Transients and Coil Displacement in Accelerator Magnets

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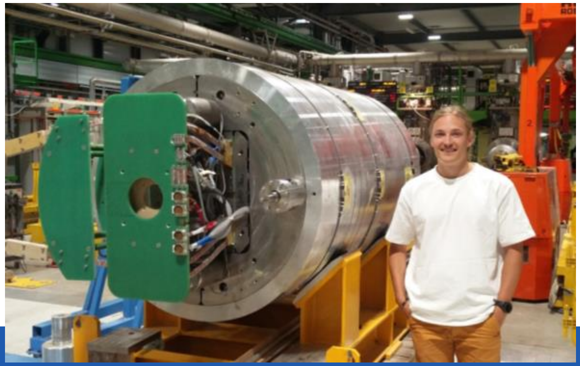
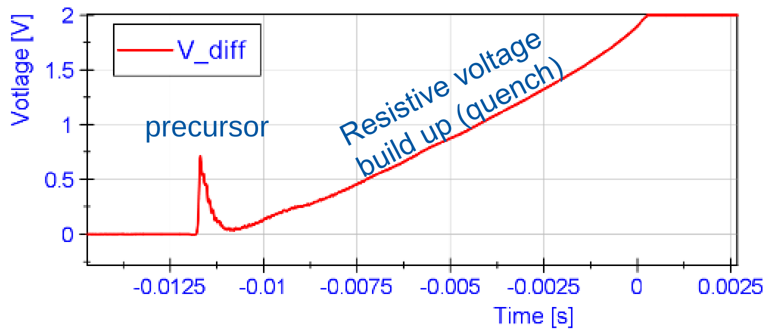
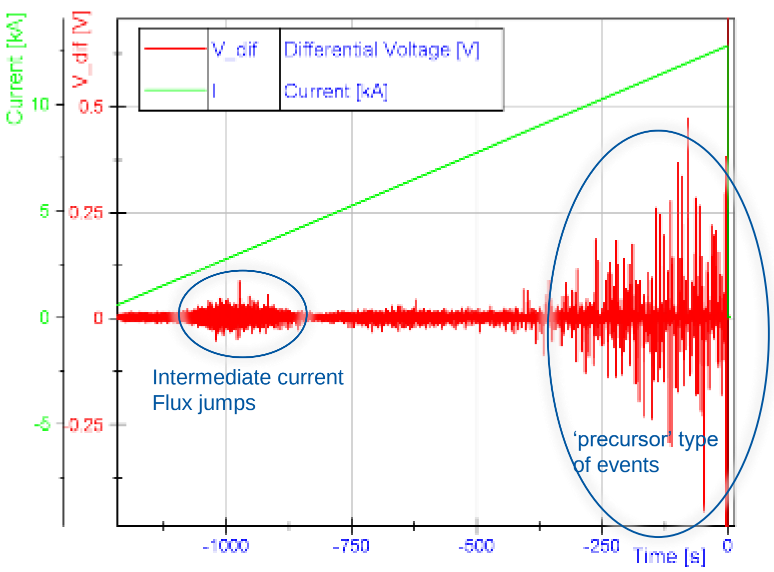


Introduction



A quench in superconducting magnets is sometimes preceded by a **precursor**.
Note that this signal is a generally a filtered signal (300 Hz low-pass) to optimize quench detection.



When measuring during a full ramp of a magnet, we can distinguish sometimes hundreds of these 'precursors' without them leading to a quench.

We know that these 'precursor' type of events are linked to **motion or "mechanical transients"** (damped oscillation, accelerometer, acoustic emission sensor, pickup coils).

See seminar by H. Arnestad, https://indico.cern.ch/event/738168/
"Measurement of Electrical and Mechanical Transients in Nb3Sn magnets", 2018

Reminder: Overview of vibrations

When using quench antenna pickup coils, we can map all the mechanical transients longitudinally

See seminar by H. Arnestad,
https://indico.cern.ch/event/738168/
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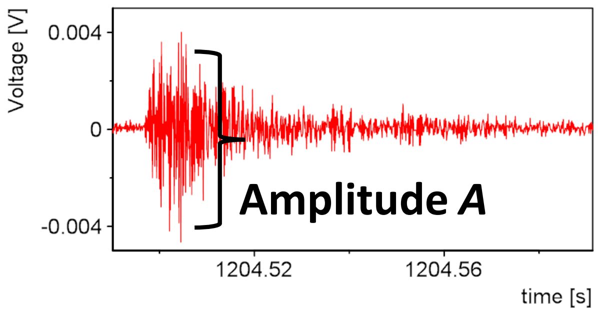
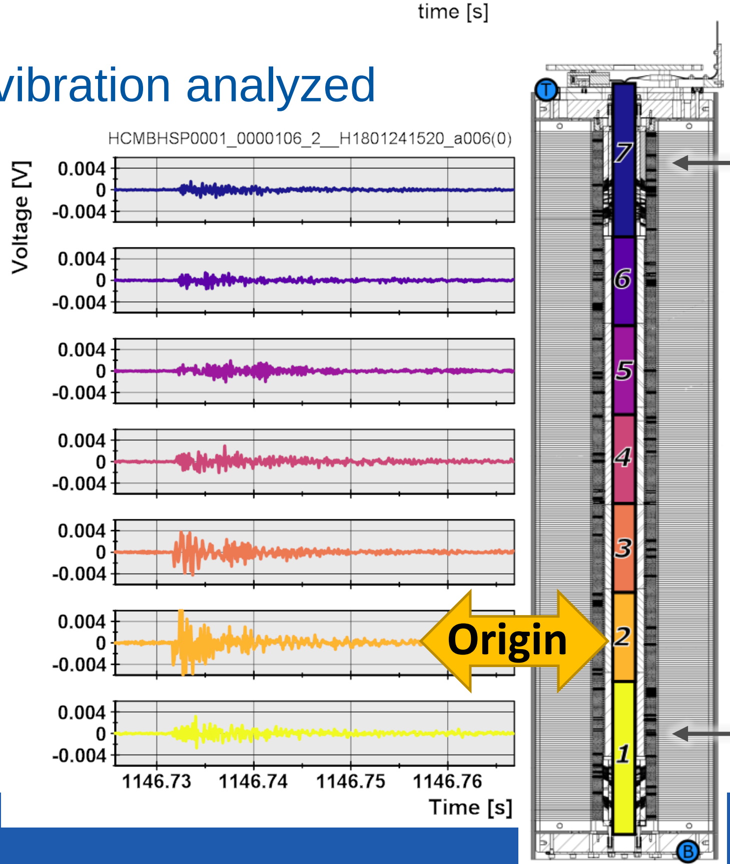
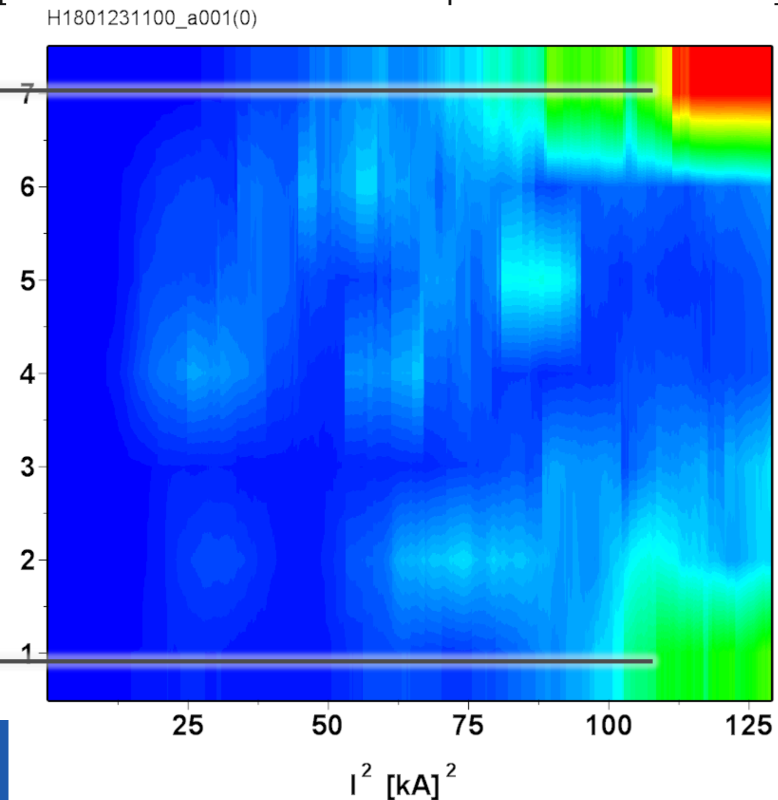


Each vibration analyzed



Activity mapped

[combination of number and amplitude of the vibrations]



History: Statistics LHC MB magnets

For LHC MB magnets mainly statistical analysis was done.
Note the use of different words to describe the same phenomenon.
Attempts to predict a magnet quench using these data has not been successful.

Mechanical Perturbations | Spike | Quench Precursor | Conductor Motion

Transient Energy Release

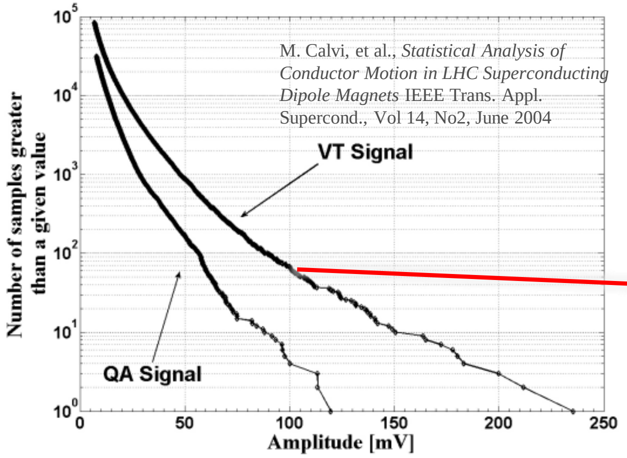
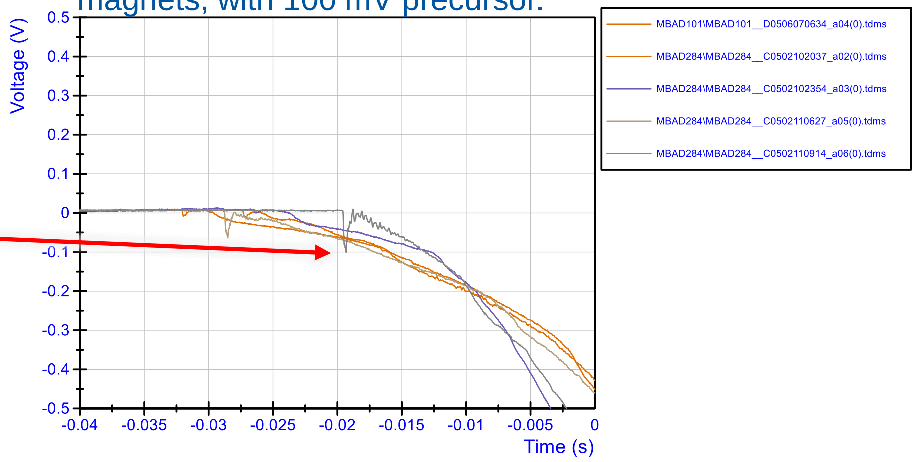


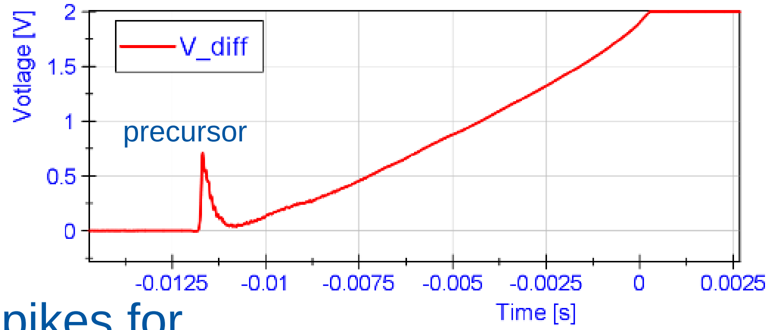
Fig. 5 The signal is represented using non normalized statistical distributions $NP_>$. Both example of VT and QA are presented.

Example of a 'random' slow training MB magnets, with 100 mV precursor.



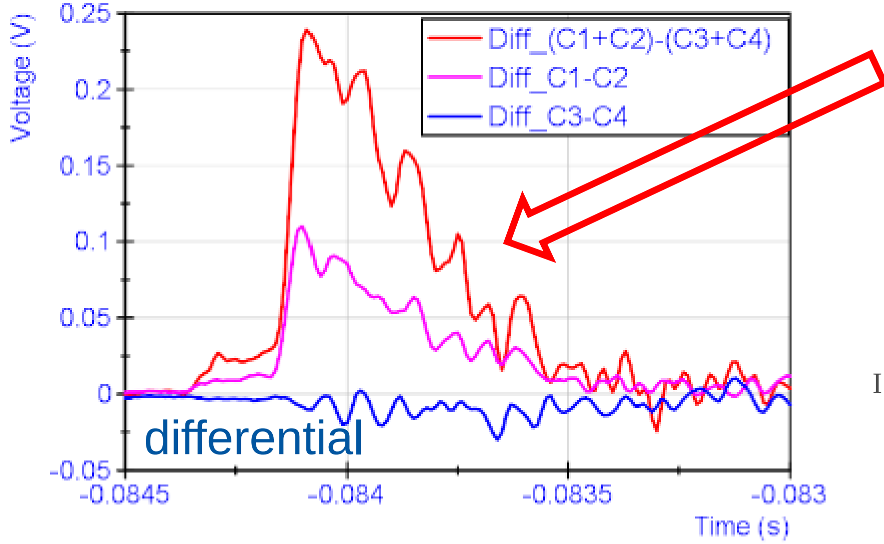
Further reading:
M. Calvi, *Impact of the Mechanical Perturbations on the Performance of the LHC superconducting Dipole Magnets*, University of Geneva, PhD thesis, 2004
M. Calvi, et al., *Data Analysis of Transient Energy Releases in the LHC Superconducting Dipole Magnets*, IMTC conference 2006, Sorrento, Italy.
P. Pugnat, et al., *Statistical Diagnosis Method of Conductor Motions in Superconducting Magnets to Predict their Quench Performance*, IEEE Trans. Appl. Supercond., Vol 11, No 1, March 2001
P. Pugnat and A. Siemko, *Review of Quench Performance of LHC Main Superconducting Magnets*, IEEE Trans. Appl. Supercond., Vol 17, No 2, June 2007
M. Calvi, et al., *Statistical Analysis of Conductor Motion in LHC Superconducting Dipole Magnets*, IEEE Trans. Appl. Supercond., Vol 14, No2, June 2004

New in this work

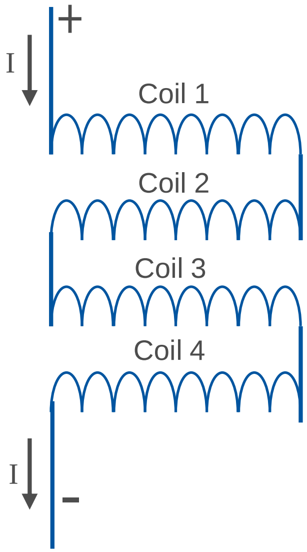


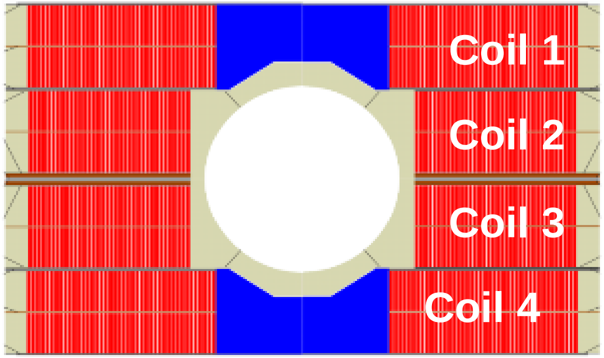
- Detailed precision measurements on single spikes for Voltage, Pickup coils and current.
- Ignore voltage ‘oscillation’ but focus on **integral**.
- Use the law of conservation of energy
- Define a simple physics model to describe mechanical motion qualitatively
- Quantify coil motion

Coil voltage measurement

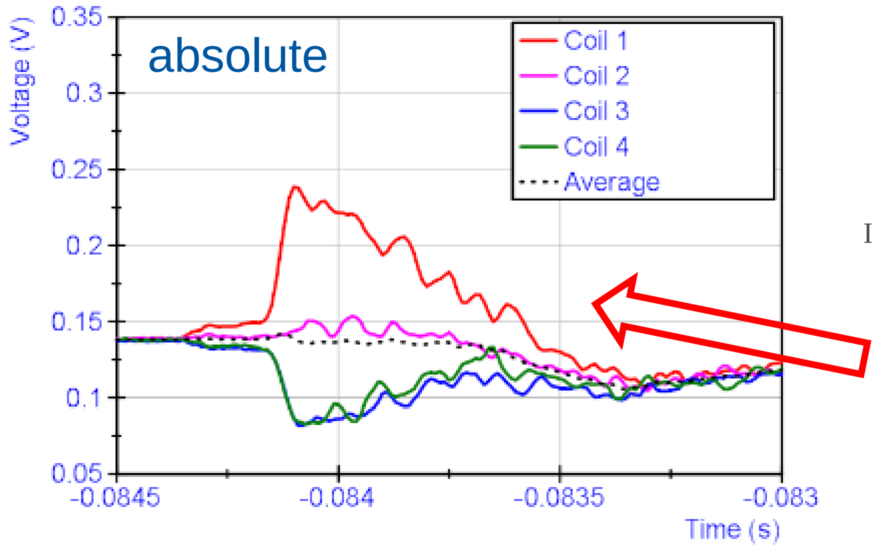


Familiar voltage data as we typically use in presentations/reports:
Differential voltage (C1+C2) – (C3+C4)
Differential voltage is also used for quench detection.



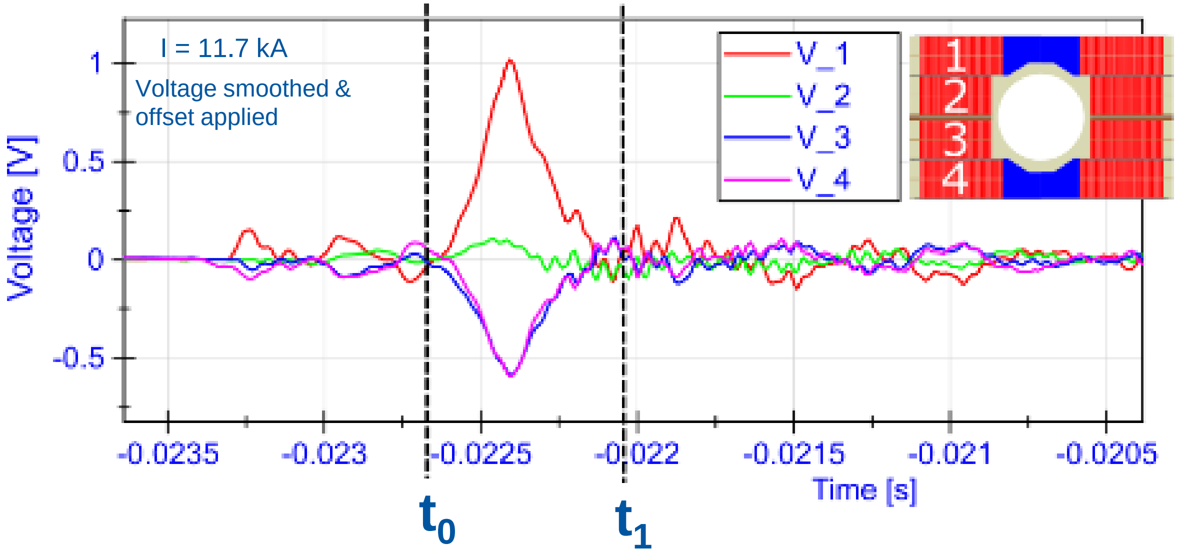


Fresca2. Block coil design. 4 coils, each coil has two layers and 36 to 42 turns per layer.



The direct voltage per coil gives additional information.
Example: positive precursor in coil 1 and negative precursor in coil 3 and 4.

Energy: from voltage measurement



Energy calculation

$$E = \int_{t_0}^{t_1} UI\,dt$$

$E_{V\_1} = 2.29$ J

$E_{V\_2} = 0.13$ J

$E_{V\_3} = -1.37$ J

$E_{V\_4} = -1.30$ J

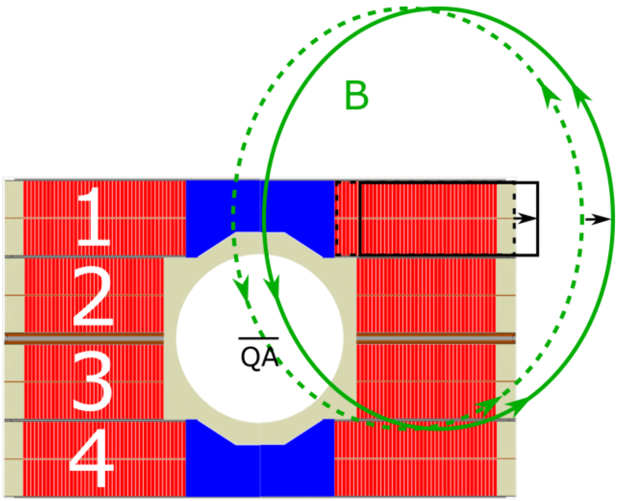
For reference: Stored energy in this magnet (1/2*L*I^2) is about 4 MJ

We know that even **10 µJ** to **1 mJ** can quench a magnet.
Why does this event not quench the magnet?

Sum of energy is about 0 J → The energy is **not dissipated** in the coil

Hypothesis → The energy is **redistributed** due to coil **geometry changes**

Main assumptions



E_{V_1} = 2.29 J
E_{V_2} = 0.13 J
E_{V_3} = -1.37 J
E_{V_4} = -1.30 J

Assumptions

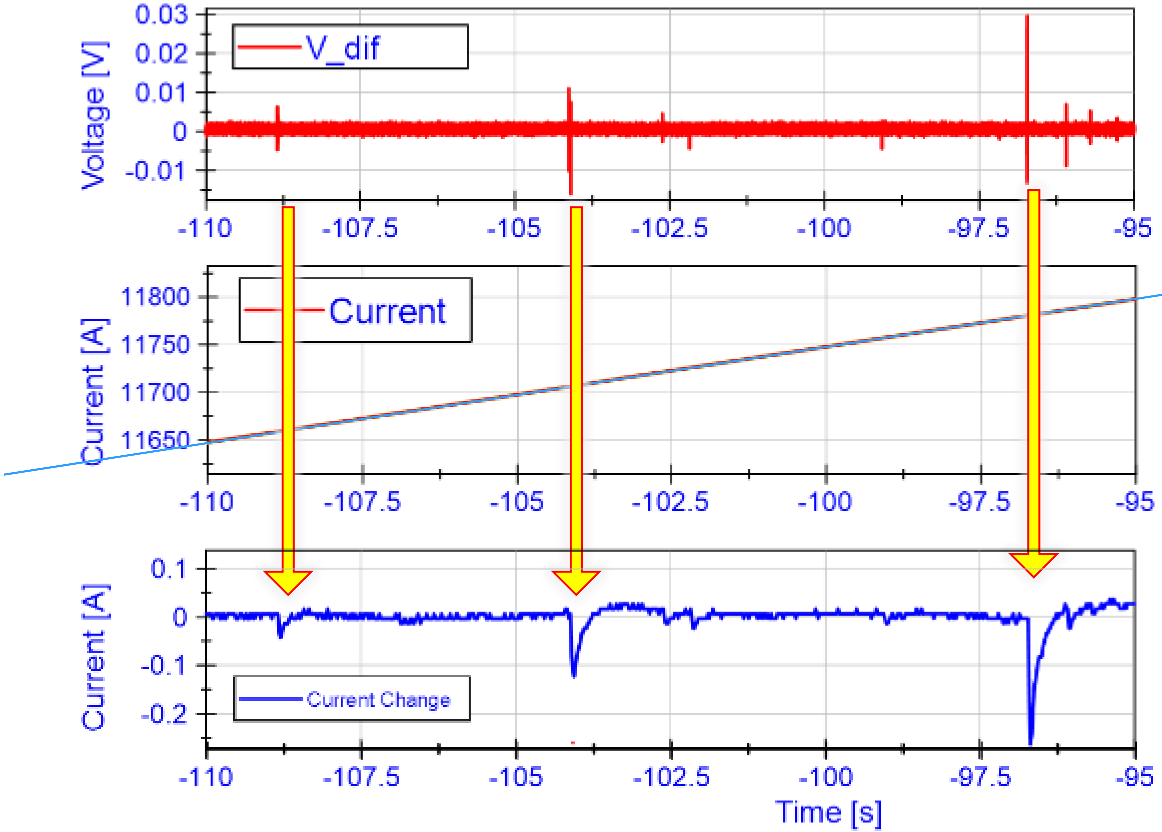
- Stick-slip is geometry change
- Geometry change is inductance change
- Outward forces would likely give coil growth.

Expectations in this case:

- Total inductance increases
- Total Energy must be conserved: $\frac{1}{2}L_{t0}I_{t0}^2 = \frac{1}{2}L_{t1}I_{t1}^2$

  so magnet current must drop (if faster than PC response)
- Redistribution of energy with net increase in coil 1.
- Changes in quench antenna pickup coils

Measured current during precursor



Current ramp seems smooth, but we can calculate the deviation of current compared to the linear ramp.

Clear correlation between 'redistributed energy' in a 'precursor' event and the drops in current.

The power supply has a regulation cycle of 20 to 100 ms and will bring back the current to the requested ramp.

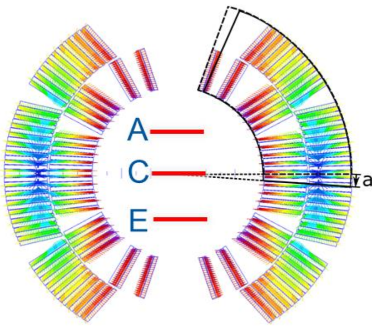
Basic physics:
Conservation of energy

$$\frac{1}{2}L_{t0}I_{t0}^2 = \frac{1}{2}L_{t1}I_{t1}^2$$

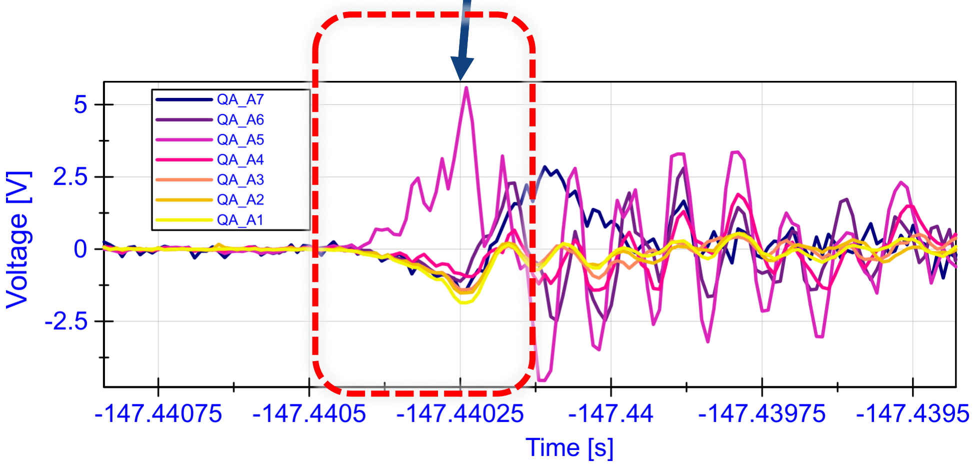
ΔI always negative
→ ΔL positive
→ suggests coil growth

Quench Antenna pickup coils during precursor

Measurements on FRESCA2 were saturated, so signals cannot be integrated.
Measurements for MBHSP 11T are shown.



7 times 3 pickup coils, each 25 cm long.
For this example the A-coils have been used with a **direct** measurement.



Local effect in quench antenna A5 suggests coil movement is limited to this segment.

Global effect in all other pickup coils: drop in magnet current drops the magnetic field.

Qualitative summary on measurements of transients

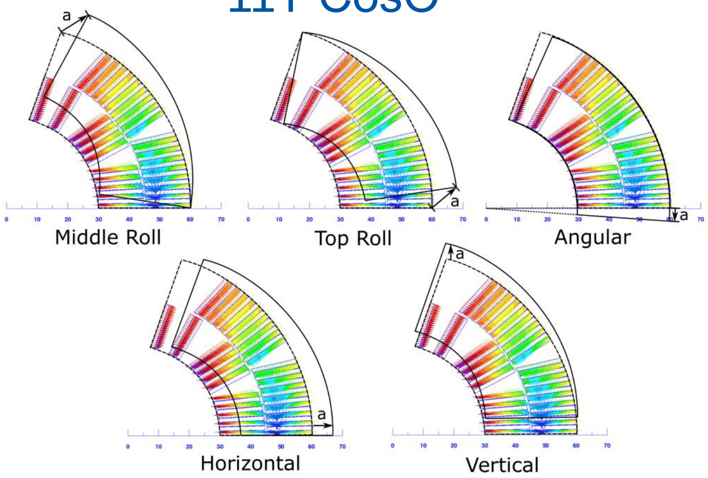
1. Conservation of energy – no energy deposited
2. Energy exchange between coils –> Coil geometry change
3. Current Drop confirmed
4. Local field change in Quench Antenna
5. Global field change in Quench Antenna

Quantification – Modeling with ROXIE

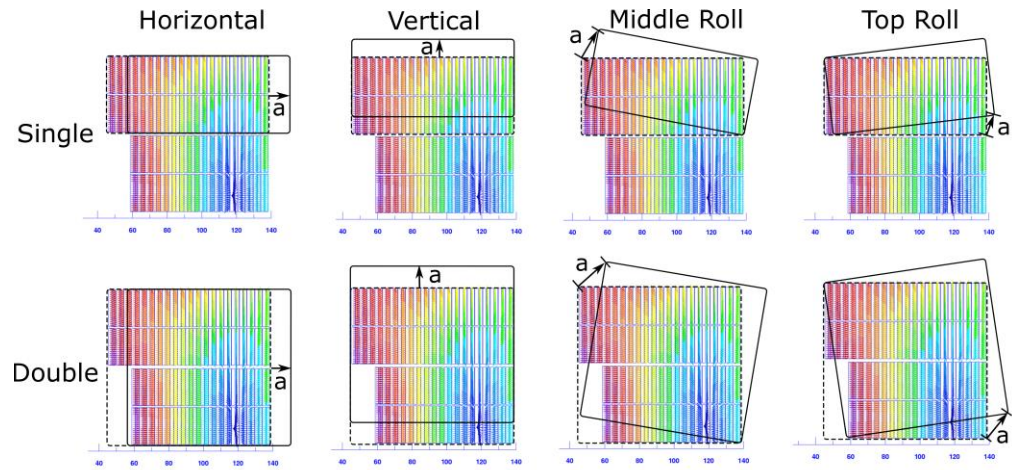
Quantification – Modeling with ROXIE

- Use ROXIE to explore the change in inductance when changing geometry.
- Include mutual inductances.
- Define the movement modes of interest.

11T CosΘ



FRESCA2 Block coil



Assumption:
- Coil blocks are impregnated and move as one piece.

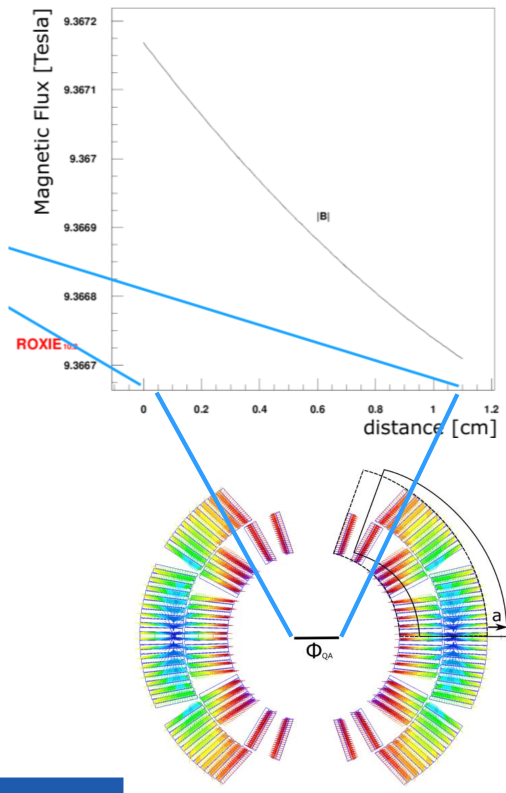
Note: There could also be flexing of the coil blocks, or a combination of modes. This has not been investigated.

Many thanks to Susana Izquierdo Bermudez for helping set up ROXIE.

How to simulate coil movement

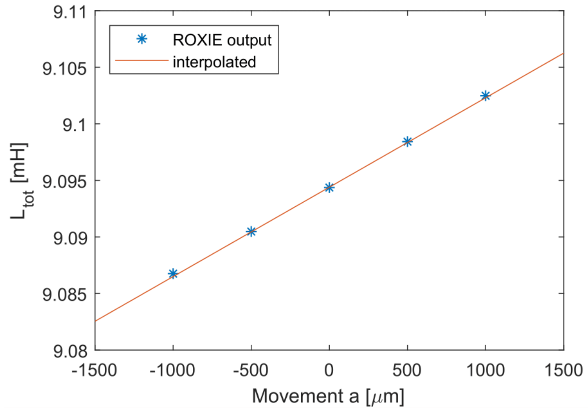
- Move part of magnet with various displacements
- Calculate field and mutual inductance
- Calculated field on a line (quench antenna)
- Calculate for several position shifts *a* it L, B, I and E.

Field on a line [T]



Mutual Inductance [mH/m]

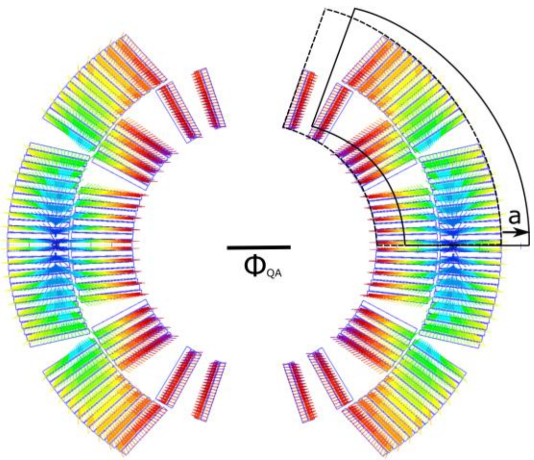
	M_{i1}	M_{i2}	M_{i3}	M_{i4}
M_{1j}	0.8473	0.3882	0.1986	0.3706
M_{2j}	0.3882	0.3166	0.1461	0.2258
M_{3j}	0.1986	0.1461	0.2869	0.3511
M_{4j}	0.3706	0.2258	0.3511	0.7983

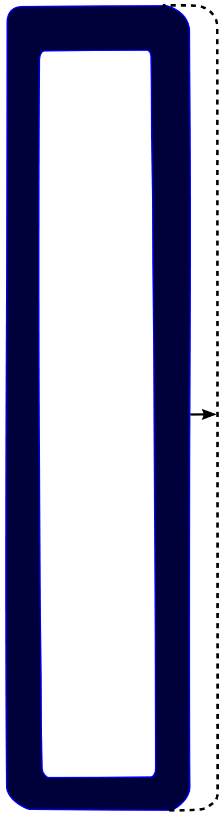


Note: in an 11T single aperture the voltage is measured on the inner and outer layer of both upper an and lower coil.

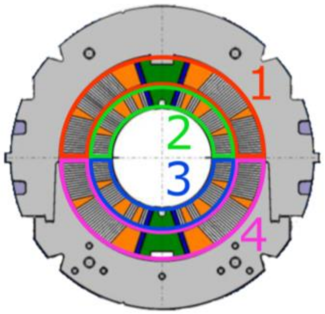
Simulation Results – horizontal shift

- Simulated movement of entire coil length

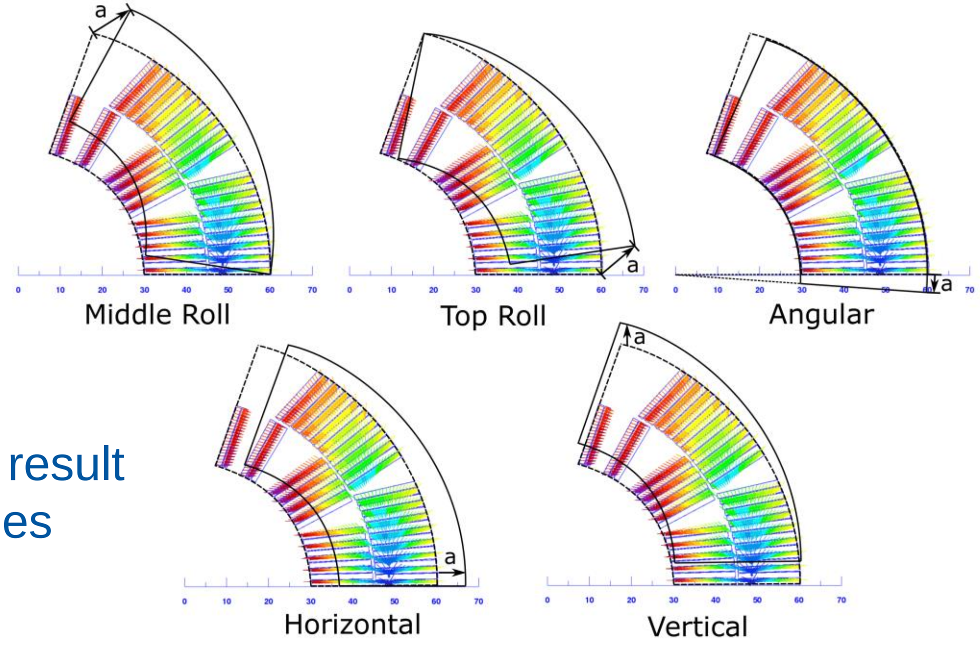




	10 µm movement
$\Delta E_1\ [J]$	2.73
$\Delta E_2\ [J]$	6.29
$\Delta E_3\ [J]$	-6.05
$\Delta E_4\ [J]$	-2.97
$\Delta I\ [A]$	-0.31
$\Delta\Phi_{QA,local}\ [Vs]$	-4.95E-03
$\Delta\Phi_{QA,global}\ [Vs]$	-2.88E-03



Normalizing calculated movements



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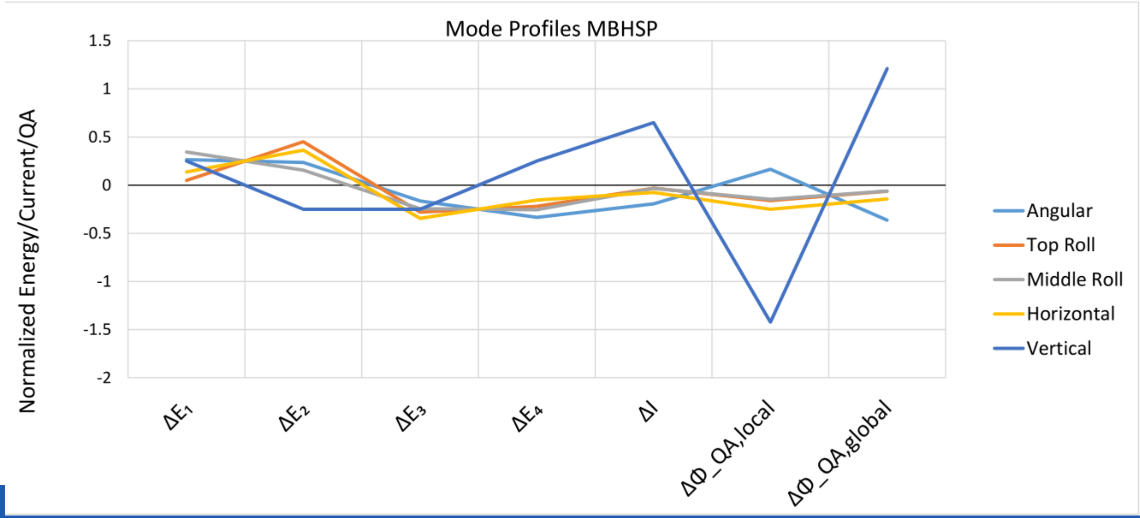
$\Delta I\ [A]$	-0.31
$\Delta\Phi_{QA,local}\ [Vs]$	-4.95E-03
$\Delta\Phi_{QA,global}\ [Vs]$	-2.88E-03

Normalize result for all modes

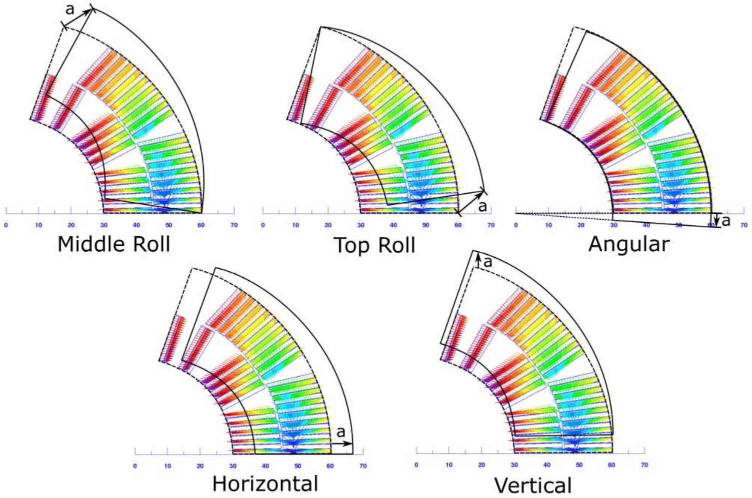


Depending on the mode, the changes in energy, pickup coil and current vary.

Measurement vs Calculation:

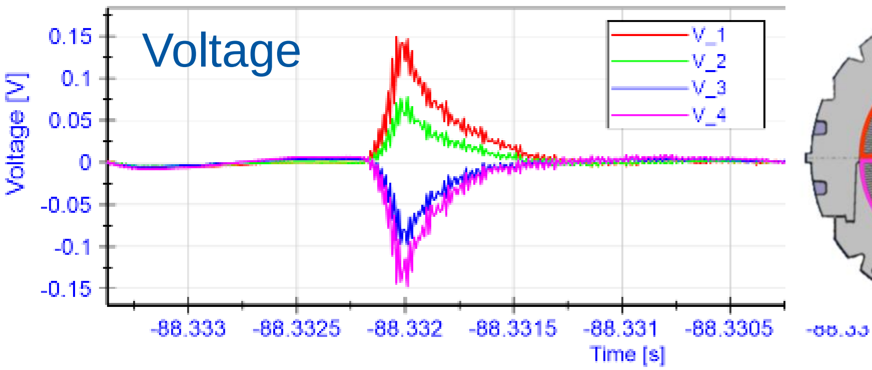
Example: 11T model coils

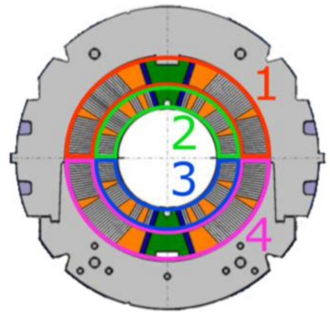
Cosine Theta design

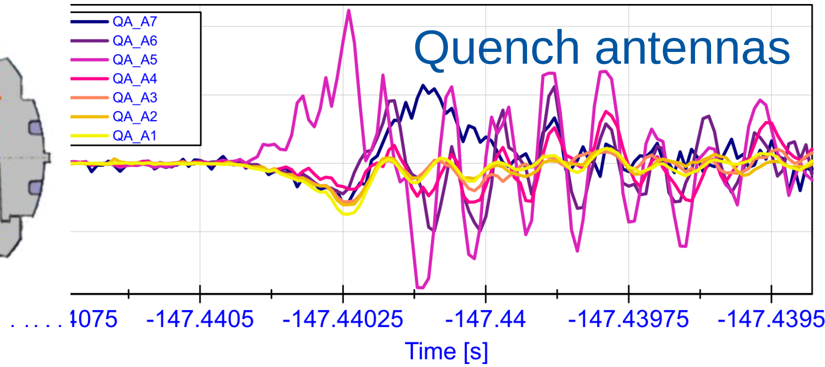


MBHSP107 example

- Gather data from transients and put in same format
- 40 transients per magnet were analyzed

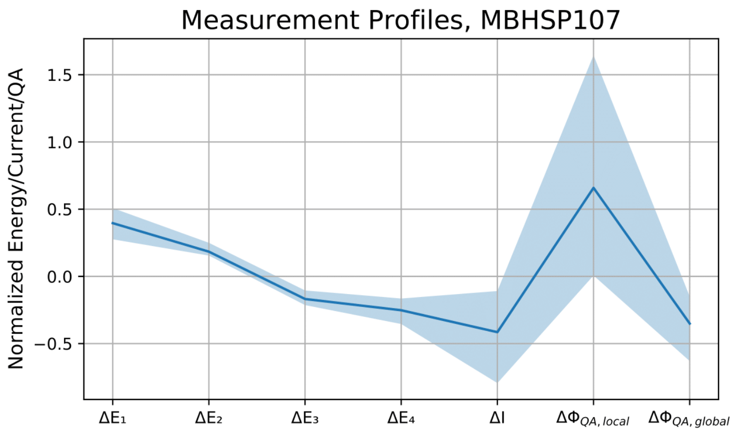




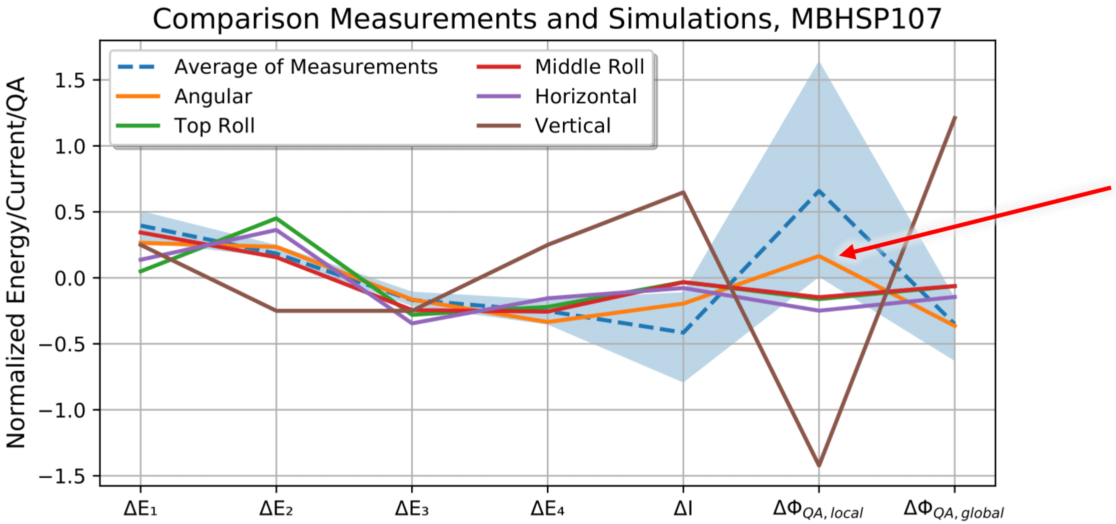


The 40 events gives a measurement profile:

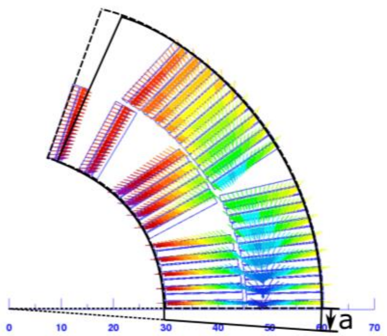
- Blue area contains all transient values
- Blue line is the average



MBHSP107: measurement vs calculation

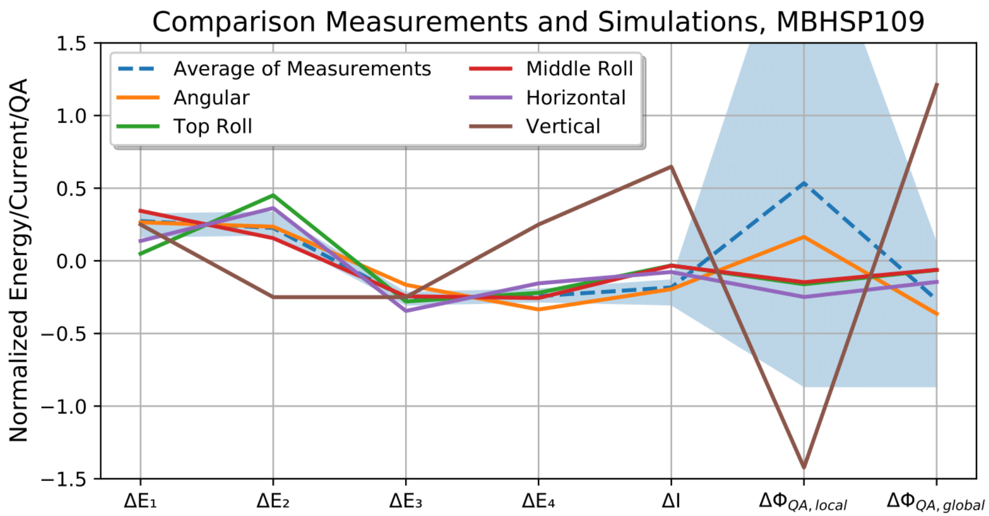


- Analyze which profile is matching the measurements the best

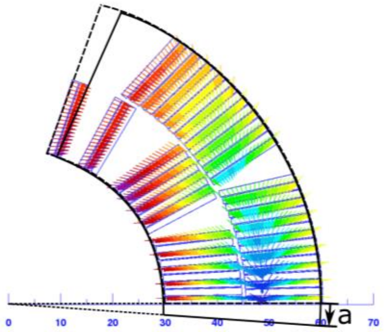


Angular motion is the most plausible from the studied modes, since the local quench antenna change is positive.
Not a perfect match.

MBHSP109 : measurement vs calculation



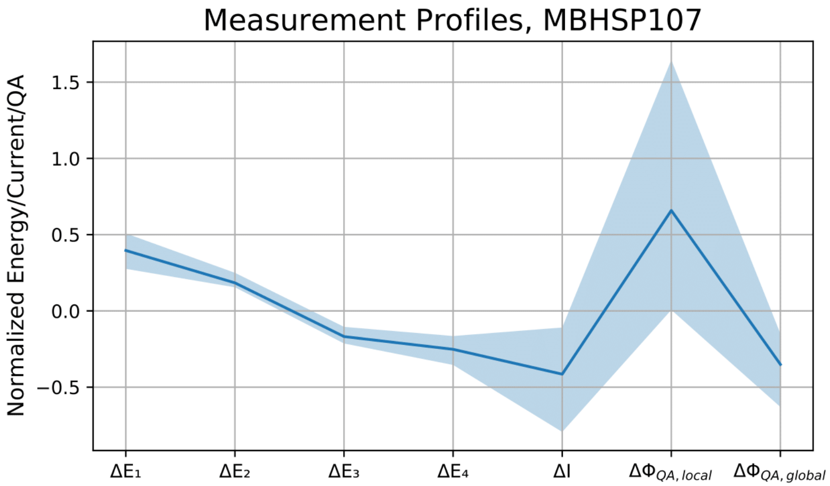
- Data rather similar to MBHSP107

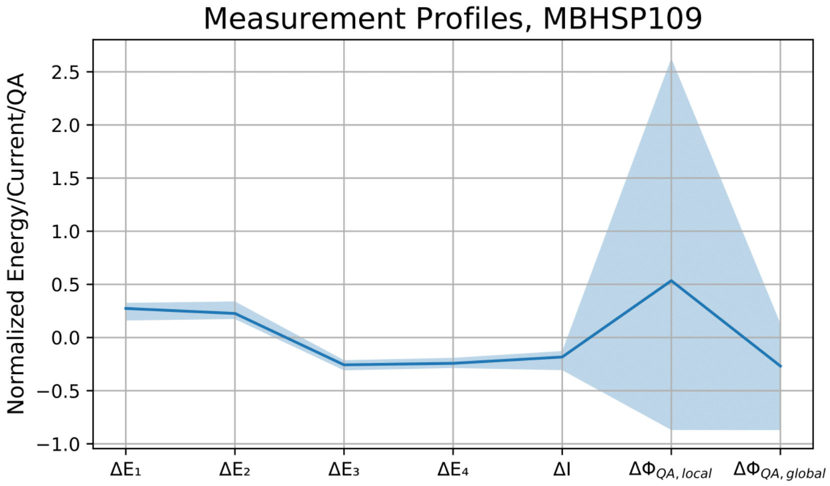


Angular motion is the most plausible from the studied modes, since the local quench antenna change is positive.
Not a perfect match.

MBHSP107 vs MBHSP109

- Two 11 T model magnets with identical design
- Average ‘profile’ rather similar.
- A bit more spread in the events of MBHSP109

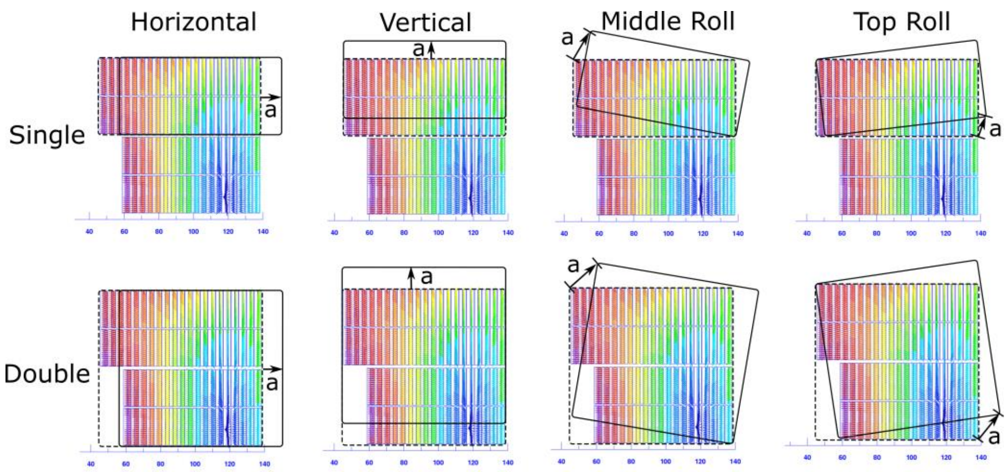




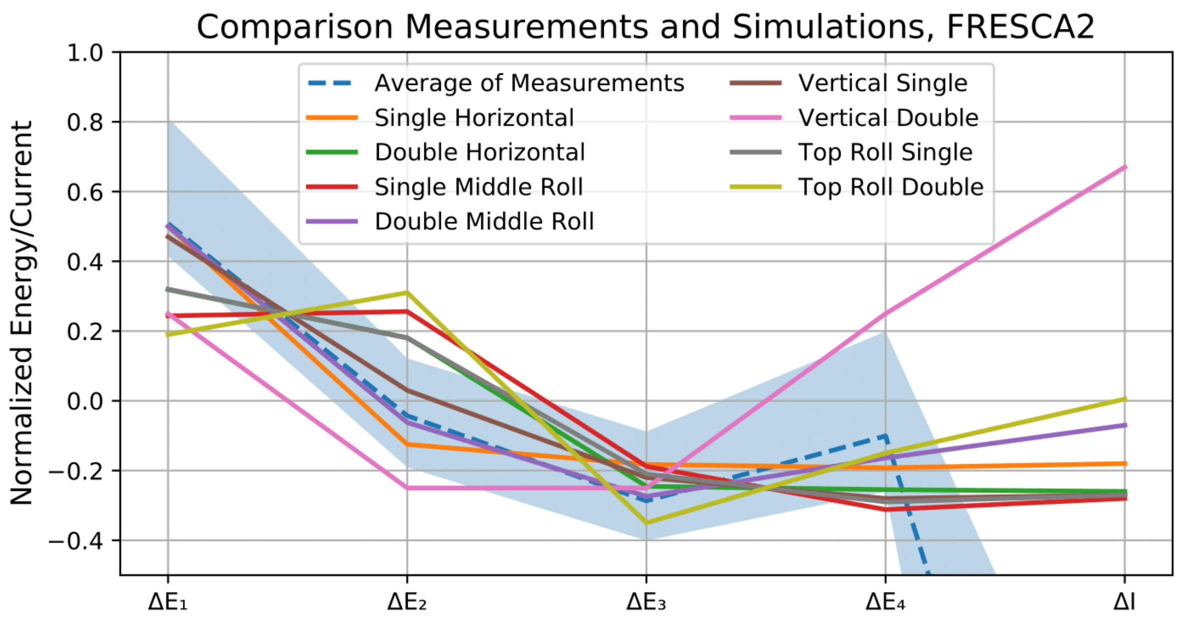
Measurement vs Calculation:

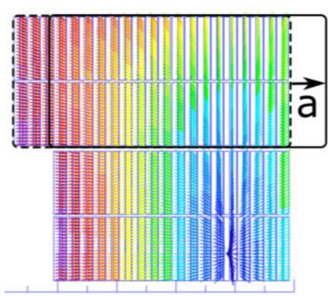
Example – FRESCA2

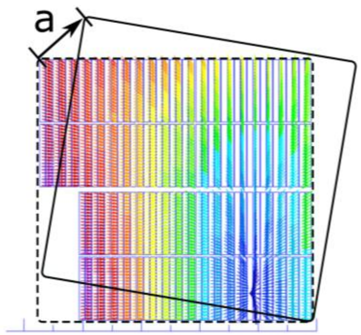
FRESCA2 Block coil



FRESCA2







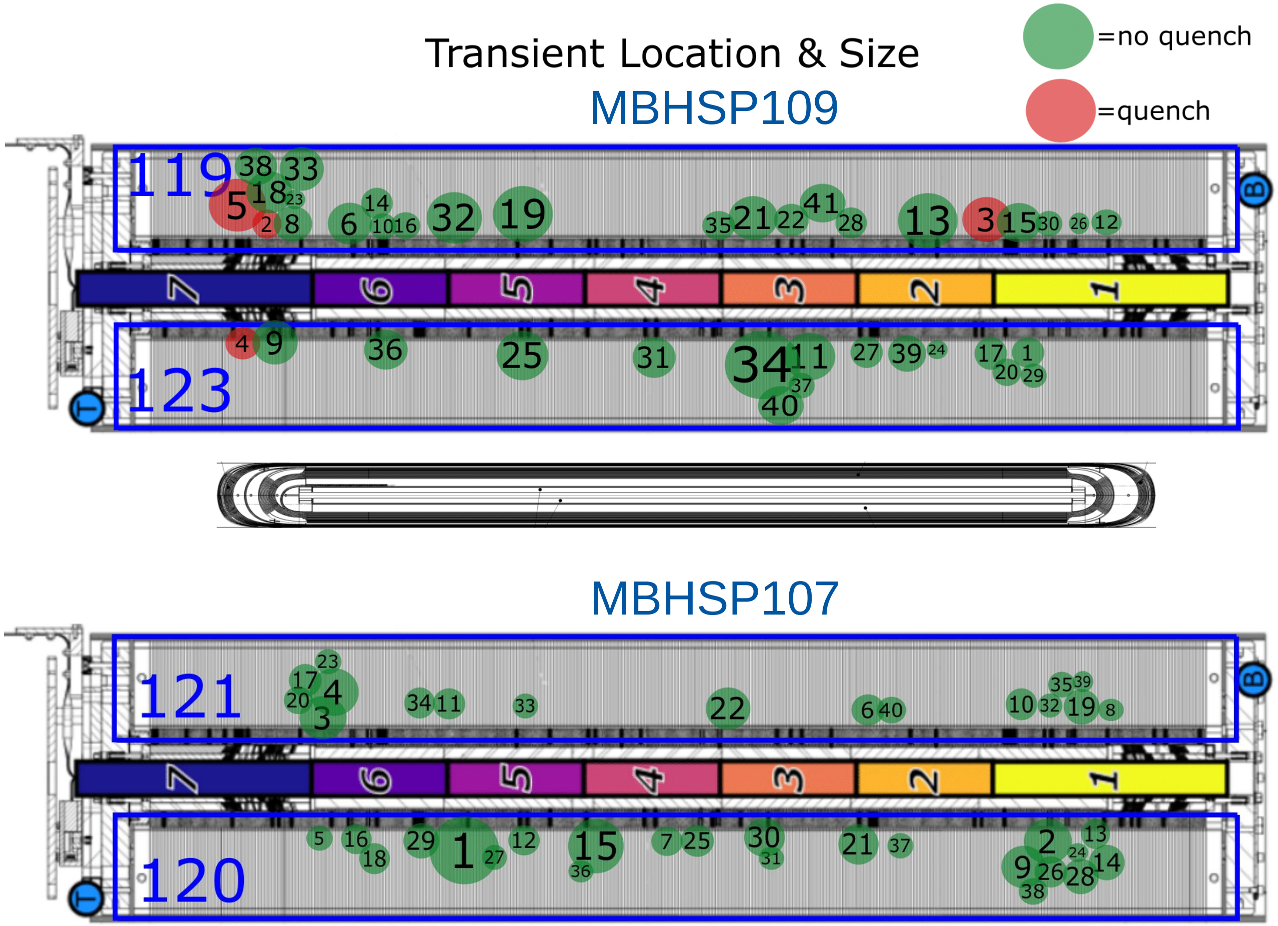
- Much larger normalized current drop than expected from any of the motion modes.
- Missing direct quench antenna measurement

Single Horizontal or Double Mid Roll have the most characteristics in common with the measurements.

Quantifying motion

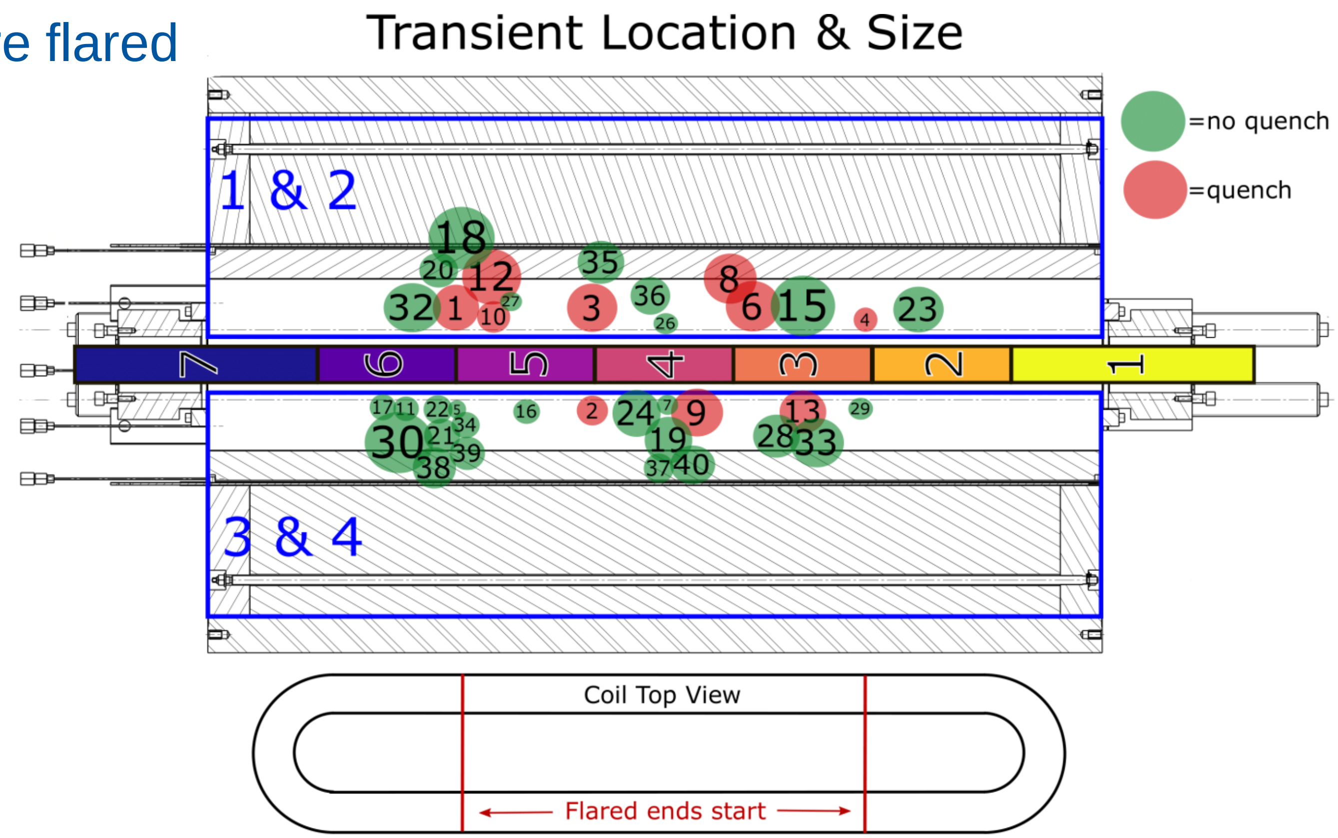
Transient Location & Size – 11 T models

- Dots show transient size
- Index is transient number as listed in thesis
- Events spread out → indicates cross-section movement
- Transients with quench are not necessarily the largest transients.



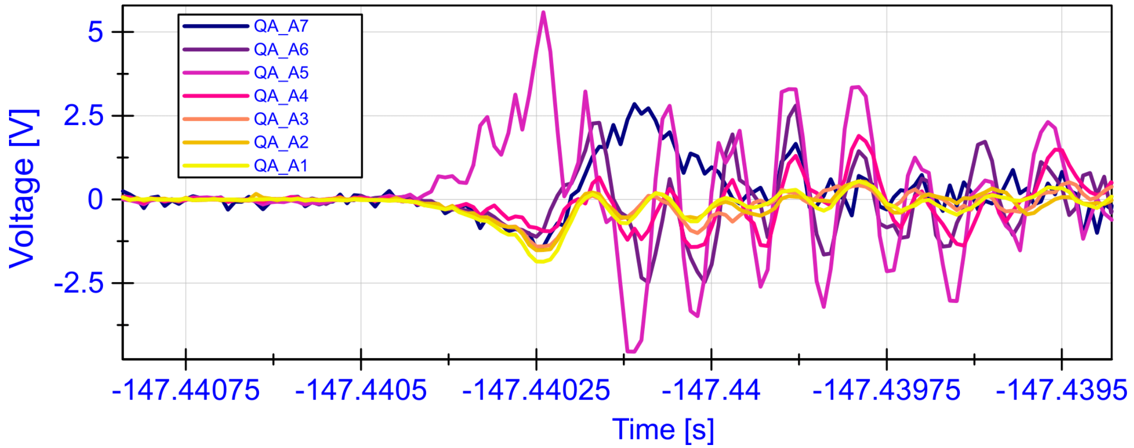
Transient Location & Size – FRESCA2

- Movements in the middle and where flared ends start



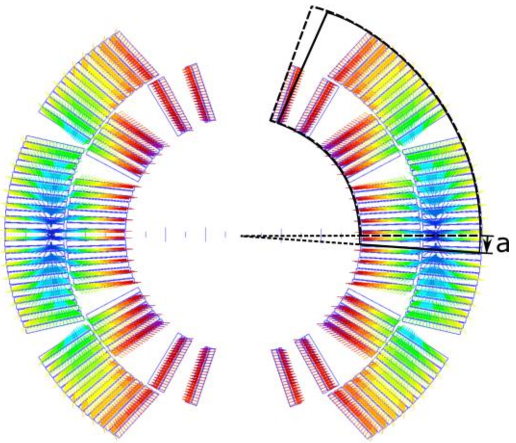
Movement length – 11T coils

- Coil near QA 5 moves first, followed by QA 6 and 7

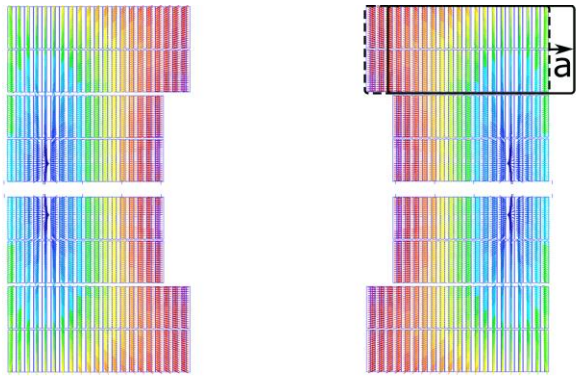


Assume this length moved

Movement length



- 50 cm 11T—max. 10 μm



- 40 cm FRESCA2—max. 5 μm
- Majority much smaller < 1 μm

Off course, if we change the length or the number of turns moving, the displacement length will change accordingly.

If we assume only 1 cable to move (instead of 56 to 80 cables impregnated in one block, the displacement length would be many times larger, and this is deemed impossible.

Conclusions

Precursors (with significant $\int VIdt$ in differential voltage) are indeed changes in coil geometry, sometimes leading to a quench, but many times not.

Combining precision measurements and simulations, we can learn something about

- Movement mode
- Displacement length

The size of the precursor (integrated energy displacement) is an important characteristic.

Possible future work

- Only 2D taken into account. 3D calculations are needed for quantifying coil displacement in the magnet head.

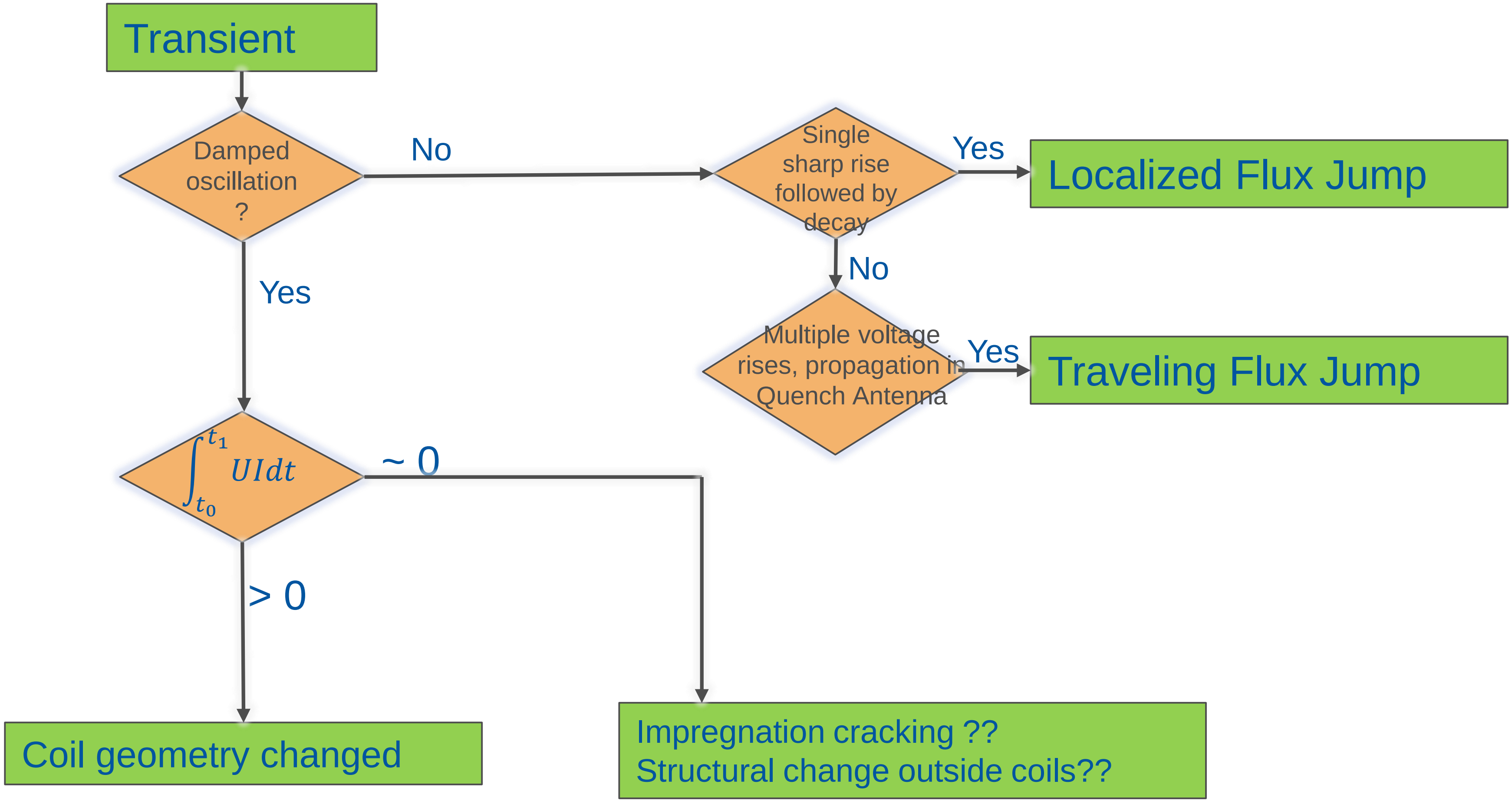
- The quench antenna pickup coils are mostly used in differential measurement mode, but in direct measurement they give valuable information (We used direct measurements for MQXF magnets)

- Looking more often at non-quench data could gives useful insight in magnet mechanics.

- Investigate possible coil block changes too, compared to only full block motion investigated now.

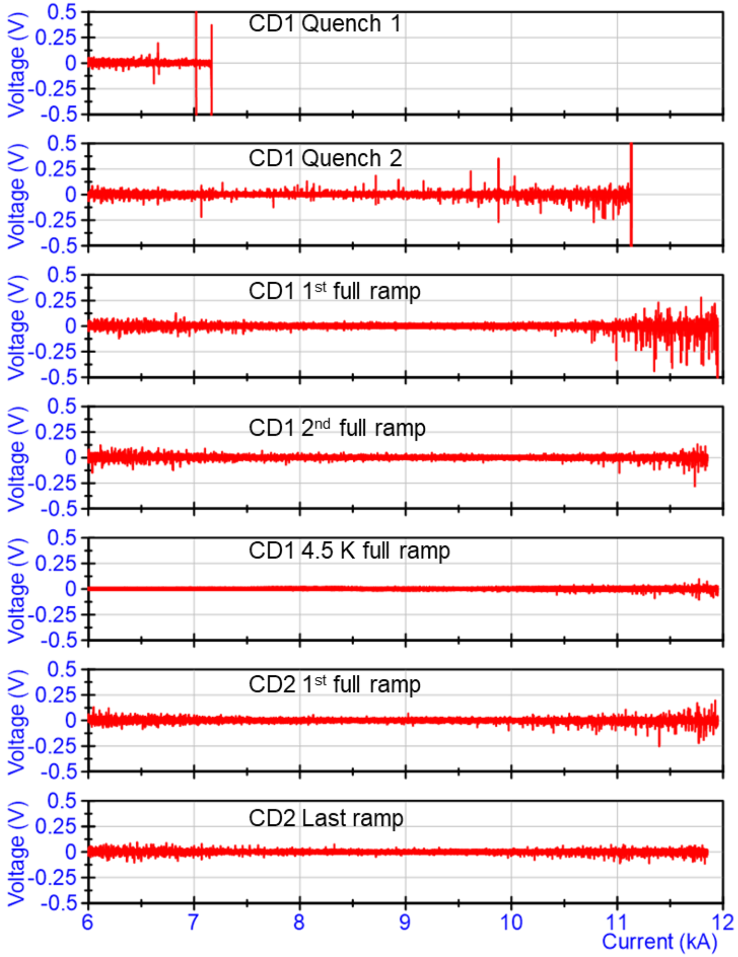
Precursor characteristics for a variety of magnets

Transient Interpretation Flow Chart



MBH – 11T

Example: MBHB-002 (S1)

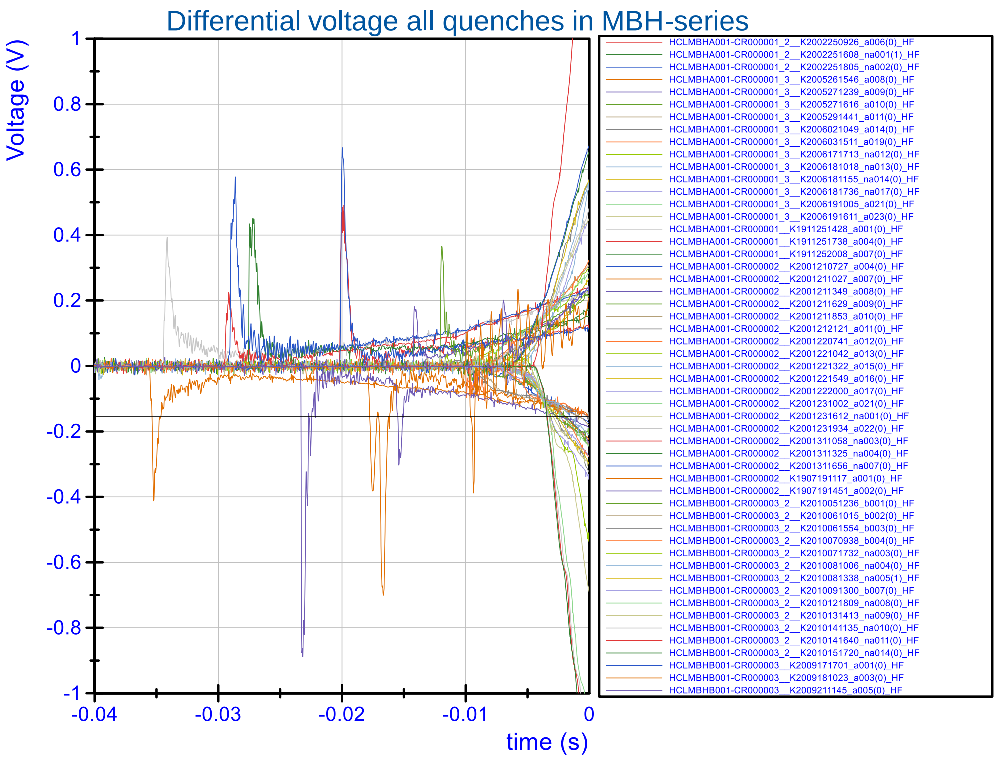


Reduction of vibration activity while training the magnet.

After thermal cycle small activity.

Conclusion:
Mechanical transients due to structural movements are **not** an issue for 11T magnets.

MBH – 11T

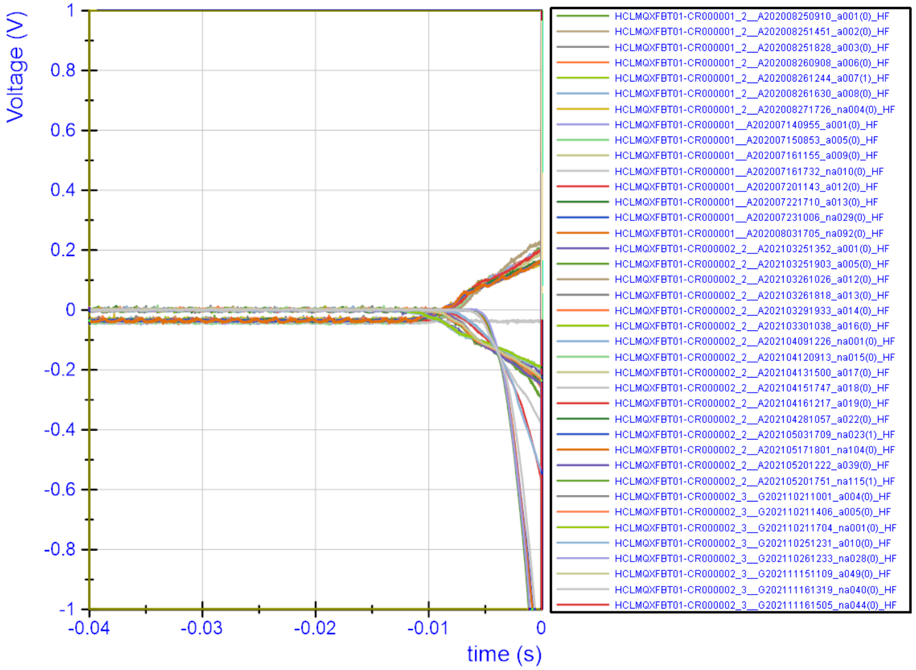


Largest precursor: ~5 J Measured in MBHB-002 in quench 2 at 11.1 kA.

Large precursors **only,** but not always during training phase of the magnets.

No precursors for quenches at **magnet limit**.

MQXF-Prototype 1 and 2



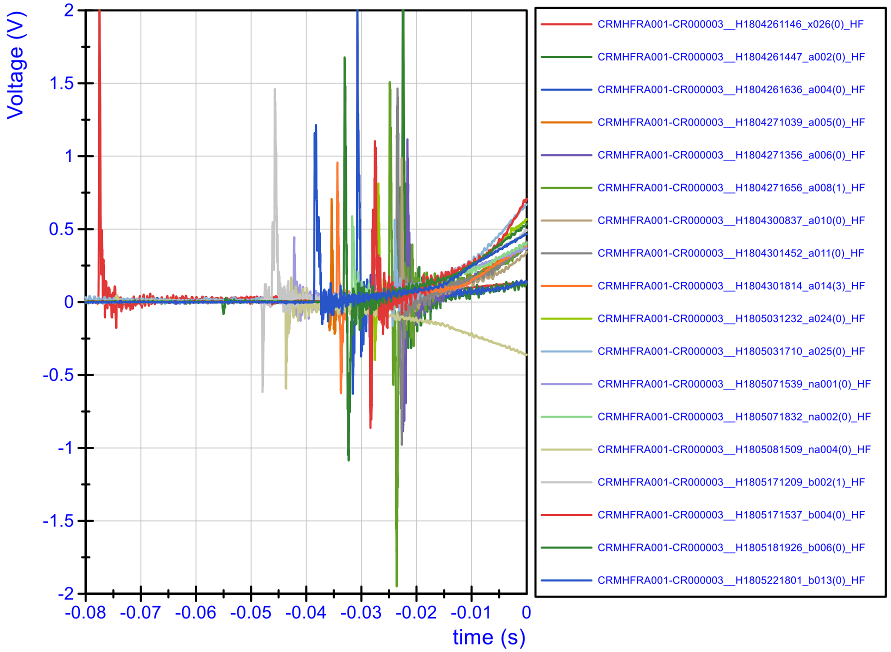
No significant precursors during training.

Note: quadrupole configuration has not been investigated and it may change sensitivity of precursor to motion.

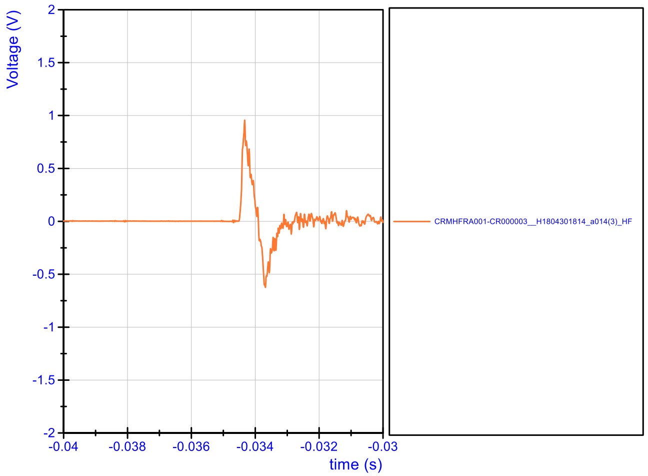
No study to movement modes possible/needed without precursors.

FRESCA2c

Always significant precursor before a quench up to 5 J



Often a double motion: example first in top half (positive) then in bottom half (negative)



Study to movement modes gives interesting information.

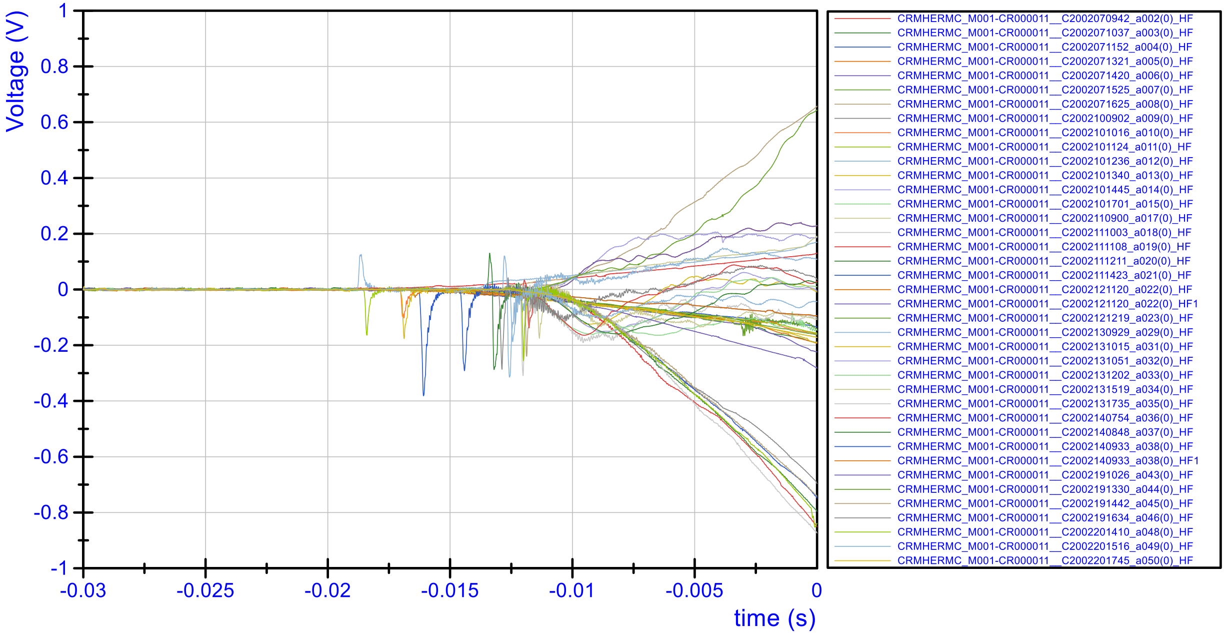
Conclusion

- Quench limit seems mainly mechanical of origin, so no sign of conductor degradation.

See also: Methods for quench localization and performance diagnostics of Nb_3Sn magnets in SM18 https://indico.cern.ch/event/820811/

Note: this is a qualified magnet and still holds a World Record, dipole with 100 mm bore at 14.6 T !!!!

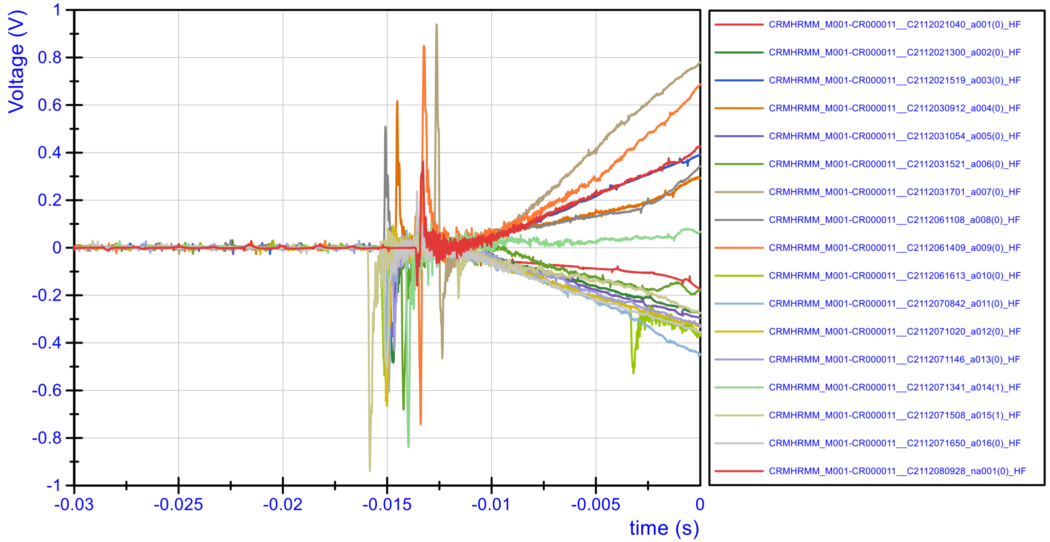
eRMC



Sometimes significant precursor before a quench.
Up to 1.5 J

Training stopped at target level.

RMM



Except for the first quench, always a significant precursor measured.

Training limited by mechanical transients, not conductor degradation.

Largest precursor ~1.5 J

Magnet has a very limited bore, and no quench antenna can be installed to identify displacement mode or location.

Many thanks to the whole team in SM18, always making an effort to get the highest precision measurement.

Thank you

TE-MSC magnet seminar contributions on magnet test result interpretation methods

2018, H. Arnestad, G. Willering, *Measurement of Electrical and Mechanical Transients in Nb_3Sn magnets,* https://indico.cern.ch/event/738168/.
2019, G. Willering, *Methods for quench localization and performance diagnostics of Nb_3Sn magnets in SM18* https://indico.cern.ch/event/820811/
2021, R. Keijzer, *Modelling V-I measurements and characterizing performance degradation in 11T and MQXF magnets* https://indico.cern.ch/event/1025824/
2022, M. Wallin, G. Willering, *Transients and Coil Displacement in Accelerator Magnets* https://indico.cern.ch/event/1112725/