QCD performance evaluation and highlights of MBHSM03 testing

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Quench Current-boosting Device (QCD)

(reminder)

- <u>LDRD project</u>
  - Completed (term ended)
  - Partial Department support for adjacent activities (like power supply modifications and update, control logic implementation) - 10-20% of all

- Capacitor based device
  - 400 mF, up to 1 kV (200 kW)
  - Boosting magnet current at quench/trip detection (for instance) aiming to affect magnet training

- First “cold” test with a “11 T mirror” magnet – MBHSM03
  - Coil (#12) never used before
  - Assembly parameters followed MBHSM01 parameters

Chris Jensen
Matt Kuffer
Howie Pfeffer

See also QCD status in https://conferences.lbl.gov/event/885/

QCD was developed and fabricated by engineers in Accelerator Division of FNAL

MBHSM03 testing – main goals

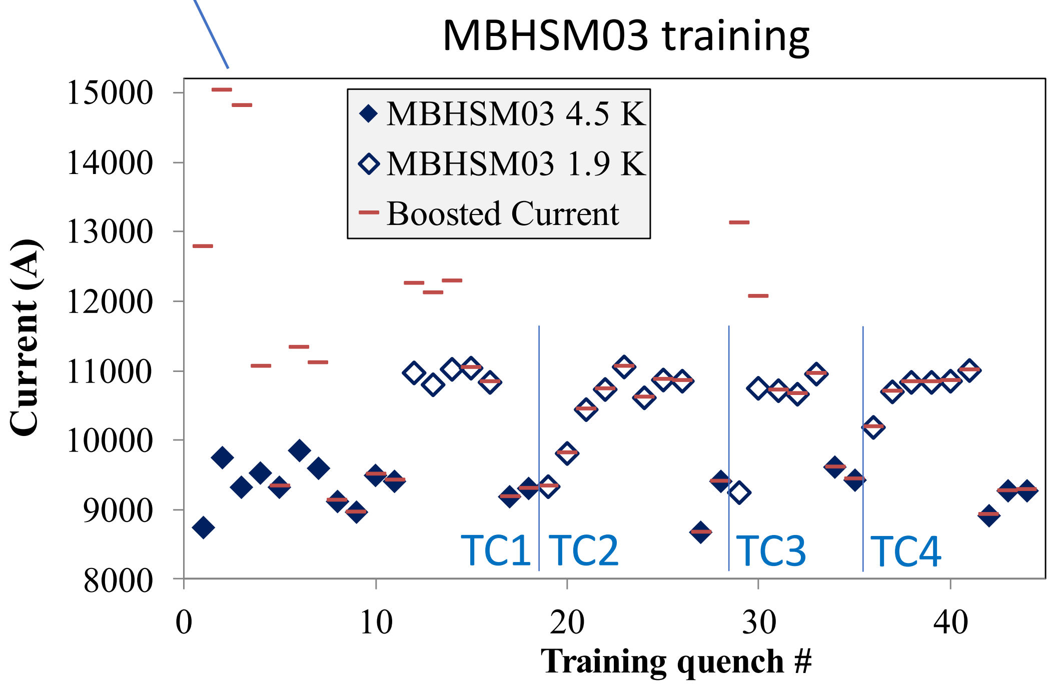
(reminder)

- Commission the QCD with a real SC magnet
- Train the magnet studying the effects of QCD on it
- Test new diagnostics capabilities

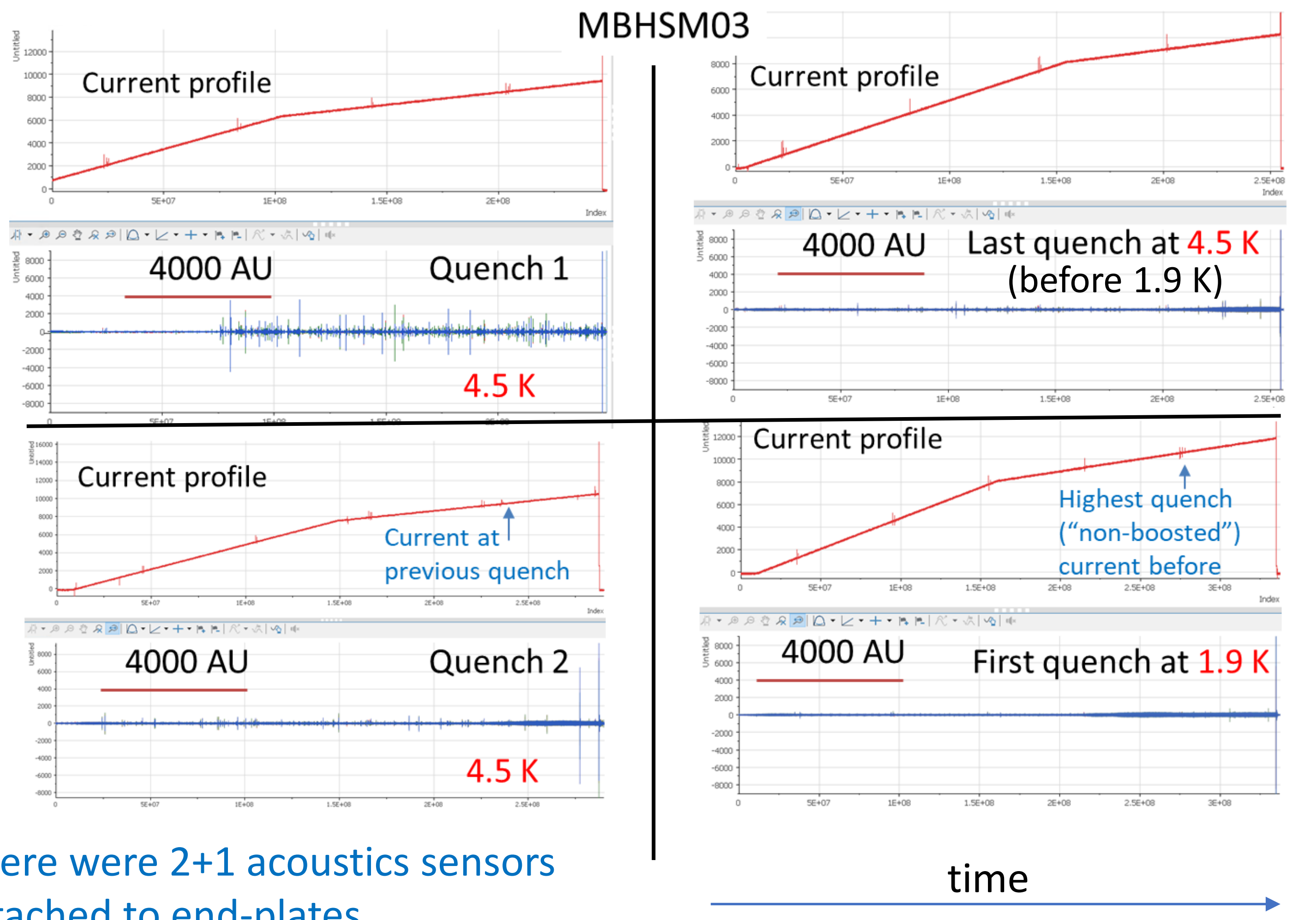
  (QA arrays, fiber-optics, acoustics real time calibration)
- Assess quality of the new diagnostics data
- Perform dedicated acoustics tests

MBHSM03 training and features

The red lines indicate QCD "boosted" current
(QCD was used if the line is above the data point)



Acoustic response in TC1 (in arbitrary units)

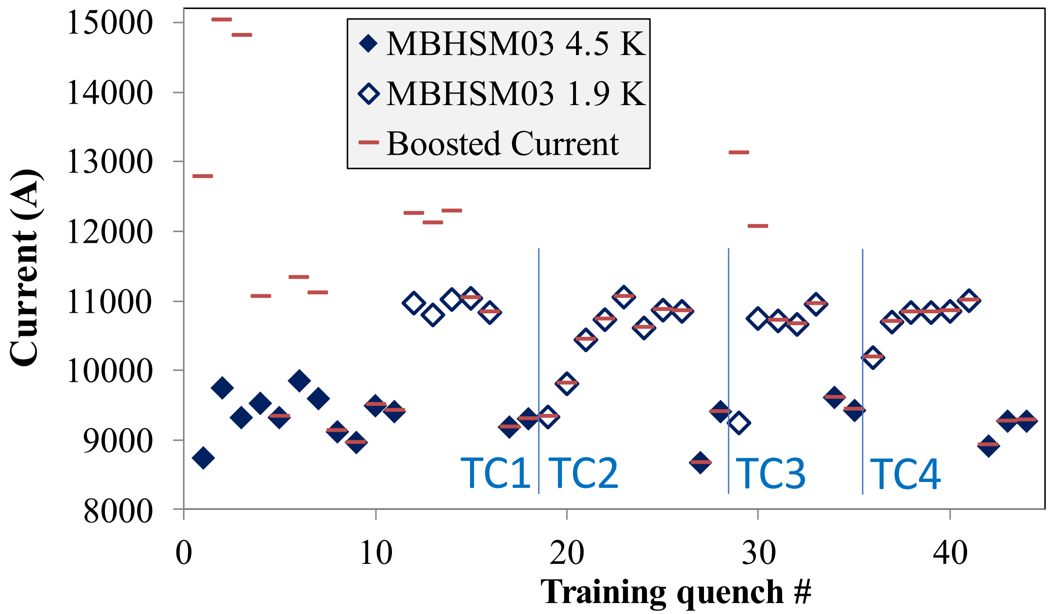


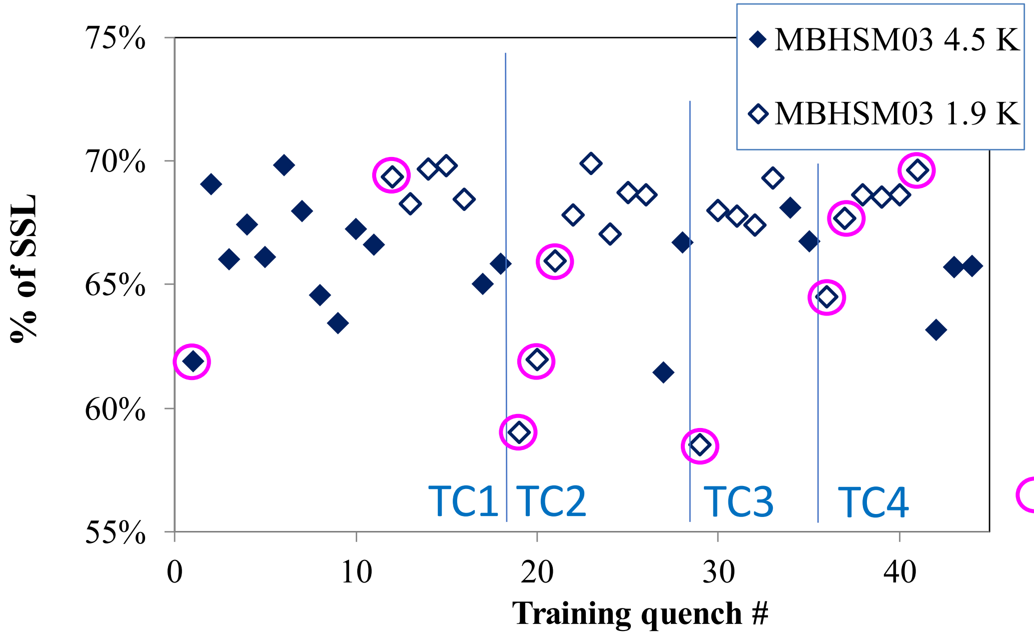
There were four thermal cycles (TC), i.e. cool-downs from 300 K (the magnet stayed in the pit all the time)

There were 2+1 acoustics sensors attached to end-plates (i.e. different longitudinal positions)

MBHS coil training comparison

MBHSM03 training



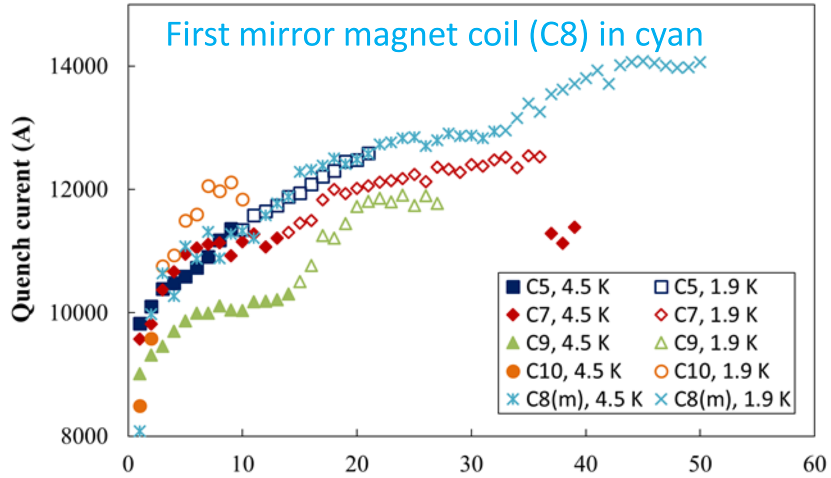


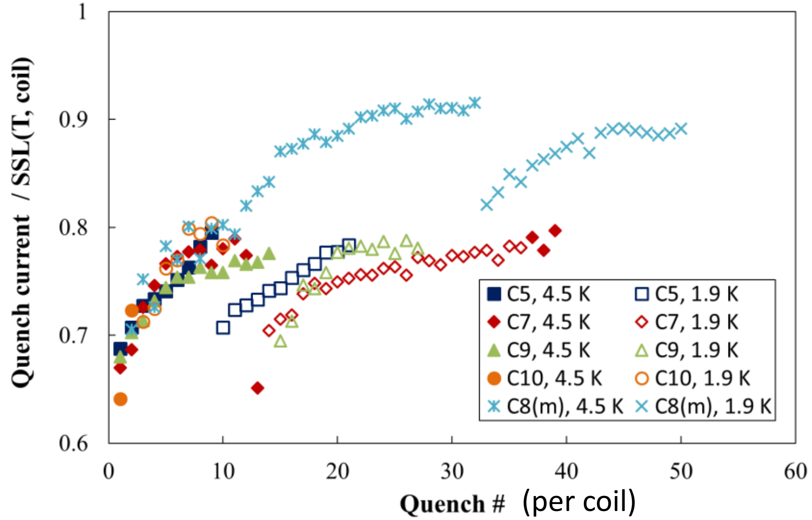
- **MBHSM01 went to ~14 kA**
- **There is nothing special about 4.5 to 1.9 K transition: all coils train**

SSL was calculated recently by Melanie T. (±6%)

○ - Indicates an IL quench (all others are OL quenches)

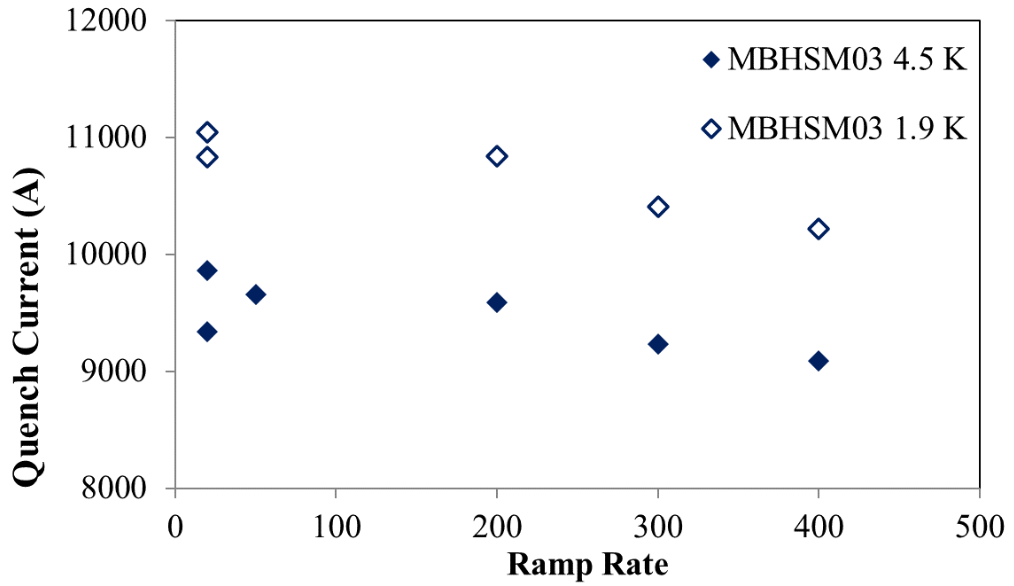
"11 T" coil training (20 A/s)

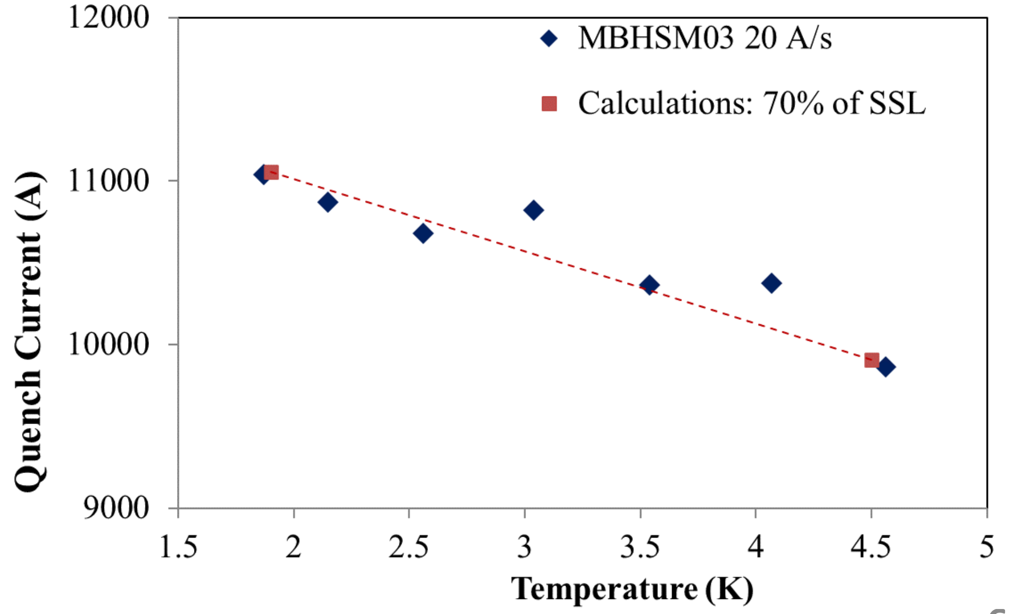




MBHSM03 ramp rate and temperature dependence

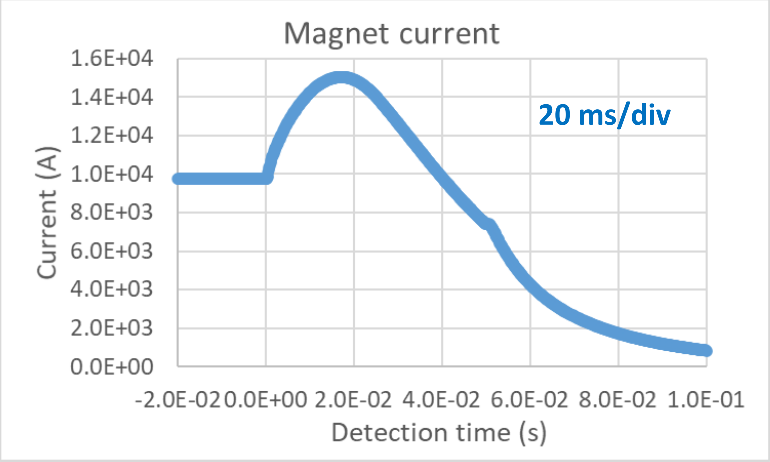
- Quench current dependence on ramp rate, at 1.9 K and 4.5 K, confirms non-abnormal behavior
  - two measurements are 20 A/s indicate observed "erratic behavior" (range)
- Along with the above, quench current dependence on temperature shows conductor limitation on performance
  - measurements at 3 K and 4 K appear to be off – it could be due to insufficiently warming the conductor to reach those temperatures though it is hard to support such large deviations



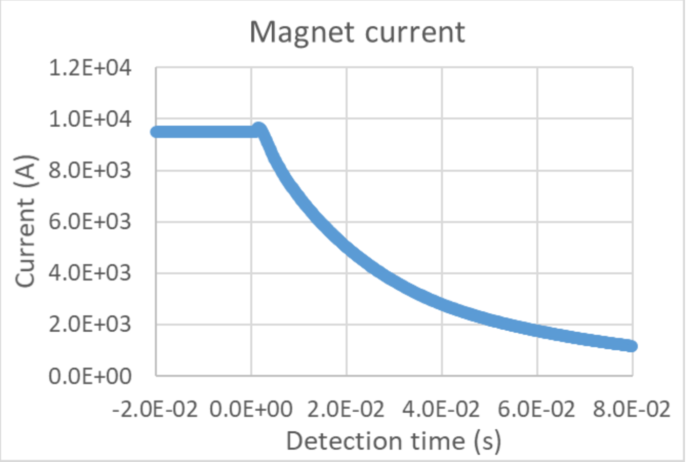


dI/dt comparisons

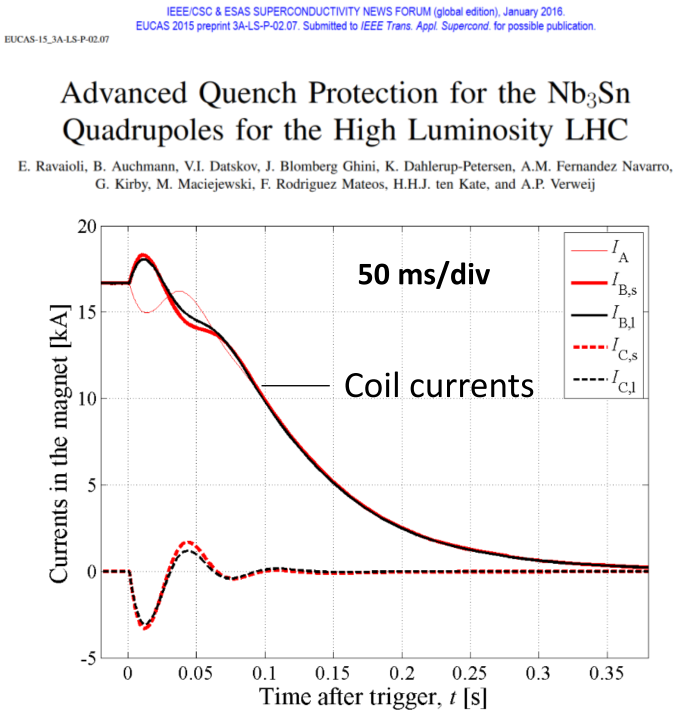
MBHSM03, with QCD



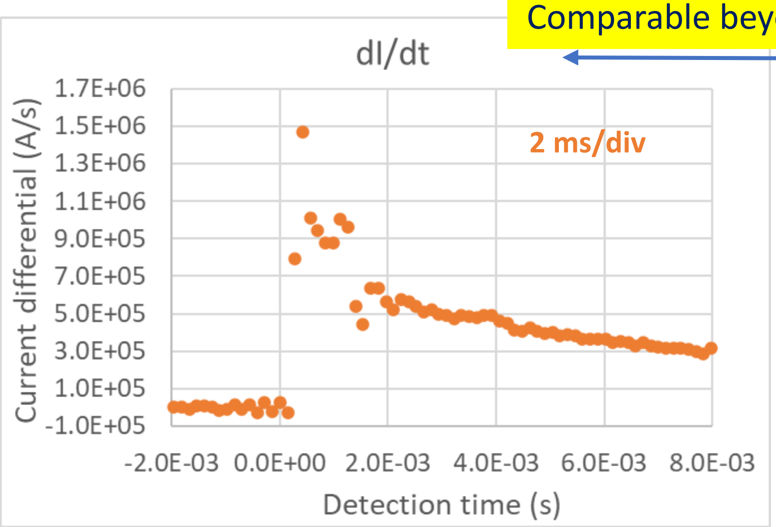
MBHSM03, no QCD

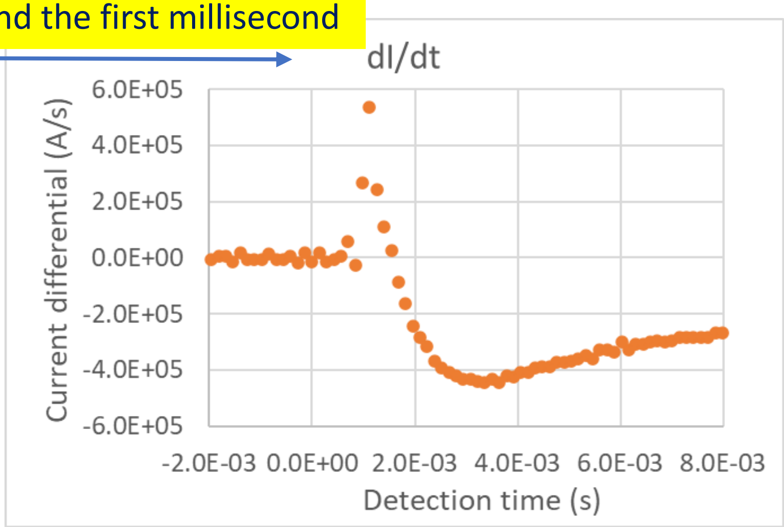


CLIQ discharges (HL-LHC study)



Comparable beyond the first millisecond





The average magnet current increase is ~ 1.5 kA /15 ms ~ **1×10^5 A/s**
(this is a "nominal" current discharge)

The average magnet current increase is 5 kA/17 ms ~ **3×10^5 A/s**
This was the maximum (quench 2), other discharges were smaller.

Those two numbers are comparable

MBHSM03 training and features

- In TC1 the magnet did not train between current levels of 4.5 K and 1.9 K plateaus
  - Those were not stable, especially at 4.5 K (“erratic” behavior)
  - Those plateaus were at conductor limit
  - All 11 T coils showed training between 4.5 K and 1.9 K current levels (like it is the case for other magnets)
- In TC2 (1.9 K) the magnet forgot its training and trained
  - No QCD used
  - Reached conductor limit
- In TC3 (1.9 K) the magnet forgot its training
  - The first quench current was at the level of the first quench current in TC2
  - QCD was used
  - MBHSM03 reached conductor limit
  - No training observed between the first quench current and the conductor limit
- In TC4 (1.9 K) the magnet only partially forgot its training
  - Much higher level for the first quench current
  - The first and second quenches were in the IL (like in TC2 during training)

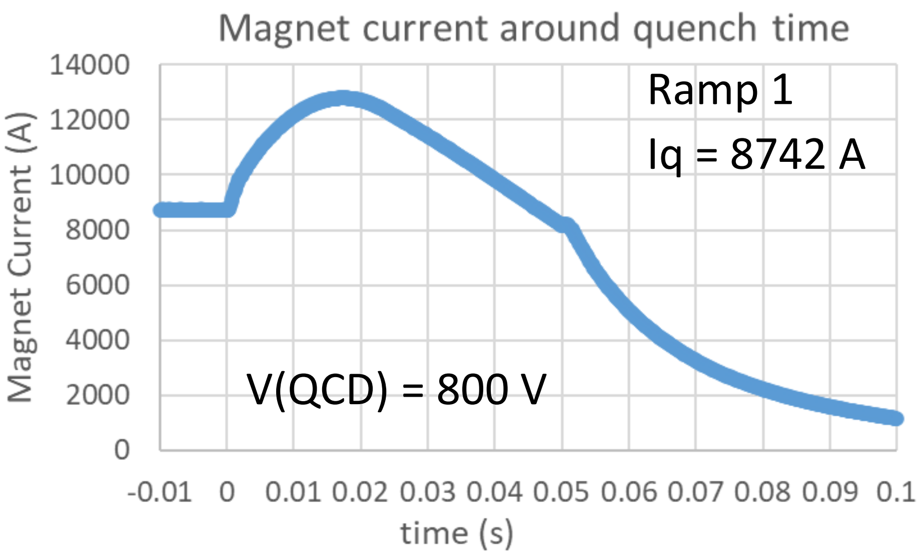
- In all cases, after QCD is used the magnet becomes “quiet” during ramping (no Kaiser effect indicates stress levels exceeded ones corresponding to quench current levels)

QCD and larger magnets - inductances

Magnet description	Inductance	Actual inductance
11 T small mirror	~1.5 mH	
11 T	~ 5.6 mH/m	
11 T 2-in1	~12 mH/m	
15 T demonstrator (4-layer)	~15 mH	
LARP small mirror	~3 mH/m	
AUP, long magnets (quads)	8.2 mH/m	33 mH
Hybrids	?	

Let’s take 33 mH as a base for a “large” magnet and see what boost can be achieved

Response normalization to MBHSM03

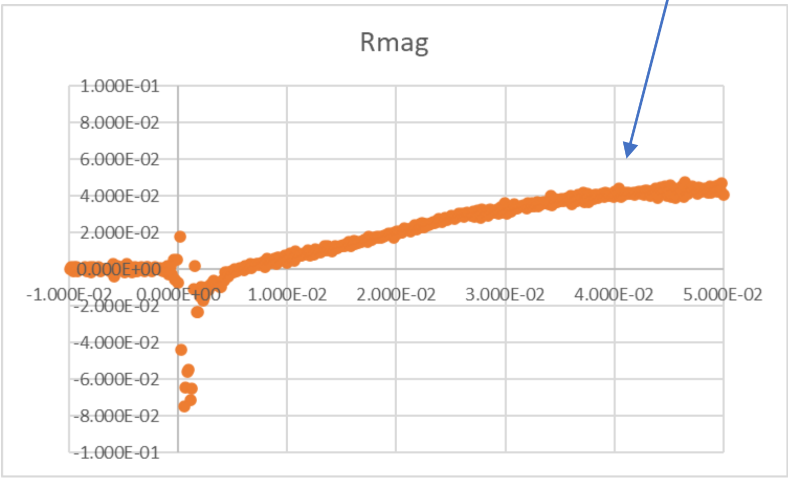


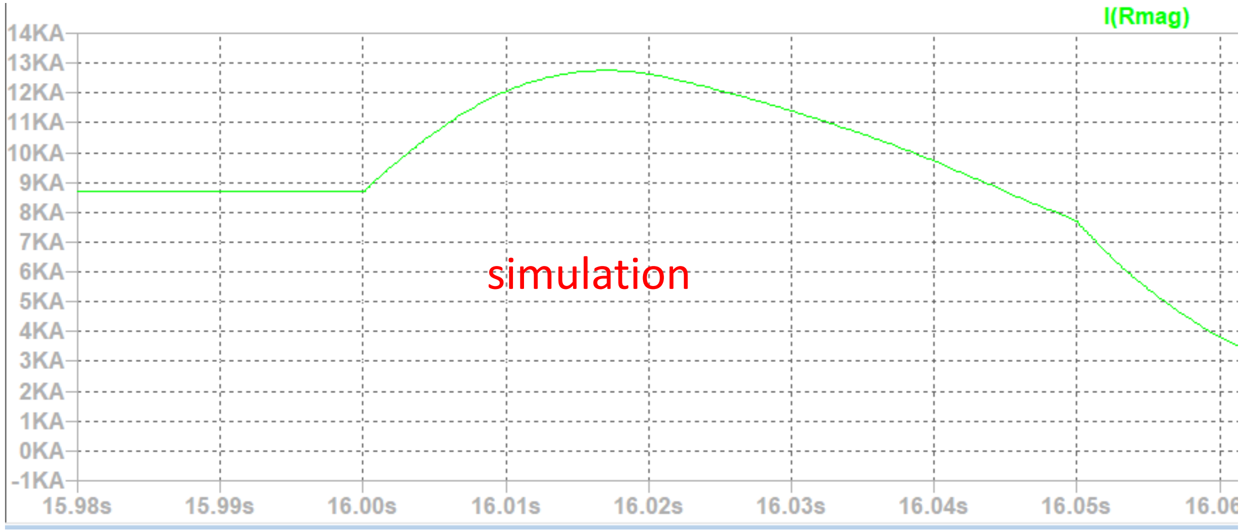
This is the first MBHSM03 natural quench

In the simulation, resistance development is approximately modeled from extracted data

PWL({QCD-30m} 1u {QCD+5m} 10u {QCD+35m} 22m {QCD+50m} 42m)
[s] [V] [s] [V] [s] [V] [s] [V]

According to data and some approximations, the magnet reaches ~40 mΩ in ~40 ms





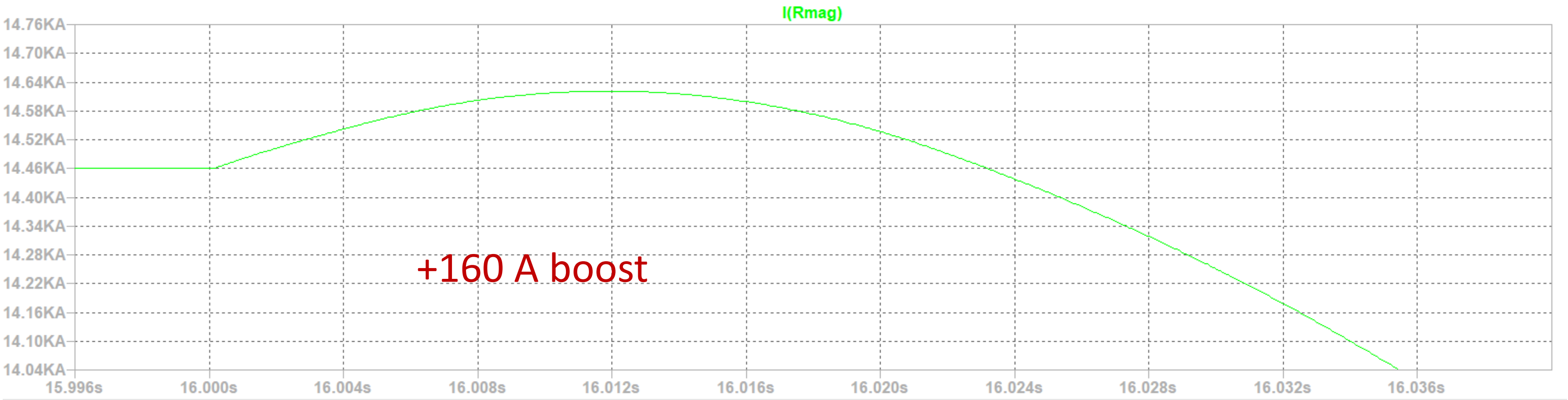
Simulation results are adequate (not perfect)

Simulation basics were presented earlier

https://conferences.lbl.gov/event/885/

Current boost (simulation) in a large magnet

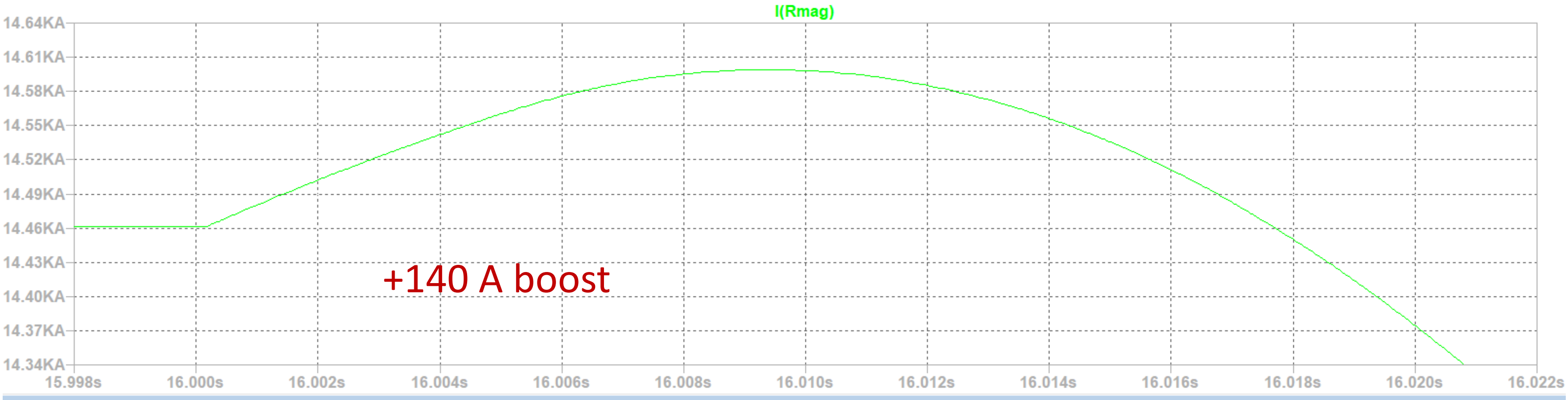
33 mH, resistance scale **factor of 5** with respect to MBHSM03



~14.5 kA is the typical level of first quench for AUP quads

0.4 F
1000 V

33 mH, resistance scale **factor of 10** with respect to MBHSM03 (to use as base)

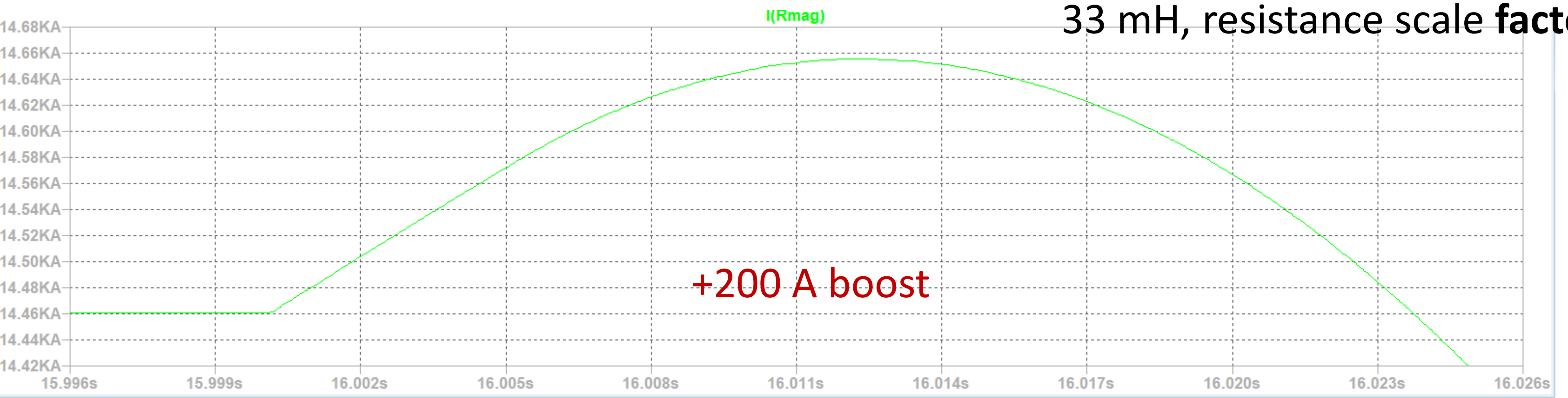


The 11 T mirror magnet has resistance of 0.2 Ω (300 K) (RRR ≈ 95)

The large AUP magnet has resistance of 2.4 Ω (300 K) (RRR = 200-300)

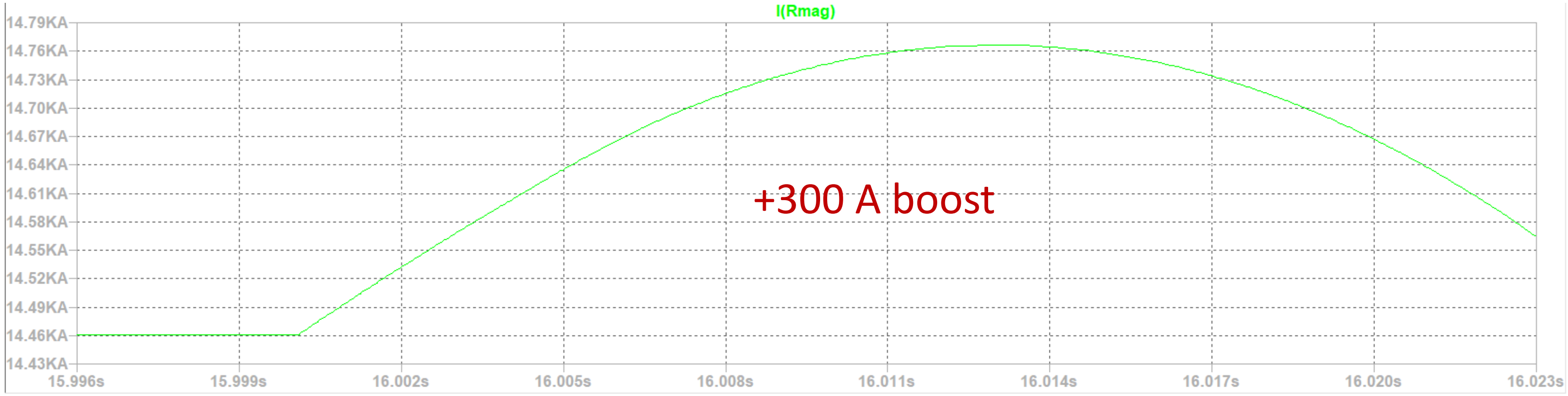
Current boost (simulation) in a large magnet

33 mH, resistance scale **factor of 10** with respect to MBHSM03



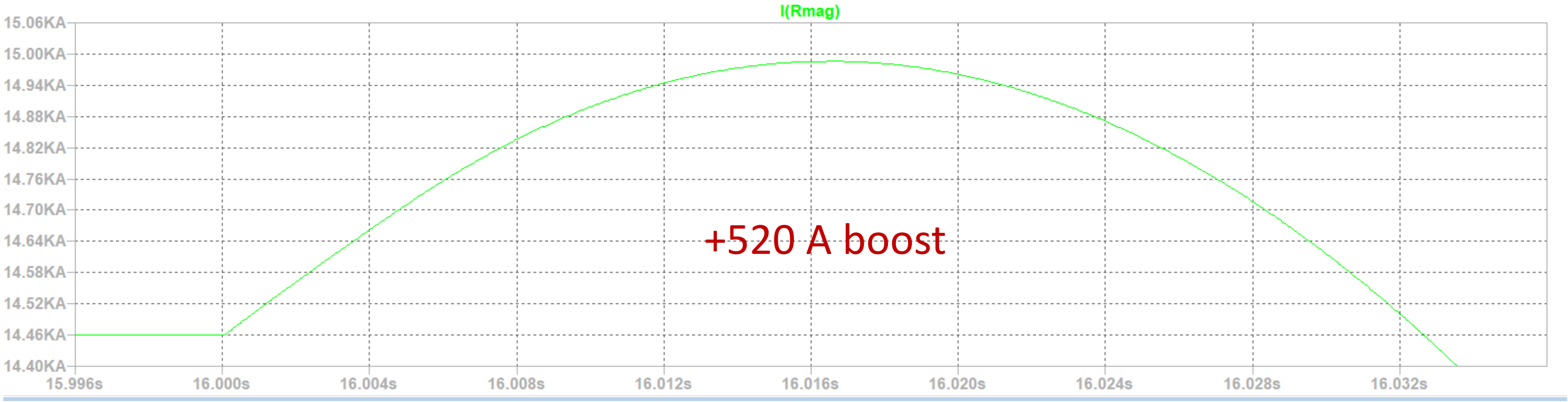
4.0 F
1000 V

Large capacitance increase does not provide much benefits
($E_{cap} = \frac{CV^2}{2}$ $\tau \equiv R \times C$)



0.4 F
1500 V

Modest voltage increase provides benefits



0.4 F
2000 V

Planning further QCD investigations

- The original LDRD plan was for QCD tests on two magnets
  - We emphasized importance of statistics
  - MBHSM03 re-training features helped resolve this partially

- Re-training seems to be partially reproducible in MBHSM03 (we have a LARP coil with perfect re-training reproducibility) which makes it a possible tool for further QCD investigations
  - Study over-current level (which relates to boost duration as well) effect on training
  - “Training” without natural quenches (QCD discharge below quench level) – this improves the protection time budget and there is no hot-spot (!)

- We have an option to assemble a LARP mirror magnet with never before used coil
- We have to plan for a CCT test with QCD
  - This was set as an MDP milestone
  - Any magnet will do as we are to test it directly at 1.9 K (there were no CCT tests at this temperature on US soil, AFAIK)

- We could plan to use QCD on AUP magnets
  - It requires quite substantial negotiations, studies and adjustments (no CLIQ probably)
  - The effect is likely to be limited with the existing QCD (~ +150 A boost)

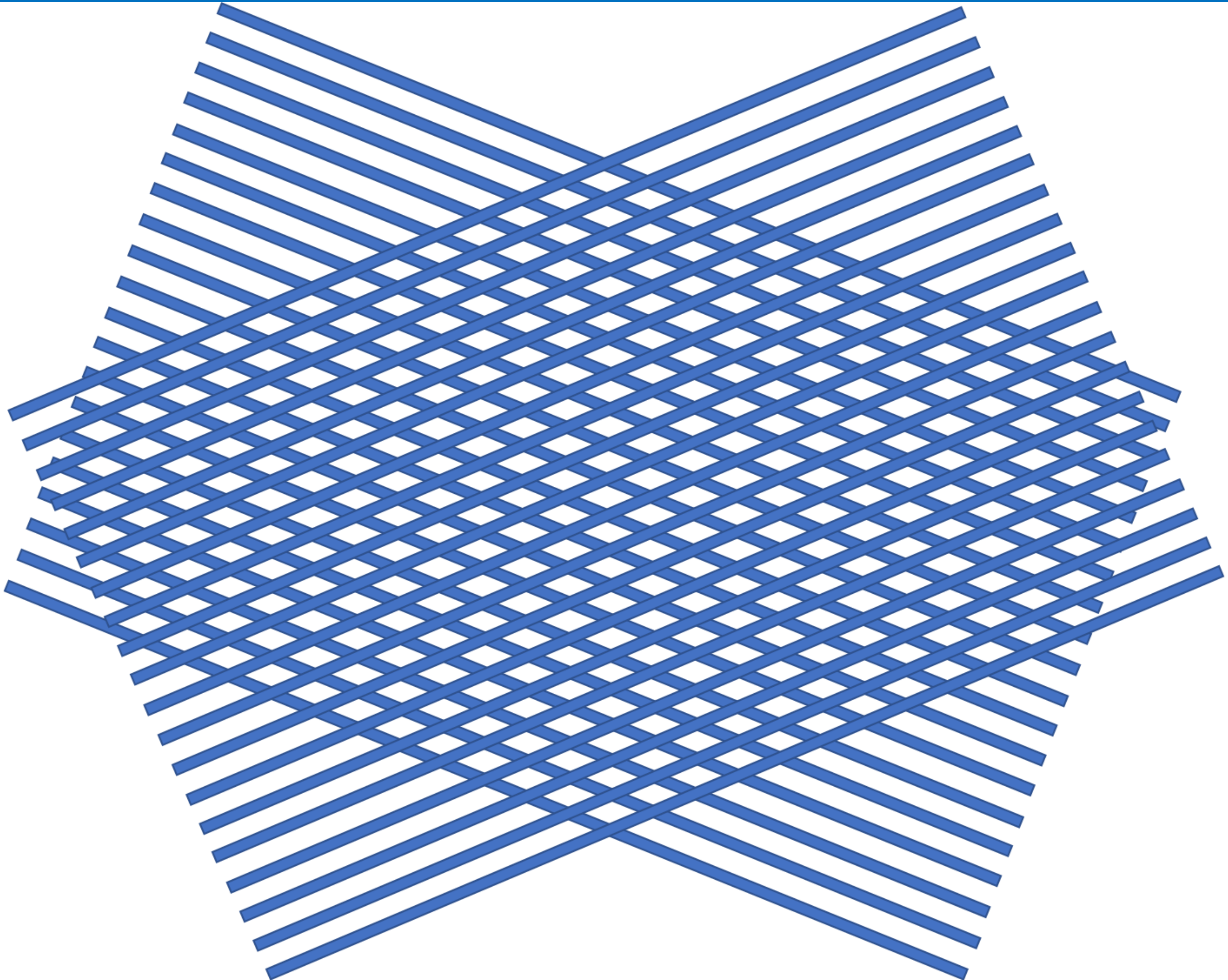
Quench locations in MBHSM03

- First quenches in all thermal cycles were in the inner layer along with the first quench at 1.9 K
  - Based on VTs, locations were close to the second wedge (all in the same VT segment)
  - The same (rough) location was limiting for performance in previous “11 T” coils

- In addition, several other training quenches, at 1.9 K, were also in the inner layer
  - In total 3 out of 9 IL quenches , were in the long VT segment consistent with the mid-plane with the rest (probably) around the second wedge
  - We have no VTs in the outer layer beyond splice VTs (and both splices are below 1 nΩ in resistance)

- We have **quench antenna arrays (flex-QA)** and acoustics to tell us more about quenches

Flex-QA arrays



Flex-QA arrays for MBHSM03

- <u>LDRD project</u>
  - Completed (term ended)
- It is the first time where this kind of QA precision and grid-like structure is applied
  - We suggested it in August 2019 for CCT but it wasn't endorsed: https://conferences.lbl.gov/event/235/
  - For AUP we (Joe) had larger sensor flex-QAs as part of a more complex QA grid-like structure
- Multiple versions fabricated
  - Not yet fully tested
  - Also, various support devices fabricated
- The version shown was specifically developed to fit this magnet/coil

Plans in 2017

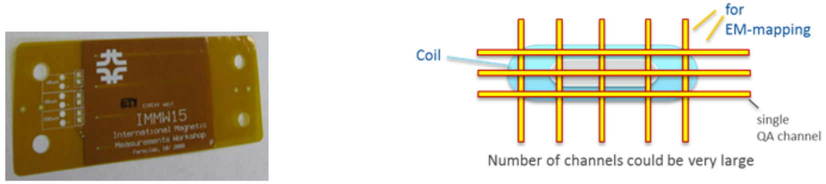
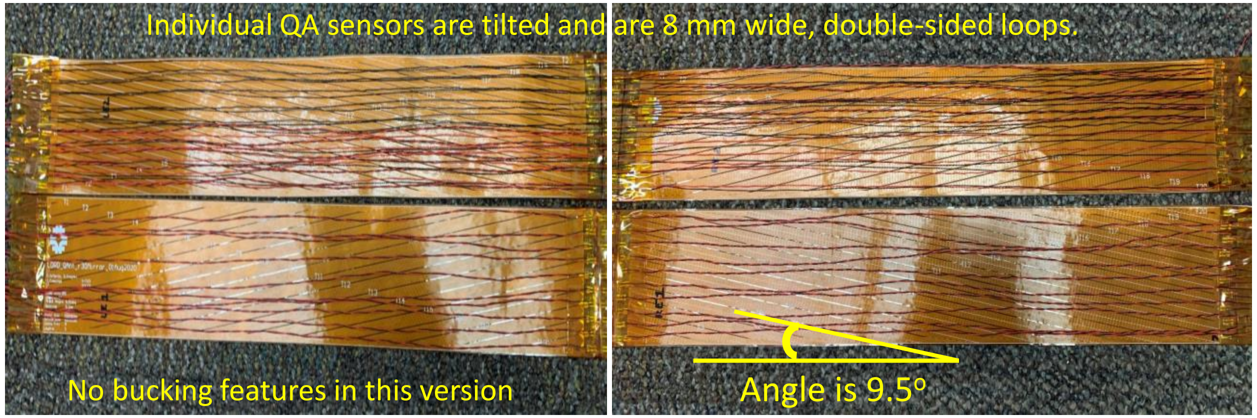
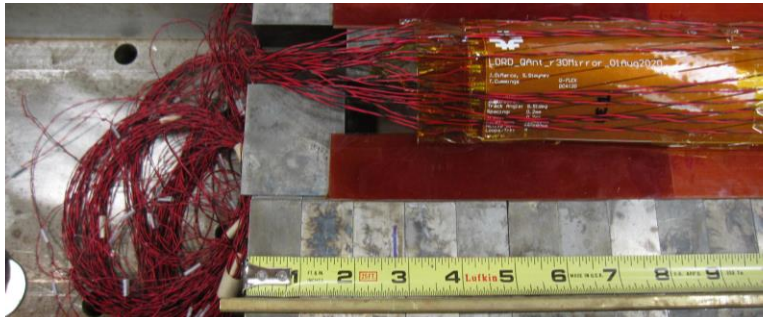
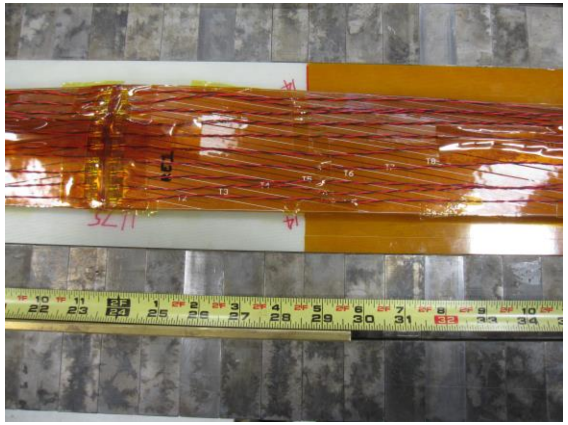


Figure 5.3 – Quench antenna on a "trace" with three channels (left) and simplified drawing (right) of the proposed 2D-grid with quench antenna sensors. The grid could be 3D with the addition of a differently designed antenna placed in depth along the cable (a much more complicated option).

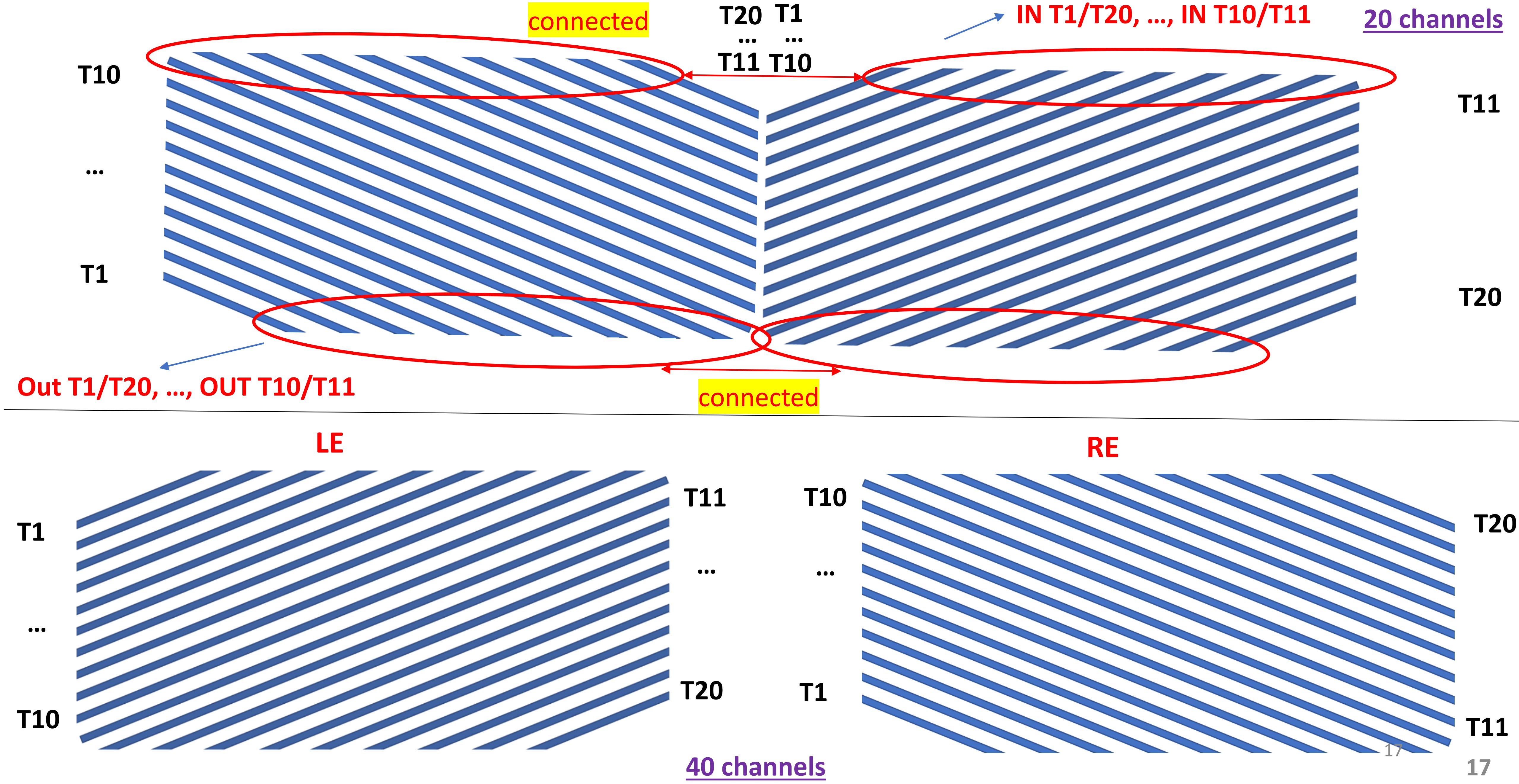
Realization in 2021





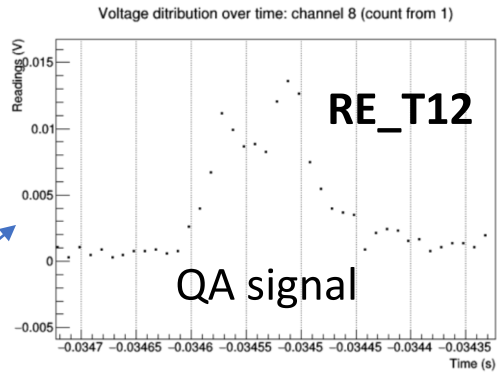


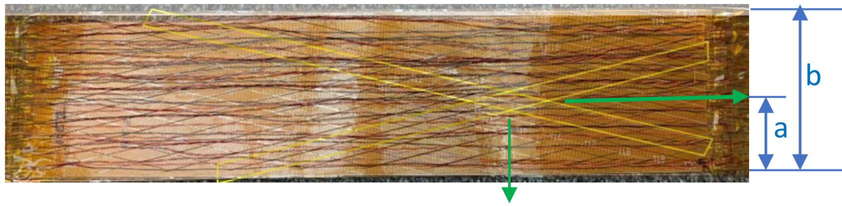
Flex-QA connections and channels



Resolving the first quench

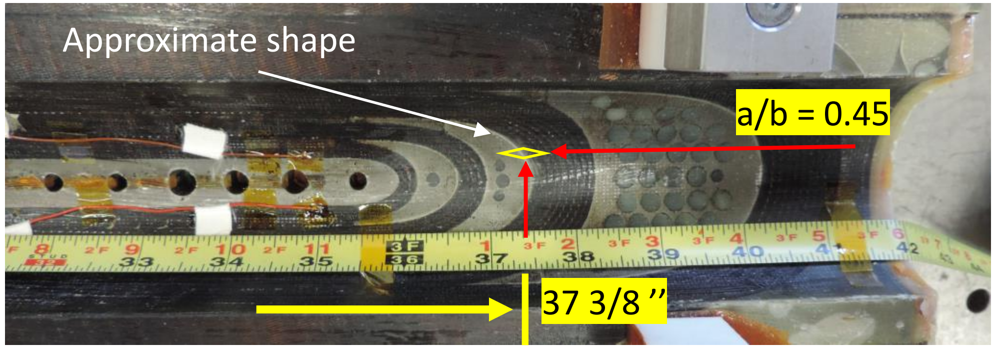
Channel name with prompt signal	Magnitude of signal (mV)
RE_T8	5
RE_T9	5
RE_T10	~10
RE_T11	7
RE_T12	**14**
RE_T13	7
RE_T14	2
RE_T15	7
RE_T17	4
IN_T9_T12	6
OUT_T6_T15	6
OUT_T7_T14	8
OUT_T8_T13	**16**
OUT_T9_T12	5
OUT_T10_T11	3



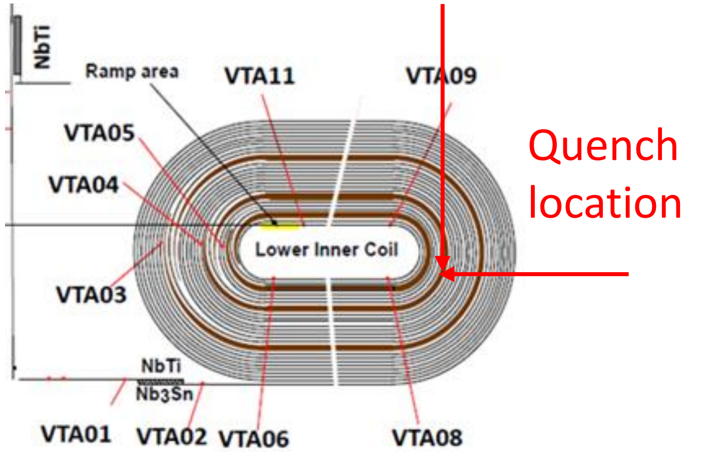


The diagonals of the rhombus formed are 8.1 mm and 48 mm (its side is 24.6 mm).

Linking QA, positioning and coil geometry leads to:



Transition side is down on this picture



We could be few mm off in any direction (to be improved by cross-checks)

VT segment a4_a5 gave -32.5 ms as the quench start and a3_a4 started quenching at -14.5 ms

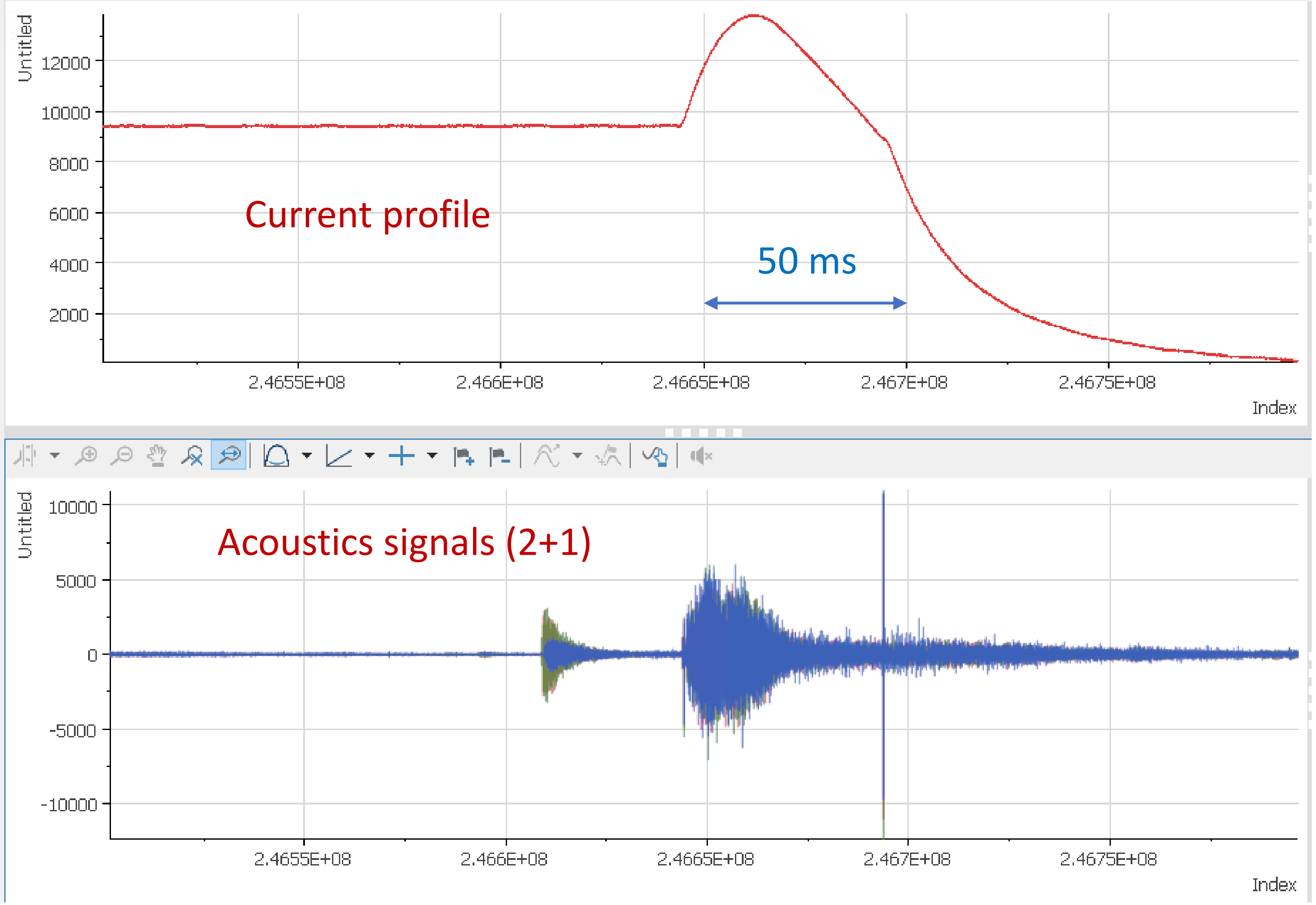
From QA location (~75 cm from VT A04) one can conclude quench velocity is 40 mm/ms

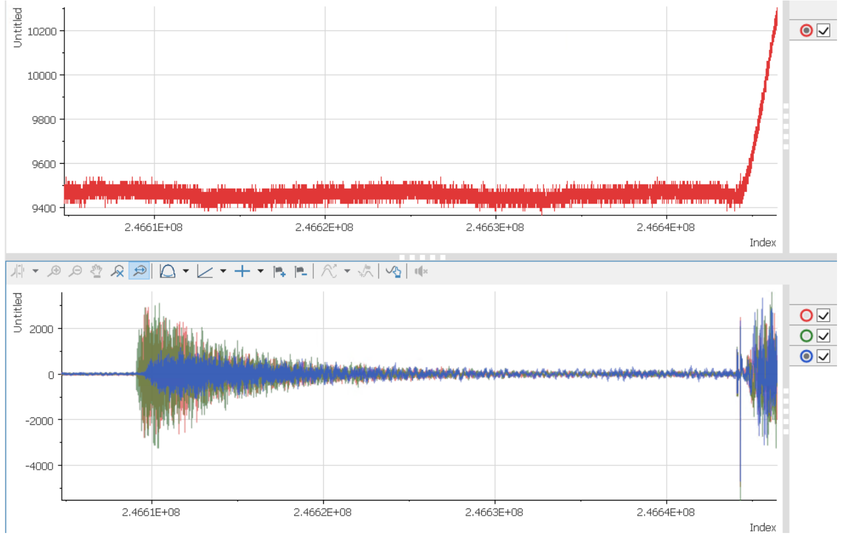
VTs and QA unambiguously confirm that the quench is on the wedge turn (what was assumed so far)

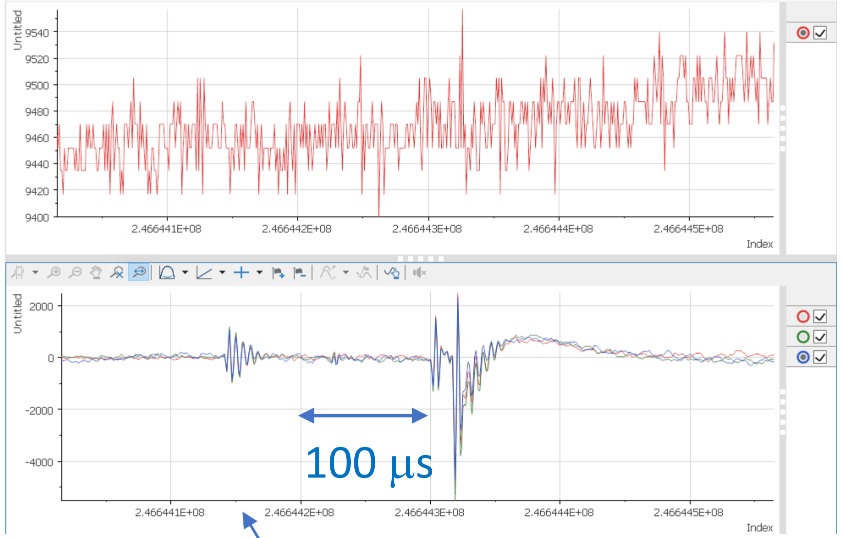
Acoustics in the first quench

LBNL sensors

Acoustics (quench 1)





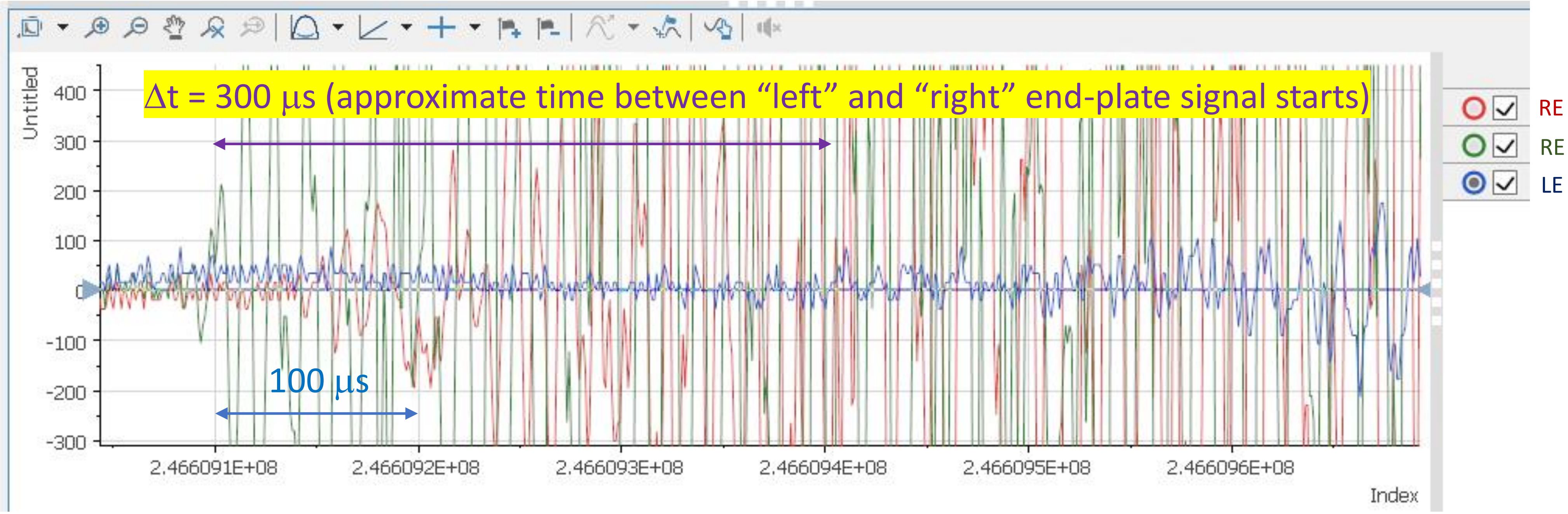


(time units)

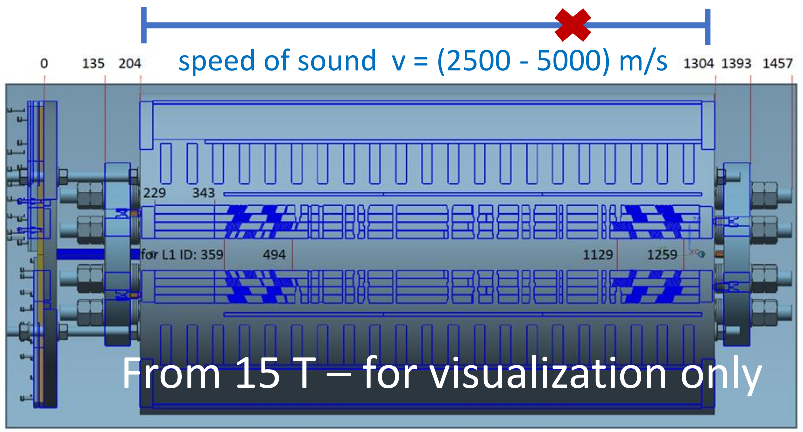
This is quench detection time

Acoustics in the first quench

The start is 35.05 ms before quench detection (QA was 34.60 ms with half of 0.01 ms uncertainty; VTs: 32.5 ms)



$a = vt_a$ $b = vt_b$



$L \equiv a + b$

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

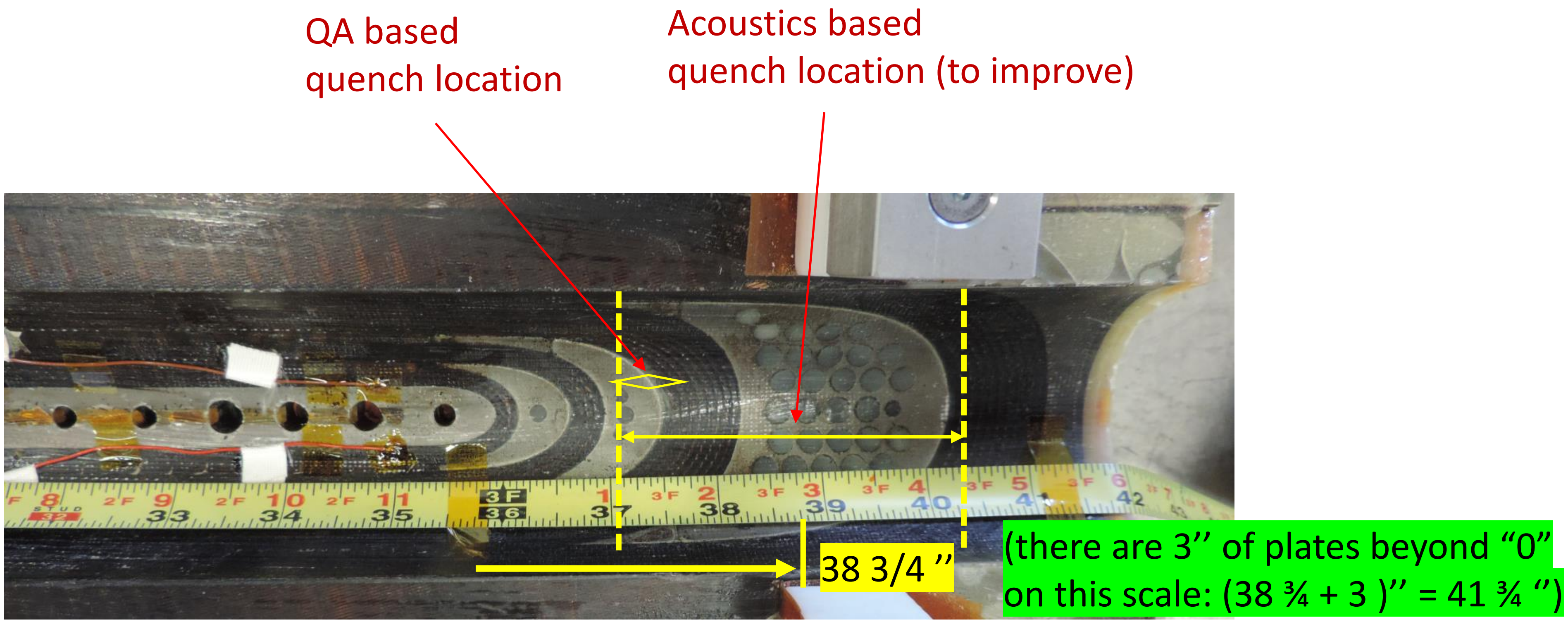
$f_L \equiv b/L = 0.5 \times [1 - \Delta t\,(v/L)\,]$

L ~ 54’’ (~137 cm)

Substituting parameters (v = 2.5 km/s): f_L=0.226 (±20%)

This is equivalent to “event” origin at $(1-f_L)*L$ **= 41 ¾ “ from LE**

Acoustics (quench 1)



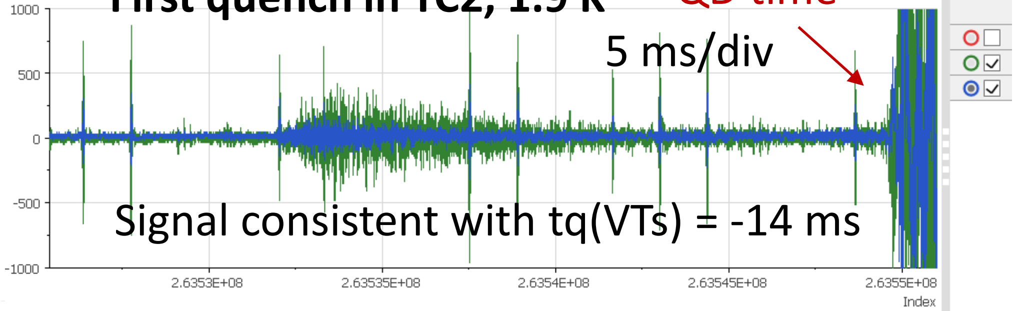
The first quench is caused by a mechanical event; its acoustic energy dissipated within 10 ms.

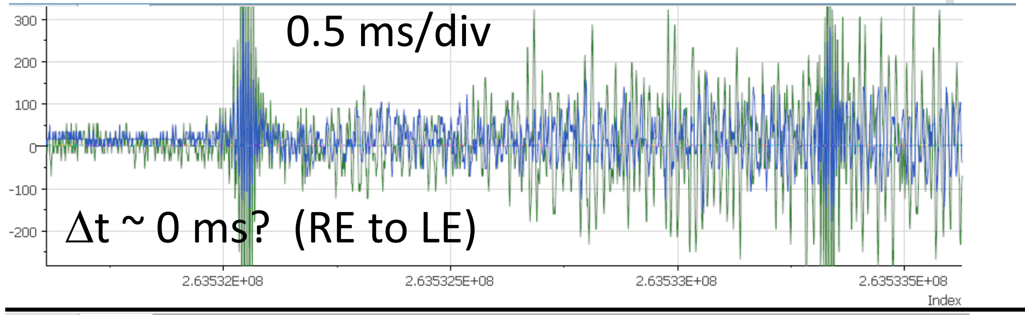
If we were to normalize event origin to the QA one, and <u>keeping the Δt</u>, then v = 2260 m/s.

In TC1 there was little to none activity before quenches after quench 1.

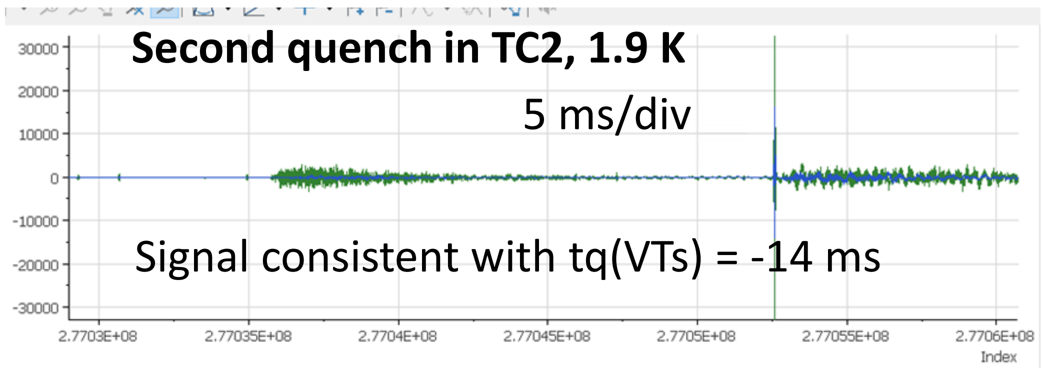
Acoustics at quench times

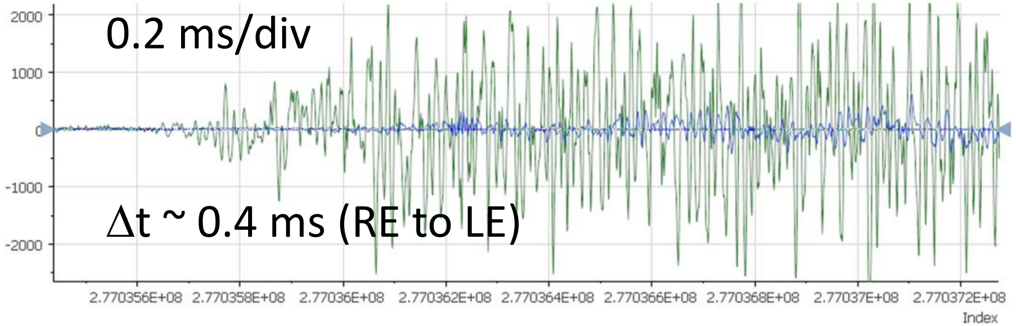
First quench in TC2, 1.9 K



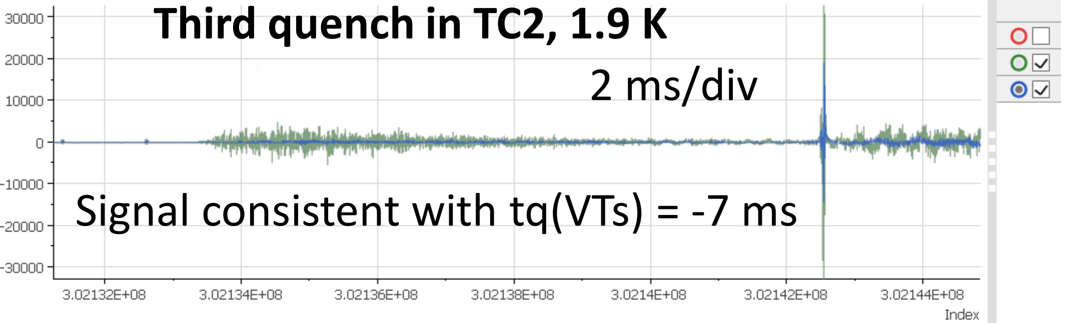


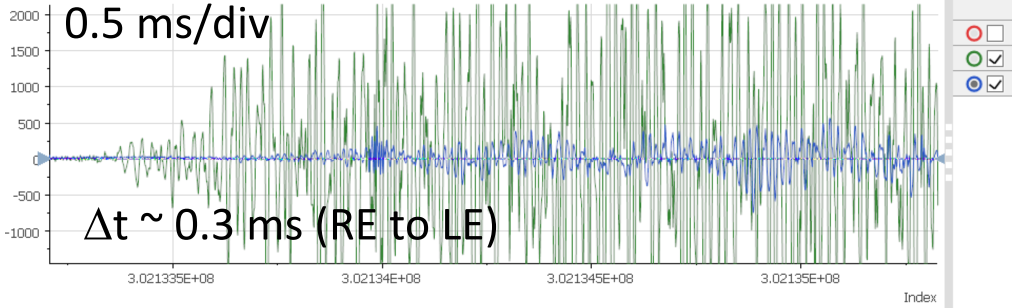
Second quench in TC2, 1.9 K



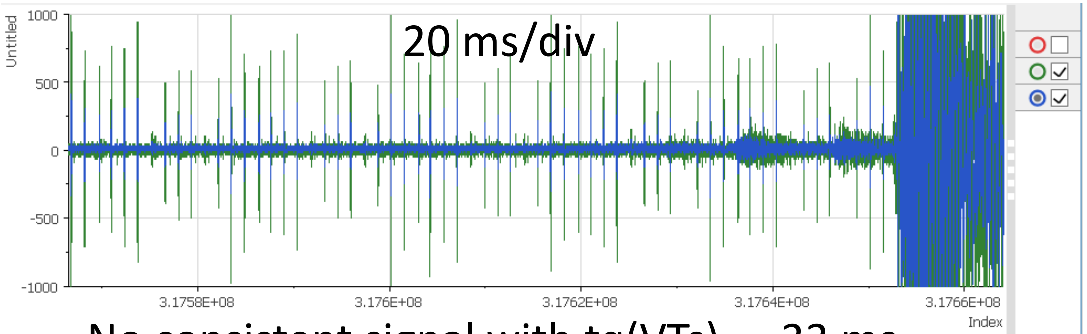


Third quench in TC2, 1.9 K





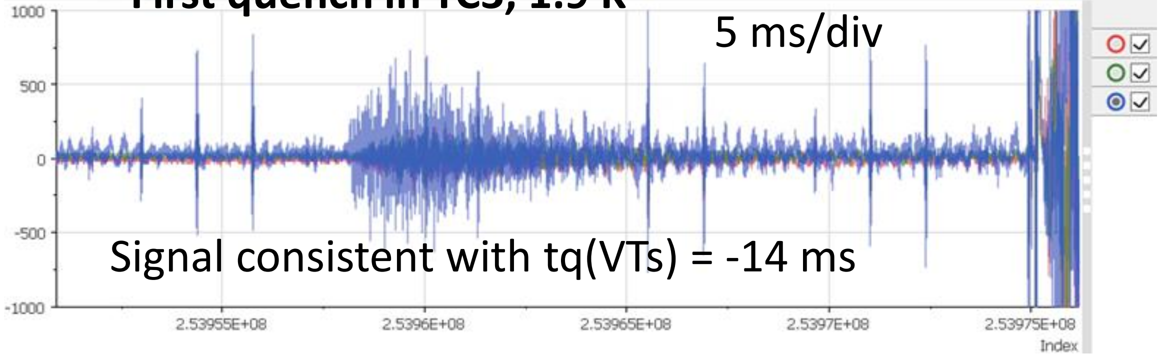
Forth quench in TC2, 1.9 K

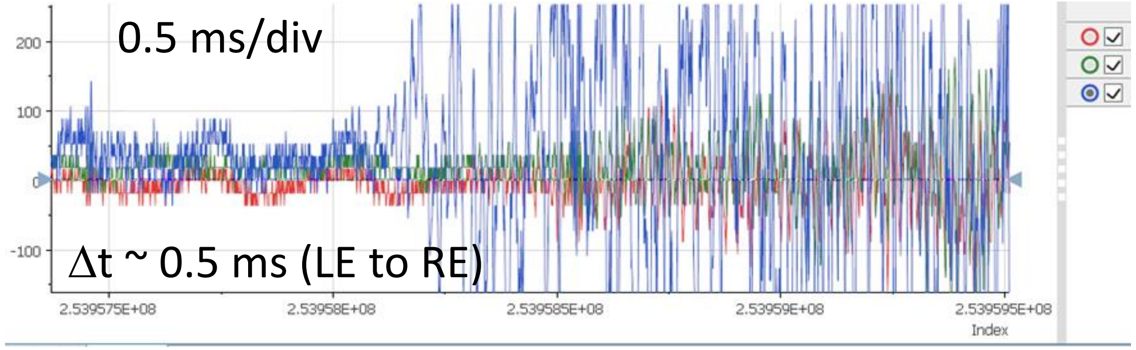


No consistent signal with tq(VTs) = -33 ms

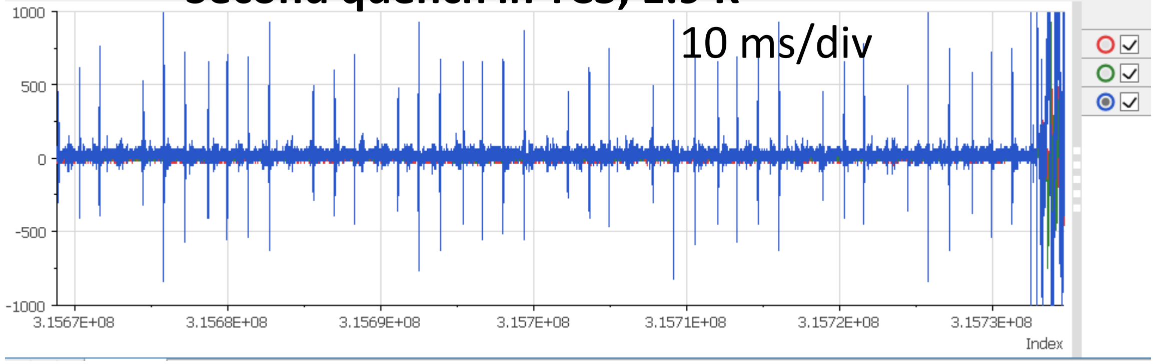
Acoustics at quench times

First quench in TC3, 1.9 K



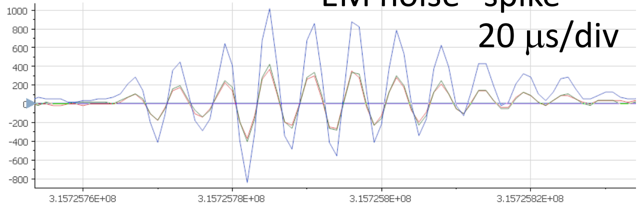


Second quench in TC3, 1.9 K



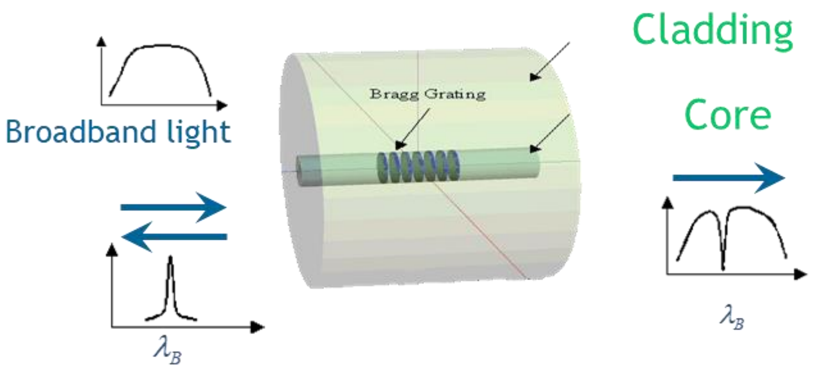
Apparent noise spectrum concentrates on
66 Hz (I assume it is 60 Hz), 667 Hz and 175 kHz

EM noise "spike"



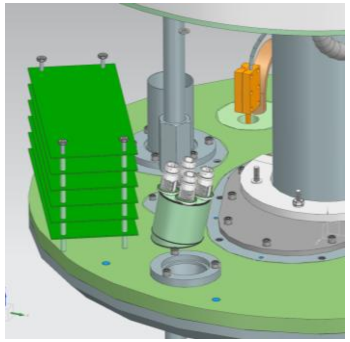
Non-avoidable (probably) noise at much lower level

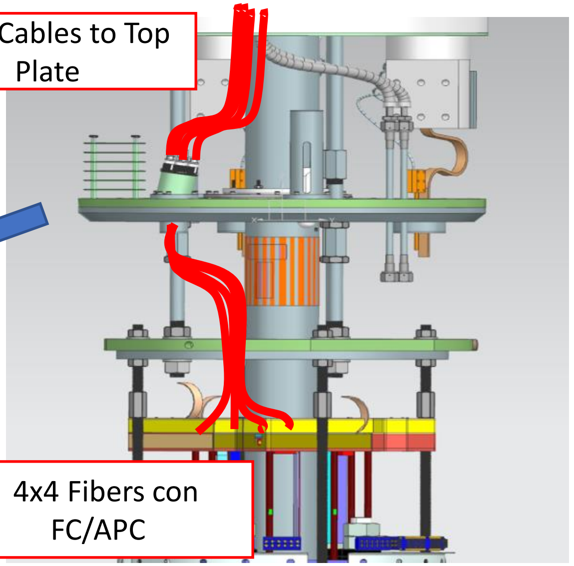
The vast majority of quenches (starting with quench 2 in TC1) are quiet, like the one above, right
(the spikes are EM noise; we are investigating, likely coming from power supply given some current dependencies)

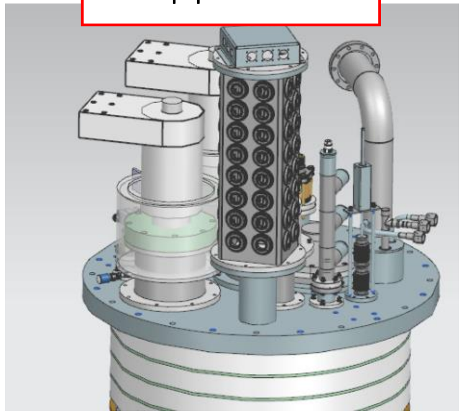


FBG: longitudinal periodic variation of the refractive index in the optical fiber core

First test of FBG fibers on a magnet at FNAL



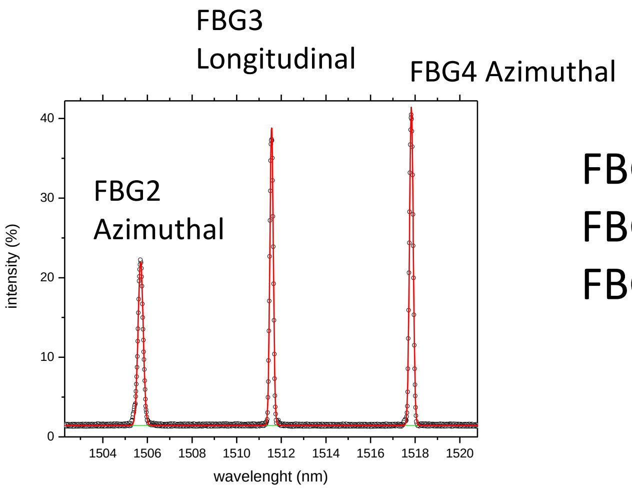




- The vertical test facility has been modified to allocate a dedicated fiber optics tree. Strain signals from16 optical fibers can be extracted.
- The stainless-steel skin of a mirror magnet has been instrumented with one fiber with four FBG sensors

FBG sensors were installed on stainless-steel skin of a mirror magnet

Mirror magnet cool-down



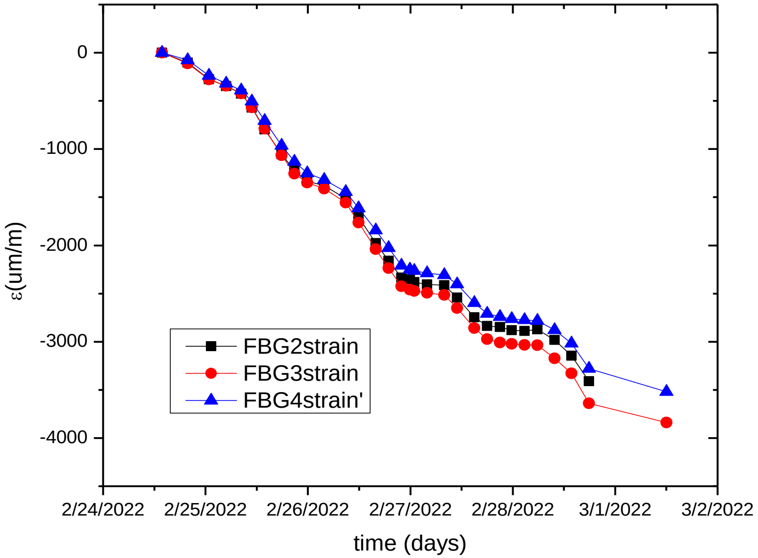
[nm]

FBG2= 1508.013

FBG3= 1514.049

FBG4=1520.063

cooldown

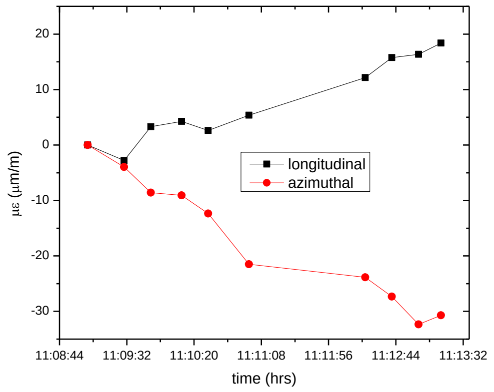


- @4.5 K only two sensors are still alive
- Strain is consistent for each FBG sensor
- At cold the strain variation without T compensation is around 4000 um/m

The first strain data have been successfully collected using FBG fiber sensors during cooldown and training of a mirror magnet

Prepared by M. Baldini

Mirror magnet powering

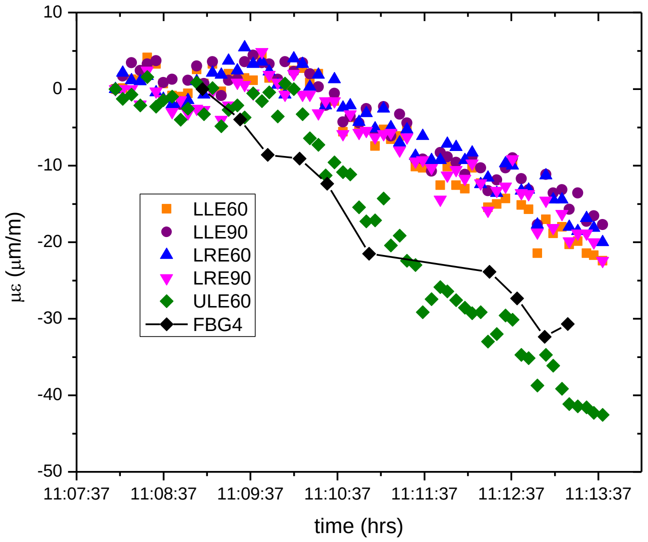


At cold only two sensors are still alive
FBG3 is longitudinal
FBG4 is azimuthal
The closest strain gauge is labeled ULE60

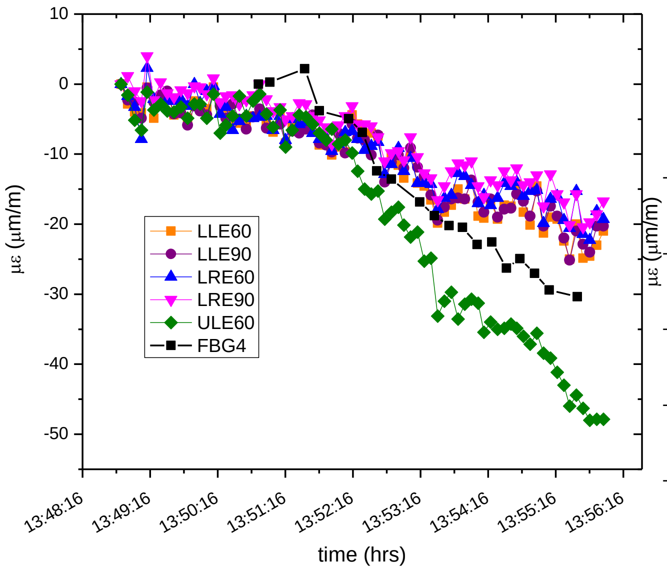
Lesson learned: modifications of fiber feedthrough of the vertical test facility will be needed to avoid signal loss at 1.9K

The data collected with FBG sensors are in good agreement with data collected with strain gauge

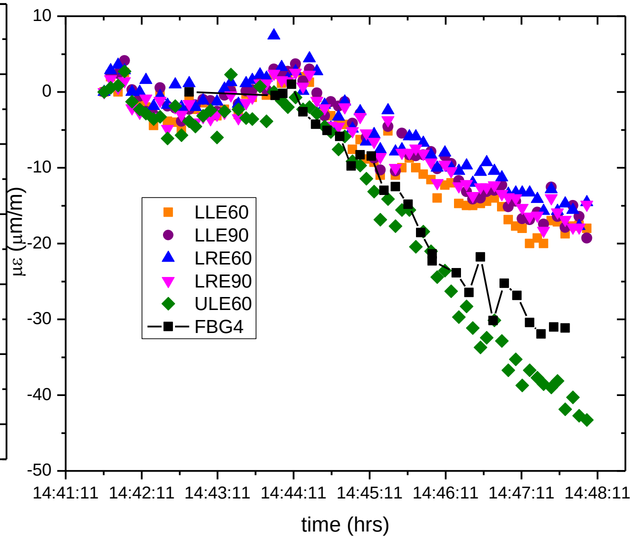
Training and quench 1



Training and quench 2



Training and quench 3



The first strain data have been successfully collected using FBG fiber sensors during cooldown and training of a mirror magnet

Prepared by M. Baldini

Diagnostics and instrumentation with MBHSM03 testing

- Still analyzing QA data
  - Details on all inner layer quenches
  - Outer layer quenches
  - Ramp developments
  - Signal interpretation

- Working on acoustics
  - Classification of events, although most quenches were “quiet”
  - Ramp developments
  - Filtering options
  - Noise investigations
  - We are failing, so far, on transducer studies (too much noise) – planning to take more data at various conditions to determine origin of issues

- Fiber optics
  - Complete data analysis and plan for next phase of development/testing

- Summary on integrated response (all data)
  - We’ll try to describe what happened in “main” quenches based on different (complimentary) types of data