COMPENSATION OF BEAM INDUCED EFFECTS IN LHC CRYOGENIC SYSTEMS

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Abstract

This paper presents the different control strategies deployed in the LHC cryogenic system in order to compensate the beam induced effects in real-time. The LHC beam is inducing important heat loads along the 27 km of beam screens due to synchrotron radiation, image current and electron clouds. These dynamic heat loads significantly disturb the cryogenic plants and automatic compensation is mandatory to operate the LHC at full energy. The LHC beam screens must be maintained in an acceptable temperature range around 20 K to ensure a good beam vacuum, especially during beam injections and energy ramping where the dynamic responses of cryogenic systems cannot be managed with conventional feedback control techniques. Consequently, several control strategies such as feed-forward compensation have been developed and deployed successfully on the machine during 2015 where the beam induced heat loads are forecast in real-time to anticipate their future effects on cryogenic systems. All these developments have been first entirely modelled and simulated dynamically in order to be validated, allowing then a smooth deployment during the LHC operation.

INTRODUCTION

In most superconducting particle accelerators such as the LHC (Large Hadron Collider) at CERN (European Organisation for Nuclear Research), the dedicated cryogenic systems are used to maintain the superconductivity in the magnets and RF cavities. Nevertheless, particle beams travelling through the magnets can generate important heat losses in the beam vacuum chambers and these dynamic heat loads must be removed as well by the cryogenic systems. For this reason, the LHC embeds a *beam screen* within the beam pipe in order to remove the beam induced effects and to ensure an ultra-high vacuum [1].

LHC BEAM SCREENS

The LHC beam screens are cooled by supercritical helium at 3 bar and 4.6 K provided by cryogenic refrigerators located at the surface. Helium is then heated up to 20 K by the beam induced effects or by an electrical heater when the beam is not present. The beam screen temperature has to be maintained as stable as possible to ensure an ultra high vacuum in the beam pipe and a stable gaseous helium return flow to the refrigerators. The temperature is controlled by a heater at the inlet and by a control valve at the outlet, see Figure 1. In total, the LHC contains 485 beam screen cooling loops over the 27 km and a typical loop in the arc measures 53 m (half-cell).

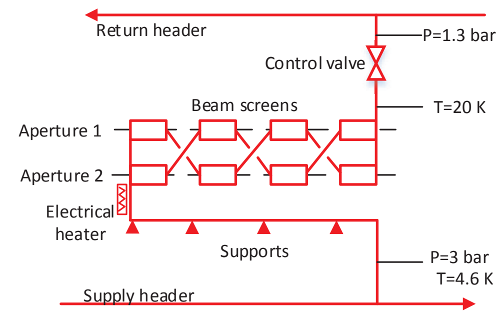

Figure 1: LHC beam screen cooling scheme.

During Run 1 of the LHC in 2010-2012, the deposited beam screen heat loads (Q_{dbs}) were pretty low, about 0.1 W/m per aperture, corresponding to only 1.7 % of the total LHC refrigeration capacity at 4.5 K. As particle bunches were separated by a gap of 50 ns only, these heat loads were induced by synchrotron radiations and image current [2]. For LHC Run 2 (2015-2018), the bunch spacing was reduced to 25 ns in order to get higher beam intensity and thus electron cloud effects become dominant in the beam screen heat loads [3]. The LHC design report forecasts a total beam screen heat load of about 0.8 W/m per aperture at nominal conditions [4] which represents a significant part of the installed cryogenic capacity at 4.5 K (about 12 %). As these heat loads are dynamic and can evolve rapidly compared to the cryogenic system inertia, automatic compensation is mandatory in the cryogenic control system.

BEAM SCREENS TEMPERATURE CONTROL

The beam screen inlet temperature is maintained above a minimum temperature using the electrical heater at the entrance of the circuit to avoid thermo-hydraulic oscillations and the outlet temperature is controlled at 20 K using the control valve. To perform these controls, classical PID (Proportional-Integral-Derivative) controllers are used. Unfortunately, the time constants and delays of the cryogenic systems regarding the beam induced heat load dynamics are not suitable for such feedback loops and the PID controllers cannot reject these disturbances efficiently [5].

To improve the control of the temperature ensuring its stability, *feed-forward* actions on the valve and on the heater have been added to prevent the beam disturbances. These feed-forward contributions are calculated from the available beam information (energy, intensities, number of bunches

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and bunch length means) to estimate the beam induced heat loads and to position the valve and the heater close to their final expected values, see Figure 2 where the control scheme is represented, embedding the feed-forward transfer functions $FF1$ and $FF2$. Moreover, the inlet temperature set-point is switched between 13 K and 6 K according to the presence of the beam to save energy.

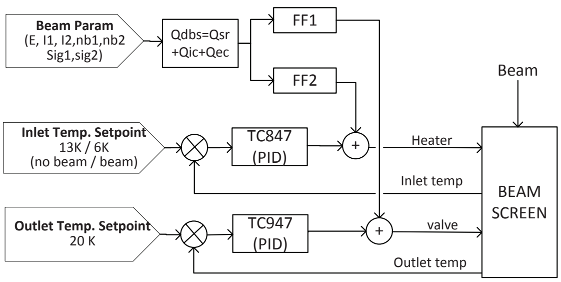

Figure 2: LHC beam screen control scheme.

This control scheme has been validated using dynamic simulations performed with the modeling and simulation software EcosimPro and the cryogenic library CRYOLIB [6], see Figure 3, where two dynamic simulations are compared. Once validated in simulation, this improved control scheme has been successfully deployed in 2015 throughout the entire LHC cryogenic control system. Nevertheless, to have these feed-forward actions working in an efficient way, it is necessary to correctly estimate the deposited heat load on the beam screens in real-time, otherwise a temperature overshoot or a sub-cooling of the beam screens can be observed.

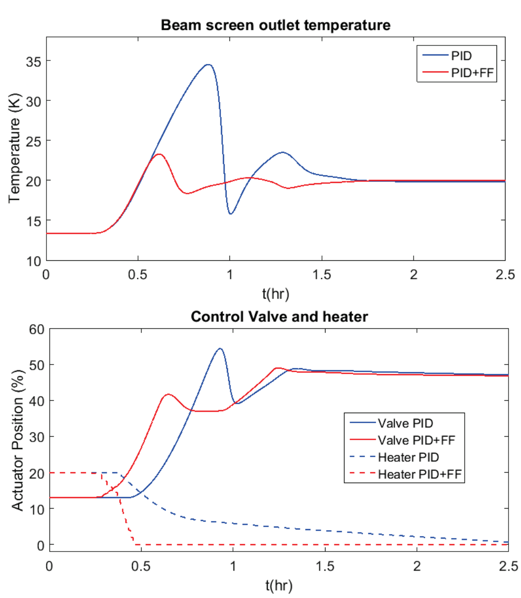

Figure 3: Simulations of the beam screen cryogenic circuit during a beam injection generating 1.2 W/m per aperture with and without Feed-Forward actions (FF).

DEPOSITED HEAT LOAD ESTIMATIONS IN BEAM SCREENS

Computation of beam screen heat loads

The deposited heat load on the beam screens Q_{dbs} can be computed as the sum of three main induced heat loads contributions as represented in equation (1): synchrotron radiations Q_{sr}, image current Q_{ic} and electron clouds Q_{ec}.

$$Q_{dbs} = Q_{sr} + Q_{ic} + Q_{ec} \tag{1}$$

Synchrotron radiation and image current contributions can be estimated by scaling their design values with the beam parameters [7] as represented in equations (2) and (3). The Table 1 describes all constants.

$$Q_{sr} = \bar{Q}_{sr} \cdot L \cdot \left(\frac{E}{\bar{E}}\right)^4 \cdot \left(\frac{N_b}{\bar{N}_b}\right) \cdot \left(\frac{n_b}{\bar{n}_b}\right) \tag{2}$$

$$Q_{ic} = \bar{Q}_{ic} \cdot L \cdot \sqrt{\frac{0.6 \cdot E + 2800}{\bar{E}}} \cdot \left(\frac{N_b}{\bar{N}_b}\right)^2 \cdot \left(\frac{n_b}{\bar{n}_b}\right) \cdot \left(\frac{\sigma}{\bar{\sigma}}\right)^p \tag{3}$$

Concerning the electron cloud contribution Q_{ec}, there is no such simple scaling as it depends on the injection scheme of the machine (*i.e.* including the number and length of the gaps that are present in the bunch train) and on the conditioning of the surface where electrons are generated. Moreover, this term has a tendency to decrease with the running time of the machine as the beam circulation gradually conditions the surface.

Nevertheless, the electron cloud heat load increases with the intensity and the energy of the beam. It is then possible to establish from measurements along the ring an electron cloud heat load value per bunch for each part of the machine at the injection energy (q_{eci}) and at the final energy after the ramp (q_{ecr}). Finally, the equation (4) was used to model the electron cloud contribution for each LHC sector. The terms q_{eci} and q_{ecr} are the measured electron cloud heat load per bunch at the beginning of the run. The terms K_{ecr} and K_{eci} are tuning parameters to adjust the heat load estimations according to the conditioning taking place in the machine along the run: these two terms are equal to 1.0 at the beginning of the run and they are then decreased manually by operators according to the cleaning effect.

$$\begin{aligned} Q_{ec} &= K_{eci} \cdot \frac{q_{eci}}{2} \cdot \left(1 - \frac{E - E_{inj}}{E_{ramp} - E_{inj}}\right) \cdot n_b \cdot \frac{N_b}{\bar{N}_b} \\ &+ K_{ecr} \cdot \frac{q_{ecr}}{2} \cdot \left(\frac{E - E_{inj}}{E_{ramp} - E_{inj}}\right) \cdot n_b \cdot \frac{N_b}{\bar{N}_b} \end{aligned} \tag{4}$$

Comparisons with real measurements

During Run 1, the synchrotron radiation and the image current contributions could easily be calculated because the electron cloud effect could be neglected as the LHC was running with a bunch spacing of 50 ns. Results were satisfactory in arc cells but extra heat loads were measured

Table 1: LHC Beam Screen Heat Load Constants

Name	Description	Value
L	Beam screen length	$53\ m$
$\bar{E}$	Nominal energy	$7\ TeV$
E_{inj}	Injection energy	$0.45\ TeV$
E_{ramp}	Final energy after ramp	$6.5\ TeV$
$\bar{N}_b$	Nominal protons per bunch	$1.15 \cdot 10^{11}$
$\bar{n}_b$	Nominal bunches per beam	2808
$\bar{\sigma}$	Nominal bunch length mean	$1.06\ ns$
$\bar{Q}_{sr}$	Nominal synch. rad. load	$0.165\ W/m$
$\bar{Q}_{ic}$	Nominal image current load	$0.135\ W/m$
p	Bunch dependence factor	-1.5

in Inner Triplets [7] due to the increase of the electron cloud contribution, coming from the presence of the two counter rotating beams in the same beam screen [8].

From 2015, all beam screen heat loads are directly calculated and displayed online performing an energy balance in the beam screen cooling loops [9]. The measured heat loads were much higher than expected when the bunch spacing was reduced to 25 ns and very important differences between sectors were observed (1.4 W/m per aperture in arc12 and 0.42 W/m in arc34). Nevertheless, the set of equations (2), (3) and (4) allows us to properly estimate these heat loads thanks to the tuning parameters in the electron cloud term. Beam screen heat loads and their estimations are compared in Figure 4. Hence, this set of equations is suitable to perform efficient feed-forward actions.

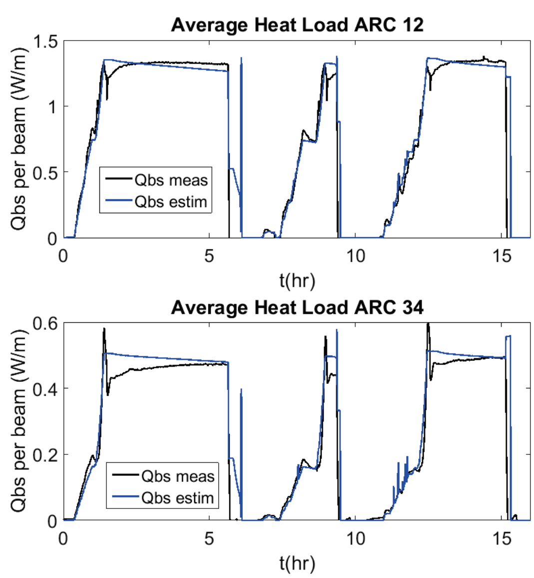

Figure 4: Measured and estimated deposited beam screen heat loads in November 2015.

RESULTS OBTAINED IN 2015

During 2015 the improved control scheme embedding the feed-forward compensations has been deployed progressively in the 16 Siemens PLCs (Programmable Logic Controller) in charge of the LHC cryogenic control along the ring. After the parameter tuning, the improved control scheme yielded very good results where all temperatures were correctly controlled at 20 K without overshoot. Moreover, the refrigeration power was optimized during transients by quickly shutting-off all beam screen heaters during the injection, see Figure 5.

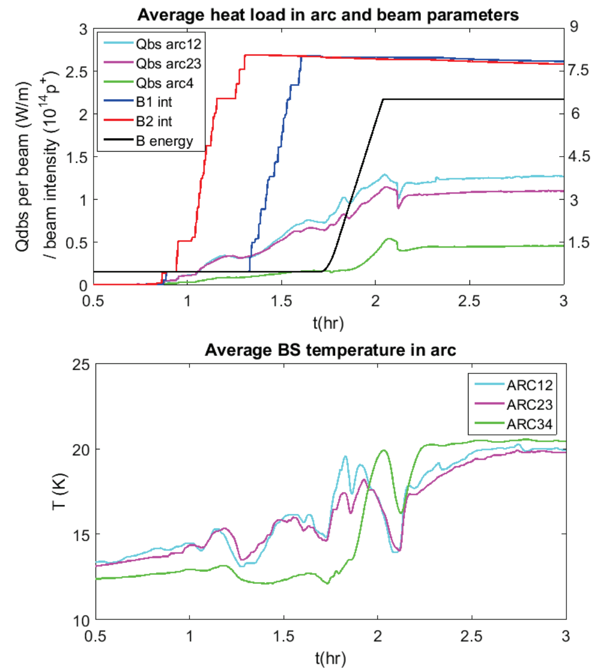

Figure 5: Measurements in November 2015 during the fill # 4569 in 3 LHC sectors (2244 bunches at 6.5 TeV).

CONCLUSION

Since 2015 the LHC cryogenic system is significantly disturbed by beam induced effects, mainly because of the electron cloud effect when the bunch spacing is 25 ns. These fast dynamic heat loads represent up to 25% of the installed cryogenic refrigeration power and automatic compensation is then mandatory in the cryogenic control system to correctly manage the transients. To handle these heat loads, a feed-forward control based on the beam information has been deployed on the 485 beam screen cooling loops along the LHC, allowing to ramp the beam intensity up to 2244 bunches in 2015. For the rest of the LHC Run 2, the beam screen heat loads estimation will be refined and the LHC refrigeration power should be ready for 1.5 W/m per aperture, as compared to the 0.8 W/m initially forecast thanks to less heat load on the 1.9 K cold mass than expected.

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