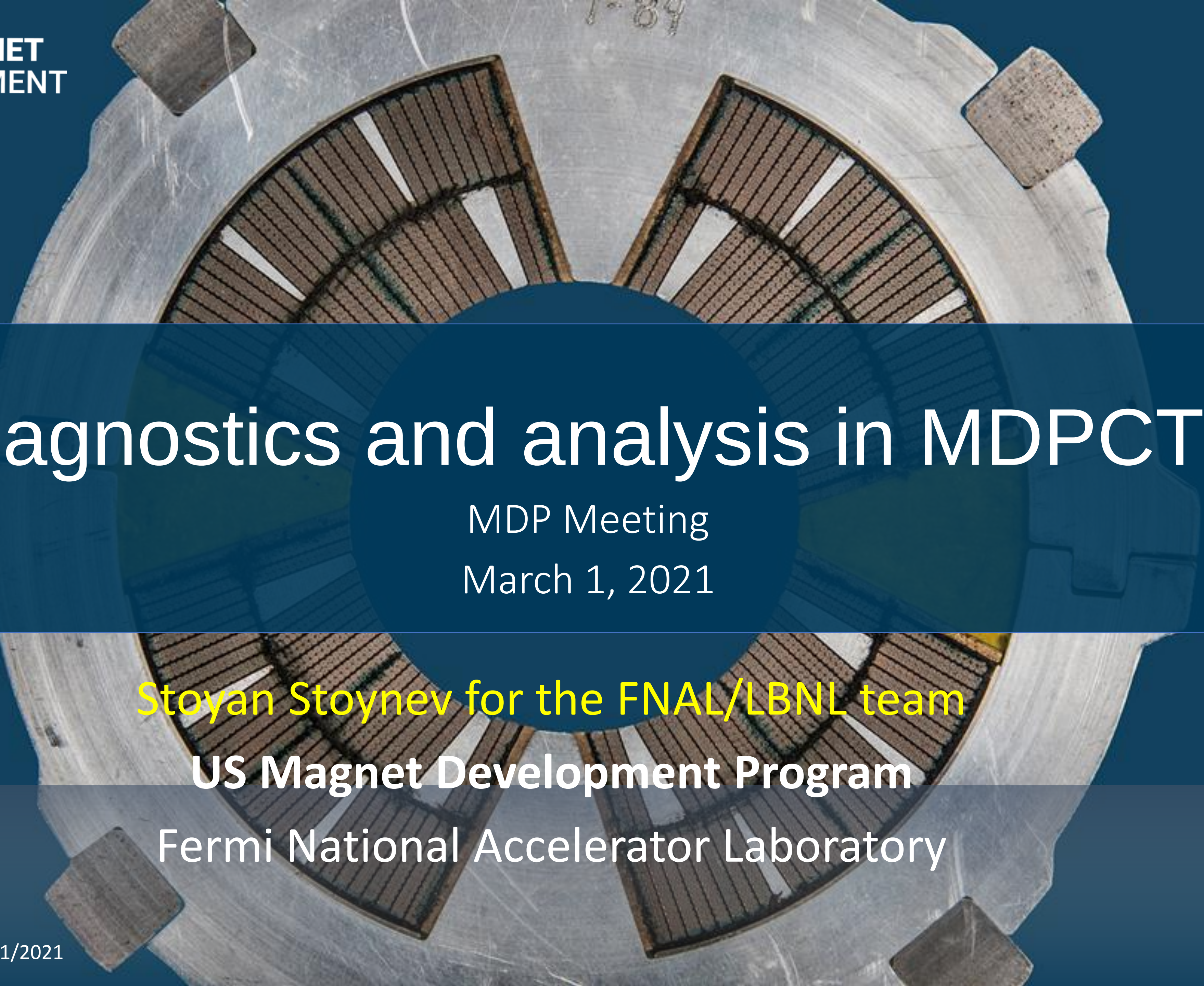

U.S. MAGNET DEVELOPMENT PROGRAM

Diagnostics and analysis in MDPCT1

MDP Meeting

March 1, 2021

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US Magnet Development Program

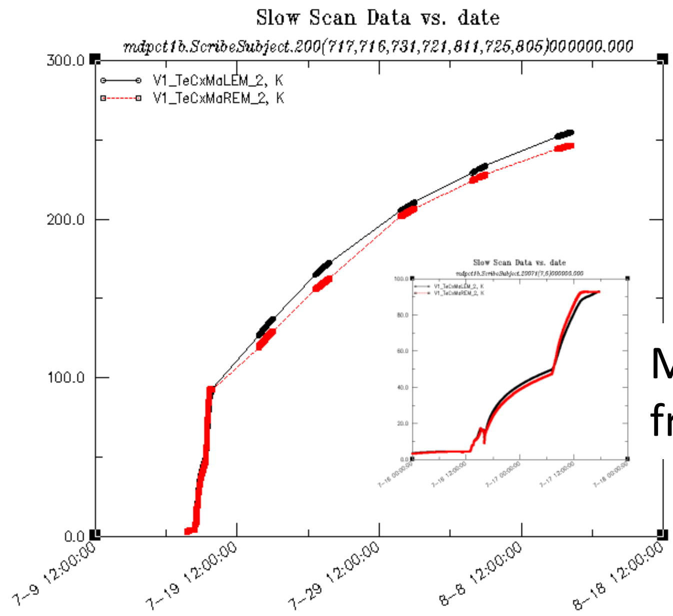
Fermi National Accelerator Laboratory

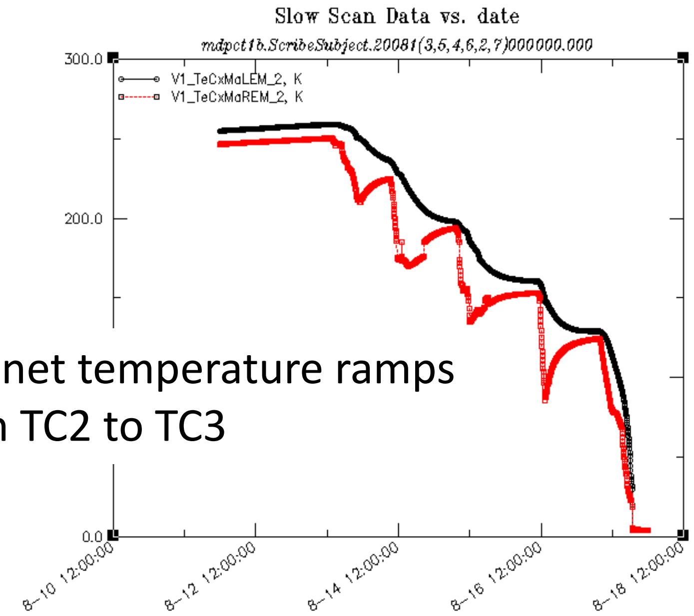
MDPCT1 tests

- ❑ The magnet was first tested in Summer 2019 – TC1
  - ✓ The training was stopped after we crossed a pre-defined quench current limit

- ❑ After some modifications related to end-support (discussed elsewhere) it was retested in Summer 2020

- ❑ MDPCT1 went through two more thermal cycles (TC2 and TC3)
  - ✓ In TC2 the magnet retrained
  - ✓ In TC3 the magnet showed very limited performance





Magnet temperature ramps from TC2 to TC3

MDPCT1 instrumentation

- Voltage taps
- Strain gauges on coils, poles, bullets/rods and shell – strain monitoring during cool down, warm up and quenches to build the full stress picture vs conditions
- Protection heaters – for quench protection of the superconducting magnet
  - ✓ In addition to heaters the magnet is protected by an energy extraction system
- Quench antenna – for independent quench characterization
- Acoustic sensors - for independent quench characterization
- Temperature sensors – outside magnet or bore temperature

“Non-standard” instrumentation and diagnostics

- We deployed two types of **quench antenna** sensitive to the innermost layer transients
  - ✓ There were only two quenches there, both in TC1
  - ✓ Very good data but not much use for the overall quench analysis

- **Acoustic sensors**
  - ✓ Attempted new (“better”) types in MDPCT1, failed to extract good data
  - ✓ Reverted to “old” style in TC2/TC3, most ramps; **very good data**, useful for performance analysis

- **Temperature sensors** in the bore
  - ✓ Interesting data but also not much relevant for quenches in outer layers

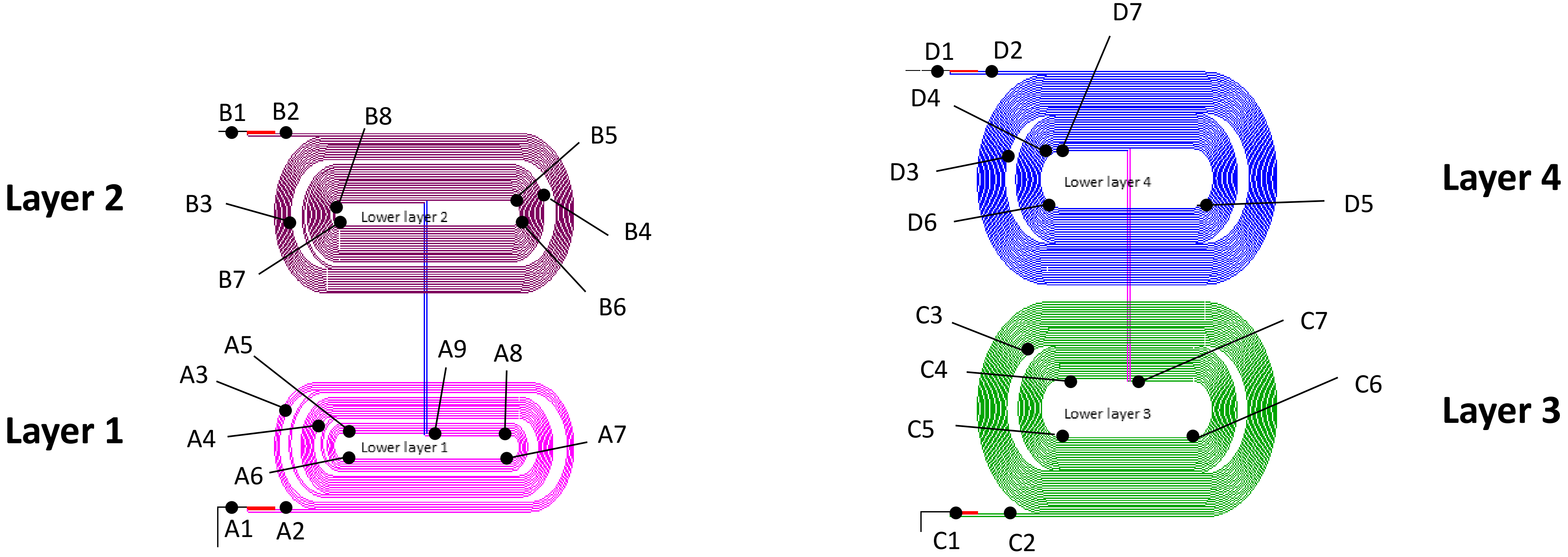
- **Multi-channel nano-voltmeter**
  - ✓ Much upgraded version of our single channel splice measurement system (different electronics)

I will concentrate on the performance of non-standard (not universal at FNAL) techniques and/or ones crucial for analysis.

We did not have resources to analyze “spike data” yet though we took data in many ramps.

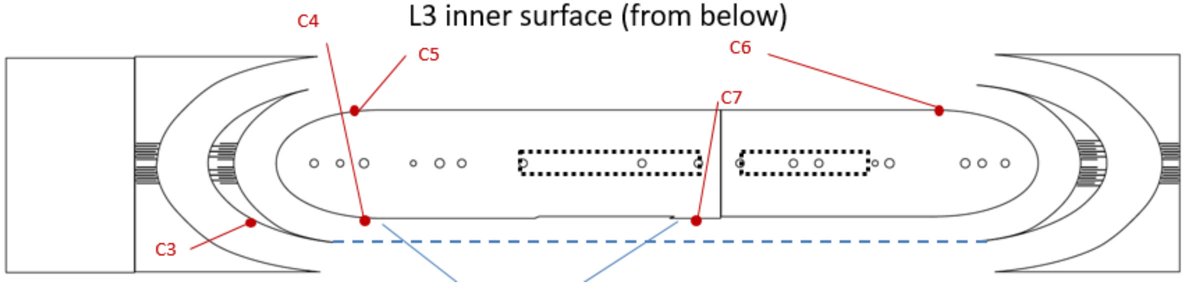
MDPCT1 voltage taps

Coil instrumentation (seen from "above")



At TC1, MDPCT1 lost virtually all its voltage taps in layer 3 and 4 where all but two quenches occurred

L3 inner surface (from below)



Most TC2 quenches (and all in TC3) were in coil 5C

Voltage tap data

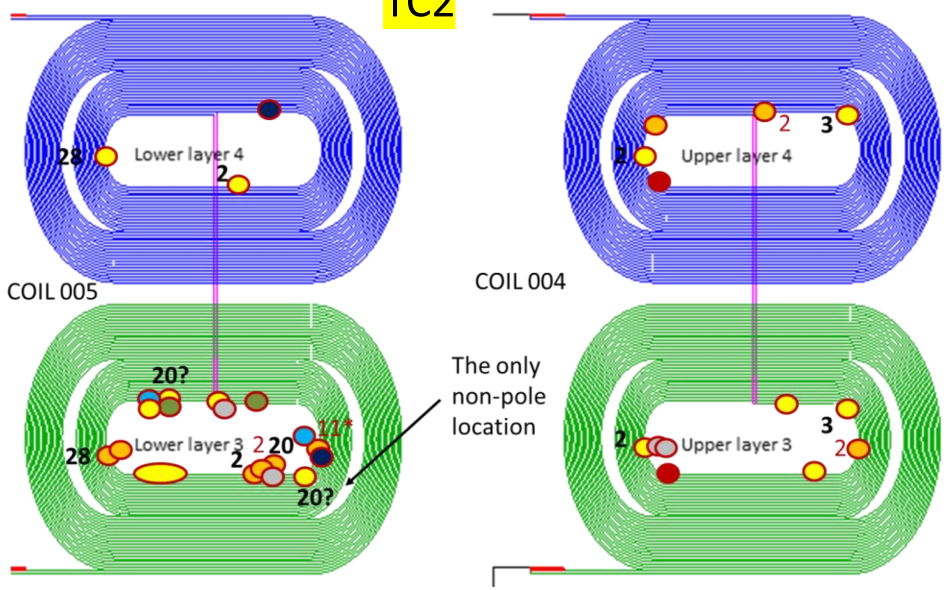
- TC1 - virtually all of layer 3 and 4 VTs lost due to cuts in layer 4 traces
  - ✓ Also lost all strain gauges there
  - ✓ Recovered all but one VT for TC2 and TC3 tests
- Other VTs were continuously fine
- We managed to identify well all quenches in TC2/TC3 tests

TC2 data (segments with voltage rise, ordered)

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 additic

This table shows many quenches had similar patterns

TC2



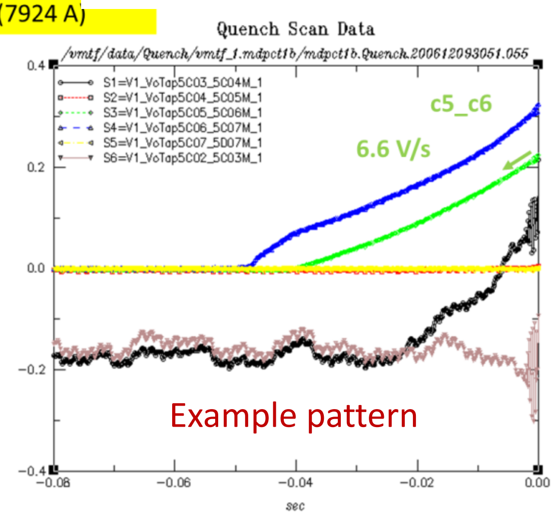
Those colors indicate quenches in different non-adjacent segments (often in different layers/coils)

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

Ramp 2 (7924 A) TC2

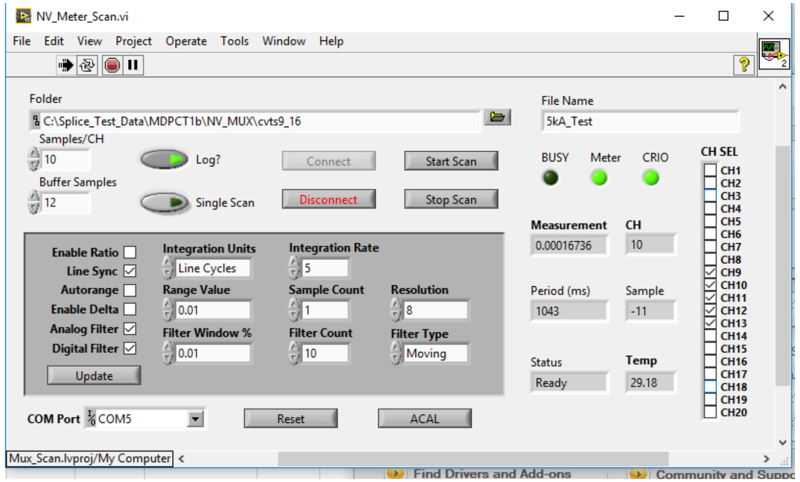


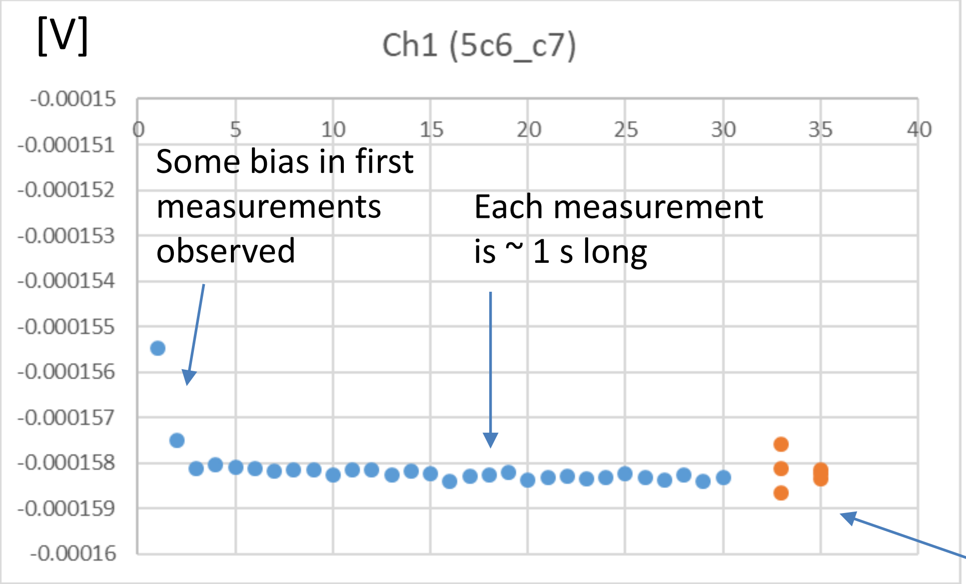
Multi-channel nano-voltmeter (“MUX”)

- ❑ Temporarily in our hands
  - ✓ Not perfectly fitted for our needs
  - ✓ Few channels we couldn’t measure
  - ✓ Some had large noise (long segments)
  - ✓ Partially a “black box”
- ❑ We are developing a dedicated “MUX“

Front and back panels (20 channels)

Configuration panel





All measurements are sequential (no parallel read out)

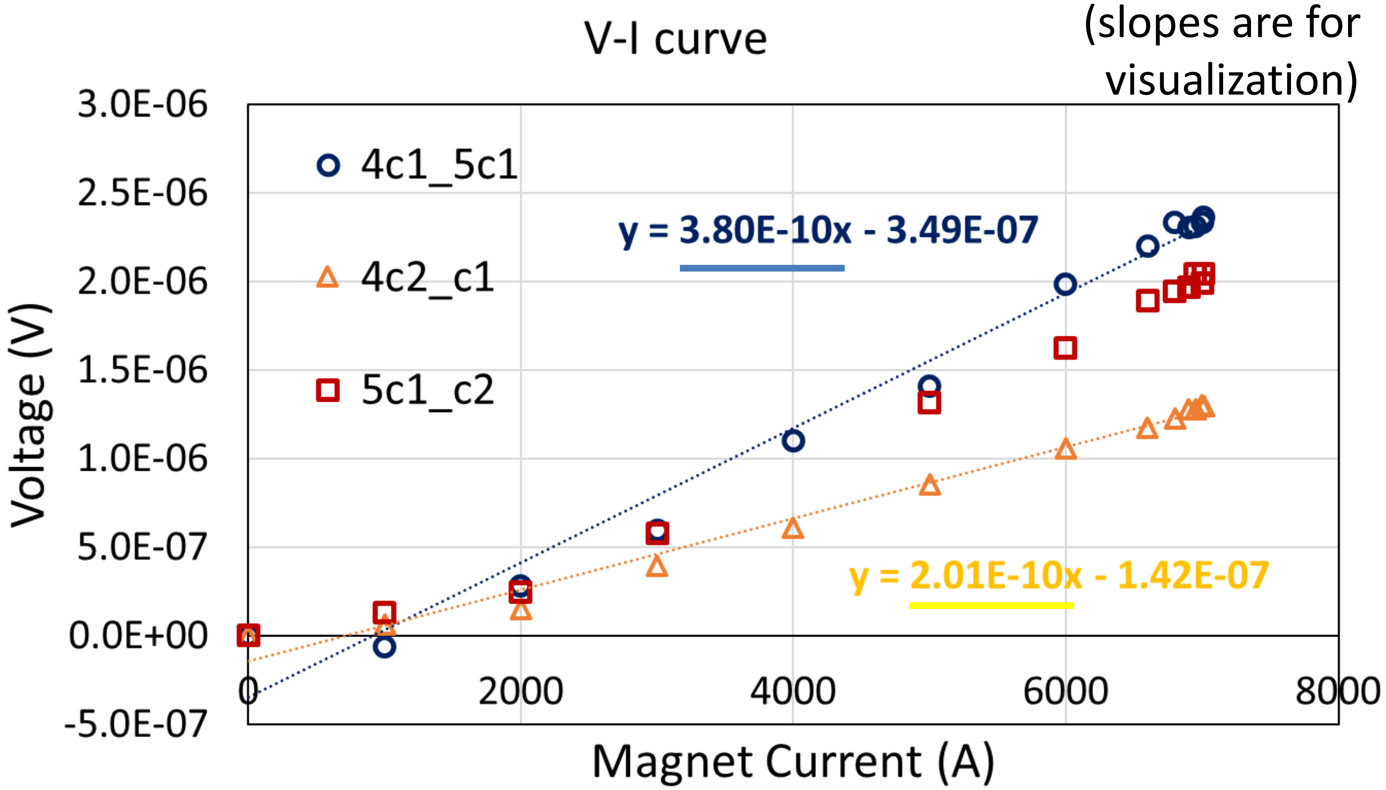
Averages with limits (w   w/o bias)

primarily Tom Cummings (engineer)

Splice resistance measurements with MUX

New DAQ (MUX)!

TC3



Old DAQ

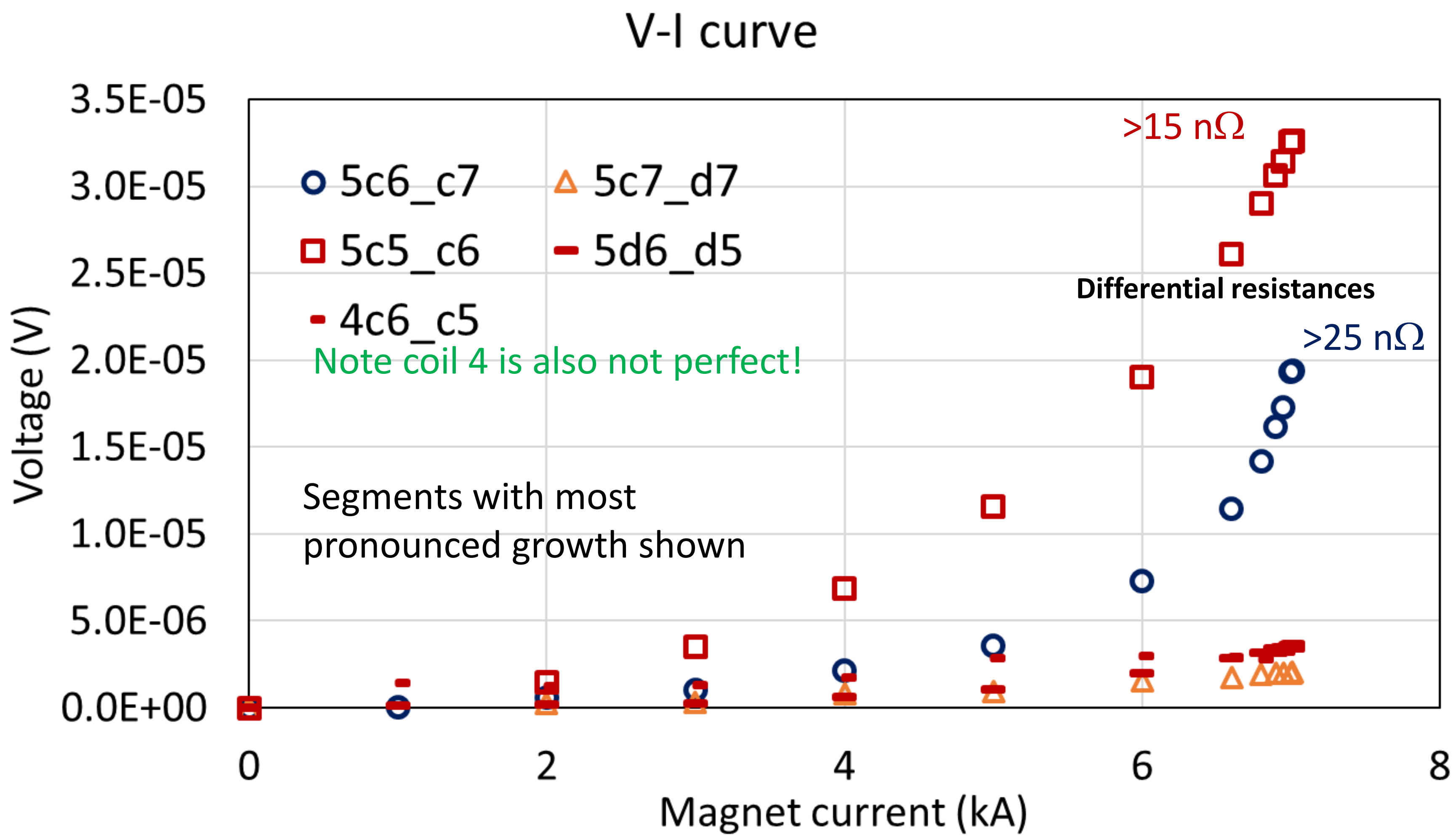
TC1

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.

All splices < 1 nΩ

V-I measurements with MUX (TC3)



… 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.

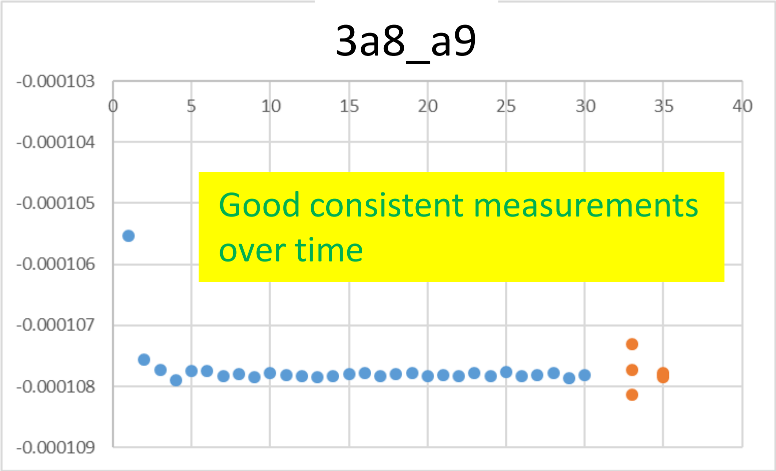
Some other segments are showing similar signs but at much lower level. Most segments don't show this behavior but some we can't measure.

This and other tests showed that quenches happen due to gradual approach to critical surface.

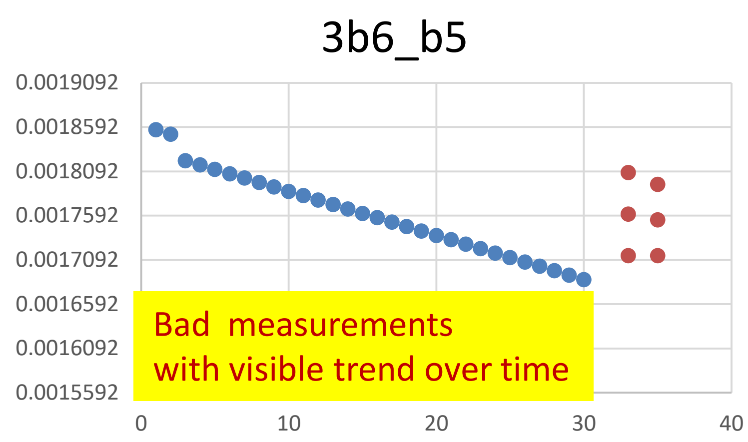
Segments in MUX measurements

There are three types of segment readings we see:

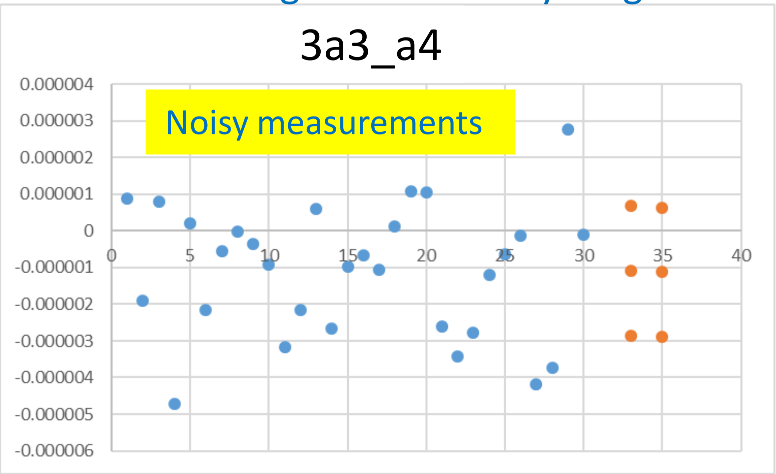
Most of the segments are like that



Non-negligible part is like that, we do not know the reason



Those are in fact “good”, it is just that some segments are very long and thus noisy



Differential resistances (2 kA to 6.8 kA) seen, some “bad” measurements omitted:

	3b2_b1	3a8_a9	3a3_a4	3a5_a6	3a7_a8	3a9_b8	2a5_a4	garbage	2a2_a1	3a1_a2	2a8_a7	2b5_b6	2b7_b8	2a9_a8	2a7_a6
R(Ohm)	4.6844E-10	2.11756E-11	5.6548E-11	3.95752E-09	8.04315E-12	-7.411E-12	-1.10342E-11	1.43998E-07	5.3581E-10	3.5946E-10	4.7827E-11	4.6585E-11	-2.225E-12	1.2455E-11	-4.149E-11
err(Ohm)	6.0078E-12	1.08428E-11	4.68E-10	7.08039E-09	6.45922E-12	7.8616E-12	1.46786E-10	2.29114E-09	2.1663E-11	6.5192E-12	3.4921E-11	5.4112E-11	8.3124E-12	1.0306E-11	2.9946E-11

	5d1_2b1	5d4_d3	5d2_d1	2b1_b2	2b3_b4	4d6_d7	4d1_d2	4d3_d4	4d5_d6	4d7_c7
R(Ohm)	6.24479E-10	1.5079E-08	9.94219E-10	1.264E-10	4.58333E-11	-4.16168E-10	8.0191E-10	3.3381E-10	3.62641E-10	5.6793E-10
err(Ohm)	9.17173E-11	6.17918E-09	1.02358E-11	1.1103E-10	5.8363E-11	5.05593E-11	8.77E-12	7.27141E-10	8.29624E-12	1.2022E-11

	5c6_c7	5c3_c4	5c5_c6	5c7_d7	5d6_d5	4c1_5c1	4c6_c5	4c4_c3	4c2_c1	5c1_c2
R(Ohm)	2.82422E-09	-2.67411E-11	5.74708E-09	3.431E-10	6.1604E-10	4.283E-10	3.1885E-10	1.968E-10	2.2414E-10	3.535E-10
err(Ohm)	2.4848E-11	1.04173E-09	2.96407E-11	1.2418E-11	9.7945E-12	5.1613E-12	2.9243E-11	7.3568E-10	6.1179E-12	7.0493E-12

Red/brown – bad/not reliable

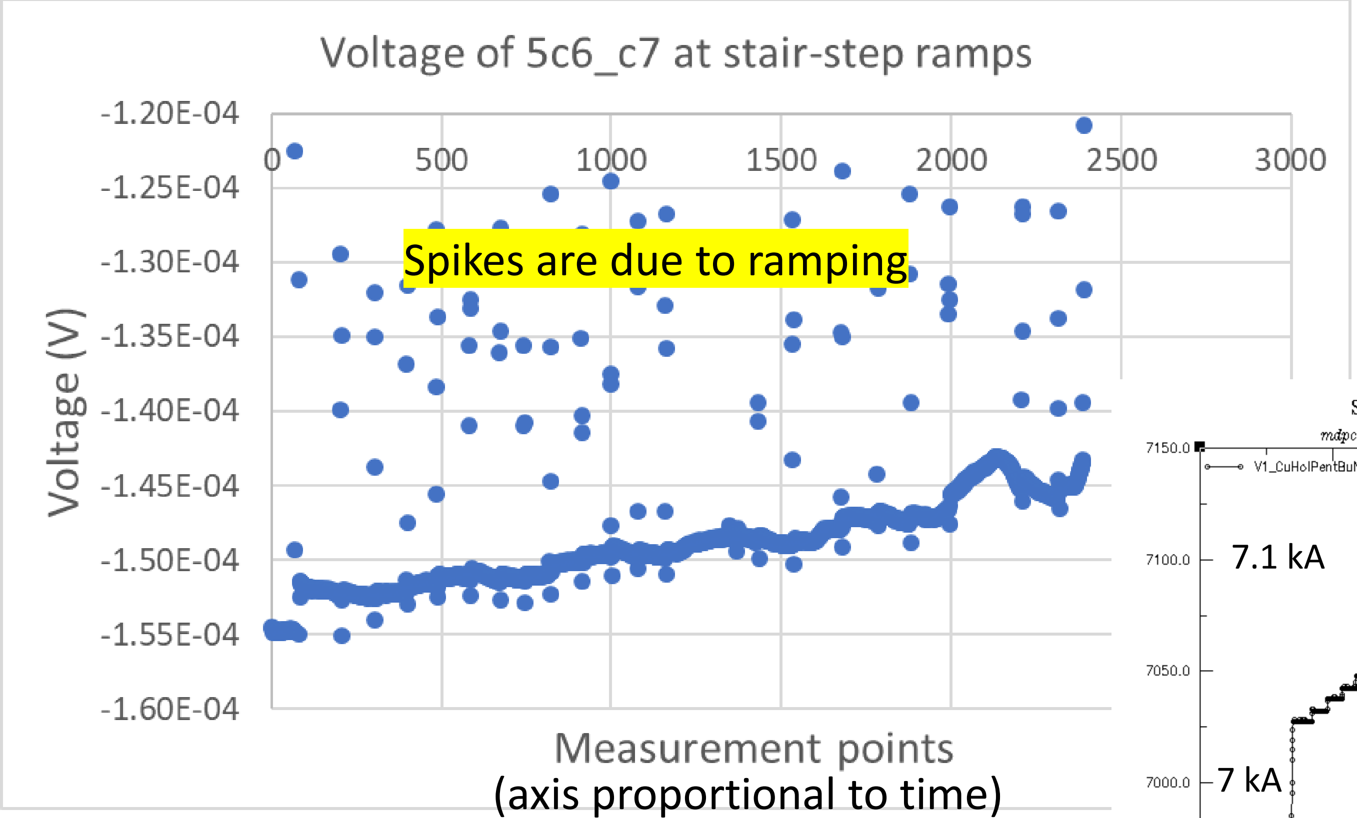
Purple – inconsistent (only one)

Green - splices

Blue – clear resistance developed

Voltage rise and behavior before quench (TC3)

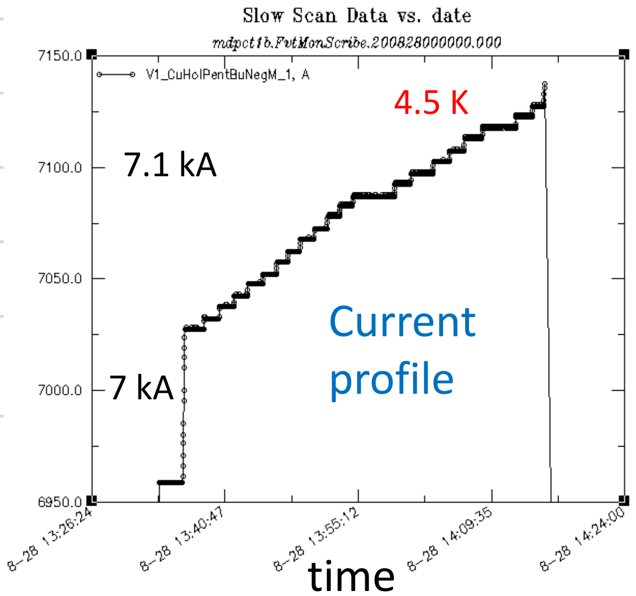
MUX as a single channel



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 (higher quench level at lower ramp rate).

No particular "event" causes those quenches

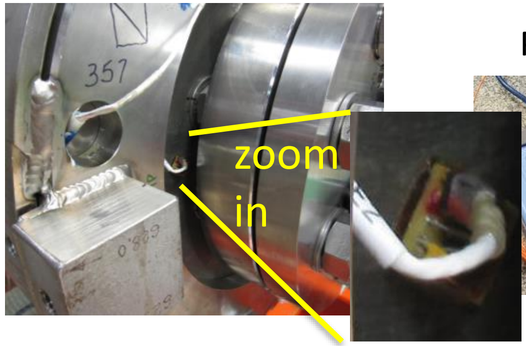
Acoustics

- In TC1 we failed to extract good data from "new" style sensors
  - ✓ We can't read anything above large noise
- In TC2/TC3 we read two sensors on both ends (plates) with 0.5-1 MHz
  - ✓ we had back up ones too – ultimately, three out of four worked all the time
- We find the old style more reliable
  - ✓ Screw instead of glue for surface attachment
  - ✓ Single polarity power supply
  - ✓ More sturdy (easier to handle)

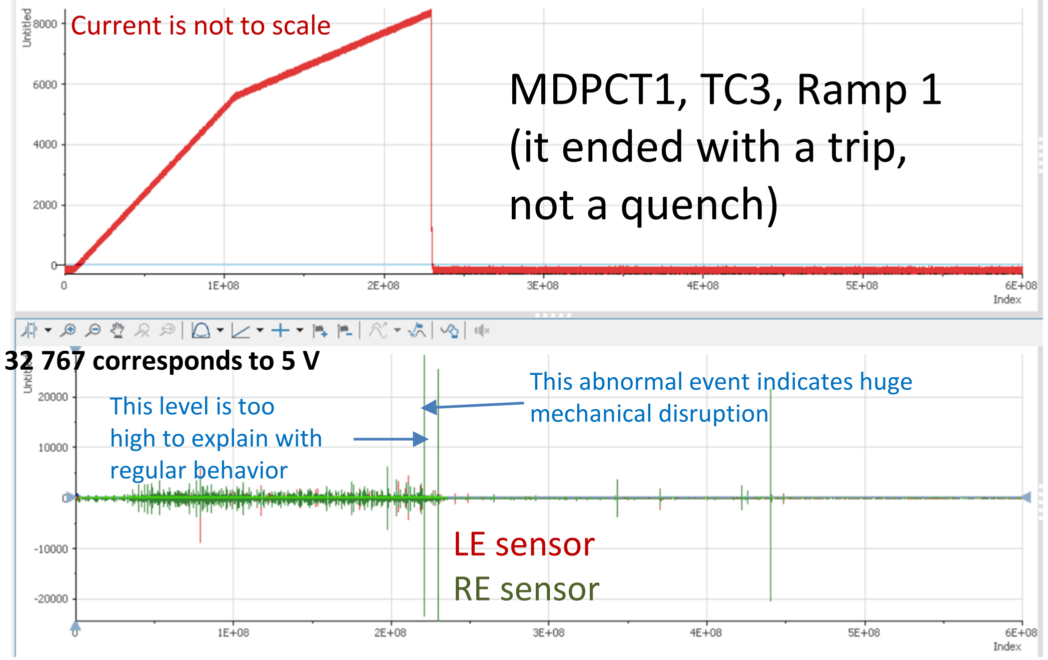
Acoustics was used to identify abnormal "events"

"new style"

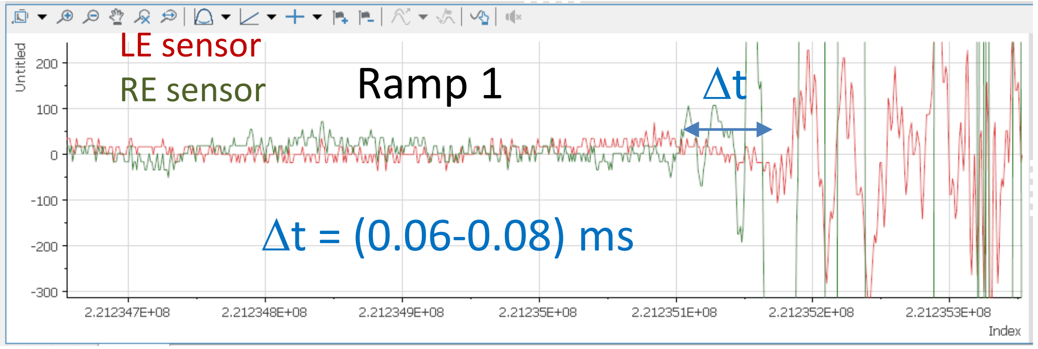
"old style"

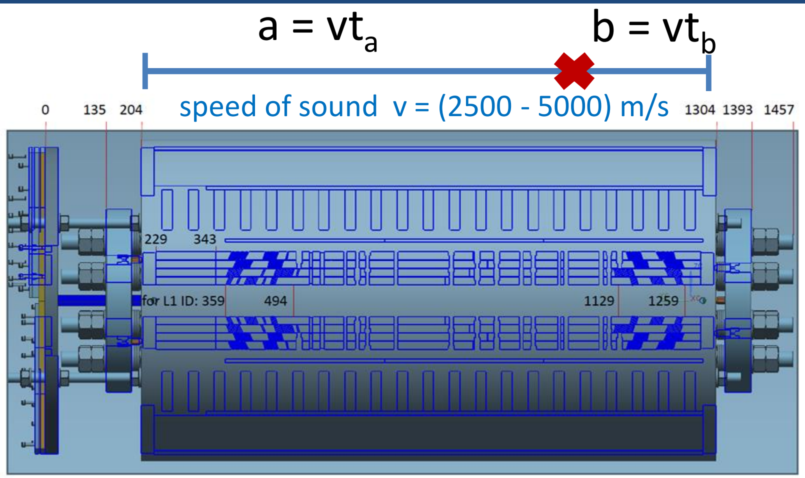


Pico-scope



Acoustics – MDPCT1, TC3



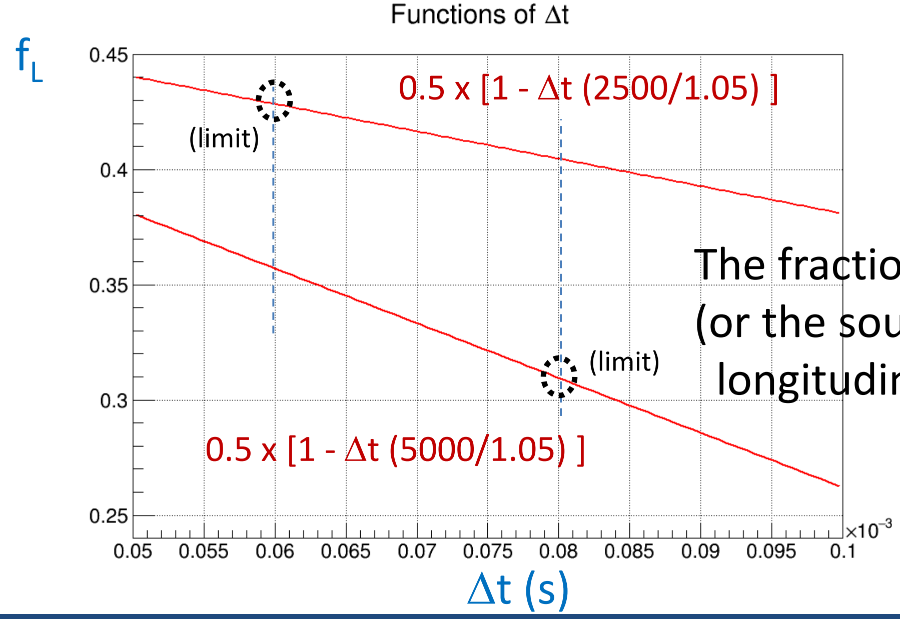


$L \equiv a + b$

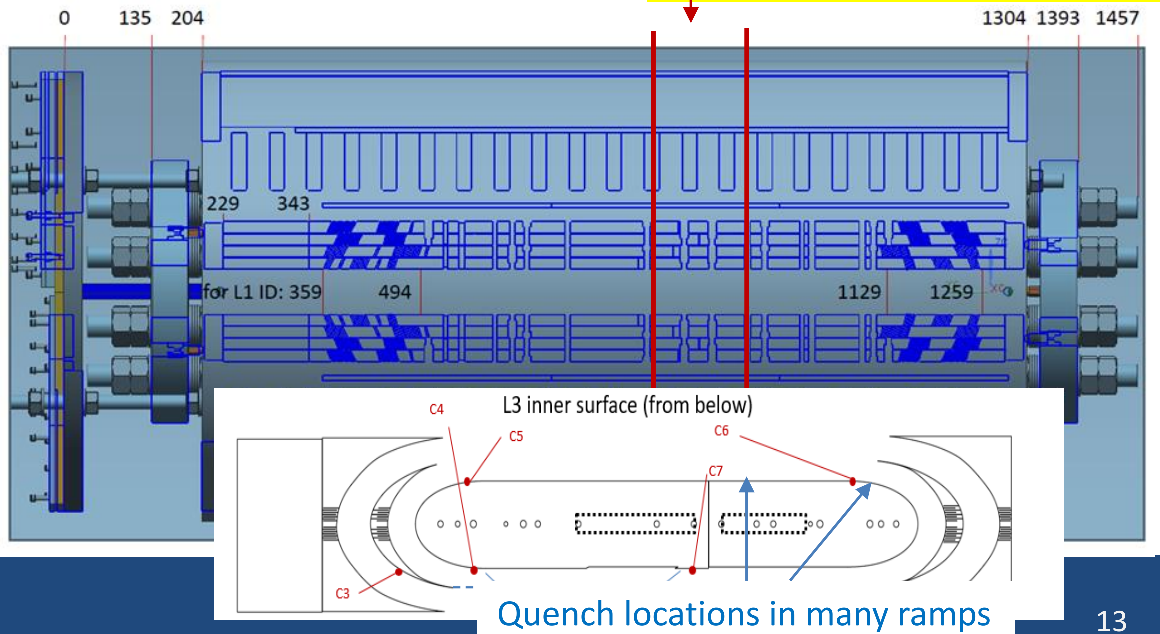
$t_b - t_b \equiv \Delta t = (b-a)/v$

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

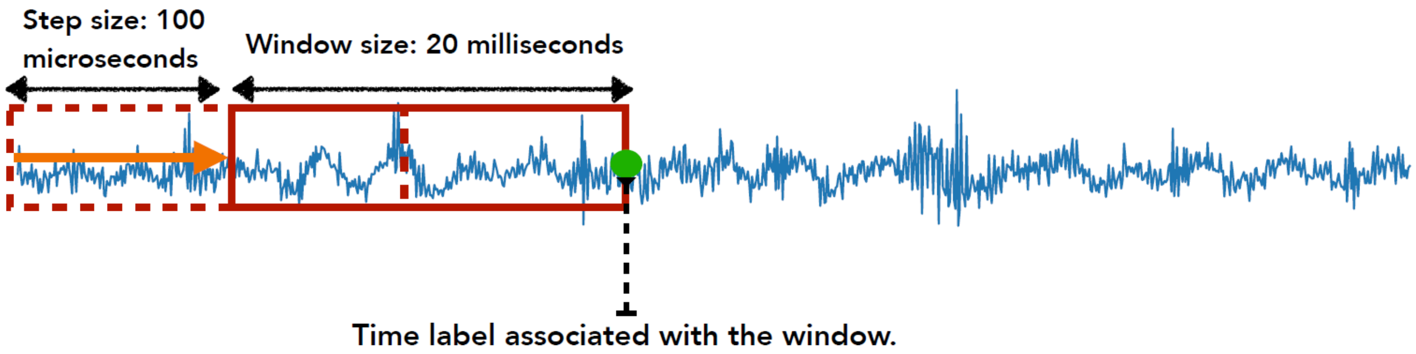
Likely acoustic signal
source zone (in ramp 1)



The fraction f_L = 0.32-0.43 (or the source is 34-45 cm longitudinally from the RE sensor)

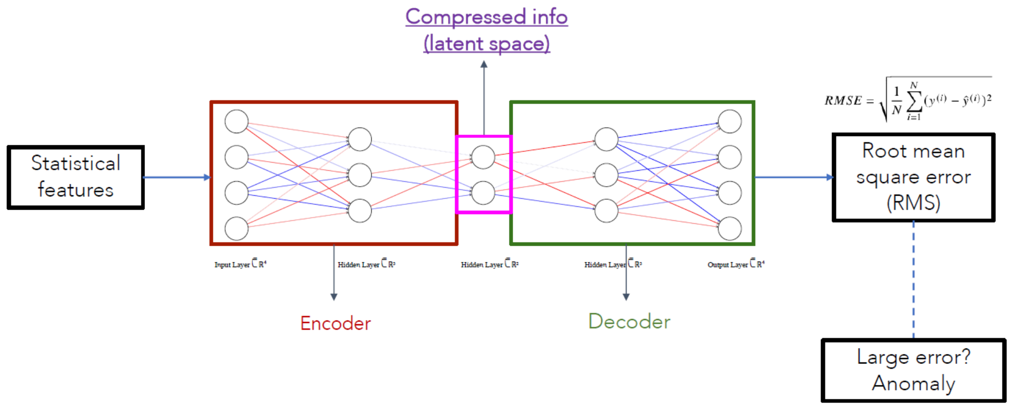


Machine learning with acoustics



In each window, calculate 2 features: standard deviation, and mean of the amplitude.
*Also features are **multiplied** across sensors to look for "coherent" spikes.*

Auto-encoder DNN (Recipe)



Scaling inputs

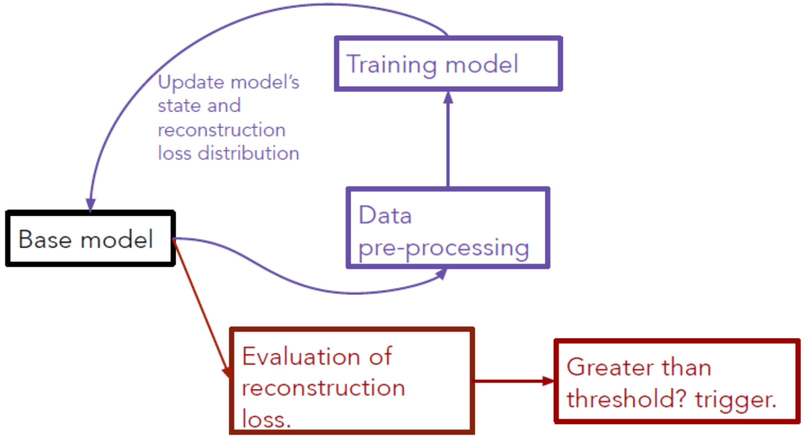
After calculations, every inputs are scaled to between (0,1) so that they can be treated equally in the algorithm when training the model.

$$x_{scaled} = \frac{x - x_{min}}{x_{max} - x_{min}}$$

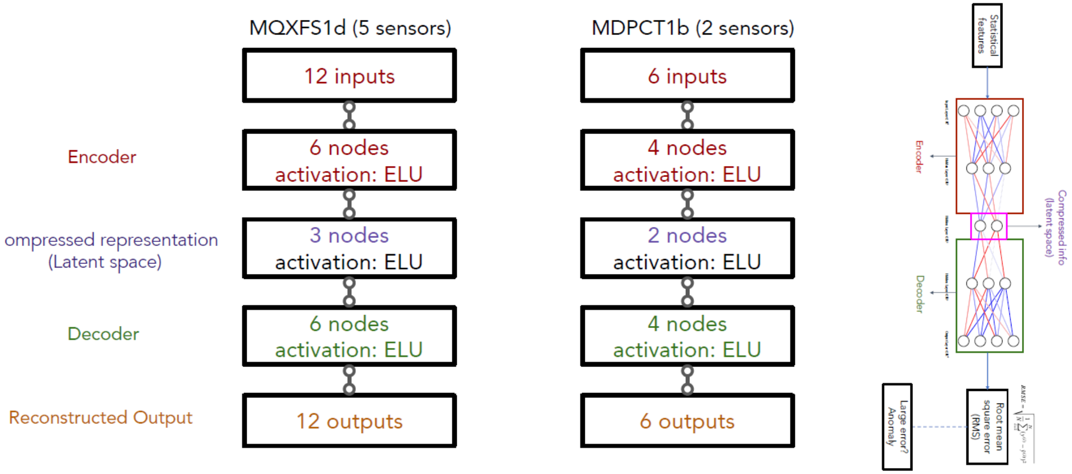
Use the same scaling factors when making predictions.

Dynamic learning

For each 10-second section (could be changed)



Network architecture



Anomalous events visualization

Anomalous event visualization

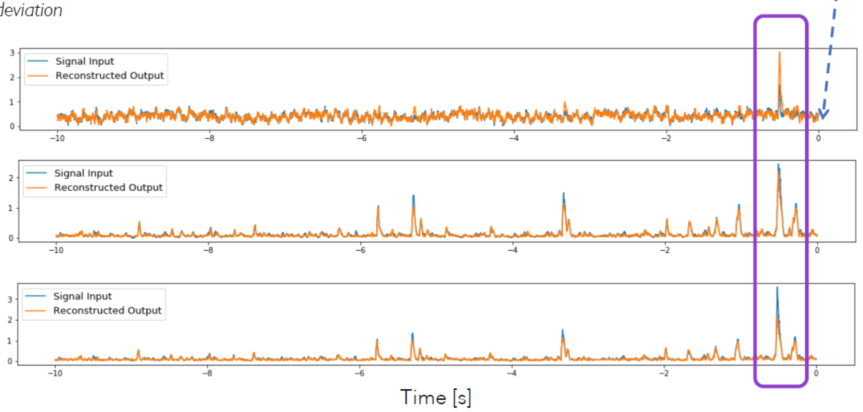
0 is quench detection time

SD = Standard deviation

SD–1

SD–2

SD–1*2



Anomalous event visualization – 2

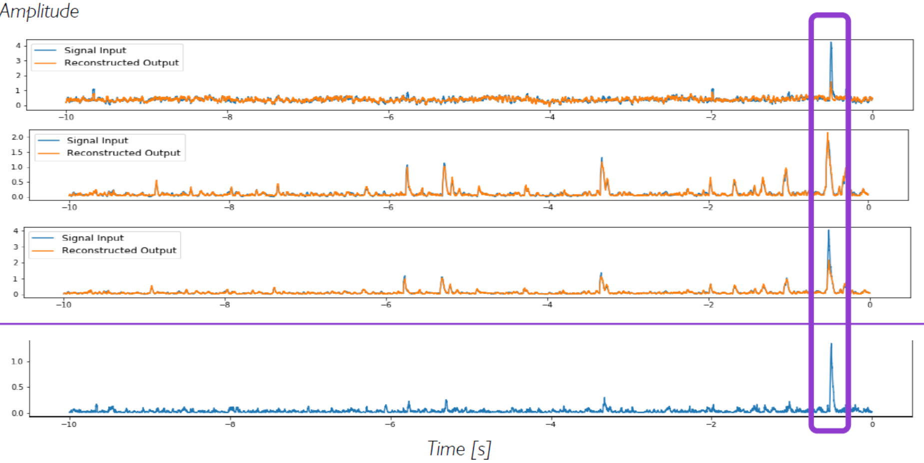
MA = Mean Amplitude

MA–I

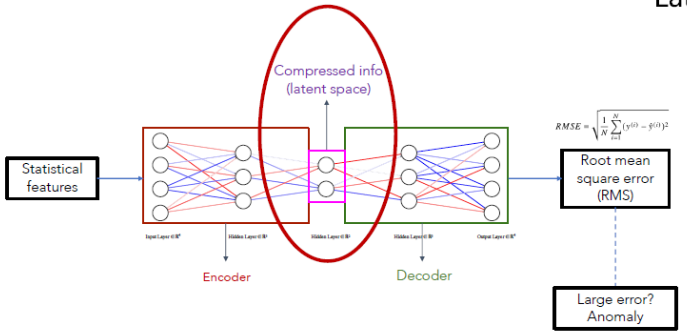
MA–2

*MA–I *2*

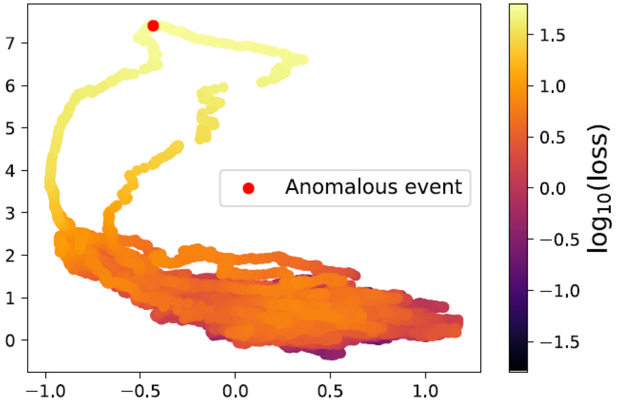
Reconstruction Loss



Visualize latent space



Latent space of an anomalous event in MDPCT1b data

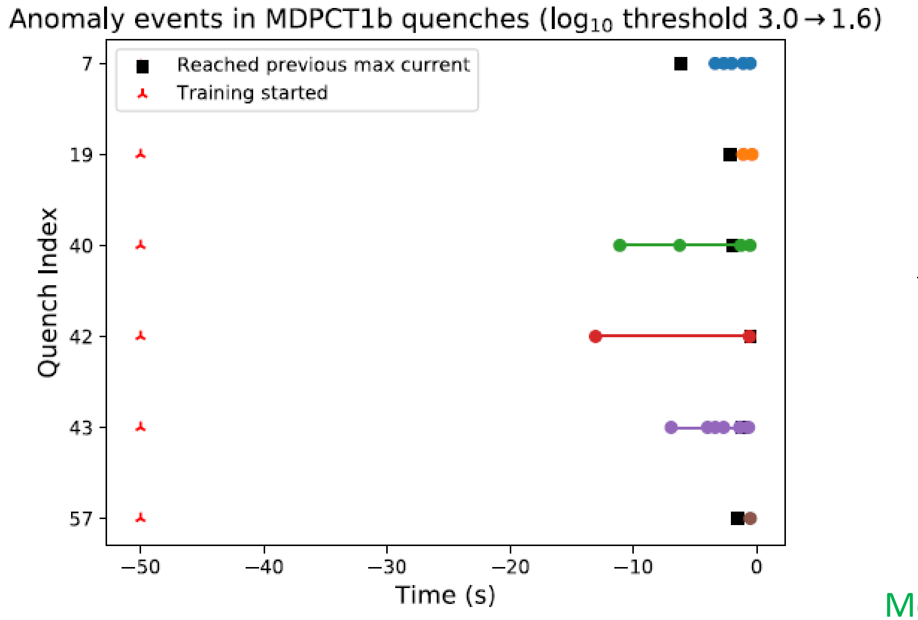


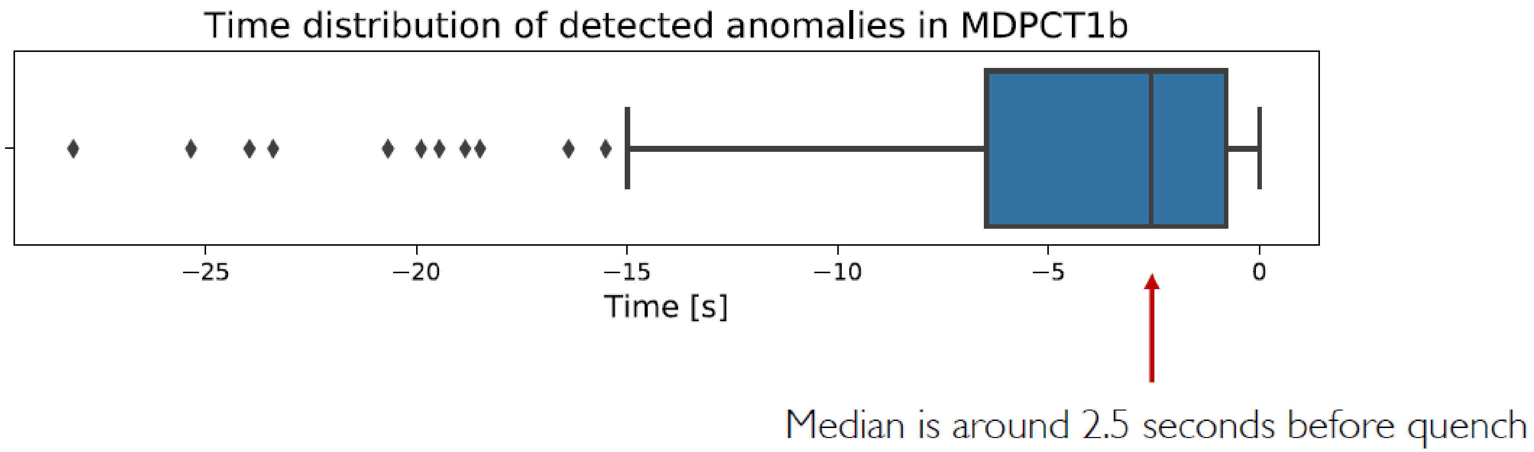
The “loss” is proportional to the RMS estimator

MDPCT1

Anomalies time distribution in MDPCT1b (2 sensors)

- Nearly all the detected events fall within 15 seconds.

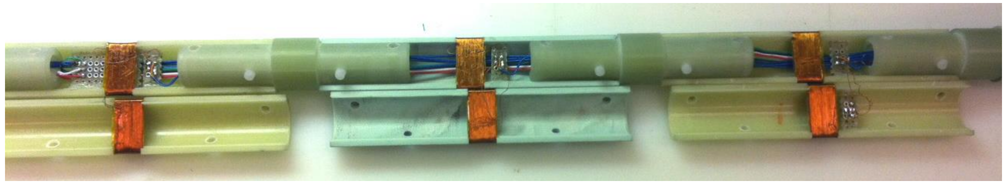




More in (https://ieeexplore.ieee.org/document/9354037) :
Intelliquench: an adaptive machine learning system for detection of superconducting magnet quenches

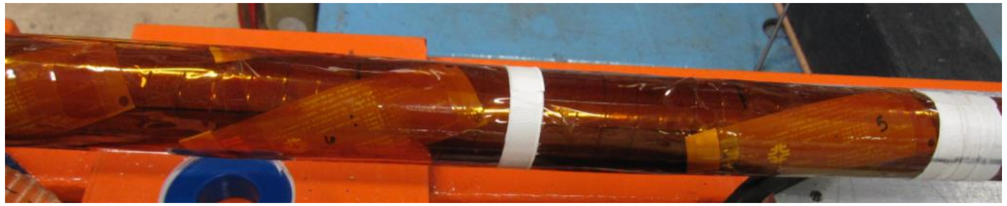
primarily Duc Hoang (2020 summer student)

Quench antenna



warm

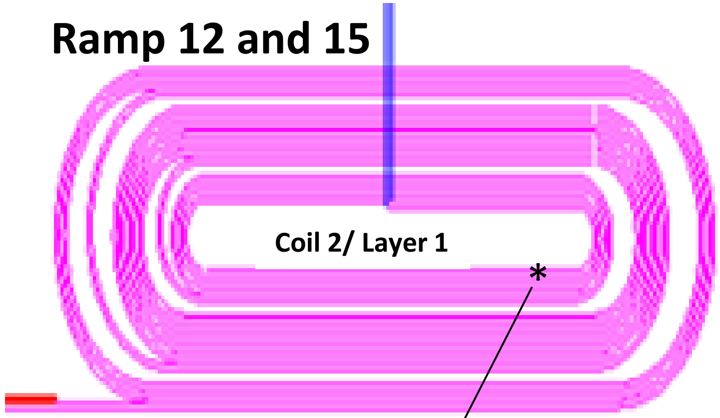
LBNL: seven axially placed elements



cold

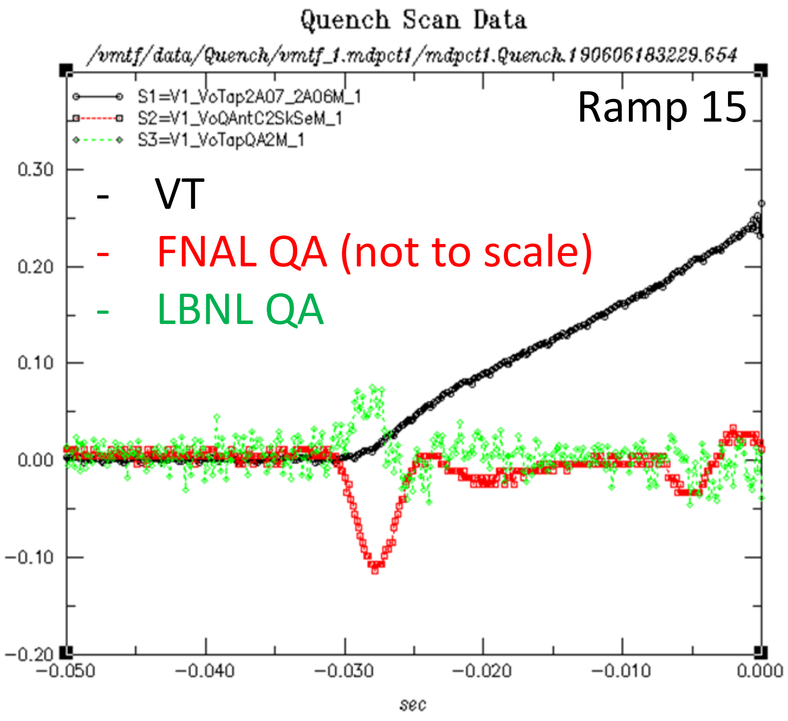
FNAL: two sets of six axially placed elements (each set faces a coil)

Ramp 12 and 15



Quench location

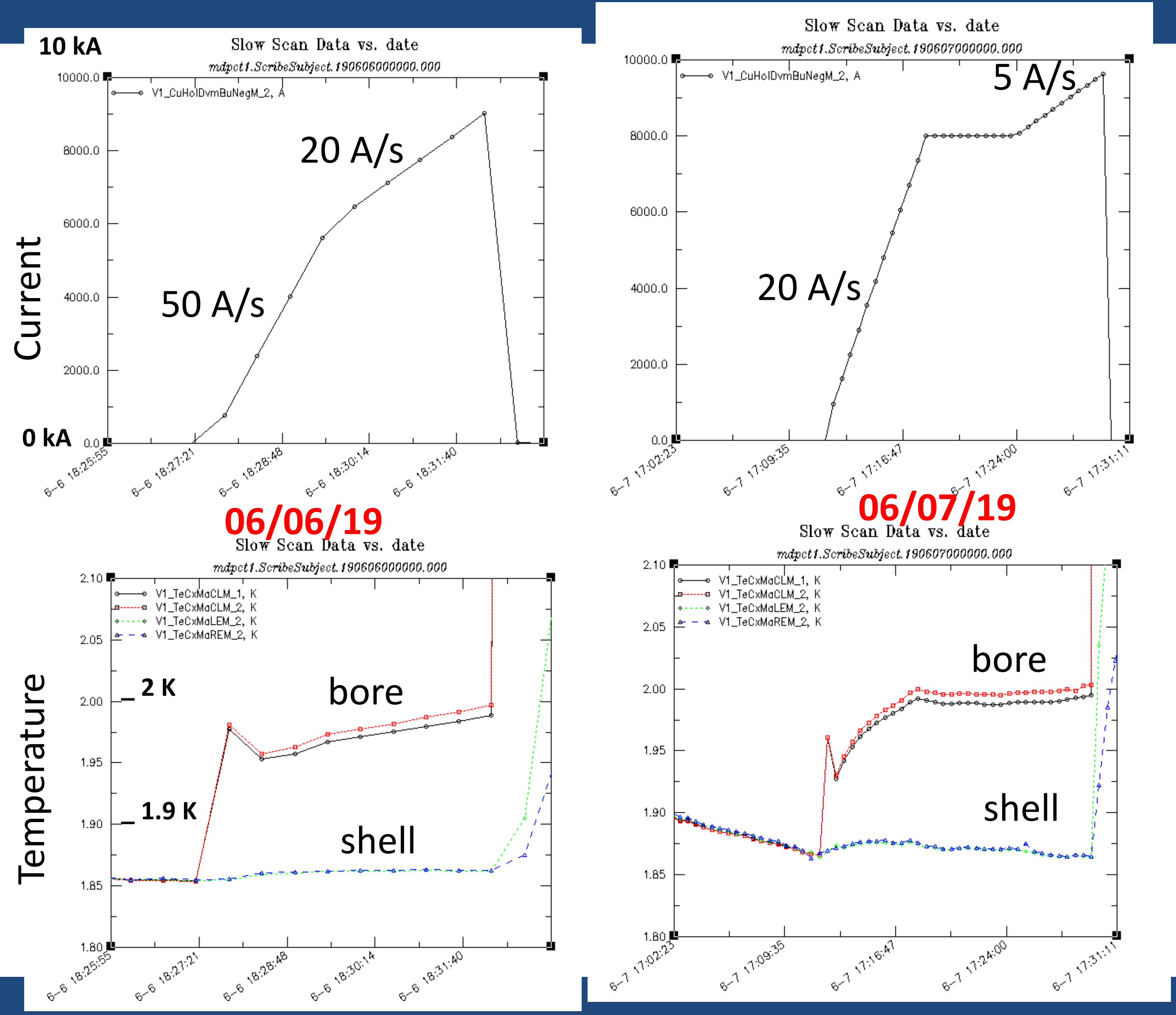
For the two quenches in layer 1 (MDPCT1) the QA and VT based locations are consistent within few cm.
We also know the quench propagation velocity (~ 2 cm/ms) although, interestingly, there is some inconsistency between VT and QA data.



Only relevant in TC1, two quenches

Temperature sensors in the bore

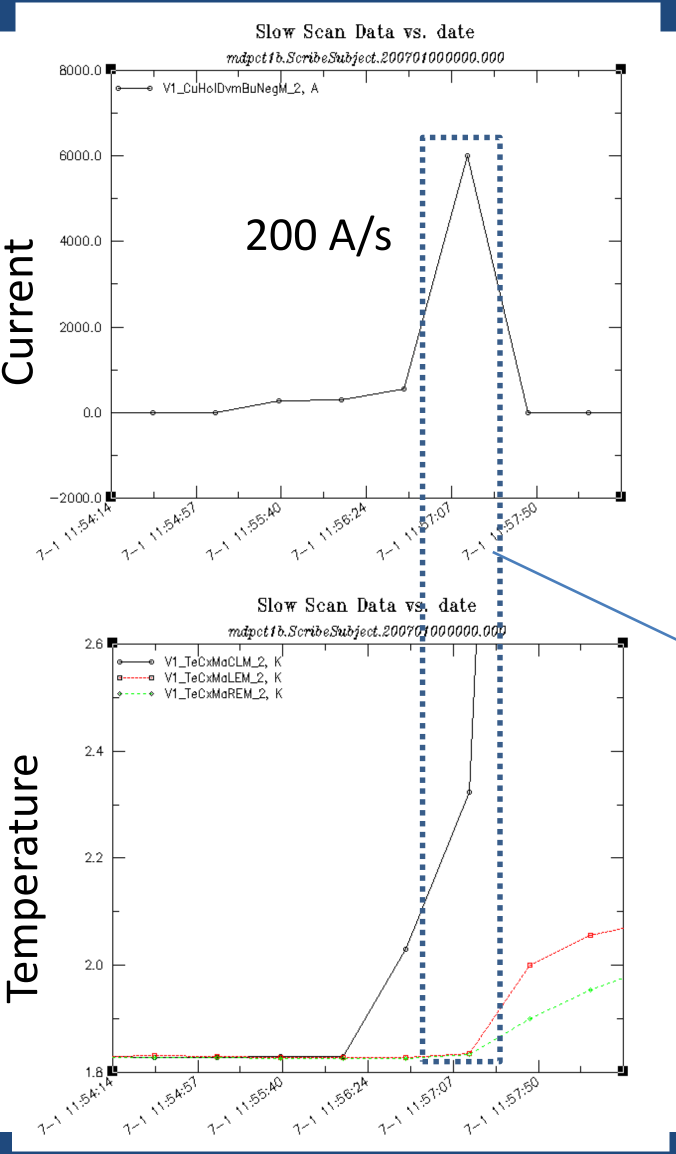
- In addition to sensors on the shell (top/bottom) two temperature sensors were installed in the bore (LE endshoe)
  - ✓ Opposite site in azimuthal direction
- They showed bore temperature is sensitive to ramp rate



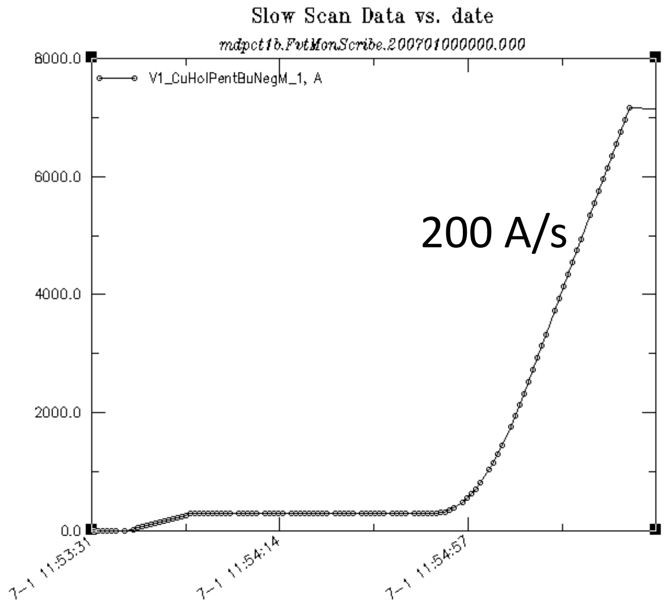
After the temperature rises it recovers very slowly – in practice it doesn't recover.

Temperature rise rate is clearly dependent on current ramp rate. Typical current ramp rates keep us below 2 K in the bore before quench.

High ramp rates at TC2



This is the same ramp but with a different DAQ frequency



This says that at ~ 6 kA (a quench occurred at ~ 7.5 kA) the bore temperature was already 2.3 K while the shell barely saw any temperature change.

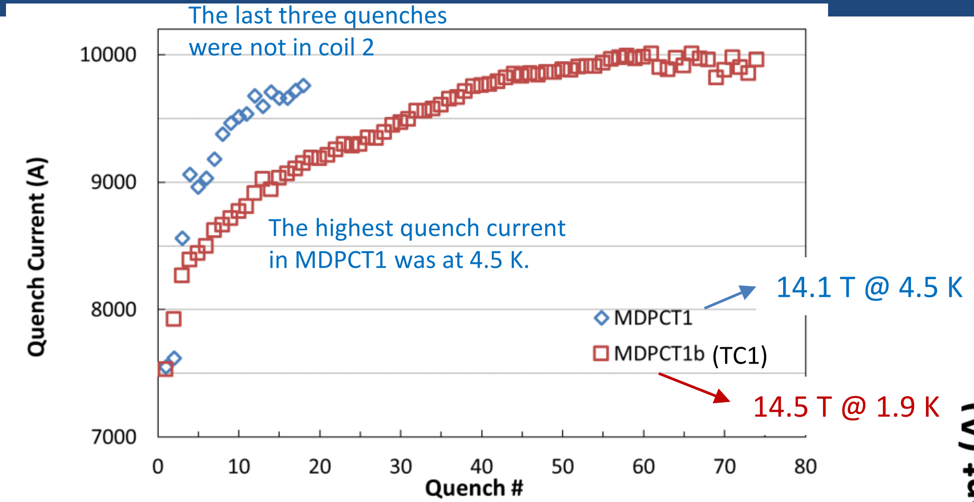
If inner coils were quenching bore temperature has effect on relevant SSL (~ -700 A/K) and especially cooling as we can't rely anymore on super-fluid He.
(fair note: we don't measure the actual temperature of the superconductor)

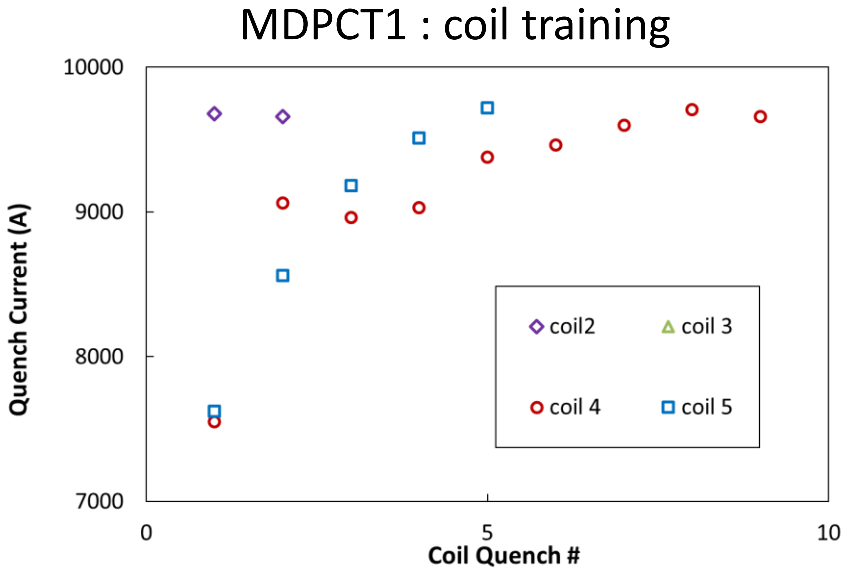
Summary

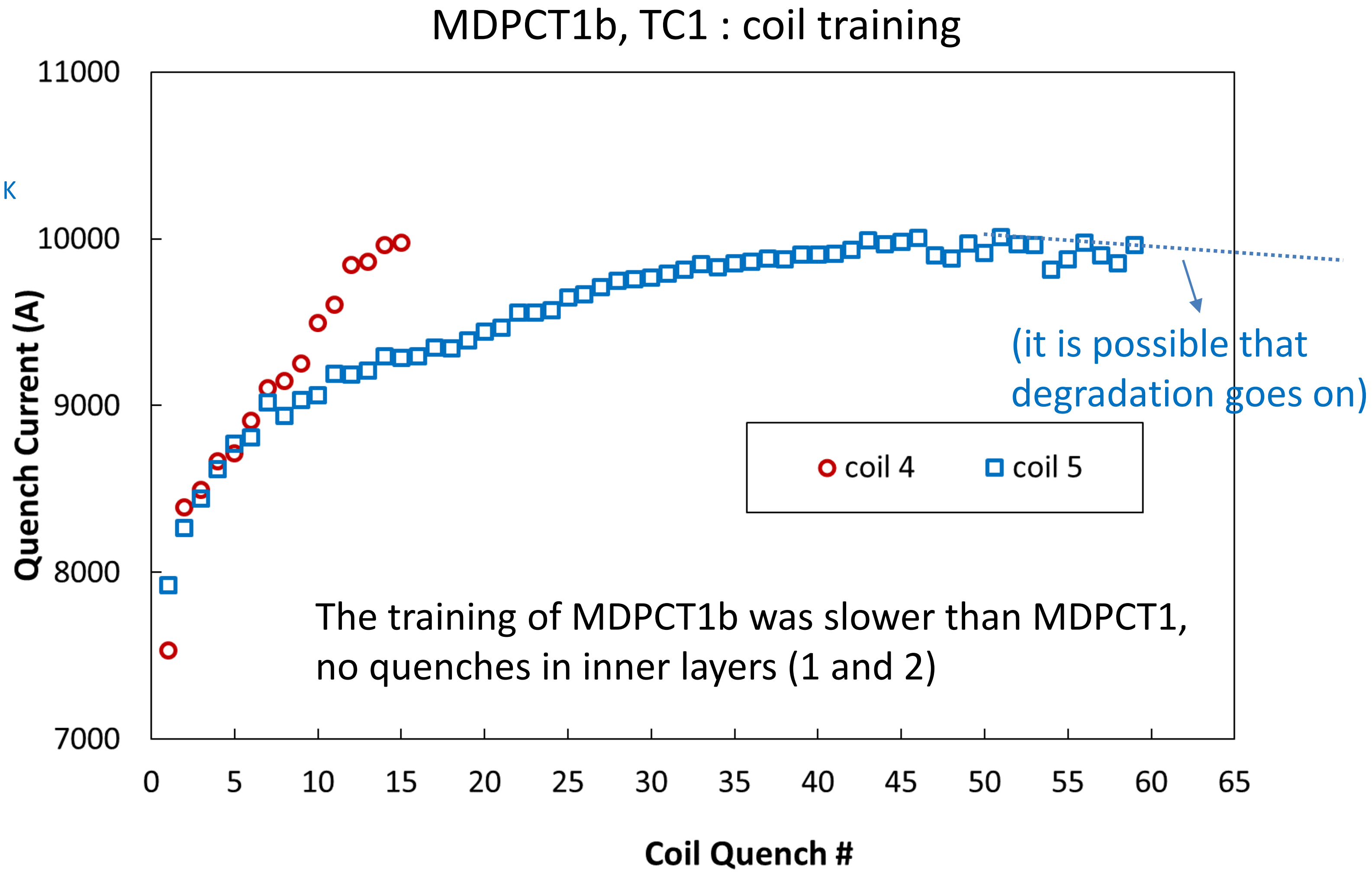
- Voltage tap data in TC2/TC3 are very good
- VTs and QA in TC1 provide rich information about the two quenches in layer 1
- Very useful information from “MUX” (multi-channel nano-voltmeter) in TC3
- Important hints from acoustics obtained in TC2 and TC3
- Potential for “anomalous events” hunting with acoustics and machine learning (more hints/evidence)
- Bore temperature sensors of potential future use, good data for studies of inner layer events
  - ✓ Could extend to in-magnet-body measurements?

Spare

MDPCT1 Training

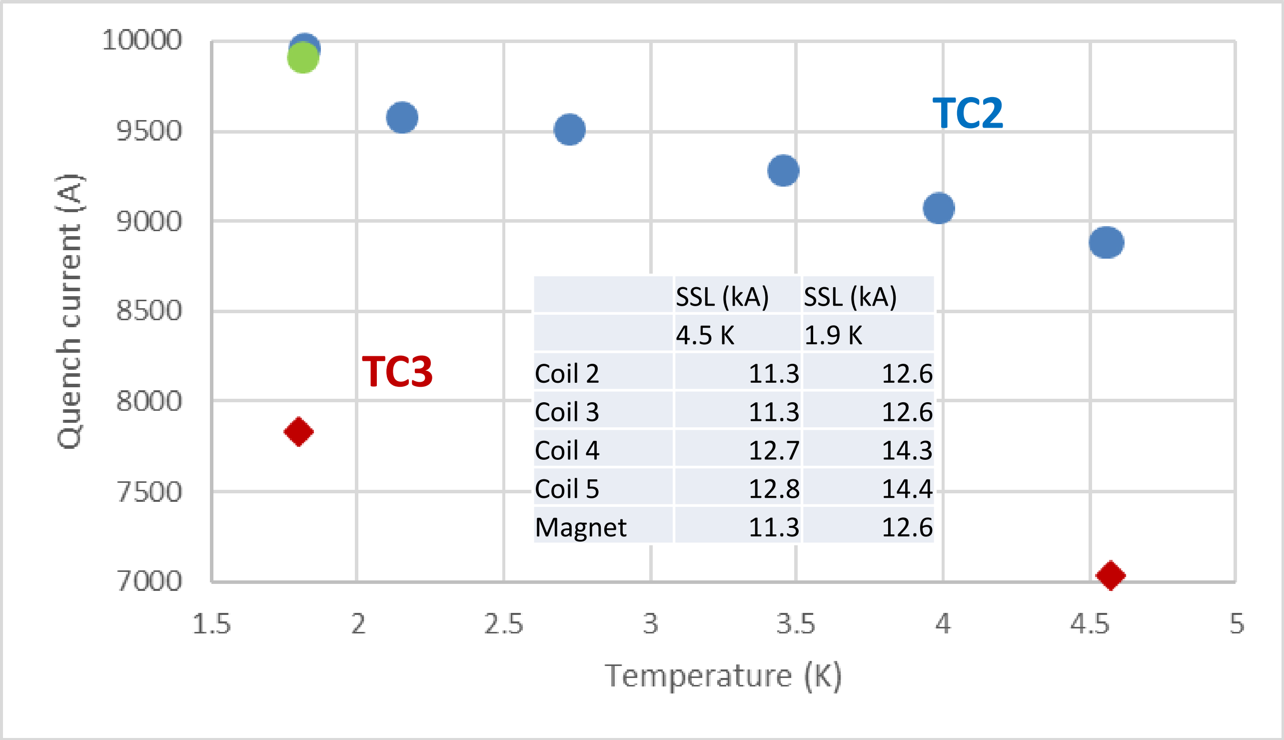






Temperature and ramp rate quench current dependence

MDPCT1b



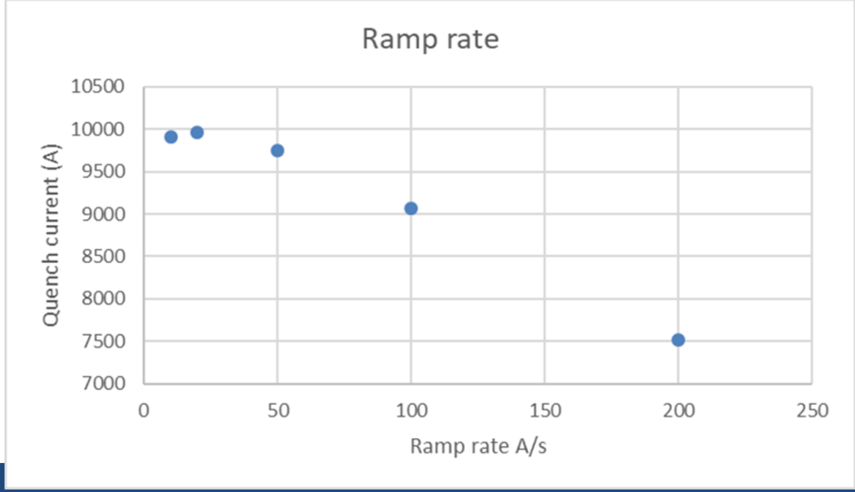
	SSL (kA)	SSL (kA)
	4.5 K	1.9 K
Coil 2	11.3	12.6
Coil 3	11.3	12.6
Coil 4	12.7	14.3
Coil 5	12.8	14.4
Magnet	11.3	12.6

The quench current dropped more than 20% between TC2 and TC3 suggesting significant conductor degradation (same SSL vs temperature within one percentage point).

Also, from TC1 to TC2 the current at 4.5 K dropped by ~9% (though the magnet was not fully trained in TC1).

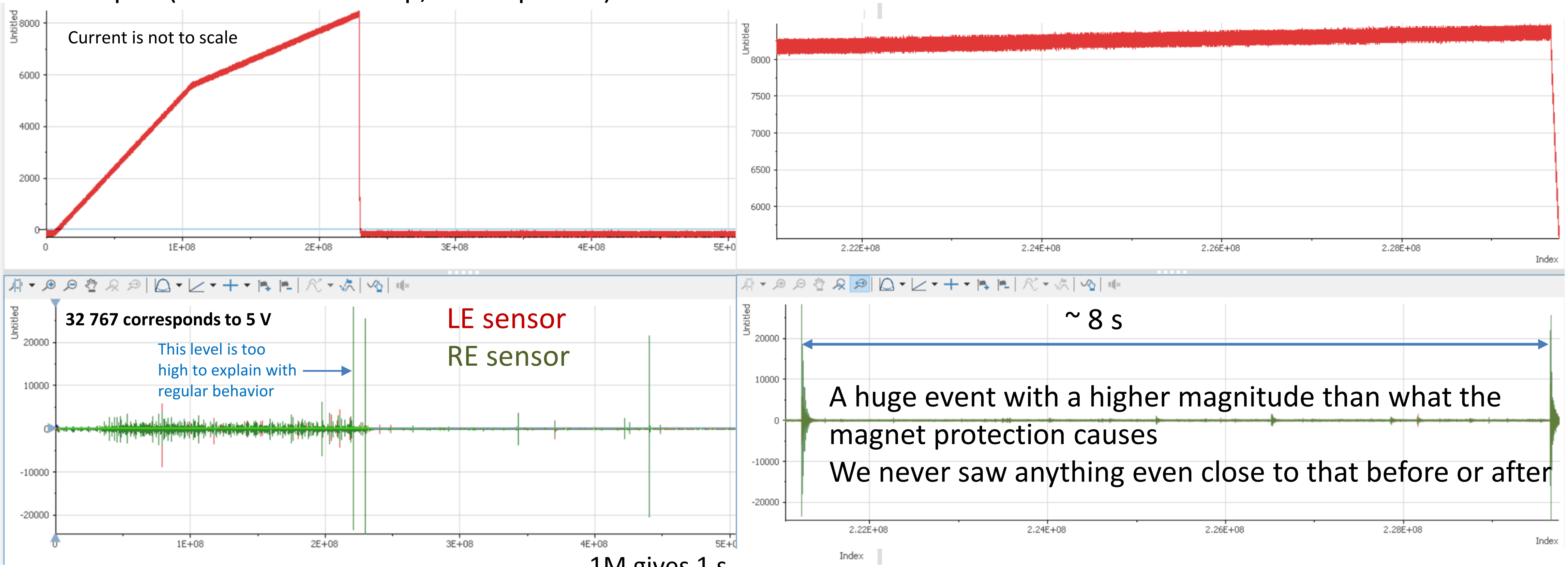
We saw a significant degradation after TC1 in TC2 and then more in TC3.
The quench levels at the two temperatures at TC3 (1.9 K and 4.5 K) were reproducible within 10 A each.

Acoustics data analysis suggests it is plausible that this large degradation was caused by a loud mechanical event (longitudinally consistent will all relevant quenches) observed in the first ramp of TC3.



Acoustics – MDPCT1, TC3

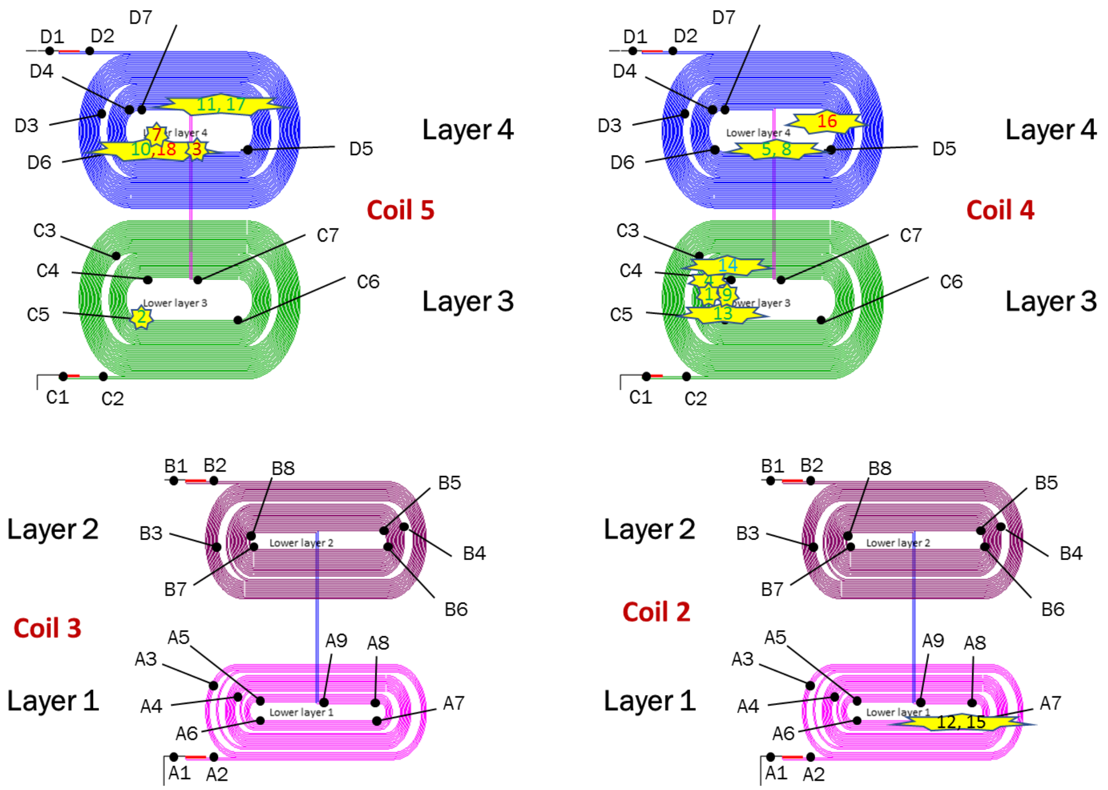
Ramp 1 (it ended with a trip, not a quench)



1M gives 1 s

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

Quenches in MDPCT1, TC1



Color codes (size is meaningless):

12 Well known location

1 Reasonably well known location

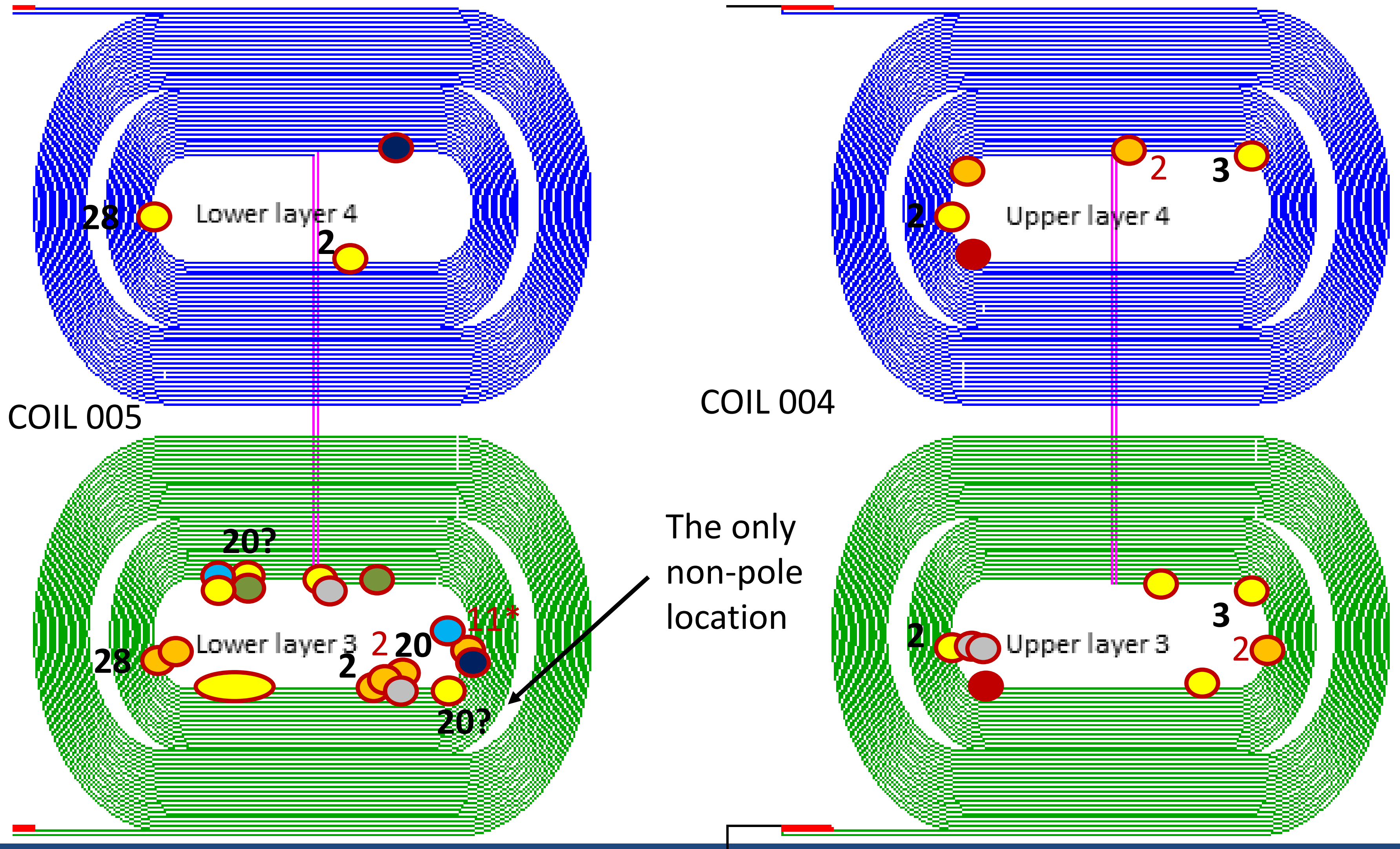
4 Not precise location

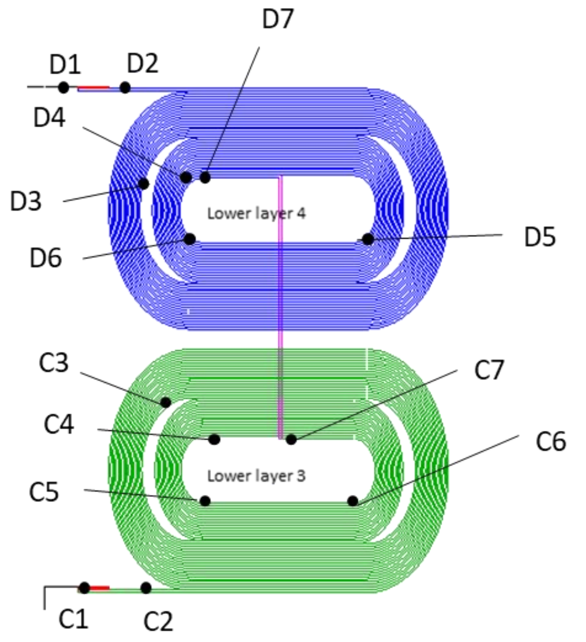
Note that there is only one quench in coil 5C (layer 3).

Because of open VTs many quench locations are not well known

Open:
c3,4,5,7 (coils 4 and 5) – after cool-down
d5 (coil 4) – after ramp 5/6
d6 (coil 5) – after ramp 5/6
d3 (coil 5) – from coil fabrication

Quench locations in MDPCT1, TC2





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

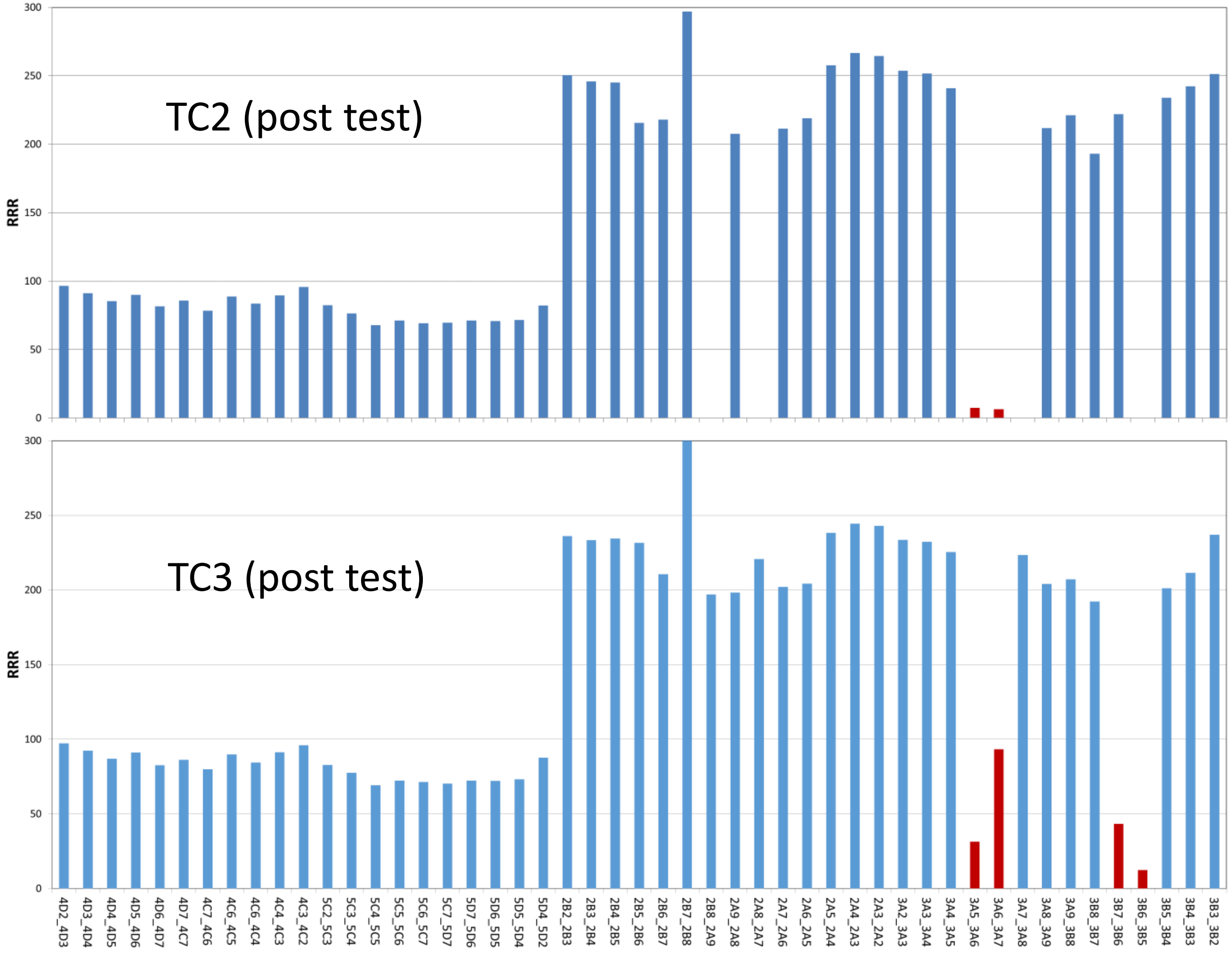
This color indicates fairly well known location

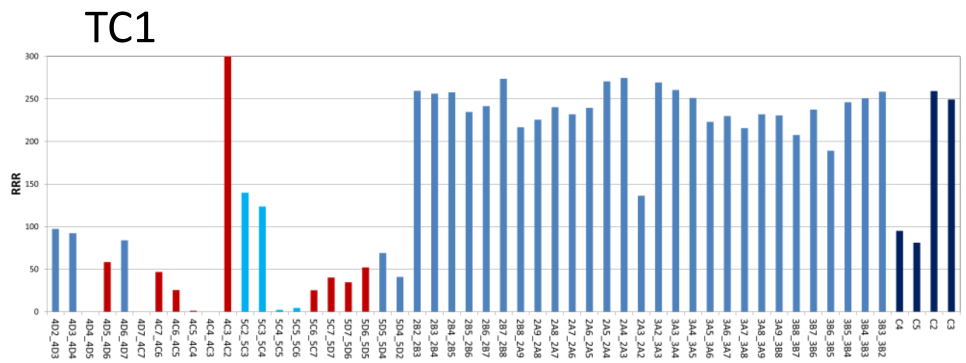
This color indicates not so well known location

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

*7 of them are RR and TD quenches

MDPCT1 RRR

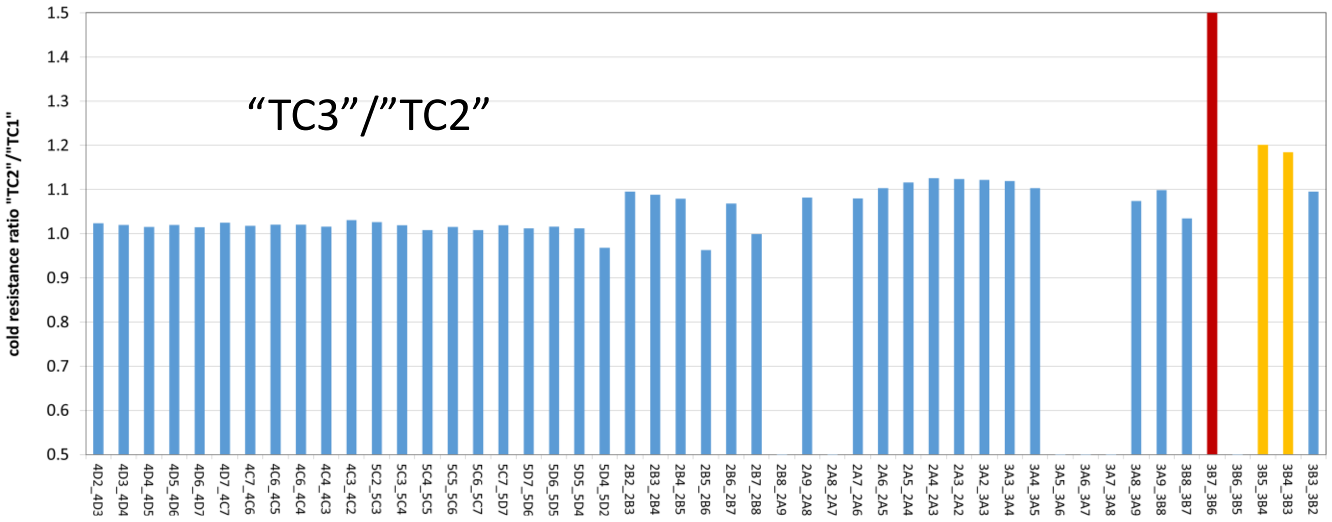


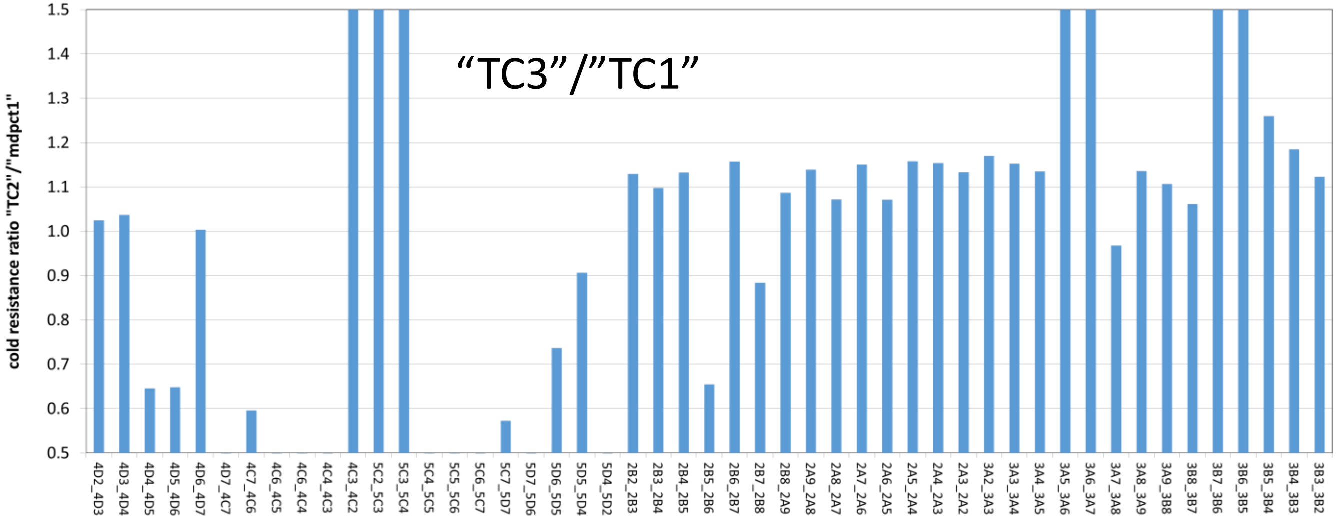


No abnormal RRR behavior in TC3

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

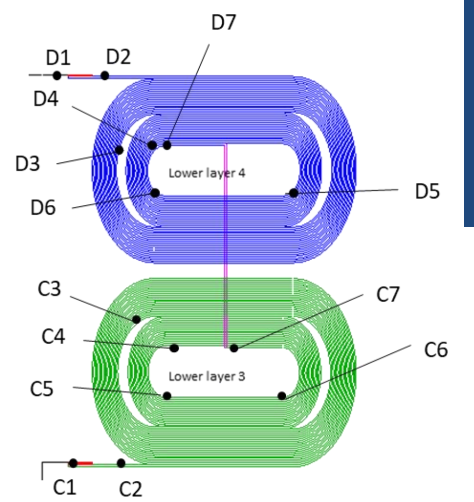
MDPCT1b cold resistance ratio

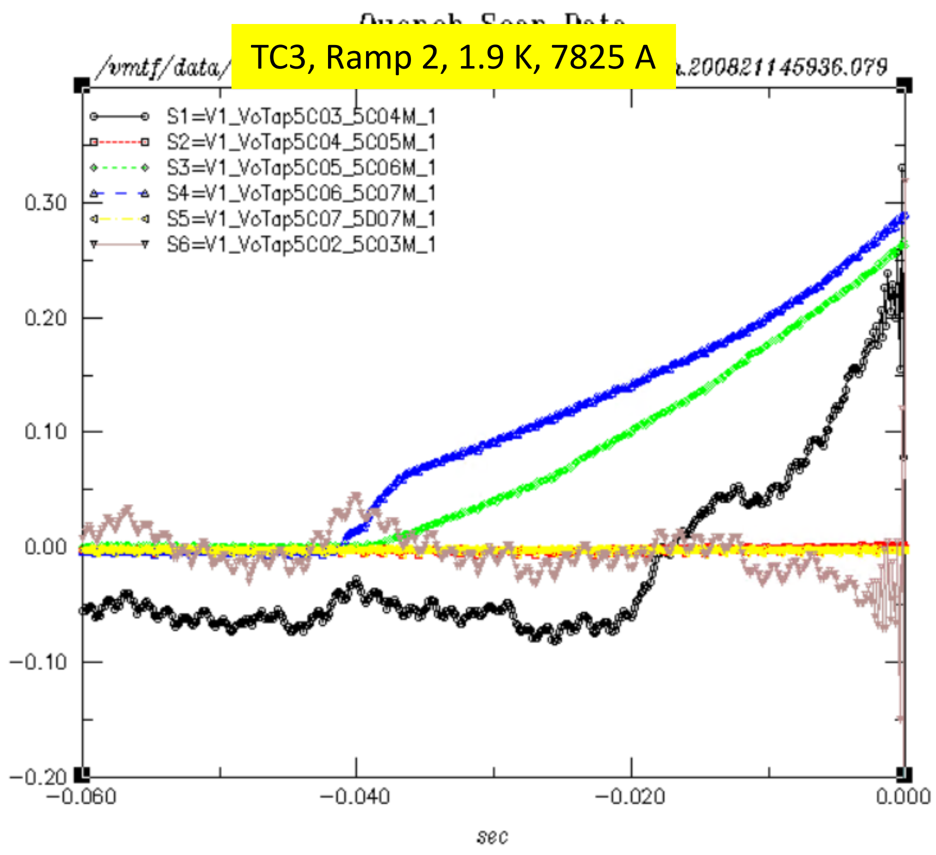




No abnormal behavior in TC3 except 10% higher resistance in inner coils (which don't quench)

TC3 quench pattern

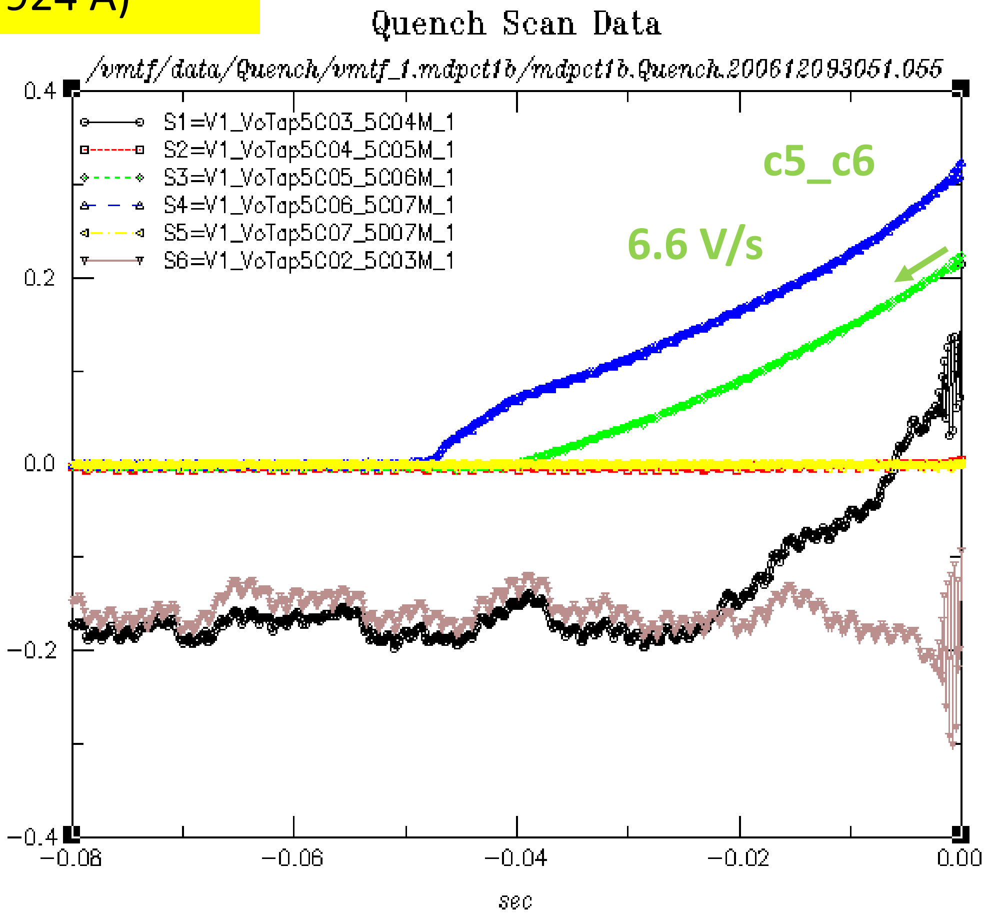




In TC3 all 1.9 K quenches were at ~7.82 kA and 4.5 K quenches at 7.03 kA (20 A/s).
All quenches started in 5c6_c7 with a familiar pattern to some TC2 quenches.
In TC2 this pattern was seen in the very beginning of training at 1.9 K as well as in all > 2.2 K quenches and high ramp rate quenches.
So the quenching segment (and pattern) changed from 5c5_c6 in the end of training at 1.9 K to 5c6_c7 in TC3 but remain the same at 4.5 K.

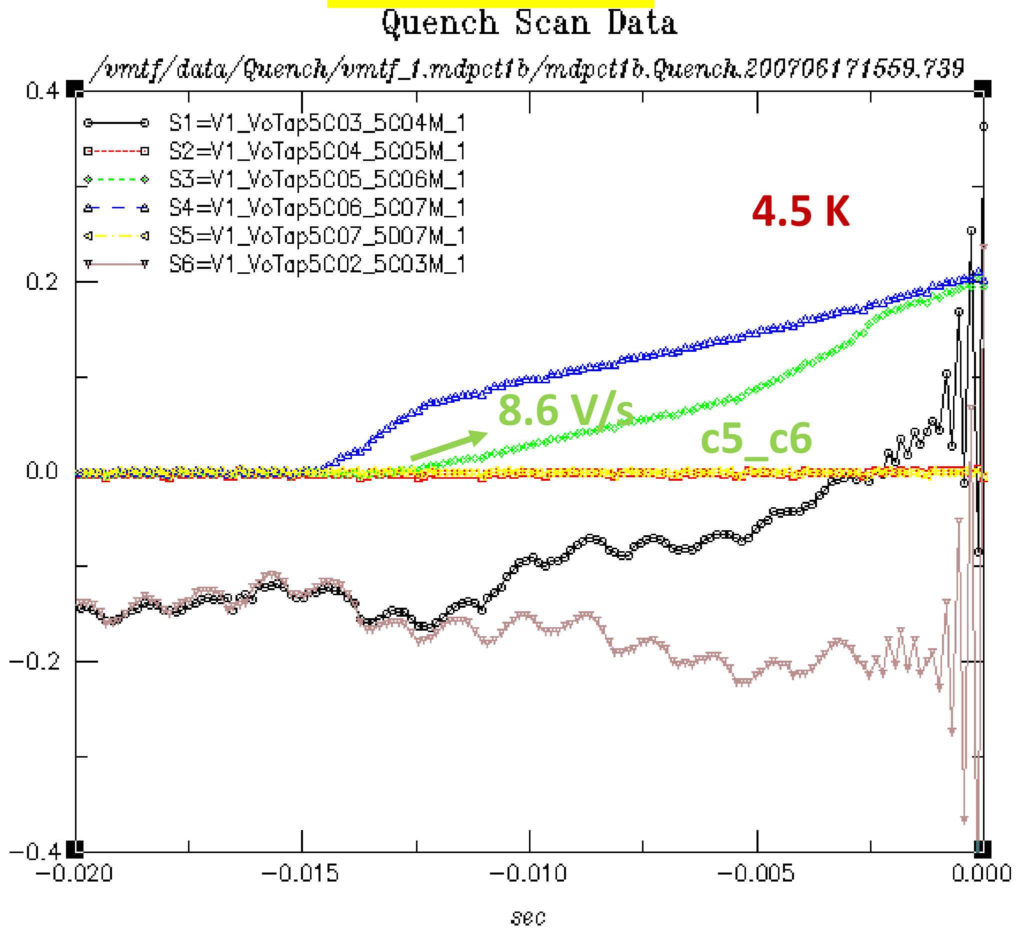
Quench profiles in TC2

Ramp 2 (TC2)
(7924 A)

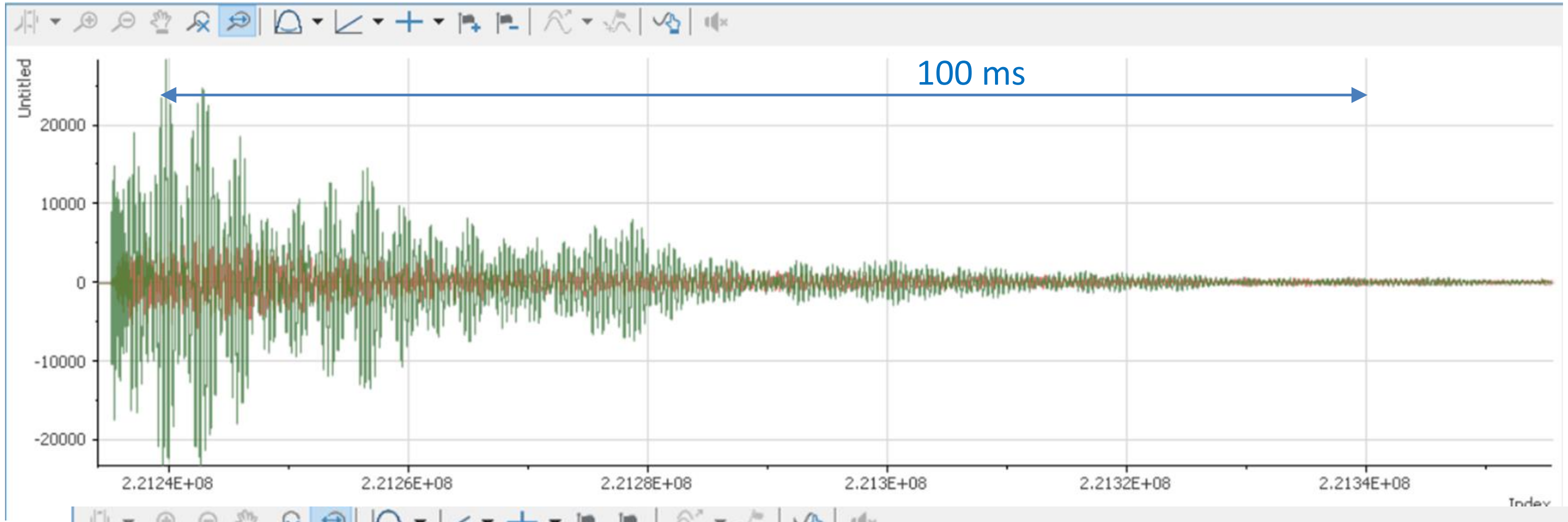


Ramp 86 (TC2)
(8886 A)

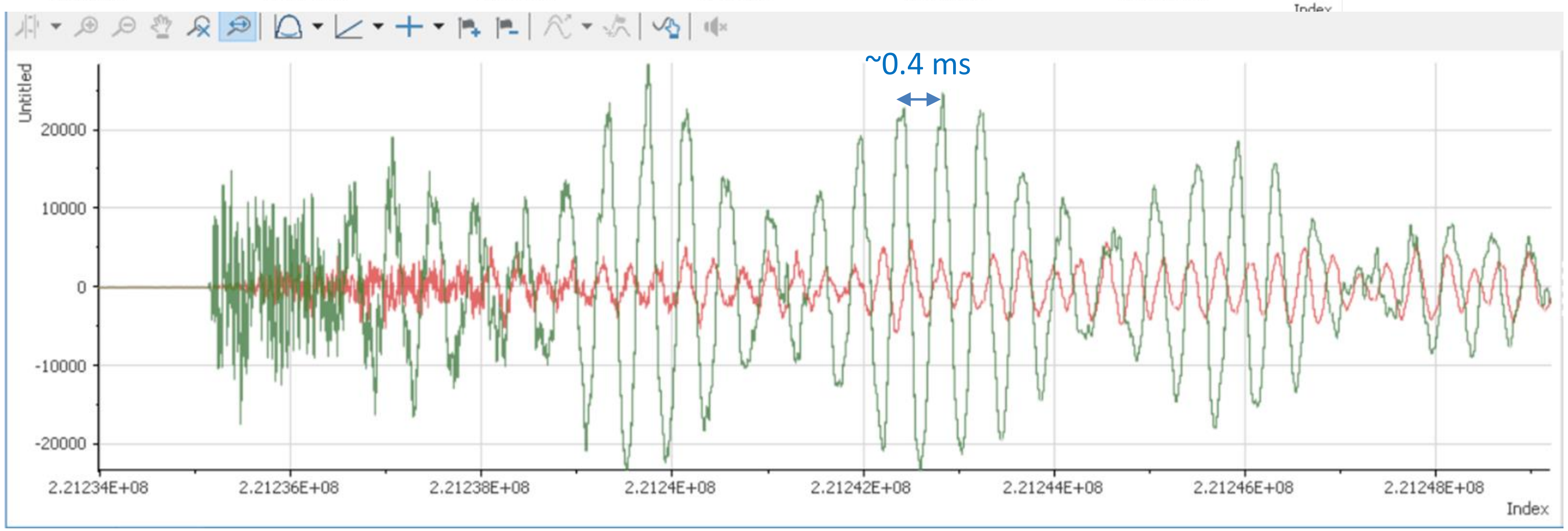
(last quench in TC1)



Acoustics – MDPCT1, TC3



Ramp 1



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

Acoustics – MDPCT1, TC3

Ramp 4