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CONSOLIDATION OF RE-TRIGGERING SYSTEM OF LHC BEAM DUMPING SYSTEM AT CERN

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Abstract

The Trigger Synchronisation and Distribution System (TSDS) is a core part of the Large Hadron Collider (LHC) Beam Dumping System (LBDS). It comprises redundant Re-Trigger Lines (RTLs) that allow fast re-triggering of all high-voltage pulsed generators in case one of them self-triggers, resulting in a so-called asynchronous dump. For reliability reasons, the TSDS relies on many RTL redundant trigger sources that do not participate directly in the execution of a normal dump. After every dump, signals propagating on the RTLs are analyzed by Post Operation Check (POC) systems, to validate the correct performance and synchronisation of all redundant triggers. The LBDS operated reliably since the start-up of LHC in 2008, but during its Run 2, new failure modes were identified that could induce damage for the beam dump block and the dump protection elements. In order to correct these failure modes, an upgrade of the TSDS is realized. This paper reviews the experience gained with the LBDS during LHC operation and describes the new architecture of the TSDS being implemented. Measurements and simulations of signals propagating on the RTL are presented, and the analysis performed by the POC systems are explained.

INTRODUCTION

The LHC Beam Dumping System

The LBDS is a critical system, ensuring safe extraction of the beam from LHC. The beam is sent to the extraction channel using 15 extraction kicker magnets (MKD) and 15 extraction septa (MSD). It is then diluted by 4 horizontal (MKBH) and 6 vertical dilution magnets (MKBV) on the beam dump absorber (TDE). To allow for the rising edge of MKD magnetic field, a particle free Beam Abort Gap (BAG) of 3 µs is maintained in LHC [1].

The High Voltage Pulsed Generators (HVPG) power the MKDs and MKBs. At the reception of a trigger, four Power Trigger Modules (PTM) will start the conduction of two switches composed of Fast High Current Thyristors (FHCT) that discharge capacitors into the magnet.

The Beam Energy Tracking System (BETS) is a surveillance system within the LBDS, continuously checking that the voltages inside each HVPG correspond to the beam energy, to guarantee a correct extraction angle at any time. In case one HVPG exceeds tolerances, the BETS requests a beam dump [1].

The Beam Interlock System (BIS) is connected to thousands of devices around LHC, and in case a problem is reported by one of them, the BIS requests a beam dump [2].

Trigger Synchronisation and Distribution System

The TSDS is built around the two redundant Trigger Synchronisation Units (TSU), responsible for the detection of a dump request (DR) coming from various sources and the dispatch of the Synchronous Beam Dump Trigger (SBDT) to the HVPGs, synchronously with the passage of BAG in MKDs [3].

The TSDS also comprises a Re-Triggering System (RTS), allowing the asynchronous fast re-trigger of all HVPG in case of one MKD HVPG self-triggers.

Each MKD HVPG is equipped with a Re-Trigger Box (RTB), that couples internal pickup signals to the RTL to generate a pulse when the HVPG is triggered, and also to capture the pulses on the RTL, and send them to their PTMs. Each MKB HVPG is equipped with only a Re-Trigger Receiver (RTR), that will capture the pulses on the RTL, and send them to their PTMs.

These RTBs are interconnected by the RTL cable, composed of 4 conductors that are used as two pairs, with a common shielding. One pair is used for the RTL pulses, the other for a Continuity Monitoring (CM), where a constant current is used to check the RTL continuity, see Fig. 1.

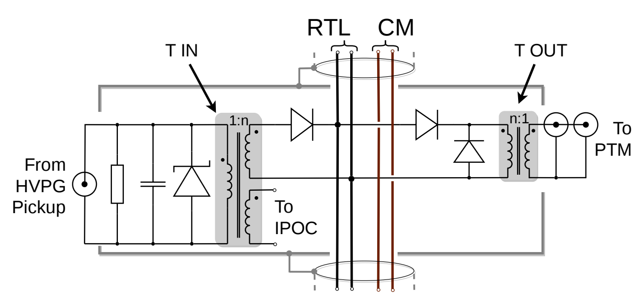

Figure 1: Simplified schema of RTB.

The TSDS was already upgraded before LHC Run 2, to add a redundant direct connection from BIS to the RTLs as a second layer of protection in case of failure of the TSU cards [4, 5].

A simplified view of the current architecture of TSDS is shown in Fig. 2. We can see from left to right the 15 MKD (A-O) HVPG (blue) connected to the RTL through their RTB, and the 10 MKBs (MKBHA-D to MKBVA-F) HVPG connected to the RTL through their RTR. About 300 m separate the MKDs from the MKBs in LHC tunnel.

At reception of a DR, the TSU cards send an Asynchronous Beam Dump Trigger (ABDT) to the RTLs through

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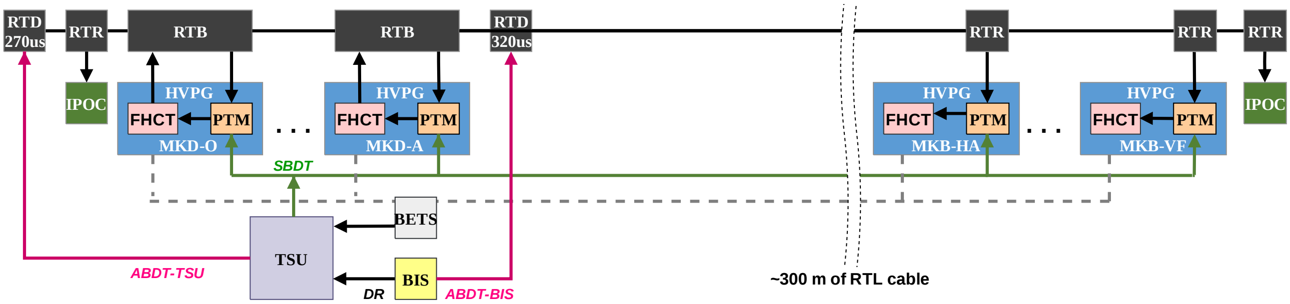

Figure 2: Simplified view of current TSDS architecture.

a Re-Trigger Delay (RTD) of 270 µs. This delay gives 3 LHC revolutions time to the TSU to send the SBDT at the passage of BAG in MKDs. When activated, the BIS issues a DR to the TSU cards, and sends a second ABDT to the RTLs through a RTD of 320 µs.

Normal Beam Dump Scenario The TSU cards receive the DR from BIS, and send their SBDT to the 25 HVPG. All HVPG pulse synchronously with the BAG. The TSU and BIS redundant trigger are sent on the line after the beam dump.

MKD HVPG Self-Trigger Scenario In case of one MKD HVPG self-triggers, the RTB connected to the HVPG internal pickups injects pulses on the two RTLs that propagate, and are detected by the 24 other HVPGs, yielding in a so called asynchronous beam dump, as the MKDs pulse outside the BAG. Beam present on the rising edge of MKDs is absorbed by dedicated protection elements.

MKB HVPG Self-Trigger Scenario In case of self-trigger of one MKB HVPG, no pulses are injected on the RTLs. The BETS detects the discharge of the HVPG, and will issue a DR. The TSUs sends the SBDT, and all MKDs and remaining MKBs pulse synchronously with the BAG.

Diagnosis of Redundant Pulses on the RTL

In case of a normal beam dump, the TSU and BIS ABDT are sent on the line after the beam dump. They do not participate directly in the dump action, but are needed in case of failure of the TSUs. So to make sure that these redundant protections are functioning properly, two Internal Post Operation Check (IPOC) [6] systems (green in Fig. 2) will capture the pulses on both ends of the RTLs, and the XPOC system will check for their correct amplitude and synchronisation after every beam dump execution [7].

Figure 3 shows the signals measured on the RTLs by IPOC systems in case of synchronous beam dump: The 15 MKD HVPG pulsing, then the ABDT-TSU max 270 µs after dump, and then the ABDT-BIS max 320 µs after dump.

EXPERIENCE WITH LBDS

Since the beginning of LHC operation, the TSDS performed very well, and all beams were properly extracted, but

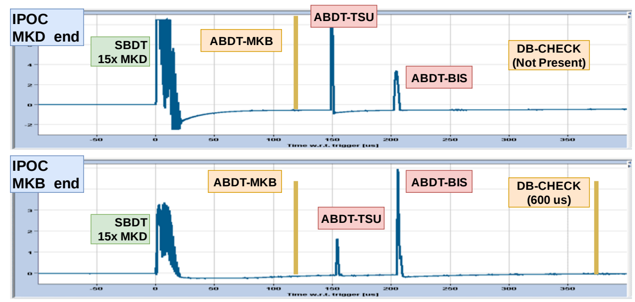

Figure 3: Pulses captured by IPOC on the current RTLs (blue), and illustrated for new RTLs (yellow).

the LBDS suffered from unforeseen failure modes, which, in view of HiLumi-LHC and the increasing beam intensity, could yield to damage of the TDE and LBDS protection absorbers. The following subsections summarise the most relevant events noticed since the beginning of LHC operation.

Redundancy Loss of RTL

When we installed the IPOC on both ends of RTL to validate the BIS/TSU pulses, we realised that one of the two RTL was open on one of its many connections [5]. This proved the inefficiency of the CM system, and made IPOC the only reliable way to validate the good health of the RTLs.

Attenuation of Pulses Propagated on the RTL

With these new RTL IPOC systems, we realised that the ABDT coming from TSU and BIS propagating on the RTLs after every synchronous beam dump were sometimes seriously attenuated. This problem was not understood at the start of LHC Run 2, but was identified as only a diagnosis problem, not a safety issue [5].

Self-Triggering of MKB Generators

As explained in the scenario above, the SBDT is sent by the TSU based on a DR issued by the BETS. Depending on the BETS detection time (~250 µs to ~1 ms) and the TSU synchronisation time (0 - ~90 µs), the remaining current in the self-triggered MKB at dump time presents variable amplitude due to damping, and can be in phase opposition with the other synchronously triggered MKBs, as shown in

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Fig. 4. This can yield the loss of almost two MKB instead of one expected [8].

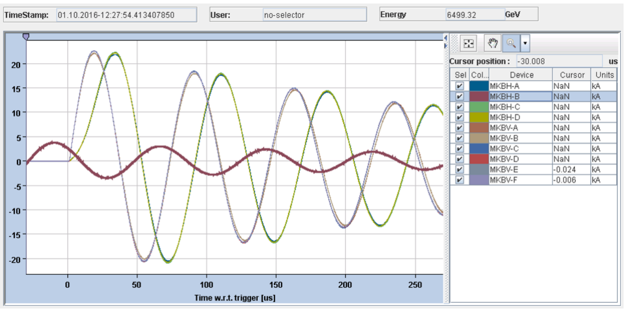

Figure 4: Currents in MKB magnets captured by IPOC after one MKB HVPG self-triggered

Coupling between MKB Generators

When performing tests during technical stop, we spotted an event where an MKBH HVPG self-triggered, and its neighbour HVPG was also triggered. This was not expected, as MKB HVPG do not inject triggers on the RTL. This was traced down to a problem of current flowing from the self-triggered HVPG to its neighbour through the RTL shielding. This problem was immediately mitigated by installing nanocrystalline cores around RTL cables connected to MKBH HVPGs.

MOTIVATION FOR CONSOLIDATION

Various upgrades in LBDS HVPGs are already performed, to reduce the probability of self-trigger, like lowering HVPG voltage or using higher rated semiconductors for renovated PTMs [9].

But the combination of the coupling between MKB HVPGs and the possible MKB phase opposition could yield the loss of more than half the horisontal dilution, which is an unacceptable failure mode for the TDE [8].

So it was decided to upgrade the architecture of the RTS, to remove the problem of MKB HVPG coupling, and phase opposition between MKBs.

NEW ARCHITECTURE OF TSDS

Figure 5 shows a simplified view of the new chosen architecture of TSDS. Added elements are shown in orange.

MKB RTRs are replaced by RTBs, so in case of self-trigger of MKB HVPG, pulses are injected on the RTLs to re-trigger all other MKB HVPGs, solving the problem of coupling.

In order to avoid an asynchronous beam dump in case of MKB HVPG self-triggering, a decoupling box (DB) is inserted on the RTLs where the BIS RTDs are located. This DB contains decoupling diodes to block the propagation of pulses from MKB side to MKD side of the RTL. A new RTR is inserted on MKB side before the diodes, with electronics to detect pulses on the RTL and issue a DR to the TSUs.

In case the connections from the DBs to the TSUs fail, the MKB self-trigger would be detected by the BETS, but the beam dump could be executed almost without dilution, depending on the BETS reaction time. This is an unacceptable scenario which could yield in serious damage to the TDE.

To cover this case, this DB-RTR also send an ABDT to the RTLs on MKD side through an RTD of 120 µs, so in case the SBDT are not sent by TSUs after this delay, an asynchronous dump is performed, which is less critical for the TDE than a synchronous dump without dilution.

Eventually, a last pulse is sent on the RTLs from the SBDT through a RTD of 600 µs, to make sure that the diodes in the DBs are still blocking after the execution of the beam dump.

New MKB HVPG Self-Trigger Scenario

1) When an MKB HVPG self-triggers, it injects pulses on the RTLs thanks to the new MKB RTBs. 2) All other MKB HVPG are re-triggered, injecting even more energy on the RTLs. 3) These pulses will propagate on the RTLs 300 m up to the DB located before MKD HVPGs, and are blocked here. 4) These pulses are detected in DB-RTR, and a DR is issued to the TSUs. 5) The TSUs will send the SBDT to trigger the MKDs.

Reliability Analysis

An analysis was conducted to evaluate the impact of this new architecture on the LBDS reliability. Different solutions were compared in terms of failure modes and resulting reliability and availability [10]. This study shows, that as coupling between the MKB generators cannot be excluded, the new TSDS architecture reduces the probability of the failure case 'Insufficient/ No Dilution' in comparison to the current system. The probability for 'no dilution' failure in new architecture is negligible (~ 1e12 years mean time to failure) and expected increase of asynchronous dumps per year is very small (1 per 1000 years and beam) The results of this study have been discussed in the CERN Machine Protection Panel, together with energy deposition studies for the dump absorber and the associated vacuum windows.

DESIGN OF NEW RTS COMPONENTS

To implement this new TSDS architecture, we have to make sure that in case of one MKB HVPG self-triggering, the pulses injected on the RTL are propagated up to the DB and properly detected. Also the new ABDT-MKB sent 120 µs after SBDT must be detected and analysed by IPOC after every dump. The problem of pulses attenuation discussed before could prevent both features. So a simulation of the RTS was launched to understand this pulse attenuation observed on the RTL.

Simulation Model

The RTL comprises multiple components equipped with nonlinear devices (diodes, TVS). In such a configuration the time-domain simulation does not allow a linear approximation of the entire system being studied. In the light of

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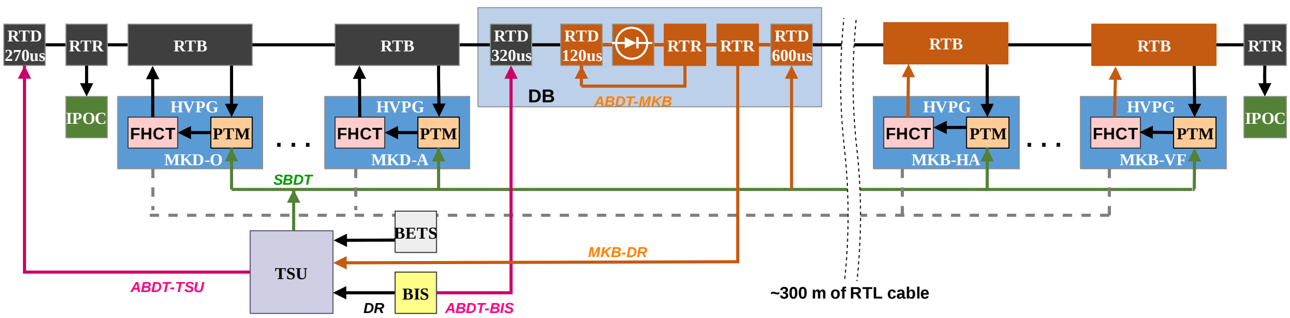

Figure 5: Simplified view of new TSDS architecture

this fact, a circuit-block simulation of the RTS was captured in order to predict its behaviour in view of worst-case fault scenarios, such as self-triggered HVPG or failures of RTB components. In addition, the gain from minor changes could be evaluated: increase of signal amplitudes at the source level, replacement of obsolete components, suppression of additional load from the line.

Analysis of Pulse Attenuation on RTL

Further analysis of pulse amplitude and time for thousands of normal beam dumps showed that the ABDT suffered an attenuation depending on both beam energy (HVPG voltage) and pulse time after SBDT. Figure 6 shows ABDT-BIS measured by IPOC on MKD side, after travelling trough 15 MKD RTBs. Pulses at low energy (blue) are less attenuated than at higher energy (red), and the attenuation depends strongly on the time between SBDT and ABDT.

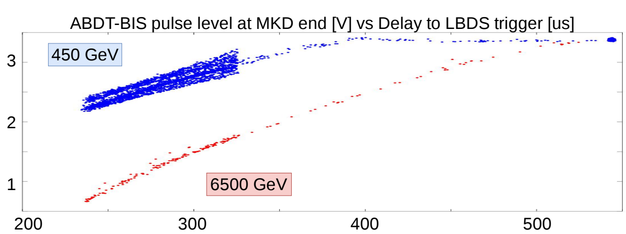

Figure 6: Analysis of pulses attenuation on the RTLs

First simulations of RTL could not reproduce this attenuation phenomenon.

Attenuation in RTB Using a more detailed model, including RTB transformer core hysteresis, we could make an estimate of the flux seen by the output transformers, and their impedance loading the line. This attenuation phenomenon was understood to be due to magnetic core saturation in the RTB, illustrated in Fig. 1. At time of dump all MKD HVPGs pulse and inject energy on the RTL, and depending on HVPG voltage, this can saturate the output transformers of the RTBs, which will then absorb any pulse sent on the line subsequently. The transformers start to de-saturate slowly after the dump, so depending on when the TSU and BIS ABDT are sent on the line, they will see transformers in various saturation states, which explains the variable attenuation observed depending on both HVPG voltage and ABDT time shown in Fig. 6.

The duration of the pulses delivered to the line by the RTB should be limited through correct selection criteria of the RTB I/O transformers, depicted in Fig. 1. The allowable flux parameter of the input should be high enough in order to trigger the power stage of the generator; the allowable flux of the output transformer however should not be lower than the voltage-time product of the RTL signal present at this point. New RTB design assumes 80 µVs and 250 µVs for the input and output transformer respectively.

Attenuation in Cable One of the main concerns of the simulation work was the characterisation of the RTL cable. The measurements performed in the LHC tunnel over the 300 m-long section of RTL cable has shown an important attenuation and distortion, which could not be explained based on cable manufacturer specification. Measured cable attenuation characteristics were fit into simulation model, to be able to perform predictions on the renovated RTL.

Only recently has it been noticed that the RTL cable is star-quad type, not two separated twisted-pairs as expected. It is not designed for the transmission of two pulsed signals, but only one, even if cable convention at CERN shows two pairs, but recommended for DC controls signals only.

This could explain the loss observed in the cables, due to cross-talk from RTL pair to the CM pair, as visible on Fig. 1. Non-trivial simulation of this cable in unbalanced mode will start soon and results will be compared against measurements. The removal of the CM system could be a solution to use the cable correctly, as its efficiency was proven poor anyway.

Re-Trigger Time Improvement

The re-triggering time, from self-triggered MKD HVPG to the last triggered MKD HVPG, should be minimised to limit the energy deposited on protection elements in case of asynchronous dump. Figure 7 shows a measure of re-triggering time, by simulating self-trigger of each MKD HVPG one after the other.

The Detection Time (blue) is mainly due to the PTM and FHCT turn-on delay, and is almost constant ~ 0.5 µs. Propagation time reduction at the level of the RTB is difficult

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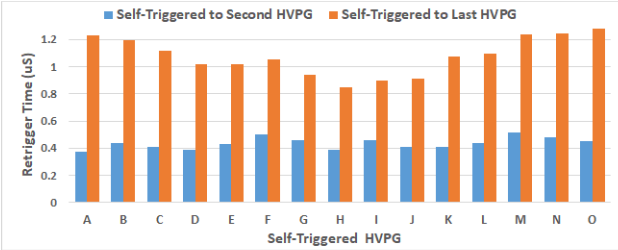

Figure 7: Re-trigger time for each MKD HVPG self-trigger.

because of unavoidable inductance of the I/O transformers, and it has low contribution to the overall re-triggering time (tens of ns). This time was already reduced by faster electronics used in new PTM [9].

The Propagation Time (orange - blue) depends on RTL cable, and varies from ~0.3 to ~0.8 µs. Currently the RTL cables are following cable trays above racks, and are about 5 m long between each generators. By straighter routing we could gain probably up to 3 m of cable per generator, so around 0.2 µs gain on MKD section.

Also, a prospect for a RTS based on optical power transmission has been studied as an alternative approach [11].

Insulation of RTL from HVPG

In order to prevent a possible cross-talk of neighbouring generators (uncontrolled and unwanted couplings) the shielding of the RTL will not be connected to the chassis of the LBDS generators. As depicted in the schematic Fig. 1 a new RTB grounding scheme also foresees the I/O decoupled from each other and the generator chassis.

Improvement of Diagnosis of Pulses on the RTB

The IPOC systems on both ends of the RTL must now analyse the amplitude and time of the two added ABDT-MKD and DB-CHECK, as illustrated in Fig. 3 in orange. The IPOC systems of all HVPG are also extended to capture the I/O signals of RTBs. This will allow us to have a measurement of the ABDT on the RTL at the level of every HVPG, to check the attenuation profile of the line. Also in case of self-triggering of one HVPG, the waveforms of HVPG pickups and RTL signals will be available for diagnosis.

TEST AND COMMISSIONING

The test of this new implementation will start Q2 2020, when all renovated HVPGs will be ready in LHC tunnel. Before the restart of LHC we are planning a long reliability run period, to simulate operational conditions and validate the performance of the consolidated LBDS.

CONCLUSION

LBDS performed very well since the beginning of LHC operation, but unforeseen failure modes occurred, that could yield damage to TDE and the dump protection elements in condition of HiLumi-LHC beams. A new architecture of TSDS is being implemented, solving problems related to the retrigger system observed in operation since the start-up of LHC. The new LBDS re-triggering system will have to be carefully validated before the start of LHC Run 3, during a long reliability run without beam.

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