Run 2 with respect to the values expected from the LHC design report. Then, in a second part, the different mitigation techniques developed during the Run 2 are presented with the obtained results. Note that only the cold mass and the beam screens dynamic heat loads are considered in this paper as other contributions (RF cavities, current leads, etc.) represent about 1 % of dynamic heat loads.

2. Dynamic heat load computation

2.1. Cold mass dynamic heat loads

The dynamic heat loads applied on the LHC 1.9 K cold masses are coming from different origins as described in the LHC design report [1]:

- **Resistive heating (RH)**: heat loads due to the resistive welds on superconducting circuits.
- **Beam induced heat loads (BIHL)**: different beam losses can occur in LHC resulting by high energetic particles passing though the cold masses and inducing heat loads (beam gas scattering and beam losses).
- **Secondaries (Sec)**: during collisions in interaction points, secondary particles are produced and generate heat loads in the Inner Triplet superconducting magnets located on each side of each interaction point.
- **Magnetization losses (ML)**: eddy currents are generated in magnets during the magnetic field transients resulting by significant heat load deposition on cold masses. This transient was 20 min in case of the LHC Run 2 at each ramp-up and the ramp-down of magnet current.

The available cryogenic instrumentation associated to the cryogenic plant configuration used during the LHC Run 2 allows us to compute the total cold mass heat loads for two adjacent sectors, representing $6.6 \, km$ of the machine. The dynamic cold mass heat load for one sector is computed using the following energy balance:

$$\Delta Q_{CM} = \frac{1}{2} \cdot \Delta \dot{m}_{CC} \cdot L_{He} + (M_{He} \cdot Cv_{He} + M_{mag} \cdot Cp_{mag}) \cdot \frac{\Delta T_{mag}}{\Delta t} - \Delta Q_{EH} \qquad (1)$$

where $\dot{m}_{CC}$ is the cold-compressor massflow, L_{He} is the helium latent heat of vaporization, M_{He} and Cv_{He} are the static helium bath mass and heat capacity, M_{mag} and Cp_{mag} are the magnet mass and heat capacity, $\Delta T_{mag}/\Delta t$ is the magnet temperature derivative over the sector and ΔQ_{EH} is the electrical heating variation over the sector. The total error on this calculation is estimated at about 10 % due to the massflow imprecision and because the steady-state is not always perfectly reached. To distinguish the different heat load contributors, several fills were selected in order to distinguish the different heat load sources.

Table 1. LHC fills used to estimate cold mass dynamic heat loads

Fill	Date	Energy (GeV)	Intensity $(p^+/beam)$	Luminosity $(cm^{-2} \cdot s^{-1})$	Dyn. Heat loads
No Beam	28 July 2018	450	0.0	0.0	None
6975	25 July 2018	450/6500	$1.0 \cdot 10^{11}$	0.0	ML
6868	01 July 2018	6500	$1.0 \cdot 10^{13}$	0.0	RH
6909	10 July 2018	6500	$1.8 \cdot 10^{14}$	$5 \cdot 10^{32}$	RH+BIHL
6675	12 May 2018	6500	$3.0 \cdot 10^{14}$	$2 \cdot 10^{34}$	RH+BIHL+Sec

Applying equation (1) to the fills defined in the table 1, the different heat load contributions can be easily deduced. Results are presented in the Figure 1 for the LHC fill no 6675 in comparison with the forecast heat loads using the numbers and the scaling laws defined in the LHC design report [1].

The measured *RH heat loads* are half the design report values in all sectors, which is in agreement with a previous measurement campaign of resistive heat loads performed in 2010 due to the very low splice resistance [2]. Then, it was not possible to distinguish any heat load directly induced by the beam intensity and the *BIHL* seem to be lower than what is possible to measure by using this method (i.e. about 5 W). This new measurement demonstrates that there are no significant beam losses in the cryogenic area and that the beam vacuum is better than expected. The *secondaries* generate significant heat loads in the inner triplets but they are about 30 % lower than the expected values. *Magnetization Losses* are certainly the most

complicated heat load to calculate due to the very short transient (only 20 minutes) during which this heat load is applied. Using the technique mentioned above, a heat load half the nominal design value (about 1 kW per sector) has been considered but it is difficult to quantify the error in this particular case where there is no steady state observed.
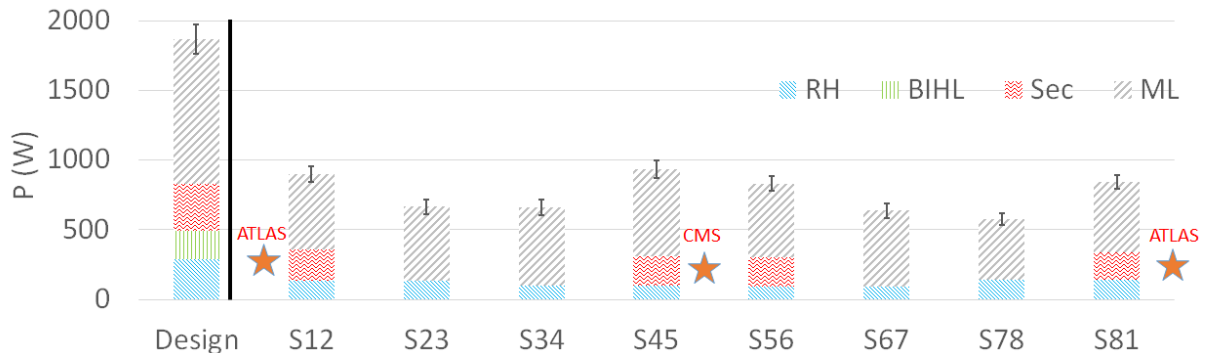

Figure 1. Cold mass dynamic heat loads at 1.8 K in each LHC sector during the fill 6675 (typical Run 2 fill)

2.2. Beam screen dynamic heat loads
The dynamic heat loads applied on the LHC beam screens are [1]:

- **Synchrotron Radiation (SR)**: heat loads generated by the interception by the beam screen of the synchrotron radiation.

- **Image current (IC)**: heat load generated by the current induced by the beam on the beam screen surface due to the beam screen impedance.

- **Electron clouds (EC)**: when the bunch spacing is 25 ns, a multipacting effect appears with the photo-electrons generated by the beam due to the secondary electron emission yield (SEY) occurring on the beam screens surface.

An enthalpy balance is performed in each beam screen cooling loop as described in [3] and a sum is performed over the 52 parallel cooling loops to obtain the total heat load over one LHC sector. After various campaign of valve parameter calibration in 2018 to estimate the massflow in each cooling loop, the total error on the sector heat load measurement has been reduced to 6 %. Then, in order to assess the different beam screen heat load contributors, the two fills defined in table 2 have been used. Synchrotron radiation and image current are always present whereas the electron-cloud phenomenon is strongly visible only when the injection scheme uses a 25 ns bunch spacing. The fill 6675 uses the so-called *BCMS* injection scheme (the most used one during the Run 2) as other schemes generating less heat loads alter significantly the LHC luminosity performances [4].

Table 2. LHC fills used to estimate beam screen dynamic heat loads

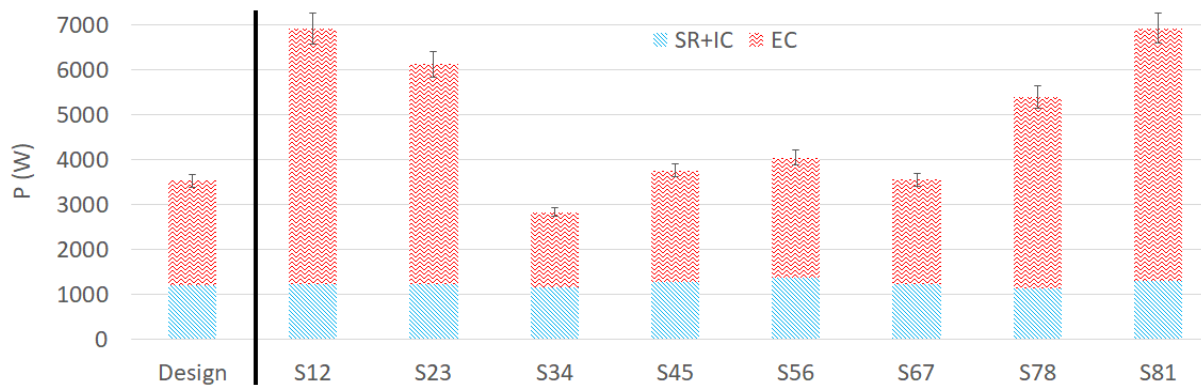| Fill	Date	Energy (GeV)	Intensity $(p^+/beam)$	Inj. scheme	Dyn. Heat loads
Fill 5980	22 July 2017	6500 GeV	$1.4 \cdot 10^{14}$	STD-50ns	SR+IC
Fill 6675	12 May 2018	6500 GeV	$3.0 \cdot 10^{14}$	BCMS-25ns	SR+IC+EC

Figure 2. Beam screen dynamic heat loads between 4.6 K and 20 K in each LHC sector during the fill 6675 (typical Run 2 fill)

Results are presented in figure 2 for the fill 6675 where the SR and IC contributions have been estimated using the fill 5980 as reference and scaled as function of the actual beam parameters, see [5] for details. The balance of the measured power is then the contribution of the heat load related to the EC. We can first notice a very good agreement of heat load measurements with respect to the LHC design report for the SR and IC induced heat loads. On the other hand, there are important differences on the EC contribution on four sectors showing clearly extra heat loads. These differences are probably due to differences of the beam screen surface SEY around the machine, but this issue is still under investigation by a dedicated task force at CERN [4].

2.3. Overall dynamic heat loads
In order to assess the overall dynamic heat loads of each LHC sector, the equivalent heat loads for 4.5 K isothermal refrigeration power can be computed using an exergetic balance. The RF cavities in S34 and S45 also generate dynamic heat loads but they are negligible compared to other dynamic heat loads (about 40 W per sector). Note that the magnetization losses are not considered here as they are present during only 20 minutes and damped using the superfluid helium heat capacity in magnet cold masses. Figure 3 represents the dynamic heat load summary for the fill 6675. As noticed before, the cold mass heat loads are half the expected values, ones but the beam screen heat loads are higher in four sectors. In total, we measured up to 4.6 kW equivalent heat load at 4.5 K for one sector, which represents more than 25 % of the total refrigeration capacity of a LHC cryoplant (18 kW).

3. Dynamic heat load induced transient management
3.1. Cold mass transient management
The magnet cold mass temperatures are controlled using valves supplied by supercritical helium at 3 bar and 4.5 K, performing a Joule-Thomson expansion to a very low pressure of 16 $mbar$. The saturated helium is then circulating in a bayonet heat exchanger, cooling the magnets immersed in a pressurized helium static bath (Claudet bath) [1].

The temperature set points are setup at 100 mK above the helium saturation temperature of the bayonet heat exchanger, hence, the magnets are regulated at about 1.95 K. If a magnet overpasses 2.15 K (called *cryo maintain*: interlock limit for the electrical powering of superconducting magnets), the LHC beam is automatically dumped and the magnets are automatically discharged for safety reasons. There is then a strong requirement to never
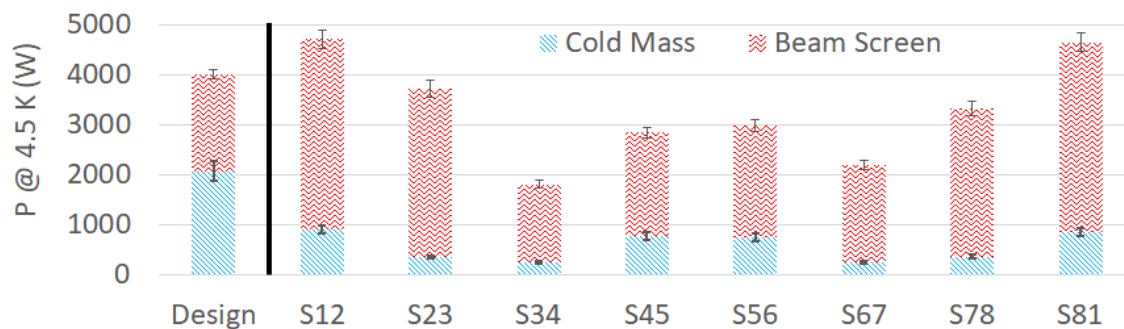
Figure 3. Total equivalent dynamic heat loads at 4.5 K in each LHC sector during the fill 6675 (typical Run 2 fill)

overshoot above this *cryo maintain* limit at any time during the normal operation.

The resistive heating and the beam induced heat loads are such that the local PID controllers are sufficient to ensure a correct cold masses temperature control. Then, the magnetization losses are present during a sufficiently short time (20 minutes) to be naturally handled by the superfluid helium heat capacity.

The heat loads coming from the *secondaries* in the inner triplet magnets are very large and appear instantaneously. In this case, the classical PID controllers cannot sufficiently manage the temperature control and the *cryo maintain* limit would be reached after few minutes of collisions. One solution to solve this issue is to pre-load the inner triplet magnets with electrical heaters located on cold masses ($EH821$) and to introduce a Feed-Forward control in parallel of the classical PID feedback temperature control ($TC910$) to anticipate the secondaries heat loads, as shown in figure 4. The secondaries heat loads Q_{sec} are estimated using the luminosity provided by ATLAS and CMS experiments in real time using a linear scaling law (for a nominal luminosity $L_{nom} = 10^{34}$, a nominal secondaries heat load $Qsec_{nom} = 130 \ W$ is setup). Then, the corresponding heating power is removed from the electrical heaters $EH821$ using the PID feedback power controller $HC821$ ensuring that the requested power is effective in case of heater fault or discrepancies. Then, if the heat load is higher than the preloading, another feed-forward action FF_2 is applied on the valve to open it in advance.

This technique was very efficient during the Run 2 and allows the LHC to run with the double nominal luminosity; see figure 5 where an inner triplet response is represented for a high luminosity fill. The temperature deviation is only 40 mK for a heat load of 230 W.

3.2. Beam screen transient management

Beam screens have to be maintained between 4.6 K and 20 K during the LHC normal operation to ensure an ultra high vacuum in the beam pipe and the beam screen helium cooling loop outlets have to be maintained as stable as possible at 20 K to ensure a correct return temperature to cryogenic refrigerators.

Beam screens are exposed to significant transient heat loads due to beam induced effects as described in section 2.2. The conventional PID controllers cannot fully compensate for these strong disturbances. Consequently, the beam screen cooling loops are also preloaded using electrical heaters and feed-forward actions have been implemented in parallel of the PID feedback loops as represented in figure 5. The beam induced heat loads (synchrotron radiation, image current and electron cloud) are estimated from the real-time beam parameters using some scaling laws and specific tuning parameters for each of the 485 cooling loops as the electron cloud heat load can be significantly different between different cooling loops. Then, the corresponding
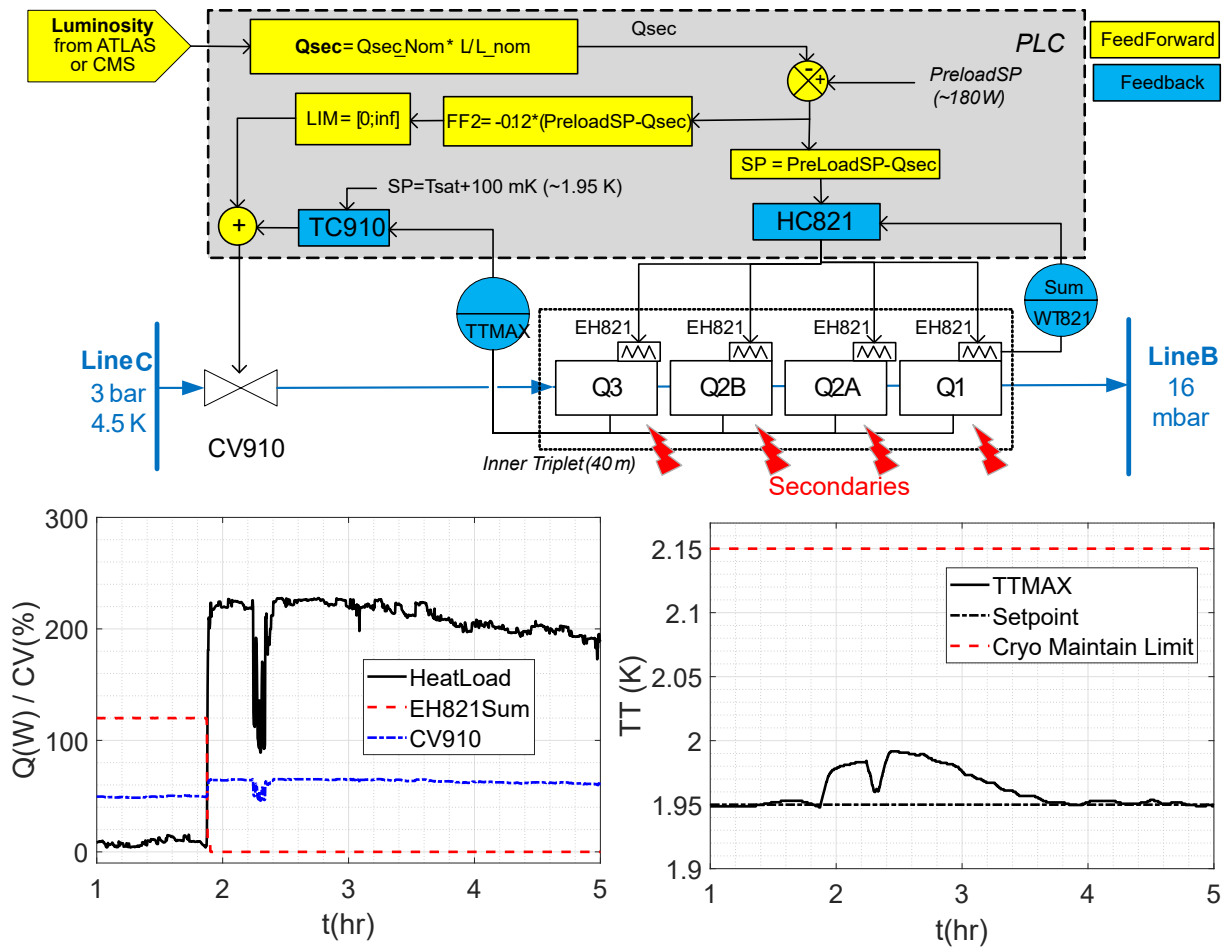
Figure 4. Inner Triplet cold mass temperature control scheme and results obtained on the triplet *L1* during a high luminosity fill (fill 6675 in May 2018)

heat load is removed from the electrical heater $EH847$ using the feedforward action FF_1 and if the heat load is higher than the initial electrical heater value, the control valve $CV947$ is also receiving a feed-forward action FF_2 to compensate the remaining power, see [6] for details.

This technique was progressively deployed and tuned over the 485 beam screen cooling loops during the LHC Run 2 and results were satisfactory with transients staying within the required constraints, ensuring a stable behavior for cryogenic refrigerators. One beam screen loop result is represented on figure 5 where an overshoot of only $3\,K$ is observed for a dynamic heat load of $180\,W$.

4. Conclusion

The LHC Run 2 was a challenge for the cryogenic system as the accelerator reached its nominal beam intensity and the double nominal luminosity. LHC generated significant dynamic heat loads representing up to 25 % of the cryogenic installed capacity for one LHC cryoplant.

In order to handle the dynamic heat loads, several new control strategies have been implemented during the Run 2 to avoid limiting the LHC performances. The Inner Triplet temperature control was improved by preloading the magnets with electrical heaters and adding feed-forward actions from experiments measured luminosity. The same strategy has been applied on the beam screen cooling loops, where the feed-forward actions are computed from the different
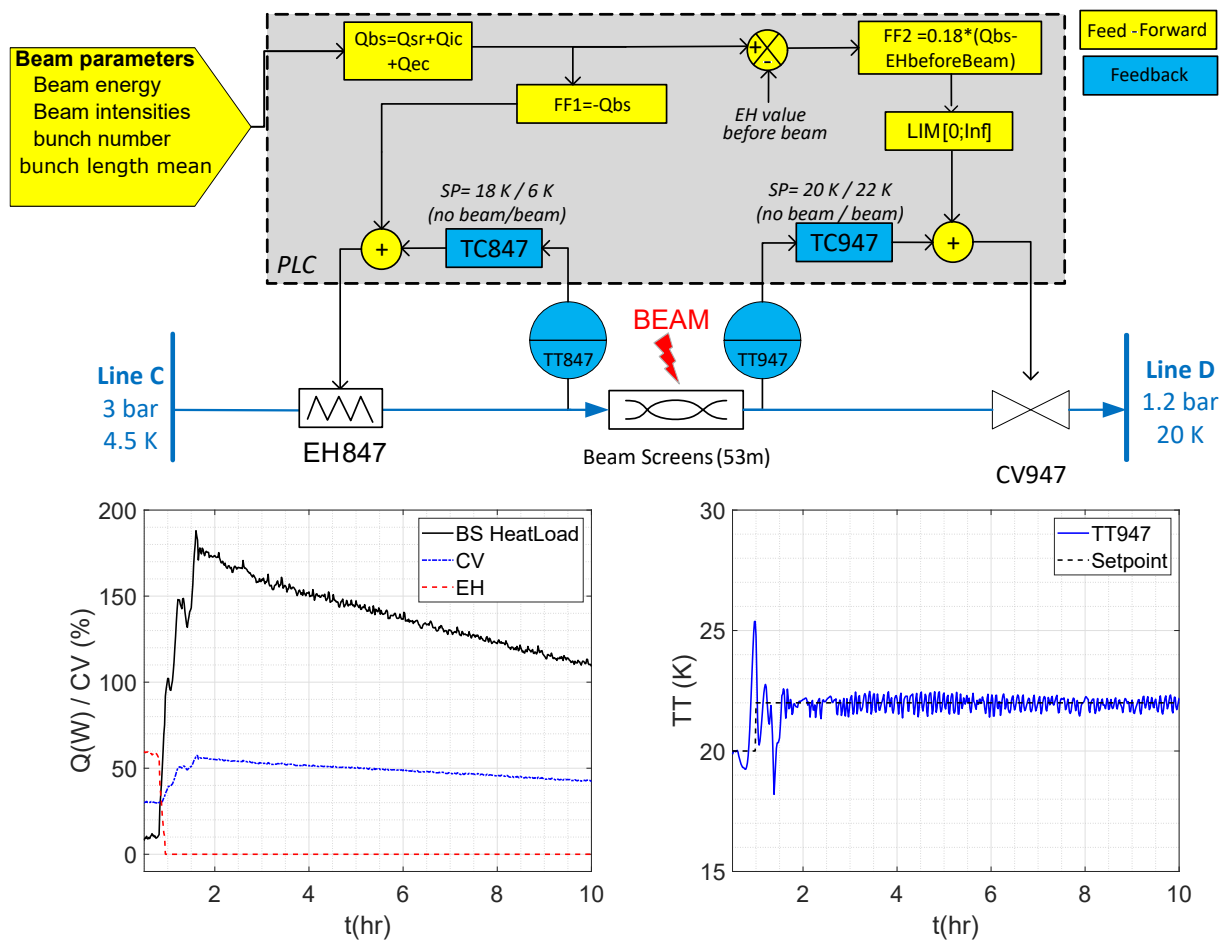
Figure 5. Beam screen temperatures control scheme and results obtained on one beam screen loop during a LHC nominal fill (fill 6675 in May 2018)

beam parameters.

Finally, the cryogenic system was not a limiting factor for LHC performance during this Run 2. For the coming Run 3 where the beam intensities should almost be doubled but with the same luminosity, the current strategies should be still valid but the maximum cryogenic cooling capacities could be reached in several places.

References
[1] Bruning O, Collier P, Lebrun P, Myers S, Ostojic R, Poole J and Proudlock P 2004 *LHC Design Report* (CERN, Geneva)
[2] Ferlin G, Claudet S, Tavian L and Wagner U 2010 *1.9 K heat inleak and resistive heating measurements on LHC cryomagnets* (Advances in Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference)
[3] Brodzinski K and Tavian L 2012 *First Measurements of Beam-Induced Heating on the LHC Cryonic System* (24th Int. Cryo. Eng. Conf., Fukuoka, Japan)

[4] Iadarola G, Bradu B, Dijkstall P, Mether L, Rumolo G, Romano A, Skripka G and Tavian L 2019 *Electron cloud and heat loads in Run2* (9th Evian Workshop on LHC beam operation, Evian, France)

[5] Bradu B, Rogez E, Iadarola G, Blanco E, Ferlin G and Tovar A 2016 *Compensation of Beam Induced Effects in LHC Cryogenic Systems* (7th Int. Part. Accel. Conf., Busan, South Korea)

[6] Bradu B, Rogez E, Blanco E, Ferlin G and Tovar A 2016 *Beam screen cryogenic control improvements for the LHC run 2* (26th Int. Cryo. Eng. Conf., New-Delhi, India)