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Effect of CLIQ on training of HL-LHC quadrupole magnets

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MQXFA training data and analysis

As part of HL-LHC upgrade, MQXFA quadrupole Nb_3Sn magnets [1] are developed by AUP [2] with many magnets already tested at BNL [3]. We investigate training performance of those, concentrating on "coil training" [4]. We test hypotheses employing Fisher's and Barnard's exact tests [5] on 2x2 contingency tables constructed from quench data of the tested magnets. We utilize coil positions in each magnet (four coils in four quadrants, Q1 to Q4).

MQXFA MAGNET QUENCH DATA

Magnet	Q1	Q2	Q3	Q4
MQXFA03	204 0/0/0 0	110 0/0/0 0	202 0/0/0 0	111 4/7/8 1
MQXFA04	203 1/1/1 0	113 3/4/4 1	206 0/0/0 0	112 0/0/0 0
MQXFA05	207 3/4/4 0	116 0/0/1 0	209 1/1/1 0	115 0/0/0 0
MQXFA06	122 1/1/1 0	119 0/0/0 0	211 0/2/2 0	123 0/0/0 0
MQXFA07	212 1/1/1 0	124 0/0/0 0	214 6/7/7 1	114 0/0/0 0
MQXFA08	215 0/0/0 0	126 0/0/1 0	213 0/0/0 0	128 0/0/0 0
MQXFA08b	-	-	219 2/2/3 0	-
MQXFA10	132 8/8/8 0	221 0/0/0 0	131 5/6/6 0	129 0/0/0 0
MQXFA11	223 1/1/1 0	222 0/0/0 0	134 5/6/6 0	135 0/0/0 0
MQXFA13	227 14/14/14 0	139 0/0/1 0	229 3/4/4 0	141 0/0/0 0

For each magnet and quadrant there are three rows:

- **the top one shows the coil number in the quadrant with FNAL fabricated coils starting with "1" and BNL fabricated coil (same design) starting with "2";**
- **the second one shows number of quenches to threshold current, 16240 A, at 1.9 K, not counting the first quench in a magnet, for three inclusive tiers of data – with quench current gain of "< 300 A", gain of "< 600 A", and "no limits"**
- **the bottom raw shows number of detraining quenches with current <u>loss</u> above 300 A - "weak" coils with such non-zero detraining quenches are highlighted.**

For MQXFA08b, only the new coil, a substitute, is shown.

The threshold current is 10 A above the "nominal current" (16230 A), which is the operational level to which magnet parameters (pre-stress) are tuned.

The unit of 300 A used is the difference between the "acceptance current" at magnet training (not to be exceeded, 16530 A) and the "nominal current". This level can be considered a "safety margin" to avoid quenches at nominal current.

An example of a 2x2 contingency table is this:

	Q1||Q3	Q2||Q4
unquenched	5	16
quenched	13	0

also denoted as **5/13 vs 16/0.**

It shows quenched (at least once) and unquenched coils in Q1 or Q3, and the same for Q2 or Q4 coils. We test the following hypothesis, <u>H0: the fraction of quenching coils is not related to their position in the magnet (Q1||Q3 vs Q2||Q4).</u> Results are in the following table and include all three tiers of data, and coil conditions. There are 34 "non-weak" coils out of 37 total ("all").

TABLE II
HYPOTHESIS TESTING FOR QUENCHING OF COILS IN Q1||Q3 VS Q2||Q4

Conditions and Data	Test	p-value (1-s)	p-value (2-s)
("non-weak", "<300 A") **6/12 vs 16/0**	FT BT	3.4×10^{-5} 2.1×10^{-5}	3.7×10^{-5} 4.1×10^{-5}
("non-weak", "<600 A") **5/13 vs 16/0**	FT BT	9.2×10^{-6} 3.6×10^{-6}	9.8×10^{-6} 7.2×10^{-6}
("non-weak", "no limit") **5/13 vs 13/3**	FT BT	2.4×10^{-3} 9.9×10^{-4}	2.6×10^{-3} 1.9×10^{-3}
("all", "<300 A") **6/13 vs 16/2**	FT BT	4.7×10^{-4} 1.7×10^{-4}	6.3×10^{-4} 2.8×10^{-4}
("all", "<600 A") **5/14 vs 16/2**	FT BT	1.4×10^{-4} 4.8×10^{-5}	1.9×10^{-4} 8.2×10^{-5}
("all", "no limit") **5/14 vs 13/5**	FT BT	6.4×10^{-3} 3.9×10^{-3}	8.6×10^{-3} 7.7×10^{-3}

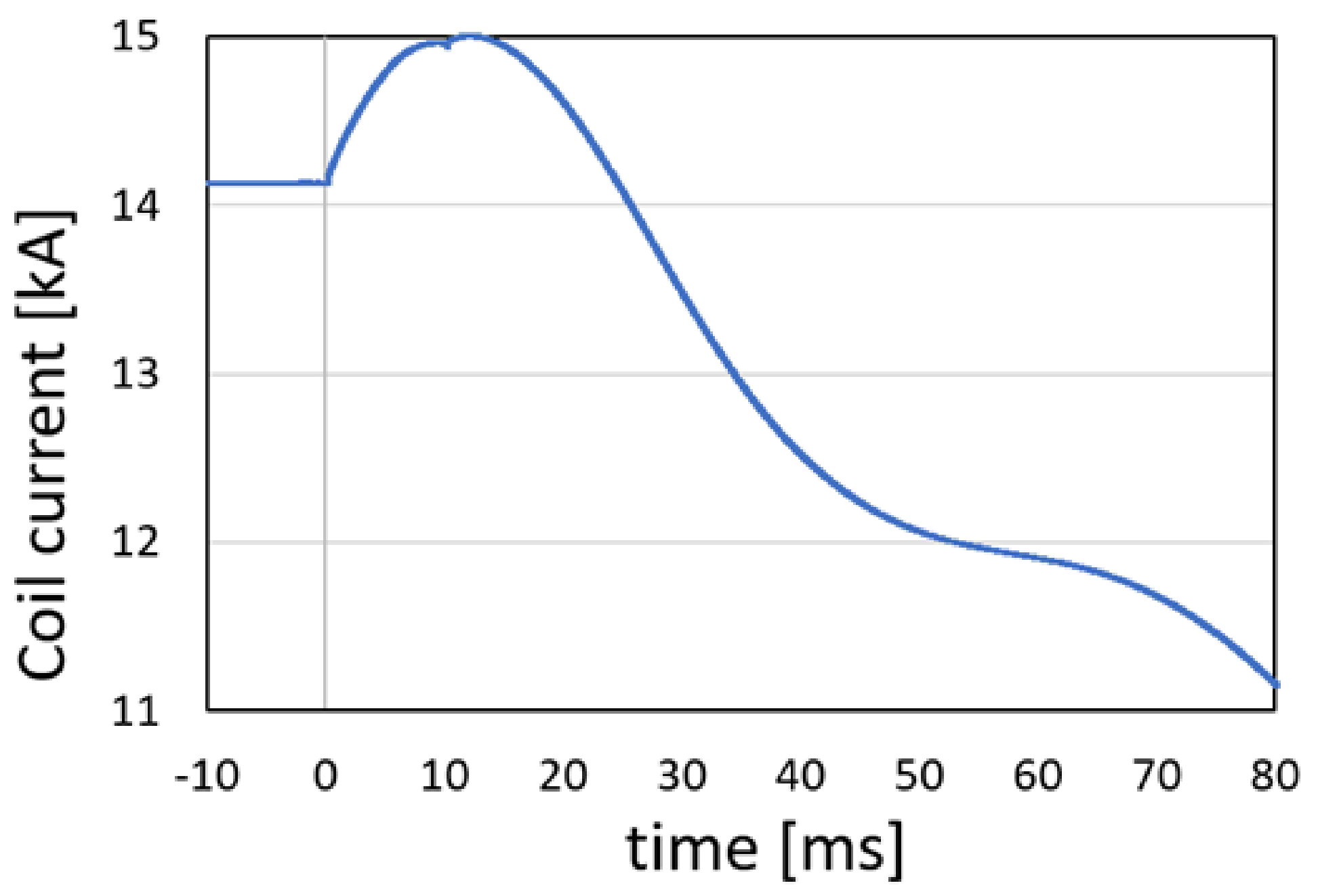
For each data condition, we show the 2x2 contingency table in the notations introduced earlier in the text. Fisher's test (FT) and Barnard's test (BT) are performed with one-sided (1-s) and two-sided (2-s) p-values as results. As a reminder, the p-value is the (integrated) probability to have the Null Hypothesis (H0) rejected when in fact it is true; p-value is calculated based on observed data and test statistics.

Usually, H0 is rejected if the p-value is below some threshold (Significance Limit, SL; we can set 0.1%). The table shows that removing the quench current gain threshold of "< 600 A" changes results significantly. Taking the case with minimum p-values **("non-weak", "< 600 A")**, we investigate the importance of the first quench in a magnet, which is absent in nominal counting of quenches. The following coils quenched first in a magnet: Q2 in MQXFA03/04/05/06/08 and Q4 in MQXFA07; Q1 in MQXFA13 and Q3 in MQXFA10. Explicitly including those quenches in quench counting, for coils they occurred in, gives the following 2x2 contingency table: **5/13 vs 10/6**, and it yields one-sided p-values of 4.50 % (Fisher's) and 3.09 % (Barnard's). This is a huge difference from the test excluding first quenches. Let's test specifically on FNAL coils, <u>H0: there is no relation between quenching in FNAL coils and where they are placed in a magnet (Q1||Q3 vs Q2||Q4)</u>, for the case **("non-week", "<600 A")**. The 2x2 contingency table is **0/4 vs 14/0**. The one-sided p-values are 3.3 x 10^{-4} (Fisher's) and 7.2 x 10^{-5} (Barnard's), low values suggesting that H0 shall be rejected and the alternative accepted. Other tests performed support the same findings but with less statistical power. We explored and quantified how Q2/Q4 coils do not train, with three exceptions, all of them at current gain > 600 A. What drives this behavior?

Discussion, enters CLIQ

The data analysis suggests that Q2||Q4, unlike Q1||Q3, coils do not train, and this is not related to their origin. Further, there is a current gain threshold (600 A or more above quench current) that starts to affect the absolute validity of those observations. Adding the first quench in a magnet to the analysis drastically changes the picture.

There is a single "parameter" that can explain all those features – CLIQ [6]. As reported in [7] "overcurrent", i.e. current above quench current, in magnets immediately after quench affects training in coils. As reported in [4], coils train largely independently. CLIQ was expected [7] to affect "coil training" in coils with overcurrent. For MQXFA magnets coils with overcurrent are in positions Q2 and Q4, Q1 and Q3 see "undercurrent" oscillation after CLIQ discharge. The figure below shows Q2/Q4 current shape around quench detection and protection initiation time. However, training of "next quench" is affected only up to some current level, related to but not necessarily the same as, the peak current from previous CLIQ discharges [7]. Finally, CLIQ is discharged to the magnet (at high enough current) only at the first training quench detection, so it has no effect on the first in a magnet training quench current and coil.

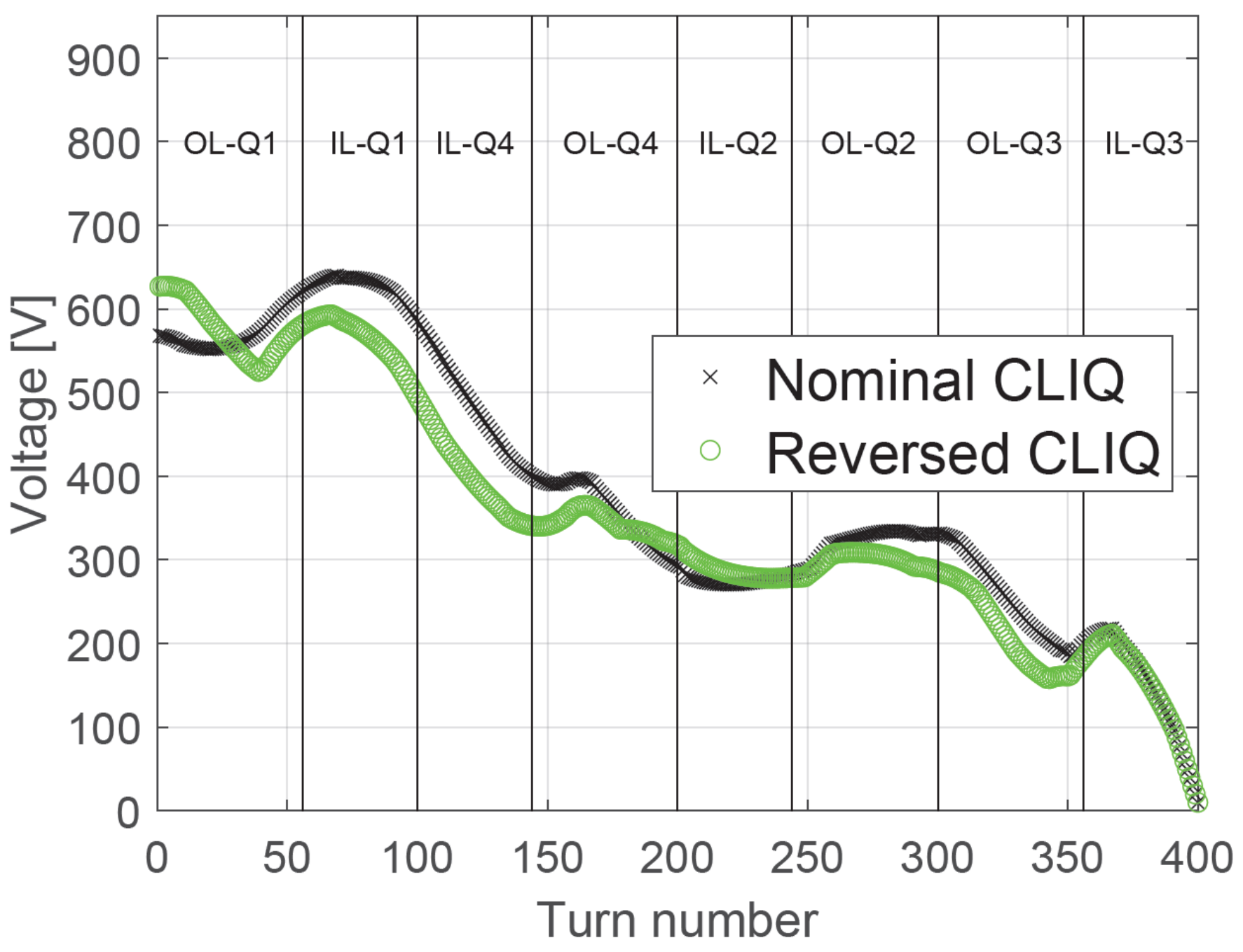


Current through coils with "overcurrent" – data from the first ramp (quench) in MQXFA13. Quench is detected at "0 ms" and CLIQ is discharged without delay causing the current to peak in ~ 12.5 ms. At the 10 ms mark the dump resistor switch is opened which is seen as a small disturbance on the plot. The current boost (quench-to-peak level) is ~ 900 A at this quench current level. CLIQ parameters (voltage, capacitance) remained the same in all magnet tests.

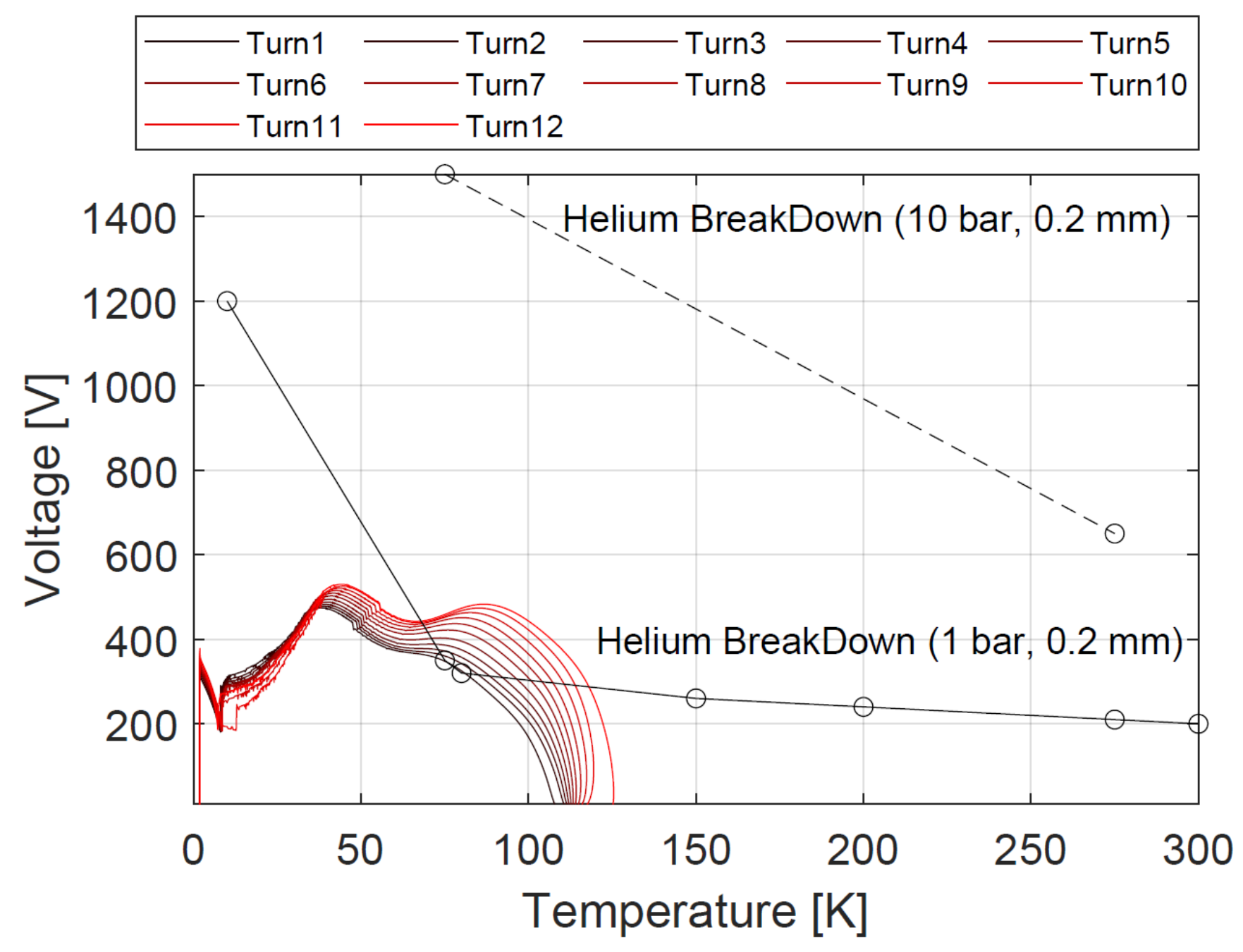
If we accept that CLIQ affects coil training as described, then we also support the statement made in [6] that coils in magnets train largely independently. In this context, **"magnet training" is a misleading term**.

Magnet training optimization with CLIQ

A way to optimize training with CLIQ is by changing CLIQ polarity after each training quench or in a succession of stair-steps-like high-current trips, a.k.a. "quenchless" training [7]. We investigated feasibility of reversing CLIQ polarity in MQXFA magnets. The main constraint coming from CLIQ usage is voltage development, withing the coils, to protection heaters, and to ground. STEAM-LEDET [8], [9] **simulations on MQXFA coils** demonstrate how voltage distributions differ between CLIQ applications with opposite polarities. The only relevant difference is that with flipped CLIQ polarity heater-to-coil voltages increase because configurations were tuned for the "nominal" polarity (in "reversed" polarity heater-to-ground voltage adds up instead of subtracting). However, this is a spike increase with a quick decay, the worst conditions in terms of insulation occur after CLIQ discharges - when the coil temperature is higher (due to coil resistance increase and Joule heating). Those conditions do not depend on CLIQ polarity. Thus, CLIQ polarity has no detrimental effects on magnet protection. A polarity swapping procedure remains to be developed.



Simulation results: Maximum voltages to ground in coil-turns (outer layers, OL; inner layers, IL) for "nominal" and "reversed" CLIQ polarity.



Simulation results ("nominal" CLIQ polarity): Coil-turn-to-heater voltage development vs temperature (worst case) and breakdown voltage contours in He gas for relevant distance.

<u>CONCLUSIONS</u>: Training features among coils have clear patterns which are all directly relatable to CLIQ asymmetric effects on coils. We find that CLIQ overcurrent eliminates training, within limits, with no alternative explanations we can suggest. Further improvements to magnet training can be made by reversing CLIQ polarity (quench-by-quench or in stair-steps-like high-current trips) which was found to be safe for the MQXFA magnets.

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