SMC
Cold Test Results

SMC#1 and SMC#3

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TE-MSC-TF for electrical signal analysis

Some info is coming from :

L. Oberli TE-MSC-SCD concerning the Sc cable

M. Guinchard EN-MME concerning the strain gauge measurements

Discussions during analysis made with :

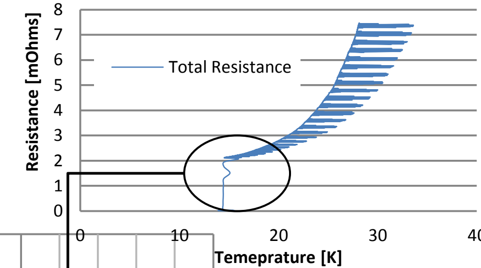
B. Bordini TE-MSC-SCD , P. Fessia and A. Milanese TE-MSC-MDT

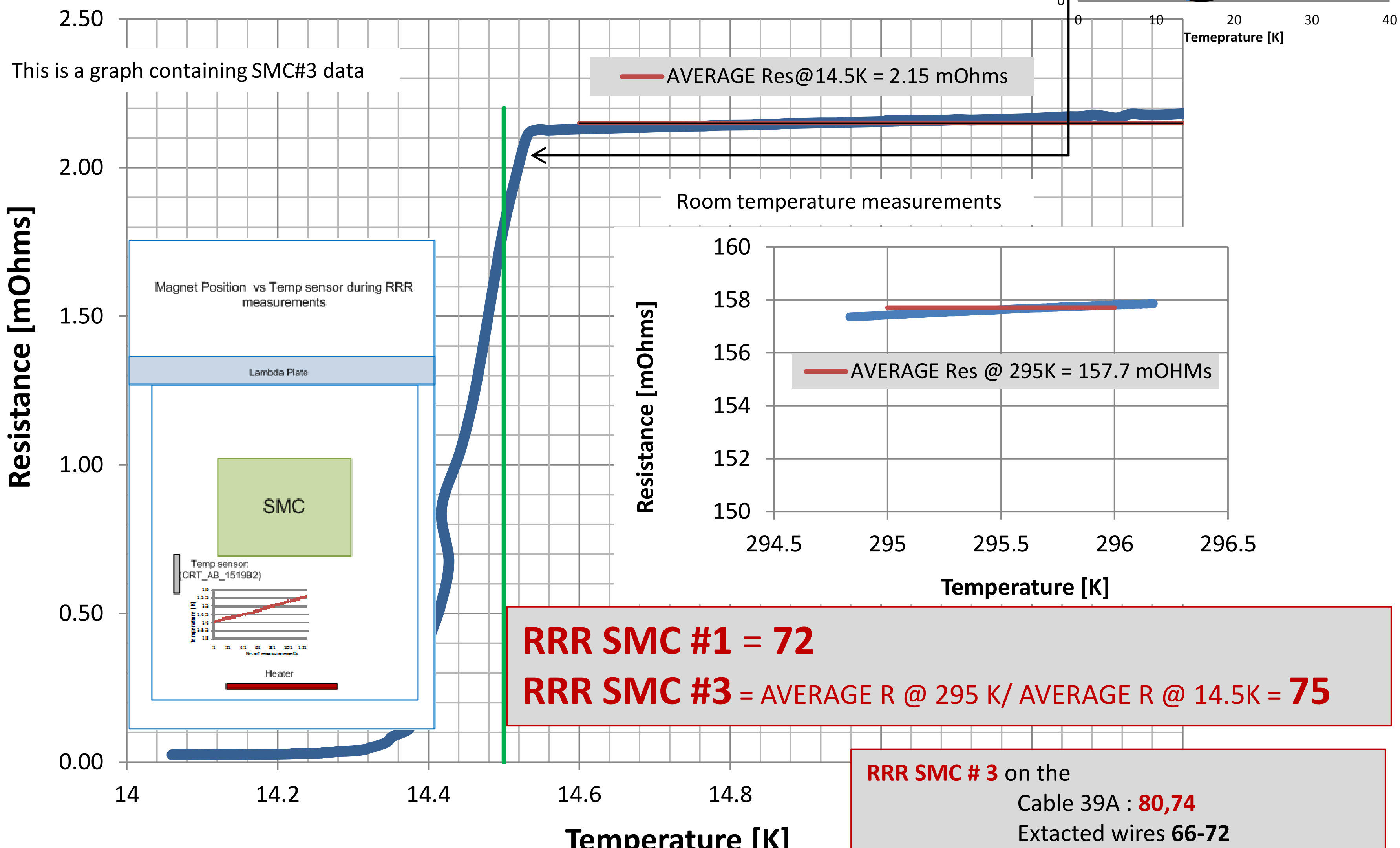
Summary

- RRR
- Splice Resistance Measurements
- Detection and Protection
- Training history
- Quenches out of the magnet
- Longitudinal quench propagation velocity
- Quench location. Statistics.
- Quenches and Strain
- Temperature estimation during quench (by Hugo Bajas)
- Conclusions

RRR measurements of SMC

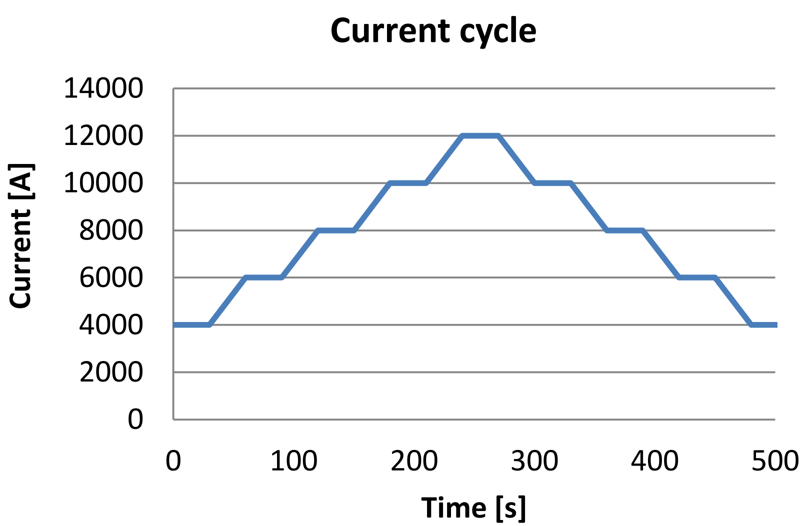
Measurements performed while the magnet was powered with 2 A
During the **WARM UP** from 4.2K to 300K

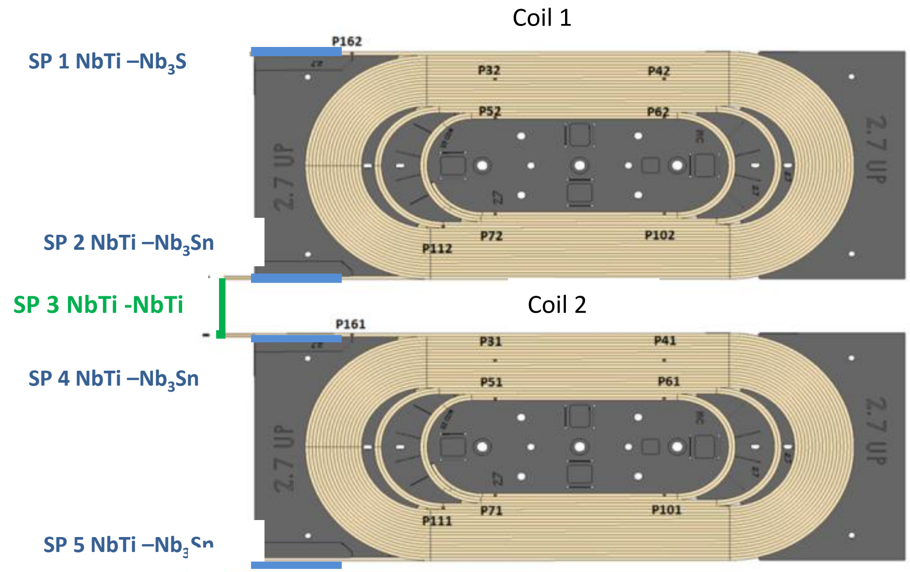




Splice measurements of SMC#3

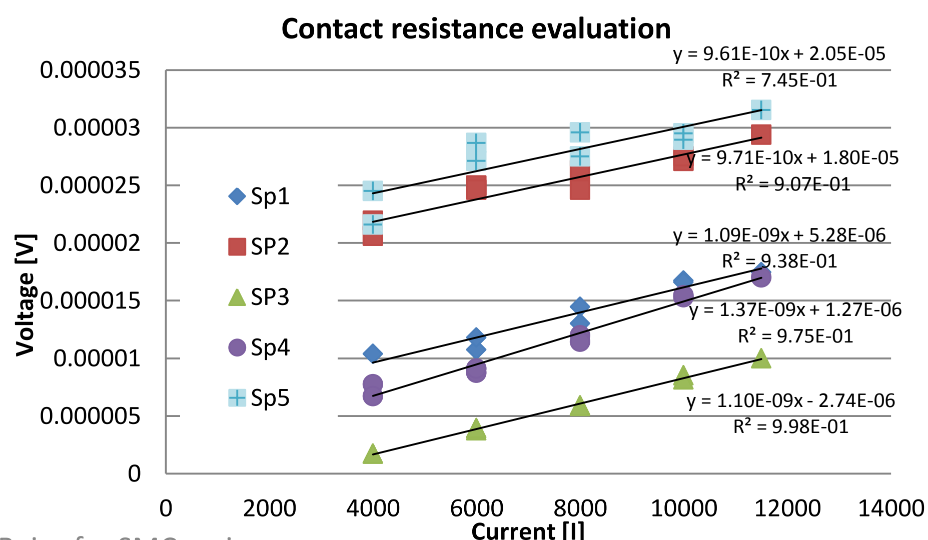
Measurements performed while the magnet was powered with I= 2000 - 1000 A





LHC dipole splice acceptance : 3 nOHM

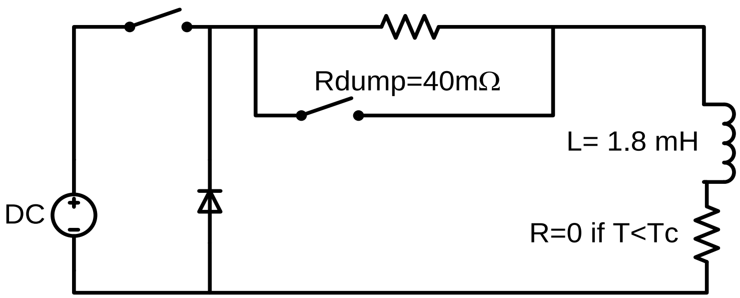
Splice	Resistance [nOhm]
Inter coil Sp3(NbTi-NbTi)	1.1
Coil 1 Sp1 (NbTi-Nb3Sn)	1.0
Coil 1 Sp2(NbTi-Nb3Sn)	0.9
Coil 2 Sp4(NbTi-Nb3Sn)	1.3
Coil 2 Sp5(NbTi-Nb3Sn)	0.9

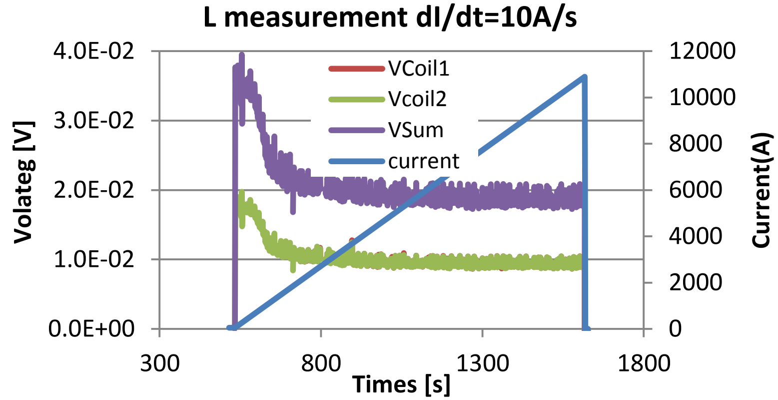


Protection of SMC

Training performed at 4.2K and 1.9K , 10-200 A/s RR

The protection **circuit**

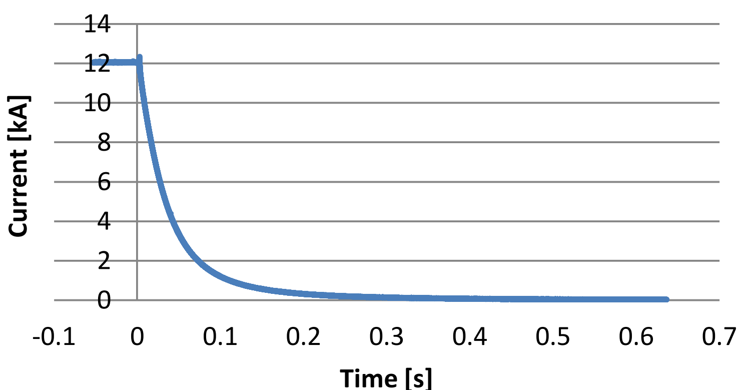




Estimated inductance is **L= 1.8 mH**
Confirmed by the model

For a faster **extraction of the energy** from the magnet, when the quench occurs, an external **dump resistor of 40 mΩ** was used, leading to a coil voltage during a quench of **550 V at 14 kA with a typical time constant of 35 ms**.

Typical current decay after quench



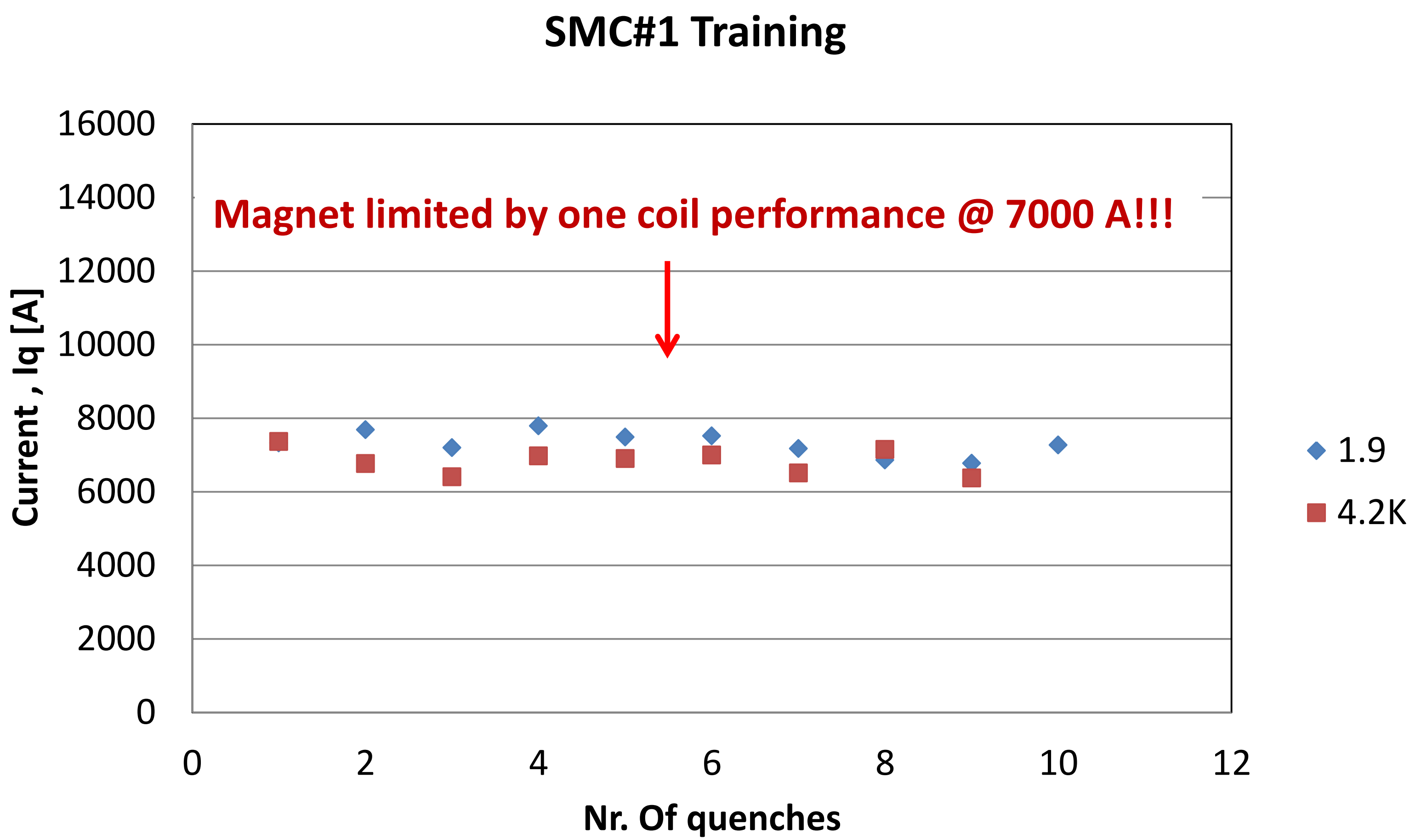
Detection and protection **threshold and time windows**

$Ucoil_1$-$Ucoil_2$ ≥ 100 mV x 10 ms
$Uupper_1$-U lower $_1$ ≥ 100 mV x 10 ms
$Uupper_2$-U lower $_2$ ≥ 100 mV x 10 ms
U splice and leads ≥ 50 mV x 8 ms

In order to complete the hot spot temperature estimation we performed quenches with variable time windows (see the slides of Hugo Bajas)

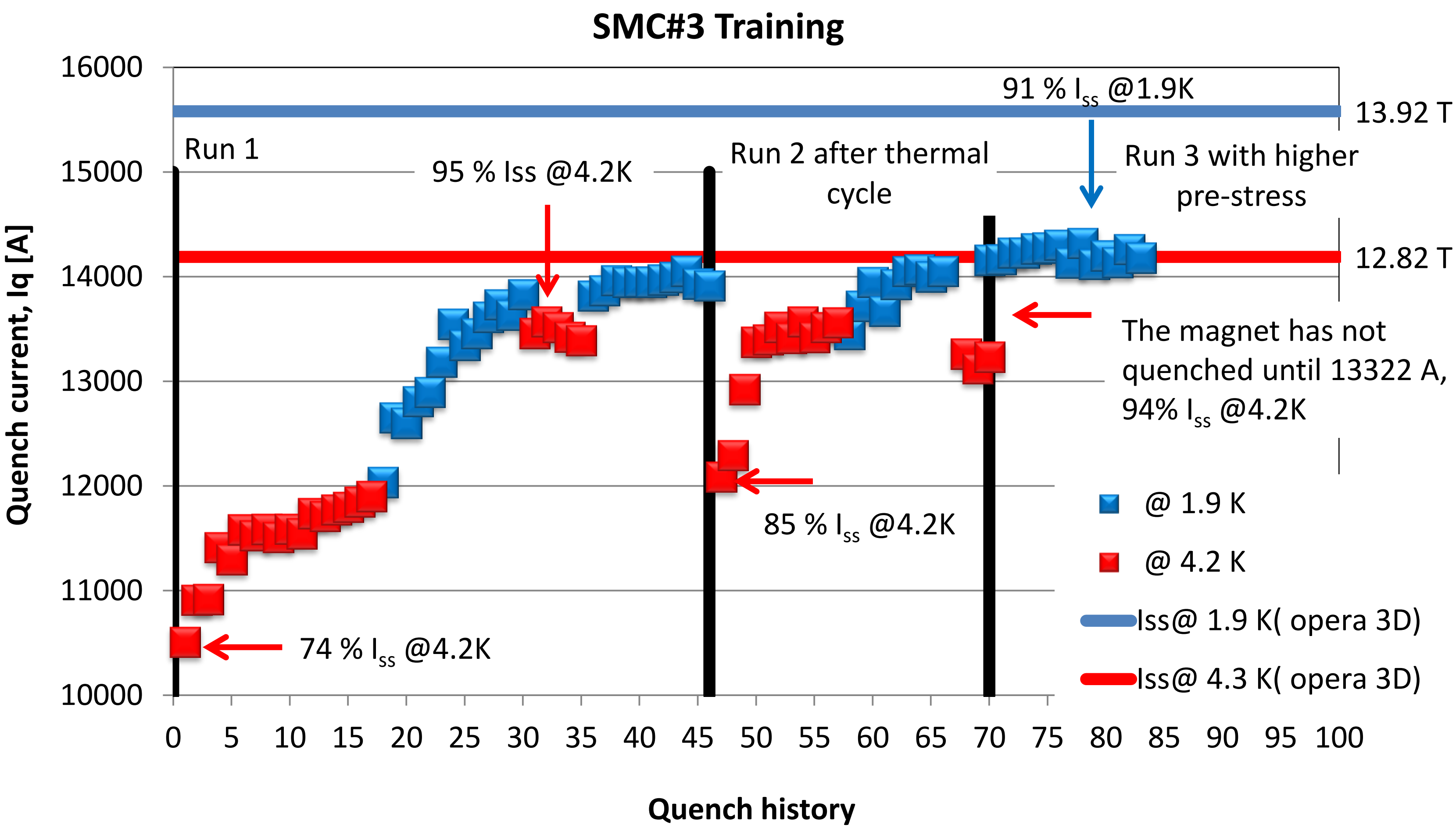
Training quenches in the magnet SMC#1

Training performed @4.2K and @1.9K ,
with one single coil to avoid limitation at 3 kA of one splice



Training quenches in the magnet SMC#3

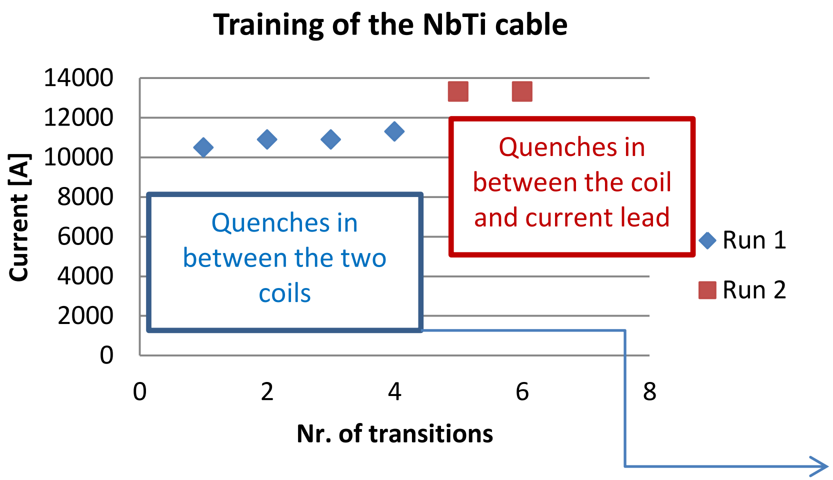
Training performed @4.2K and @1.9K , quenches performed with ramp rate (RR) of 20 A/s

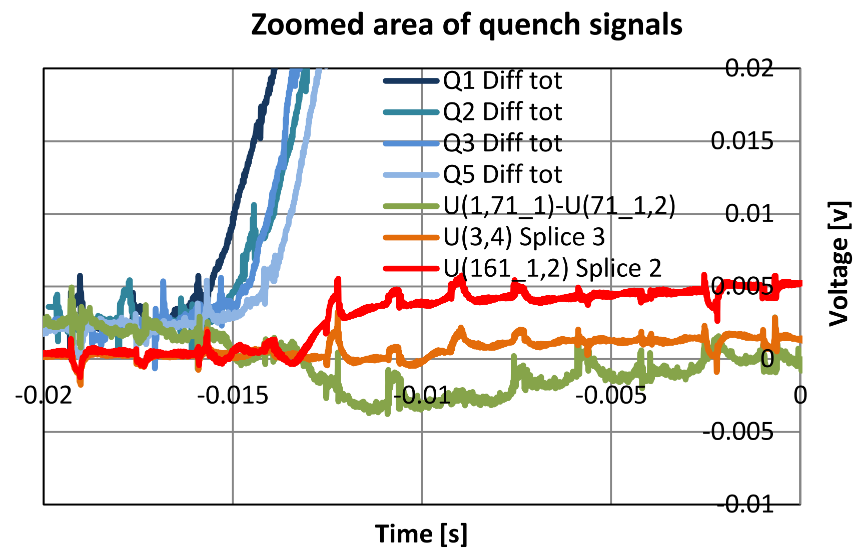


The strain is not considered for the estimate of the Iss

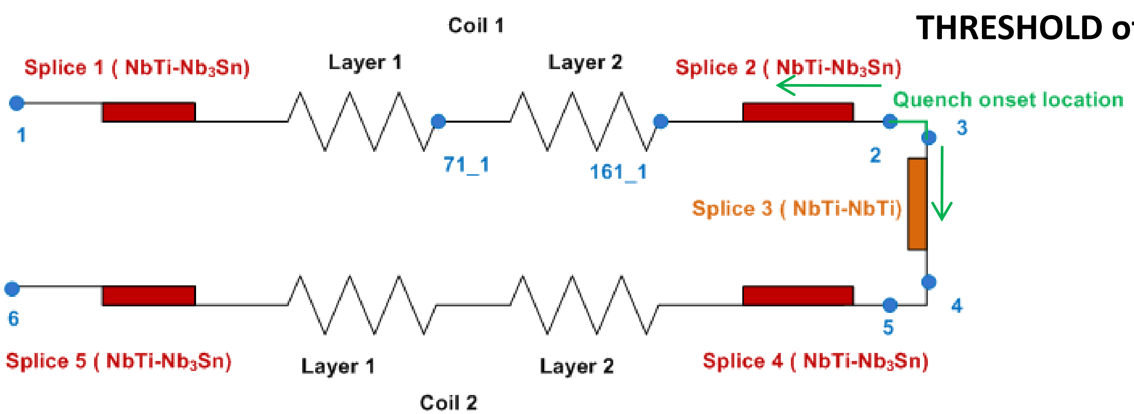
Quenches outside the SMC#3

quenches detected not in the magnet but in the cable connecting the two coils or the coils with the current leads





THRESHOLD of detection and protection: 50 mV, 10 ms



$$Diff_{tot} = U(1,4) - U(4,6) > 0$$

Indicates a quench onset in: $U(1,4)$

which is composed as following:

$$U(1,4) = U(1,2) + U(2,3) + U(3,4)$$

the signals $U(1,2) = 0$

because:

$$U(1,71\_1) - U(71\_1,2) = 0$$

and

$$U(3,4) = 0$$

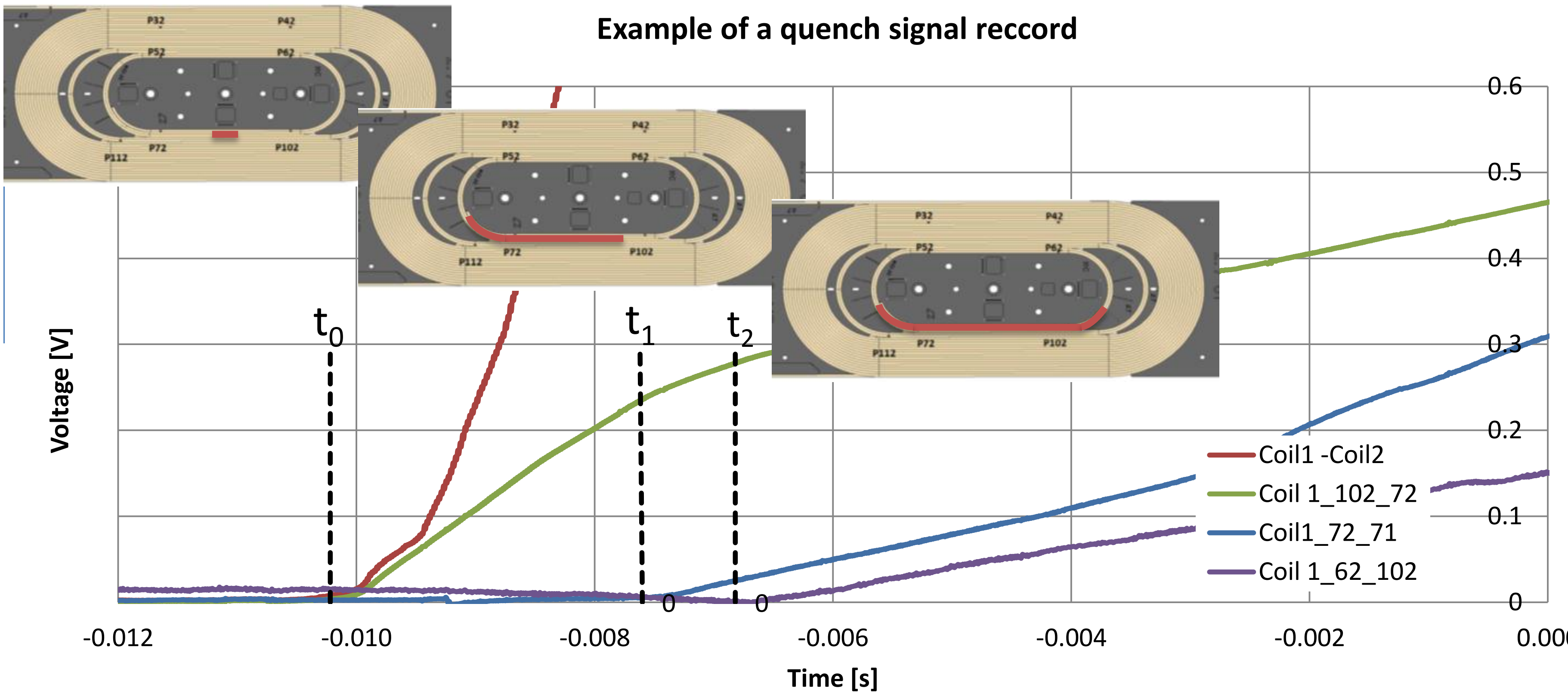
therefore we can only conclude that:

$$U(1,4) = U(2,3)$$

The quench onset is in-between Vtaps 2 and 3 . **Not in the coil** and **not in the splices. It is** located in **the NbTi cable** linking the two coils. Heat is propagating from this portion of cable to Splice 2 and Splice 3.

Quench propagation velocity. Time of Flight (ToF) method. SMC#3

Quench localized in HFS between Vtap72 and 102 of COIL 1



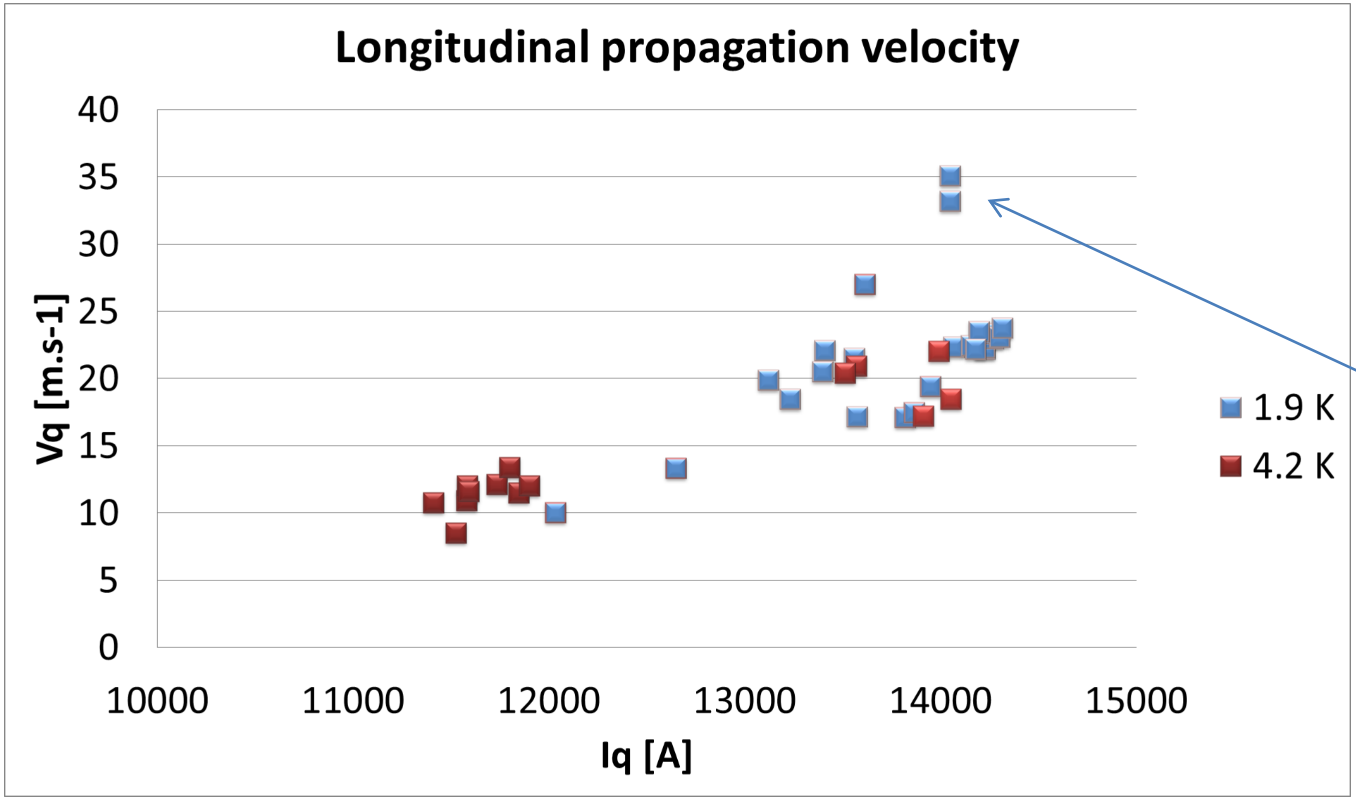
$$v = \frac{d(Vtap72, Vtap102)}{ToF}$$

$$ToF = (t_1 - t_0) + (t_2 - t_0)$$

$$v_{example} = \frac{130mm}{2.6ms + 3.4ms} = 21.6m/s$$

Quench propagation velocity in SMC #3 based on the ToF

Training performed @4.2K and @ 1.9K , 20 A/s ramp rate, localized in HFS between Vtap72 and 102 of COIL 1

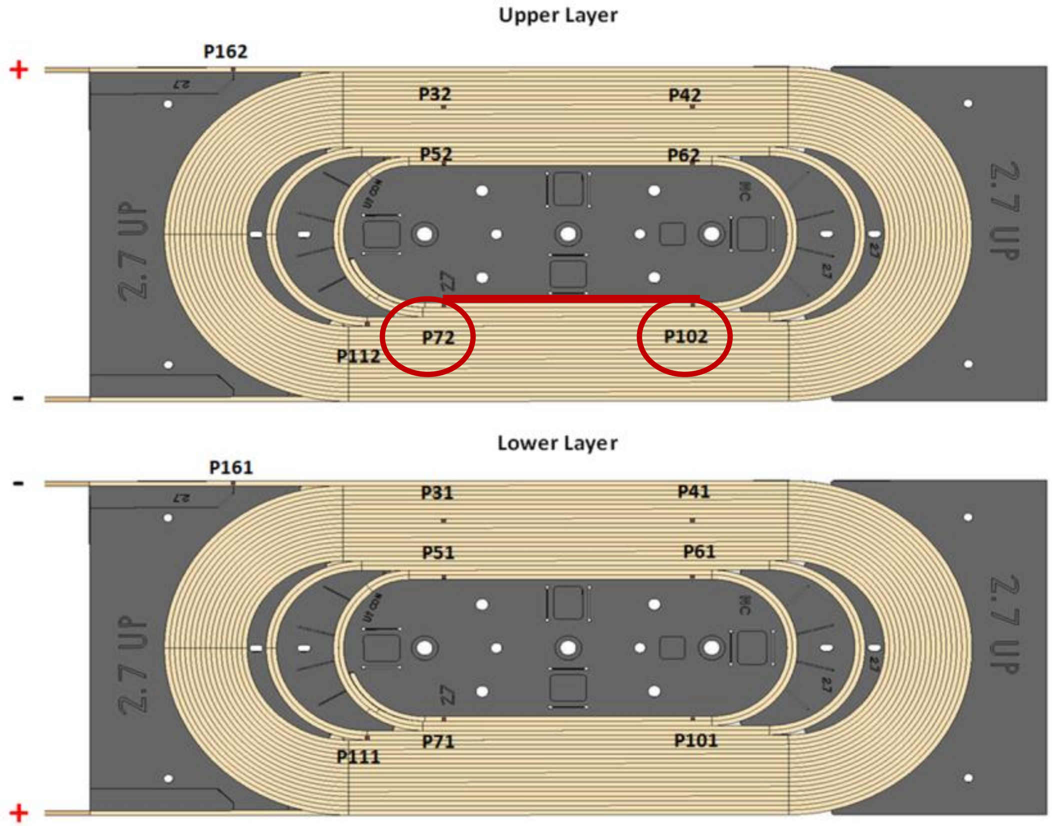


Outliers indicates that there is a transverse propagation effect. To be confirmed by more detailed study.

Increase of the velocity with training and current.

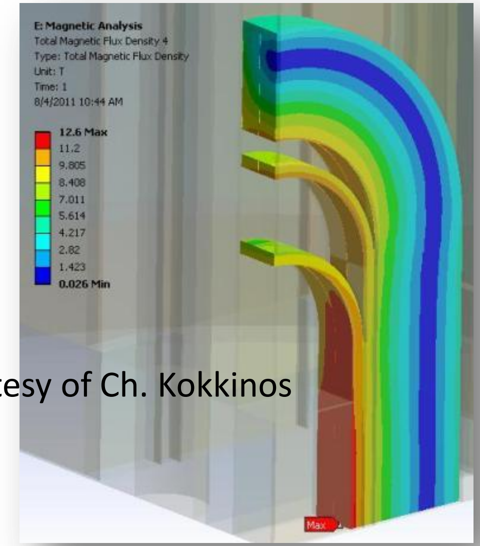
Quench location. Statistics on run 2. SMC#3

Training performed @ 4.2K and a@1.9K , quenches performed with 20 A/s ramp rate



	72-102	HFS	14
	112-52	MT HF	1
	51-111	MT HF	1
	52-62	HFS	1
	101-61	H	1
	71-101	HFS	2
4.2 K	71-72		1

	72-102	HFS	11
	112-52	MT HF	1
	51-111	MT HF	1
	52-62	HFS	3
	101-61	H	1
	71-101	HFS	1
	62-102	H	1
	71-72	LJ	4
1.9 K	61-51	HFS	2

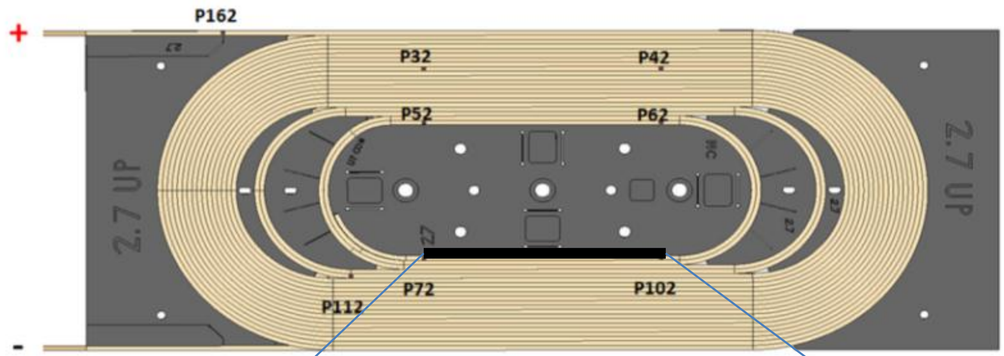


Courtesy of Ch. Kokkinos

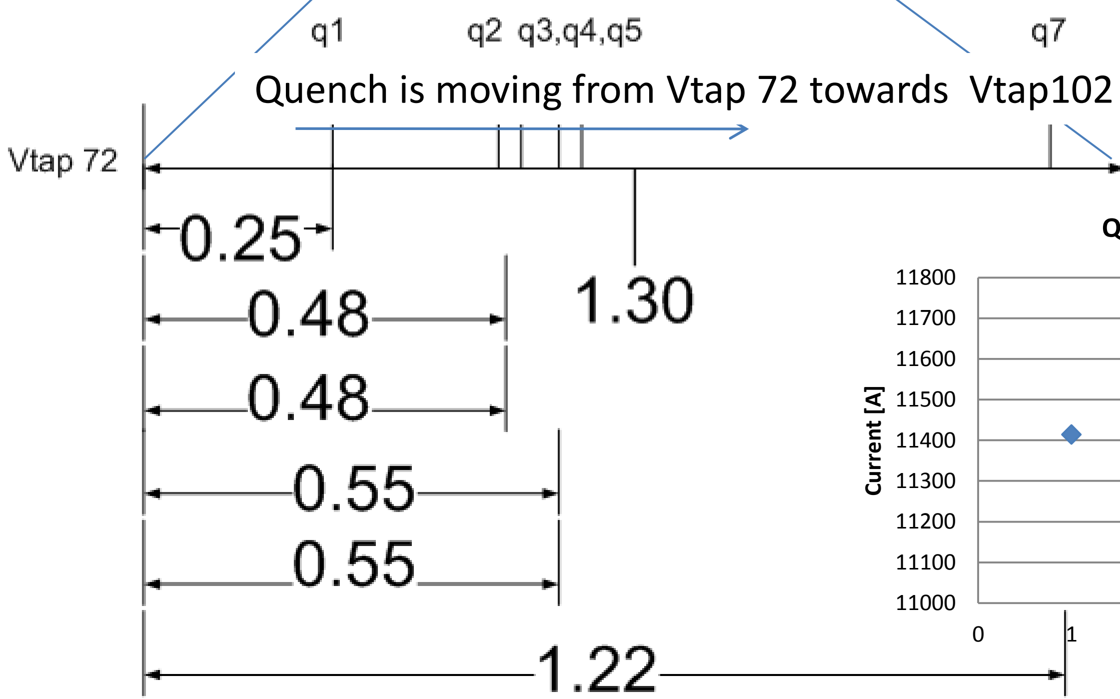
- approx. **74 %** of quenches occurs in the High(H) Field(F) zone on the Straight(S) part (**HFS**) in coil1
- approx. **73%** of HFS occurs in between **Vtap 72 and V tap 102** in coil 1
- **No quenches in the splices !!!!**
- Only 10% of quenches on the Layer Jump; few are on coil 2.

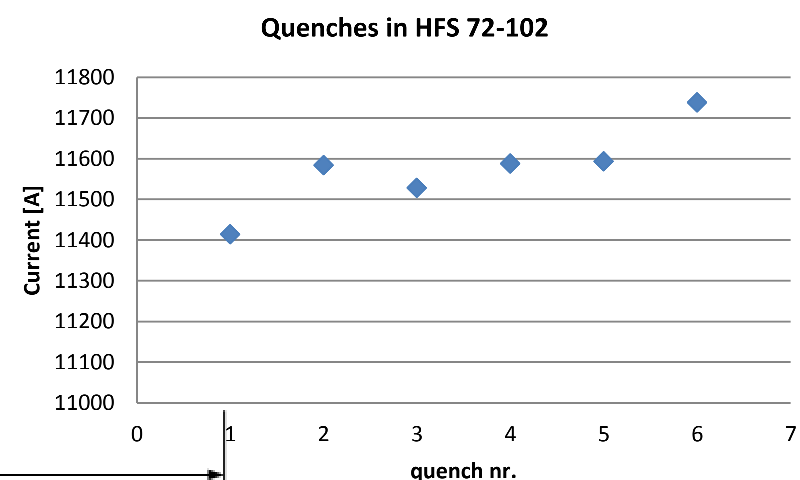
Quench location during training in run 2: HFS SMC#3

Training performed at 4.2K , 20 A/s ramp rate, localized in HFS between Vtap72 and 102 of COIL 1



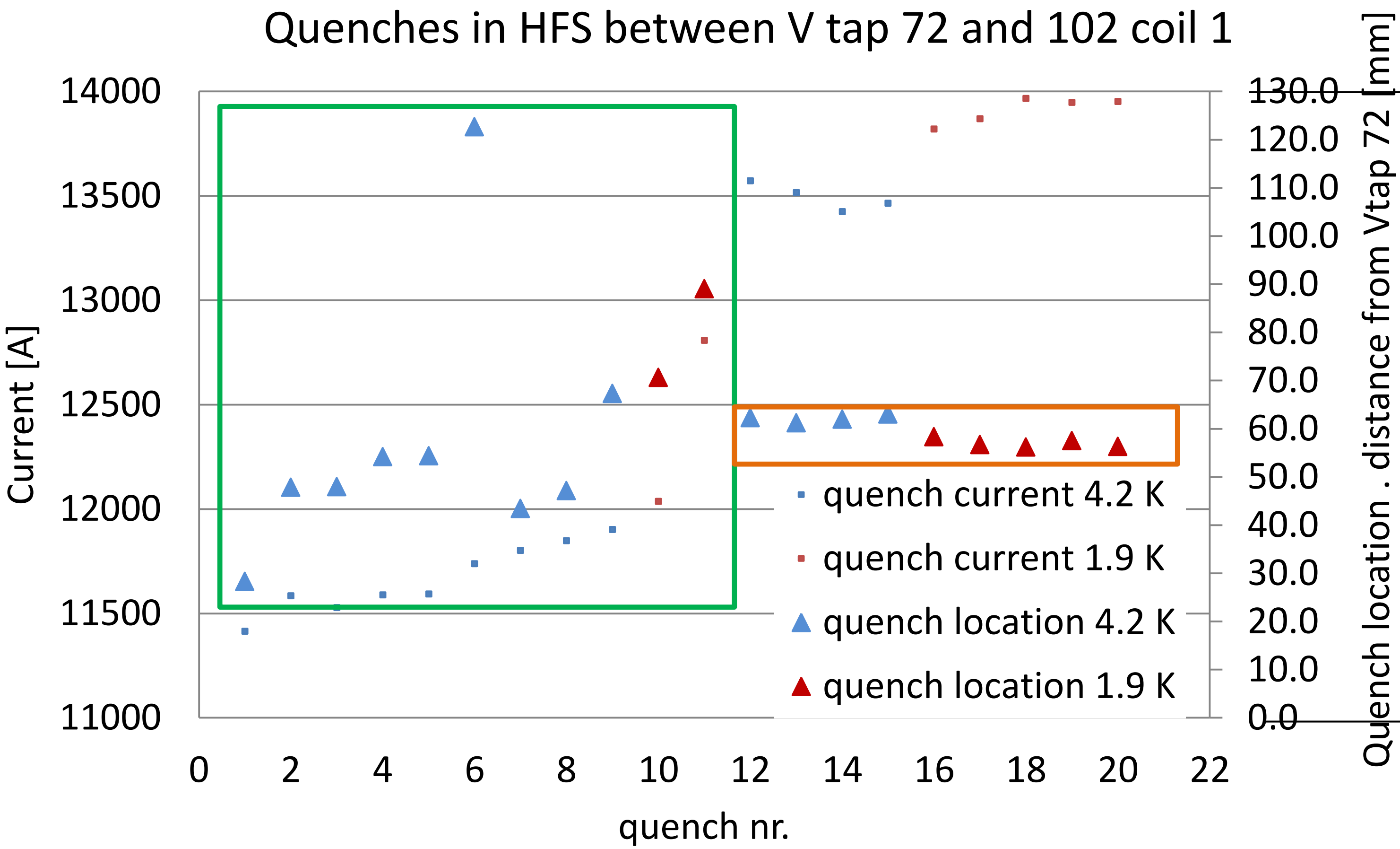
Quench propagation velocity: **12 m/s**

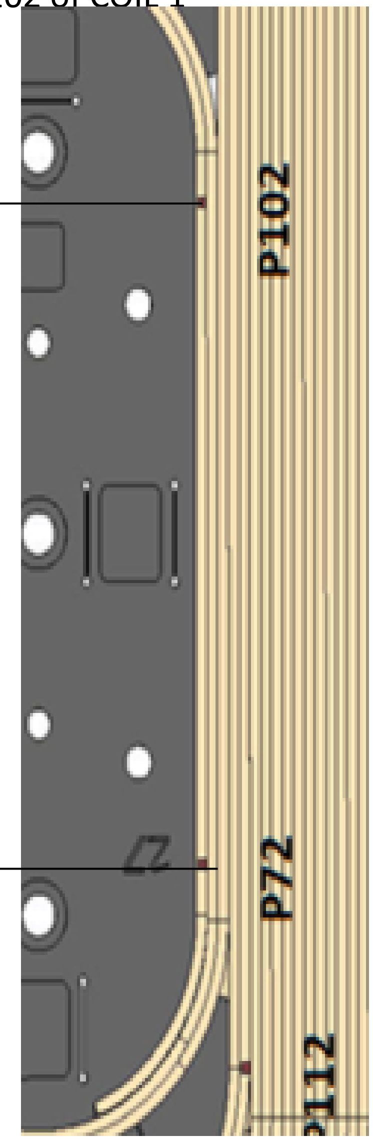




Quench location in run 2 :HFS SMC#3

Training performed at 4.2K and 1.9K , 20 A/s ramp rate, localized in HFS between Vtap72 and 102 of COIL 1



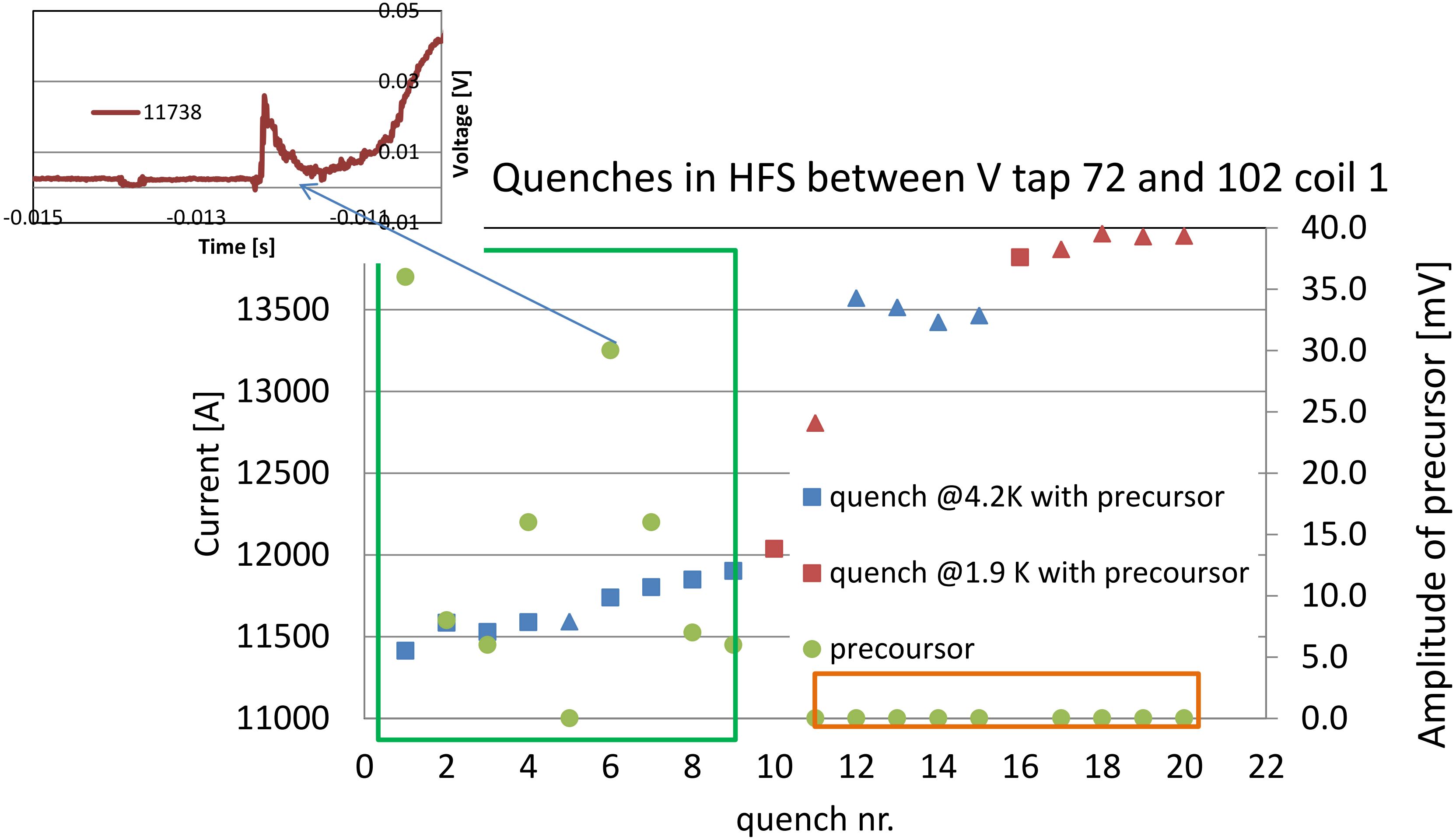


Quench during **training are located between Vtap 72 & Vtap 102:**

Quench on the **plateau are located at "the mid distance" between Vtap72,Vtap 102**
To be linked to the **highest field and strain**

Quenches with and without precursors in run 2 :m HFS SMC#3

Training performed at 4.2K and 1.9K , 20 A/s ramp rate, localized in HFS between Vtap72 and 102 of COIL 1

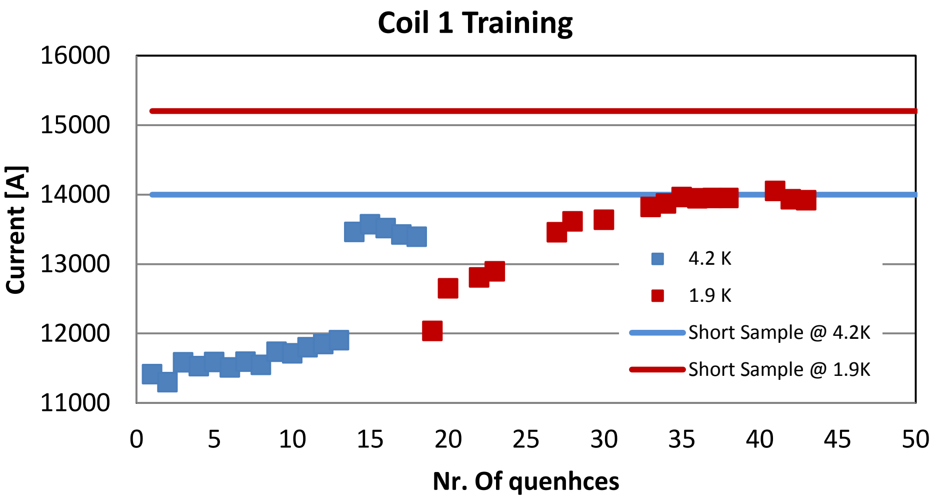


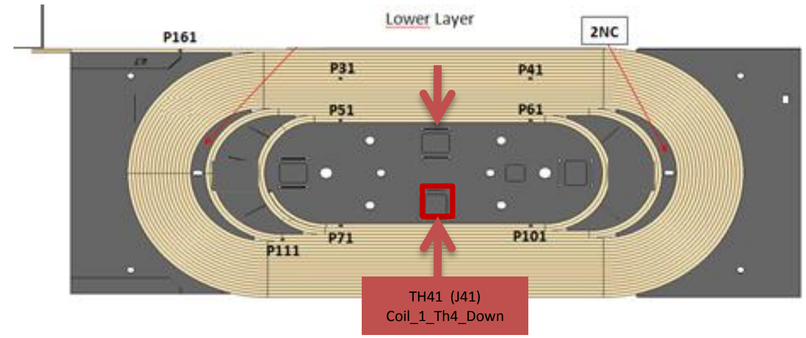
Quench during **training has precursors** of an amplitude between 6-30 mV

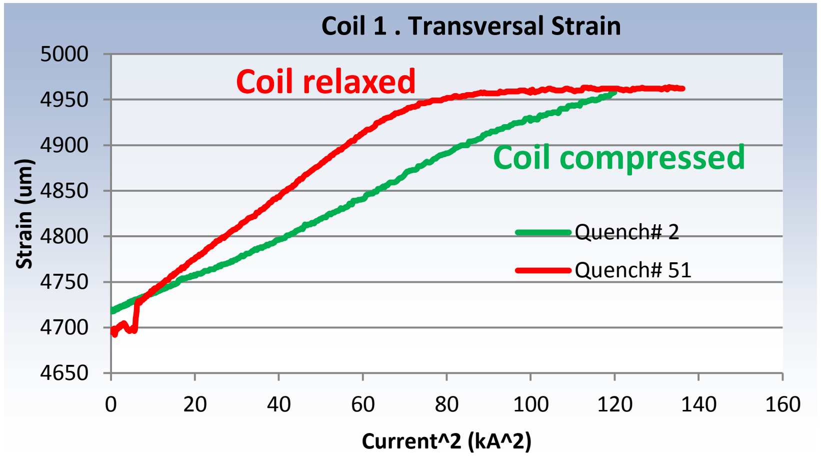
Quench on the **plateau are not having precursors**
Or they are very small !!!

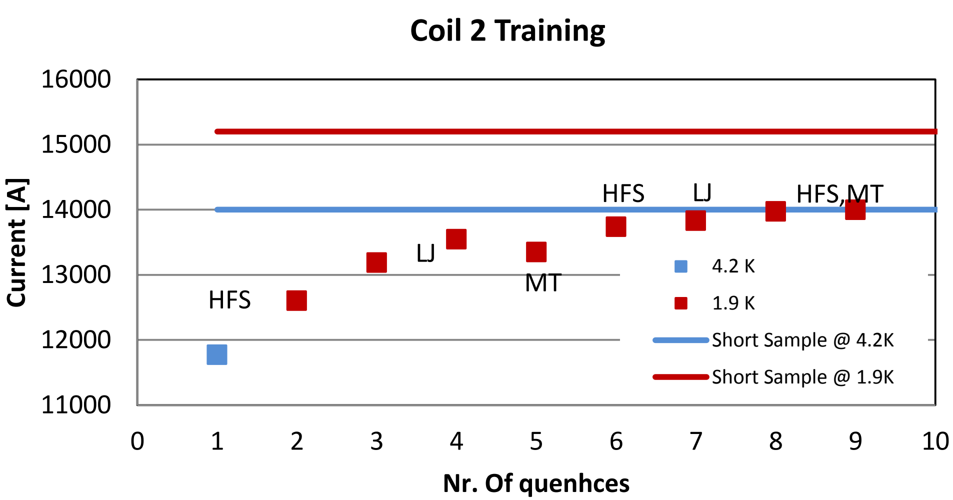
Training quenches coil by coil. Strain on the coil 1 of run 2. SMC#3

Training performed at 4.2K and at 1.9K , quenches performed with 20 A/s ramp rate







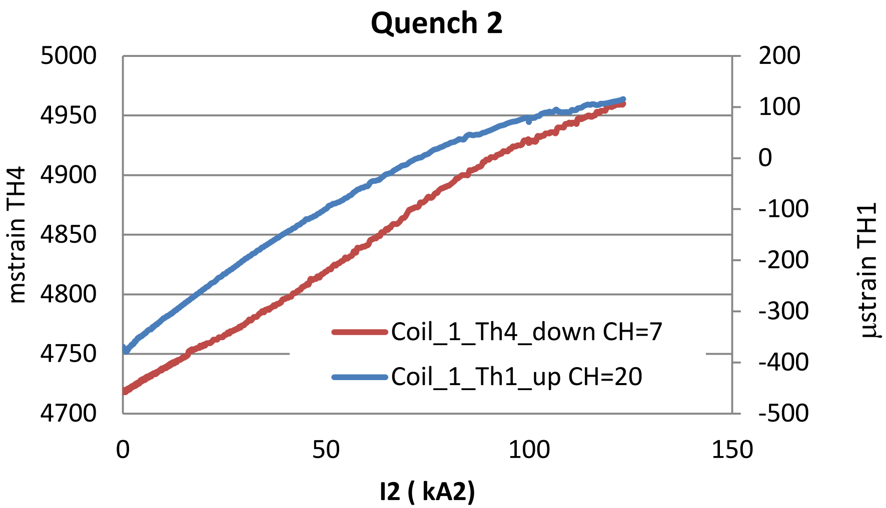


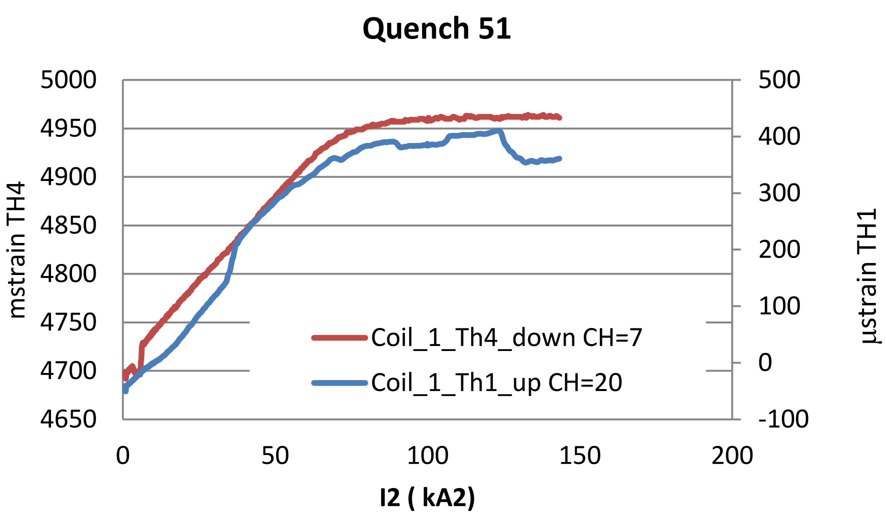
Nothing special for the moment was seen on the gauges **on COIL 2**

Quenches are on **LJ** or **HFS**

Training quenches coil by coil. Strain on the coil 1 in run 2. SMC#3

Training performed at 4.2K and at 1.9K , quenches performed with 20 A/s ramp rate

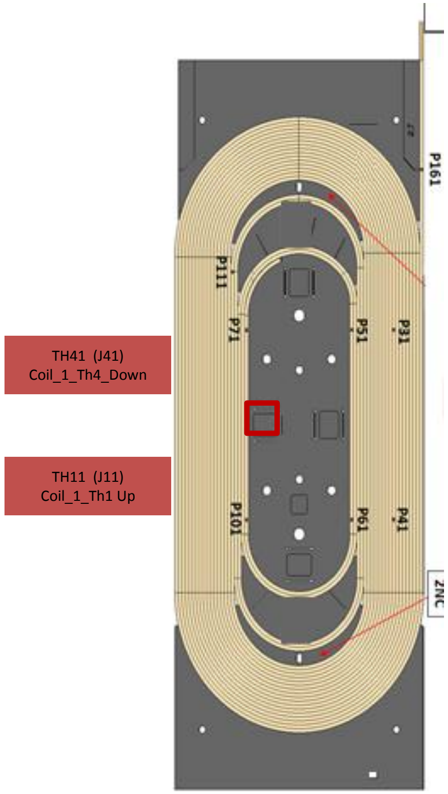




These two gauges should measure the same value….

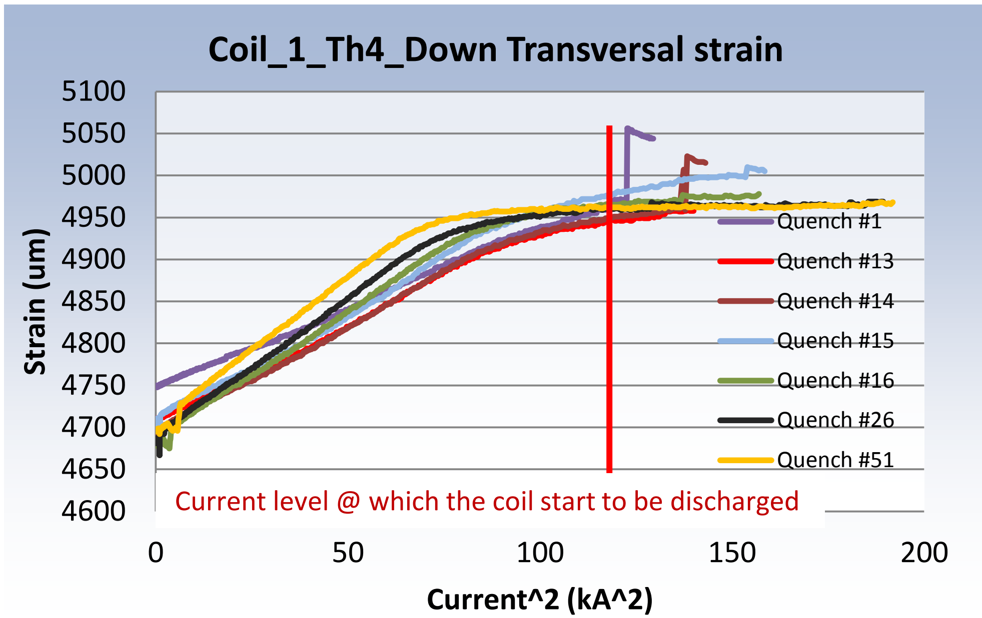
Is not the case ….**see the scales**

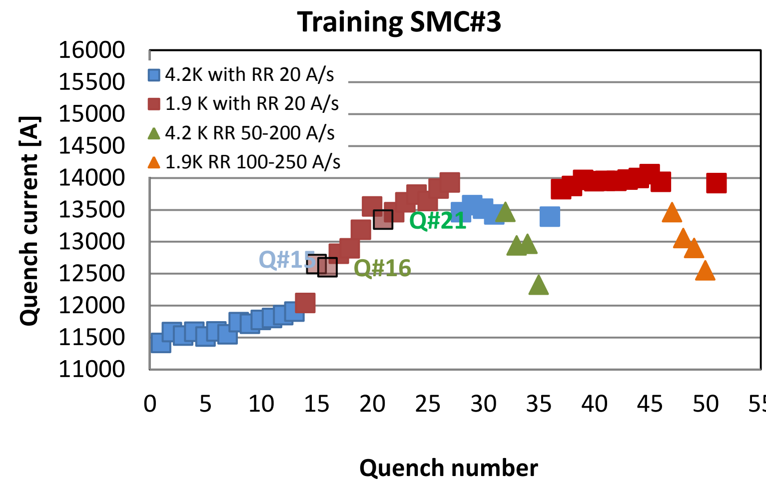
BUT
They have the same variation with current ^{2} …**see the shape**

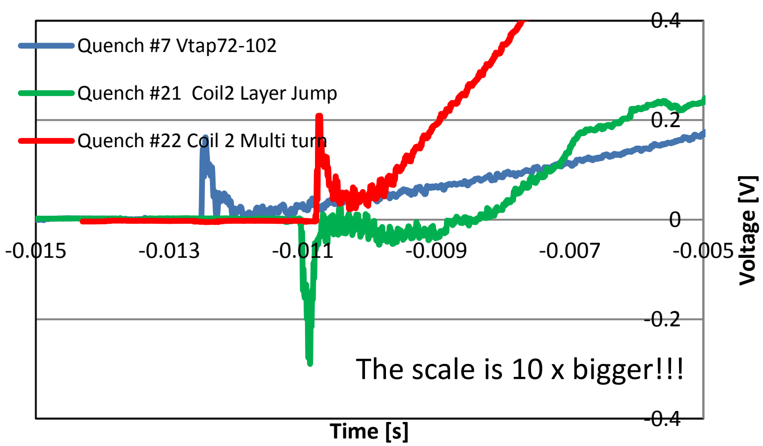


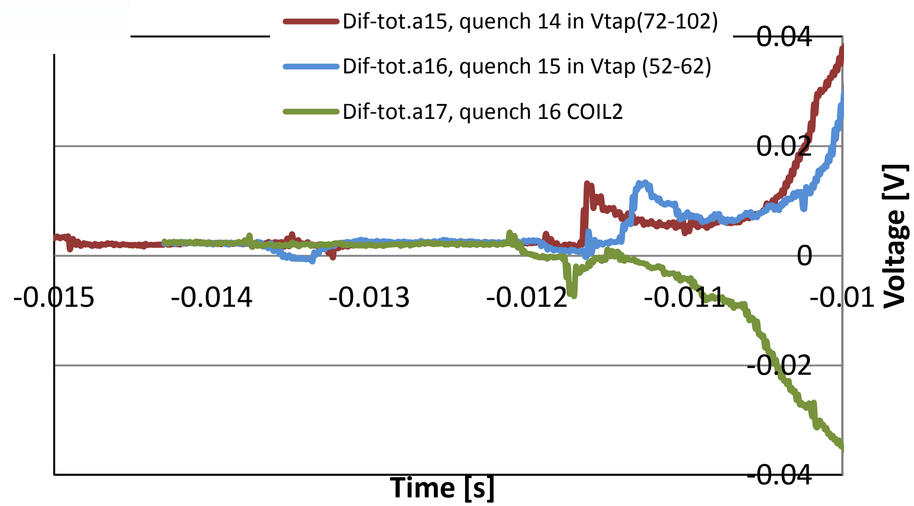
Strain gauges on COIL and spikes in the V signals I run 2. SMC#3

Training performed at 4.2K and 1.9K , 10-20 A/s RR, and variable RR



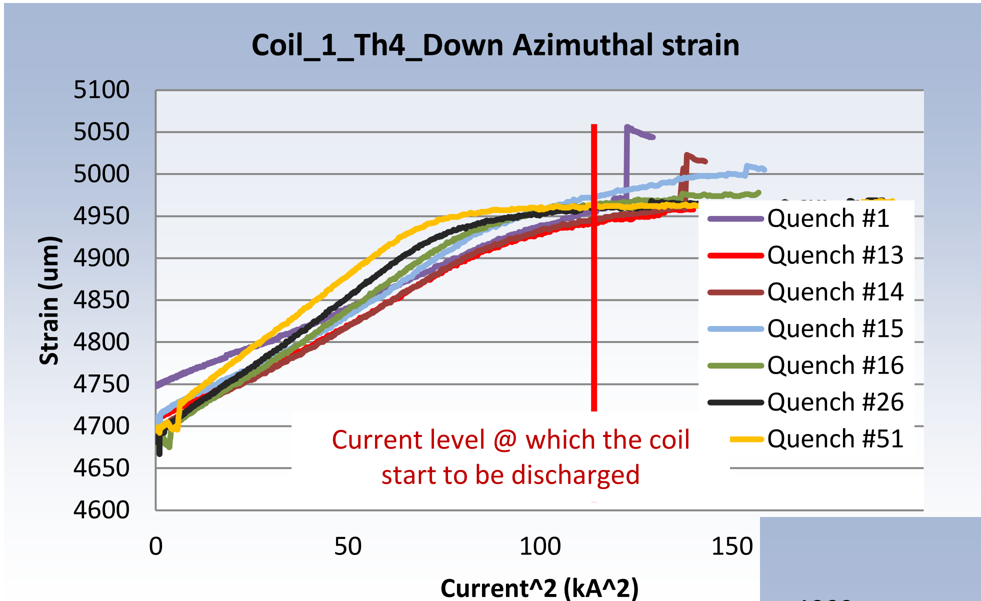


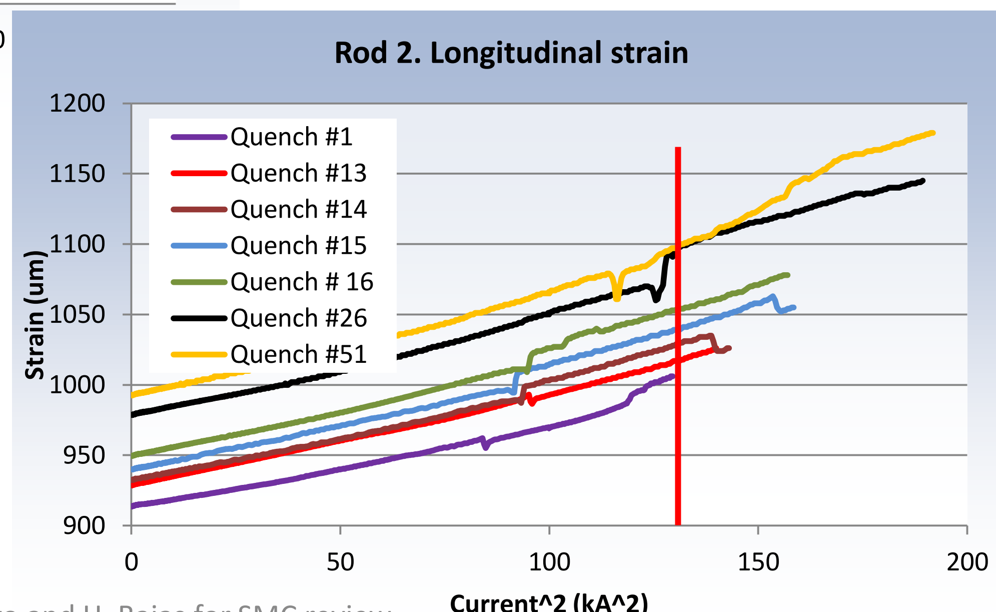




Strain gauges on Coil and Rod In run 2. SMC#3

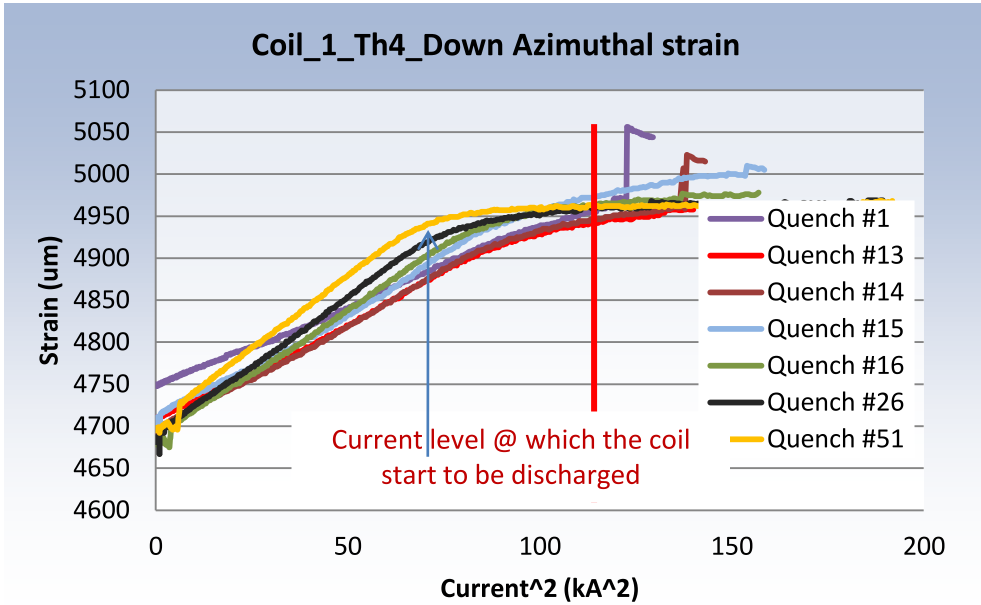
Training performed at 4.2K and 1.9K , 10-20 A/s RR, and variable RR

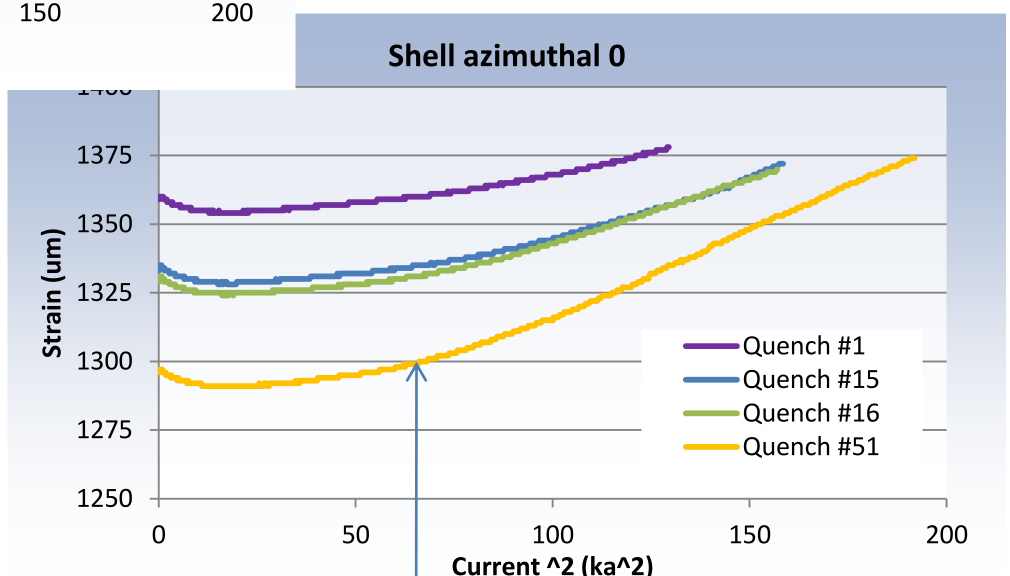




Strain gauges on Coil and Shell in run 2. SMC#3

Training performed at 4.2K and 1.9K , 10-20 A/s RR, and variable RR

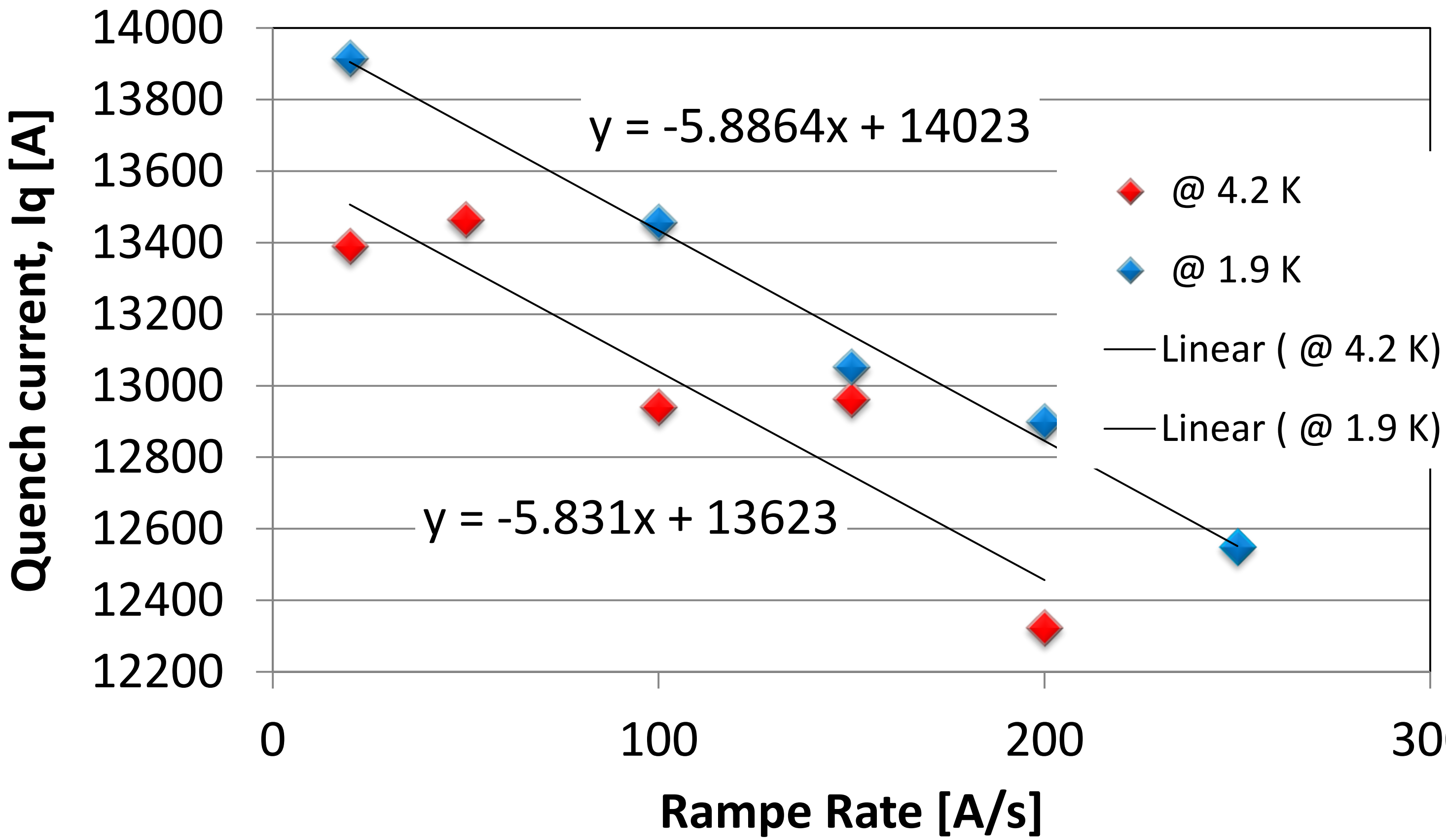




In the shell :100 $\mu\varepsilon$= 7 MPa

High Ramp Rate quenches. SMC#3

Training performed at 4.2K and at 1.9K , quenches performed with ramp rates up to 250 A/s



High propagation velocity **30-60 m/s**
and multi zones quench :
in the **high field zone** first then in the low field zone

Temperature rise in the coil after quench. Run 1, 2 and 3. SMC#3

Goal: Assessment of the temperature rise in the cable during a quench using analytical method.

Mean : Resolution of the energy balance between Joule effect and rate of heat.

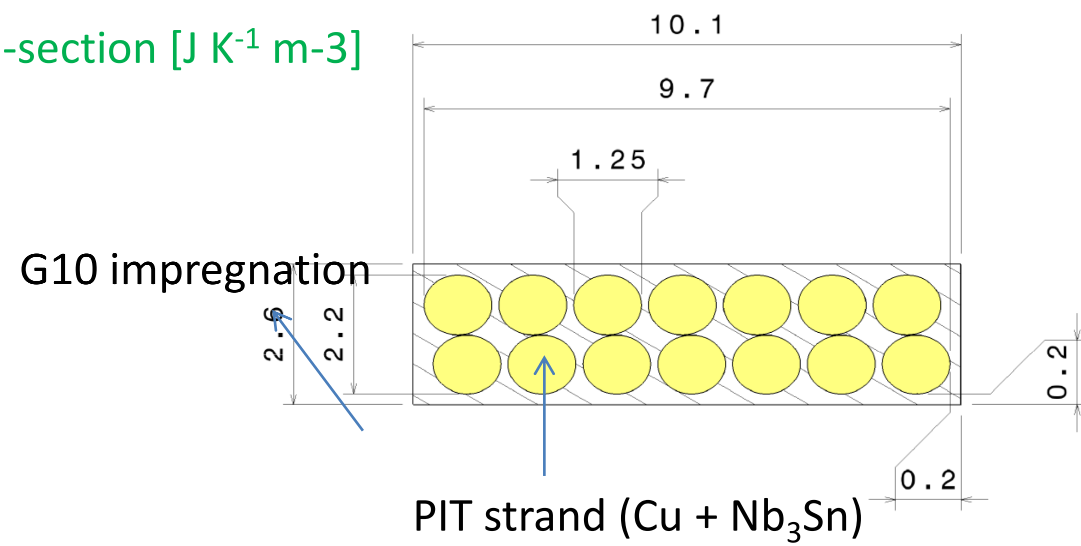
Rearranged equation:

$$\int_0^{t_{trigger}} I(t)^2\,dt = a_{Cu}\,a_t \int_{T_0}^{T_{max}} \frac{\rho.c_p(T)}{\rho_E(RRR, B, T)}\,dT$$

Volumetric heat capacity of the total cross-section [J K^{-1} m-3]

Electrical resistivity of copper [Ω m]

Solve the equation to retrieve T_{max} [K]



[1]
Stephan Russenschuck

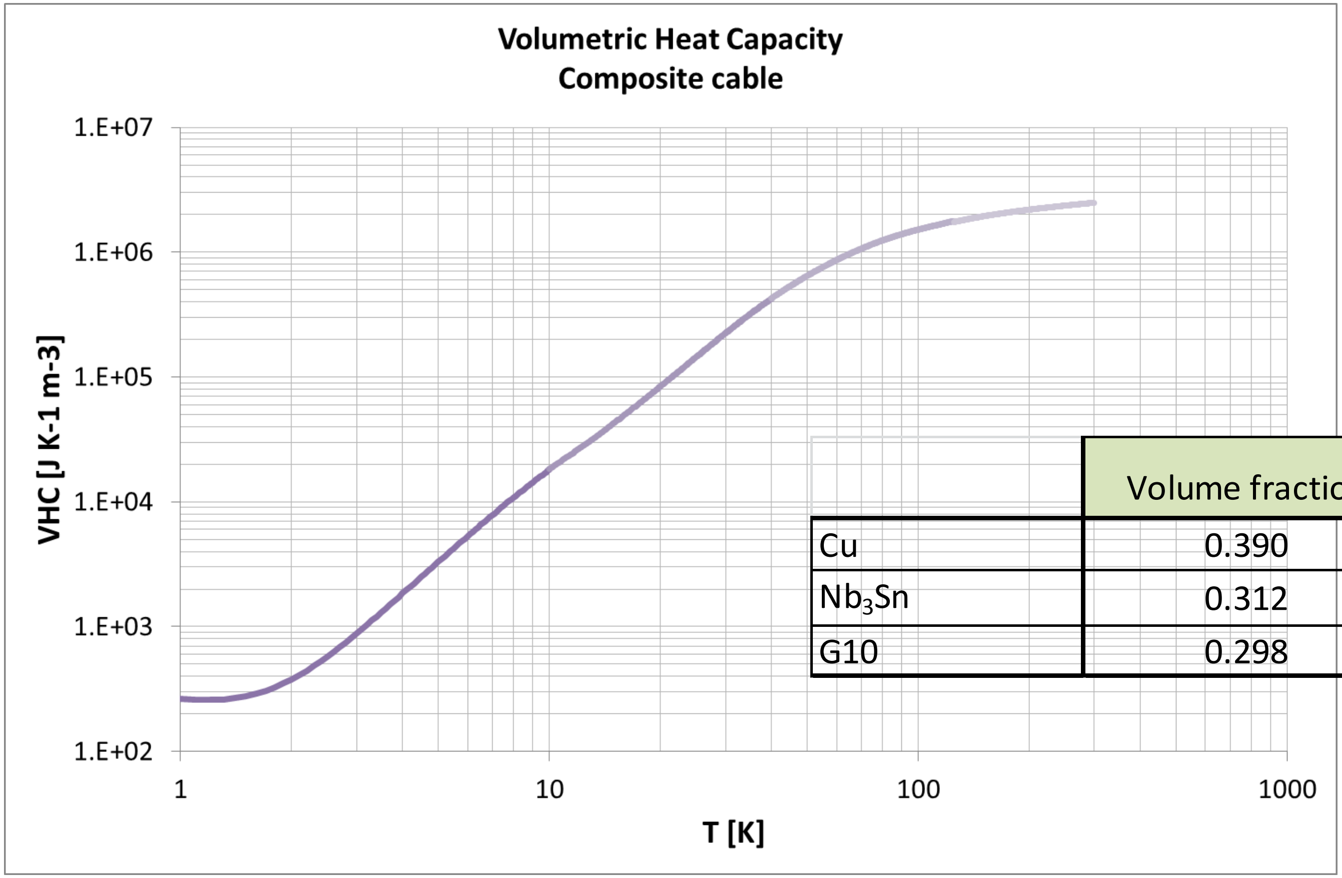
[2]
Pierre Manil, Federico Regis,

Temperature rise in the coil after quench. Run 1, 2 and 3. SMC#3

Volumetric Heat Capacity [J K^{-1} m-3]

Mixture law:

$$\color{red}{VHC_{composite}} = \nu_{Cu} * VHC_{Cu} + \nu_{Nb_3Sn} * VHC_{Nb_3Sn} + \nu_{G10} * VHC_{G10}$$

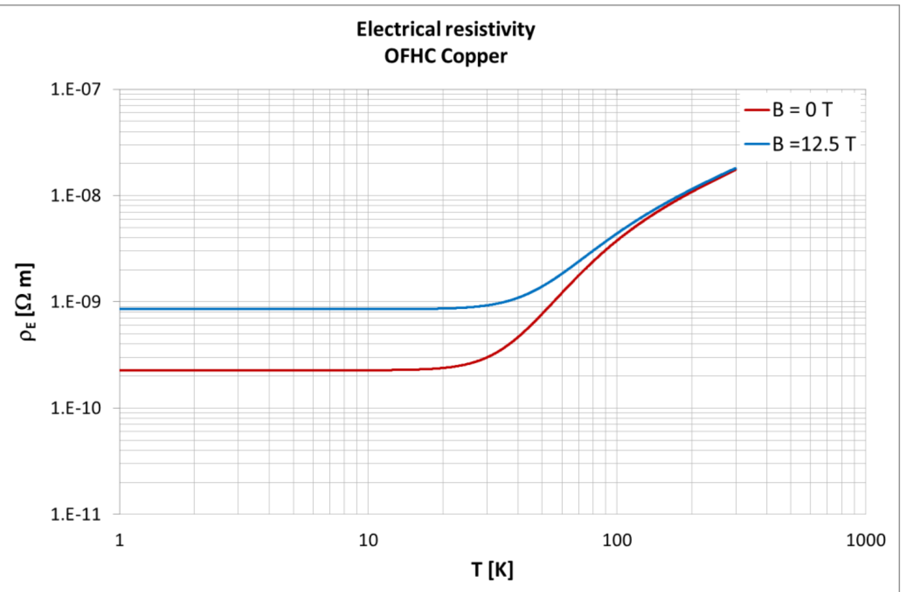


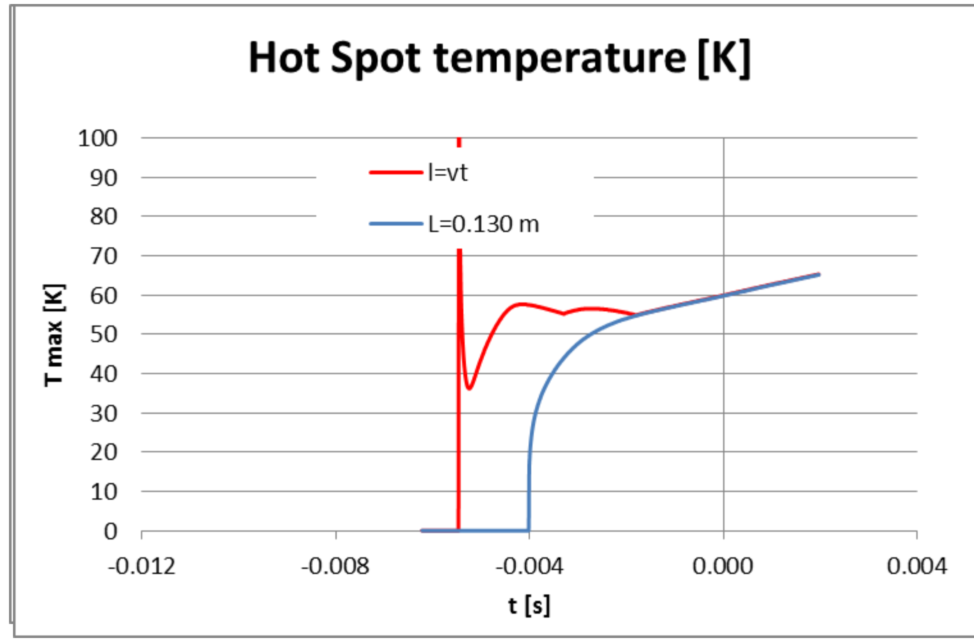
	Volume fraction
Cu	0.390
Nb_3Sn	0.312
G10	0.298

Temperature rise in the coil after quench. Run 1, 2 and 3. SMC#3

Electrical resistivity of copper

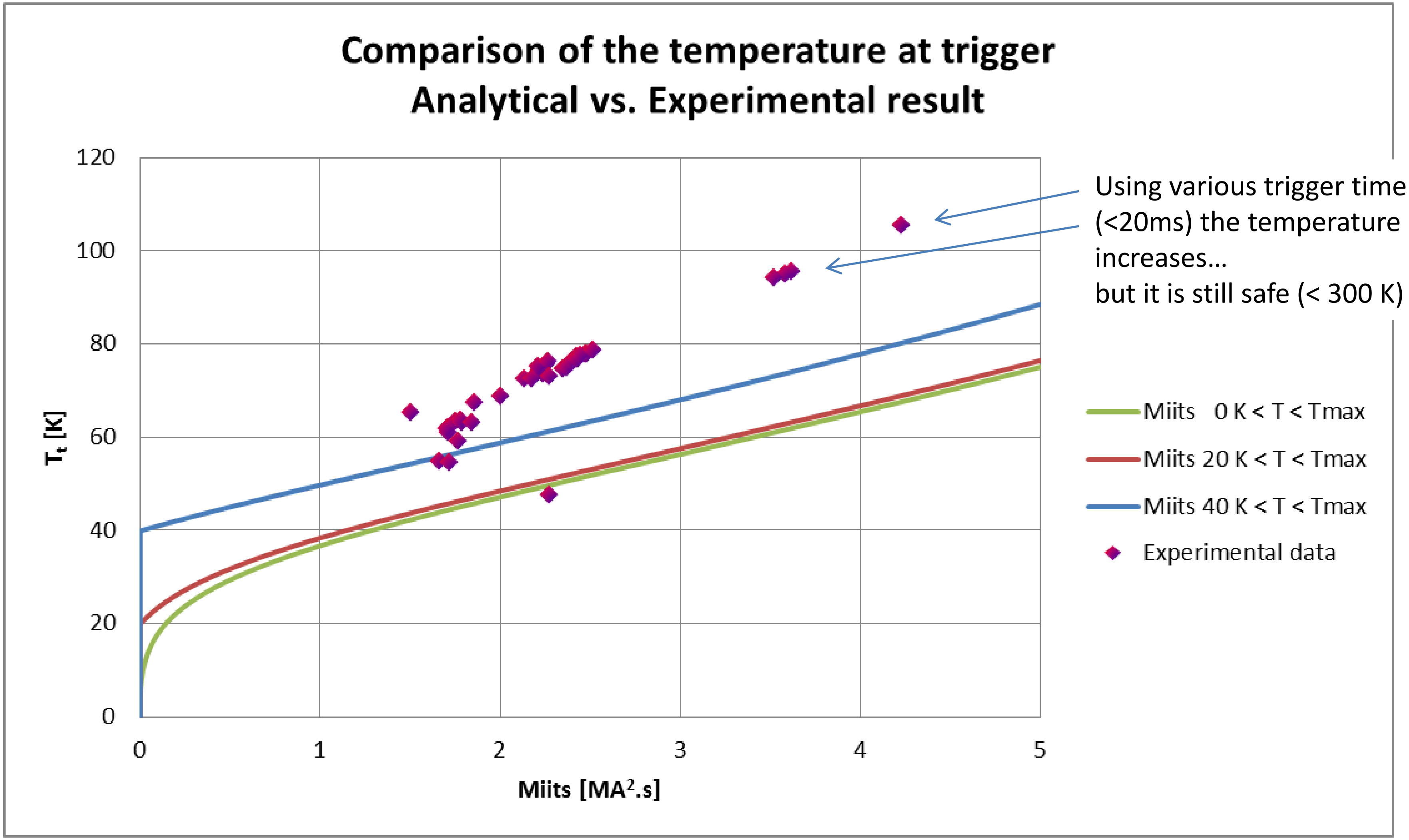
$$\rho_E\ [\Omega\ m] = f\,(\ B(I),\ T,\ RRR\ )$$





Assessment of the temperature in the copper using the measured resistivity between V_72-102. Attempt to using propagation velocity…

Temperature rise in the coil after quench. Run 1, 2 and 3. SMC#3



Simple model in relatively good agreement … FEM to go any further.

SMC. Conclusions

- SMC#1 could tell us little info as it was limited by a splice at 7 kA @ < 50% of the Iss

- **SMC#3 is** a nice magnet **TELLING US A LOT** ABOUTH THE Nb_3Sn CABELS!
  - Most of the quenches occurs in the HFS so the correlation between max. filed and stress can be studied
  - 95% of SS current attained at 4.2K
  - No quenches in the splices (Nb_3Sn-NbTi). Low contact resistance, comparable with those made with NbTi cables.
  - NbTi lead cable is limiting the SMC #3 performance at 4.2K
  - Measurement results:
    - RRR= 75
    - Splice resistances < 1 nOhm
    - Inductance = 1.8 mH/coil and symmetric
    - Protection with external dump resistor of 40 mOhm: ok, Temperature < 100 K
    - Detection threshold 100 mV for 10 ms: adequate for propagation study
    - Longitudinal quench propagation velocity 10-20 m/s
    - 74 % of quenches occurs in the HFS mainly in coil1
    - No flux jumps at low or intermediate currents
    - Most of the quenches occurs in coil1.

- **SMC#3 run 3 test results should be carefully analyzed in the next coming weeks to correlate its quench behavior with its new strain status**