Mechanical and electrical transients measured with quench antennas and accelerometers in the MBHSP106

Measurement and analysis techniques

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With thanks to Daniel Turi, Christian Löffler, Franco Mangiarotti, Michal Duda, Jerome Feuvrier, Vincent Desboilles, Emelie Nilsson, Maxim Marchevsky and Matthias Probst for discussions, data collection and contributions.

Outline

Part 1: Method

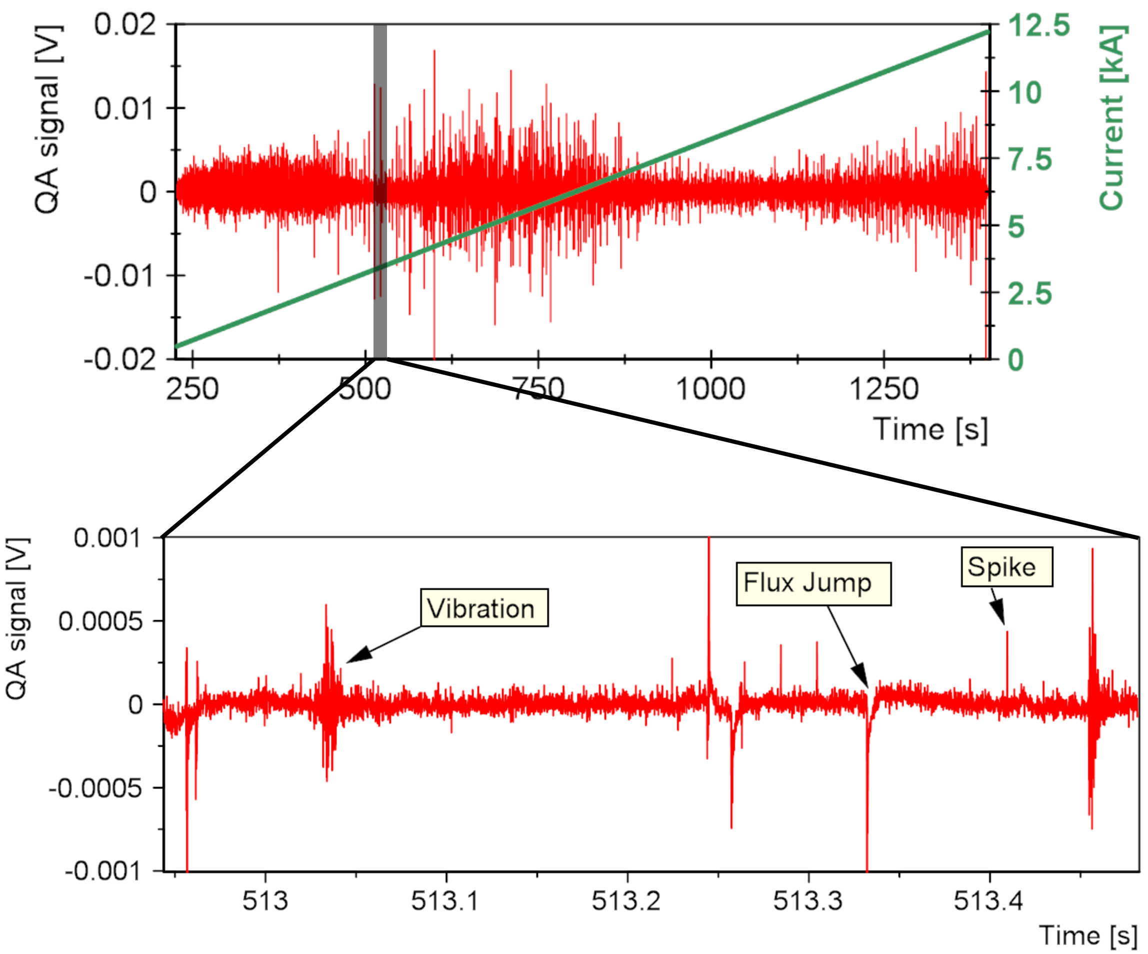
- Measurements
- Analysis techniques

Part 2: Results from MBHSP106

- Flux jumps
- Vibrations

Summary

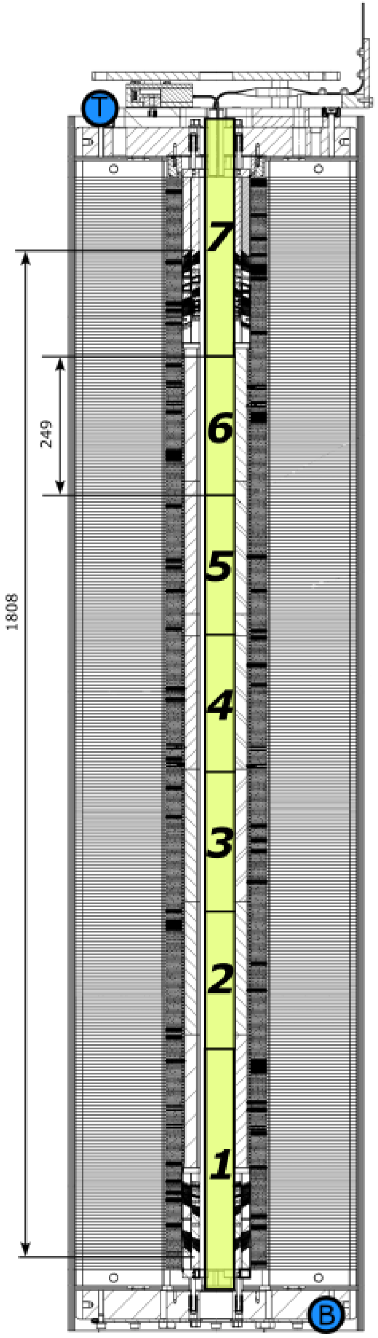
What has been studied?



The full 20 minute ramps of SP106 with **quench antennas (QA)** and **accelerometers** have been recorded at 10 kHz and a ramp rate of 10 A/s.

Signals contain different event types:

- In **accelerometers** only vibrations.
- In **QA** also flux jumps and spikes.



Quench Antennas

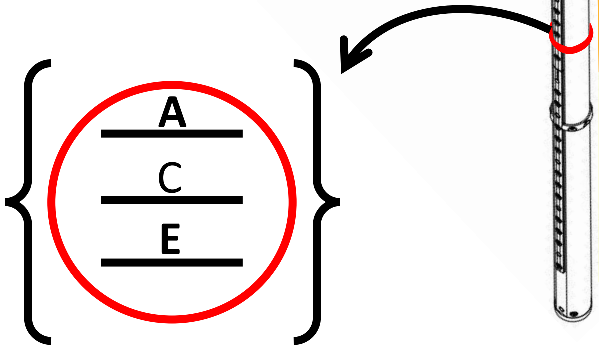
The quench antenna is an array of pickup coils placed in the magnet aperture.
The pickup of each coil is given by:

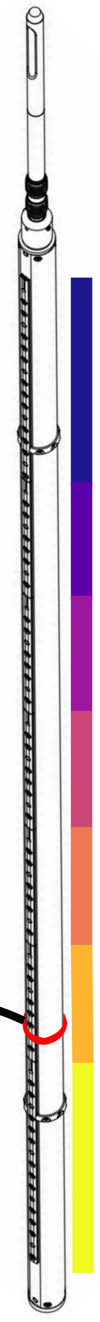
$$V(t) = -\frac{\partial}{\partial t} N \int_S \boldsymbol{B}(\boldsymbol{x}, t) d\boldsymbol{A}$$

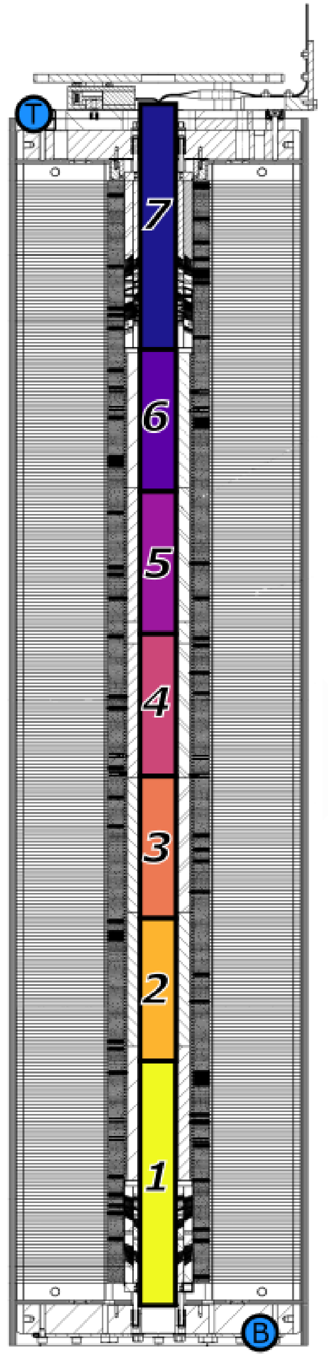
Each segment has 3 coils, where the difference between two (**A-E**) is taken to get the local variations in the magnetic field.

Magnetic measurement shaft as quench antenna (QA).

Dedicated QAs of printed circuit boards was made last year.



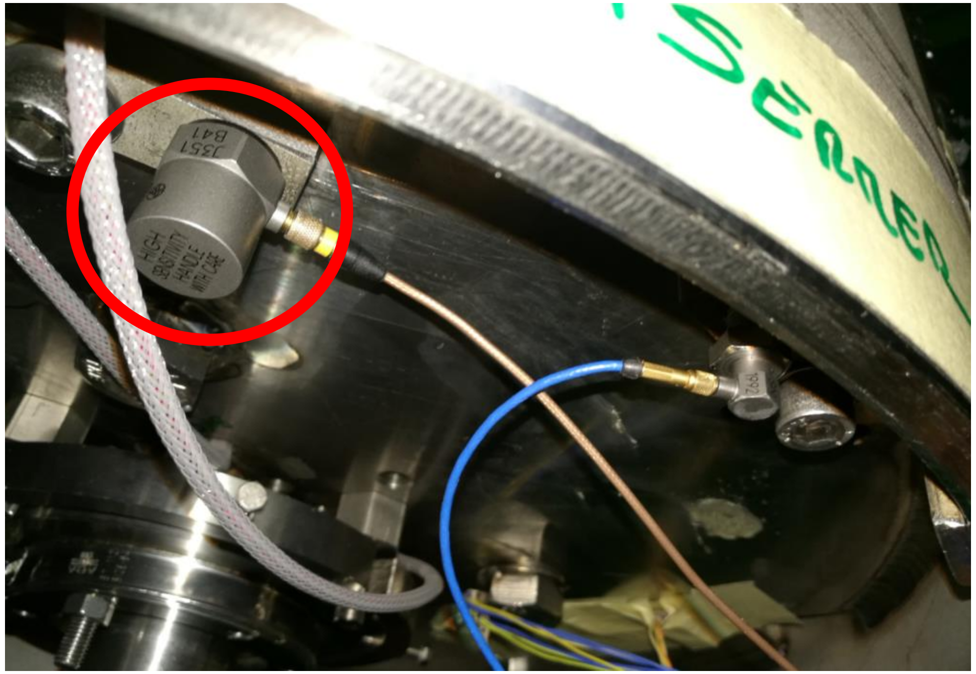




Accelerometers

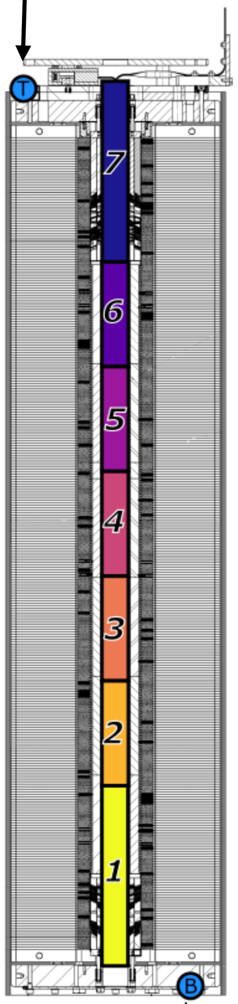
Mounted on the end plates (Top and Bottom) of the magnet to measure longitudinal vibrations.

Useful range 0-3000 Hz



Pictures by courtesy of Daniel Turi

Located near weld line



Located under the negative current lead

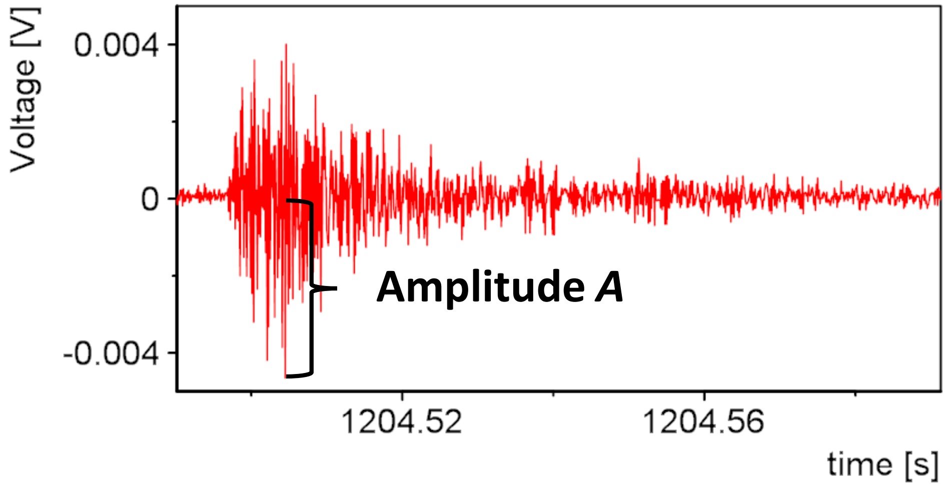
Acoustic emission sensors, relevant for the discussion:

- **NOT** on the SP106
- Mounted on the magnet surface
- Useful range 0.1-300 kHz
- In use at LBNL (M. Marchevsky)

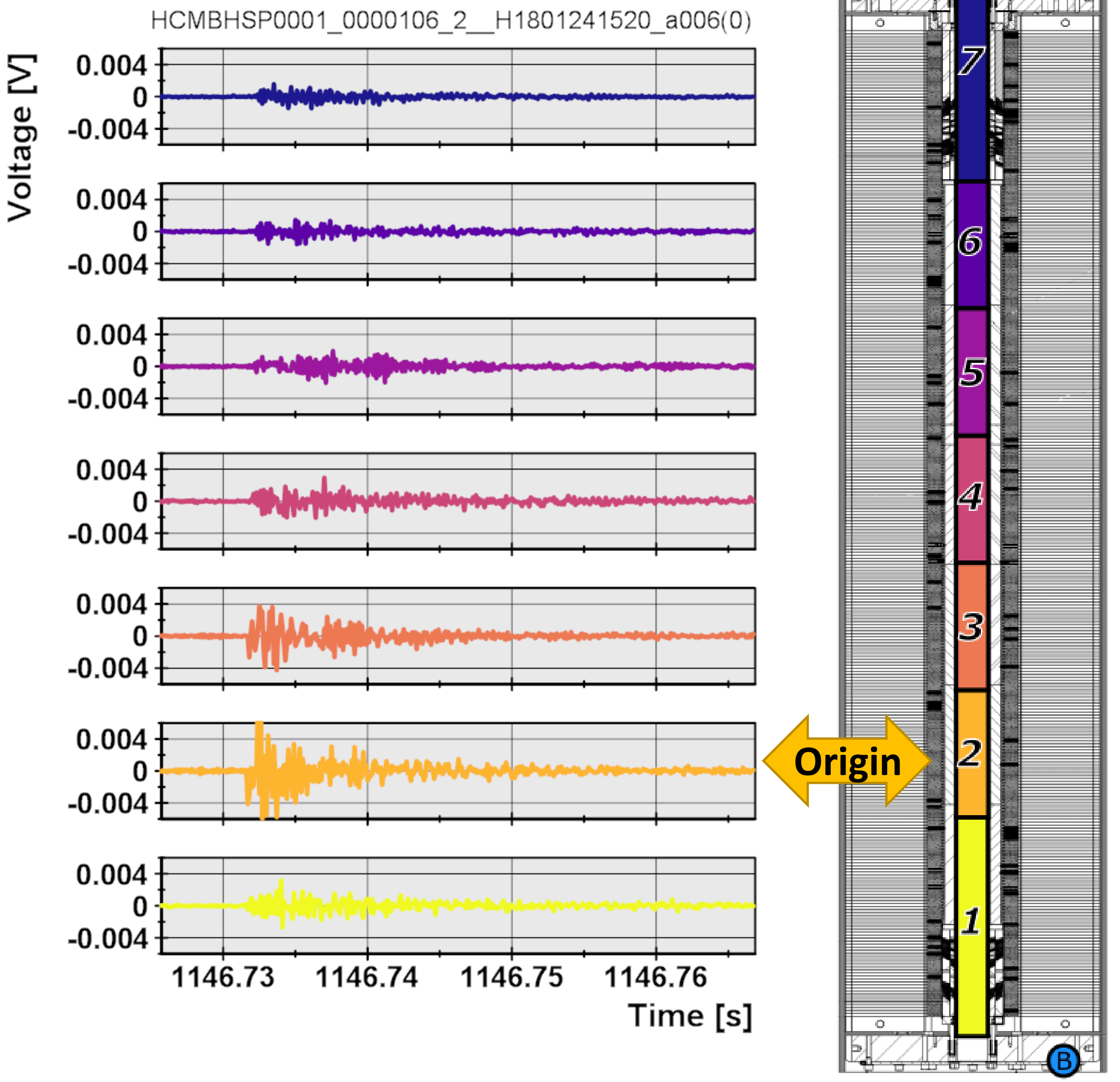
Overview of Vibrations

- Amplitudes spans a few orders of magnitude.
- Smaller events are more common than big.
- Difficult to identify in differential voltage signal.
- Origin characterized by sharper onset and larger amplitude.

Example of a vibration:

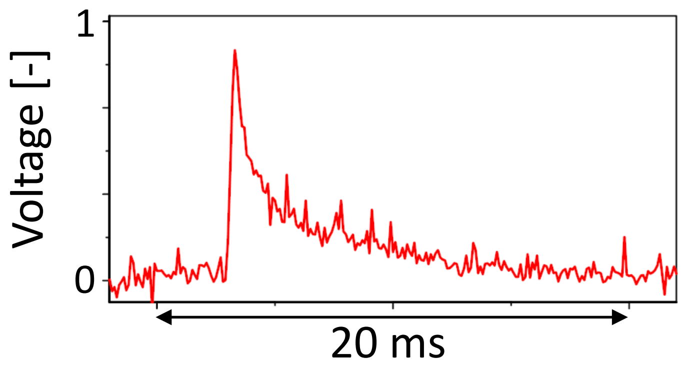


Sometimes seen throughout the magnet.
Propagation velocity here: 1300 m/s.

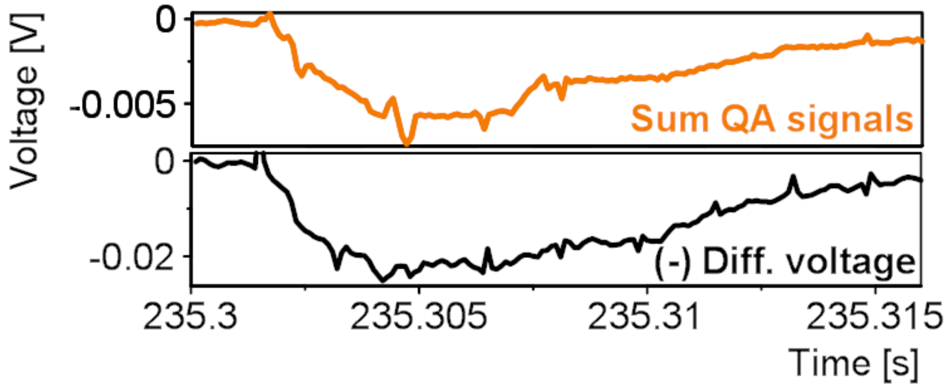


Overview of Flux Jumps

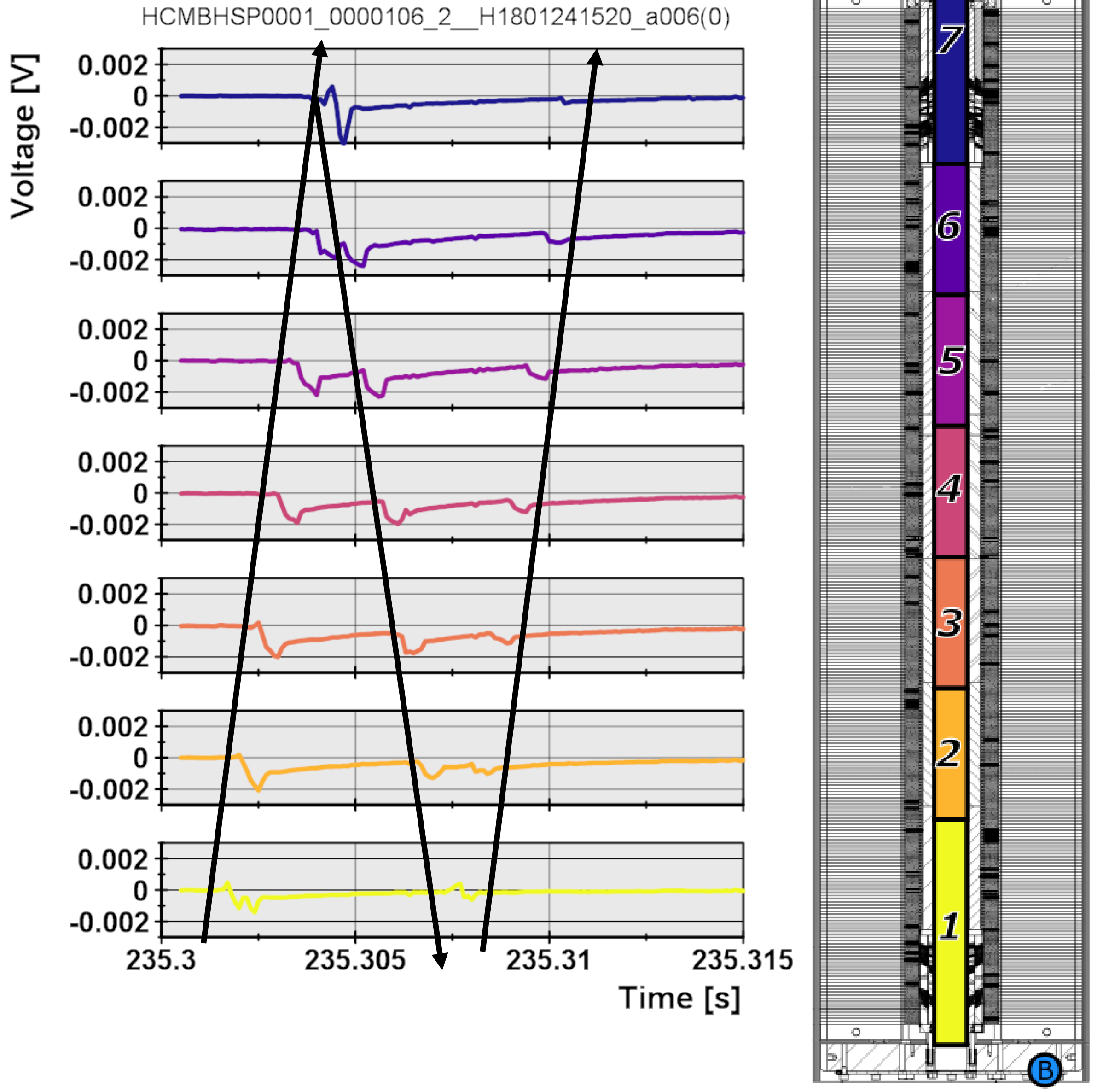
Example of flux jump in QA:



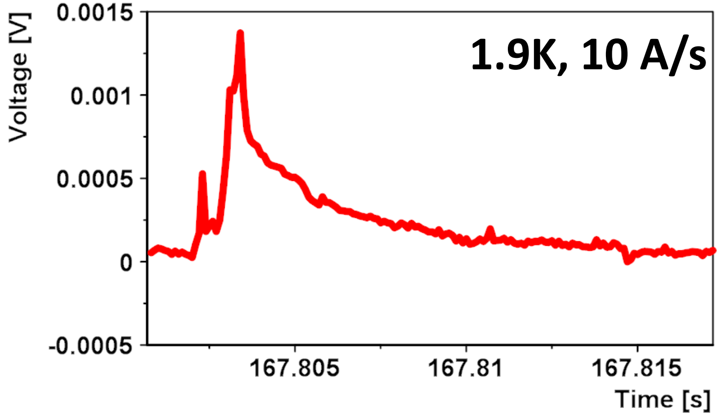
The sum of QA signals is similar to what is picked up by the differential voltage:

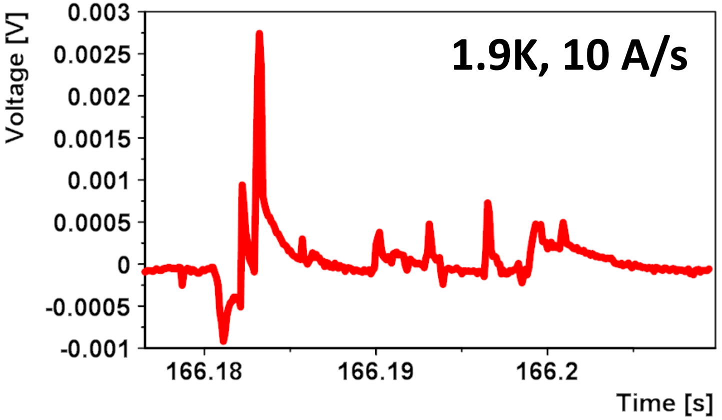


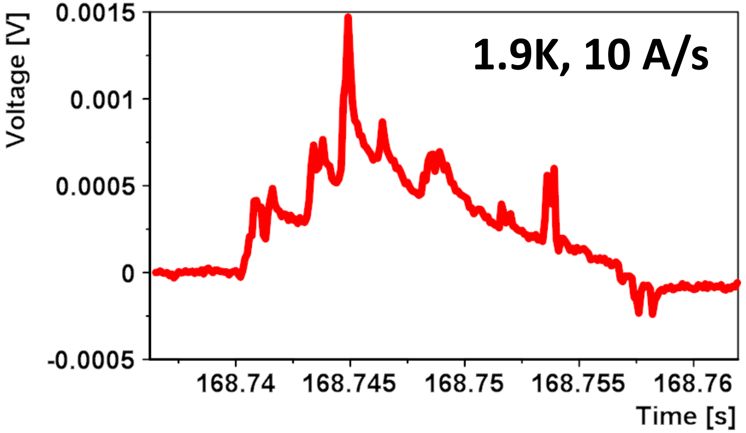
Flux jumps can be seen to propagate with velocities between 500 – 1000 m/s:

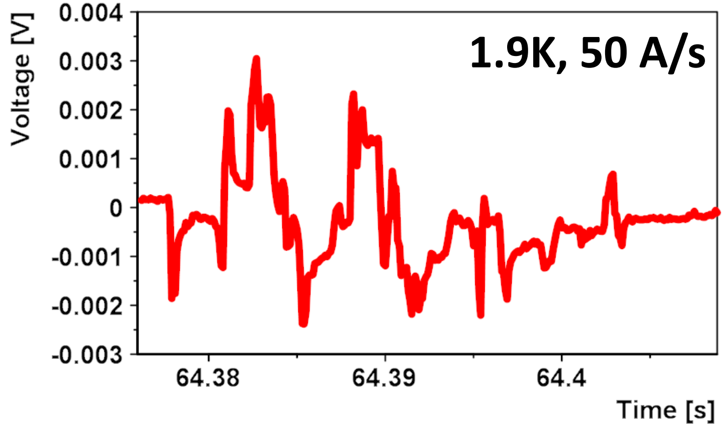


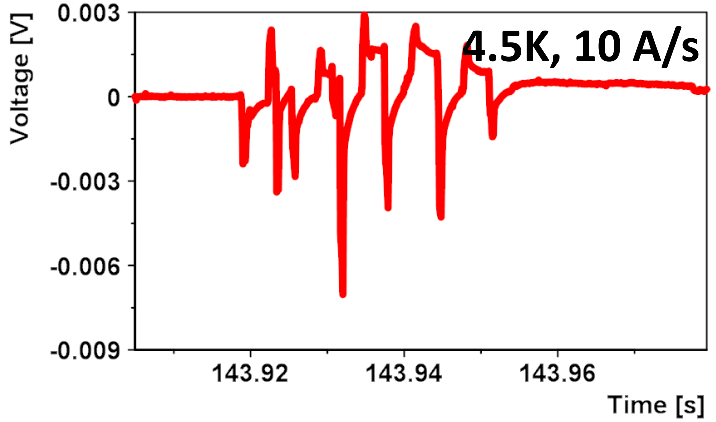
Examples of flux jumps

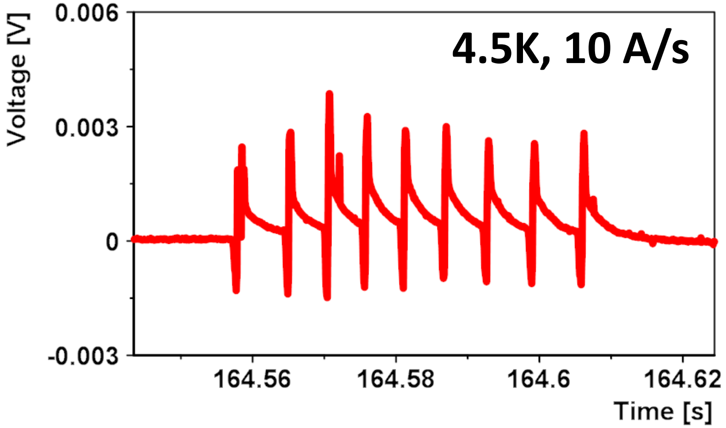










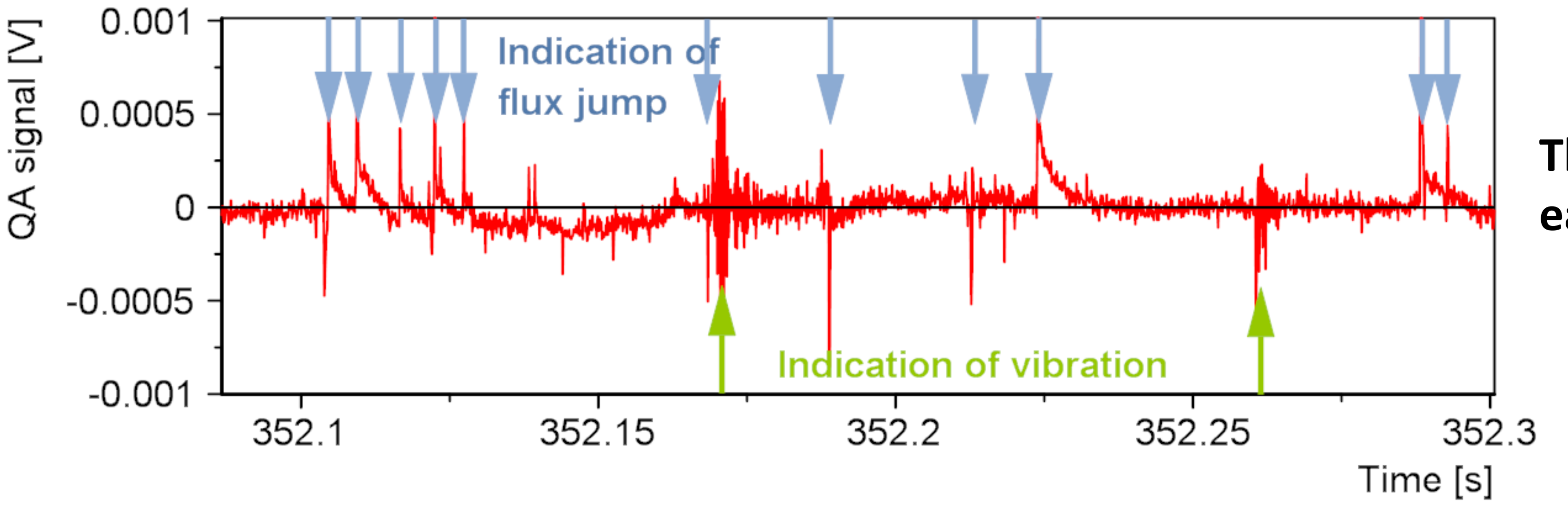


Analysis of raw signal

Procedure

- Filter data (high-pass)
- Find events
- Determine type: flux jump or vibration
- Collect data: time, amplitude, duration, rise time, FFT peak, etc…

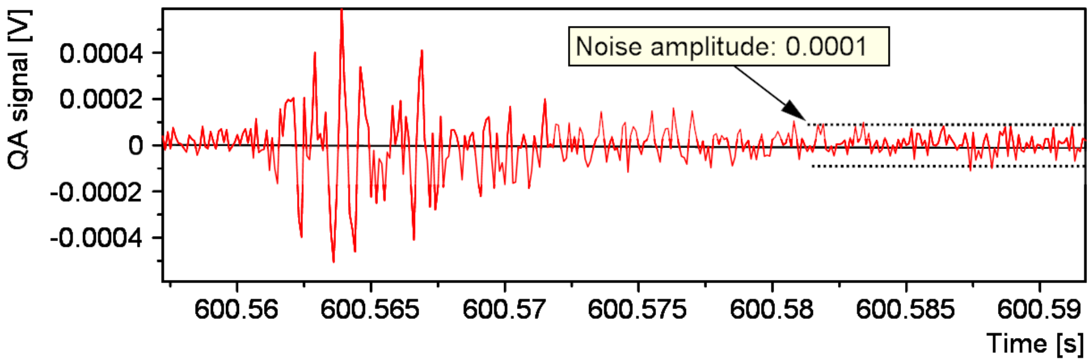
… Not perfect, but quite good!



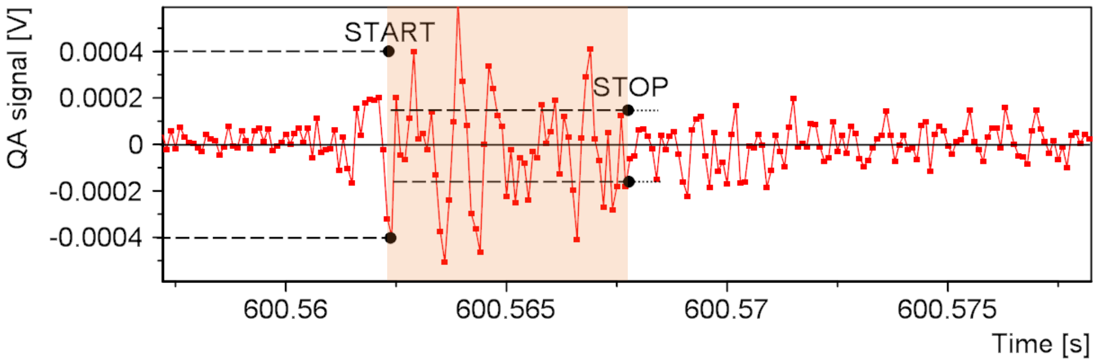
Thousands of events each ramp!

The algorithm with an example

Take the following vibration as example:

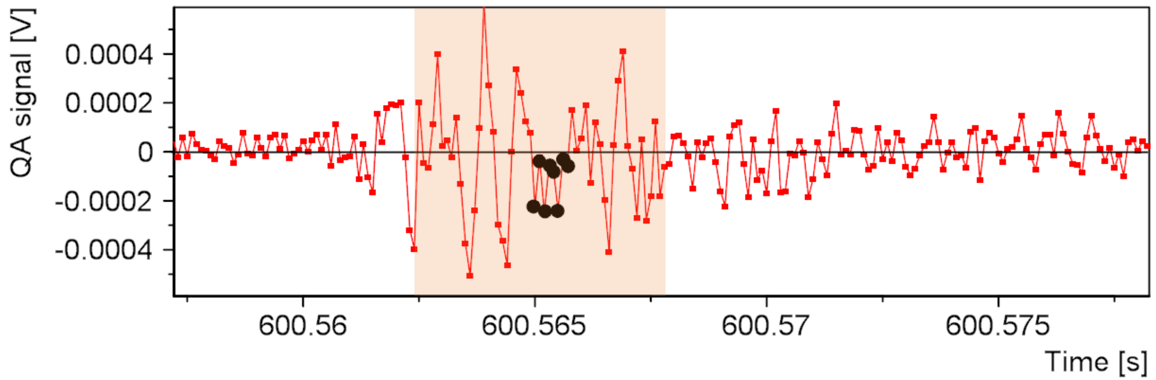


Find start: When signal > threshold$_1$
Find stop: When the next *n* samples < threshold$_2$

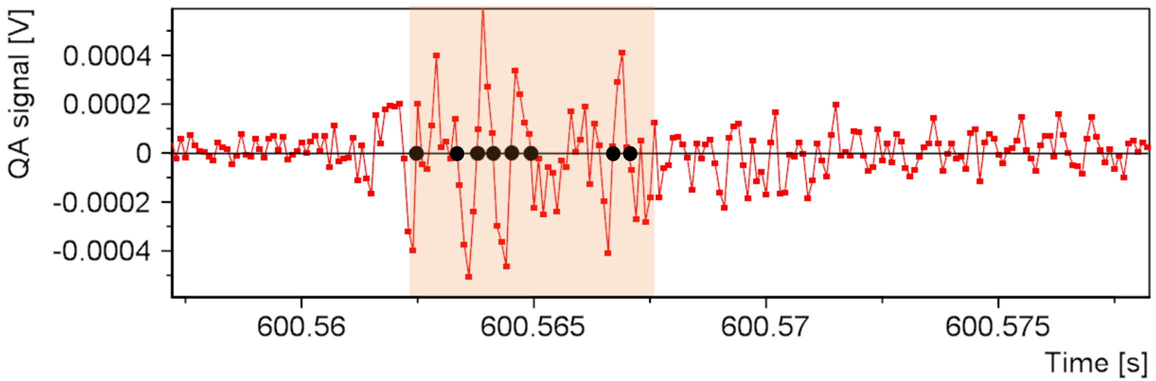


(1) A vibration signal should have a certain length

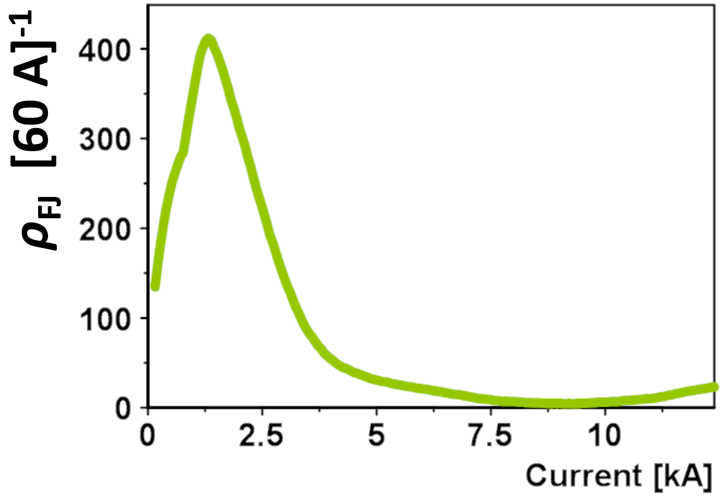
(2) A vibration signal should have an even distribution of positive and negative values.
(3) Also, not too many consecutive points should have equal sign:



(4) A vibration signal should clearly cross the x-axis a few times.



Further analysis of collected data

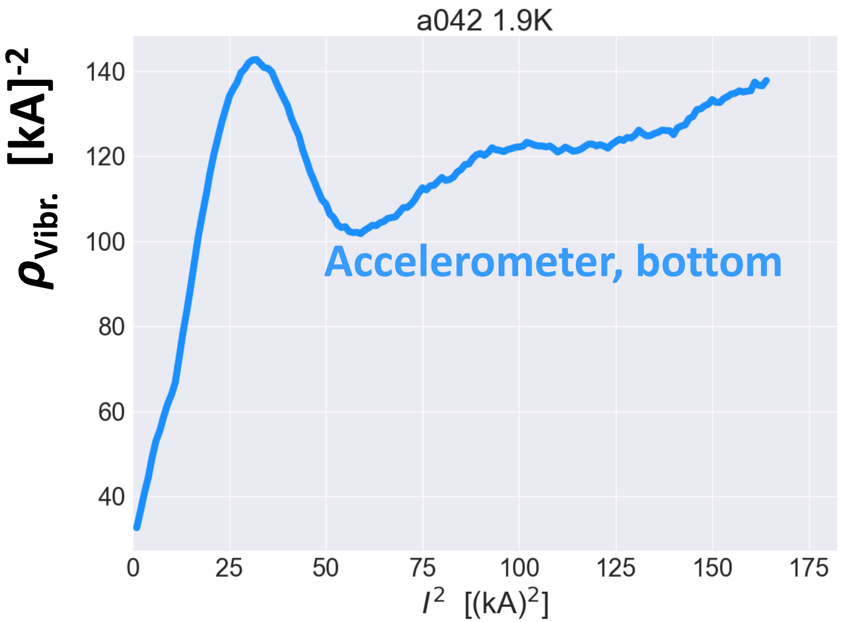


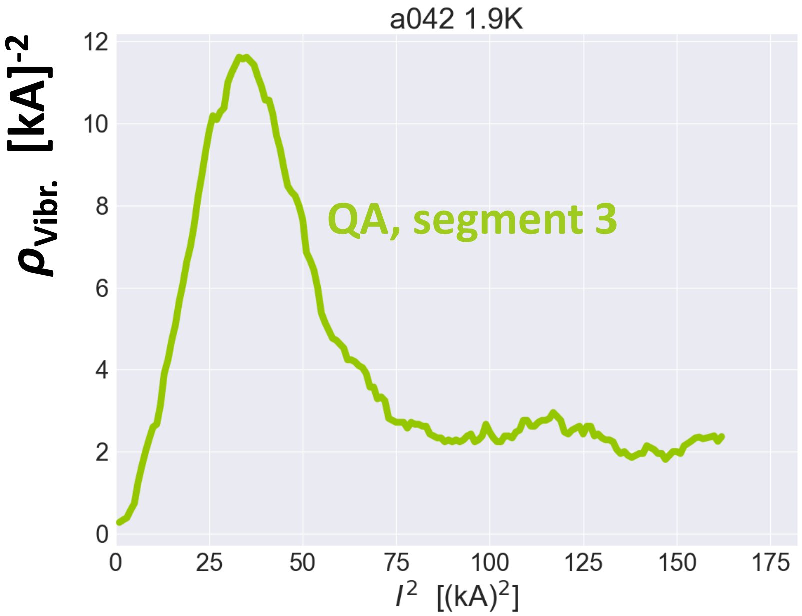
Flux jumps

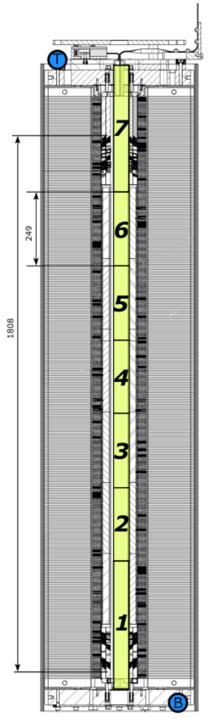
Number of flux jumps: ρ_{FJ} = #flux jumps / ΔI , plotted against I.

Vibrations

Number of vibrations: $\rho_{Vibr.}$ = #vibrations / $\Delta(I^2)$, plotted against I^2 (≈ forces in magnet).



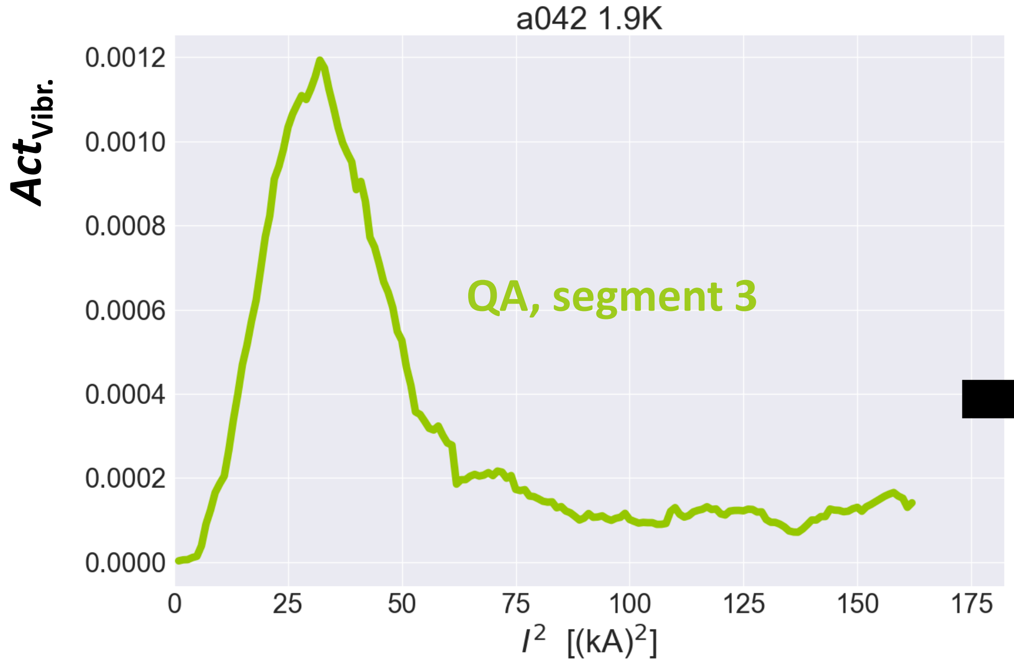


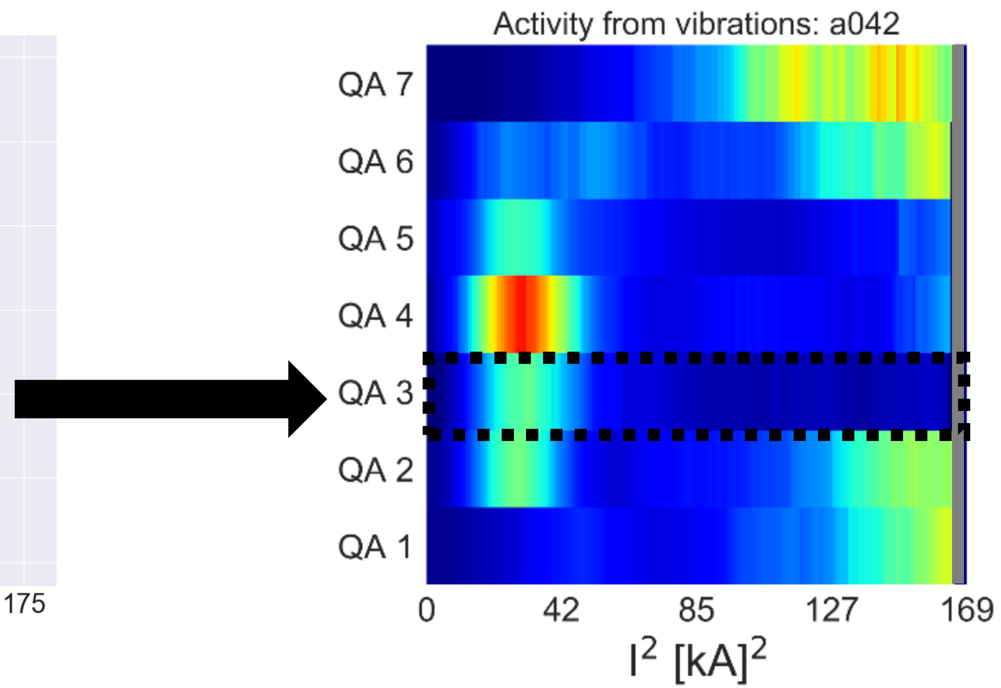


Expanding analysis to include amplitudes

Define activity: $\boldsymbol{Act}_{\mathbf{Vibr.}}$ = sum($A^{1.5}$)/ Δ(I^2), plotted against I^2.

- $A^{1.5}$ is in earthquake sciences correlated with energy release.
- *NOTE:* Apparent energy release can come from different sources (yoke, collars, coil, shell, helium, etc.).





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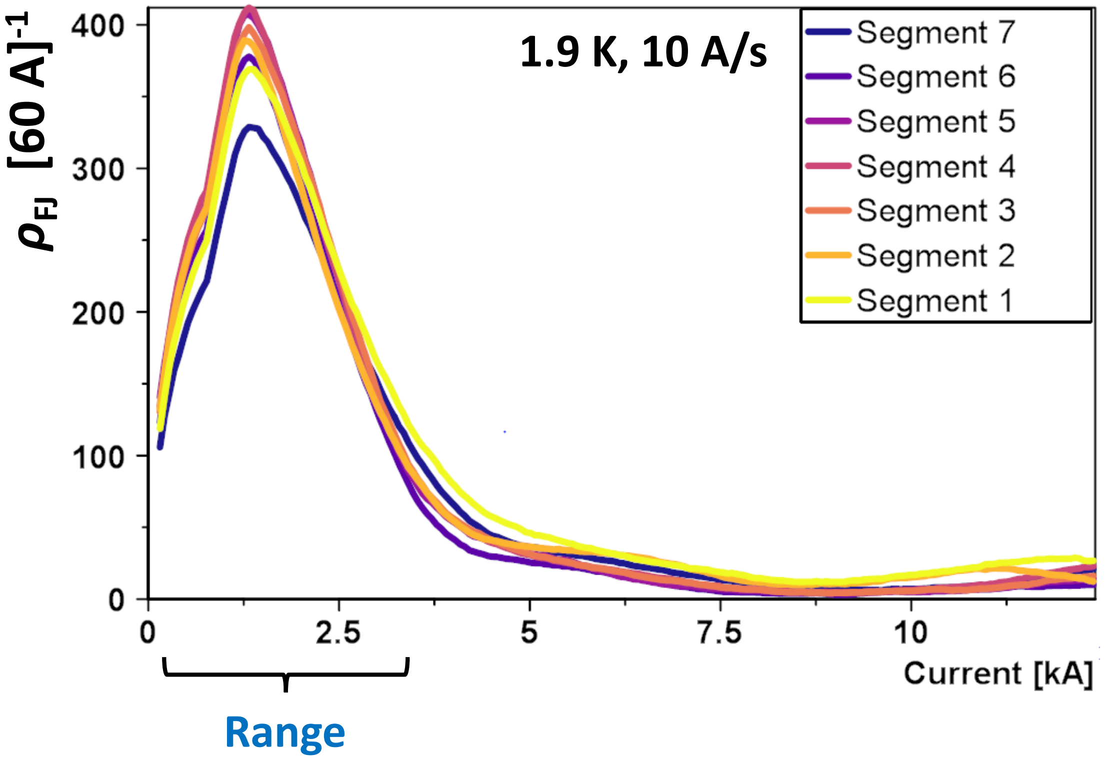
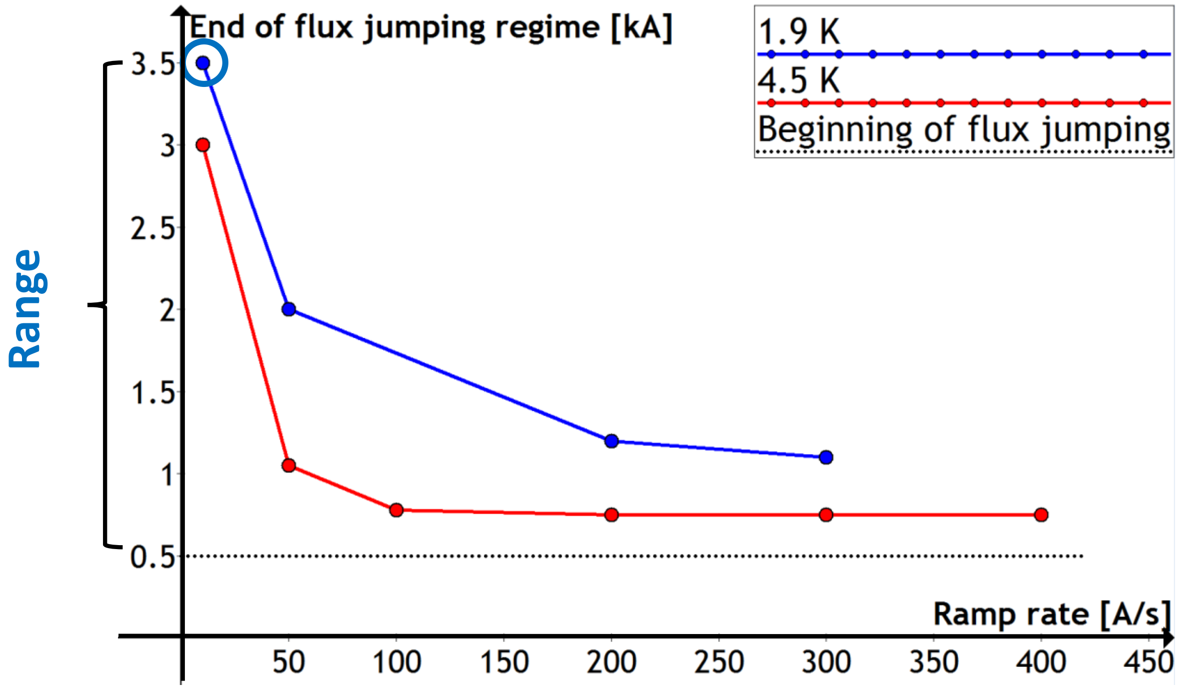
Summary

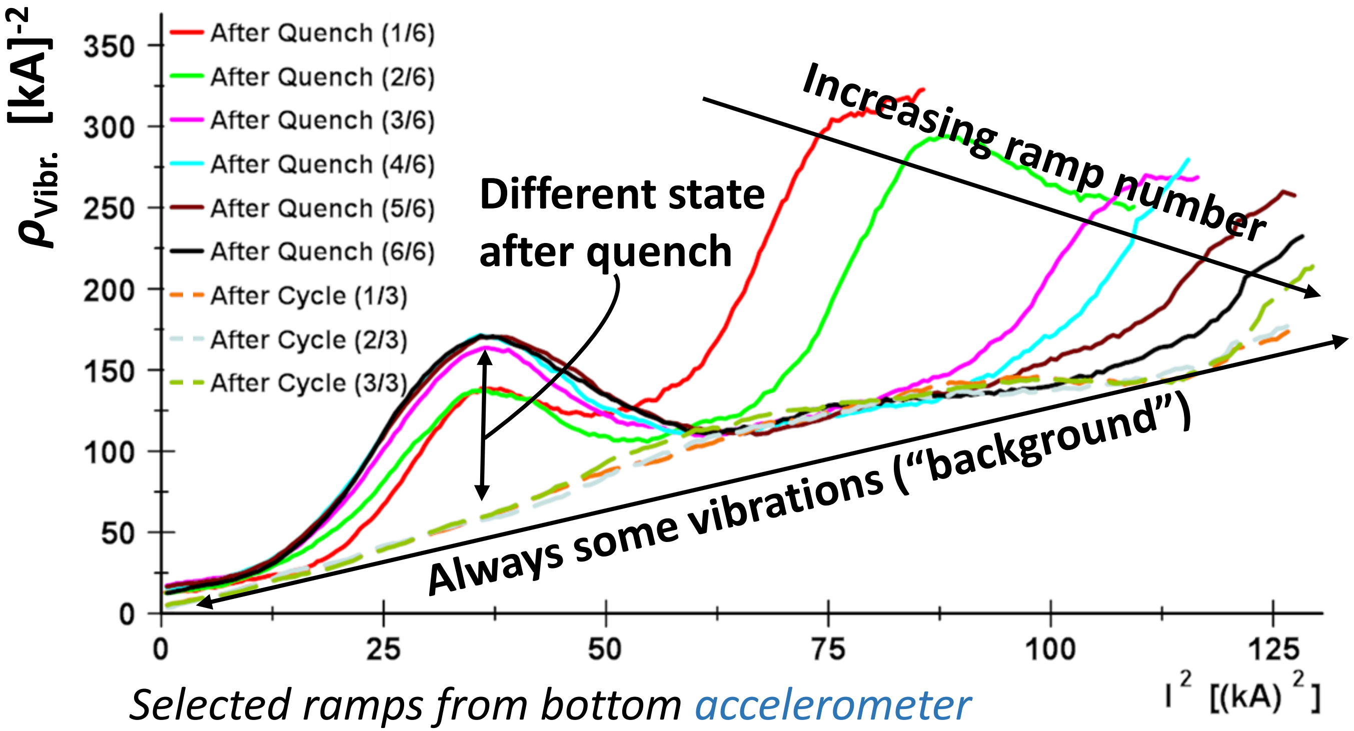
Flux Jumps in MBHSP106

- Many flux jumps at 1.9K.
- Much fewer, but bigger flux jumps at 4.5 K.
- **Range** is ramp rate and temperature dependent.
- Not always seen - depends on magnet history.





Analysis of vibrations in MBHSP106



Selected ramps from bottom accelerometer

Three main trends:

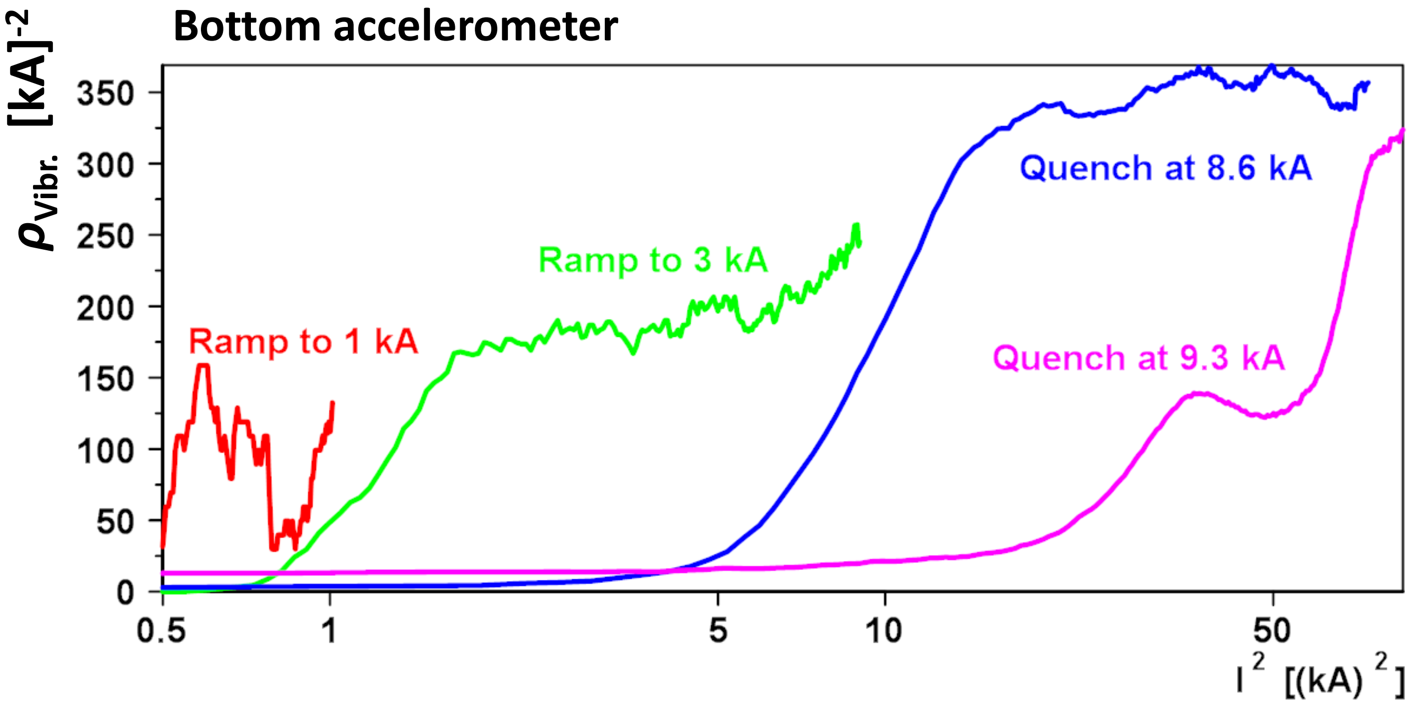
I) Consistent training when higher currents are reached.

II) There are always some number of vibrations.

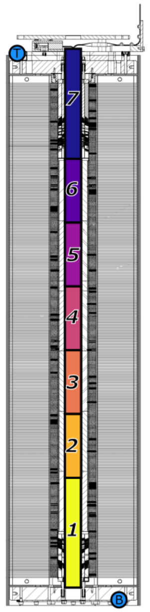
III) After a quench there are extra vibrations at intermediate current level.

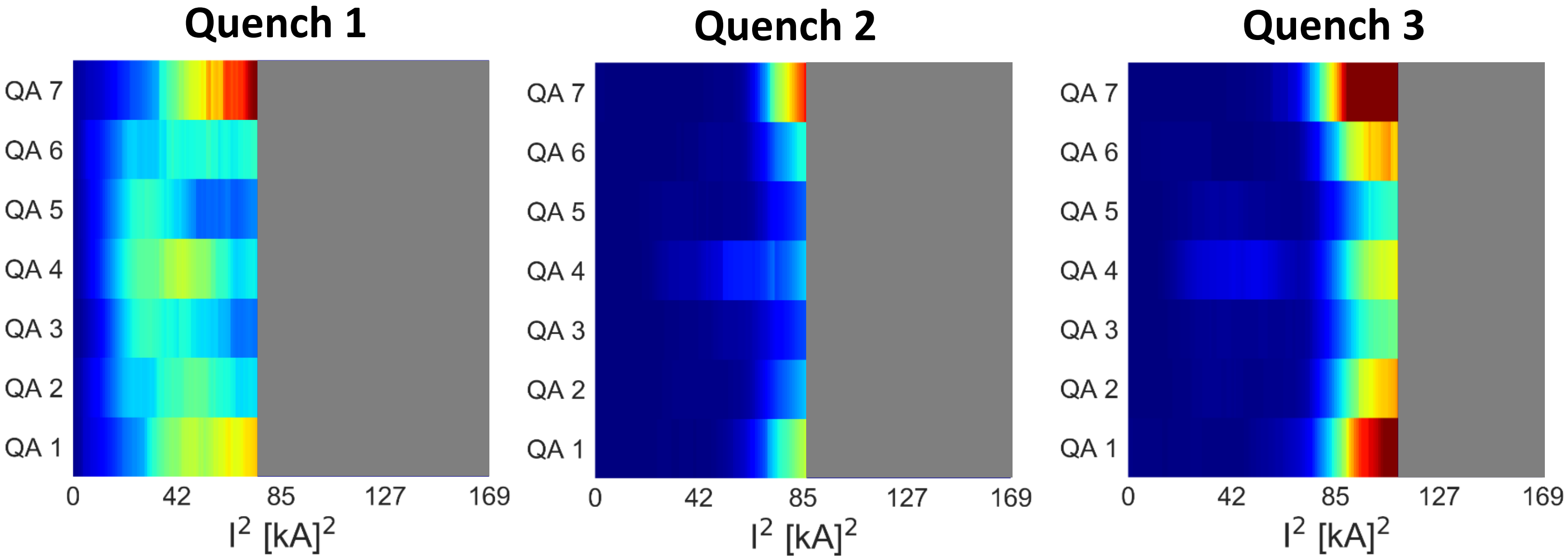
Training from virgin state

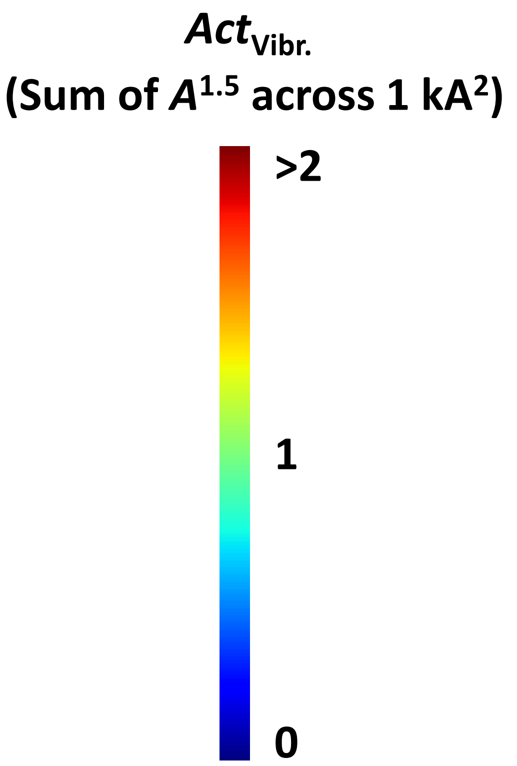
- The curves show the very first ramps of the magnet.
- When new currents are reached, the number of vibrations increase drastically.
- Training effect: Expected result!



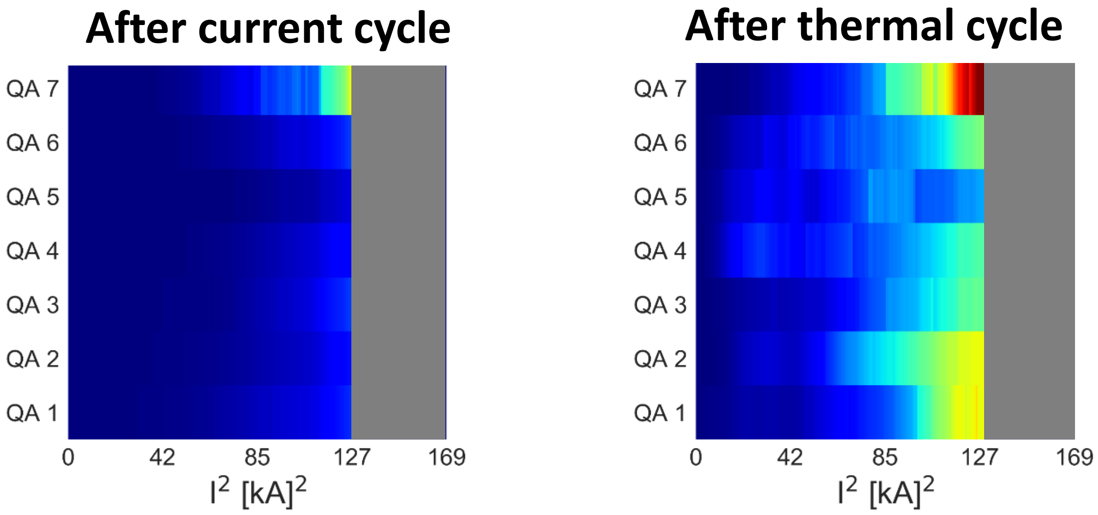
Localization of activity with QA







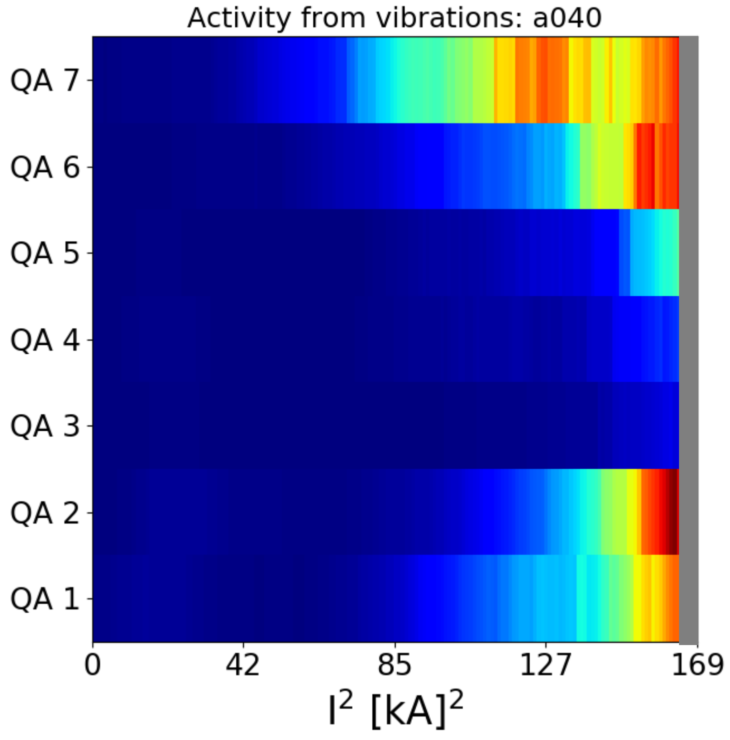
... many quenches later

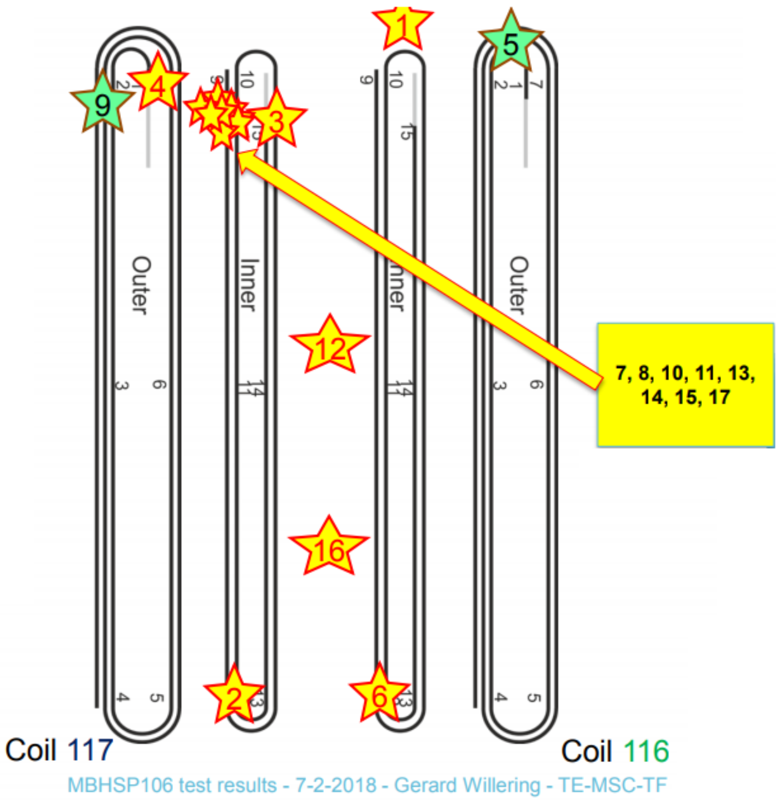


- **Activity mainly in the heads**
- **Reduces with number of ramps**
- **Evidently not 100% permanent after a thermal cycle**

Background activity vs. training/detraining

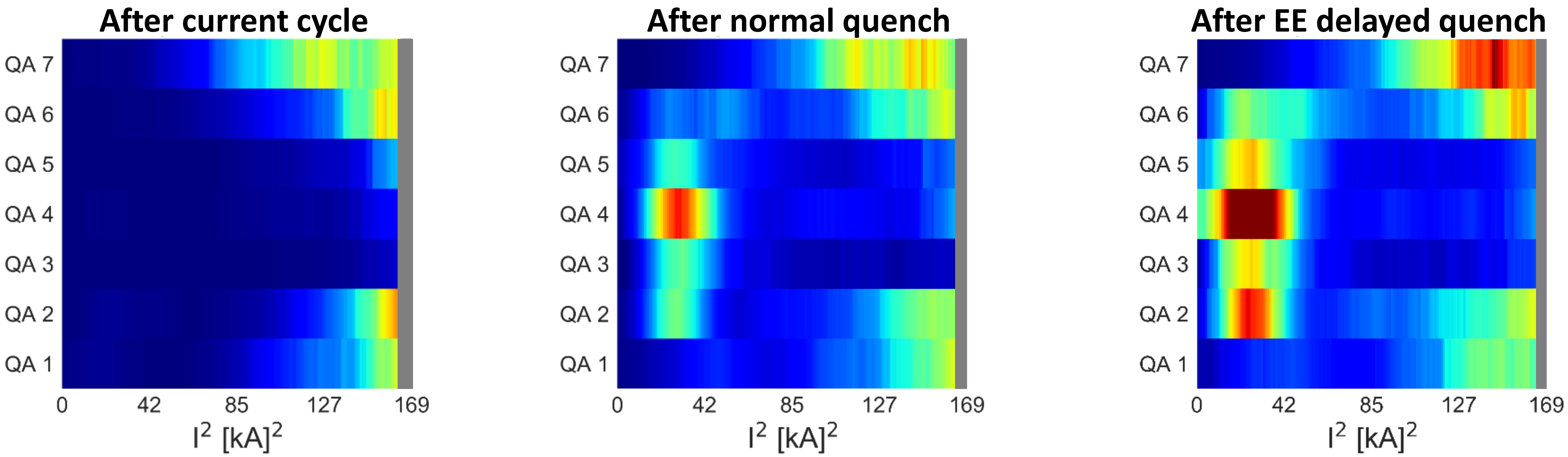
- In a trained magnet most of the activity is still in the heads as seen with QAs.
- Good correlation with training and detraining locations.



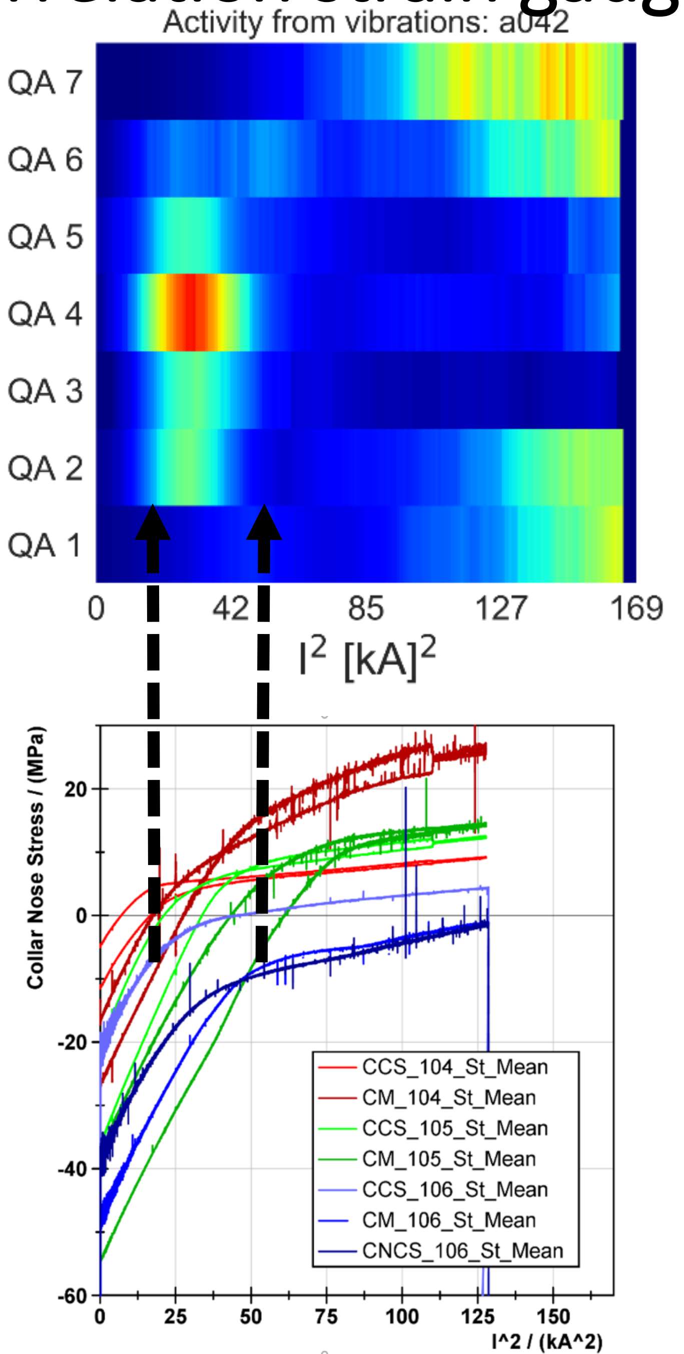


Intermediate current activity

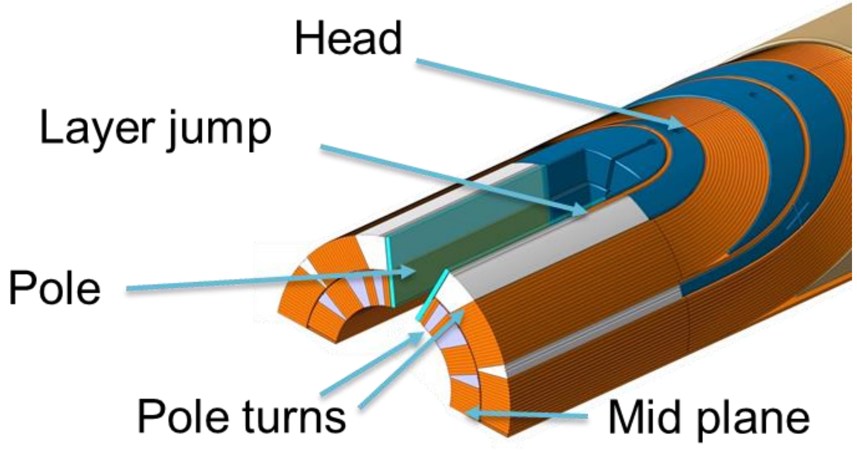
- The activity is present exclusively after a quench.
- Clear from cycling to 6 kA that something settles mechanically.
- More activity after quench with delayed energy extraction, but seems unrelated to previous quench current.



Correlation strain gauges and vibrations



Likely a link between unloading of the pole and oscillations, but not easy to have direct evidence.

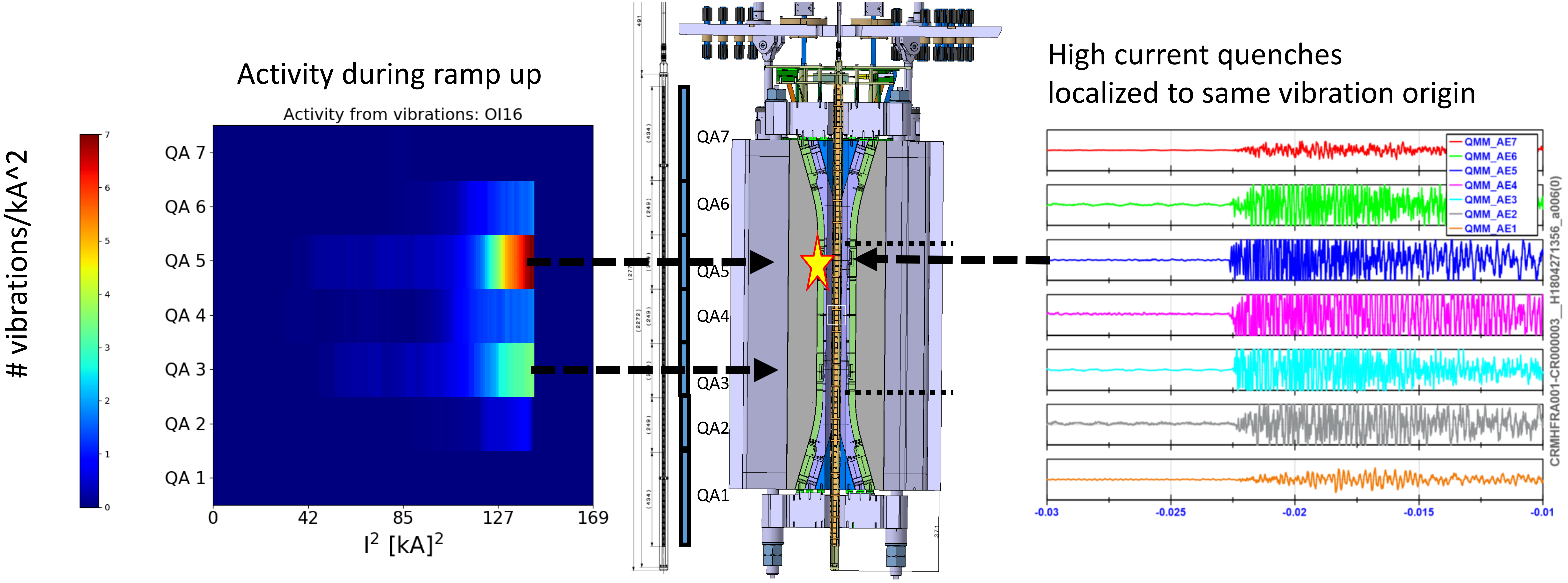


Courtesy Christian Löffler
& Philippe Grosclaude

Another recent magnet example:
FRESCA2

Block coil magnet
Same measurement shaft

Another recent magnet example



Summary

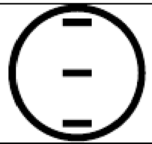
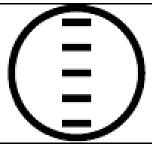
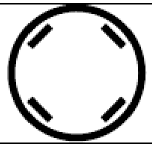
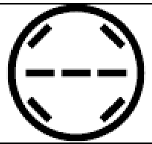
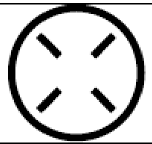
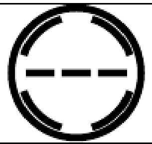
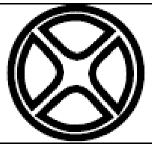
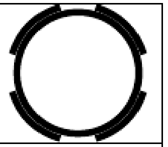
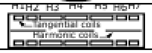
- The quench antenna are a strong tool for looking at the mechanics of the magnet.
- Hundreds to thousands of events are analysed, compared to a few tens of quenches in normal cases.

Plans at CERN:

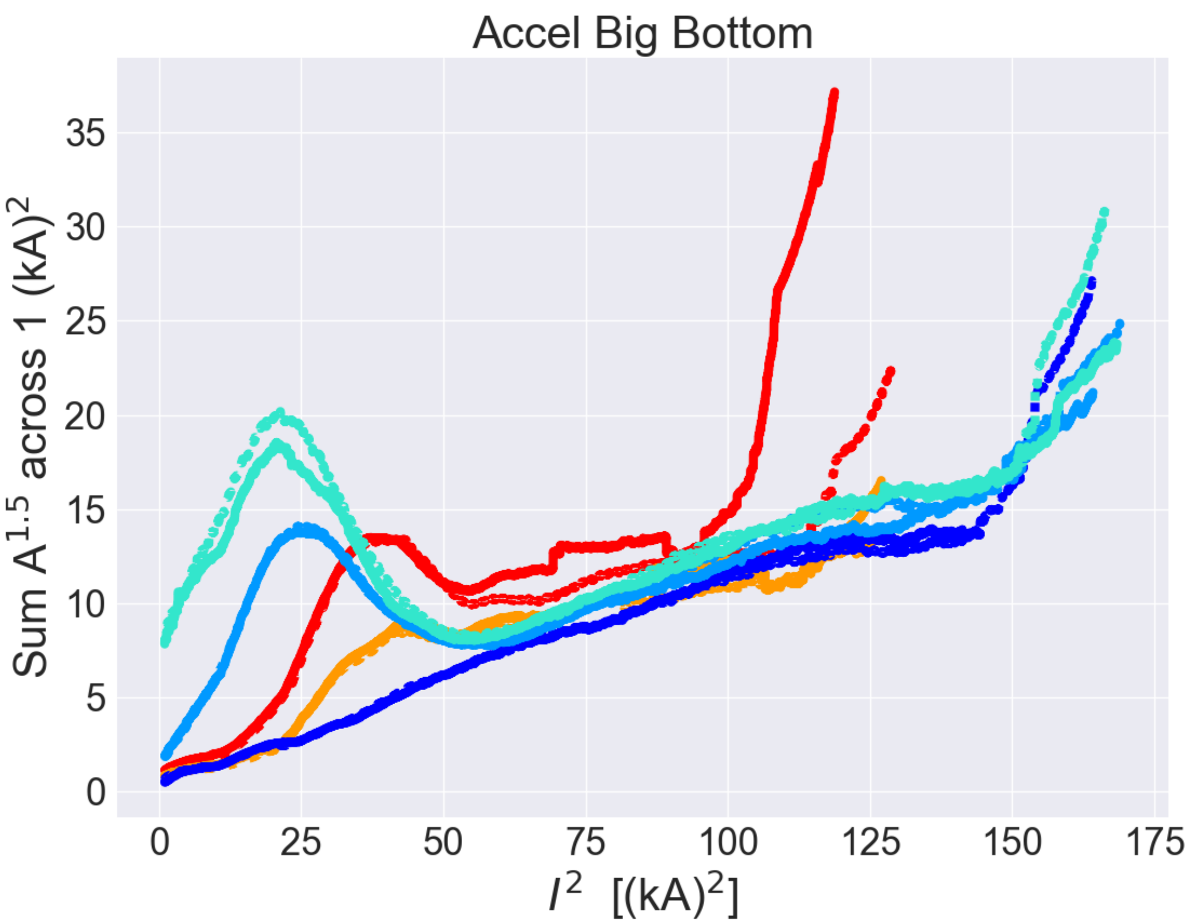
- Deploy wherever possible this method to learn more about the magnet and give better feedback.
- Starting with **MBH 11T prototype** (hardly any voltage taps).

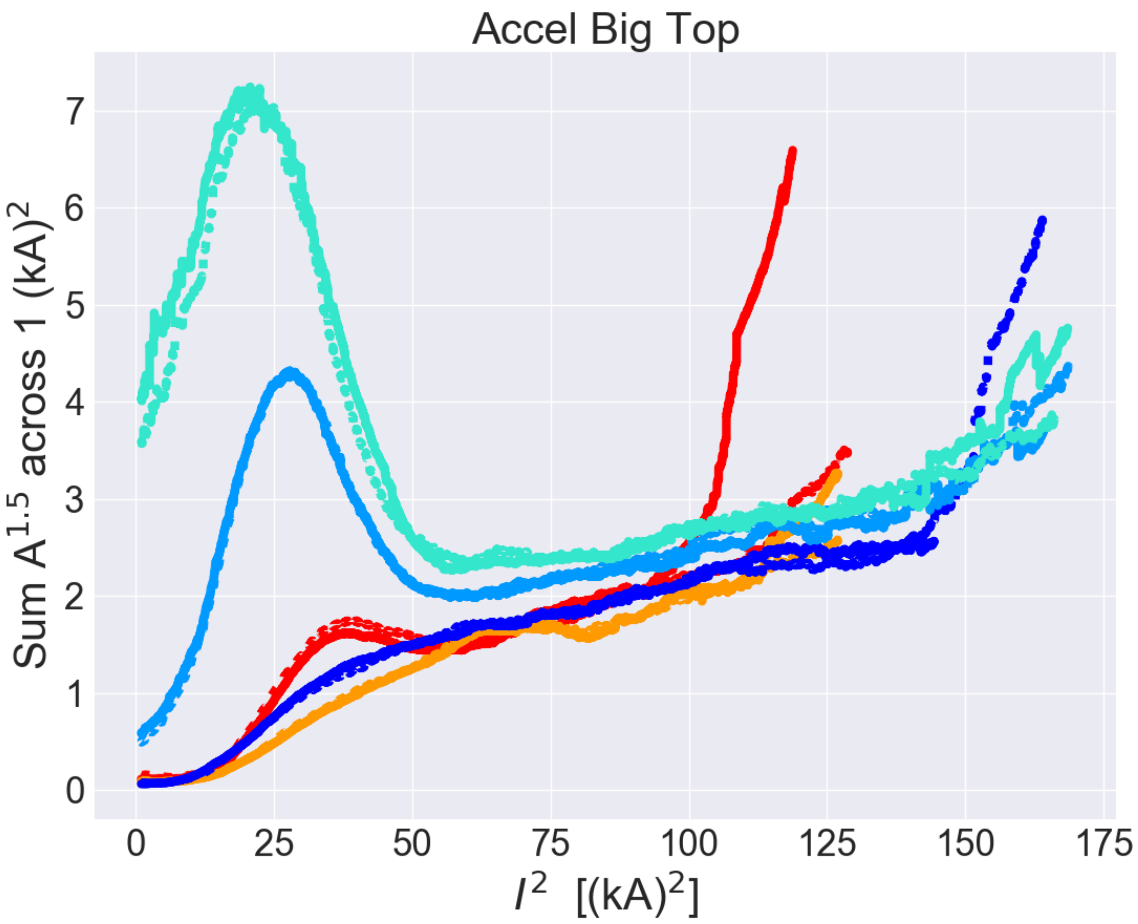
- Furhter development is ongoing in automation. More data has to be gathered to see real influence of temperature (1.9 K, 4.5 K).

Various quench antenna as used in the past and recently

Name	D11	MQXC	LQA	Siemko short	Siemko long	Leroy[3]	Axial	FPCB
Ref. number	MM-1	MM-2	QA-1	LQA	QA-3	QA-4	QA-5	QA-6
cross section view								
side view								
bore	cold	cold	warm	cold	cold	cold	warm	independent
MM	✓	✓		✓		✓		
DQA[4]			✓	✓	✓	✓	✓	✓
Special Feature				MM and QA		FPCB, MM and QA	Axial	FPCB & outside bore
Year	?	?	?	1995	1995	1993	2013	2017
Reference	?	?	?	[17]	[17]	[6]	[9], [11], [13], [14]	this report
nb. of turns N_t	36	36	400	?	?	tangential 12, harmonic 44	?	40 (2 layers)
magnetic surface $A \cdot N_t$ $[m^2]$	0.099 to 0.170	?	0.16	?	?	h.: 0.1056, t. middle: 0.06, t. end: 0.036	?	?

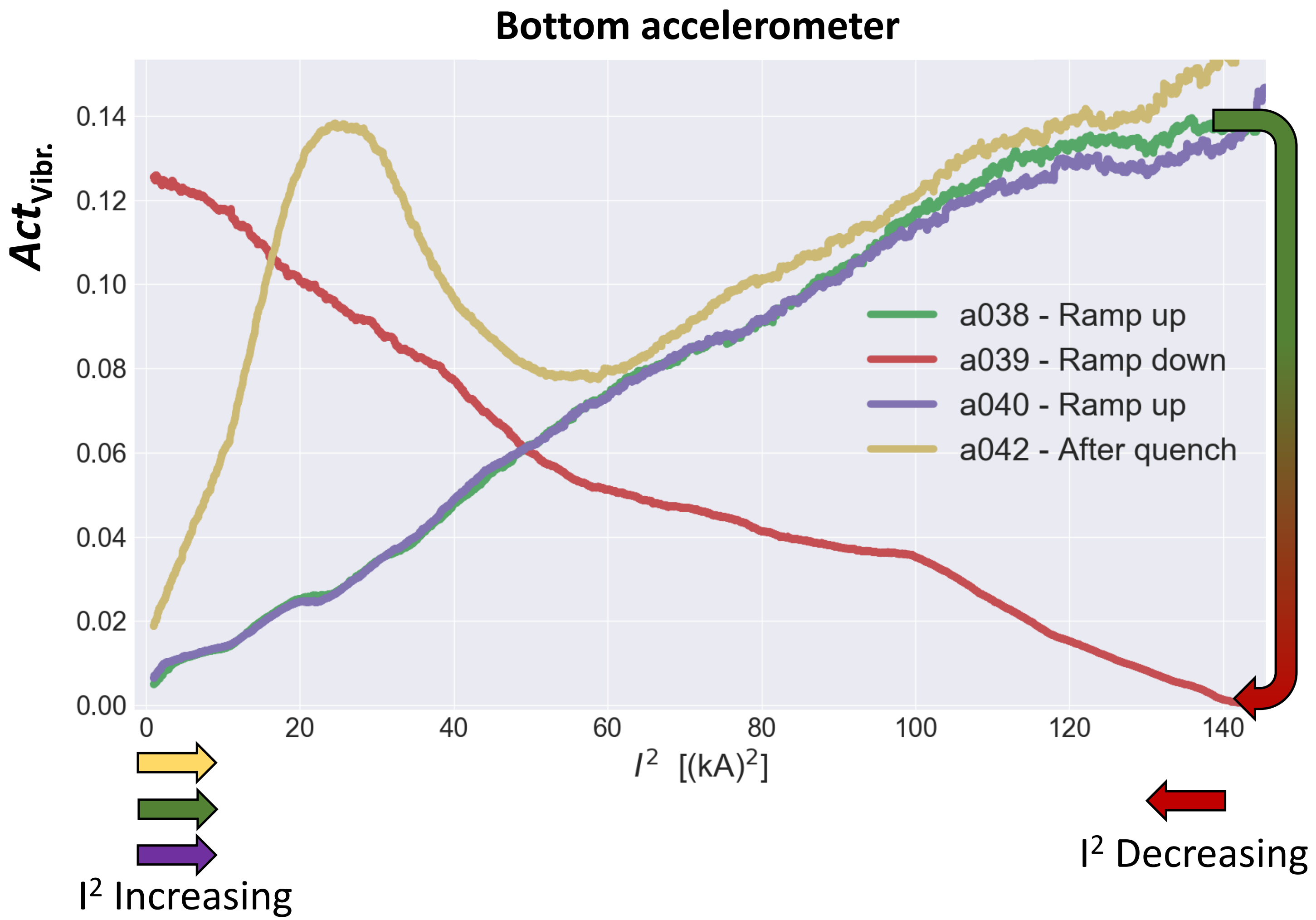
Top vs. Bottom accelerometer





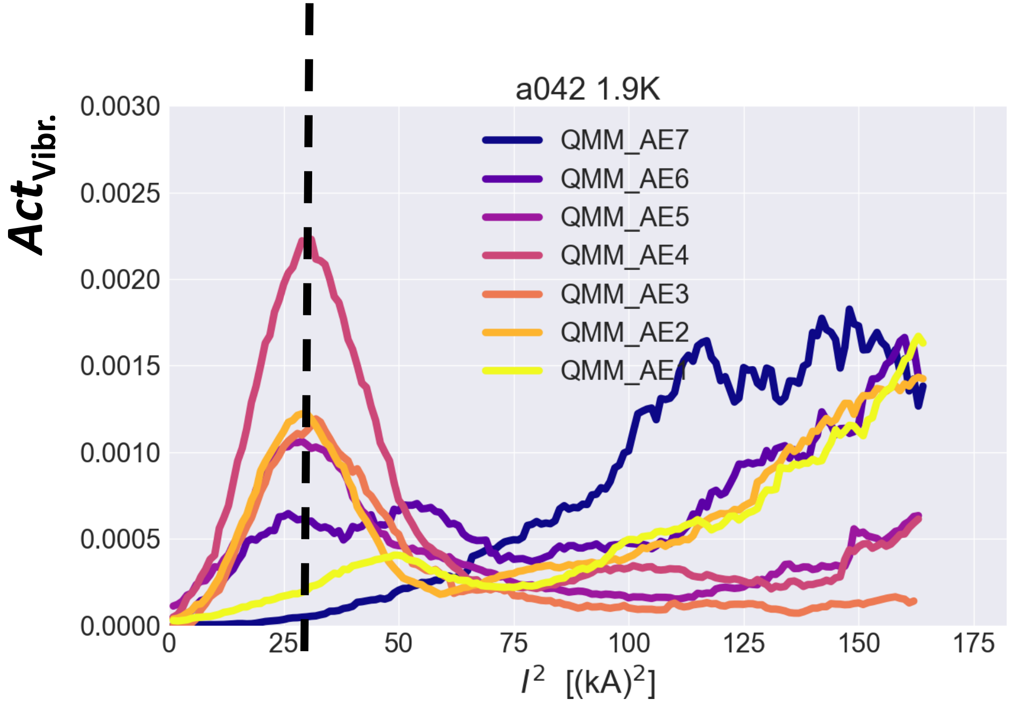
Background activity

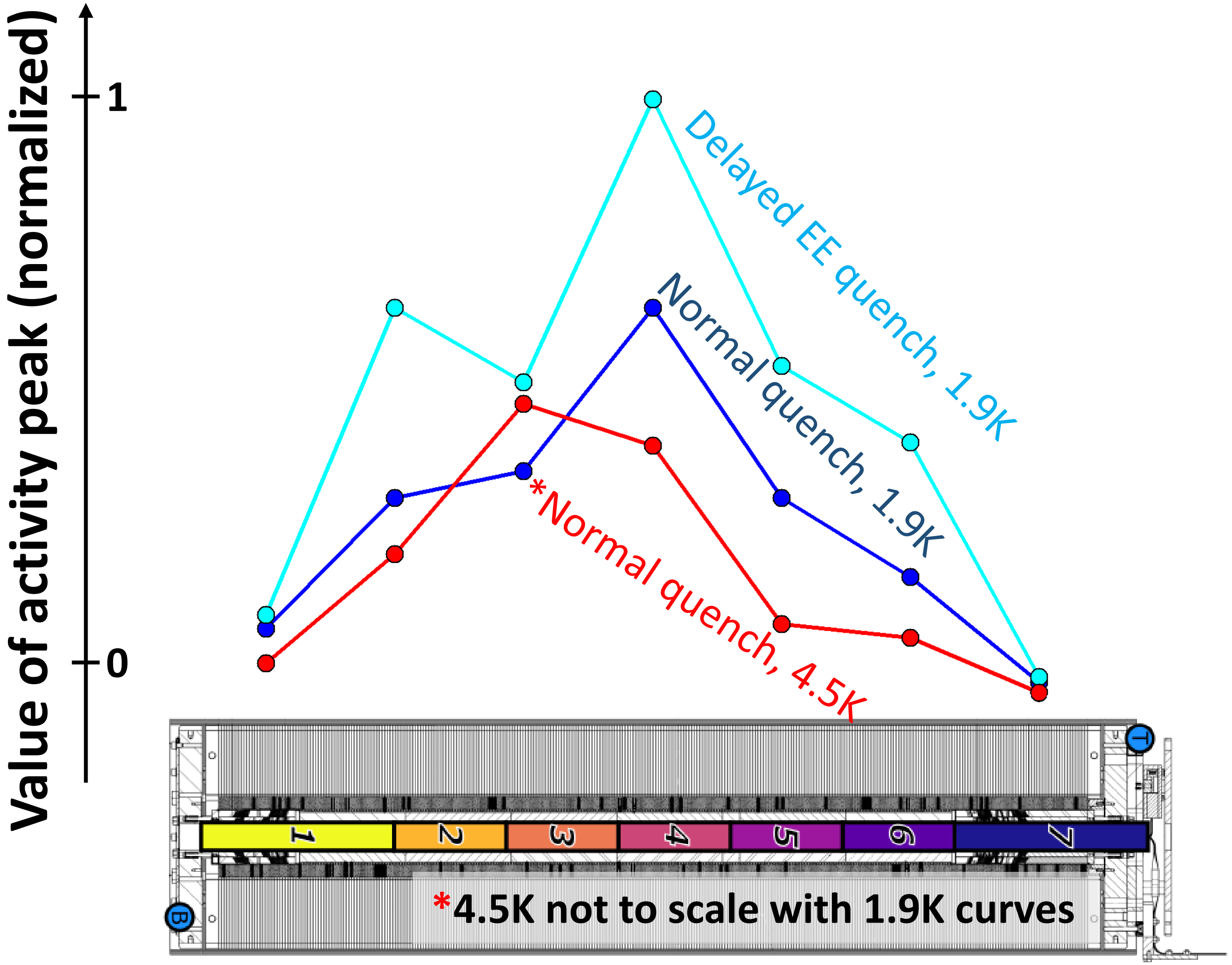
- Even in a trained magnet there are vibrations.
- Accelerometer gives insight when ramping the current up and down.
- Activity a linear function of I^2.



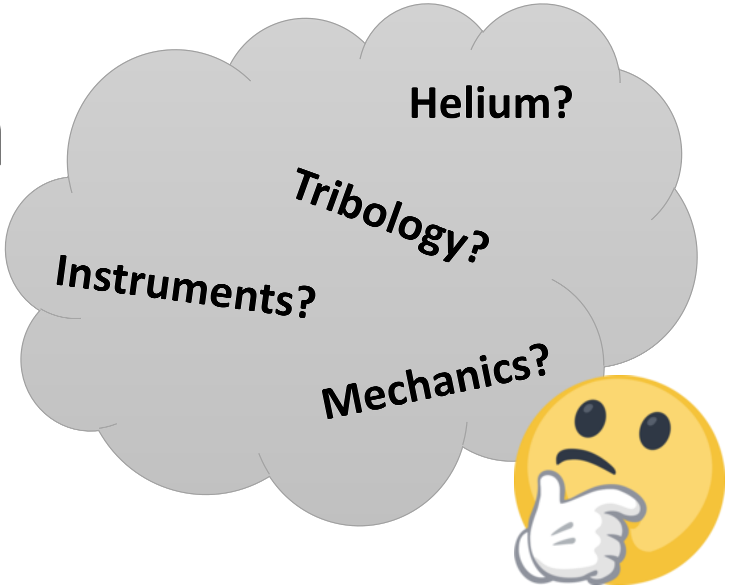
Intermediate current peak activity

Plot peaks around this line against position in magnet



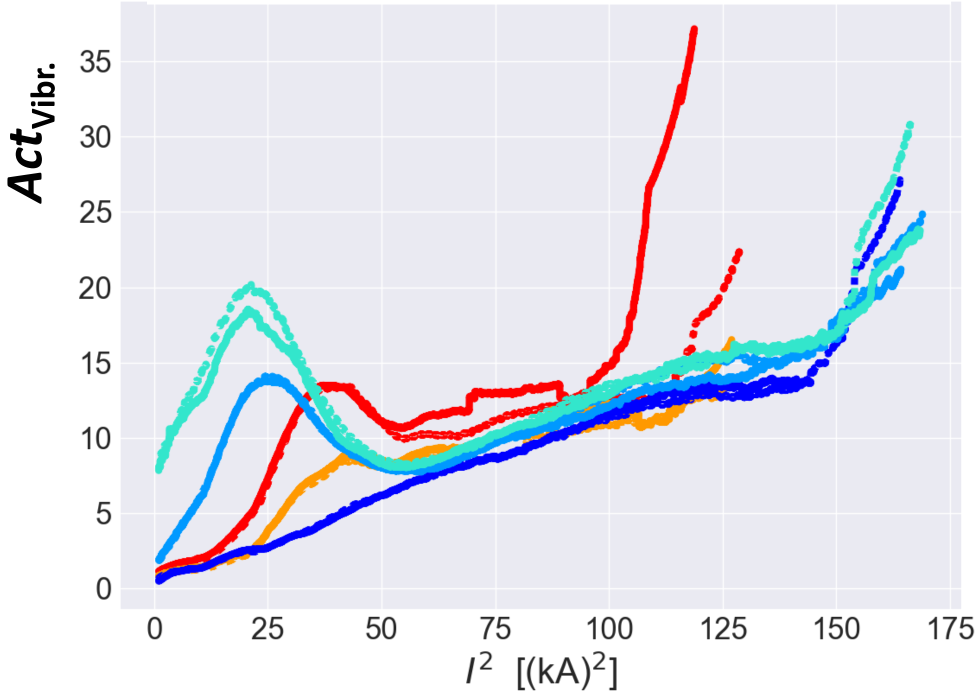


QA and accelerometer comparison



- **Huge** difference in accelerometer top and QA between 4.5K and 1.9K after a quench.
- Peak shifts to the left from 4.5K to 1.9K.
- For similar ramps, the curves are consistent.
- Will be interesting to see how it looks in prototype magnet!

Accelerometer Bottom



Preceding:

EE delay, 1.9K
Quench, 1.9K
Current Cycle, 1.9K

Quench, 4.5K
Current Cycle, 4.5K

(One pair of each)

Quench antenna (segment 4)