Consolidation of the Superconducting Circuits Energy Extraction Systems at the Large Hadron Collider

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***Abstract*—At the beginning of the next long shutdown, foreseen mid 2026, the Large Hadron Collider (LHC) will have been in operation for almost 20 years. After this period, the operation of the present Energy Extraction (EE) systems, that are part of the protection of the superconducting circuits of the LHC, will present significant challenges. As many system components will have exceeded their expected lifetimes, the risks of failure, system degradation, and obsolescence increase, ultimately compromising operational performance and safety. Although preventive maintenance is regularly performed on the EE facilities, an extensive consolidation program of these facilities has started, to improve their dependability and assure their performance till the end of operation of the LHC. This paper illustrates the two projects of consolidation of the 600 A and 13 kA EE systems, which aim to modernize and optimize these systems, ensuring that they continue to provide reliable protection while reducing maintenance costs and integrating the latest advances in materials, control technologies, and diagnostics, together with enhanced safety.**

***Index Terms*—Aging, breakers, DC contactors, energy extraction, lifetime, obsolescence, radiation-tolerant electronics.**

I. INTRODUCTION

AFTER nearly two decades of operation, CERN's Large Hadron Collider (LHC) is entering its final year before undergoing a major upgrade designed to significantly enhance its performance beyond its original specifications. Beginning in mid-2026, and spanning a period of four years, the LHC will go through extensive modifications as it transitions into the High Luminosity LHC (HL-LHC) era [1]. Taking advantage of this extended shutdown, numerous teams at CERN will carry out interventions on their systems to extend equipment lifespan and ensure more reliable operation of the HL-LHC. Among these efforts, the energy extraction systems (EES) for the superconducting circuits will be extensively refurbished or replaced to ensure safe and stable functioning well into the middle of the century. The consolidation of these systems is also the occasion to test new, faster and more reliable method of breaking the circuit current; together with the vacuum-switch-based EES [2], developed in the frame of HL-LHC, they broaden the list of available energy extraction systems to protect superconducting magnets.

II. THE ENERGY EXTRACTION SYSTEMS

During normal operation, the accelerator superconducting magnets store a very high energy in their magnetic field. In case of resistive transition (quench), following the temporary loss of the superconducting state, this energy can potentially cause serious damages to the quenching superconducting magnet. Depending on many factors (among which the value of the stored magnetic energy, the superconducting magnet design and the circuit parameters), the protection scheme may require the installation of an energy extraction system to dissipate externally a large fraction of the magnet's stored energy.

The EES provide a safe and reliable discharge of the energy stored in the magnetic field of the superconducting magnet circuits and prevent damage in their valuable elements (magnets, bus bars, current leads).

When applied as part of the quench protection strategy, the energy extraction system is connected to the terminals of the superconducting circuit (see Fig. 1), in series to the power converters, the magnets and other ancillary equipment, and dumps the energy when requested. Once the opening command is issued, the power converter is switched off and bypassed with its crowbar circuit. The current continues flowing but through the dump resistor and quickly decaying. The presence of snubber capacitors reduces the appearance of arcing on the breaker contacts.

III. THE TWO CLASSES OF EES AT THE LHC

In the jungle of circuit types and current/energy ranges at the LHC, one can distinguish two classes of EES: the 13 kA (protecting the main dipole and quadrupole circuits of the machine) and the 600 A EES (for multipolar correctors), according to the current rating. These are indeed grouping the magnet

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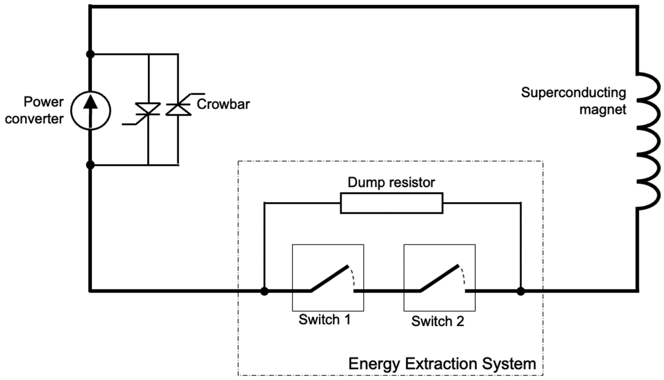


Fig. 1. Generic integration of the energy extraction system into a superconducting circuit.

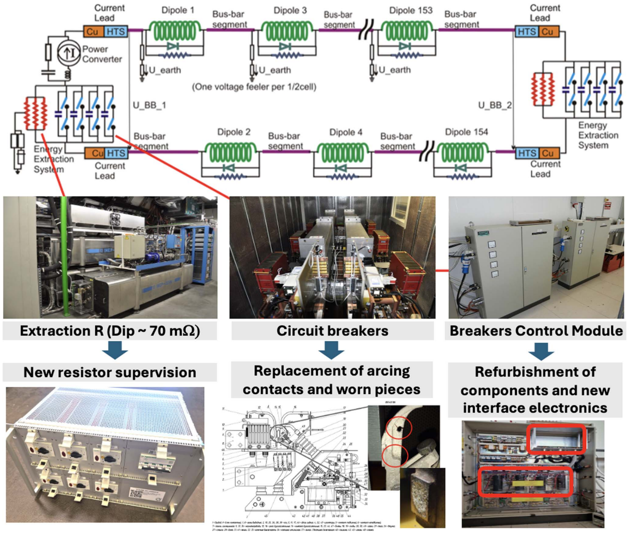


Fig. 2. Schematic view of a 13-kA circuit: the components constituting the EES are shown, with the proposed upgrade. In the case of a main dipole circuit, four parallel sets of two serialized breakers, at each extremity of the circuit, are controlled by BCM and extract energy in three 70-mΩ resistors.

circuits with larger energy on a long loop, and they use different technologies and different topologies.

A. 13 kA EES

In the case of the high current energy extraction systems, the two switches of Fig. 1 are actually two sets of four 4-kA-breakers in parallel, as shown in Fig. 2. They are controlled by two Breaker Control Modules (BCM) sitting nearby. The dump resistors have a 70 mΩ resistance for each main dipole circuit and around 7 mΩ for each main quadrupole circuit, monitored by a basic supervision unit. The EES is present at both ends of the circuit for the dipole lines.

The control electronics consists of several boards managing the digital and analog I/O, which are in use since the early phase of development and installation.

B. 600 A EES

For the low current circuits, three electromagnetic circuit breakers (EMCB) in parallel are assuring the protection redundancy and dumping the circuit energy on an external 700 mΩ resistor (Fig. 3). Two of the breakers (named A and B) are triggered in the event of a quench, while the last one (Z) is only triggered in case of opening failure of the first two. A series of electronic boards is individually triggering the breakers, monitoring their status and supervising the whole system in terms of digital and analog I/O. Two systems are contained in a single rack, with a total of 202 systems around the LHC.

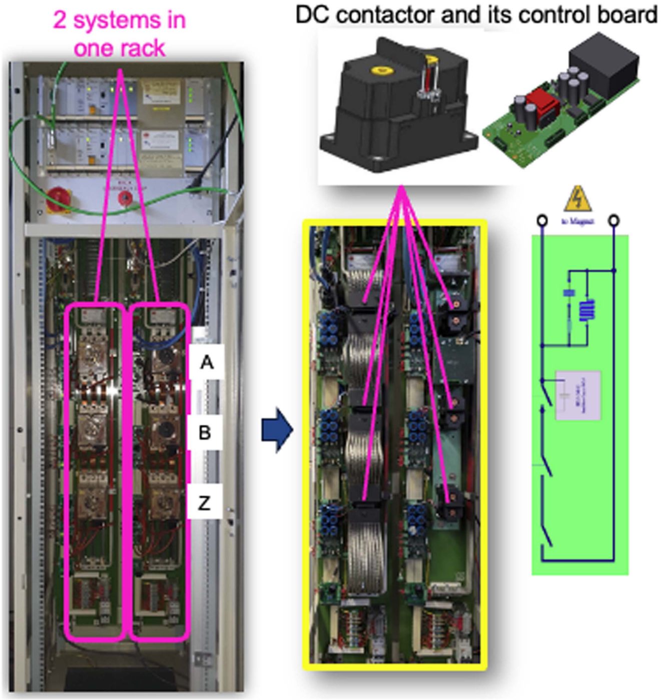


Fig. 3. View of a 600 A EES rack, containing 2 systems: the upgrade with DC contactors is shown, with a 1-to-1 replacement strategy.

IV. LIFETIME AND MAINTENANCE

There are several key factors that play a role in equipment lifetime reduction. Among them, ambient conditions (temperature and humidity), mechanical stress, duty cycle and electromagnetic stresses like surges are the most relevant. On the other side, the maintenance performed on a system can increase its lifespan.

Most high-end scientific facilities like CERN use a hybrid strategy for the maintenance of their equipment. A balanced mix of preventive, predictive and corrective maintenance has been since long time established for the LHC, which foresees periodic stops along the year (either beam stops of few days, or technical stops that last for few months at the end of each year) and use sensors (vibration, temperature, current draw, etc.) or software tools to foresee failures. The corrective maintenance interventions are used only as a backup and not as a strategy.

As the EES of superconducting magnets are critical safety mechanisms in particle accelerators, monitoring their performance and carrying on a continuous maintenance on these systems is not only recommendable but also compulsory.

It is important to say that, thanks to the designed multi-layer redundancy of the EES and their fail-safe mechanism, a viable option could be to operate until failure (privileging corrective actions), but ensuring a high-quality maintenance is vital in establishing an equally high level of system availability and therefore machine uptime.

Both 13 kA and 600 A EES are systematically inspected and maintained during every year end technical stop, when critical components are submitted to rigorous checks and some of them (those that can wear faster) preventively replaced to ensure perfect functioning for the next year run.

A. *Lifetime and Failures*

Searching engineering standards textbooks (e.g., [3], [4]), it appears that the following values have to be taken as a reference for the lifetime of components in the EES:

- Electromagnetic circuit breakers – 10 to 15 years, due to contact erosion, coil fatigue, arc damage;
- Trigger circuits – 10 to 15 years, due to mechanical relay wear, electro-optical aging;
- Control electronics – 10 to 30 years, especially limited by capacitor aging;
- Monitoring/diagnostic PCBs – 10 to 15 years, again limited by capacitor aging, but also affected by thermal cycling.

One would expect that after these time intervals are exceeded, an increased failure rate is observed, in agreement with a classical 'bath-tub curve'. Thanks to the adopted strategy of continuous monitoring and maintenance of these systems, together with big campaigns of consolidation of critical components during the two passed long shutdowns (LSs), the lifetime of the EE systems has been constantly extended. Also, the number of faults observed on the two families of EES has been so far low.

For the 600 A EE, the present statistics of faults includes:

- Electro-mechanical breakers: 86 breakers replaced (most of them preventively);
- Power supplies: 35 replaced (infant mortality, plus failure of the on-board ±15V power supply);
- Electronics chassis exchanges: 8 (some of these were due to collateral damage from the power supply failures)
- Electronics PCBs: 9 cases (4 fast power abort boards, 3 interface cards and 2 communication cards).

For the 13 kA, the list of experienced faults is:

- 2 EMCB replaced (holding coil issue);
- 10 BCMs (important consolidation done in LS2);
- Arcing contacts: ∼15/year due to mini-cracks, 2 broken in operation – all were replaced in 2024;
- Resistor supervision: 2 cases;
- Microswitches: 30-40 cases fixed – all replaced in LS2;
- Ventilators: 3-4 burnt cases;
- PT100: 3-4 cases - all replaced in LS1;
- Thermostats: all replaced in LS1;
- Electronic chassis: 10 full chassis replaced.

B. *Components Obsolescence*

Another critical aspect to consider for the lifetime of an equipment is the obsolescence of components (mostly electronics) that happens when demand for the component drops, or newer, more advanced components become available, or when the materials or technologies needed to produce it are no longer available. This brings with it the inability to repair or maintain existing equipment, resulting in the need for hybrid solutions or re-design of hardware and software.

C. *Radiation to Electronics*

Radiation is playing a key role in determining the lifespan of electronic components. In fact, in some cases, the electronics is sitting just a few meters away from the circulating beam and only partially protected from the radiation associated to it and, in particular, produced by the collision debris.

If the present level of radiation is such that no sensitive effect could be observed on the EES electronics, the increased particle beam luminosity that the HL-LHC project foresees in the two experiments ATLAS and CMS will bring an increase of High Energy Hadrons and thermal neutron fluences (likely causing Single Events Effects on the electronics) and an increase on the Total Ionising Dose (TID), which could produce end-of-life failures on the non-radiation-tolerant equipment. Estimates were drawn [5], which indicate a TID rate of 25 Gy per year in the alcoves where EES are installed, with a cumulative dose till 2041 of nearly 300 Gy.

There are multiple ways of avoiding the non-destructive effects of radiation on the electronics (mainly shielding, relocation or voting logic to enhance reliability and faults tolerance), but the best approach is the design and production of radiation tolerant electronics, which might still be based on COTS, but stress on redundant logics and extensive radiation tests at both components and system levels.

V. CONSOLIDATION PLANS FOR EES

The presently installed EMCB's lifetime will come close to an end before the LS4, planned in 2034; in addition, their maintenance is permanently requiring the intervention of a specialised team to ensure high reliability and availability during the operation period. Therefore, to improve the dependability of these systems till the end of the operation of the LHC, a robust plan of R&D was launched a few years ago, to identify possible candidate for the replacement of those circuit breakers and their control electronics.

The strategy chosen to consolidate the two classes of EES is diametrically opposed. If for the 13 kA circuits, the choice was to concentrate on the replacement of the obsolete electronics and refurbish the breakers, for the 600 A, the priority was to replace the outdated EMCB and reduce the need for maintenance in the future. The development of the new electronics for the 13 kA EES will serve as well the replacement of the electronics for the low current circuits.

A. *13 kA EES Consolidation*

The argument of aging of the mechanical components is not applicable to the 13 kA breakers. In fact, they have been heavily maintained in few occasions and they are constantly undergoing strict verification and replacement of worn components. It is the case for the replacement of the arcing contacts (see Fig. 2) that took place at the end of 2024, because of fissures appearing on the contact body (some of them due to metallic inclusions). Non-conformities were indeed observed in the past, provoked by the severe conditions during the operation of the breakers (high temperature gradient due to the arc created during the current commutation and high mechanical stress when moving). Several prototypes were tested to find a stiffer contact with good magnetic properties to extinguish the arc.

For the 13 kA EES, the stress was put on the electronics, due to its obsolescence and the need for improved radiation tolerance.

For the BCM, most of the components are passive, with an extended lifetime. Focus is on the replacement of the electrolytic capacitors with equivalent models with the same form factor. The only critical electronic part will be deported and integrated in the new electronic chassis under development. Even the resistor supervision does not pose any complexity: the new design contains exclusively passive components (to power resistor fans and monitor their status) and it has already been produced and tested for all units.

B. 600 A EES

In the search for alternative switching elements, hermetically sealed DC contactors were extensively characterized and resulted to be ideal, providing fast opening (≤20ms) and the needed power cycle lifetime of more than 2000 cycles. In addition, the advantages of hermetically sealed contactors are the very low costs in comparison with EMCB or semi-conductors and the absence of preventive maintenance. Extensive testing was performed on several models [6] and one was selected to replace the present EMCB. An ad-hoc contactor control board was designed, to trigger the contactor and monitor its status.

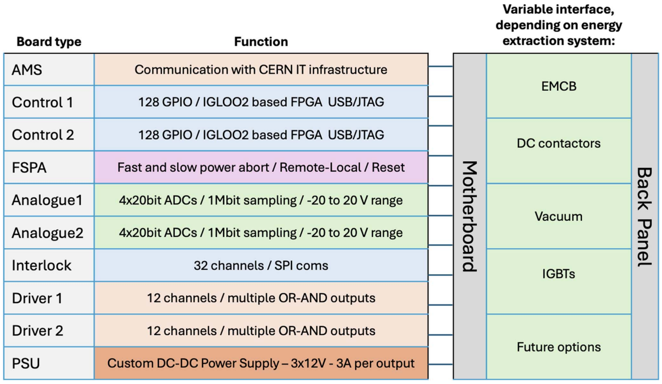
The replacement of all components of the 600 A EES will be done in the tunnel, with the idea of re-using most of the infrastructure and the 1-to-1 replacement of the different parts.

C. The Universal Control Electronics for the EES (UCE3)

Originally born to supersede the obsolete and non-radiation tolerant electronics of the 13 kA EES, the development of a new control electronics was expanded to cover the entire set of EES at CERN. Currently, each EES employs distinct control electronics tailored to its specific system topology, which inherently increases the complexity of production, documentation, inventory management, and maintenance.

To mitigate this problem, common control electronics has been developed, where all electronic chassis are identical, apart for the backplane interface. A sketch of the boards used in this universal electronic solution is shown in Fig. 4 and has been recently presented in [7].

The development of such architecture was started 3 years ago and it was focused to be rad-tolerant by design: components were duly selected for their radiation hardness and the design itself was done to mitigate possible radiation effects. An extensive phase of testing at CERN radiation facilities followed, both at component as well as system level. The project is finally converging to a solution that proved to be extremely tolerant to radiations: preliminary results indicate that the target of 300 Gy is feasible for most of the electronic elements. Additional tests are schedule in 2025 and 2026.



Board type	Function
AMS	Communication with CERN IT infrastructure
Control 1	128 GPIO / IGLOO2 based FPGA USB/JTAG
Control 2	128 GPIO / IGLOO2 based FPGA USB/JTAG
FSPA	Fast and slow power abort / Remote-Local / Reset
Analogue1	4x20bit ADCs / 1Mbit sampling / -20 to 20 V range
Analogue2	4x20bit ADCs / 1Mbit sampling / -20 to 20 V range
Interlock	32 channels / SPI coms
Driver 1	12 channels / multiple OR-AND outputs
Driver 2	12 channels / multiple OR-AND outputs
PSU	Custom DC-DC Power Supply – 3x12V - 3A per output

Fig. 4. Schematic view of the Universal Control Electronics.

All energy extraction systems at the LHC will be equipped with these electronics by the end of LS3. Future system expansion or update are also possible, thanks to the presence of several additional spare channels.

VI. CONCLUSION

The energy extraction systems of the superconducting circuits of the LHC have been in operation for two decades. The reduced number of faults so far experienced is the result of a constant monitoring and a continuous maintenance.The Long Shutdown 3 is the optimal opportunity for an important consolidation of both the 600 A and 13 kA EES. Both consolidation projects were initiated several years ago and benefit from large resources and manpower. They will see the replacement of an important amount of hardware.

Thanks to these important interventions of consolidation, the LHC will be able to run till its planned end of life in 2041 with improved performance of the EES, enhanced monitoring, increased tolerance to radiation and reduced maintenance needs. The use of a new technology for the 600 A energy extraction systems also paves the way for their application in multiple protection domains.

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