BEAM INTERLOCKS FOR LHC AND SPS

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Abstract

The Large Hadron Collider at CERN (LHC) will operate at 7 TeV/c with a luminosity of 10^{34} cm^{-2}s^{-1}. This requires two beams with about $3 \cdot 10^{14}$ protons/beam, corresponding to a stored energy of about 350 MJ, sufficient to heat and melt 500 kg of copper. Protection of equipment from damage in case of uncontrolled beam losses is challenging. Injection of the beam from the SPS to the LHC could already damage equipment and is only permitted when all LHC systems are correctly prepared. In case of an uncontrolled loss of the circulating LHC beams, it is required to extract the beams into a specially designed target as soon as possible. Beam loss monitors and equipment for hardware surveillance are distributed around the 26 km long accelerator. In case of failures or beam losses, the beam interlock system is informed and sends a dump request to the beam dumping system. The beam interlock system also inhibits injection when the LHC is not ready for beam. In this paper the requirements for the beam interlock system are discussed, with particular emphasis on its reliability. The architecture with 16 VME based controllers distributed around the LHC and linked by optical fibres is described. Identical hardware will be used to modernise the interlock system for the SPS (CERN Super Proton Synchrotron). This will provide validation of the controllers in a working accelerator before the LHC startup. Results from a first prototype controller tested in the SPS are presented.

BEAM INTERLOCKS FOR LHC

Safe operation of an accelerator with high intensity and small emittance beams requires careful interlocking of dangerous situations or anomalous equipment conditions to avoid damage to the machine components. The role of the beam interlock system is to collect the interlock signals from the client systems and to generate a "beam permit" flag that permits operation with beam. It permits injection into the LHC when all systems are ready for beam and when there is no anomalous condition. With circulating beam, it transmits any beam dump request to the beam dumping system.

The beam interlock system provides one beam permit flag for each of the two beams. To inject beam, the beam dumping system must be ready, all vacuum valves must be in "open" position, magnets must be correctly powered, etc. In case of a beam dump request, the beams have to be dumped as fast as possible. Following the failure of certain magnets, particle losses could damage equipment close to the beam, in particular the collimators, already with a delay as short as one ms [1]. The delay between dump requests received by the beam interlock controller and the end of the beam dump has several sources:

- The beam interlock system must inform the beam dumping system, which takes up to 50 μs if the signal travels half around the ring.
- The synchronisation of the beam dump kicker with the particle free gap takes up to one turn (89 μs).
- It takes about one turn from the start of the extraction to dump all bunches circulating in the LHC.

Together with the delay in the electronics, this determines the achievable response time of up to 270 μs between reception of a beam dump request by the beam interlock controller and the completion of a beam dump.

Architecture of the interlock system

One beam interlock controller module will be installed right and left of each of the eight LHC insertions [2] (see Fig.1). The controllers are inter-connected by "beam permit loops". There is one redundant loop with two optical fibres for each beam. A high frequency signal (10 MHz) is transmitted along the fibres [3]. The permit signal for one beam travels clockwise in one fibre and counter clockwise in the other fibre. This minimises the time for a dump request to travel from any controller module to the beam dumping system. The presence of the signal indicates beam permit. If one of the controllers receives a dump request from a client system, it interrupts the loop to remove the beam permit. Both beam interlock controllers in Pt.6, the insertion with the beam dumping systems, receive the beam permit signal. Whenever the two controllers detect the loss of signal, they instantaneously send hardware signals to fire the extraction kickers in order to dump the beam.
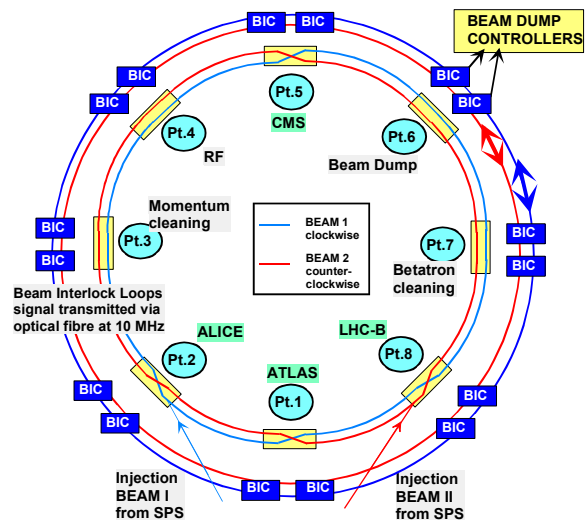

Figure 1: Architecture of the LHC beam interlock system with 16 beam interlock controllers. Each permit loop transmits twgo signals, clockwise and counter-clockwise.

BEAM INTERLOCKS FOR THE SPS

The CERN Super Proton Synchrotron (SPS) has recently been upgraded to operate as LHC injector. Two new 2.8 km long transfer lines for the 450 GeV/c beam are being built between SPS and LHC. Two new extraction systems are being added in the SPS. Although the stored beam energy is about 100 times less than for 7 TeV/c in the LHC, the beams can still severely damage equipment in the SPS or the transfer lines. The present SPS interlock system, designed and build many years ago, must be renovated and adapted for the new extractions to the LHC. Since most requirements are identical, the new SPS and LHC interlock system are built with the same hardware [4]. For the first extraction tests from the SPS towards one of the transfer lines in autumn 2003, an interlock controller prototype was built and tested.

SPS extraction interlock system

Beam extraction from the SPS to the LHC is performed within one turn (23 μs) at a well defined moment in the SPS cycle. The beam interlock controller gives permission for extraction when all client systems provide permission. Extraction permission is only required for a short moment of about some millisecond in the ~20 second long SPS cycle. The output signal of the interlock controller ("extraction enable") is send to the extraction kicker. No beam permit loop is required.

SPS ring interlock system

The architecture will be similar to the LHC, with six interlock controllers installed in the six SPS straight sections inter-connected with optical fibres. The SPS operates with a single beam. Only one beam permit loop is required.

COMMON FUNCTIONALITY

First priority for the interlock systems is to guarantee safe operation of the accelerators. It also should:

- Protect the beams: the system should not generate beam dumps if it is not strictly necessary. Faulty trigger signals that lead to a beam dump should be avoided.
- Provide the evidence: in case of beam dump, correct diagnostic messages should get to the operator. In case of multiple alarms when one initial failure causes subsequent failures, the system should identify the initial failure.
- Assist the operation crew: the diagnostics for failures should be easy to understand. The status of the system must be presented clearly to the operator in the control room.

The safety critical part of the interlock electronics consists of a simple logic that decides if permission for beam/extraction can be given, depending on the status of the input signals from several systems. Depending on its criticality, it will be possible to disable (mask) the signal of a given system. Fail safe logic signals are used. An active signal is required to grant permission (for example, at TTL 5 V level, or a current circulating in a current loop). The beam interlock controllers monitor all inputs and outputs with precise time-stamps for post-mortem information. The accuracy of the time stamps should be about 1 μs.

HARDWARE

VME was selected as hardware platform for the controller because it is one of the standards supported at CERN and it allows fast processing with a response time in the order of μs. The connection to the controls system and to the accelerator timing system is straightforward. The VME crate will host several modules built in-house (see Fig. 2):

- A core module provides the programmable logic for the decision for beam/extraction permit and records state changes. The actual status and the history of state changes are read over the VME bus. Input signals to the programmable logic unit may be masked. In addition, the module includes an interface to the timing system for time stamping.
- A module to exchange the signals with the client systems. Via this module the beam permit status can be transmitted to the clients.
- A link module of the controller to the optical fibre loops. This module is not required for the SPS extraction interlock system.

The controller is connected to the control system via Ethernet for monitoring, input masking, testing and post mortem data collection. All input and output state changes and the time of occurrence are recorded and stored in memory.

The VME crates hosting the controllers are installed around the LHC and SPS. The distance to the client systems varies between several metres and several hundred metres. For each client, a "beam interlock interface" module is installed in the client's rack. The client's system must provide a signal to the interface box using a TTL (+5 Volt) or a PLC compatible level (+24 Volt). To be failsafe, the signal must always be present to provide the beam permit for the associated controller. In case of signal loss, the beam permit loops are interrupted by the controller and the beams will be dumped. The module will also be used to simulate the permit signal from the client for beam interlock system tests.

Supervision for the beam interlock systems

The most important information from the beam interlock system to be displayed in the control room is the status of the beam/extraction permit. The supervision of the beam interlock system also reads and displays the status of all input signals to each beam interlock controller, as well as the output status.

Input signal masking is performed through the supervision. The status of the modules is displayed, showing, for example, which channels are masked. All

state changes and the associated time stamps that are recorded in the controllers are read and archived.

Operational and technical features of the beam interlock system determine the choice of a supervision tool:

- The beam interlock systems are VME based.
- 16 controllers for the LHC, several for each SPS extraction site, and six controllers for the SPS ring.
- Hardware-based control and embedded real-time application.
- Response time in the order of some microseconds.

The data from the beam interlock system will be integrated into the logging, alarm and post-mortem systems. For the prototype used during the SPS extraction tests, 3-tier architecture with JAVA as supervision tool was employed [5]. Together with the newly developed CERN controls middleware described in [6] the same will be used for the LHC.

RELIABILITY

The beam interlock system transmits beam dump requests to the beam dumping system. Both systems should have the same Safety Integrity Level SIL3 [7].

The beam interlock system is therefore designed in a redundant way. Each client provides interlock signals through a failsafe interface module. For the LHC, the beam interlock system provides two independent paths for a dump request with two beam permit loops for each beam. Redundancy is provided throughout the chain.

For safe beam operation not only beam interlocks and beam dumping system, but all systems for machine protection must operate correctly. The Safety Integrity Level for the entire system is being assessed.

EXPERIENCE FROM THE SPS TESTS

A prototype interlock controller was used during recent tests of the new fast extraction system from the SPS into the first part of the transfer line. The beam intensity was limited to one bunch with less than $5 \cdot 10^9$ protons to exclude equipment damage in case of failures. The controller module managed interlock signals related to the current of all critical magnets of the extraction channel, the beam position at the entrance of the extraction channel, the status of the vacuum valves and of the extraction kicker. When all conditions were met, the interlock controller enabled extraction.

Since only theoretical reference values for the magnet current were available, steering of the beam by changing the current was required. When the magnet current was outside the predefined range, the interlock system inhibited extraction. Since operation was with low intensity, the input from the power converters could be disabled, and extraction tests could continue. This cannot be tolerated for operation with high beam intensity. It is therefore foreseen to take the intensity of the circulating

SPS beam into account and to prevent masking of input signals for beam intensities above a certain threshold.

Monitoring turned out to be essential: the operator sees immediately if extraction was permitted, and, if not, which system blocked the extraction. The measurement of the exact time when the clients gave permission provided confirmation of the correct synchronisation.
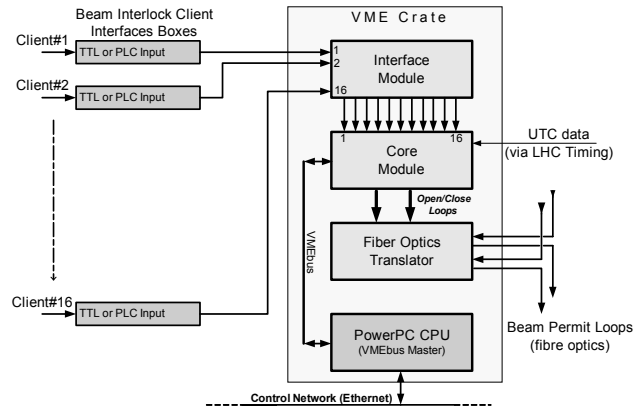

Figure 2: Beam Interlock controller

ACKNOWLEDGEMENTS

REFERENCES

[1] V.Kain, Power converter failure of the normal conducting D1 magnet at experiment insertions IR1 and IR5, CERN-LHC Project Note 322, CERN, October 2003

[2] F.Bordry et al., CERN-LHC Project Report 521, December 2001

[3] C.Conkling, RHIC Beam Permit and Quench Detection Communication System, 1997 Particle Accelerator Conference, New York, 1997

[4] R.Giachino et al., CERN-AB-2003-010-OP, May 2003

[5] E.Hatziangeli, private communication and LHC Design Report, in preparation

[6] K.Kostro et al., The Controls Middleware (CMW) at CERN - Status and Usage, these proceedings

[7] E.Carlier et al., Design Aspect Related to the Reliability of the Control Architecture of the LHC Beam Dump Kicker Systems, these proceedings