

ETHERNET-ENABLED DATA ACQUISITION AND SUPERVISION SYSTEMS FOR THE HL-LHC QUENCH PROTECTION SYSTEM

P. J. Oliveras Cejas*, T. Podzorny†, M. Christensen, D. del Castillo, R. Denz,
L. Flores Sanz De Acedo, M.-A. Galilée, J. Steckert, J. Uythoven
European Organization for Nuclear Research, Geneva, Switzerland

Abstract

Ethernet-enabled Data Acquisition and Supervision (EDAQ) systems have become the standard platform for commissioning, controlling, and supervising the next generation of Quench Protection Systems (QPS) for superconducting magnets at CERN. EDAQ-equipped QPS devices have been installed in recent upgrades to magnet test facilities, most notably in the Inner Triplet String (IT String) test facility for the high luminosity LHC (HL-LHC) upgrade. This contribution summarizes the operational experience gained during these installations and highlights the key advancements that have enabled the EDAQ ecosystem to mature into a production-ready solution. Notable developments include a configuration validation system, improved error-recovery strategies, remote firmware update, and seamless integration with the full range of QPS equipment that will be installed for the HL-LHC upgrade. The results of a comprehensive set of performance tests are presented and discussed, confirming that the EDAQ system is ready for deployment as part of the HL-LHC upgrade, for which installation will start in summer 2026.

INTRODUCTION

The superconducting magnets on each side of Interaction Regions IR1 (housing the ATLAS experiment) and IR5 (housing the CMS experiment) in the LHC accelerator are to be replaced as part of the the High Luminosity Upgrade of the LHC project (HL-LHC). The collection of magnets at either side of these interaction regions form what is known as the inner-triplet magnet chain. Their replacement is one of the core activities of the HL-LHC project, allowing the significant increase in the overall luminosity to be delivered to the experiments [1].

The elements to be replaced include the superconducting magnets, superconducting links, current leads and bus-bars. They must be protected to avoid serious damage and downtime in case of a quench. This function is achieved by the Quench Protection Systems (QPS) which include the detection of the quench by the Quench Detection Systems (QDS) and triggering the systems which actively protect the circuit (e.g. Quench heaters or the new CLIQ system, bypass diodes, energy extraction systems and others).

The safe powering of the inner triplet circuit requires all these protection systems to function reliably, with Supervisory Control And Data Acquisition (SCADA) systems providing accurate data representing the circuit and

protection status. This is crucial for all phases of machine operation, including testing, commissioning and beam operation. To this end, the QPS is designed with data acquisition in mind, with communication interfaces allowing information to be transmitted to CERN's SCADA infrastructure.

In the QPS of the presently operational LHC this is achieved by interfacing QPS equipment with radiation-tolerant WorldFip communication cards. The WorldFip field-bus connects a number of devices to a Front-End Computer (FEC), which aggregates and relays data to the supervision and control infrastructure, while providing timing to devices and delivering control commands.

For the future HL-LHC, Ethernet-enabled Data Acquisition and Supervision (EDAQ) will be used as the communication interface between multiple kinds of QPS equipment and the SCADA. QPS devices which support EDAQ usually include a MCU-based communication card (EDAQ Controller) which is also connected to a FEC. In this case connections are made using Ethernet cables through a network switch in a star network topology. Timing is distributed to devices via Precision Time Protocol (PTP), while data acquisition and control traffic is sent by UDP [2].

Since its introduction in 2021, EDAQ has been used for the QPS in magnet test facilities at CERN, including in SM18, FRESCA and the Super-FRS Magnet Test Facility testing magnets for the Facility for Antiproton and Ion Research (FAIR) at GSI. QPS devices with EDAQ support have also recently been installed in the Inner Triplet String (IT String) facility, a testbed for HL-LHC. These installations provided the necessary experience to transition from a development project to the present production solution.

EDAQ IN HL-LHC

Integration with QPS

Five different EDAQ Controllers have been developed to supervise six types of QPS equipment to be installed as part of the HL-LHC upgrade. The EDAQ firmware modules and core components are identical for all systems, while the hardware design of the PCBs and application-specific firmware modules are adapted to each system. EDAQ integration with all these systems is complete up to the SCADA level. From left to right in Fig. 1:

- Universal Quench Detection System (UQDS) [3]: The same EDAQ Controller is used for the five different UQDS configurations in use to protect different elements. EDAQ controller instances are likewise configured for the different number of signals according

* pau.oliveras@cern.ch

† tomasz.podzorny@cern.ch

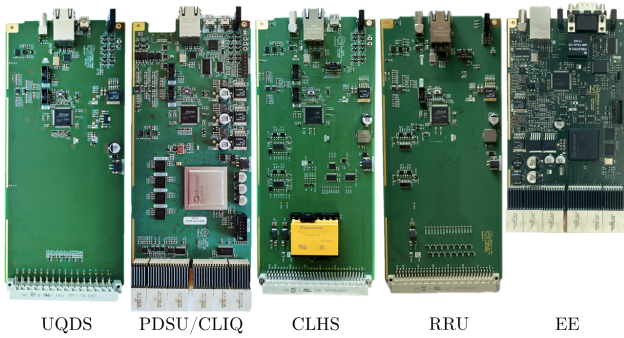


Figure 1: EDAQ Controller PCBs for HL-LHC QPS.

to the type of the magnet circuit to be protected. For example, Fig. 2 contains signals from an event from a skew quadrupole magnet (MQSXF) acquired with an EDAQ-equipped UQDS.

- **Protection Devices Supervision Unit (PDSU):** Two different configurations exist, acquiring more than a hundred analogue signals. Protection hardware is combined with the EDAQ Controller in a single PCB, resulting in a more performant, compact, and cost-effective design for the overall system. The Coupling Loss Induced Quench (CLIQ) version is compatible with the PDSU EDAQ Controller, with only changes to the firmware needed.
- **Current Lead Heating System (CLHS):** A single controller simultaneously supervises seven independent Current Lead Heating System Solid-State Relay Driving Cards (DQLSU). In addition, the EDAQ Controller hardware has been extended to incorporate extra device-specific functionality, namely a power-cycle relay and voltage and current monitoring. The physical and electrical interface is kept identical to the equivalent WorldFip communication card, retaining backwards compatibility with existing designs.
- **Remote Reset Unit (RRU):** In this case, the MCU of the base EDAQ Controller also carries out the core function of the device. Physical and electrical interfaces to the equivalent WorldFip design have been retained.
- **Energy Extraction (EE):** A hybrid communication card containing both EDAQ and WorldFip interfaces is used to cover HL-LHC requirements as well as for consolidation of the LHC's existing EE systems.

Two EDAQ networks for QPS equipment have been installed and tested in the IT String facility. One network serves 37 UQDS, while the other serves 8 PDSU, 2 CLHS, 1 RRU, 7 EE, and 7 CLIQ. The EDAQ systems are in operation and have demonstrated its stability over several months of commissioning.

Configuration

QPS devices like UQDS are highly configurable through EDAQ. This flexibility is an advantage, but it also intro-

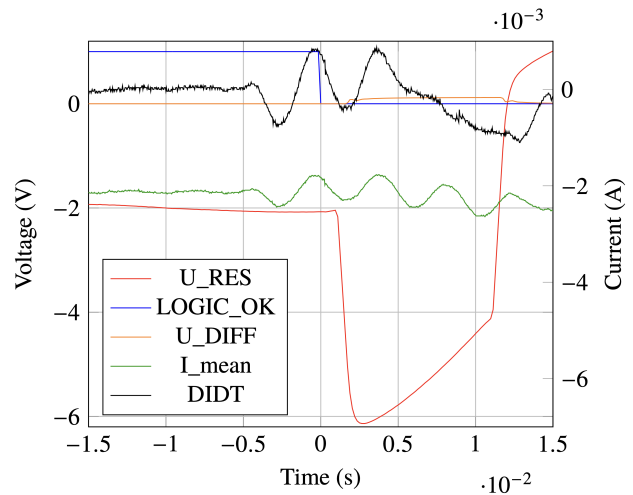


Figure 2: Example UQDS signals acquired using EDAQ.

duces the risk of not adequately performing a protection function due to a configuration error. To address this, EDAQ Controllers periodically publish the relevant subset of the configuration so it can be verified against a reference. The periodic configuration transmission is parametrized and easy to adapt to other types of equipment. The controller can also use the same structure to send its own configuration, read-only data, or any other monitoring information.

Important configuration settings become fully visible in SCADA. In the event of a configuration change (e.g. hardware replacement), configuration differences can be automatically detected, reviewed, and corrected.

Data Specifications for SCADA

The EDAQ protocol employs lean binary data formats when sending acquisition data. While efficient, this method requires the receiver to have knowledge about data encoding. The QPS signals and data formats match the SCADA layout for each different type of equipment. To streamline the process, a file-based specification format has been defined. The format is based on .toml [4] files and it is human-readable and easy to edit, while machine parsing is straightforward.

The specifications include the necessary information to decode analog and digital signals from data acquisition frames, read and modify configuration registers, and match EDAQ protocol identifying information. In addition, optional extra information can be included and used by tools for data analysis and visualization. This allows a more generic design approach for any software processing the acquired data.

The inclusion of the specification files in a version control system enables more efficient coordination between teams designing the protection systems, the SCADA systems, and the expert tools, while making changes less error-prone.

Remote Firmware Update

The EDAQ Controller is able to upgrade its firmware while installed. The MCU's non-volatile FLASH memory has two banks, one active and one inactive. Each bank has two firmware images, the boot-loader and the application.

The application is executed by default and performs the required DAQ and control functions. By issuing a command through the SCADA, the user can request to instead execute the bootloader, which can perform service functions. Once the bootloader is executing, the user can program the inactive bank of the memory by uploading the new images using the TFTP protocol [5]. The images in the inactive bank are then hashed and verified before the two banks are swapped, making the newly programmed bank active.

This approach has a number of advantages:

- **Ease of use** with existing interfaces without special tools: The already existing Ethernet connection is used, allowing the update to be performed remotely from a computer. Only a TFTP client is needed, which is often already bundled with the operating system.
- **Fail-safe**: In case of a power or network loss during the update, the existing firmware is still present and is executed normally, guaranteeing a successful boot in all cases, and allowing to re-attempt the update. In addition, the boot-loader checks for image integrity at every startup, preventing the execution of a corrupted image.
- **Extensible**: The bootloader can update itself, the application, and other programmable ICs in off-board devices (e.g. UQDS, PDSU, etc). This is particularly useful during installation or during an intervention where the hardware is replaced.
- **Traceability**: Images are automatically tagged during compilation, embedding version and unique build information. This can then be checked using the configuration system to ensure the correct images are being used in each device. All images include a hash which is used to ensure the integrity of the image.

Testing

A set of Python packages implementing a user-friendly API to QPS devices has been developed. User python scripts can connect to QPS equipment through EDAQ and directly control them and acquire data, without the need for the full SCADA stack. Device-specific features are exposed in Python modules which are generated from the specification files.

This approach is extremely useful during manual or automatic equipment testing and validation, and reduces the development time for software tools. At the same time, it reduces the need for auxiliary interfaces. The same communication interface that is used during normal operation is also used during testing.

PERFORMANCE

Key metrics and performance tests for the EDAQ data acquisition and supervision system have been measured and confirm that the design requirements are met. A comparison between WorldFip and the initial and current versions of EDAQ is shown in Table 1.

Table 1: Field-Bus Performance Comparison (Per Node)

Metric	WorldFip	EDAQ 2021	EDAQ
Throughput	8 kbps	5.5 Mbps	13.7 Mbps
Sample-rate	10 Hz	4 kHz	10 kHz
Cmd. latency	100 ms	1 ms	1 ms
Max phase Δ	-	350 ns	350 ns
PM upload	~25 min	~20 s	~10 s

Throughput

The MCU firmware of the EDAQ Controller has been optimized to increase the data acquisition throughput to 13.7 Mbps, which is an improvement over the 5.5 Mbps measured for UQDS in [2]. This enables a PDSU to stream its 107 analogue signals at a 4 kHz sampling rate in real time, or UQDS devices (which have less signals) at 10 kHz or higher.

For post-mortem data, EDAQ does not impose a limit on the sampling rate, as the data is not sent in real time. However, the improved throughput reduces the waiting time for operators during upload of the data. For a typical UQDS configuration in HL-LHC, this is about ten seconds, compared to up to 25 minutes for the present LHC system.

Control Interface

Commands to the controller are executed on average in 1.02 ± 0.08 ms. This figure includes network transport delays, and enables efficient scripting and configuration of devices.

Timing Accuracy

PTP is used to maintain the long-term stability of the internal data acquisition clock. The control loop is implemented in the EDAQ Controller MCU. Timing accuracy is measured to ensure that additions and modifications to the firmware do not affect timing quality. Pulse Per Second (PPS) output is measured against the reference clock over 48 h duration tests. Measurements show a similar performance as observed in [2]. Maximum phase deviation during the measurements is 350 ns. In addition, a configuration in which the network switch acts as PTP boundary clock has also been tested. This removes the need for the PTP Grand-Master in the FEC, reducing system complexity and cost.

CONCLUSION

The EDAQ system is ready to be used for the HL-LHC quench protection system. Since its introduction, 134 QPS devices with EDAQ are already in operation in CERN's magnet test facilities, including the IT String. In all these installations, the hardware and firmware platforms have proven the reliable operation of the EDAQ systems, with the operational experience gained translated into improvements which have subsequently increased the maturity of the solution.

ACKNOWLEDGMENTS

This research is funded by the HL-LHC project.

REFERENCES

- [1] I. Béjar *et al.*, “High-Luminosity Large Hadron Collider (HL-LHC) Technical Design Report, CERN, Geneva, Switzerland”. [doi:10.23731/CYRM-2020-0010](https://doi.org/10.23731/CYRM-2020-0010)
- [2] T. Podzorny *et al.*, “Data acquisition and supervision systems for the HL-LHC quench protection system - part I the hardware”, in *Proc. IPAC'23*, Venice, Italy, pp. 3992–3995, Sep. 2023. [doi:10.18429/JACoW-IPAC2023-THPA023](https://doi.org/10.18429/JACoW-IPAC2023-THPA023)
- [3] J. Steckert, R. Denz, S. Mundra, T. Podzorny, J. Spasic, and D. G. Vancea, “Application of the universal quench detection system to the protection of the high-luminosity lhc magnets at cern”, *IEEE Trans. Appl. Supercond.*, vol. 32, no. 6, pp. 1–5, Sep. 2022. [doi:10.1109/TASC.2022.3152125](https://doi.org/10.1109/TASC.2022.3152125)
- [4] T. Preston-Werner and T. Contributors, “Toml: tom’s obvious, minimal language”, 2021. <https://toml.io/en/>
- [5] D. K. R. Sollins, “The TFTP Protocol (Revision 2)”, Rep. 1350, Jul. 1992. [doi:10.17487/RFC1350](https://doi.org/10.17487/RFC1350)

PREPRINT