Automatic LHC accelerator warm-up and cool-down experience during the Long Shutdown 2

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Abstract. During the so-called Long Shutdown 2 (LS2), the Large Hadron Collider (LHC) has been entirely warmed-up in 2019 and cooled-down in 2020/2021 after an important maintenance period. For the first time, these complex and delicate operations have been performed in an automatic way, using a new control logic implemented in the Process Logic Controllers (PLC). This new control logic is based on similar experiences that occurred in 2008, 2013 and 2014 where many manual operations were still needed to ensure all the constraints around the machine. After a short presentation of the general LHC warm-up and cool-down principles and constraints, this paper details the global control logic that has been chosen to fulfil all requirements. This new approach is using thermodynamic considerations to spread efficiently the available helium massflows and refrigeration capacity along a LHC sector of 3.3 km (the accelerator totalizing eight cryogenic sectors), optimizing the transient time and respecting the constraints. Finally, the warm-up and cool-down achieved on the eight LHC sectors between 2019 and 2021 are presented and discussed, validating this new approach.

1. Introduction

In the Large Hadron Collider (LHC) lifetime, it has been foreseen entire warm-up and cool-down during the so-called Long Shutdown (LS) happening every 4 years in average. Before the Long Shutdown 2 (LS2), started in 2019, the LHC has been entirely cooled-down twice in 2008 and 2014, and warmed-up only once in 2013.

These cryogenic operations are complex and delicate tasks and the automatic control logic to perform these tasks were not fully satisfactory due to many manual interventions still mandatory to ensure the different constraints and allowing a reasonable transient time. Using the existing cool-down and warm-up experiences, it was decided to update and optimise the associated automatic control logic to perform these transients in an improved automated way for the LS2.

2. General LHC cool-down and warm-up principles and constraints

The LHC cryogenics system is divided in eight sectors of 3.3 *km* each, embedding a total cold-mass of 4600 *tons* each that must remain at 1.9 *K*. The helium inventory for a LHC sector is 10 *tons* in the magnets and 4 *tons* in the cryogenic distribution line (QRL). Since the very beginning of the LHC project, the different cool-down and warm-up scenarios have been carefully studied and even simulated for validation, see for instance [1] or [2]. In practice, each sector cool-down can be achieved in about five weeks, including four main stages :

(i) From 300 *K* to 80 *K*: Pre-cooling helium with liquid nitrogen (LN2) delivered in about 52 transportable ISO-containers of 21 *tons* each (1100 *tons* of LN2 in total) in about 3 weeks.

(ii) From 80 K to 20 K: Cool-down with helium expansion turbines in about 3 days.

(iii) From 20 K to 4.5 K: Continued with helium expansion turbines and filling some 10 *tons* of helium in the machine in about 1 week.

(iv) From 4.5 K to 1.9 K: Continued with helium expansion turbines and pumping using cold compressors down to 15 *mbar* in 4 days to reach 1.9 K in magnets.

For the warm-up, it takes a bit less than five weeks using the following sequence:

(i) From 1.9 K to 4.2 K: warm-up of the sub-cooled liquid helium using the electrical heaters distributed all over the magnets in about 2 days (2 kW of electrical power is available in total).

(ii) From 4.2 K to 20 K: Vaporization and recovery in the helium storage premises of some 10 *tons* of helium located in the magnets, still using the electrical power distributed over the magnets in about 5 days.

(iii) From 20 K to 300 K: Active warm-up of the magnets during about 25 days by circulation of warm helium using a large electrical heater (600 kW are available) located in the cryogenic interconnection box of each sector. Note that two degradations of the insulation vacuum are performed around 80 K and 250 K to accelerate the warm-up.

Moreover, during all these transient operations, several constraints must be always fulfilled in order to ensure the integrity of all the accelerator components (magnets, interconnections, bellows, thermal insulation, etc.). Today, the following constraints are retained for the LHC:

- The **gas speed** in the cryogenic circuits shall remain below 50 m/s to avoid extra mechanical stress on the flexibles and to avoid Kapton pulling in the magnets.
- The **temperature gradient** between two consecutive magnets (15 m) shall remains below 75 K to ensure a moderate mechanical stress between each magnet (i.e. a local thermal gradient below 5 K/m).
- The **cool-down speed** between 300 K and 80 K shall be lower than 10 K/hr to limit the mechanical stress on the compensators of the cryogenic distribution line (QRL).
- The **quench valves** used to select the left or right cells during warm-up and cool-down shall not be manipulated too frequently. A minimum time of 12 hours shall be respected between each switch to conserve an efficient sealing system during their lifetime.

3. Process control logic definition and implementation

The general principles previously defined remain valid and have proven their efficiency in the past. The novel approach proposed here concerns the way the helium flows are distributed *along the arc* (the central curved section of 2.9 km of the sector containing the 1.9 K main magnets) and *inside the double-cells*. Note that the same approach has been setup for cool-down and warm-up operations as these operations are mirrored.

Each LHC arc is divided in 27 cells of 107 m each. All cells are almost identical (190 *tons* of cold mass for 2500 *litres* of helium), except at the extremities where cells are slightly smaller. To cool-down and warm-up the magnets, there is one helium supply control valve (CV_{920}) for each double-cell and there is one on/off outlet valve per cell (QV_{923} on the left cell and QV_{927} on the right cell) that are also used in case of quench, see Figures 1 and 2. Hence, during the cool-down/warm-up phases, the flow is controlled by the CV_{920} and the one needs to choose if we circulate either in the left, either in the right cell by opening the corresponding quench valve.

Thus, the challenge for the cool-down and warm-up automatic logic is to spread the available helium flow over the parallel cells in an efficient manner, while respecting all the constraints to achieve it in a minimum of time. To achieve that, the principle is to first *share the flows along the arc* minimizing the temperature gradient between each double-cell and then to *switch the flows inside each double-cell* minimizing the temperature gradient between each single cell.

3.1. Flow sharing along the arc

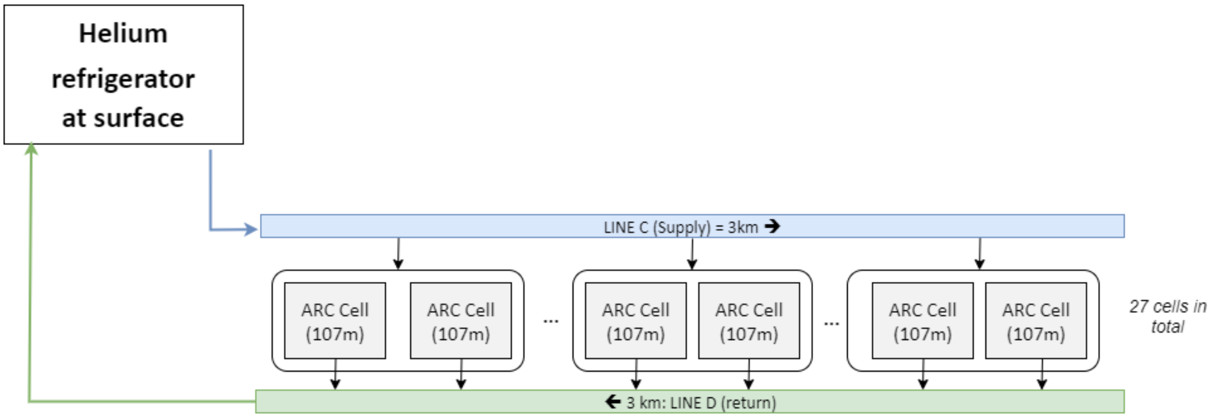

Figure 1. LHC ARC cooling scheme (3 km)

The main idea proposed here is to first compute the remaining energy to be spent in each double-cell to finish its cool-down/warm-up as defined in Eq. (1) where M_i is the double-cell cold-mass, T_1 and T_2 are the starting and the final temperatures and $Cp(T)$ is the heat capacity of the cold-mass (considered as stainless steel 304).

$$E_i = M_i \cdot \int_{T_1}^{T_2} Cp(T) \cdot dT \tag{1}$$

Then, the massflows $\dot{m}_i$ of each double-cell is computed to spread the total available massflow of the arc $\dot{m}_{arc}$ (parameter provided by the cryogenic operators with a nominal value of 700 g/s) as function of the remaining cool-down/warm-up energy, see Eq. (2). Moreover, to never over-pass the gas speed limits in the circuits and to maximise the massflows, the supply and return line pressures are setup as high as possible to maximize the gas densities (Line C at 16 *bar* and line D at 4 *bar*) with a massflow high limit setup at 70 g/s for each double-cell. This setup allows to not exceed the 50 m/s speed limit in the worst case at warm temperature.

$$\dot{m}_i = \max(\dot{m}_{arc} \cdot \frac{E_i}{\sum E_i}, 70) \tag{2}$$

As consequence, all the available massflow will be distributed over the arc and the double-cells needing more cooling/warming power will benefit from more massflow than others and vice-versa. As consequence, all the double-cells will be cooled-down/warmed-up at similar speeds, guarantying a minimum thermal gradient over the arc. Note that to ensure these massflows, each CV_{920} is driven by a PID controller (FC) regulating the flow over the circuit using a Virtual Flow-meter (VFT), see [3] for details.

3.2. Flow management inside a double-cell

The next challenge is to maintain a reasonable temperature gradient between the magnets and between the left and the right cells by switching at appropriate time the quench valves.

After the existing experiences in the previous years, the following switching logic has been selected for the cool-down if the last switch occurred more than 12 hr ago (the warm-up logic is symmetrical):

- if $dTT_{min} > 45\ K$: Switch to the hottest cell;
- if $TT_{AVG} > 50\ K$ and if $\frac{dTT_{max}}{TT_{AVG}} > 10\ \%$: Switch to the hottest cell;
- if $TT_{AVG} < 50\ K$ and if $dTT_{max} > 5\ K$: Switch to the hottest cell;

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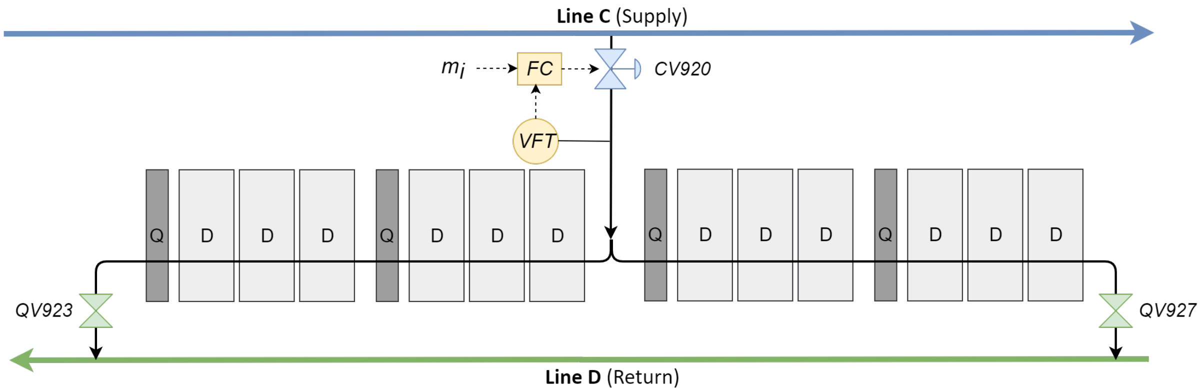

Figure 2. A double cell cooling scheme (2x107 m). Each cell is constituted by 6 dipoles magnets (D=15 m) and 2 quadrupoles magnets (Q=8 m).

where TT_{AVG} is the average temperature of the double cell, dTT_{min} and dTT_{max} are respectively the difference between the coldest and the warmest magnet in the right and the left cell. Moreover, in parallel of this switching logic, the supply helium temperature (Line C) is decreased by steps of 50 K (with a speed of about 6 K/hr at each step) when the cold wave has over-passed at least one magnet on the right and on the left cell of each double-cell. This rule allows to never exceed a gradient of more than 75 K between each magnet and to respect the 150 K of total gradient over the sector.

3.3. Code implementation

The LHC cryogenic control system is based on a control standard called UNICOS [4] and it is interacting with many process logic of thousand variables and loops. Over the years, CERN has continuously investigating innovative methods looking for improvements in code quality assurance and in manpower optimization for the control system production. Thus, CERN is using continuous integration practices, allowing a more reliable and versatile process control system [5].

To update the existing control system related to these cool-down and warm-up operations, the code of 312 valves and 104 PID controllers have been updated easily using dedicated generic Python templates to instantiate each of these devices. Moreover, additional alarms to prevent too high thermal gradients between each cell and between each magnet have been added to help operators in the constraint monitoring during the cool-down and warm-up transient periods.

4. Results obtained during the LS2

This new control logic has been used during the LS2 warm-up and cool-down of LHC. The Figures 3 and 4 represent the magnet temperatures (average, max and min) and the difference between the warmest and the coldest magnet in each arc during each LS2 warm-up and cool-down.

We can first notice that all warm-up and cool-down time have been similar on all the sectors (about five weeks). Nevertheless, some slow-down of few days can be noticed above 80 K on some arcs due to some voluntary interruptions needed for some tunnel interventions (helium circulation during the transients above 80 K must be reduced during accesses for safety reasons). Note also that the stops of the cool-down observed at the end in some sectors are due to the cool-down interruption for the *Yearly End Technical Stop* period where CERN was closed.

Moreover, this new automatic approach allowed us to better respect all constraints during the warm-up and cool-down transients. As example, the different constraints have been plotted for the ARC34 during the LS2 warm-up and cool-down in the Figures 5 and 6 where we can appreciate the local gradient between each of the 200 magnets (max 5 K/m) and the maximum gas speed inside each cooling circuits

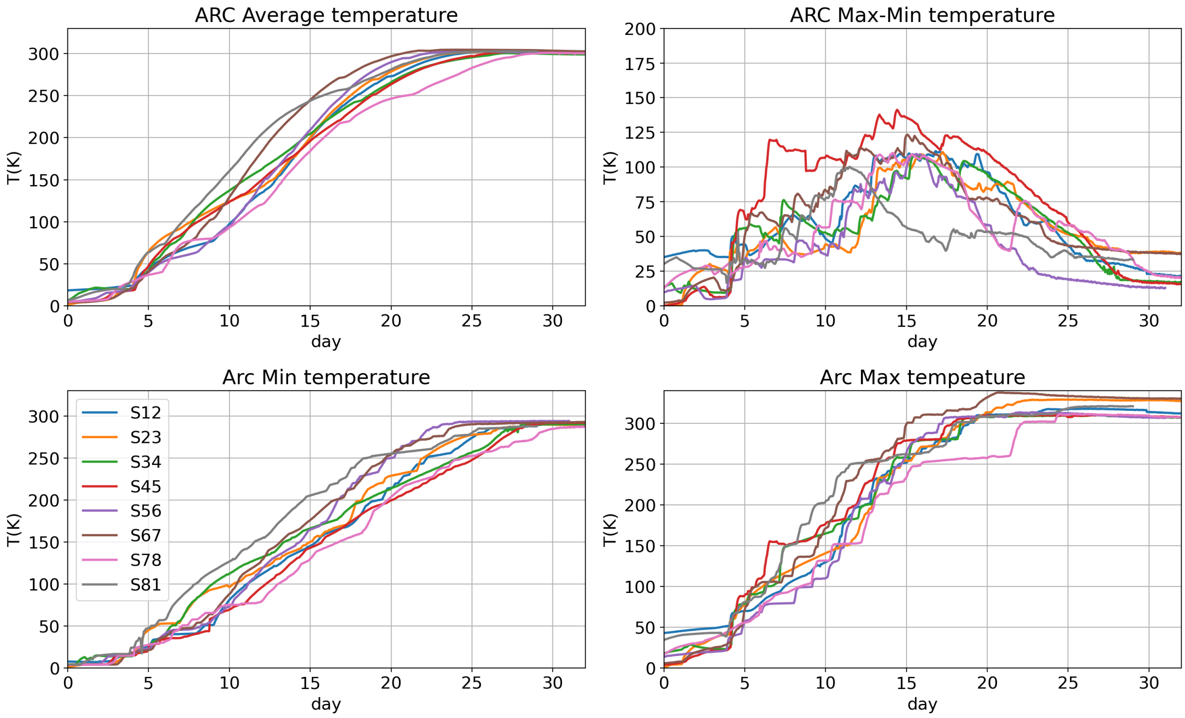

Figure 3. LHC temperatures during the LS2 warm-up between January and April 2019

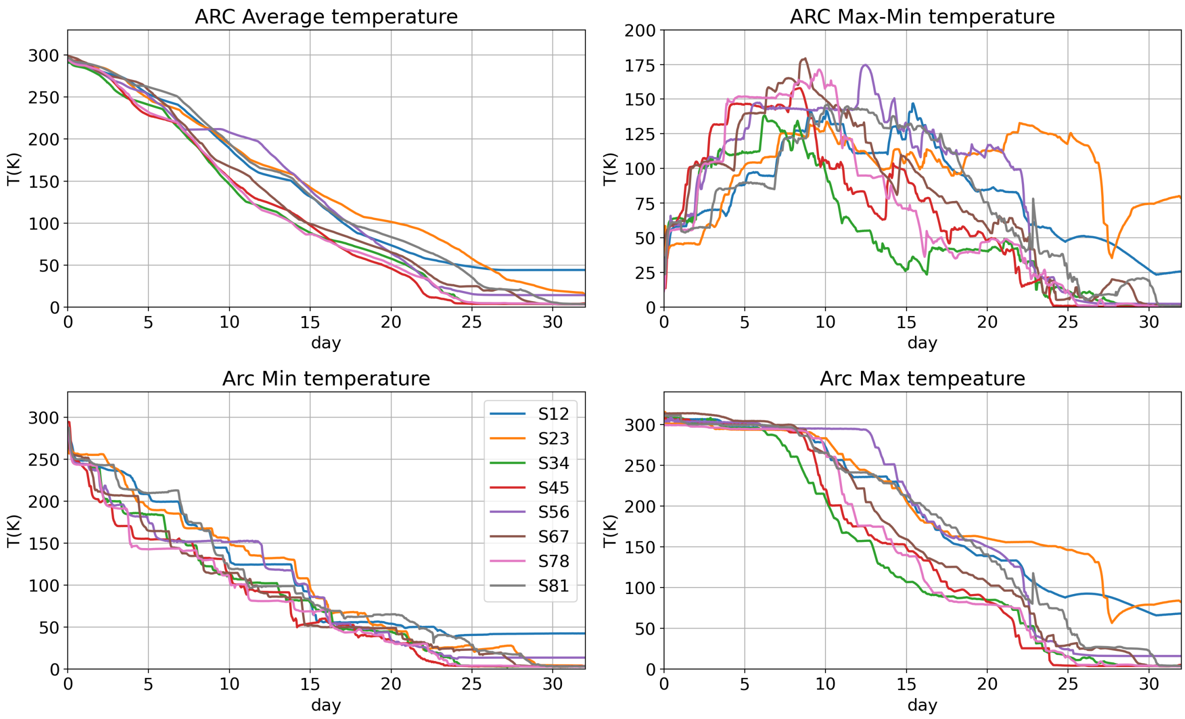

Figure 4. LHC temperatures during the LS2 cool-down between October 2020 and May 2021

(max 50 m/s). We can notice that all constraints have been correctly ensured during these periods (dotted black lines), except for very short time periods where some small deviations were observed but they were fully acceptable. Note that the observations detailed here about the ARC34 are representative of all other sectors where similar observations have been made.

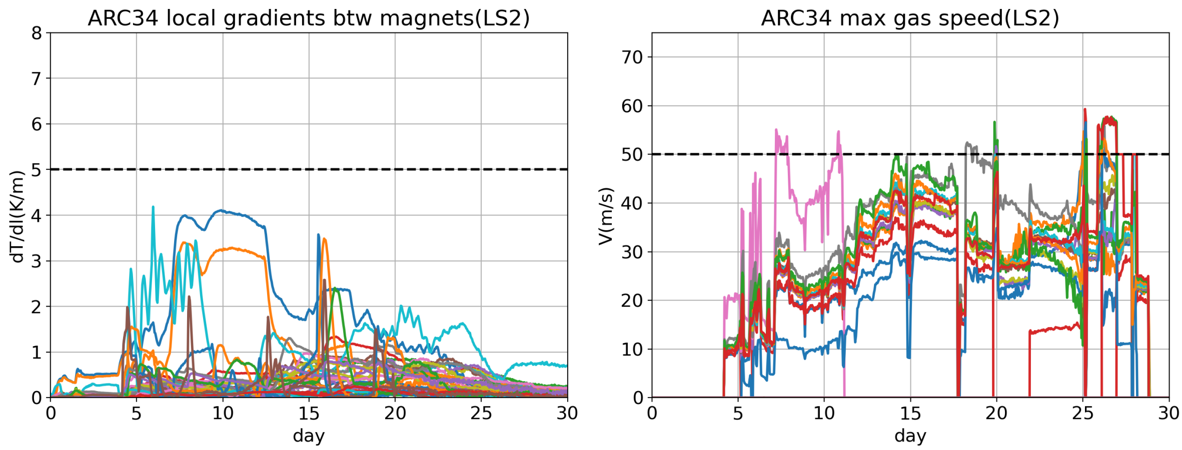

Figure 5. ARC34 constraints during the LS2 warm-up (March 2019)

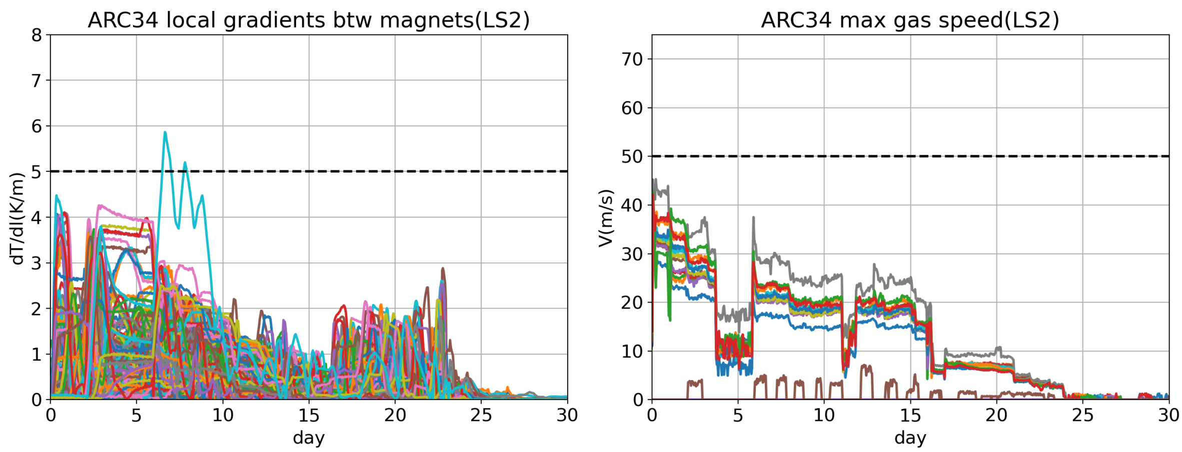

Figure 6. ARC34 constraints during the LS2 cool-down (November 2020)

5. Conclusion

The LHC cool-down and warm-up operations are complex and delicate tasks due to the size of the machine inducing a large amount of constraints to be respected. As we can have up to four parallel cool-down or warm-up over the LHC, it means that about 1000 indicators must be monitored and followed to respect the different constraints 24h/24h and 7 days/week during about six months.

Since the beginning of the LHC cryogenic operation in 2008, many actions were still ensured manually and it was very challenging to manage all these constraints everywhere at any time. The cool-down and warm-up automatisations proposed here have alleviated significantly the cryogenic operation team duties during these intense periods. Moreover, results were fully satisfactory as the constraints were better monitored and respected than before, reducing the stress on the operation teams.

6. References

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