

E-CLIQ Quench Protection for High-Field Magnets

Tim Mulder, 21-03-2025

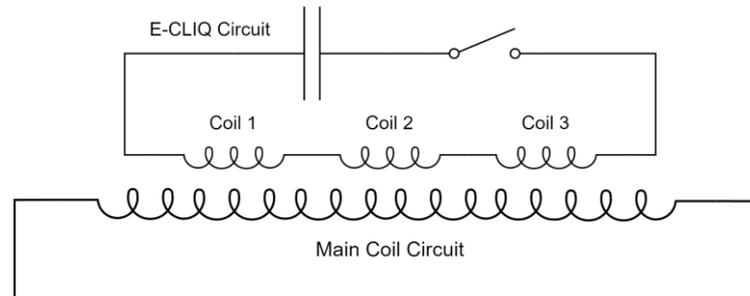


The Concept

External Coil Coupled Loss Induced Quench (E-CLIQ)

Inductive quench heater

- ✓ Set of compact resistive coils positioned near the main magnet coils.
- ✓ Loss generated directly inside the superconducting cables.
- ✓ Potential to be faster than resistive quench heaters.
- ✓ Thick insulation between magnet and E-CLIQ coils is possible.
- ✓ Separate electrical circuit.
- ✓ Small envelope, can withstand large mechanical preload.
- ✓ Can be designed for use with a power supply or with a capacitor bank.



Compact E-CLIQ demonstrators

Development of 3 types of small demonstrators:

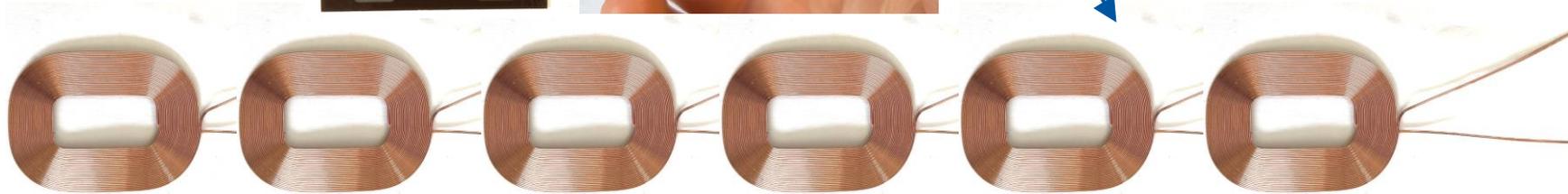
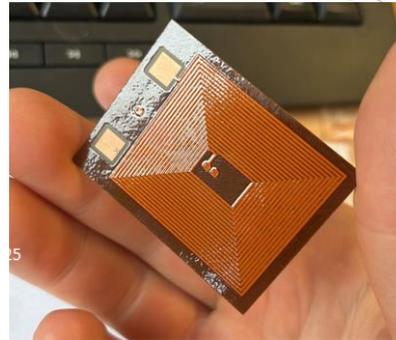
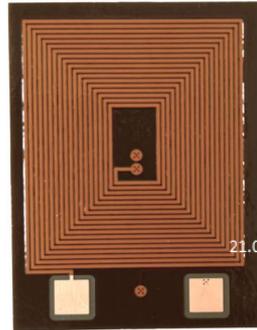
- based on copper wound (thicker) coils,
- based on, commercially available, inductive charging coils,
- based on tracks on polyimide film.



Non-flexible, very robust and easily mountable.

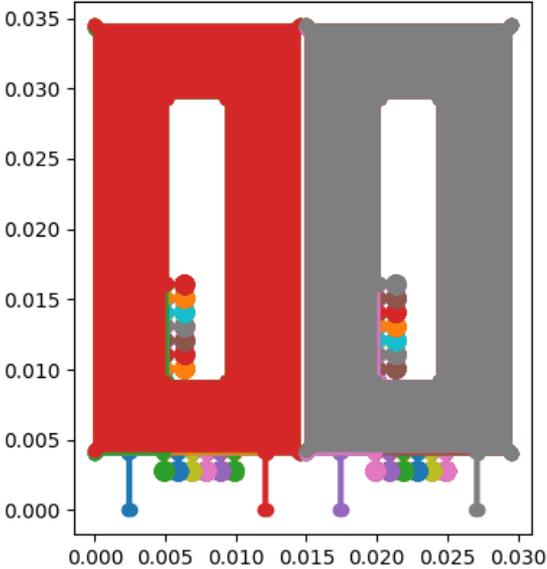
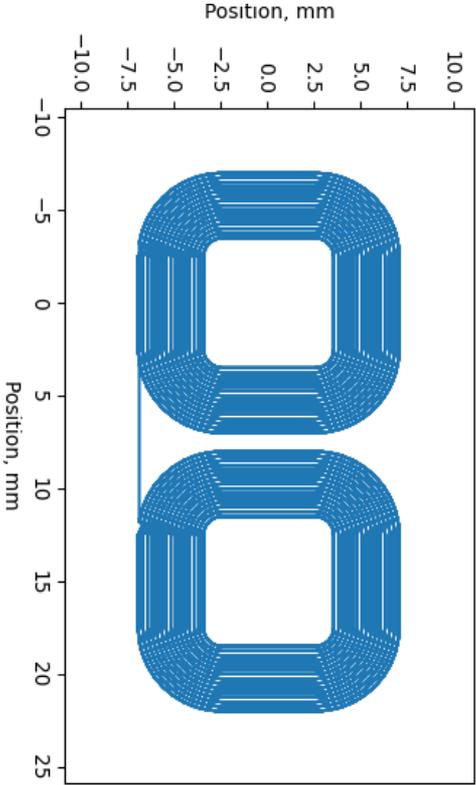


Non-optimized, yet quite flexible.

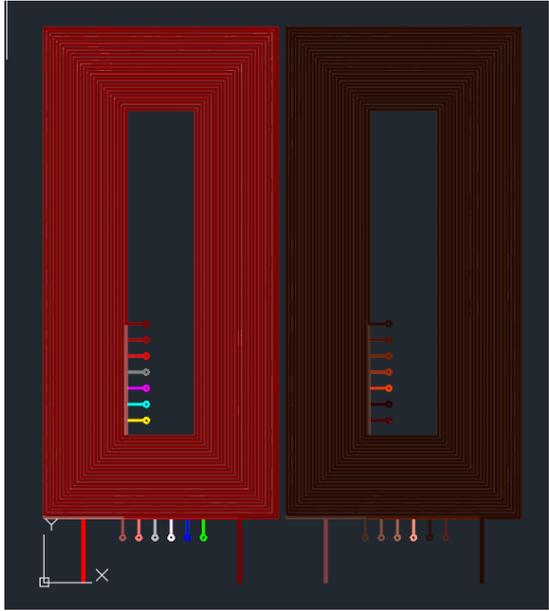


Design software in Python

Step 1: E-CLIQ design



to .dxf



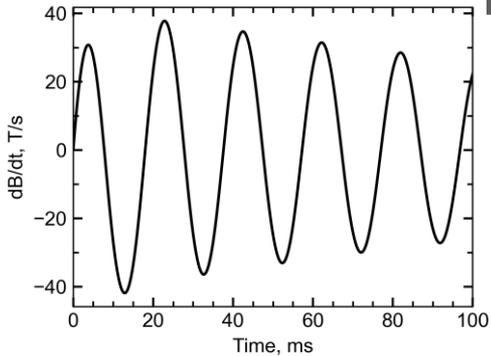
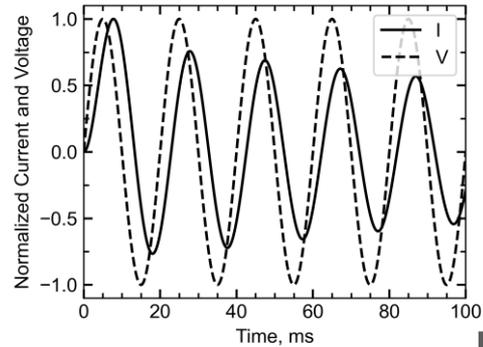
Calc. properties

- Inductance
- Field/Ampere
- Track length
- Expected resistance



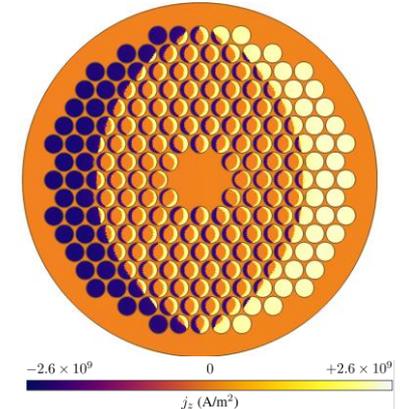
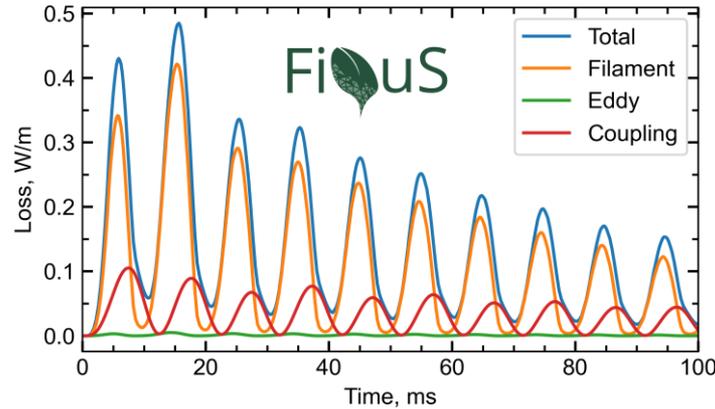
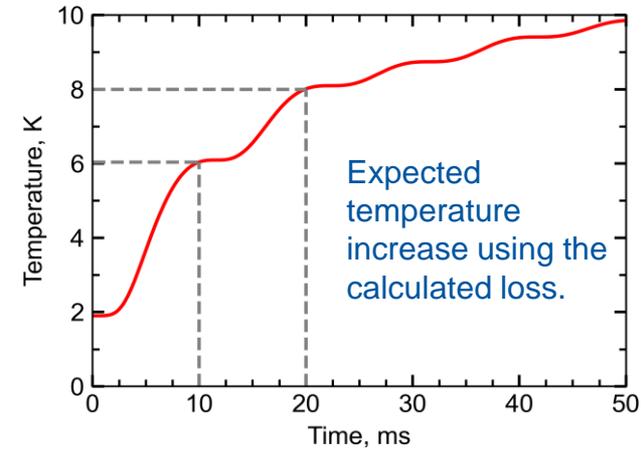
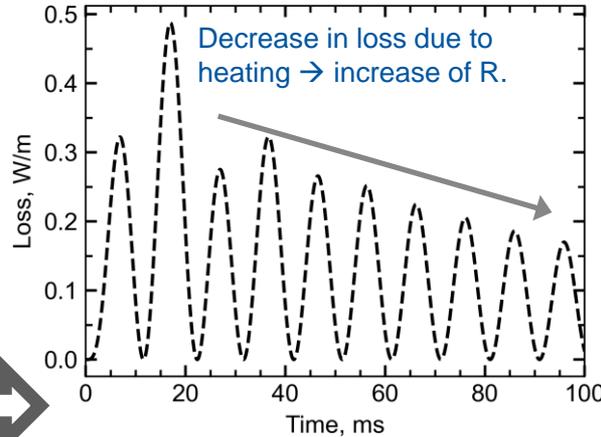
Design software in Python

Step 2: Powering response

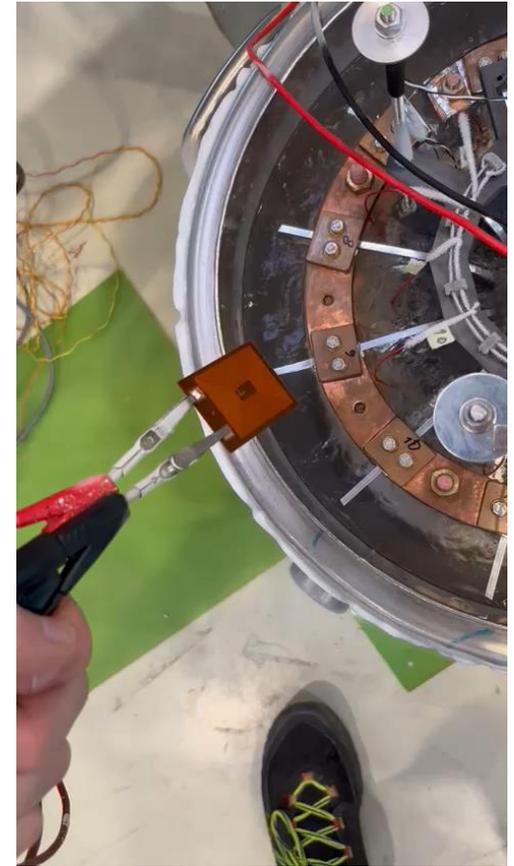
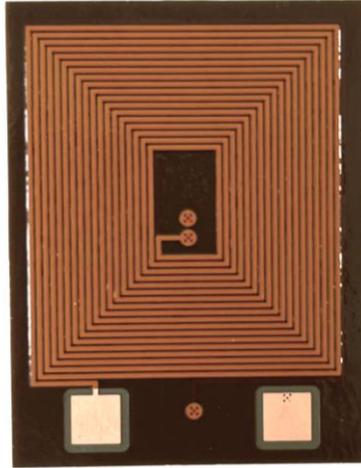
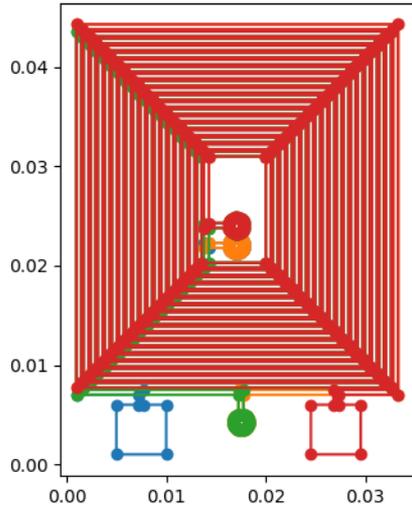


Example E-CLIQ EM behavior (change in temperature considered).

Step 3: Loss calculations



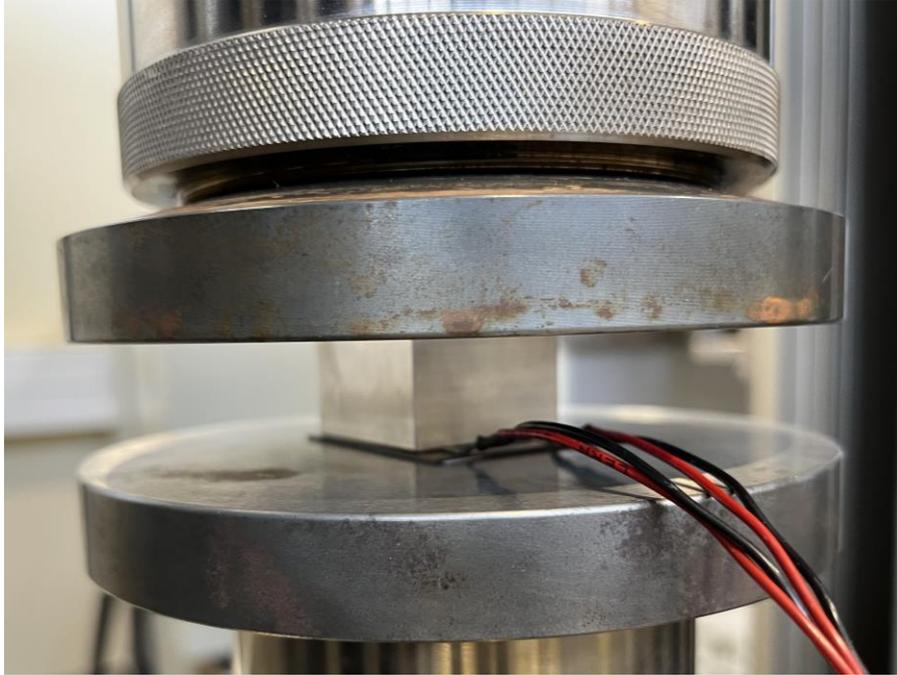
1st Generation of E-CLIQ



	Designed	Measured	Unit
Layers	4	4	
Turns	18	18	
Inductance	118.0	124.5	μH
Resistance (293K)	3.16	3.25	Ω
Resistance (77K)	0.39 (RRR=80)	0.44 (RRR= \sim 45)	Ω
T/A (center)	0.003	-	T/A



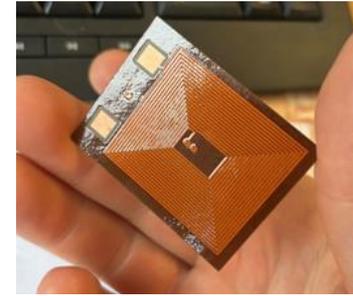
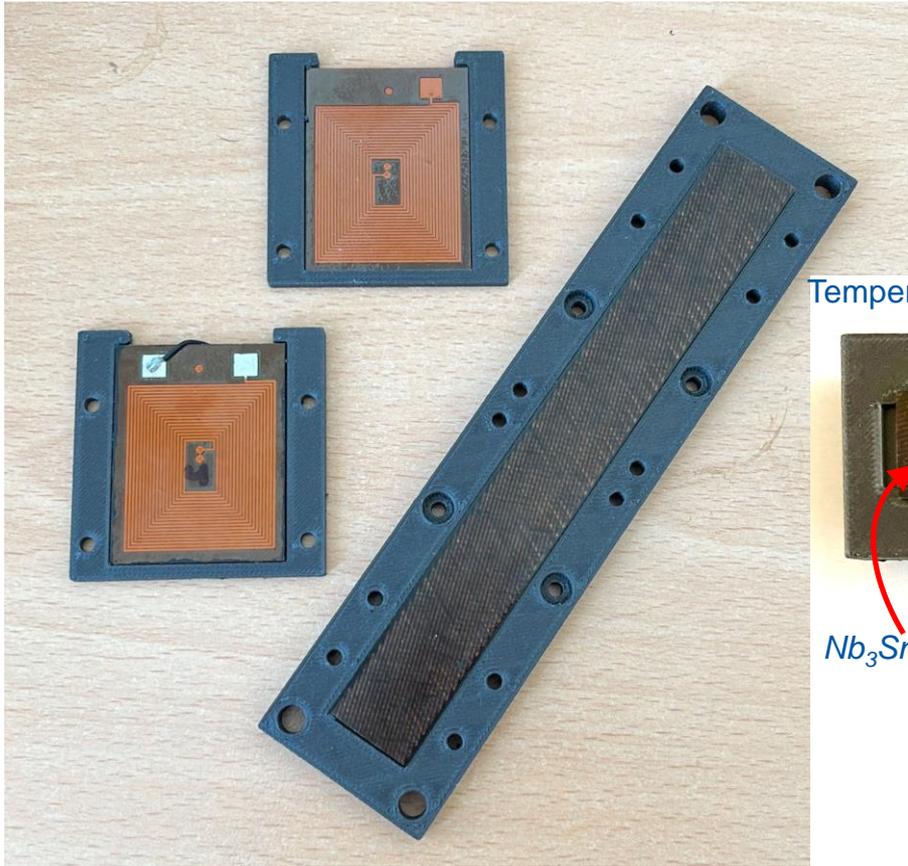
Robustness Testing



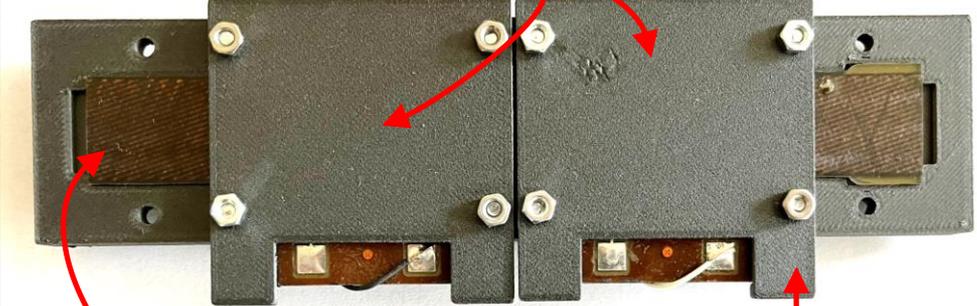
- Tested up to 240 kN, no change in resistance/inductance (together with EN-MME).
- Banana shape remained, no change in electrical parameters.
- Tested with DC current of 6A for ~ 15 seconds. E-CLIQ ballooned, no change in electrical parameters.



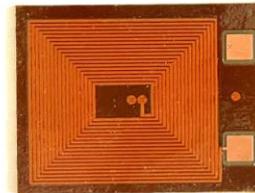
1st Generation of E-CLIQ



Temperature sensors + pickup coils



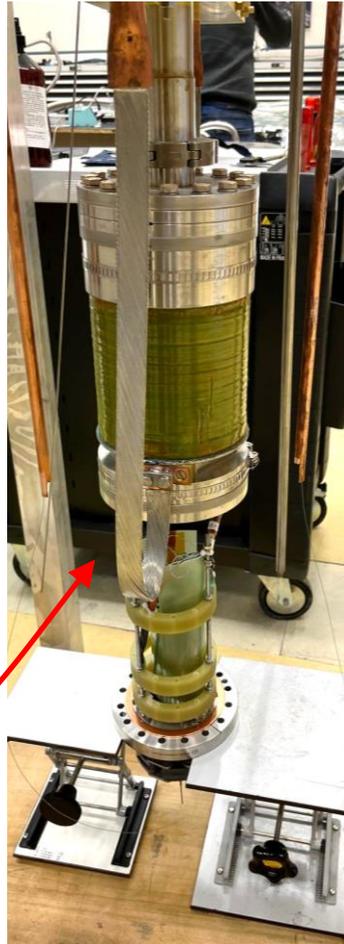
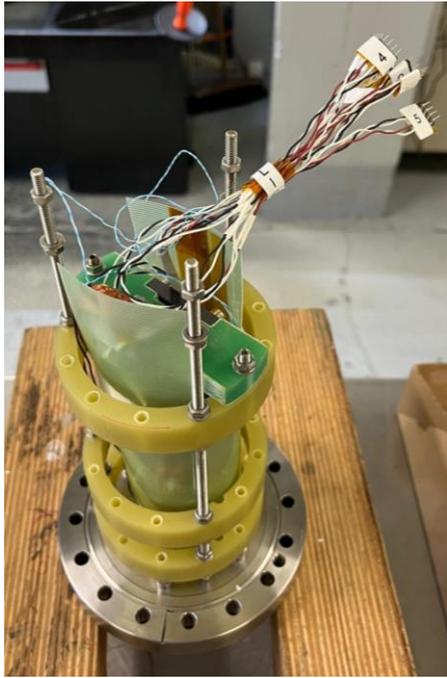
Nb₃Sn cable sample



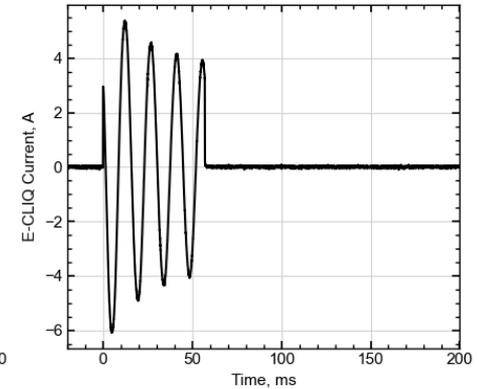
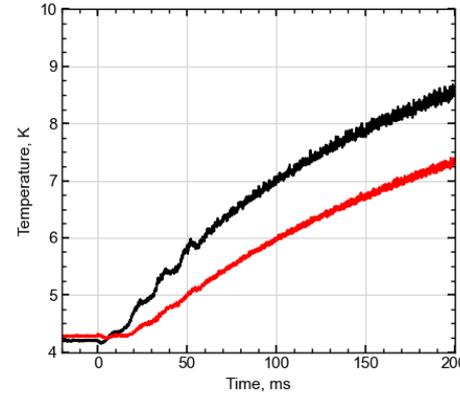
E-CLIQ Devices

3D-printed sample holder

First E-CLIQ test on an Nb₃Sn cable sample



Exemplary result:



Results are promising, but still many unknowns:

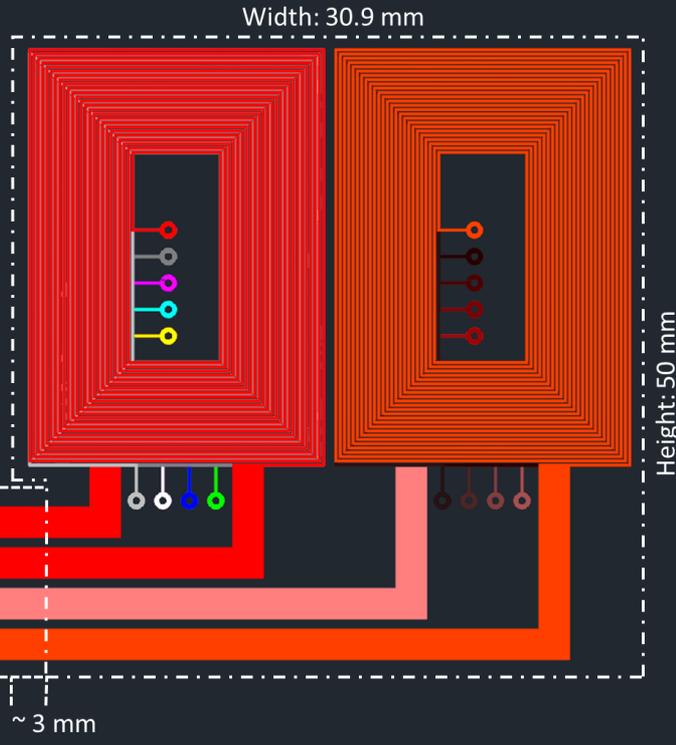
- E-CLIQs clamped directly on the Nb₃Sn cable.
- Heating due to AC loss or conductive heating?
- Large conductive heat flow out of the E-CLIQ 'loss' area.
- Unknown thermal resistance between the cable and temperature sensors.

Setup + sample inserted in to a 5 T magnet. Magnet cooled by LHe, E-CLIQ sample cooled by GHe (< mBar).

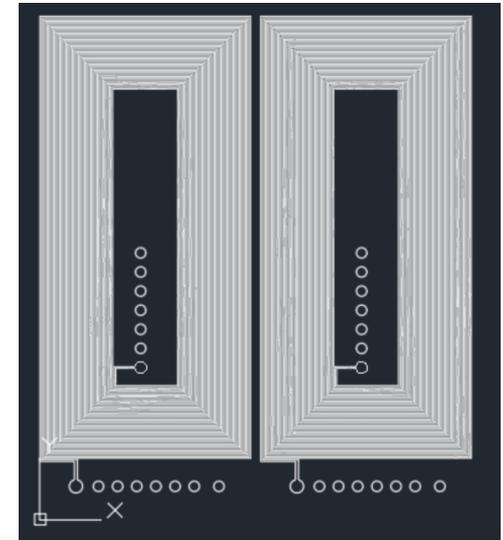
2nd Generation of E-CLIQ

- Designed for use with an Nb₃Sn Short Model Coil (SMC)
- Two coils: one for each layer of Nb₃Sn racetracks.
- Flexible connector, needs to make a bend.
- Optimized for use with an existing amplifier for the frequency range of 50-300 Hz.
- Several design iterations to make optimal use of the available envelope.

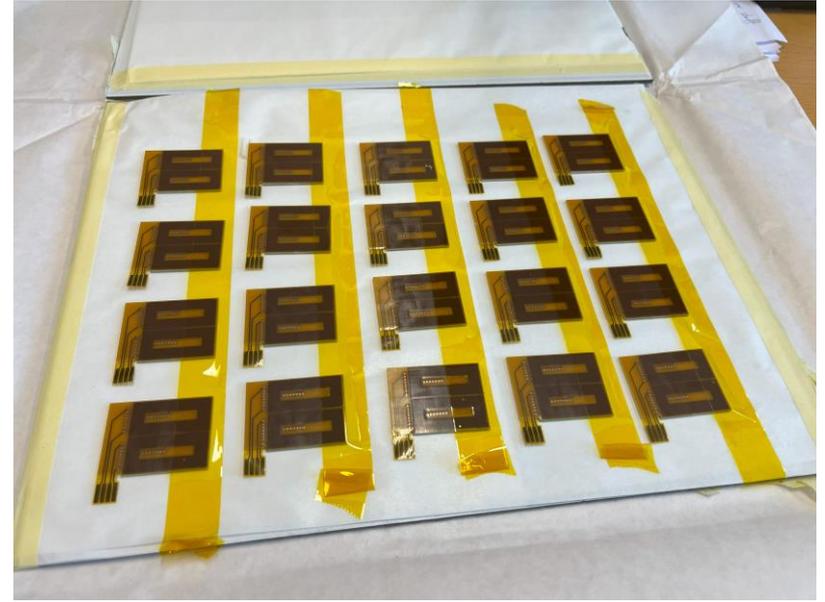
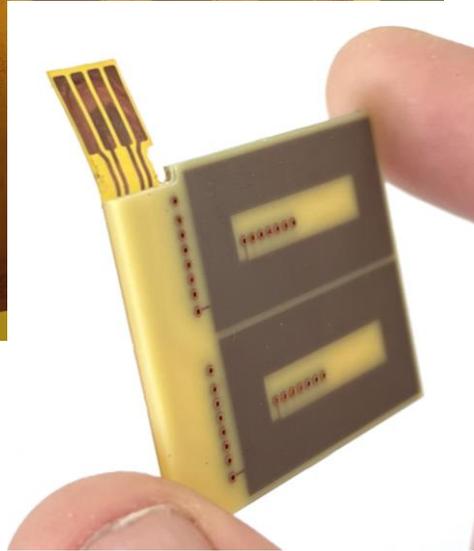
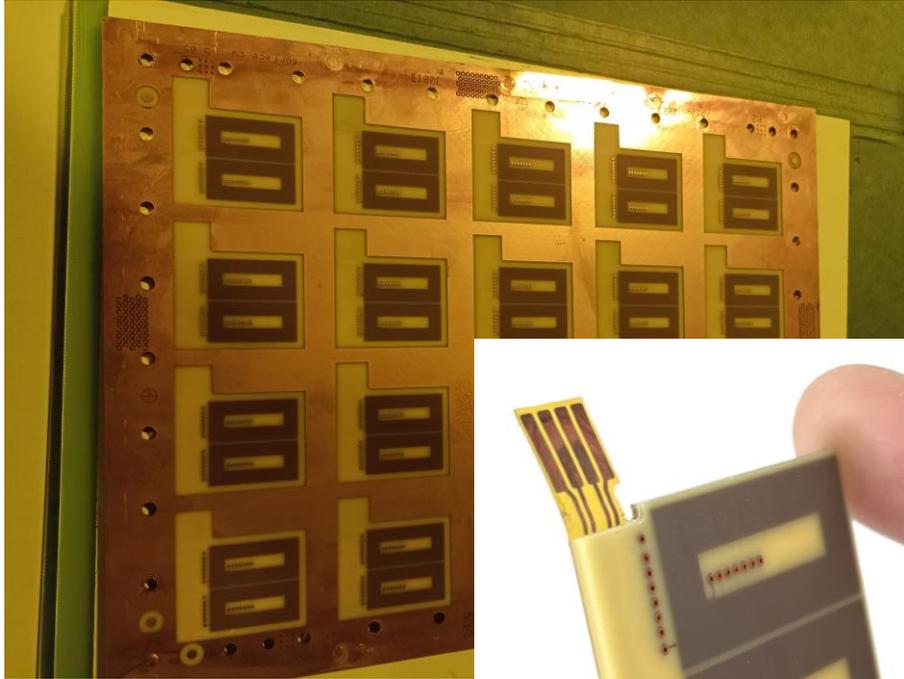
Initial design



Final design



2nd Generation of E-CLIQ

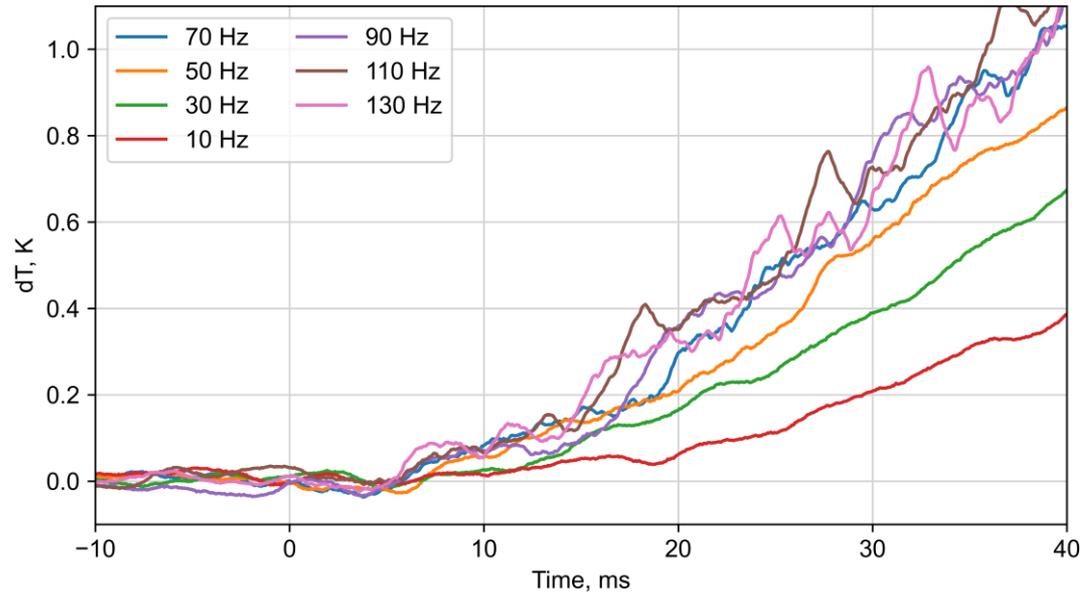


	Value	Unit
Layers	14	-
Turns	24	-
Inductance	3.2	mH
Magnetic Field	0.05	T/A

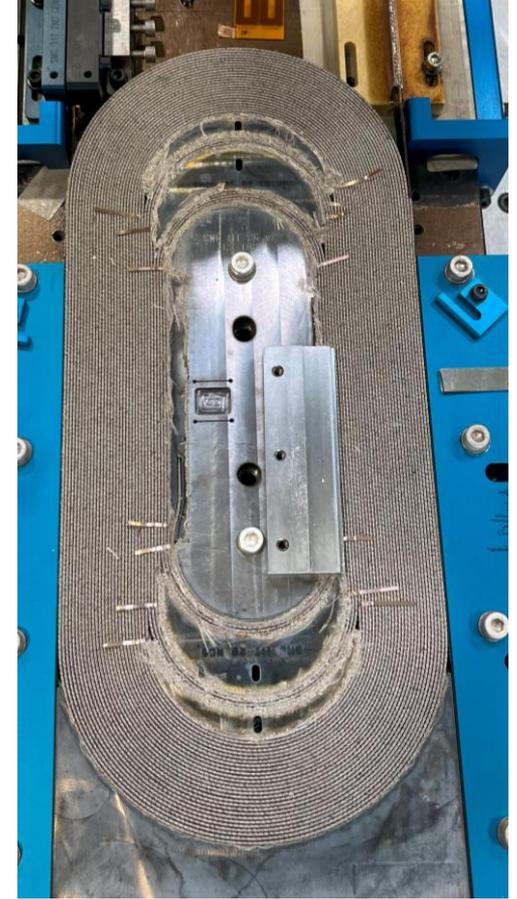
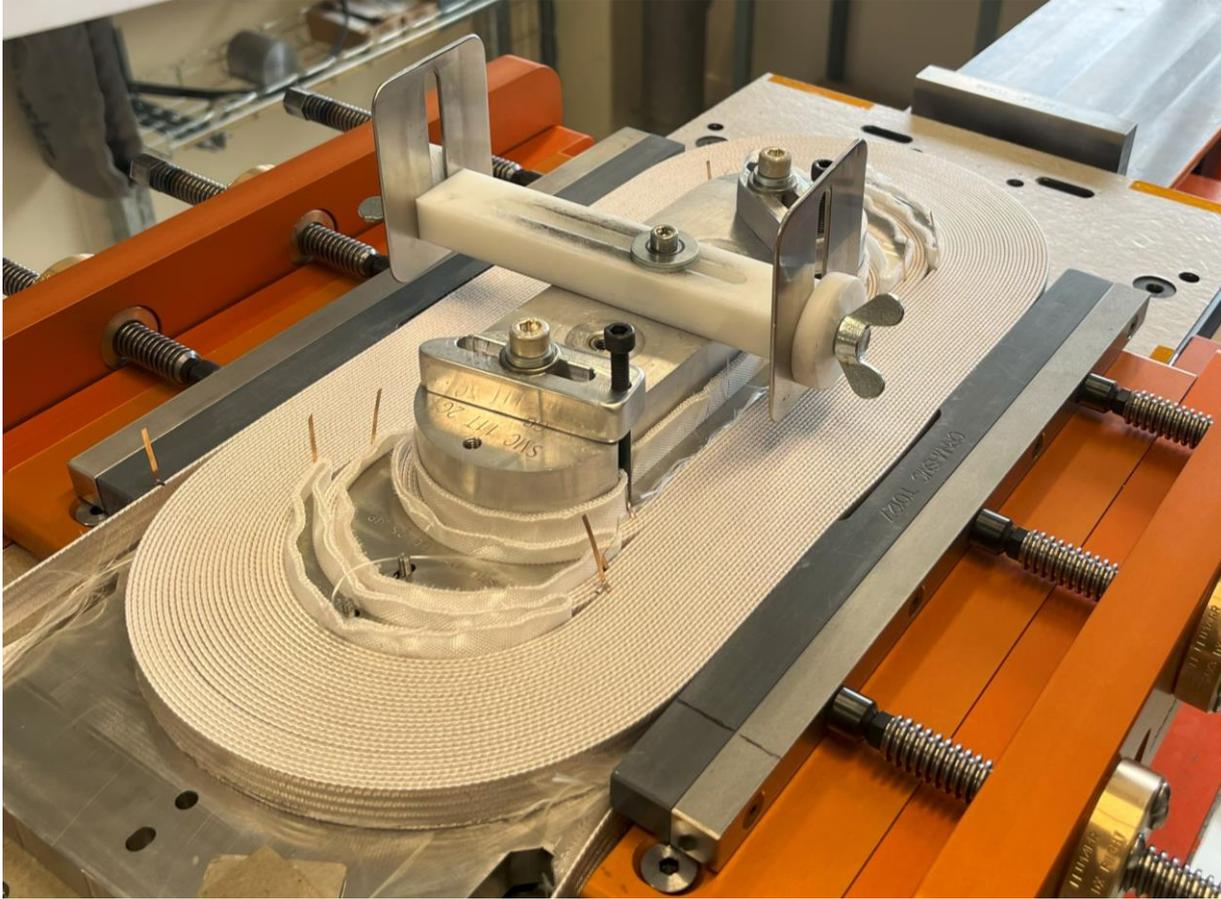
Second E-CLIQ test on an Nb₃Sn cable sample

2nd Generation of E-CLIQ coils in the setup in cryolab:

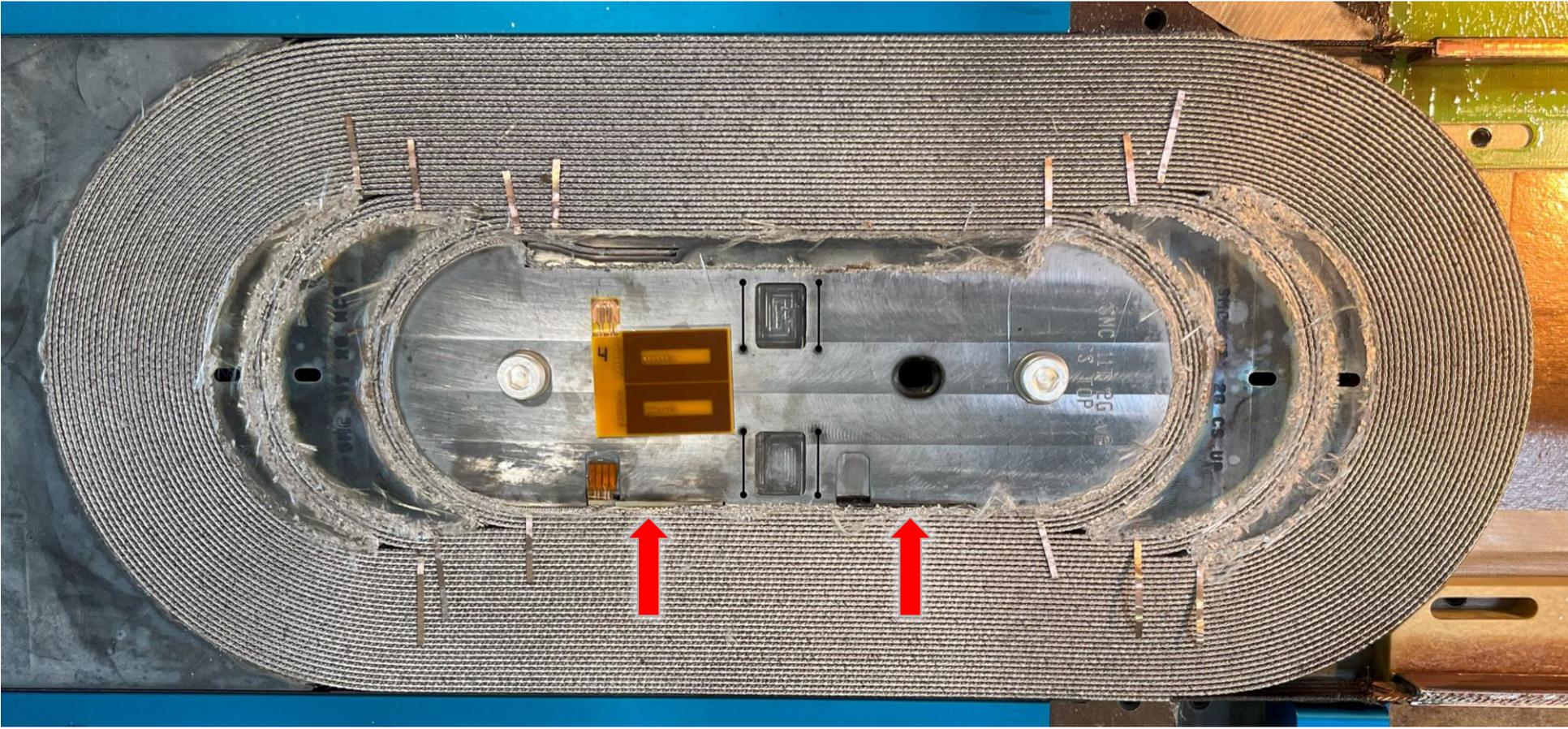
- 1 mm spacing between the E-CLIQ coils and the cable sample.
- Very similar temperature rise observed in the 70-130 Hz range in the 0 to 50 ms timespan.
- PSU issue, max 3 A E-CLIQ current, significant reduction in loss compared to max power.



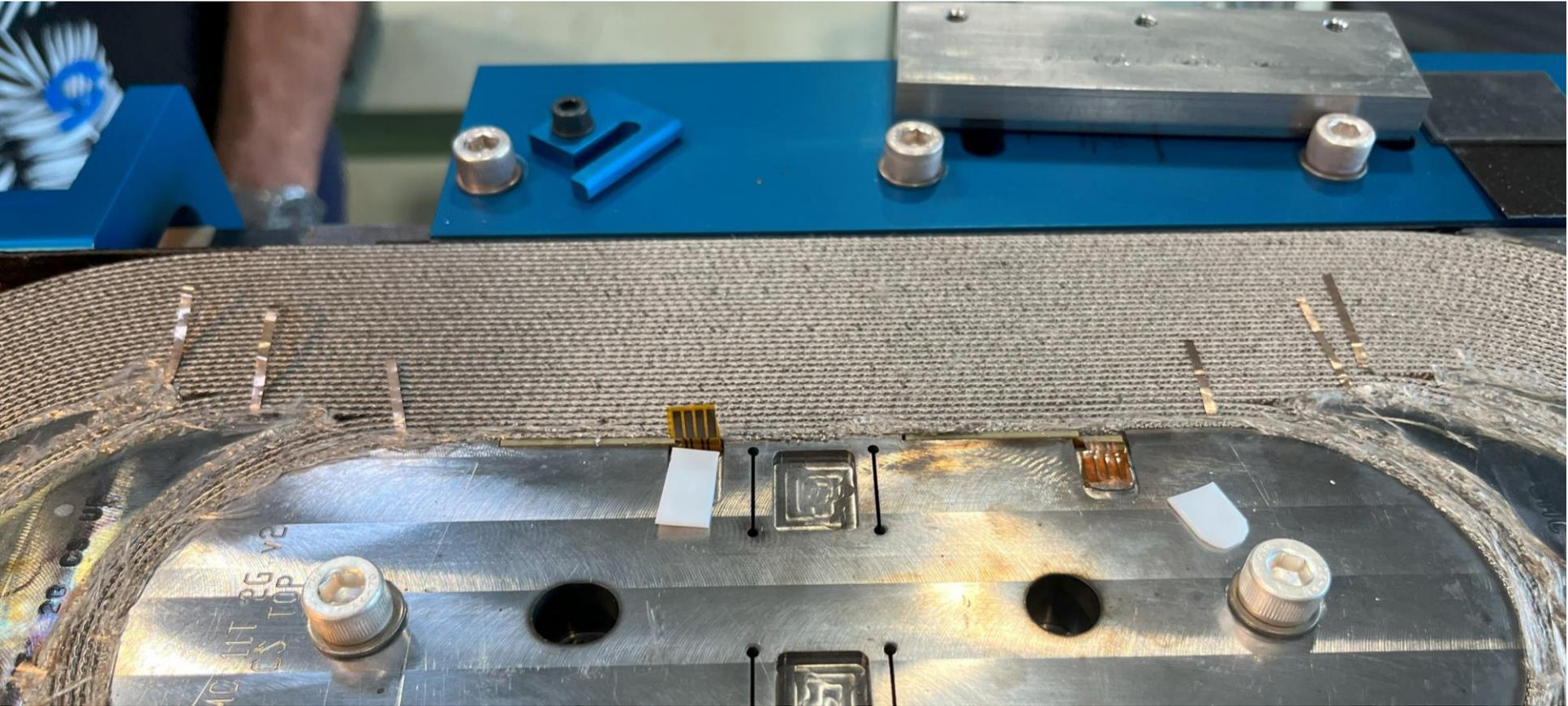
SMC is wound (B927, CERN)



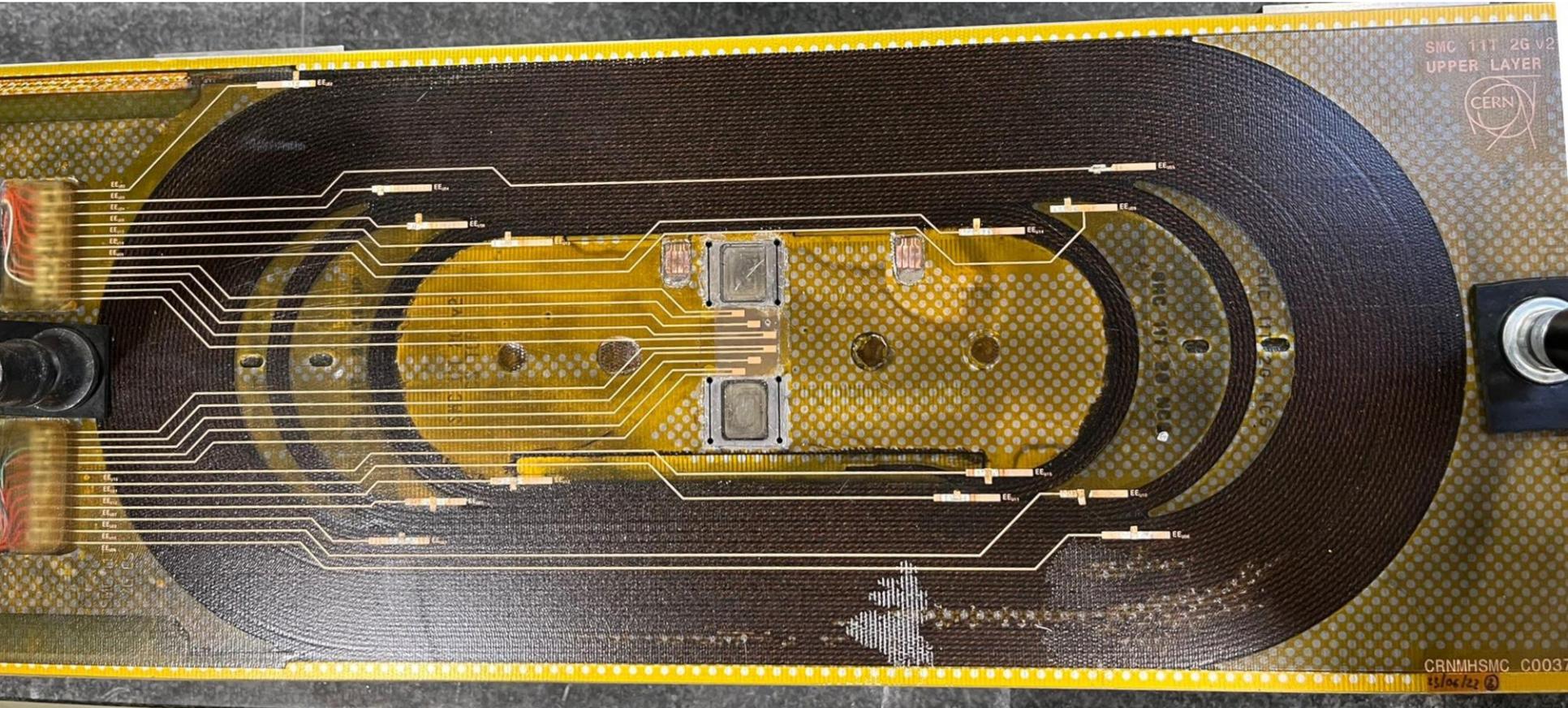
Insertion of the E-CLIQ coils (before impregnation)



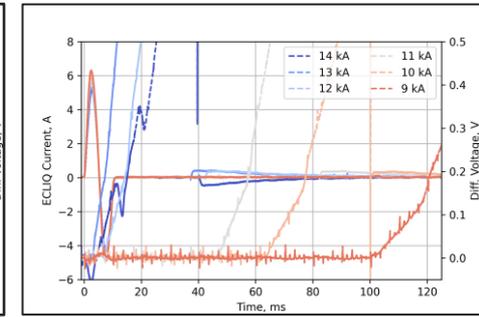
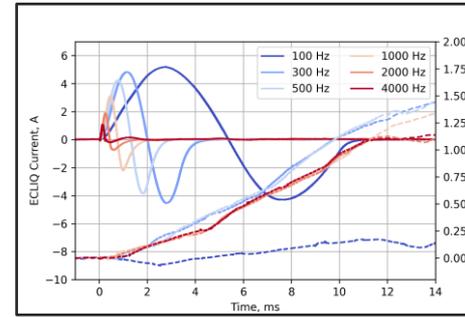
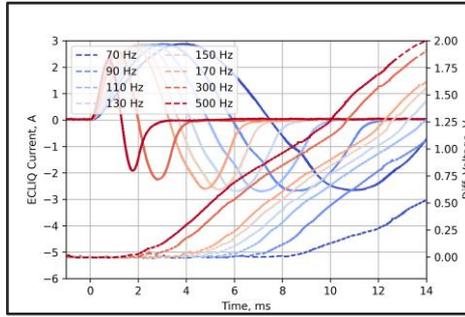
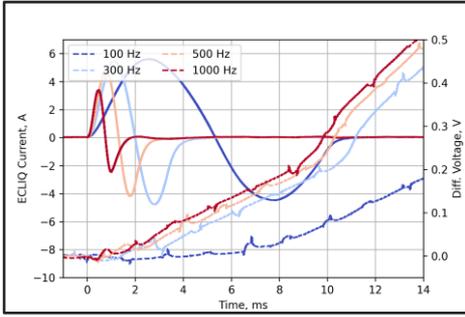
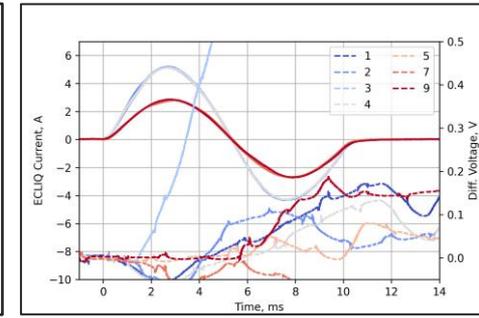
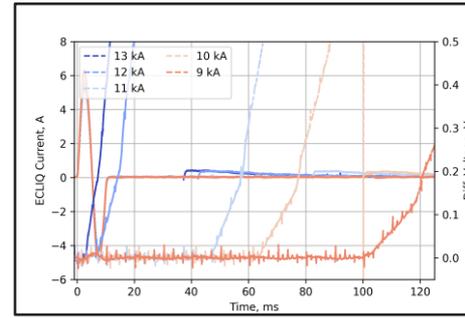
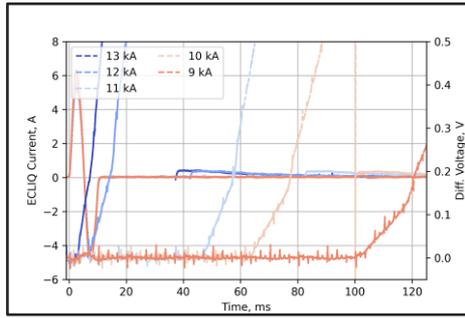
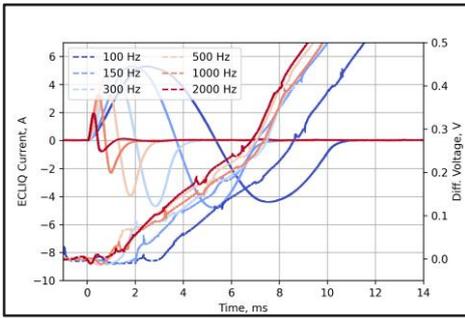
Insertion of the E-CLIQ coils (before impregnation)



Trace is added.



Measurement Results: 2nd generation of SMC11T



SMC108 (Feb 2025)

- ✓ 64 measurements at 4.5 K
- ✓ 12 measurements at 1.9 K
- ✓ E-CLIQ frequency of 70 Hz to 10 kHz
- ✓ Magnet current of 2.5 kA to 14 kA
- ✓ 7 different E-CLIQ configurations

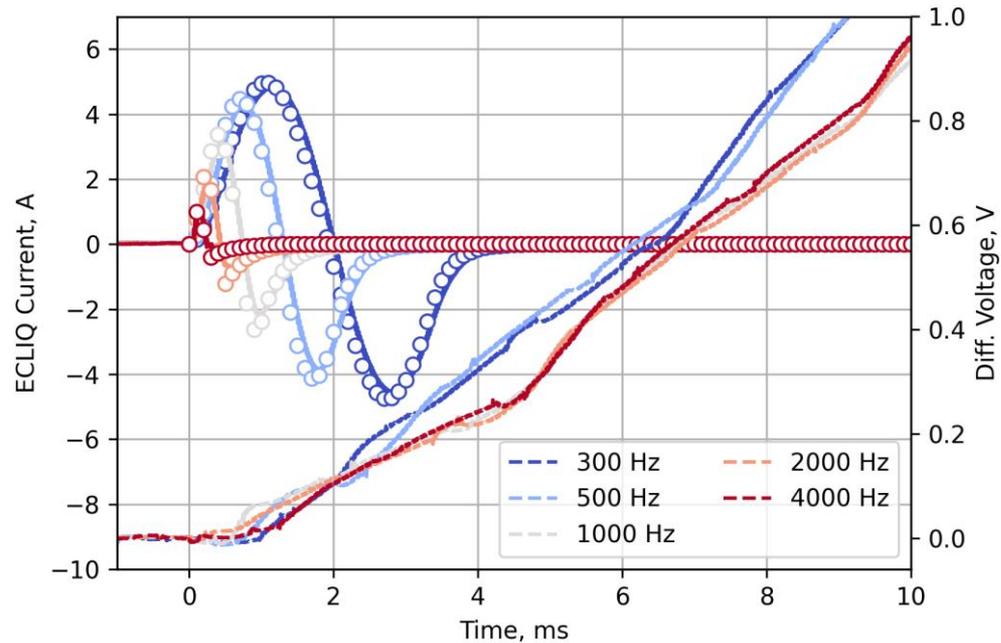
SMC109 (March 2025)

- ✓ 27 measurements at 4.5 K
- ✓ E-CLIQ frequency of 50 Hz to 1000 Hz
- ✓ Magnet current of 12 kA to 14 kA
- ✓ 2 different E-CLIQ configurations



Success!

- Quench initiation within a ms at a magnet current of 14 kA followed by NZP.
 - Quench initiation with some ms at lower currents.



Magnet current of 14 kA, frequency range of 300 to 4000 Hz, E-CLIQ voltage of 70 V, 4.5 K.

Four modes of possible quench initiation

1. AC loss

- *Loss due to dB/dt by the E-CLIQ coils. Mix between interstrand- and interfilament coupling loss, eddy current loss and hysteresis loss.*

2. Resistive heating

- *E-CLIQ comprises resistive copper coils and thus produce heat upon activation.*

3. Increase in peak field

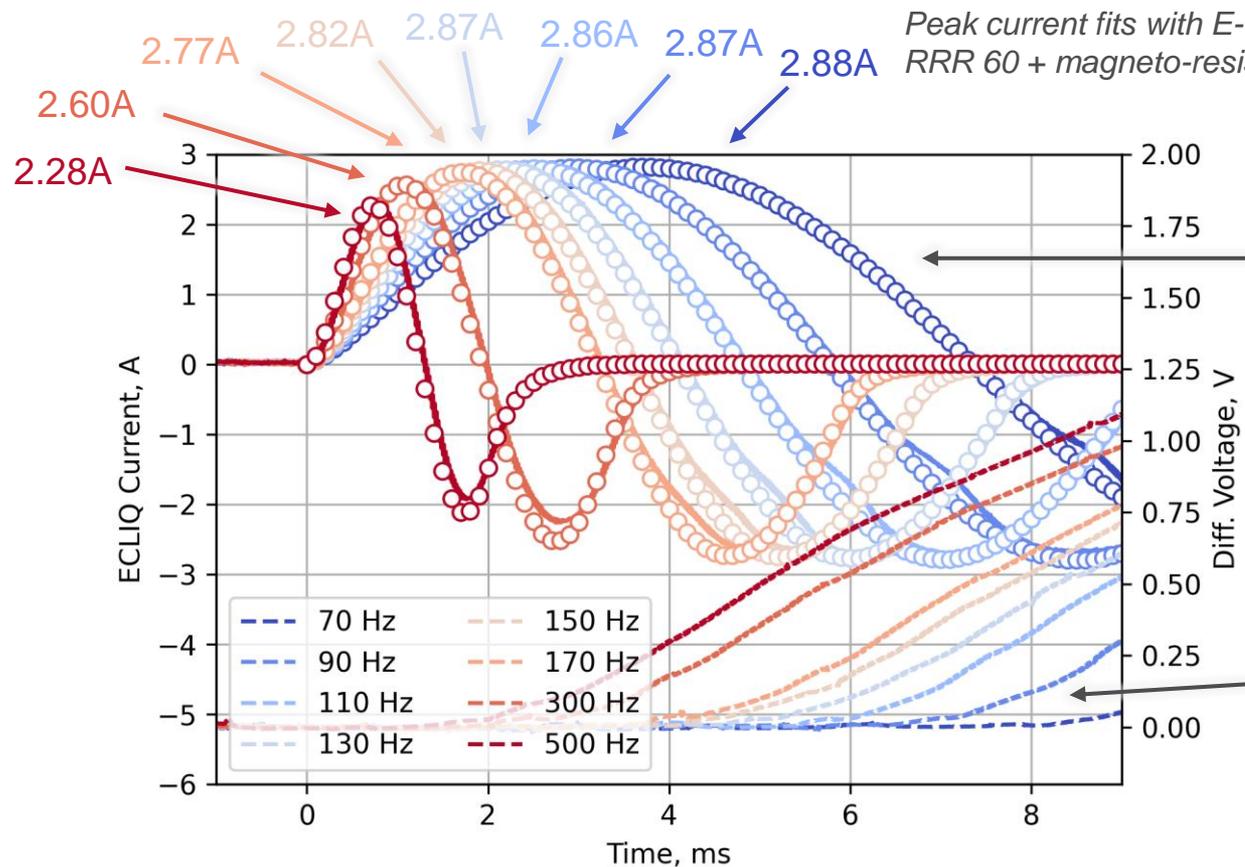
- *The peak field on the conductor increases by a few hundred mT due to the E-CLIQ field and affect the local conductor I_c .*

4. Forces and Vibrations

- *The E-CLIQ coils are in parallel field and upon activation will vibrate due to Lorentz force.*



Understanding the measurement results



Peak current fits with E-CLIQ resistance, RRR 60 + magneto-resistivity

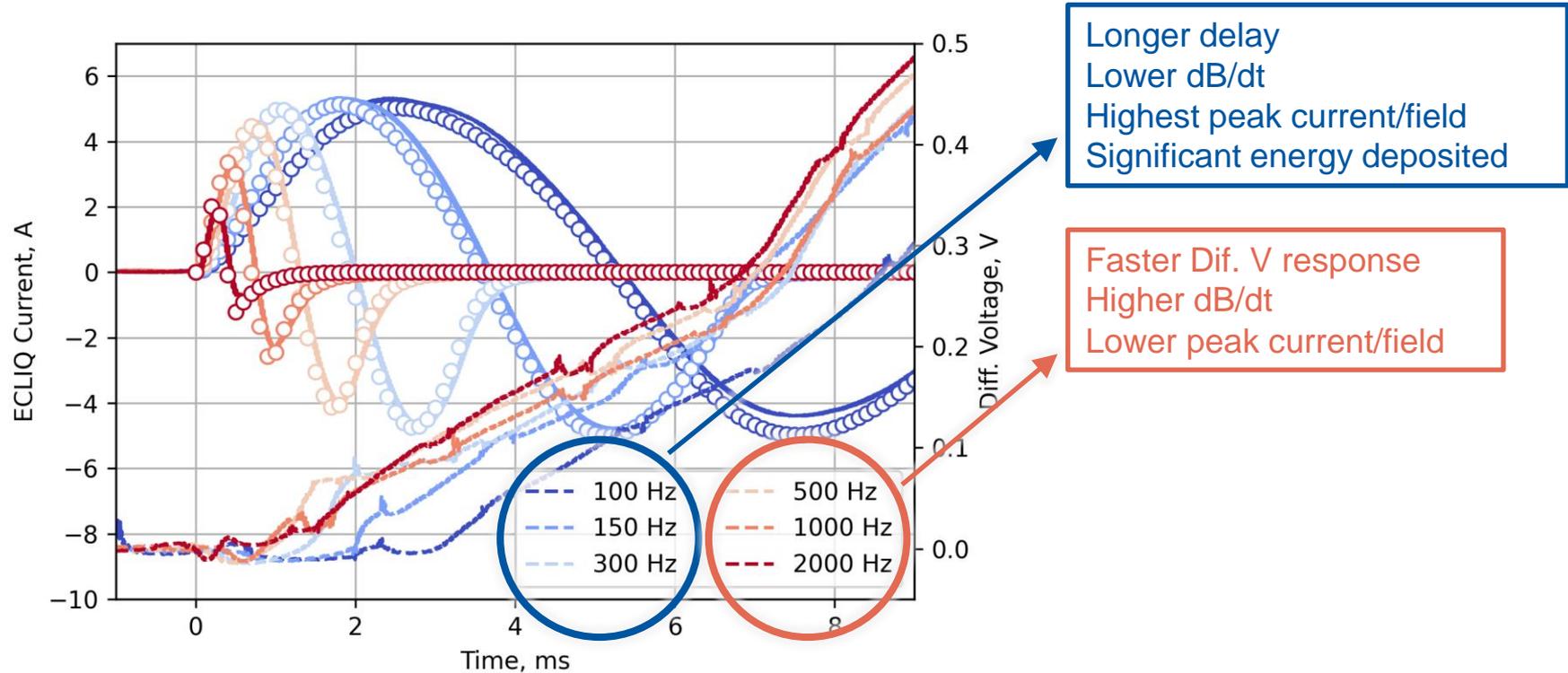
Using the measured input voltage, the expected E-CLIQ current is calculated ('o' markers).

Clear example of the time to quench as a function of E-CLIQ frequency.

Magnet current of 14 kA, frequency range of 70 to 500 Hz, E-CLIQ voltage of 35 V, 4.5 K.

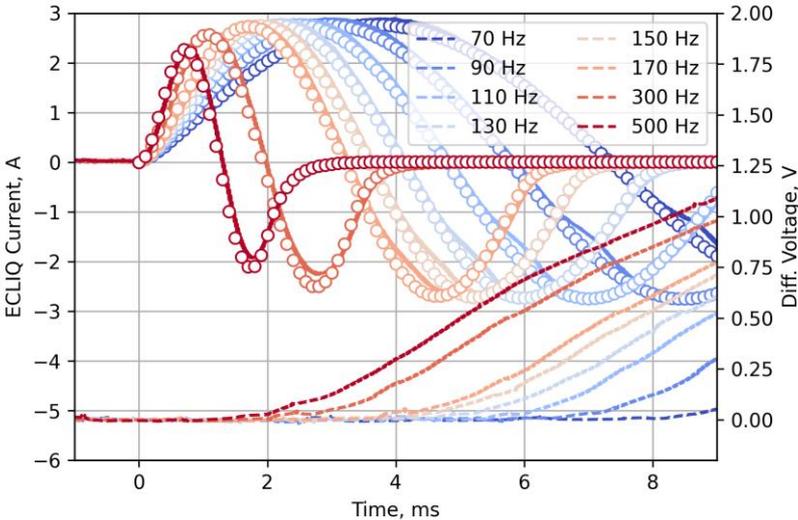


Magnet current of 13 kA, 100-500 Hz

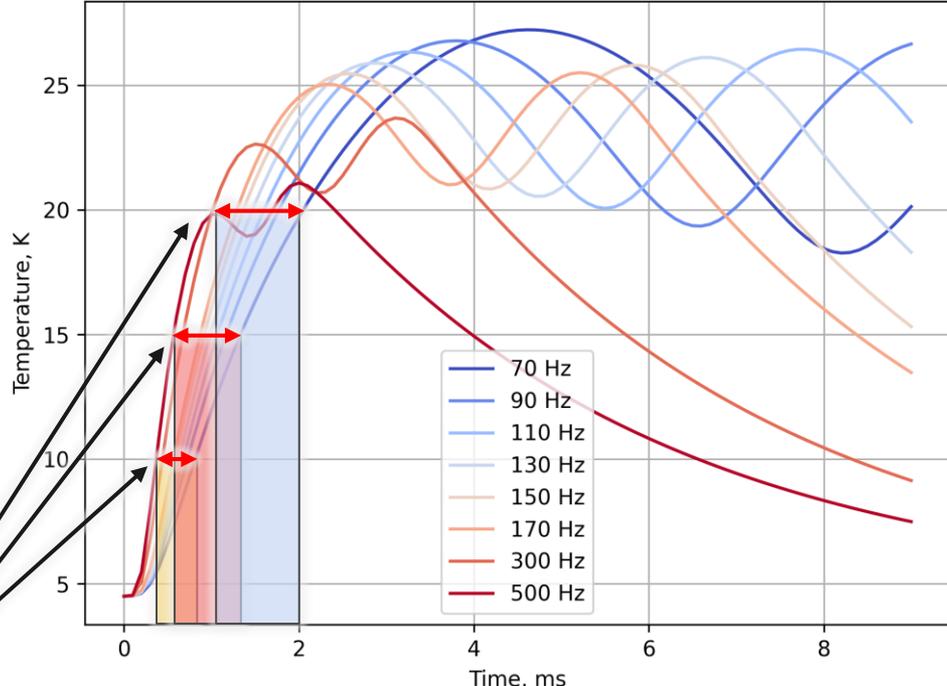


Magnet current of 14 kA, frequency range of 100 to 2000 Hz, E-CLIQ voltage of 70 V, 4.5 K.

Effect of E-CLIQ temperature



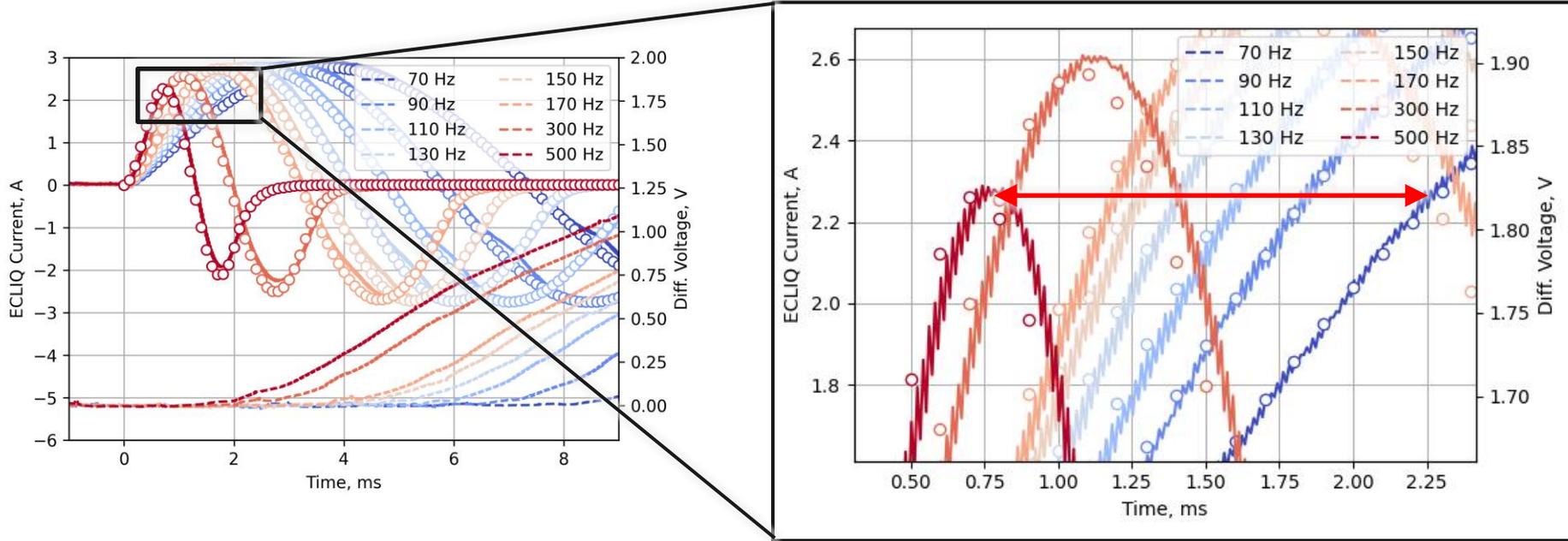
10 K: 0.4-0.8 ms range
 15 K: 0.6-1.3 ms range
 20 K: 1-2 ms range



Simulated E-CLIQ temperatures

E-CLIQ temperature does not seem to be a dominant factor for initiating a quench when the magnet is at or near nominal operating conditions.

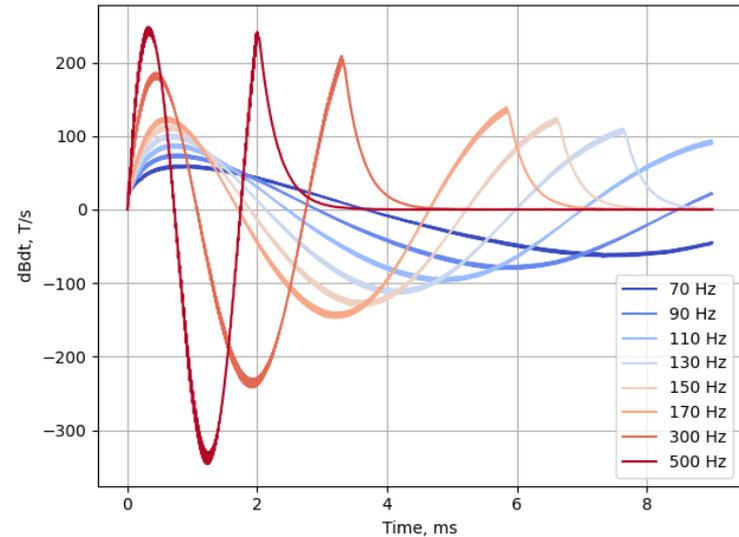
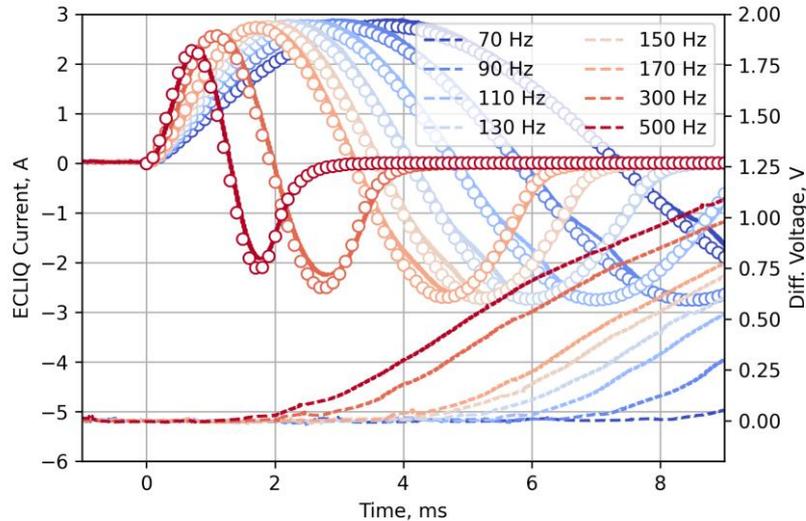
Effect of the peak produced magnetic field



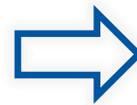
Using the peak current of the 500 Hz test as a reference: all E-CLIQ currents reach 2.3 A (~ 115 mT) within the timespan of 0.75 – 2.1 ms.

E-CLIQ peak produced magnetic field does not seem to be a dominant factor for initiating a quench when the magnet is at or near nominal operating conditions.

Effect of the change in magnetic field

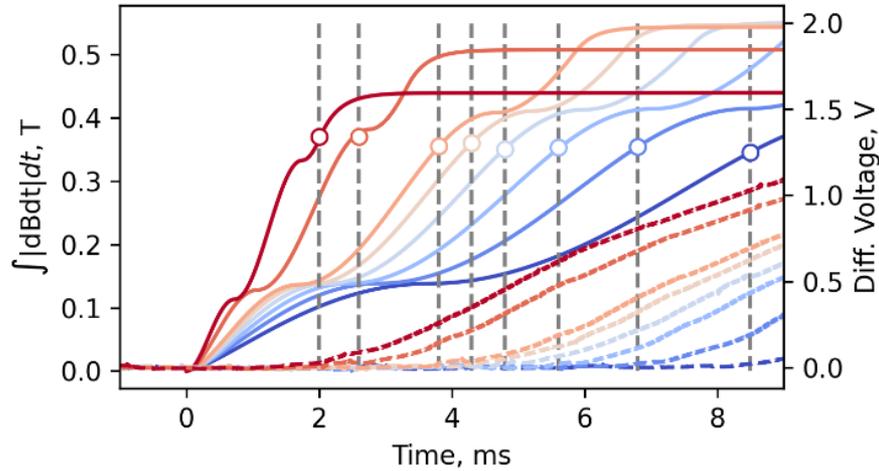


Using the input signal of E-CLIQ
the output is simulated.
(cleaner signal to integrate
compared to measured current)

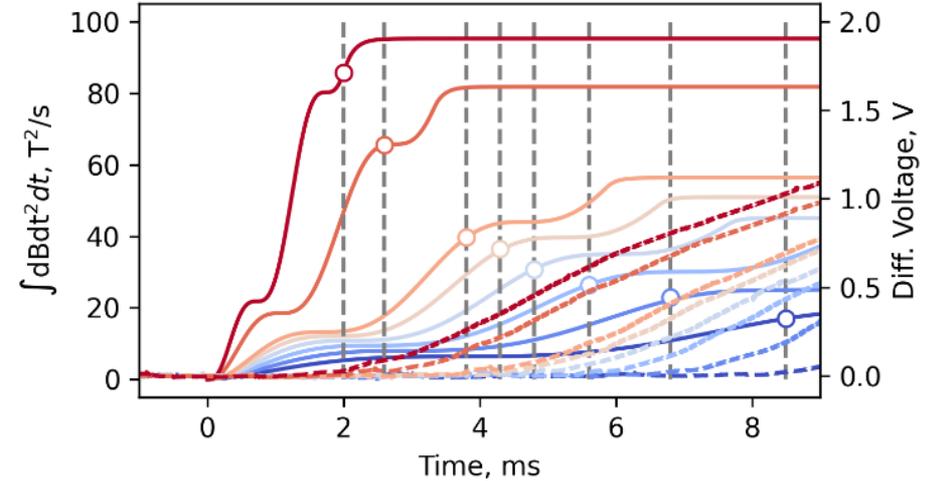


Simulated dl/dt translated to dB/dt
on the cable strand
(1 mm from the E-CLIQ surface)

Effect of the AC-loss

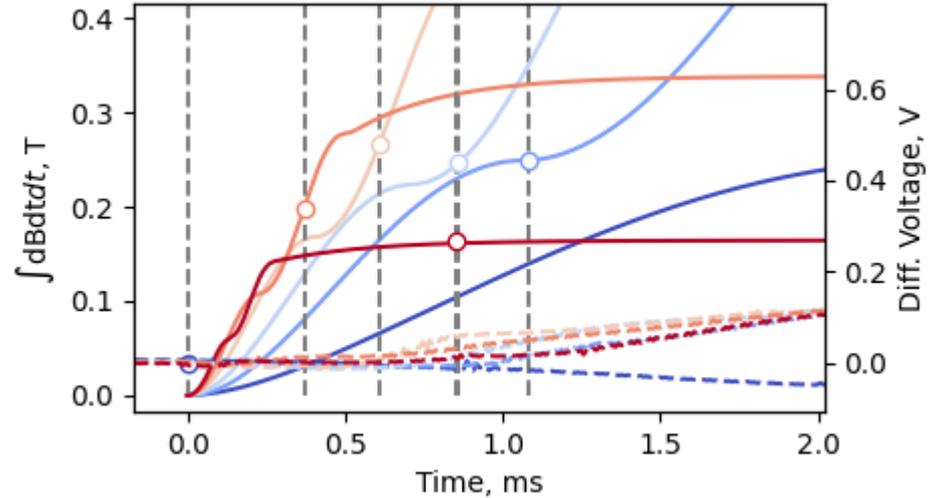
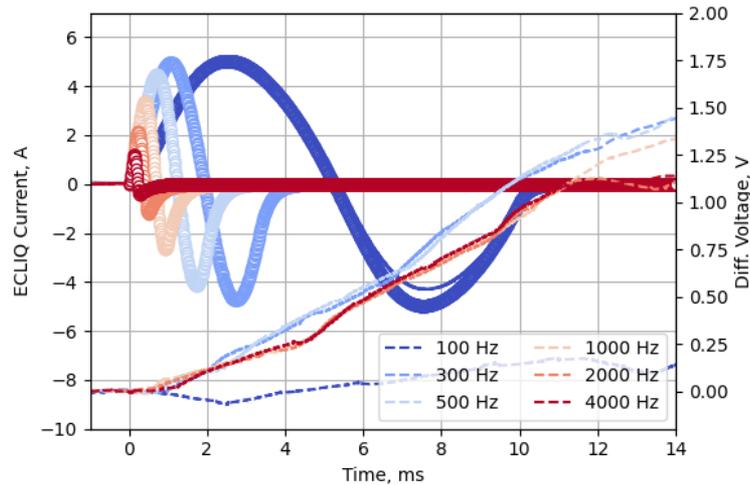


A clear correlation observed between integrated dB/dt and measured differential voltage. This indicates that the majority of the loss is hysteresis loss.



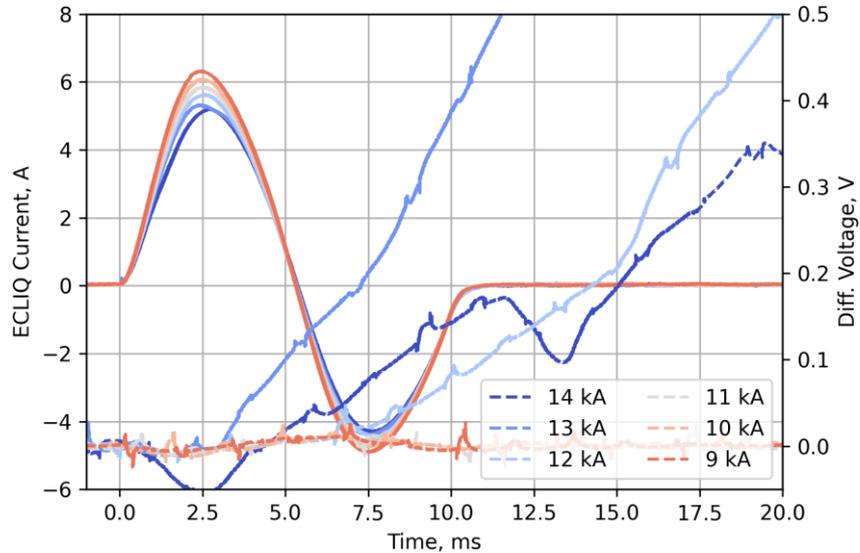
No clear correlation between the integrated (dB/dt)² and the time to quench.

Same method, but for higher E-CLIQ voltage.

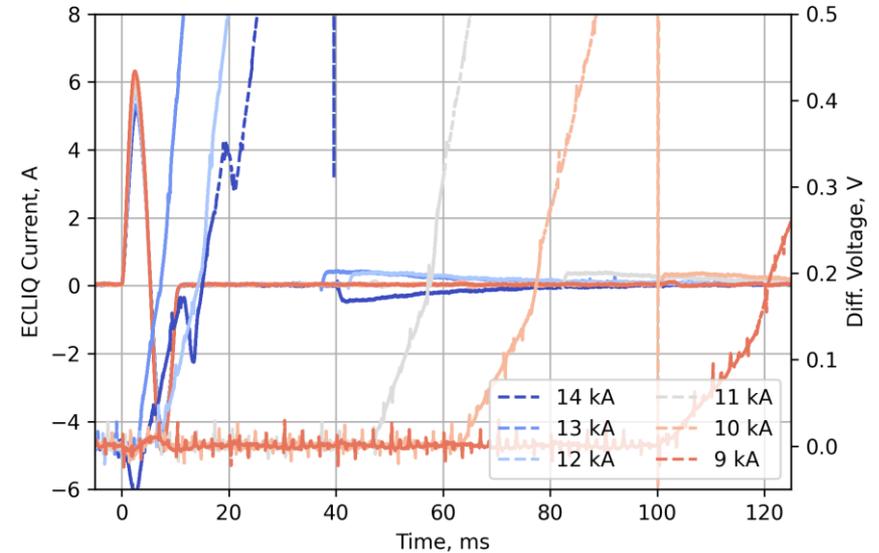


- A similar correlation was observed with a higher E-CLIQ voltage (thus also E-CLIQ current).
- Successful E-CLIQ activation and quench up to 4000 Hz with a single sine wave.
- At higher frequencies, inductive effects prevent effective current injection -> higher E-CLIQ voltage needed.
- E-CLIQ heats up, many cycles at high frequencies (≥ 2000 Hz) are not very effective with the current amplifier setup.

Lower operating currents

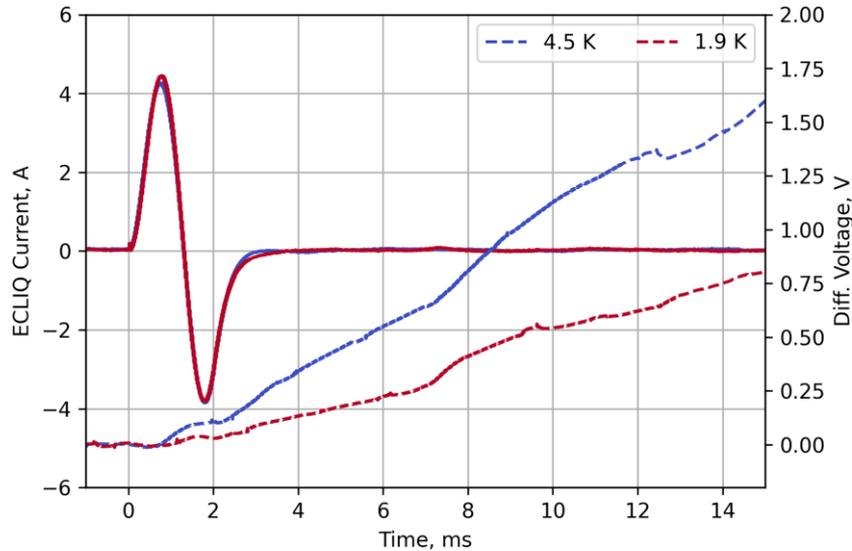


Down to 12 kA a quench could be initiated by AC-loss with a single sine wave.

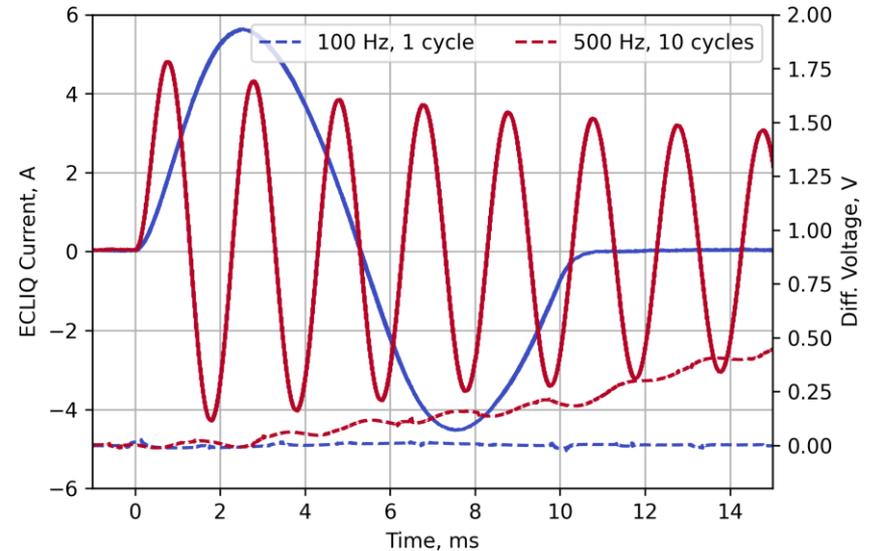


At lower currents, it was not sufficient, and a quench would occur later due to thermal conduction of heat from the E-CLIQ coils towards the conductor.

4.5 K vs 1.9 K



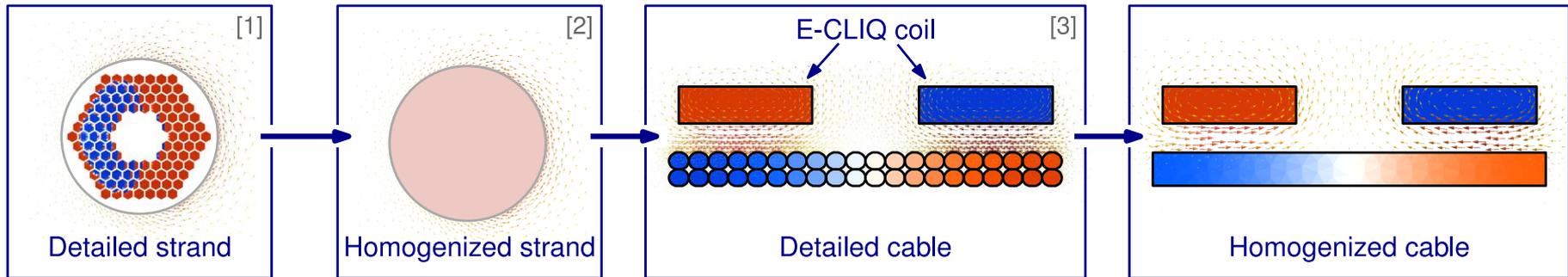
Magnet current of 14 kA, frequency range of 500 Hz, E-CLIQ voltage of 70 V.



Magnet current of 12 kA @ 1.9K, frequency range of 100 Hz and 500 Hz, E-CLIQ voltage of 70 V.

- Magnet is more stable at 1.9 K, more energy needed to initiate a quench.
- Lower NZPV is observed.
- Higher frequencies are more efficient at lower magnet current.

- **Modelling framework (work in progress):**
 - Open-source implementation in FiouS (Python code based on Gmsh/GetDP),
 - Multi-scale homogenization including various **loss** and **magnetization** contributions:
 - **hysteresis** in Nb_3Sn filaments (external field and transport current),
 - **inter-filament coupling** currents in Cu matrix,
 - **eddy** currents in Cu matrix,
 - **inter-strand coupling** currents at strand interfaces.



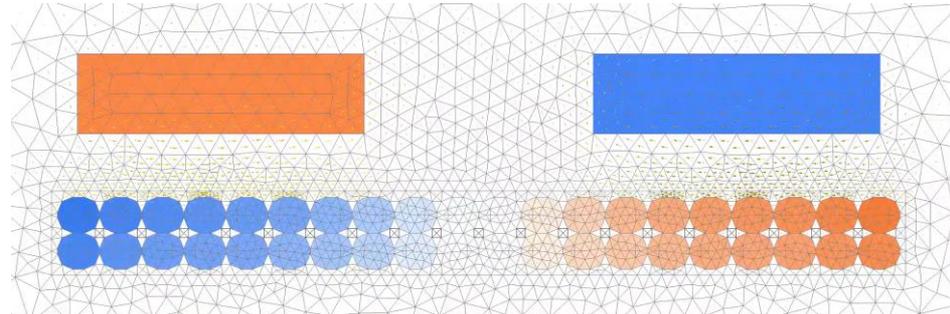
- **Next steps:**
 - Validate model parameters,
 - Investigate different configurations (E-CLIQ coil position, multiple cables, frequency ...).

[1] J. Dular *et al* 2024 *IOP SUST* **37** 095002.
[2] J. Dular *et al* 2025 *IOP SUST* **38** 035017.
[3] J. Dular *et al* 2025 *IEEE TASC* **35** 4700605.

Finite Element Modelling of induced AC losses

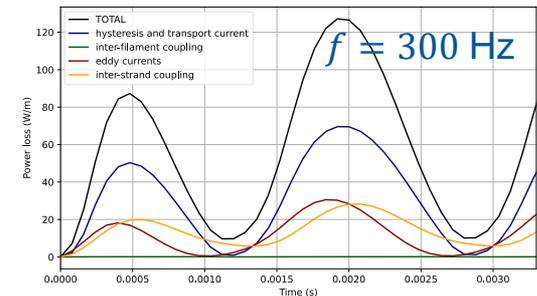
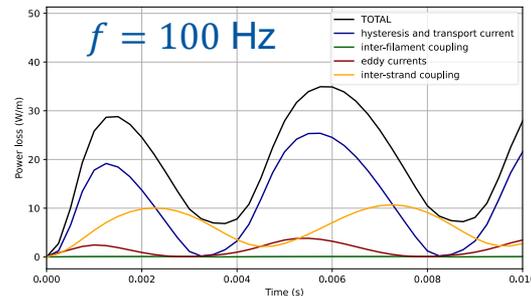
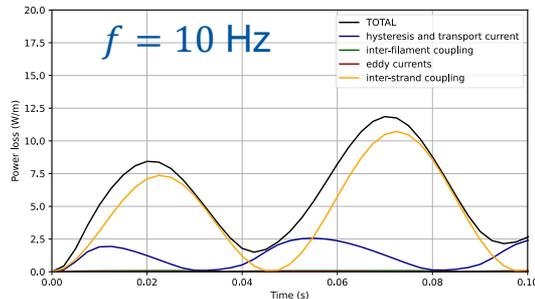


- **Preliminary results (work in progress):**
 - Nb₃Sn strand; 40-strand cable (contact resistance $R_c = 20 \mu\Omega$).
 - Parallel background field up to 13 T; transport current up to 14 kA; temperature 4.5 K.
 - E-CLIQ excitation current 6 A (2016 A-turns), various frequencies.



Shown without background field and transport current for easier visualization

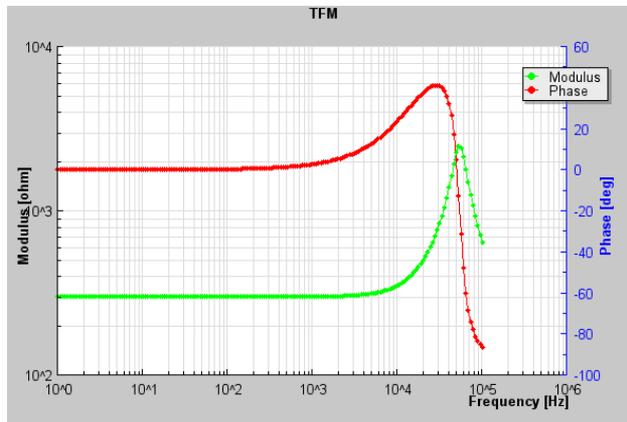
Instantaneous power loss for various frequencies:



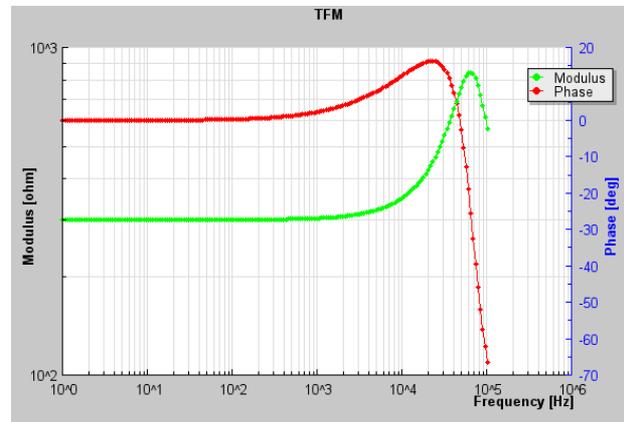
Transfer Function Measurements (TFMs)

- TFM to get a better understanding of the coupling between E-CLIQ and cable.
- TFM done on an isolated single E-CLIQ coil.
- TFM have been done on the E-CLIQs in SMC109 at RT and 4.5 K.
- Data still has to be analyzed.

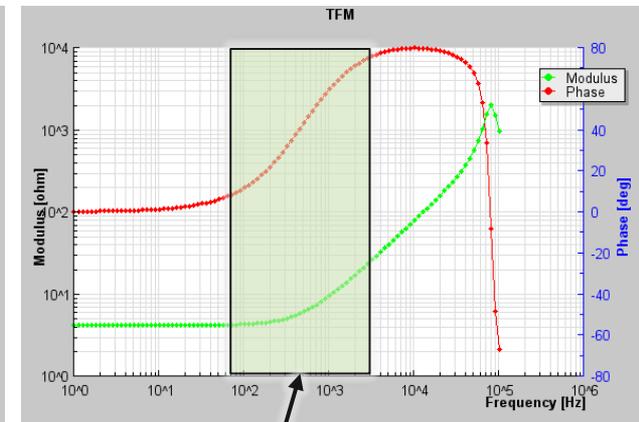
Isolated



RT



4.5 K (magnet is not powered)

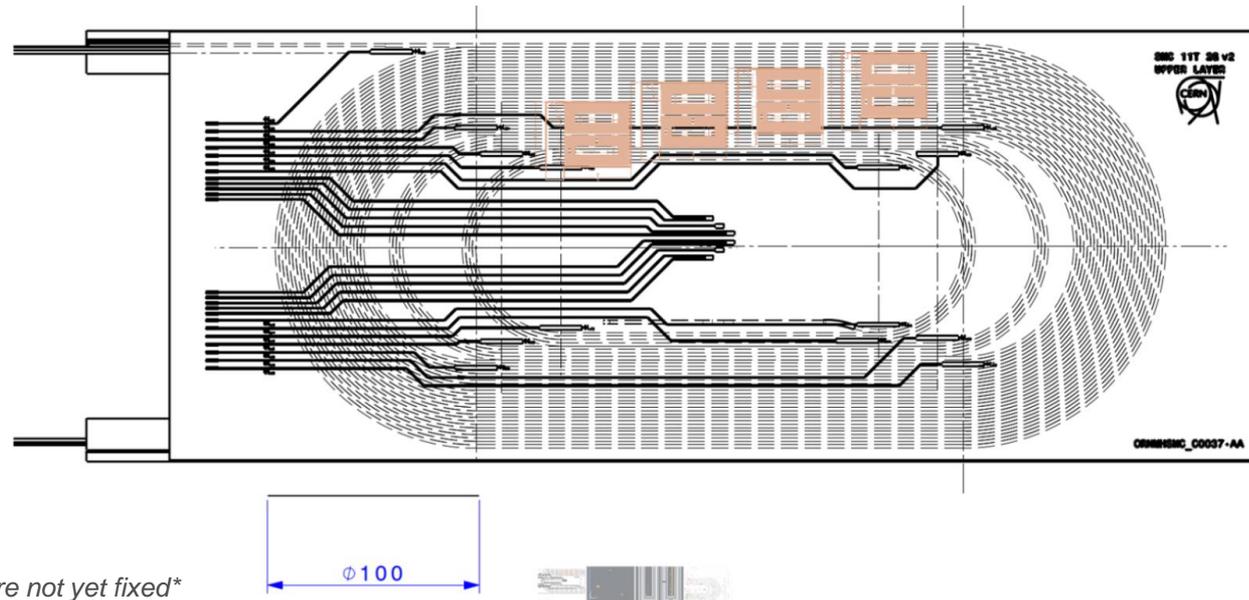


Region of interest.

*Y-axes of the different plots are scaled differently.
Resistance is exactly as expected.*

What is next?

- E-CLIQ placement on the top/bottom sides of the coil.
- Similar to where a traditional quench heater would be placed.
- Allows probing of high and low field performance.
- Effect of distance between E-CLIQ and SMC, electrical robustness.



*E-CLIQ positions are not yet fixed**

What is next?

Protection studies:

- Quantify what kind of E-CLIQ configuration is needed to protect a full-sized accelerator magnet.
- Realistically achievable?

New E-CLIQ devices:

- Design new E-CLIQ devices optimized for use with a capacitor bank.
- Size and quantify capacitor bank needs for the new E-CLIQs.



Conclusions

- E-CLIQ v2 has been **successfully demonstrated** on SMC108 & SMC109.
- Fast quench initiation in high field of < 1 ms.
- Demonstrated effectiveness in a wide frequency range from 50 to 4000 Hz.
- Demonstrated the ability to induce a quench down to low magnet currents.
- Primarily loss mechanism is hysteresis loss, strongly suggested by experimental results and by simulation.

How does its performance scale to a full-size magnet?



Special thanks to:

927 Team

- J.C. Perez, A. Haziot, N. Peray, C. Fernandes, F. Garnier, G. Maury, D. Cote and B. Fornes.

SM18 Team

- G. Willering, M. Boczan, J.-L. Guyon and J. Feuvrier

PCB Manufacturing

- B. Mehl

Cryolab

- P. Borges de Sousa

Machine Protection

- A. Verweij, M. Wozniak, J. Dular and G. West



Questions?

