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THE CONSOLIDATION OF THE CERN BEAM INTERLOCK SYSTEM

R. Johnson†, C. Martin, T. Podzorny, I. Romera, R. Secondo, J. Uythoven
CERN, Geneva, Switzerland

Abstract

The Beam Interlock System (BIS) is a machine protection system that provides essential interlock control throughout the CERN accelerator complex. The current BIS has been in service since 2006; as such, it is approaching the end of its operational lifetime, with most components being obsolete. A second version of the Beam Interlock System, “BIS2”, is currently under development and will replace the current system. BIS2 aims to be more flexible by supplying additional on-board diagnostic tools, while also improving the overall safety by adding more redundancy. Crucially, BIS2 increases the number of critical paths that can be interlocked by almost 50%, providing an important flexibility for future additional interlocking requests. BIS2 will come into operation for the LHC in run 4 (2027) and will remain in operation until the end of the planned lifetime of HL-LHC. In this paper, we will focus on the Beam Interlock Controller Manager board (CIBM), which is at the heart of BIS2. Since this module works closely with many other systems that are similar in design to those in BIS1, we will compare how BIS2 improves upon BIS1, and justify the reasons why these changes were made.

BEAM INTERLOCK SYSTEM HISTORY AND TOPOGRAPHICAL HIERARCHY

The core modules of BIS1 were designed in 2006 [1], with modular additions and iterations over the past 15 years, leading to the current version that has enjoyed an extremely good record of machine protection, without a single operational blind failure [2].

BIS1 in its current form comprises several sub-systems positioned in a hierarchal arrangement, allowing critical signals to be focussed into a single system that determine the overall “safe state”. These critical signals are known as “User Permits”, and are given by the equipment of users whose roles vary. Some examples of typical uses include electrical power converters, vacuum instrumentation, and quench protection systems. In all cases, for users that need to report their status to the BIS, their equipment issues two redundant signals referred to as “A” and “B”.

User Permits are handled by a Beam Interlock Controller User board (CIBU), shown in Fig. 1, for distances of up to 1.2 km [3] from the CIBM or a Beam Interlock Controller Fibre board (CIBF) for distances over 1.2 km. Since CIBUs communicate with the CIBM via RS-485, the maximum safe distance of permit propagation is limited, thereby necessitating the need for a fibre-optic-based solution [4].

Functionally, the critical path circuitry of a CIBF is identical to a CIBU, so for the purposes of this paper, we will be referring to the CIBU only as there are many more instances of CIBUs connected to the CIBM.

Figure 1: BIS1 CIBU. The majority of the circuitry for the CIBU in BIS2 will be the same as it is in BIS1.

These CIBUs can be remotely tested by a CIBT (Beam Interlock Controller Test board), a CIBM-based system, using an NRZ-based Manchester Encoded communications link [1]. A downside of this function is that the CIBM cannot test and monitor the CIBUs alone, and instead requires the CIBT to propagate the command and response signals to and from the CIBUs. This information is displayed by way of LEDs on the front panel, and is returned to the CIBM by means of a fast Manchester-encoded link. Both the CIBM and CIBT, shown in Fig. 2, contain multiple LEDs on their front panels which take a lot of space in the crate – two CIBMs paired with CIBTs take 12 slots total.

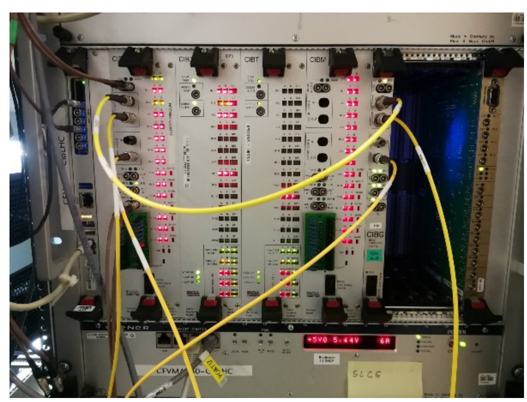

Figure 2: BIS1 crate, containing a pair of CIBMs and CIBTs.

The CIBM of BIS2 aims to completely remove the CIBT altogether, and instead handle all test and monitor capabilities by itself, greatly improving reliability since there will be fewer components in the arbitrated path. Since the CIBM has few LEDs on the Front Panel, each board will require only one slot width, thereby requiring four slots total, shown in Fig. 3. Communication with CIBUs in BIS2 is currently foreseen to be Manchester Encoded, however

† roland.johnson@cern.ch

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studies are underway to explore the possibility of upgrading the channel to (63,57) Hamming [5]. Furthermore, the majority of LEDs that were displayed on the CIBMs and CIBTs of BIS1 will be located on a lab-based, optional "LED board" that will communicate with all CIBMs via a single I2C link.

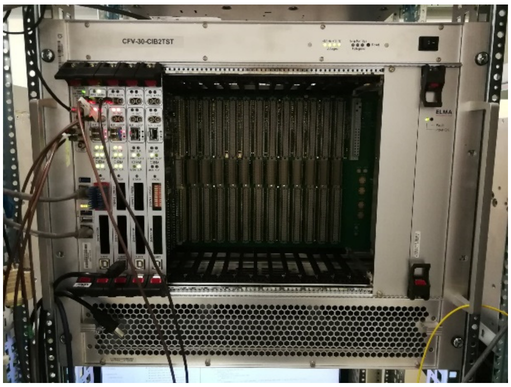

Figure 3: BIS2 crate, containing 4 CIBMs.

Up to 14 CIBUs can be interfaced with a CIBM of BIS1, which interlocks both the A and B paths on one board. The CIBM in BIS2 will interlock up to 20 CIBUs, and dedicates an entire board to each redundant path. The paths taken by the User Permits between Users and CIBMs for BIS1 and BIS2 are shown in Fig. 4, along with the changes to the CIBT paths for BIS2.

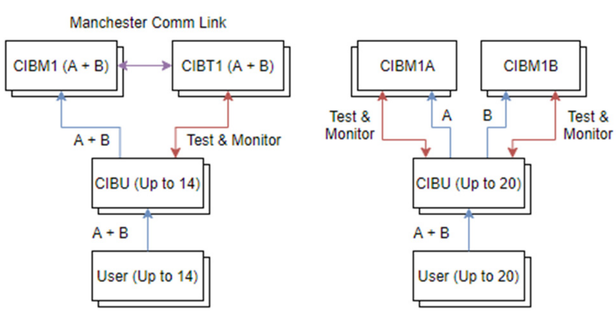

Figure 4: Basic overview of BIS1 (left) vs BIS2 (right) architecture.

The CIBMs propagate their permit states around the LHC by way of frequency encoded information, known as the Beam Permit Loop that is set by a generator at one point in the LHC. Path A oscillates at 9.375 MHz, and B oscillates at 8.375 MHz. If any of the users report a false condition, the CIBM (which registered this false condition) stops the frequency, and the lack of frequency propagates around the LHC. When the LHC Beam Dumping System (LBDS), detects this lack of frequency, it instructs a beam dump. The CIBM2 differs from this approach, as it instead produces a "False" frequency of 0.937 MHz, for both A and B paths, indicative of a conscious decision to dump the beam, since a lack of frequency is indistinguishable from a beam dump command and a connection failure in the Permit Loop. The top-level BIS crate (BIC) locations, for the LHC installation, are shown in Fig. 5.

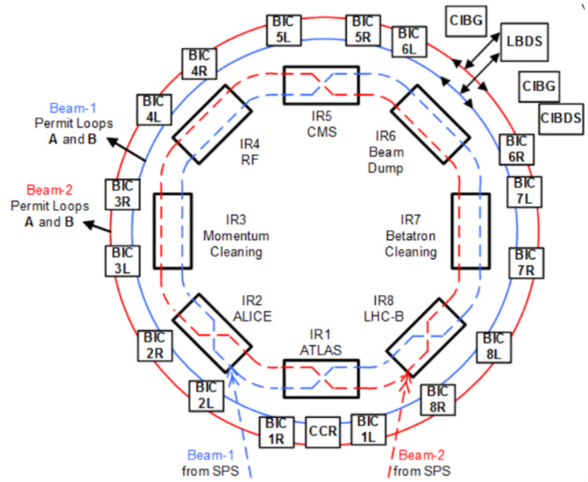

Figure 5: BIS installations around the LHC. These locations will remain the same for BIS2.

Each CIBM uses a Beam Interlock Controller Optical board (CIBO), shown in Fig. 6, to propagate the Beam Permit Loop. However, these are in-house designs and lack any diagnostic capability – they must be removed from the CIBM in order to test and evaluate properly, and cannot report warnings or faults during operation.

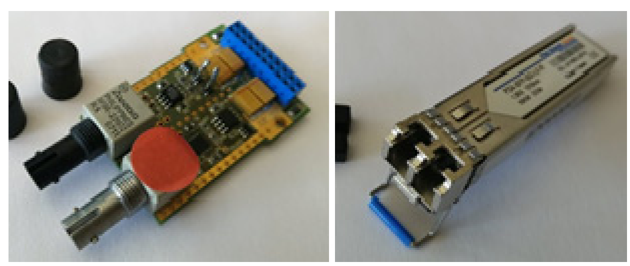

Figure 6: CIBO (left), SFP (right).

BIS2 CIBM: NEW DESIGNS FOR NEW CHALLENGES

The luminosity of the LHC will be increased for the High-Luminosity Upgrade, and new requirements have been demanded of the BIS. These changes cannot simply be added to the current design, as the fundamental implementation of the interlocking structure prevents big changes being made. This new design is built upon the lessons learned from the original design, and therefore is more an evolution rather than a brand new concept.

The CIBM for BIS2 is very similar in structure and functionality to that of the CIBM in BIS1, but includes the modifications required by the High-Luminosity upgrade, as well as some modularity upgrades that aim to keep the design relevant and upgradeable for the foreseeable future, such that further complete redesigns will not be necessary. These requirements are not only "the original BIS, but better", but demand tighter timing tolerances, particularly in the Beam Permit Loop, and also demands that the CIBM

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Table 1: BIS1 vs BIS2 Motivation for Change

Requirement	**BIS 1**	**BIS 2**	**Comments**
More user permits	14	20	Greater flexibility
Enhanced optical communications	CIBO (beam permit loop only)	SFP (beam permit loop + diagnostics)	Higher bandwidth, based on standard, and give much better diagnostics
Greater redundancy in CIBM paths	1 CIBM for A + B	1 CIBM for A, 1 for B	Separating the redundant systems reduces availability but increases reliability
Reduction in form factor of BIC boards	3 slots CIBM, 3 slots CIBT (12 slots total)	1 Slot per CIBM, 2 Slots for LED board (6 total)	All operation will be handled by the CIBM, New crates have 4 slots fewer
Better on-board Analytical peripherals	Basic analysis, UART	Temperature, RTC, UART, Power Management, EEPROM, ADC	No longer require specific instance testers
Upgrade backplane communication	VME64	VME64x	VME64x gives greater bandwidth, has a big surface area for circuitry
Maintain or improve reliability	No blind-dumps, MTBF >1000 years	No blind-dumps, MTBF >1000 years	Improved functionality = greater risk of failure, requiring better design

be able to self-diagnose with a much broader suite of diagnostic tools, as well as being able to perform auxiliary functions on a single board, rather than separating secondary functionality across multiple boards.

The requirements can thus be summarised: The new CIBM must be able to interlock more User Permits, be able to self-diagnose through diagnostic sensors, use a faster backplane protocol, be able to generate its own timing signal if one is unavailable, use a profile smaller than the cards in BIS1, propagate True/False frequency using SFPs rather than the CIBO, and last but not least, be as or more reliable than the CIBM of BIS1. These improvements can thus be summarised and are briefly discussed in Table 1.

Possibly the renovation with the biggest impact, is the change of interface protocol from VME64 to VME64x, which allows the CIBM to use an additional backplane connector that makes the CIBT completely obsolete. Additionally, since slot addresses are hard-set on the backplane of the VME64x crate, the function of the card can be set in firmware, and can then program itself dynamically depending on the slot in which it is placed. This allows two separate firmware codes to be written for the A and B Critical Paths tied into the same configuration file which are then loaded onto the same configuration storage device. Then, the CIBM can load the appropriate firmware for the slot, thereby greatly increasing operational simplicity as it less prone to human error during installation and maintenance.

At present, the CIBM for BIS1 is only capable of testing and monitoring CIBUs (via a CIBT), but beyond this, it is unable to test board-level operations, like power supplies or board temperatures. This means that once the board has been tested with the suite of testers available to the BIS team, and is commissioned in the machine, the only way that the experts will be able to detect a problem is when a failure occurs and a beam dump ensues. The CIBM for BIS2 however has a multitude of on-board tools available for instantaneously self-assessing system performance and faults that may arise, including temperature sensors, ADCs to monitor power supplies, a UART transceiver system, and a Serial ID EEPROM with a hard-encoded unique 48-bit ID code. Complementing the EEPROM is an RTC module that generates a precision timing signal, which the CIBM's circuitry uses to count the total amount of time that the board has been in operation, which will allow the experts to calculate how long certain components may last before they fail. This device will be very useful for tracking where the board is, and for how long, as the current lifespan of current boards in BIS1 is unknown.

Lastly, and perhaps most critically, the CIBM for BIS2 uses a Small Form Factor Hot-Swappable Pluggable Transceiver module (SFP) to propagate the Beam Permit Loop, instead of the CIBO, each shown in Fig. 6. The selected model of SFP has been tested thoroughly by the BIS experts [6] and has been found to be capable of oscillating at hundreds of kilohertz, and generates no glitches in the thousands of kilohertz band [7]. SFPs also contain on-board diagnostics drivers, communicated via I2C, and submit information such as the manufacturer and batch production date, the conditions at which it is most ideally suited, and also instantaneous temperature, voltage, bias current and TX/RX power of the optical instruments.

CONCLUSION

A comparison between the CIBM of BIS1 and BIS2 has been presented. The almost 15 years of experience with the CIBM of BIS1 has made the process of critically specifying the CIBM for BIS2 easier, and the project has proceeded smoothly and without delay. Several prototypes of the CIBM have been designed and evaluated, and a final CIBM design is currently in development.

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