Quench data analysis and interpretation of magnet behaviour or *“Troubleshooting”*

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With special thanks to Marta Bajko, Jerome Feuvrier, Vincent Desbiolles, Max Andre Pascal, Gaëlle Dib, Hugo Bajas, Franco Mangiarotti, Håvard Arnestad, Daniel Turi, Javier Villena Pulgar and many more.

Magnet test stand workshop, 9 May 2018, BNL

Contents

- **Tools to understand a quench**
  - Quench localisation and propagation with voltage taps
  - Quench localisation and propagation with quench antenna
  - Distinguishing mechanical origin from conductor limit origin

- **Additional methods to understand the magnet behavior**
  - A case study of homogeneous conductor degradation
  - A case study of a non-homogeneous defect

Quench Phenomena and tools

Phenomena

Phenomena to investigate around quench event

- Resistive voltage and quench propagation
- Temperature (HTS)
- Current redistribution at quench front
- Mechanical transients
- Mechanical strain
- Flux jumps

Additional analysis

- Conductor degradation Local or distributed
- Splice resistance
- AC loss impact

Tools

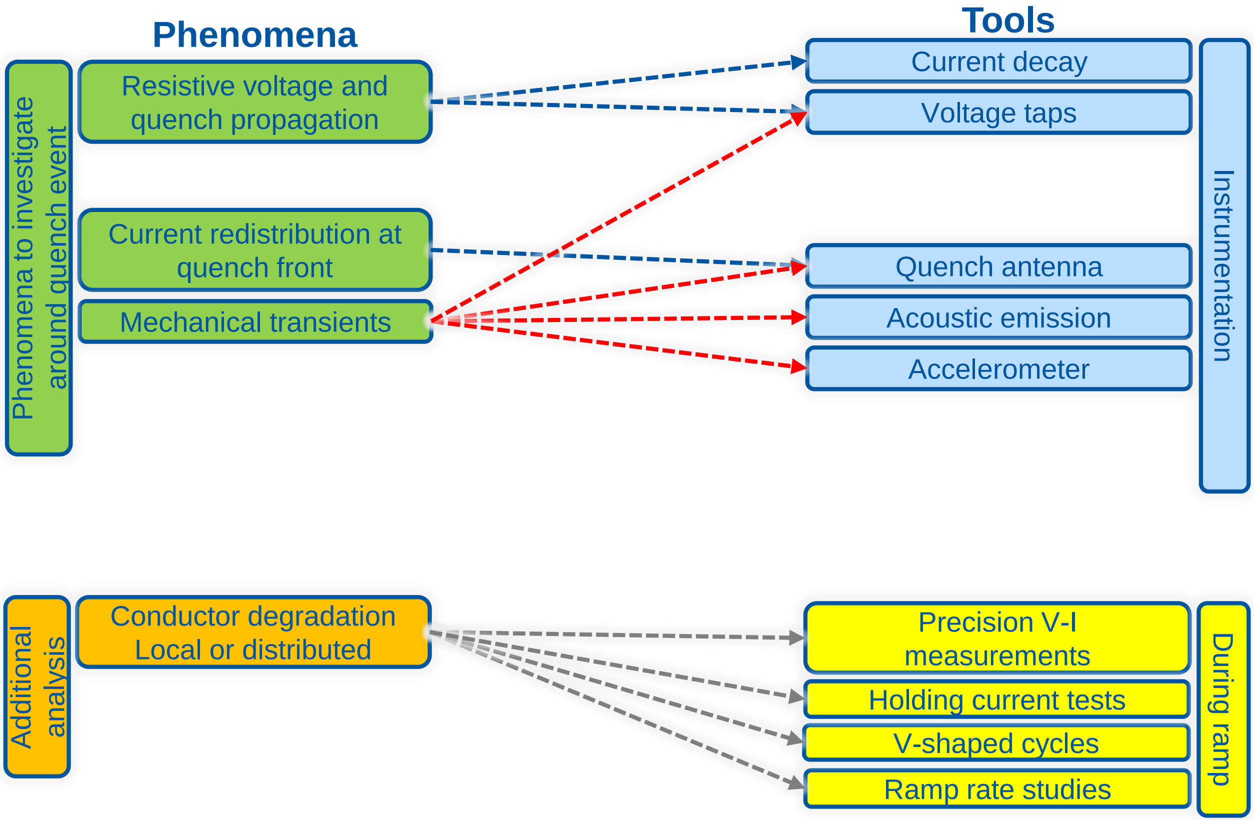
Instrumentation

- Current decay
- Voltage taps
- Temperature probes
- Optical fibers
- Quench antenna
- Acoustic emission
- Accelerometer
- Strain gauges
- Magnetic measurements

During ramp

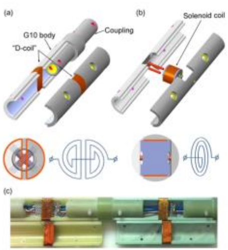
- Precision V-I measurements
- Holding current tests
- V-shaped cycles
- Ramp rate studies

Quench Phenomena and tools



Tools for quench propagation, quench antenna & voltage

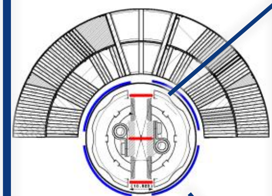
Axial-Field Magnetic Quench Antenna



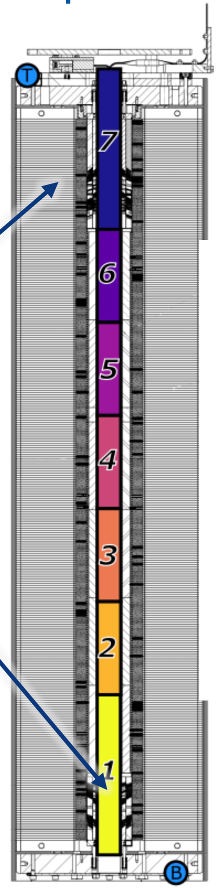
M. Marchevsky et al., “Axial-Field Magnetic Quench Antenna for the Superconducting Accelerator Magnets”, IEEE Trans. Appl. Supercond., Vol 25, No 3, June 2015

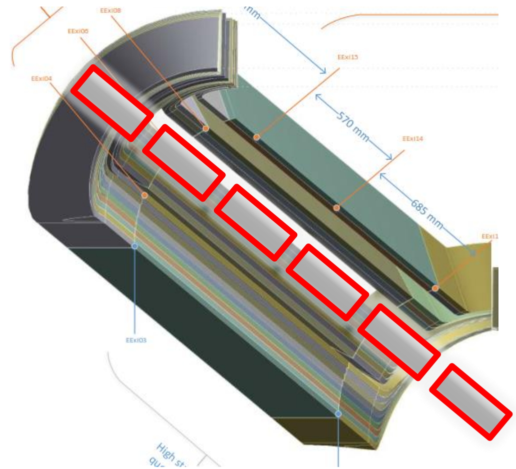
Longitudinal Quench Antenna

Type MM shaft (red bars)

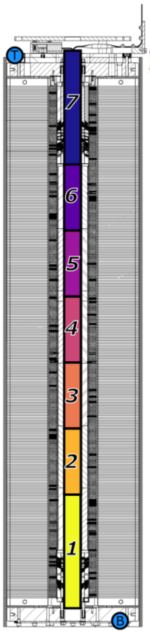


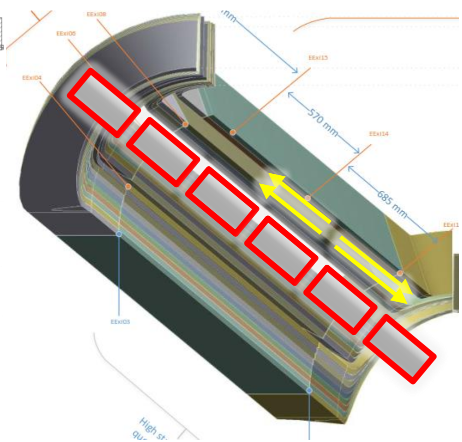
Type flexible PCB (blue lines), placed around bore tube.





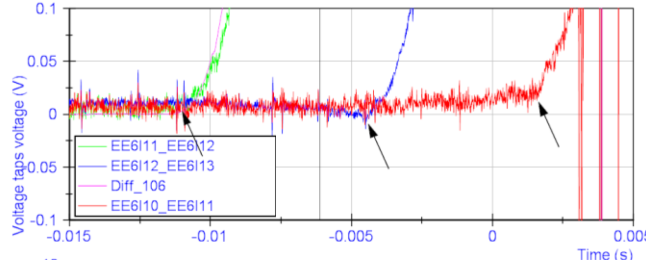
Measuring quench location and propagation: Classical, example

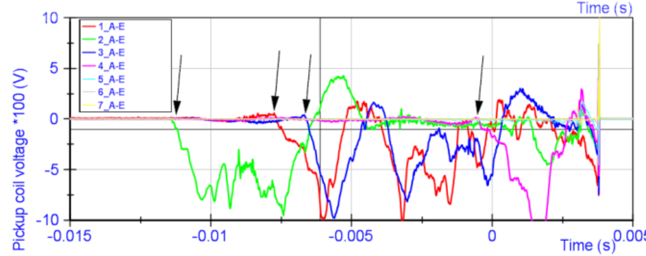


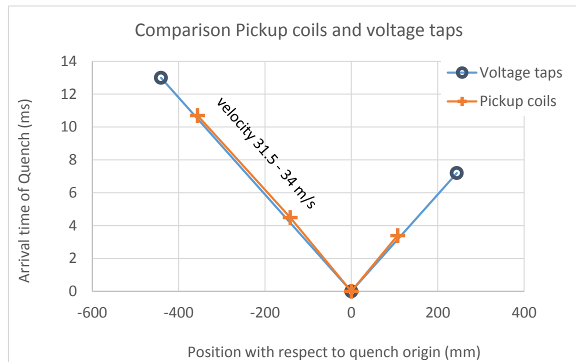


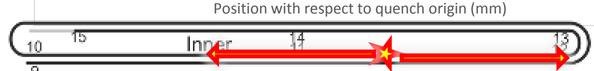
Quench localization:
Old topic, many people have worked on it

Having many voltage taps helps a lot to localize a quench. Quench antenna may help to localise better



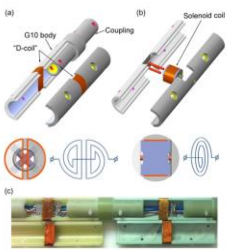






Tools for quench classification, looking at vibrations

Axial-Field Magnetic Quench Antenna



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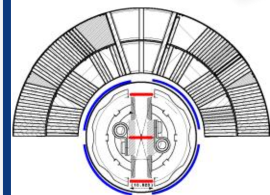

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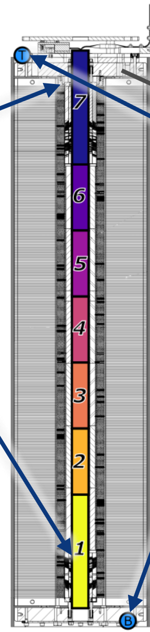
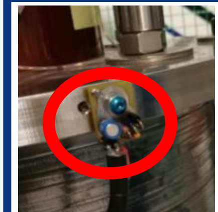


Accelerometers

In SP106 mounted on the end plates (Top and Bottom) of the magnet to measure longitudinal vibrations.

Useful range 0 to 3 kHz

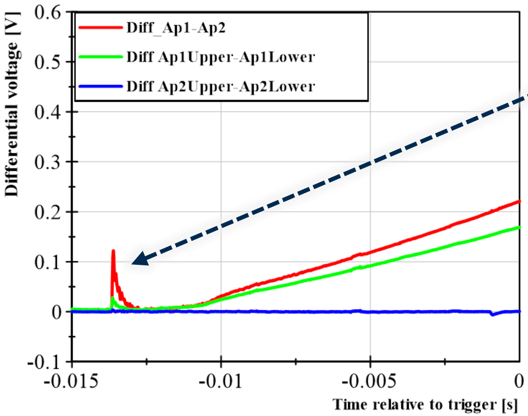
Accoustic emission sensors



- Useful range 0.1-300 kHz
- In use at LBNL (M. Marchevsky)

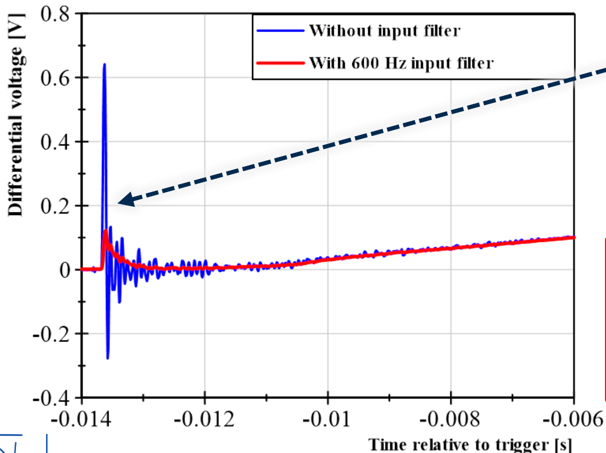
Quench classification: Precursors.

Example data: fifth quench in MBHSP106 at 10.8 kA



As always done in SM18 until recently:
Using a 600 Hz first order **low-pass filter** for all voltages
This setting is optimized for **protection** and getting **smoother signals**, and avoids resetting validation delay.

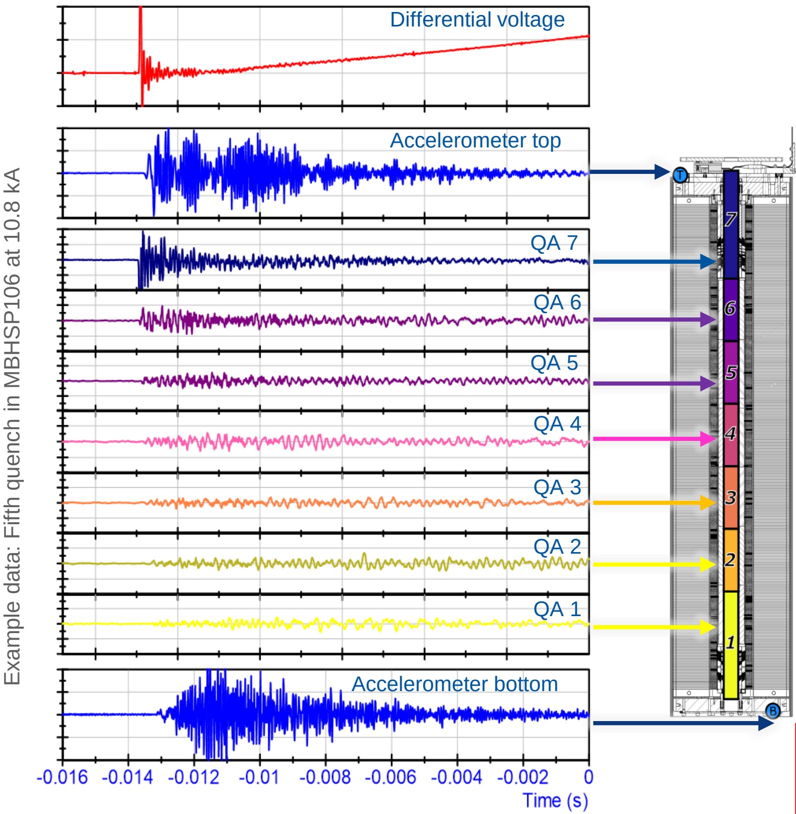
We can distinguish a precursor: difficult to distinguish flux jump from mechanical oscillation.



Recent change
Removing the 600 Hz filter reveals much more details
A damped oscillation is clearly showing in this case.

Possible strategy:
1 channel with low pass filter for optimized protection
1 channel without low pass filter for obtaining more info on the events

Distinguish mechanical from electrical quench origin: Example 1



Thanks to D. Turi, J. Villena Pulgar, M. Pascal, H. Arnestad

With voltage:
Differential voltage shows clear indication of mechanical oscillations.

With quench antenna clear localisation of vibration:

- Largest amplitude in QA 7
- Earliest onset in QA 7
- Stepwise onset in QA 7, compared to slow onset further away.

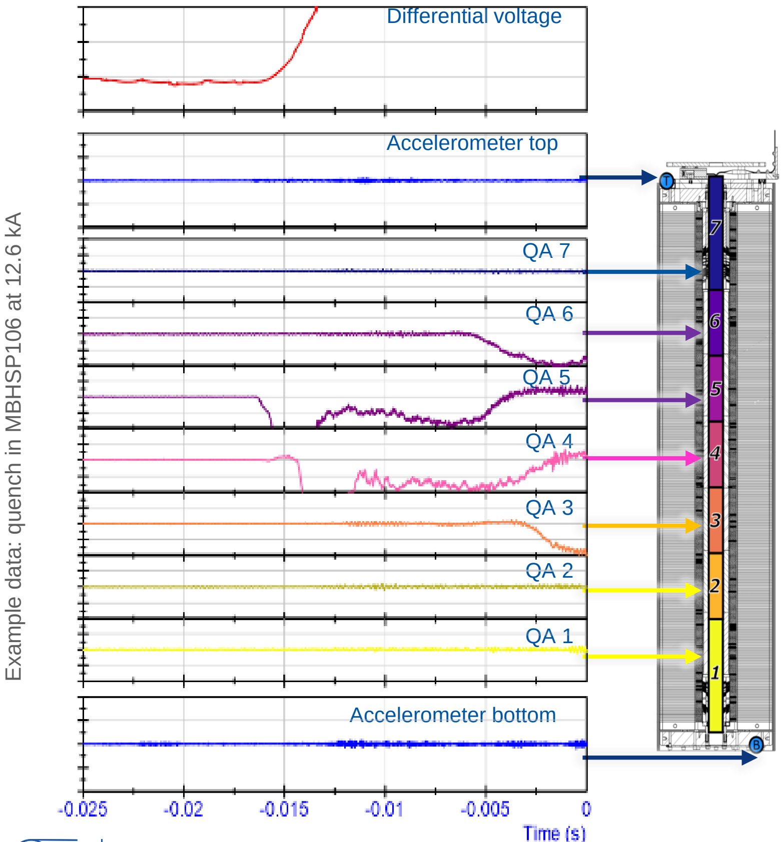
→ clear localisation possible

With accelerometers:

- Earliest onset in the top
- Slow onset on the bottom (far away from source)
- Amplitude in top seems a bit smaller and more irregular. Difficult to say if this is due to probe or to the sound transfer through magnet structure.

Verdict for this event:
Mechanical origin, clearly a damped oscillation at the start of the quench.

Distinguish mechanical from electrical quench origin: Example 2



Differential voltage shows no oscillation

With quench antenna: No vibration, but clear localisation of quench:

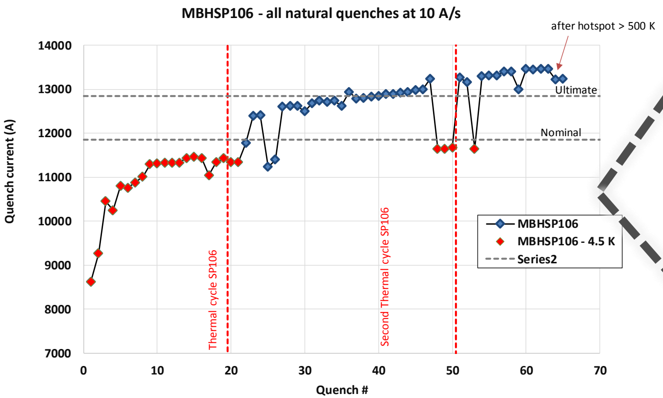
- Onset of the signal start in QA 5, propagates to QA 4 within a few ms. Quench does not arrive in segment 3 or 6.
- Clear theories have been presented on the current redistribution at the propagating quench front which cause the signal rise.

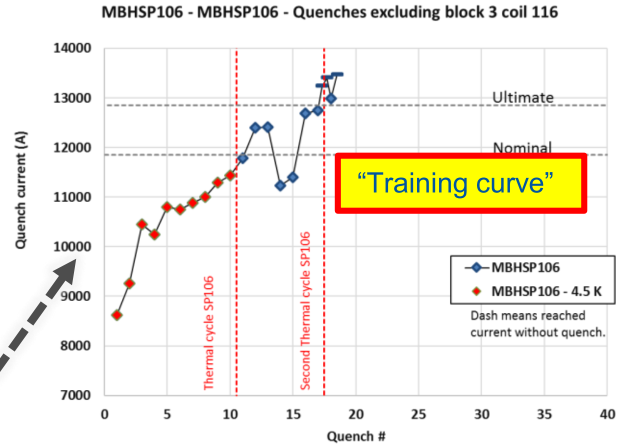
With accelerometers:
No activity at the start
Possible small activity during quench development.

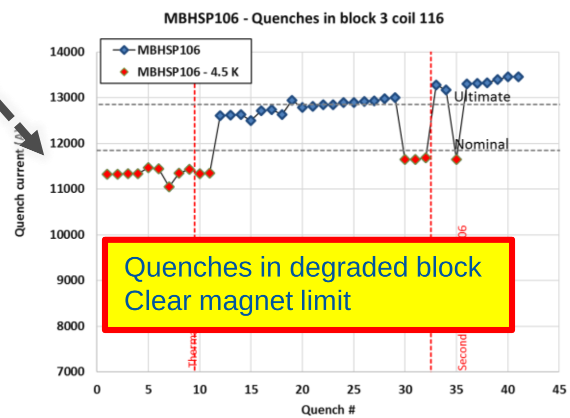
Verdict for this event:
No vibration. (Difficult to say if we are sensitive enough to micro-cracks.)

The “Manager view”: showing what matters

Splitting up the quench curve in “training” and quenches at specific location with issue.







Note: For reporting it is of highest importance to show all the data, clearly and honestly.
For understanding the magnet, splitting could help.

Conclusion part 1: Understanding the quench

Differential voltage:

- Can give already a good indication of the precursor. **Not filtering** can help a lot!

Quench antenna

- Can hint if the origin of the quench is mechanical
- Good localization of a vibration
- If no clear vibration: Good measurement of quench propagation and of quench location
- Can distinguish flux jump from mechanics and show flux jump propagation (see next talk)

Note: Typically the vibration signal hides signal of propagating front.

Accelerometers / accoustic emission sensors

- Can indicate the mechanical nature of a quench.
- Accoustic emission sensors measure much higher frequency events compared to accelerometers.

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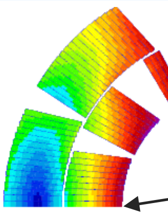
V-I curves in magnets – MBH 11T model as example

Expected electric field.
Note: for a magnet the field dependence is included.

$$E(I,B) = E_c \left(\frac{I}{I_c(B)}\right)^{(n(B))}$$

(with E_c = 10 uV/m)

Field input (dB/dx over cable width)



Peak field

block3 (segment I7-I8, 3.1 meter between V-taps)

Midplane (segment II-I1, 1.4 meter between V-taps)

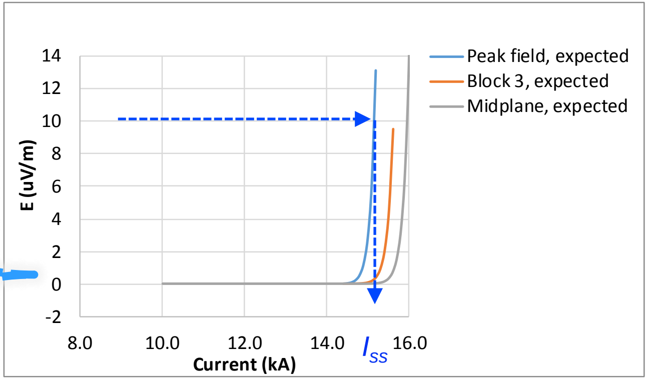
Witness sample data

Table V – I_c Parameters for extracted samples

Temp [K]	B_{c2} [T]	C (low) [kA/T]	C (high) [kA/T]
1.9	26.3	38.1	39.7
4.3	23.9	31.9	33.3

n-value as function of B
~60 at 10.5 T
~45 at 12.3 T

Expected field in the different segments



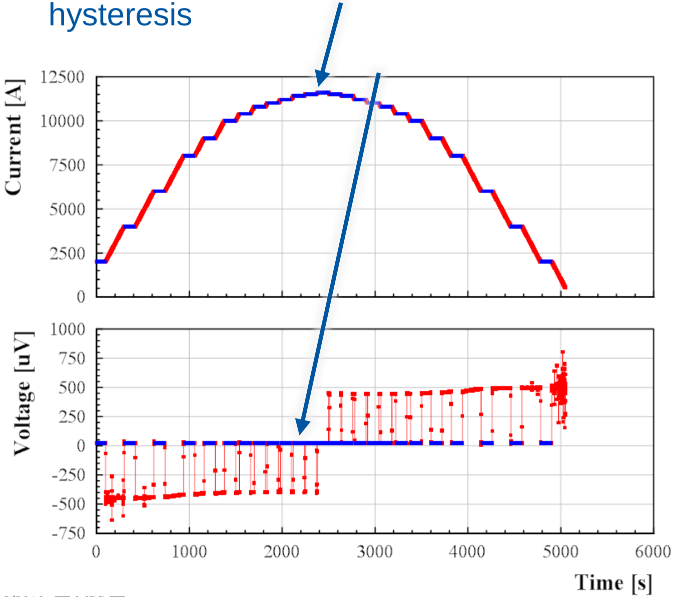
Why don't we measure the V-I curve in general?

- Apparent n-value is high, generally no stable current at this level.
- Inductive component can be large with large voltage segments.

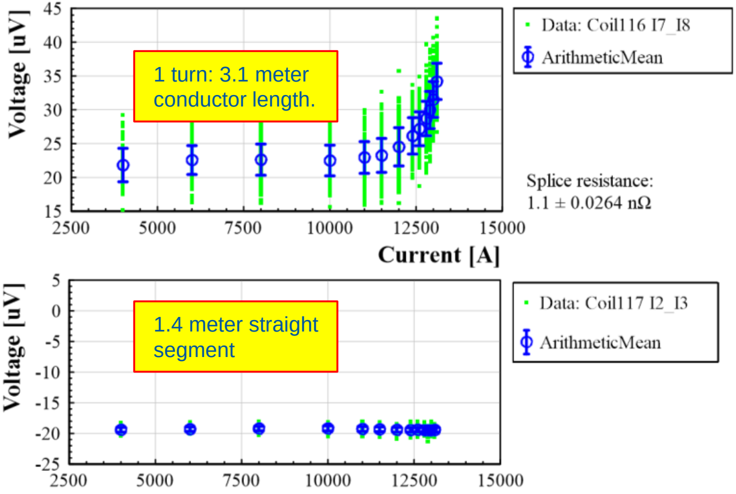
V-I curves in magnets – Method

In general:

- Use small current stepsize at high current for resolution
- Measure voltage at each plateau to ignore inductive voltage component.
- Measure plateaus up and down to see hysteresis

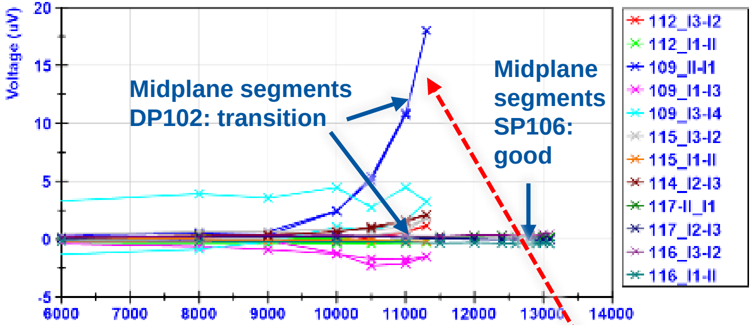


Example in MBHSP106:



Segments with a small inductive component are easier to measure with higher precision, see curves above.

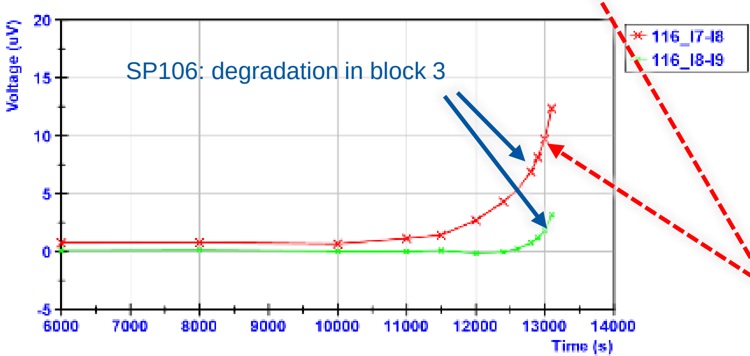
V-I curves in magnets – MBH 11T model as example



For DP102:
4 out of 8 segments showed a start of the transition.

Clear reason for reduced quench performance of the coil.

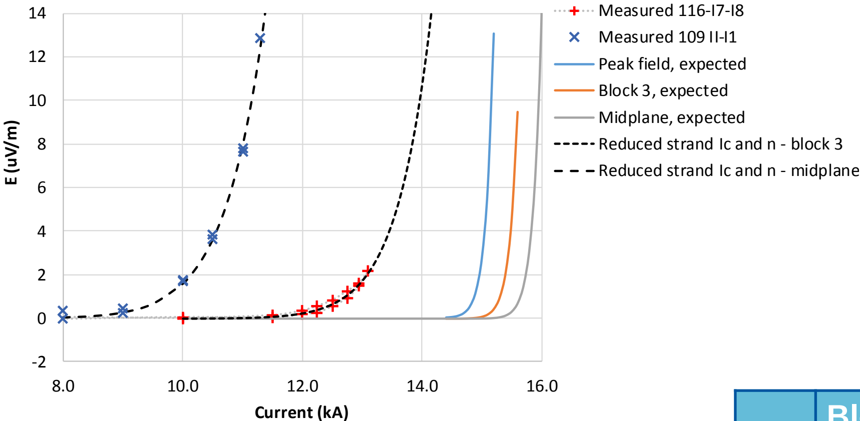
For SP106:
No transition up to 13.3 kA, well beyond ultimate current.



Unfortunately the SP106 model had an issue in block 3, although it still could reach ultimate current.

In the next slide the worst case examples are used to quantify degradation

V-I curves in magnets – Definition of degradation



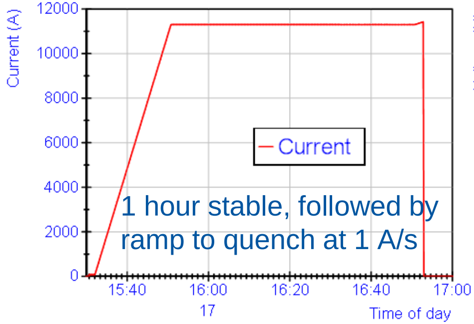
Expected electric field in a degraded conductor.
Simply adding
- a reduction factor (f_{I_c}) for I_c
- a reduction factor (f_n) for n

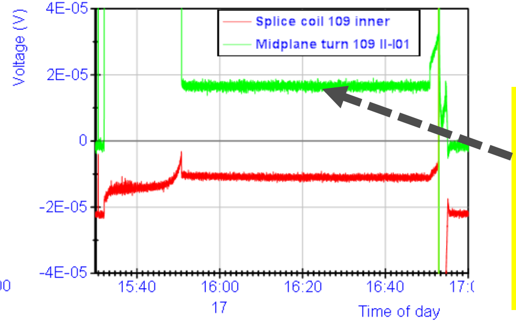
$$E(I,B) = E_c \left(\frac{I}{f_{I_c} I_c(B)} \right)^{(f_n n(B))}$$

	Block 3 coil 116	**Midplane coil 109**
f_{Ic}	0.62 (38 % reduced)	0.26 (74 % reduced)
f_n	0.20 (80 % reduced)	0.12 (88 % reduced)

Very good fit.
Simple quantification of the measured degradation.

V-I curves and ramp rate study – MBH 11T model as example

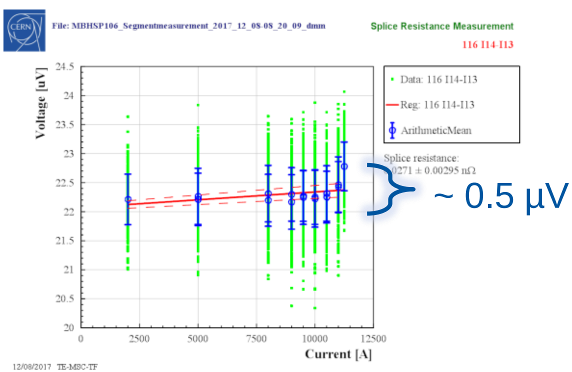


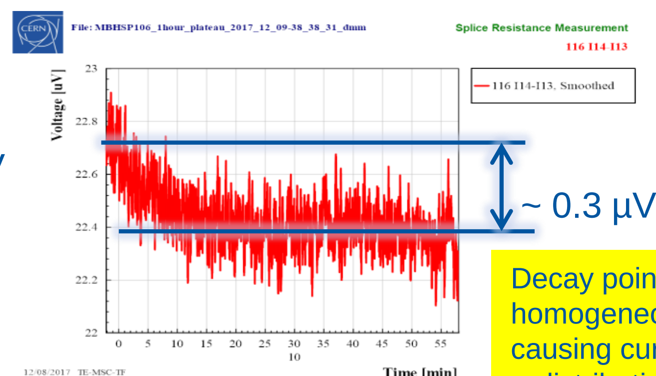


Stable voltage (18 µV) in the segment and splice at the plateau!

This indicates stable current distribution at the plateau.

Another example. This has a voltage decay with time constant of about 10 minutes.





Decay points at non-homogeneous effect causing current redistribution

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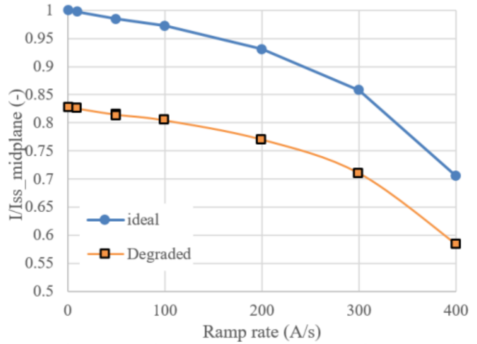
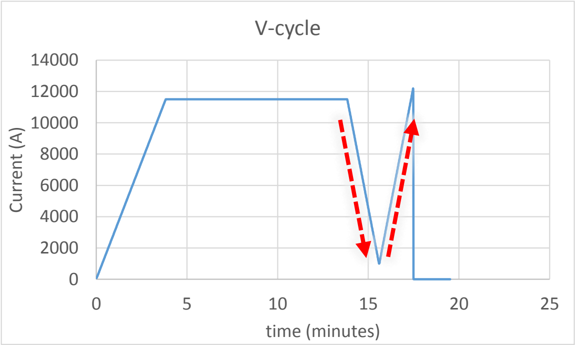
Ramp rate studies

Homogeneous case: only AC loss and reduction of temperature margin influence quench current.

Ideal homogeneous: Magnet reaches short sample limit – calculated AC loss dependency
Degraded: Degradation of the conductor – shift of quench current

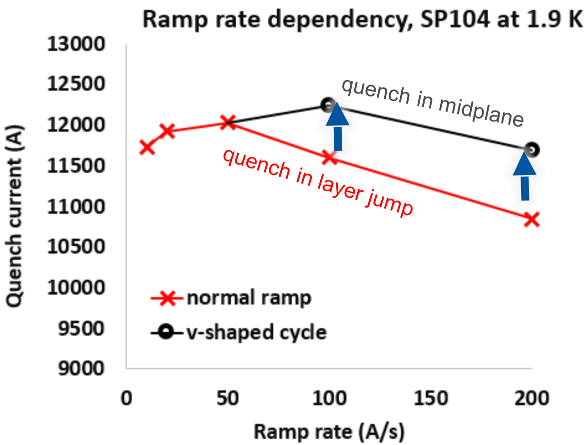


Non-homogeneous case:
→ Optimum in ramp rate studies
→ V-shape cycles could increase quench current
→ Holding current tests



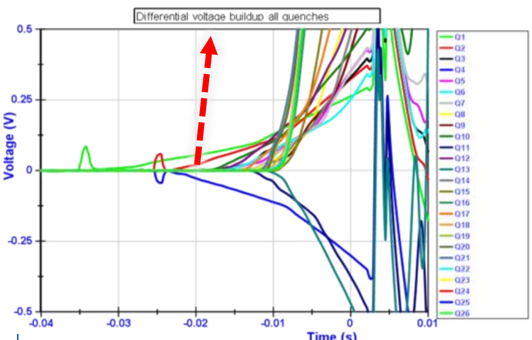
V-cycle, designed to induce coupling currents with opposite signs during ramp down so they have reduced impact

Ramp rate studies example: layer jump in MBHSP104



Normal ramp rate studies:
Initial training at 10 A/s limited at 11.7 kA. Optimum at 50 A/s at 12 kA

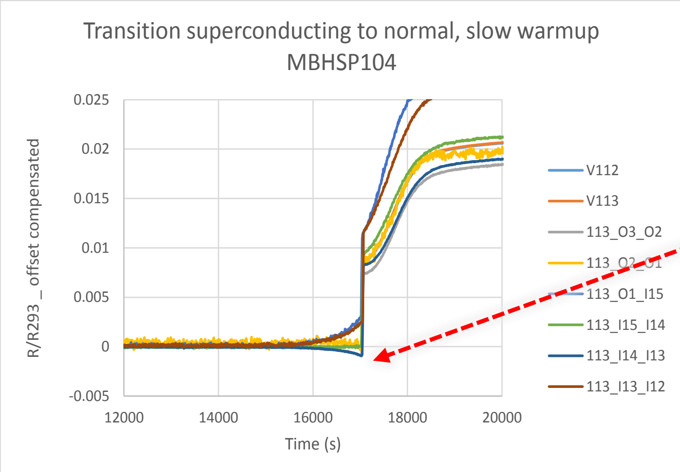
V-cycle:
Could overcome the limitation in the layer jump at ramp rates of 100 and 200 A/s, reached limitation in the mid-plane.



Additional info:
Very fast quench propagation through the inner layer pole turn after quench >150 m/s, about 5 times higher than normal.

Verdict for this case:
Non-homogeneous issue in layer jump

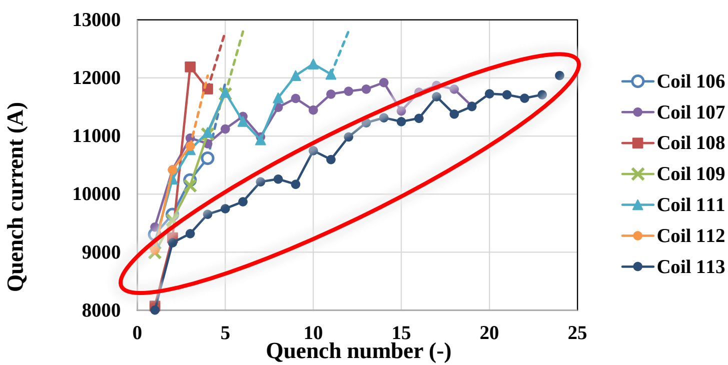
Ramp rate studies example: layer jump in MBHSP104



RRR measurements:
20 K transition normally sharp.
Around layer-jump in coil 113 the voltage drifts in some segments positive and other negative before the global transition.

Clear sign on non-homogeneities in the cable.

Consistent verdict with previous slide:
Non-homogeneous issue in layer jump



Some thoughts:
Non-homogeneous current distribution throughout the pole turns reduces the local margin to quench.

In this coil (113) the much slower training may be induced by higher sensitivity to mechanical movement, not by a higher number of mechanical movements.

Conclusions

Many tools and methods are available to investigate quenches

Combined they give the most complete picture of magnet performance and its weaknesses.

Just comparing “quench curves” may miss the important information that the models give us.

Thank you