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# EVALUATION OF AN SFP BASED TEST LOOP FOR A FUTURE UPGRADE OF THE OPTICAL TRANSMISSION FOR CERN's BEAM INTERLOCK SYSTEM

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*Abstract*

The Beam Interlock System (BIS) is the backbone of CERN's machine protection system. The BIS is responsible for relaying the so-called Beam Permit signal, initiating in case of need the controlled removal of the beam by the LHC Beam Dumping System. The Beam Permit is encoded as a frequency signal travelling over a more than 30 km long network of optical fibres all around the LHC ring. The progressive degradation of the optical fibres and the aging of electronics affect the decoding of the Beam Permit, thus potentially resulting in an undesired beam dump event and by this reducing the machine availability. Commercial off-the-shelf SFP transceivers were studied with the aim to improve the performance and continuous monitoring of the optical transmission of the Beam Permit Network. This paper describes the tests carried out in the LHC accelerator to evaluate the selected SFP transceivers and it reports the results of the test loop reaction time measurements during operation. The use of SFPs to optically transmit safety critical signals is being considered as an interesting option not only for the planned major upgrade of the BIS for the HL-LHC era but also for other interlock systems in use at CERN.

## INTRODUCTION

The Beam Permit Loops are one of the most critical parts of the BIS [1]. They are used to carry User Permit requests from the Beam Interlock Controllers (BICs) to the LHC Beam Dumping System (LBDS). Its working principle is simple (see Fig. 1); the Beam Permit is encoded as a frequency signal and sent over optical fibres around the LHC ring. When the Beam Permit is TRUE, the frequency is generated and re-transmitted by every BIC crate, arriving back to the generator. When one of the users connected to the BIS network opens the loop, the Beam Permit becomes FALSE and the re-transmission is interrupted, stopping the generator. The missing frequency signal is detected by the beam dumping system, resulting in the activation of the beam dumping system. A failure to remove the beam when requested can potentially result in massive damage to the LHC machine [2].

The layout of the LHC BIS is reported in Fig. 2. The Beam Permit information is broadcasted over two separate channels A and B, respectively anticlockwise and clockwise for each beam of the LHC. A pair of BIC crates is located in each point of the LHC, plus one in the CERN control center (CCR). In addition, a board for the generation of a redundant asynchronous dump request (CIBDS) is located in point 6, together with the generator of the TRUE frequency

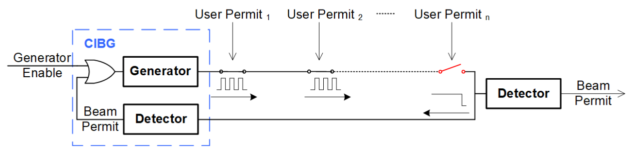


Figure 1: Basic principle of the Beam Permit Loop: a generator (CIBG) creates a TRUE frequency signal. User Permits are issued by users connected on each BIC, in order to open the Beam Permit loop and trigger a dump

(CIBG) and the Trigger Synchronization Unit (TSU), which ultimately triggers a synchronous dump by the LBDS. The frequencies associated to a TRUE value of the Beam Permit were chosen as 9.375 MHz for channel A and 8.375 MHz for channel B.

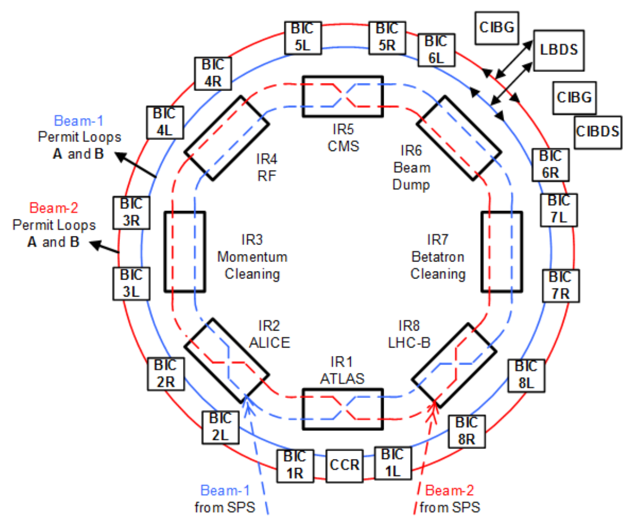


Figure 2: Layout of the operational BIS, showing the particle beams and the optical loops. BIC crates are located in the CCR and at the eight LHC interaction points.

### *Limitations of the Present System*

The BIS has proven to be an extremely reliable system which has been working without major issues since the LHC started beam operation in 2009 [3, 4]. Nevertheless, operational experience has shown that the progressive degradation of optical elements, e.g., due to the exposure to ionizing radiation, could compromise the availability of the LHC. As a result, one of the main limitations of the present BIS is given by the characteristics of the ELED based transceivers used for the optical communications. Among them:

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- low optical budget and lack of gain compensation over temperature variations;
- absence of diagnostics regarding the RX/TX power, operating temperature, bias current, etc;
- erratic operation in DC mode. Switching from a frequency to a DC level signal, i.e. during a beam dump event, provokes an undesired ringing of the Beam Permit signal which could coincide with the Beam Permit loop frequency momentarily;

In order to address these limitations, measurement campaigns are scheduled on a regular basis, typically during long shutdowns, to guarantee that the available optical margin is sufficient to ensure the integrity of the optical communication. At the same time, it is verified that the attenuation of the single mode fibres does not largely differ from the typical loss of about 0.5 dB per km for the 1310 nm source.

### *Advantages of using Commercial SFPs*

The Small Form-factor Pluggable transceivers (SFPs) are network interface modules widely used for data communication applications. Their popularity has grown in the last years and they are currently supported by many network component vendors. The main advantages over the ELED technology presently used for the BIS are the following:

- embedded diagnostic features [5] (such as RX/TX power, operating temperature, bias current and internal supply voltage among others);
- large optical budget, adequate for links of up to 20 km;
- standardised (designed to Multi-Source Agreement - MSA), compact and hot-pluggable;
- available in a large variety of bit rate, power, wavelength and fibre type;

The hot-plug capability and the embedded diagnostics can largely improve the maintenance of the system, allowing to remotely monitor the transceiver status and perform the measurements normally carried out during restart of the LHC without the need of disconnecting the fibres. In addition, the large power margin and gain compensation can overcome the limits imposed by degradation of the optical networks, thus ensuring safe broadcasting of the Beam Permit information at long distances. As a consequence a beam permit loop based on SFP transceivers (BIS-SFP) was laid out in parallel to the operational LHC BIS (BIS-OP), in order to compare the two interlocking loops and validate the hardware based on SFP transmission under operational conditions.

## THE BIS-SFP TESTBED

The new setup required to pull ≈27 km of new fibres, to install new interlock hardware with upgraded firmware and to deploy new diagnostics software. Concerning the hardware, 6U ELMA VME64x crates were used to host the interlock boards. A BIS-SFP crate is shown in Fig. 3, containing a SVEC board [6] that was used to collect data from the diagnostic registers of the SFP transceivers.

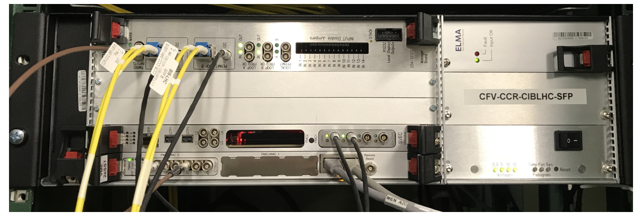


Figure 3: An ELMA VME64X based BIC-SFP crate.

To overcome the limitations of both ELED and SFP transceivers to work with DC signals, a dual frequency approach was implemented, meaning that the FALSE status of the Beam Permit was not anymore represented by a constant signal but by a frequency. A FALSE frequency of 920 kHz is generated from an external oscillator and re-transmitted if a User Permit issues a dump request due to conditions not adequate for beam operation. In this case the operational state of the BIS becomes as shown in Figure 4: when a User Permit becomes FALSE, (i.e. the Beam Permit loop is opened), the loop switches from transmitting the TRUE frequency to broadcasting a 920 kHz frequency, detected as FALSE. This strategy allows to overcome any unwanted oscillation previously observed when transitioning from a frequency signal to a constant DC value. This approach was selected after evaluation of other solutions based on more complex transmission protocols [7]. The value of the FALSE frequency was chosen to be 10 times lower and highly diverging from any harmonics of the TRUE frequency, to achieve a reliable detection of the two states. Moreover the detection of a FALSE frequency, as opposed to the reception of any other unwanted signal, provides an additional information over the status of the communication network.

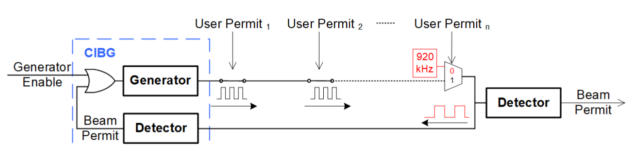


Figure 4: Principle of the Beam Permit Loop with a Dual Frequency Transmission.

A link was established between the two interlock systems, BIS-OP and BIS-SFP, with the goal to compare the reaction time performance of the optical networks. For each node of the BIS-OP the Local Permit signal, calculated from the logical AND of all the User Permits connected at that specific node, is routed as a single User Permit input to the corresponding BIS-SFP crate. In this way, when the BIS-OP Beam Permit opens due to issue a dump request, the BIS-SFP optical loop is opened as well. In both systems the Beam Permit values are monitored with an FPGA, using a frequency counter with a detection window of 3.2 µs width

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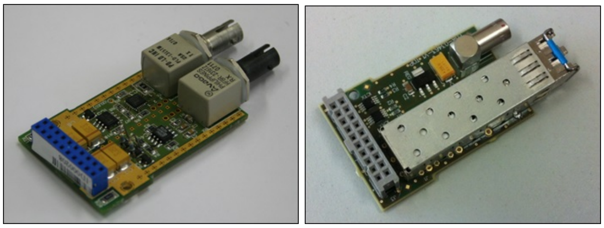

(a) CIBO (b) CIBSFP

Figure 5: The ELED based CIBO and SFP based CIBSFP mezzanine optical modules, used in the BIS-OP and BIS-SFP respectively for the transmission/reception of the Beam Permit signal

to identify the input frequency and send the calculated value to a logging server.

The operational BIS uses an ELED based transceiver mounted on a pluggable mezzanine PCB called CIBO module, designed to achieve zero Bit Error Rate (BER) in the transmission of the Beam Permit frequency, [8, 9]. A PCB with an SFP interface (CIBSFP) was realized maintaining the pin compatibility with the CIBO. As a result, the main hardware of the interlock boards was maintained, and the only changes applied were related to the generation and detection of the FALSE frequency. Figure 5 shows the two mezzanine PCB used by the BIS-OP and BIS-SFP.

For our application, SFPs from different vendors (FINISAR, MRV and OPTOKON) were evaluated. Several characteristics were assessed, such as TX power, RX sensitivity, linearity, precision, accuracy, etc. Finally, the MRV SFP-GD-LX was selected. Table 1 shows a comparison between the main characteristics of the CIBO, mounting the ELED TX/RX modules PLD1315TM and PLD2317TM [10], and the CIBSFP, with an MRV SFP-GD-LX transceiver.

Table 1: Comparison of the ELED and SFP Transceivers Used in the BIS-OP and BIS-SFP Respectively

| Characteristics | CIBO | CIBSFP |
|---|---|---|
| Max TX Power | −17.5 dBm | −3 dBm |
| Max RX Sensitivity | −24 dBm | −20 dBm |
| Monitoring Functions | No | Yes |
| Tx Wavelength | 1310 nm | 1310 nm |
| Fibre Type | Single Mode | Single Mode |
| Data Rate | up to 150 Mb/s | up to 1.25 Gb/s |

## EXPERIMENTAL RESULTS

The use of a false frequency to open the beam permit loop, as well as the overall performance of the BIS-SFP hardware, were evaluated over the period from July 2017 to October 2018. The reaction time of the two optical loops was compared each time a dump request was triggered on the operational BIS. Assuming as $t_{BIS-OP}$ the timestamp at which the Beam Permit on the operational BIS changes its value from TRUE to FALSE for a given node on the LHC ring, and $t_{BIS-SFP}$ the timestamp of the equivalent transition occurring on the BIS-SFP at the same node, the delay time $t_{delay}$ between the two optical loops was calculated as

$$t_{delay} = t_{BIS-OP} - t_{BIS-SFP} \quad (1)$$

The analysis of $t_{delay}$ was carried out with the objectives of (i) functionally comparing the two optical loops and the related hardware during real operation of the machine, and (ii) validate the FPGA firmware for the generation/detection of the FALSE frequency, together with the selected SFP transceiver.

A total of 31668 Beam Permit transitions along the LHC were analysed, initiating a total of 1832 dump events on Beam-1 of the BIS-OP, taking into account both Beam Permit channels A and B. The calculation of $t_{delay}$ is affected by the following parameters:

- The delay of the Local Permit connection between the two loops: +1.7 µs
- The frequency detection window, for both BIS: up to ± 3.2 µs
- 10% difference between the lengths of the optical fibres: ± 1 µs
- up to ≈ ± 2 µs due to the synchronisation accuracy of the respective BIC

Figure 6 shows all 31668 $t_{delay}$ values calculated at each beam permit transition from TRUE to FALSE. The mean $t_{delay}$ was 0.363 µs with a standard deviation $\sigma$ of 2.85 µs which is compatible with the ≈ 3.2 µs delay imposed by the frequency detection window in the monitoring FPGA.

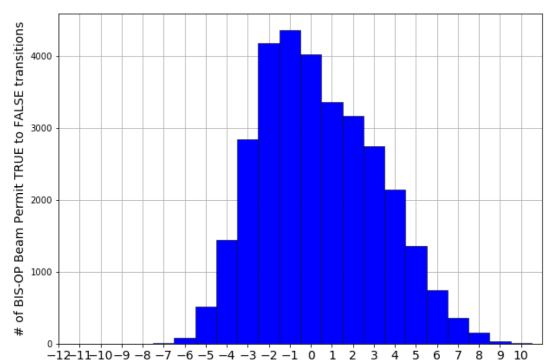


Figure 6: All 31668 $t_{delay}$ values calculated for each dump event on the operational BIS.

Similar results were observed calculating the mean $t_{delay}$ for each node of the BIS, as shown in Figure 7. The minimum and maximum $t_{delay}$ values were respectively -7 µs and +10 µs. These cases refer to particular events in which the BIS-SFP opened 10 µs after or even 7 µs earlier than the operational BIS on Beam-1. These events were analyzed and

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found compatible to the nominal operation of the LHC, as a result of multiple users triggering dump requests leading to a large delay with respect to the link between Beam-1 of BIS-OP and the BIS-SFP (e.g., Beam Energy Trackers or Beam-2 on BIS-OP).

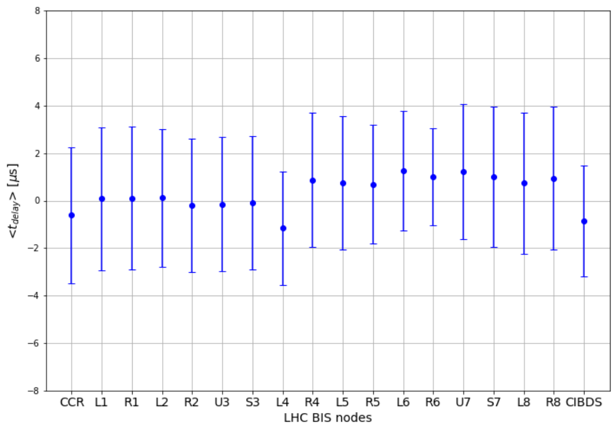


Figure 7: Mean $t_{delay}$ for each node along the BIS optical loop.

No missed beam dump requests were recorded on the BIS-SFP setup and the FALSE frequency was correctly detected at each Beam Permit value transition.

Data from the diagnostics registers embedded on each SFP transceiver was collected during all year 2018. The transceiver characteristics of temperature, bias current, operating voltage, power transmitted and power received were recorded with a period of 1 second. Figures 8 and 9 show respectively the transmitted and received power recorded by all 36 SFP transceivers on both loops A and B. The average transmitted power on all SFPs was ≈ -6 dBm, while the received power was in the range between ≈ -5 dBm and -11 dBm. These values are measured by the transceiver diagnostic circuitry with an accuracy of 3 dB. The main point of interest for the BIS application is the observation of the uncertainty of each measurement, for instance a drift vs time of the power quantities can be related to the degradation of the optical links, or to a misplaced connector. During each dump event the false frequency was correctly detected on all nodes of the SFP optical loop and all the SFP showed values of received and transmitted power within the range of specifications.

## CONCLUSIONS

The use of SFP transceivers has proven to be appropriate for the transmission of safety critical signals at short and long distances along the LHC Beam Interlock System. Test results over more than a year of LHC operation showed a reliable reaction time of the BIS-SFP optical network, using a dual frequency to encode the Beam Permit status. A stress test inducing thousands of dump requests on the BIS-SFP loop will be performed, with the goal to ensure an even higher confidence level in terms of reliability of the system.

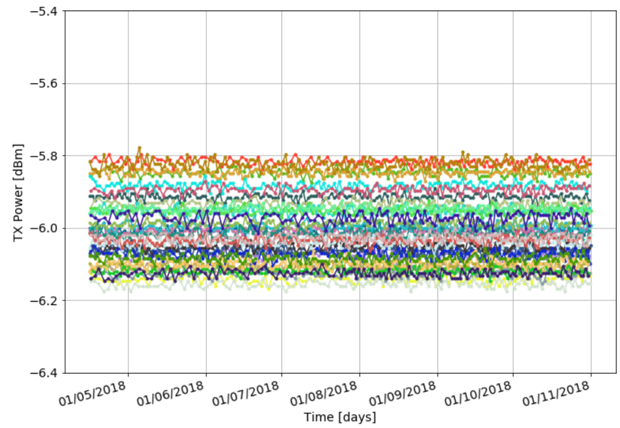


Figure 8: Power transmitted for each node on the SFP optical loops A and B, for a total of 36 SFP transceivers.

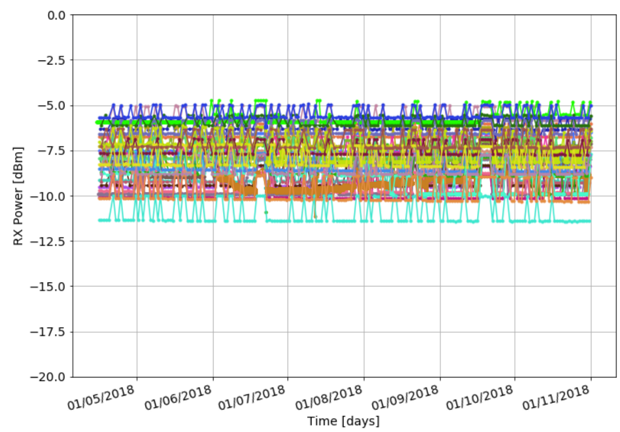


Figure 9: Power received for each node on the SFP optical loops A and B, for a total of 36 SFP transceivers. The power peaks correspond to a Beam Permit value transition detected.

The collected data demonstrated the justification of using SFPs for several reasons, such as their large power margin to overcome effects of fibre optics degradation, embedded diagnostics capabilities for easier monitoring of the optical network status, and the reduced maintenance needs. As a result, the use of SFPs for the transmission of critical and non-critical information, (e.g., monitoring diagnostics), is being envisaged for future upgrades and applications of the LHC BIS, as well as for other BIS configurations [11].

## REFERENCES


[1] B. Puccio *et al.*, “The beam interlock system for the LHC”, CERN, Geneva, Switzerland, LHC Project Document No. LHC-CIB-ES-0001-00-10, CERN, 17 Feb. 2005, https://edms.cern.ch/file/567256/0.2/LHC-CIB-ES-0001-00-10.pdf

[2] R. Schmidt *et al.*, “Protection of the CERN Large Hadron Collider”, *New Journal of Physics*, vol. 8, no. 11, Nov. 2006. https://doi.org/10.1088/1367-2630/8/11/290

[3] B. Todd, M. Kwiatkowski, B. Puccio, R. Schmidt, S. Wagner, and M. Zerlauth, “Machine Protection of the Large Hadron

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-WEPHA131

Collider", in *Proc. 6th IET Int. Conf. on System Safety 2011*, Birmingham, UK, Sep. 2011, pp. 1–6. https://doi.org/10.1049/cp.2011.0264

[4] A. Apollonio *et al.*, "Chapter 7: Machine Protection, Interlocks and Availability", in *High-Luminosity Large Hadron Collider (HL-LHC)*, CERN, Geneva, Switzerland, CERN Yellow Report, 26 May 2017, pp.147-156. https://doi.org/10.5170/CERN-2015-005.147

[5] "SFF-8472 Specification for Diagnostic Monitoring Interface for Optical Transceivers", SFF Committee, Rev 11.0, 2010, https://cdn.hackaday.io/files/943124035044608/SFF-8472-(Diagnostic\%20Monitoring\%20Interface).pdf

[6] "Simple VME FMC Carrier SVEC", Open Hardware Repository, https://www.ohwr.org/project/svec/wikis/home

[7] A. Balatsoukas-Stimming, T. Podzorny, and J. Uythoven,"Polar Coding for the Large Hadron Collider: Challenges in Code Concatenation", 1 Dec. 2017. arXiv:1712.00376

[8] B. Todd, "A beam interlock system for CERN high energy accelerators", Ph.D. dissertation, Brunel University, UK, Nov. 2006, http://cds.cern.ch/record/1019495

[9] "Physical layer performance: Testing the bit error ratio (BER)", Maxim Semiconductor Technical Report, October 2004, https://pdfserv.maximintegrated.com/en/an/3419.pdf

[10] PLD-1315 and PLD-2331X Series, FiberOptic TX & RX Modules Datasheet, Laser Components GmbH. https://www.lasercomponents.com/de/?embedded=1&file=fileadmin/user_upload/home/Datasheets/pd_ld/pld-1315_23xx.pdf&no_cache=1

[11] B.Puccio, R.Schmidt, and J.Wenninger, "Beam Interlocking Stragety between the LHC and its Injector", in *Proc. 10th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'05)*, Geneva, Switzerland, Oct. 2005, paper PO2.037-3.