Experience with new Energy Extraction Systems and CLIQ in the SM18 test benches and plans

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Spyridon Georgakakis – Electronics design Leader
and
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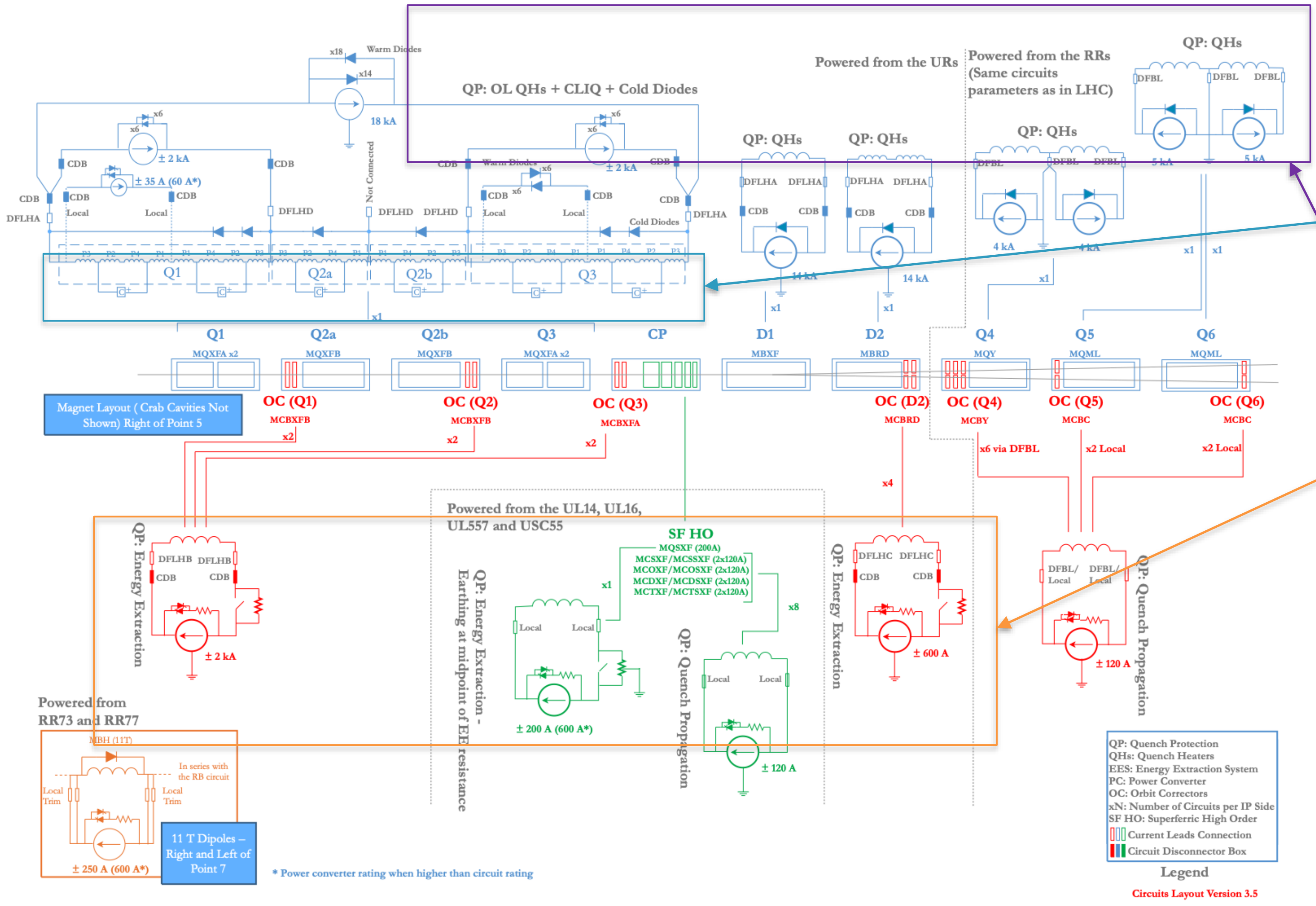
HL-LHC baseline for magnet protection systems



Protection hardware per IP side:

6 CLIQ units

11 Energy Extraction Systems (EES)
- 6 x 2 kA
- 1 x 600 A - single config
- 2 x 600 A - double config

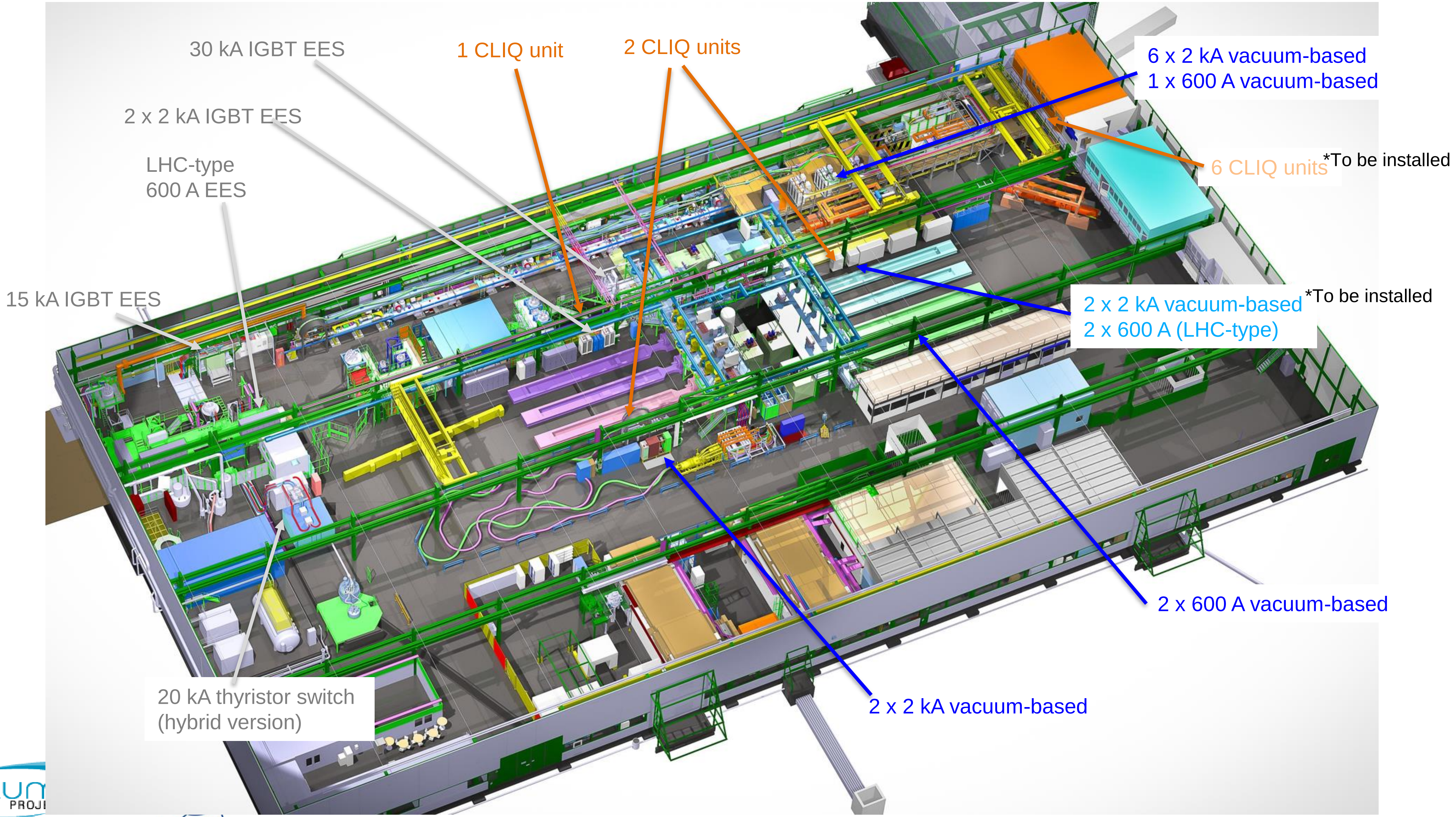
60 Quench Heaters PS (DQHDS)
- 16 for Q1
- 8+8 for Q2a/b
- 16 for Q3
- 4 for D1
- 8 for D2

8 DQLIMs

Outline

- Distribution of HL protection devices in SM18
- CLIQ
  - Project recap and milestones
  - Experience in bldg. 272 and in SM18
  - CLIQ v3
- Vacuum-switches-based Energy Extraction System (EES)
  - Project milestones
  - Overview of the system
  - Experience in bldg. 272 and in SM18
  - New control electronics
  - Safety remarks
- Extra: DQHDS procurement and testing status

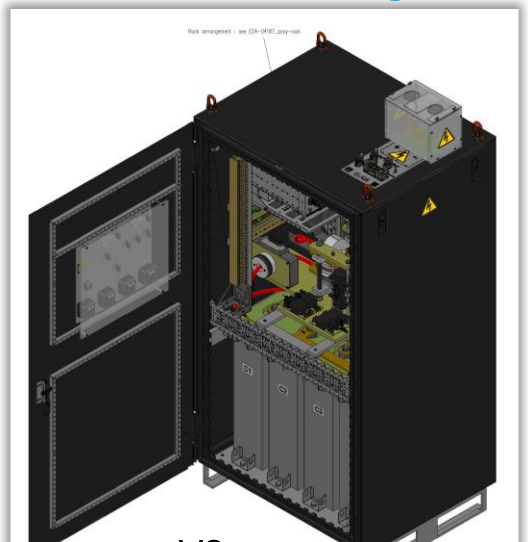
EES and CLIQ(v2) in SM18



CLIQ system – Project recap

V1

V2



V3

CLIQ prototypes timeline

2015 **2017** **2021**

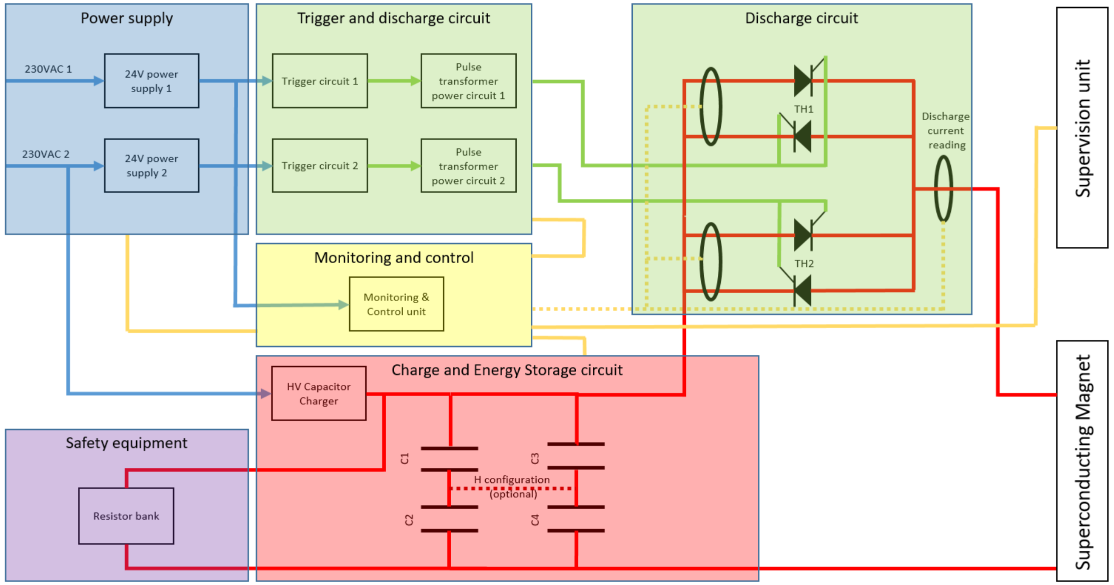
Coupling-Loss Induced Quench (CLIQ) is a quench protection method based on a capacitor discharge resulting in high inter-filament and inter-strand coupling losses.

The core system of CLIQv1, v2 and v3 is the same, so previous prototypes (already used in SM18 and Fermilab) implement the same protection strategy and reliability.

CLIQ v3 main parameters

Redundant 230 VAC power supply
Redundant trigger
Capacitor bank in square configuration (4x40 mF, 1000 V DC)
Monitoring and control unit

Q1 and Q3: 2 CLIQ units each, with V=600 V, 40 mF
Q2a and Q2b: 1 CLIQ unit each, with V=1000 V, 40 mF
I peak ~ 2- 3 kA / f = 10-20 Hz



Project milestones

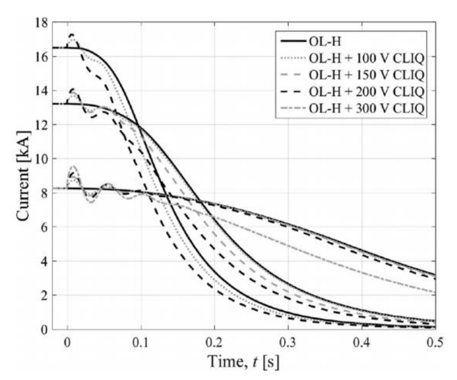
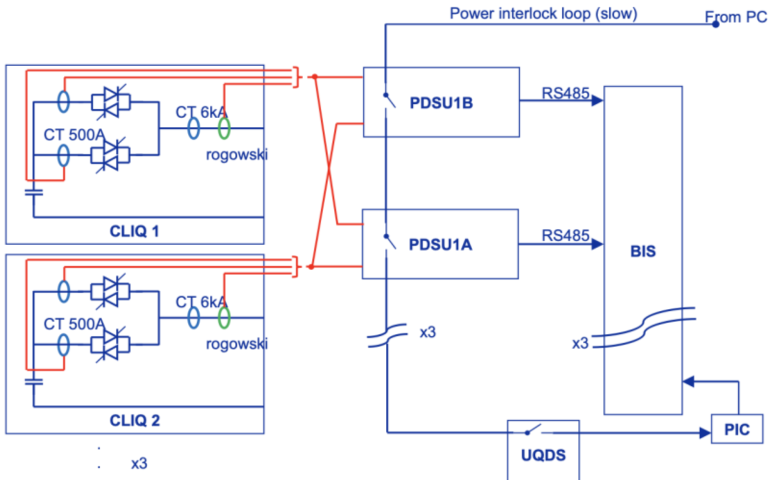


Fig. 4. Comparison between MQXFS1b magnet discharges obtained by triggering outer-layer heaters only, or outer-layer heaters and one CLIQ unit charged to different voltage levels. Measured magnet current I_m versus time.

- Extensive R&D program in SM18 and at Fermilab
- Initial two CLIQ versions fully validated
- Industrialization of CLIQv2 units (11 units manufactured)
- Conceptual Design Review – Apr 2020
- CE marking studies of CLIQv2 – Q4/20
- Market Survey for series production – Q4/20
- Reliability Run with CLIQv2
  - 8000 discharges done on a 2.1 mH/85 mΩ coil – Q2/21
- Invitation to Tender for series production – Q2/21
- Production Readiness Review – Dec 2021
- Immunity campaign on current sensors for spurious triggering detection – Q2/22
  - Improvement of current measurement scheme and direct connection to BIS
- Qualification of CLIQv3 pre-series – Mar 2023
- World-wide shortage of electronic components obliged to redesign most boards
- CE and environmental studies with pre-series unit – Apr 2023
- Green light for production of the String units – Q3/23



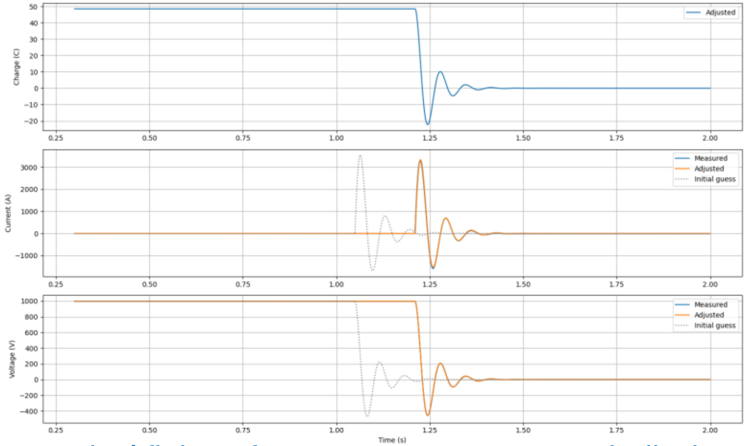
CLIQ reliability run

- Recommended by the panel of the Conceptual Design Review held in April 2020
- 8000 discharges between 2 units were done, to prove the lifetime of the system of 20 years (number of expected CLIQ activations in 20 years is below 200)

✓ No failure was detected on both units in either the power stage nor the control and processing stage

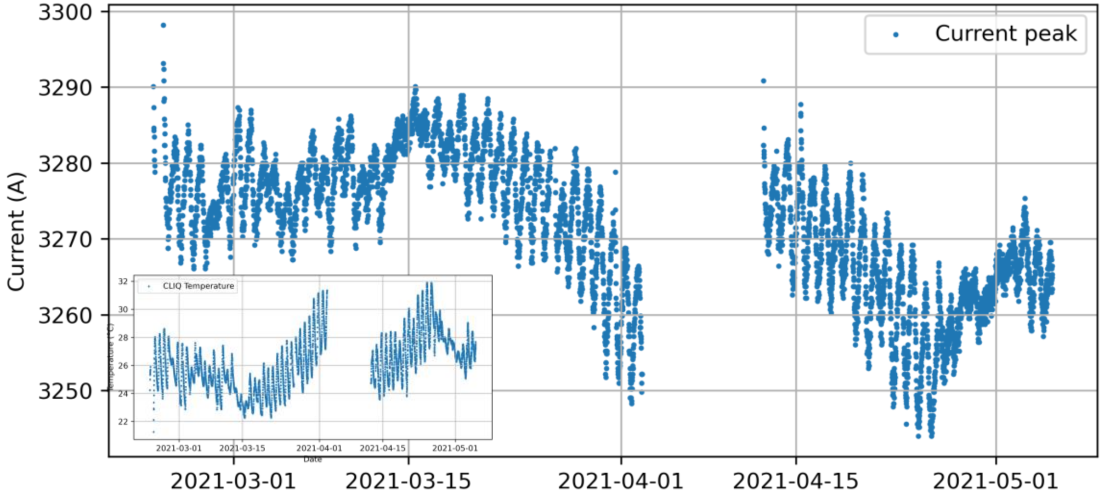
✓ No meaningful variation in resistance and capacitance values

✓ Current and voltage amplitude variations are merely due to ambient temperature

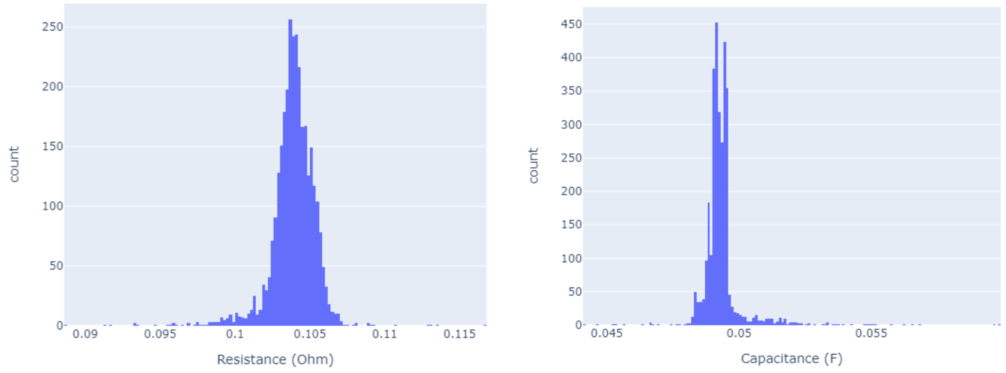


Numerical fitting of RLC components to each discharge

Current first positive peak



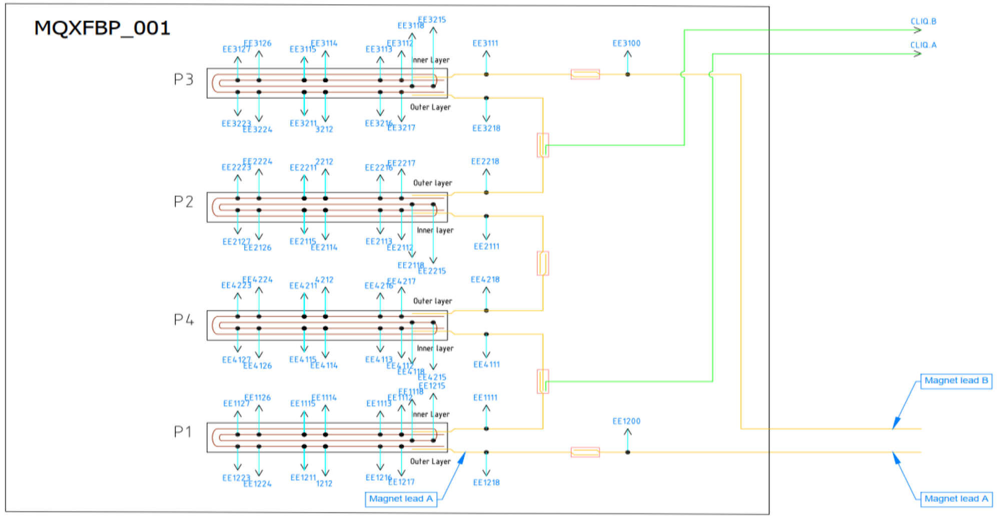
High reliability and no noticeable variations due to aging

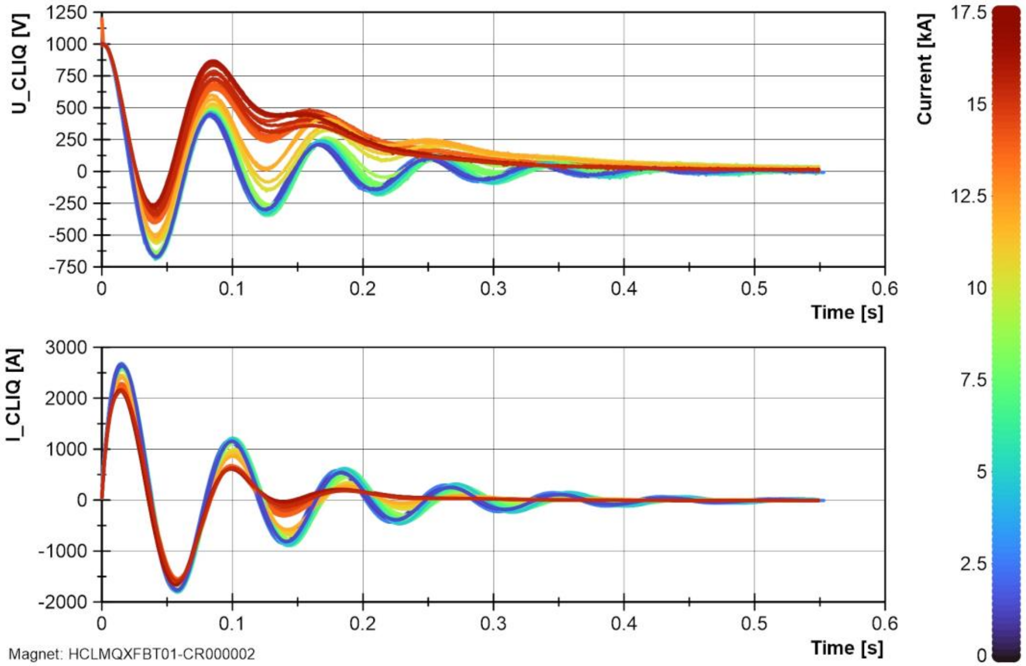


Resistance and capacitance values during the tests

Experience in SM18

- The return of experience from SM18 (and from Fermilab) shows that **CLIQ is a reliable system for the protection of superconducting magnets**. Three units were used in more than 300 tests without problems in SM18:
  - MQXFBP1: 56
  - MQXFBP2: 98
  - MQXFBP3: 31
  - MQXFB02: 61
  - MQXFBMT4: ~25
  - MQXFB03 (ongoing): ~25





Example of voltage and current measurements for all CLIQ discharges on MQXFBP2. *(courtesy of SM18 team)*

CLIQ	In the LHC	On the test bench
Voltage	1000 V	1000 V
Capacitance	40 mF	40 mF
Discharge circuit resistance	50-100 mΩ	TBD
Additional variable resistance	-	TBD if possible
Total circuit resistance	50-100 mΩ	TBD
Peak current	Low current: 2650 A Inom: 2450 A	Low current: 2650 A Inom: 2450 A
First oscillation period	Low current: 78 ms Inom: 82 ms	Low current: 78 ms Inom: 82 ms

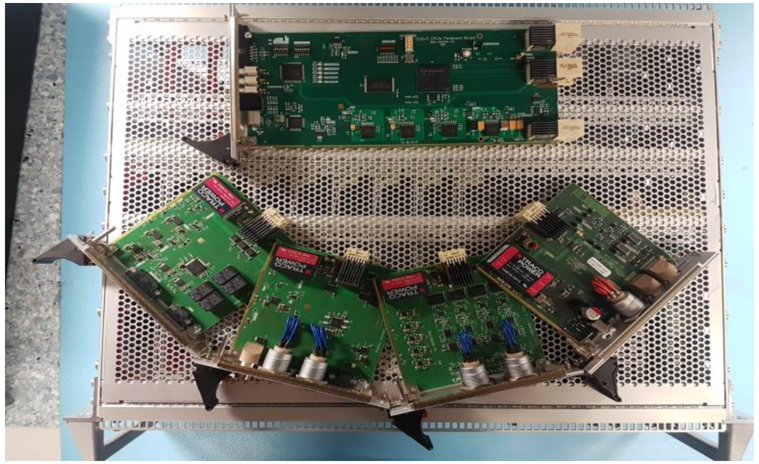
Quench heaters	In the LHC	On the test bench
Voltage	870-960 V	900-940 V
	7.05 mF ±20%	7.1 mF ± 0.2 mF
Strip resistance	4.0 Ω	4.0 Ω
Wire resistance	~0.5 Ω	~0.2 Ω
Additional variable resistance	-	~0.3 Ω (Reostat)
Total circuit resistance	4.5 Ω	~4.5 Ω
Peak current	190-210 A	200 A
Time constant	25-38 ms	32 ms

Quench protection setup (CLIQ and outer layer quench heaters). *(courtesy of SM18 team)*

The failure of 2 chargers was reported along the years (the second one related to a wrong manipulation), but this is not safety critical as only impacts the availability and not the protection. The charger was changed with a more robust model!

CLIQ v3 – machine version

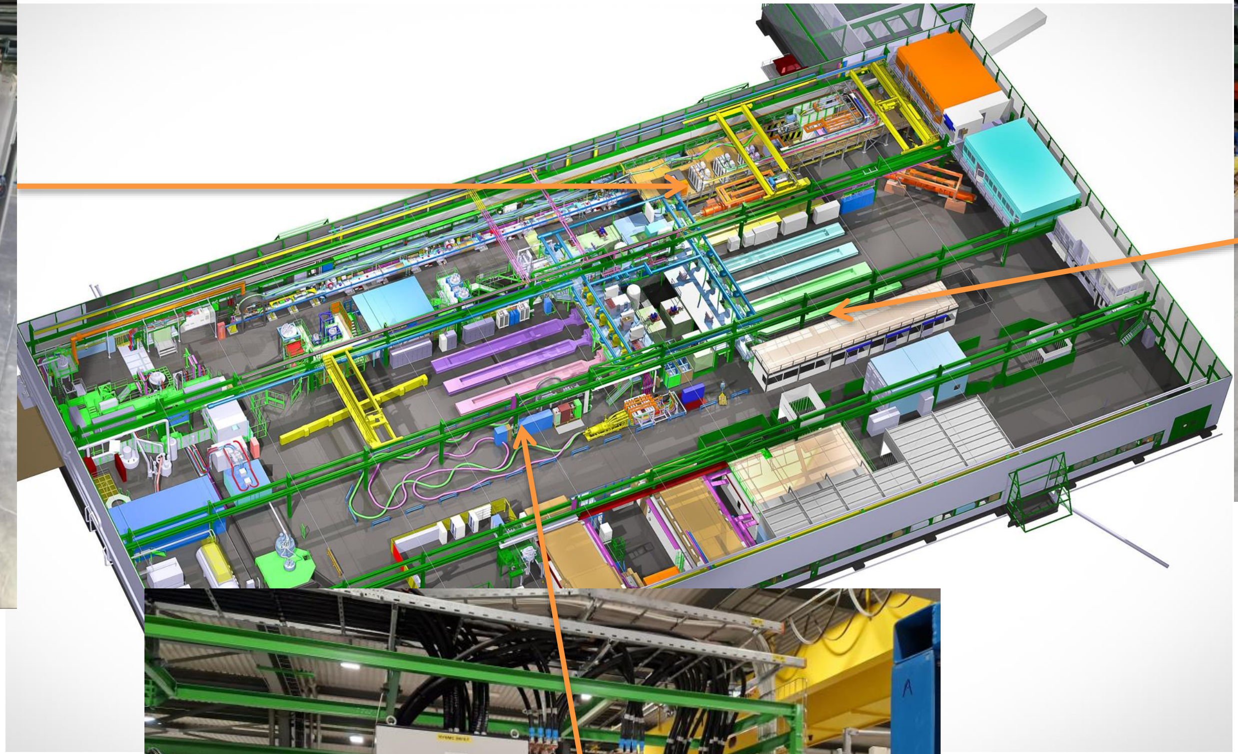
- CLIQ v3 incorporates **several improvements** vs to v2
  - The core of the discharge system is the same
  - v3 has 4 capacitors vs 5 of v2, connected in a more reliable configuration (square configuration instead of parallel connection)
  - Different charger, providing increased robustness
  - Redundant powering and triggering
  - More current sensors for fast spurious triggering detection
  - DI/OT was implemented for an extended diagnostic of the unit and improved reliability

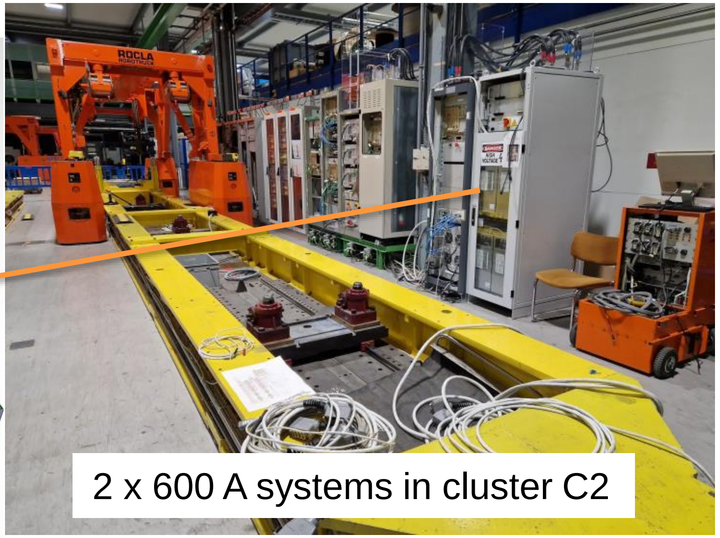


Despite the electronic components crisis, the objective is to deliver the units to the String by the end of this year.

HL-LHC EES in SM18

6 x 2 kA systems in String
+ 1 x 600 A system





2 x 600 A systems in cluster C2

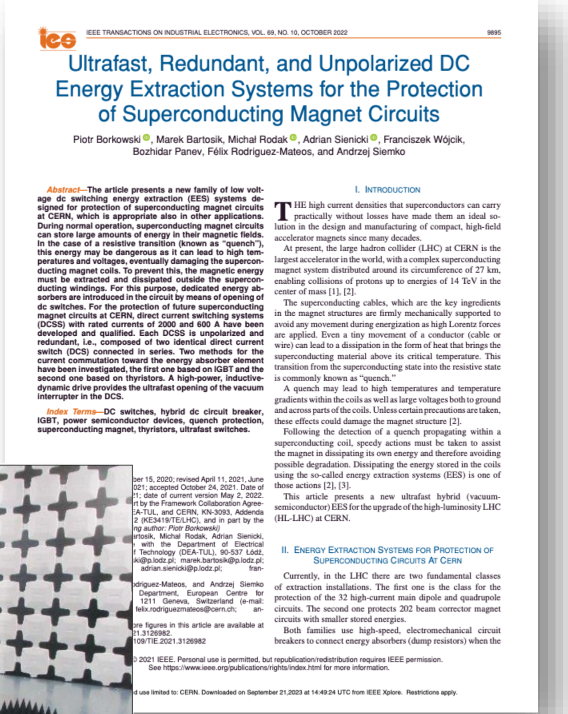
2 x 2 kA systems in cluster F1

In addition:

2 x 2 kA EES will be installed in cluster A2 by Feb 2024

Project milestones

- Start of development of the vacuum-switch-based EES in collaboration with the Lodz University of Technology (Poland) – 2017
- 2 prototypes (2 kA and 600 A) built and successfully tested – 2018
- 8 systems produced and tested in SM18 – 2019
- Implementation of redundancy on the power electronics – 2020
- CE marking studies of the improved version – Q4/20
- Market Survey for the production of the String units – Apr 2021
- Invitation to Tender for the production of the String units – Aug 2021
- Delivery of the first two units for the String – Nov 2022
- Delivery of all units for the String – Jan 2023
- Installation of 6+1 units in the String – Q2/23
- Market Survey for series production re-issued – Mar 2023
- Invitation to Tender for series production – Jul 2023
- Proposal for the attribution of the contract for the series to be presented at the CERN FC on October 4



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Ultrafast, Redundant, and Unpolarized DC Energy Extraction Systems for the Protection of Superconducting Magnet Circuits

Piotr Borkowski, Marek Bartosik, Michał Rodak, Adrian Sienicki, Franciszek Wójcik, Bozhidar Panev, Félix Rodriguez-Mateos, and Andrzej Siemko

Abstract—The article presents a new family of low voltage dc switching energy extraction (EES) systems designed for protection of superconducting magnet circuits at CERN, which is appropriate also in other applications. During normal operation, superconducting magnet circuits can store large amounts of energy in their magnetic fields. In the case of a resistive transition (known as "quench"), this energy may be dangerous as it can lead to high temperatures and voltages, eventually damaging the superconducting magnet coils. To prevent this, the magnetic energy must be extracted and dissipated outside the superconducting windings. For this purpose, dedicated energy absorbers are introduced in the circuit by means of opening of dc switches. For the protection of future superconducting magnet circuits at CERN, direct current switching systems (DCSS) with rated currents of 2000 and 600 A have been developed and qualified. Each DCSS is unpolarized and redundant, i.e., composed of two identical direct current switch (DCS) connected in series. Two methods for the current commutation toward the energy absorber element have been investigated, the first one based on IGBT and the second one based on thyristors. A high-power, inductive-dynamic drive provides the ultrafast opening of the vacuum interrupter in the DCS.

Index Terms—DC switches, hybrid dc circuit breaker, IGBT, power semiconductor devices, quench protection, superconducting magnet, thyristors, ultrafast switches.

ber 15, 2020; revised April 11, 2021, June 021; accepted October 24, 2021. Date of 21; date of current version May 2, 2022. rt by the Framework Collaboration Agree- EA-TUL, and CERN, KN-3093, Addenda 2 (KE3419/TE/LHC), and in part by the ng author: Piotr Borkowski) artosik, Michal Rodak, Adrian Sienicki, with the Department of Electrical f Technology (DEA-TUL), 90-537 Łódź, ki@p.lodz.pl; marek.bartosik@p.lodz.pl; adrian.sienicki@p.lodz.pl; fran- odriguez-Mateos, and Andrzej Siemko Department, European Centre for 1211 Geneva, Switzerland (e-mail: felix.rodriguezmateos@cern.ch; an- ore figures in this article are available at 21.3126982. 109/TIE.2021.3126982

I. INTRODUCTION

THE high current densities that superconductors can carry practically without losses have made them an ideal solution in the design and manufacturing of compact, high-field accelerator magnets since many decades.

At present, the large hadron collider (LHC) at CERN is the largest accelerator in the world, with a complex superconducting magnet system distributed around its circumference of 27 km, enabling collisions of protons up to energies of 14 TeV in the center of mass [1], [2].

The superconducting cables, which are the key ingredients in the magnet structures are firmly mechanically supported to avoid any movement during energization as high Lorentz forces are applied. Even a tiny movement of a conductor (cable or wire) can lead to a dissipation in the form of heat that brings the superconducting material above its critical temperature. This transition from the superconducting state into the resistive state is commonly known as "quench."

A quench may lead to high temperatures and temperature gradients within the coils as well as large voltages both to ground and across parts of the coils. Unless certain precautions are taken, these effects could damage the magnet structure [2].

Following the detection of a quench propagating within a superconducting coil, speedy actions must be taken to assist the magnet in dissipating its own energy and therefore avoiding possible degradation. Dissipating the energy stored in the coils using the so-called energy extraction systems (EES) is one of those actions [2], [3].

This article presents a new ultrafast hybrid (vacuum-semiconductor) EES for the upgrade of the high-luminosity LHC (HL-LHC) at CERN.

II. ENERGY EXTRACTION SYSTEMS FOR PROTECTION OF SUPERCONDUCTING CIRCUITS AT CERN

Currently, in the LHC there are two fundamental classes of extraction installations. The first one is the class for the protection of the 32 high-current main dipole and quadrupole circuits. The second one protects 202 beam corrector magnet circuits with smaller stored energies.

Both families use high-speed, electromechanical circuit breakers to connect energy absorbers (dump resistors) when the

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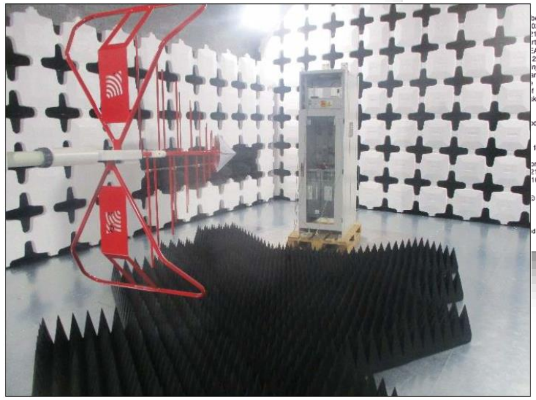


HL-LHC EE systems - overview

Power IO terminals

New development ongoing (see later)

Dump resistors

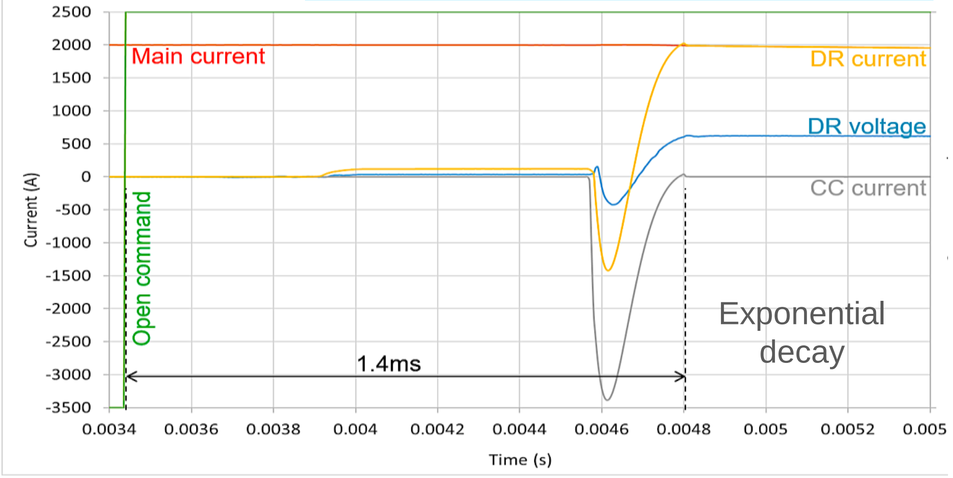
Switch cassette

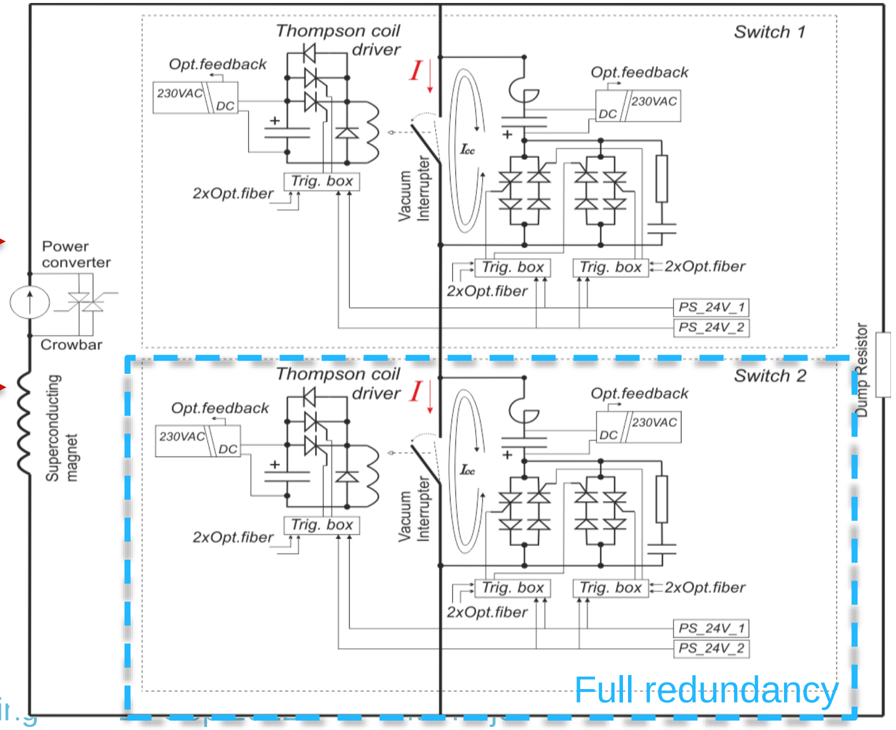
Standard EURO rack (60x90x200)

Vacuum interrupter

Auxiliary circuits

Opening sequence of the 2 kA EES





Open command

IDD opens vacuum contact — 450 us

Arc ignition

700 us

Trigger CC1

250 us

Trigger CC2

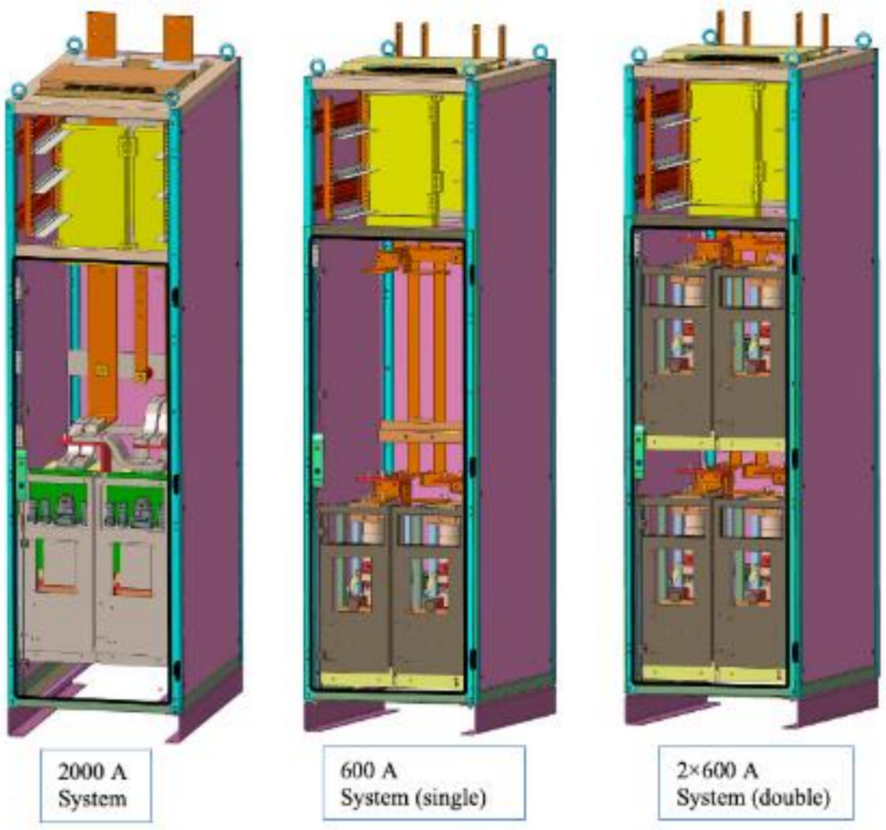
200 us

Exp decay

* IDD = Inductive dynamic driver   CC = Counter-current

HL-LHC EE systems – main parameters

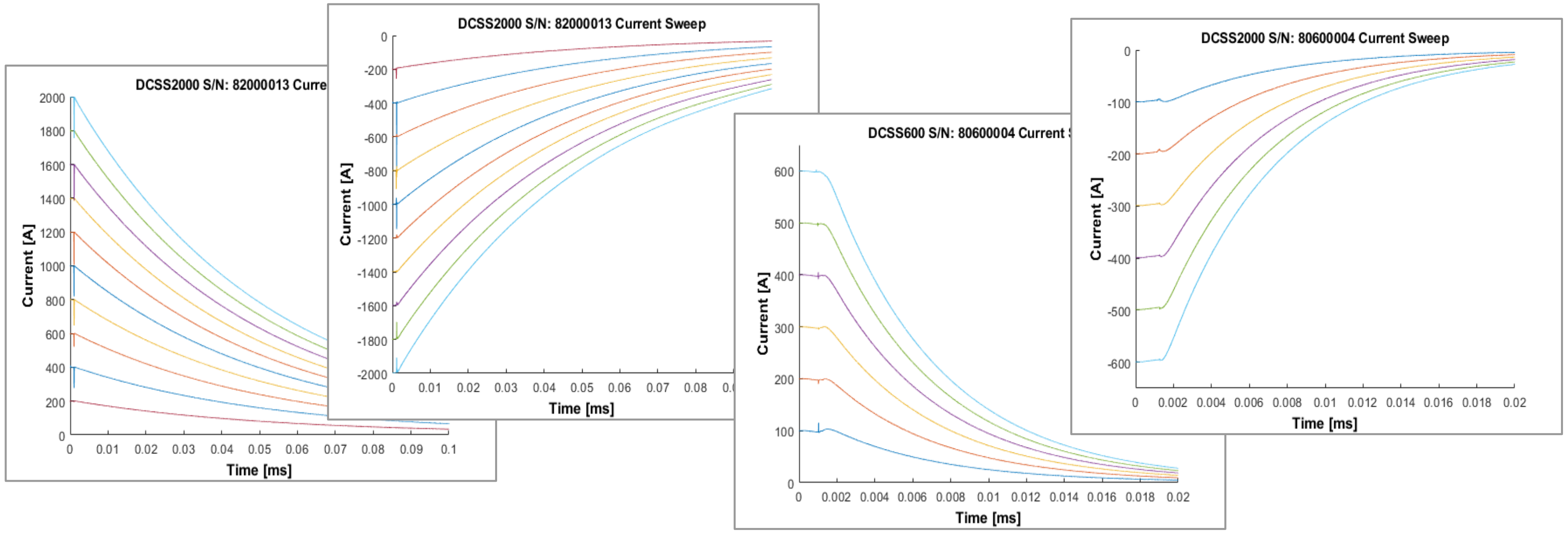
- Two industrial bipolar vacuum switches for 2 kA / 600 A connected in series
- The opening sequence can be initiated by
  - sending an open command (locally or remotely)
  - by rupturing the FPA loop
- Max. rated voltage: 1 kV
- Dump resistors
  - 0.15 Ω for 2 kA systems
  - 1.4 Ω for 600 A systems
- Switch opening time: < 2 ms
- Mechanical cycles: > 20 000 cycles
- Opening at nominal current: > 10 000 cycles
- **Maintenance-free** operation
- Standard Euro rack (900/600/2000) mm
- **Full redundancy** ensured at power and control parts

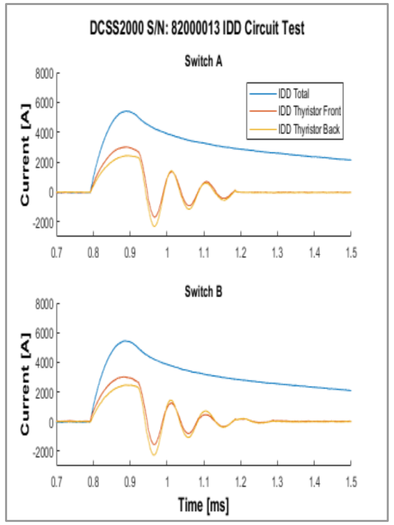


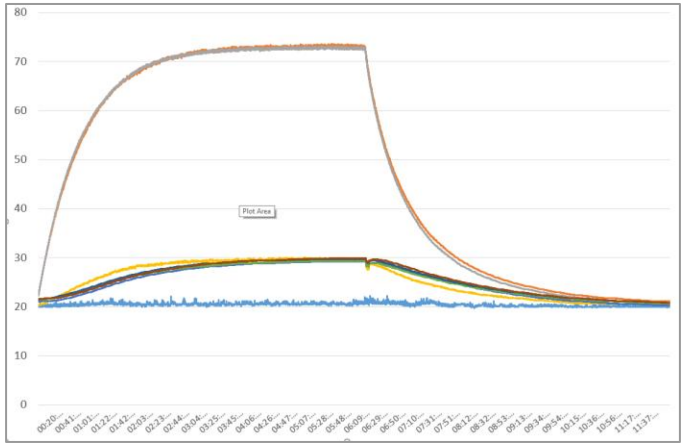
Bld.272 validation tests

Before their installation in SM18, all units are thoroughly tested in the test area in bldg 272 with plenty of discharges on a 10 mH load. Heat runs to validate the thermal performance are also done.

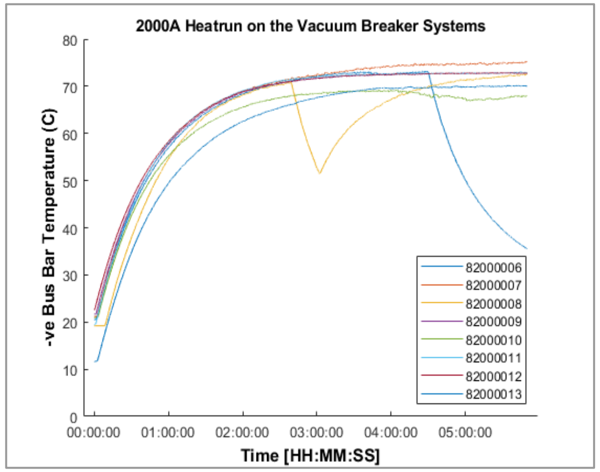
Test setup







8 hours heat run

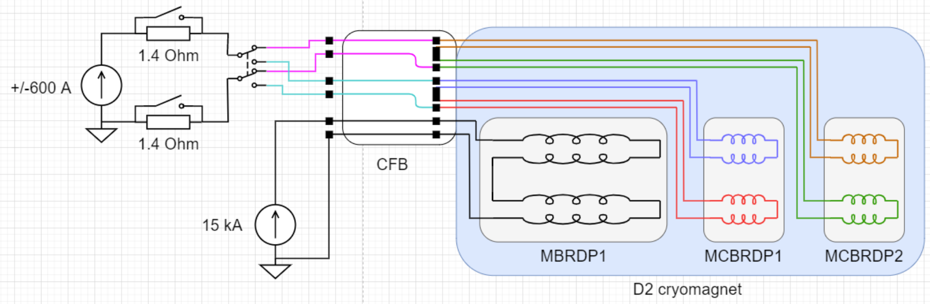


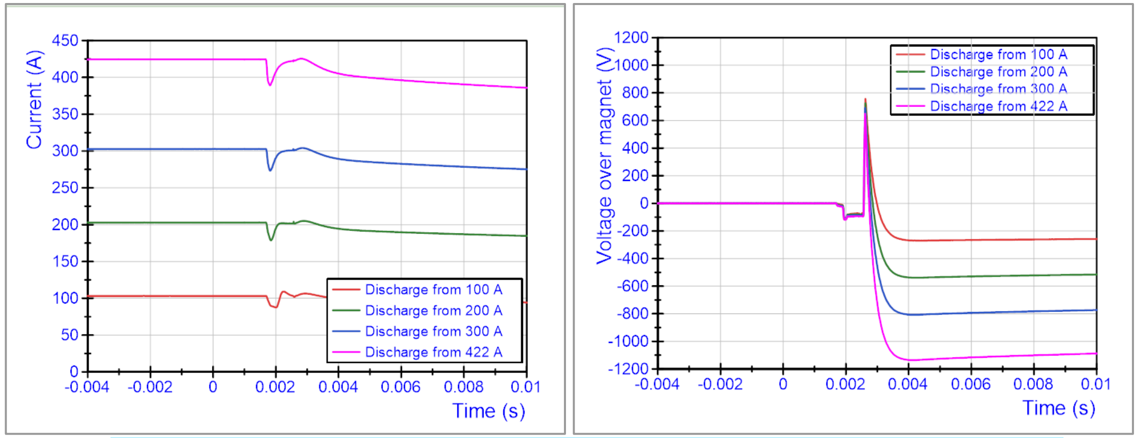
All EE systems max. temperatures

Thermocouples installation

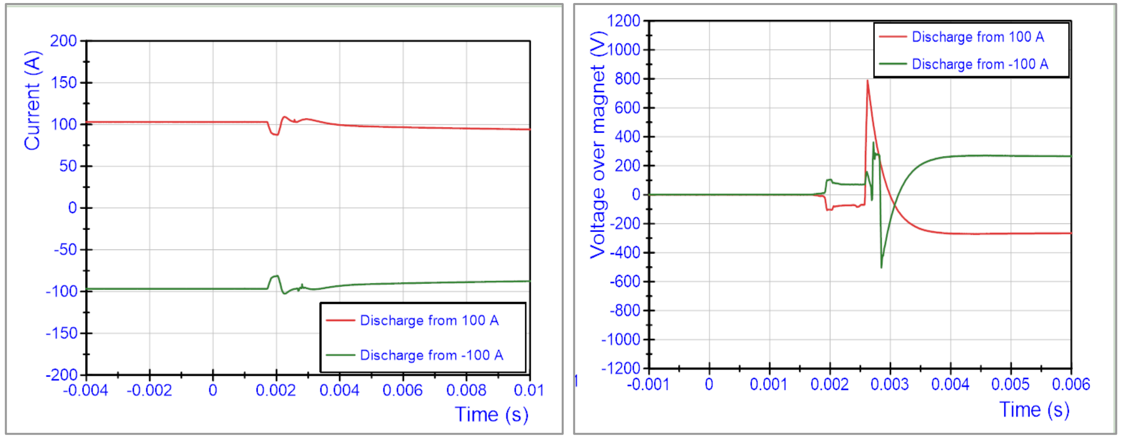
Experience with the test in SM18

- This new technology was tested on a small number of magnets in SM18. Nonetheless, it is based on a **conventional protection mechanisms, industrial breakers and an improved redundancy that guarantee a solid and reliable operation**.
- Extensive tests, with few hundred openings at 2 kA, were done in SM18 in 2019 with a prototype system on the vertical test bench with an MCBXF magnet. Up to 20 000 cycles were also done in LUT-Poland. The test results showed the excellent performance of this system with no failure.
- Recently, the new vacuum switch system with the 600 A circuit was used in the D2 prototype to protect the MCBRD magnets on test bench C2 and the system is still installed for the series magnets (between 20 and 100 discharges done up to now).





Current and voltage on the magnet during extractions at different current levels *(courtesy of G. Willering).*

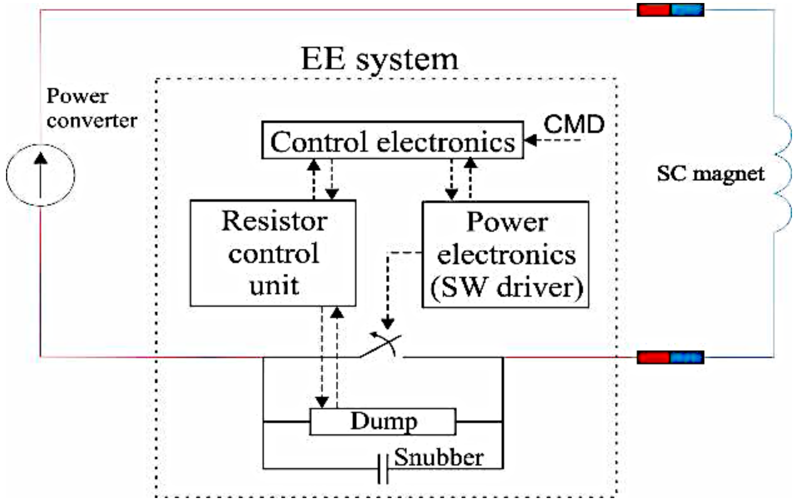


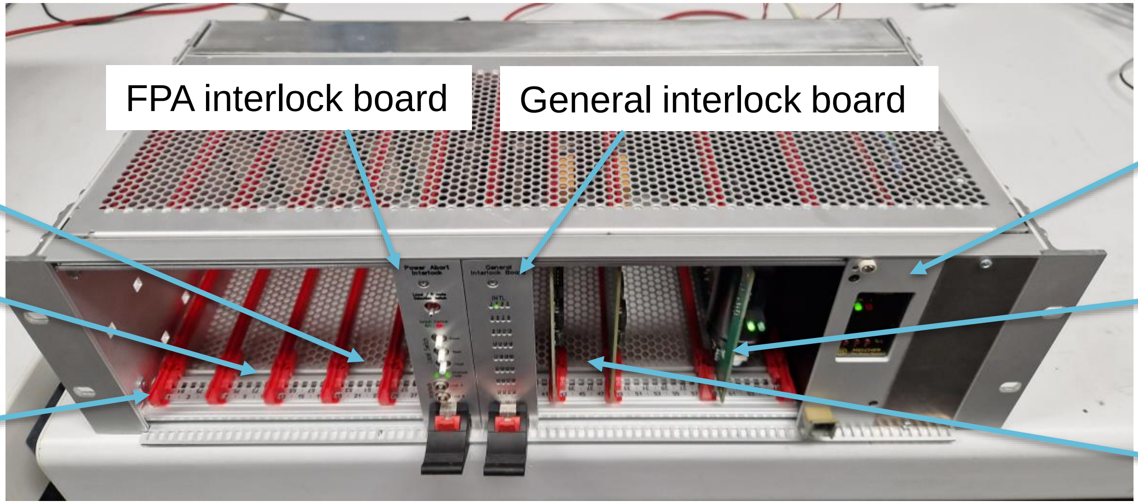
Comparison of current and voltage on the magnet during extractions at 2 different polarities *(courtesy of G. Willering).*

Tests will start soon on test bench F1, where two 2 kA EES are installed and ready for operation.

New control electronics for EES

- An additional improvement on the vacuum-switch-based EES is under development and it is planned to be tested and validated by the end of the year.
- It foresees the complete separation of control an power electronics, with the implementation of a design developed by B. Panev and S. Georgakakis.
- All boards are ordered (part of them already tested) and two cassettes of an EES system are being modified to comply with this new electronics.
- The String is ready to use the old electronics, but the new one could be retrofitted as soon as the qualifications tests are completed.





Safety remark

- HL will be the first case in the LHC when an active source of high voltage/current (other than the power converter) will be connected to the main magnet circuits.
  - For CLIQ: 40 mH, 1000 V capacitors (20 kJ stored)
  - For EES: 530 V, 57J pulse stored energy

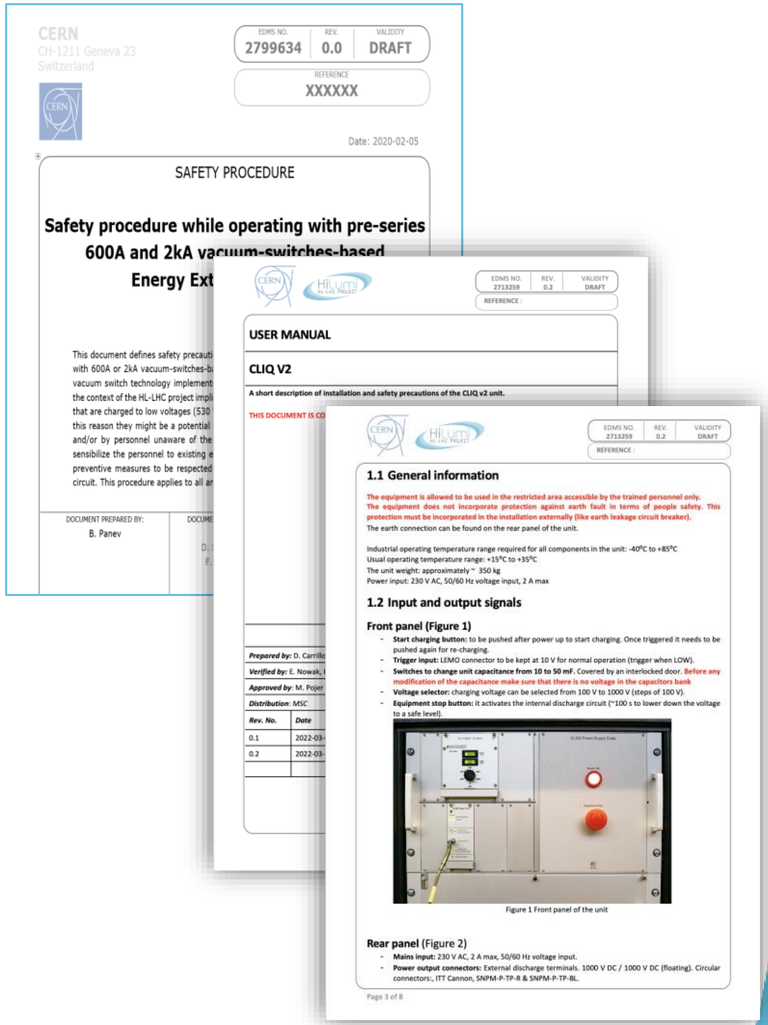
- Therefore, the consequences at the level of personnel and equipment safety are important.

  Personnel
  - Both equipment types must be locked-out before any intervention on the live parts of the circuit!

  Equipment
  - 2kA EE incompatible with PC in absence of inductive load: in case of a trigger, a 530 V surge could destroy the PC diodes.

- In addition, for CLIQv2, differently from the machine unit, the capacitance value of can be changed by using the mechanical switches behind the front panel. Opening the door to the capacitance selector will automatically disconnect the power supply and activate the internal discharge of the unit.
- The internal discharge of the unit takes nevertheless approximately 100 s.

- Detailed procedure were written to illustrate these risks.



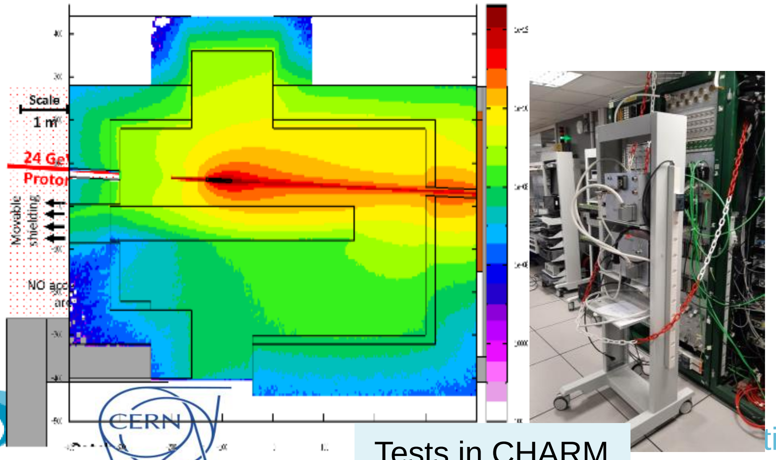
Following the CE marking studies and subsequent fixing of minor recommendations, CLIQv2 and v3 and the vacuum-switch-based EES are compliant with the CE standards of safety!

DQHDS procurement and testing status

- 52 units + 8 spare for the String were produced at CERN and are ready to be tested.
  - Automatic tester almost operational.
- The series production has been secured with an in-kind contribution from Japan, through KEK
  - Issues of yearly budget activation
  - Extremely good collaboration with KEK.
- Irradiation tests in CHARM proved that the units could operate up to an integrated dose of 350 Gy:
  - In the two irradiated crates, the failing component was the thyristor
  - The expected total maximum dose will be around 100 Gy for HL units.

- The 7 + 2 spare DQLIM units for the String are produced and ready to test as well.

DQHDS production at CERN



Tests in CHARM

DQLIM units


Automatic tester

Concluding remarks

- CLIQ and the vacuum-switch-based EES have demonstrated to be reliable elements of the protection system.
  - CLIQ units are systematically used in SM18 and a big statistics has already been cumulated
  - The EES have proven their performance, but a big step will be done with the test of the magnets in test benches F1 and A2 in the coming months.
- After many problems related to the global market, the production of the CLIQ units for the String is assured and they should soon be at CERN for validation.
- The EE systems are already installed in the String and ready for commissioning.
- The String will be the most important verification of all protection system in a real machine configuration.
- New safety requirements will be needed in the LHC when the systems are operated.

Thanks for the attention!

Questions?