Experimental Program of the HL-LHC Inner Triplet String Test at CERN

S. Yammine, M. Bajko, A. Ballarino, M. J. Bednarek, D. Bozzini, S. Blanchard, O. Brüning, P. Cruikshank, R. Denz, D. Duarte Ramos, J. Fleiter, D. Gamba, N. Heredia Garcia, A. Herty, Y. Leclercq, W. Maan, M. Martino, M. Modena, A. Onufrena, A. Perin, M. Pojer, H. Prin, E. Ravaioli, F. Rodriguez Mateos, S. Seshadri, J. Steckert, H. Thiesen, E. Todesco, R. Tomas Garcia, A. Verweij, D. Wollmann, and M. Zerlauth

***Abstract*—This contribution describes the experimental program already undergoing and to be completed on the High Luminosity Large Hadron Collider (HL-LHC) Inner Triplet (IT) String, an important intermediate milestone of the HL-LHC project at CERN. First, it describes the magnet circuits of the HL-LHC IT String. Afterwards, the different systems installed to perform the experimental program are detailed. The proposed tests are defined for the validation of the cryogenic system, the full remote alignment system, the powering system, and the protection schemes of all magnets working in unison. This strategy will allow for a verification of the integrated powering system before the final installation and commissioning in the HL-LHC's underground areas.**

***Index Terms*—HL-LHC, superconducting, magnet, quench, protection, testing.**

I. Introduction

The goal of the High Luminosity-Large Hadron Collider (HL-LHC) Inner Triplet (IT) String test [1], representing an important intermediate milestone of the HL-LHC project at CERN [2], [3], is to validate in a surface building the collective behavior of the superconducting IT magnet chain in conditions as close as possible to those of their later operation in the LHC. The HL-LHC IT String includes the systems required for operation at nominal conditions, such as the vacuum, cryogenic feed boxes, superconducting link, powering equipment, quench detection and protection systems. The magnet chain comprises the main IT quadrupoles (Q1a, Q1b, Q2a, Q2b, Q3a and Q3b) based on the Nb_3Sn superconductor technology. It also includes superconducting magnets based on more conventional NbTi superconductor, i.e., the nested orbit correctors, the higher order correctors, and the separation dipole D1. The novel remote alignment system foreseen for the HL-LHC is also an integral part of the IT String test facility as well as the Superconducting Link (Sc Link) using MgB_2 superconducting cables. In total, the HL-LHC IT String integrates 19 superconducting magnets, which compose its 17 magnet circuits.

This contribution describes the experimental program of the HL-LHC IT String. The program is designed to ensure the validation of the cryogenic layout, the powering system, and the protection schemes of all the magnet chain. This strategy establishes a verification before the final installation in the LHC underground areas. The HL-LHC IT String experimental program includes the Hardware Commissioning (HWC) phase, which comprises the same steps foreseen after the installation in the LHC. As such, the program ultimately is intended to ensure a smooth and time-efficient execution of the activities in the tunnel. The HWC tests hereby include Individual Systems Tests (IST), Short Circuit Tests (SCT) and magnet powering tests with several tests already ongoing in the facility. The main difference between the HL-LHC IT String and the HL-LHC is the absence of the particle beam in the String facility. However, as shown in this contribution, String-specific tests are foreseen in the experimental program to complete the understanding of the eventual cross-talks and operation modes of systems not necessarily visible during the individual test of the major components.

In this contribution, the HL-LHC IT String magnet circuits and their ancillary systems that are validated in the HL-LHC IT String experimental program are described. Finally, the tests within the experimental program including the HWC steps and the String-specific tests are defined.

II. Magnets and Circuits of the HL-LHC IT String Experimental Program

The cryo-assemblies of the HL-LHC IT String contain magnets produced at CERN or through the HL-LHC collaborations [4]. Moreover, the magnets are, to a large extent, prototypes or first of series. Table I summarizes the main characteristics of the magnets and circuits which are identical to the HL-LHC ones. All the magnets in the HL-LHC IT String except for the IT quadrupoles (RQX) are individually powered, i.e., by one Power Converter (PC) per magnet circuit. The RQX consists of a main branch powered by an 18 kA PC and trim branches to adjust locally the magnetic field where necessary. The Q1 and Q3 magnets are fed by trim PC that inject or extract 2 kA (±2 kA) with respect to the main branch. Over the Q1a magnet (the first magnet inside the Q1 cryo-assembly), a ±35 A trim is added. The MCBXF(A/B) corrector magnets are nested where two independent circuits are powered for the horizontal and vertical beam orbit corrections [5], [6].

Manuscript received 26 September 2023; revised 24 November 2023; accepted 8 December 2023. Date of publication 9 January 2024; date of current version 17 January 2024. This work was supported by the HL-LHC Project at CERN. *(Corresponding author: Samer Yammine.)*

The authors are with CERN, 1211 Geneva, Switzerland (e-mail: samer.yammine@cern.ch).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TASC.2023.3349356.

Digital Object Identifier 10.1109/TASC.2023.3349356

TABLE I
HL-LHC IT STRING MAGNET CIRCUIT GENERAL PARAMETERS

Magnet Circuit	Magnet	Nominal Current, Inom [kA]	Circuit Inductance at Inom [mH]	Stored Energy at Inom [kJ]	No. of Circuits in HL-LHC IT String	Quench Protection Method
IT Quadrupoles (RQX)	MQXFA/B	16.23	255.4	36380	1	QH + CLIQ
Separation Dipole (RD1)	MBXF	12.11	24.9	2130	1	QH
IT Orbit Correctors (RCBX)	MCBXFA/B	1.34-1.74	58.4-232.3	77-239	6	EE
Skew Quad Corrector (RQSX3)	MQSXF	0.174	1530	31	1	EE
High Order Correctors (HOC)	MC(S,O,D,T)XF	0.084-0.102	120-805	0.7-3.7	8	Self-protected by quench propagation

QH: Quench Heaters; CLIQ: Coupling-Loss Induced Quench system; EE: Energy Extraction System.

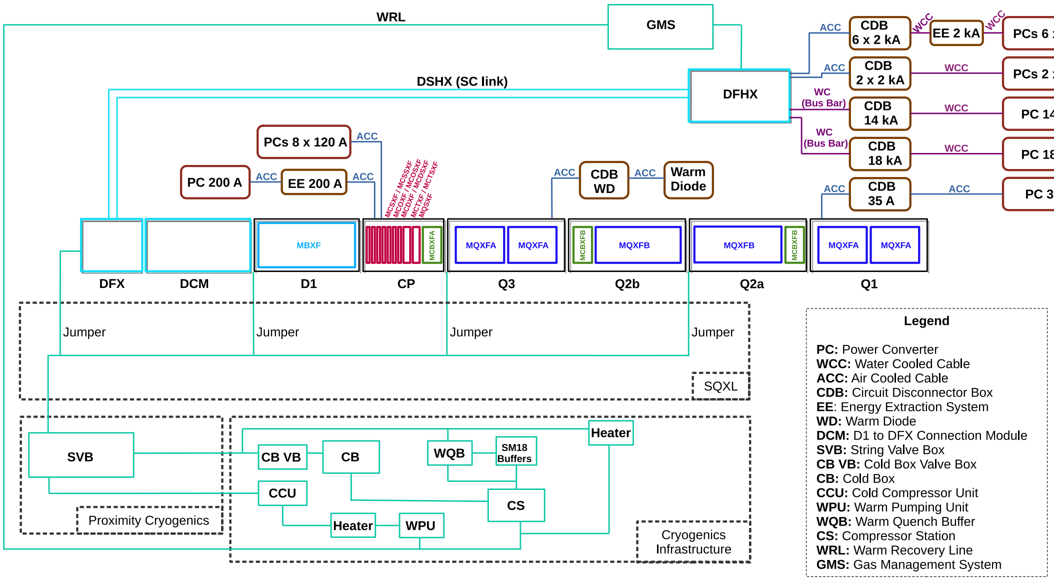

Fig. 1. Systems in the HL-LHC IT String.

III. VALIDATED SYSTEMS IN THE HL-LHC IT STRING EXPERIMENTAL PROGRAM

The core of the HL-LHC IT String experimental program is to validate the powering and the quench protection in addition to the performance of the connected systems. Fig. 1 shows a layout and the connections between the different systems to which the HL-LHC IT String provides a unique opportunity to validate.

A. Superconducting Link System

In the IT String, as in the final configuration of HL-LHC, the magnets will be powered via the ∼70 m long Sc Link composed of a MgB_2 multi-conductor cable operating at 17 K [5]. High-Temperature Superconductor (HTS) Current Leads (CL), located in the DFHX cryogenic feedbox and operating between 50 K and room temperature, connect the Sc Link to the PC. The DFX feedbox includes the MgB2-NbTi joints and connects to the DCM connection module housing the lambda plate and connecting to the magnet chain.

B. Power Converters and Room Temperature Connections

The CL are connected to the new generation HL-LHC PC through normal conducting high-current bus bars, water-cooled cables, and air-cooled cables. New systems, the Circuit Disconnector Boxes (CDB), are installed between the PC and the CL, enabling a fast galvanic disconnection between the magnets and the PC to allow for safe electrical interventions and electrical quality assurance of the superconducting portion.

C. Cryogenic and Vacuum System

As for the HL-LHC, the magnets in the IT String will operate at a nominal temperature of 1.9 K, cooled with superfluid helium. A dedicated cryogenic system and a transfer line (SQXL) are used to directly feed the cryo-assemblies with superfluid helium [8], [9]. The IT String test will also validate the configuration of the insulation vacuum layout of the cryogenic, the Sc Link and the magnet systems comprising few minor differences with respect to the insulation vacuum in the HL-LHC machine. The beam vacuum and beam screens are not included in the HL-LHC IT String.

D. Alignment System

An innovative remote alignment system has been developed for the HL-LHC [10] and will be deployed for validation in the HL-LHC IT String. Precise alignment of the cryo-assemblies will be possible remotely during operation. The new system will monitor the position of the cold masses inside the cryostat, guiding any adjustment through motorized jacks. A hydrostatic levelling system will provide vertical and roll measurements, a wire positioning system determines the radial position. The innovative technology of Frequency Scanning Interferometry (FSI) will provide the longitudinal position of the magnets and

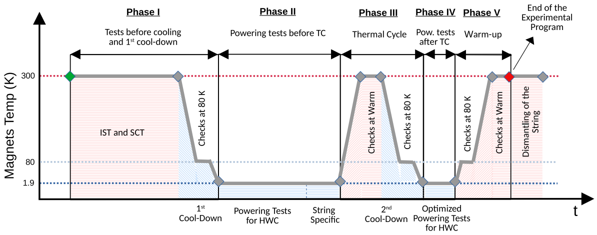

Fig. 2. Phases of the HL-LHC IT String experimental program.

can, together with developed targets that operate under cryogenic conditions, accurately determine the position of the cold mass inside the cryostat.

E. Quench Detection and Protection Systems

The Quench Detection System (QDS) relies on newly developed HL-LHC systems [16]. Upon the detection of a quench of any superconducting element, the quench protection system of the associated magnet is triggered. The quench protection of the IT String will reproduce the nominal HL-LHC protection scheme as described in [11], [12], [13], [14], [15].

IV. HL-LHC IT STRING EXPERIMENTAL PROGRAM

A. General Overview of the Experimental Program

The HL-LHC IT String experimental program is divided into 5 phases as shown on Fig. 2:

- *Phase I:* Tests before cool-down and the first cool-down
- *Phase II:* Powering tests before the thermal cycle
- *Phase III:* Thermal cycle
- *Phase IV:* Powering tests after the thermal cycle
- *Phase V:* Warm-up of the String

The tests in *Phase I* mainly include the IST and the SCT. These tests are part of the HWC phase of the systems and are representative for the tests that will be done in the HL-LHC. During the cool-downs of the magnet chain (in *Phases I and III*) and the last warm-up (*Phase V*), a plateau at 80 K temperature will be imposed to perform electrical quality assurance steps similar to the ones defined for the LHC [17] and validate the magnets' movement through the alignment system. In addition, after every warm-up (*Phases III and V*), a leak tightness validation is performed to ensure that no leaks are generated between the insulation vacuum, the outside environment, and the helium enclosure. After the first cool-down of the magnets, the powering tests (*Phase II*) are divided into two parts: the powering tests for HWC and the String-specific ones.

The powering tests for HWC are required to validate the correct operation of the diverse systems in nominal conditions (as will be done in the HL-LHC). Their sequence and the goals are listed in Table II. These tests are repeated in *Phase IV*, with the experience from the first iteration, and will help to prepare the procedures and the teams at CERN for a smooth and efficient commissioning in the final HL-LHC. String-specific tests are performed with the aim of producing similar conditions as foreseen in the HL-LHC and to be able to deepen the understanding of the magnet circuits' performance. These tests and their goals are listed in Table III.

TABLE II
HL-LHC IT STRING POWERING TEST SEQUENCE AND GOALS FOR HARDWARE COMMISSIONING

Test Name	Test Goal
IST and SCT	Final check of the different systems after installation in the HL-LHC IT String.
Powering Tests of the 120 A HOC	Validate the - PC control loops and precision (including the decoupling control of the RQX and impact of flux jumps), - Energy recovery mechanisms, - N+1 redundancy, - Quench detection and protection, - Performance of the Sc Link system, - Cryogenic system performance, - Movement of the magnets and the interconnections after quench events by the alignment system.
Powering Tests of the RQSX3	
Powering Tests of the RCBX	
Powering Tests of the RD1	
Powering Tests of the RQX	
Powering Tests of Grouped Circuits	Validate the simultaneous powering of the complete circuits of the HL-LHC IT String.

TABLE III
HL-LHC IT STRING-SPECIFIC POWERING TESTS SEQUENCE AND GOALS

Test Name	Test Goal
Bayonet Heat Exchanger Test	Validate the bayonet heat exchanger heat removal capacity (up to 500 W).
Crosstalk Studies	Validate transient effects and electromagnetic coupling in the magnet chain and Sc Link during operation and protective actions (QPS firing).
Operation Powering Cycles	Validate operation cycles intended for the machine (e.g., K-modulation, IT trim powering, tests simulating correctors in beam orbit feedback, etc.).
Flux Jump Measurements	Validate stability of the RQX current control and magnetic field in the presence of flux jumps.
Powering Cycle Endurance Test	Validate the endurance of the HL-LHC IT String systems in terms of powering cycles.
Warm-up Tests of the Cold Powering	Assess the warm-up time of the Sc Link system starting from different initial conditions.

B. Individual System Tests and Short Circuit Tests

The IST are performed after the installation of the individual systems and ancillaries. It applies to the PC, CDB, room temperature cables and bus bars, QDS, EE systems, CLIQ, QH power supplies, cryogenic system, and magnet interconnections. These tests are aimed to verify the dielectrical withstand, signal interface, interlocks and leak tightness of the interconnections. For the cryogenic system, the IST include a cool-down phase down to 1.9 K without magnets, which serves to validate the mechanical and hydraulic performance of the cryogenic installation as well as to tune the control and the interlocking of the system in preparation for the connection to the magnets and the Sc Link. This step was successfully done in the IT String without encountering any significant issues. During the IST, vibration mode measurements will be done on two of the main quadrupole magnets, before and after interconnection, in order to estimate the impact of vibrations on the HL-LHC beam.

Furthermore, the SCT serve as final validation of the warm part (PC, CDB, EE systems, water-cooled and air-cooled cables) before connecting to the cold part (i.e., operating at cryogenic temperature). The SCT include a heat-run test of eight hours until ultimate current ($\sim 8\%$ above the nominal current) to ensure the correct thermal performance of the warm parts.

C. Powering Tests for HWC

The powering tests for HWC are aimed to validate, among other systems, the new generation and high-precision HL-LHC

PC [17] with the nominal parameters. These PC are designed with a modular approach and provide an N+1 redundancy if one of the PC modules fails during operation, increasing the availability of the machine. Moreover, a novel energy storage system is introduced for the RQX that uses the Lithium-Titanium-Oxide (LTO) battery to restore the stored magnet energy as described in [19]. This not only leads to a more energy-efficient system, but also permits the reduced sizing of the PC input power to provide only the losses to the battery and not the full peak power during operation. The coupled nature of the RQX where four PC are acting on the same circuit leads to the necessity of Multi-Input Multi-Output (MIMO) control. For this reason, a decoupling matrix is proposed in the PC controllers to render the MIMO control into the equivalent of four Single-Input Single-Output (SISO) controllers [20]. Furthermore, the Nb_3Sn magnets exhibit flux jumps [21] which could impact the precision and the performance of the RQX control loop. The unique opportunity that the String provides to the commissioning of the RQX control loop is, therefore, considered as a critical milestone allowing for the smooth and efficient implementation in the tunnel after initial debugging at the String facility.

In addition, one of the main goals of the HWC powering tests is to verify the efficiency of the protection systems as a part of the String, and especially in the RQX. The quench protection relies on Quench Heater (QH) strips and the Coupling-Loss Induced Quench (CLIQ) system [22], [23]. The latter is galvanically connected to the magnet and its discharge generates losses in the superconductor, thus rapidly spreading the volume of the quench. If any superconducting element quenches (magnet, Sc Link, CL, or bus bar), the quench protection system is simultaneously activated on all main quadrupole magnets. Cold diodes are added in parallel to the magnets to absorb any transient current during quenches.

The protection of the magnet in RD1 is ensured by QH strips, whereas the protection of the IT orbit correctors and the skew quadrupole corrector relies on EE systems based on electro-mechanical switches operating in vacuum with a capacitor acting as an arc extinguisher. The quench detection scheme of the magnets relies on voltage measurement and comparison between magnet poles for asymmetric quenches. For symmetric quenches of the correctors (RCBX and RQSX3), DC Current Transducers (DCCT) are used to evaluate the dI/dt and re-construct the magnet's quench resistance. For the RQX and RD1, since the DCCTs are costly and more difficult to integrate, alternative solutions are implemented. For the RQX, neighboring magnets are compared together. For the RD1, an absolute threshold on the magnet voltage is imposed. Current-dependent quench detection thresholds and validation times are deployed for the IT quadrupoles to circumvent trips due to flux jumps [21]. The quench detection and protection of the mentioned magnets are validated in stand-alone tests in dedicated test facilities. However, the String provides the first occasion to test the fully integrated system.

For the powering tests, quenches (triggered or natural) are part of the experimental program. Fig. 3 shows the estimated number of this type of events and the associated deposited energy in the helium bath. 390 quench events are estimated for the String experimental program with a deposited energy in the helium bath varying from less than 3 kJ for HOC up to 39 MJ for the combined powering, after which the cryogenic system would require around 8 hours to restore nominal operating conditions. For the circuits with EE, a large part of the magnet energy is deposited in the extraction resistance, whereas the main circuits with QH and CLIQ deposit most of the energy in the helium bath. The impact of the quenches and the different phases of cool-down and powering on the magnet and interconnections alignment will be studied in detail in the IT String.

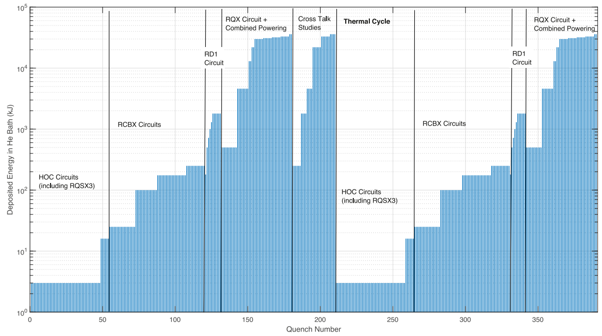

Fig. 3. Deposited energy in the helium bath following a quench in the HL-LHC IT String experimental program.

D. String-Specific Tests

String-specific tests will be performed in the experimental program *Phase II*. Albeit not repeated as dedicated tests in the HL-LHC, these tests permit to gain a deeper understanding for the operation in the HL-LHC. For instance, as described in Table III, as the different magnets are powered through the Sc Link, the crosstalk during the discharges will be studied. The operation powering cycles foreseen for HL-LHC will be also tested to validate the QDS configuration for these operations.

Additional measurements will be done to collect data considered crucial for the operation of the HL-LHC. For example, the flux jumps will be recorded for several ramps of the RQX, and the response and the signals of the power converters will be logged. The performance of the heat exchanger in the magnets to extract the specified 500 W power generated during the ramps of the magnets (mainly the IT main quadrupoles) will be also evaluated during the String-specific tests. The warm-up of the String systems after a simulated failure in the cryogenic systems for a variety of initial conditions will be evaluated in the String-specific tests.

V. CONCLUSION

The experimental program for the HL-LHC IT String has been carefully defined and extensively discussed among various equipment owners prior to receiving approval from the HL-LHC project. The primary objective of these tests is to validate the collective performance of the systems during operation. The test sequence, procedures, and operating conditions were initially designed for the HL-LHC HWC but are now being implemented for the first time in the HL-LHC IT String to verify and optimize their functionality.

In November 2023, the IST in the HWC phase are underway, with the power converters and cryogenic line in place. Notably, the cryogenic line has already successfully undergone its first cool down to 1.9 K. The *Phase I* of the experimental program will be considered complete once all major components have been installed and the magnets cooled. Beyond that stage, it is estimated that the program will span for a total of 12–15 months.

REFERENCES

[1] M. Bajko et al., "HL-LHC IT string: Status and perspectives," in *Proc. LHC Perform. Workshop*, 2023, pp. 1–37.

[2] O. Brüning et al., "High-luminosity large hadron collider (HL-LHC): Technical design report," CERN, Geneva, Switzerland, Tech. Rep. CERN-2020-010, Oct. 2020.

[3] O. Brüning et al., "The HL-LHC project gets ready for its deployment," in *Proc. 13th Int. Part. Accel. Conf.*, 2022, pp. 50–53, doi: 10.18429/JACoW-IPAC2022-MOPOST005.

[4] E. Todesco et al., "The high luminosity LHC interaction region magnets towards series production," *Supercond. Sci. Technol.*, vol. 34, Mar. 2021, Art. no. 053001, doi: 10.1088/1361-6668/abdba4.

[5] J. A. García-Matos et al., "Fine tuning of the inner dipole design of MCBXF magnets," *IEEE Trans. Appl. Supercond.*, vol. 32, no. 6, Sep. 2022, Art. no. 4000405, doi: 10.1109/TASC.2022.3148688.

[6] Ó. Durán et al., "Assembly and power tests of the long orbit nested corrector prototype for HL-LHC," *IEEE Trans. Supercond.*, vol. 30, no. 4, Jun. 2020, Art. no. 4002005.

[7] J. Fleiter and A. Ballarino, "Results of the cold powering tests of the demonstrators of HL-LHC SC-Links," *IEEE Trans. Appl. Supercond.*, vol. 32, no. 4, Jun. 2022, Art. no. 4802905, doi: 10.1109/TASC.2022.3172053.

[8] A. Perin, M. Sisti, S. Claudet, R. van Weelderen, M. Bajko, and F. Dhalla, "The cryogenic system and planned cryogenic tests for the future high luminosity LHC IT magnet string," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, Aug. 2019, Art. no. 0604004, doi: 10.1109/TASC.2019.2905080.

[9] G. Rolando et al., "Functional analysis and design of the cryogenic system for the HL-LHC IT string test bench at CERN," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1240, 2022, Art. no. 012093, doi: 10.1088/1757-899X/1240/1/012093.

[10] A. Herty et al., "HL-LHC full remote alignment study," in *Proc. 10th Int. Part. Accel. Conf.*, 2019, pp. 3716–3719, doi: 10.18429/JACoW-IPAC2019-THPGW057.

[11] D. Wollmann et al., "Machine protection," in *High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report*, Vol. 10. Geneva, Switzerland: CERN Yellow Reports: Monographs, 2020, ch. 7, pp. 153–168.

[12] E. Ravaioli et al., "Quench protection studies for the high luminosity LHC Nb_3Sn quadrupole magnets," *IEEE Trans. Appl. Supercond.*, vol. 31, no. 5, Aug. 2021, Art. no. 4700405, doi: 10.1109/TASC.2021.3055160.

[13] K. Suzuki et al., "Performance of the quench protection heater for the HL-LHC beam separation dipole," *IEEE Trans. Appl. Supercond.*, vol. 30, no. 4, Jun. 2020, Art. no. 4701206, doi: 10.1109/TASC.2020.2971458.

[14] F. Toral et al., "Protection strategy and quench study of MCBXF magnets," *IEEE Trans. Appl. Supercond.*, vol. 32, no. 6, Sep. 2022, Art. no. 4004005, doi: 10.1109/TASC.2022.3159776.

[15] D. Mayr et al., "Simulating quench transients in the self-protected HL-LHC high order corrector magnets," *IEEE Trans. Supercond.*, submitted for publication.

[16] R. Denz, E. de Matteis, A. Siemko, and J. Steckert, "Next generation of quench detection systems for the high-luminosity upgrade of the LHC," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Art. no. 4700204, doi: 10.1109/TASC.2016.2628031.

[17] J. Ludwin et al., "Preparation and execution of the electrical quality assurance program on the LHC superconducting circuits during the second long shutdown," *IEEE Trans. Appl. Supercond.*, vol. 31, no. 5, Aug. 2021, Art. no. 4002404, doi: 10.1109/TASC.2021.3065978.

[18] M. Martino et al., "Warm powering of the superconducting circuits," in *High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report*. Vol. 10. Geneva, Switzerland: CERN Yellow Reports: Monographs, 2020, ch. 6B, pp. 139–151.

[19] E. Coulinge, S. Pittet, and D. Dujic, "Design optimization of two-quadrant high-current low-voltage power supply," *IEEE Trans. Power Electron.*, vol. 35, no. 11, pp. 11602–11611, Nov. 2020, doi: 10.1109/TPEL.2020.2988901.

[20] S. Yammine and H. Thiesen, "Modelling and control of the HL-LHC nested magnet circuits at CERN," in *Proc. 20th Workshop Control Model. Power Electron.*, 2019, pp. 1–6, doi: 10.1109/COMPEL.2019.8769677.

[21] H. Bajas et al., "Cold test results of the LARP HQ Nb_3Sn quadrupole magnet at 1.9 K," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, Jun. 2013, Art. no. 4002606, doi: 10.1109/TASC.2013.2245281.

[22] E. Ravaioli, V. I. Datskov, C. Giloux, G. Kirby, H. H. J. ten Kate, and A. P. Verweij, "New, coupling loss induced, quench protection system for superconducting accelerator magnets," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, Jun. 2014, Art. no. 0500905, doi: 10.1109/TASC.2013.2281223.

[23] E. Ravaioli, "CLIQ. A new quench protection technology for superconducting magnets," Ph.D. dissertation, Univ. Twente, Enschede, The Netherlands, 2015. Accessed: Jun. 19, 2015. [Online]. Available: http://doc.utwente.nl/96069/