Quench Protection Analysis of 20 T Hybrid Accelerator Dipole Magnets

E. Ravaioli, G. Ambrosio, D. Araujo, M. D'Addazio, P. Ferracin, R. Gupta, V. Marinozzi, E. Rochepault, G. Vallone, A. Verweij, M. Wozniak, A. Zlobin

***Abstract*—The US Magnet Development Program is leading an effort to design and manufacture a 20 T accelerator dipole magnet. Various designs are under development featuring cos-theta, block-coil, or common-coil geometries. To achieve the target field while maintaining cost-effectiveness the magnet cross-section includes high-temperature superconductor (HTS) inner coils and Nb_3Sn outer coils, which are all powered in series. The quench protection of this class of high-field accelerator magnets is extremely challenging due to the high energy density, high current density, slow quench propagation, in particular in the HTS coils, and highly inhomogeneous thermal properties of HTS and Nb_3Sn coils. The magnet quench discharge is simulated with the STEAM-LEDET program as coupled electro-magnetic and thermal transients. The peak temperature and voltage to ground in the magnet coils during the transient are presented. The performance of a CLIQ-based quench protection system applied to 1 m long model magnets in terms of peak temperature and voltage to ground is investigated. Furthermore, the scalability of the proposed solution to full-scale, 15 m long magnets is discussed.**

***Index Terms*—accelerator magnet, CLIQ, magnet design, quench protection, simulation, superconducting coil.**

I. Introduction

ACCELERATOR magnets targeting a bore magnetic field of 20 T are under development by a design study group led by the US Magnet Development Program [1]–[3]. Reaching this field level in a compact magnet requires the use of high-temperature superconductors (HTS), such as Bi-2212 [4] or REBCO [5], which are characterized by significantly higher critical magnetic field with respect to low-temperature superconductors (LTS), such as Nb_3Sn.

Hybrid magnets composed of HTS and LTS coils powered in series are a promising option. A main advantage of the hybrid solution is the use of a less expensive superconductor, i.e. Nb_3Sn, in the coil windings that are located in lower field regions. Conversely, an important drawback of a hybrid design is the need to operate the magnet at temperatures below 4.5 K, which requires the use of helium as a coolant and hence higher cooling power.

In this contribution, the quench protection of three 20 T hybrid magnet designs with different geometries, namely block-coil (BC), common-coil (CC), and cos-θ (CT), are studied. The three magnets under study, whose main parameters are summarized in Table I [3], are designed to generate a magnetic field of 20 T in a circular bore with a 50 mm diameter when powered at a temperature of 1.9 K. Their cross-sections are shown later in Section II. The BC and CT designs only include one aperture, while the CC design comprises two apertures whose centers are 400 mm apart. The Nb_3Sn layers of the CC and CT designs are graded, i.e. different conductors are used in the different layers. The conductor parameters that are most relevant for quench protection are summarized in Table II.

TABLE I
Main Parameters of the Three 20 T Magnet Designs [3]

	Block-Coil	Common-Coil	Cos-θ
Bore magnetic field [T]	20.0	20.0	20.0
Bore diameter [mm]	50	50	50
Operating temperature [K]	1.9	1.9	1.9
Operating current, I_{nom} [A]	10275	14380	11584
Margin, $I_{\mathrm{nom}}/I_{\mathrm{ss}}$ [-]	86%	87%	84%
Self-inductance at I_{nom} [mH/m]	102	58	84
Stored energy at I_{nom} [MJ/m]	5.8	6.8	6.2
Number of turns per quadrant [-]	266	144	217

Protecting these magnets from the potentially damaging consequences of a quench is particularly challenging due to the high energy density, high current density, slow propagation velocity, in particular in the HTS coils, and highly inhomogeneous thermal properties of HTS and Nb_3Sn coils [6]. It is proposed to design the magnet and its protection system such that the magnet's stored energy is mostly deposited in the LTS windings, which are easier to transfer to the normal-conducting state. An active heating protection system based on the Coupling-Loss Induced Quench (CLIQ) method [7], [8] is selected due to its fast and effective heating mechanism relying on transient losses [9]–[11].

The quench protection of 1 m long short models, without relying on energy extraction, is analyzed for the three different designs. Furthermore, the protection performance in the case of full-scale, 2 aperture magnets is investigated.

II. Quench Protection of Short Model Magnets

The electro-magnetic and thermal transients following a quench in the magnets are simulated with the STEAM-LEDET program [12], [13], which allows multiphysics transient simulations including thermal diffusion in the coil windings, ohmic loss, and inter-filament [9], [10] and inter-strand coupling losses [11]. LEDET was validated against

E. Ravaioli, A. Verweij, and M. Wozniak are with CERN, Geneva, CH (e-mail: Emmanuele.Ravaioli@cern.ch). R. Gupta is with BNL, Upton, NY. E. Rochepault is with IRFU, CEA, Université Paris-Saclay, France. G. Ambrosio, V. Marinozzi, and A. Zlobin are with FNAL, Batavia, IL. P. Ferracin and G. Vallone are with LBNL, Berkeley, CA. M. D'Addazio is with LBNL, Berkeley, CA and with the Politecnico di Torino, Turin, Italy. D. Araujo is with PSI, Villigen, CH.

Manuscript received September 2024.

TABLE II
MAIN CONDUCTOR PARAMETERS FOR THE THREE MAGNET DESIGNS [3]

Parameter	Block-coil		Common-coil			Cos-θ		
	L1-L6	L7-L12	L1-L3	L4	L5-L6	L1-L2	L3-L4	L5-L6
Superconductor/Stabilizer	Bi-2212/Ag	Nb_3Sn/Cu	Bi-2212/Ag	Nb_3Sn/Cu	Nb_3Sn/Cu	Bi-2212/Ag	Nb_3Sn/Cu	Nb_3Sn/Cu
Number of strands [-]	28	24	43	34	34	32	50	50
Strand diameter [mm]	1.00	1.13	0.85	0.90	0.90	0.90	0.80	0.70
Cu/noCu or Ag/noAg ratio [-]	4.00	1.15	4.00	1.80	2.50	4.00	0.90	2.00
Cable width [mm]	14.70	14.70	19.73	16.15	16.15	14.87	22.16	19.39
Cable average thickness [mm]	1.80	2.03	1.52	1.60	1.60	1.70	1.52	1.33
Insulation thickness [mm]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Conductor current density [A/mm^2]	467	427	589	665	665	569	461	602
Peak magnetic field at I_{op} [T]	20.83	16.05	20.60	13.16	11.82	20.46	16.12	13.06

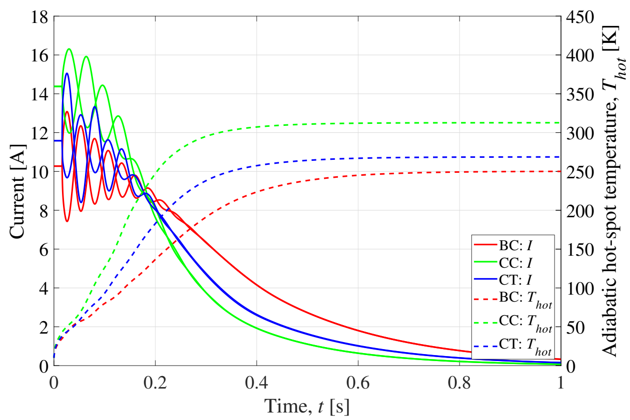

Fig. 1. Simulation of the transient following a quench at nominal current in 1 m long, 20 T magnets. Currents in the coil sections and adiabatic hot-spot temperature versus time.

TABLE III
MAIN QUENCH PROTECTION RESULTS FOR 1-M LONG MAGNETS

	Block-Coil	Common-Coil	Cos-θ
Hot-spot temperature [K]	250	313	269
Peak voltage to ground [V]	762	501	537
Peak CLIQ current [kA]	5.7	4.3	5.4
$t_{\mathrm{q},10\%}$ [ms]	1.4	1.5	1.0
$t_{\mathrm{q},90\%}$ [ms]	11.3	7.9	5.1

experimental results collected while testing Nb_3Sn and Nb-Ti magnets [14]–[19].

For each magnet design, the case of a quench occurring at t=0 at the nominal current I_{nom} [A] in a 1 m long magnet is presented. The time required for quench detection, validation, and protection triggering is assumed to be 16 ms, both in the case of a quench in the LTS or HTS conductor. Each magnet is protected by discharging one 50 mF, 1 kV CLIQ unit connected to two magnet coil locations via dedicated current leads. The simulated currents are shown in Fig. 1.

Upon CLIQ triggering, the currents I [A] of the magnet coil sections are subject to fast changes with opposite polarities. As a result, high magnetic-field change is generated in the superconductor, which results in high transient losses. In turn, this causes very fast quench initiation in the Nb_3Sn windings. As can be observed in Table III, the time to quench 10% and 90% of the Nb_3Sn windings ($t_{\mathrm{q},10\%}$, $t_{\mathrm{q},90\%}$) range between 1-1.5 ms and 5-12 ms, respectively, for all three designs. Transient losses are also generated in the Bi-2212 windings, but their local temperature remains below 30 K and a thermal runaway is not induced. The resistance of the Nb_3Sn windings is sufficient to effectively discharge the magnet current while depositing the entire magnet stored energy in the LTS volume.

For each magnet, the hot-spot temperature T_{hot} [K] is calculated, under adiabatic assumptions, multiple times to evaluate the case of a quench occurring in any coil location, including in the Bi-2212 turns. The highest T_{hot} for each design is plotted in Fig. 1. For all three magnet designs T_{hot} remains well below 350 K, which is considered an acceptable limit to avoid permanent degradation [20]. The simulated peak voltage to ground is dominated by the CLIQ-induced voltage and remains below 550 V in all cases.

Some bias is present when comparing the quench protection performance of the three designs. In fact, the BC design has a significantly larger cross-section than the other designs, and hence the lower current density makes it less challenging to protect. The CT design was studied more in depth and the Cu/noCu ratio in its outer layers was optimized. Finally, by principle the CC option comprises two apertures. Thus, it has a disadvantage when compared to the other two designs, since they have a self-inductance approximately twice lower than the twin-aperture case. In the case of a hadron collider, such one-aperture designs would be irrelevant.

A. *Protection of the Block-Coil Magnet*

The magnetic-field change generated by triggering a CLIQ unit connected to the BC magnet is shown in Fig. 2a. This CLIQ configuration does not require current leads between the layers forming the same coil, but only between coils.

The introduction of opposite current-changes in adjacent coil sections is key for reaching good performance in a CLIQ system [8], [21], because it allows achieving high transient losses, and hence fast quench, in many turns simultaneously. As a result, the magnet stored energy is deposited rather uniformly in the LTS windings and the temperature distribution is rather uniform, as shown in Fig. 2b, and the hot-spot temperature is maintained around 250 K.

B. *Protection of the Common-Coil Magnet*

The common-coil design features higher current density in the conductor than the other two designs. However, CLIQ is particularly well suited to protect CC magnets due to the enhanced flexibility of the CLIQ lead positioning, since individual CC layers can be wound stand-alone, and due to

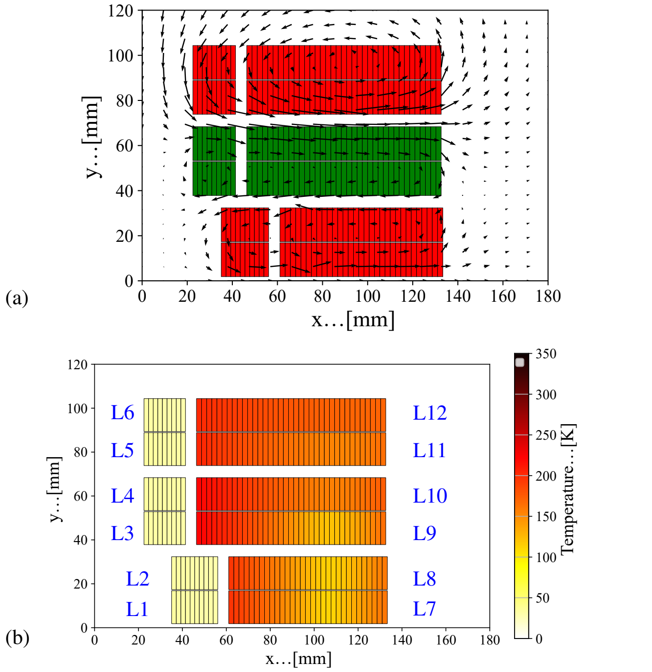

Fig. 2. Protection of the 20 T block-coil magnet (only 1 quadrant shown). (a) CLIQ-imposed positive (green) or negative (red) current change and resulting magnetic field. (b) Simulated temperature distribution in the turns.

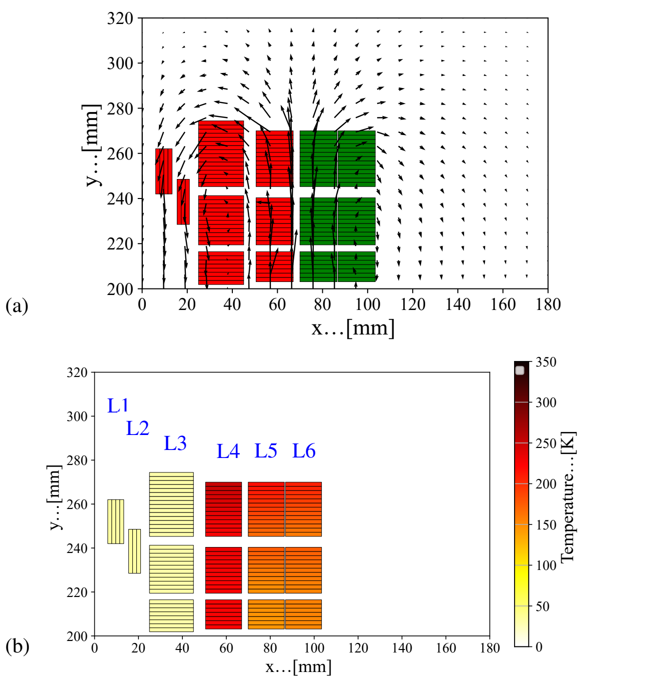

Fig. 3. Protection of the 20 T common-coil magnet (only 1 quadrant shown). (a) CLIQ-imposed positive (green) or negative (red) current change and resulting magnetic field. (b) Simulated temperature distribution in the turns.

the width of the region where high magnetic-field change is introduced, which encompasses most turns, as shown in Fig. 3a. As a result, 90% of the Nb_3Sn windings are transferred to the normal state in <8 ms, the temperature distribution in the LTS windings is quite uniform (see Fig. 3b), and the hot-spot temperature is maintained below 315 K.

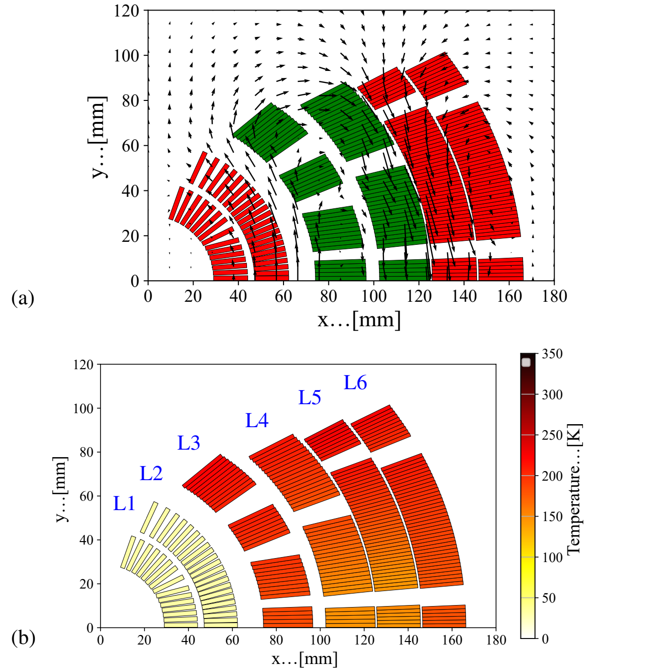

Fig. 4. Protection of the 20 T cos-θ magnet (only 1 quadrant shown). (a) CLIQ-imposed positive (green) or negative (red) current change and resulting magnetic field. (b) Simulated temperature distribution in the turns.

This performance is remarkable considering that this magnet includes two apertures, but is protected by the same 1 kV CLIQ unit as the other two designs.

C. Protection of the Cos-θ Magnet

The current and magnetic-field changes generated by triggering the CLIQ for the cos-θ design, which only relies on current leads between 2-layer coils, are shown in Fig. 4a. The protection of this magnet achieves the fastest induced quench, with 90% of the Nb_3Sn turns turned resistive in about 5 ms, and the most uniform temperature distribution in the Nb_3Sn windings (see Fig. 4b). The hot-spot temperature remains below 270 K, which is slightly above the BC result, which features a substantially lower current density. One reason for this good performance is that the CT design includes less Bi-2212 conductor than the alternative options, and hence the relative volume where the magnet stored energy is dissipated is higher.

III. Quench Protection of Full-Scale Magnets

While it is useful to study the quench protection of 1 m long magnets, as this is relevant to the short model magnets that might be manufactured in the near future, the most relevant case to future hadron colliders is the protection of full-scale, 2 aperture magnets. The CLIQ protection effectiveness depends strongly on the magnetic length l_m [m]. In fact, CLIQ performance is determined by inter-filament coupling loss, which in first approximation is proportional to the square of the magnetic-field change, and hence to $(U_0/l_\mathrm{m})^2$ [8], [21], [22]. Thus, the longer the magnet, the less effective CLIQ protection is. In this section, a simplified

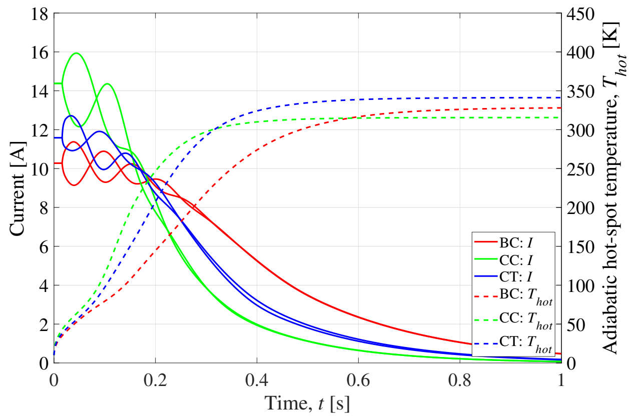

Fig. 5. Simulation of the transient following a quench at nominal current in 5 m long, 20 T magnets. Currents in the coil sections and adiabatic hot-spot temperature versus time. For CC (2 apertures) the CLIQ unit is charged to 2 kV, for BC and CT (1 aperture) to 1 kV.

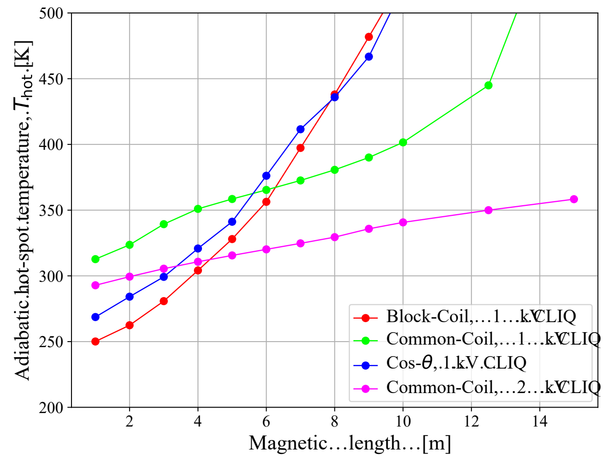

Fig. 6. Simulated hot-spot temperature after a quench at I_{nom}, as a function of the magnetic length, for the three magnet designs.

approach is taken by considering the BC and CT one aperture magnets presented in the previous sections with longer magnetic length. In a particle accelerator, one could obtain similar performance by connecting one CLIQ unit per aperture and installing by-pass diodes [23]–[26] across each aperture coil rather than across each full magnet. Since the CC magnet by design has two apertures, 2 kV CLIQ units connected across the two coils are considered. This is equivalent to connecting one 1 kV CLIQ unit per coil, and installing a by-pass diode across each coil. While failure cases should be carefully considered in such a case, and are not covered in this work, these assumptions allow a reasonable comparison between the three designs.

The simulated currents and hot-spot temperatures obtained after a quench at nominal current in 5 m long magnets are shown in Fig. 5. The rate of change, the peak value, and the oscillating frequency of the current introduced by CLIQ are smaller with respect to the 1 m long magnet case since the CLIQ discharge circuit has higher impedance. Although the CLIQ protection performance is less effective, T_{hot} can be maintained below 350 K for all three designs.

The simulated hot-spot temperature reached after a quench increases with the magnetic length, as shown in Fig. 6. None of the three designs can be protected by one CLIQ unit charged to U_0=1 kV if l_{m}>5 m. The CC magnet could be protected up to a length of about 12 m using a 2 kV CLIQ protection.

The results of this study stress that it is crucial to include quench protection optimization from the start of the magnet design phase. Various options could be taken to achieve satisfactory performance when protecting full-scale 20 T magnets. Magnet designs with fewer turns and higher current could be easier to protect with CLIQ, since the CLIQ circuit impedance would be lower. CLIQ configurations relying on current leads between layers of the same coil could be adopted. This would improve the quench protection performance, but would make it more difficult to integrate the CLIQ leads. The CLIQ charging voltage could be increased, which has the disadvantage of increasing the peak voltage to ground and the voltage rating of the CLIQ unit. The conductor cross-section could be increased, which would make the magnet less compact. Finally, innovative quench protection systems, such as Secondary CLIQ [27], [28], External coil CLIQ [29], or the Energy Shift with Coupling (ESC) system [30], which have the potential to offer even better quench protection performance and redundancy, could be deployed.

IV. Conclusion

Hybrid magnets composed of high-temperature superconductor and low-temperature superconductor coils powered in series are a promising option for 20 T-class accelerator magnets. The US Magnet Development Program is leading a design study aimed at demonstrating the feasibility of such magnets. Three geometry options are being explored, namely block-coil, common-coil, and cos-θ.

The proposed quench protection strategy for Bi-2212/Nb_3Sn hybrid magnets relies on an active system that detects the quench occurrence and activates a Coupling-Loss Induced Quench (CLIQ) system, which rapidly transfers to the normal state most of the Nb_3Sn windings. The magnet stored energy is then dissipated primarily in the low-temperature superconductor.

It is shown that one 1 kV CLIQ unit is sufficient to protect 1 m long versions of the three magnets. The transient simulations performed with the STEAM-LEDET software show that the hot-spot temperature can be maintained between 250 K and 315 K, and the peak voltage to ground below 550 V, for any of the three designs.

Protecting full-scale magnets, which is the most relevant case for future circular colliders, is significantly more challenging. None of the designs can be protected with a 1 kV unit for a magnetic length larger than 5 m. The common-coil option seems more promising than the alternatives due to its more convenient geometry for CLIQ applications, higher flexibility for conductor grading, and lower peak field in the Nb_3Sn windings. Innovative quench protection techniques will likely be needed to effectively protect 20 T hybrid magnets with comfortable margin and reliability.

References

[1] P. Ferracin, G. Ambrosio, D. Arbelaez, L. Brouwer, E. Barzi, L. Cooley, L. Garcia Fajardo, R. Gupta, M. Juchno, V. Kashikhin, V. Marinozzi, I. Novitski, E. Rochepault, J. Stern, A. Zlobin, and N. Zucchi, "Towards 20 T hybrid accelerator dipole magnets," *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 6, p. 16, Sep. 2022. [Online]. Available: http://dx.doi.org/10.1109/TASC.2022.3152715

[2] P. Ferracin, G. Ambrosio, M. Anerella, D. Arbelaez, L. Brouwer, E. Barzi, L. D. Cooley, J. Cozzolino, L. Garcia Fajardo, R. Gupta, M. Juchno, V. V. Kashikhin, F. Kurian, V. Marinozzi, I. Novitski, E. Rochepault, J. Stern, G. Vallone, B. Yahia, and A. Zlobin, "Conceptual design of 20 T hybrid accelerator dipole magnets," *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, p. 17, Aug. 2023. [Online]. Available: http://dx.doi.org/10.1109/TASC.2023.3250382

[3] P. Ferracin, G. Ambrosio, K. Amm, M. Anerella, D. Araujo, D. Arbelaez, M. Baldini, L. Brouwer, M. DAddazio, E. Barzi, L. Cooley, J. Cozzolino, L. Garcia Fajardo, S. Gourlay, R. Gupta, M. Juchno, V. Kashikhin, D. Larbalestier, V. Marinozzi, I. Novitski, S. Prestemon, E. Ravaioli, E. Rochepault, J. Rudeiros Fernandez, T. Shen, R. Teyber, G. Vallone, G. Velev, B. Yahia, A. Zlobin, and X. Wang, "HTS/LTS hybrid dipole magnets by the us magnet development program," *IEEE Transactions on Applied Superconductivity*, submitted for publication.

[4] D. C. Larbalestier, J. Jiang, U. P. Trociewitz, F. Kametani, C. Scheuerlein, M. Dalban-Canassy, M. Matras, P. Chen, N. C. Craig, P. J. Lee, and E. E. Hellstrom, "Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 t," *Nature Materials*, vol. 13, no. 4, pp. 375–381, Apr 2014. [Online]. Available: https://doi.org/10.1038/nmat3887

[5] V. Selvamanickam, *High temperature superconductor (HTS) wires and tapes*, 12 2012, pp. 34–68.

[6] M. Marchevsky, "Quench detection and protection for high-temperature superconductor accelerator magnets," *Instruments*, vol. 5, no. 3, 2021. [Online]. Available: https://www.mdpi.com/2410-390X/5/3/27

[7] 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 Transactions on Applied Superconductivity*, vol. 24, no. 3, pp. 1–5, June 2014.

[8] E. Ravaioli, "CLIQ," Ph.D. dissertation, Enschede, 2015, presented on 19 June 2015. [Online]. Available: http://doc.utwente.nl/96069/

[9] G. H. Morgan, "Theoretical behavior of twisted multicore superconducting wire in a time-varying uniform magnetic field," *Journal of Applied Physics*, vol. 41, no. 9, pp. 3673–3679, 1970. [Online]. Available: http://scitation.aip.org/content/aip/journal/jap/41/9/10.1063/1.1659491

[10] W. J. Carr, "AC loss in a twisted filamentary superconducting wire," *Journal of Applied Physics*, vol. 45, no. 2, pp. 929–938, 1974. [Online]. Available: http://scitation.aip.org/content/aip/journal/jap/45/2/10.1063/1.1663341

[11] A. P. Verweij, "Electrodynamics of superconducting cables in accelerator magnets," Ph.D. dissertation, Twente U., Twente, 1995, presented on 15 Sep 1995. [Online]. Available: https://cds.cern.ch/record/292595

[12] E. Ravaioli, B. Auchmann, M. Maciejewski, H. ten Kate, and A. Verweij, "Lumped-element dynamic electro-thermal model of a superconducting magnet," *Cryogenics*, 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0011227516300832

[13] "STEAM website," https://cern.ch/steam.

[14] E. Ravaioli, B. Auchmann, G. Chlachidze, M. Maciejewski, G. Sabbi, S. E. Stoynev, and A. Verweij, "Modeling of inter-filament coupling currents and their effect on magnet quench protection," *IEEE Transactions on Applied Superconductivity*, vol. 27, no. 4, pp. 1–8, June 2017.

[15] M. Mentink and E. Ravaioli, "Analysis of MQXFS5 CLIQ tests of November 2017," CERN, Geneva, Tech. Rep. EDMS 1930202, 2020.

[16] E. Ravaioli, G. Ambrosio, L. Bortot, P. Ferracin, S. I. Bermudez, P. Joshi, M. Maciejewski, V. Marinozzi, M. Mentink, J. F. Muratore, F. Rodriguez-Mateos, G. Sabbi, E. Todesco, and A. Verweij, "Quench protection of the first 4-m-long prototype of the HL-LHC Nb_3Sn quadrupole magnet," *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 5, pp. 1–5, 2019.

[17] M. Janitschke, M. Mentink, F. Murgia, D. Pracht, E. Ravaioli, and A. P. Verweij, "A simplified approach to simulate quench development in a superconducting magnet," *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 5, pp. 1–5, 2021.

[18] D. Mayr, L. Bender, E. Gautheron, S. Mariotto, M. Prioli, E. Ravaioli, M. Statera, E. Todesco, A. Verweij, and M. Wozniak, "Simulating quench transients in the self-protected hl-lhc high order corrector magnets," *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, pp. 1–5, 2024.

[19] B. Caiffi, L. Bender, A. Bersani, S. Farinon, A. Foussat, F. Levi, F. Mangiarotti, R. Musenich, D. Novelli, A. Pampaloni, E. Ravaioli, E. Todesco, and G. Willering, "Protection scheme effectiveness study for the High-Luminosity LHC MBRD magnet," *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, pp. 1–4, 2023.

[20] G. Ambrosio, "Maximum allowable temperature during quench in Nb_3Sn accelerator magnets," in *Proceedings, WAMSDO 2013 Workshop on Accelerator Magnet, Superconductor, Design and Optimization: CERN Geneva, Switzerland, 15-16 Jan 2013*, no. FERMILAB-CONF-13-593-TD, 2013, pp. 43–46. [Online]. Available: https://inspirehep.net/record/1277941/files/arXiv:1401.3955.pdf

[21] E. Ravaioli, V. I. Datskov, V. Desbiolles, J. Feuvrier, G. Kirby, M. Maciejewski, K. A. Sperin, H. H. ten Kate, A. P. Verweij, and G. Willering, "Towards an optimized Coupling-loss Induced Quench protection system (CLIQ) for quadrupole magnets," *Physics Procedia*, vol. 67, pp. 215–220, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1875389215004186

[22] E. Ravaioli, H. Bajas, V. I. Datskov, V. Desbiolles, J. Feuvrier, G. Kirby, M. Maciejewski, G. Sabbi, H. H. J. ten Kate, and A. P. Verweij, "Protecting a full-scale Nb_3Sn magnet with CLIQ, the new Coupling-Loss-Induced Quench system," *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 3, pp. 1–5, June 2015.

[23] D. Hagedorn, F. Rodriguez-Mateos, and R. Schmidt, "Protection of LHC superconducting corrector magnets," *Conf. Proc. C*, vol. 960610, pp. 2255–2257, 1996.

[24] R. Schmidt, C. Giloux, A. Hilaire, A. Ijspeert, F. Rodrguez-Mateos, and F. Sonnemann, "Protection of the Superconducting Corrector Magnets for the LHC," 2000. [Online]. Available: https://cds.cern.ch/record/466521

[25] F. Sonnemann, "Resistive transition and protection of LHC superconducting cables and magnets," 2001, presented on 12 Feb 2001. [Online]. Available: https://cds.cern.ch/record/499591

[26] E. Ravaioli, V. I. Datskov, G. Kirby, M. Maciejewski, H. H. J. ten Kate, and A. P. Verweij, "CLIQ-based quench protection of a chain of high-field superconducting magnets," *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 4, pp. 1–5, June 2016.

[27] M. Mentink and E. Ravaioli, "Secondary CLIQ, a robust, redundant, and cost-effective means of protecting high-field accelerator magnets," *Superconductor Science and Technology*, vol. 33, no. 8, p. 085005, jun 2020. [Online]. Available: https://dx.doi.org/10.1088/1361-6668/ab951f

[28] E. Ravaioli, T. Mulder, A. Verweij, and M. Wozniak, "Optimizing Secondary CLIQ for protecting high-field accelerator magnets," *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, pp. 1–5, 2024.

[29] T. Mulder, B. Bordini, E. Ravaioli, E. Schnaubelt, M. Wozniak, and A. Verweij, "External coil coupled loss induced quench (E-CLIQ) system for the protection of LTS magnets," *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, pp. 1–5, 2023.

[30] E. Ravaioli, A. Verweij, and M. Wozniak, "Energy Shift with Coupling (ESC): a New Quench Protection System," *to be submitted*, 2024.