ISBN: 978-3-95450-255-4 ISSN: 2226-0358 doi: 10.18429/JACoW-ICALEPCS2025-TUPD015

CONSOLIDATION OF THE STATE CONTROL AND SURVEILLANCE SYSTEM OF THE LHC BEAM DUMP SYSTEM

C. Monier*, C. Boucly*, N. Magnin, V. Senaj, L. Strobino, O.Y. Yagci
CERN, Geneva, Switzerland

Abstract

The Large Hadron Collider (LHC) Beam Dump System (LBDS) includes 15 extraction kickers (MKD) and 10 dilution kickers (MKB), each powered by a High Voltage Pulse Generator (HVPG), controlled by the State Control and Surveillance System (SCSS) based on industrial PLC technology. After almost 20 years of reliable operation, a software and hardware consolidation is planned during Long Shutdown 3 (2026–2029) to meet the increased demand for diagnostics and functionalities, and to ensure component longevity until the end of LHC operation in 2041. This paper describes the analysis conducted through a detailed review of the existing hardware, software, network layers, and aging field-bus components. It presents the motivations for modernising the SCSS and the new control architecture, including improvements to the safety functionalities implemented. It provides an overview of the new system's interlock state machine with its integration in CERN control middleware.

MOTIVATION

The LBDS control system, though highly reliable, faces increasing challenges due to hardware obsolescence and limited communication capabilities. These constraints restrict diagnostics and hinder the implementation of advanced functionalities—particularly as data requirements grow to support predictive maintenance and system optimisation. To address these limitations, the Accelerator Beam Transfer (ABT) group has validated a consolidation strategy aimed at modernising the control architecture. This initiative will replace aging field-bus technologies with high-bandwidth communication protocols, enabling richer data exchange and enhanced system supervision. The consolidation also aligns with an ABT strategy to harmonise control across CERN's accelerator infrastructure. By upgrading both hardware and software, the LBDS will be equipped to support future functionalities such as fault analysis tools and automatic conditioning of kicker systems—ensuring operational efficiency and system longevity through 2041.

Introduction to the Current LBDS System

The LBDS controls ensure safe beam extraction from the LHC. Its control architecture is built around four subsystems [1].

- **State Control and Surveillance System (SCSS)**: Based on a fail-safe multi-PLC architecture. Manages global and subsystem states, integrates safety functions and expert test features.
- **Trigger Synchronisation and Distribution System (TSDS)**: Coordinates timing and synchronisation of beam dump triggers.
- **Beam Energy Tracking System (BETS)**: Tracks beam energy and adjusts HVPG output accordingly.
- **Post Operational Checks (IPOC/XPOC)**: Verify that all subsystems reacted correctly during execution of the last dump.

SCSS OVERVIEW

The SCSS ensures safe and reliable control of the beam extraction and dilution systems using a fail-safe multi-PLC architecture composed of one master PLC and 25 generator PLC. The PLC technologies underpinning the SCSS were initially deployed in 2006, forming the foundation for its safety and control functions throughout the system's operational life-cycle.

SCSS Functionalities

- Person protection with Electrical Discharge Switch (EDS), Manual Earthing Switch (MES), Emergency Stops (AUE).
- Machine protection with a communication with the Trigger Synchronisation Unit (TSU [2]), Beam Interlock System (BIS), TSDS.
- Reception of LHC energy with Beam Energy Tracking System (BETS [3]), computation of HVPG voltage reference through reference tables.
- Voltage control for Power Trigger Module (PTM).
- Acquisition and checking of HVPG voltages.
- Check of trigger signals throught the Power Trigger Controller (PTC [4]).
- Check of HVPG voltages with tracking tables.
- Sequential test with simulation of pulses, cycles, energy scan, IPOC/SAM trigger, retrigger lines.

Safety System

- Designed to meet SIL2 and SIL3 standards (IEC 61508, EN 954-1, IEC 62061, EN ISO 13849-1).
- Implements safety functions for both personnel and machine protection.
- Includes emergency stop monitoring, HV interlocks, and power distribution safety.

Current Control Architecture

- Centralised master controller (Siemens S7-400) with distributed generator controllers.
- Communication via MPI, PROFIBUS-DP, AS-Interface and CERN Ethernet (TN).

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[*] colin.monier@cern.ch

Table 1: SCSS State Machine – Sequential Steps

Step	Function Description
1	Emergency stop validation via AS-Interface; ensures all safety buttons are acknowledged.
2	Activation of power distribution; verifies contactors and electrical sources.
3	Earthing and discharge checks; monitors HV protection and grounding.
4	HV power supply control; manages DCPS and environmental conditions.
5	Trigger system readiness; prepares PTU for HV pulse generation.
6	Voltage tracking; compares measured voltage with beam energy reference.
7	Trigger pulse monitoring; checks PTU/PTM status and re-trigger logic.
8	Final readiness validation; confirms all conditions met for beam injection.

- Supports automatic testing and recommissioning of HVPG.

State Machine

The SCSS operates through a structured state machine that ensures safe and sequential activation of the LBDS components. The system transitions through predefined modes and states, with each step validated by interlocks and feedback mechanisms (details in Table 1).

Modes of Operation

- **LOCAL-AUTO** – Local control of the PLC master system on the on-site touch panel, generator controls in remote.
- **LOCAL-MANU** – Full local control of PLC master and generator controls on the on-site touch panel.
- **REMOTE-AUTO** – Full remote control from the LHC control room and from the Siemens WinCC supervision.

System States

- **OFF** – System powered down.
- **STAND-BY** – Power and HV protection ready.
- **ON** – HV and trigger systems ready.
- **ARMED** – Fully operational and extraction system armed / Pulse generator ready.
- **FAULTY** – Interlock or error detected.
- **BUSY** – Transitioning between steps.

Network Architecture

The current communication architecture of the LBDS is designed around several field-buses, as explained in Fig. 1.

- **Multi Point Interface (MPI)** – Used for PLC management tasks such as program downloads and Siemens diagnostics. It ensures asynchronous data exchange between the master controller and generator PLCs.
- **Profibus Master** – A set of PROFIBUS-DP networks that connect the master PLC to all generator controllers. These buses handle both standard and safety-critical data exchanges.
- **Profibus Generators** – Each generator PLC operates its own PROFIBUS sub-net, linked to the master via a DP/DP coupler. This enables communication with I/O stations and power trigger units, ensuring modular control and redundancy.
- **AS-Interface (ASI)** – A dedicated field-bus for managing emergency stop signals and safety modules. It supports SIL3-level safety functions and integrates seamlessly with the SCSS safety logic.

Limitations, Issues and Obsolescence

This architecture needs to be consolidated to increase the amount of data exchanged, enabling the development and implementation of new functionalities and diagnostics. Another issue is the obsolescence of the hardware; to mitigate future risks, it will be replaced during the upcoming consolidation phase.

The communication between a PLC generator and the PLC master is constrained by the DP/DP coupler modules, as illustrated Fig. 1. These modules impose a strict limit of 288 bytes per exchange cycle. Within this frame, approximately 244 bytes are allocated for non-safety data, while 44 bytes are reserved for safety-critical information using PROFIBUS safety encoding. This partitioning is essential for maintaining SIL2/SIL3 integrity but significantly restricts the bandwidth available for operational diagnostics, feedback, and control commands. The DP/DP coupler operates with two independent DP interfaces, each acting as a slave on its respective network. Data exchange occurs via internal memory copying, which introduces latency and limits dynamic reconfiguration. The safety data, encrypted and verified using PROFIsafe protocols, consumes a fixed portion of the bandwidth, leaving limited room for expansion or integration of advanced monitoring features.

Additionally, the MPI communication used for transferring voltage reference and tracking tables between the master controller and generator PLCs presents further limitations. This legacy field-bus operates at 187.5 kbps and lacks native support for advanced diagnostics or flexible topology. Each generator requires the transmission of five floating-point tables, totaling 1920 bytes per unit. Given the asynchronous nature of MPI and its reliance on external triggers, the system cannot perform real-time validation or read-back of critical settings. The functions `X_PUT` and `X_GET` are used for table uploads, but they do not support dynamic feedback or error correction mechanisms. These constraints—both in DP/DP and MPI—highlight the need for a modernised communication backbone that supports higher throughput, deterministic timing, and integrated safety diagnostics.

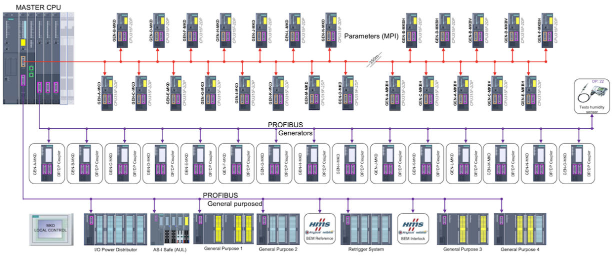

Figure 1: Current - SCSS architecture.

Figure 2: LS3 - SCSS architecture.

Beyond communication constraints, the multi-PLC architecture also limits the implementation of generic software solutions. Each HVPG requires a separate PLC code-base, increasing the complexity of maintenance and the risk of human error during updates or troubleshooting. This duplication of logic and configuration across controllers makes the system fragile and more complicated to evolve without a complete consolidation.

CONSOLIDATION

The consolidation is planned during the long shutdown 3 (LS3), an operational stop period defined at CERN to allow systems teams to upgrade systems. The control part and surveillance system of the LBDS will be upgraded to fit the requirements of the operation, fix the limitations of the current system and allowing the integration of this system into the new control strategy of ABT group.

Hardware and Fields-Bus Architecture

As seen in the previous part, the current communication architecture induces some data transfer limitations. In the new hardware architecture, we replace the HVPG PLC by an Siemens ET200SP deported station and move all the generator program inside the master PLC (Siemens S7-1518F). This technology allow more performance than the previous PLC (see comparison with current master PLC, Table 2), and allow us to get rid of the DP/DP coupler modules and their limitation of data.

At the fields-bus level, it is then planned to remove all Profibus and MPI networks to install a unique Profinet network that will link all the different generator deported stations (GCC) to the master PLC (Fig. 2). This technology will allow more data transfers, increasing the data rate, the number of variables in the communication, the addition of Profinet diagnostics and reduce the complexity of the maintenance and commissioning.

To ensure more availability on this network, the Profinet bus will be installed in a ring architecture, using the protocol Multi Ring Process (MRP). In this configuration, in case of failure of the continuity of the bus, the stations will be able to auto-reconfigure to communicate on the remaining part.

To fit the new architecture, the Power Trigger Controller (PTC [4]) will be updated to its Profinet version to be directly connected to the Profinet network.

Generator Control Crate (GCC)

To modernise the system, reduce maintenance, and reduce hardware obsolescence, only one control crate will be designed and installed per generator instead of three for the MKD and two for the MKB. This control crate will be composed of one Siemens ET200SP deported station with its associated I/O cards.

An example of the Generator Control Crate (GCC) designed for MKD generators is shown in Fig. 3.

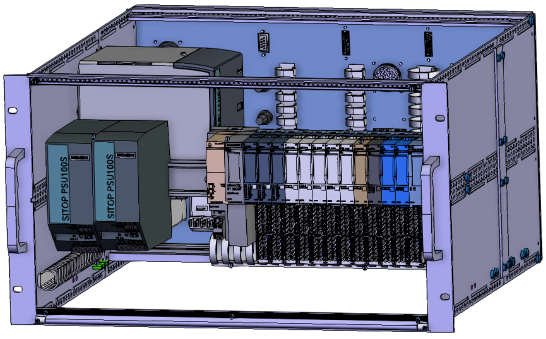

Figure 3: MKD GCC

Validation Platform

A prototype has been installed in an operational test cage allowing us to perform tests on an operational replica of one LBDS HVPG.

A global LBDS structure will be replicated to test the control of multiple HVPG; the test structure will be composed of 2 MKD and 1 MKB HVPG controlled by one master PLC. At the software level, such an update will allow easier maintenance on the program.

Software and Functionalities

This new architecture and design will allow us to improve current functionalities and implement new ones. To facilitate

Table 2: PLC Comparison S7-1518F/S7-400, from Siemens Datasheets

Siemens© CPU	**S7-1518F** **6ES7518-3FT10-0AB0**	**S7-416F** **6ES7416-2FN05-0AB0**
Memory		
work memory (for program)	18 Mbytes	2.8 Mbytes
work memory (for data)	150 Mbytes	2.8 Mbytes
load memory (card)	32 Gbytes (max)	64 Mbytes (max)
CPU time processing		
bit operations	0.3 ns	30 ns
word operations	0.8 ns	30 ns
fixed point arithmetic	0.8 ns	30 ns
floating point arithmetic	2.5 ns	90 ns

the maintenance, as we are using only one PLC, and thanks to the new state machine (see subsection: New state machine), a generic function will be created for a MKD generator type and one for a MKB generator type. These functions will be instantiated for each HVPG and attached to one GCC. Thanks to the new structure and communication, the rework and the addition of functions is possible. ABT will then integrate its generic PLC functions into the LBDS systems.

Here is a non-exhaustive list of the functionalities that will be implemented during the development of the software:

- Replacement of the hard coded reference and tracking tables which requires the download of all PLC to a remote auto loading from CMW.
- Automatic Peltier temperature management: to avoid manual action from the operator, the set point of the temperature inside the MKD generator will be automatically computed depending on the tunnel temperature and the rules defined by experts.
- Integration of conditioning for MKB magnet: To reduce the number of sparks in the MKB magnets, an automatic conditioning (NACOND [5]) will be integrated in the system to allow operators and experts to gain some time in conditioning the magnets.
- Spark Activity Monitoring (SAM [6]) integration into LBDS control to allow interlocking in case of critical activity.
- Modification of the IPOC [1] interlock communication with the PLC: replacement of the current hardware solution with a software communication using SILECS. The logic of the interlock will be upgraded to detect more fault from the subsystem as a IPOC no trigger interlock.
- Rework of sequential test (simulation of pulses, cycles, energy scan, IPOC/SAM trigger, retrigger lines): This functionality will be standardised in multiple ABT systems.
- Checking of Power Trigger Controller (PTC [4]) version and cabling: The PTC will be connected over the Profinet network and therefore will allow all the Profinet diagnostics and the I&M status. With these statuses, the PLC will be able to check if the right version of the firmware is loaded into each PTC, and thanks to the topology defined in the software, check if all the physical positions of the PTC are correct. Also more diagnostics details will be added in the communication with the PTC (e.g. several sources of interlocks merged into one today) thanks to the increased bandwidth of PROFINET.
- Slow control test: An update of the slow control test will be needed to fit the new system. This functionality enables an expert to test and validate the control and safety aspects of a single HVPG in case of replacement or intervention on the HVPG and to generate a report summarising all the tests and results conducted.

INTEGRATION INTO CERN CONTROLS ENVIRONMENT

To standardise the supervision of the control in ABT, during the consolidation, this part of the LBDS system will be upgraded. The benefits of this new supervision will be to increase the number of data published over the CERN Middleware (CMW) layer [7] and logged to NXCALS [8], enabling more diagnostics for users and analysis for anomaly detection, and automatic controls. Also the standardisation is here to have only one way of providing data (see Fig. 4).

To provide these data to the CMW layer, each standardised functions of ABT control (as for example: conditioning, power supply management, power distributor, timing...) will be linked to one PLC standardised function, one Silecs (was IEPLC [9]) communication class, one FESA class [10].

During the consolidation the expert supervision will be updated, a GUI using a CERN framework for GUI development based on PyQt will be designed to auto integrate all widget from the different standardised function present in the LBDS. The state machine will also be reworked to allow more flexibility in the development, more functionalities and a better integration into the CERN environment.

CONCLUSION AND OUTLOOK

This consolidation will allow the LBDS to have new hardware that prevent obsolescence and malfunctions, to allow the best availability until the end of LHC operation. This new hardware architecture with the migration of the field-bus to Profinet will allow more diagnostics and the development

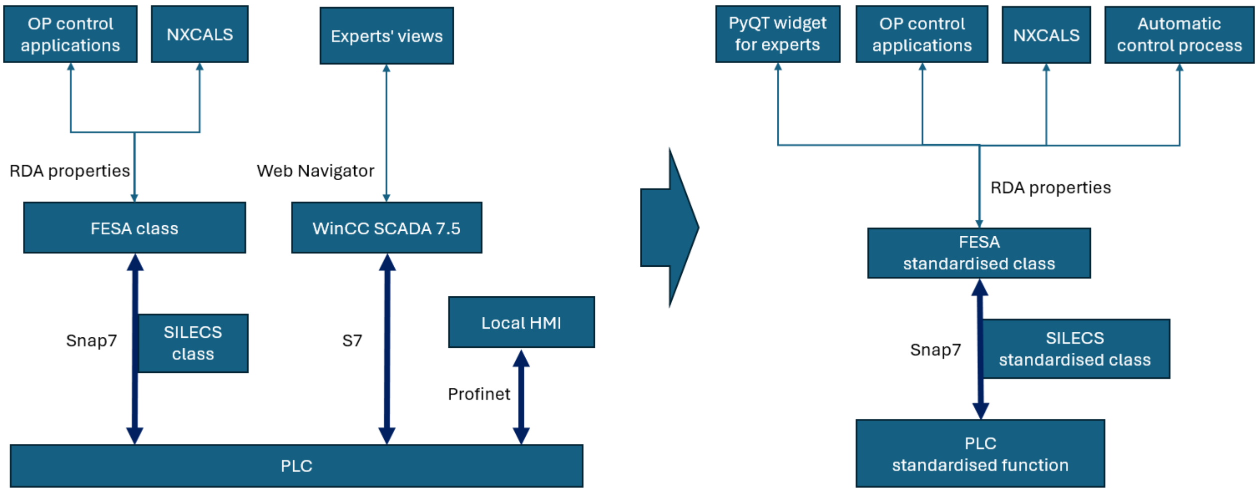

Figure 4: Current control architecture - new control architecture.

and implementation of more functionalities. Thanks to this possibility the LBDS will be fully integrated into the CERN controls environment, using standardised ABT functions that will reduce the time of maintenance and diagnostics. This better integration in CERN controls will allow for more data analysis, like anomaly detection to have a better preventive maintenance, or automatic fault diagnosis and automatic control.

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