

# INTERLOCK SYSTEM UPGRADES AT THE CERN ACCELERATOR COMPLEX DURING LONG SHUTDOWN 2

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## Abstract

The CERN accelerator complex stopped operation at the end of 2018 for the Long Shutdown 2 (LS2), allowing for the LHC Injector Upgrade program (LIU) and consolidation work to be accomplished. A gradual restart of the different accelerators is ongoing in 2021, culminating with the LHC foreseen to be back in operation early 2022. During LS2 a very large range of systems was modified throughout the accelerator complex. This includes the so-called Machine Interlock systems, which are at the heart of the overall machine protection system. This paper gives an overview of the Machine Interlock systems changes during LS2. It includes the installation of a Beam Interlock System (BIS) at the new linear accelerator LINAC4, at the PS-Booster and the installation of a new Injection BIS for the SPS synchrotron. New Safe Machine Parameter flags were put in place to protect the SPS transfer line mobile beam dumps against high intensity beams. The new Warm Magnet Controller (WIC) installations at LINAC4, the PS Booster and the different transfer lines and experimental areas are presented together with the modifications to the Power Interlock Controller (PIC) protecting the LHC superconducting magnets.

## INTRODUCTION

The operation of the accelerators at CERN stopped at the end of 2018 to allow for maintenance and the upgrade of the injector complex in the light of the LHC Injector Upgrade Project (LIU) [1]. At the moment of the writing of this paper, beams are progressively coming back throughout the injector chain, starting with the new LINAC4 and the upgraded PS Booster, which both took beams again towards the end of 2020. The PS and the SPS are taking beams again since the beginning of 2021 and the LHC will see its first beam tests towards the end of 2021. Since the first collisions in the LHC in 2009, Long Shutdown 2 is the second time that the accelerators are stopped for physics for about two years for maintenance and upgrades.

Throughout the CERN accelerator chain interlock systems play an important role for the protection of the machine elements against damage. This can be damage due to important beam losses but also due to overheating or quenching of magnets. Since the construction of the LHC the different interlock systems used in the accelerator complex have been standardised and are under the responsibility of the Machine Interlock section within the Machine Protection and Electrical Integrity group (MPE-MI) at CERN. This paper describes for each of the interlock systems the main changes implemented during LS2.

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## THE BEAM INTERLOCK SYSTEM

The Beam Interlock Systems collect the inputs from a large range of equipment and connects to various actuators to stop the beam operation. In LS2 the final commissioning of a new BIS took place at the new H<sup>-</sup> linear accelerator LINAC4, which is at the very start of all proton beams at CERN, at the PS Booster and for the injection at the SPS. These systems are described in more detail below.

It is to note that with these new BIS systems, the CERN wide number of connections (or Users) to the BIS has increased significantly. An overview is given in Table 1. It shows that in LS2 the number of connections to the BIS has increased by 35%.

Table 1: Number of Connections to the BIS Added During LS2 for the Different Projects

Connections before LS2	333
New connections LINAC4	49
New connections PSB	55
New connections SPS Inj.	14
Total BIS connections	451

## LINAC4 and PS Booster BIS

Following LS2 the new H<sup>-</sup> linear accelerator LINAC4 at the start of the proton chain is brought into operation. The negatively charged protons are injected via a stripping foil into the PS Booster at the new injection energy of 160 MeV. The extraction energy of the PS Booster has been increased from 1.4 GeV to 2.0 GeV. Both machines have a new Beam Interlock System. A schematic view of the new BIS put in operation in Linac4 and PSB is given in Fig. 1 [2]. The figure shows the three Master Beam Interlock Controllers (BIC) which collect the different User inputs and transmit the request to stop the beam to the actuators:

- The Source RF Master BIC which takes 12 inputs related to the RF source and acts on the RF control of the source and the pre-chopper to stop the beam.
- The Chopper Master BIC is the central BIC of LINAC4, it connects to some source RF inputs and to 4 slave BICs related to LINAC4 and another four slave BIC related to the PS Booster. In total the Chopper Master BIC collects about 80 different inputs and acts on the pre-chopper, chopper and the RF-system in the PS Booster.
- The Extraction Master BIC collects 14 different inputs related to the extraction from the PS Booster and acts on the extraction kicker.

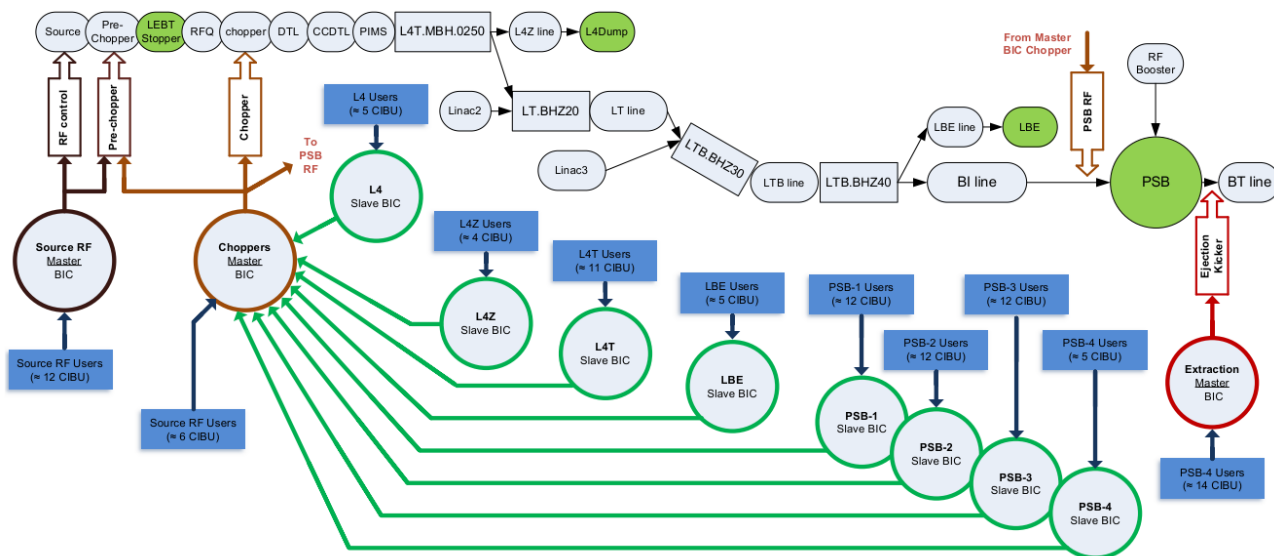


Figure 1: Overview of the new Beam Interlock Systems installed for the LINAC4 and PS Booster.

Following the installation of the BIS at LINAC4 and the PSB, all accelerators in the proton injection chain up to the LHC have an operational BIS, except the PS accelerators. The installation of a BIS at the PS is foreseen for a future Long Shutdown.

itself acts on the injection kickers MKP and a small dipole magnet which centres the non-injected beam on the injection dump MDSH. The Injection BIS receives over optical fibre the SPS Beam Permit from the existing SPS Ring BIS and also receives the status of the renovated SPS Beam Dumping System.

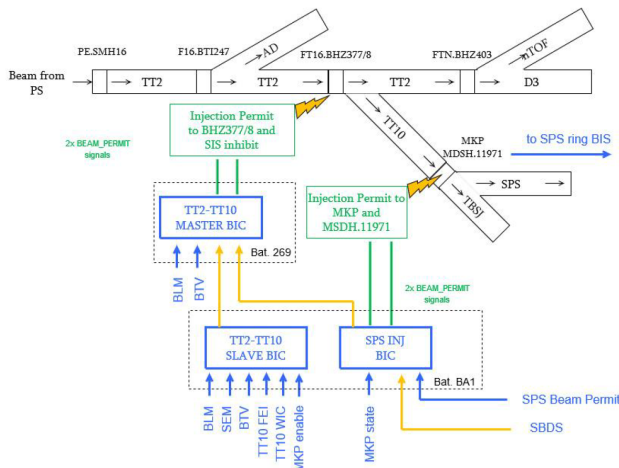


Figure 2: Schematic presentation of the SPS injection BIS.

### SPS Injection BIS

Taking into account the higher bunch intensities following the upgrade of the injector chain as part of the LIU program, a dedicated BIS protecting the SPS injection has been put in place [3]. Depending on the beam type, the injection energy is either 14 GeV or 26 GeV. An overview of the injection protection interlocking is given in Fig. 2. Based on the same VME system hardware as for the LINAC4 and the PSB, two BIC crates have been installed. The TT2-TT10 master BIC collects the signals from one slave BIC and the SPS injection BIC and acts on the switching magnets BHZ377/8 which deviate the beam towards the SPS. The SPS injection BIC

## THE SAFE MACHINE PARAMETER SYSTEM

The Safe Machine Parameter System (SMP) [4] provides a set of different parameters, related in particular to beam energy and intensity, to the BIS as well as to other clients. The crossing of thresholds is transmitted by so-called flags. They are transmitted to the BIS via optical fibres or over the general timing network to reach multiple end-users. Following LS2, new SMP flags are provided to protect the beam stoppers in the SPS-to-LHC transfer lines. These beam stoppers cannot withstand the higher LIU beam intensities above  $3.5 \times 10^{13}$  protons [5]. If the control system of the beam stopper receives the new flag as false while the stopper is in beam, extraction from the SPS will be inhibited.

Two other changes were made to the SMP system during LS2. The implementation of SPS Set-up Beam Flag, which is used to avoid the injection of high intensity beams into an empty LHC and is received by the SPS extraction BIS, was made redundant. In the LHC the SMP flag 'Restricted', mainly used during LHC Machine Development, was updated to be set to  $4 \times 10^{10}$  protons, independent of the beam energy.

## THE POWER INTERLOCK CONTROLLER

The Power Interlock Controller (PIC) is part of the LHC superconducting magnet protection system. It interfaces to the Quench Protection System, the power converters, the BIS, the cryogenics and the electrical powering. There are

36 PIC systems installed in the LHC. During LS2 changes have been made to the PIC system and its configuration.

The automated masking of the Global Protection Mechanism (GPM) of the PIC for low energy superconducting circuits [6] has been changed. The GPM triggers a preventive energy discharge of all circuits in a powering sub-sector in case one of the main circuits develops a quench. Analysis of Run 2 data revealed that in 30% of the cases, the activation of the GPM was not necessary due to the low energy stored in these circuits. The newly implemented automated masking takes into account the currents of the main dipole and main quadrupole circuits and disables the GPM in the case that the currents in both these circuits are below 1 kA.

Before LS2, 202 energy extraction systems were active on superconducting magnet circuits with currents up to 600 A. These are mainly corrector circuits and the current is to be compared to the main circuits with currents up to 12 kA. Based on operational experience, for about 10% of the circuits the operational current has been limited to 200 A and the energy extraction disabled [7]. This has been integrated in the quench loop configuration and related firmware. Due to the reduced number of energy extraction switches in operation, a reduction in maintenance and repair of these systems is expected.

## THE FAST MAGNET CURRENT CHANGE MONITOR

There are 12 Fast Magnet Current Change Monitors (FMCM) installed in the LHC and another 16 in the SPS beam transfer lines. They survey the current of some critical power converters, all connected to dipole magnets with relatively low inductance and installed in regions with high beta functions. The FMCM initiates a beam dump or inhibit extraction via the BIS in case of a rapid change of the current. For those specific magnets the reaction time of the power converters would not be sufficiently fast.

In the SPS extraction line TT60, towards the HiRadMat set-up, older FMCM equipment with limited diagnostics has been replaced by two new FMCMs, which are part of a recently produced series of 25 spare FMCM systems. No other changes have been made to the FMCM system in LS2.

## THE WARM MAGNET INTERLOCK CONTROLLER

A general overview of the functioning of the Warm Magnet Interlock Controller (WIC) is given in Fig. 3. The WIC takes into account the signals from thermoswitches installed on resistive magnets, flow meters and the state of the power converters. In case of abnormal conditions, it stops the power converter and subsequently stops the beam via the BIS. Recently the WIC has been used to interlock electro-static and pulsed systems such as septa and bumpers.

In LS2 the WIC has been upgraded to survey the Beam-Beam Compensation Wires (BBCW) installed in the LHC collimators in Points 1 and 5. It will request a beam dump in case of overheating of the wire or a fault on the BBCW

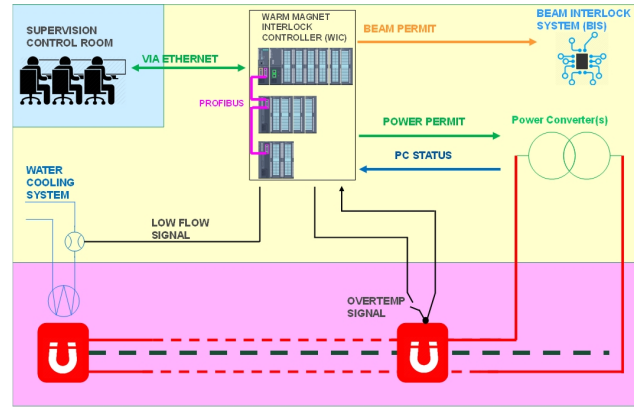


Figure 3: Overview of the functionalities and system connections of the Warm Interlock System.

power converter. Detailed measurements have been made and show that the overall response time between a power converter fault and the time to make the beam abort request is below 1 ms.

In the injector chain several new WIC systems have been installed. An overview of the number of existing and new systems connected is given in Table 2, showing an increase of 30% of the number of systems connected. These systems have been successfully commissioned, with the exception of the East Area, which will be taken into operation in autumn 2021. Moreover, in the SPS the connection of the power converters of the main magnet systems, dipoles and quadrupoles, to the BIS is now implemented via the WIC, replacing the outdated interface between Hardware Interlock Loops (HIL) and the BIS [8]. For this functionality the WIC, which is a PLC based system, is making use of special high speed processors to achieve the requested reaction time.

Table 2: Number of Magnets and Power Converters Connected to the Different WIC Systems

Connections before LS2	3218
PS auxiliary magnets	220
Transfer line LINAC4 to PS Booster	179
Transfer line PS Booster to PS	151
Transfer line TT2-nTOF	107
Transfer line TT10 (SPS inj.)	47
East Area (experimental area PS)	126
Elena II (experimental area)	165
<b>Total WIC connections after LS2</b>	<b>4213</b>

## CONCLUSIONS

Many changes to the different interlock systems at CERN have been made during the Long Shutdown 2, increasing significantly the number of systems connected. The limited space in this paper does not allow to go into technical details, but aims at illustrating the diversity and at the same time the standardisation of the different interlock systems in use.

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