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# Cryogenic operational experience from the LHC physics run2 (2015 – 2018 inclusive)

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# Cryogenic operational experience from the LHC physics run2 (2015 – 2018 inclusive)

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**Abstract**. With end of year 2018 the LHC has completed its second physics run and started its second two-years long shut down period dedicated to planned consolidation, maintenance and upgrade activities. The run2 – four-year physics operation period started in spring 2015 – was used mainly for luminosity production but also to allow the optimization and adaptability of the cryogenic system capacity to compensate for generated operational heat loads. Several tests and qualifications were studied and applied to the configuration of the available equipment in order to reach a deep understanding of the real operation limits. Dedicated global improvements were implemented in the control system, especially in regards of handling the beam induced dynamic heat load during transitory operational states. Adequate modifications were also applied for the Inner Triplet magnets control system to compensate for dynamic heat load related to secondaries, close to the interaction points of the ATLAS and CMS detectors. This paper will give a general overview of the LHC cryogenics operation with specific information on encountered operational difficulties and applied solutions on the system. Helium inventory management, including process use and leaks, as well as the system overall availability indicators will be presented.

## 1. Introduction

The LHC physics operation started in 2009 with so-called run1. After four years of operation with reduced beam parameters (3.5 and 4 TeV/beam), long shutdown 1 (LS1) allowed for the consolidation of superconducting magnet interconnections and other major overhaul maintenance activities. The LHC physics run2 was initiated in 2015 and completed in December of 2018 allowing for the significant increase in integrated luminosity production. During run2 the LHC was operated at 6.5 TeV with intensity up to 3.2 $10^{14}$ protons/beam. The peak luminosity reached the level of 2.1 $10^{34}$ $cm^{-2}/s$, which represents double the value with relation to the original design. In consequence, optimization of the cryogenic process was necessary to deal with increased dynamic heat load generated on all LHC beam screen circuits and cold masses of the Inner Triplet magnets close to the interaction points of ATLAS and CMS.

In the middle of run2, during extended technical stop in winter of 2016/17, the complete warm up of sector 1-2 was performed to allow for the replacement of a defective dipole magnet. In winter of 2017/18, tentative action for regeneration of the beam chamber (cleaning from suspected gaseous impurities) required partial warm up of the same sector. The second long shut down period (LS2) started from beginning of 2019 and is mainly dedicated to installation of additional electrical insulation for the diodes of energy extraction system. Several major maintenance, upgrade, and repair activities are planned for

LS2 on the cryogenic system, including upgrade of one of the LHC helium refrigerators in regards to the LHC HiLumi project. The global overview of the LHC cold masses average temperature evolution for run2 is presented in figure 1.

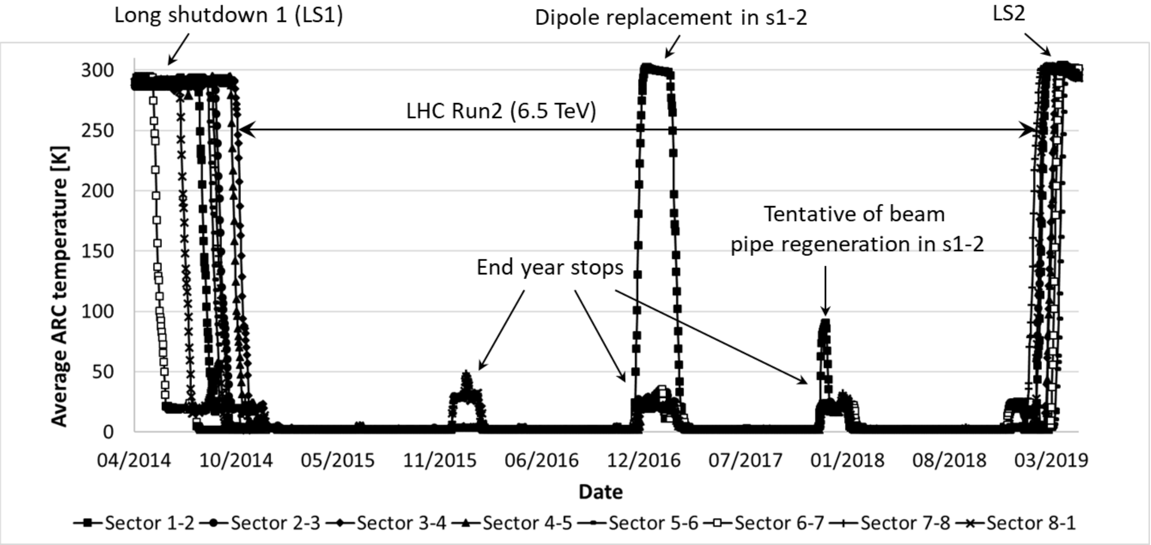

**Figure 1.** Evolution of average temperatures in LHC sectors during run2.

## 2. Beam operation and dynamic heat load

The second LHC physics operation period is considered as very successful. During run2 (2015 – 2018 inclusive) the production of integrated luminosity reached 158.71 fb$^{-1}$ and 162.62 fb$^{-1}$ for ATLAS and CMS respectively (for comparison: run1 between 2009 and 2012 allowed to obtain 28.87 fb$^{-1}$ and 29.38 fb$^{-1}$). The run2 production rate is directly related to modified beam parameters together with adapted beam injection scheme with 25 ns of the inter-bunches spacing. The evolution of the luminosity production for entire LHC operation period is presented in figure 2.

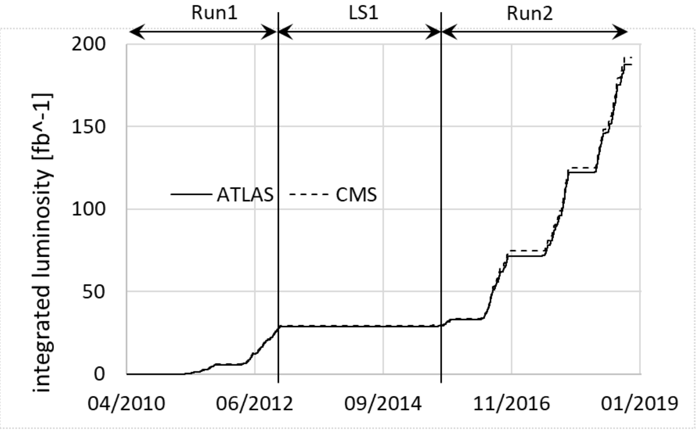

**Figure 2.** ATLAS and CMS integrated luminosity production for entire LHC operation period.

Naturally, applied changes of operating parameters had considerable influence on dynamic heat load generation with direct impact on the LHC cryogenic system. The higher values of the beam parameters resulted in increased dynamic heat load, which is mainly due to the beam-induced photo-electron cloud and higher energy and luminosity on the inner triplet magnets close to ATLAS and CMS interaction points.

It is important to mention, that the dynamic heat load generation due to beam-induced photo-electron cloud was considerably higher than expected design values (presented in more detail in section 3.2).

## 3. Cryogenic capacity optimization and control logic update

In order to adapt to the significantly increased dynamic heat load, the cryogenic system was optimized from the global cryoplant configuration point of view. In addition, specially adapted feed-forward process control loops were developed and applied on local cooling circuits. Both actions together resulted in highly efficient system being able to provide necessary cooling power during different operation stages of the machine.

### *3.1. Global capacity optimization*

The LHC is equipped with eight large independent cryogenic plants feeding eight accelerator sectors and located in defined places on the accelerator circumference [1]. The reduced heat load during run1 allowed for stop of two cryoplants, one at P6 and one at P8. Such a solution was not possible to be applied for run2 because of increased heat load on the beam screen cooling loops. However, following several measurements and tests it was confirmed that operation of one 1.8 K pumping unit is sufficient to cope with the heat load coming from magnet cold masses of two adjacent sectors [2]. In practice, thanks to installed interplants bypasses, the operation scenario of the cryogenic system was optimized as presented in figure 3 (hatched area – equipment not coupled to the accelerator).

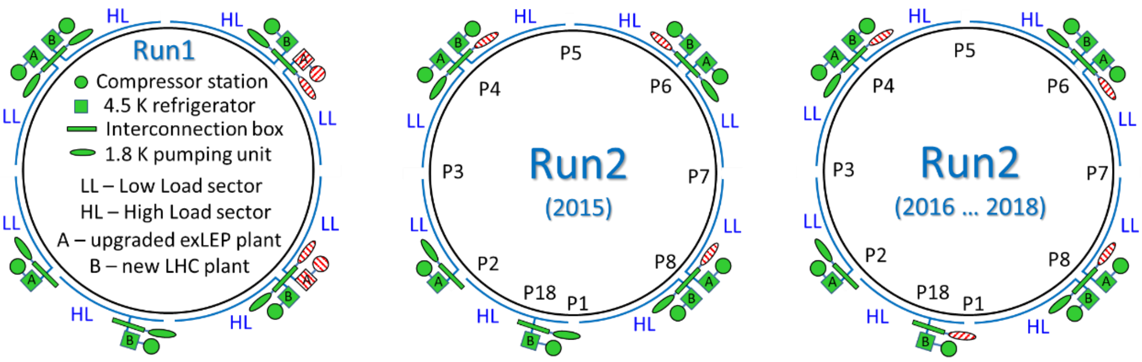

**Figure 3.** Optimization of the cryogenic operation scenario for the LHC during run1 and run2.

Nevertheless, run2 scenario required re-balancing of the flows and capacities between two adjacent cold boxes. The capacity differences were adjusted using interplant bypasses on thermal shield circuit. The related circulating helium flow diagram is presented in figure 4. The estimated gain of applied solution is to provide an additional ~1500 W at 4.6 K – 20 K for the beam screen cooling for each of two LHC sectors i.e. to increase the cooling capacity available for one 53 m long half-cell by nearly 30 W [3].

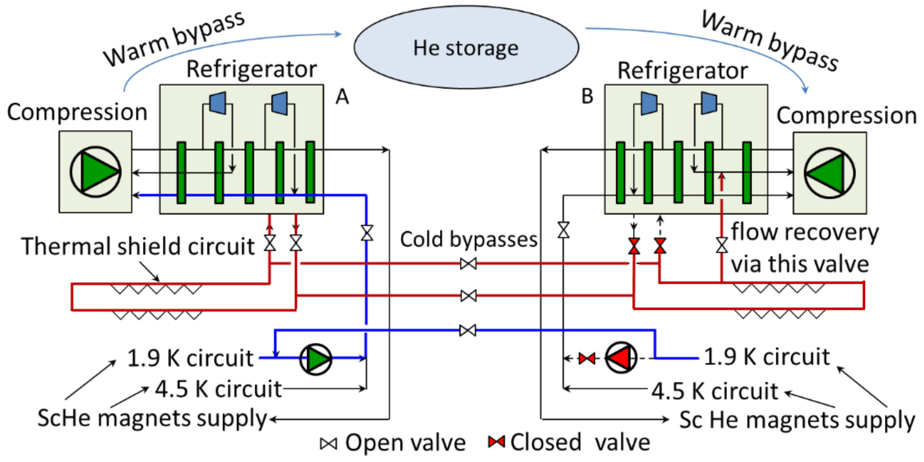

**Figure 4**. Principle of the flow circulation between adjacent cryoplants during run2.

### *3.2. Beam screen dynamic heat load and control logic update*

The LHC beam screen has a double function, which is to protect the 1.9 K cold mass from dynamic heat load generated by circulating beams and to maintain ultra-high vacuum in the beam pipes [4]. The beam screen is actively cooled with helium at 3 bar between 4.6 and 20 K as shown in figure 5.

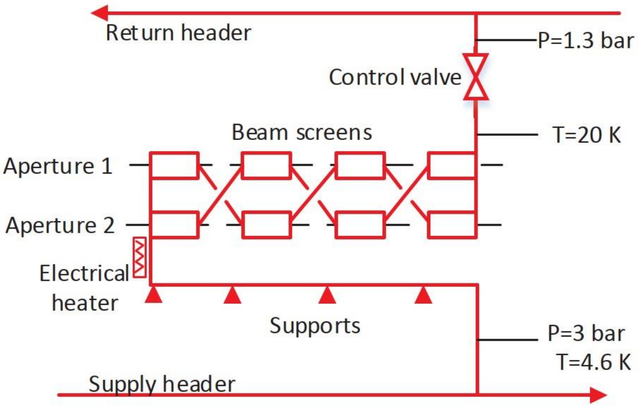

**Figure 5.** LHC beam screen cooling circuit.

The dynamic heat load on the beam screen comes from three contributors: synchrotron radiation, image current and photo-electron effect so-called electron cloud. Knowing main beam parameters, the heat load from first two contributors can be precisely calculated [5, 6]. However, analysis of thermal effect coming from electron cloud is much more complex and depends mainly on surface condition, beam intensity, and inter-bunch spacing.

During Run2, the LHC was operated with 6.5 TeV/beam of energy and intensity up to 3.2 $10^{14}$ protons/beam, running with 25 ns of the inter-bunches spacing. Such operation scheme generated particularly high values of dynamic heat load in four LHC sectors, which significantly exceeded the design values [7].

The evolution of dynamic heat load deposition on the beam screen circuit for a representative LHC beam fill (#5979) is presented in figure 6 (the values are given for one beam screen local cooling loop called half-cell, corresponding to 53 m of the machine length).

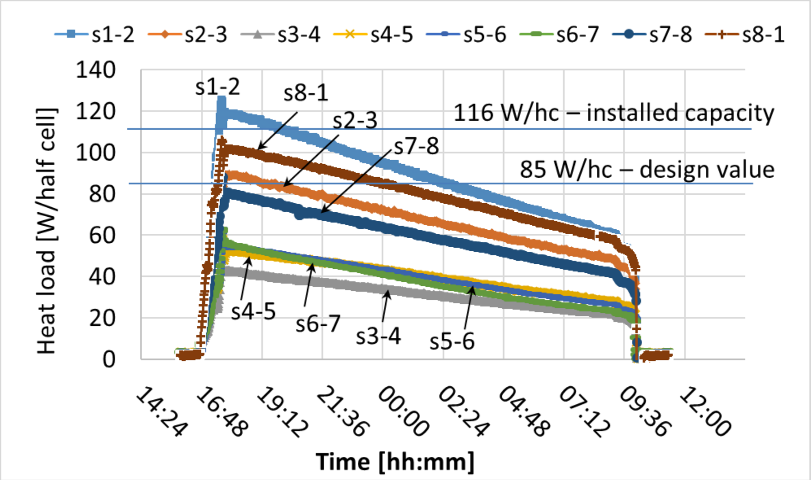

**Figure 6**. Beam screen heat load evolution for LHC run2 fill #5979.

In order to cope with generated heat load, specially developed Feed-Forward logic was introduced to the control system to optimize the helium consumption for each of 485 individual cooling loops. It allows for smoothing of thermal behavior of the screening system during transients (beam injection, current rump and beam dump). Referring to beam input parameters such as energy, intensity, number and length of the bunches, it acts on the inlet heater and the outlet valve smoothing thermal behavior of the cooling loop [7].

### *3.3. IT dynamic heat load and control logic update*

The inner triplet (IT) cold mass heat load comes mainly from secondaries (debris of the particles after collisions in related interaction points). This heat load is transferred to 1.9 K pressurized superfluid helium bath and then extracted via a bayonet heat exchanger to the cryogenic system [7]. It depends mainly on luminosity and appears instantaneously with the beam collisions. Regarding dynamics and amplitude of the heat load variation, standard feedback control loop is not able to guarantee continuous operation of the superfluid helium bath below lambda point. In order to cope with these dynamic changes, similarly to principles applied on the beam screen circuits, specially developed Feed-Forward control solution was adapted for the 1.9 K cooling loop of the ITs. Referring to beam luminosity, the system acts on the cold mass heaters preloading the system prior to the collisions as well as on the J-T valve for intensification of the cooling when necessary [7].

## 4. Performance indicators

Run2 period from 2015 to 2018 inclusive showed excellent results with an average availability of 97.2% of the LHC cryogenic system for the four years of operation, this being calculated based on the cryogenic interlock allowing for keeping superconducting magnets electrically powered – the Cryo Maintain (CM).

### *4.1. Availability*

Run2 started on April 5th 2015 and ended on December 3rd 2018 with an average operation time to allow for physics with beam of 5600 hours (234 days) per year.

As mentioned in previous sections, this second operation period was strongly thermally affected by electron cloud effect – up to 130 W / half-cell for beam-induced heat load in average with respect to the previous value of around 10 W / half-cell during run1.

In parallel, cryogenic equipment installed more than 10 years ago with a first sector cooled down to nominal in 2007 was also suffering from normal and expected ageing and thus having a direct impact on the availability of the whole system.

These two factors, in addition to a strong dependency on cooling water and electrical utilities, were the key issues the operation and maintenance teams of the cryogenic group had to face during these four years.

In order to maintain high availability for the system (on top of an adapted and efficient maintenance policy [9] together with an optimized operation scenario of the cryoplants depicted in section 3.1), systematic analysis and treatment of cryoplant failures was performed by operation and support teams to minimize downtime as much as technically possible. Doing that, it was possible to record and regroup the most time consuming and the most frequent losses into six main categories. Accurate statistics helped to focus on and to address the main sources of unavailability. Almost two thirds (63%) of the 230 Cryo Maintain interlock losses (loss of cryogenic conditions for beams) which occurred during run2 were due to only three factors: electrical feedboxes helium level oscillations, supercritical helium quality degradation and beam screen temperatures evolution, all of them being corrected during dedicated technical stops [10]. Most time-consuming losses analysis revealed three major contributors accounting for more than three quarters (77%) of total run2 cryo downtime: PLC failures, cryoplants stops and tunnel instrumentation failures. In total, LHC cryogenic system went through 230 losses / 630 hours of unavailability out of the 22400 hours of due operation time as seen from LHC accelerator operation teams. Achieved figures are presented in figure 7 hereafter.

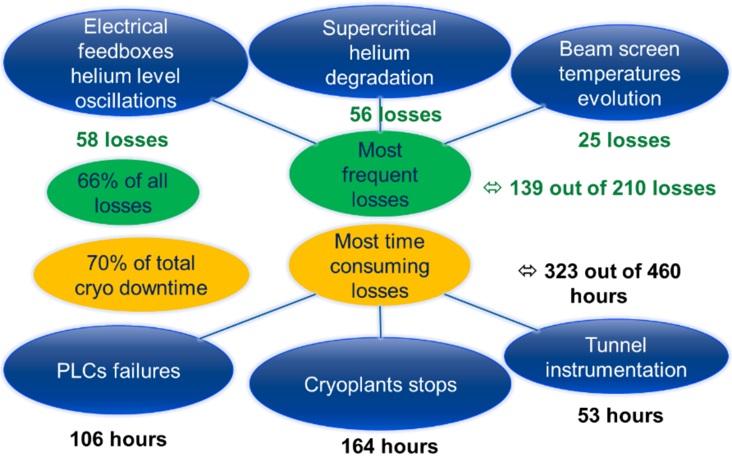

**Figure 7.** Run2 LHC Cryogenics CryoMaintain Downtime Origins.

Figure 8 presents the achieved cryogenic availability over the years from run1 to run2. Despite ageing of the equipment and constraining operation conditions with an improving overall availability trend since 2010.

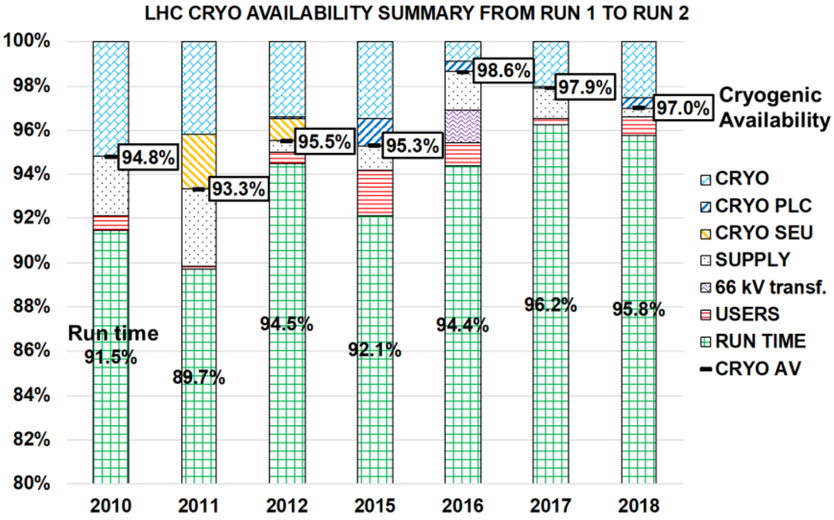

**Figure 8.** LHC Cryogenics availability from 2010 to 2018.

### 4.2. *Helium consumption*

With respect to run1, lessons learned from experience and an adapted helium management strategy allowed for better results in terms of helium consumption over run2. Helium recurrent losses were significantly reduced from 1500 kg / month in 2012 (end of run1) down to 800 kg / month in 2018 (end of run2), which represents 3 kg per day per running cryoplant.

In addition to constant on-line helium inventory follow-up, systematic checks of calculation accuracy were done with automatic scripted tools. Specific verification on leak-tightness of gaseous helium storages and search for helium losses in the ventilation of surface buildings and in the LHC tunnel were done. The helium management strategy during so-called "end-of-the-year-technical-stops" systematized the emptying of all LHC sectors of liquid and maintaining the sectors at 20 K, thus inducing the use of external industrial storage and in the meantime reducing the demand on the operation and support teams during this period. Figure 9 presents LHC cryogenics helium consumption over the past twelve years. From run1 to run2, average annual helium losses rate decreased from 25 % of the total inventory of 130 tons down to 11 %.

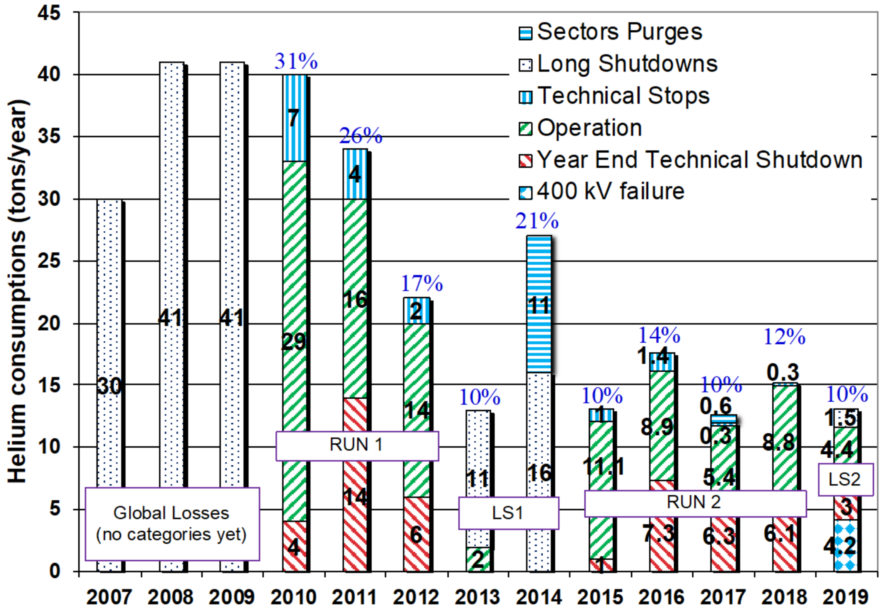

**Figure 9**. Helium consumption of the LHC cryogenics since 2007.

## 5. Training quench and long shut down period

The increase of energy to the nominal value of 7 TeV/beam still requires so-called training of the LHC magnets to allow for their electrical powering at adequate current values. Tentative training of sector 1-2 was done at the end of run2.

### *5.1. Training and cryogenic response for quench recoveries*

The magnet qualification process for operation at defined beam energy consists of progressive increases of the current in the electrical circuits up to required value. During magnet training, several quenches may occur before reaching expected current level. As a quench consequence, adequate energy is dissipated in both dedicated dump resistors and to the cryogenic system, resulting in a magnet temperature increase and the loss of the required cryogenic conditions. The illustration of recovery time after quenches versus total dissipated quench energy is summarized for the LHC sector 1-2 training in figure 10.

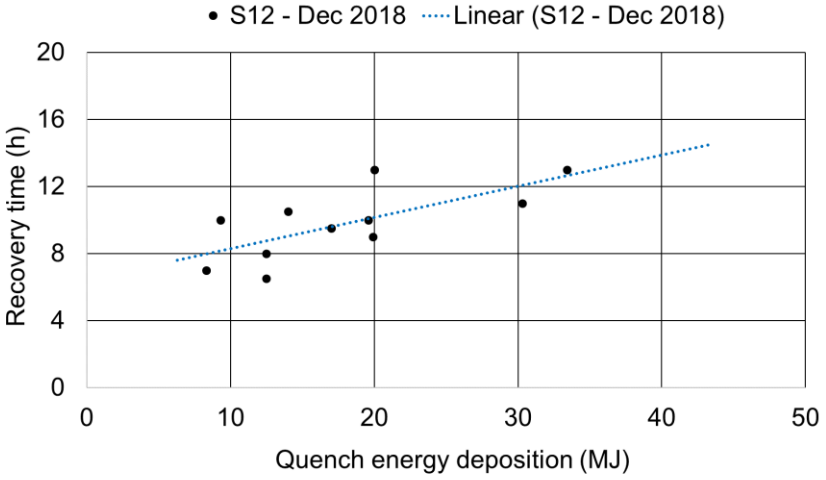

**Figure 10.** Cryogenic recovery time vs quench energy deposition

### *5.2. Long shutdown activities*

Starting from early 2019, after warm up and required tightness and electrical qualifications, the LHC started its second long shut down period (LS2). In parallel to planned activities on the machine itself, several maintenance, consolidation and upgrade actions were undertaken for the cryogenic system. The most important ones are: major overhaul of all warm and cold compressors, electrical refurbishment for four ex-LEP cryogenic plants (25 year old) and upgrade of one cryogenic refrigerator at P4 regarding the HL-LHC project [8]. In addition, several standard maintenance, repairs and upgrade activities will be applied to the cryogenic system during LS2. The LHC cool down activities for its physics run3 are foreseen to start in summer 2020.

## 6. Conclusions and perspectives

The LHC run2 is considered as successful and challenging for the cryogenic operation team. Dealing with higher than expected beam screen heat load implied necessity for non-standard optimizations in operation of the cryogenic plants. Stable operation of one 1.8 K pumping unit over two sectors, with thermal rebalancing on two adjacent cryogenic plants, was confirmed as smart option for run2. Such an operation scenario is recommended for start-up of the cryogenic system for next run in 2020.

The feed-forward process control solutions applied on beam screen circuit and IT cold mass cooling loop brought new experience in dynamic method to control the LHC cryogenic system versus beam induced heat load. The gained experience in dynamic feed-forward control gives now more confidence for application of such a solution in systems requiring fast dynamic response for appearing heat load compensation. This kind of control method is seen as inevitable for heat load management in cryogenic regions of low beta magnets of the future HiLumi LHC.

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