BEAM INTERLOCKING STRATEGY BETWEEN THE LHC AND ITS INJECTOR

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INTRODUCTION

For nominal beam parameters at 7 TeV/c, each of the two LHC proton beams has a stored energy of 360 MJ threatening to damage accelerator equipment in case of uncontrolled beam loss, two orders of magnitude above other accelerators such as SPS, HERA, RHIC and TEVATRON. Already during the transfer from the SPS pre-injector to the LHC, beam that is wrongly deflected into accelerator components would cause substantial equipment damage.

Not only beam operation for the LHC must rely on efficient protection system, also beam operation for the SPS fixed target program, for CNGS *(CERN Neutrinos to Gran Sasso experiment)* and during LHC injection needs to consider the protection of equipment from misguided beams. A large number of elements are involved in protection: beam absorbers must be in the correct position, the magnet powering system is monitored and failures are detected, safe operation necessitates the use of beam instrumentation. Failures must be detected sufficiently early to take appropriate actions, such as extracting the beams into the dump blocks, or blocking extraction and injection. The Beam Interlock System provides a safe and reliable link between systems to monitor accelerator and beam parameters, and the injection and extraction elements.

The Beam Interlock System was originally conceived and designed for protecting the LHC [1]. During the development it was always foreseen that it would be capable of providing a robust modular solution for other Beam Interlock Systems required by CERN. The system will be deployed in three other distinct, yet related environments: the SPS ring, the SPS-LHC transfer lines, and the LHC injection regions.

FUNCTIONALITY OF A BEAM INTERLOCK SYSTEM

The purpose of a Beam Interlock System is to permit beam operation in ensuring that all required conditions for safe process are present. Its first role is to gather the status of the involved systems for beam operation; each User System must give its “green light” (USER_PERMIT) if there is no failure and it is ready for beam. The Beam Interlock System performs an AND function of the received signals. As an end result, a global signal (named BEAM_PERMIT) is produced. This signal is immediately transmitted to a kicker system either to dump circulating beam or to inhibit extraction (or injection) for a transferred beam.

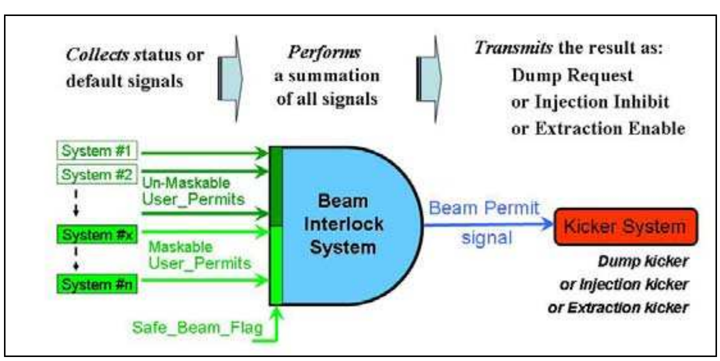

Figure 1 : Functional basis of a Beam Interlock System.

MAIN FEATURES OF A CERN BEAM INTERLOCK SYSTEM

The Beam Interlock System to be used at CERN has been conceived for providing a fast, reliable and dependable mechanism for safe operation of the accelerators.

The priority in its development has been safety. Consequently, the system has been designed to respond when requested to with a very high level of safety (SIL 3). The main features are [2]:

- Safe with a **full redundant** system from the users that provide the USER_PERMIT to the trigger sent to the injection of extraction kicker system

- Simple in using **only binary** information (TRUE or FALSE) with fail-safe implementation for critical systems.
- Flexible with interlock **masking possible** but secure with the **SAFE_BEAM_FLAG condition**.
- **Fast** with an internal process duration of some micro-seconds.
- **Maintainable** and easy to check with self diagnosis of internal faults.
- Helpful with its **real-time monitoring** for accelerator operation and with its embedded history buffers for post-mortem analysis.

User Permits

The BIS collects, via hardware links, the USER_PERMITS from the different connected systems. The USER_PERMIT can be TRUE (*User System is ready and beam operation is possible*) or FALSE. In this case, the connected system is either not ready for beam or has detected a failure that should stop beam operation.

Beam Permit

A Beam Interlock System (BIS) produces BEAM_PERMIT information and distributes it via a hardware link to the dedicated kicker system (*dump kicker, extraction kicker or injection kicker*). BEAM_PERMIT can be TRUE (*corresponding beam operation is permitted*) or FALSE. In this case, for a beam transfer, the extraction (or the injection) is blocked. In case of a circulating beam and when BEAM_PERMIT changes from TRUE to FALSE, the beam is extracted by the Beam Dumping system.

Masking of the User Permits

To allow for some flexibility while maintaining safety, the systems connected to the BIS are classified in two families: MASKABLE and NOT MASKABLE. This partition is fixed and remotely readable from the supervision of the Beam Interlock System.

The signal issued from a User System classified as MASKABLE could be temporary ignored (*mask set by the operator*). Then the USER_PERMIT is not taken into account to produce the BEAM_PERMIT. If a User System is classified as NOT MASKABLE, the corresponding USER_PERMIT will never be ignored.

Conditional masking with the Safe Beam Flag concept

Masking is only possible if the beam is “safe” and cannot result in damaging equipment. This condition is defined by distributed information called SAFE_BEAM_FLAG. It indicates that the machine is operating with beam below damage threshold; in this case not all protection devices are required. This will be the case during commissioning, but also for re-commissioning, and for beam studies. The value of the SAFE_BEAM_FLAG can be TRUE (*masking is taken in account*) or FALSE.

For the LHC, the flag is derived from the beam intensity and from the energy. For the SPS and the transfer lines the flag is only derived from the beam intensity. In both cases, the information is produced and distributed by a dedicated system using reliable solutions [3].

Failsafe Safe Logic

Failsafe state logic is always implemented for the different I/O signals managed by the BIS. If a cable is unplugged or interrupted, if there is a power loss, or for many other any kinds of failure, the surveyed condition is always interpreted as FALSE (i.e. equal to ‘high intensity’ for the SAFE_BEAM_FLAG).

INTERLOCKING REQUIREMENTS FOR BEAM OPERATIONS

The energy stored in the circulating LHC beams is unprecedented and an uncontrolled release could lead to serious damage of equipment. Therefore, the dedicated Beam Interlock System collects beam dump requests and send a trigger to the Beam Dumping system in order to extract the beams as fast as possible.

In the SPS the energy stored in the beam is about two orders of magnitude less than the LHC. The SPS is used as LHC injector, and must produce in fast cycle change mode beams for fixed target experiments and deliver high intensity (between 10^{13} and 10^{14} protons) beams to LHC and CNGS. Therefore an independent interlock system is also required to ensure that the SPS can be operated separately from LHC and is well protected from beam induced damage.

The beam transfer between SPS and LHC is also potentially dangerous. If high intensity beam is wrongly deflected, equipment damage will occur. To avoid such accidents, a dedicated and reliable interlock system is required that only allows extraction from the SPS if all connected elements provide a permit signal when they are in the correct state. Only when Extraction Permit is present for the corresponding beam line, the SPS extraction kicker can fire.

A complement of this interlock system is for the injection into the LHC, in view of the different failure scenarios associated with the fast transfer and injection process and the very small aperture of the transfer lines and the LHC at injection energy (450 GeV). Only when the corresponding Injection Permit is present, the LHC injection kicker can fire.

LAYOUT OF THE LHC TRANSFER LINES LHC AND ITS INJECTOR

Beam transfer from SPS to LHC is made through the two new SPS extraction systems and the two new beam transfer lines TI 2 and TI 8. The beam is injected into the LHC using the injection systems in IR 2 and IR 8. In addition, the CNGS experiment makes use of the separate TT41 transfer line, which branches off from TT40, upstream of TI 8.

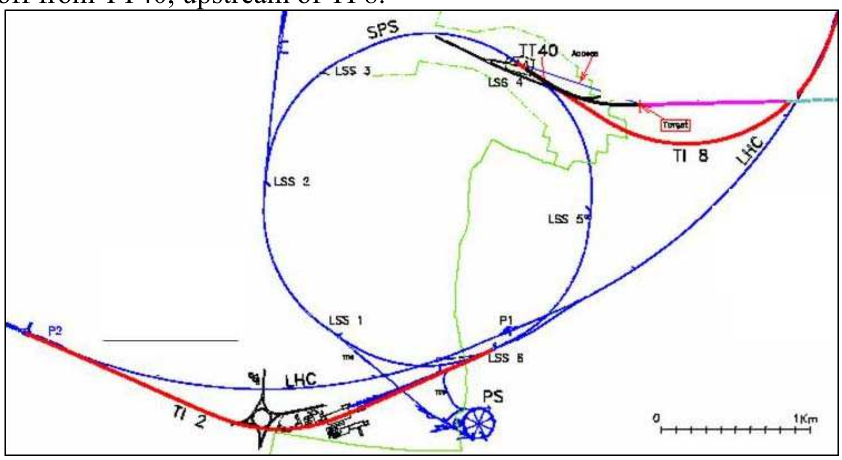

Figure 2: Overview of the SPS complex with the new transfer lines TT40, TT41, and TI8 (extraction from LSS4) and TI2 (extraction from LSS6)

LHC Beam 2 Injection

For LHC beam 2 and CNGS, the beam is extracted from the SPS in the extraction channel in LSS4 (LSS=Long Straight Section), and transferred via the TT40 transfer line either to the TI 8 LHC transfer line or to the TT41 CNGS transfer line. TI 8 transfers the beam over about 2.5 km to the LHC injection system in IR8, while TT41 transfers the beam over about 1 km to the neutrino production target. For interlocking purposes [4] the systems are grouped into four blocks:

- **LSS4/TT40:** SPS LSS4 extraction and TT40 transfer line, to TT40 TED beam stopper;
- **TT41:** the CNGS beam line TT41, to the CNGS neutrino target;
- **TI 8**: TI 8 transfer line, to the TI 8 TED beam stopper at the end of TI 8;
- **IR8 injection**: last part of TI 8 and the IR8 injection region, to the TDI collimator.

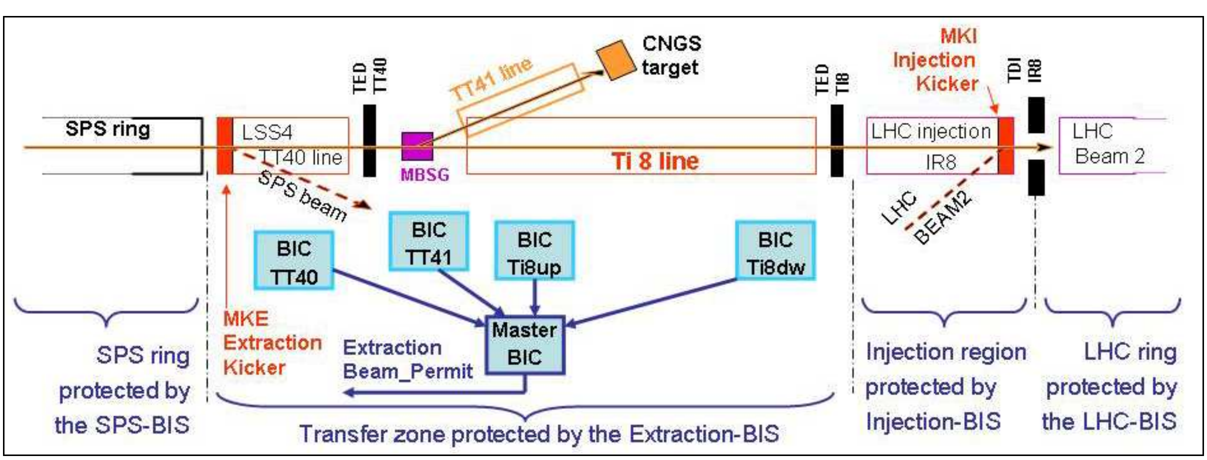

Figure 3: Interlocking layout for the LHC Beam 2 transfer

LHC Beam 1 Injection

For LHC beam 1, the interlock architecture is similar though simpler since there is no CNGS beam line.

THE DIFFERENT BEAM INTERLOCK SYSTEMS

LHC Beam Interlocks

The LHC BIS uses 16 controllers (BIC) distributed around the ring to gather about 140 USER_PERMITS and transmit them around the ring. All systems for protection during beam operation have an interface with the BIS: beam dumping system, collimators, beam dilutors, beam monitors, powering interlock systems, RF system, vacuum system, access safety system, LHC experiments...

The LHC BIS provides a BEAM_PERMIT signal based on the status of the above inputs, and also on the status of the mask settings and the LHC SAFE_BEAM_FLAG. When the LHC BEAM_PERMIT signal changes from TRUE to FALSE, injection into the LHC is inhibited, and the LHC Beam Dumping system is immediately triggered to remove safely any circulating beam.

The LHC BIS is split into a system for beam 1 and a system for beam 2 and carries the two independent BEAM_PERMIT signals, one for each beam.

SPS Beam Interlocks

The interlock system for the main SPS ring is presently being updated, with the same system used for the LHC. As for this one, the Beam Interlock System provides a SPS BEAM_PERMIT signal based on the status of the connected systems, of the mask settings and of the SPS SAFE_BEAM_FLAG. The SPS BIS is composed of 6 BICs distributed all around the SPS ring and linked to about 30 *User Interfaces* [5]. When the BEAM_PERMIT signal is not longer present, a trigger is instantly sent to the SPS Beam Dumping System in order to extract the beam.

SPS Transfer Lines interlocking

For each transfer line between the SPS and the LHC, the Extraction BIS provides an enable signal to the corresponding Extraction Kicker System. The extraction and transfer systems comprise the magnets necessary to deflect and focus the beams, the instrumentation, vacuum elements, the safety and protection beam absorbers and collimators, together with the powering, positioning and controls equipment. All the involved systems have an interface to the Extraction BIS in order to enable safe extraction.

The BIS used for protecting the transfer lines has hierarchical architecture with one “master” and several “slaves” BICs, each one managing a part of the transfer line. They are 2 independent systems: one for LHC beam-1 extraction and one for LHC beam-2 and CNGS beam extraction. In total, around 60 *User Interfaces* are used.

LHC Injection Interlocks

For the injection regions, the (LHC) Injection Beam Interlock System is composed of only two independent BICs (one per injection region); in total, around 20 *User Interfaces* are used. The system provides a BEAM_PERMIT signal to the Injection Kicker System.

Interface with a Kicker system

For all BIS, the corresponding BEAM_PERMIT output is available twice and distributed via two independent optical fibre loops. The Kicker system is included in the two loops and surveys permanently the BEAM_PERMIT’ status (named BEAM_PERMIT_A and BEAM_PERMIT_B). Only if both BEAM_PERMITS are equal to TRUE, beam operation can continue. In the other hand, beam operation is stopped if either of the BEAM_PERMIT signals is absent.

Interlocking Hierarchy

For its proper operation, the LHC ring is decoupled from the SPS, transfer lines and injection interlocking. In reverse, the LHC interlock system must provide its BEAM_PERMIT to the injection interlock system, and the transfer and injection interlocking system must provide the injection permit to the SPS extraction and LHC injection kickers.

A hierarchy is established in order to ensure safe beam transfer between the 2 machines:

- The LHC BIS must provide a permit signal in order to inject into the ring. Therefore, the LHC BEAM_PERMIT is connected as a USER_PERMIT to the Injection Beam Interlock System.
- The Injection BIS must provide a permit signal in order to perform a safe beam transfer from the SPS to the LHC. The Injection BEAM_PERMIT is connected as a USER_PERMIT to the Extraction Beam Interlock system.

REQUIRED OPERATING MODES AND ASSOCIATED INTERLOCK CONDITIONS

Filling the LHC is preceded by setting up of the transfer lines and injection systems. If we consider the transfer line used for beam 2, interleaved CNGS operation is also required. The following operational modes must be possible and correctly interlocked [4]:

I) **Beam to a beam stopper (TED) at the end of TT40** (setting up of the SPS extractions),
II) **Beam onto downstream Transfer Line beam stopper** (setting up of the transfer lines),
III) **Low intensity beam into the LHC** (setting up of the LHC injections, etc),
IV) **High intensity beam into the LHC** (filling the LHC),
V) **Beam to CNGS** (for LSS4/TT40/TT41/CNGS/TI 8 only).

The particular states required for safe operation in each of these five modes are dictated by the beam conditions and by the positions of some beam stopper blocks (TED) in the transfer lines (see table 1).

Operating modes	I	II	III	IV	V
USER_PERMITS for BIC managing Extraction BEAM_PERMIT in LSS4	**Beam to TED TT40**	**Beam to TED TI8**	**Low intensity beam to LHC**	**High intensity beam to LHC**	**Beam to CNGS**
LHC cycle in the SPS	X	TRUE	TRUE	TRUE	FALSE
CNGS cycle in the SPS	X	FALSE	FALSE	FALSE	TRUE
BEAM_PERMIT from BIC-TT40	TRUE	TRUE	TRUE	TRUE	TRUE
TED-TT40 in "IN position"	TRUE	FALSE	FALSE	FALSE	FALSE
TED-TT40 in "OUT position"	FALSE	TRUE	TRUE	TRUE	TRUE
BEAM_PERMIT from BIC-TT41	X	FALSE	FALSE	FALSE	TRUE
BEAM_PERMIT from BIC-TI8	X	TRUE	TRUE	TRUE	X
TED-TI8 in "IN position"	X	TRUE	FALSE	FALSE	X
BEAM_PERMIT from BIC-IR8	X	X	TRUE	TRUE	X
LHC BEAM2_PRESENCE_FLAG	X	X	X	TRUE	X
SPS SAFE_BEAM_FLAG	X	X	TRUE	X	X
LHC SAFE_BEAM_FLAG	X	X	X	FALSE	X

Table 1: Truth table for the generation of the Extraction BEAM_PERMIT signal

FUNCTIONAL ORGANISATION FOR BEAM TRANSFER INTERLOCKING

Beam Presence Flag concept

Extracting high intensity beam from the SPS and injecting it into the LHC is potentially damaging. There must be a beam already circulating in the LHC, the presence of which must be guaranteed to within 1 millisecond of the injection. The BEAM_PRESENCE_FLAG is a parameter derived from the corresponding beam current in the LHC indicating that the current is above a predefined threshold. There are two BEAM_PRESENCE_FLAGS (one per beam). They are used, as USER_PERMITS, in the two Beam Interlock Controllers that permit extractions (LSS4 & LSS6) from the SPS to the LHC.

Slave BICs

The interlock signals are grouped together logically by function (extraction), by transfer line, or by part of transfer line. Each one is associated with a "Slave BIC". Therefore, each interlock controller concentrates interlock signal from systems associated to a given transfer line part or function. There is a Slave BIC for interlocking the TT40 line, another one for interlocking the TT41 line, etc…

The BEAM_PERMIT signals also depend on the status of the mask settings and on the SPS SAFE_BEAM_FLAG. For low (safe) beam intensity injection (for example for setting-up LHC injection), some of the injection conditions can be relaxed.

Master BIC

The "Master BIC" has the same basic functionality than the Slave BIC. The only difference stems from the fact that this second component must be able to (de-)activate selected input signals according to the beam operating mode. Therefore, the different BEAM_PERMIT signals of the Slave BICs are forwarded, as USER_PERMITS, to the Master BIC. As a result, this module produces an Extraction BEAM_PERMIT signal for the extraction kicker. This signal is based on the status of the Slave BICs, some individual USER_PERMITS, the SPS SAFE_BEAM_FLAG and LHC BEAM_PRESENCE_FLAG.

The Slave BICs as the other BICs have been explicitly designed to rely only on simple AND logic. Following the architecture shown in Figure 3, the Master BIC requires additional 'OR' logic in order to be able to reproduce the specified conditions (Table 1) for the extraction BEAM_PERMIT. Its logical matrix is therefore depending on the SPS cycle and on conditions related to a defined beam operation.

LOGGING, POST-MORTEM AND APPLICATION SOFTWARE

The BIS hardware monitors internally all its I/O channels. The interface between the operators and the interlock system is made via application software. The application reads and displays the status of all USER_PERMITS for each BIC, as well as the BEAM_PERMIT status. The application allows masking of some channels with the SAFE_BEAM_FLAG. The status of the hardware is displayed, showing which channels are masked. All state changes and time stamps recorded in the controllers are read and archived. When beam operation is stopped by the interlock system, a clear display is provided for the machine operators, with precise time-stamping for post-mortem information. The time stamps are synchronised to universal time (UTC) and are given with 1 µs accuracy. In addition, there is an interface to the general logging, alarm and post-mortem systems.

CONCLUSIONS

The Beam Interlock System presented in this paper provides a flexible and a very safe protection system for SPS and LHC. Identical Beam Interlock Controllers are used for the various interlock sub-systems. This ensures identical hardware configurations, simple test routines, inter-changeability and homogenous application and diagnostic software. The interfaces to User Systems and to kickers are uniform. Flexibility is provided in the form of safe interlock masking that is achieved with the concept of the Safe Beam Flag: masking is only taken into account for beams that may not cause damage to equipment. Efficient machine operation is provided by the BIS hardware flexibility where BEAM_PERMIT signal from one BIC module may be used as USER_PERMIT to another BIC (LHC BEAM_PERMIT is a USER_PERMIT to the Injection interlock system), and by adequate partitioning of transfer lines interlock system to allow safe operation of different beams. For a few isolated cases where differences are unavoidable (for example in the requirement for OR logic conditions in the Extraction Master BIC), these differences are minimised to facilitate use of common components, test routines, software, maintenance, spares and analysis.

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