LBDS KICKERS OPERATIONAL EXPERIENCE DURING LHC RUN 1 AND PLANNED CHANGES DURING LHC LONG SHUTDOWN 1

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Abstract

The LHC Beam Dump System (LBDS) operational experience acquired during LHC Run 1 is presented. The major problems encountered during this period, along with the actions taken as a consequence, are summarized. The various changes foreseen for LS1 are explained, in particular the implementation of a redundant triggering path by the BIS, the release of the card TSU-v3, the upgrade of the PTU, the consolidation of the high voltage generators and the modification of the UPS powering to a full redundant architecture. The interlocking policy in place is discussed, and the foreseen improvements in post-mortem analysis systems are shown. The strategy for the reliability run and the re-commissioning of LBDS is presented.

OPERATIONAL EXPERIENCE

LBDS usage analysis

Analyses on the usage of the LBDS during LHC Run 1 were performed, based on the data extracted from the logging of the Internal Post Operation Check (IPOC) system and the eXternal Post Operational Check (XPOC) system [1]. They show that the system has been much more solicited than what was expected. For instance, for LBDS beam 1, during 3 years of operation more than 40000 pulses were executed in LOCAL mode (i.e. the LBDS is controlled locally from the tunnel), and more than 12000 pulses in REMOTE mode (i.e. the LBDS is controlled remotely from the CCC). This is much more than the 400 physics fills per year initially foreseen [2].

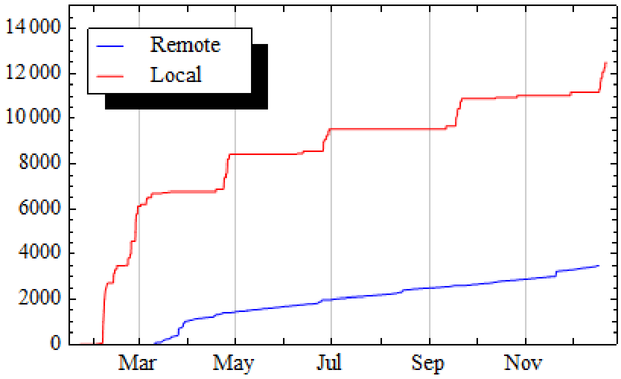

Figure 1: Cumulative number of pulses for LBDS beam 1 during 2012.

Figure 1 shows the cumulative number of pulses recorded during year 2012. We see that the many pulses in LOCAL mode correspond to the end of the Winter Shutdown (WS) and the various Technical Stops (TS), during each of which one or two MKD HV generators were upgraded (see section 'Changes to HV generators'), and subsequently many pulses were performed to recalculate and revalidate the numerous LBDS parameters. The number of pulses in REMOTE mode also includes the commissioning and the Machine Development (MD) periods, which explains why it is much larger than the 585 physics fills dumped during 2012 [3].

From the logging of the Beam Energy Tracking System (BETS), an analysis of the LBDS operational energy during LHC Run 1 was performed. Figure 2 shows that during 2012 most of the time (~110 days) was spend at full energy (4 TeV), and roughly equal time (~85 days) at injection energy (450 GeV) and in standby (400 GeV). The time spent during energy ramps is small (~15 days), and the system has been turned OFF mostly during the WS (~50 days).

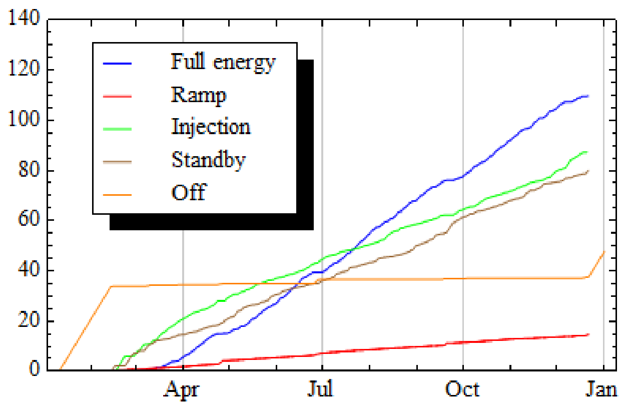

Figure 2: Cumulative number of days spent at each energy for LBDS beam 1 during 2012.

Of course this LBDS utilisation depends entirely on the LHC operation. It is nevertheless interesting information as it shows the periods of stress on the LBDS high voltage equipment. At the beginning of the year we spent more time in standby or at injection energy, but around May the trend is inverted and we spent most of the time at full energy until the end of the year.

LBDS failure events analysis

The list of failure events that occurred on the many devices composing the LBDS during LHC Run 1 has been extracted from the TE-ABT and the OP logbooks [4]. These numerous failure events have then been classified w.r.t. various criteria such as the control mode (LOCAL/REMOTE), the beam mode (No beam, Injection, Beam in, Stable beam, etc.), the type of failure (detected or silent) and the type of intervention needed to solve the problem.

Figure 3 shows the cumulative number of failure events that occurred during the year 2012. Over a total of 33 recorded failure events (blue curve), 16 occurred with beam in the machine, called ‘false dumps’ (red curve). Almost half of the failure events occurred without beam. They correspond mainly to problems that occurred during the WS when upgrades were performed on the LBDS, or to problems in arming the LBDS that were caused by faults in external systems such as Vacuum, RF or Beam Interlock System (BIS).

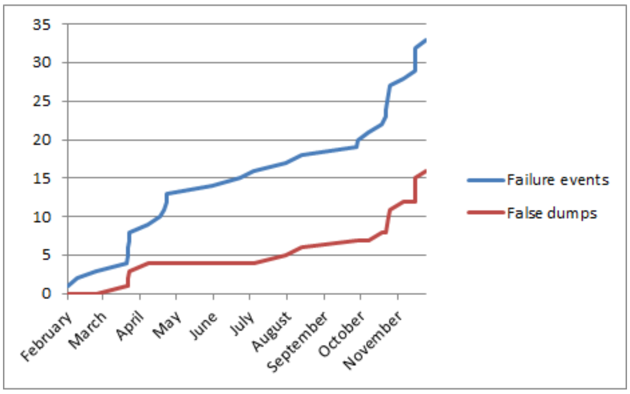

Figure 3: Cumulative number of LBDS failure events during 2012 (LOCAL & REMOTE).

Figure 3 also shows an increase of the number of ‘false dumps’ at the end of 2012, corresponding to various recurrent failures that needed many interventions before the problem could be identified and fixed. This concerns for instance AS-i bus or Anybus industrial components.

To be noted that all of these failure events resulted in a beam dump properly executed.

Of the 28 failure events that were catalogued for 2012 operation in REMOTE mode (with or without beam), 25 were detected and 3 were silent.

Detected faults are related to fail-safe parts of the LBDS, where surveillance guarantees the detection of the fault, and the execution of a beam dump before the situation degrades.

Silent failures are those occurring in fault-tolerant parts of the LBDS, where redundancy guarantees a correct execution of the dump, even with a redundant path that is not working. The problem is then detected during Post-Operation Checks, and will be corrected before the next beam injection.

Only 5 failure events occurred in LOCAL mode during 2012, corresponding mainly to various power supply failures during WS and TS.

Failure follow-up interventions

The interventions executed after a failure event are classified in four categories:

- **Remote**: A reset using an expert application is enough to solve the problem, no access is needed.
- **Masked & Postponed**: The problem is not critical in the current operational conditions, and it is decided to mask the error and to proceed with the LHC operation.
- **Postponed**: The access is needed but is postponed, for instance to wait for the end of operation with the other beam during an MD.
- **Immediate access**: The problem is critical and needs an access before beam is allowed in the machine.

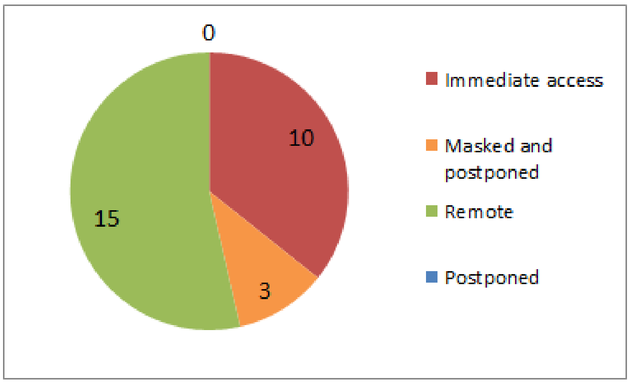

Figure 4: Statistic on the interventions performed during 2012.

Over 28 recorded interventions during 2012, more than 50% were performed remotely, and only 30% needed an immediate access, as shown in Fig. 4.

XPOC errors

After every beam dump execution, the XPOC server [5] performs a number of checks on the LBDS behaviour, using data coming from the various LBDS surveillance and diagnosis systems. Depending on the XPOC module that fails, an LBDS expert has to be called to analyse the situation and reset the XPOC error.

During the operation in 2012-2013, a large number of ‘false XPOC errors’ occurred, i.e. errors that are not due to a bad behaviour of the LBDS but to a bad execution of an XPOC analysis session. These errors are often related to missing data.

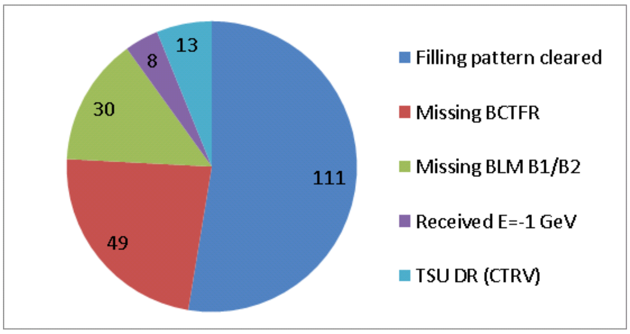

Figure 5: Statistics on the false XPOC errors during 2012.

Over a total of 430 errors detected by XPOC in 2012-2013, 211 were ‘false errors’, due to 5 recurrent problems as shown in Fig. 5.

The identified problems are:

- **Filling pattern cleared (111):** The filling pattern has been cleared by the LHC operator before performing the 'over injection' of a bunch over the circulating pilot. The dump occurred between the clearing of the filling pattern and the injection of the bunch, so an error is issued by XPOC because the measured intensity does not correspond to the filling pattern content.
- **Missing BCTFR (49):** The fast BCT ring (BCTFR) failed and did not publish the circulating beam intensity. As many check limits depend on the beam intensity, XPOC generates an error when this information is missing.
- **Missing BLM B1/B2 (30):** The BLM hardware contains only one XPOC buffer for both beams (200 ms). When the two beams are dumped within a short time interval, data related to both dump events will be included in the BLM buffers. But when beams are dumped more than 100 ms after each other, the XPOC doesn't find data regarding the second dump in the BLM buffers, and issues an error.
- **TSU DR (CTRV) (13):** The two dump requests and the synchronous trigger generated by the two Trigger Synchronisation Unit (TSU) cards are captured by two CERN Timing Receiver for VME (CTRV) cards to precisely timestamp them. Due to a problem not yet clearly identified in the driver of the CTRV card, sometime a dump request is not recorded by the CTRV card. In this case the XPOC generates an error because apparently one TSU did not generate its dump request.
- **Received E=-1 GeV (8):** The XPOC needs timing telegram data such as beam energy to compute many check limits. Sometime the beam energy is not saved properly by the XPOC server at the time of dump, and an invalid value of -1 GeV is send to the XPOC analyses, resulting in an error.

For most errors a reset by the LHC operator is possible. But for the following errors, an LBDS expert had to be called:

- Received energy E=-1 GeV;
- TSU DR not detected (CTRV).

There were far too many 'false XPOC errors' during LHC Run 1 (almost 50% of total XPOC errors) and LHC operators spend way too much time to address them. An LBDS Expert had to be called for 10% of the cases.

All these problems have to be solved during LS1. Discussions have already started with the concerned groups and we are confident that solutions will be found.

LBDS self-trigger with beam

The statistics of MPS show that only 4 physics beams were dumped by an internal fault in the LBDS [3]. However, it should be noted that only beam dumped at energies higher that 450 GeV were accounted. (At 450 GeV, the beams were lost 40 times due to an LBDS self-trigger).

Table 1 shows that these four physics beams were dumped due to two recurrent hardware problems:

- AS-i bus error: SIEMENS AS-i bus power supply was delivering unstable voltage;
- BEM Anybus error: Anybus communication module on Beam Energy Meter (BEM) card, part of the BETS, was not functioning properly.

Table 1: Physics Beams Dumped in 2012 by LBDS Self-Trigger

Date	*Energy*	*Cause*
02-OCT-12 16.17.38	3310	AS-i bus error
27-OCT-12 07.58.38	4000	AS-i bus error
28-OCT-12 11.11.05	494	BEM Anybus error
29-OCT-12 19.50.47	458	BEM Anybus error

These errors were also responsible for many dump events at the end of 2012, as shown in Fig. 3, and needed many interventions until the source of the problem was identified and definitely solved.

Industrial component failures

Many failure events were due to design problems with off-the-shelf industrial component, i.e. the component did not meet the announced performances in terms of MTBF. A list of hardware problems encountered during LHC Run 1 is shown in Table 2. These components had all to be sent back to their manufacturer for repair or upgrade, or had to be repaired at CERN.

Table 2: Industrial Component Redundant Failures

Component	*Items in operation*	*Problem description*
National Instruments PXI-5122	61	Weak fuse.
VERO PK55 PSU	50	Bad electrolytic capacitor.
Heinzinger 3kV HVPS	80	Bad electrolytic capacitor.
Heinzinger 35kV HVPS	40	HV transformer sparking.
SIEMENS AS-i bus PS	4	Bad electrolytic capacitor.

Electrolytic capacitors are the most predominant source of failure, and many bad quality capacitors were replaced by more reliable ones in many power supplies units.

Potentially dangerous failures

Four failure events were identified to be potentially dangerous, i.e. if they had occurred in other operational conditions they could have yield to significant machine down time. These four events are described below:

- **TFOT Driver IC burned:** The Trigger Fan-Out Transmitter (TFOT) cards are responsible for driving the 60 redundant synchronous triggers to the 15 MKD generators. A line driver IC burned in one of the TFOT cards, generating a pulse at its outputs. The way the redundant triggers are cabled between the output of the TFOT and the input of the generators lead to two generators receiving the bad trigger. As a result two generators triggered erratically, and then the 13 others were triggered ~800 ns later by the retrigger lines.
  Following this incident, the TFOT were re-cabled in a way that, if the same line driver problem occurs, only one generator would be triggered erratically, which is acceptable. A review of the design of the TFOT card was conducted, and concluded that no design problem could account for this event [6].
- **WIENER Power Supply Failure:** The power supply of a WIENER cPCI crate failed during a TS with its main power input in short circuit (failure of the Power Factor Correction circuit). This provoked the trip of the main circuit breaker of the UPS, leading to 8 racks of LBDS control electronics being out of power simultaneously. As a consequence only asynchronous triggers were issued.
  This problem of selectivity in the UPS electrical distribution was not expected, and a review of the whole LBDS powering was conducted [7]. As an outcome the power distribution of the LBDS has been upgraded: a second UPS source was provided (from QPS), and individual fuses were installed on every LBDS control crate.
  During LS1, the LBDS power distribution will be consolidated by adding a second independent UPS (from US65) and an individual circuit breaker for every crate.
- **+12V Power Supply loss on TSU crate:** During analyses performed for the preparation of the LBDS powering review, we identified a scenario that could yield to a potentially catastrophic situation. In this scenario the +12V power supply fails in the crate that contains the two Trigger Synchronisation Unit (TSU) cards. In this case no triggers, neither synchronous nor asynchronous, are generated and so any dump requests will be discarded. This scenario never occurred. When the problem was discovered an immediate beam dump was requested, and the LHC operation was stopped. A temporary solution that monitors the +12V power supply in the TSU crate and generates an asynchronous beam dump in case a failure is detected was implemented.
  This fix was consolidated during the following TS, and to definitively avoid this problem in the future, a new TSU card is designed and will be deployed on two separate crates during LS1.
- **MKD generator HV sparking above 6 TeV:** As the MKD generator GTO switches are very sensitive to temperature change, we added a Peltier cell inside each generator to maintain the switches at a constant temperature. These modifications were made after the LBDS reliability run that took place during 2009.
  After the addition of the Peltier cells, we realised that the MKD generators could not handle the full operational voltage anymore. For a voltage corresponding to an energy higher than 6 TeV, sparking occurred in the generators, causing a self-trigger of the GTO switches. An explanation for this complex phenomena could be that the air is dried by the Peltier cells, and becomes so insulating that the charges produced on the surface of the Plexiglass insulators cannot flow away anymore so they accumulate and after a certain voltage is reach, they eventually discharge on the GTO deflectors, sometimes igniting a self-trigger of the GTO stack.
  As the operational energy foreseen for LHC Run 1 was 3500 - 4000 GeV, it was decided to limit the LBDS operational energy to 5000 GeV.
  Studies for the upgrade of the GTO stacks were immediately initiated and insulating pieces avoiding sparking will be installed during LS1.

Missing procedures

Operational procedures are also needed to help experts to take decisions based on risk evaluation, and to limit the LHC operation with beam when the LBDS is used in degraded mode (masking of switch ratio, enlarging of XPOC tolerances, etc.). Moreover, the fact that the LBDS is in degraded mode is not clearly visible in the CCC and, at least, a warning indication should be added on the LBDS fixed display.

Operational procedures to be followed after hardware changes in the LBDS are needed, to enforce the revalidation of the system by performing standard tests.

PLANNED CHANGES DURING LS1

Additional re-trigger from BIS

The LBDS comprises a complex Trigger Synchronisation and Distribution System (TSDS) [8], which includes two re-trigger lines that connect every MKD and MKB generators with each other, shown in red and blue in Fig. 6. In the case an MKD generator self-triggers, the re-trigger lines will propagate a trigger to all the other generators, resulting in an asynchronous dump with the 15 generators pulsing.

Each time a dump request is sent to the TSDS, the TSU cards generate synchronous triggers that will be distributed to the 15 generators, plus redundant asynchronous triggers 200 μs later that will be sent over the re-trigger lines to cover the case were the synchronous dump has not been executed properly.

To cover the case where a dump request is not handled by the TSDS and no dump triggers are issued at all, such as the +12V power supply problem discussed previously, a direct connection from the BIS to the LBDS re-trigger lines is recommended.

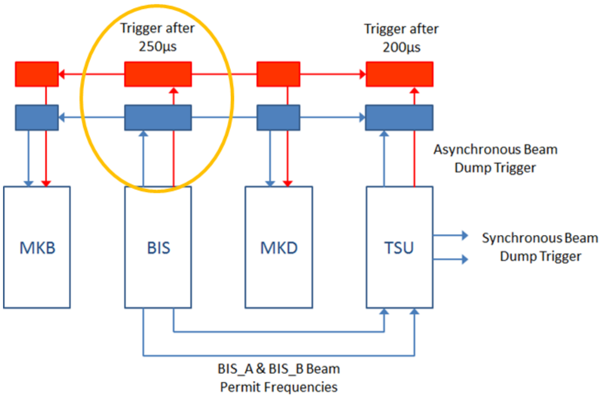

Figure 6: BIS connection to the LBDS re-trigger lines.

Each time the BIS loops open, a pulse would be sent over the re-trigger lines 250 µs later. This would guarantee at least an asynchronous beam dump in the case the TSDS does not react to a dump request.

The presence of this pulse on the re-trigger lines will be checked after every beam dump by the TSDS IPOC system.

The drawback of such a solution could be an increase of the asynchronous beam dump rate, due to a malfunctioning of the hardware added between the BIS and the re-trigger lines.

During LS1, functional and engineering specifications of the connection between BIS and LBDS re-trigger lines will be written [9], and a reliability analysis of the new hardware will be conducted [10].

Upgrade of TSU card

Following an external review of TSU card design [11], the problems foreseen regarding the loss of +12V power supply on the TSU crate and the review of LBDS powering [7], a new hardware design of the TSU card will be implemented during LS1. The new TSU cards will be deployed over two separate crates, and a surveillance of all the power supplies will be added on the TSU card itself, hence the redundant TSU will trigger in case the first one loses one of its power supplies. The diagnostics will be improved as well, as many additional TSU internal signals will be acquired and analysed by the IPOC system, such as all the redundant dump requests from all the clients.

LBDS powering modifications

Following the LBDS powering review [7], a separated connection to a second UPS (in US65) will be installed for LBDS and an individual circuit breaker will be installed on every crate Power Supply Unit (PSU). Moreover a monitoring of the state of all the redundant PSU of LBDS crates will be performed, and the Software Interlock System (SIS) will request a dump in case a failure is detected in a PSU.

MKB vacuum interlocking problems

The dilution kicker magnets (MKB) are installed in a vacuum tank. They can be operated only under defined vacuum conditions to avoid sparking. During LHC Run 1 we experienced many problems due to noise present on the vacuum probe signals. The analogue vacuum signal is very noisy and was always masked since the beginning of LHC Run 1. The digital interlock signal is very noisy as well (spikes and glitches) and is at the origin of more than 13 beam dumps during 2011-2012 operation.

Discussions with TE-VSC have started, and a solution to all these vacuum probe problems must be provided during LS1.

Changes to HV generators

As explained in the section “Potentially dangerous failures” above, the operation of the LBDS has been limited to 5 TeV during LHC Run 1, due to electrostatic discharge occurring inside the MKD generators for energies above 6 TeV.

The sparks appear between the GTO HV deflectors and the Plexiglass insulated return current rods [12].

To avoid the electrical breakdown for voltages corresponding to an energy higher than 6 TeV, insulators between the GTO HV deflectors and the return current rods will be added to all generators during LS1, as shown in Fig. 7.

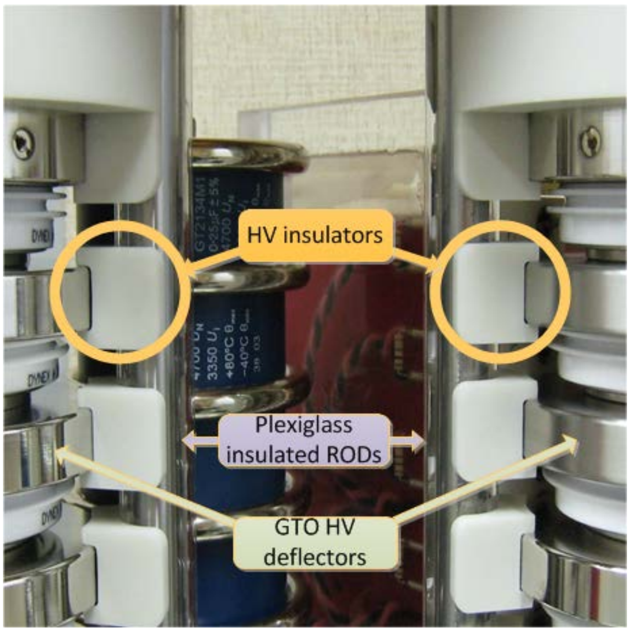

Figure 7: Details of two GTO stacks in an MKD generator showing the added HV insulators.

During Run 1 the GTO stacks were provided by two different manufacturers. After LS1, only ABB GTO will be used as they have better Single Event Breakdown (SEB) test results and have a more stable turn-on delay [12]. Nevertheless, a common mode failure could appear due to this choice of a unique technology and will be evaluated.

Upgrade of Power Trigger Units

The GTO stacks in the HV generators are triggered by Power Trigger Units (PTUs) that deliver the current in the GTO gates. These PTUs are composed of a High Voltage Power Supply (HVPS) that charges a capacitor, which is then discharged into the GTO gates using IGBT switches.

During Run 1 the PTU HVPS voltage was continuously adjusted w.r.t. the beam energy varying roughly from 600 V to 3000 V. These adjustments, which were specific for each generator, were made to maintain the rising edge of every kicker magnet currents within a window of 2.7 µs at all energies [12].

During LS1 the 3kV HVPS will be replaced with a 4kV one, and the 1.2kV IGBTs will be replaced by 1.7kV ones. SEB tests show that the new 1.7kV IGBT is substantially less sensitive to SEB than the previous one [13].

With this increased PTU voltage, the GTO gate currents are higher, leading to lower GTO turn-on delays. Moreover the GTO turn-on delays becomes less dependent on the GTO anode-cathode voltage, so the adjustment of the PTU voltage w.r.t. the beam energy would not be necessary anymore.

After LS1 we plan to use the PTUs with a constant voltage of ~3300 V, and we expect that no increase of the beam abort gap duration would be needed when operating the LBDS under these conditions.

Other changes…

Many other changes will be performed in the LBDS during LS1. The main changes are:

- **Upgrade of the 30 MKD generator IPOC systems**: Four digitizer channels will be added on each MKD generator to capture and analyse the PTU current waveforms.
- **Upgrade of the 30 MKD -300V DCPS**: One operational amplifier will be replaced in the compensation DCPS (-300V) of all MKD generators, to solve a problem with its offset. This will facilitate the replacement of a defective DCPS.
- **Upgrade of the 30 MKD generator temperature probes**: Absolute temperature measurements, used to maintain the GTO stacks at a constant temperature using the Peltier cells, are not precise enough. We will replace the temperature probes by more precise ones (± 0.1 ^{O}C instead of ± 0.3 ^{O}C), and connect them using 4 wires instead of 3 to reduce the sensitivity to cable length and contact resistances.
- **Improve shielding in MKD&MKB cable ducts between UA and RA**: Presently only ducts in front of TCDQ are filled with rods made of lead. All the cable ducts between UA and RA will be filled.
- **Add 2 MKB magnets (1 tank) per beam**: During Run 1 only 4 vertical dilution magnets were installed per beam instead of the 6 initially planned. This was sufficient to dilute the beam up to 4 TeV. During LS1 the two remaining vertical dilution magnets will be installed.

FULL RE-COMMISSIONING

After all the changes that will be performed on the LBDS during Run 1, a full re-commissioning of the LBDS is mandatory.

After a first revalidation period, a reliability run will be conducted for approximately 3 months. It will consist in running the LBDS in LOCAL mode and performing pulses at various energies, keeping the LBDS at full energy for long periods, simulating ramp-up and ramp-down, etc…

This will be followed by the re-commissioning of the LBDS in REMOTE mode without beam, so called ‘dry-run’. The LBDS will be controlled from the CCC to validate the various control software interfaces, and a local BIS loop will be installed to check the functionality of the new link between BIS and LBDS with sufficient operational statistics.

This is followed by a commissioning with beam which allows validating all the LBDS parameters by checking the position of the beam on the Beam TV Direct Dump (BTVDD) screen, located 30 meters upstream of the beam dump absorber block.

Additional tests have to be conducted after the commissioning, such as the measurement with beam of the effective rise time of MKD extraction kicker magnets. The procedure for this test is still to be defined, but it will certainly rely on a scan of the MKD ‘threshold’ and ‘start’ points with a pilot, and the measure of the effect on the beam using BTVDD and BPMs.

Another obligatory test will be to provoke a beam dump triggered from the Beam Loss Monitor Direct Dump (BLMDD), which is a BLM located at point 6 and directly connected to the TSU cards. This TSU client has never been activated up to now during operation.

All the existing commissioning procedures [14] will be reviewed and updated, in the light of the LBDS operational experience during LHC Run 1.

Procedures for a non-working LBDS trigger

A procedure has been established to cover the case where the various dump triggers are not generated on request and so the beam dump is not executed [15].

This procedure must be updated taking into account all the changes performed on the LBDS during LS1, such as the new TSU cards deployment over three separate crates, or the changes in the LBDS power distribution including the addition of a UPS. The new procedure must be carefully validated.

Safety and Reliability analyses

An expert has been mandated during LS1 to analyse and classify all the failure events that occurred in the LBDS during the LHC Run 1, in a manner to validate the safety and reliability analyses of the LBDS performed in 2003-2006 [16]. The first statistics on failure events are presented at the beginning of this paper. The results of this study confirm the agreement of the calculated statistics with the predicted estimates, in terms of impact on the LHC operation and safety [2].

Another part of the safety analysis was to model the TSDS in the light of all the changes that will be performed during LS1. This modelling was not included in the analysis before. The analysis showed the TSDS to be largely SIL4, thanks to the changes performed during LS1 such as improvements in power distribution and surveillance, and a different routing of synchronous trigger signals [17].

SUMMARY

Operation of the LBDS during the LHC Run 1 was completely satisfactory as all dump requests were correctly executed and the availability of the LBDS was good. However, there were some negative surprises, which did not affect operation directly but could have led to dangerous situations. Many changes to the LBDS are foreseen for LS1, which will mitigate all the potential problems identified. An extensive re-commissioning of the LBDS, including a reliability run, a dry run and beam tests will be required at the start-up of LHC Run 2.

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