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Liquid helium level regulation improvement in the LHC electrical distribution feedboxes

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Abstract. An important cryogenic equipment of the Large Hadron Collider (LHC) consists in the electrical distribution feedboxes (DFBs) which are used to power the superconducting magnets of the accelerator. These feedboxes contain the current leads achieving the electrical transition between the copper cables at ambient temperature to the Niobium-Titanium wires at cryogenic temperature, immersed in a liquid helium bath at 4.5 K. This liquid helium bath must be regulated at a defined level to allow the powering of the LHC, and this regulation often caused non-availabilities in the past. This paper presents the development of a new control scheme, coupled to the existing PID level controller, significantly improving this regulation, and rejecting disturbances in a highly efficient manner. First, a dynamic model of the DFBs was developed in the EcosimPro software using the CRYOLIB library to reproduce in simulation the regulation issues. In a second step, the new proposed regulation modes were tested and validated in simulation. Finally, the paper will present the results obtained in 2021 on a real DFBs operation in the LHC, validating the new control approach prior its massive deployment all around the LHC cryogenics.

1. Introduction

The European Organization for Nuclear Research (CERN) is operating the cryogenic system for the Large Hadron Collider (LHC) since 2008. The proton beams inside the LHC are driven by superconducting magnets maintained at 1.9 K over the 27 km ring thanks to large helium refrigeration plants.

The electrical Distribution Feed-Boxes (*DFB*) have been designed by CERN and allow the feeding of the electric currents into the superconducting magnets. They perform the electrical transition between the power supplies at room temperature towards the superconducting coils working at cryogenic temperatures. In total, the LHC embeds 56 DFBs to supply the different superconducting magnets and links around the machine and these feedboxes include more than 1200 superconducting current leads ranging from 120 A to 13 kA [1].

A DFB consists in a liquid helium bath at 4.5 K where different chimneys holding several current leads are immersed. Each DFB is almost unique and they have very different sizes. The smallest one is only 30 liters whereof 6 liters of liquid helium and the largest one is about 400 liters whereof about 100 liters of liquid helium, see Figure 1 where a DFB is represented in the LHC tunnel.

To operate these DFBs, the liquid helium level must be regulated at a predefined level to ensure the proper cooling of the current leads. To allow the powering of current leads in a DFB, the liquid helium level must be maintained in an interval of ± 10 mm and once the DFB is powered, a deviation of more than ± 20 mm will trigger an interlock on the LHC powering system, impacting as consequence the LHC accelerator availability. Due to the specific DFB geometry holding narrow chimneys in a limited helium volume, the liquid level can vary rapidly, and maintaining the liquid level in the correct range is a real

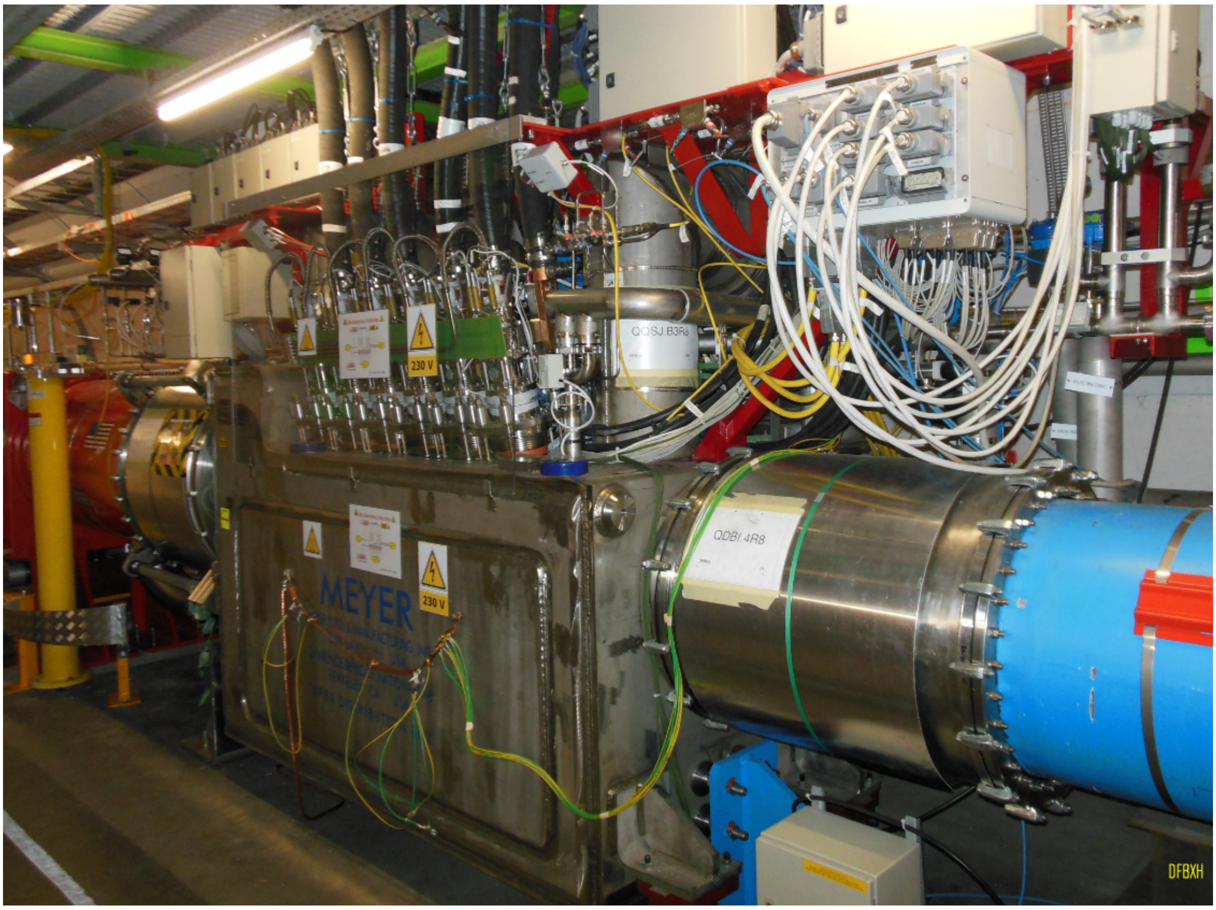

Figure 1. A DFB in the LHC tunnel supplying 16 electrical circuits between 120 *A* and 7.5 *kA*

challenge. This regulation challenge is very similar to the liquid helium level control for superconducting RF cavities, see [2] for instance.

During the Run 1 of LHC (2009-2012), many DFB level instabilities exceeding these thresholds were observed and some tuning were consequently performed to improve the PID (Proportional-Integral-Derivative) controllers in charge of these regulations. The Run 2 (2015-2018) was then better but several oscillations were still observed [3]. For instance, during 2018, 95 level oscillations larger than 10 *mm* and 8 oscillations larger than 20 *mm* were identified but their global impact on the LHC availability was relatively small: in the overall Run 2 representing 40 000 hours of cryogenic operation, there were 800 hours of cryogenic downtime whereof 11 hours due to the DFB level extra oscillations ($\approx 1.5\%$ of the cryogenic downtime). The aim of this study is therefore to implement a better DFB level regulation to minimize the cryogenic downtime for the future.

First, a dynamic modelling of the DFB level with its regulation loop is detailed in order to reproduce the observed issue in simulation. Then, an improvement of the DFB level control is proposed and validated in simulation. Finally some experimental results are presented and discussed at the end of the paper.

2. Dynamic modelling of a DFB

Before proposing a new control, a dynamic model integrating the former control for the DFB liquid helium level must be performed to reproduce in simulation the current issue. To achieve this task, the modelling and simulation software EcosimPro has been used with the specialised cryogenics library

CRYOLIB, see [4] for more details about these tools.

As we are only interested in the level control dynamics, a DFB can be simplified by assuming a single cylindrical phase separator having an equivalent volume than the DFB with a diameter and a height chosen in such a way that the liquid surface is equivalent to the one of the DFB (the sum of the cross sections of each chimney). This equivalent geometry would then allow to reproduce the same level dynamic than the real one.

Moreover, the Joule-Thomson valve (*CV933*) at the inlet port regulating the DFB level via a PID controller (*LC*933) and the On/Off valve at the gas outlet (*PV930*) are considered. The boundary conditions of the models are the inlet pressure/temperature of the CV933 (supply cryogenic distribution line called *Line C*), the outlet pressure of the PV930 (Warm Recovery Line called *WRL*) and the DFB static heat load, see the Figure 2 where the Ecosimpro schematic of the model is represented.

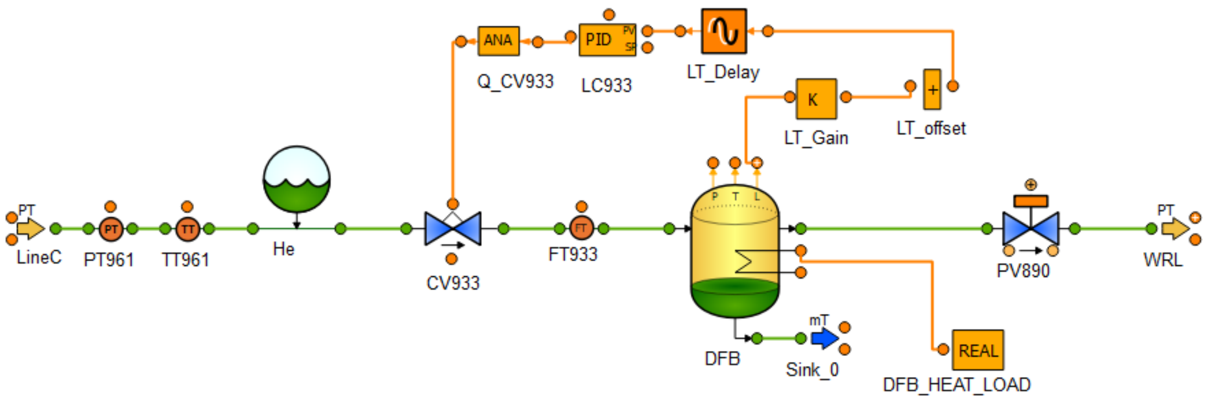

Figure 2. DFB model schmematic in EcosimPro

To validate the model, a small DFB having significant level oscillations in the last years was selected as example (called *DFBMC*). Based on the experimental data obtained during the previous years for this DFBMC, a static loss of 30 *W* was estimated and the additional heat load induced by the powering of the current leads is negligible (no dynamic heat loads measured). Moreover, a time-delay of about 2 seconds is observed between the valve order and the DFB level reaction and this delay was also introduced in the model.

The level oscillations observed in this DFB are mainly due to the PID regulation loop that cannot reject efficiently the disturbances coming from the variations of the *flash evaporation* generated by the Joule-Thomson expansion in the inlet valve (weight ratio of vaporized liquid over the total massflow). Thus, if some experimental pressures/temperatures are applied as boundary conditions, the dynamic model should be able to reproduce correctly the level dynamics.

Results are represented in the Figure 3 where about 8 hours have been simulated during a disturbance on the inlet pressure and temperature (line C) impacting the flash evaporation. The level dynamics are correctly reproduced by our model in terms of time evolution and amplitudes, validating this dynamic model for our future developments.

3. Regulation improvement proposal

After analysis of the simulation results, it was decided to implement a new principle in order to increase the performances of our regulation. Indeed, to solve this problem in an efficient and simple manner, the existing PID level controller should not manipulate directly the valve position but the amount of liquid helium falling into the DFB as the liquid level is proportional to the inlet liquid massflow supplied by the inlet valve.

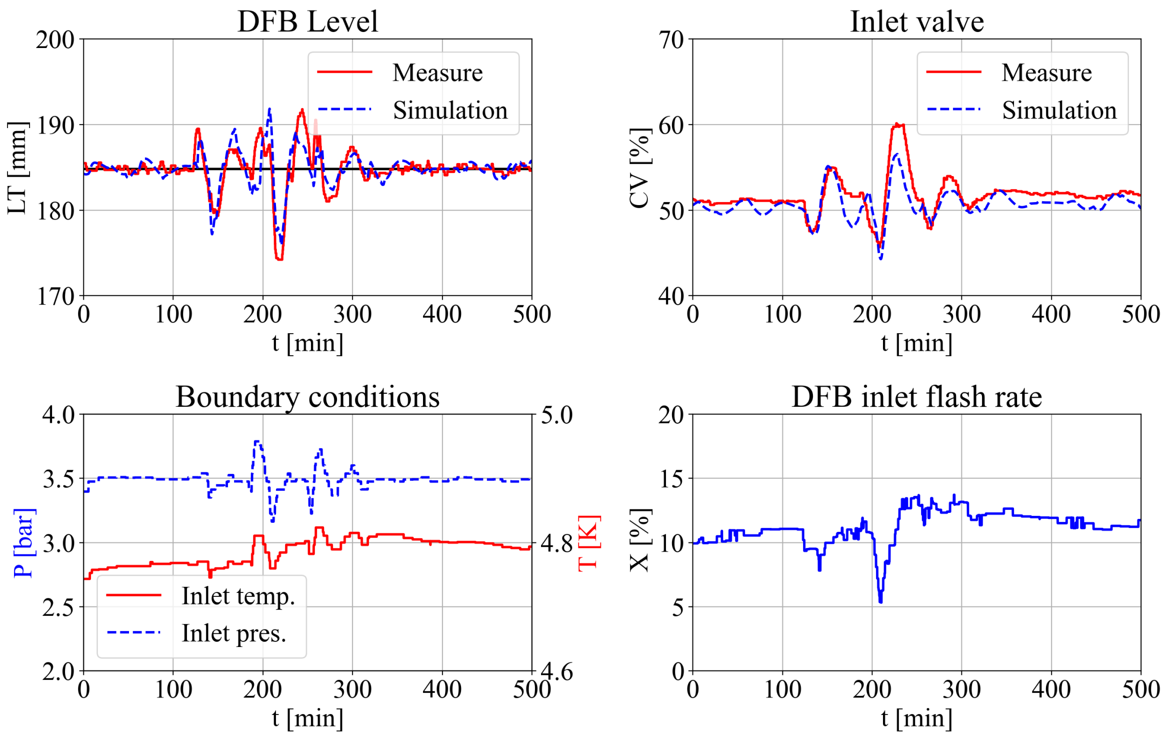

Figure 3. Simulation results compared with experimental data during a disturbance

To perform such a control, it is proposed to first calculate the flash X as function of the inlet pressure/temperature and the outlet pressure using the helium thermodynamic properties. Then, the PID output in percentage (LC_{out}) is converted in liquid massflow (m_{liq}) based on a predefined massflow range that can be achieved (Δm), see Eq. (1). The total massflow m_{tot} can be then deduced from the flash as defined in Eq. (2). Finally, the valve position can be computed using the standard valve equation as defined in Eq. (3) where ρ, K_v and CV_0 are respectively the inlet density, the valve flow coefficient and the valve pre-constraint, noting that the valve has a sub-sonic flow with a linear opening. The Figure 4 is representing the overall control scheme of this new proposal.

$$m_{liq} = \Delta m \cdot \frac{LC_{out}}{100} \tag{1}$$

$$m_{tot} = \frac{m_{liq}}{1-X} \tag{2}$$

$$CV = CV_0 + \frac{m_{tot}}{(2.77 \cdot 10^{-5} \cdot K_v \cdot \sqrt{10^5 \cdot \rho \cdot (Pin - Pout)}} \tag{3}$$

3.1. Validation in simulation

To validate this new control scheme, a dedicated simulation was setup to reproduce a typical disturbance on the line C causing significant oscillations by applying as boundary conditions some experimental data where the line C pressure and temperature influenced significantly the flash.

The former PID control can be then fairly compared with this new proposed regulation scheme. First of all, the dynamic model was used to tune properly the PID parameters that were not optimal, even

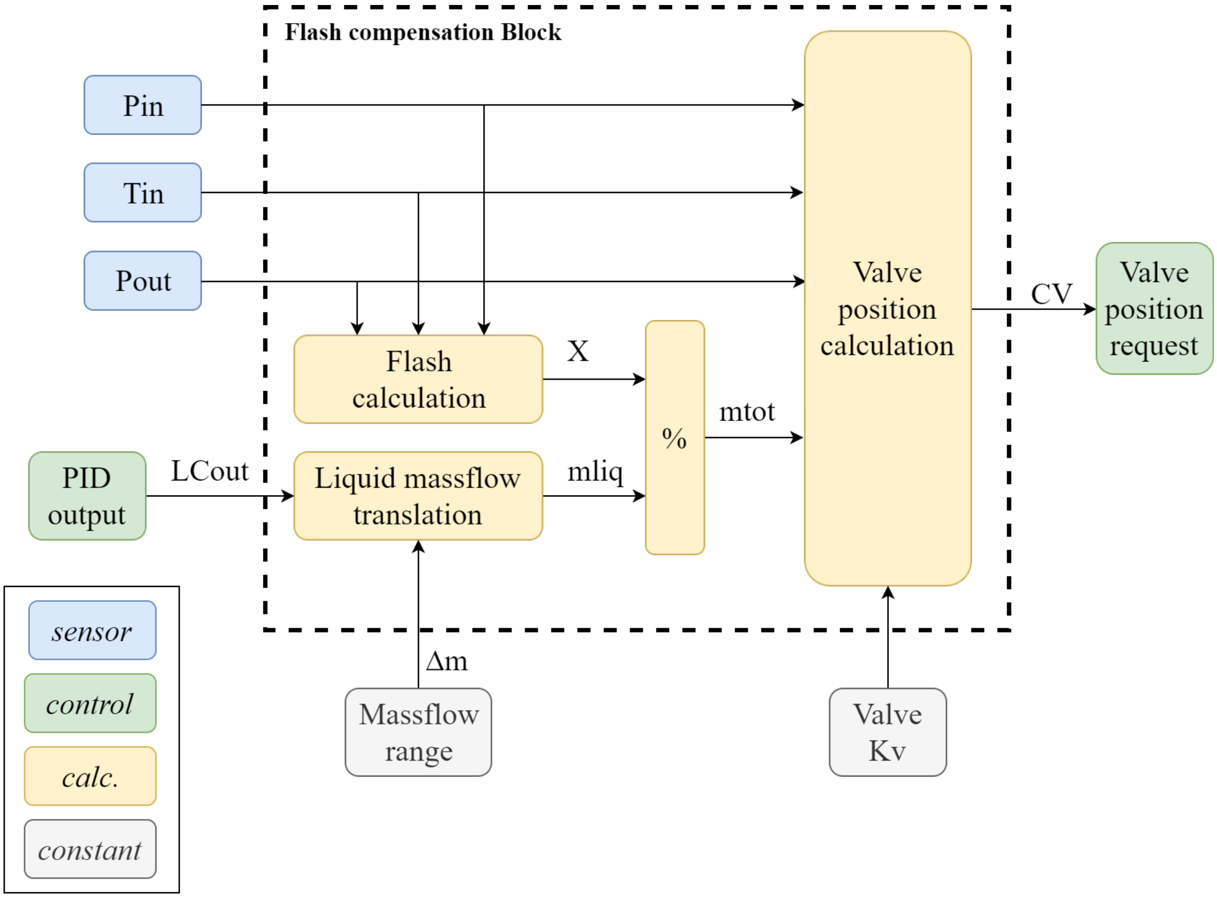

Figure 4. New control principle compensating the flash disturbance

after some years of operation due to the very limited slots to tune these controllers. Then, once a better PID tuning was found, the flash compensation was activated to evaluate its contribution. Note that the level measurements are time-filtered beforehand (using a sliding moving average) in the control system to remove the small fluctuations that can cause undesirable responses when the PID gain is significant.

Results are represented in the Figure 5 where the three simulations are shown: the former PID, the newly tuned PID and the newly tuned PID in association with the flash compensation. It is clearly visible that the new PID tuning improved significantly the regulation and that the addition of the flash compensation block improved it even more.

To compare quantitatively the three dynamic responses, the mean square error (*MSE*) was computed as defined in Eq. (4) where *SP*, *MV* and *N* are respectively the set-point, the measured value and the number of data sample. The new PID tuning reduced the *MSE* by more than two orders of magnitude and the addition of the flash compensation improved again the *MSE* by a factor three.

$$MSE = \frac{\sum_{i=1}^{N} (SP_i - MV_i)^2}{N} \tag{4}$$

4. Experimental results on LHC

The improved regulation described in the previous section has been deployed in this DFBMC in early 2021 for an experimental validation before a massive deployment over the LHC. The new proposed regulation was regularly activated during the five months of operation between January and May 2021

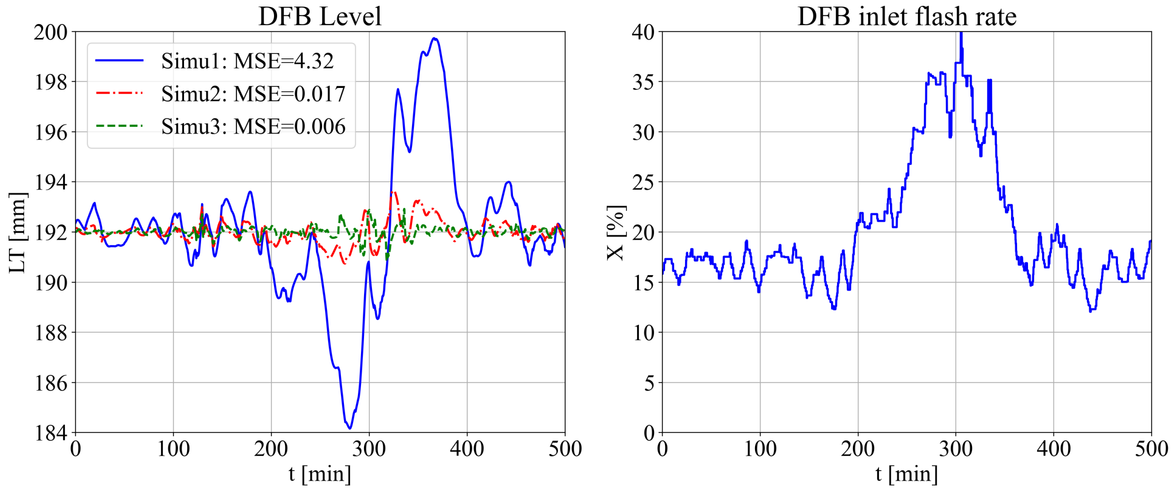

Figure 5. Simulation results during a disturbance between the former PID tuning (Simu 1), the newly tuned PID (Simu 2), and the newly tuned PID with the flash compensation (Simu 3)

without any special incident. A clear improvement of the regulation was observed in comparison with the former one.

The Figure 6 represents three similar events that occurred on this DFBMC during April 2021 where the flash at the entrance rise from 15 % to about 30 %. In the first event where the former PID parameters was used, the disturbance was significant with a MSE of 3.7 *mm*. For the second event with the newly tuned PID parameters, the level disturbance was clearly better attenuated with a MSE of 1.2 *mm*. For the third event using the newly tuned PID parameters in association with the flash compensation, the measured disturbance on the flash was clearly stronger than the two others but its impact on the level was nicely smoothed with a MSE of only 0.9 *mm*.

Thus, the experimental results are confirming the simulation observations where the new PID tuning improved significantly the rejection of the disturbances, and with better results when the flash compensation is activated.

5. Conclusion

Since the start of the LHC cryogenics, the liquid helium level regulation of the DFBs was identified as a delicate regulation for several reasons: first, the regulation margin for this regulation is very small and the flash of the Joule-Thomson valve is an important source of disturbance that regularly happens during the usual operation, impacting the LHC availability in case of excessive level oscillation. Moreover, all the DFBs are almost unique, with different helium volumes and dynamics, and they consequently need to be tuned independently.

The first step to improve these regulations is naturally to properly tune the PID controller for each DFB. It was demonstrated here that the dynamic simulations can help significantly this tuning without disturbing the DFB operation where the allocated time windows for such a tuning are very limited. The second step proposed and validated in this paper is the development of a flash compensation in the existing PID control loop in order to better reject these disturbances in a simple and efficient way.

Finally, these control improvements have been validated in simulation and in the real operation on one DFB for several months. The next step will be the massive deployment of this improved regulation in all the DFBs to improve the LHC cryogenic availability in the future.

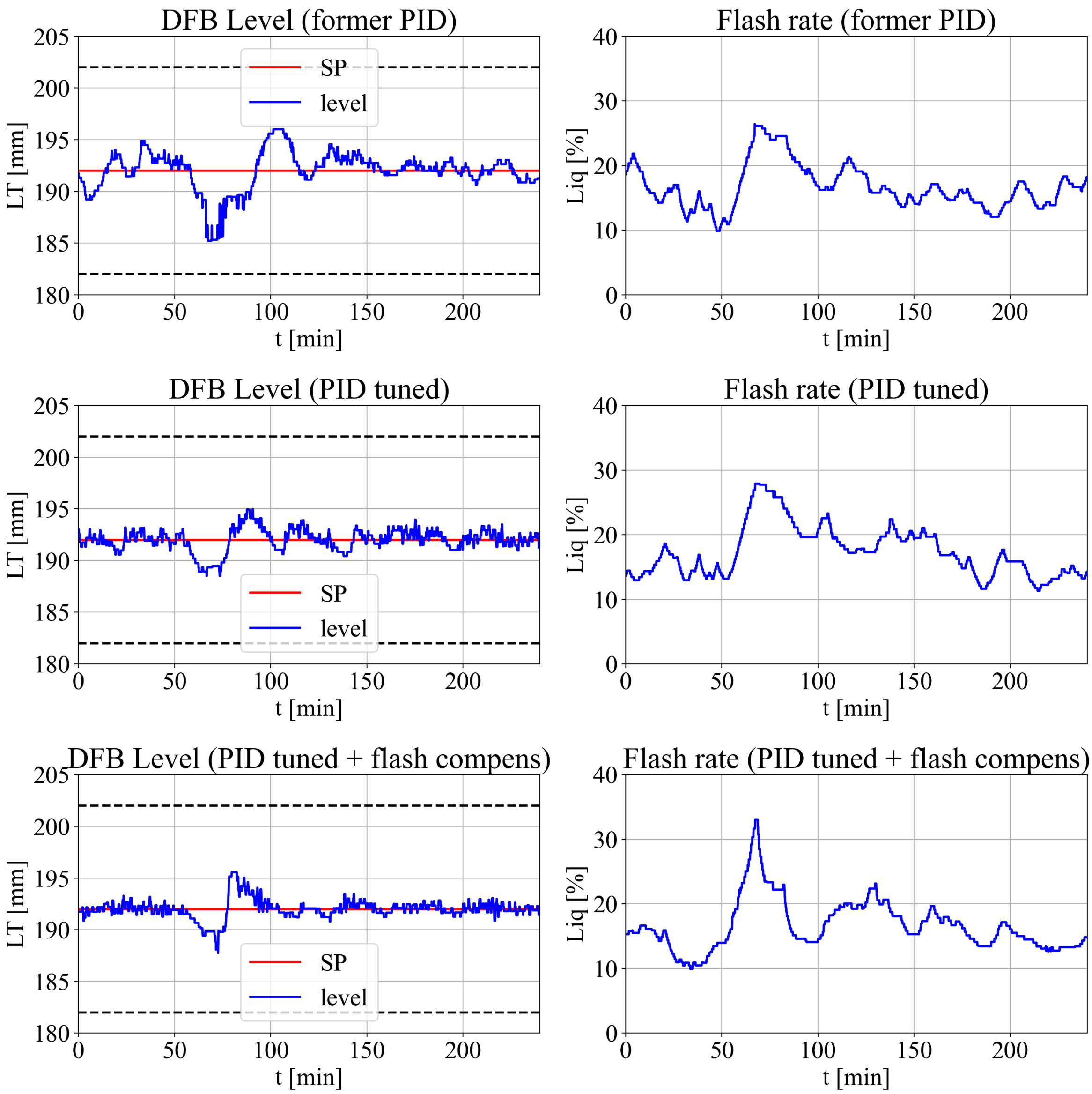

Figure 6. Experimental data between the former PID tuning, the newly tuned PID, and the newly tuned PID associated with the flash compensation on a real DFB during April 2021

6. References

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