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# AUTOMATIC PID PERFORMANCE MONITORING APPLIED TO LHC CRYOGENICS

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## *Abstract*

At CERN, the LHC (Large Hadron Collider) cryogenic system employs about 5000 PID (Proportional Integral Derivative) regulation loops distributed over the 27 km of the accelerator. Tuning all these regulation loops is a complex task and the systematic monitoring of them should be done in an automated way to be sure that the overall plant performance is improved by identifying the poorest performing PID controllers. It is nearly impossible to check the performance of a regulation loop with a classical threshold technique as the controlled variables could evolve in large operation ranges and the amount of data cannot be manually checked daily. This paper presents the adaptation and the application of an existing regulation indicator performance algorithm on the LHC cryogenic system and the different results obtained in the past year of operation. This technique is generic for any PID feedback control loop, it does not use any process model and needs only a few tuning parameters. The publication also describes the data analytic architecture and the different tools deployed on the CERN control infrastructure to implement the indicator performance algorithm.

## INTRODUCTION

The LHC cryogenic control system is now very mature after more than 12 years of operation using the CERN control framework UNICOS (UNIfied COntrol System) [1]. Nevertheless, the cryogenic operation team is still optimizing the cryogenic system as much as possible and this task is demanding significant efforts due to the large amount of data generated by the whole LHC cryogenic system (about 4 GB per day).

In this context, advanced diagnostics methods based on data analytic have been developed and tested in collaboration between the CERN industrial controls and safety group and the cryogenic group. A method to automatically detect oscillations of sensors or actuators [2] and a model learning algorithm to detect abnormal behaviours [3] have already been developed.

This paper is presenting a method to identify poorly tuned PID (Proportional Integral Derivative) regulation loops as the LHC cryogenic systems embeds more than 5000 of those loops that cannot be permanently checked by the operators without appropriate tools. The regulation loops, which are poorly tuned, can trigger alarms whenever they exceed some thresholds. This allows engineers to adjust these loops to reach better performances and this corrective tuning has been done since the beginning. However, many regulation loops remain poorly tuned and do not provoke any critical alarms. A better tuning of these regulation loops is then necessary for several reasons:

- Too fast controllers can accelerate the aging of actuators (valves, heaters, motors, etc..) and can provoke breaking inducing significant stops of cryogenic installations during operation.
- Too slow controllers induce important oscillations of some process values (temperatures, pressures, etc.) and can induce undesirable mechanical movements provoking alignment problems in the accelerator or even breaking of components in extreme situations.
- Poorly tuned controllers can provoke undesirable interlocks and stops cryogenic installations after unexpected disturbances. These poorly tuned controllers are difficult to detect as they work acceptably most of the time and they only show bad behavior when a strong and rare disturbance appears.

For all these reasons, it was decided to implement an automatic performance monitoring of PID control loops to help operators to identify regulation loops showing abnormal behaviours. Then, operators may take the appropriate decision as for instance doing a new PID tuning, either manually, either by using the PID auto-tuning tool implemented in the UNICOS framework since 2016 [4].

After a brief description of the controller performance indicator that we have selected in a first section, its application to the LHC cryogenic system is presented and discussed with the different results. Then, in the third section, the implementation of the monitoring task within the CERN computing infrastructure is described and a conclusion summarizes the different results and outlooks.

## REGULATION LOOP PERFORMANCE INDICATOR

Since 1980, there has been a lot of research to evaluate, in a generic way, the performance of a regulation loop, whatever is the regulation technique. Some methods use the variance of the mean square error between the measured value and the set-point as performance indicator [5]. This variance can be then estimated by time series and compared to the best achievable controller to obtain the performance of the regulation loop. This concept has been re-used more recently in 2007 by a Spanish team to compute a *Predictability Index* (*PI*), more convenient for a concrete industrial case where the number of tuning parameters is reduced [6].

The first calculation to do is the estimation of the error at each sampling time $t$ for a certain prediction horizon $b$ as described in equation 1 where $m$ is the error model order.

$$\hat{e}(t+b) = a_0 + a_1 \cdot e(t) + a_2 \cdot e(t-1) + \ldots + a_m \cdot e(t-m-1) \quad (1)$$

Note that all coefficients $a_i$ have to be found to fit the measurements using the least square method for instance. Once the error estimation is calculated, the predictability index $PI$ is computed as function of the error residue variance $\sigma_r^2$ and the mean square error $mse$, see equation 2.

$$PI = \frac{\sigma_r^2}{mse} \quad (2)$$

This predictability index $PI$ is then used to quantify the quality of the regulation loop. If the loop is entirely predictable and tuned, $PI = 1.0$, whereas if the regulation loop shows an erratic unpredictable behavior (i.e white noise), the regulation loop is considered as poorly tuned and $PI = 0.0$.

### Controller Performance Parameters

To compute the predictability index, several parameters have to be defined to perform the different calculations and some recommendations can be found in [6]:

- $t_s$: the sampling interval represents the time between two samples and it should be chosen in such a way that the regulation loop dynamics can be accurately observed without polluting the data with useless information.
- $m$: the regression model order. It is recommended to use a value slightly bigger than the loop settling time as we need to see the dynamic of the system in order to predict it.
- $b$: the prediction horizon should be around the loop settling time because if $b$ is too large, the predictive error can increase significantly.
- $n$: the number of samples to be analyzed to compute the performance index. A trade off should be found to obtain enough information in a reasonable computation time.
- $PI_L$: the predictability index threshold between 0.0 and 1.0 is used to consider if the regulation loop is correctly tuned according to the expected behavior of the regulation loop.

Moreover, in order to avoid false positives as much as possible to not pollute the results, we have decided to add two additional conditions to consider a regulation loop as poorly tuned:

1. A regulation loop is considered as poorly tuned within a time window if and only if the standard deviation of the controller output (*i.e.* the actuator) is above a certain limit $\bar{\sigma}_y$. This condition allows the exclusion of all controllers which are saturating at their output and all controllers which are not in regulation mode (*i.e.* when actuator is constant).
2. A regulation loop is considered as poorly tuned if the predictability index $PI$ is below the defined threshold $PI_L$ more than $N$ time windows during 24 hours. This condition allows the exclusion of fast transients not representative of the global controller performance.

These parameters can be quite difficult to understand by process experts who have to setup these parameters. Hence, we slightly modified the user inputs to ease the tuning of the controller performance monitoring. Finally, the process experts have to provide six parameters:

- $t_s$: the sampling time.
- $t_W$: the time window represents the time interval where the predictable index is computed.
- $T$: the time constant of the loop represents the settling time of the closed loop process (*i.e.* the time to reach 63 % of the final value).
- $PI_L$: The predictability index threshold.
- $\bar{\sigma}_y$: the minimum standard deviation on the actuator to consider the regulation loop as enabled.
- $N$: The number of abnormal time windows detected over 24 hours to consider the regulation as poorly tuned.

Then, the following computations are performed to find the original parameters of the predictability index:

$$n = ceil\left(\frac{T_W}{t_s}\right) \quad (3)$$

$$b = ceil\left(\frac{T}{t_s}\right) \quad (4)$$

$$m = 2 \cdot b \quad (5)$$

## APPLICATION TO THE LHC CRYOGENIC SYSTEM

As proof of concept, this daily regulation loop monitoring has been applied in 2017 on 3000 PID controllers over the 5000 PID loops loops of the LHC cryogenic system to produce a daily report every morning to the operation team. The 2000 remaining PID loops have been excluded as they are used only during maintenance periods or exceptional phases.

The daily analysis of selected PIDs is executed every night in order to produce a daily report every morning to the operation team.

### *Grouping of Controllers and Tuning of the Monitoring Tool*

Ideally, each regulation loop should have its own parametrization to calculate its predictability index depending on its process dynamics but this is demanding too much effort for so many regulation loops. Hence, the first task consists of grouping controllers in such a way that each group should demonstrate similar performance results with the same parameters. We decided to separate the regulation loops in large groups according to the controller type: 1.8 $K$ magnet temperature controllers ($TC_{910}$), all other temperature controllers ($TC$), pressure controllers ($PC$), flow controllers ($FC$) and level controllers ($LC$), see Table 1 where the parameters for each of these groups are represented. In total, we have 220 magnet temperature controllers, 1250 other temperature controllers, 520 pressure controllers, 830 flow controllers and 200 level controllers.

Table 1: Grouping of Controllers With Their Associated Parameters

| Group | $t_s$ | $t_W$ | $T$ | $N$ | $PI_L$ | $\bar{\sigma}_y$ |
|---|---|---|---|---|---|---|
| $TC_{910}$ | 60 $s$ | 12 $hr$ | 120 $min$ | 1 | 0.2 | 1 % |
| $TC$ | 60 $s$ | 5 $hr$ | 30 $min$ | 3 | 0.4 | 1 % |
| $PC$ | 10 $s$ | 1 $hr$ | 3 $min$ | 3 | 0.4 | 1 % |
| $FC$ | 10 $s$ | 1 $hr$ | 2 $min$ | 3 | 0.4 | 1 % |
| $LC$ | 10 $s$ | 1 $hr$ | 2 $min$ | 3 | 0.4 | 1 % |

### *Results Obtained in 2017*

The online monitoring of LHC cryogenic PID loops has been setup since March 2017 when the LHC restarted and the tuning of each controller group was completed during March and April 2017. Today, there are about 150 PID loops which are identified as "*poorly tuned*" each day and we propose to review and analyze one typical day as example in this paper. We have selected the $31^{st}$ July 2017 as a representative day for the LHC operation as depicted in Figure 1 where we can observe a period of five hours without beam, a period of seventeen hours of stable beams (period of particle collisions) and it includes two beam dumps, two beam injections and two magnet pre-cycles. All these machine modes induce significant dynamic effects on the cryogenic systems and are representative of a typical operation day for the PID controllers.

In total, the monitoring tool identified 140 poorly tuned PID controllers during this day and the repartition by group and by cause is represented in Figure 2. For each loop declared as "poorly tuned", we classified the causes in the following four categories:

- **Tuning**: the controller is showing poor performance and needs to be tuned correctly.
- **Process**: the controller seems correctly tuned but the cryogenic process induces disturbances or modifications that the controller cannot handle properly. These regulation loops allow operators to detect a problem on the process which is independent of the controller itself (it can be a mechanical problem for instance).
- **Noise**: the controller seems correctly tuned but the measured value is too noisy to perform a correct regulation.
- **False Positive**: the process is correctly regulated and the parameters used to compute the predictability index are not suitable for this loop.

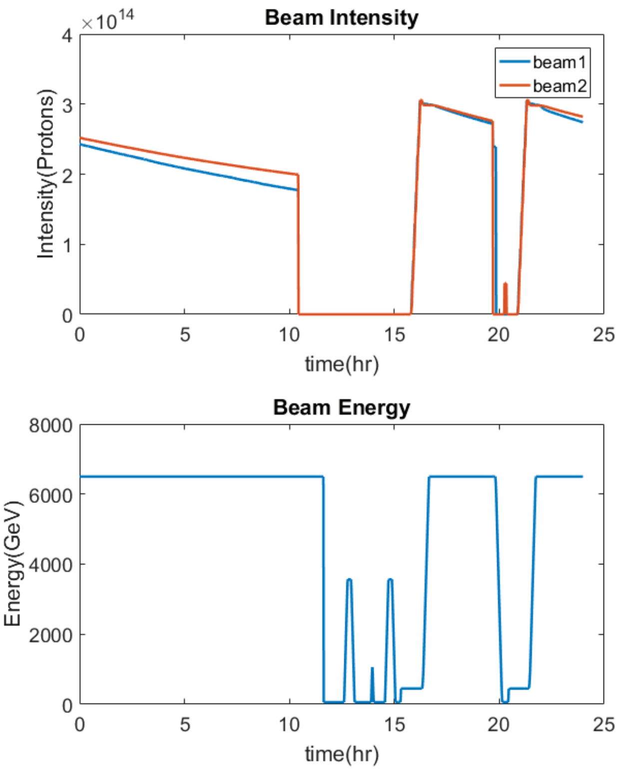

Figure 1: LHC operation during the $31^{st}$ July 2017.

It can be noticed that the cause inducing a bad predictability index highly depends on the controller type. For instance, the noise is generally the origin of the problem for pressure controllers and the false positives concern only some temperature and level controllers where the control loops were tuned for a conservative response on purpose.

In addition, we did an analysis on the cryogenic system with faulty PID loops, see Figure 4 where we observe three big families:

- Level controllers ($LC$) located in the LSS (Long Straight Sections of the LHC). Most of these controllers are controlling the liquid helium level in the Distribution Feed Boxes (DFB) used to supply to the current to the superconducting magnets. This bad regulation tuning was already known by the cryogenic operation team but this monitoring tool could allow operators to focus rapidly on the most problematic ones.
- 1.8 $K$ superconducting magnet temperature controllers ($TC_{910}$) located in the ARC (curved sections of the

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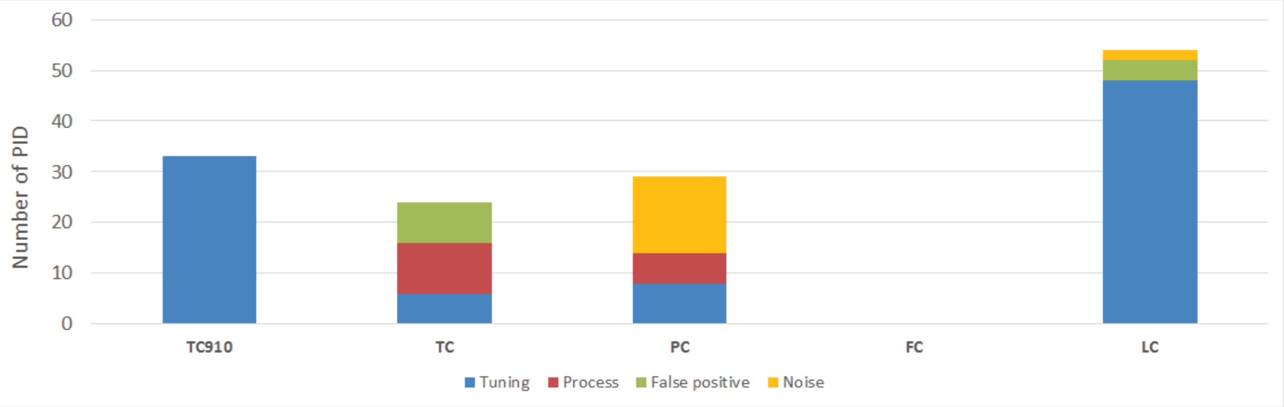

Figure 2: Repartition of faulty PID by group and by cause.

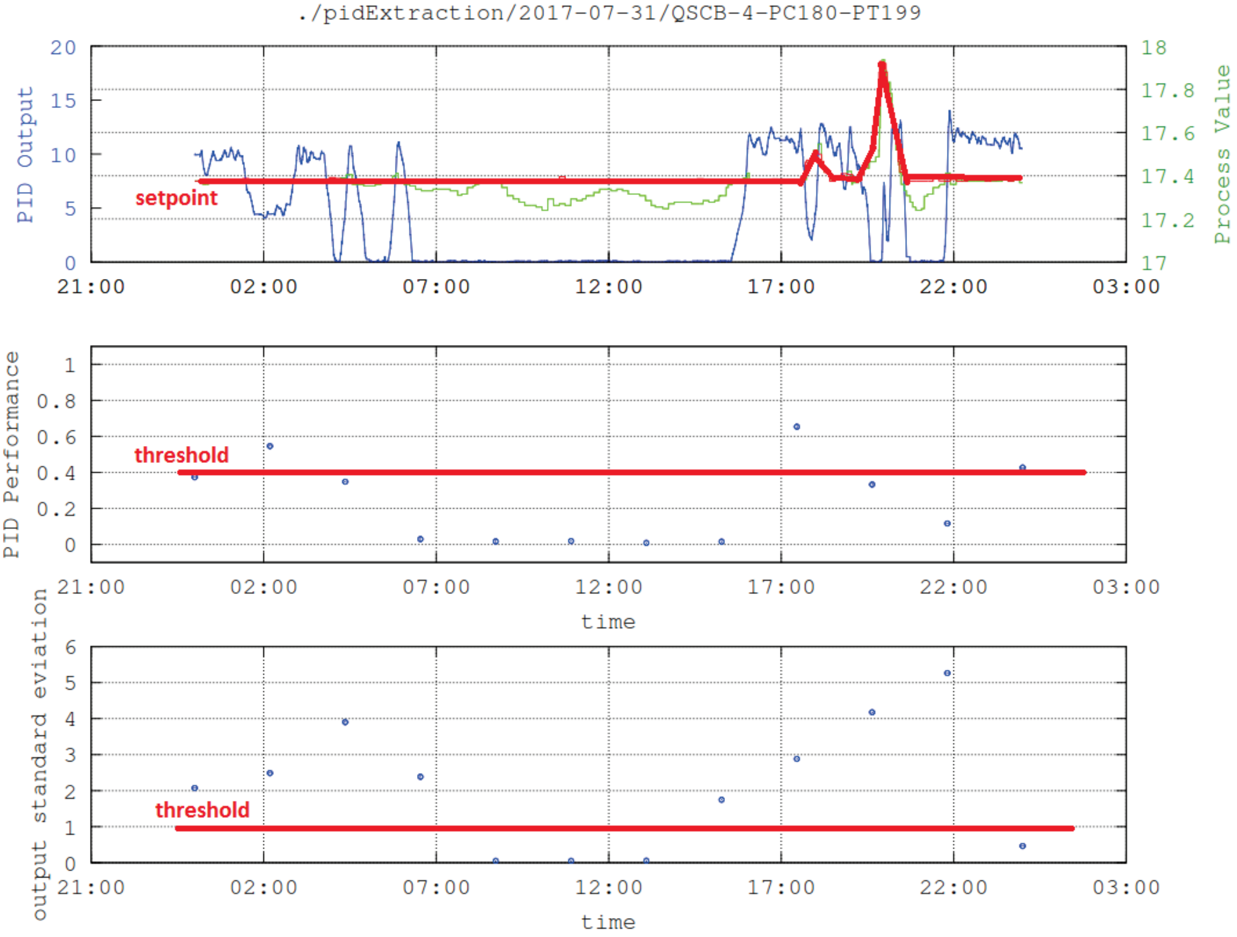

Figure 3: Generated report for the pressure control loop QSCB-4-PC180.

LHC). As magnet inertia is very slow and cryogenic operation team wants to avoid a too abrupt regulation, these controllers are clearly too slow and most of them show poor regulation performance.

- Pressure controllers (*PC*) in compression stations. These controllers are pretty important in the cryogenic systems as they guaranty the overall stability of the installations and most of them show poor performances and would need more attention. An example is provided in Figure 3 where a PID monitoring report is represented. Note that they are often working in split range together and this kind of regulation architecture can also induce false positives.

Finally, we focused on 2 different poorly tuned regulation loops detected: one very useful for the operation team and one false positive.

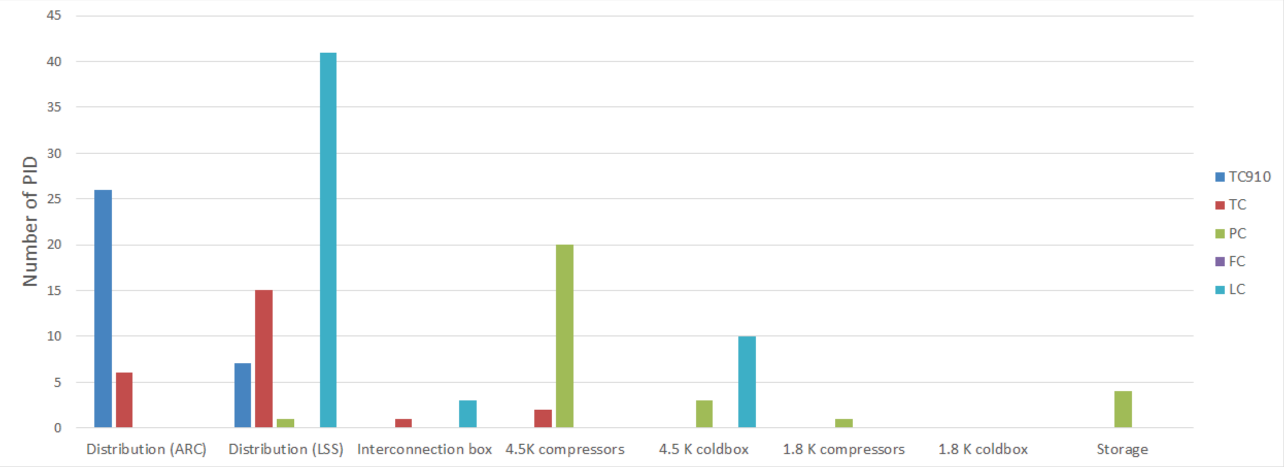

Figure 4: Repartition of faulty PID by group and by cryogenic system.

The first regulation loop represented in Figure 5 is a temperature control loop identified by "*QRLGE-03R8-TC950*" controlling the thermal shielding at 63 $K$ for the superconducting magnets in charge of the final focusing of the beams before their collision at LHC point 8 (Inner Triplets). This poorly tuned regulation loop was detected and its effects can impact the LHC as the temperature oscillation can provoke mechanical displacement of the magnets inducing a misalignment of particle beams for the collisions. After the tuning of this regulation loop by operators, the temperature was stable again and the problem was solved avoiding potential future issues.

The second regulation loop represented in Figure 6 with identifier "*QSRB-4-7LC240*" controls the liquid helium level in the phase separator of a cryogenic refrigerator at 4.5 $K$. The actuator controlling this level is an electrical heater evaporating the liquid to decrease the level. Until 9 am, the controller is considered "good" as it obtains a predictability index of about 0.7 but the actuator is oscillating a lot and this behavior can cause several issues for a long term operation. Consequently, the cryogenic operators modified the PID parameters of this loop and the actuator was clearly smoother but, on the other hand, the level was oscillating more and the controller was declared as "*poorly tuned*" as its predictability index was around 0.1, well below the setup threshold of 0.4. Nevertheless, the operation team prefered this last tuning over the former one because the level can oscillate slightly if it stays above 50 % whereas the actuator oscillation can be an issue.

These examples show that the predictability index can be very efficient for regulation loops which should always regulate their controlled value precisely. However, the control objectives are not necessarily the same for all regulation loops and this kind of difference should be taken into account to avoid false positives in future.

## IMPLEMENTATION IN THE CERN COMPUTING INFRASTRUCTURE

Currently this method is deployed as a proof of concept in a single virtual machine located in the private cloud at the CERN computer center. Every day, at midnight, a script is launched in this machine performing the following jobs:

- All data necessary to compute the predictability index (set-point, measured value and actuator) for each regulation loop are extracted in a file and sampled according to the regulation group of the loop (temperature, pressure, flow or level regulation loop).
- The predictability index $PI$ is computed for each time window over the last 24 hours.
- If the predictability index is below the defined threshold while the actuator is significantly moving during several time windows ($PI < PI_L$ and $\sigma_y > \bar{\sigma}_y$ for more than $N$ times during the last 24 hours): the regulation is considered as "poorly tuned" and a pdf file is automatically generated and stored with the corresponding plots as shown in Figures 5 and 6.
- All extracted files used to perform the calculation are removed from the machine at the end.

All these jobs take about 6 hours of computation to treat the 3000 selected regulation loops over 24 hours and most of the time is dedicated to data extraction from the Oracle database where the cryogenic control system measurements are stored. Thereafter, all the results can be consulted from a webpage available in the CERN intranet for easy access to the generated pdf files and to see the evolution of faulty regulation loops over days.

In future, the CERN Hadoop cluster could be used to parallelize the different analysis by implementing it in a Spark job as it was already done for the signal oscillation detection [2]. Moreover we have already started to build a generic web front-end as a report system to show the results in a more friendly user interface.

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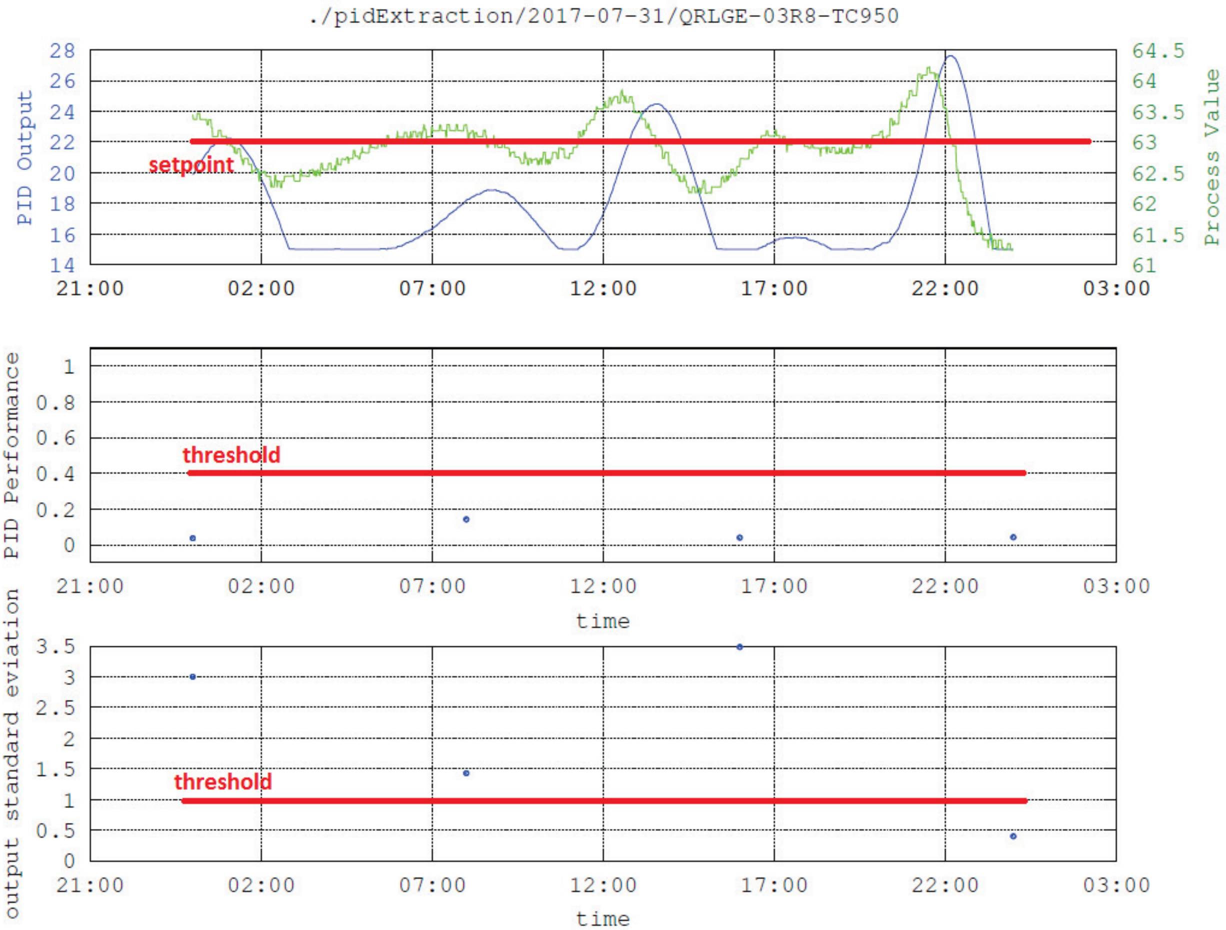

Figure 5: Generated report for the temperature controller QRLGE-03R8-TC950.

## CONCLUSION

During 2017, an automatic monitoring tool to evaluate the daily performance of the regulation loops has been set up as a proof of concept for the LHC cryogenic systems. Results are promising as it allowed to detect many poorly tuned regulation loops, not necessarily known or suspected by the cryogenic operation team. Now, this tool should evolve from a "*proof of concept*" to a daily "*operation tool*" and could be extended to other systems embedding regulation loops as most of other CERN industrial control systems (cooling, ventilation, gas systems, etc.).

Despite the positive results obtained, this predictability index is not perfect. For example, it does not fully take into consideration the different control objectives for the different regulation loops. We could for instance incorporate some weights on the control effort and on the error to take this into account.

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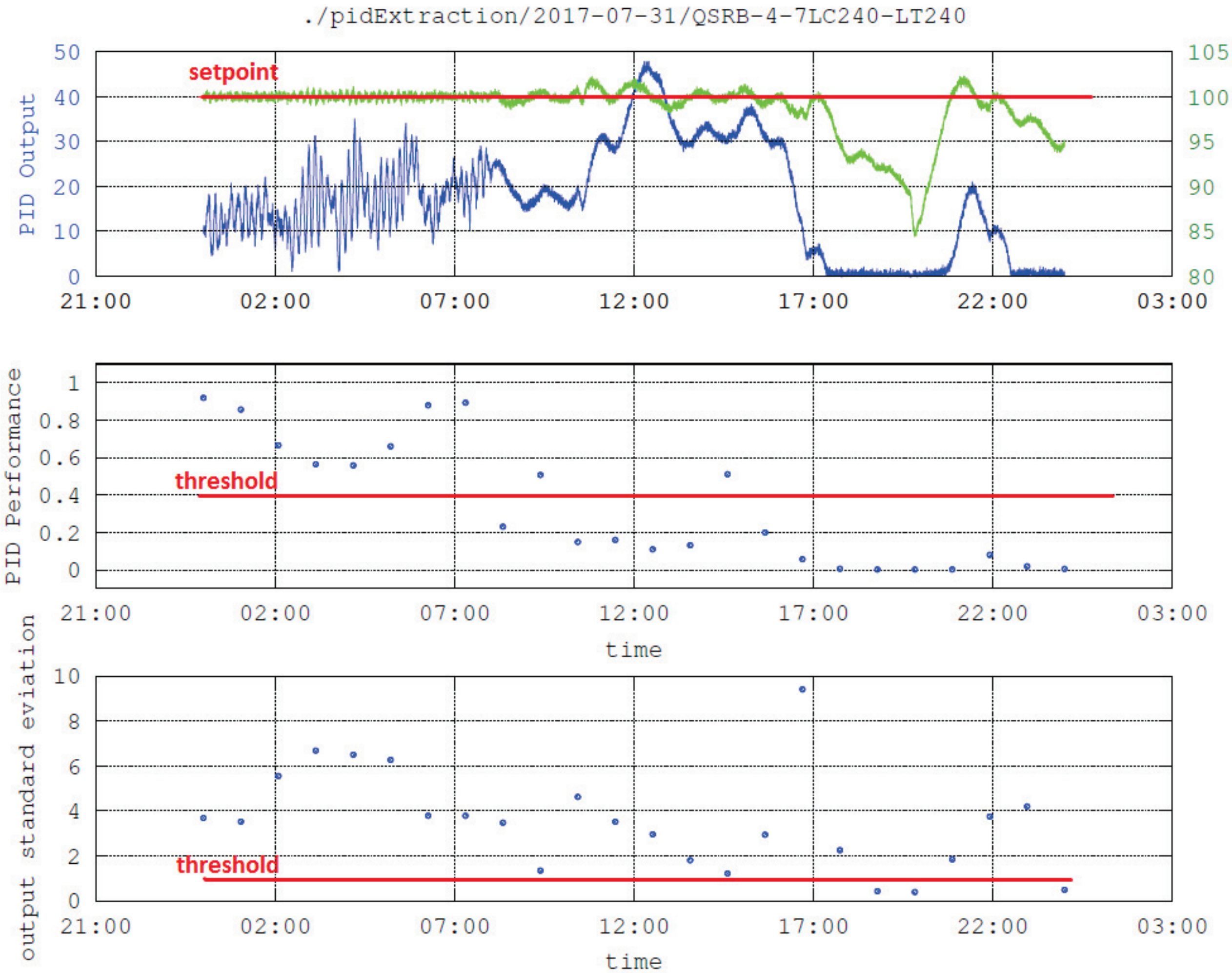

Figure 6: Generated report for the level control loop QSRB-4-7LC240.