# A look at HTS Quench Detection and Protection

***Glyn Kirby***

***17th June 2022***

# Overview

- Types of coil (the insulation zoo)
- REBCO transition (superconducting to resistive)
- types of detection (systems & signals)

# HTS Coil Designs Overview

- Coil insulation Zoo

NI
- Very low resistance (Fully soldered *long time constants days 1600 x longer time constants then dry in small solenoids tested at CERN*)

PI
- Medium resistance (Stainless steel tapes between turns *several hrs*)
- Medium + resistances (Removed tape edges + sealed + stainless steel tapes)
- Medium ++ resistance ( Dry wound coil with controlled tension *10's of min to an hr* )

VI
- Switchable insulations (fast ramping and switch to NI after quench, + heating at insulation)

  Smart insulation (switches with a temp change 150K , $V_2O_3$ insulation.)

  Varistor Insulation ( switches with a voltage SiC. )

I
- Classical fully insulated coil.

Note time constants are dependent on many variables

# Radial current path,

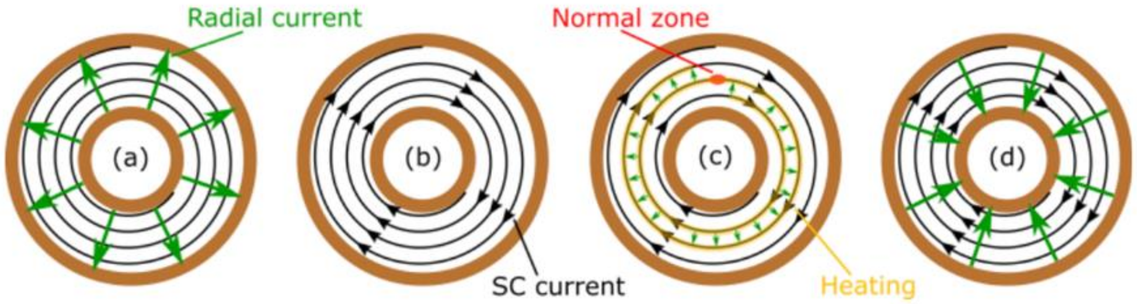
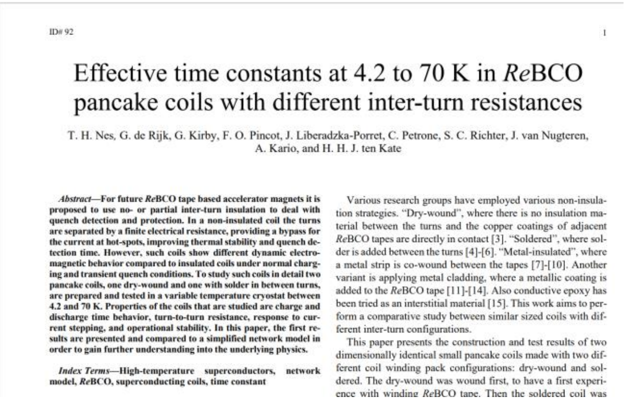



Fig. 1. Predicted current path in the case of (a) charging the coil, (b) operation in steady state, (c) in the presence of a normal zone, and (d) during discharge.



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## Effective time constants at 4.2 to 70 K in *Re*BCO pancake coils with different inter-turn resistances

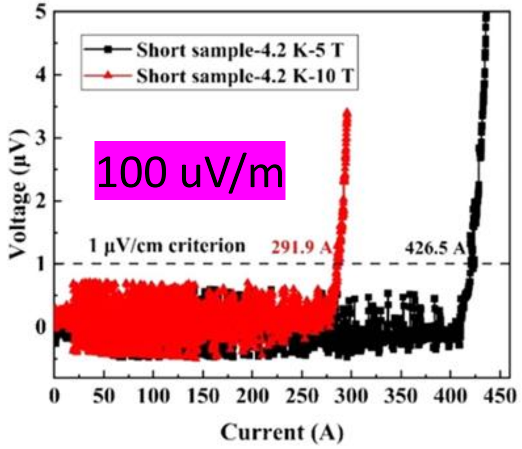
T. H. Nes, G. de Rijk, G. Kirby, F. O. Pincot, J. Liberadzka-Porret, C. Petrone, S. C. Richter, J. van Nugteren, A. Kario, and H. H. J. ten Kate

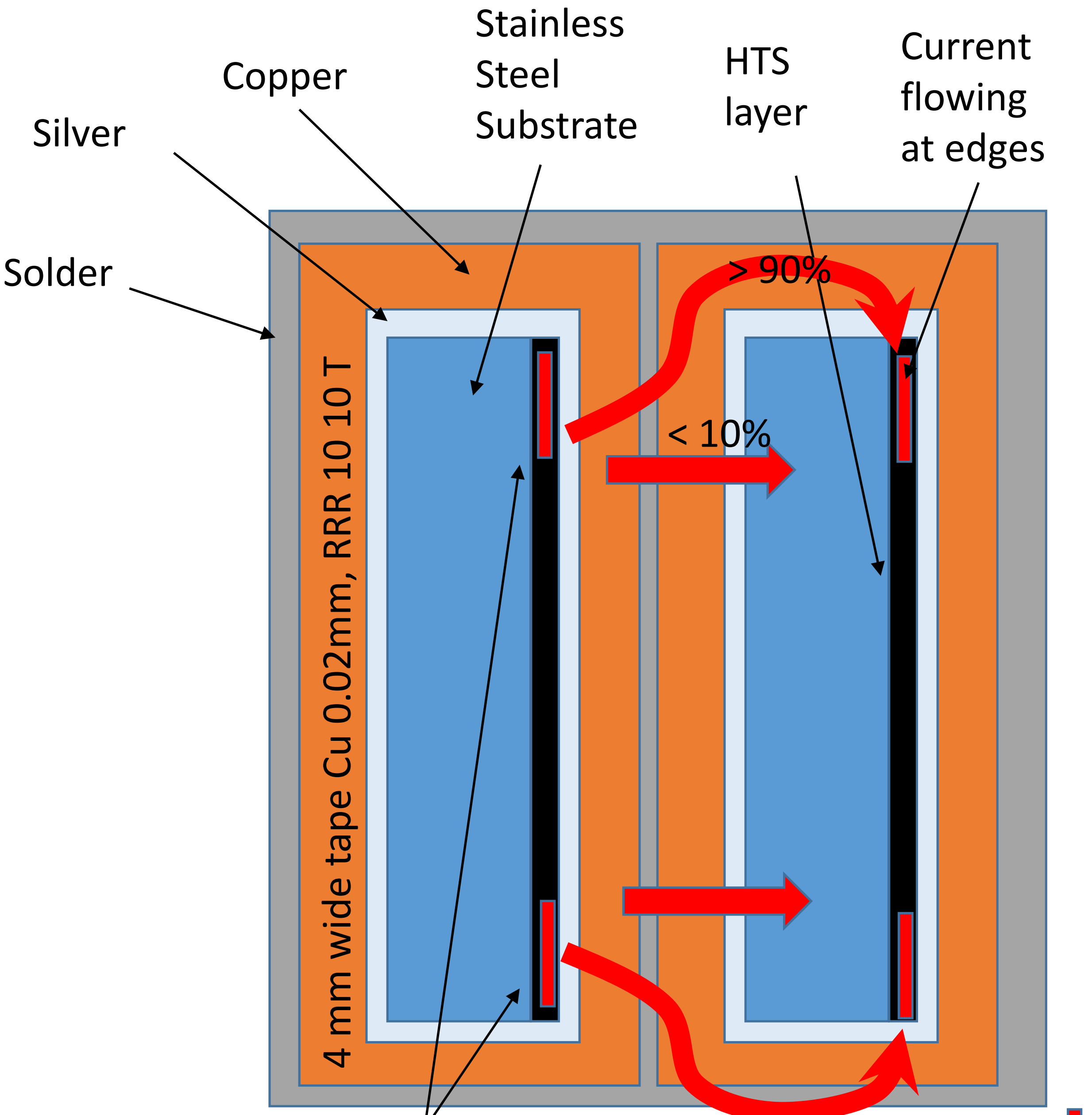
***Abstract*—For future *Re*BCO tape based accelerator magnets it is proposed to use no- or partial inter-turn insulation to deal with quench detection and protection. In a non-insulated coil the turns are separated by a finite electrical resistance, providing a bypass for the current at hot-spots, improving thermal stability and quench detection time. However, such coils show different dynamic electromagnetic behavior compared to insulated coils under normal charging and transient quench conditions. To study such coils in detail two pancake coils, one dry-wound and one with solder in between turns, are prepared and tested in a variable temperature cryostat between 4.2 and 70 K. Properties of the coils that are studied are charge and discharge time behavior, turn-to-turn resistance, response to current stepping, and operational stability. In this paper, the first results are presented and compared to a simplified network model in order to gain further understanding into the underlying physics.**

***Index Terms*—High-temperature superconductors, network model, *Re*BCO, superconducting coils, time constant**

Various research groups have employed various non-insulation strategies. "Dry-wound", where there is no insulation material between the turns and the copper coatings of adjacent *Re*BCO tapes are directly in contact [3]. "Soldered", where solder is added between the turns [4]-[6]. "Metal-insulated", where a metal strip is co-wound between the tapes [7]-[10]. Another variant is applying metal cladding, where a metallic coating is added to the *Re*BCO tape [11]-[14]. Also conductive epoxy has been tried as an interstitial material [15]. This work aims to perform a comparative study between similar sized coils with different inter-turn configurations.

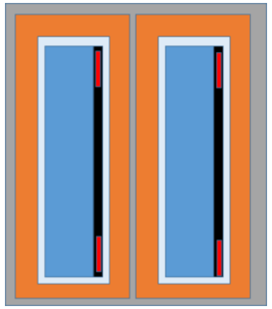
This paper presents the construction and test results of two dimensionally identical small pancake coils made with two different coil winding pack configurations: dry-wound and soldered. The dry-wound was wound first, to have a first experience with winding *Re*BCO tape. Then the soldered coil was

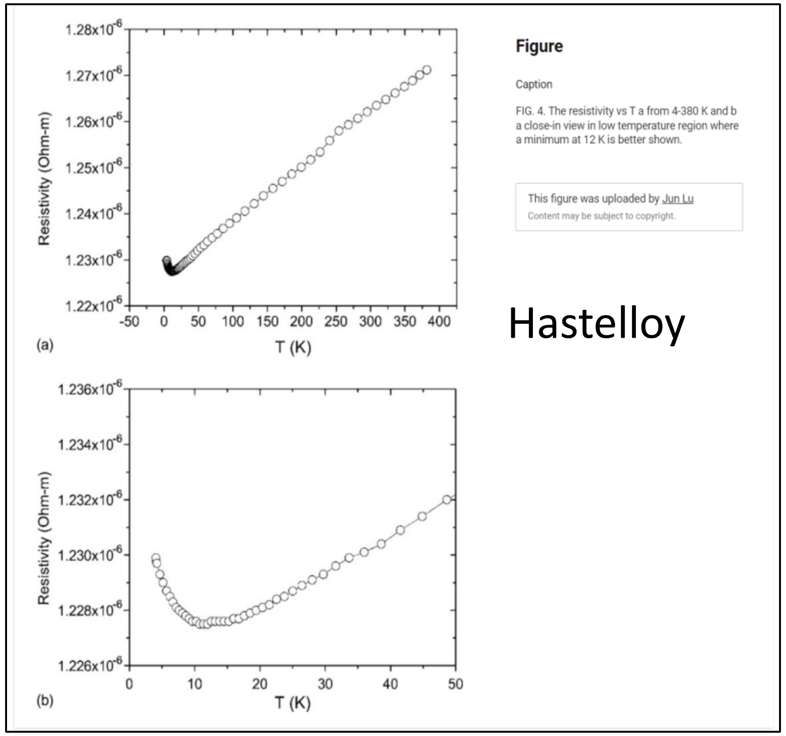


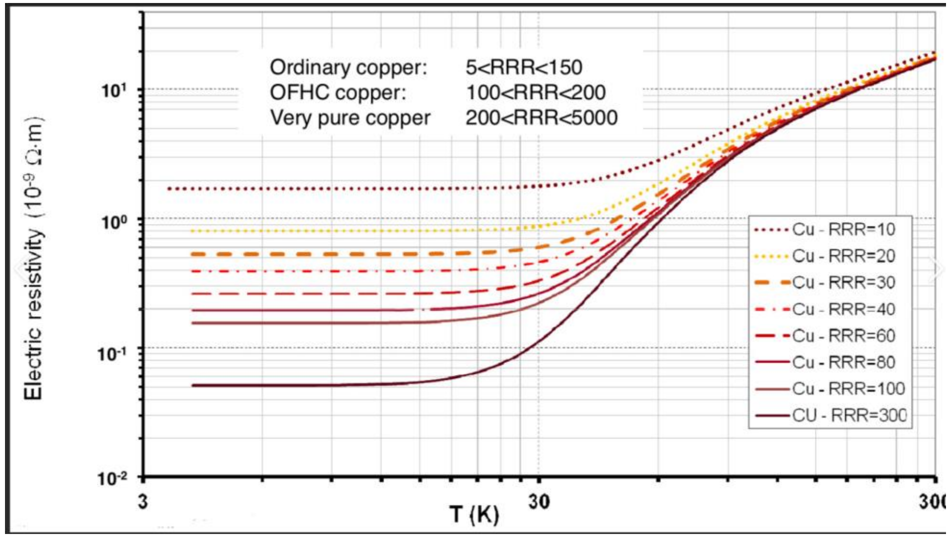



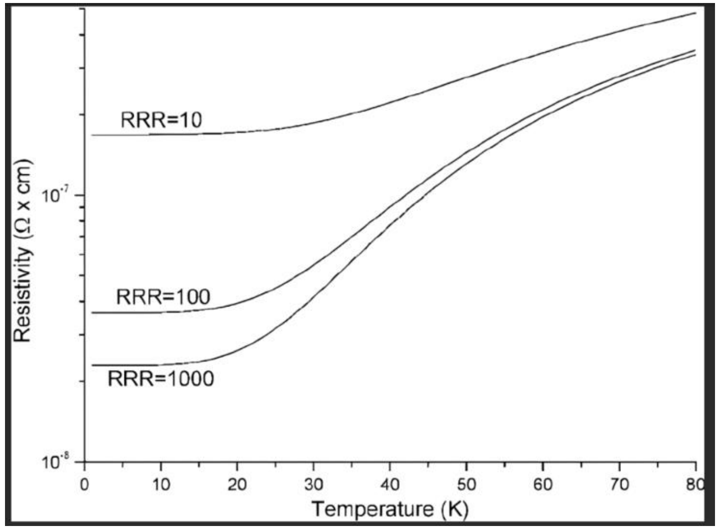

Due to angular dependence at lower than max current, the current flows at the edges

# Hastelloy v Copper (@ RRR 50 in 10 T)





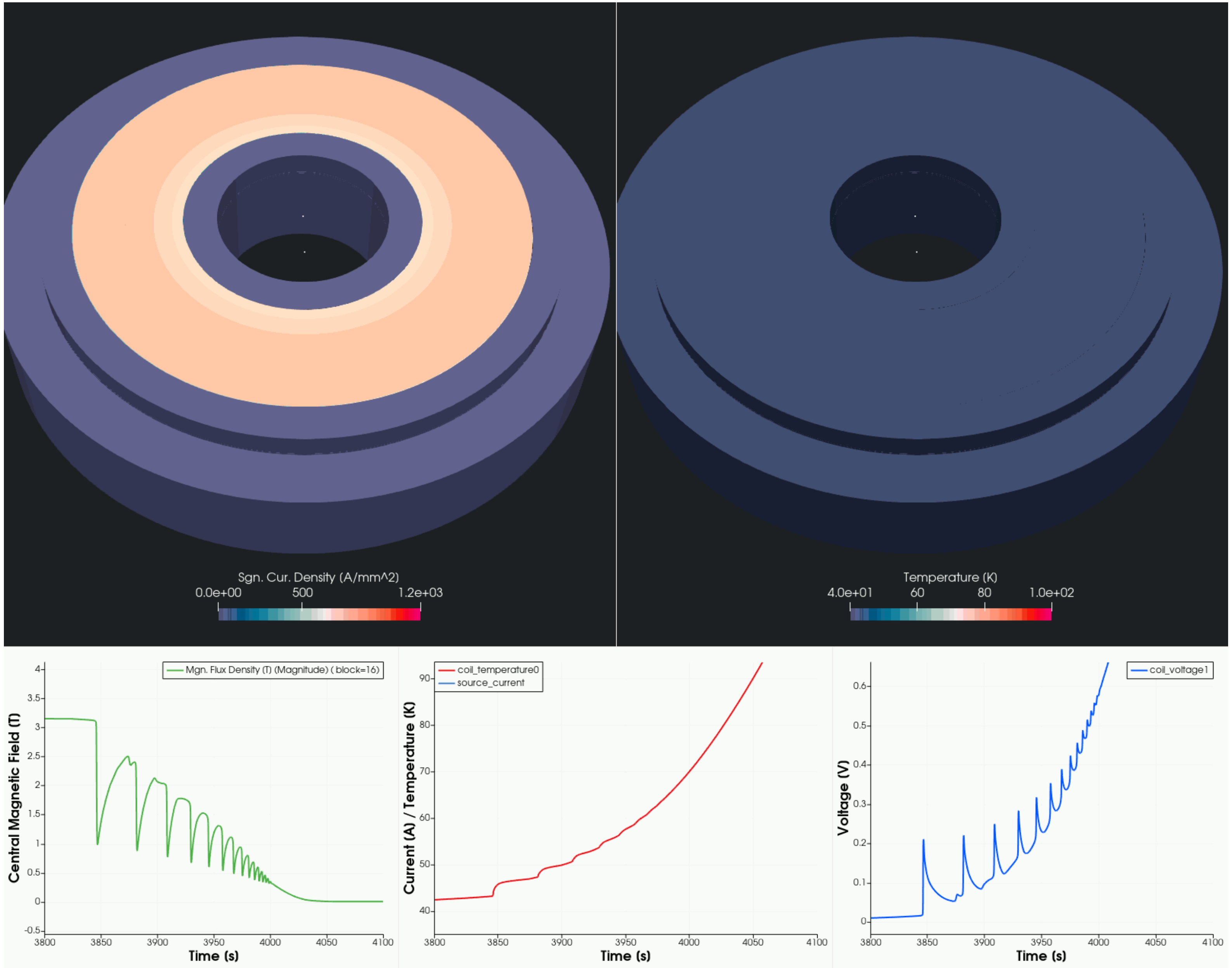




The resistivity of silver is just a little lower than copper

[(11) (PDF) Physical properties of Hastelloy (R) C-276 (TM) at cryogenic temperatures (researchgate.net)]

# HTS Quench

HTS quench in simple coil, we see the evolution of field, temperature, current density, voltage maps, during quench.

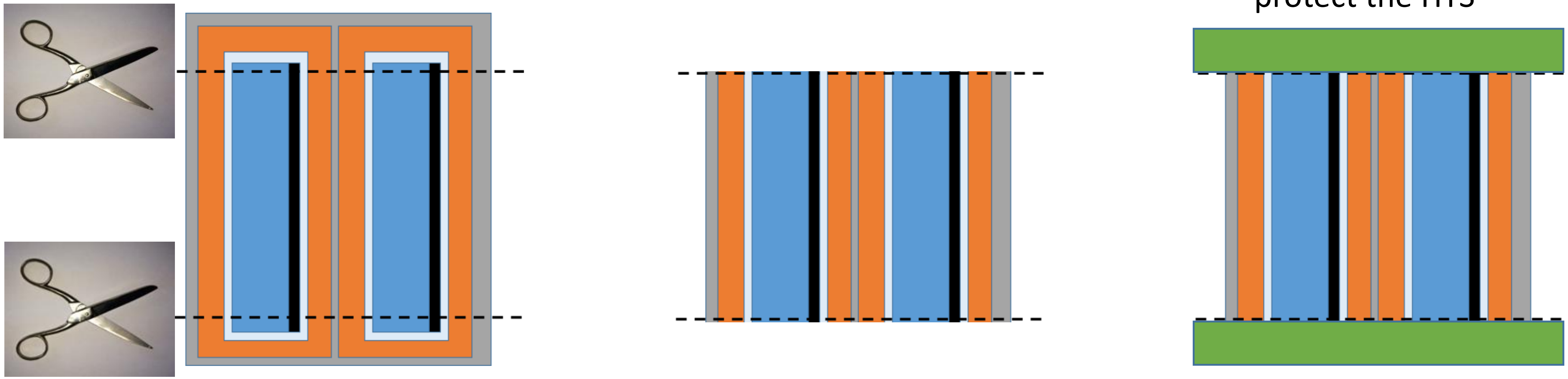



[DIPOLE HTS MAGNETS AT CERN | G. Kirby | 978 updates | 2 publications | Research Project (researchgate.net)]

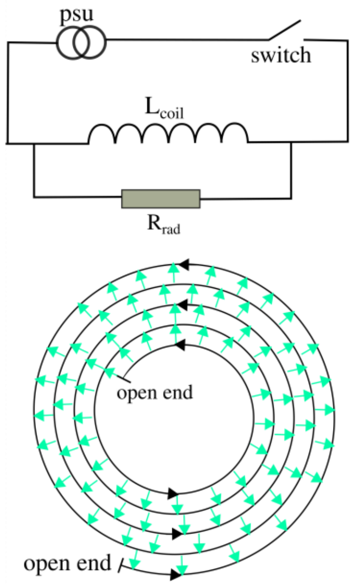
Thanks to LittleBeast engineering for the modelling
Mar 31 2021

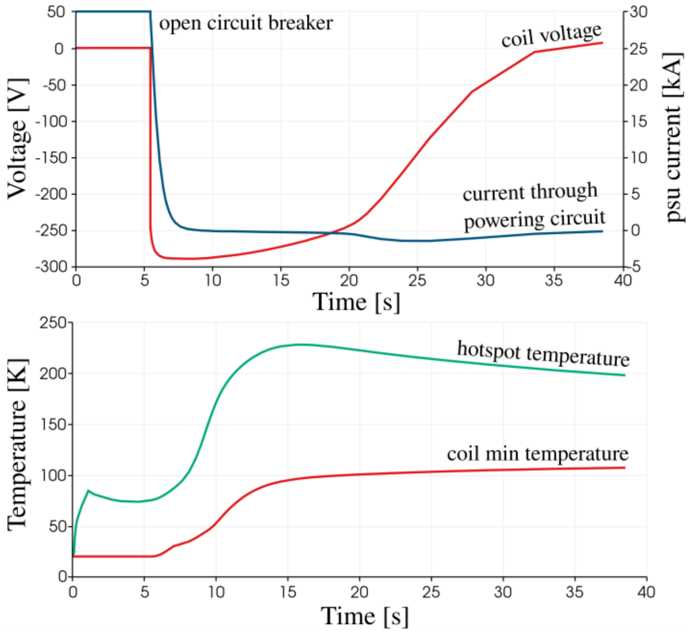
# Cutting of the coil edges to improve radial resistance

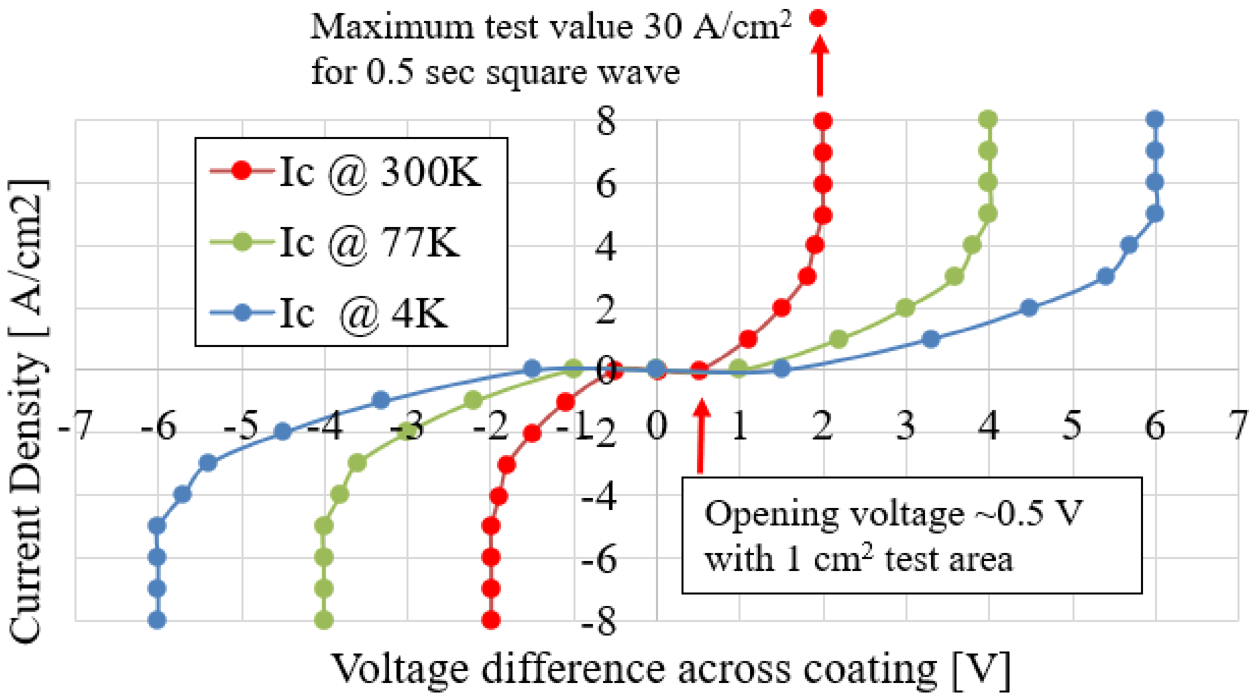
Seal the edges to
protect the HTS



Removing the edges has pros and cons!  The resistance can be increased but cutting off the silver lets the copper get to the HTS and may degrade the HTS with time, also cutting off the edges may  start cracks in the HTS layer ?



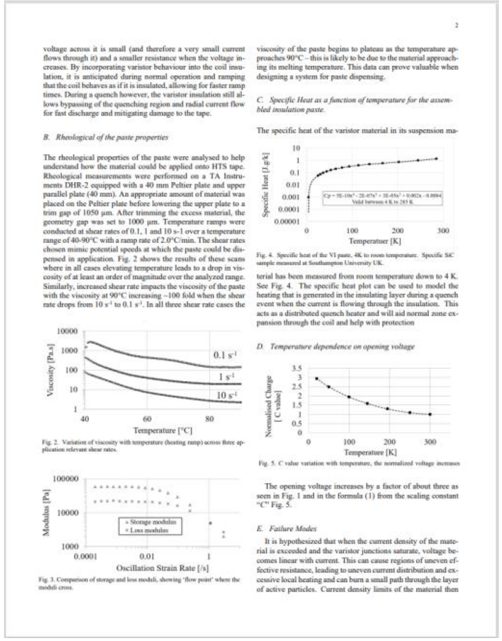



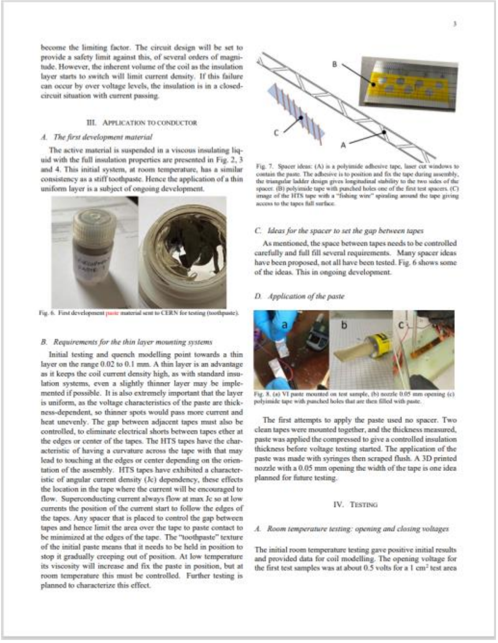



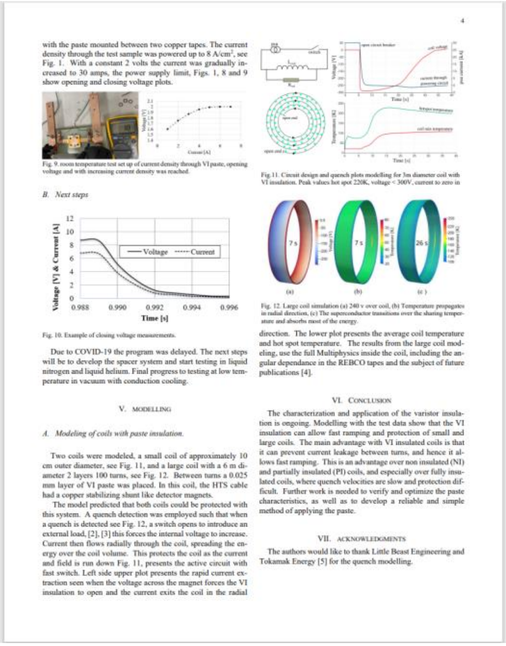


Varistor Insulation for HTS Magnets

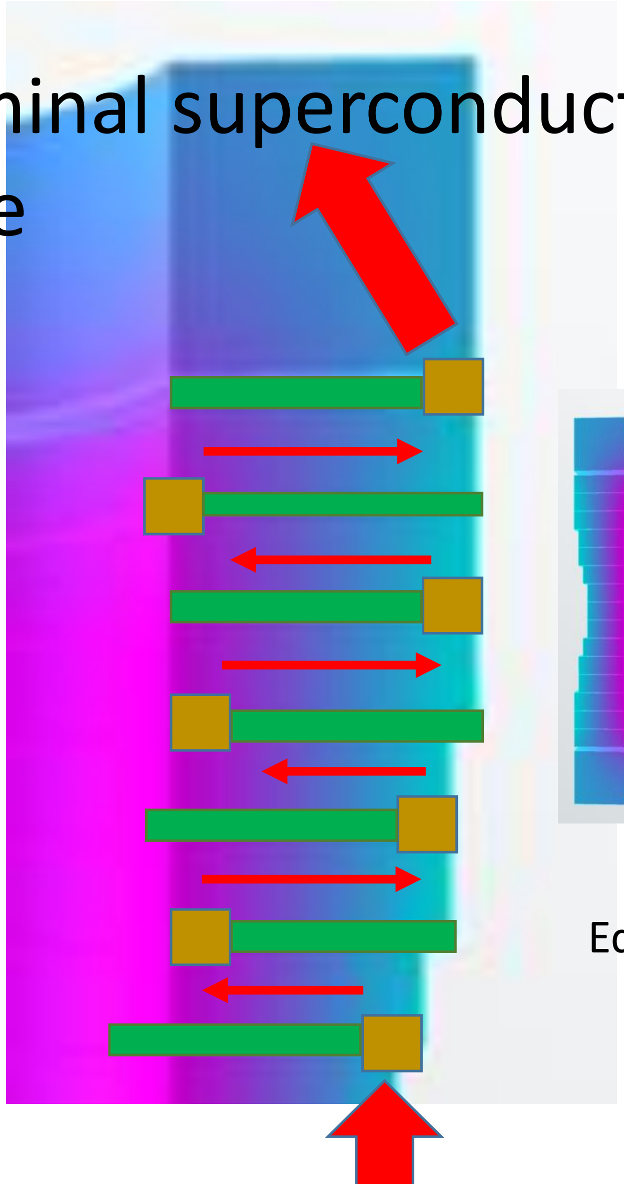
G. Kirby, T. Galvin, D. Coll, R. Stevenson, P. Livesey

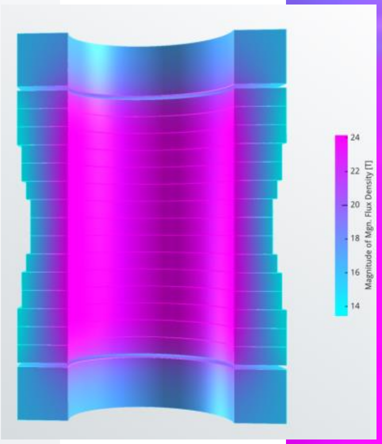


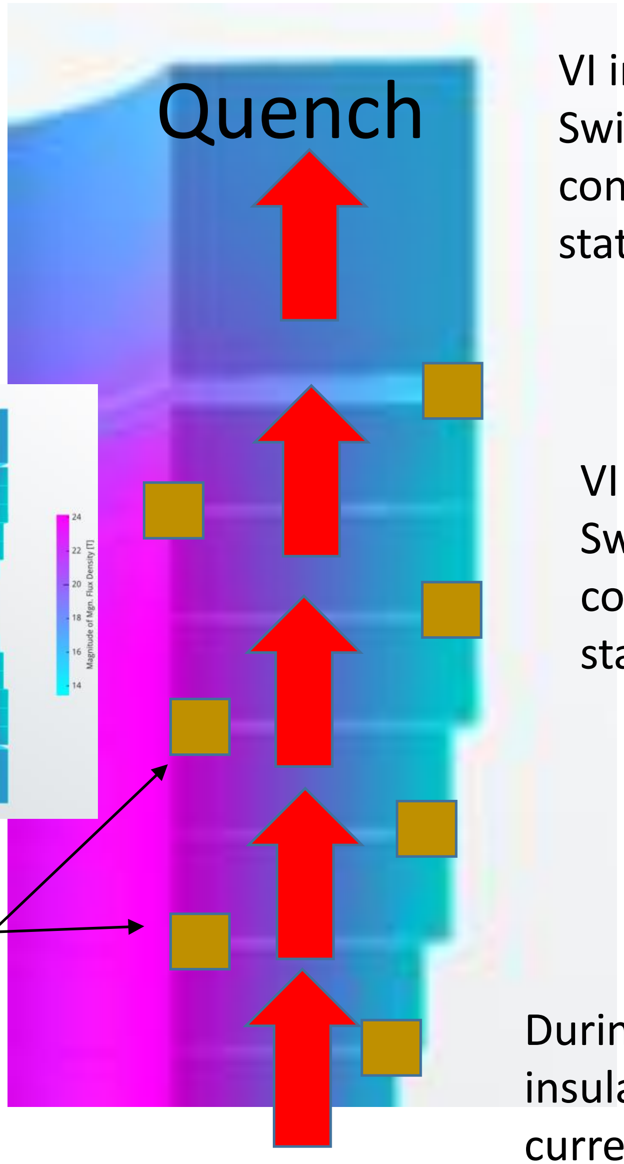


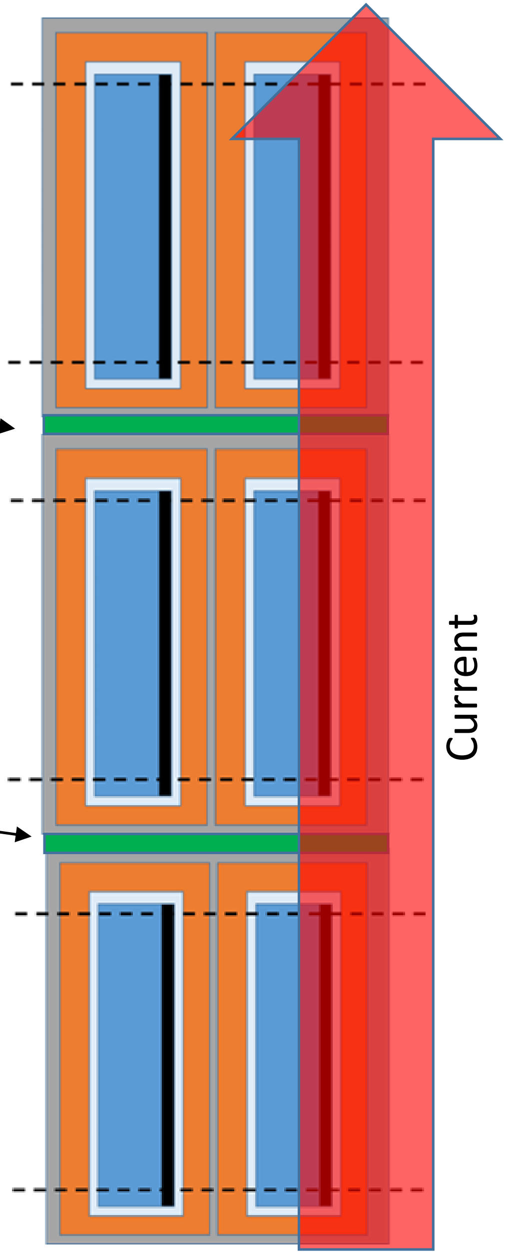


# Complex current paths:
# *Axial* current path after quench



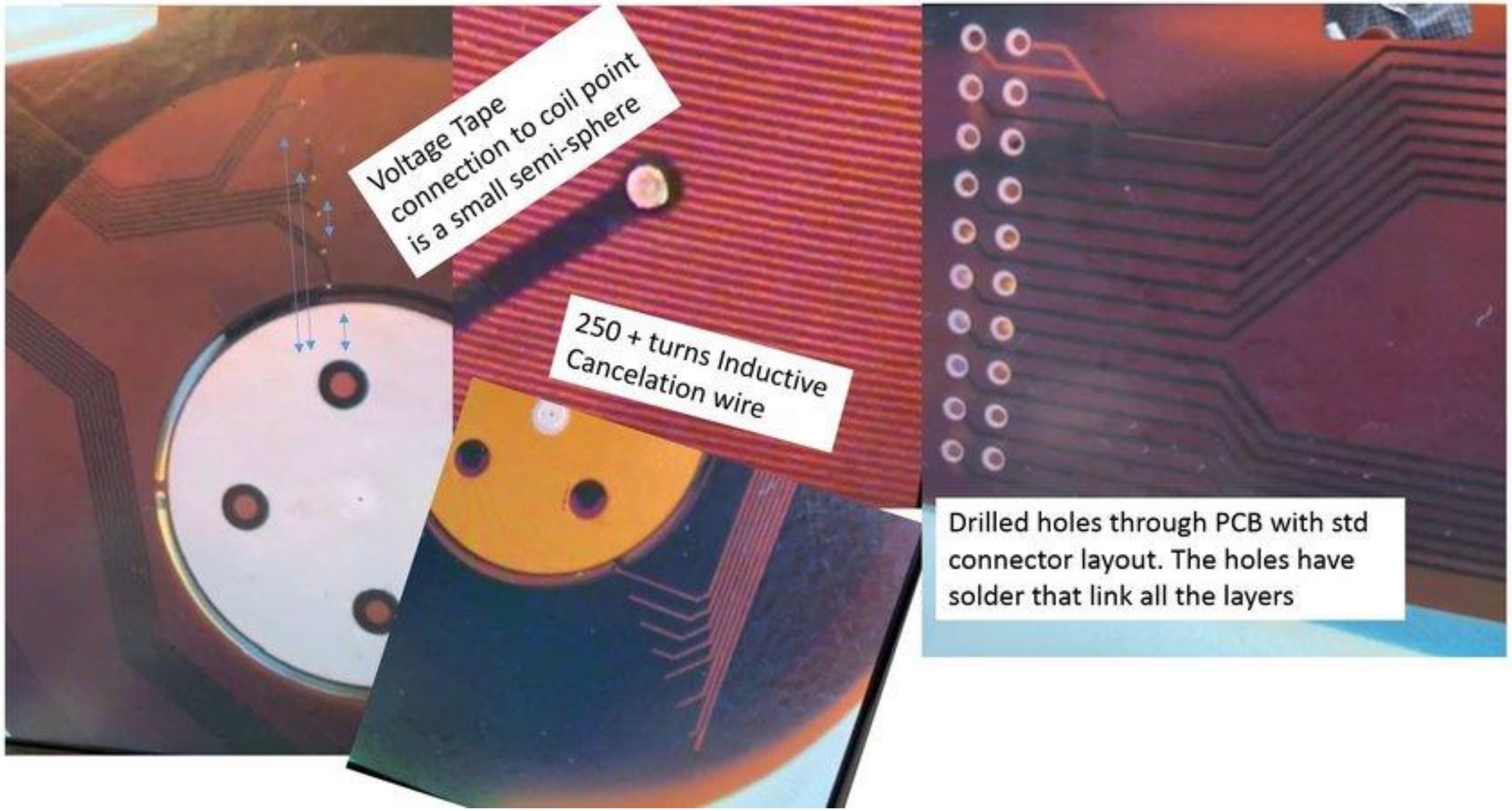



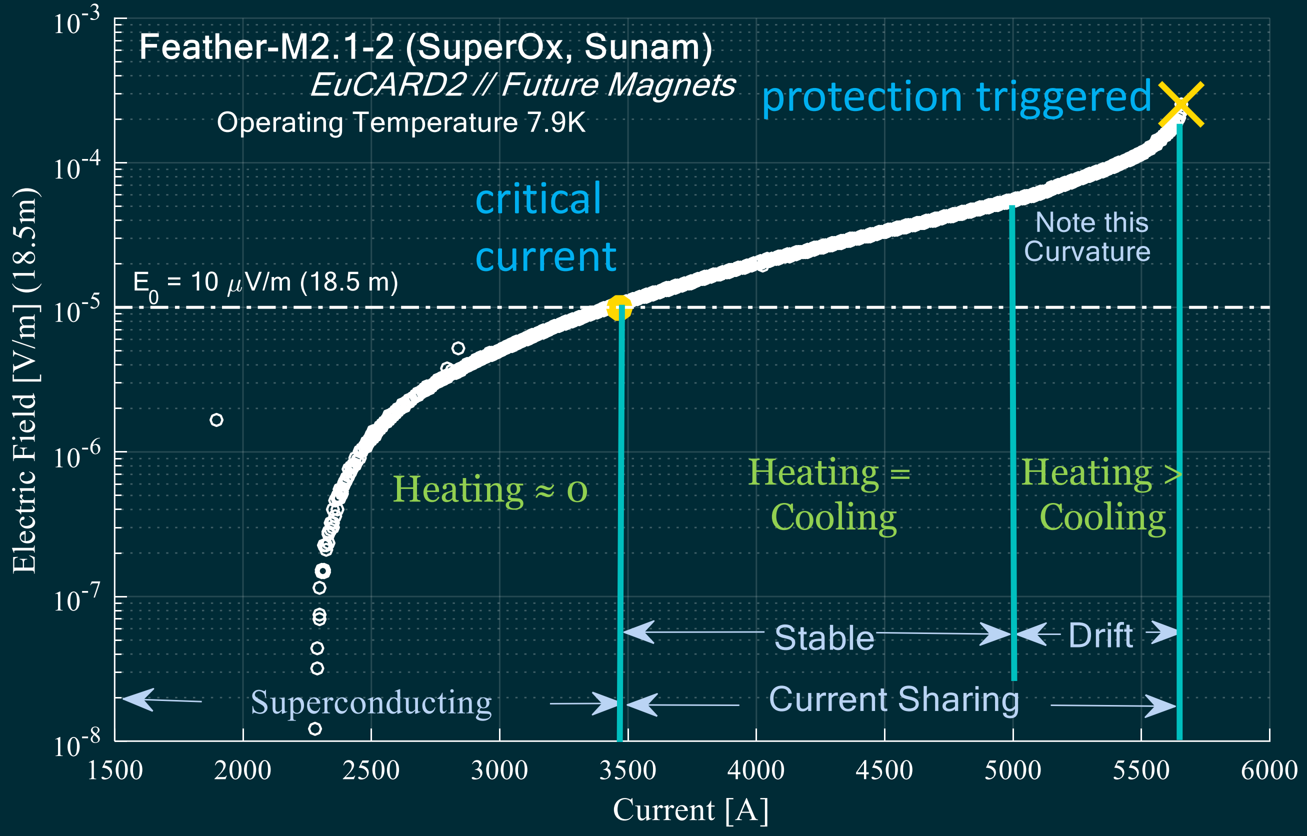

During a quench the voltage increases, the insulation switches to conducting and the current re-directs axially through the copper

# Voltage taps



# Superconducting Transition (We don't like Quench for HTS)



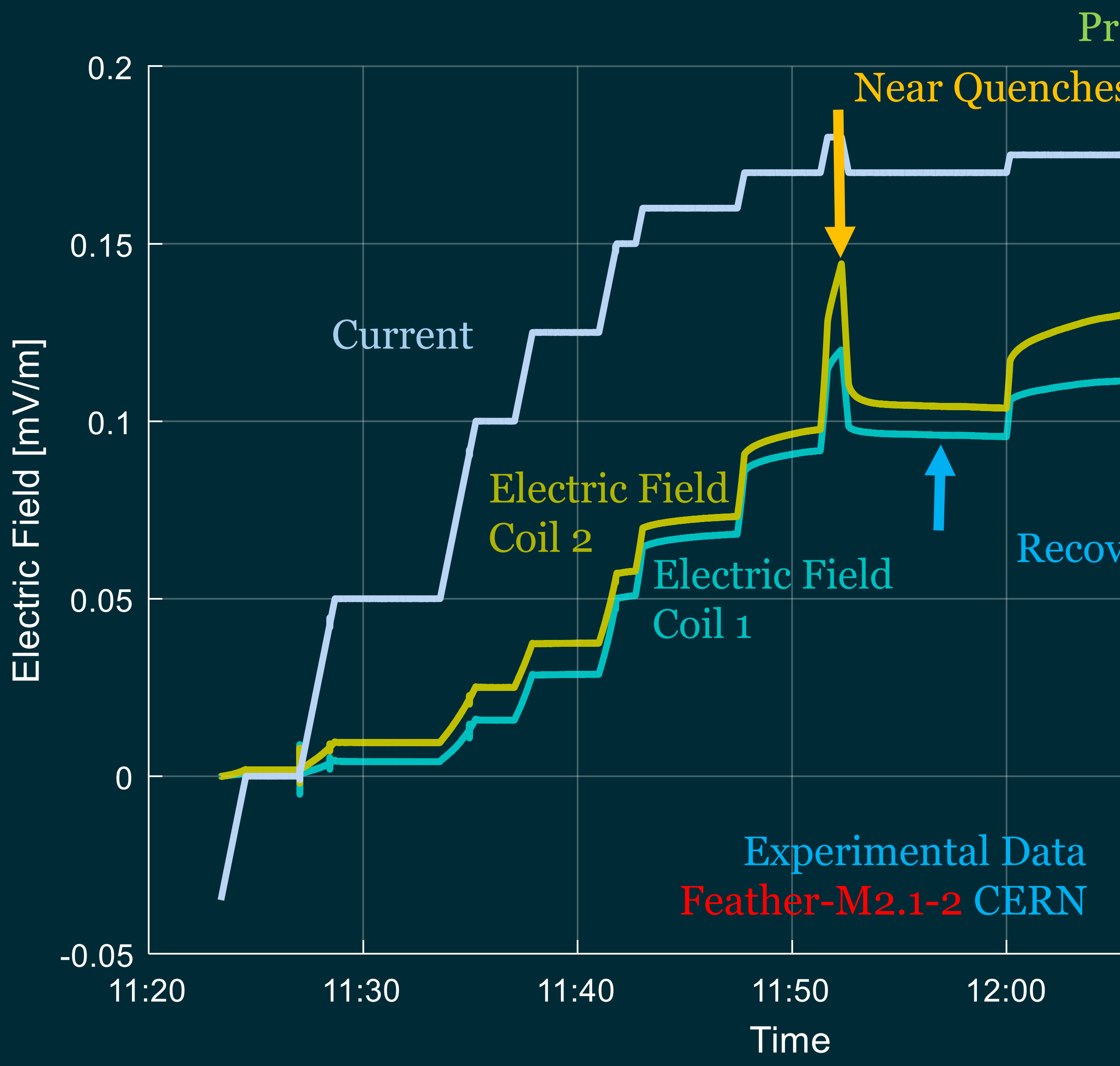


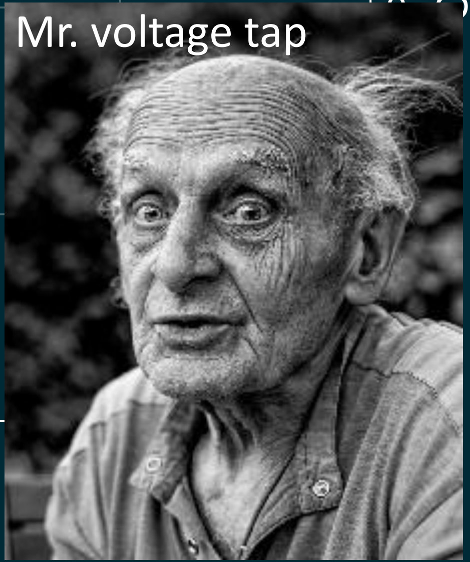

- 160% difference between critical current at 10 μV/m and quench current

# Detecting the Onset of a Quench I (electric field)

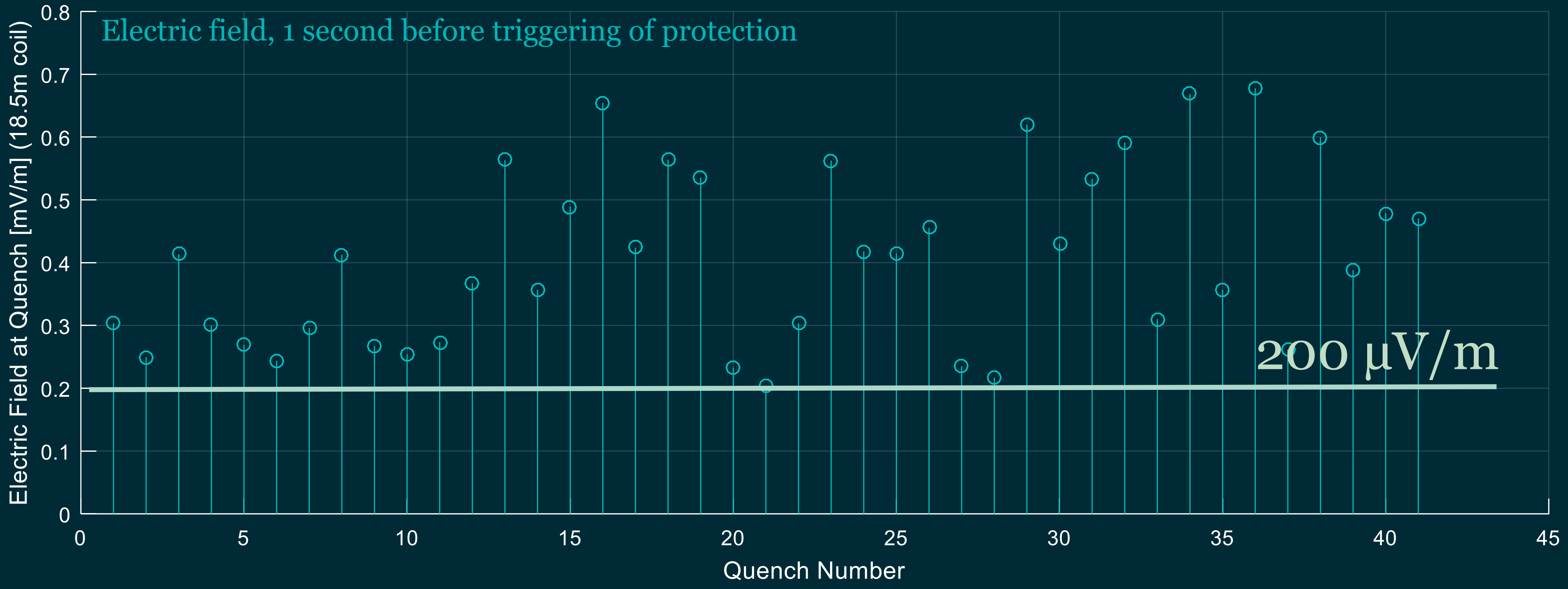
- Drift in the electric field is a clear indication that the magnet is about to quench
- If not ramped fast, the electric field starts drifting minutes ahead of time
- Reduction of only 100 A results in immediate recovery!

- Conclusion
  - If this behaviour is also present in higher current density magnets this could be a viable method for protecting future HTS magnets



# Detecting the Onset of a Quench / Transition (electric field)

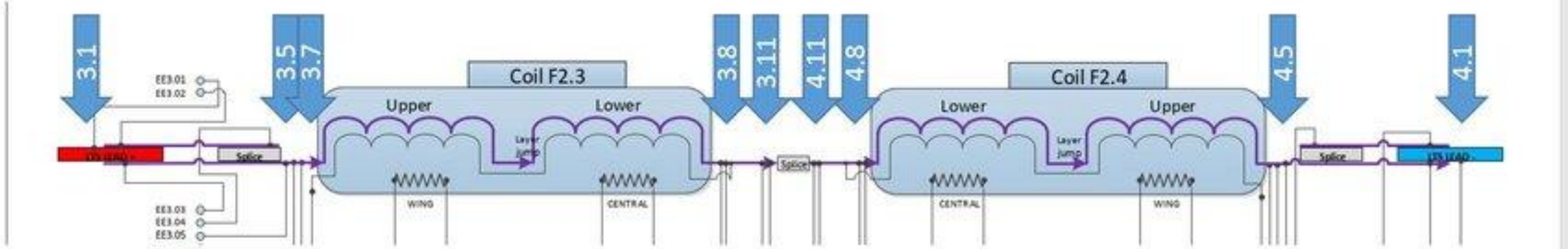



- All quenches occur over an electric field of 200 µV/m @ 3 Hz sample rate
- Only quenches due to exceeding critical current

- Conclusion
  - No unexpected quenches due to cracking of resin, flux jump, training etc.

# Frather2 Circuit

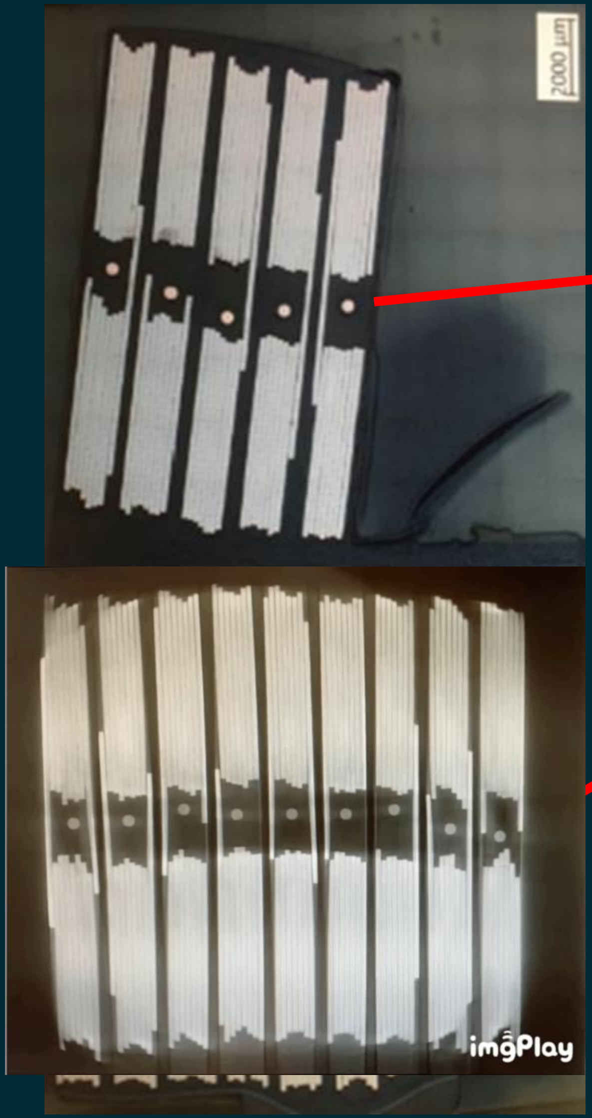




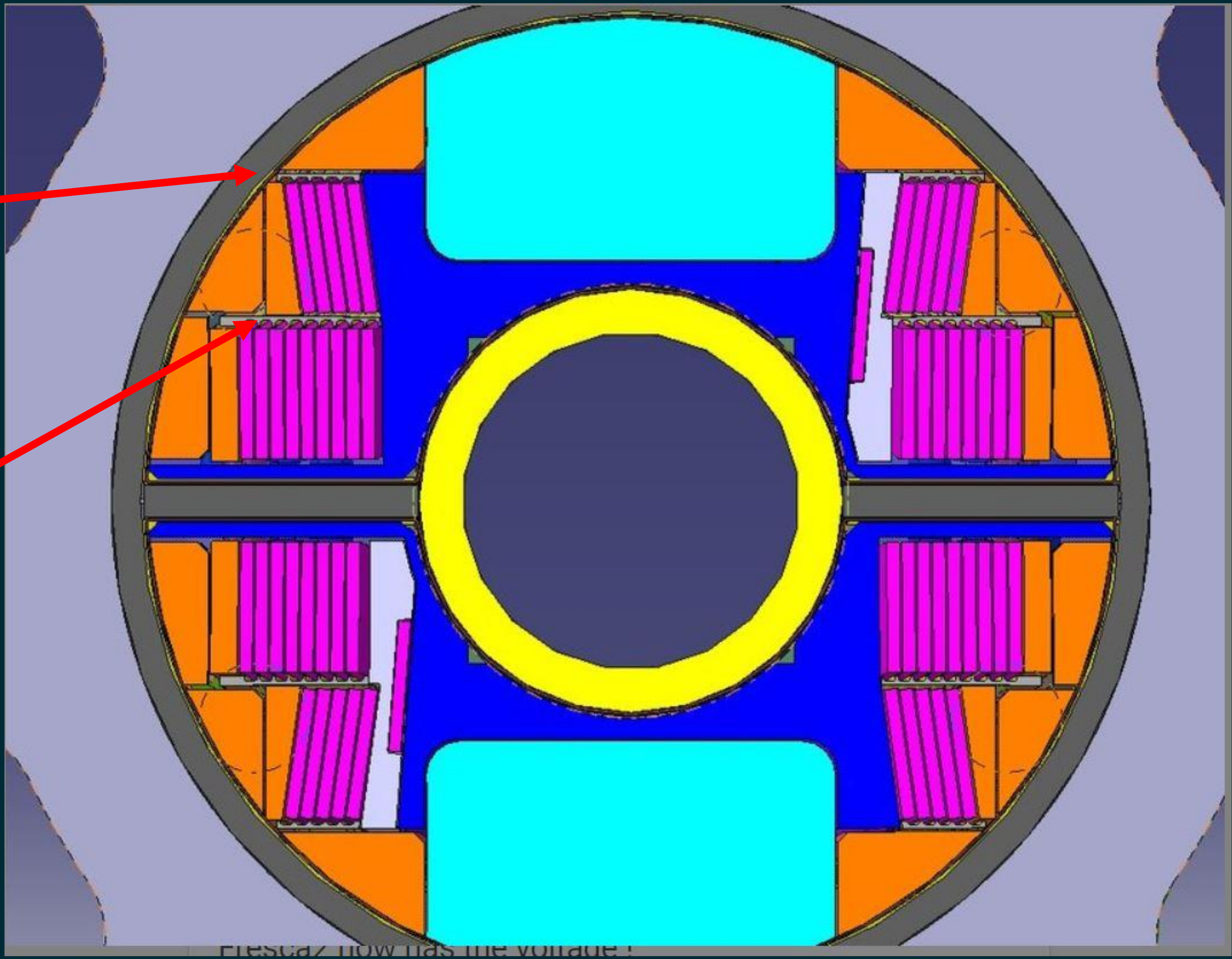
# Change of Roebel resulted in cancelation wire moving



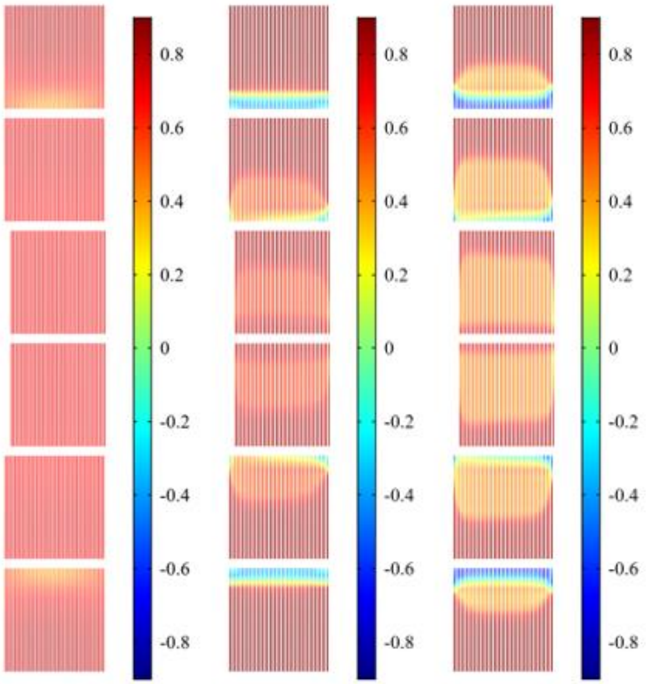
Feather2(12)

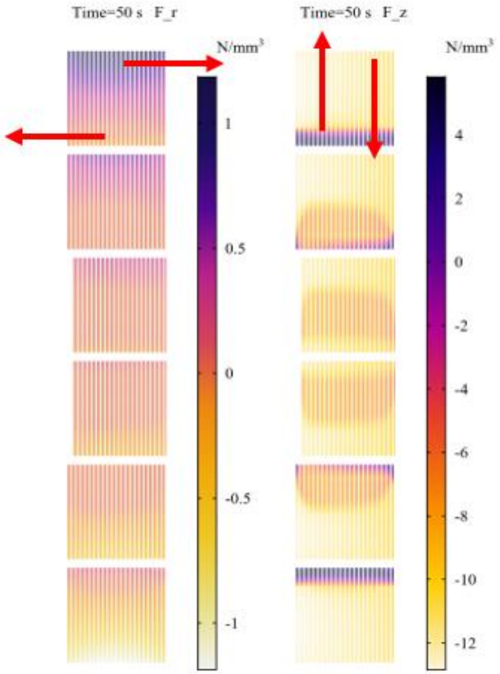


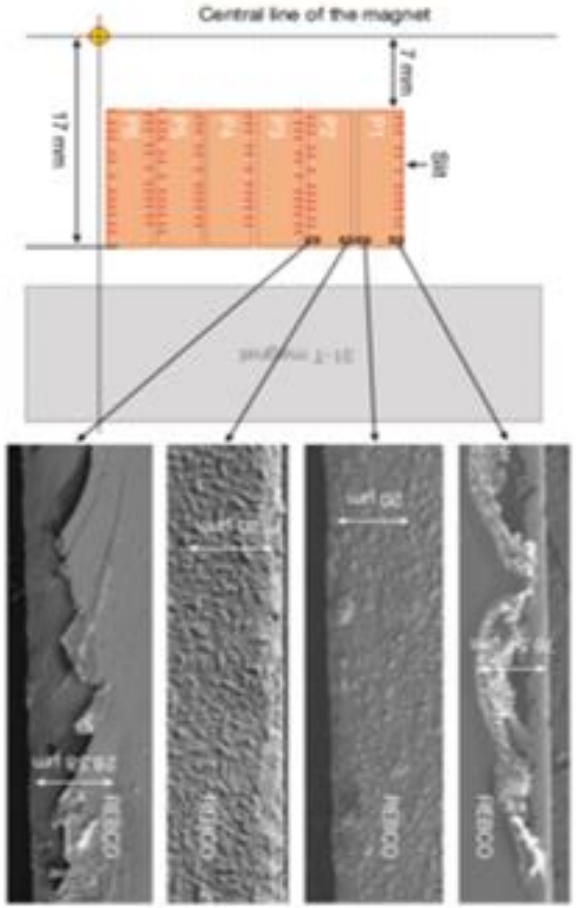

Feather2(34)



# Screening currents






## 9 Results : Lorentz forces distribution in the coil

The Lorentz forces distribution is shown for the case of high-quality cable (1kA critical current, 25 n-value), and it is calculated for t=50s after the current plateau. From left to right: radial and vertical component. The arrows represent the main direction of the forces for the upper pancake.

# Forces at the edges where the current flows

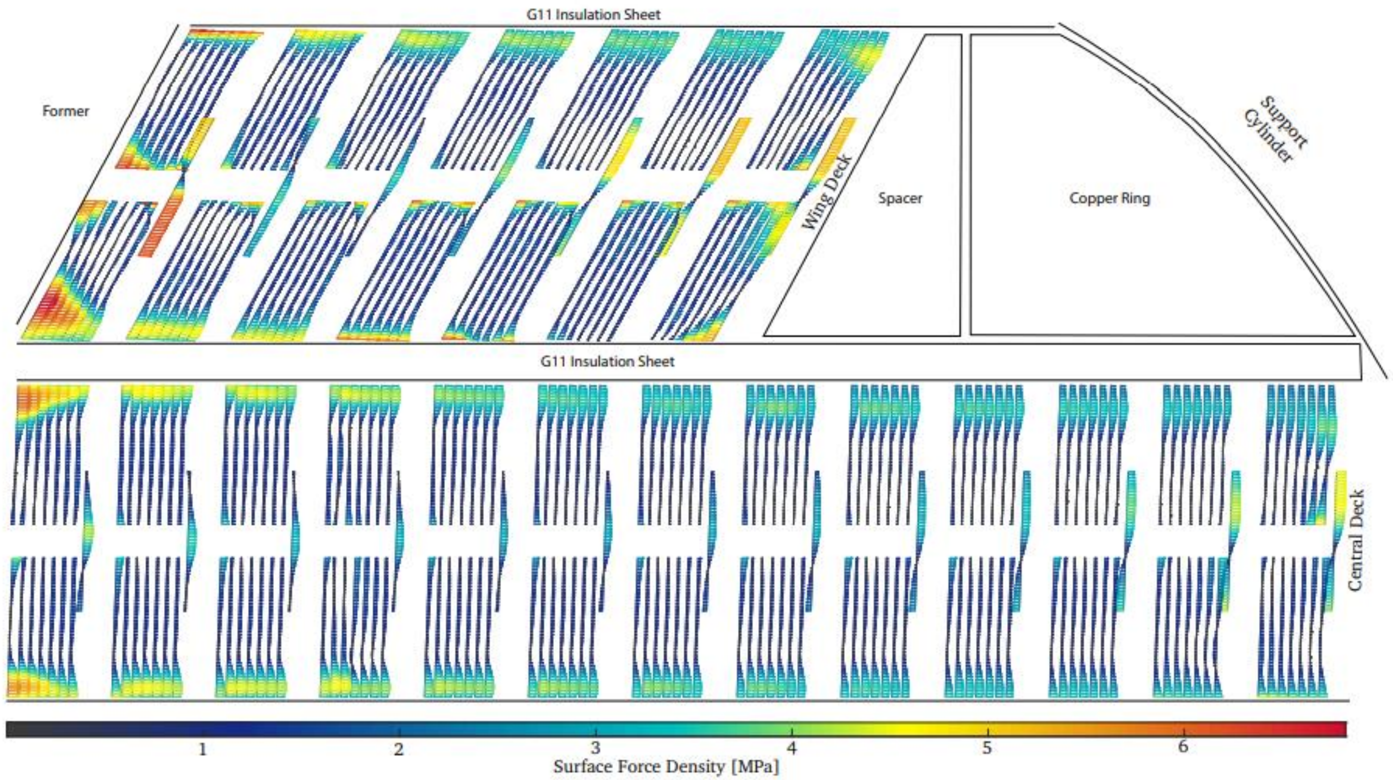



**Figure 4.29.** *Surface force density distribution (pressure) resulting from the current distribution in an aligned block coil pack when operated at 8 kA in a background field of 13 T. The vectors indicate the direction of the force and the color the magnitude. Note that the geometry is not shown to scale.*

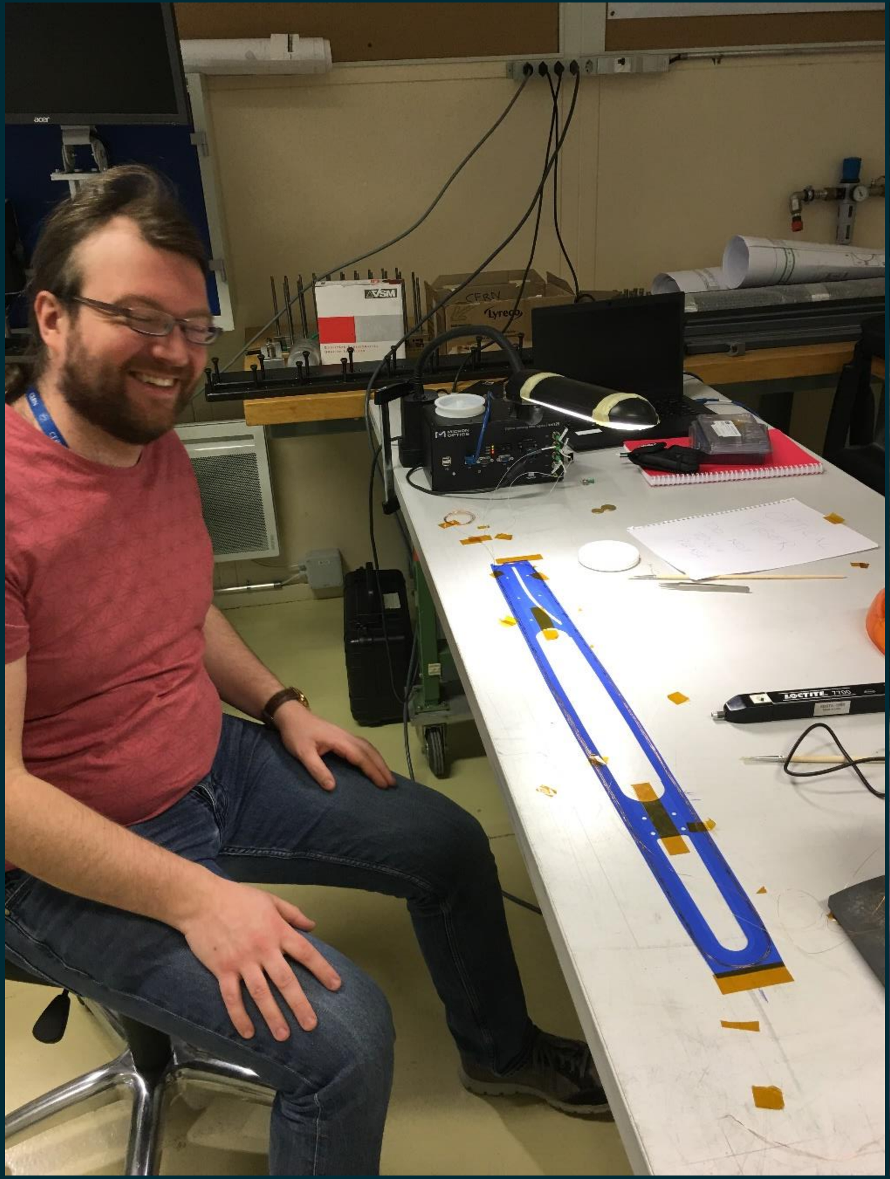


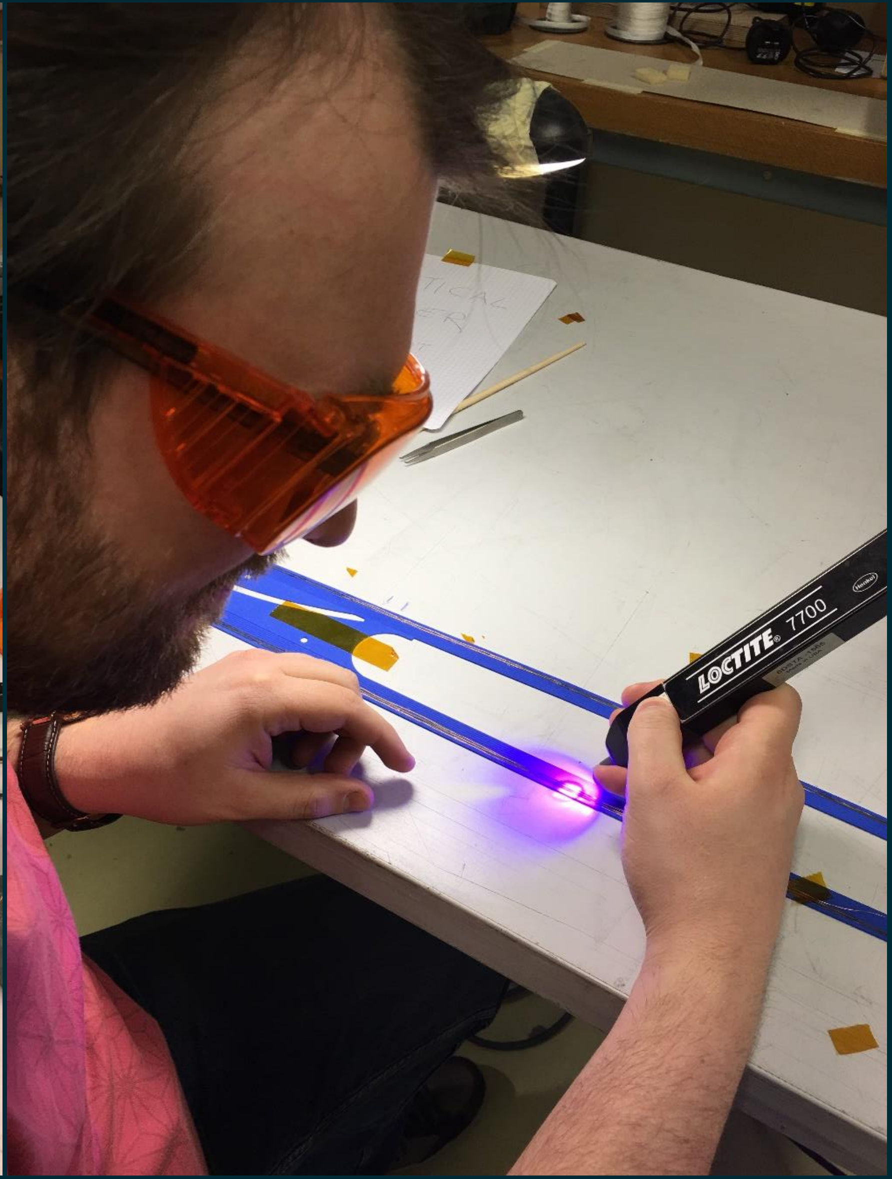


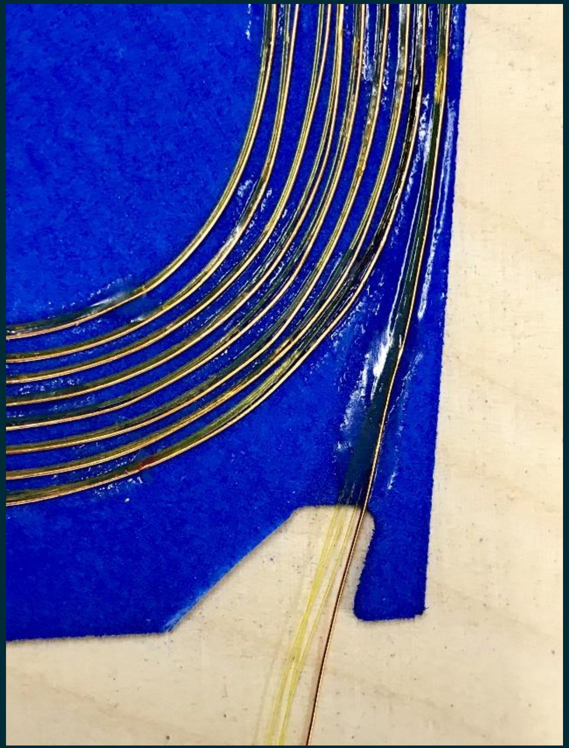
JvN's PhD

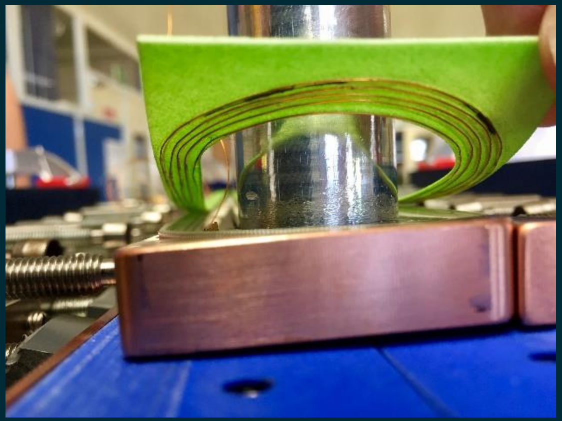
# Induction cancilation and fibre optic temp / strain

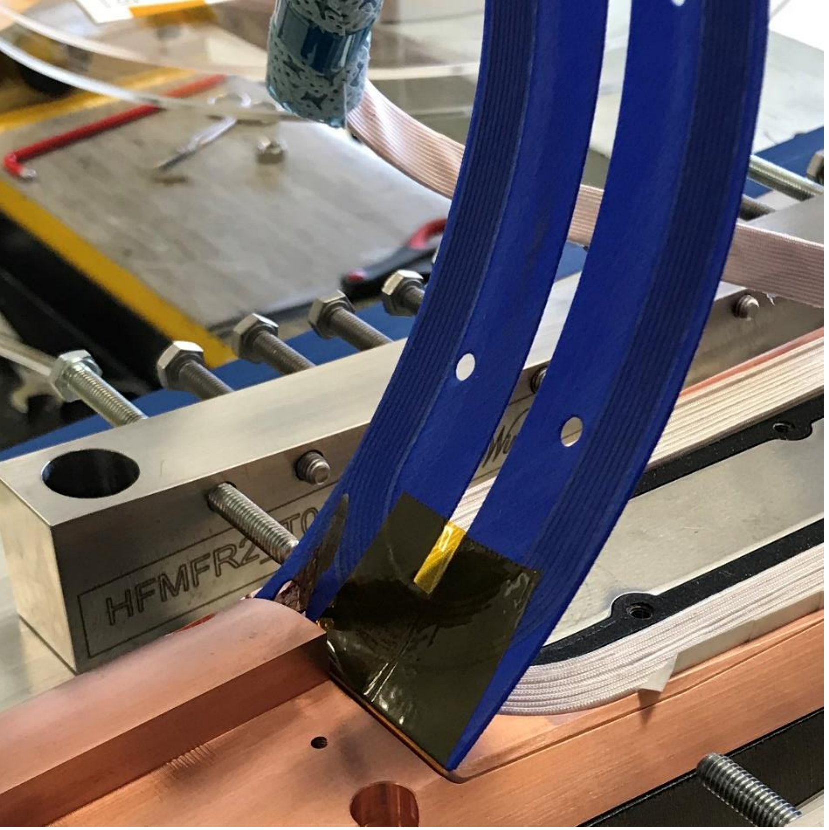


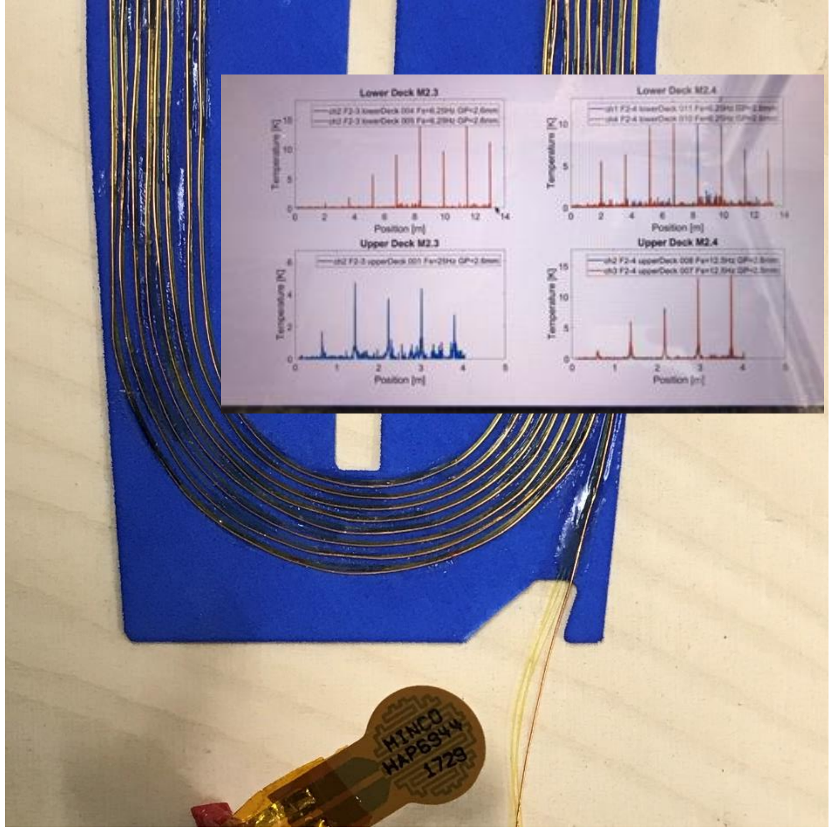


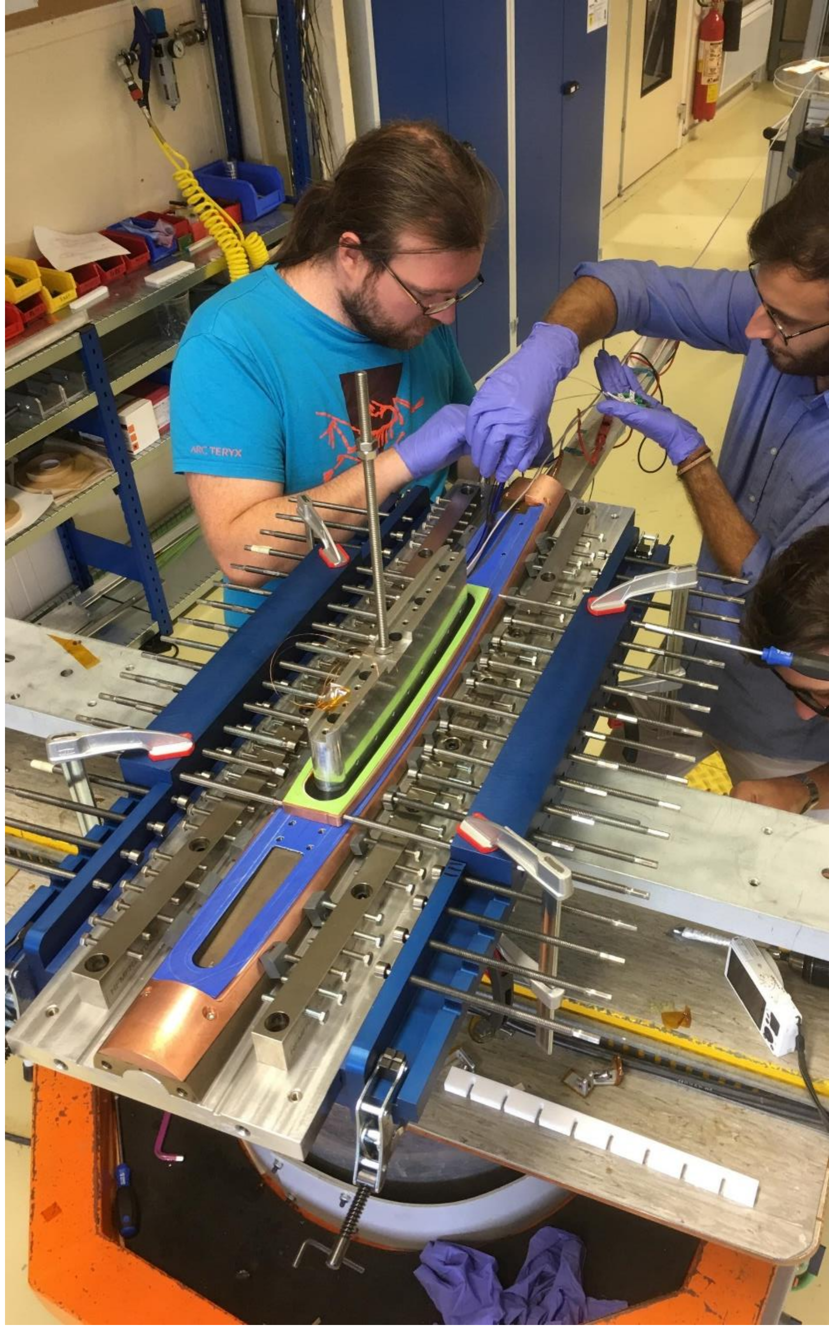








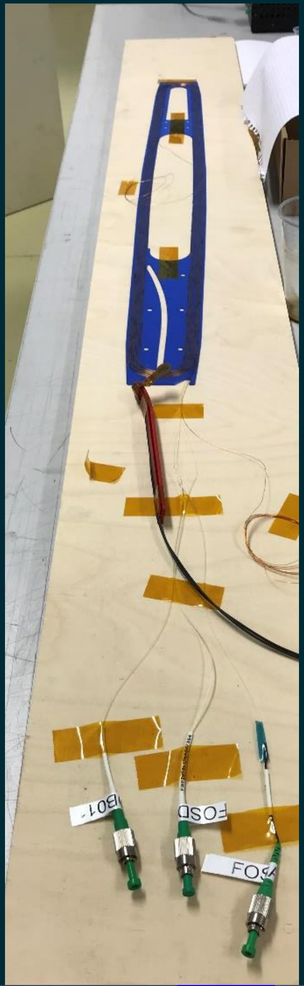
150um insulated copper

Inductive Cancelation

- Fiber temperatureand stress  sensor that looks at the over the full 30 m of cable
- Heater to calibrate the position along the fiber

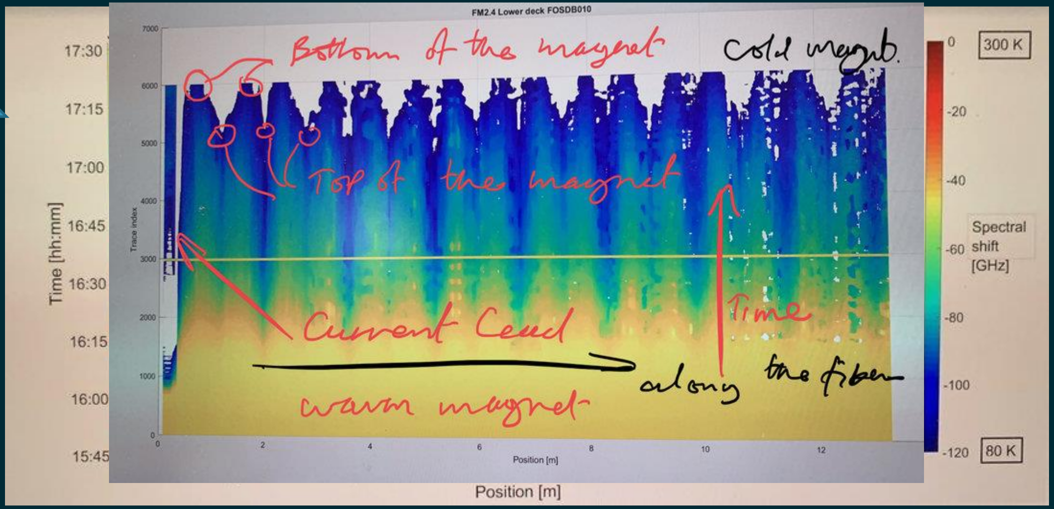
# Fiber --- temp and stress over every turn

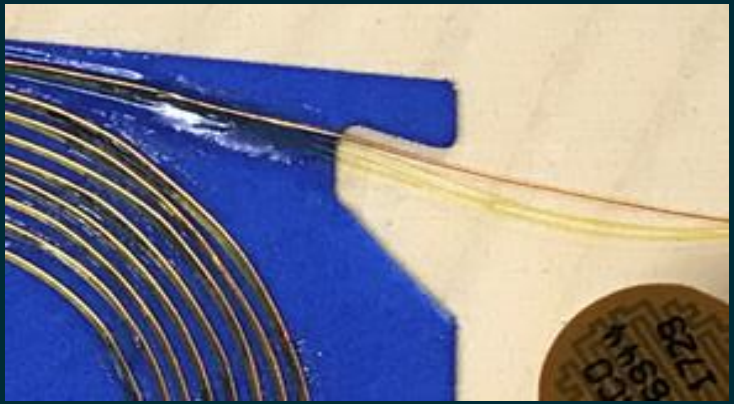


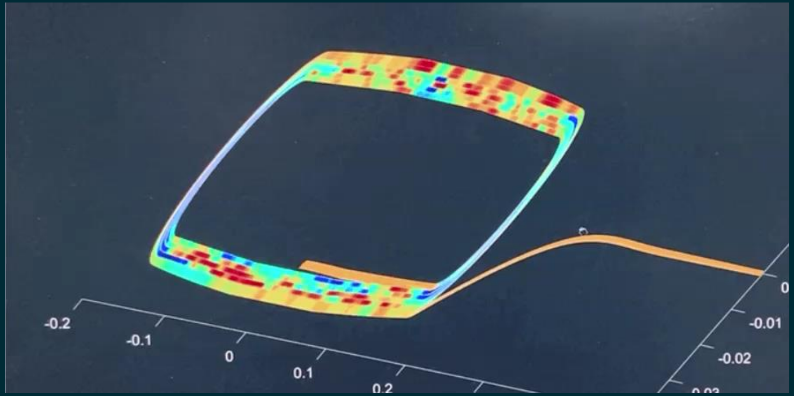


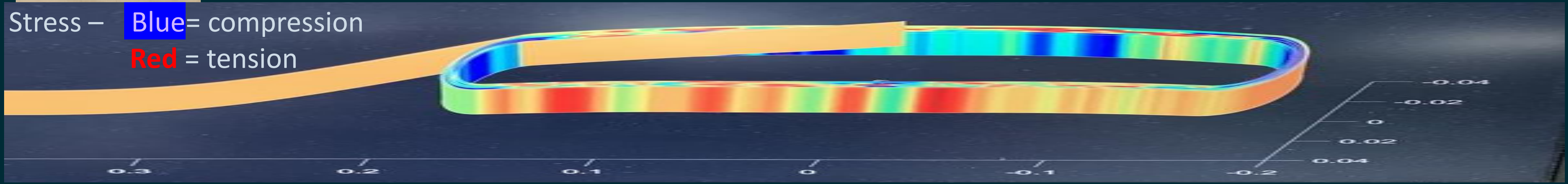
Fibre team mapping temperature and stress maps onto the feather2 coils we see cool down. Cooling from the bottom of the magnet and through the current leads. We also see stress in the coil as powering the blue is compression and red tension. So, the inner edge of the coil end is under compression. Just initial results.

time

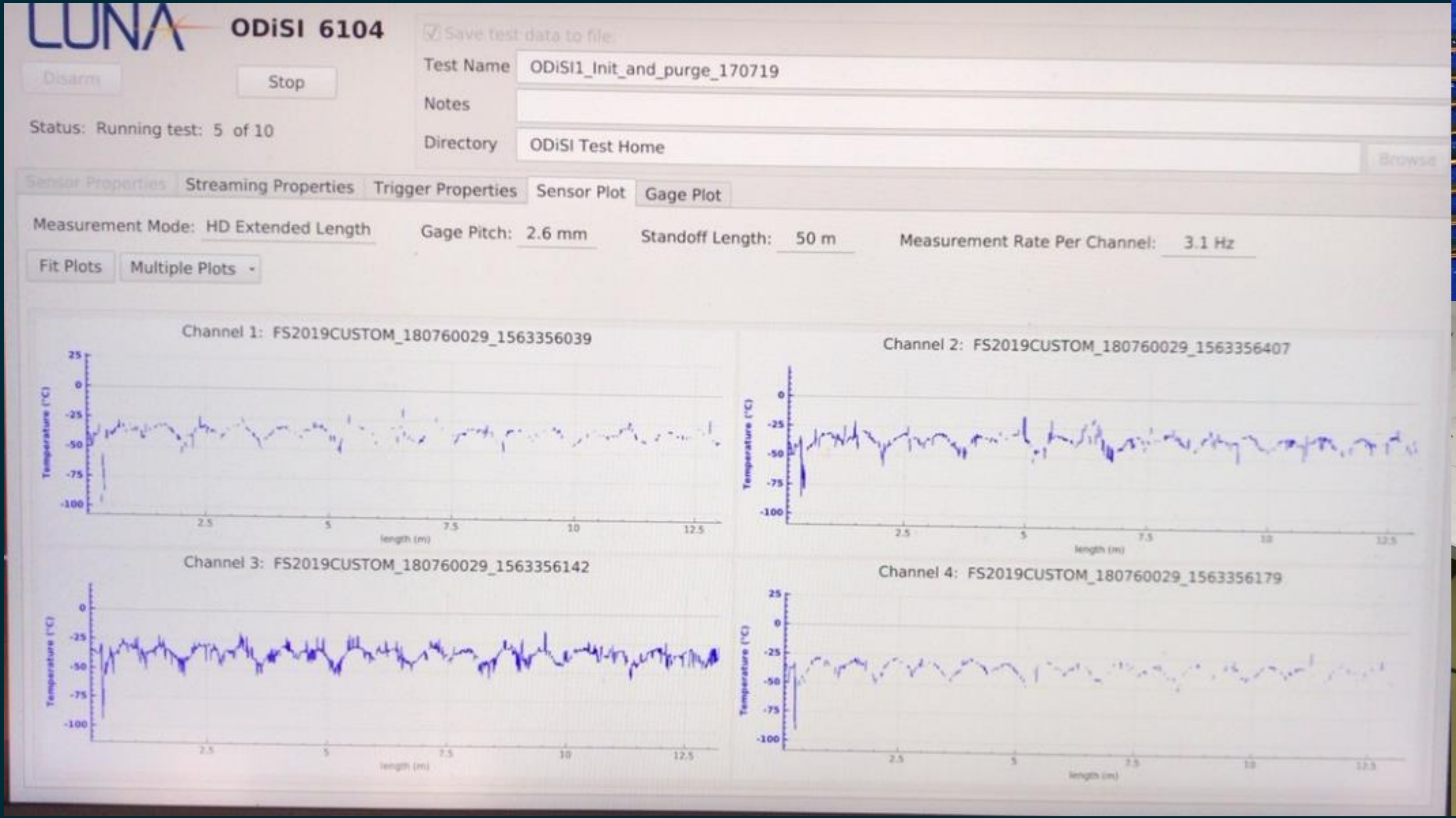


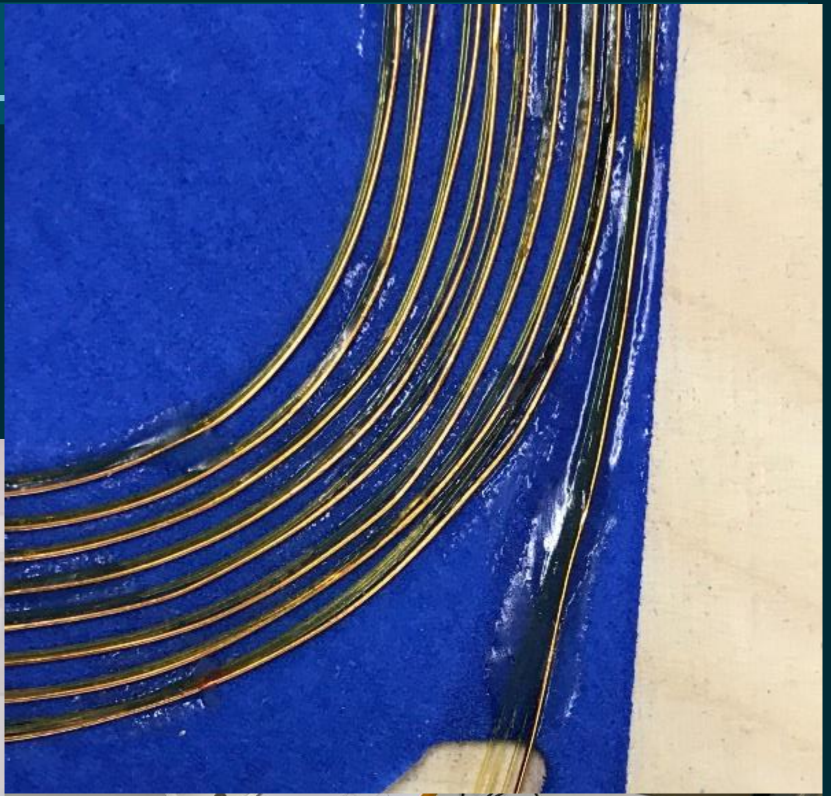



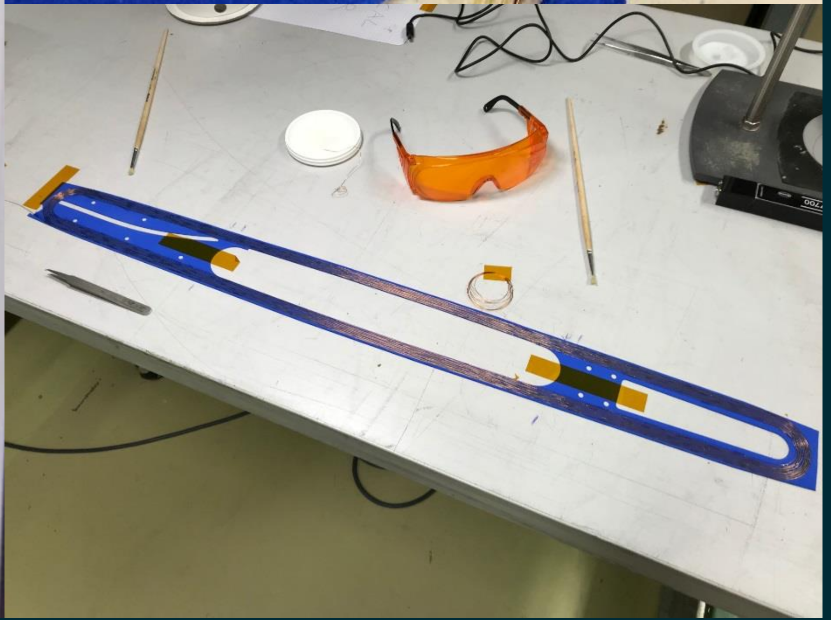




# Optical Fibber's & inductive cancelation wire





# Don’t re-invent the wheel!
# Just improve it !

4000 BC airless

2000 BC airless

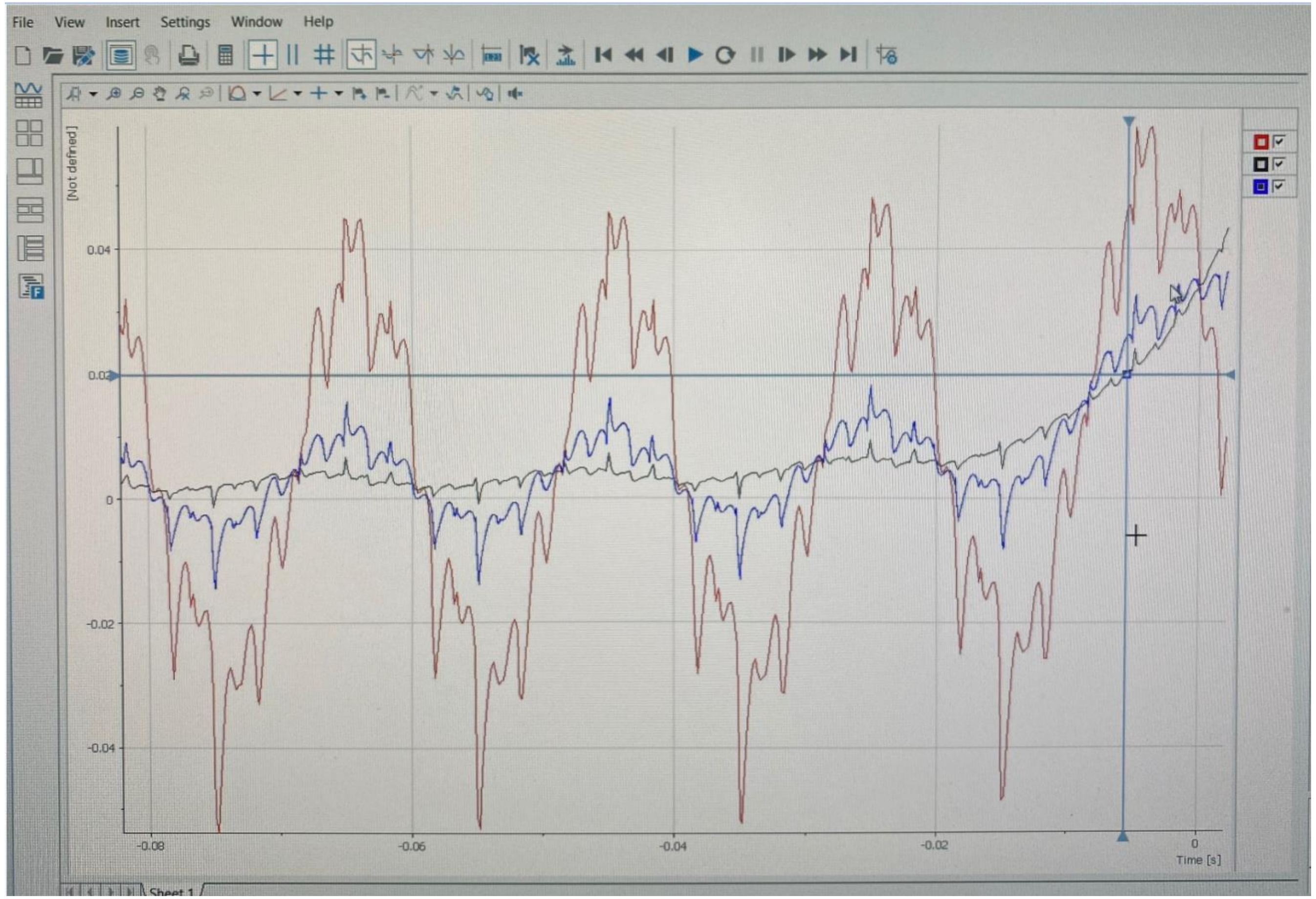

1970’s


2022


Plastic spokes support a thin tread on the Goodyear airless tyres

Future airless tiers

# Effect of single coil testing and broken cancelation wire

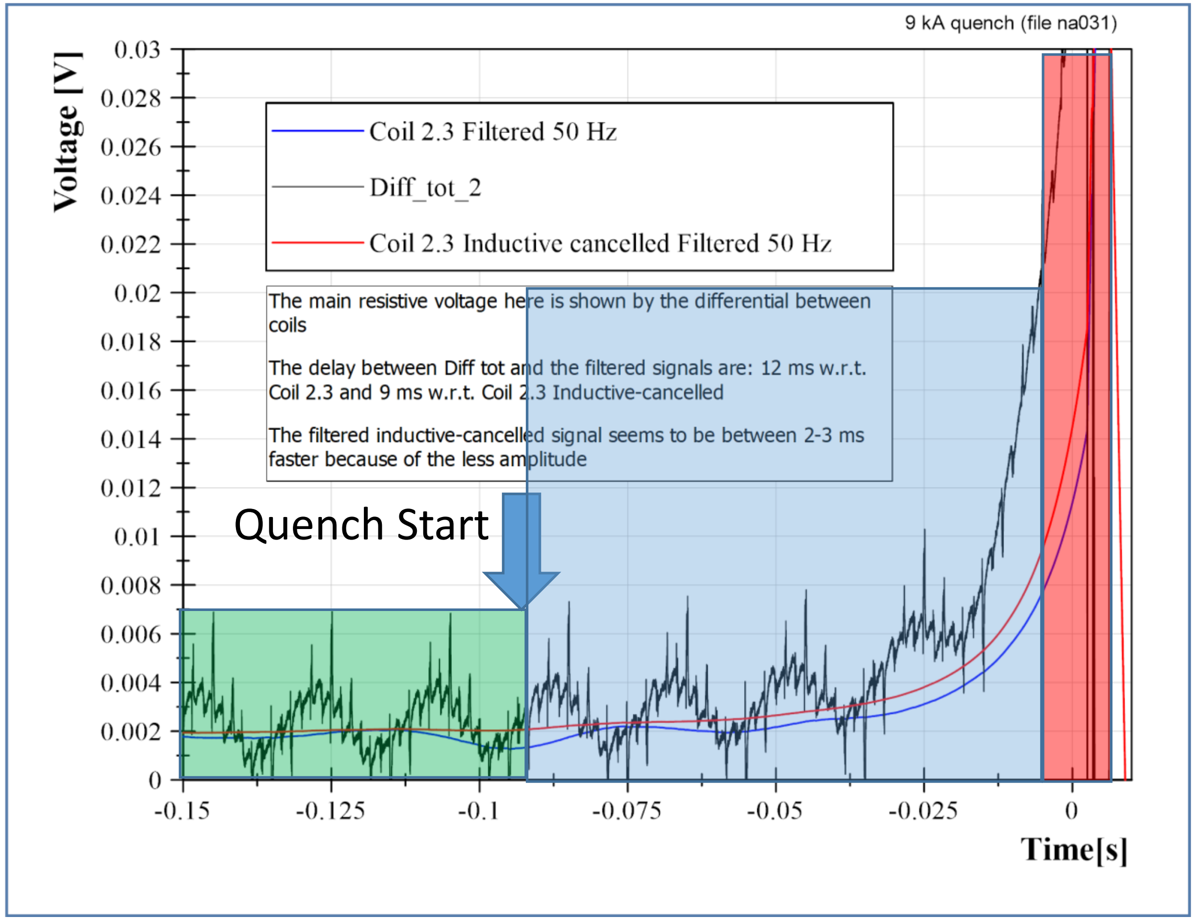



**Red: coil 3 voltage**

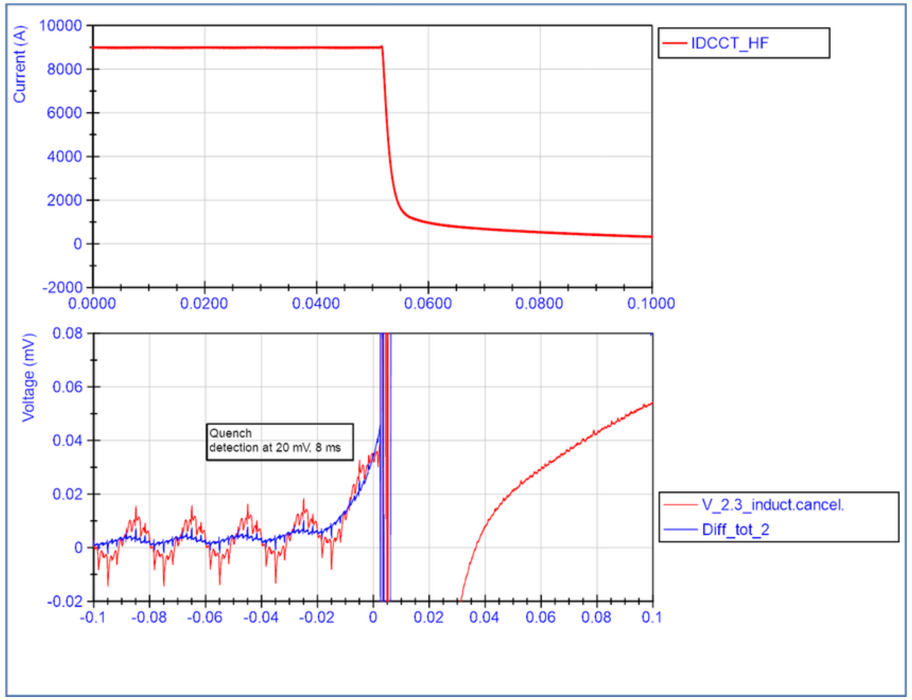
Blue: coil 3 voltage with inductive cancellation wire [ICW] but one of the 4 coils wires was broken in the magnet, we expected better result.

Black: differential voltage (i.e. coil 3 - coil 4)

8ms +2 ms
switch opening

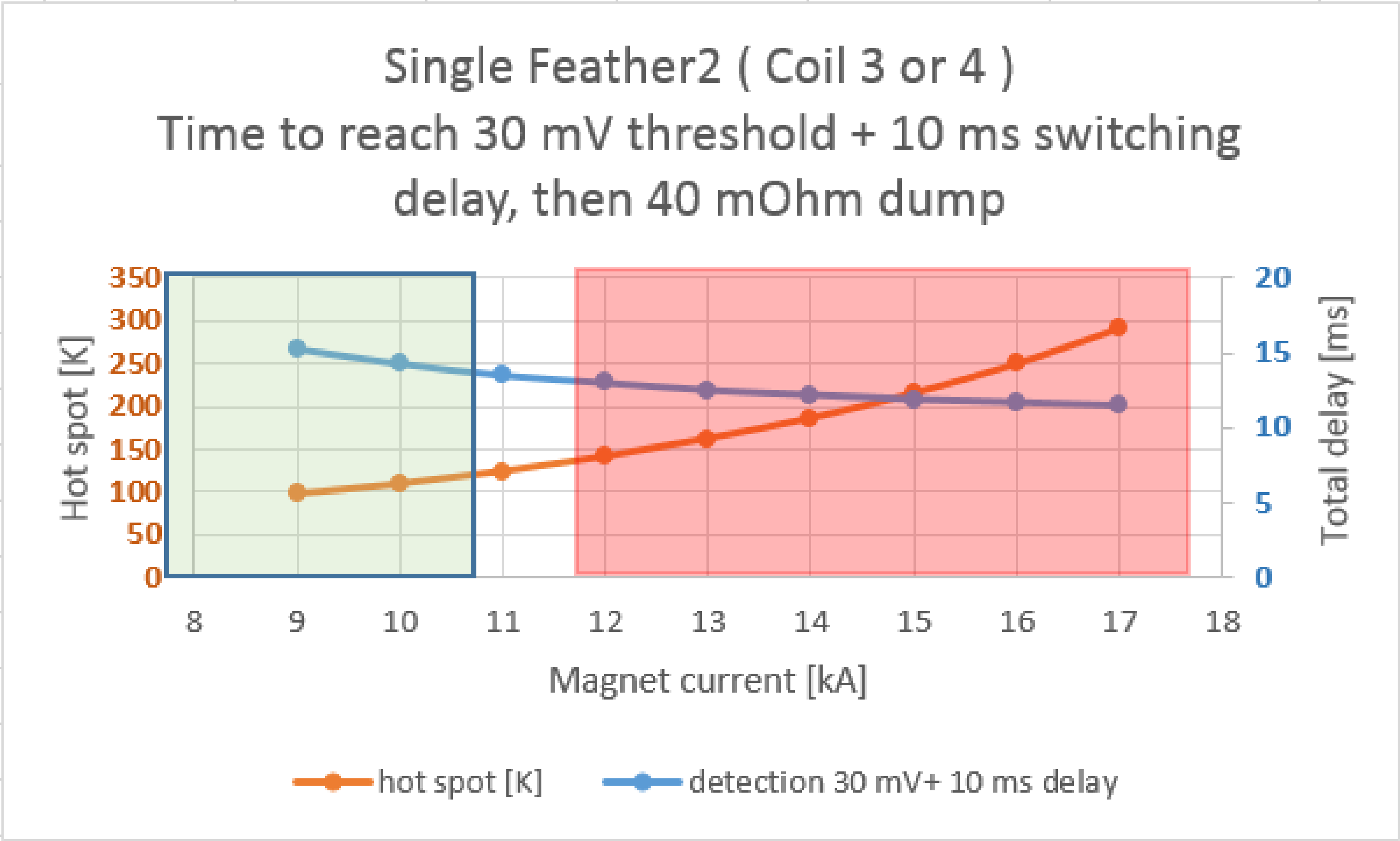



Time to reach threshold ~ 80 ms




Is this the same event ?

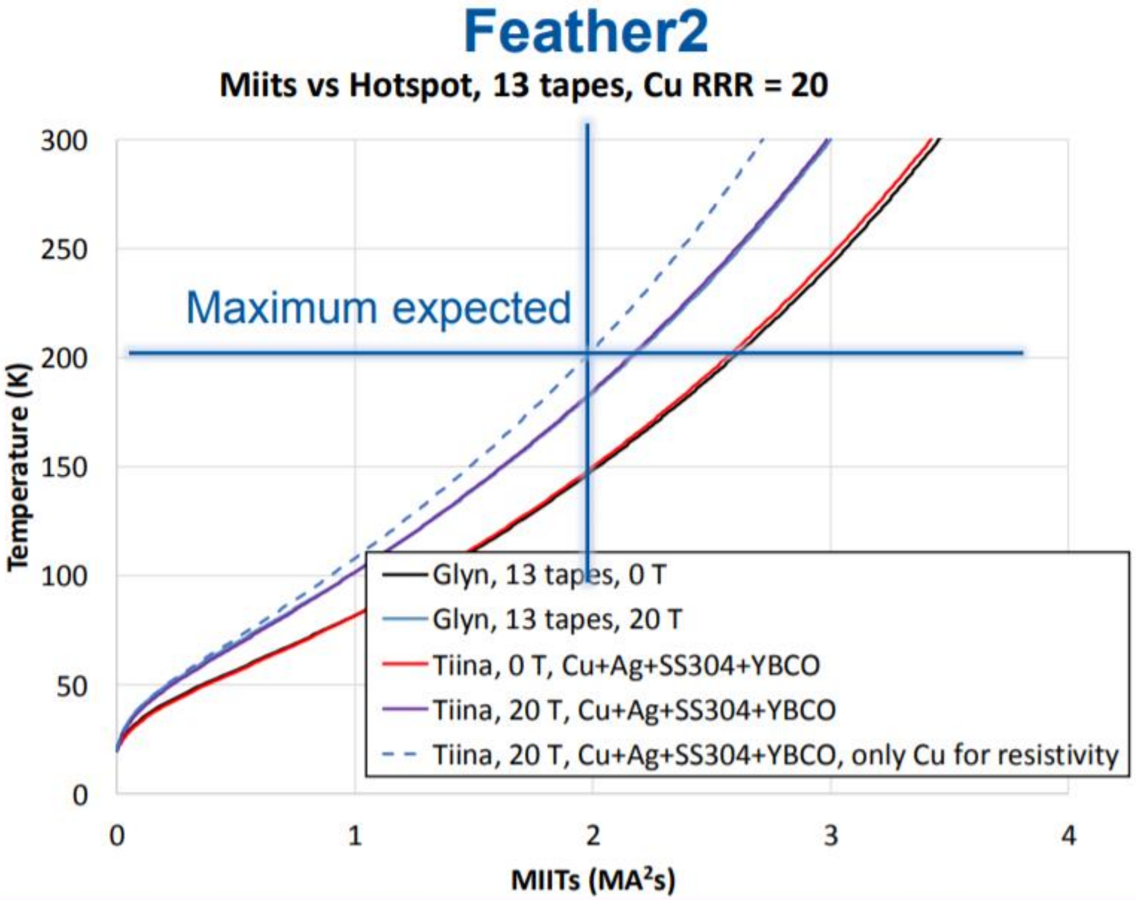
# Max test current  10 kA

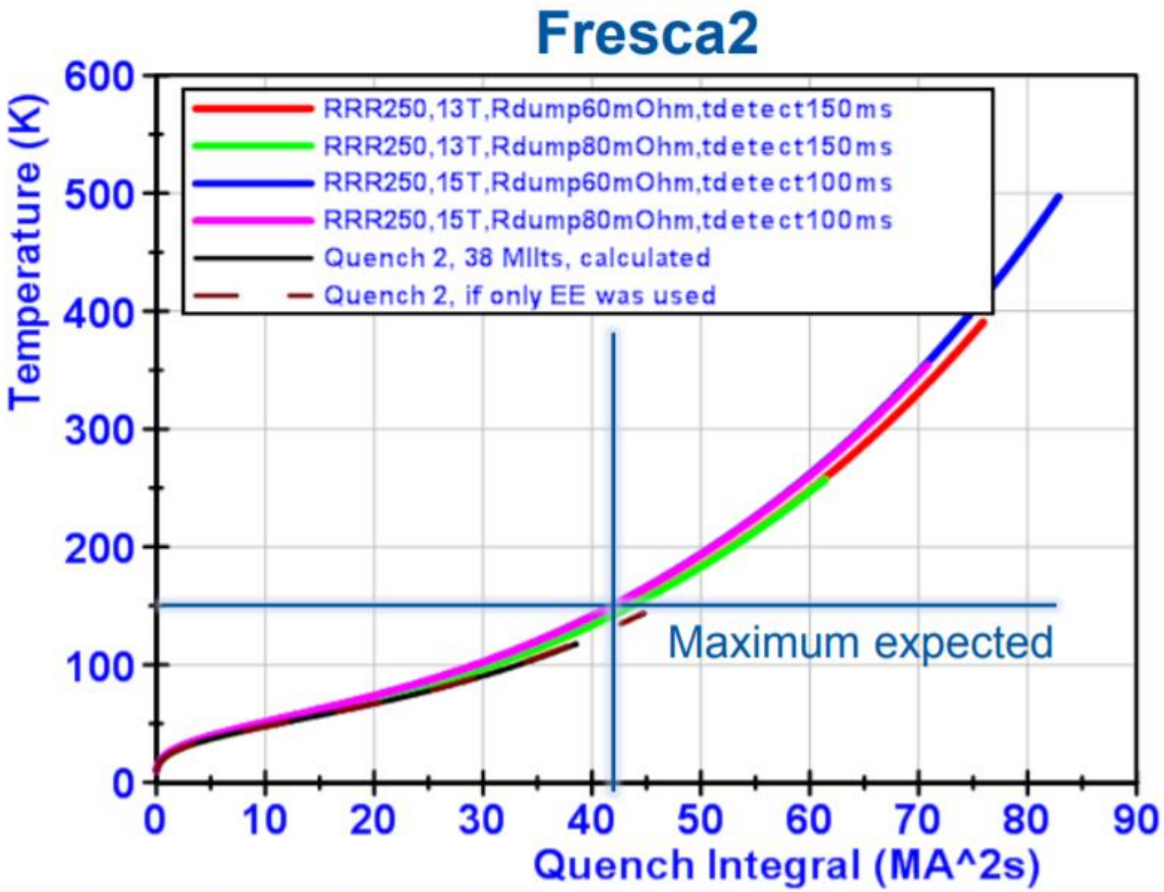



Set hot spot limit to 150 K

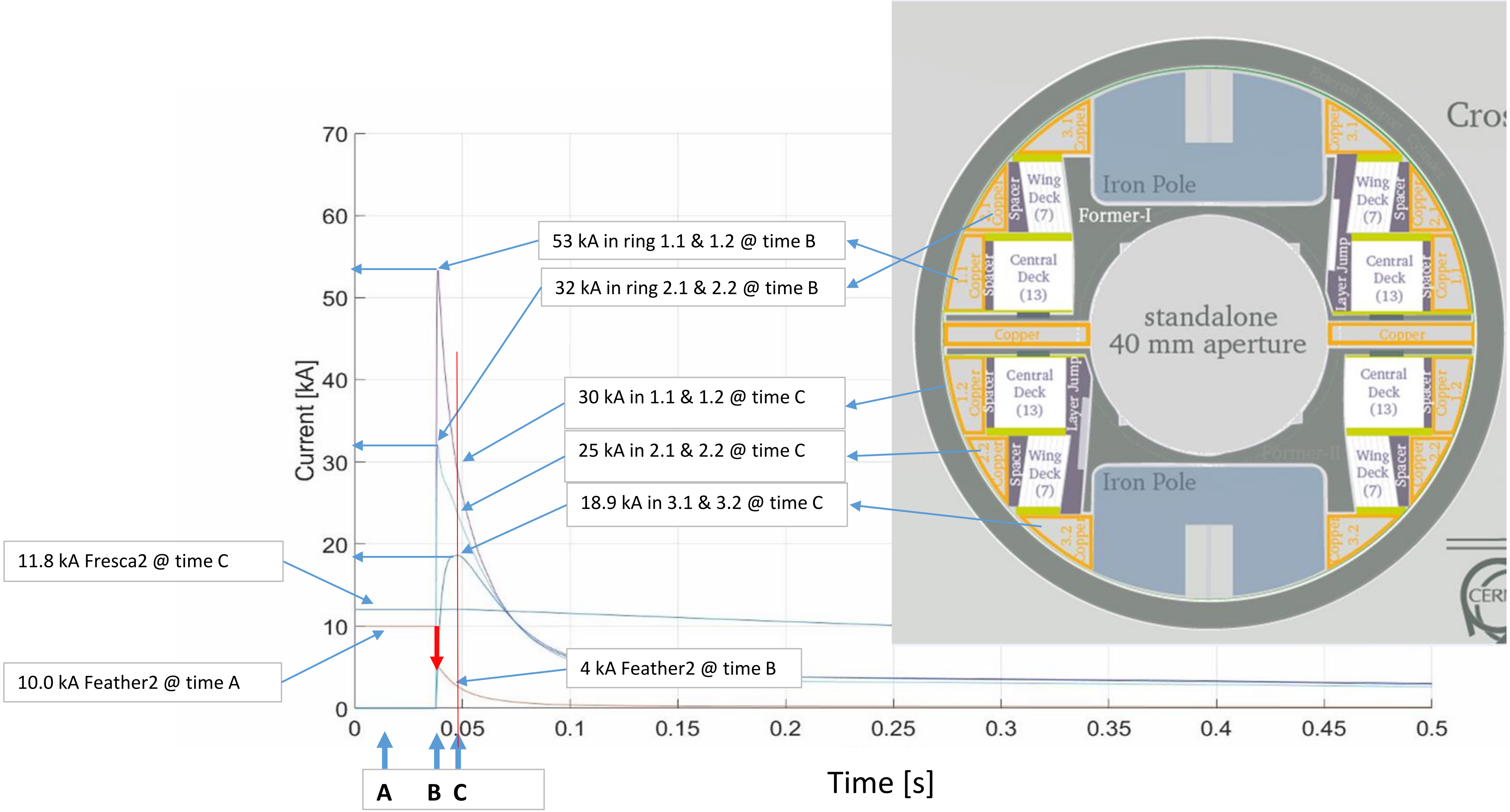
Max current to 10 kA

# Maximum expected T_hotspot

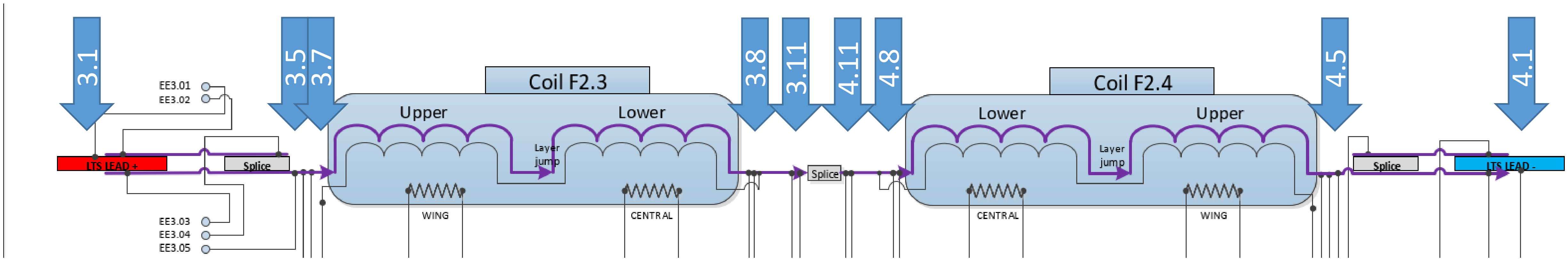


# Induction of high currents



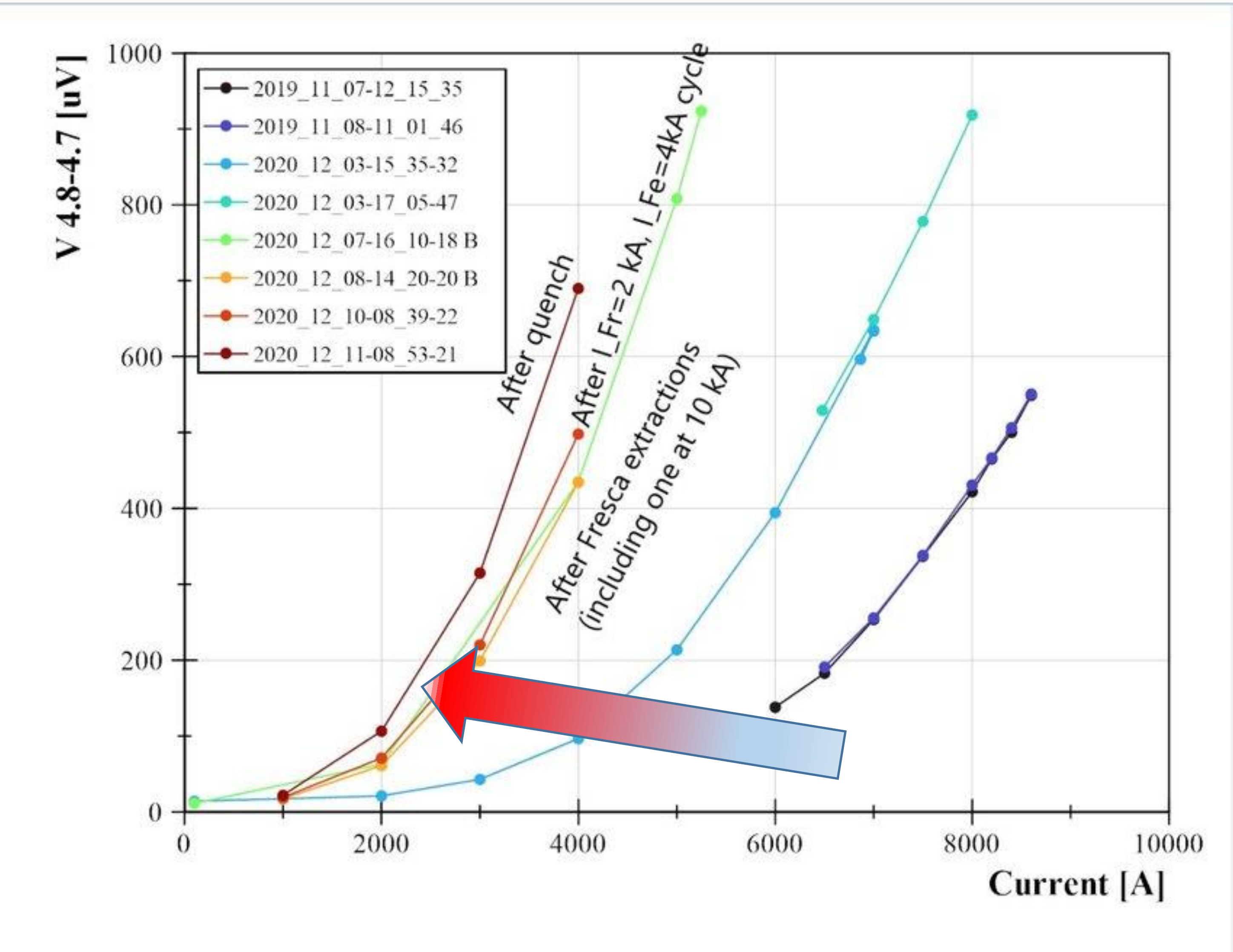
# Wiring layout



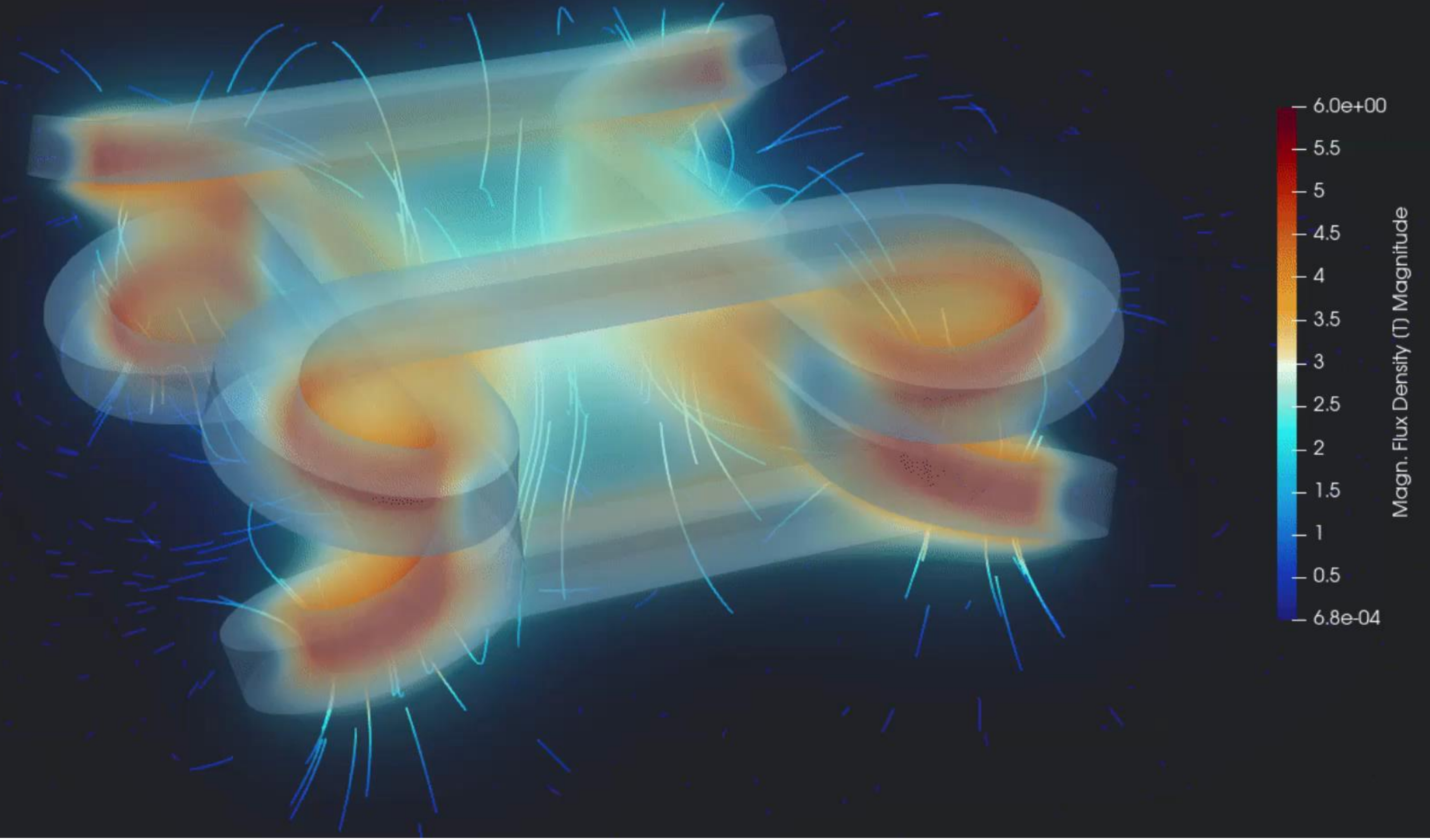
# V-I measurements in coil 2.3

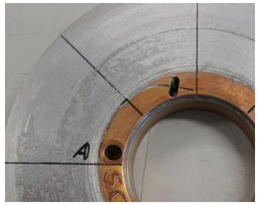
The degradation is visible from VI 2 to VI 3 (after the many extractions in Fresca2) and from VI 4 to VI 5 (after the magnetic measurements to 2 kA in Fresca, 4 kA in Feather).

Also, initial degradation from the standalone test to the first VI performed in this test campaign is visible



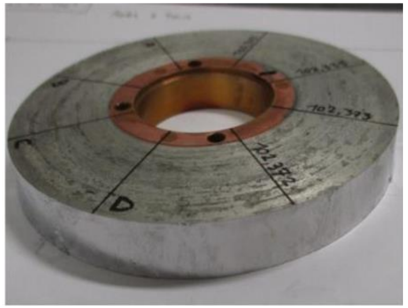
The End

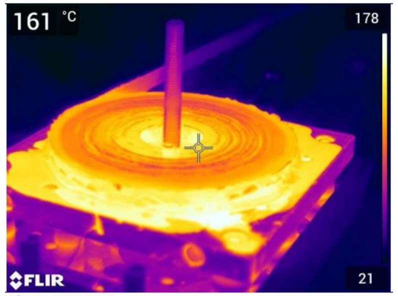

6.0e+00
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
6.8e-04
Magn. Flux Density (T) Magnitude



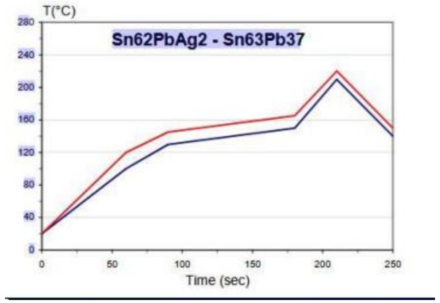
# Insulated coils - Partial insulation(PI) - No Insulation (NI)

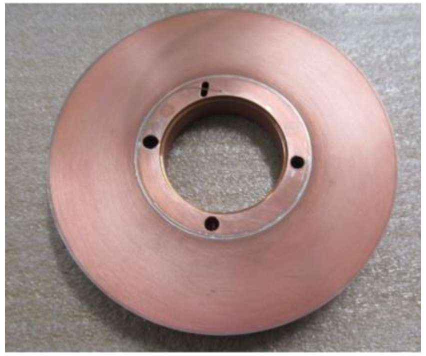
# - Variable Insulation (VI) also varistor


1st dwell 140° 2min



# Why? – 2. High Thermal Stability I



Stability of HTS Conductor illustrated


Quenching LTS wire 100 µJ

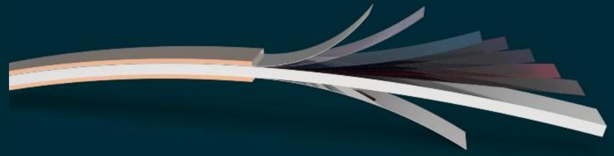

pin

10cm

Quenching an HTS Tape 100mJ

apple


10cm



Quenching an HTS cable 1J+ (depends on geometry)


cannon ball

10cm

Due to high temperature margin it is super stable and does not quench randomly and thus it does not train