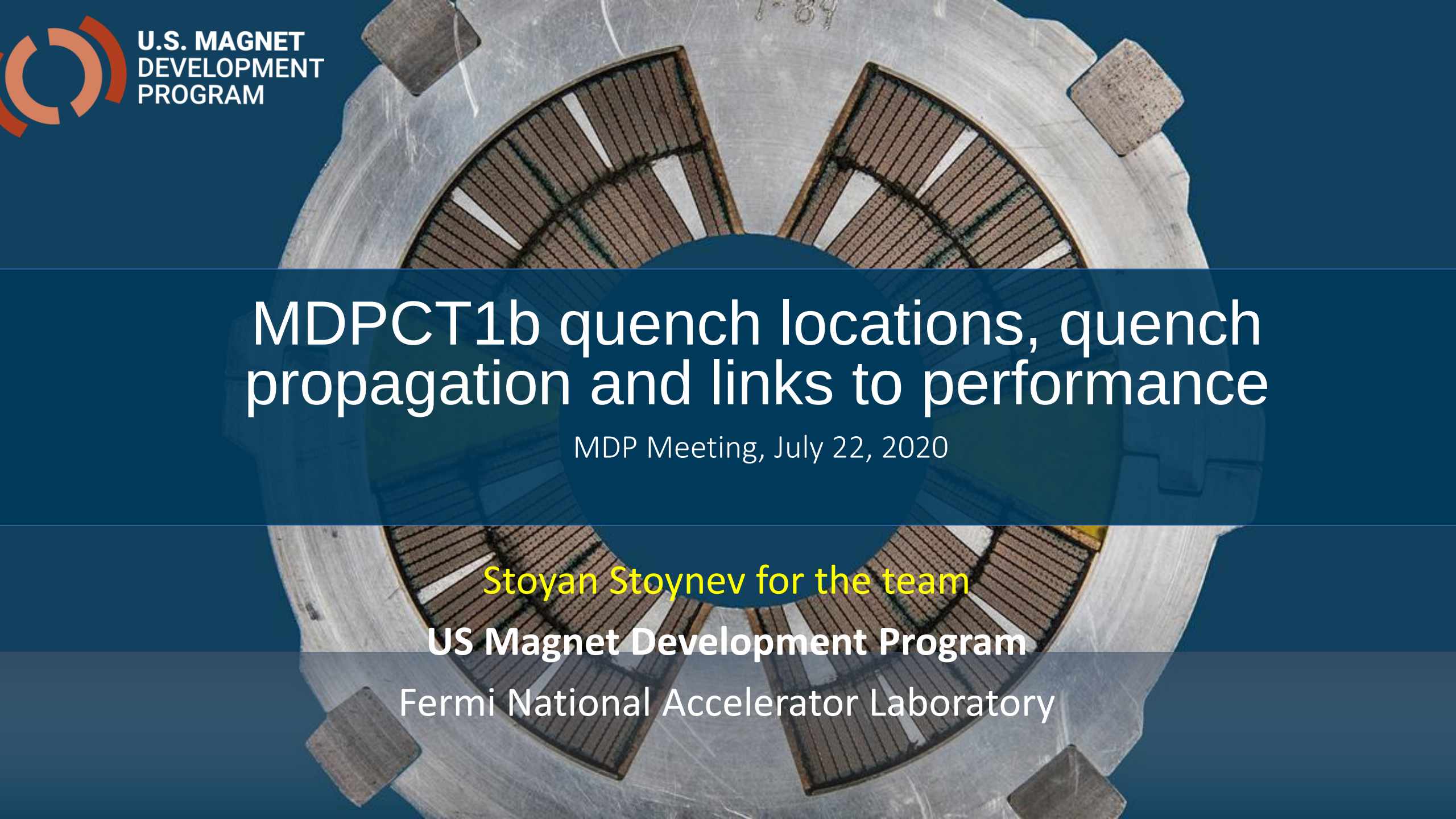


U.S. MAGNET DEVELOPMENT PROGRAM

# MDPCT1b quench locations, quench propagation and links to performance

MDP Meeting, July 22, 2020


Stoyan Stoynev for the team

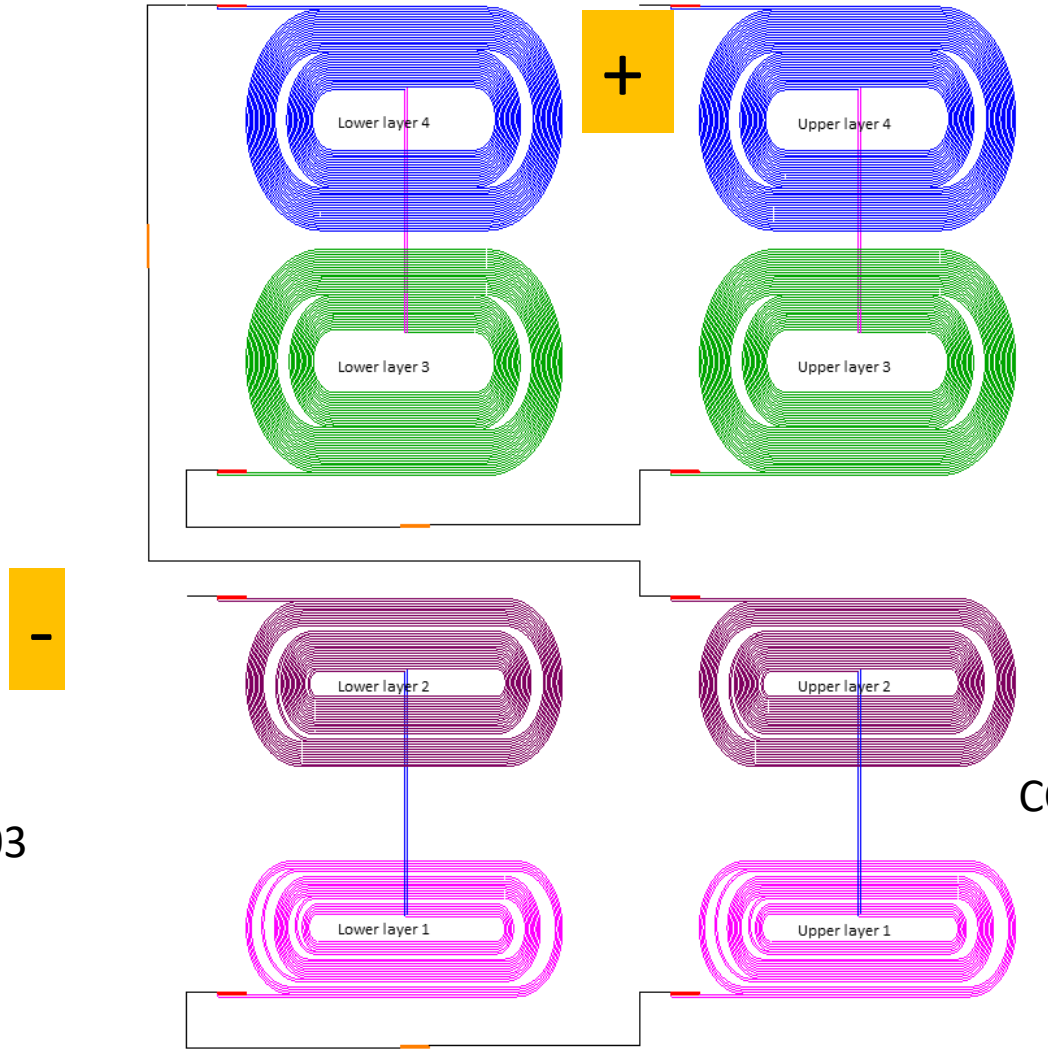
**US Magnet Development Program**

Fermi National Accelerator Laboratory

# “15 T” Coil connections

COIL 005

COIL 004

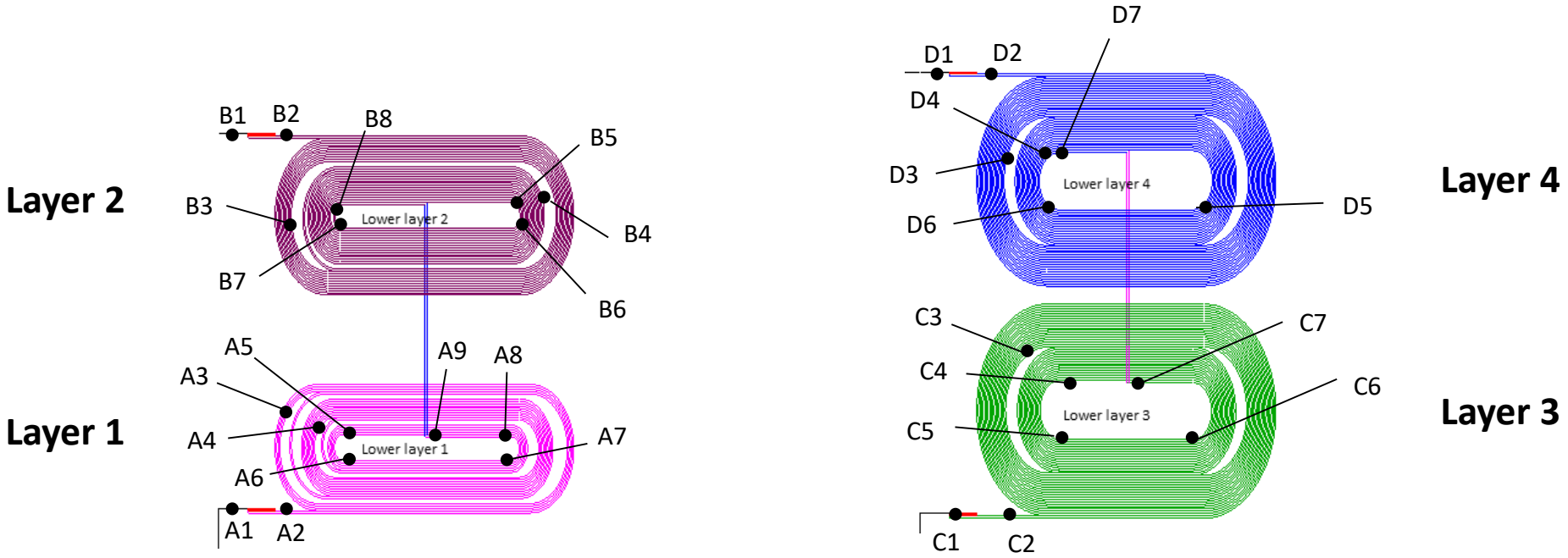



COIL 003

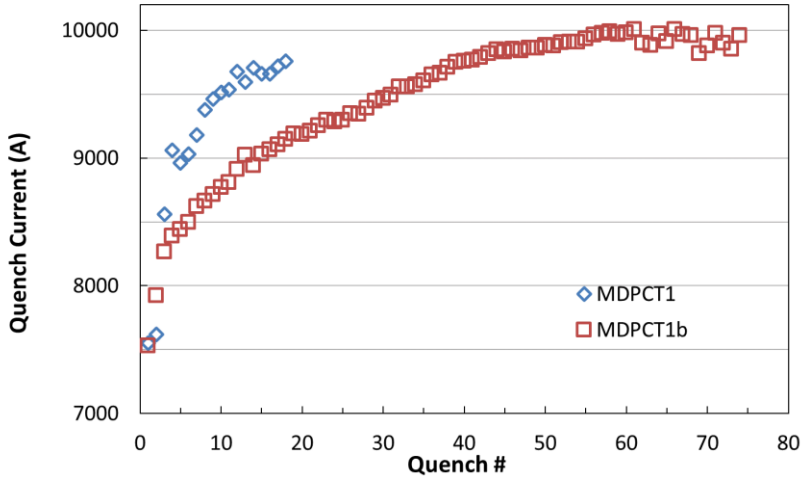
COIL 002

# “15 T” voltage taps

Coil instrumentation (seen from “above”)



# MDPCT1b Training




Ramp #s

Ramp #58
Ramp #45
62
61
63
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 #

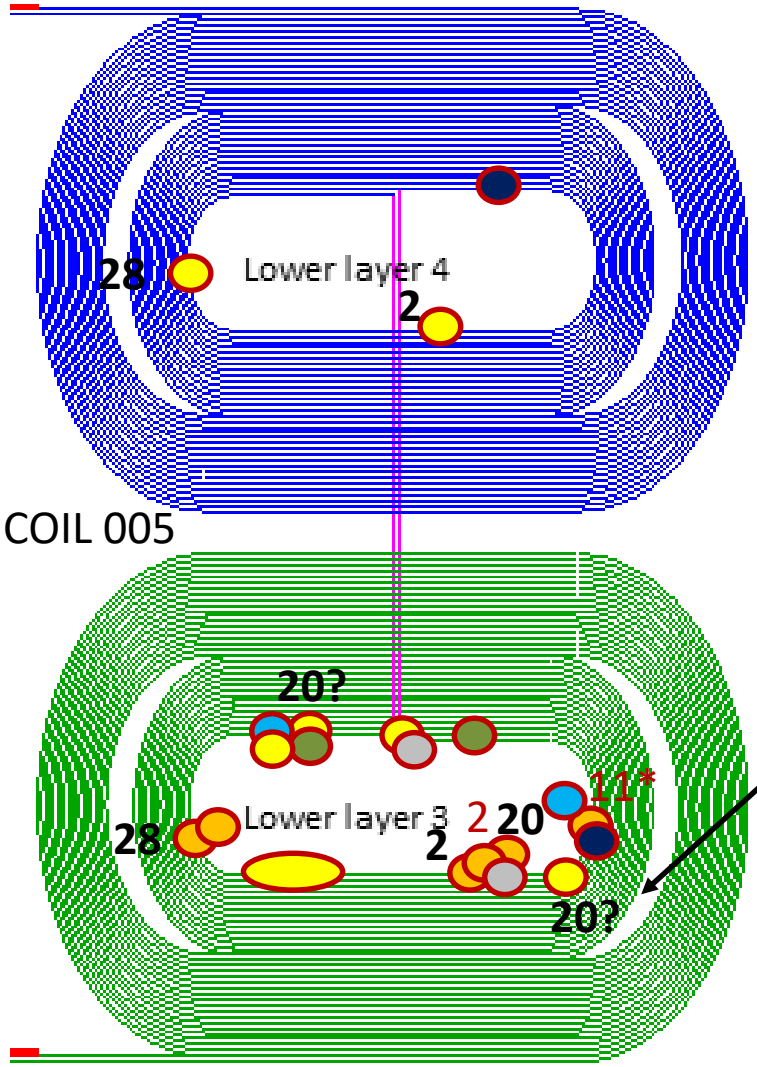
# Quench patterns

| 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)*** |

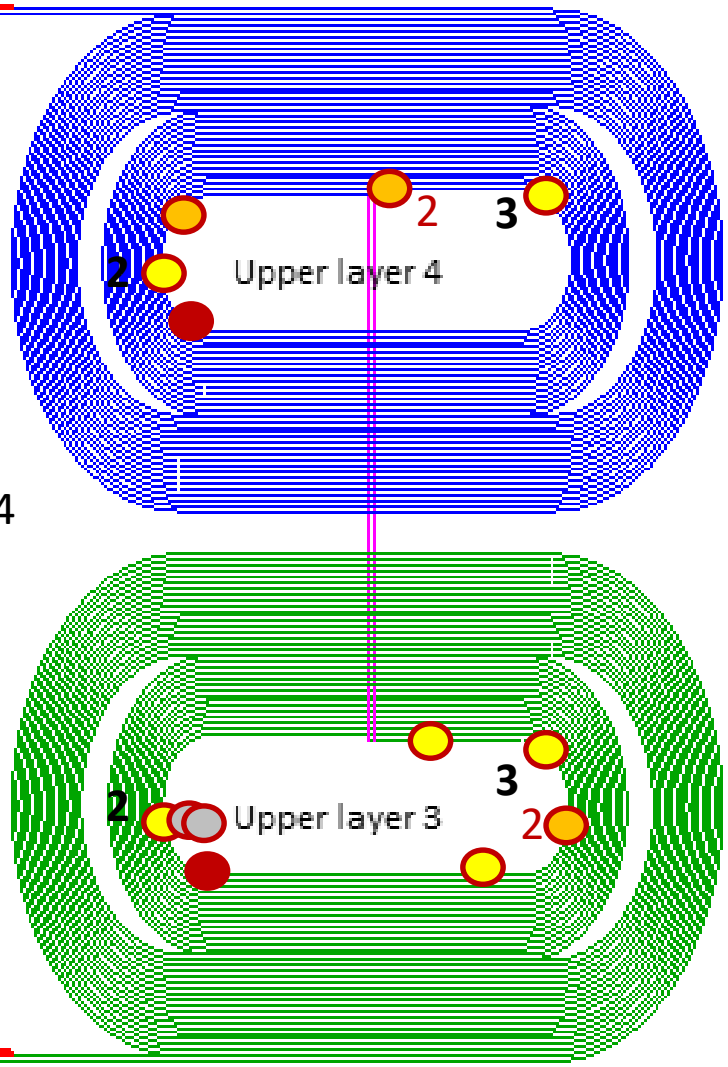
The green boxes indicate focus points to be followed in the presentation.

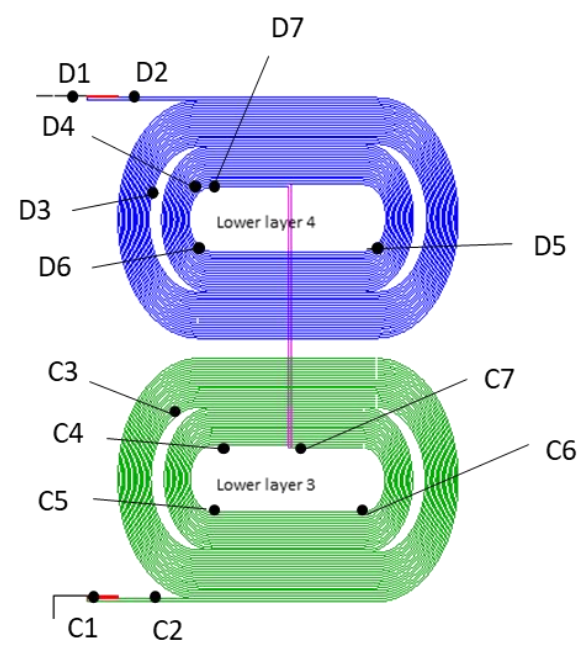
Ramp shown are the same pointed on the previous slide.

# Quench locations at a glimpse




The only non-pole location




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

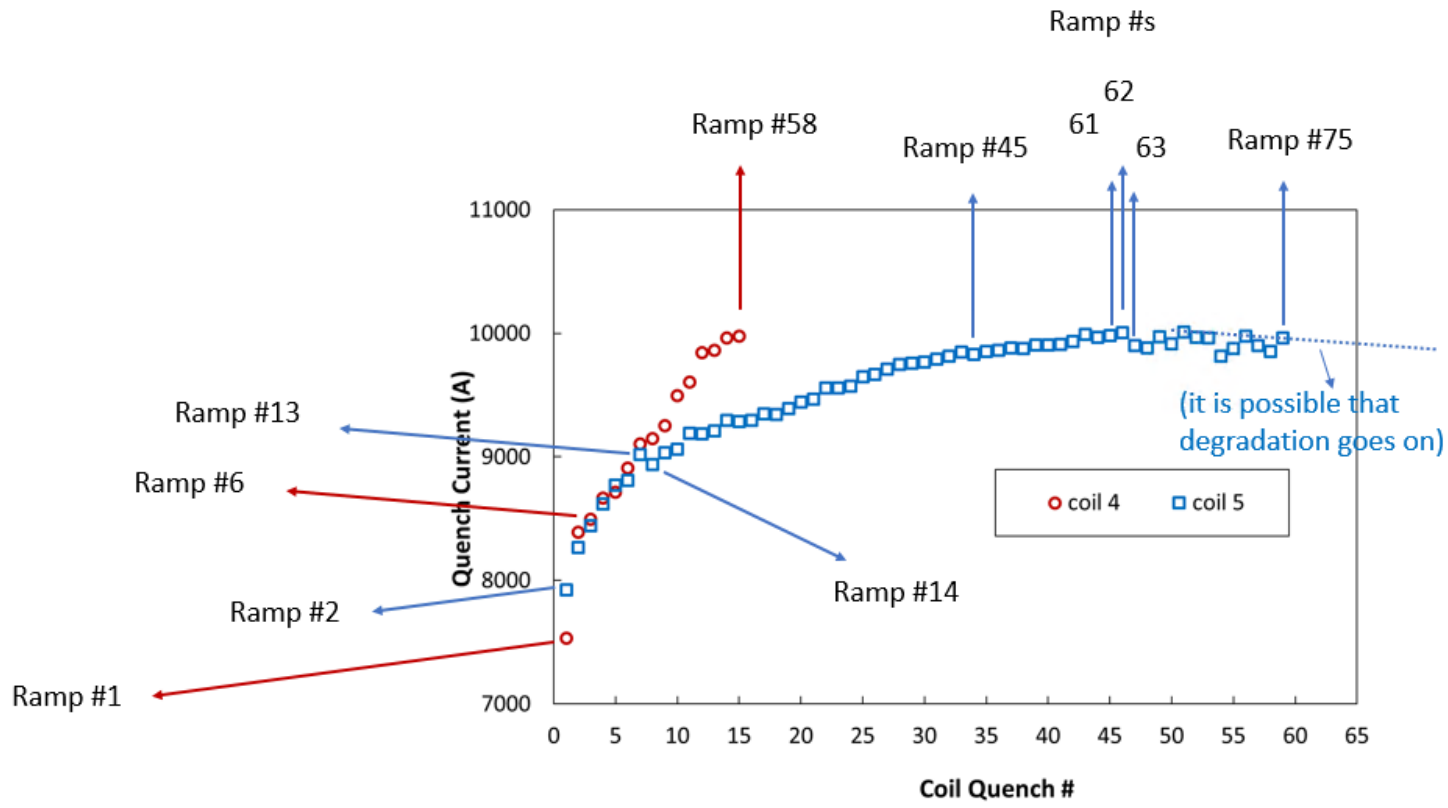
Both colors (and only them) can have associated numbers which are the numbers of similar quenches

*7 of them are RR and TD quenches

# Quenches

## Coil 4 only quenches

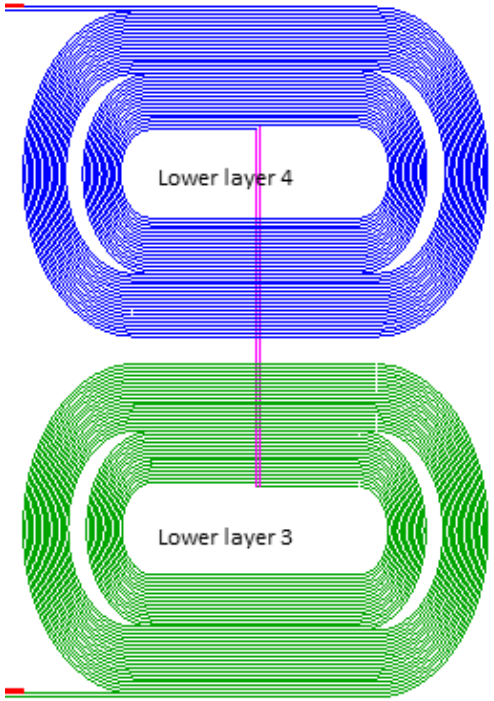
Looking at beginning-middle-end of training curve



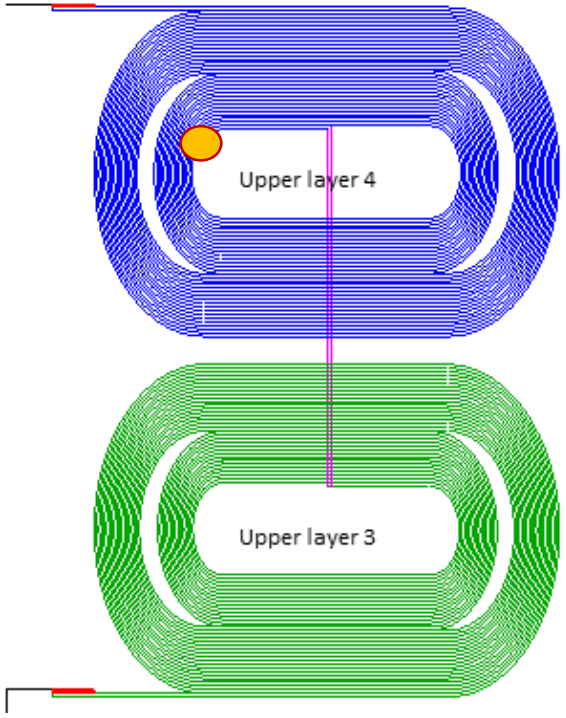
**4; d6_d7, d7_c7, c7_c6, d5_d6**

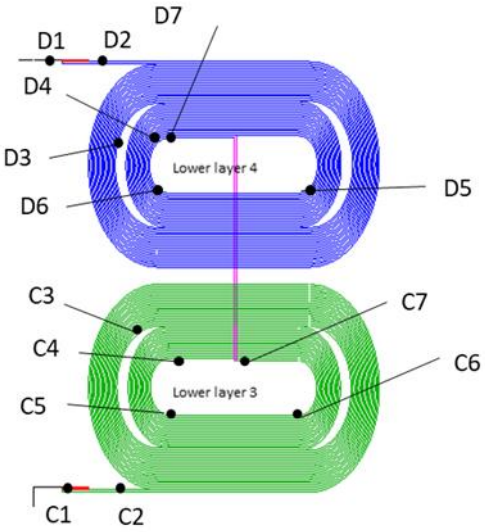
Ramp 1
(7530 A)

COIL 005




COIL 004







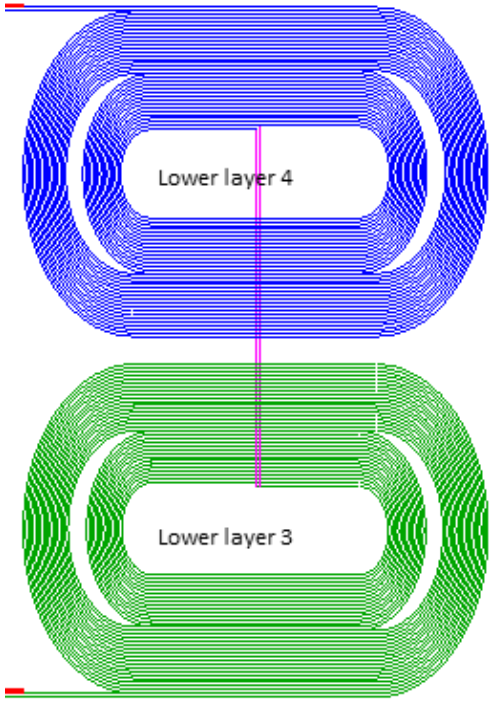
Propagation through d7_c7 (27 cm): 57 ms
Propagation through d6_d7 (27 cm): 9+71 ms

Known

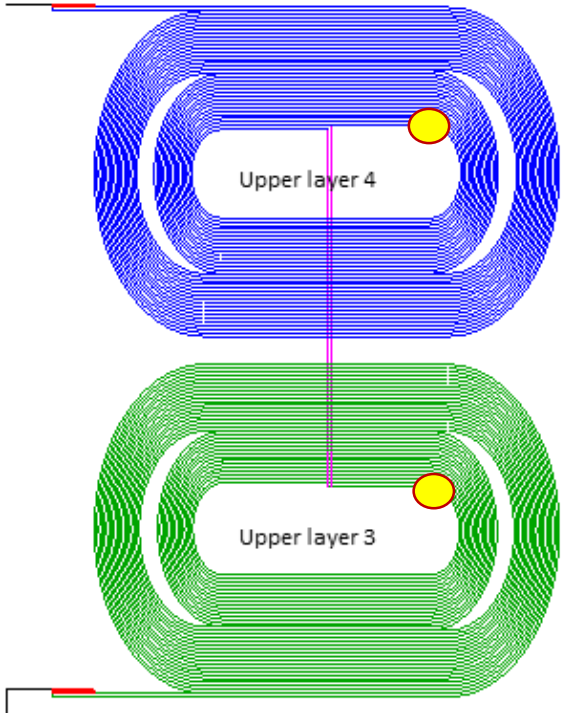
**Quench propagation V: 5 m/s and 3 m/s, respectively**

## 4; c7_c6, d4_d5

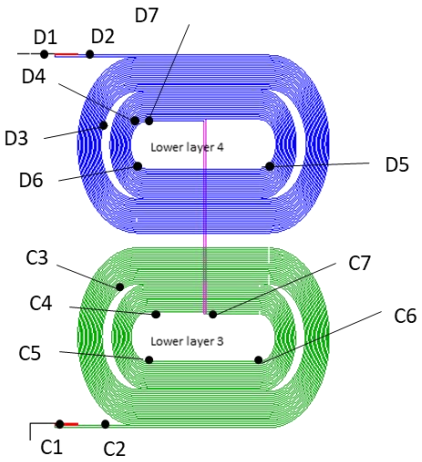
COIL 005

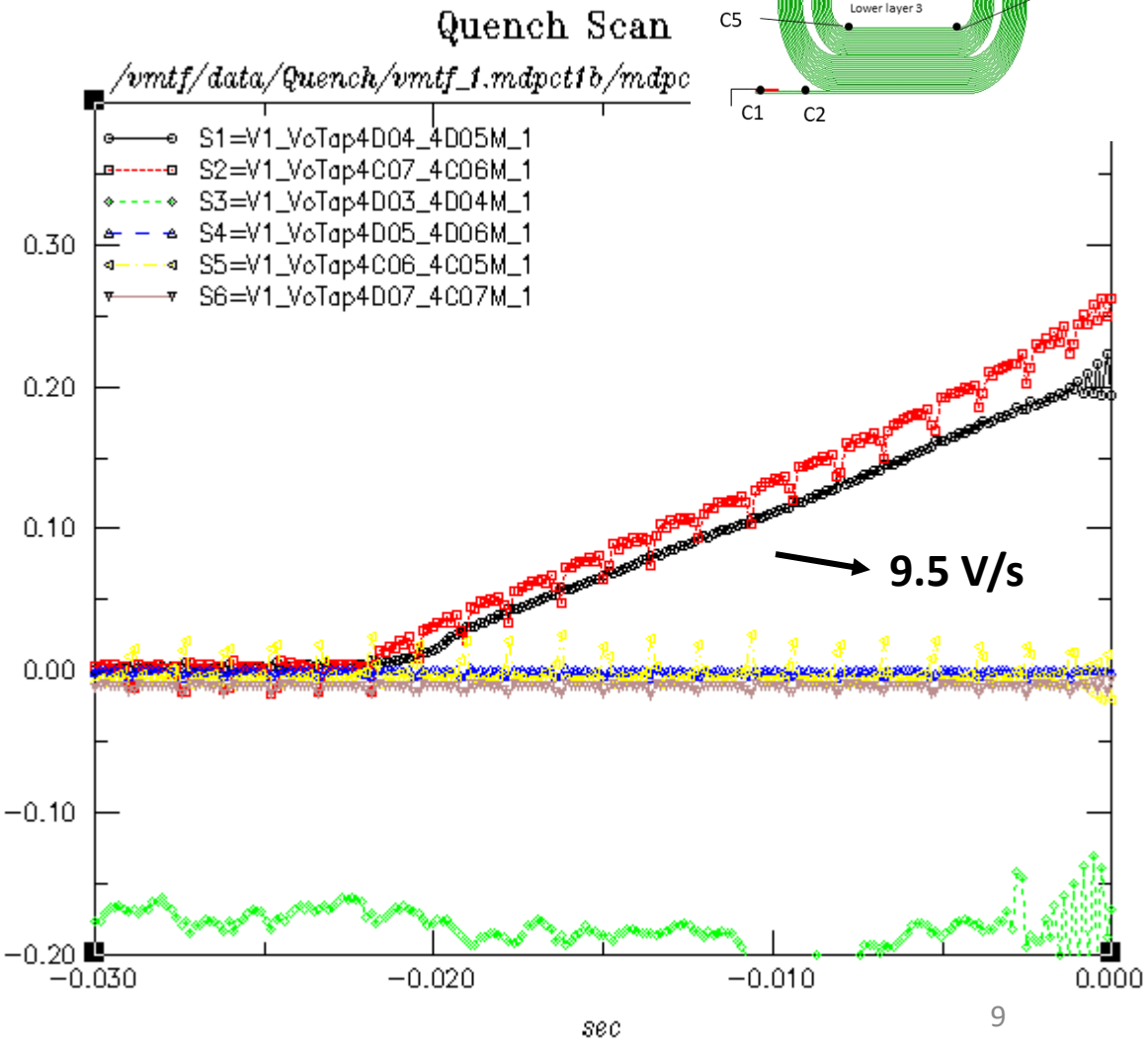



COIL 004




Ramp 6
(8497 A)



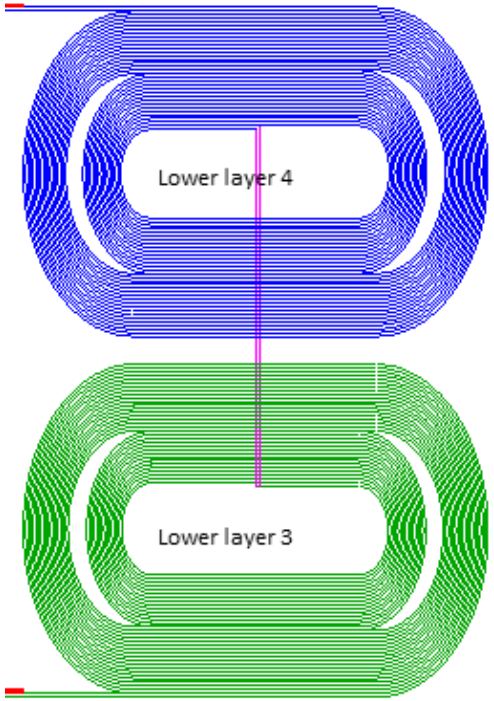




Most of the quenches don't give enough information to determine the propagation velocity but one can compare voltage rise patterns in the same segment(s)

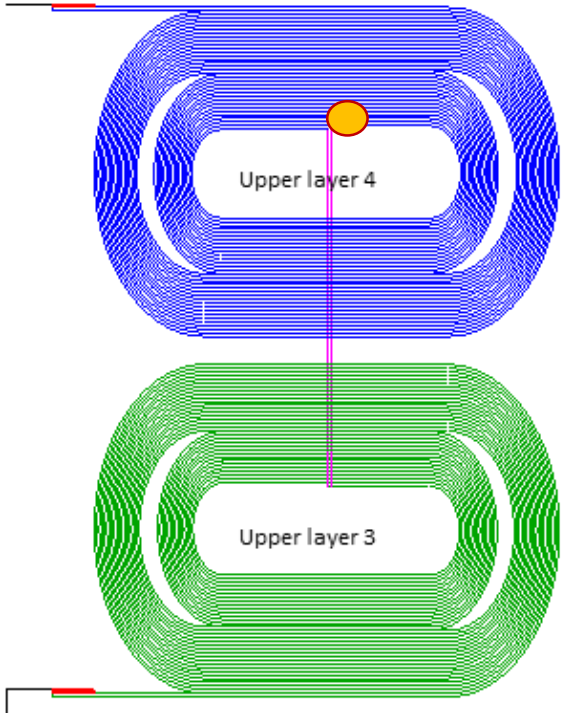
Less known

## 4; d4_d5, d3_d4

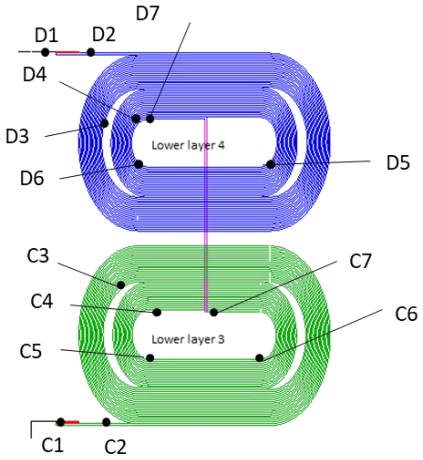
COIL 005

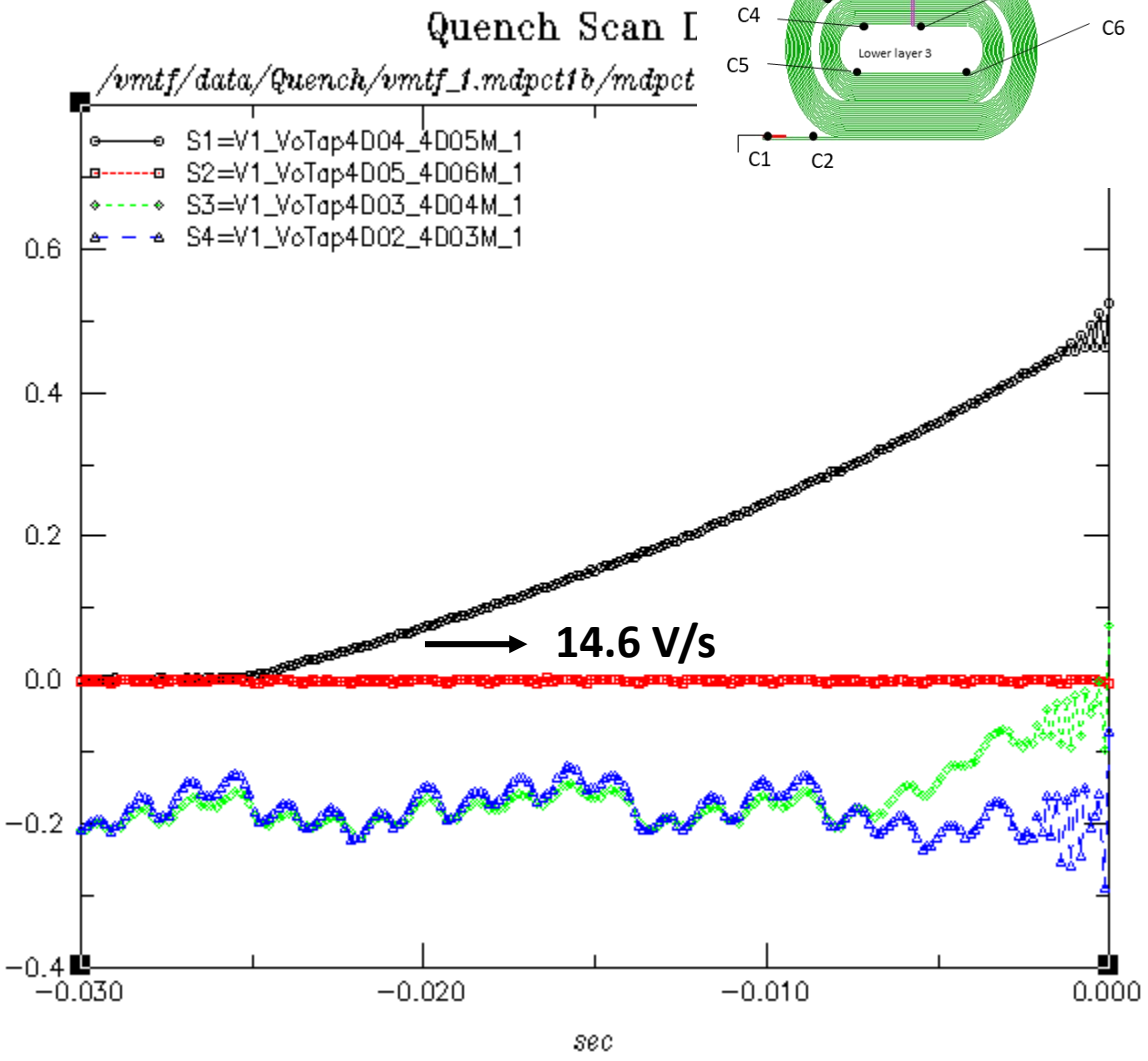



COIL 004




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).**

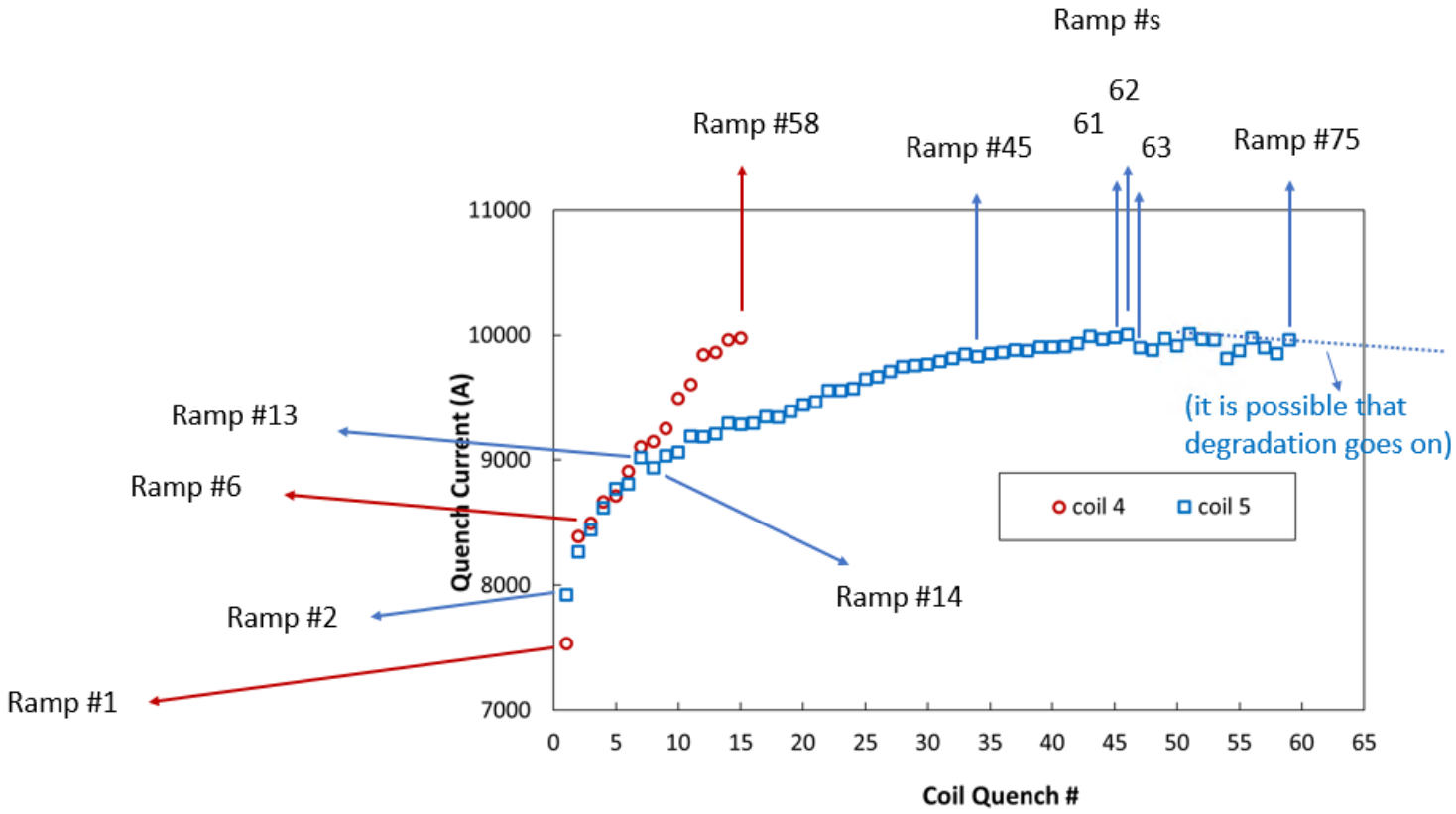
# Quenches

## 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)

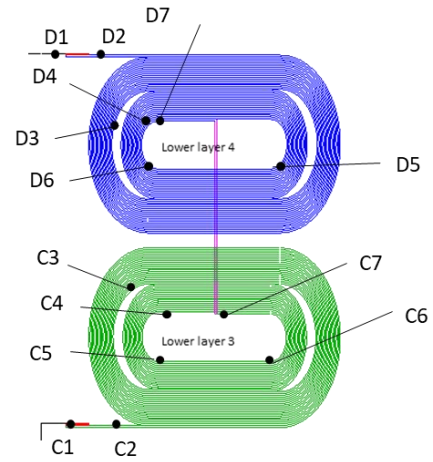
86, 85, 84, 83, 82; 79?, 78?; 76, 11 , 3 , 2,

Ramps

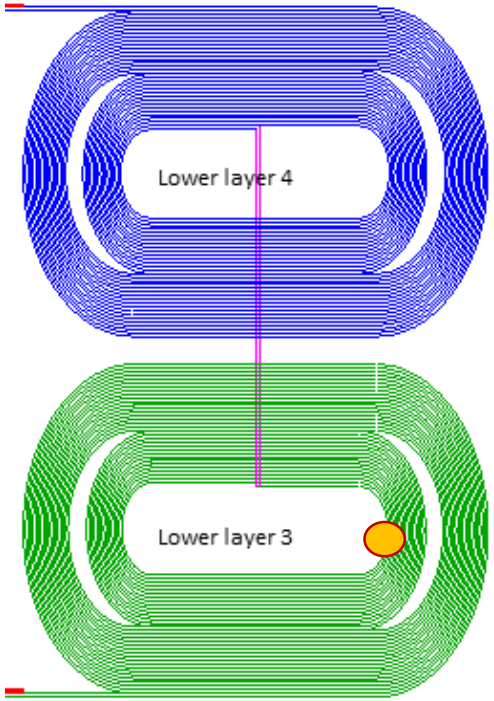
Pattern

**5; c6_c7, c5_c6, c3_c4**

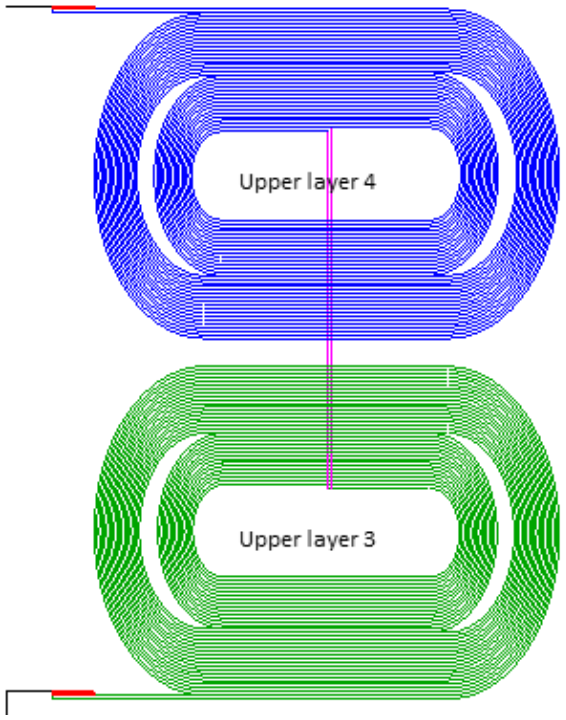
Ramp 2
(7924 A)

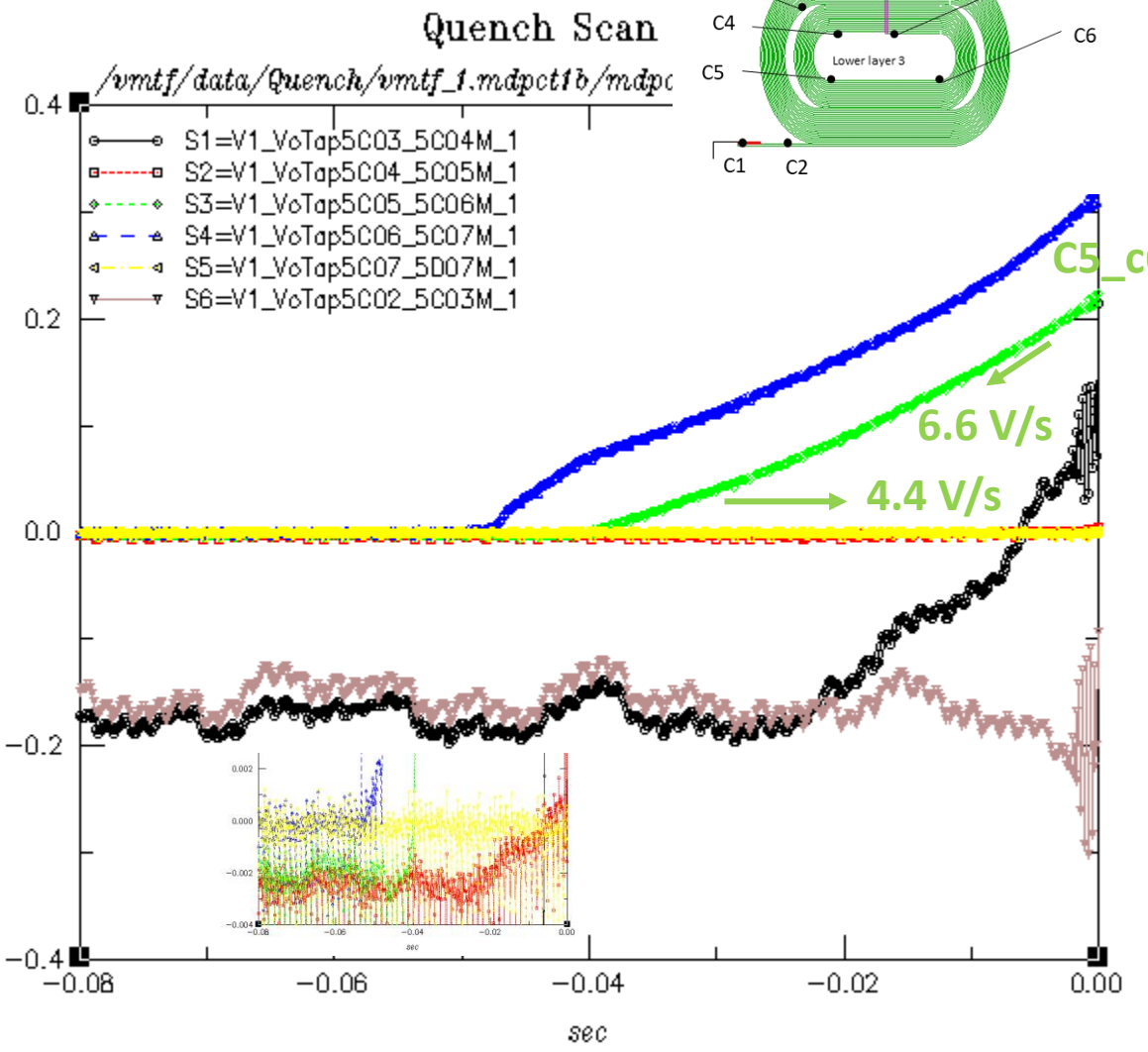



COIL 005




COIL 004




Propagation through c5_c6 ( 54 cm): 16 ms

Known

Less known

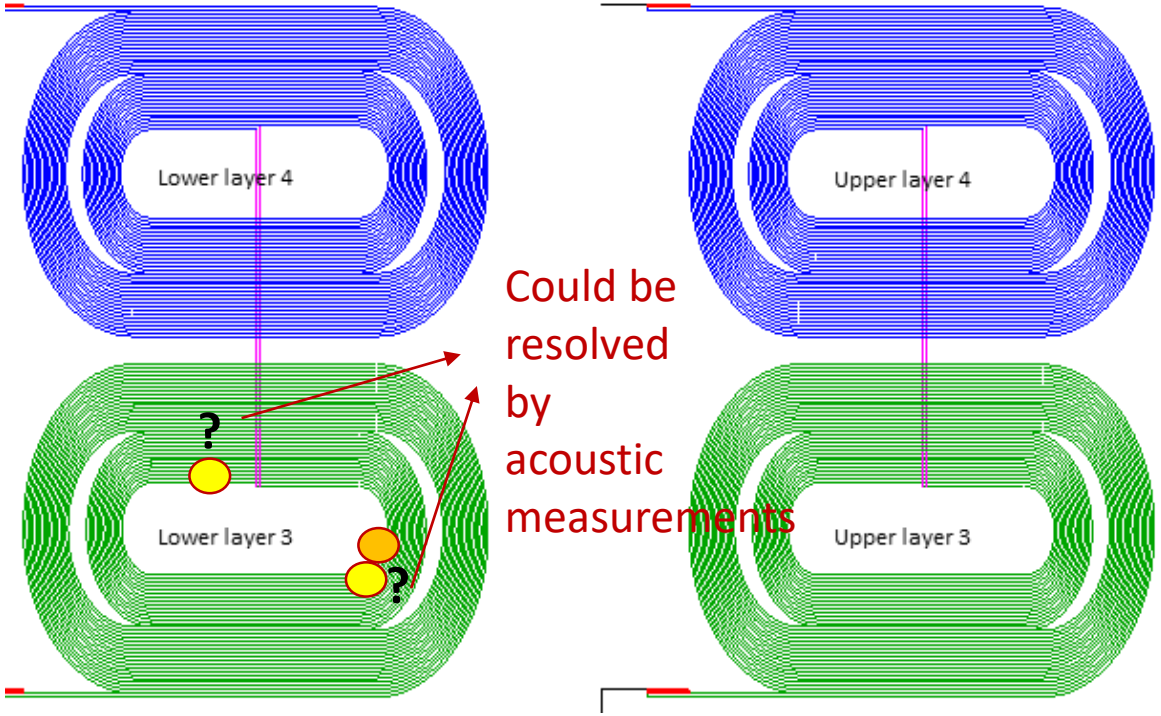
**Quench propagation V: 34 m/s (?)**
**(more likely C3_C4 is quenching independently, see later)**

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

**5; c6_c7, c5_c6, c3_c4**

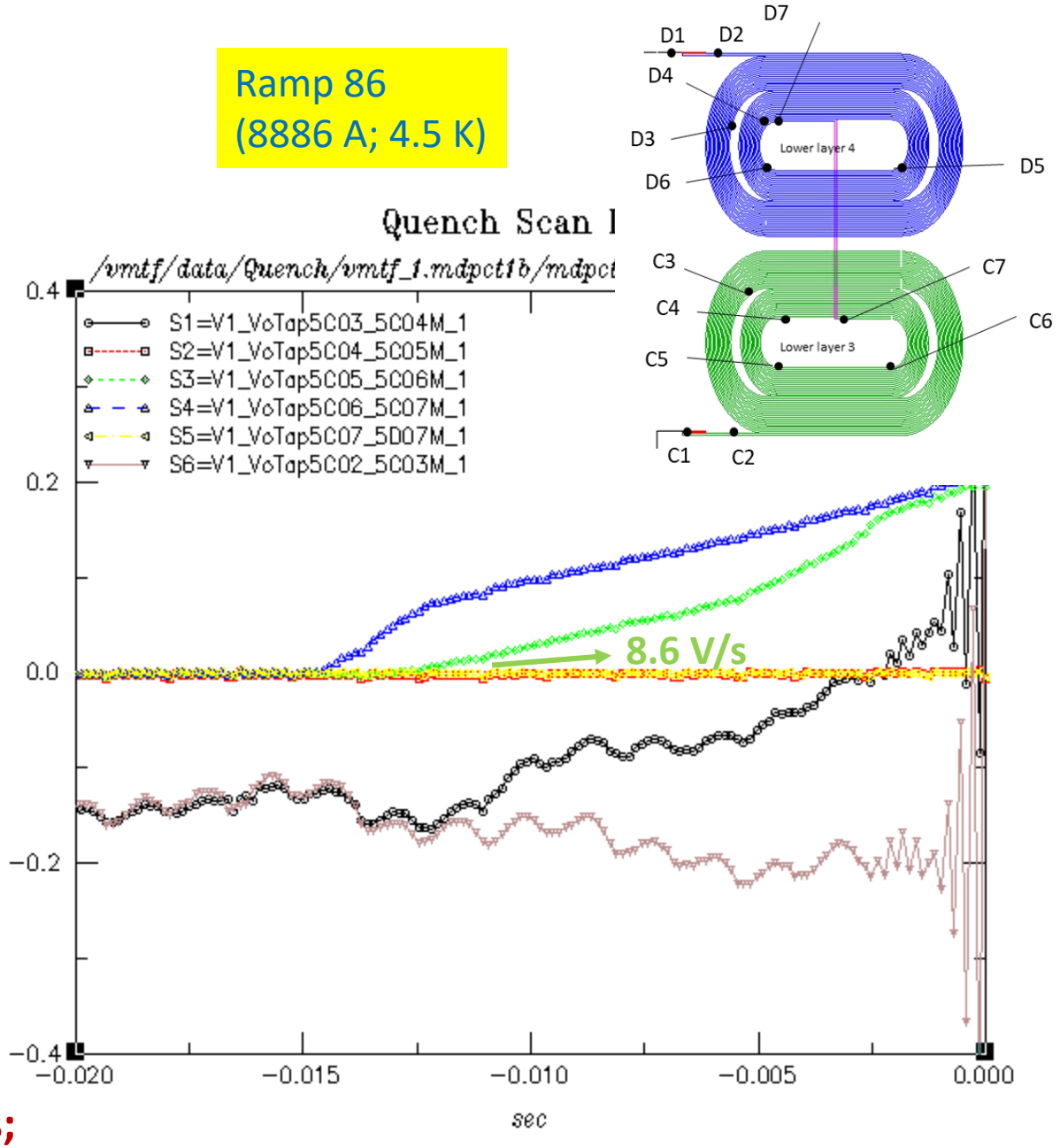
COIL 005

COIL 004




Could be resolved by acoustic measurements

Ramp 86
(8886 A; 4.5 K)




~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.**

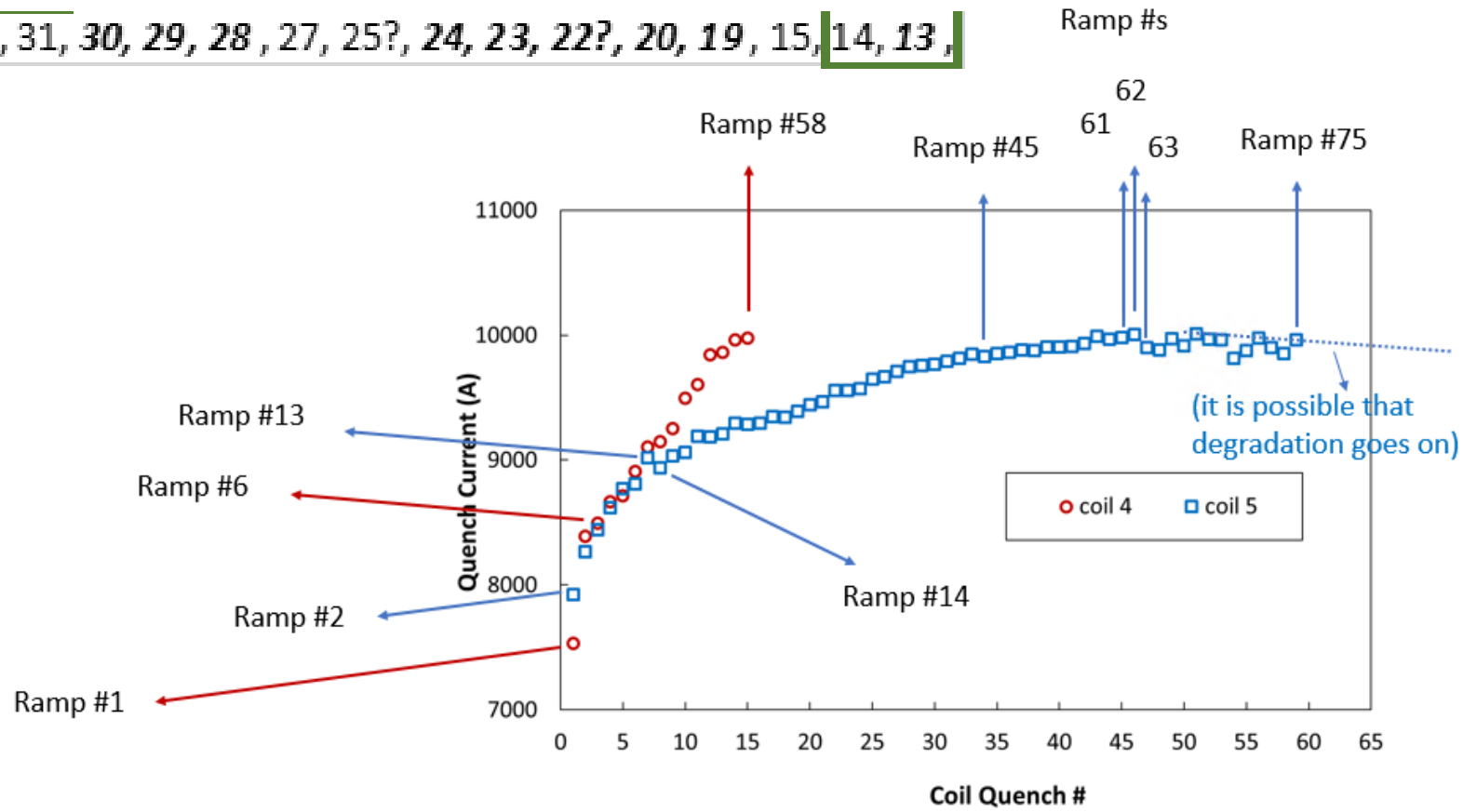
# Quenches

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

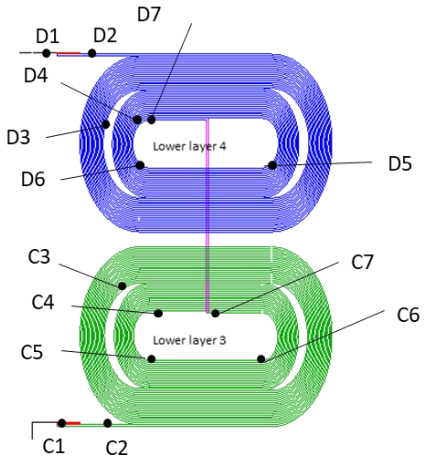
(with the two highest currents)



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 ,

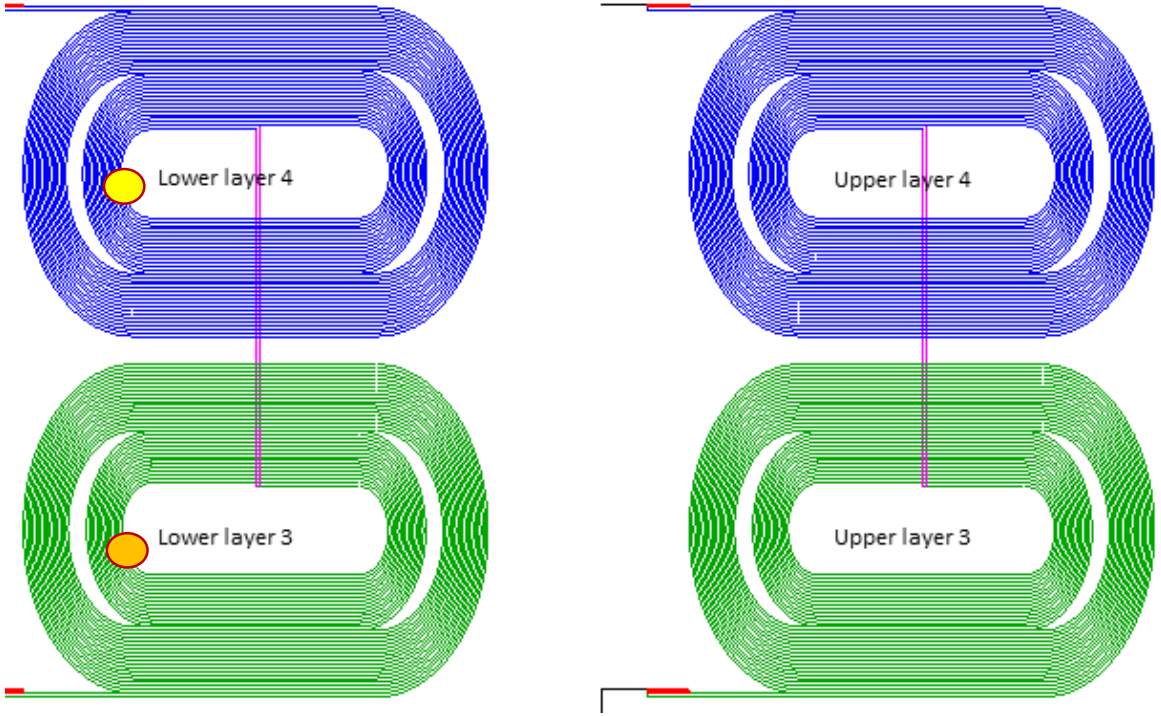
**5; c4_c5, c5_c6, d7_d6**

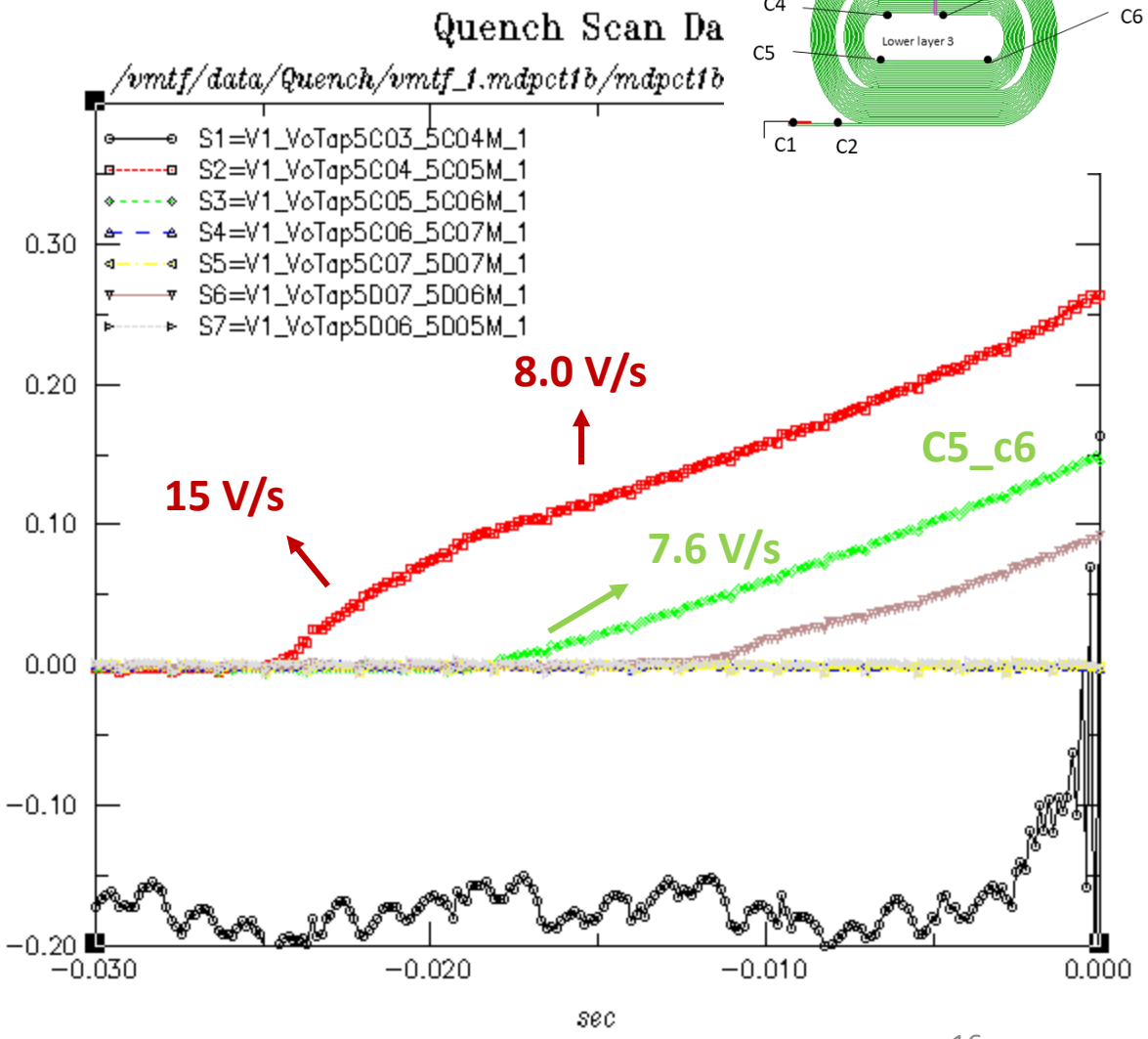
Ramp 13
(9021 A)




COIL 005

COIL 004




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

**Quench propagation V: 10 m/s**

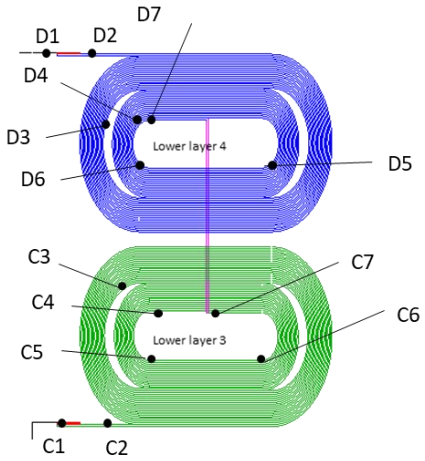
Known

Less known

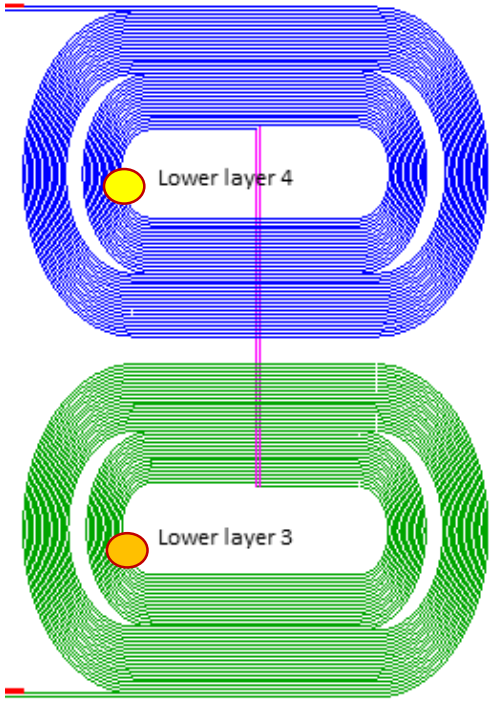
67, 62, 55, 54, 53, 52, 45, 42, 41, 40, 39, 38, 37, 34, 31, 30, 29, 28, 27, 25?, 24, 23, 22?, 20, 19, 15, 14, 13,

**5; c4_c5, c5_c6, d7_d6**

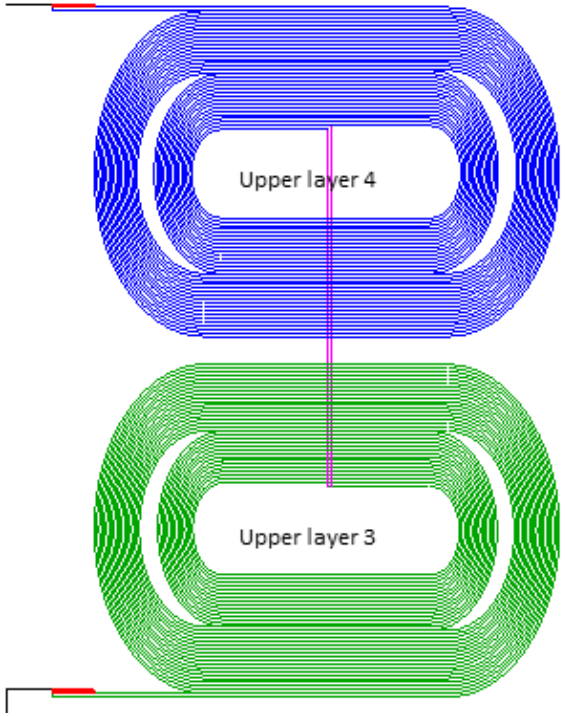
Ramp 14
(8940 A)

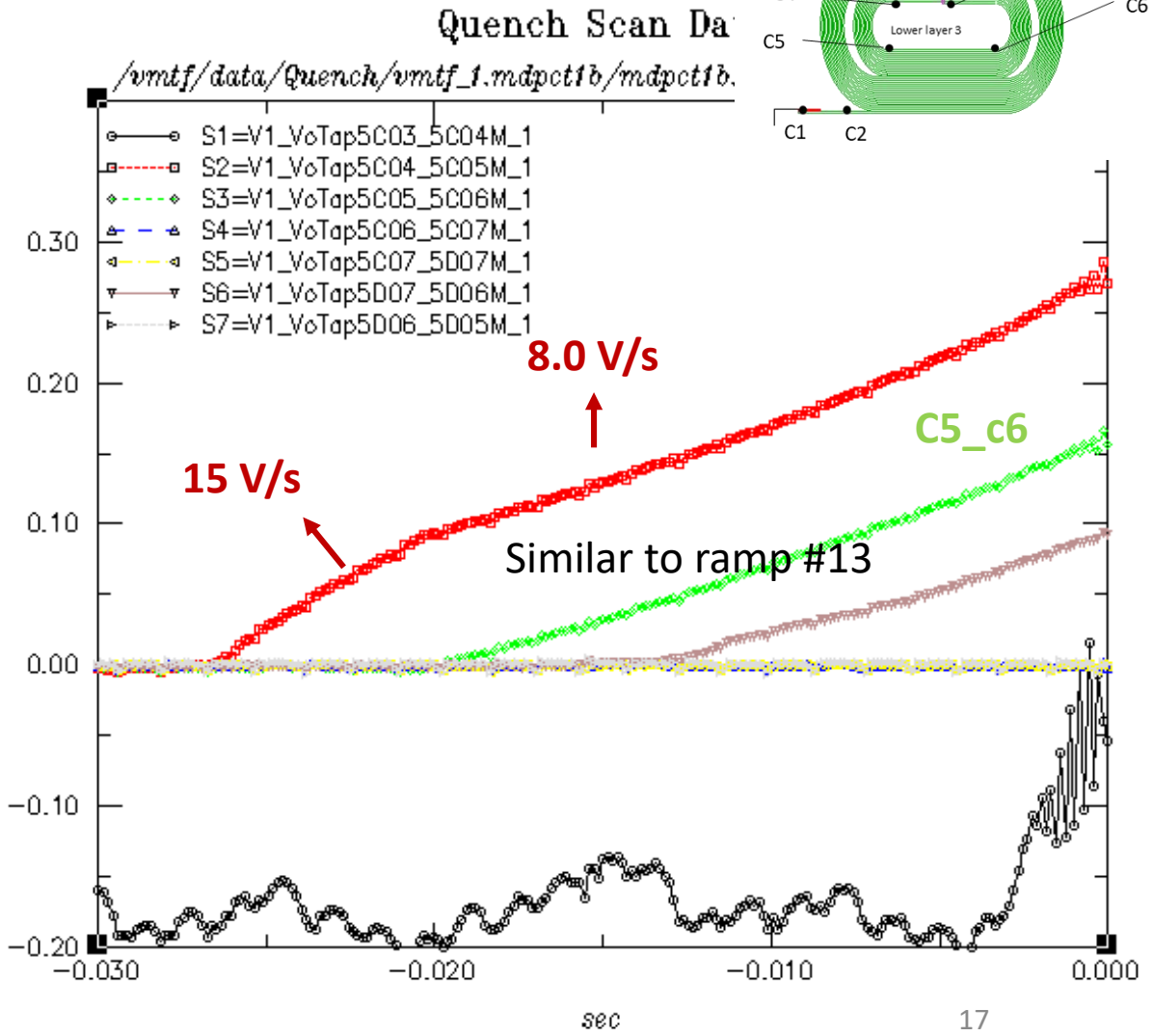



COIL 005




COIL 004




Known

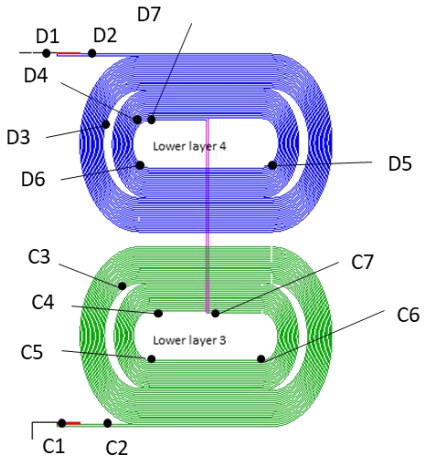
Less known

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

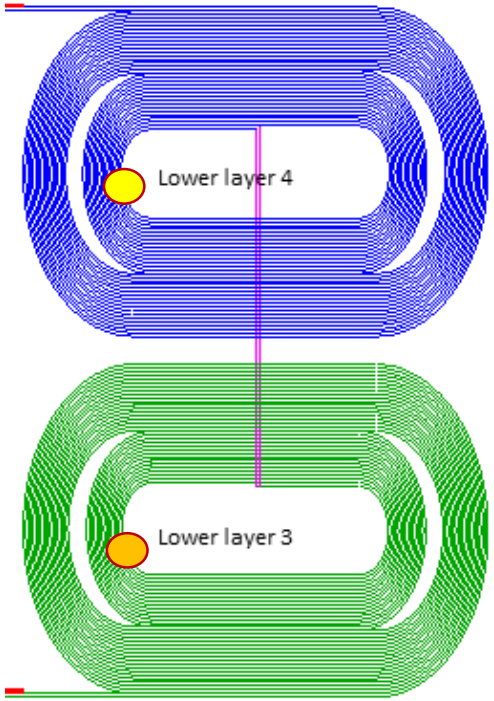
67, 62, 55, 54, 53, 52, 45, 42, 41, 40, 39, 38, 37, 34, 31, 30, 29, 28, 27, 25?, 24, 23, 22?, 20, 19, 15, 14, 13,

**5; c4_c5, c5_c6, d7_d6**

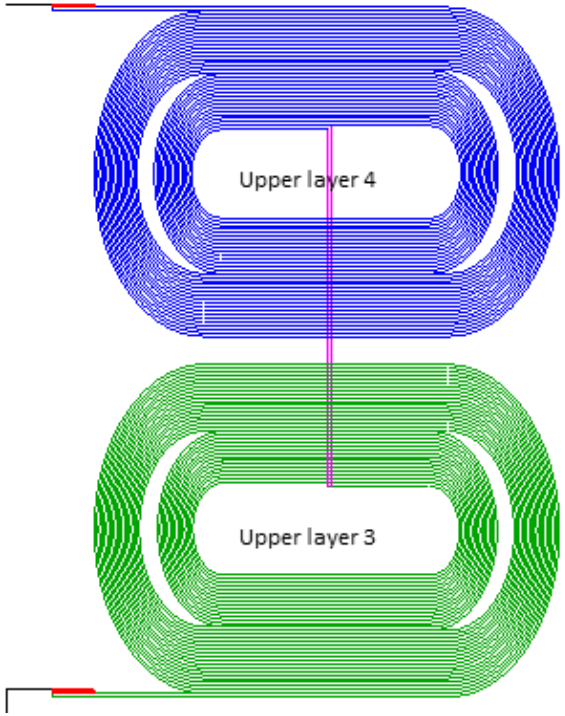
Ramp 62
(10007 A)

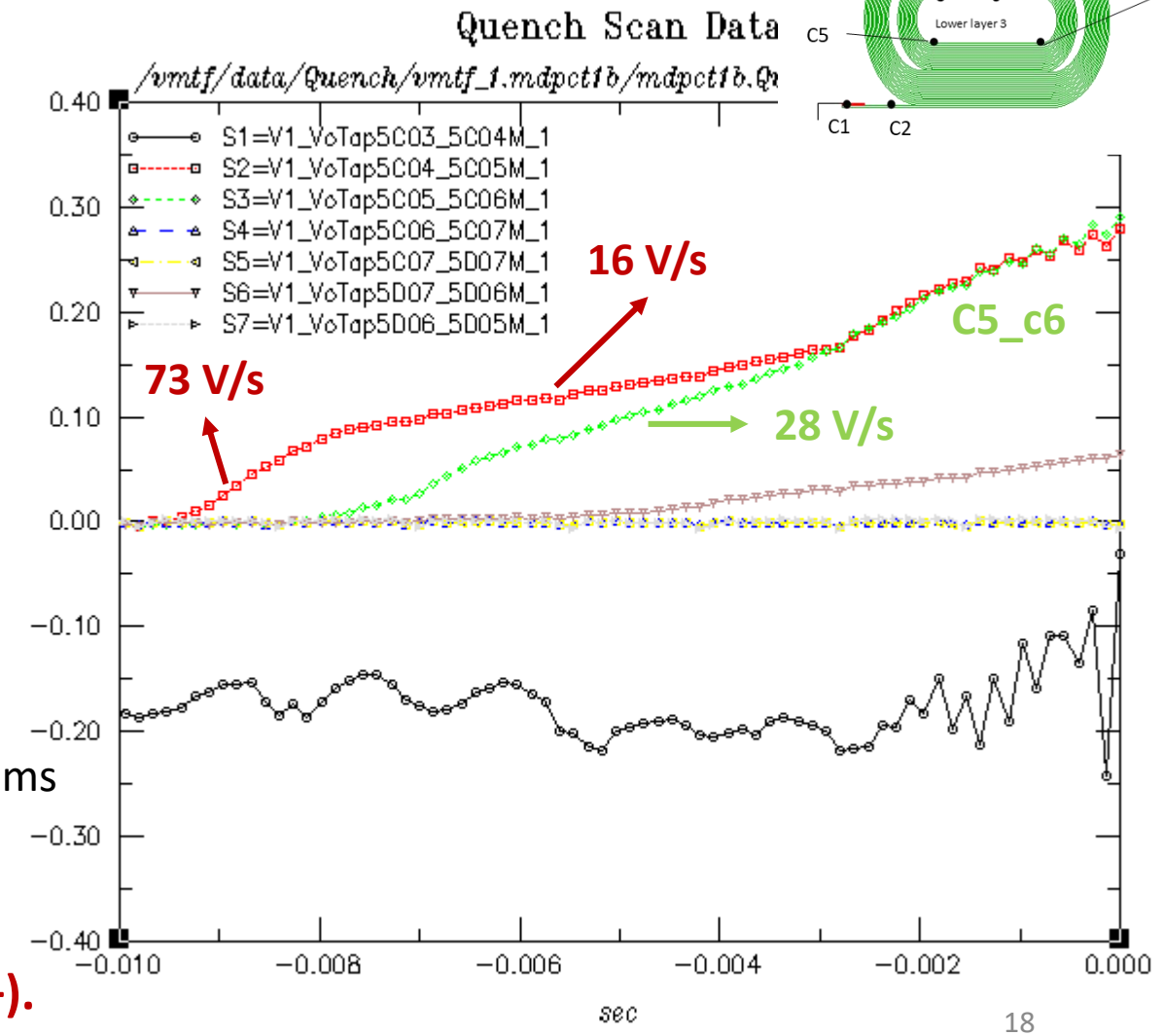



COIL 005




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!**

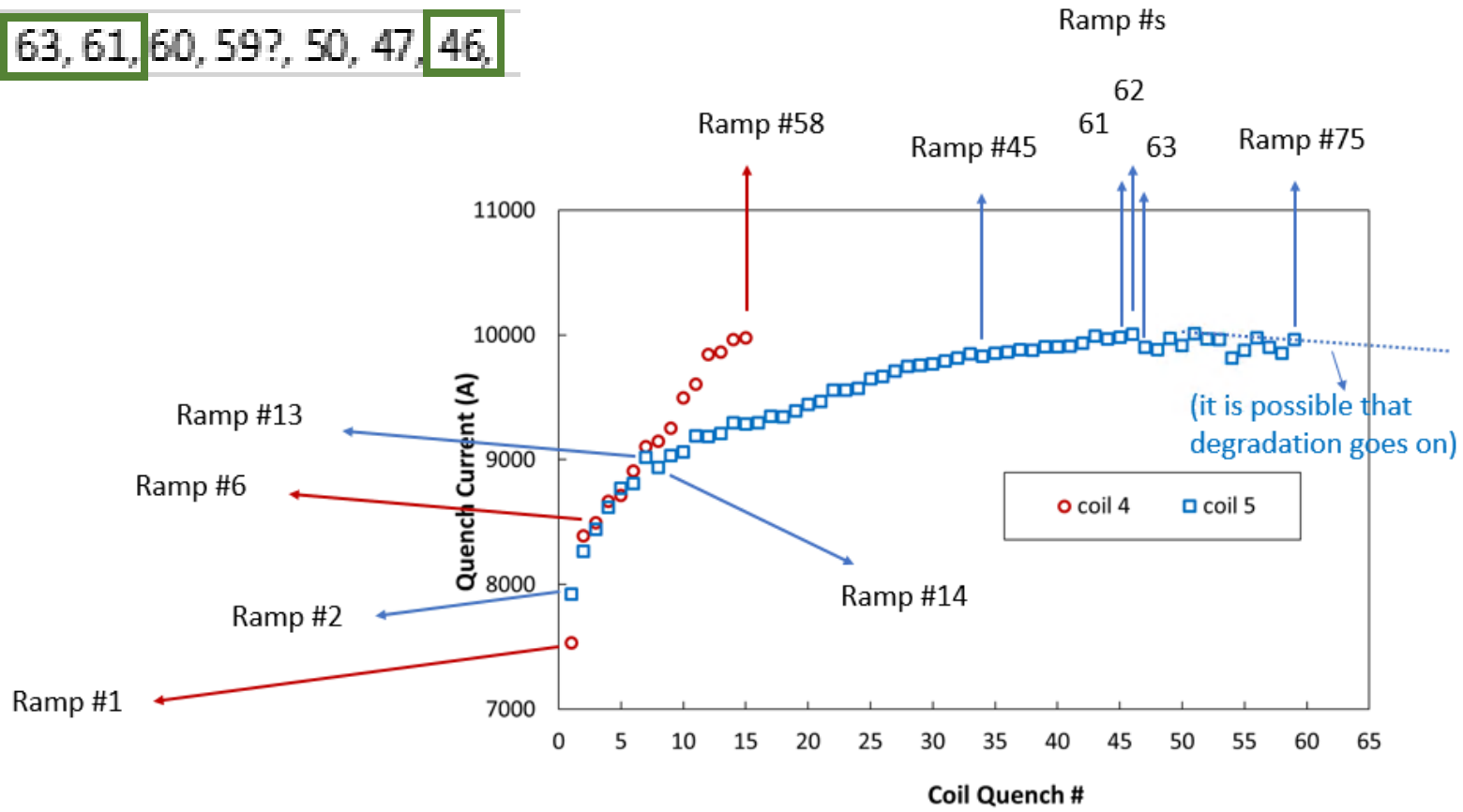
# Quenches

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

## Coil 5

## Pattern 3

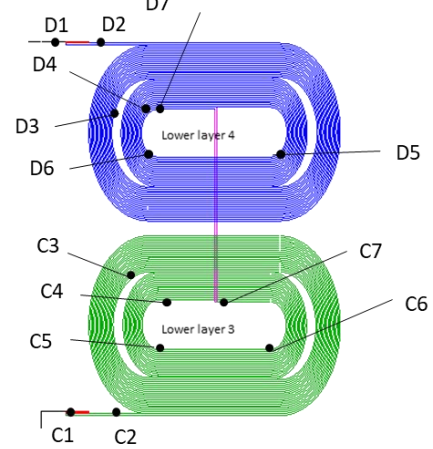
(with limiting quenches)



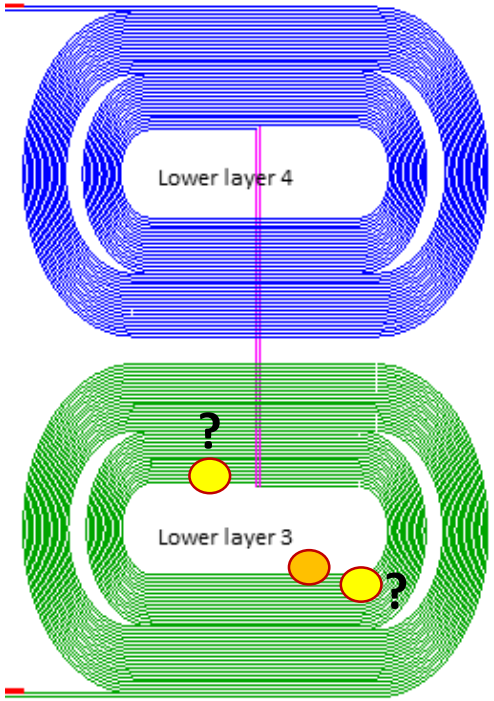
81, 80, 75, 74, 73, 72, 71, 70, 69, 68, 66, 65, 64, 63, 61, 60, 59?, 50, 47, 46,

**5; c5_c6, c6_c7, c3_c4**

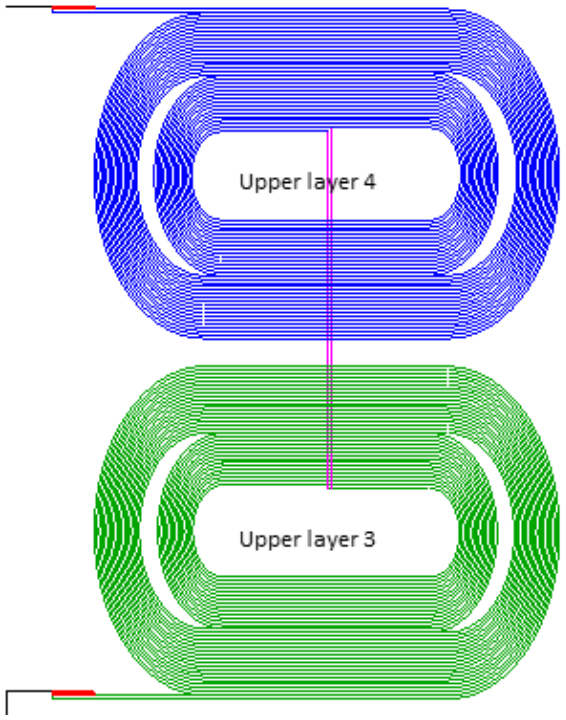
Ramp 46
(9831 A)

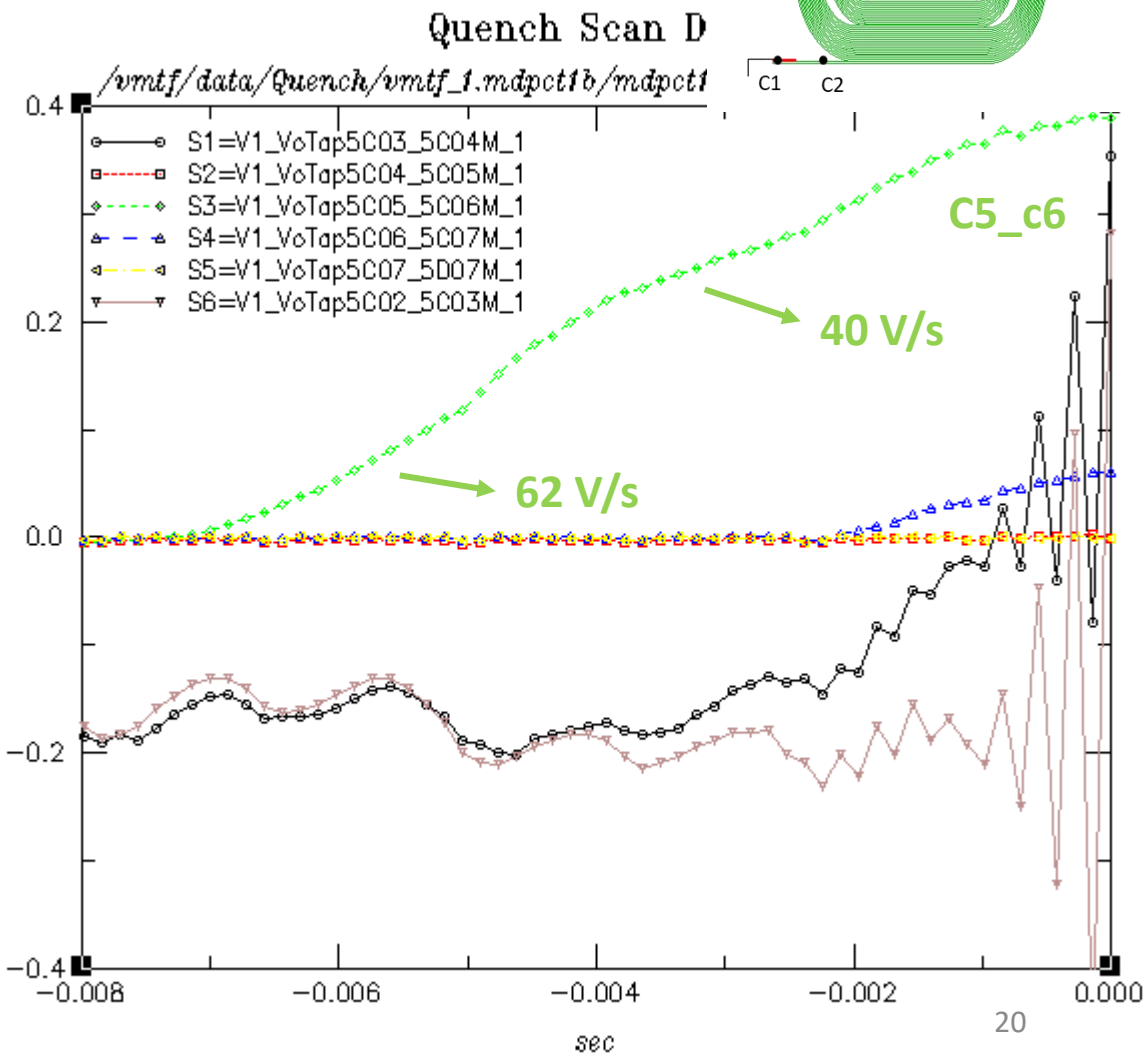



COIL 005




COIL 004




Known

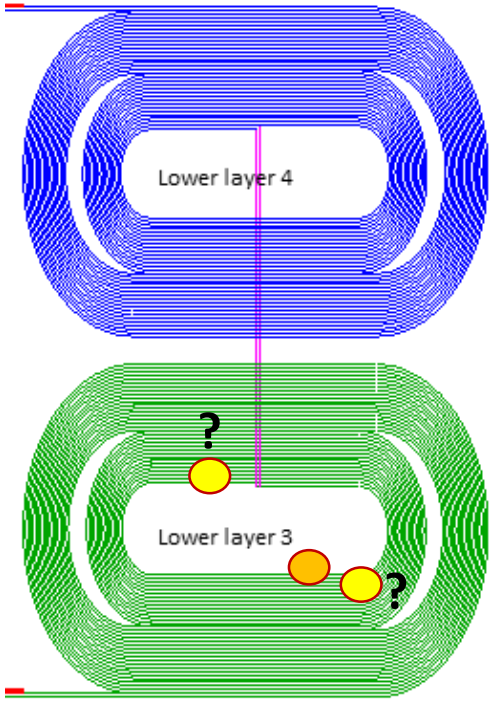
Less known

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)

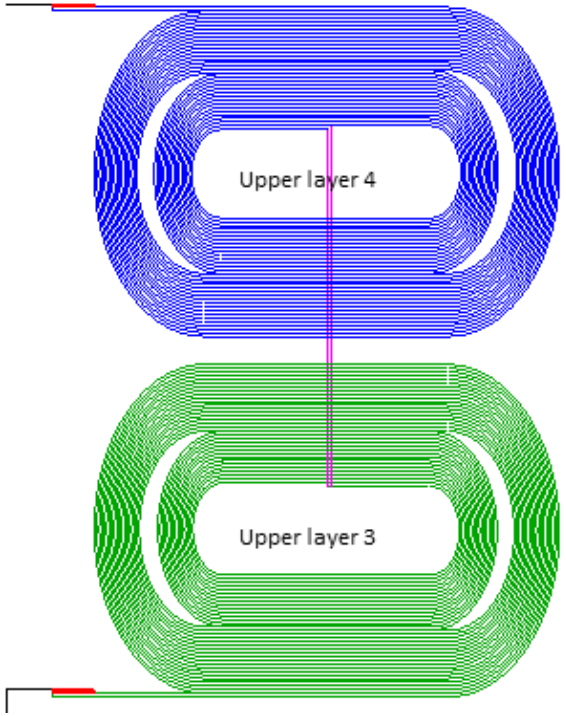
81, 80, 75, 74, 73, 72, 71, 70, 69, 68, 66, 65, 64, 63, 61, 60, 59?, 50, 47, 46,

**5; c5_c6, c6_c7, c3_c4**

COIL 005



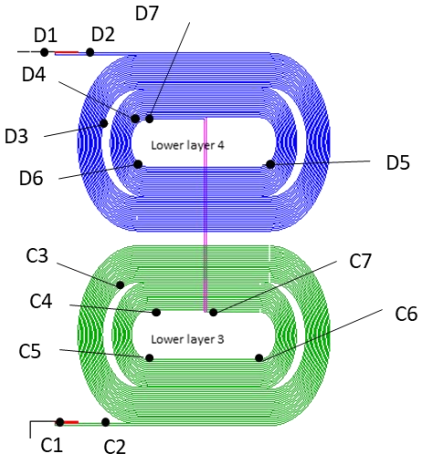

COIL 004

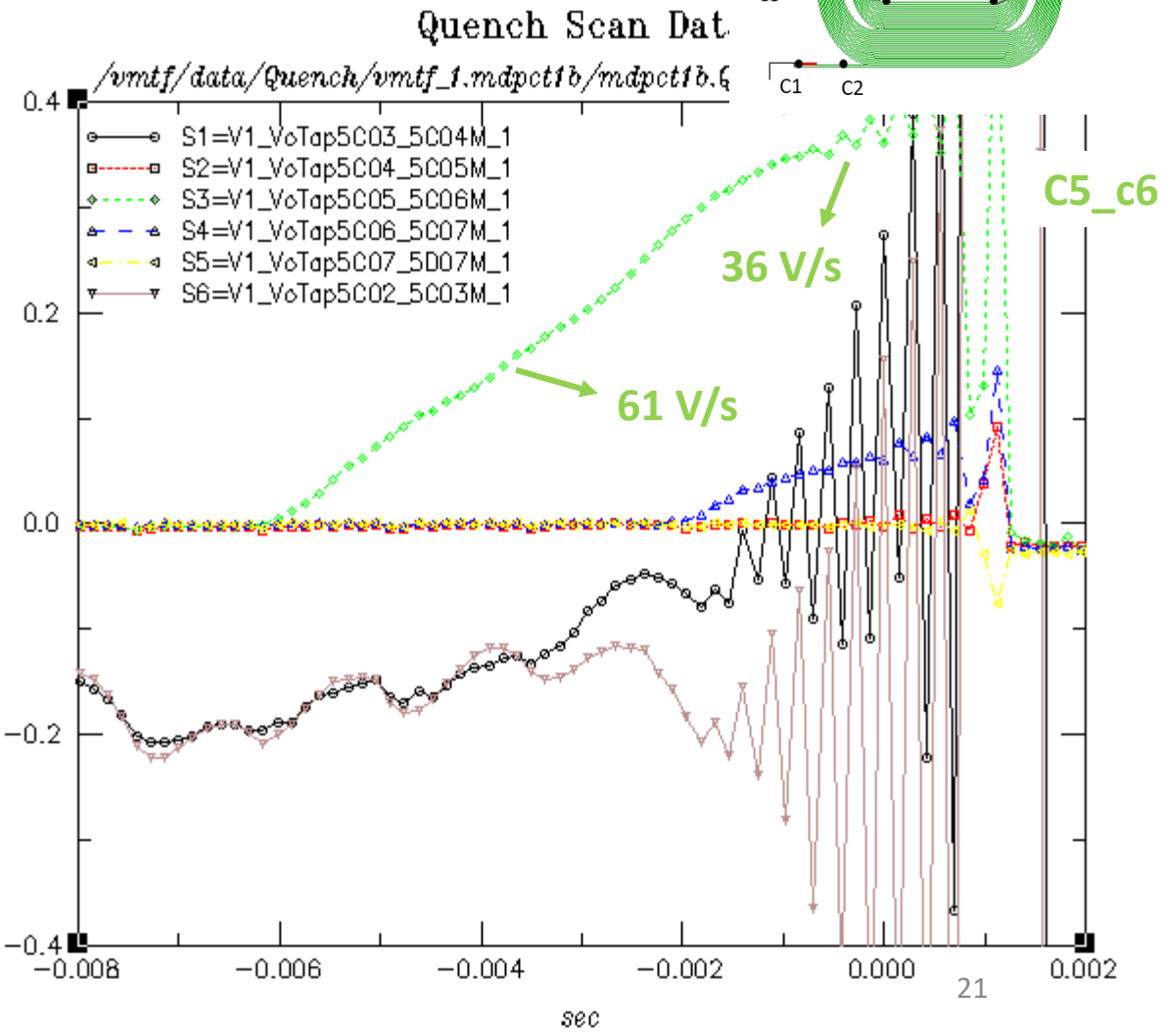



Known

Less known

Ramp 61
(9980 A)



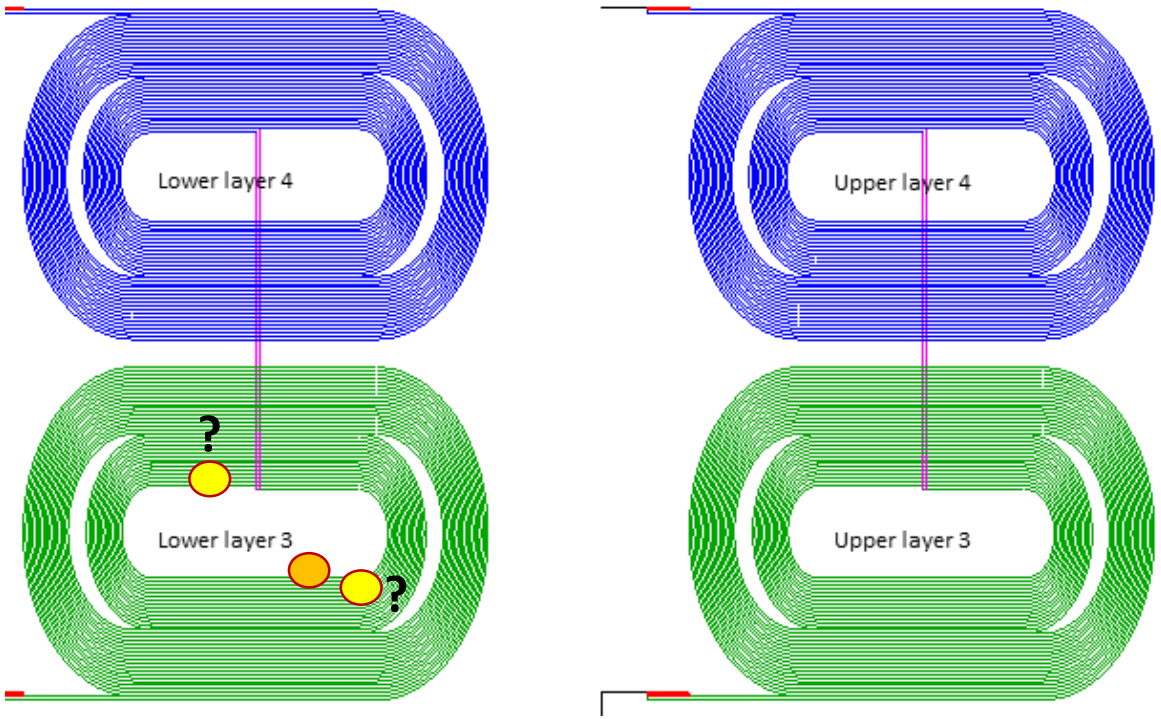
81, 80, 75, 74, 73, 72, 71, 70, 69, 68, 66, 65, 64, 63, 61, 60, 59?, 50, 47, 46,

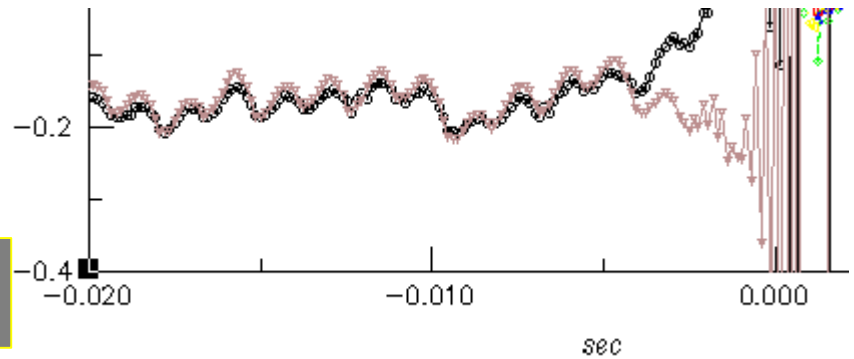
**5; c5_c6, c6_c7, c3_c4**

Ramp 63
(9900 A)

COIL 005

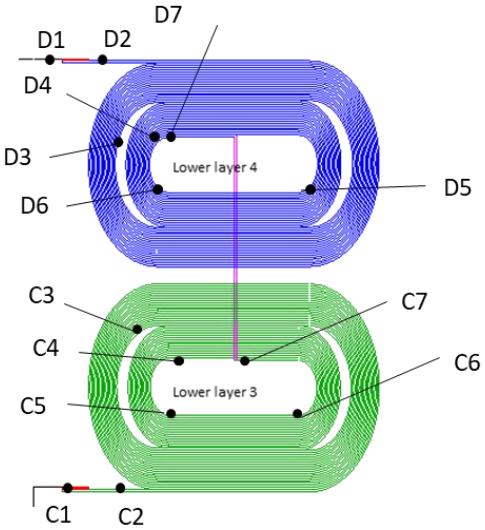
COIL 004




Known

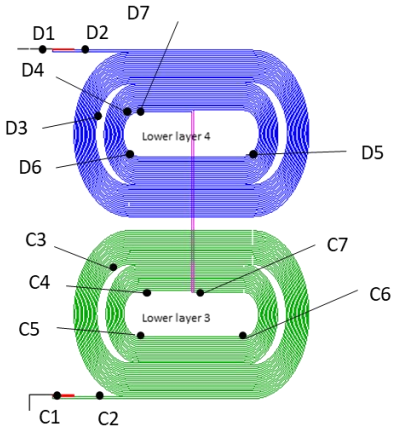
Less known



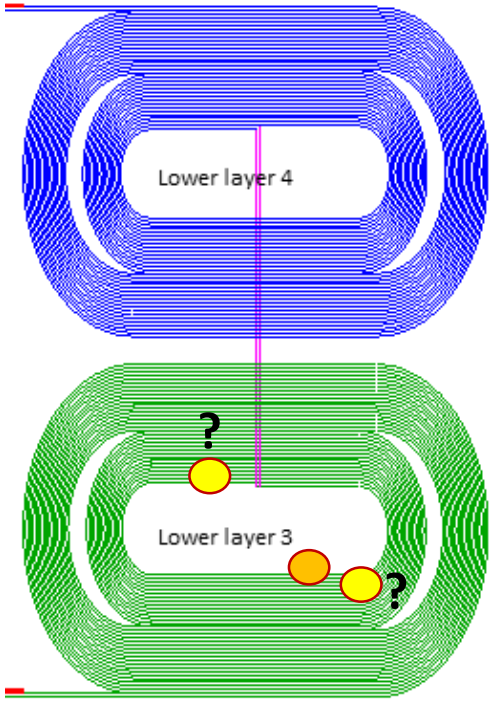
81, 80, 75, 74, 73, 72, 71, 70, 69, 68, 66, 65, 64, 63, 61, 60, 59?, 50, 47, 46,

**5; c5_c6, c6_c7, c3_c4**

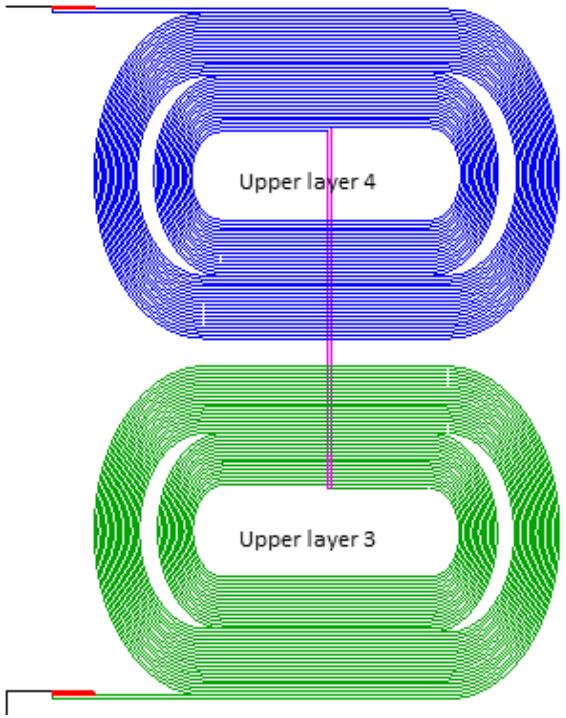
Ramp 75
(9961 A)

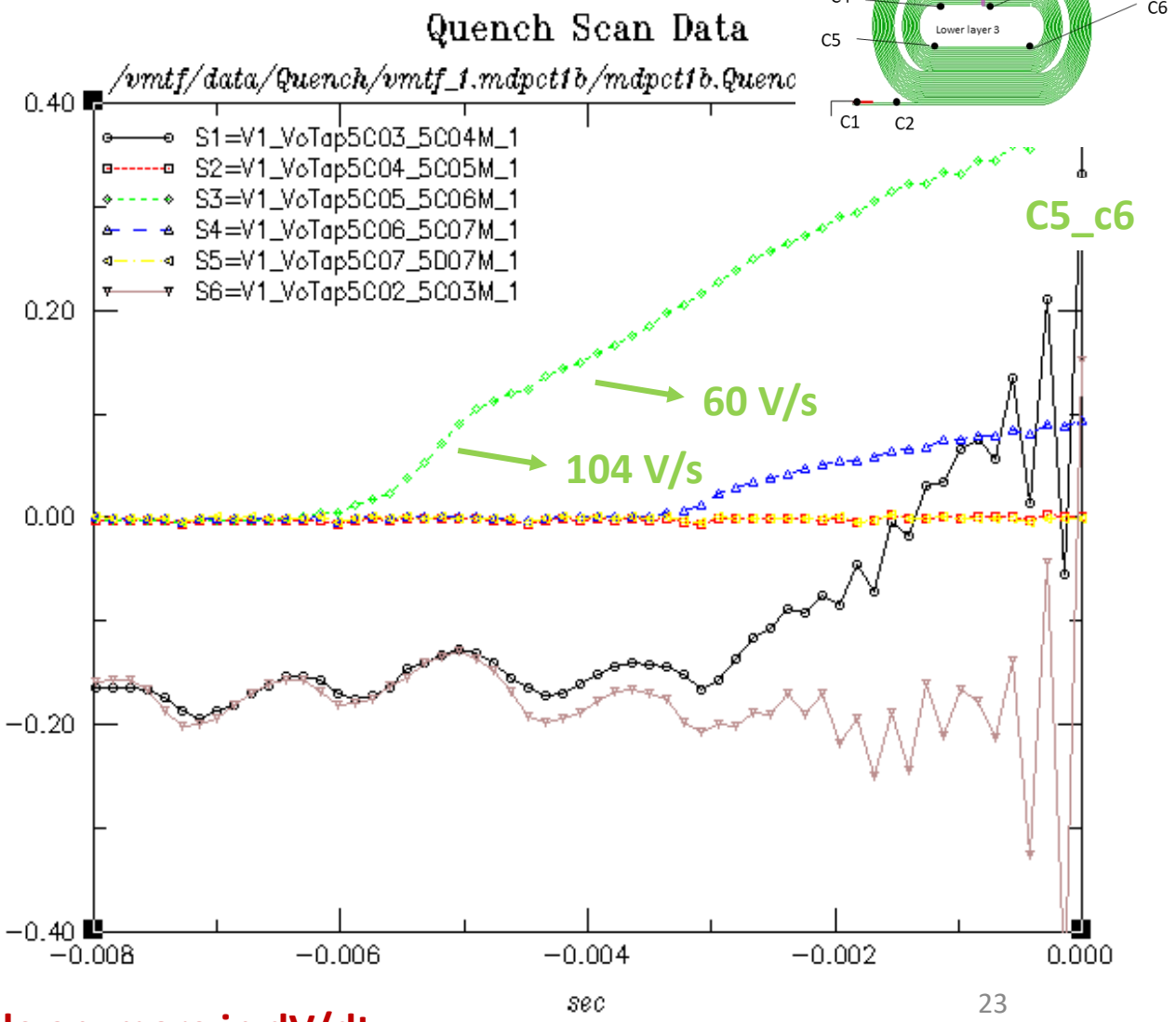



COIL 005




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.**

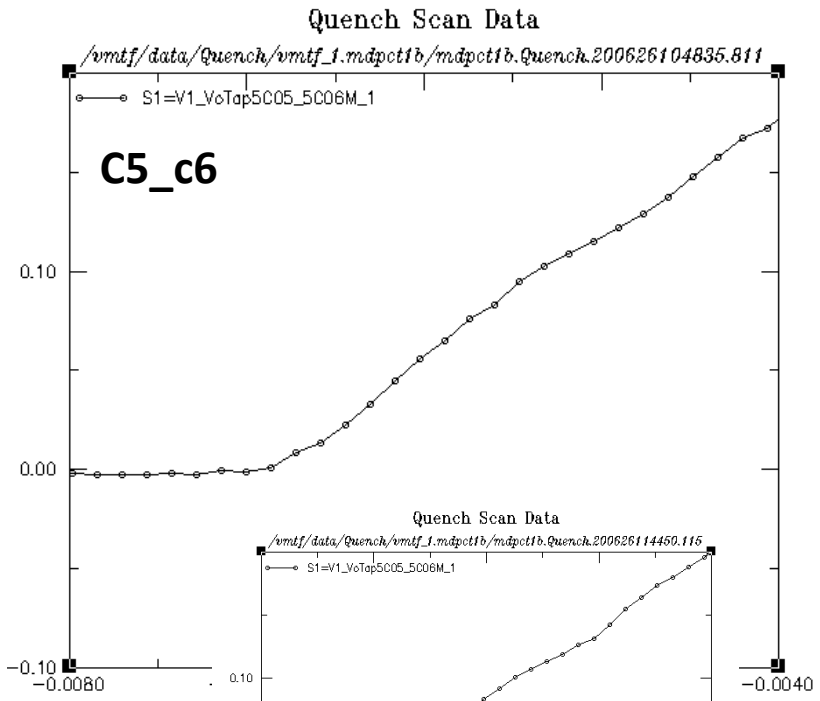
81, 80, 75, 74, 73, 72, 71, 70, 69, 68, 66, 65, 64, 63, 61, 60, 59?, 50, 47, 46,

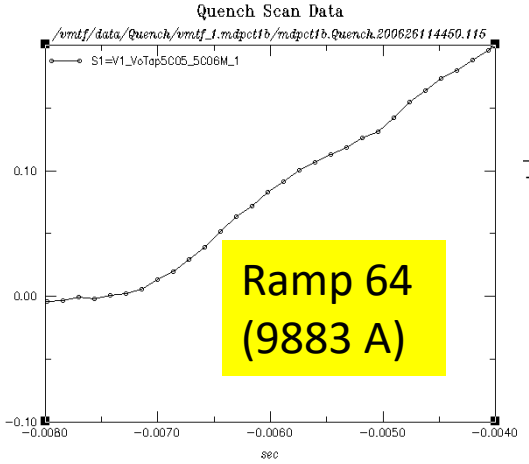
**5; c5_c6, c6_c7, c3_c4**

Ramp 63
(9900 A)

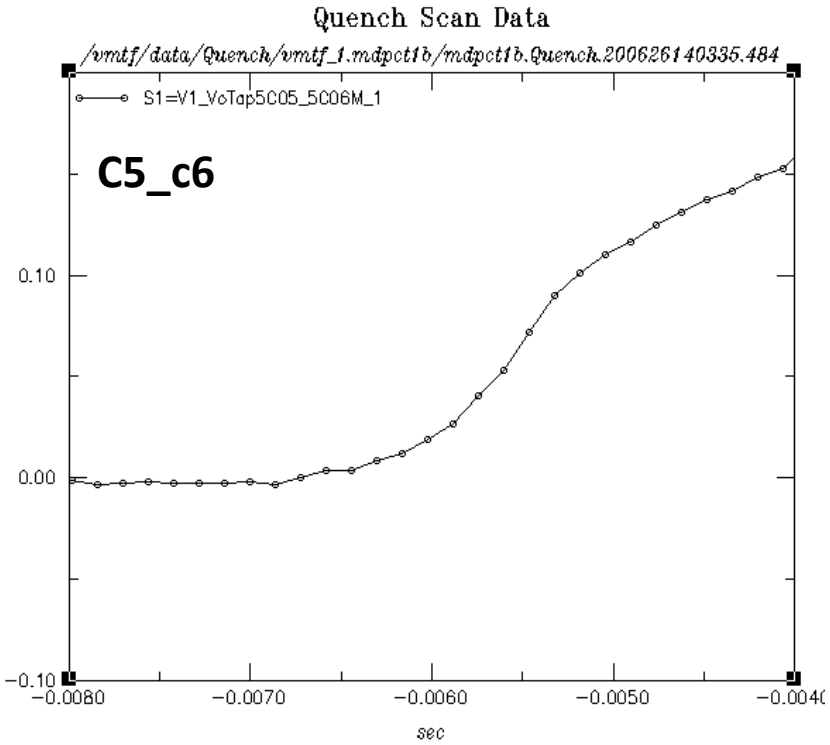
Ramp 66
(9913 A)

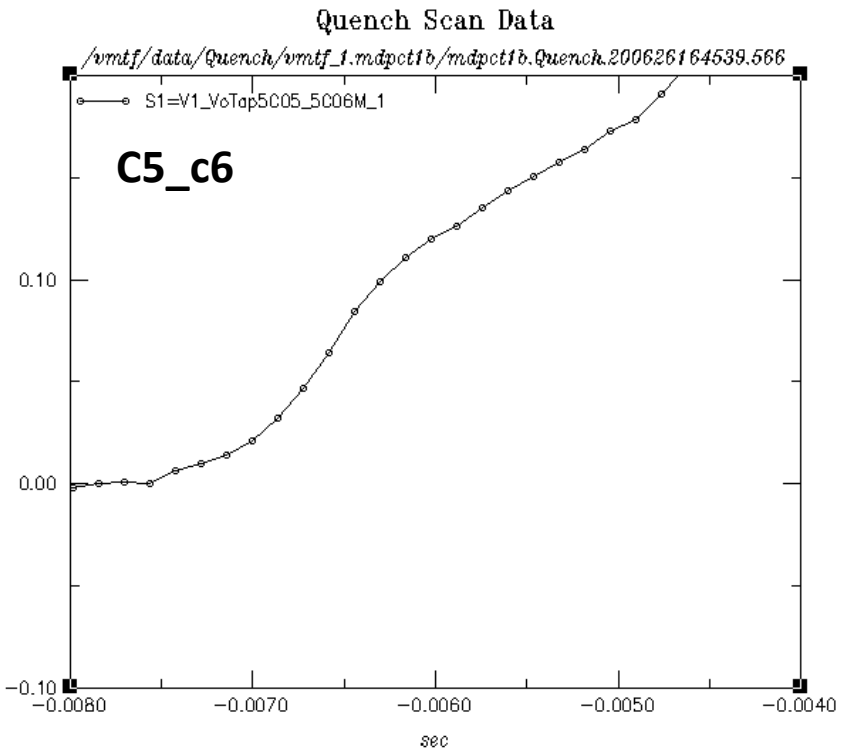
Ramp 68
(9969 A)




Ramp 64
(9883 A)

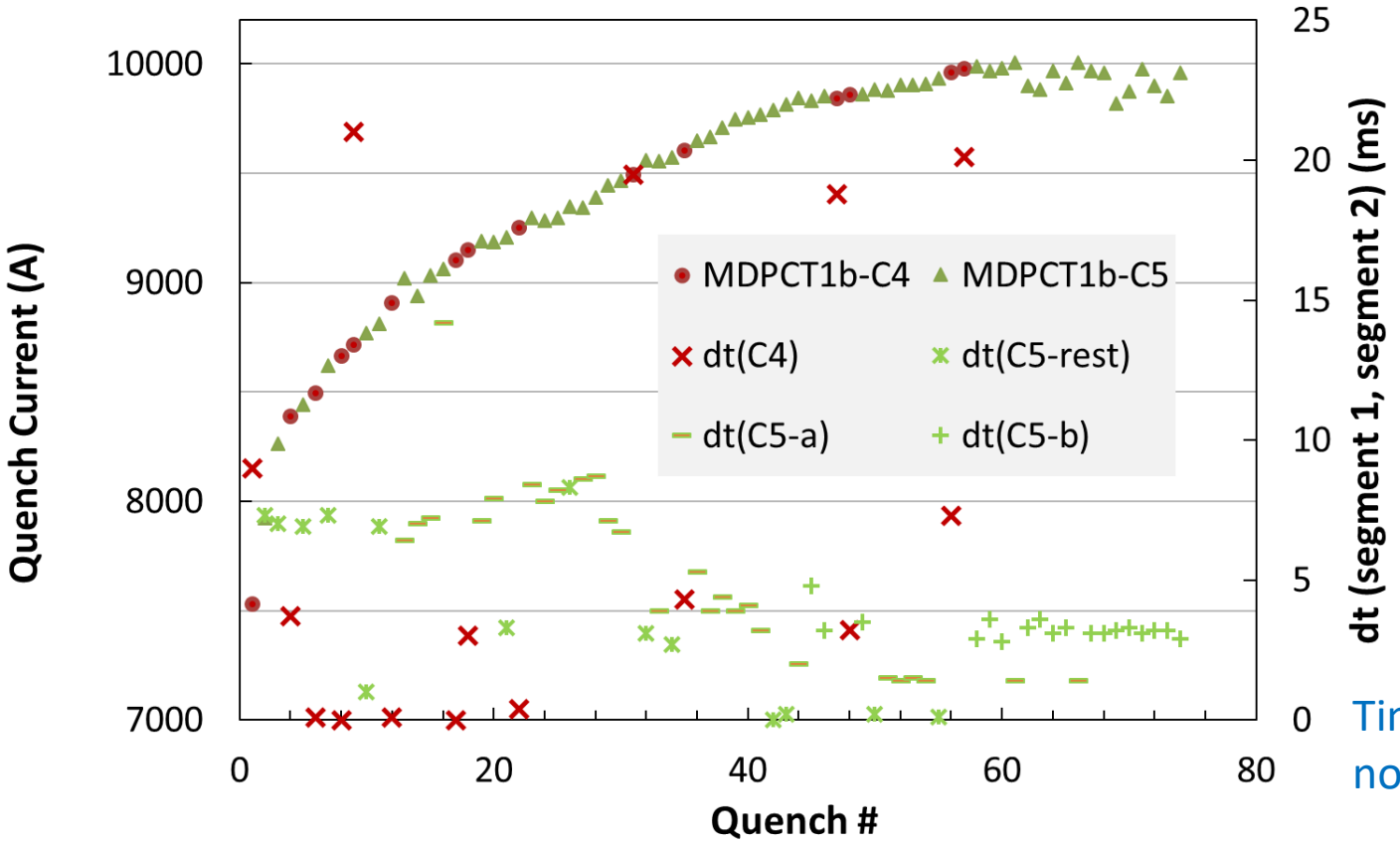



Those are all same scales.

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 $\Delta t$ 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.

# Summary

- ❑ Quench velocities can only be determined in small part of the quenches and they increase at higher currents (as expected)

- ❑ Voltage rising (dV/dt) patterns are useful to monitor change in behavior

- ❑ While the propagation speed clearly increases toward high currents, non-linear/large initial expansions are seen in multiple quenches toward the end of the training curve (coil 5)
  - ✓ may indicate degradation “initiation”
  - ✓ beyond the first milli-second dV/dt are consistent for large part of the training curve in the segment we can monitor (5C5_C6)

- ❑ Ramp rate and temperate dependence quenches are similar to some early training quenches at 1.9 K