CERN BEAM INTERLOCK REDUNDANT DUMP TRIGGER MODULE PERFORMANCE DURING LHC RUN 2

D. Calcoen, S. Gabourin, A. Siemko, CERN, 1211 Geneva 23, Switzerland

Abstract

During the Long Shutdown 1 an additional link between the Beam Interlock System and the LHC Beam Dumping System was installed. This new channel is a direct access from the Beam Interlock System to the asynchronous dump triggering lines of the LHC Beam Dumping System. This paper describes the experience collected for the first 10 months of operation and the improvements proposed for a future upgrade of the module.

INTRODUCTION

To avoid an uncontrolled beam going out of its defined trajectory, impacting the machine and discharging its energy on the equipment damaging the accelerator, the emergency removal of the beams from the CERN Large Hadron Collider (LHC) rings towards the dump blocks must be guaranteed at all times.

The implementation of the energy removal task was separated into two systems, the Beam Interlock System (BIS) [1] [2] and the LHC Beam Dumping System (LBDS). A simplified diagram is shown in Fig. 1.

The BIS surveys all the conditions that could trigger a removal of the beam from the collider rings and delivers the beam to dump request to the LBDS. To achieve this, the BIS maintains a light signal, named Beam Permit, in an optical fiber path around the LHC while all conditions are met. When any of the user permit is removed the Beam Permit signal is interrupted.

The LBDS assures the extraction of the beam to the dump blocks. It monitors the optical fiber for the presence of the Beam Permit. The absence of the Beam Permit is interpreted as request from the BIS to extract the beam.

The BIS, the LBDS and the optical fiber path are redundant.

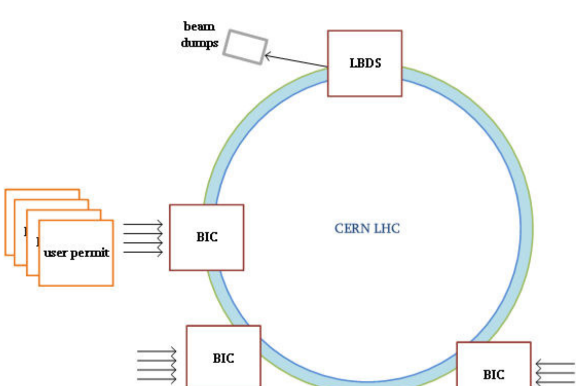

Figure 1: LHC run 1.

Both systems were built according to high reliability standards. To further reduce the risk of incapability of extracting the beam to the dump blocks a direct link from the BIS to the inner subsystem at the final stage of the LBDS (the re-triggering lines) was implemented and put in operation in 2015 [3]. This new third link for dump request for LBDS re-triggering lines (CIBDS) represents a diverse redundancy to the current implementation [4]. Two CIBDS are in operation, one for each LHC beam.

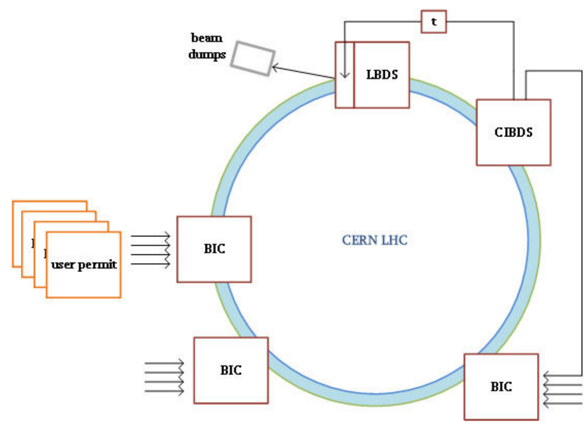

Figure 2: LHC run 2, introduction of CIBDS.

From the beginning was stated that the introduction of this new element should neither significantly increase the risk for so-called asynchronous beam dumps nor compromise machine availability.

SYNCHRONOUS BEAM DUMP

The beam dump is the extraction of the circulating beam from the collider to the dump blocks. The LBDS requires certain amount of time to rise the magnetic field in its magnets to guide the beam to the dump blocks. To avoid a shower of high energetic particles on the extraction elements during the rise time, the beams circulating on LHC contains a gap free of particles compatible with the needs of LBDS. The generator of dump pulses at the LBDS is locked with the LHC revolution frequency pulse train and synchronised with the particle free gap for the rise of the magnetic field.

When the LBDS rises the magnetic field during the particle free gap the beam is extracted without depositing its energy in the LBDS elements but diluted in order to spread the energy in the dump blocks. This is called a synchronous beam dump and is the preferred manner to dump the beam.

ASYNCHRONOUS BEAM DUMP LIMITATION

When the LBDS is triggered out of synchronization with the LHC particle free gap this is called an asynchronous beam dump.

ISBN 978-3-95450-147-2

Chances are that the kicker magnets rise time can be fully experienced by the LHC beam. Part of the beam swept over the machine aperture will be intercepted by the absorbers and collimators. This should not cause any irreparable damage, although several superconducting elements in the zone will probably quench and several electronics components will suffer a high radiation dose.

The new CIBDS has a direct access to the LBDS inner system bypassing all the synchronisation modules generating asynchronous beam dumps.

Due to the accumulative deterioration produced by this kind of beam extraction a design specification was imposed. The restriction is to not produce more than 1 improper asynchronous dump per beam over 10 years due to a CIBDS failure.

To reach this tight specification, the new CIBDS link accessing the inner system of the LBDS goes through a tuned delay line of 270μs (indicated as t in Fig. 2). The same signal without any delay is connected as a normal user permit to request a beam dump to the BIS. The time propagation from the activation of the dump request going through all the BIS logic, through the synchronisation with the free gap and the LBDS logic is 140μs. The use of the delay line and the back-connection to BIS is an aspiration to transform an assured asynchronous beam dump into a synchronous beam dump that would arrive several μs before.

AVAILABILITY TRADE-OFF

The LHC requires about 2 hours for preparation, injection and ramping to reach again exploitable physics beam conditions after a beam extraction.

In the case of a non-programmed beam dump triggered by the BIS a post-mortem analysis is mandatory. The purpose of this analysis is to determine the root cause at the origin of the protection system activation and assert if it is safe to continue operation. Only after the conclusion of the experts the collider operators could get the authorization to use the machine for another physics run. This analysis can take from half to several hours in complex cases. The average is 1.5 hours.

From the previous information can be inferred that an improper dump request generated by a CIBDS failure will impact the LHC physics with an estimated loss of 3.5 hours.

With these figures, the cost in terms of time lost for LHC physics, becomes more expensive than the benefit from the risk reduction when the CIBDS produces more than two improper dump request per year.

The advisory committee (LHC Machine Protection Panel) accepted the installation of the new system with the special condition of its removal in case of being over two improper dump request generated by a CIBDS failure per year.

ARMING SEQUENCE

The BIS and LBDS depend on each other for being in a fully operational state to operate the LHC. This creates a deadlock situation at the start-up when both systems are not operational. To overcome the deadlock both have their own arming state in which the dependency is not checked. The arming is guarded with a timeout. At the expiration of the timeout the dependency is checked and if everything is correct the system is promoted to fully operation otherwise fails.

STARTING LHC RUN 2

At the end of the commissioning phase of the LHC after the long shutdown 1 (LS1) the first uses of the computer driven sequence (called sequencer) to check the arming of the protection system (BIS + LBDS) were sometimes succeeding and others failing.

The sequencer, taking in account the timeouts, was used successfully during the previous LHC run 1.

After analysis, it was clear that the introduction of the CIBDS had added a third interdependency with its own arming state and timeout that was not took into account in the sequence to check the arming of the protection system. Several steps in the sequencer software were reordered. The propagation delay for the arming commands sent to the different elements were recalculated. And the timeouts harmonized.

After the adjustments the check for an armed protection system recovered its deterministic behaviour.

This setback spotted the weakness of the arming sequence. New discussions are taking place to find a more robust solution.

PERFORMANCE DURING LHC RUN 2

During the first 10 months of operation of LHC run 2 there were 2 beam dump request induced by a CIBDS. These beam dump request were synchronous.

The investigation showed that the root cause was not a hardware failure of the CIBDS but an interrelation of low power transmission and noise at detection of the Beam Permit in one of the redundant optical fibers. In both cases the CIBDS requested a beam dump a few tenth of microsecond before the LBDS detector effectively saw the absence of the Beam Permit and triggered itself a beam dump.

FREQUENCY DETECTION

Due to the redundancy the optical fiber and the Beam Permit are in the real implementation 4 optical fibers and 2 frequencies respectively.

The 4 fiber paths going around the LHC ring are mentioned in Table 1.

Table 1: LHC ring fibers

Fib.	Beam		Beam Permit signal	
1-A	1	clockwise	9.375 MHz	anticlockwise
1-B	1	clockwise	8.375 MHz	clockwise
2-A	2	anticlockwise	9.375 MHz	anticlockwise
2-B	2	anticlockwise	8.375 MHz	clockwise

Each fiber has a unique electronic oscillator defining a start point (CIBG). The electrical signal is converted into light by an InGaAsP 1310nm Edge Emitting LED (Tx) plugged to its corresponding optical fiber. The fiber connects to the next element of the BIS, the Beam Interlock Controller (BIC). At the BIC level the received light signal is converted to an electrical signal by an InGaAs photodiode 1310nm (Rx). If all the user permits of the BIC are correct the signal passes to the Tx. The Tx transmits the light signal through the next fiber segment towards the next BIC. This path is illustrated in Fig. 3.

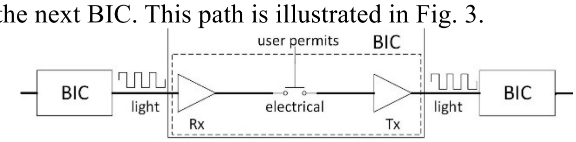

Figure 3: signal path.

The signal continues to transit through the fiber segments and the BICs up to the CIBDS and then to the LBDS which, as the last point, connects back to the CIBG, as shown in Fig. 4.

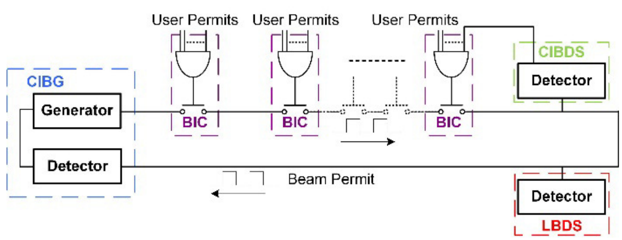

Figure 4: LHC Beam Permit Loop.

Along the ring only the CIBG, the CIBDS and the LBDS have a detection module which verifies that the signal is present and has the proper frequency.

At the CIBG level, the detection module checks the signal arriving from the last point. And its trigger stops the generation at the start point. This has the effect of latching the beam dump request.

At the CIBDS and the LBDS, as was explained before, the detection module triggers the removal of the beam.

The detection module for CIBG, CIBDS and LBDS were developed by different teams. And the module for each redundant paths A and B were developed by a different person. This resulted in non-identical implementations using different algorithms and parameters. Thus the detection modules have different sensitivity to errors in the frequency.

The investigation has shown that in the presence of a perturbation the CIBDS will trigger first due to its higher sensitivity. Followed closely by the CIBG and later by the LBDS.

During the LHC Run 2, the 2 improper beam dumps assigned to the CIBDS, were also detected by the CIBG and the LBDS but they triggered later.

If the detection systems are not identical, the wise order for triggering is first LBDS then CIBDS then CIBG. And match as much as possible the redundant paths A and B.

In the present implementation, all the frequency detection algorithms are part of the critical code and can't be changed without a consequent amount of work.

POWER MARGIN

Another result from the investigation has shown that there were perturbations in the order of half a period to two periods of the frequency of the Beam Permit regularly present at the Rx of the BIC before the CIBDS. If the perturbation lasts a couple of periods more, the detection module of the CIBDS interprets the corrupted signal as dump request.

Measurements from the previous Tx to the concerned Rx shown that due to the attenuation of the lengthy fiber, the presence of several patch panels and their connectors, the power margin at the reception was minimal.

The InGaAsP diode and the InGaAs photodiode, used to produce and to detect the 1310nm light, have a lot of dispersion on their gain from one component to another. This gain also varies with the temperature and the circuit implementation used doesn't maximize its output power.

The Tx was replaced by one with more gain. The measurements shown better power margin and the perturbations diminish.

There was already ongoing a research to replace the Rx and Tx with a Small Form-Factor Pluggable transceiver (SFP) based in new laser technologies. One of the objectives of this research is to increase the transmission power and the noise margin. Other objective is to obtain better real-time diagnostics on the received and transmitted power. This allows also to survey the state of the optical fiber suffering from radiation.

CONCLUSION

The CIBDS reached its objectives in terms of machine protection and availability and will continue in operation.

Nevertheless, the introduction of a new element in a system always teach us some lessons.

Some improvements are currently under study.

The arming sequence should be more robust. A master-slave strategy, for the start-up of BIS and LBDS could help to reduce the dead-locks produced by the concurrent arming.

The algorithms and sampling windows of the detection modules needs to be harmonized. This will take place the next time the critical code will be reviewed.

For a better power margin, the initial studies using a laser SFP are very promising.

REFERENCES

[1] B. Todd et al., "The architecture, design and realization of the LHC Beam Interlock System", *ICALEPCS 2005*.

[2] R. Schmidt et al., "The Beam Interlock System for the LHC", *CERN LHC-CIB-ES-0001, EDMS Id: 567256*.S.

[3] Gabourin et al., "Implementation of a direct link between LHC Beam Interlock System and the LHC Beam Dumping System R-triggering Lines". *IPAC2014*

[4] J. Uythoven et al., "Changes to the LHC Beam Dumping System for LHC Run 2". *IPAC2014*

ISBN 978-3-95450-147-2