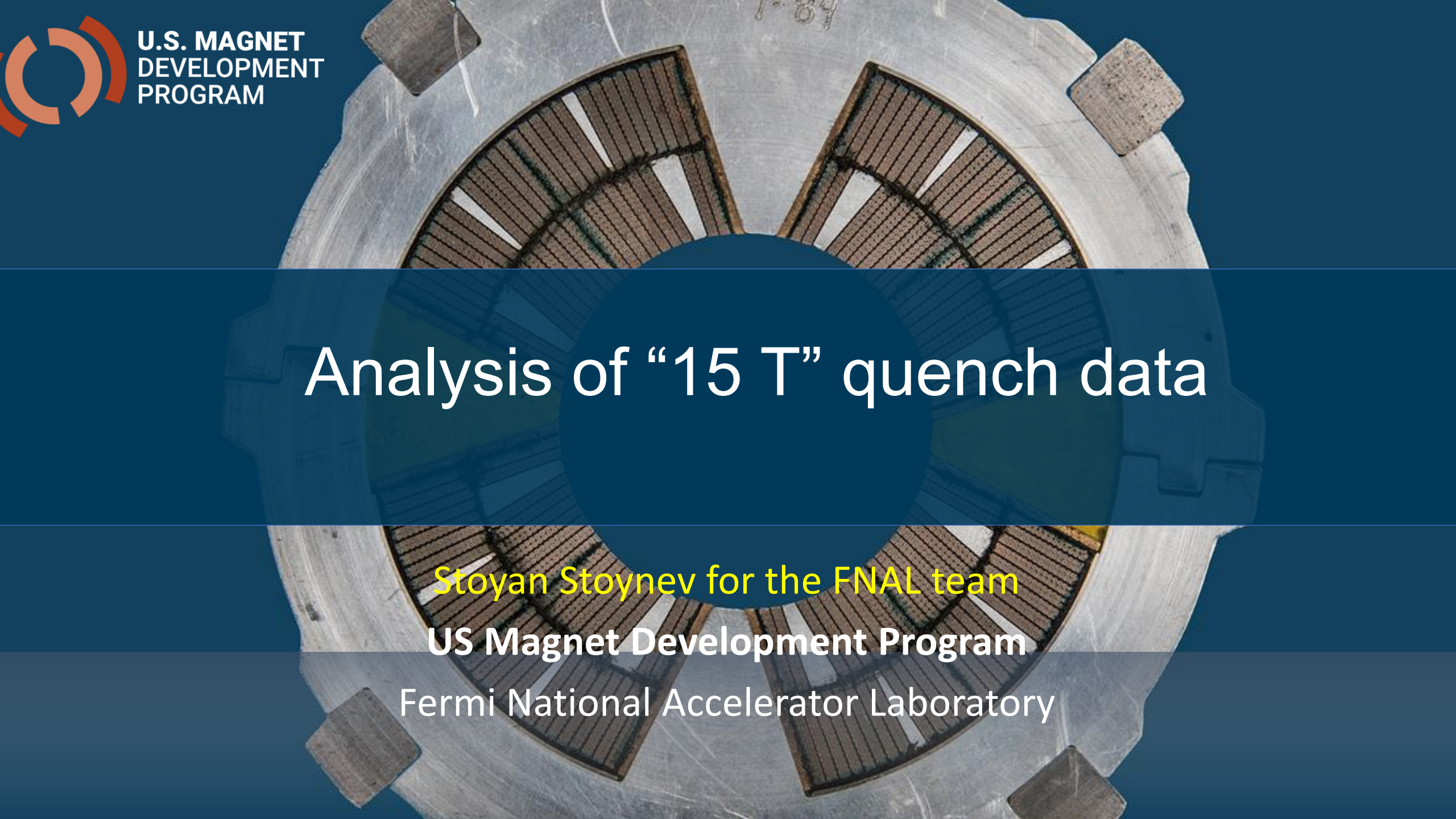


U.S. MAGNET DEVELOPMENT PROGRAM

Analysis of “15 T” quench data

Stoyan Stoynev for the FNAL team

US Magnet Development Program

Fermi National Accelerator Laboratory

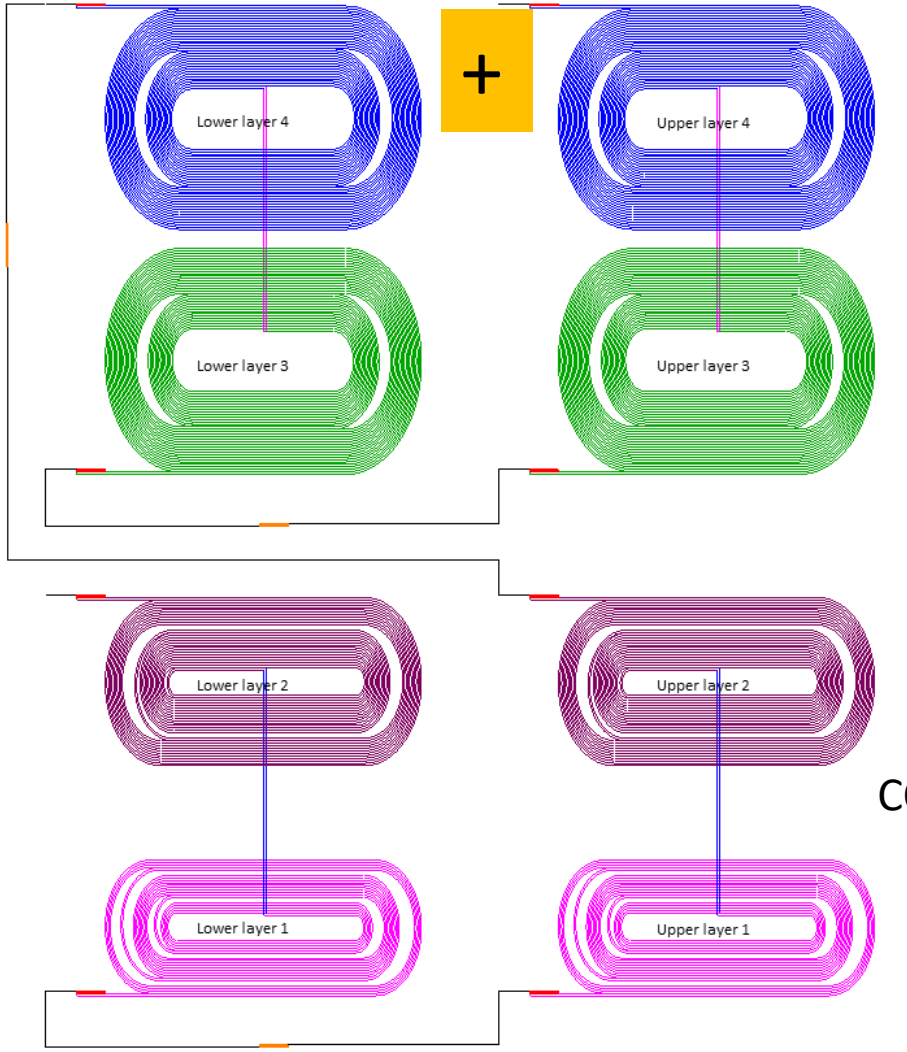
MDPCT1 (“15 T”) tests

- The magnet was first tested in Summer 2019 – MDPCT1
- After some modifications related to end-support (discussed elsewhere) it was retested in Summer 2020 – MDPCT1b
- MDPCT1b went through two thermal cycles (TC1 and TC2)
  - ✓ Performance in TC1 was previously presented and discussed, main points shown again here
  - ✓ **In TC2 the magnet showed very limited performance and we analyze this here**

“15 T” coil connections

COIL 005

COIL 004



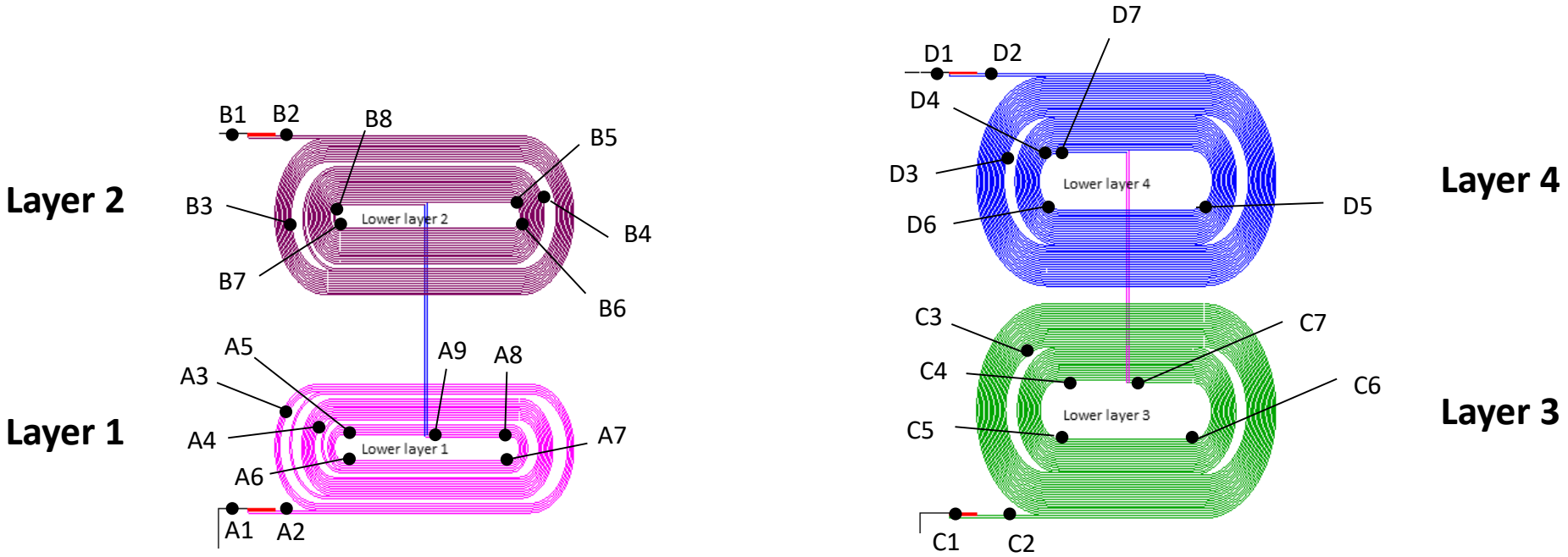
COIL 003

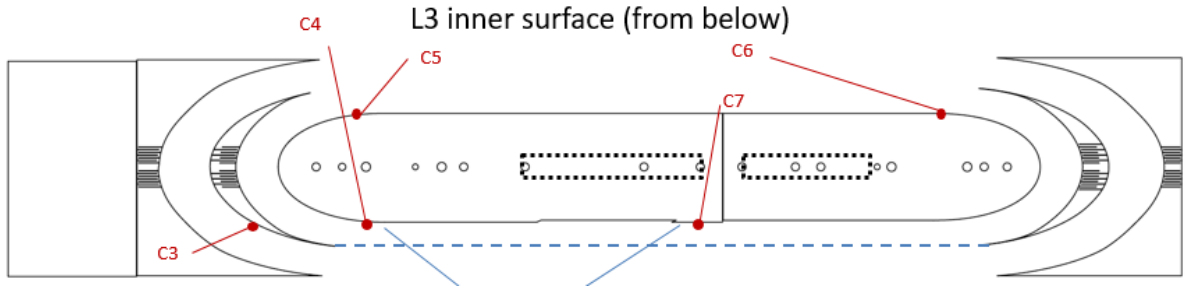
COIL 002

9/3/2020

“15 T” voltage taps

Coil instrumentation (seen from “above”)

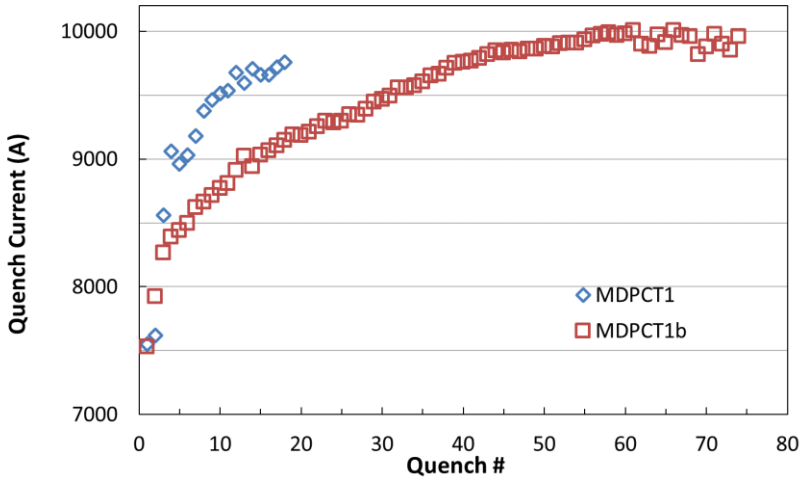




Most MDPCT1b quenches (and all in TC2) were in coil 5C

MDPCT1b Training

Ramp #s



Ramp #58

62

61

63

Ramp #45

Ramp #75

Ramp #13

Ramp #6

Ramp #2

Ramp #1

Ramp #14

(it is possible that degradation goes on)

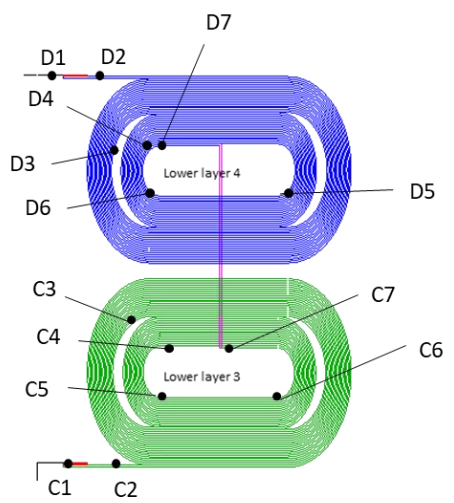
coil 4

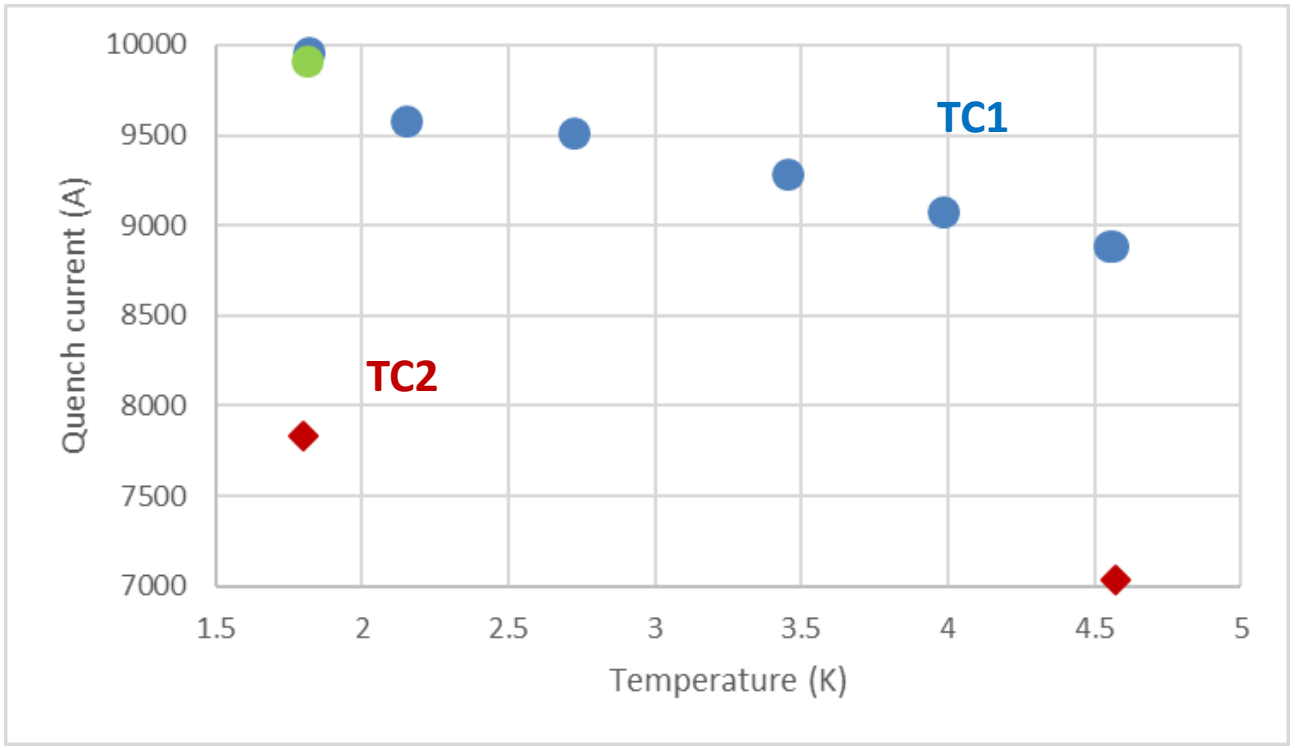
coil 5

Quench Current (A)

Coil Quench #

Temperature dependence

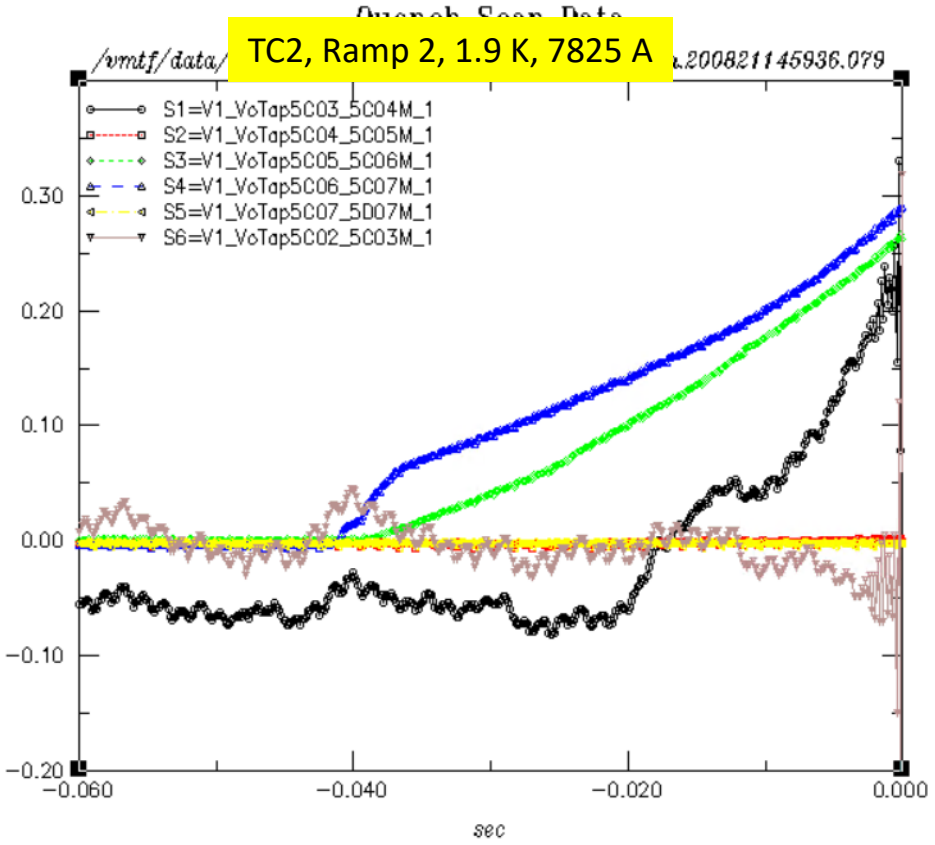


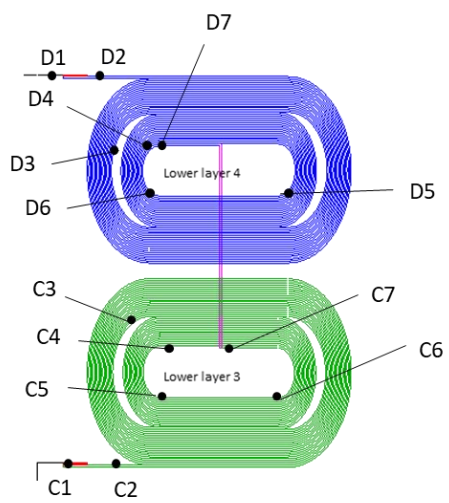


In TC2 all 1.9 K quenches were at ~7.82 kA and 4.5 K quenches at 7.03 kA (20 A/s).
All quenches started in 5c6_c7 with a familiar pattern to some TC1 quenches.
In TC1 this pattern was seen in the very beginning of training at 1.9 K as well as in all > 2.2 K quenches and high ramp rate quenches.
So the quenching segment (and pattern) changed from 5c5_c6 in the end of training at 1.9 K to 5c6_c7 in TC2 but remain the same at 4.5 K.

The quench current dropped from ~69% SSL (coil5) to ~54% SSL suggesting significant conductor degradation after the TC.

TC2 quench pattern





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Quench patterns (TC1)

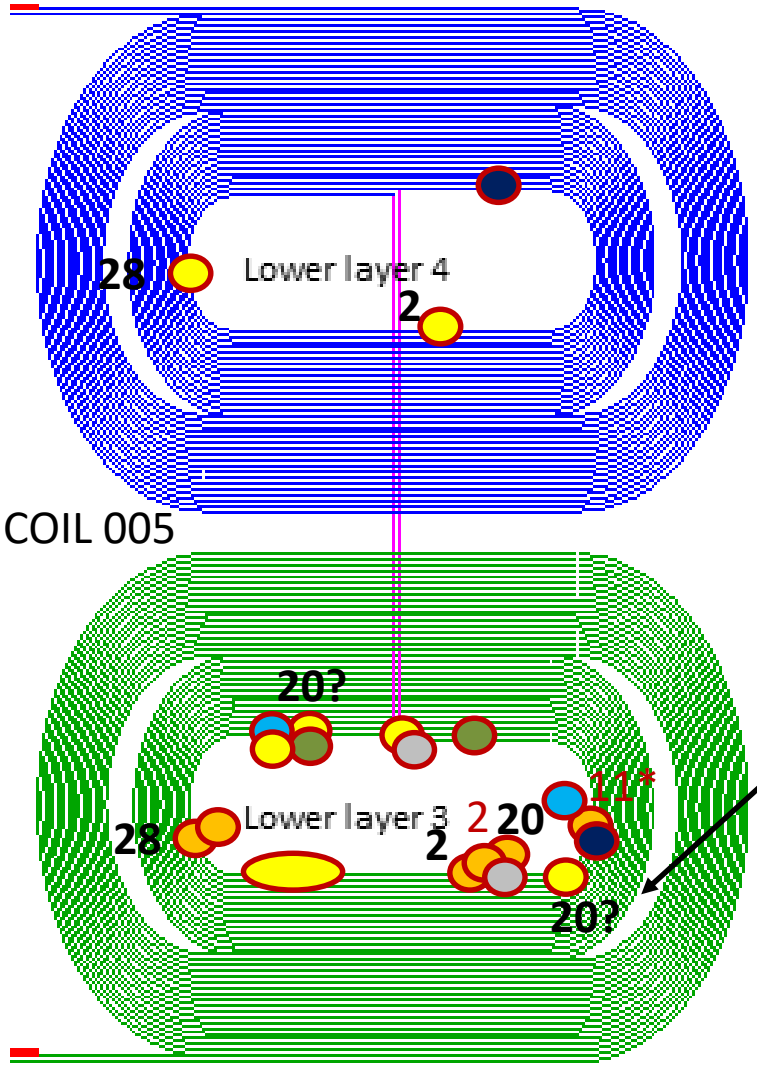
Signature	Ramps (including Ramp Rate, Temperature Dependence)
5; c6_c7, c5_c6, c3_c4	86, 85, 84, 83, 82; 79?, 78?; 76, ***11*** , ***3*** ***2***
5; c5_c6, c6_c7, c3_c4	81, 80, 75, 74, 73, 72, 71, 70, 69, 68, 66, 65, 64, 63, 61, 60, 59?, 50, 47, 46,
5; c4_c5, c5_c6, d7_d6	67, 62, 55, 54, 53, 52, 45, 42, 41, 40, 39, 38, ***37*** , 34, 31, ***30, 29, 28*** , 27, 25?, ***24, 23, 22?, 20, 19*** , 15, 14, ***13*** ,
4; d4_d5, d3_d4	58, 48,
4; c6_c4 (c6_c5), d6_d7	57, ***17?***
5; c5_c6, c6_c7, d6_d5	56, 44,
5; c5_c6, c4_c5, c6_c7, c7_d7	51
4, 5; 4c6_c4, 5c5_c6, 5c3_c4	49
5; c7_d7, c6_c7, d7_d6	43
4,5; 5c7_d7, c6_c7, 4c6_c4(4c6_c5), 4c7_c6	36
5; c6_c7, c5_c6	35, ***7*** ,
5; c6_c7, c5_c6, d5_d4	33
4; d4_d5, c7_c6, c6_c5	32, 12?, 6?
5; c6_c7, c7_d7, c3_c4	21
4; c7_c6, d7_c7	18
5; c6_c7, c3_c4, c4_c5	16
5; c3_c4, c4_c5, c5_c6	10
4; c7_c6, c6_c4 (c6_c5)	9, 4
4; d5_d6, d6_d7, c6_c4 (c6_c5)	8
5; c4_c5, c5_c6, c3_c4	5
4; d6_d7, d7_c7, c7_c6, d5_d6	1
	it: With additional segment (likely due to longer time available)

The green boxes indicate focus points to be followed in the presentation.

Ramp shown are the same pointed on the previous slide.

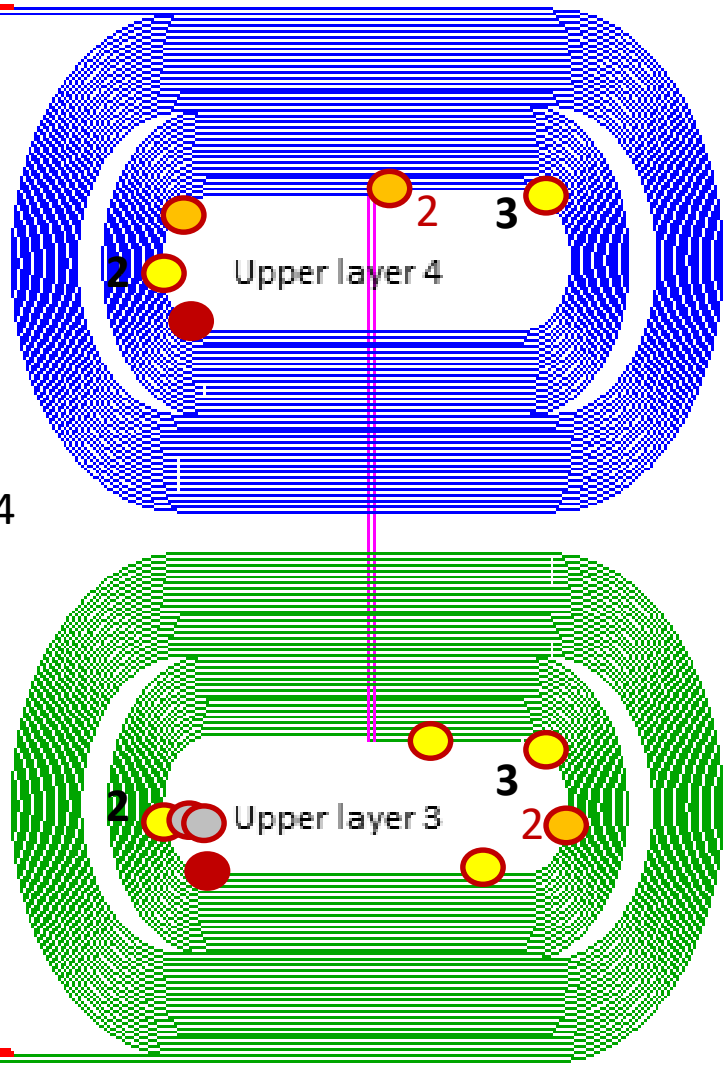
Discussed previously

Quench locations at a glimpse (TC1)

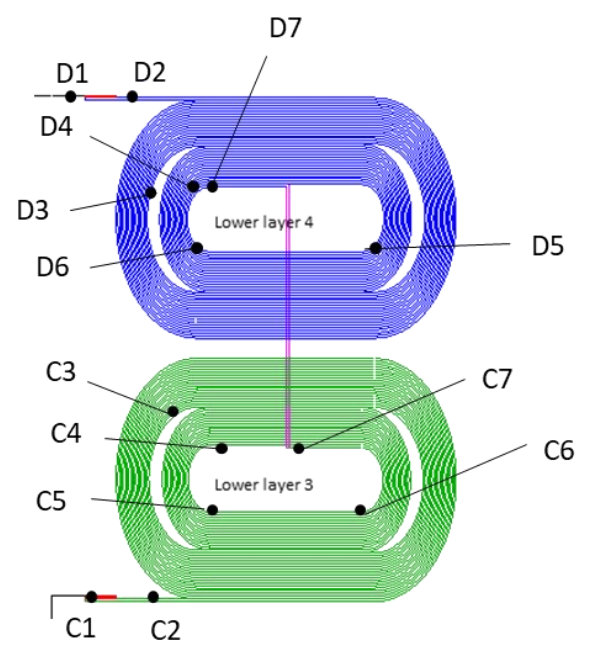


COIL 005

The only non-pole location



COIL 004



Those colors indicate quenches in different non-adjacent segments (often in different layers/coils)

This color indicates fairly well known location

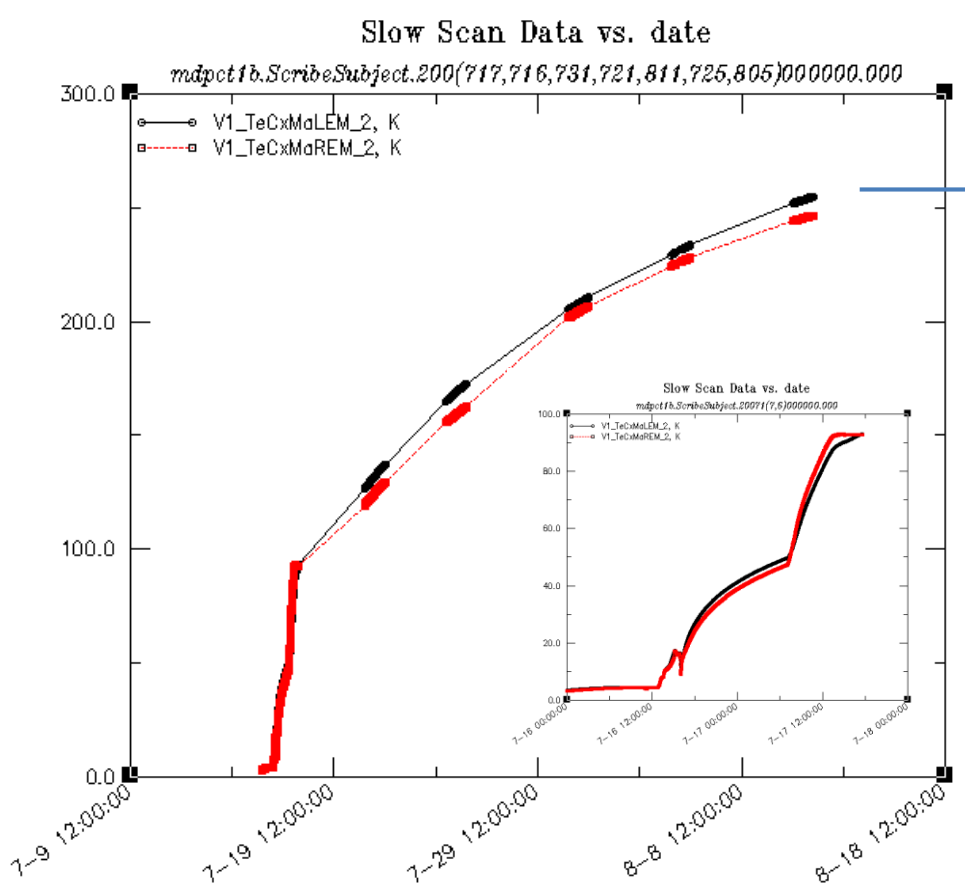
This color indicates not so well known location

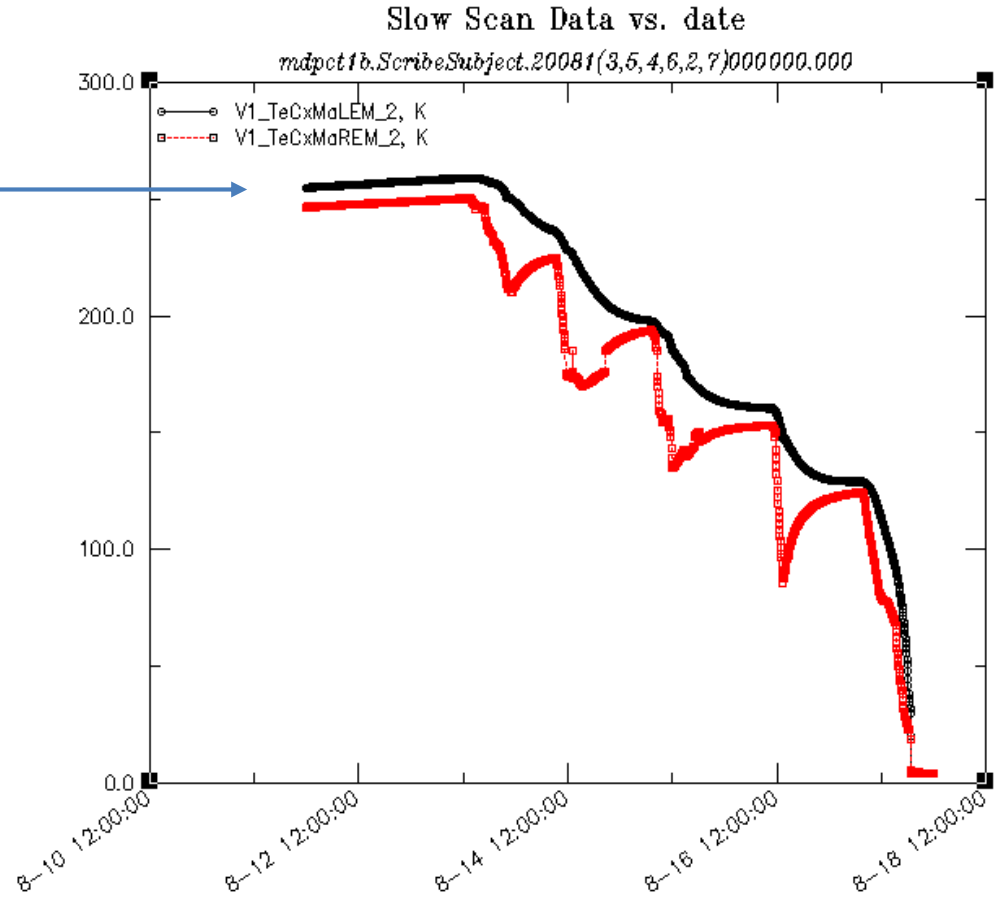
Both colors (and only them) can have associated numbers which are the numbers of similar quenches

*7 of them are RR and TD quenches

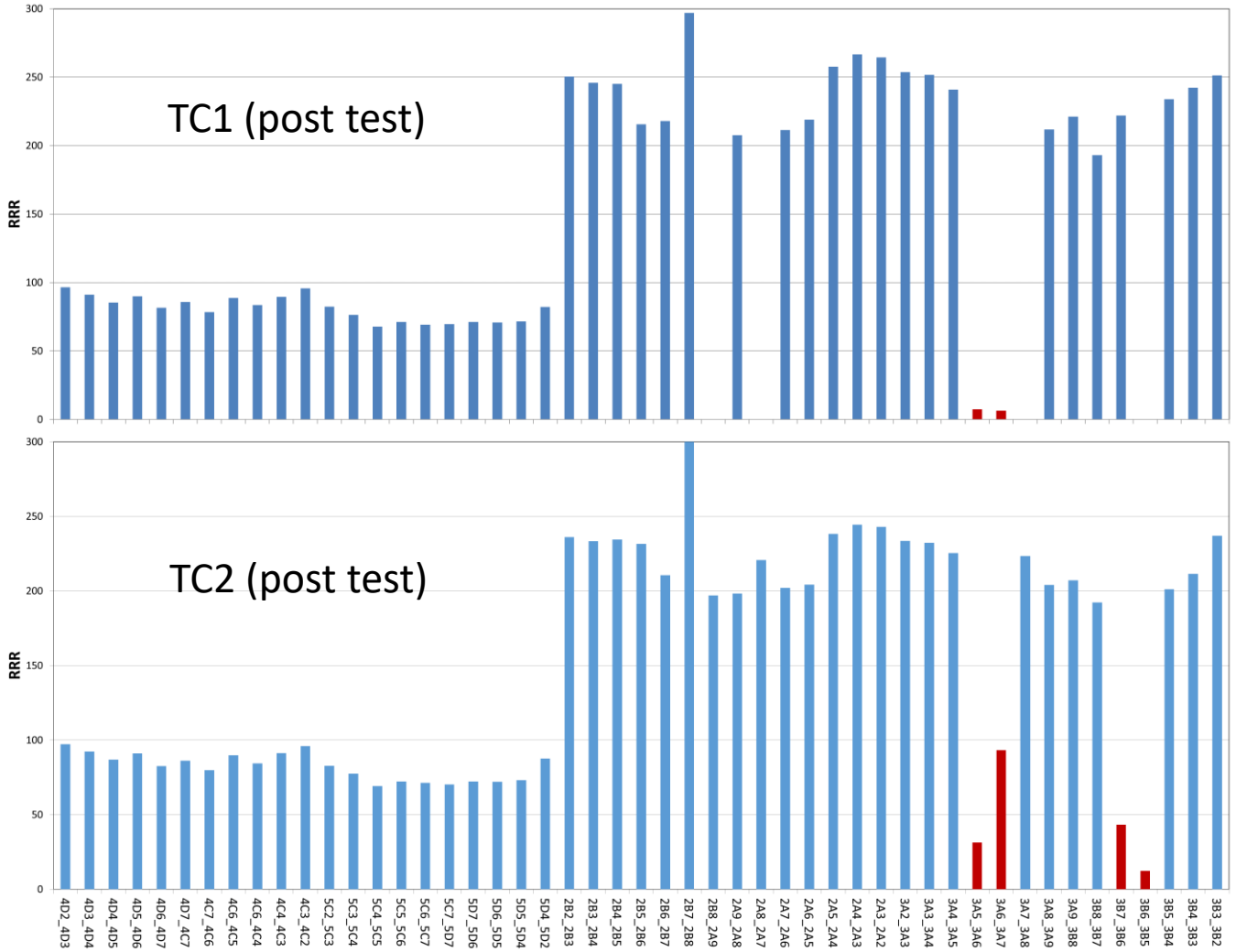
What happened to MDPCT1b after a TC

We tried to find out…

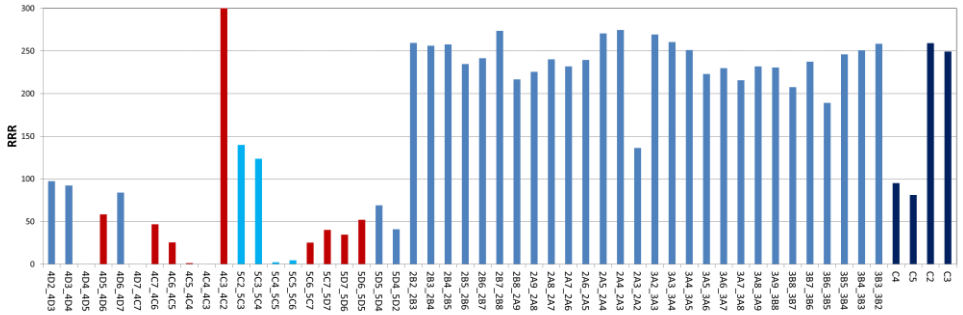




MDPCT1b RRR



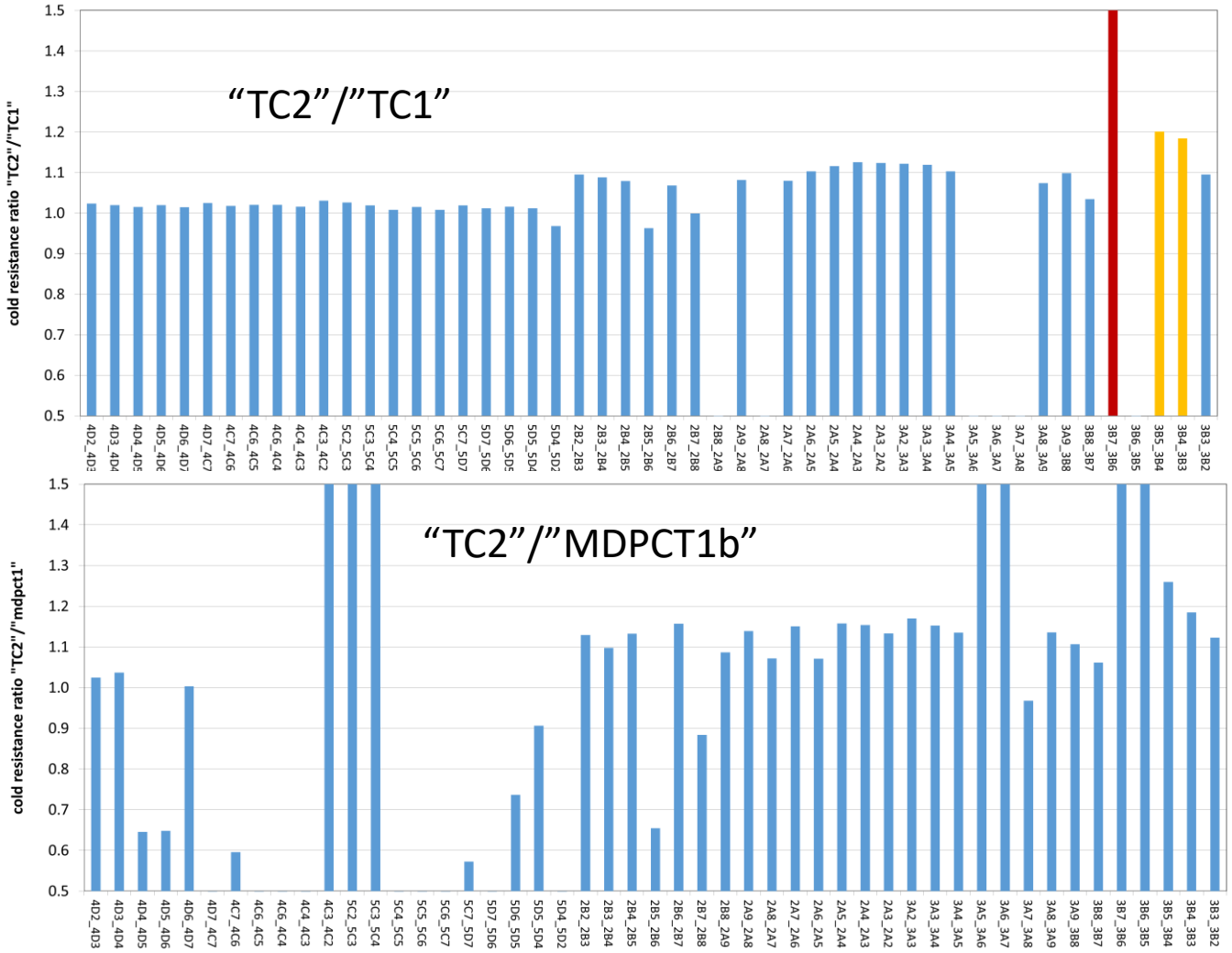
MDPCT1



No abnormal RRR behavior in TC2

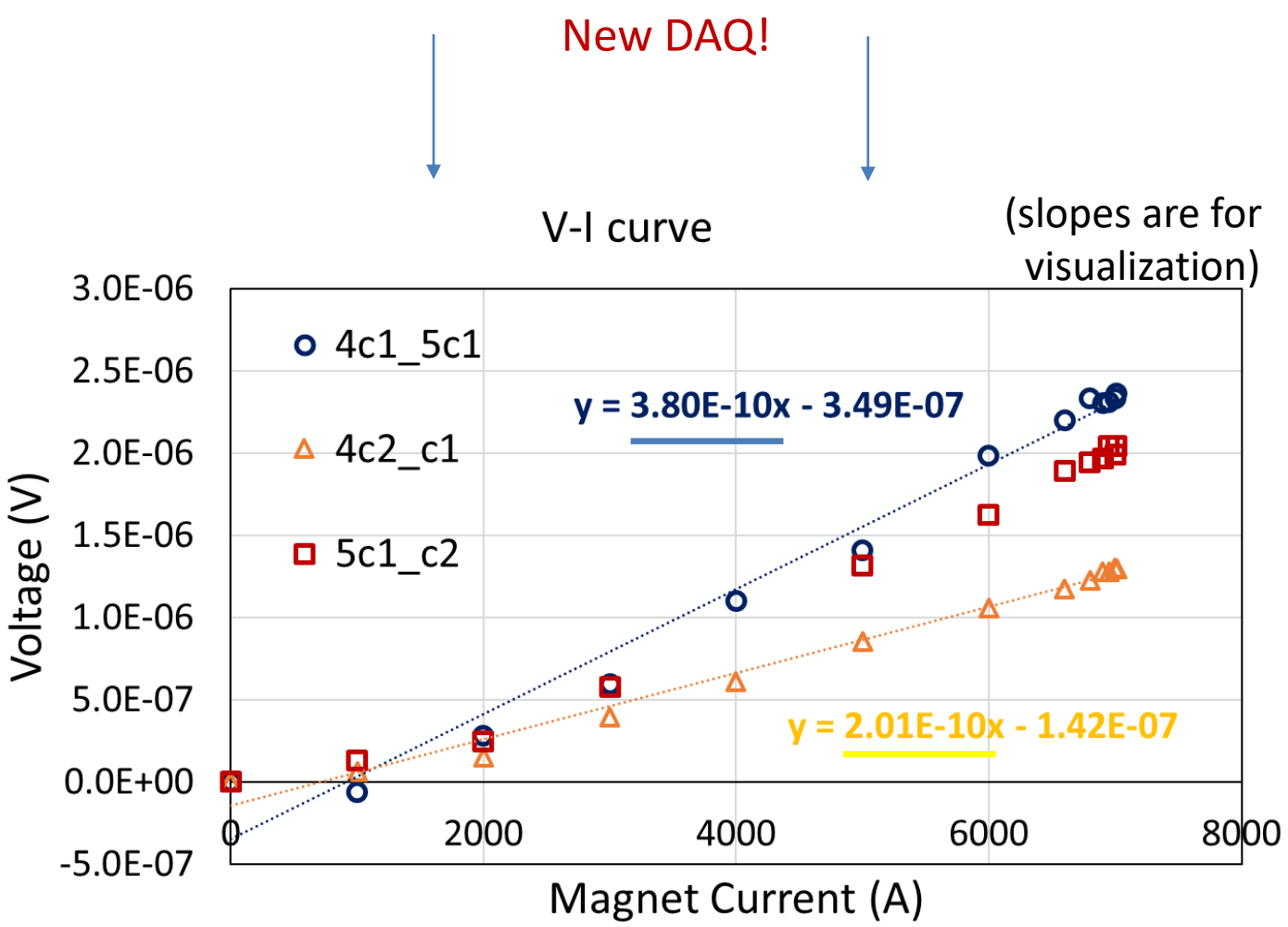
(sometimes we don't measure a segment resistance for technical reasons or segments are "bad" /lost connectivity/)

MDPCT1b cold resistance ratio



No abnormal behavior in TC2 except 10% higher resistance in inner coils (which don't quench)

MDPCT1b V-I measurements

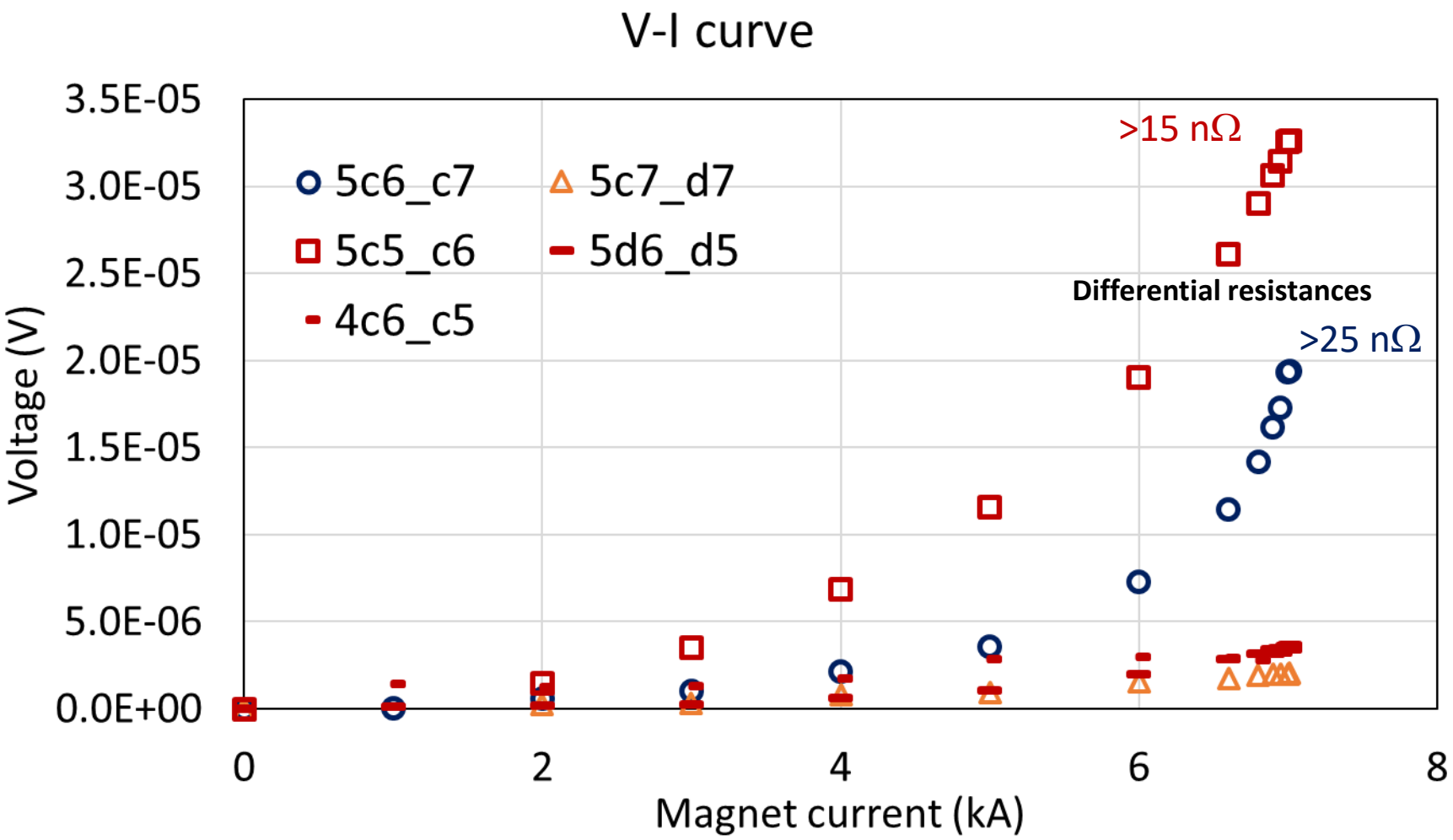


MDPCT1

Coil	Splice	R (nOhm)
2	A1-A2	0.61
2	B1-B2	0.39
3	A1-A2	0.35
3	B1-B2	0.44
4	C1-C2	0.28
4	D1-D2	0.77
5	C1-C2	0.46
5	D1-D2	0.68

Splice resistances with the new system are consistent with earlier measurements. The new system allows for simultaneous measurements of many segments.

MDPCT1b V-I measurements

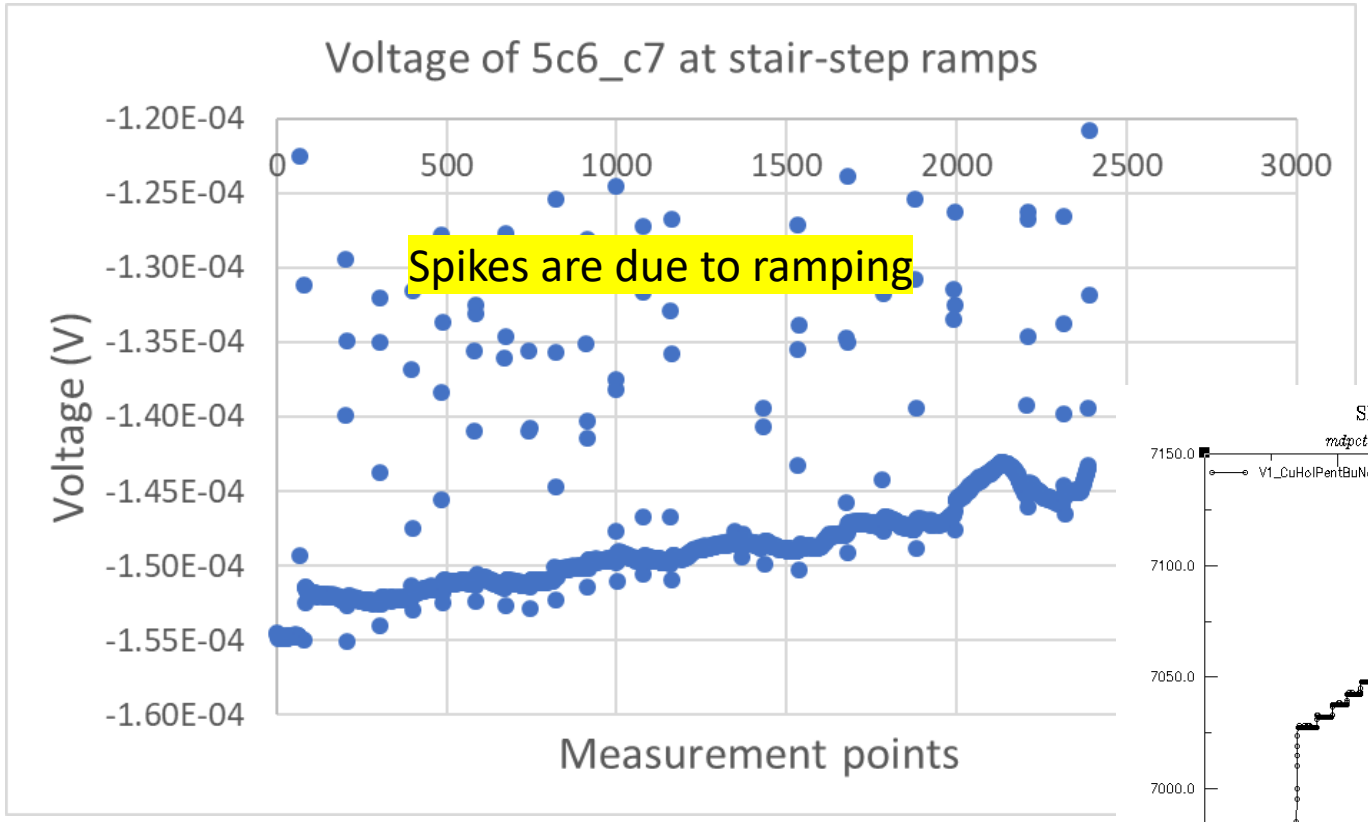


… and we see resistance in some segments starting to grow with current as low as 2 kA

A characteristic V-I curve is observed in the two segments quenching most (would result in a very bad n-value) with the limiting one showing faster growth.

Some other segments are showing similar signs but at much lower level.

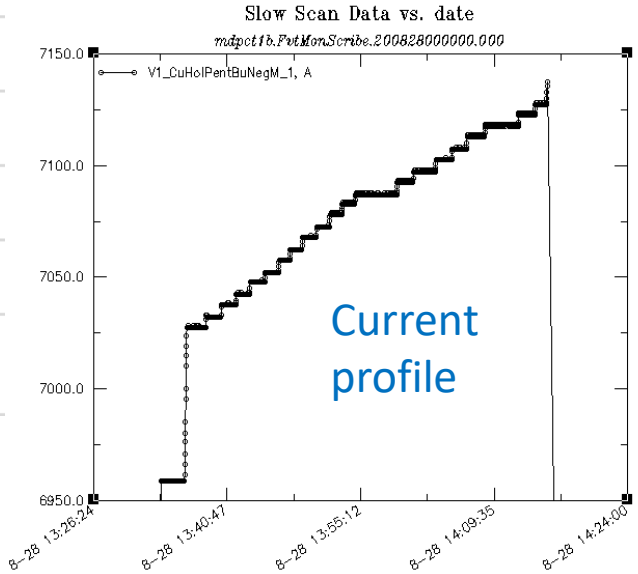
Voltage rise and behavior before quench



Stair-step current measurements, as low as 5 A step.

We managed to reach > 100 A higher quench current in that way.

Partial voltage “run-aways” are visible.



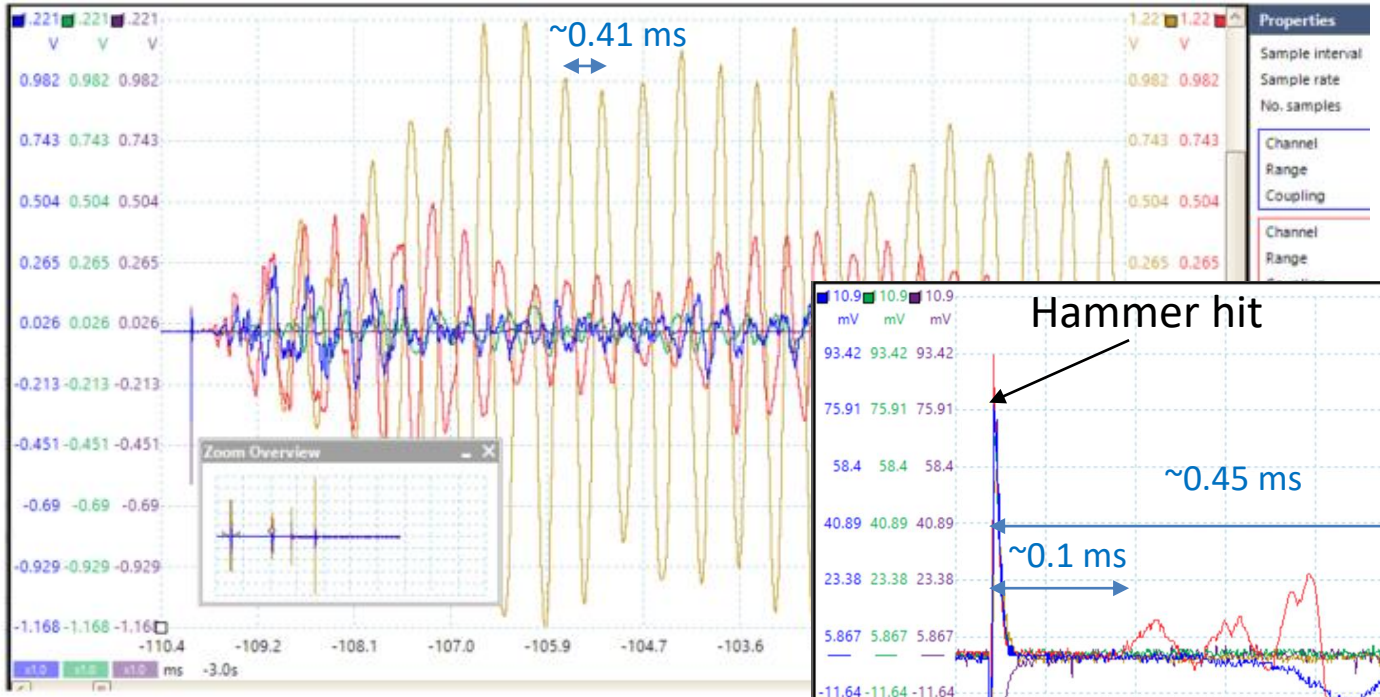
We quenched trying to increase current by 10 A instead of 5 A (same ramp rate).

Those indicate we are close to the critical surface and the AC heating is tilting the balance.

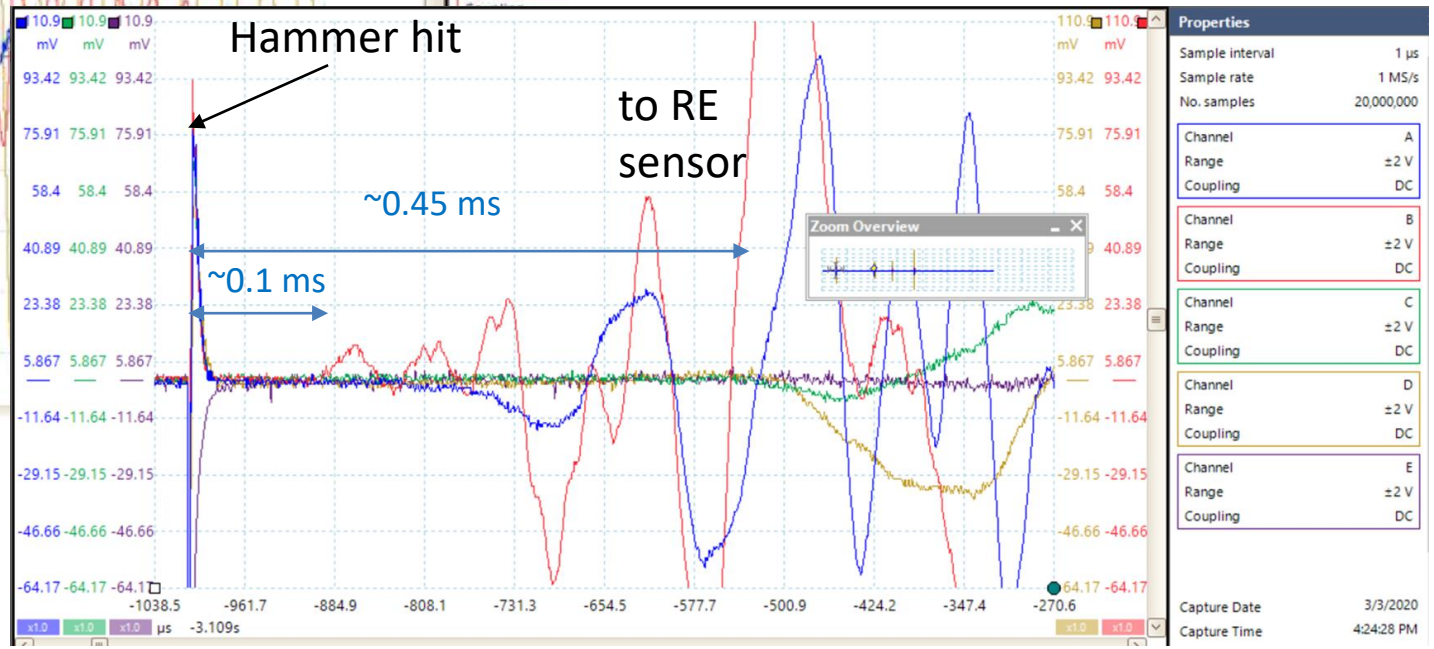
Acoustics

The magnet (shell) is a very good resonator.

1A



This is a **“4-corner” test**,
close to the “red” sensor,
vertical hit on a horizontal magnet
(shear wave propagation mostly)



LE sensors

RE sensors

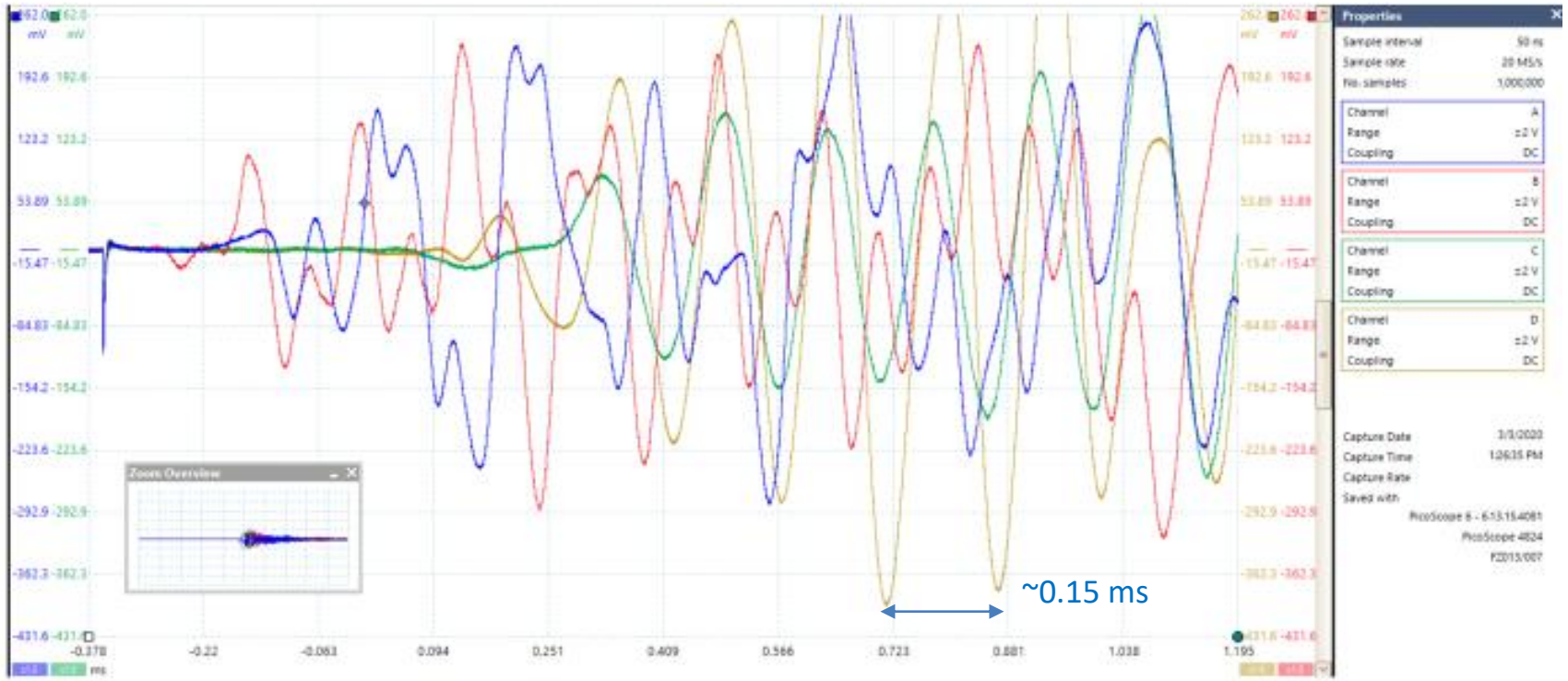
… though waves can transform at interfaces plus we are never hitting perfectly perpendicular

Acoustics

LE test

Lead end test, horizontal hit on horizontal magnet

(longitudinal waves forming)



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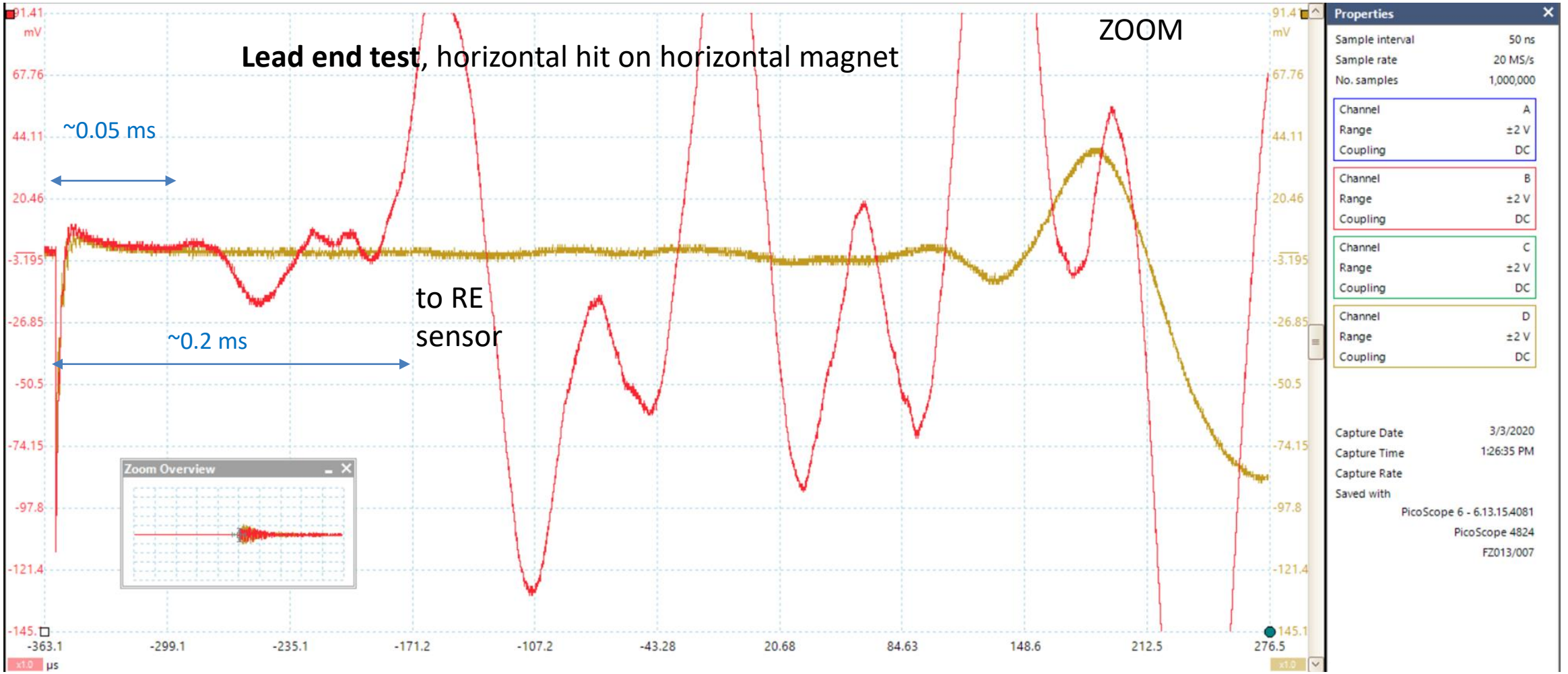
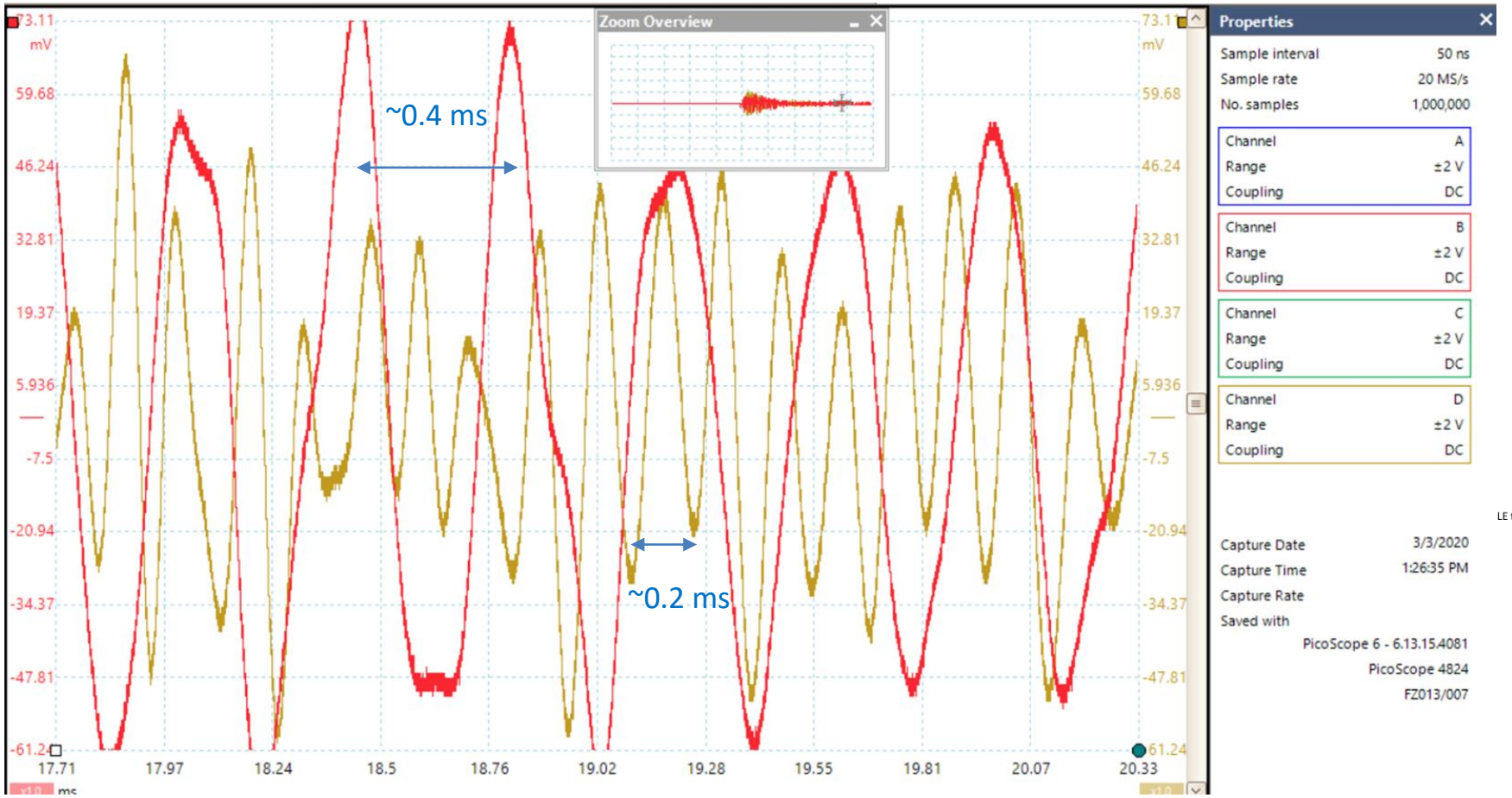
Acoustics


Lead end test, horizontal hit on horizontal magnet
ZOOM
~0.05 ms
~0.2 ms
to RE sensor
Zoom Overview
Properties
Sample interval 50 ns
Sample rate 20 MS/s
No. samples 1,000,000
Channel A
Range ±2 V
Coupling DC
Channel B
Range ±2 V
Coupling DC
Channel C
Range ±2 V
Coupling DC
Channel D
Range ±2 V
Coupling DC
Capture Date 3/3/2020
Capture Time 1:26:35 PM
Capture Rate
Saved with
PicoScope 6 - 6.13.15.4081
PicoScope 4824
FZ013/007
91.41 mV
67.76
44.11
20.46
-3.195
-26.85
-50.5
-74.15
-97.8
-121.4
-145.1
-363.1
-299.1
-235.1
-171.2
-107.2
-43.28
20.68
84.63
148.6
212.5
276.5
µs

Acoustics

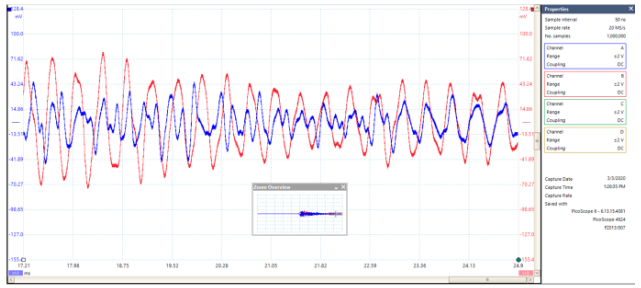
Toward the end of the “signal”

Lead end test, horizontal hit on horizontal magnet

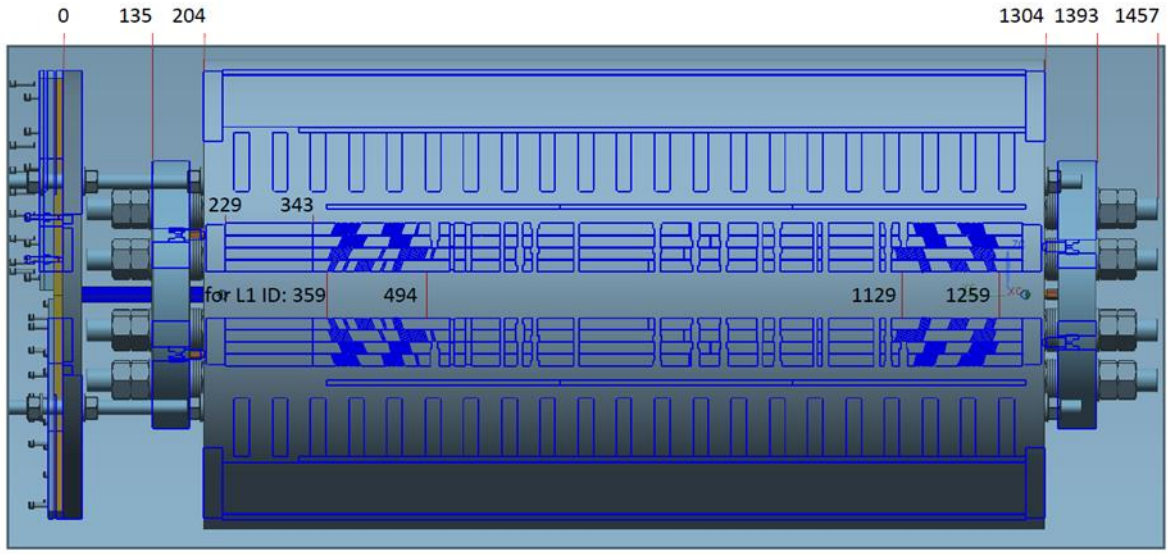


There is a mix of waves interfering but main modes can still be seen – longitudinal and sheer waves with characteristic periods

LE test



Acoustics



$$v = f\lambda$$

v : speed $(m.s^{-1})$
λ : wavelength (m)
f : frequency $(Hz$ or $s^{-1})$

Solid	Velocity (m/s) (ft/min) (ft/s)		
	Longitudal	Shear	Extensional
Copper, annealed	4760	2325	3810
Copper, rolled	5010	2270	3750
Iron, cast	4994	2809	4480
Iron, electrolytic	5950	3240	5120
Steel (1% C)	5940	3220	5180
Steel, stainless	5790	3100	5000

Longitudinal distance between outer surfaces where sensors are is ~ 105 cm.

If λ = 1 m, and f = 1/0.4 (ms) then v = 2.5 km/s
If λ = 1 m, and f = 1/0.2 (ms) then v = 5 km/s

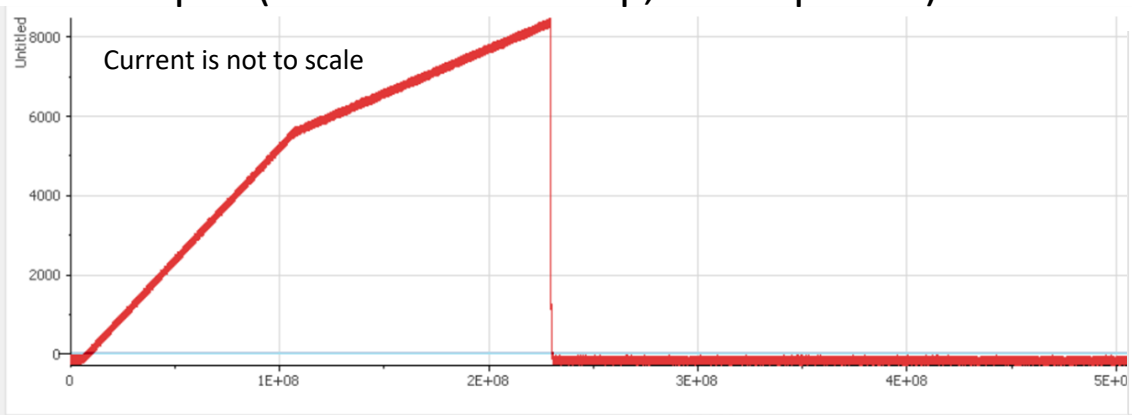
The picture so far is consistent.

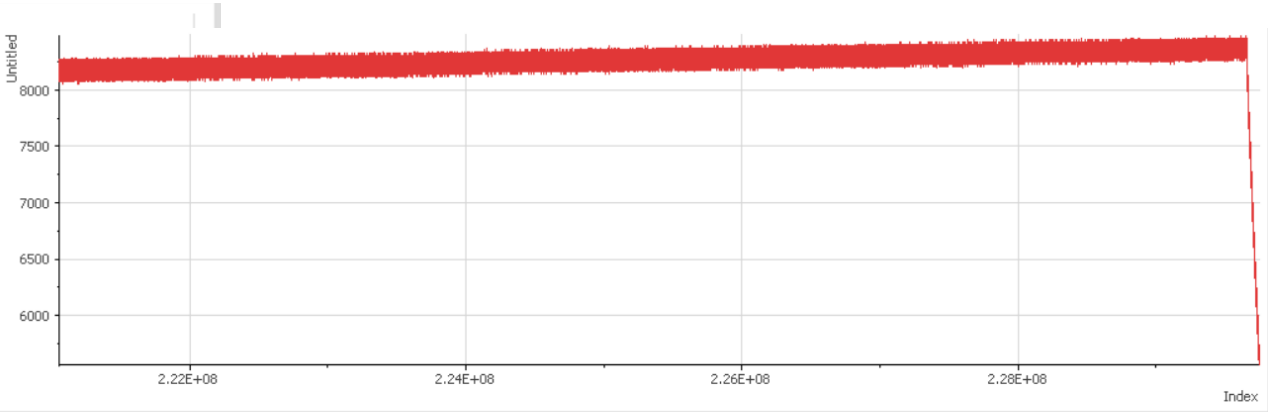
The distance between longitudinal “walls” of the magnet is a natural resonator scale.

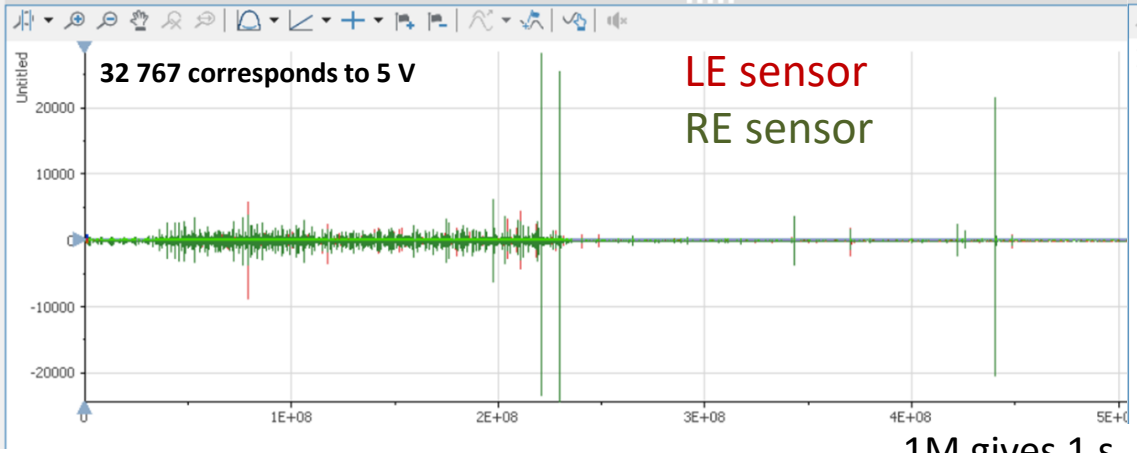
https://www.engineeringtoolbox.com/

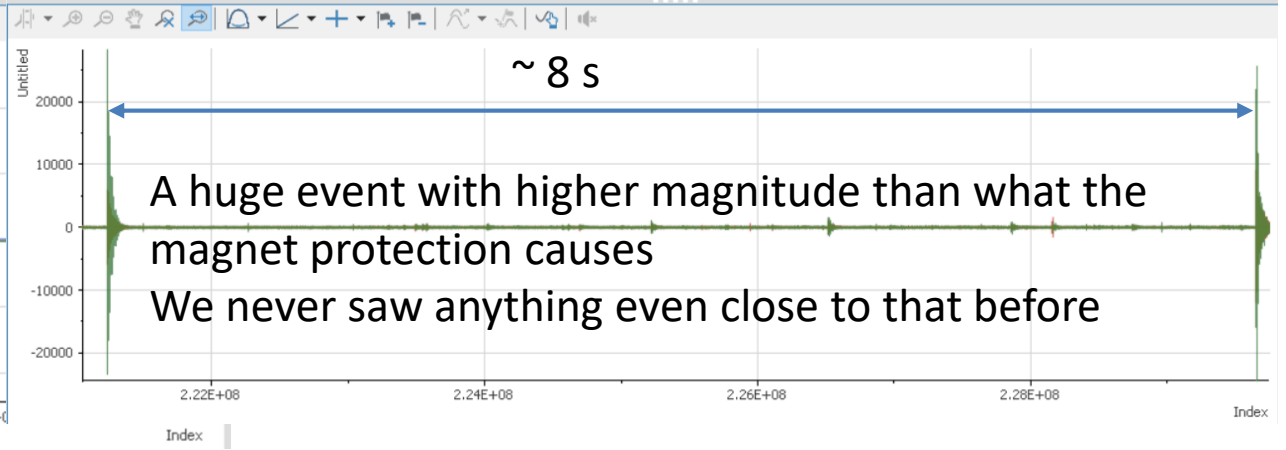
Acoustics – MDPCT1b, TC2

Ramp 1 (it ended with a trip, not a quench)





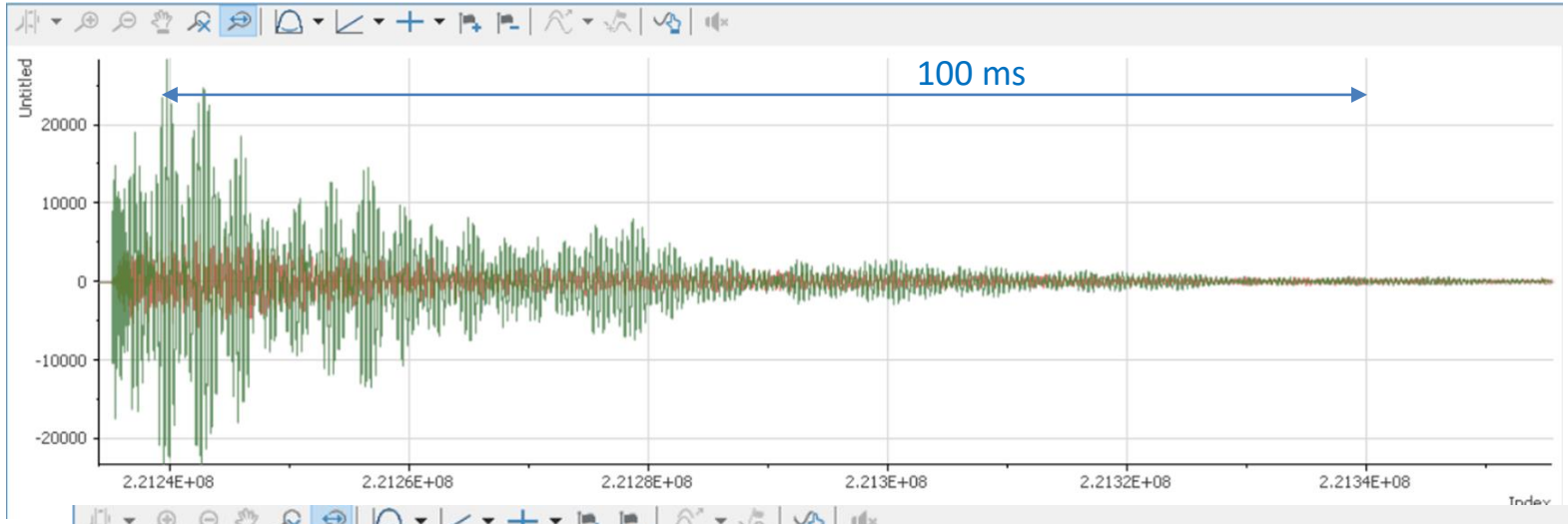




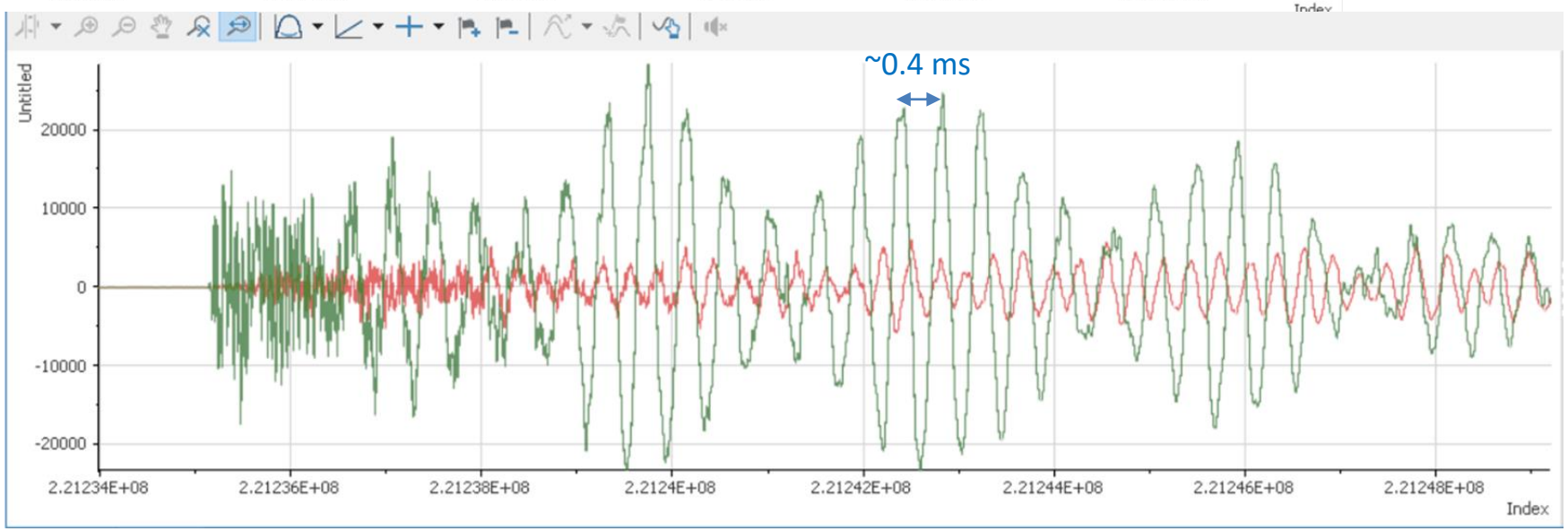
1M gives 1 s

This huge acoustic event is seen at this magnitude at the return end only

Acoustics – MDPCT1b, TC2

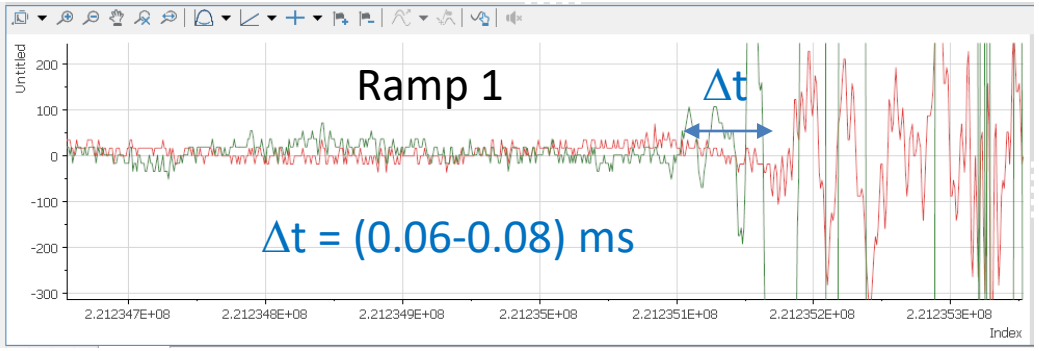


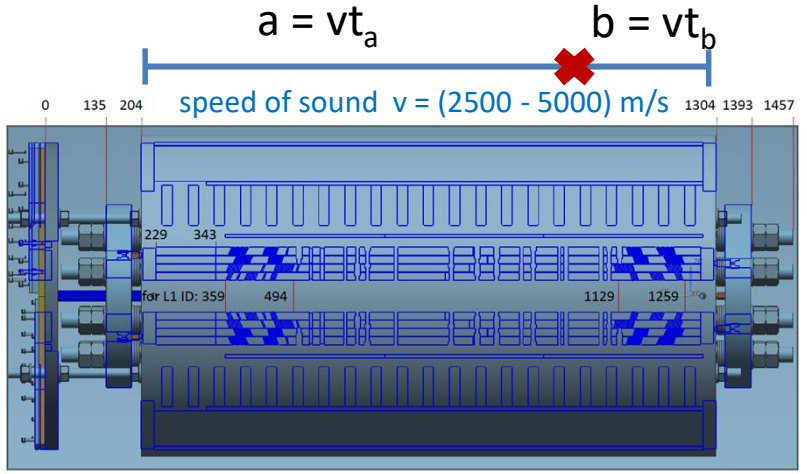
Ramp 1



The magnet (shell) rings at ~2.5 kHz for about 100 ms

Acoustics – MDPCT1b, TC2

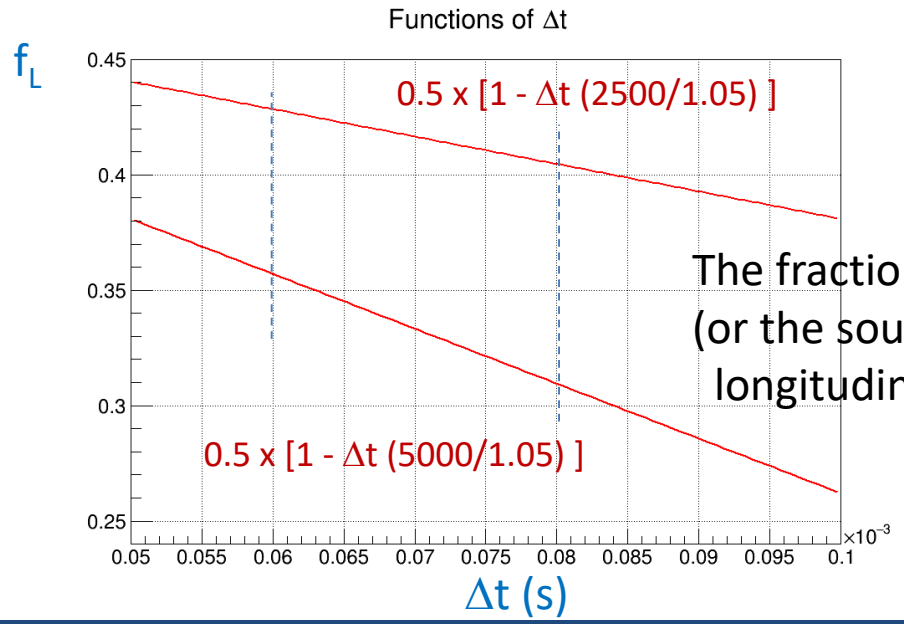




$L \equiv a + b$

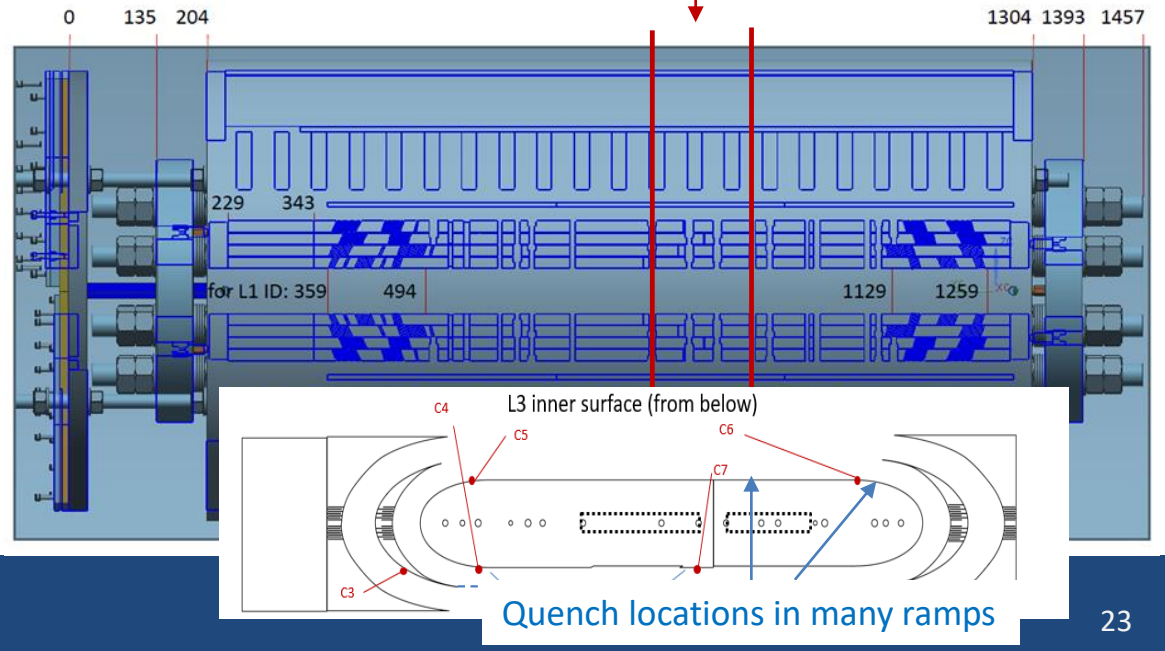
$t_b - t_b \equiv \Delta t = (b-a)/v$

$f_L \equiv b/L = 0.5 \times [1 - \Delta t\ (v/L)\ ]$



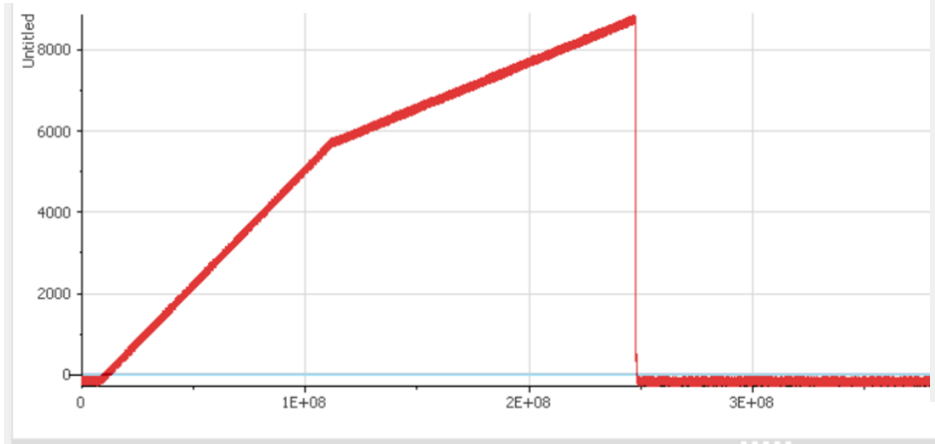
The fraction f_L = 0.32-0.46 (or the source is 34-48 cm longitudinally from the RE sensor)

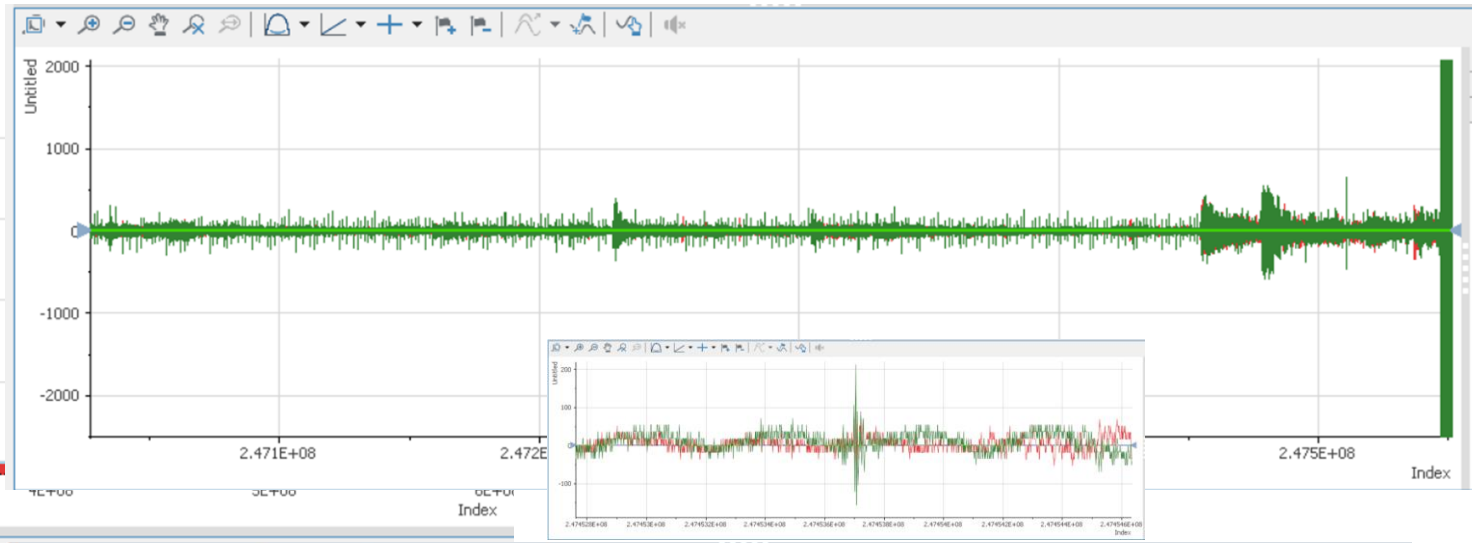
Likely acoustic signal source zone (in ramp 1)

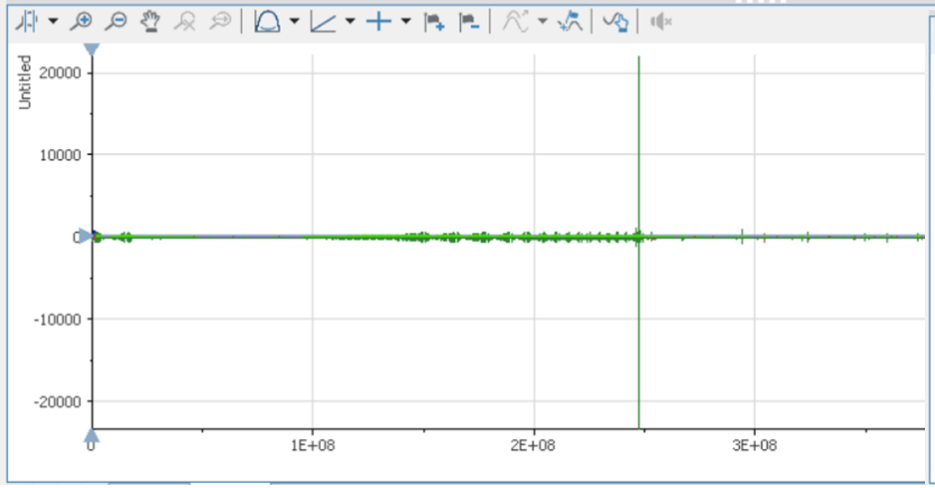


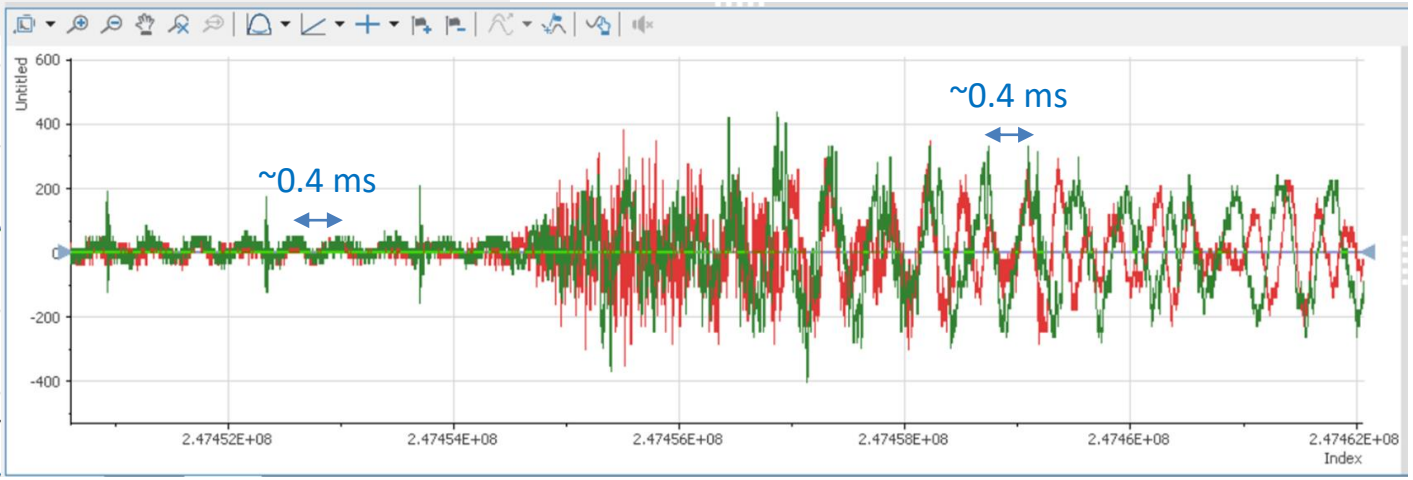
Acoustics – MDPCT1b, TC2

Ramp 4

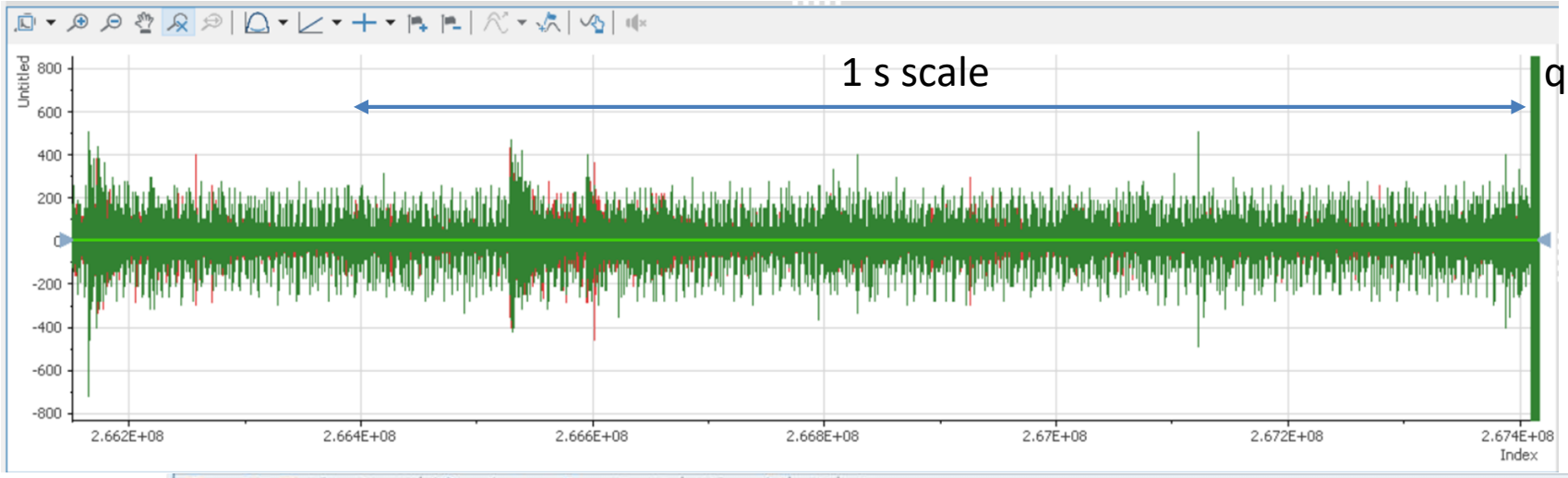








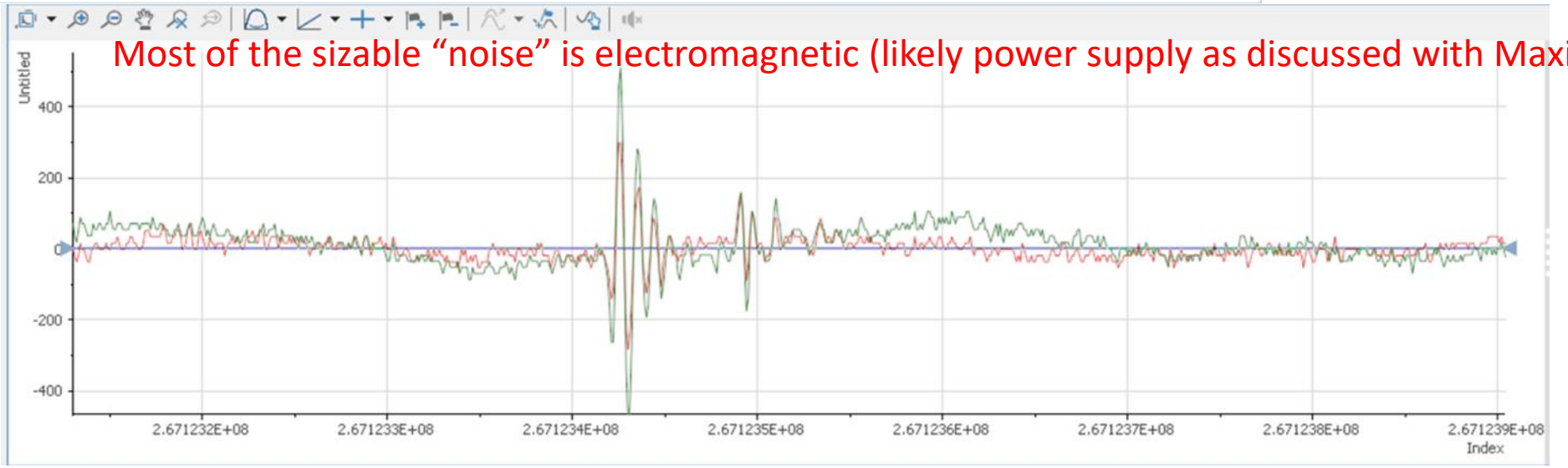
Acoustics – MDPCT1b, TC2



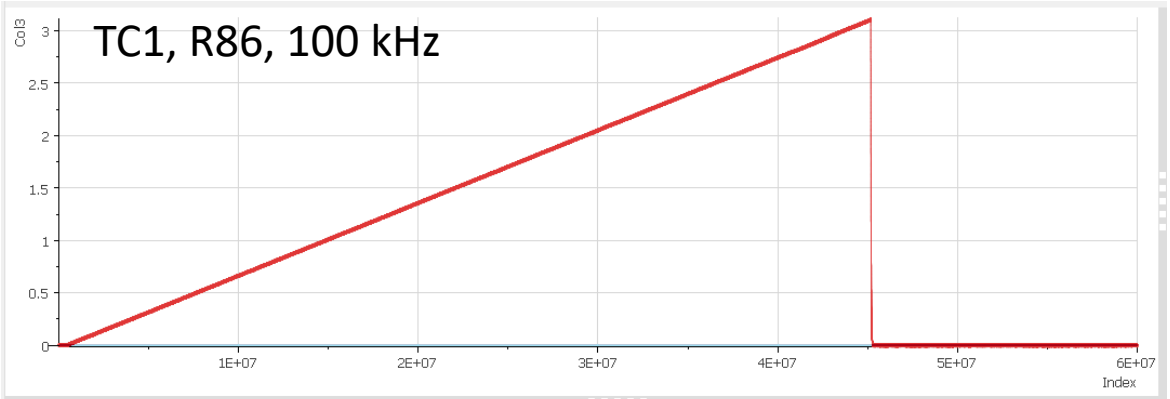
Ramp 4

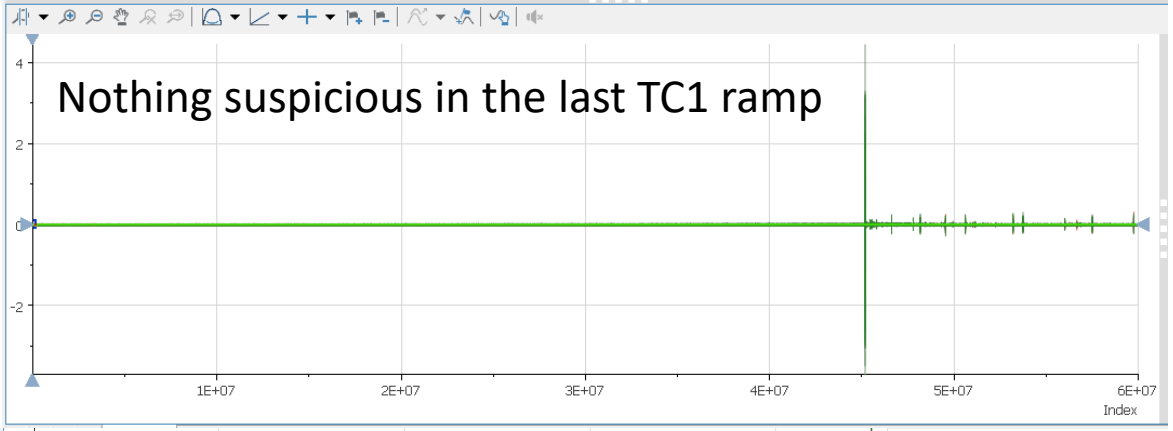
Overall: no clear “events” associated to quenching in all TC2 quenches.

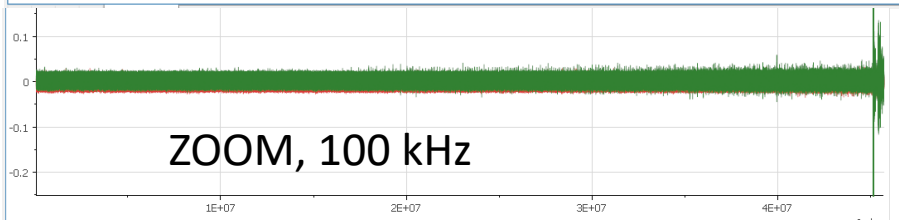
Most of the sizable “noise” is electromagnetic (likely power supply as discussed with Maxim)

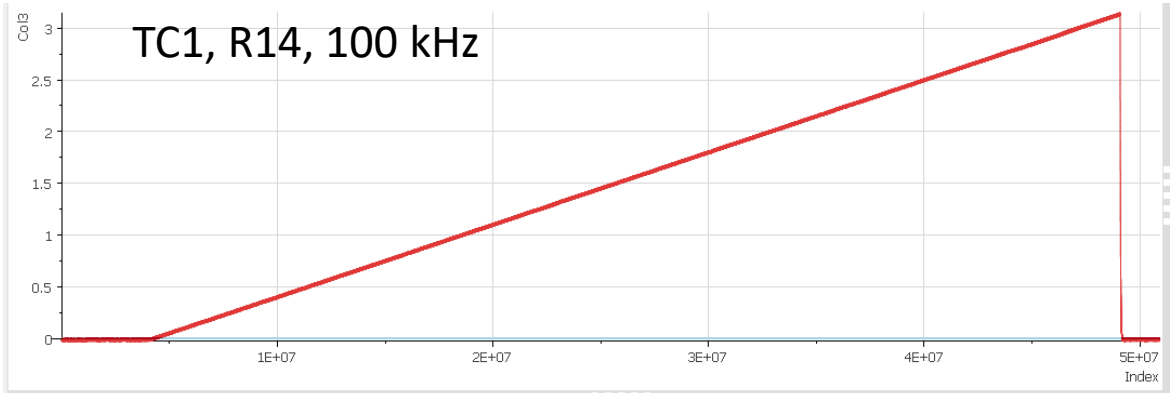


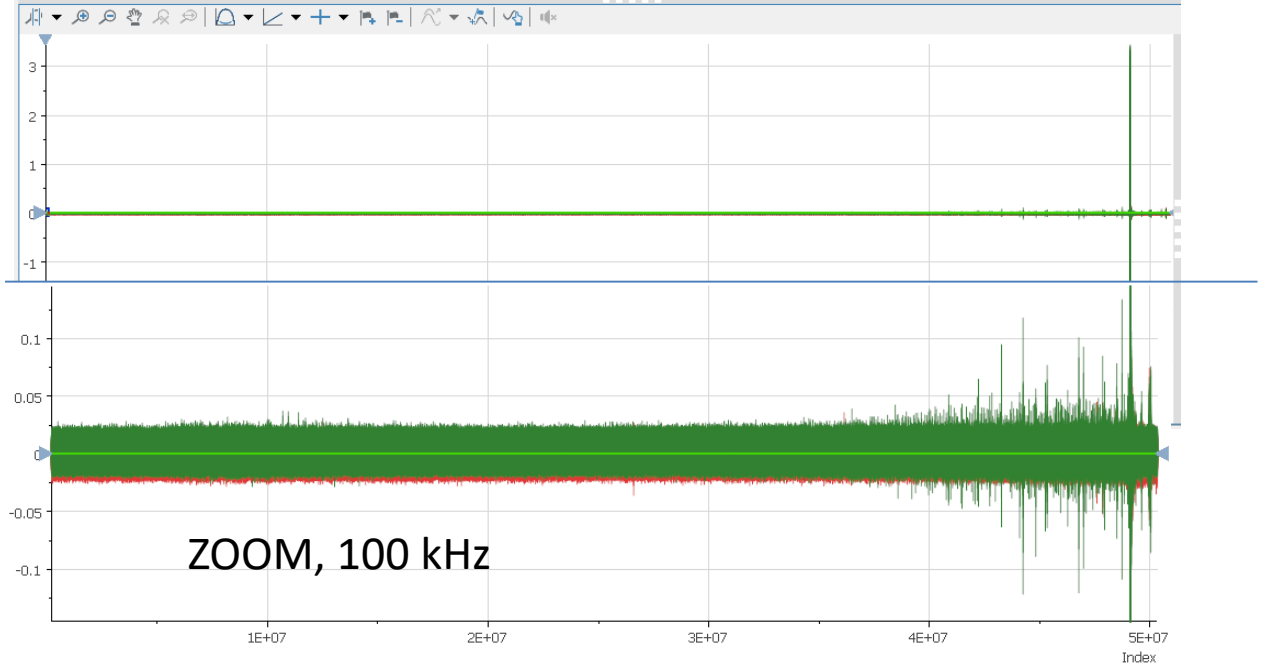
Acoustics in TC1







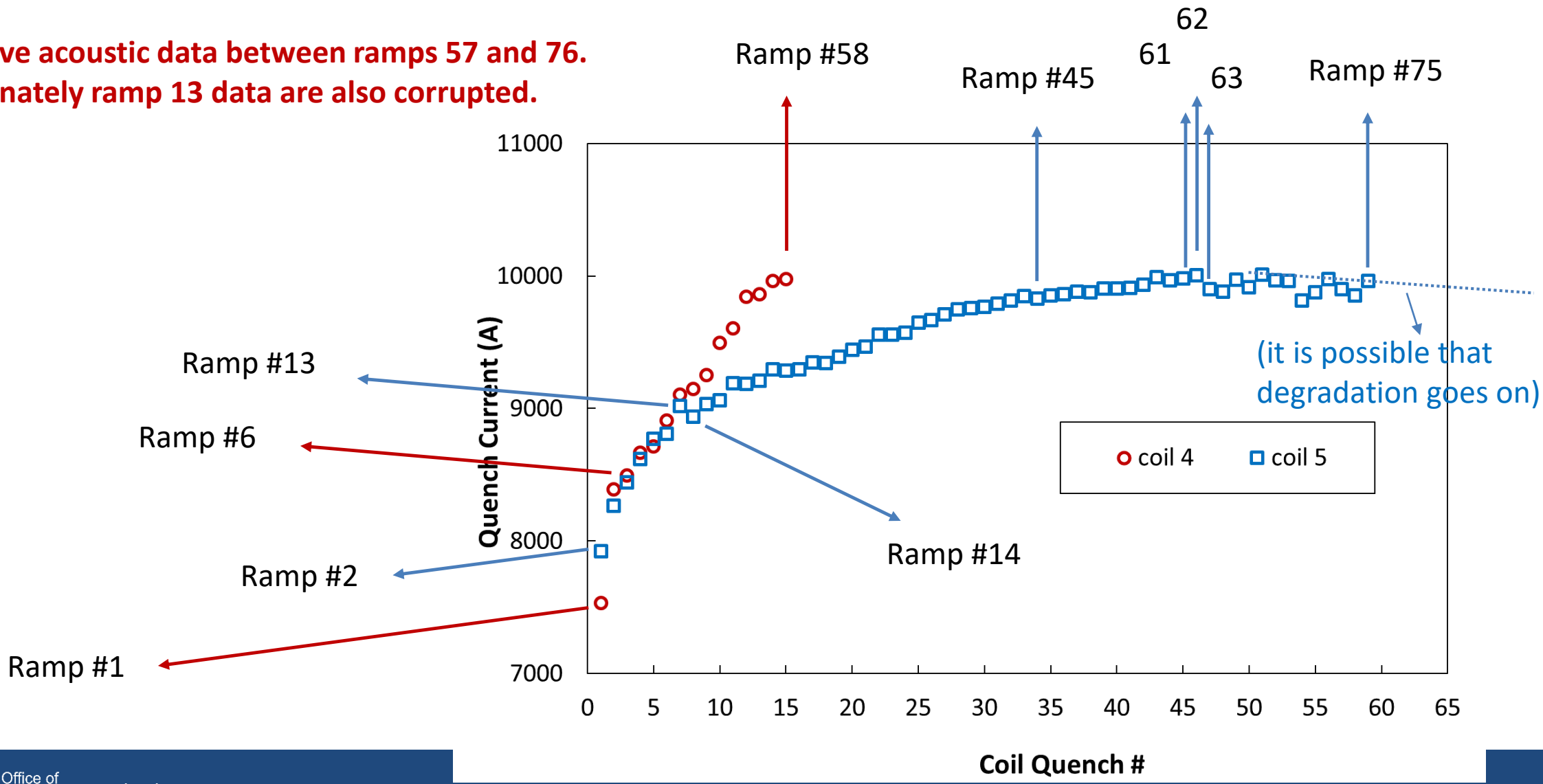




MDPCT1b Training (TC1)

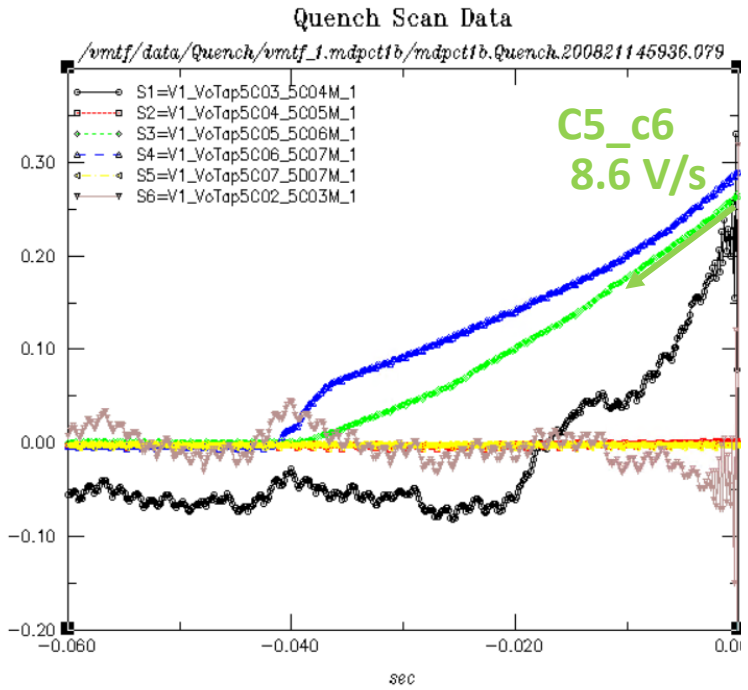
Ramp #s

We don't have acoustic data between ramps 57 and 76.
And unfortunately ramp 13 data are also corrupted.

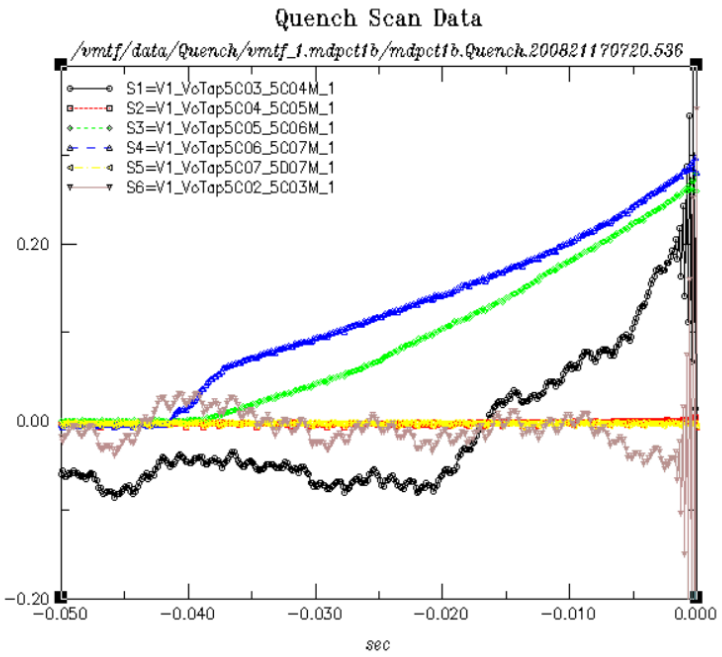


Quench profiles in TC2

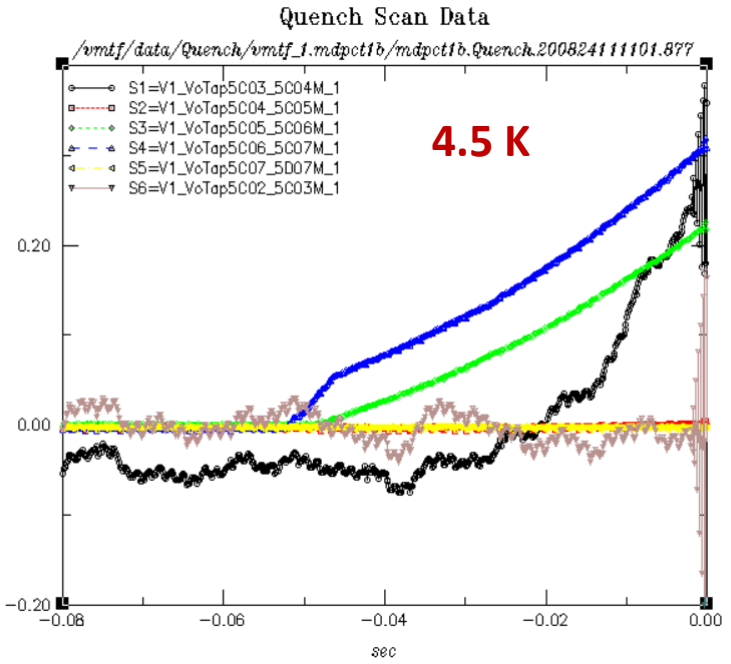
Ramp 2 (TC2)



Ramp 4 (TC2)



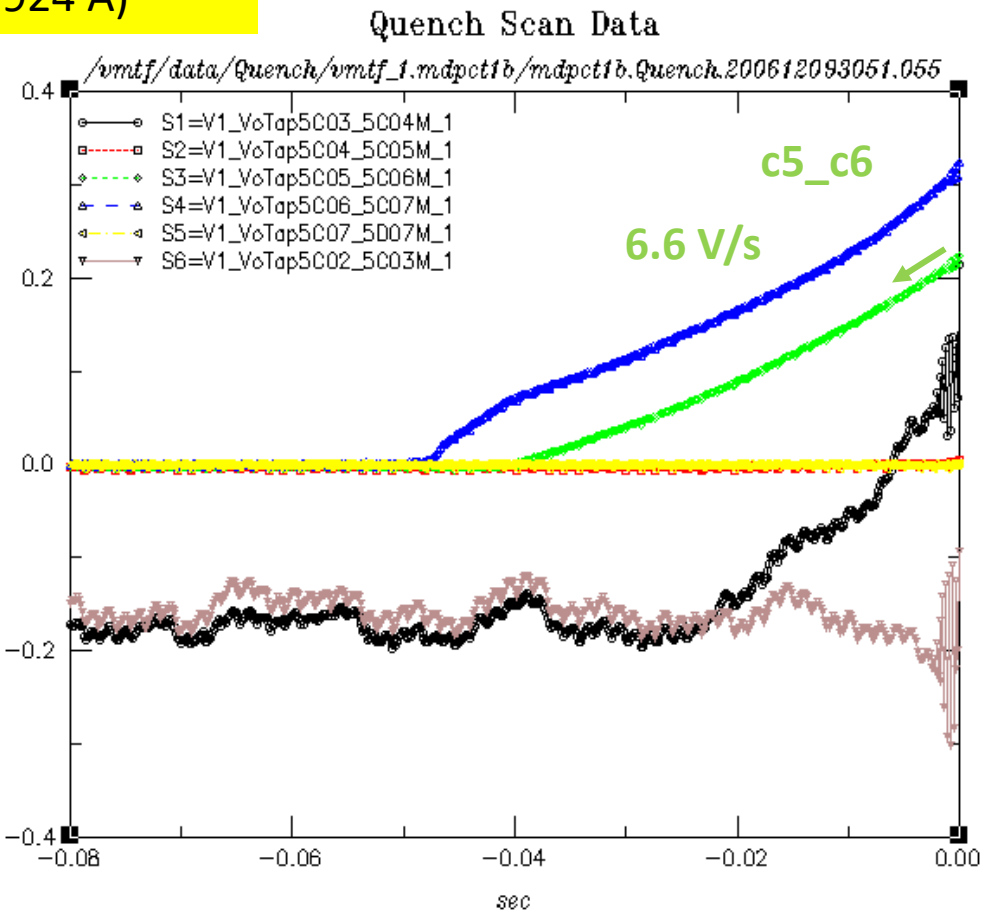
Ramp 6 (TC2)



Unlike TC1, the pattern for 1.9 K and 4.5 K is the same (c6_c7 is the quenching segment at high current)

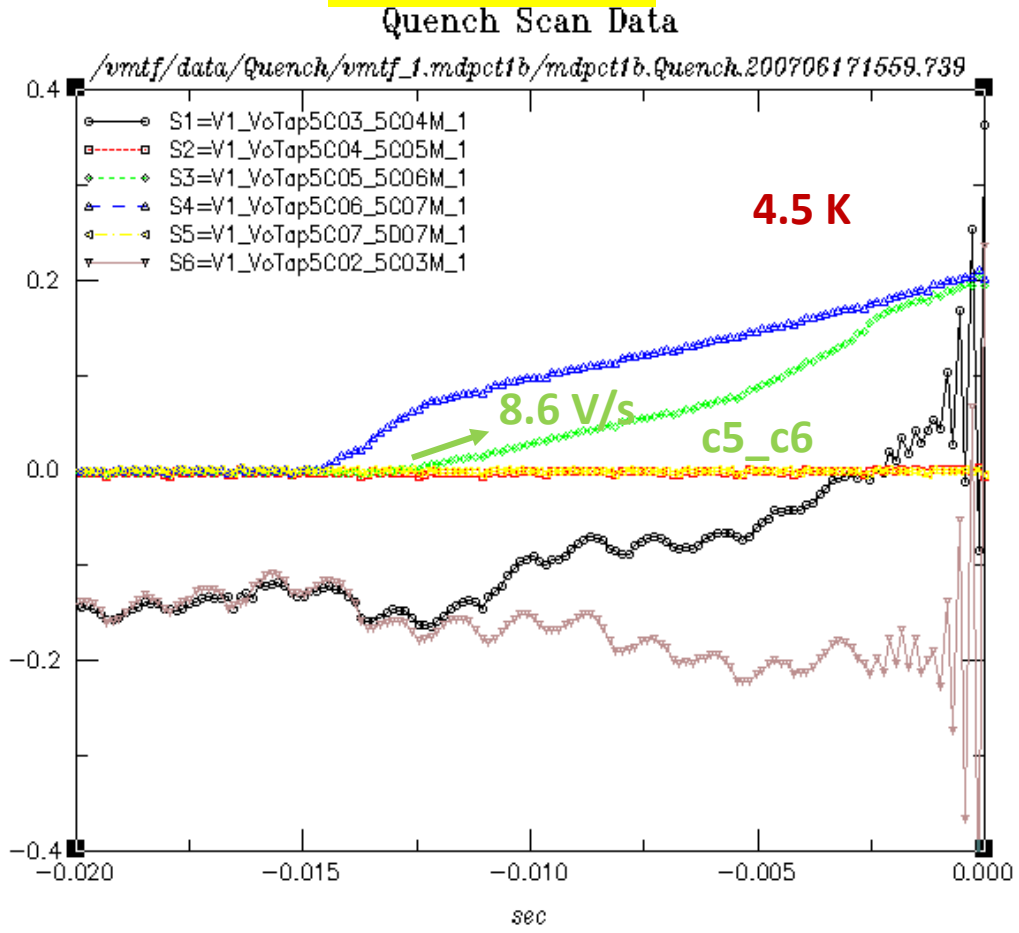
Quench profiles in TC1

Ramp 2 (TC1)
(7924 A)



Ramp 86 (TC1)
(8886 A)

(last quench in TC1)



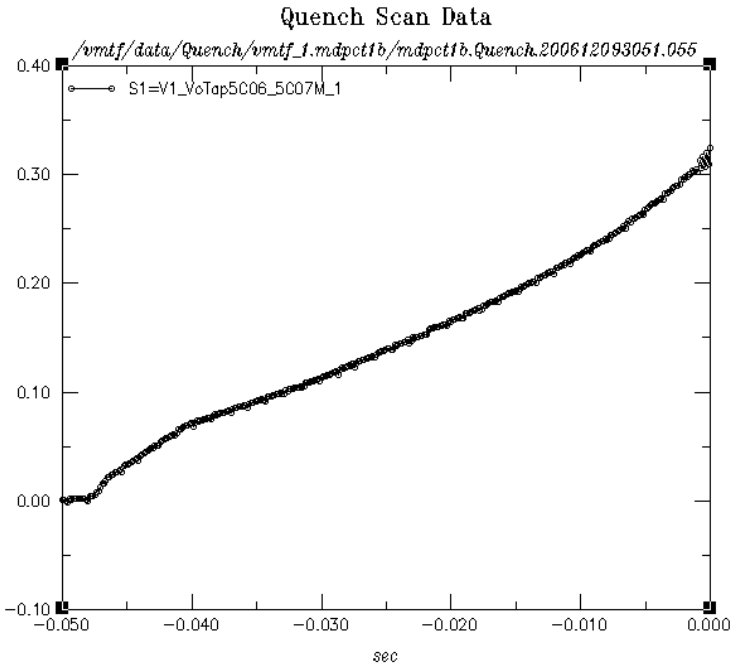
Voltage differentials

TC1, Ramp 2, 1.9 K, 7924 A

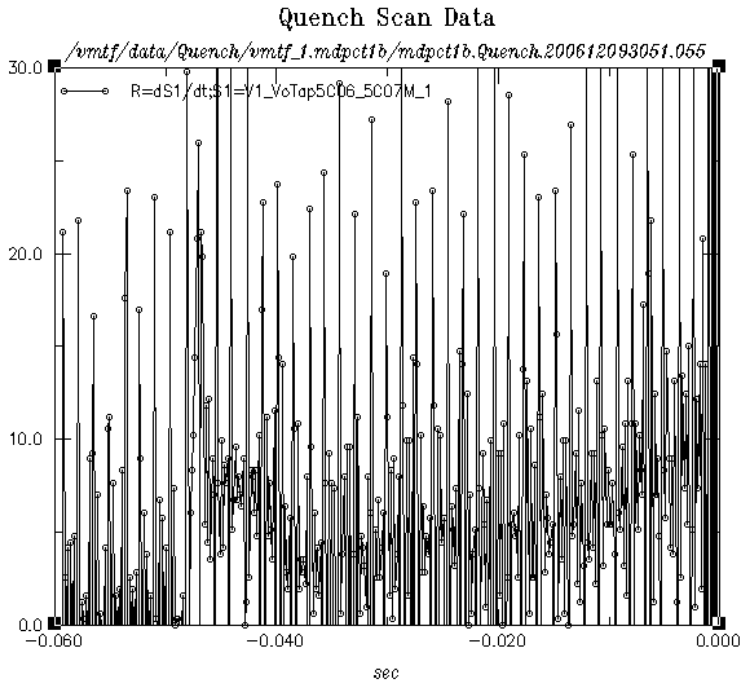
differentiate

filter

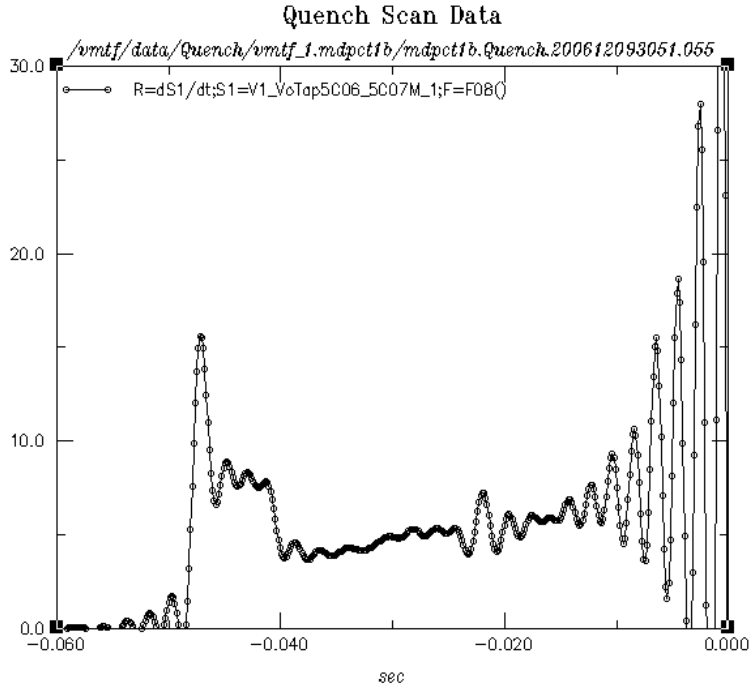
Voltage signal (V)



Voltage differential (dV/dt)

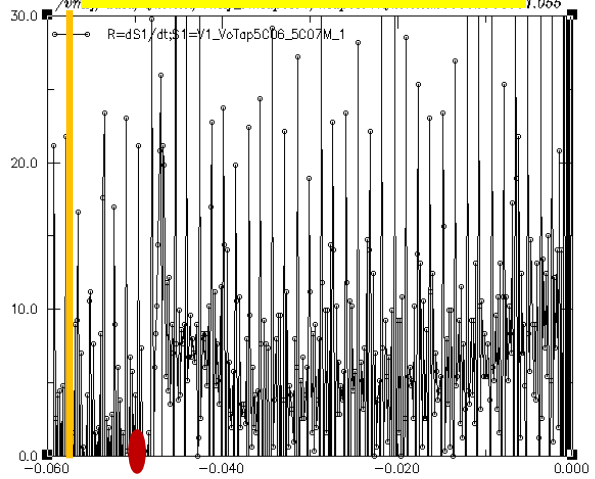


Filtered differential (dV/dt)

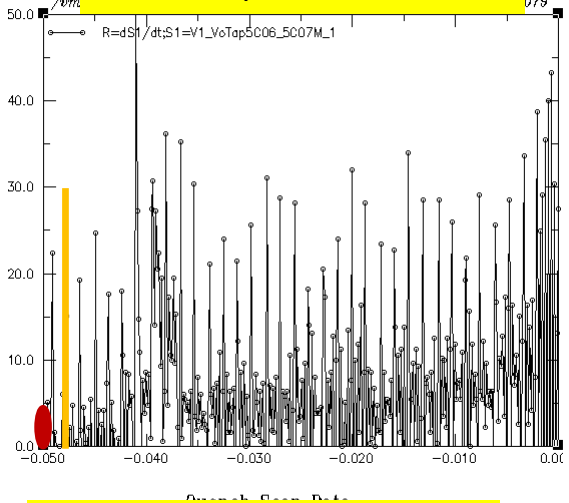


Voltage differentials in the (same) quenching segment

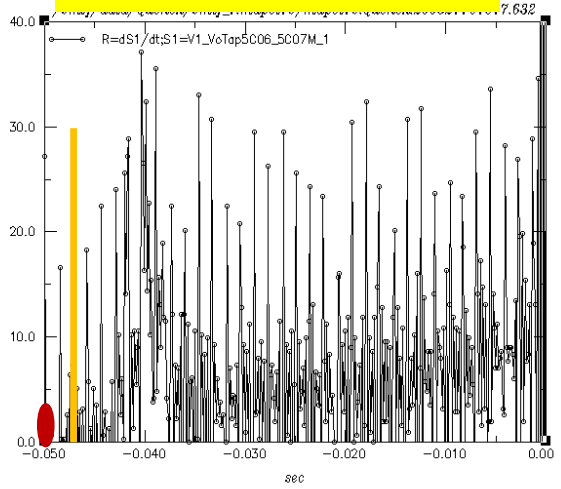
TC1, Ramp 2, 1.9 K, 7924 A



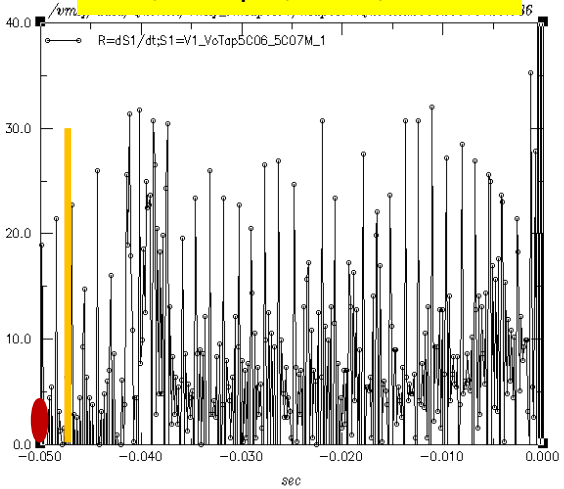
TC2, Ramp 2, 1.9 K, 7825 A



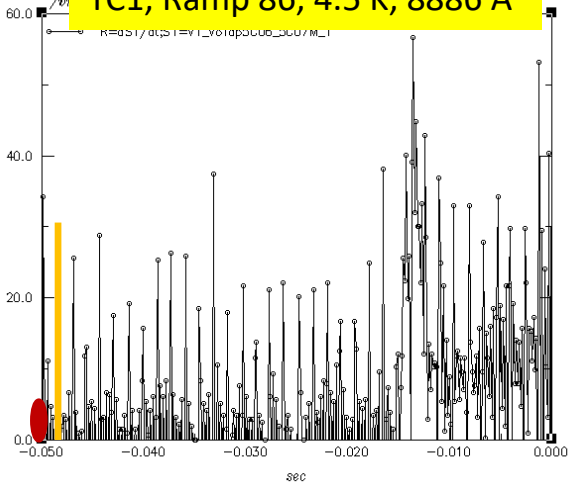
TC2, Ramp 3, 1.9 K, 7816 A



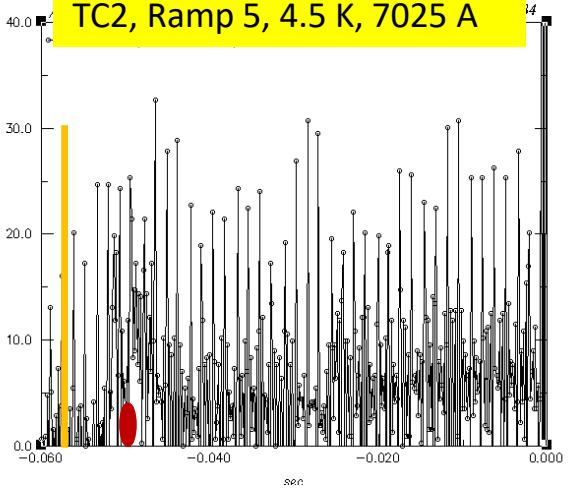
TC2, Ramp 4, 1.9 K, 7833 A



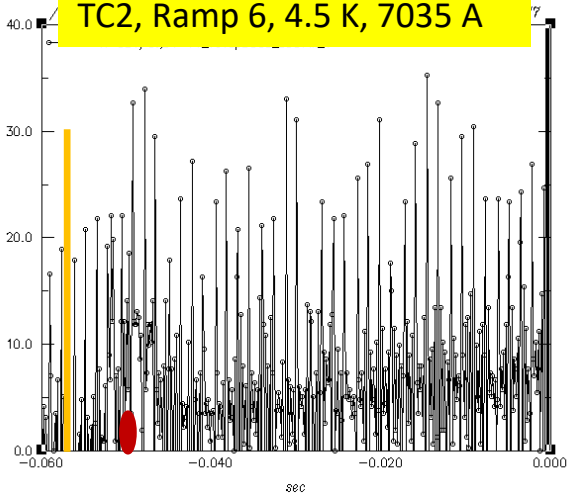
TC1, Ramp 86, 4.5 K, 8886 A



TC2, Ramp 5, 4.5 K, 7025 A



TC2, Ramp 6, 4.5 K, 7035 A

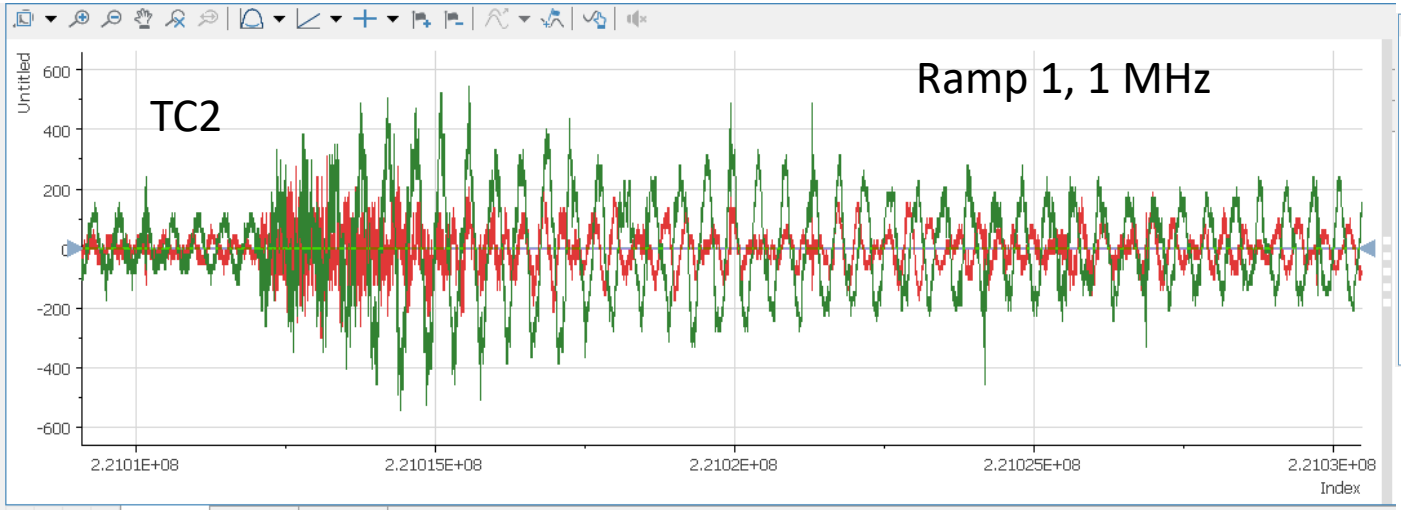


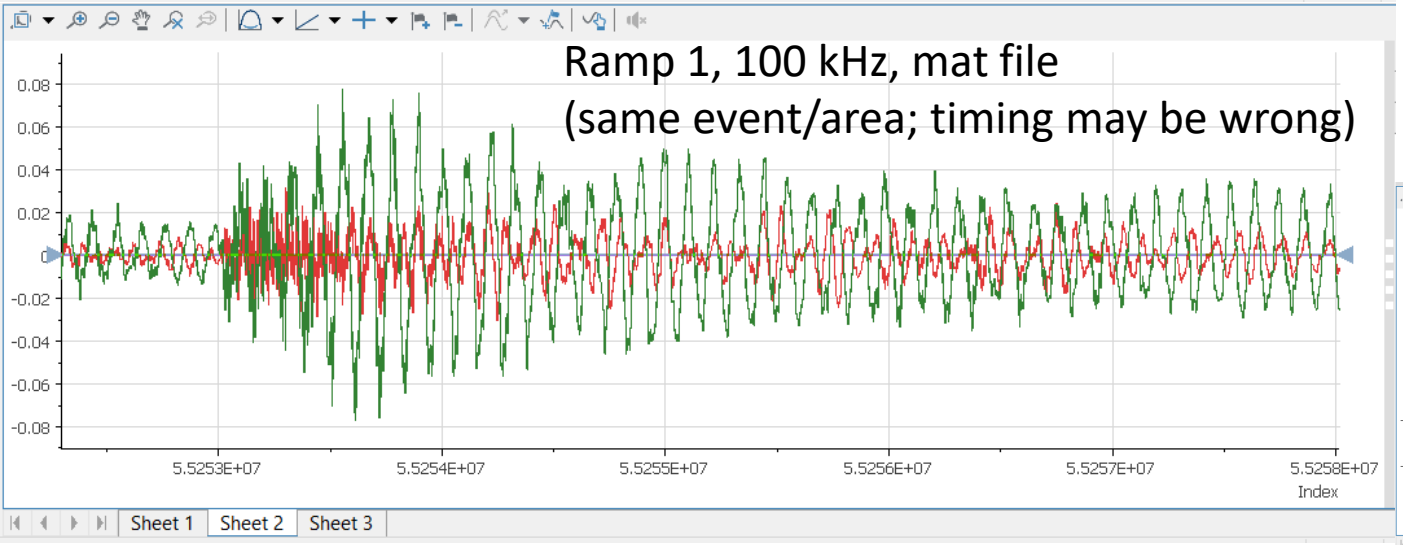
- Indicates the -50 ms mark on the X-axis

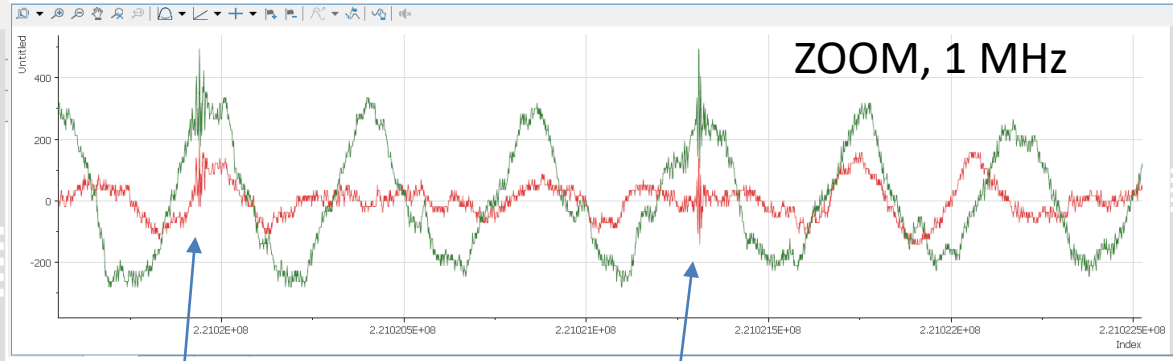
- Shows 30 V/s scale on the Y-axis

TC2 quench voltage differentials don't show any extraordinary behavior

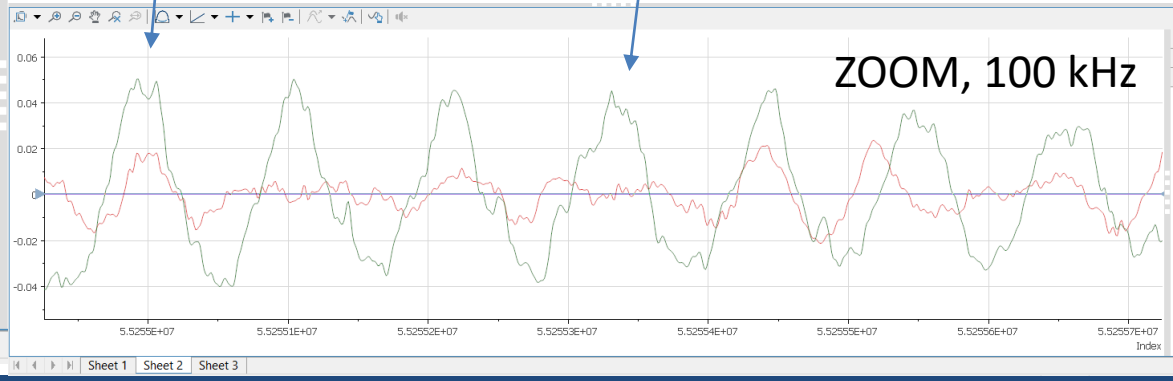
More acoustics







Features like those are not visible anymore
(those are likely due to power supply)
but the main picture persists



Summary

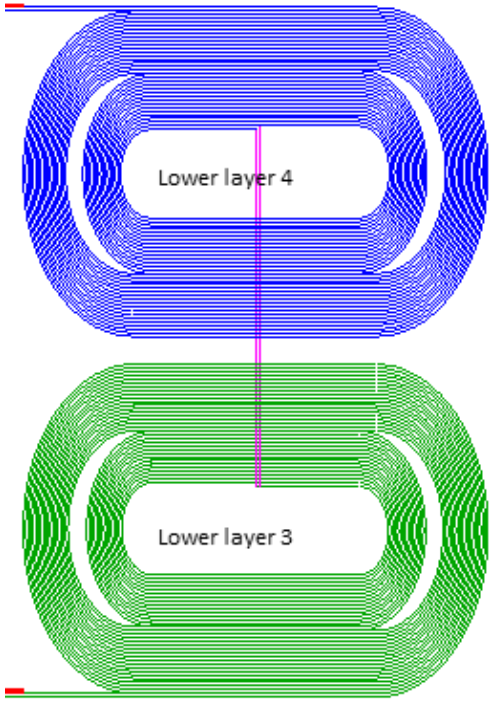
- ❑ No abnormal behavior in RRR or copper resistance in TC2 for quenching coils and segments
- ❑ No abnormal behavior in quench patterns or voltage distributions
- ❑ No significant acoustic activity near quenches observed
- ❑ Significant non-linear resistance increase with current observed in quenching segments (TC2)
  - ✓ No particular “event” quenches the magnet
- ❑ A huge mechanical event was observed in the beginning of TC2 (first ramp)
  - ✓ It did not quench the magnet
  - ✓ It originated in longitudinal area consistent with performance limiting quench locations
  - ✓ We speculate it may have caused the large conductor degradation observed
  - ✓ We do not have other candidate that may explain what happened in TC2 performance wise
  - ✓ Traces of this mechanical event shall be looked for when the magnet is disassembled

Back up

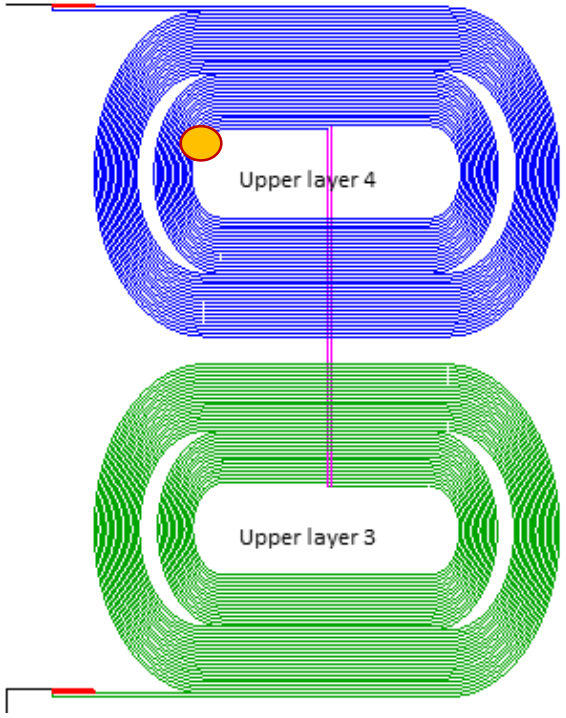
4; d6_d7, d7_c7, c7_c6, d5_d6

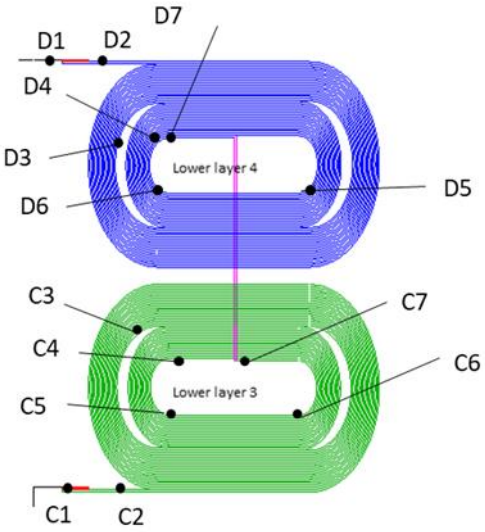
Ramp 1
(7530 A)

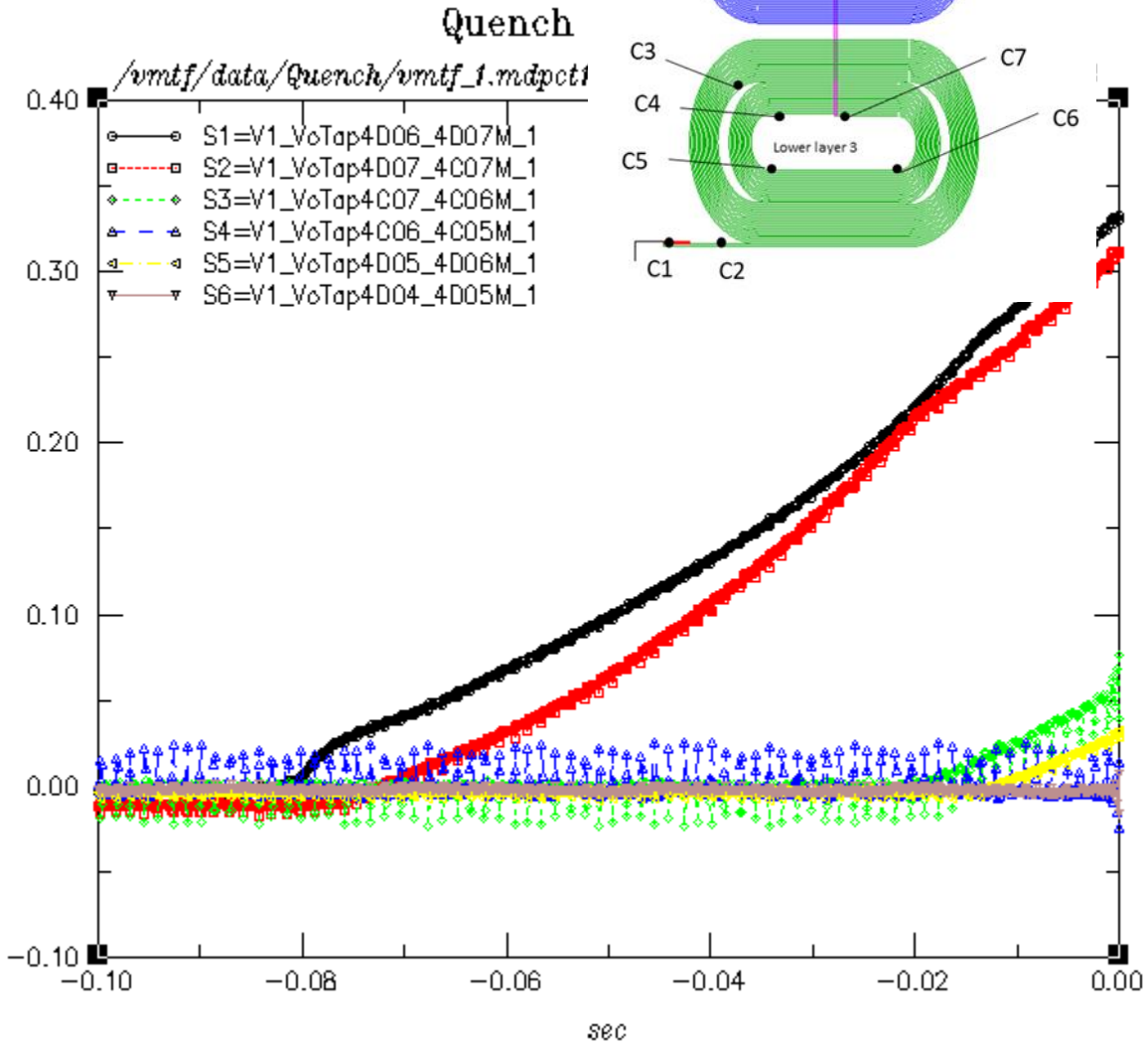
COIL 005



COIL 004







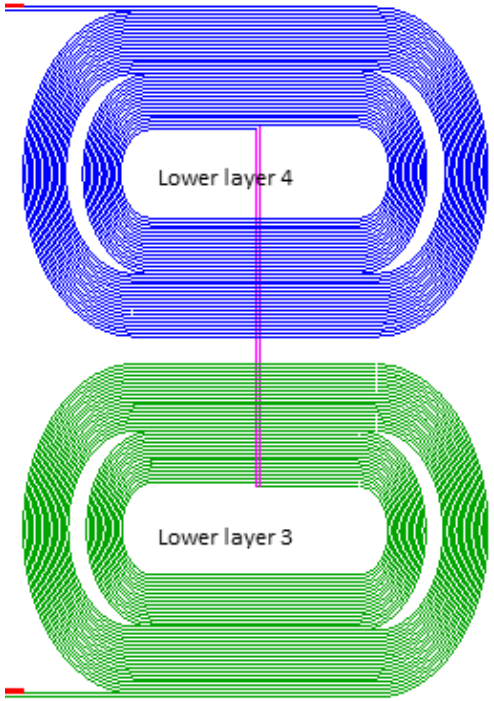
Propagation through d7_c7 (27 cm): 57 ms
Propagation through d6_d7 (27 cm): 9+71 ms

Known

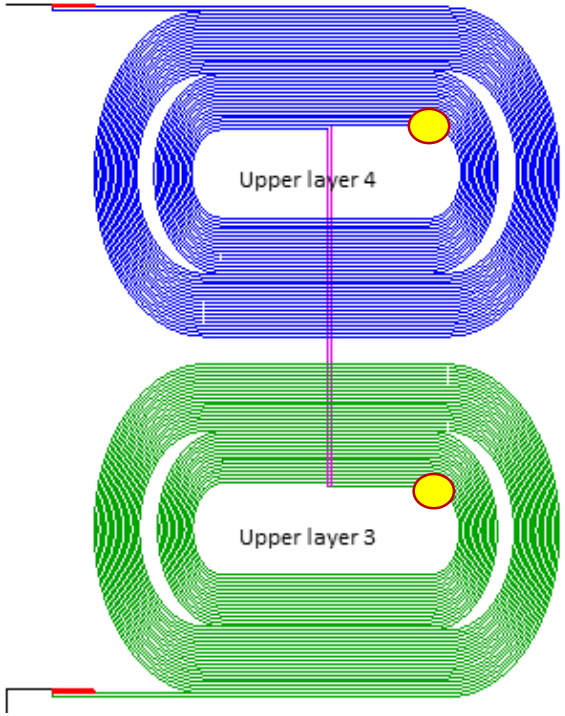
Quench propagation V: 5 m/s and 3 m/s, respectively

4; c7_c6, d4_d5

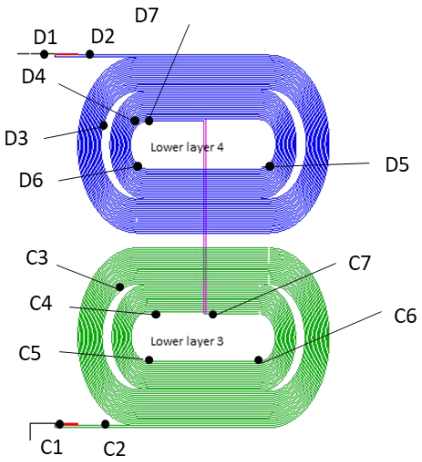
COIL 005

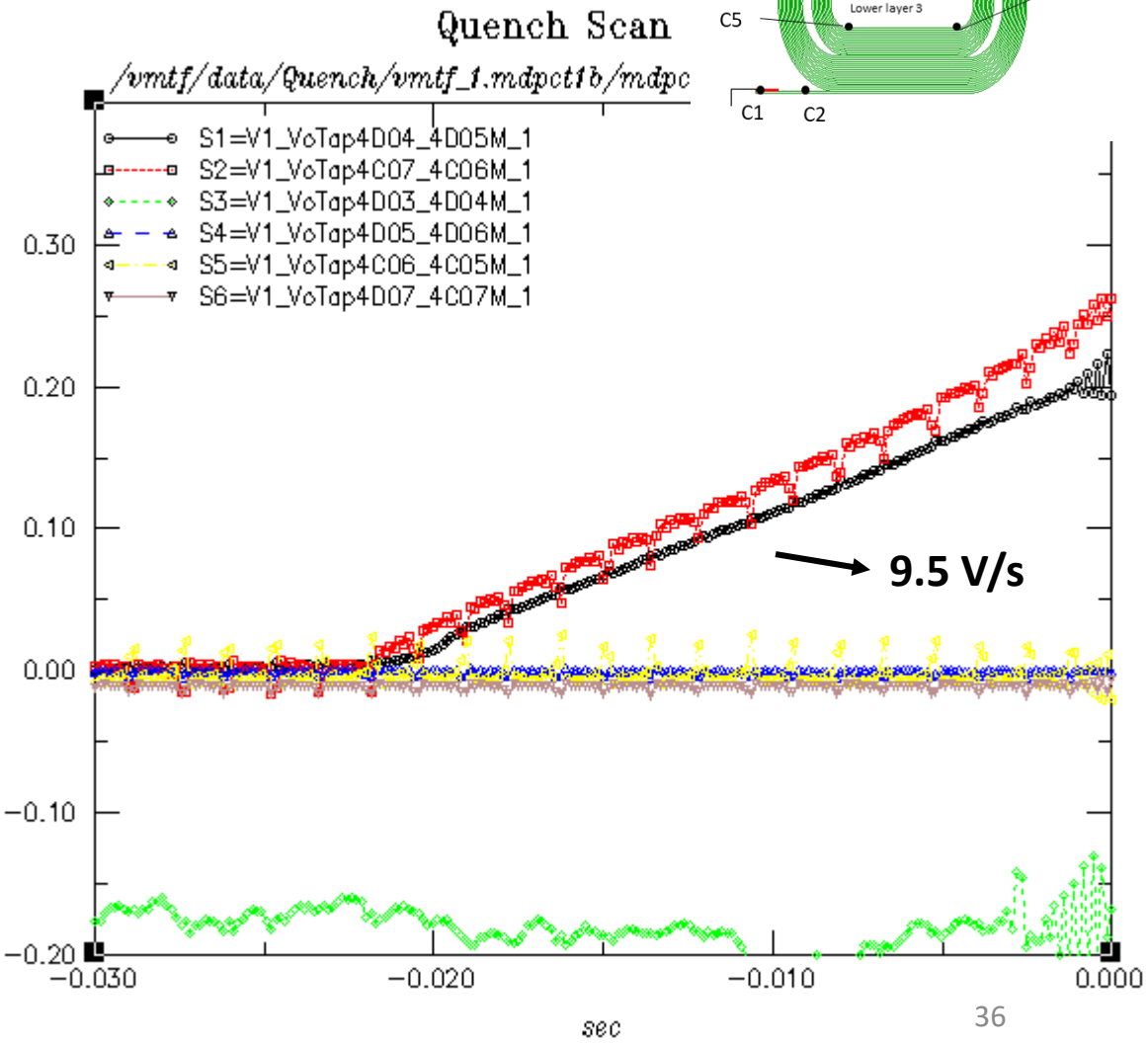


COIL 004



Ramp 6
(8497 A)



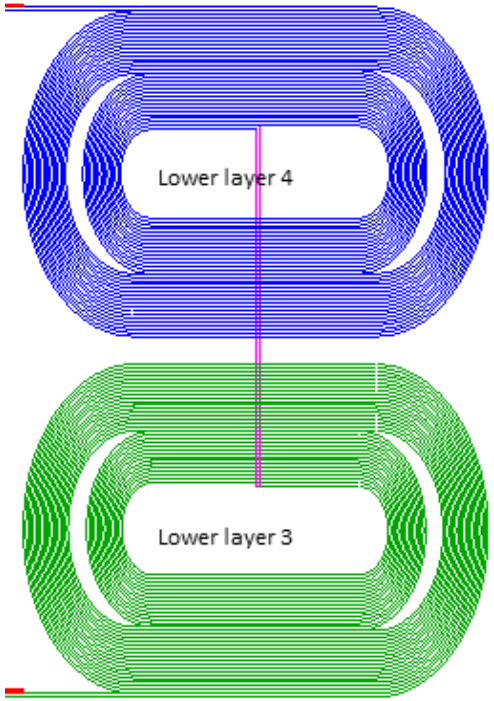


Most of the quenches don't give enough information to determine the propagation velocity but one can compare voltage rise patterns in the same segment(s)

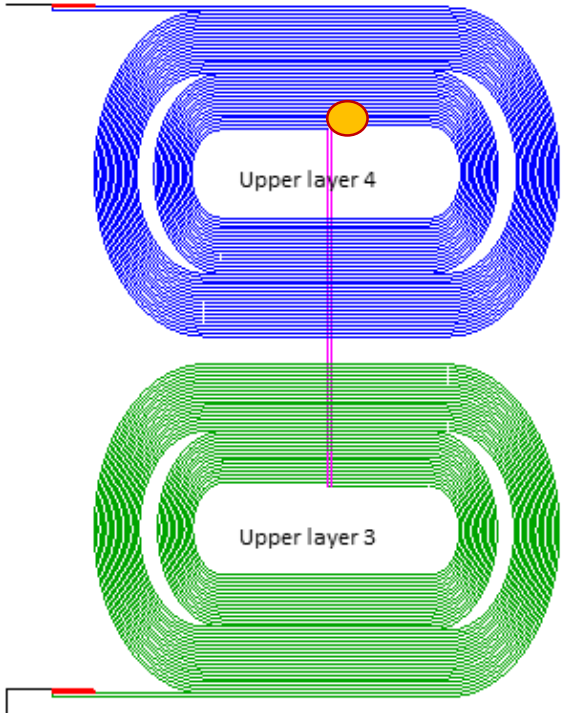
Less known

4; d4_d5, d3_d4

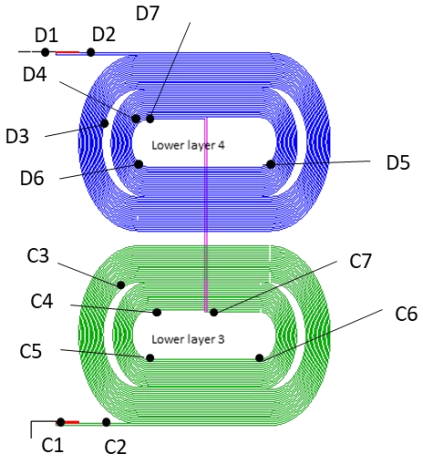
COIL 005

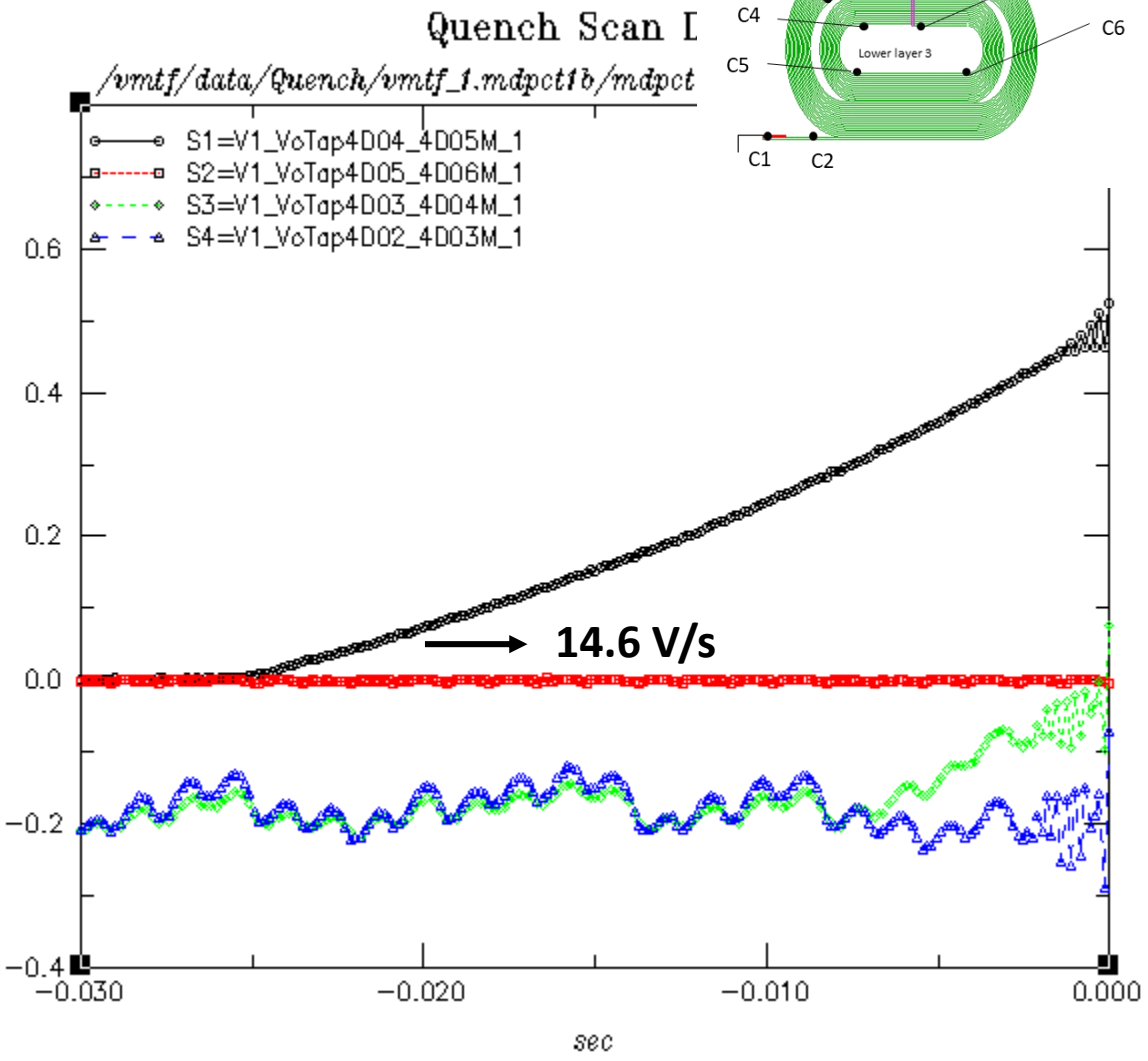


COIL 004



Ramp 58
(8978 A)





~Known

No significant differences in propagation pattern toward the end of the training curve; faster propagation at higher current (factor of ~2).

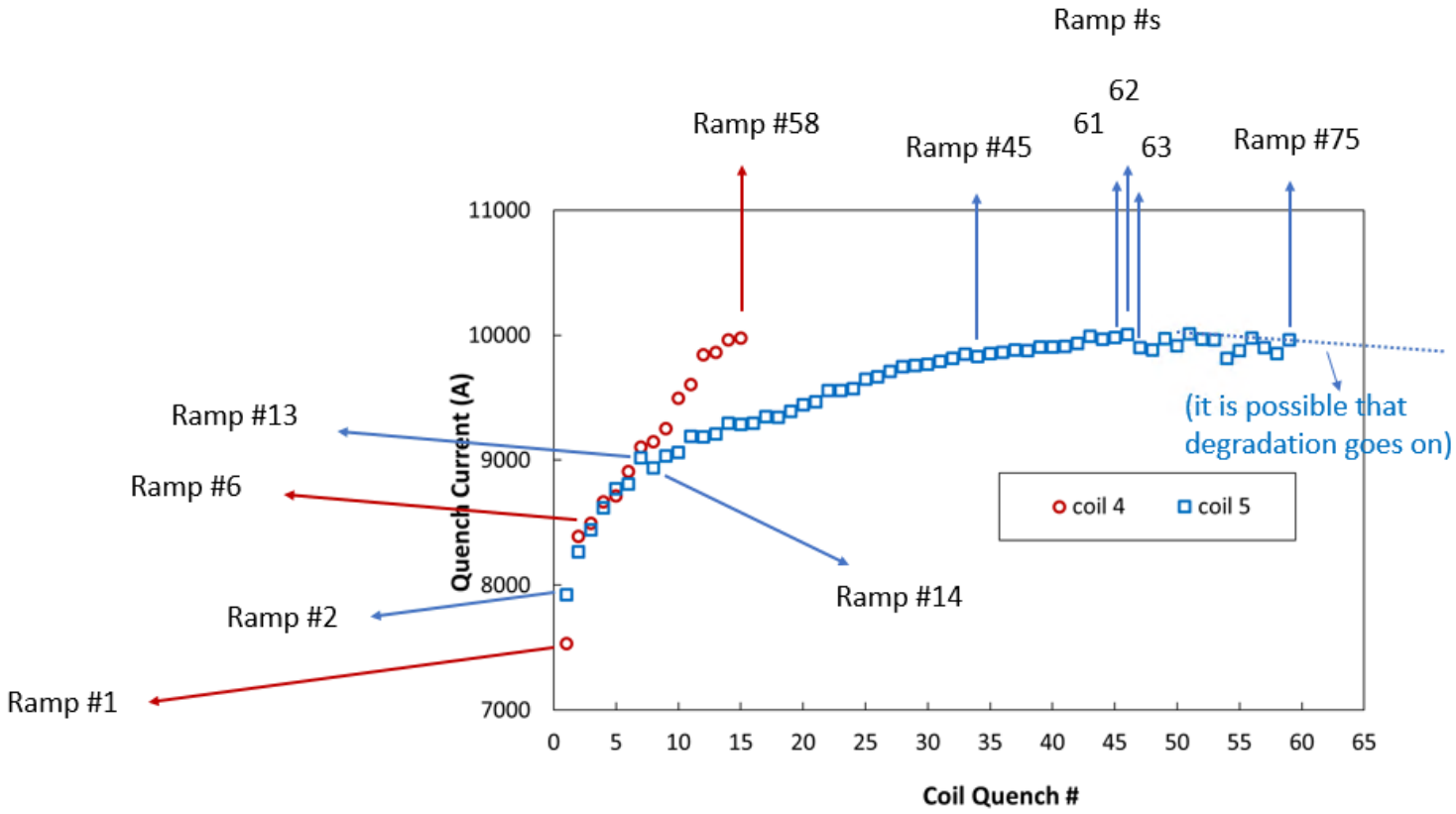
Quenches

Coil 5

Three main patterns identified, points of interest on the training curve investigated

Quenches

86, 85, 84, 83, 82; 79?, 78?; 76, 11, 3, 2,



Coil 5 Pattern 1

(beginning of training, ramp rate and temp. dependence quenches)

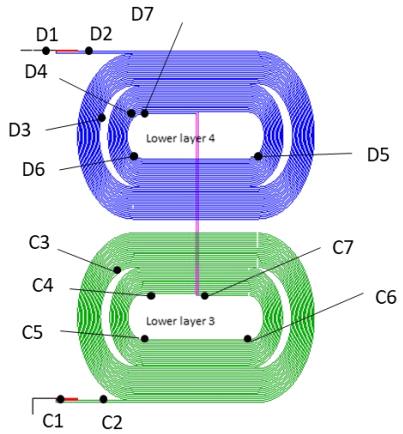
86, 85, 84, 83, 82; 79?, 78?; 76, 11 , 3 , 2,

Ramps

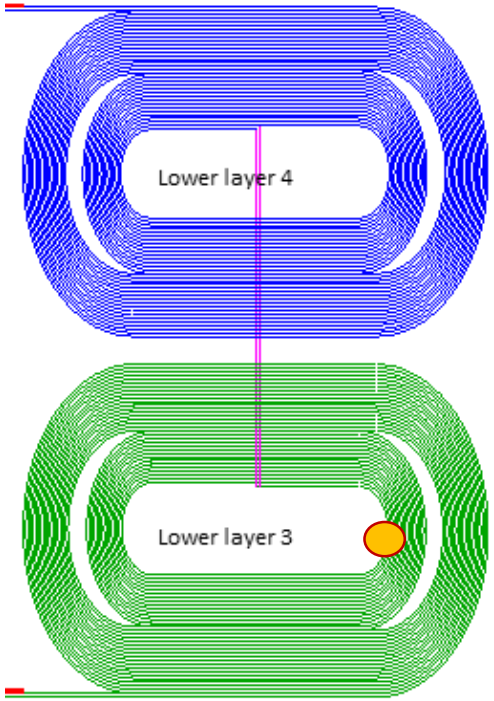
Pattern

5; c6_c7, c5_c6, c3_c4

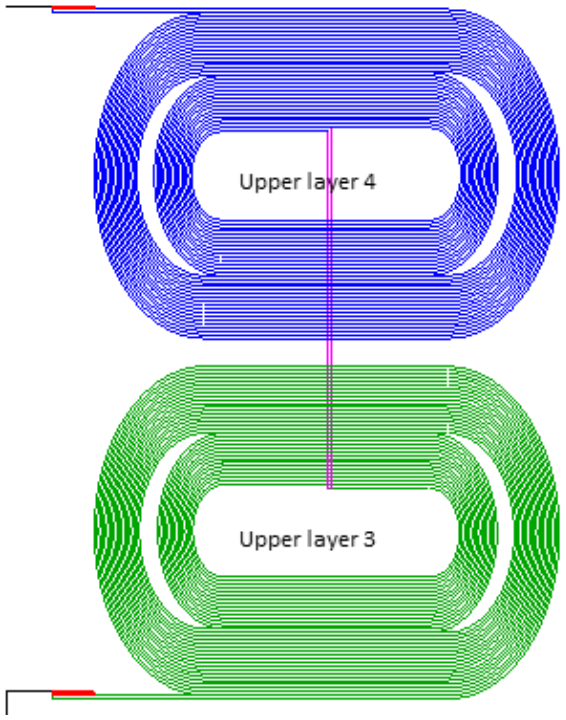
Ramp 2
(7924 A)

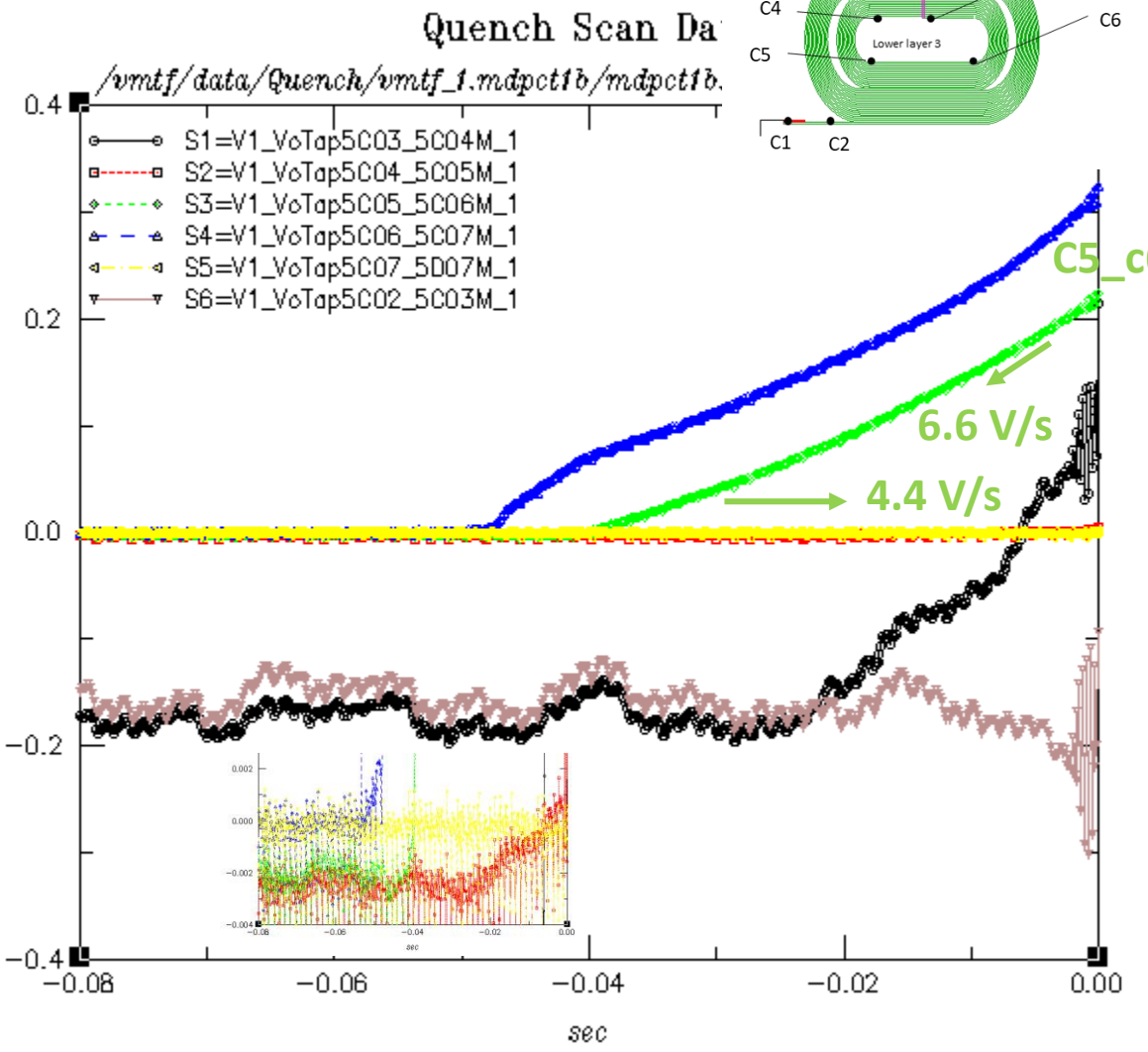


COIL 005



COIL 004





Propagation through c5_c6 (54 cm): 16 ms

Known

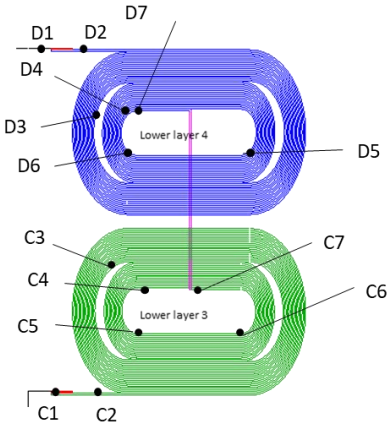
Less known

Quench propagation V: 34 m/s (?)
(more likely C3_C4 is quenching independently, see later)

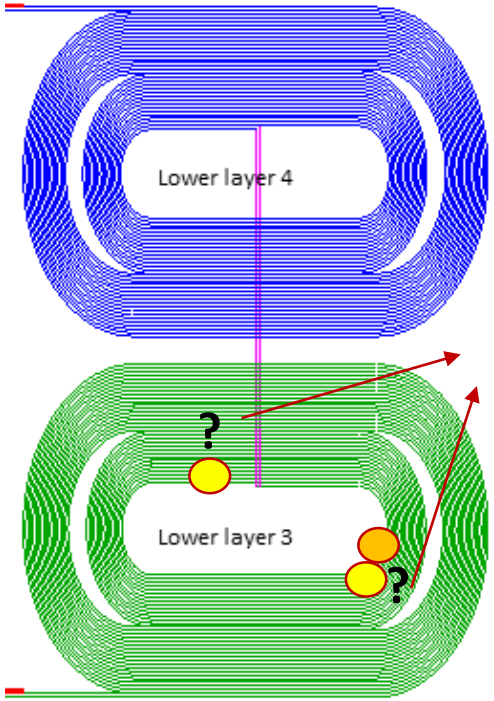
86, 85, 84, 83, 82; 79?, 78?; 76, 11, 3, 2,

5; c6_c7, c5_c6, c3_c4

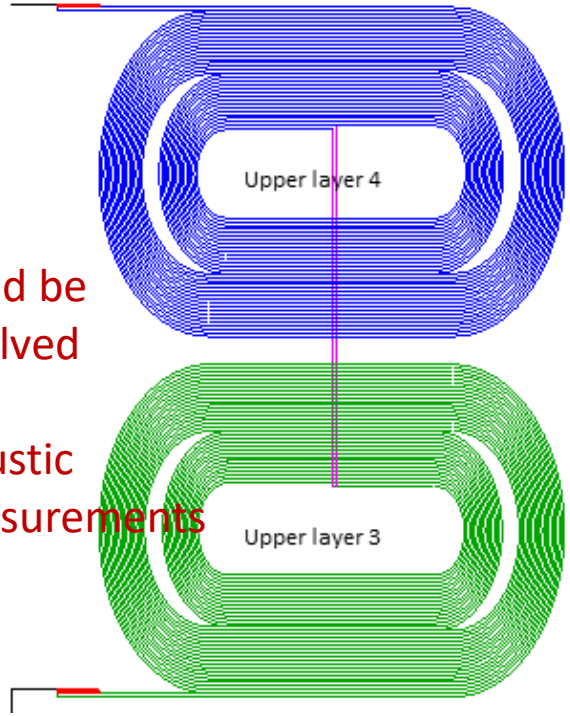
Ramp 86
(8886 A; 4.5 K)



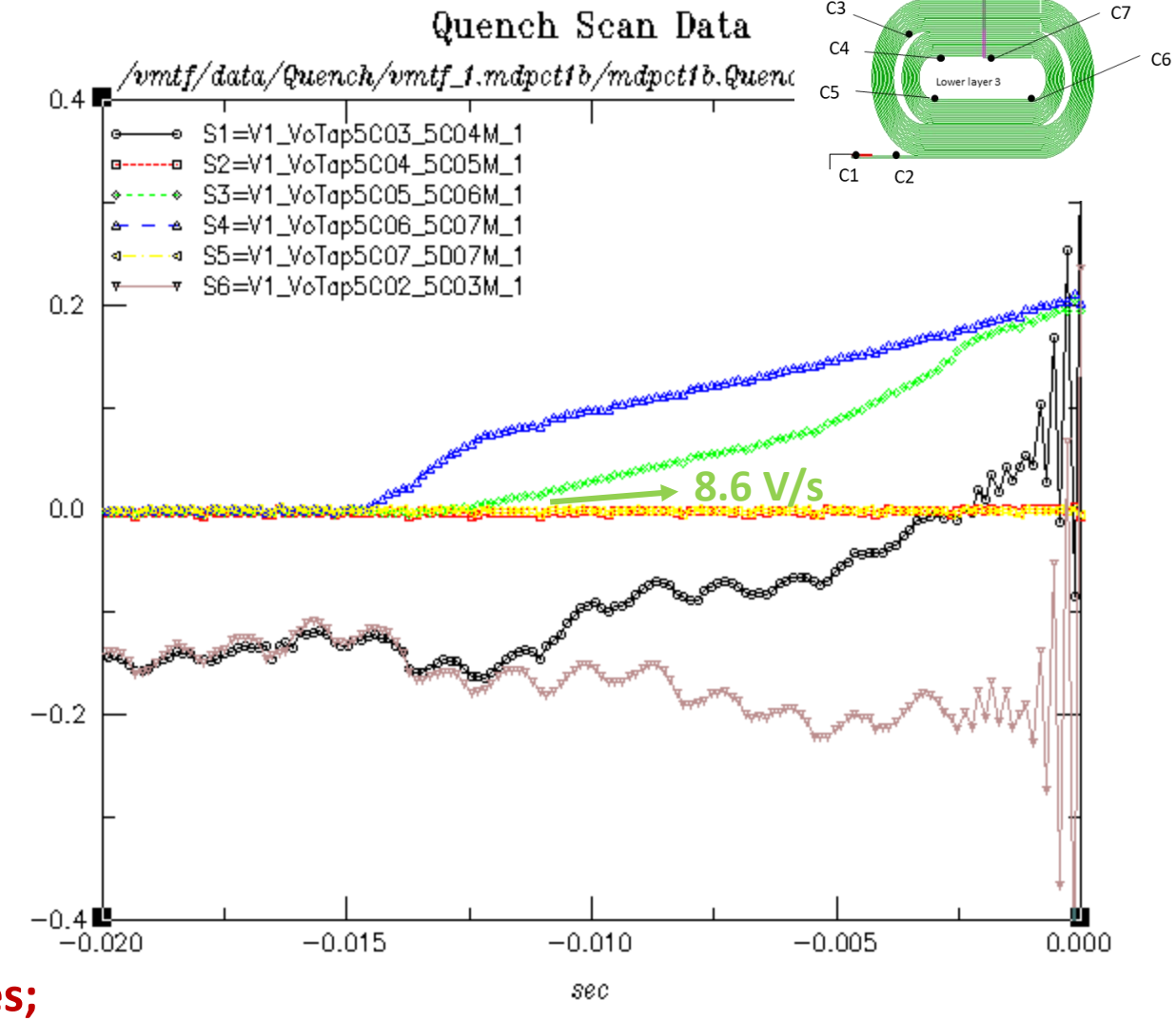
COIL 005



COIL 004



Could be resolved by acoustic measurements



~Known

Less known

No significant differences in propagation pattern between early training at 1.9 K and RR/TD quenches; faster propagation (factor of ~2); second quench location initiates earlier.

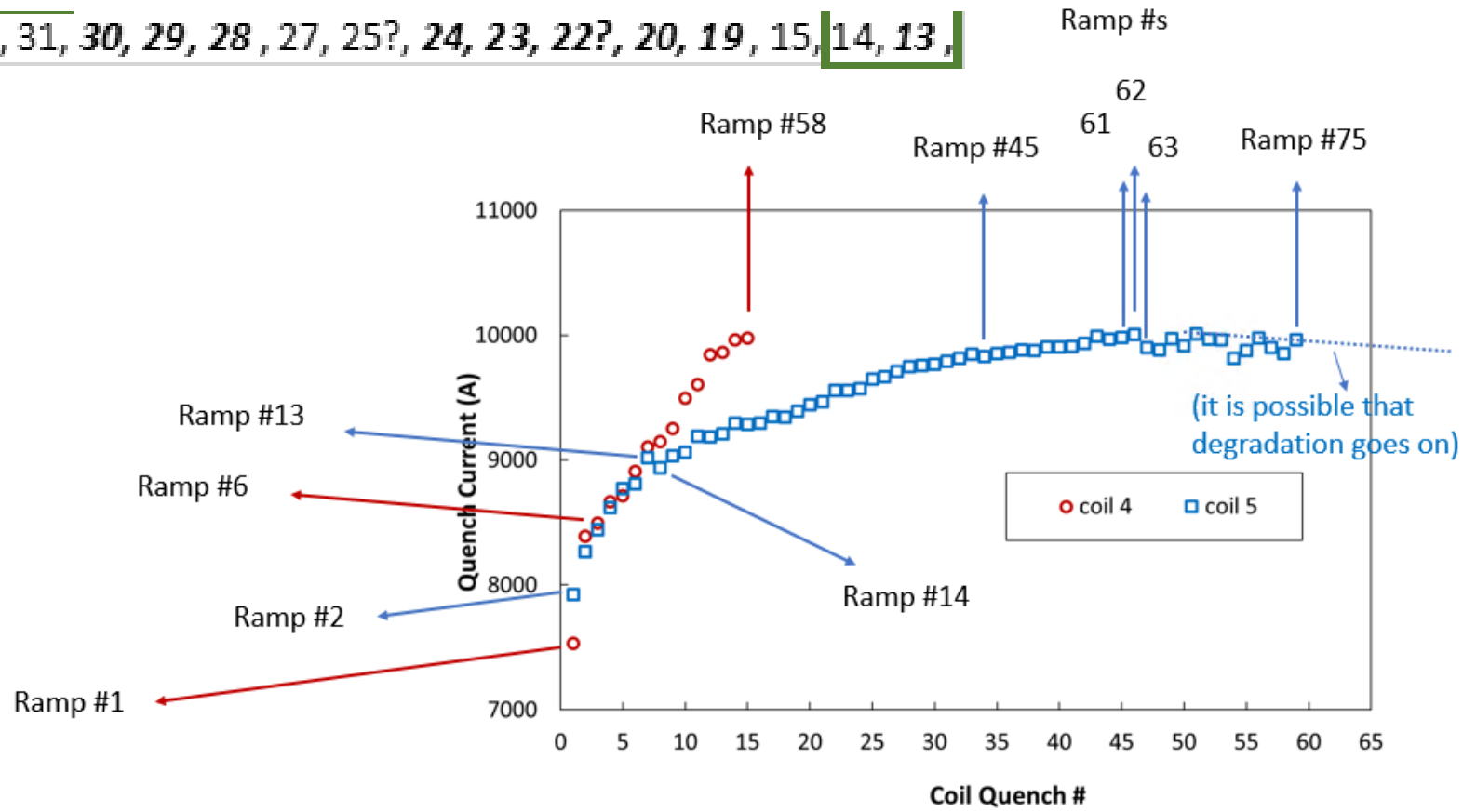
Quenches

67, 62, 55, 54, 53, 52, 45, 42, 41, 40, 39, 38, ***37***, 34, 31, ***30, 29, 28***, 27, 25?, ***24, 23, 22?, 20, 19***, 15, 14, ***13***,

Coil 5

Pattern 2

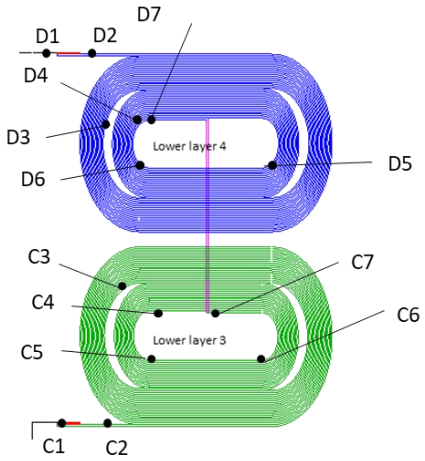
(with the two highest currents)



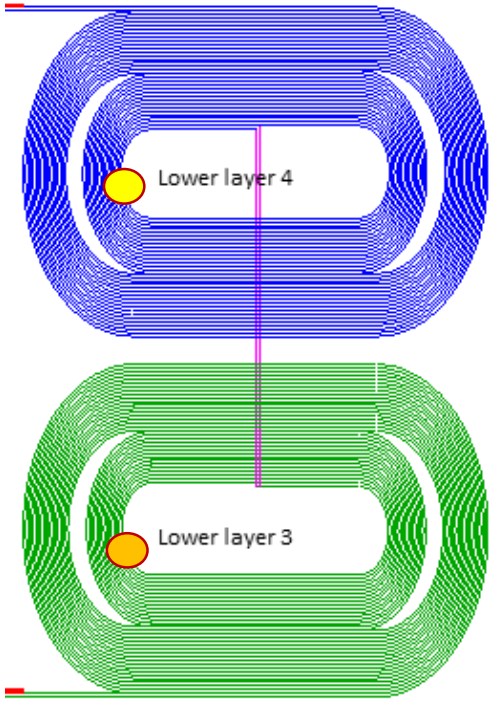
67, 62, 55, 54, 53, 52, 45, 42, 41, 40, 39, 38, **37** , 34, 31, **30, 29, 28** , 27, 25?, **24, 23, 22?, 20, 19** , 15, 14, **13** ,

5; c4_c5, c5_c6, d7_d6

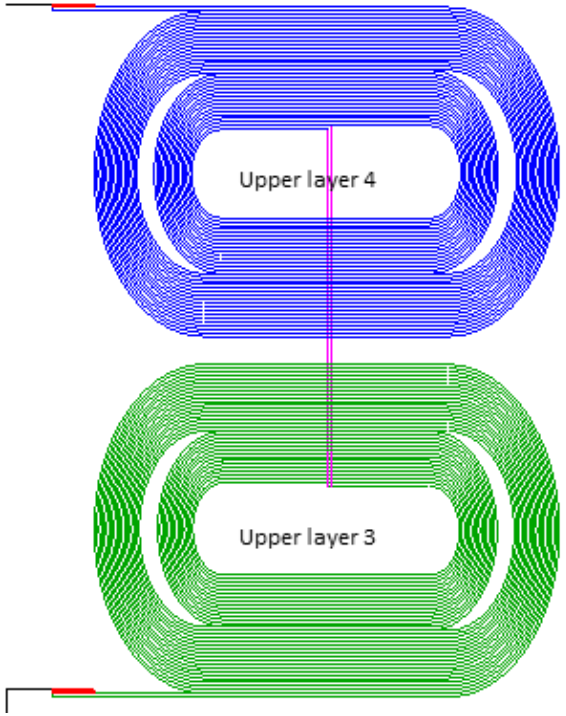
Ramp 13
(9021 A)

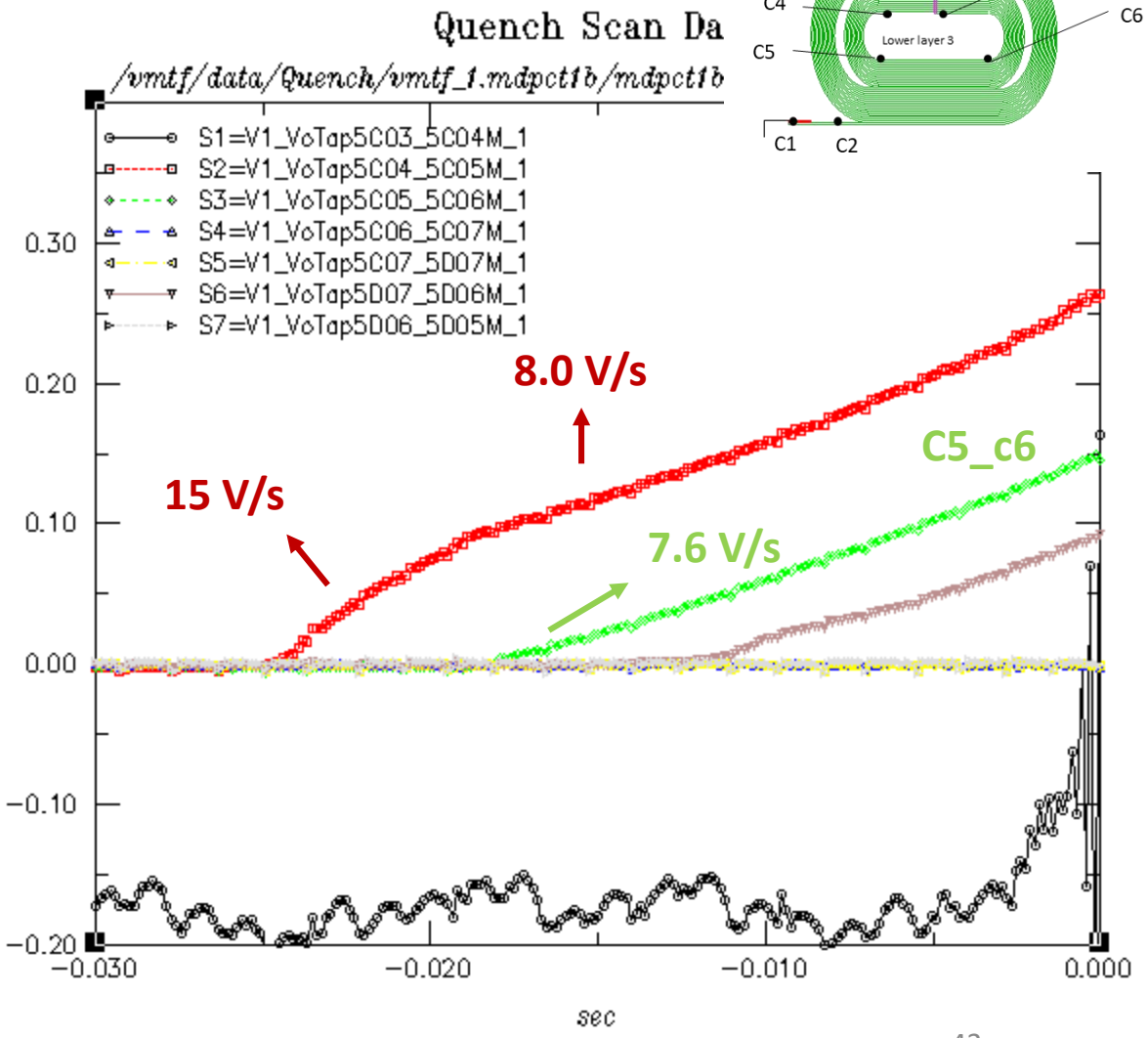


COIL 005



COIL 004





Propagation through c4_c5 (30 cm): 6.4 +23.0 ms

Quench propagation V: 10 m/s

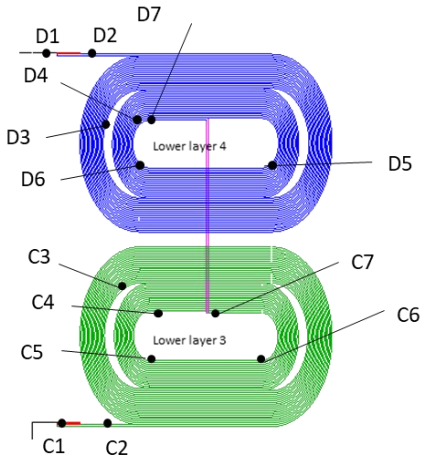
Known

Less known

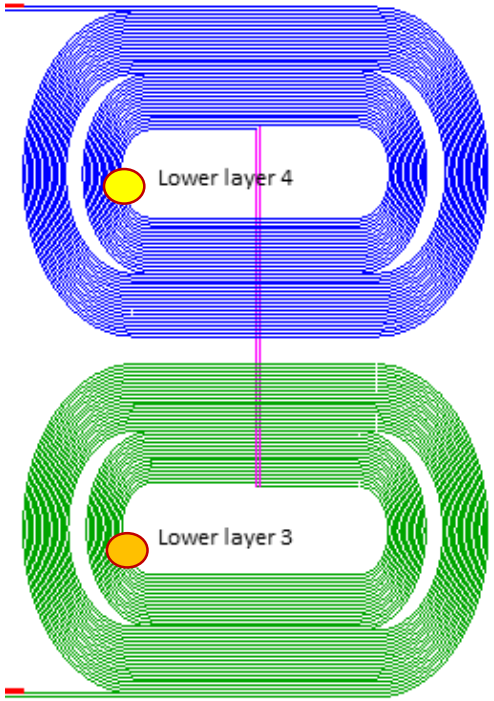
67, 62, 55, 54, 53, 52, 45, 42, 41, 40, 39, 38, 37, 34, 31, 30, 29, 28, 27, 25?, 24, 23, 22?, 20, 19, 15, 14, 13,

5; c4_c5, c5_c6, d7_d6

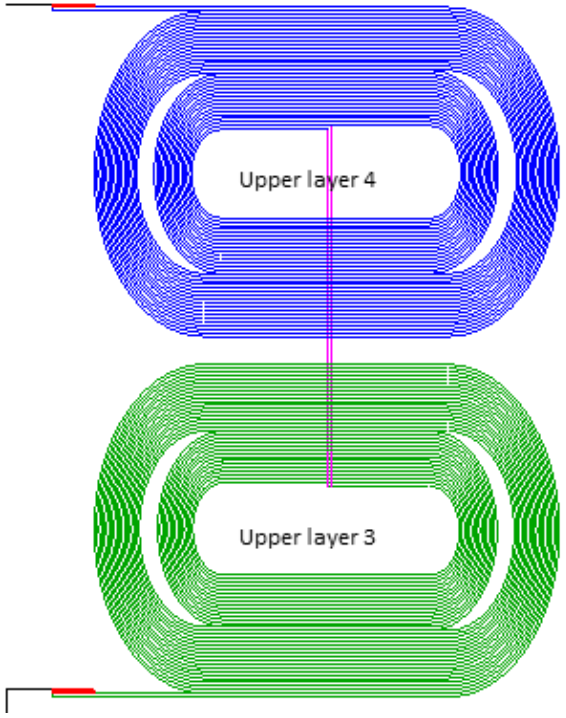
Ramp 14
(8940 A)

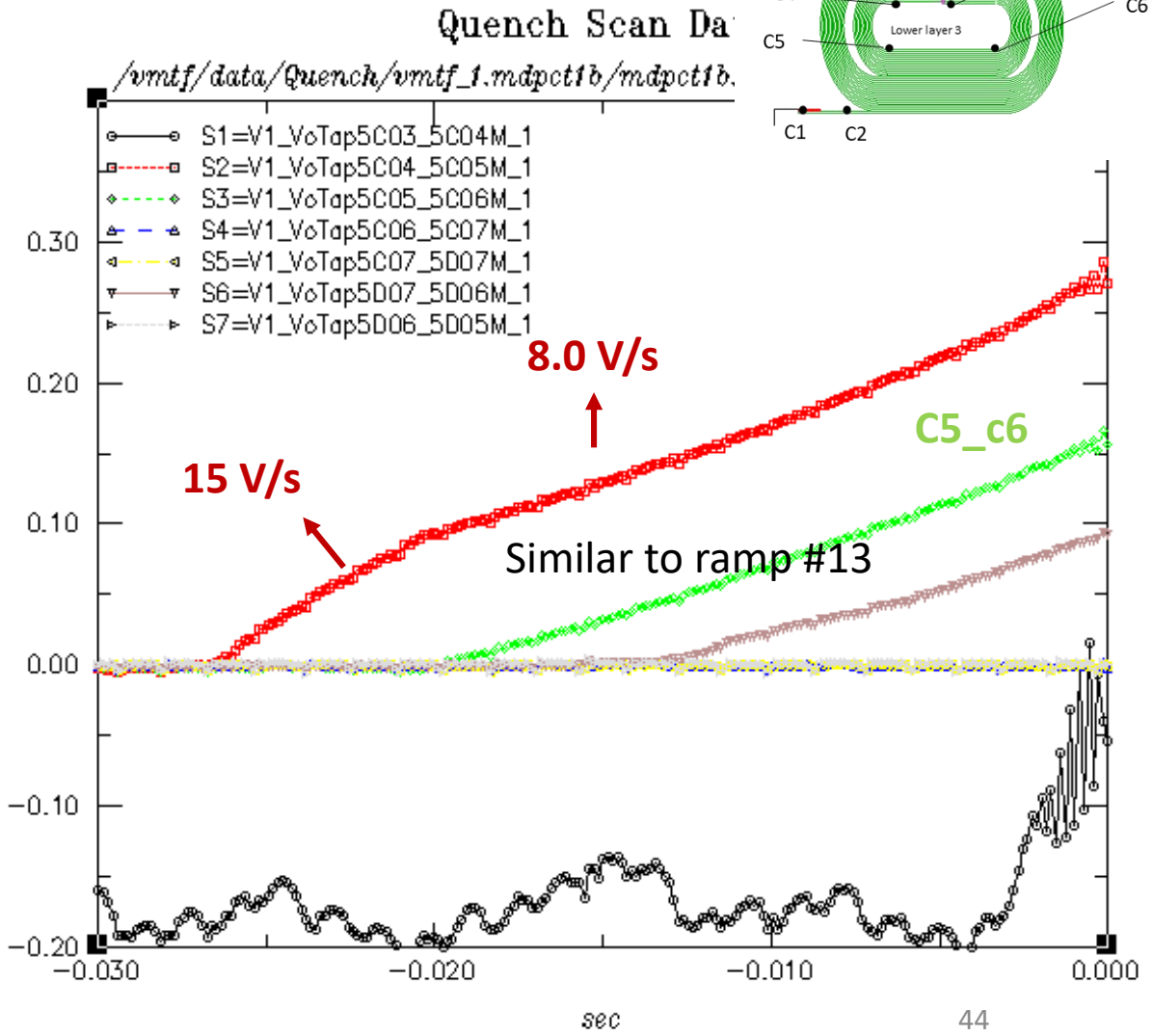


COIL 005



COIL 004





Known

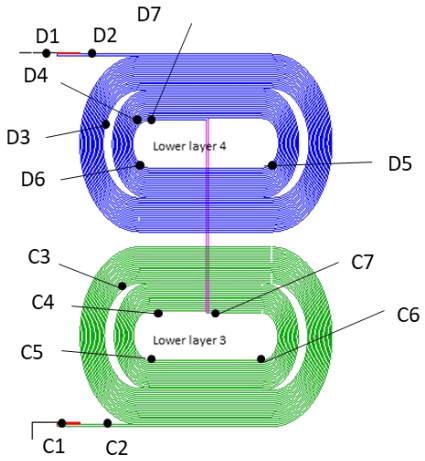
Less known

Note that the dV/dt decreases by a factor of two when the adjacent segment becomes resistive – consistent with quench propagating in the remaining segment direction

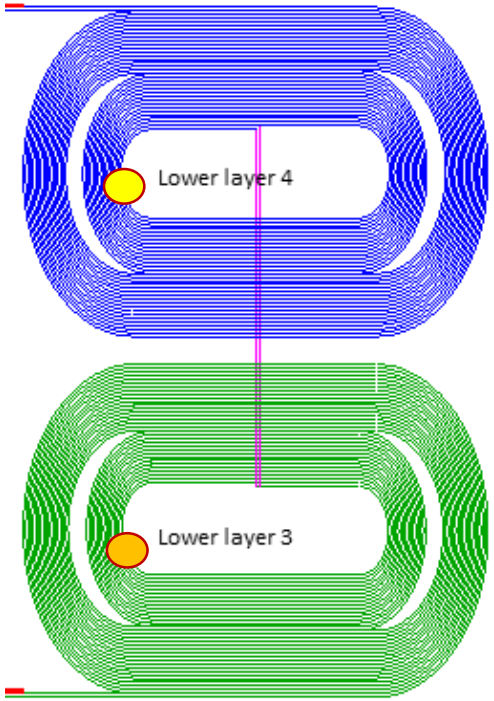
67, 62, 55, 54, 53, 52, 45, 42, 41, 40, 39, 38, 37, 34, 31, 30, 29, 28, 27, 25?, 24, 23, 22?, 20, 19, 15, 14, 13,

5; c4_c5, c5_c6, d7_d6

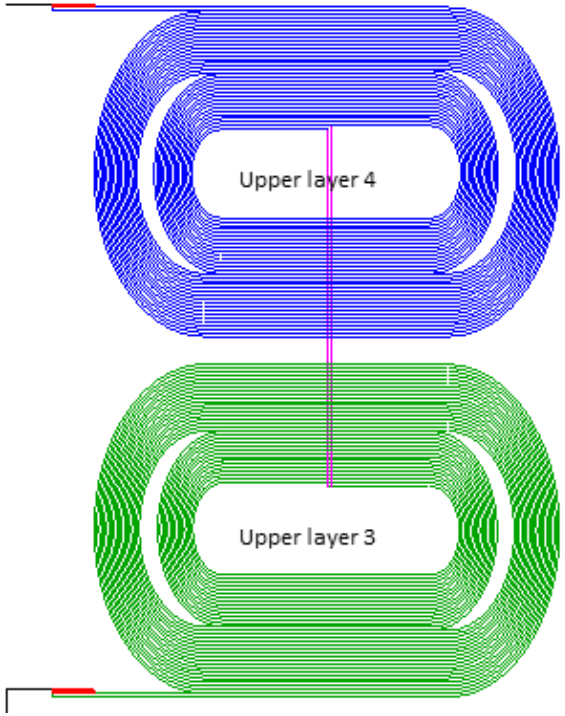
Ramp 62
(10007 A)

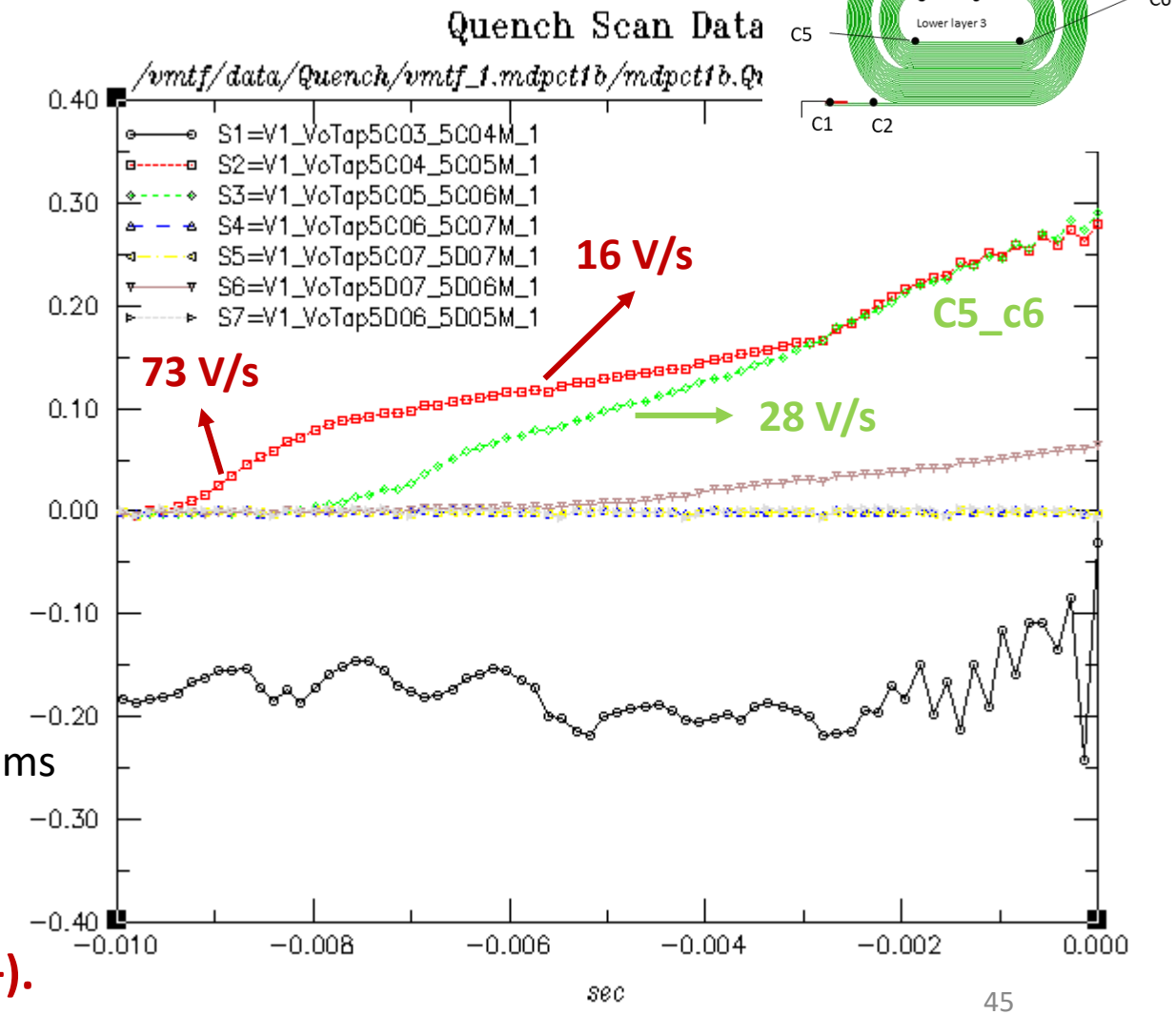


COIL 005



COIL 004





Propagation through c4_c5 (30 cm): 1.4 +6.9 ms

Quench propagation V: 36 m/s

Known

Less known

Much higher initial expansion, faster propagation later (factor of ~2+).

C5_C6 dV/dt factor of 3+ higher!

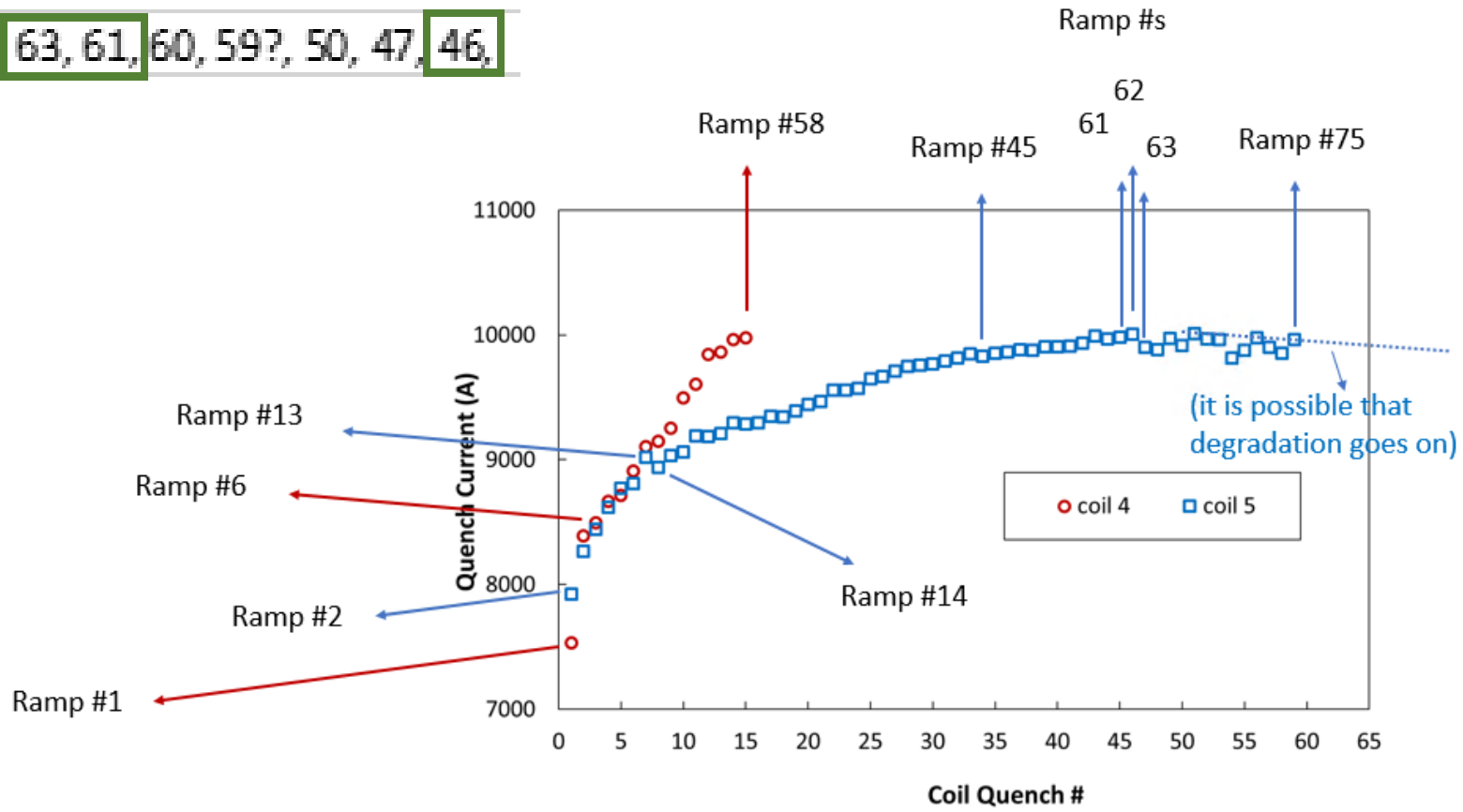
Quenches

81, 80, 75, 74, 73, 72, 71, 70, 69, 68, 66, 65, 64, 63, 61, 60, 59?, 50, 47, 46,

Coil 5

Pattern 3

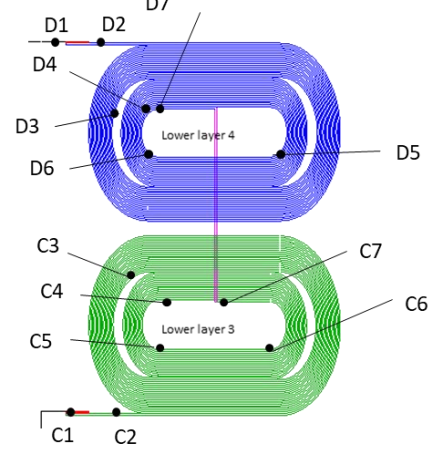
(with limiting quenches)



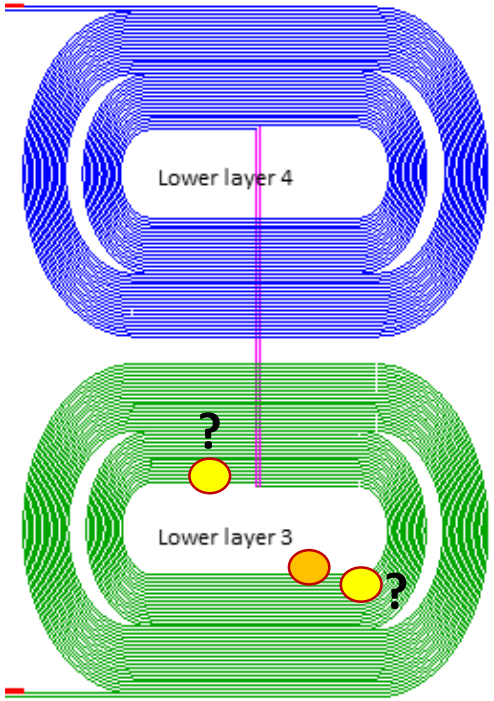
81, 80, 75, 74, 73, 72, 71, 70, 69, 68, 66, 65, 64, 63, 61, 60, 59?, 50, 47, 46,

5; c5_c6, c6_c7, c3_c4

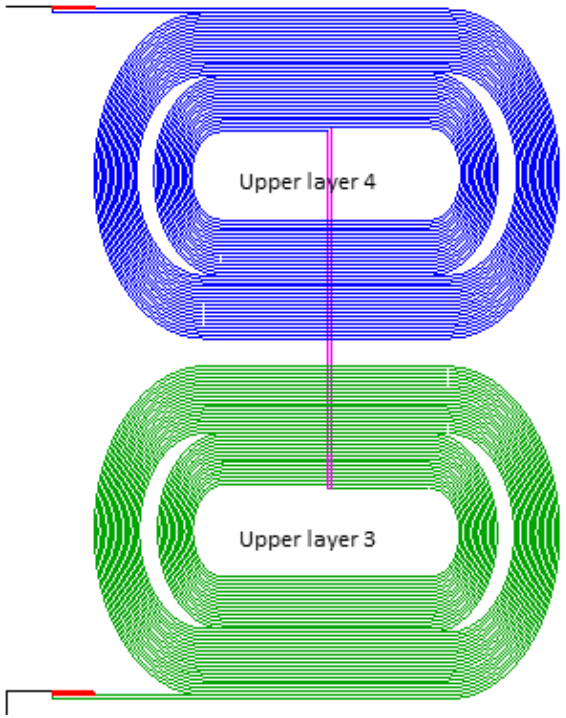
Ramp 46
(9831 A)

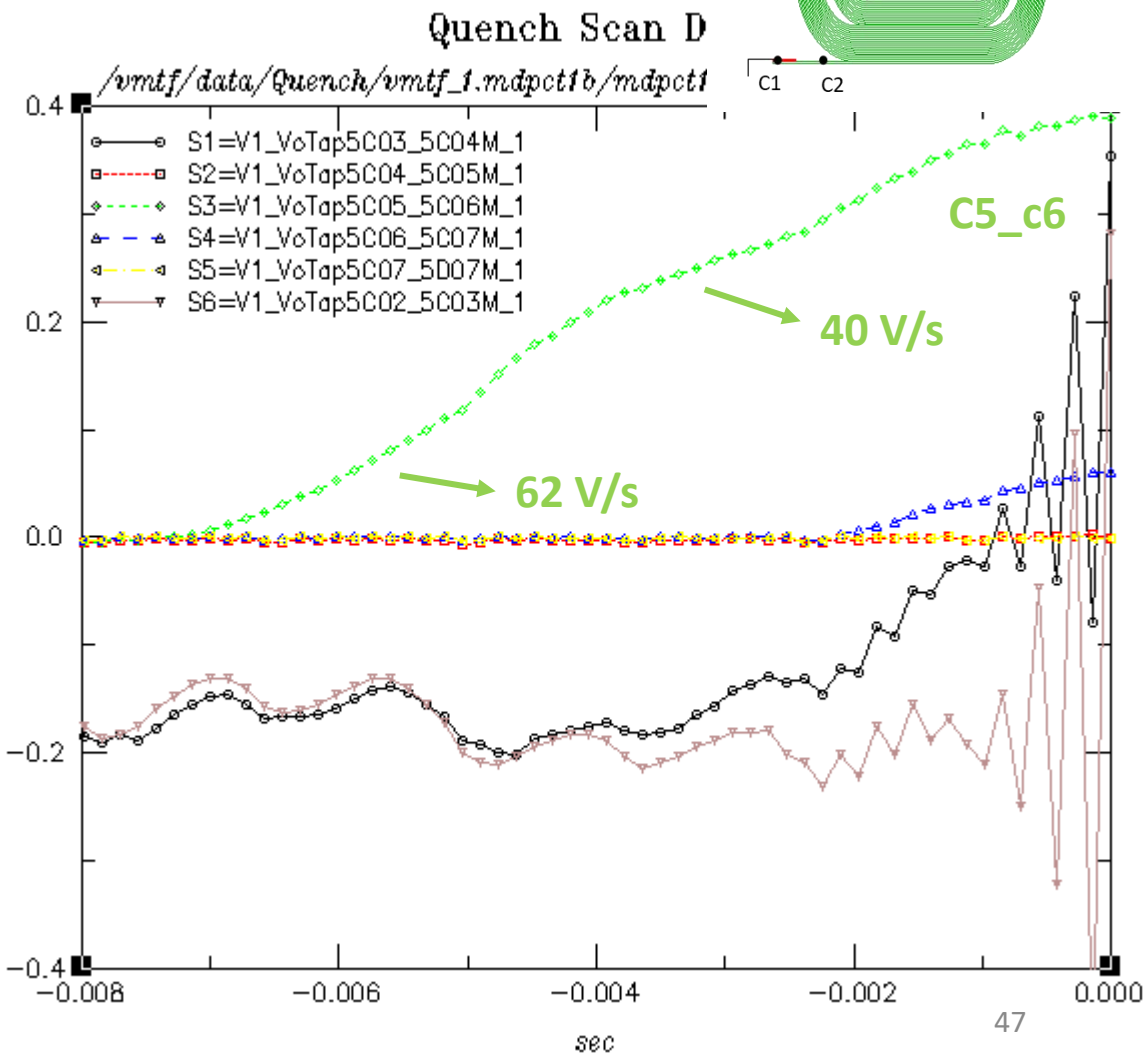


COIL 005



COIL 004





Known

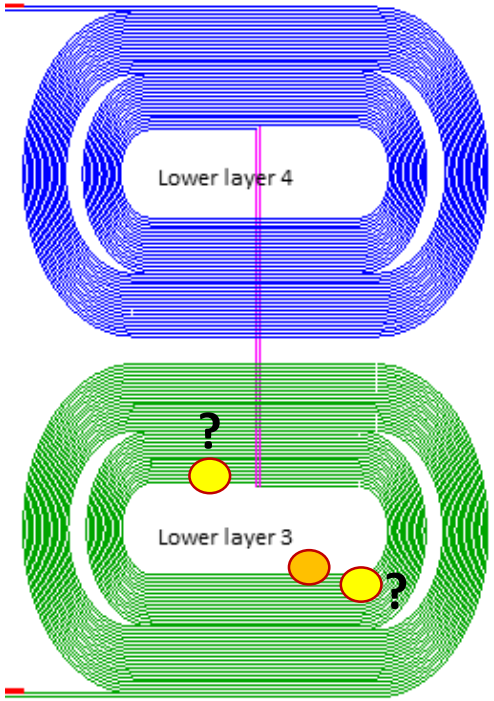
Less known

In this case the quench starts in the “green” segment and it propagates in both directions
(two-directional 62 V/s is consistent also with the one-directional 28 V/s from the previous slide)

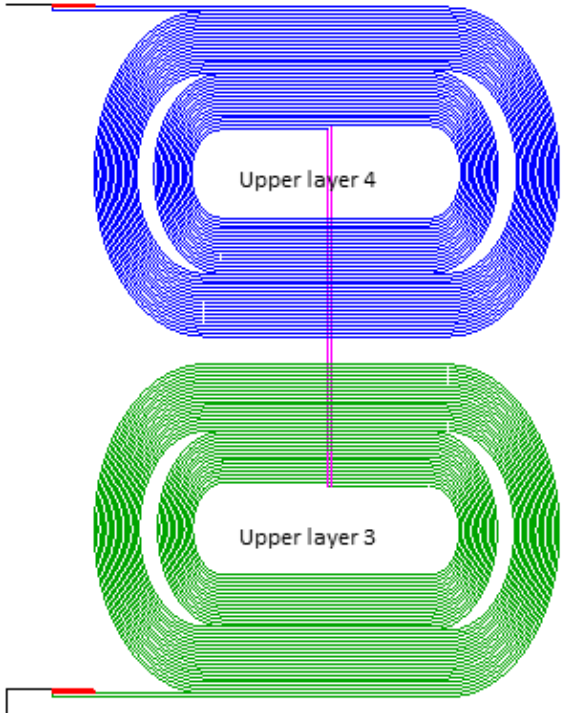
81, 80, 75, 74, 73, 72, 71, 70, 69, 68, 66, 65, 64, 63, 61, 60, 59?, 50, 47, 46,

5; c5_c6, c6_c7, c3_c4

COIL 005



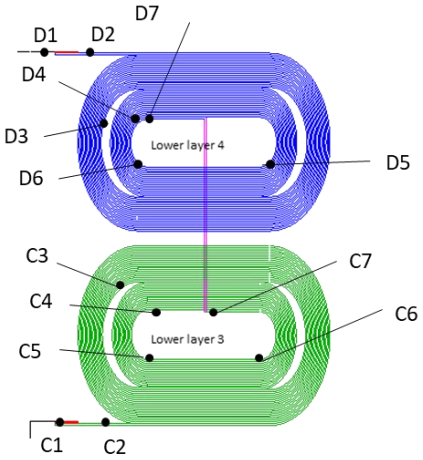
COIL 004

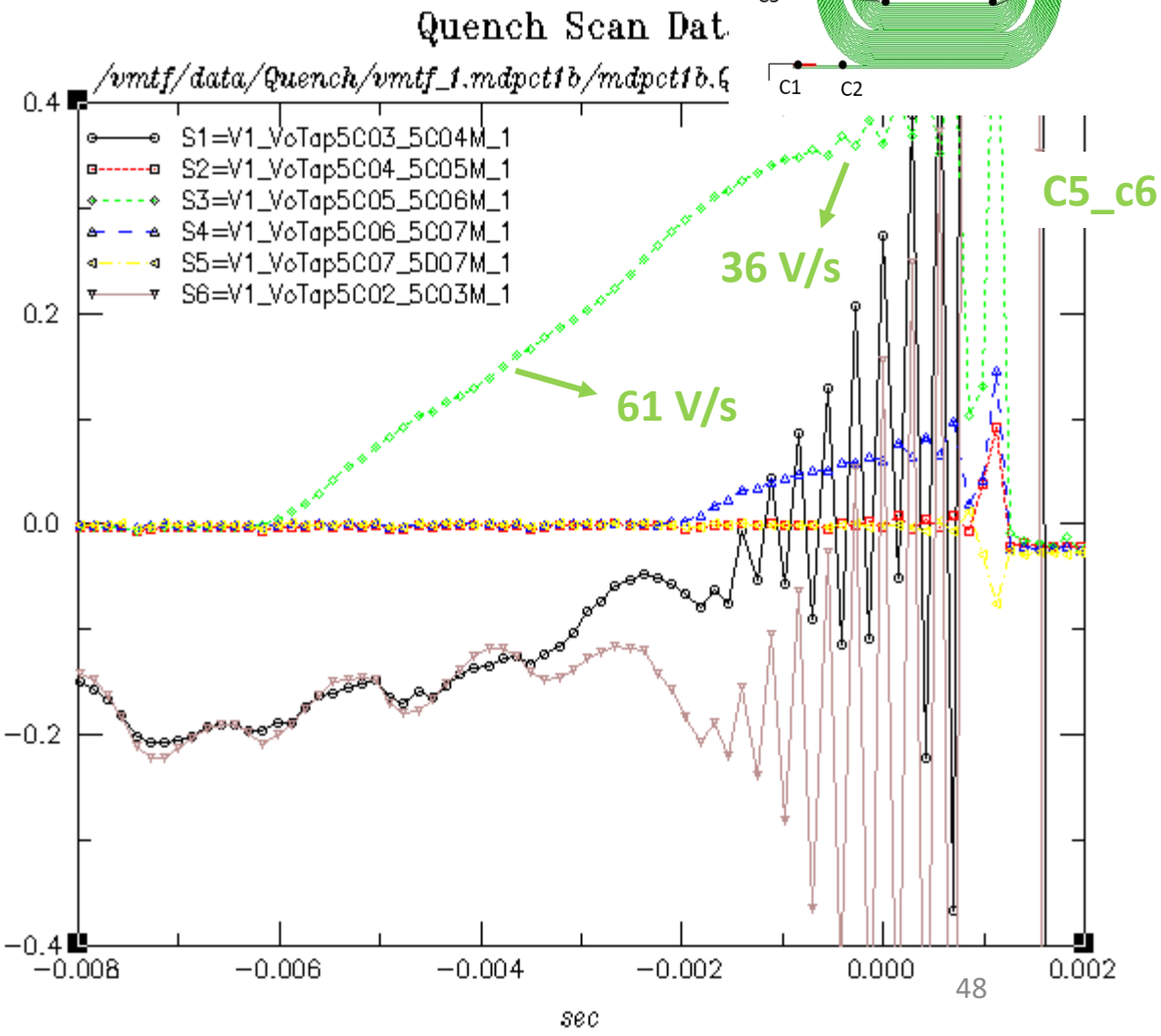


Known

Less known

Ramp 61
(9980 A)





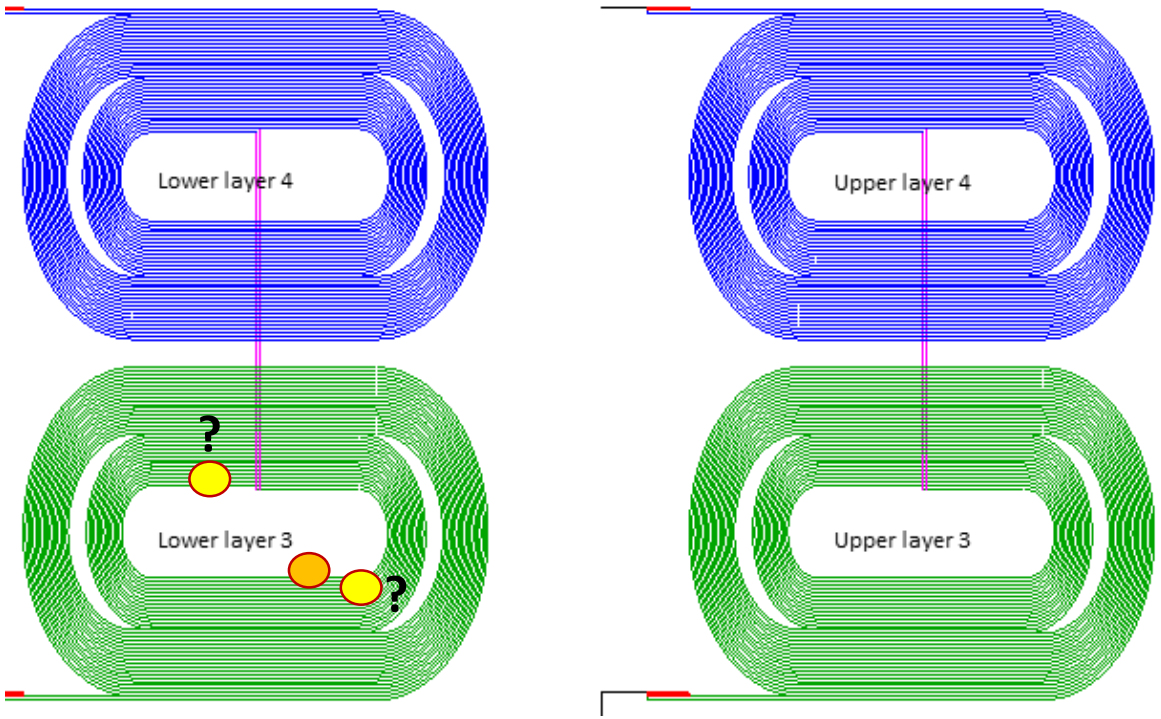
81, 80, 75, 74, 73, 72, 71, 70, 69, 68, 66, 65, 64, 63, 61, 60, 59?, 50, 47, 46,

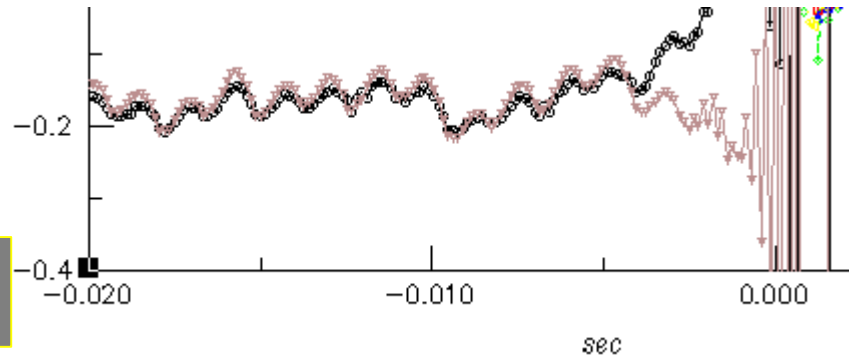
5; c5_c6, c6_c7, c3_c4

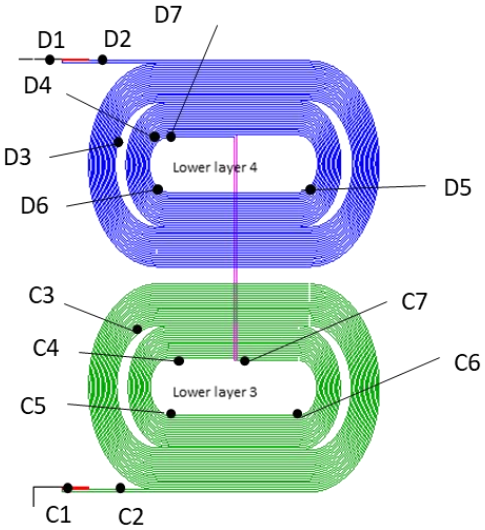
Ramp 63
(9900 A)

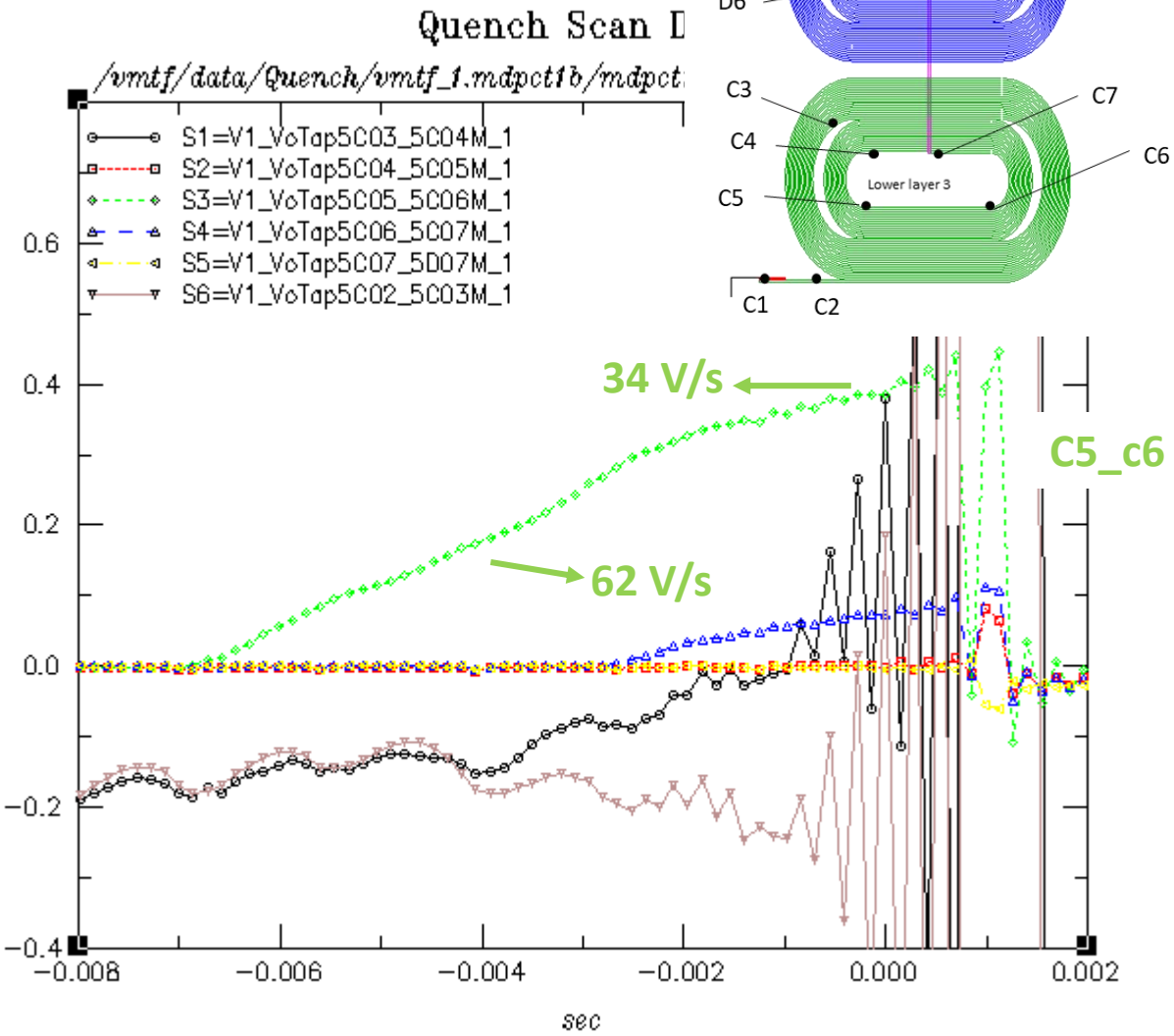
COIL 005

COIL 004









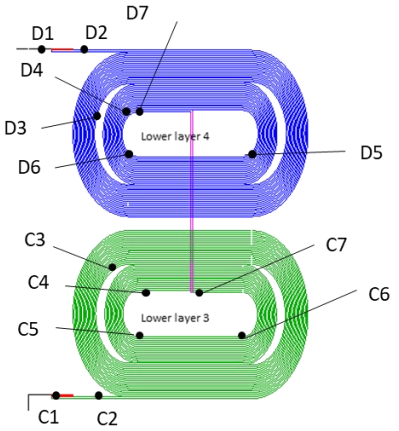
Known

Less known

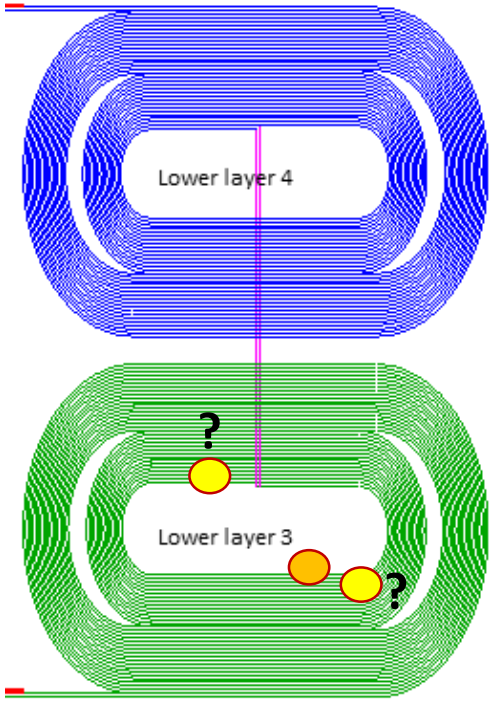
81, 80, 75, 74, 73, 72, 71, 70, 69, 68, 66, 65, 64, 63, 61, 60, 59?, 50, 47, 46,

5; c5_c6, c6_c7, c3_c4

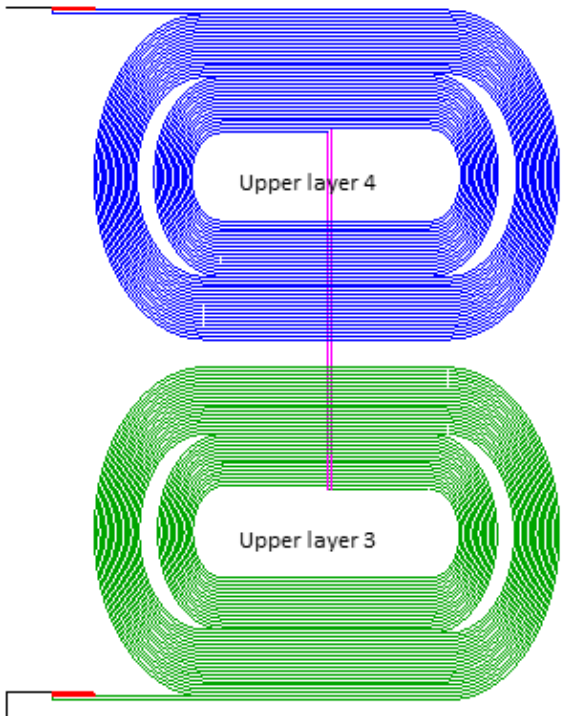
Ramp 75
(9961 A)

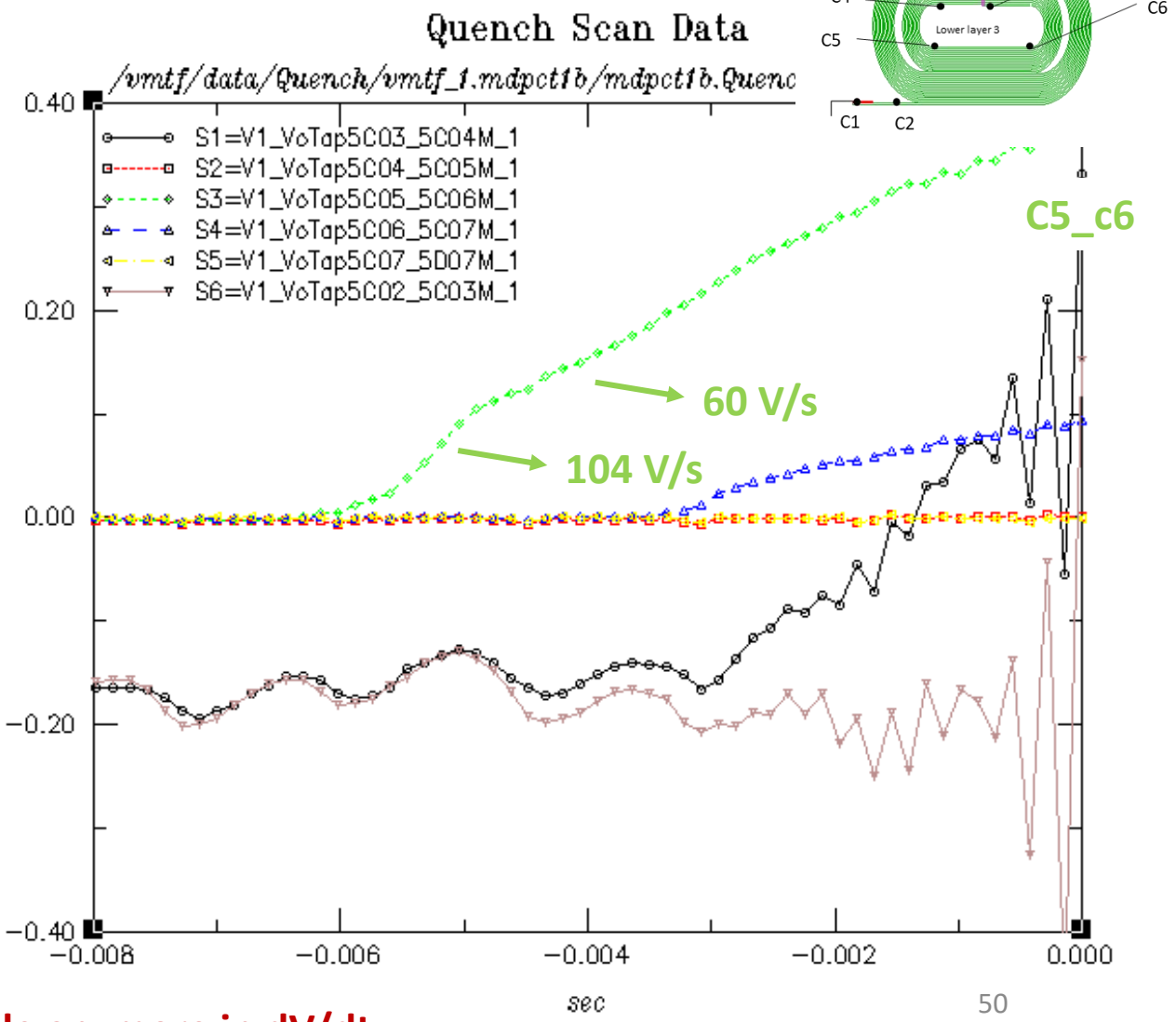


COIL 005



COIL 004





Known

Less known

Faster initial quench propagation in later ramps? Could indicate locally damaged conductor.
Segment boundary not so cleanly visible anymore in dV/dt.

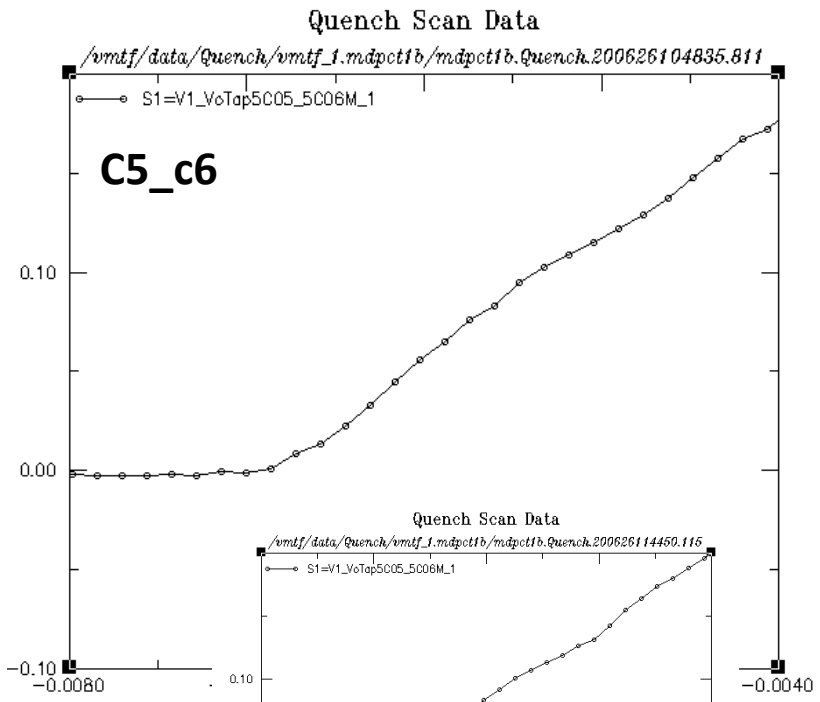
81, 80, 75, 74, 73, 72, 71, 70, 69, 68, 66, 65, 64, 63, 61, 60, 59?, 50, 47, 46,

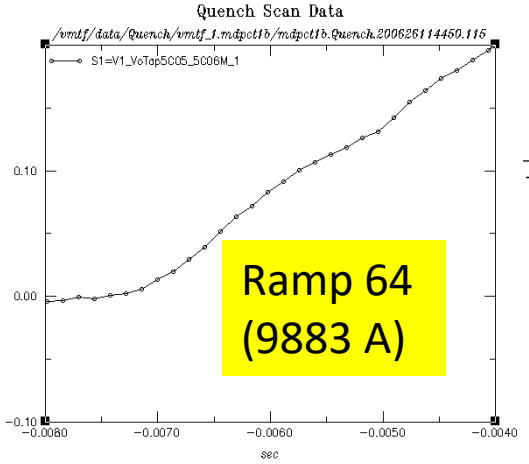
5; c5_c6, c6_c7, c3_c4

Ramp 63
(9900 A)

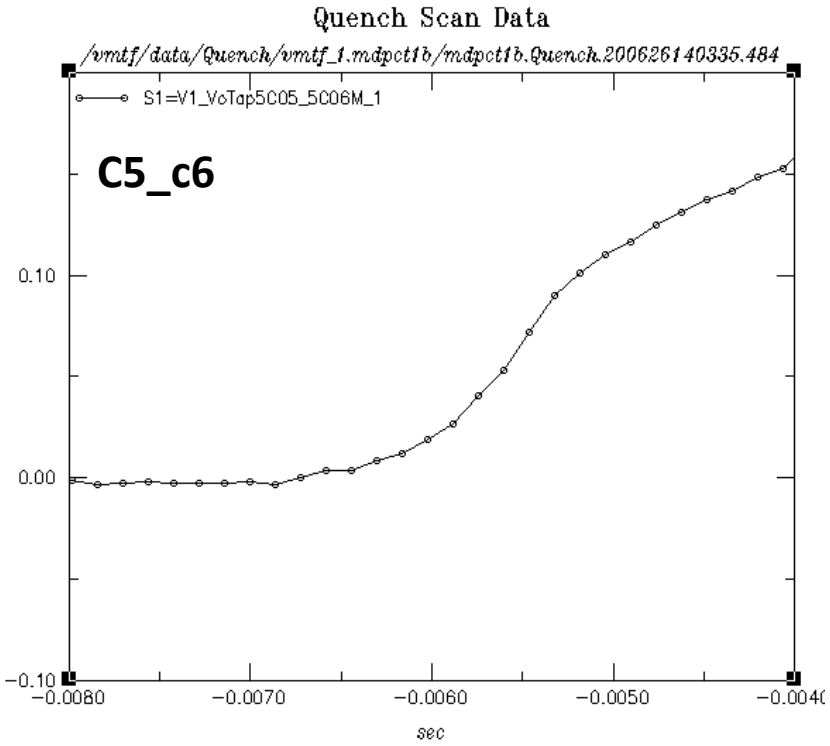
Ramp 66
(9913 A)

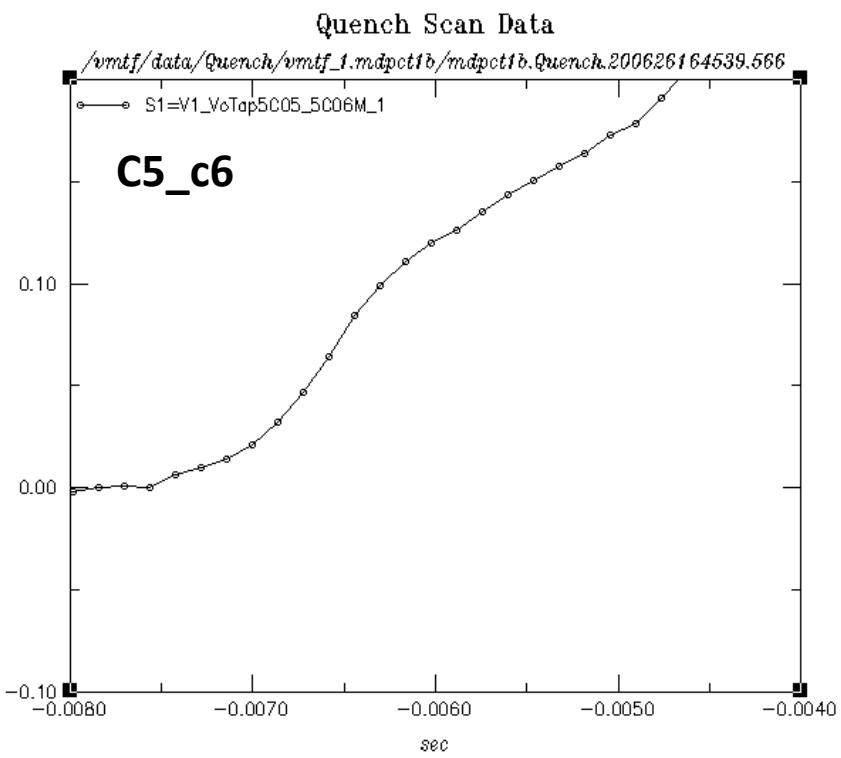
Ramp 68
(9969 A)





Ramp 64
(9883 A)

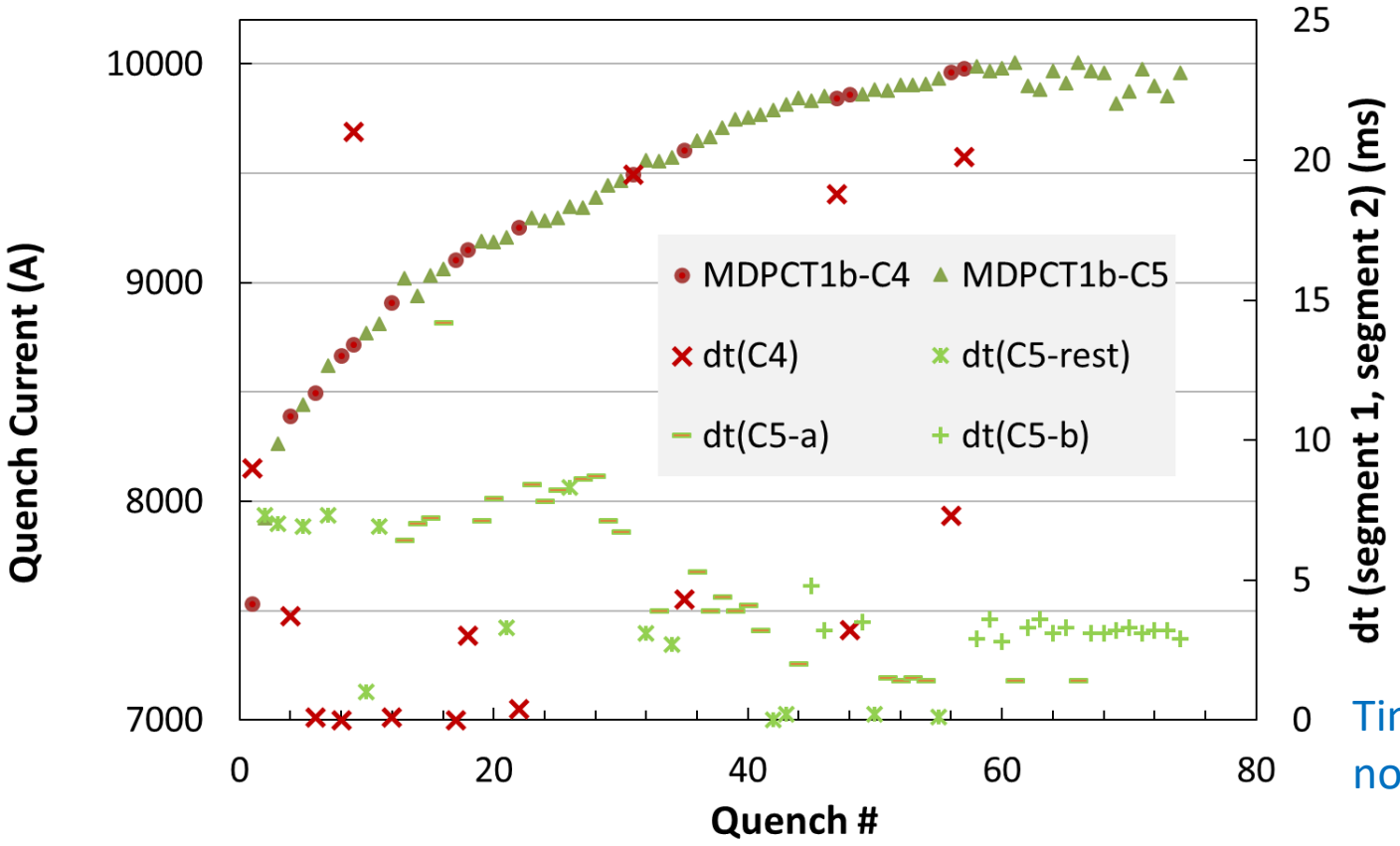




Those are all same scales.

From Ramp 66 on the profile changed,
a non-linear initial expansion is visible.
It suggests much higher quench propagation than in other quenches in the same segment (but different location, see ramp 62 which is also similar to 67).

Time between first two segments quenching



Coil 5 times (on the right vertical axis) are grouped in the main two "patterns" (denoted C5-a and C5-b) with remaining ones under another group (C5-rest).

Time ~0 usually indicates quenches in two non-adjacent segments (often in different layers or coils)

The time difference relates to "patterns" discussed. It is seen however that for one of the main pattern Δt changes significantly (after ~ quench #30). The other main pattern (where the limiting quenches are) shows consistent nearly constant times despite the short non-linear quench/voltage expansion discussed.