

Beam induced heat load instrumentation installed in LHC during the Long Shutdown 2

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Abstract. During the second run of the Large Hadron Collider (LHC) between 2015 and 2018, significant beam induced heat loads have been observed on the beam screens circuits impacting the cryogenic system capacity, mainly due to the electron clouds generated by the beams. To validate these measurements and to obtain precise heat load assessments and comparison with preliminary calculations based on existing hardware equipment at selected locations, it was decided to add new cryogenic instrumentation around the machine. In total, 23 Coriolis flowmeters (cold conditions), 4 thermal flowmeters (room temperature conditions) and 58 Cernox thermometers have been installed and commissioned between 2019 and 2021 during the so-called long shutdown 2 (LS2). This paper presents an overview of this project, including the commissioning of these instruments and confirming at first stage the original heat load estimations.

1. Introduction

The Large Hadron Collider (LHC) cryogenic system is operational since 2008 and the dynamic heat loads applied on the cryogenic system were easily compensated during the first running period between 2010 and 2012. During the second running period between 2015 and 2018, the intensity and the energy of the beams were increased and the LHC cryogenic system started to receive significant beam induced heat loads (BIHL) around the machine. These BIHL are due to the *synchrotron radiations* (proportional to the beam intensity and to the fourth power of the beam energy), to the *image current* (proportional to the square of the beam intensity) and to the *electron clouds* (proportional to the beam intensity but visible only when the bunch spacing is short enough: 25 ns in the LHC case). All these heat loads are deposited on the so-called beam screens that are cooled between 4.5 K and 20 K using supercritical helium around 3 bar.

After some extensive measurements of these beam induced heat loads, it appeared that the synchrotron radiations and the image current were perfectly fitting the predictions of about 0.7 W/m. Nevertheless, the electron-cloud heat loads, initially planned to be at about 0.9 W/m seemed to be erratically distributed over the machine with very high values in some locations (up to three times more than the expected values), see [1] for more details.

As consequence, a *Beam Induced Heat Load Task Force* has been put in place at CERN to validate these observations, to understand the underlying mechanisms, and to propose possible mitigation techniques as these heat loads could lead to a limitation of the LHC performance. As result, this task force proposed to install additional instrumentation in the LHC cryogenic system to validate definitively these measurements and to better assess the beam induced heat loads. This proposition was approved by the LHC Machine Committee and it was decided to install these new instrumentation during the Long Shutdown 2 (LS2) in 2019 and 2020.



2. New instrumentation proposal

The new instrumentation proposition concerns some *local measurements* at the beam screen level, but also some *global measurements* at the general cryoplant interfaces in order to crosscheck the local measurements and to obtain some extra information about the cryoplant operation that could be useful for future optimizations.

2.1. Local measurements

The estimate of the beam induced heat load is based on the beam screen helium massflow and on the temperature difference along the beam screen. The original beam screen instrumentation is composed by an inlet and an outlet temperature sensors in each beam screen cooling loop. A such cooling loop is called an *half-cell* and is 53 m long, embedding three dipole magnets (15 m each) and one quadrupole magnet (8 m each), see figure 1.

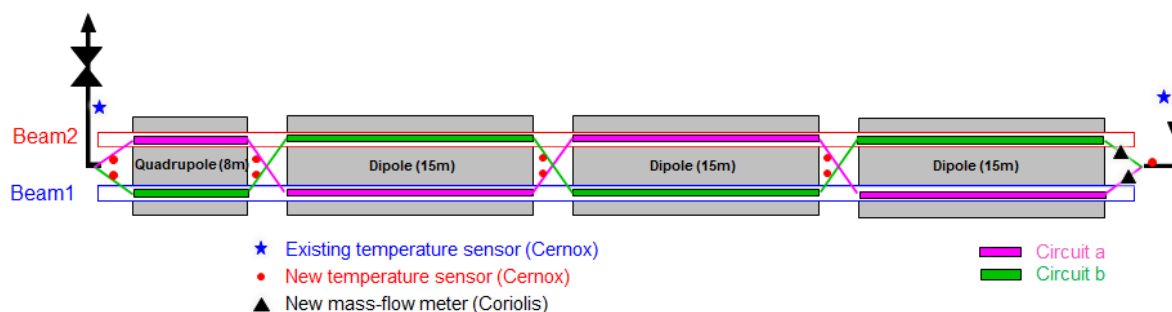


Figure 1. Beam screen cooling loop (53 m) with the existing and the new instrumentation

Hence, the massflow was unknown before this instrumentation upgrade (but the total massflow can be estimated via the outlet valve) and the heat load spatial resolution was 53 m. Note also that the beam screens are cooled via two parallel circuits (called *a* and *b*) crossing at each magnet interconnection to homogenise the temperatures between the two apertures in case of disequilibrium between the beam 1 and the beam 2 heat loads. Moreover, each circuit is composed by two parallel cooling tubes of 3.7 mm inner diameter each, see the figure 2.

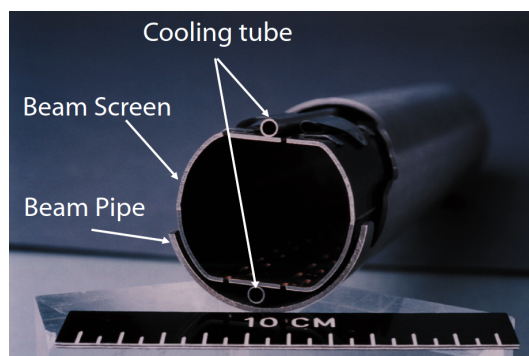


Figure 2. Beam screen cross section (one aperture)

The proposition to better assess the heat loads is to add a pair of Coriolis flowmeters in each cooling circuit to know precisely the total massflows in the half-cell and to add a pair of Cernox temperature sensors at each magnet interconnection, see figure 1.

This new set of instrumentation would allow the one to estimate the beam screen heat loads with a high accuracy thanks to the Coriolis mass flowmeters and to improve the spatial resolution to about 15 m for each aperture thanks to the additional thermometers. Moreover, it will be possible to distinguish the heat loads coming from each beam circulating in each aperture of the accelerator when the beams will be back.

Ten half-cells with such an instrumentation around the LHC were selected in order to obtain enough statistics and to cover half-cells with different heat load ranges, see figure 3 where the over-instrumented half-cells are identified around the machine by green stars.

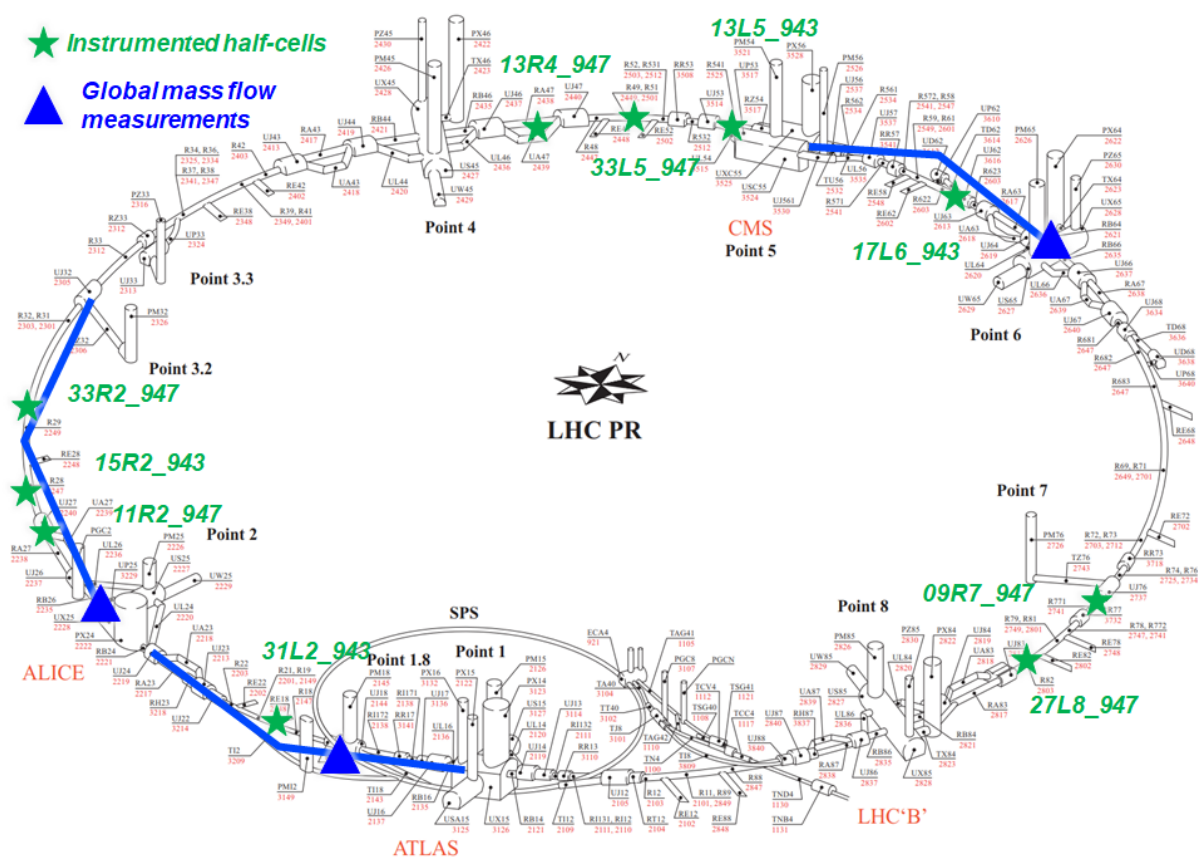


Figure 3. Locations of the new instrumentation around the LHC

2.2. Global measurements

In addition, some sectors are equipped with global massflow measurements to assess precisely the total heat loads applied over a full LHC sector of 3.3 km. It was decided to equip with flowmeters the different helium return lines as it was more complicated and risky to equip the supply lines.

As the return line for the main 1.8 K cooling loops was already equipped with a Venturi flowmeter, only two flowmeters had to be installed for a given sector: one Coriolis flowmeter on the beam screen return line at 20 K and one thermal flowmeter on the Warm Recovery Line (WRL) at ambient temperature, see figure 4. Finally, two high-load sectors (S12 and S23) and one low-load sector (S56) are equipped, see the blue stars in the figure 3.

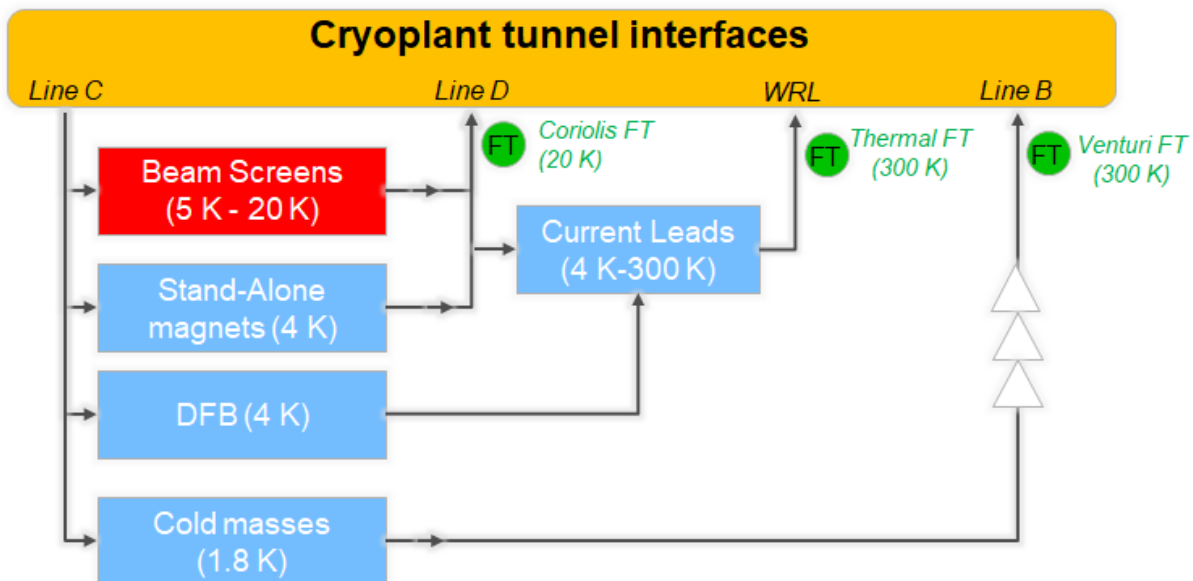


Figure 4. General LHC sector flow scheme with global massflow measurements

3. Installation during the LS2

3.1. Local measurements

The installation of the new local instrumentation in the magnet interconnections was included in the DISMAC project of the LS2 [2, 3]. Similar installations of thermometers on beam screen circuits were already done in the past and this task followed identical procedures to ensure good reproducibility. On the other hand, the integration of the Coriolis flowmeters in the magnet interconnections having a very limited available space was very challenging and several 3D modelling and prototypes were necessary to obtain a suitable and reliable solution, see figure 5 where the final 3D model of the integration is represented with an associated picture in the LHC tunnel after the first installation.

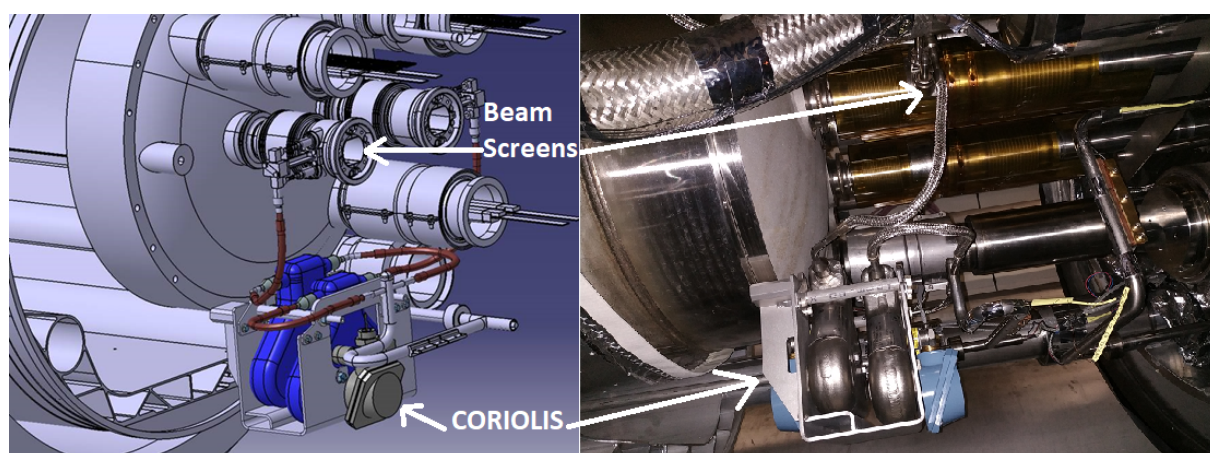


Figure 5. A pair of Coriolis flowmeters attached to a LHC dipole magnet

3.2. Global measurements

The installation of the thermal flowmeter on the warm recovery line (WRL) was a standard intervention whereas the installation of the Coriolis flowmeter inside in the cryogenic interconnection box (QUI) was a delicate task as the space was very limited, without any possibility of extension of the vacuum vessel. Again, several 3D model studies were mandatory to allow this delicate integration, see the figure 6 where the related 3D model and a photo of the flowmeter inside the QUI are shown.

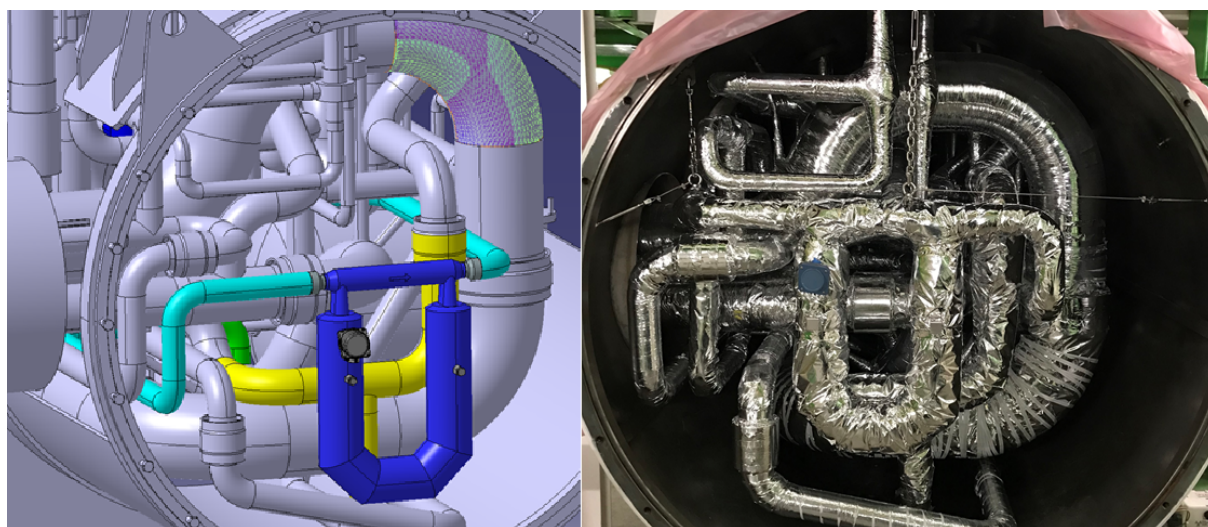


Figure 6. The Coriolis flowmeter (in blue) inside a LHC cryogenic interconnection box

4. Commissioning of the instrumentation

After having installed this new instrumentation and performed all the required qualification tests, the LHC was cooled at the end of the LS2. Then, the beam screen cooling circuits were put back in service to perform some measurements in order to validate the previous heat load estimates.

4.1. Local measurements

First of all, additional temperature sensors can be easily validated by varying the beam screen temperature over its operation range between 5 K and 20 K and calculating the standard deviation between all sensors (nine sensors per half-cell). Results were satisfactory in all half-cells where the measured standard deviations are below 0.1 K, inducing an error below 1 % in the heat load calculations.

Then, for the Coriolis flowmeters, the validation consists in increasing the control valve opening (CV) and the electrical heater power (EH) of the beam screen circuit together progressively to maintain a temperature at about 20 K along the beam screen. The massflow is then gradually increased keeping a constant temperature at the valve inlet and we can compare the massflow measured by the Coriolis flowmeters against the previous calculation done via the valve equation. As the heat load is proportional to the massflow and to the enthalpy gradient ($\dot{Q} = \dot{m} \cdot \Delta h$), the error generated by the valve equation is proportional as well. In addition to this, as in this test the beam screen circuit is heated via an electrical heater with a known power, the massflow can be also deduced such that: $\dot{m} = \frac{EH}{\Delta h}$.

Some results are represented for one half-cell in the figure 7. It can be first noticed on the bottom-left plot that the massflow measurements in the two parallel circuits are very similar, demonstrating a good hydraulic impedance equilibrium between the circuits. Then, if we compare the total massflow measured by Coriolis (black curve) against the previous calculation done via the valve equation (light grey curve) in the top-left plot, the difference is about 10 %, which is in agreement with our expectation. Note that

these values are also in agreement with the massflow calculated using the electrical heater power (dark grey curve).

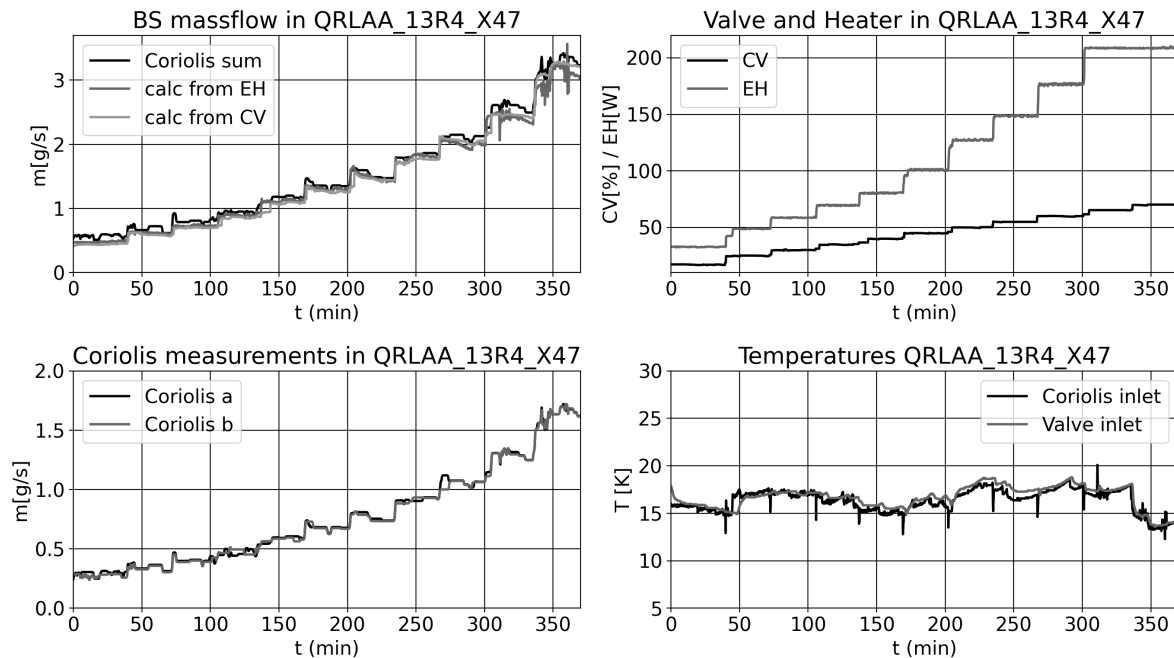


Figure 7. Coriolis massflow measurements in half-cell 13R4

Between April and June 2021, seven over the ten instrumented half-cells were validated during the LS2, and all of them have demonstrated similar results. The three remaining half-cells will be commissioned in the coming months. The figure 8 represents the beam screen heat loads (QBS) originally calculated in these seven half-cells for a typical Run 2 LHC fill using the valve equation (green hashed bars), in comparison with the corrected heat loads based on the recent measurements (red bars). These corrected heat loads have been obtained by setting the corresponding valves at the same operation conditions (pressure, temperature, opening) to correct the massflow by using the Coriolis values instead of the valve equation results. All half-cell heat loads have demonstrated a relative error below 10 %, validating the strong heat load differences observed in the previous years.

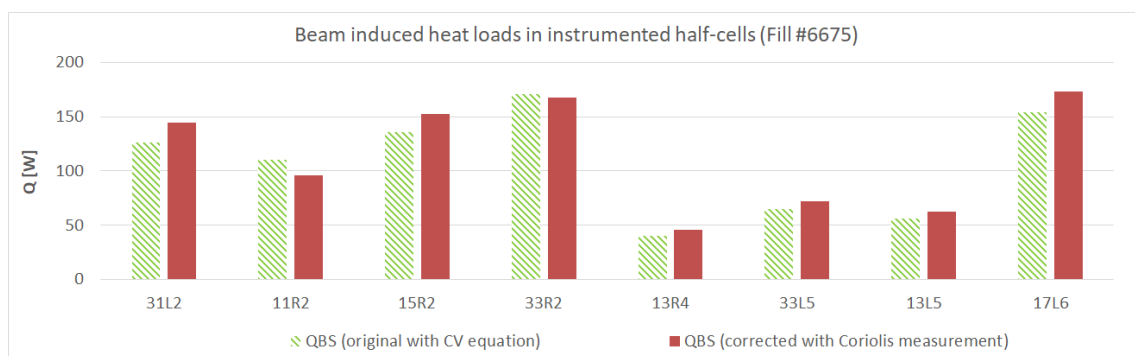


Figure 8. Original and corrected beam screen heat loads measurements in May 2018 (fill 6675)

4.2. Global measurements

To validate the global measurements over the sector, a similar exercise has been performed. Beam screen heaters were gradually increased with their valves to maintain a temperature return of about 20 K in the line D. The result is shown in the figure 9 where the Coriolis measurement (black curve) is in agreement with the massflow obtained from the sum of the beam screen heaters (dark grey curve) and the estimated massflow coming from the valve equations of each circuit (light grey curve). This measurement allow validating as well the former heat load estimations performed in the sectors.

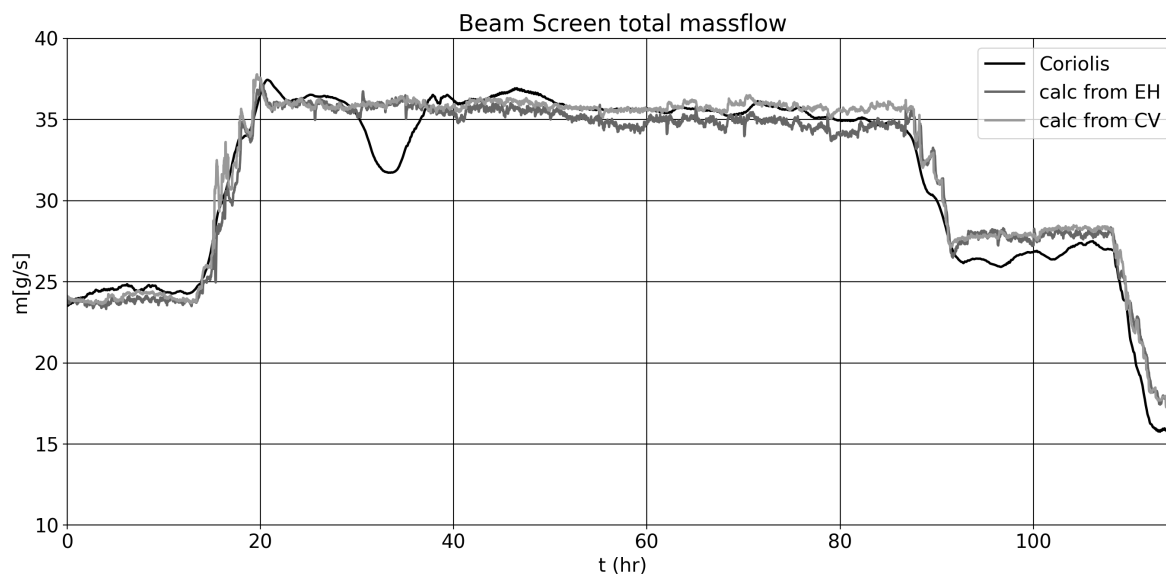


Figure 9. Coriolis massflow measurements in Sector 5-6 at 20 K (line D)

5. Conclusion and outlook

The Long Shutdown 2 of LHC allowed installing new instrumentation on different cryogenic circuits along the machine to better assess the beam induced heat loads. As these dynamic heat loads could be a bottleneck in the future LHC operation, their precise measurements and understanding is a key point to select the most suitable mitigation techniques for the future.

This additional instrumentation will be fully commissioned in 2021 (without beams) and it already allowed to validate our previous heat load estimations. Then, when the beams will be back in the LHC during 2022, we will continue to progress in the understanding of these heat loads. In particular, this new instrumentation will allow to figure out how the helium flows are shared between the beam screen parallel circuits when the heat loads are asymmetric between the two beams.

6. References

- [1] Bradu B, Brodzinski K and Ferlin G 2020 *How does a cryogenic system cope with e-cloud induced heat load?* vol 7 (CERN Yellow Rep. Conf. Proc.) pp 73–82
- [2] Tock J P, Bednarek M, Bottura L, Karentzos E, Meuter F, Naour S L, Pojer M, Scheuerlein C, Todesco E, Tommasini D, Boogaard L V D and Willering G 2018 *The second LHC Long Shutdown (LS2) for the superconducting magnets* (Proceedings of the 9th International Particle Accelerator Conference, Vancouver, Canada, April 29-May 4) pp 240–243
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Acknowledgments

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