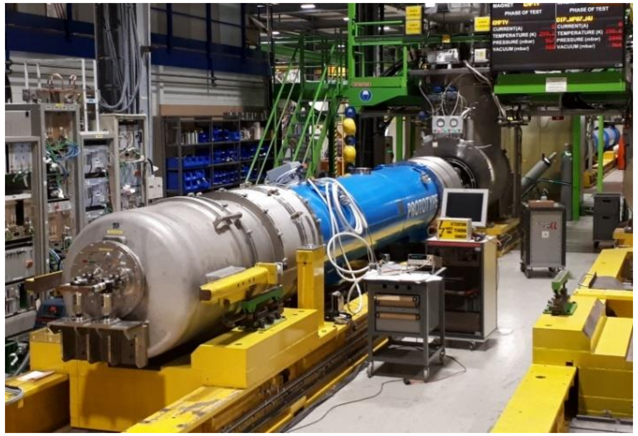
Performance diagnostics for Nb_3Sn magnets at CERN

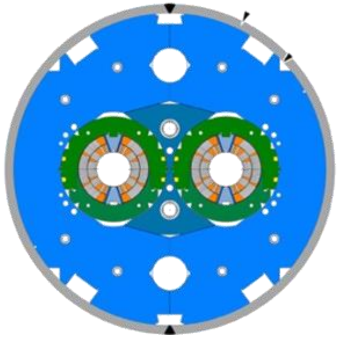
Gerard Willering

Thanks to many persons who have made the magnets and supported the tests.

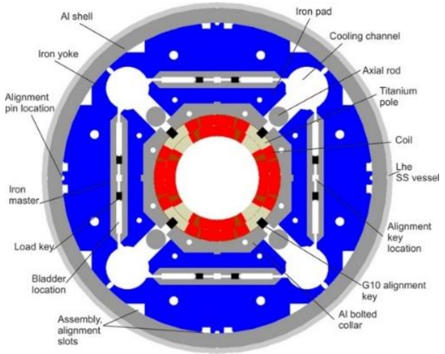
Special thanks to the direct test team, M. Bajko, H. Arnestad, H. Bajas, M. Duda, F. Mangiarotti, J. Feuvrier, V. Desbiolles, E. Karentzos, G. Ninet



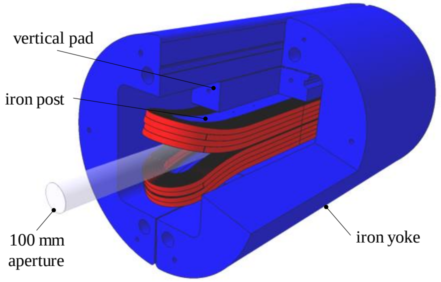
August 2019: First series MBH 11T magnet qualified for installation in the LHC.



11T dipole



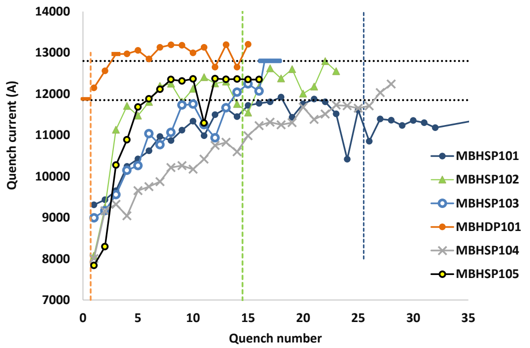
MQXF Quadrole HL-LHC

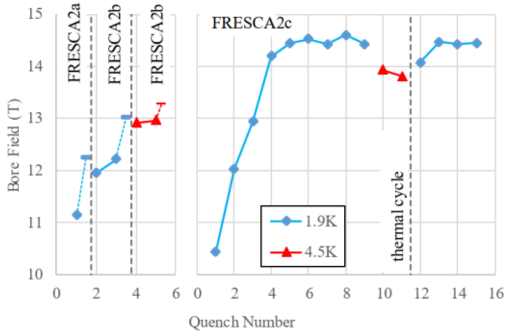


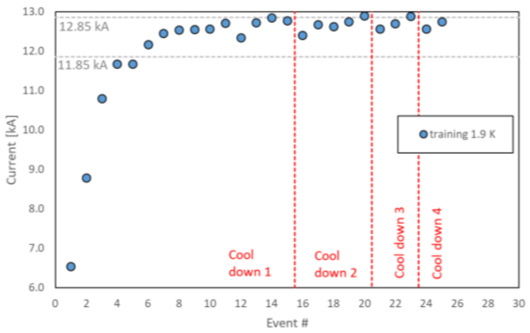
FRESCA2 14.6 T dipole

FRESCA2 14.6 T dipole attached to insert

Typical results as they are presented after a magnet test



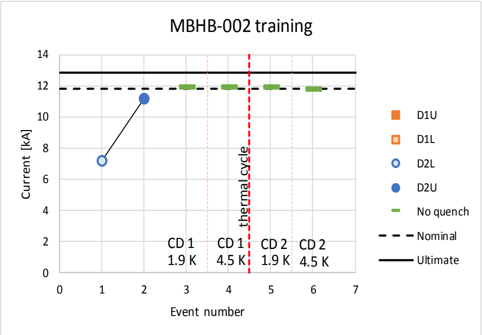


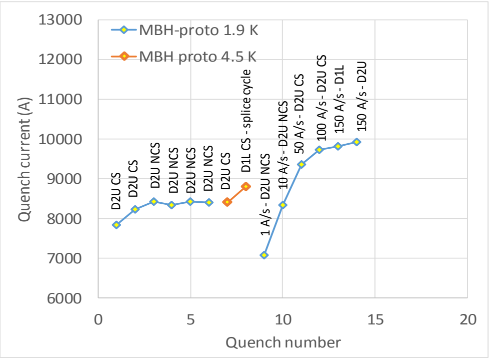


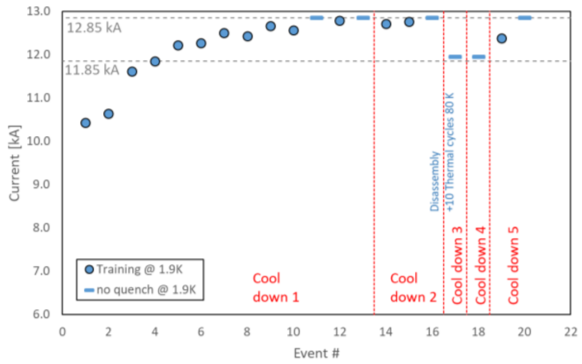
A **training plot** is the first important indicator of how the magnet performs.

However:

There is much more to learn!







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2. Tool box for performance diagnostics
3. Case studies
   - Case 1: Nb_3Sn magnet limited by mechanics
   - Case 2: Nb_3Sn magnet limited by homogeneous J_cB,T,ε) conductor degradation
   - Case 3: Nb_3Sn magnet limited by local conductor degradation

Note: This presentation focusses on the **diagnostics,** attempting to avoid the “magnet” discussion.

Performance limits dominated by mechanical transients

Dominated by **mechanical transients**

- Movements between different magnet components (slip-stick)
- (micro) cracking of epoxy
- Debonding of turns with impregnated pole
- Movement between strands
- Training, Detraining, Memory after Thermal Cycle

NbTi magnet investigations are mainly limited to this category.

Type of performance limits of a magnet

Ultimate performance for each magnet

Conductor dominated

- Design short sample limit I_{ss}
- I_{ss} homogeneously affected by strain state of conductor ($J_c(B,T,\varepsilon)$)
- I_{ss} homogeneously affected by filament damage (too high stresses at some moment in conductor lifetime)
- Local damage to conductor (one or a few strands)
- Local damage on filament level (self-field instabilities, low RRR, etc.)

We find that many **Nb_3Sn** accelerator magnets have limits dominated the conductor.

Two workshops in the past year underlined the importance of the topic:

- October 2018: “Nb_3Sn Rutherford cable characterization for accelerator magnets”, CEA Paris-Saclay, France. https://indico.cern.ch/event/743626/
- April 2019: “Instrumentation and Diagnostics for Superconducting Magnets”, Berkely, California, USA. https://idsm01.lbl.gov/

IDSM01 First Workshop on Instrumentation and Diagnostics for Superconducting Magnets
Berkeley, California, USA *24-26 April 2019*

Instrumentation tool box

At CERN there were not too many changes in the toolbox over the last years:

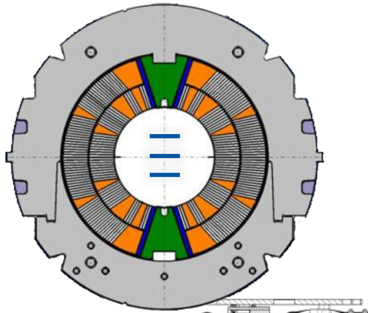
Basic instrumentation:

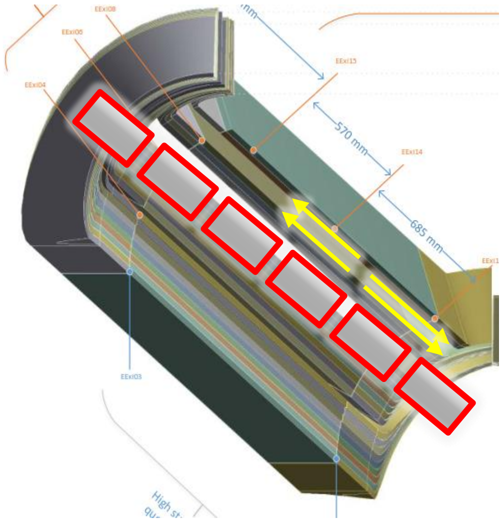
Voltage taps

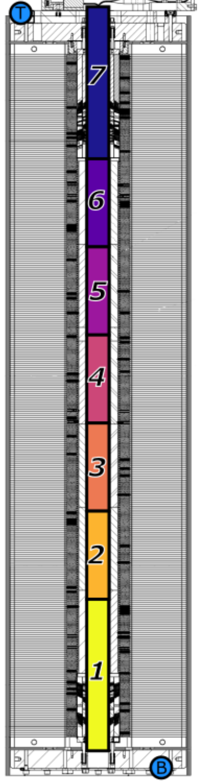
  a) In model magnets small segments are measured
  b) In series magnets only the full magnet length.

Pickup coils/Quench Antenna, typically in the bore of the magnet

  1. Long coils (1.2 m) for “normal” investigation
  2. Short coils (4 cm) “trouble shooting”.



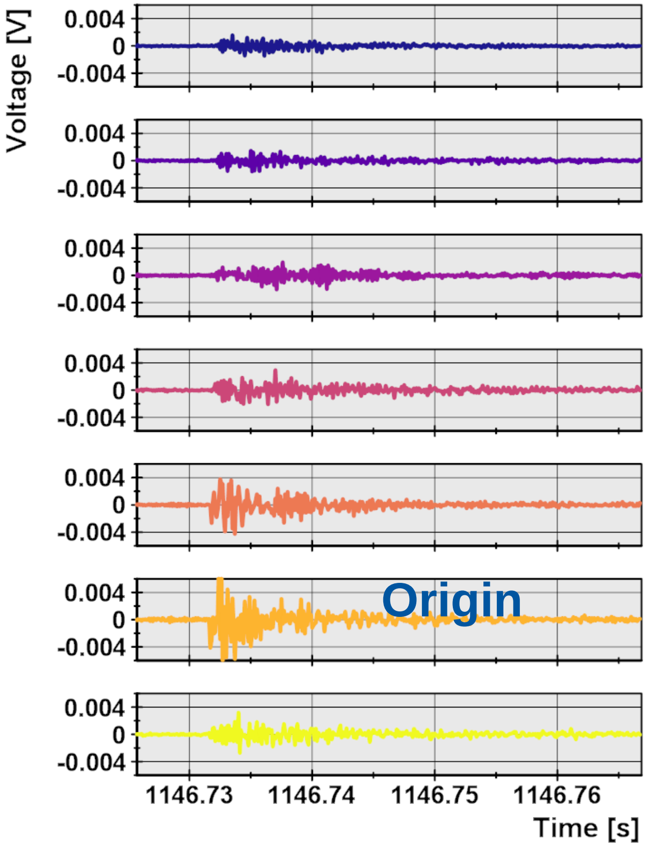


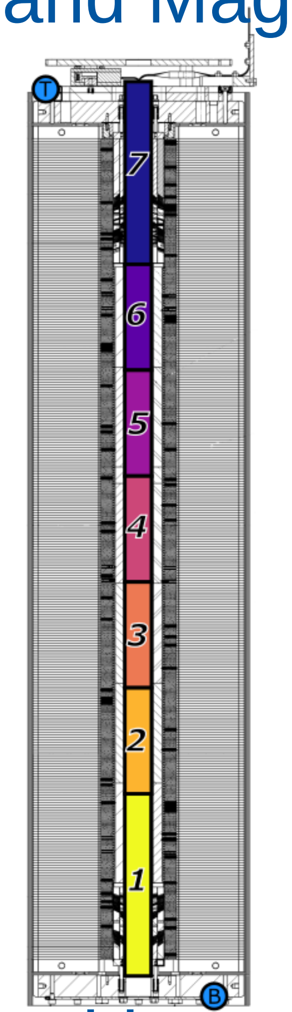


Changes mainly in Data Aquisition and Diagnostics:

a. V-I measurements
b. Signal analysis
c. Combining diagnostics data

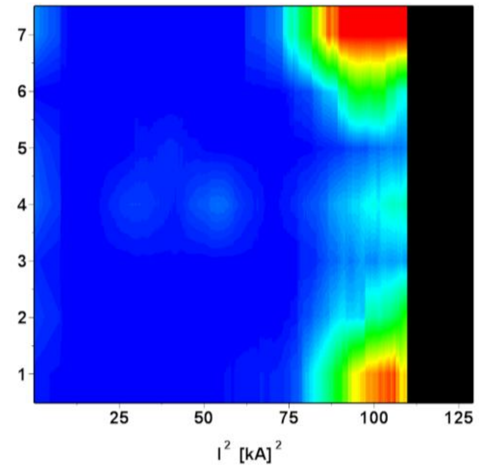
Toolbox: Vibrations and Magnet training



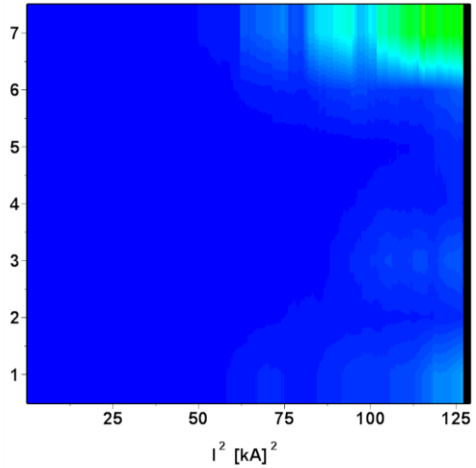


Define origin, amplitude and activity for each vibration and visualize in color map. Use earthquake analogy.

Quench # 3:
Vibrations in both heads

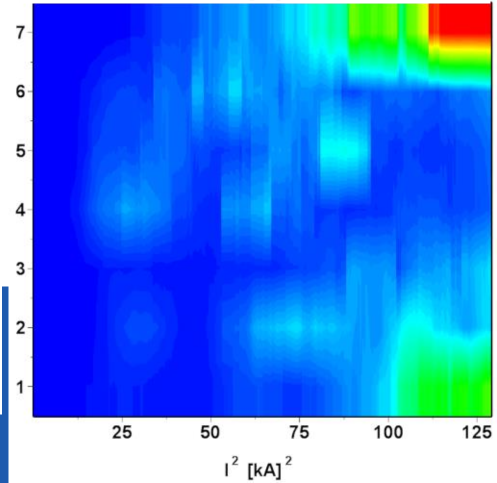


Fully trained magnet:
Some vibrations left in connection lead end



First powering after thermal cycle:
Good memory, a few vibrations still left.

Healthy magnet.



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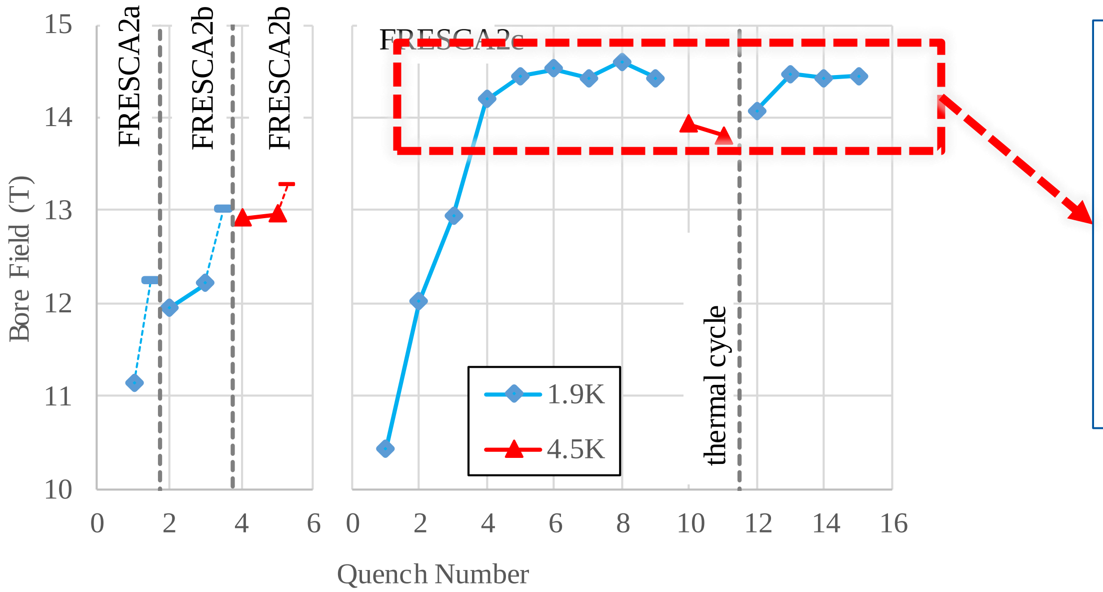
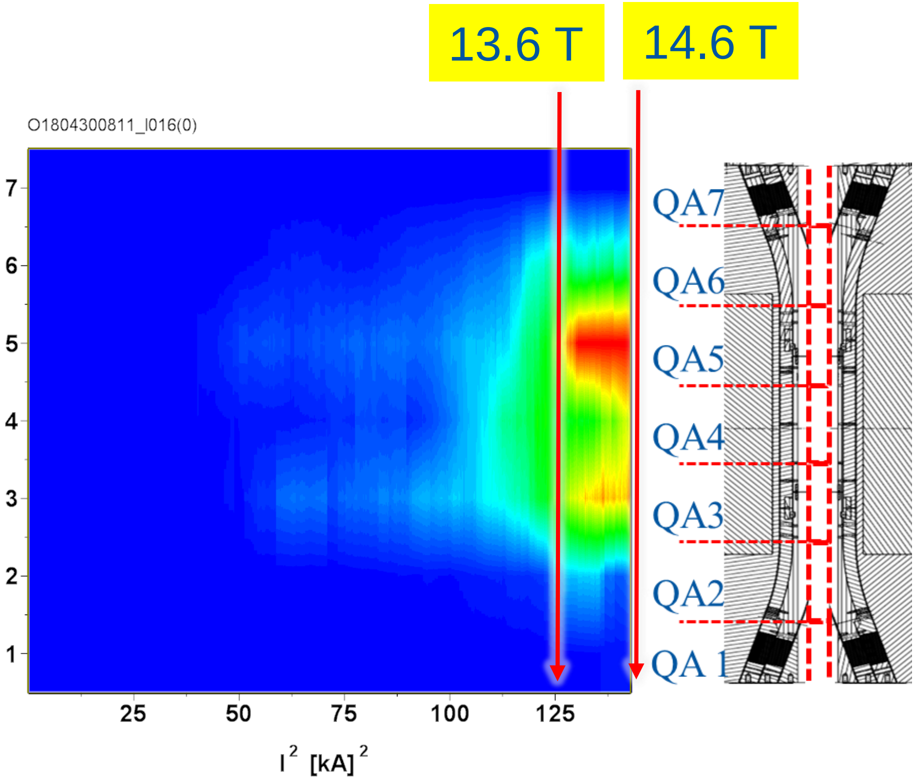
Case study 1: Coil limited by mechanical transients

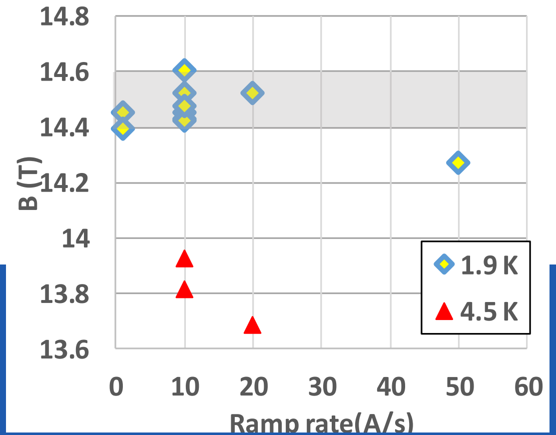


- Training ends in an “erratic” range of ±100 A
- All training quenches preceded by large precursor
- Reaching higher fraction of short sample limit at 4.5 K compared to 1.9 K, but similar quench characteristics.
- All quenches in the same coil layer.

In this case, the “circumstantial evidence” hints in the direction of a mechanical limit, so we take a look.

Case study 1: Coil limited by mechanical transients





Vibration pattern analysis

- Very repetitive pattern for vibration, main activity starting at about 13.6 T
- No training effect from ramp to ramp
- Also 4.5 K quenches fall in the zone with high vibration activity.
- Main activity next to Quench Antenna 5, end of straight segment, start of flared end.

Conclusion for this magnet:

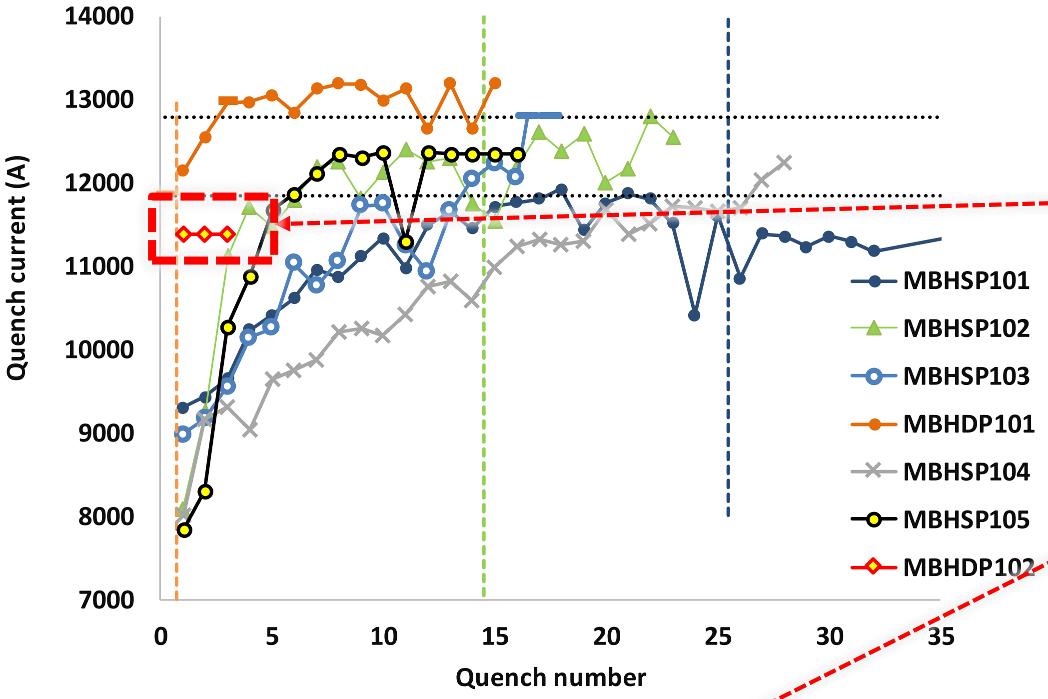
- Coil is mechanicall stable up to 13.6 T and shows more activity in mechanical transients which limits the magnet to 14.6 T.

Note that this is a World Record FRESCA2 dipole magnet with 100 mm bore has potential to go higher. This diagnostics can help to improve a magnet. Courtesy CERN, CEA Paris-Saclay.

Contents

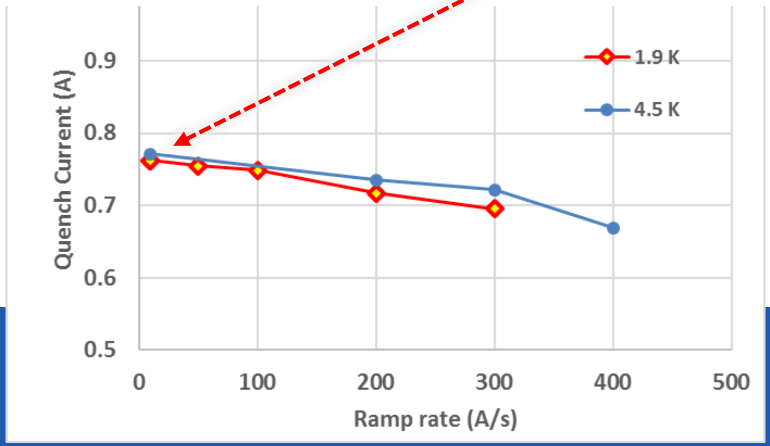
Case 2: Nb_3Sn magnet limited by homogeneous (J_cB,T,ε) conductor degradation

Case: 11 T double aperture model magnet.



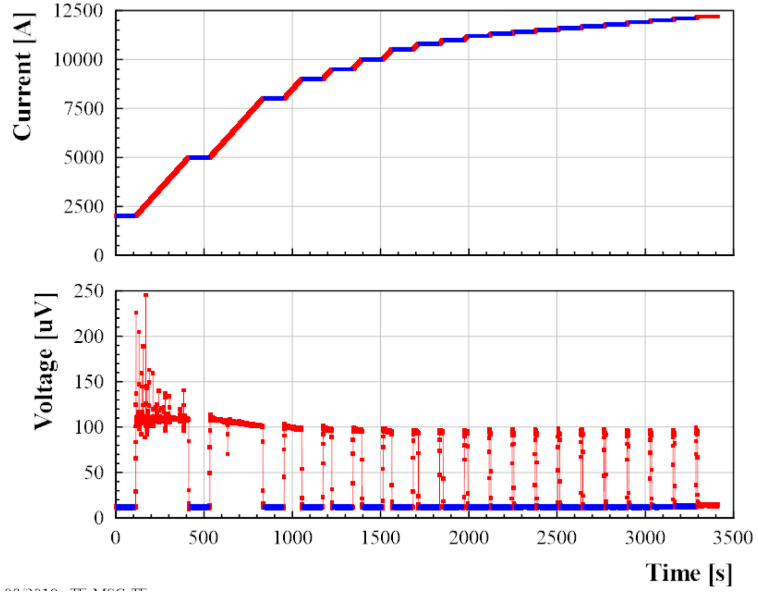
- Training immediately at coil limit.
- All quenches exactly same voltage buildup, location and pattern.
- No precursor or vibration for any of the quenches.

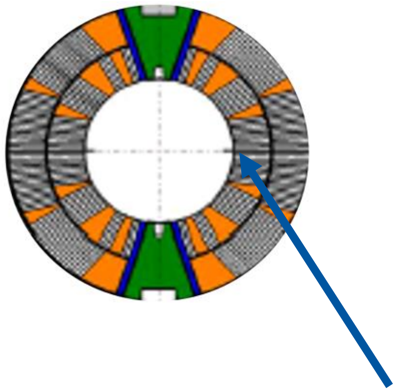
- Same fraction of Iq/Iss at 4.5 K as at 1.9 K, but far below expected value.
- “Normal” ramp-rate dependency shape.



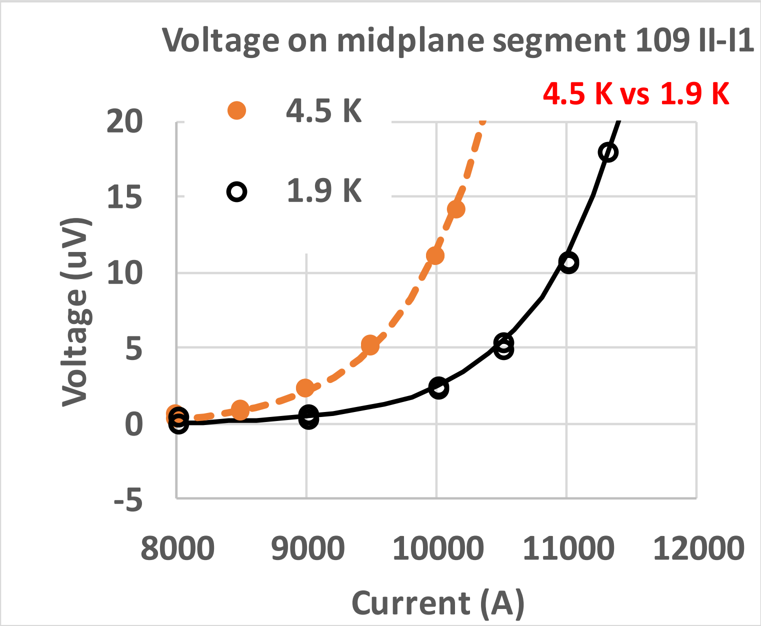
Case 2: Nb_3Sn magnet limited by homogeneous (J_cB,T,ε) conductor degradation

Method:
Measure voltage (high precision, low frequency) over short coil segments. Use 2 minute current plateaus.





V-I measurement of the quenching segment of 1.3 meter long mid-plane



Results in this case:

- SC-to-normal transition visible.
- Expected shift in from 4.5 K to 1.9 K.
- Stable voltage of 18 µV at 11.3 kA shows no current redistribution effect.

Conclusion

Homogeneous critical current reduction (affecting all strands over width or over > cable twist pitch). Could be reversible strain effects or irreversible degradation or combination of both.

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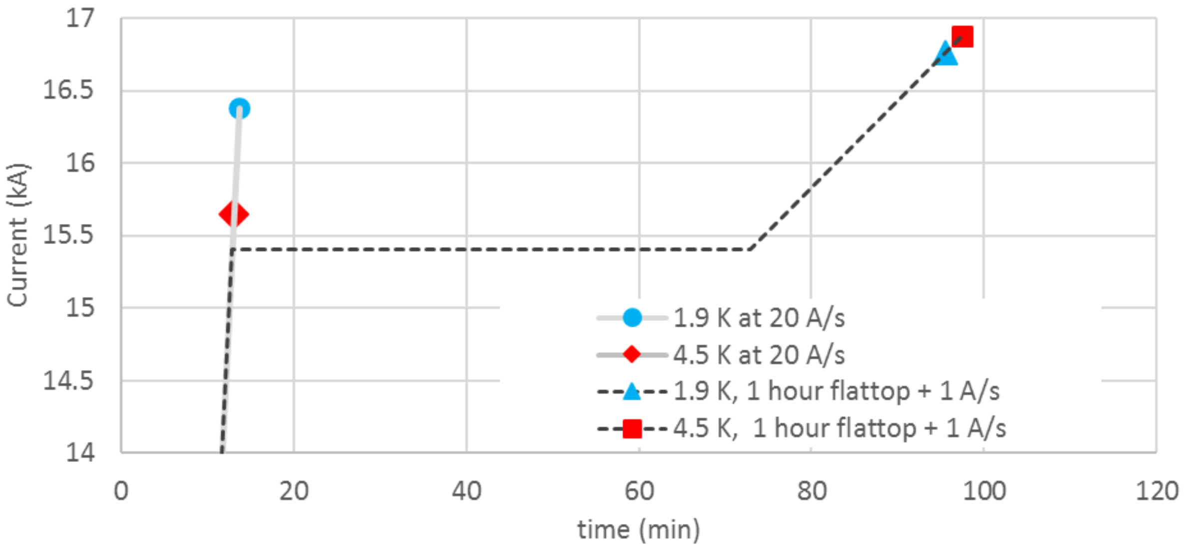
Case 3: Nb3Sn magnet limited by local conductor degradation



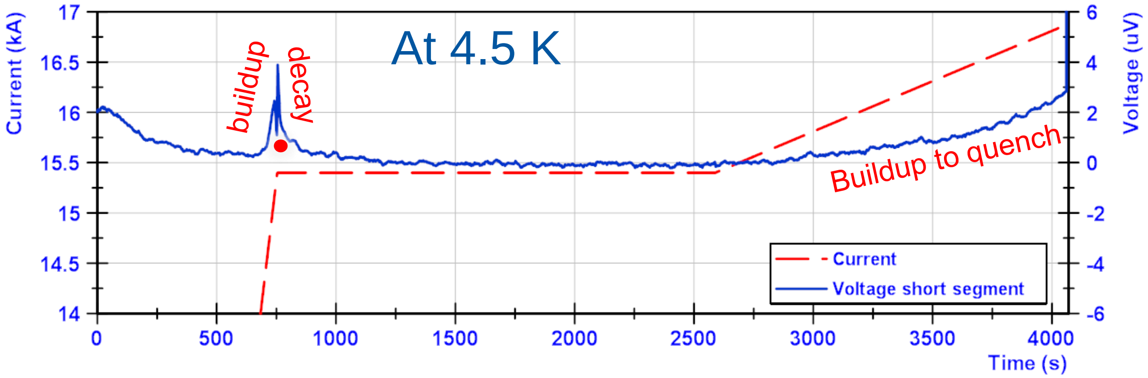
At normal ramp of 20 A/s

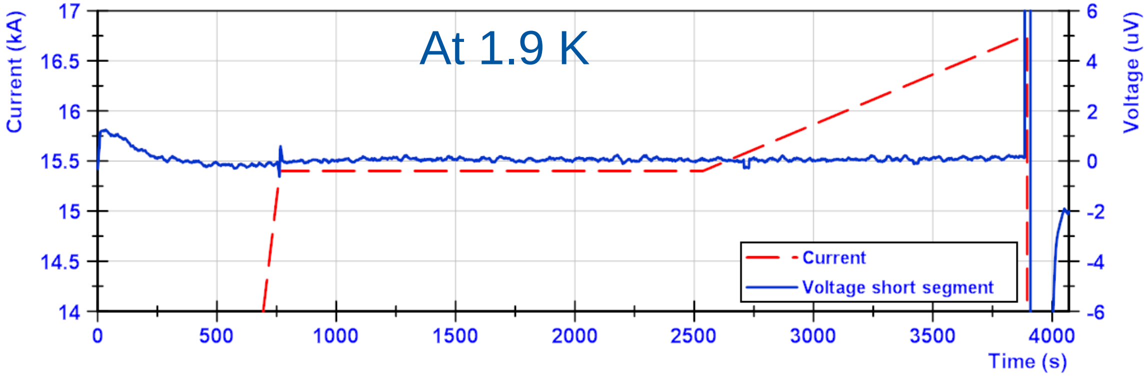
- Absence of vibrations and precursors.
- Repetitive quench levels (no training effect)
- 1.9 K quench current higher than at 4.5 K
- At 4.5 K large improvement in quench current after 1 hour flat-top.
- Each temperature has its own quenches pattern.

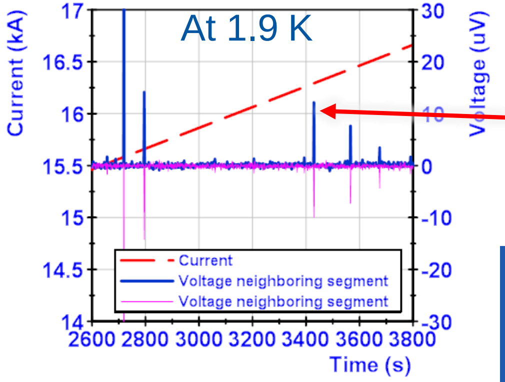
- Different fraction of Iq/Iss at 4.5 K compared to 1.9 K,
- “Abnormal” ramp-rate dependency shape.

-> Gives a suspicion of local conductor degradation.

Case 3: Nb3Sn magnet limited by local conductor degradation







V-I measurement over the short quenching segment

At 4.5 K

- We stop ramping just before quench.
- Voltage was building up, but decays in short time
- When ramping slowly at 1 A/s later, voltage builds up again until quench.
- Clear sign of **current redistribution effect.**

At 1.9 K

- Same current cycle
- Too far from local critical surface to see any voltage buildup.

Why quenches at 1.9 K at a current lower than 4.5 K without voltage buildup?

- Spikes in voltages, only seen at 1.9 K, suggest **self-field instabilities** that quench the magnet.

Complex case combining multiple types of coil limits

Performance Diagnostics Summary

Even a small tool box can give a lot of possibilities for **diagnostics**

Combining results of different tests with correct interpretation is **very powerful** for giving feedback to magnet performance.

Thank you

With many thanks to all groups give us nice magnets to “play” with:
CERN, TE-MSC group
CEA, Paris-Saclay
Ciemat, Madrid

Suggestions for talks this conference touching this topic

Tu-Mo-PL2-01**, Helen Felice**, Advances in Nb3Sn Superconducting Accelerator Magnets

Wed-Mo-PL4-02, **Franco Mangiarotti**, “Superconducting Magnet Testing: The Art of Giving Feedback on Magnet Design”

Fri-Mo-Or25-07, **Maxim Marchevsky**, “Analysis of the transient mechanics behind superconducting accelerator magnet training”

Wed-Af-Or14-06, **Bernardo Bordini**, The effect of transverse loads on Nb3Sn Rutherford cables for accelerator magnets

Backup slides

Typical work flow for investigation of performance limits

Look for circumstantial evidence

Variability of quench current
Temperature dependency (1.9 K and 4.5 K)
Holding current tests
Inversed or normal ramp rate dependency
Look for presence of precursors/vibration at quench onset

If any anomaly shows up:

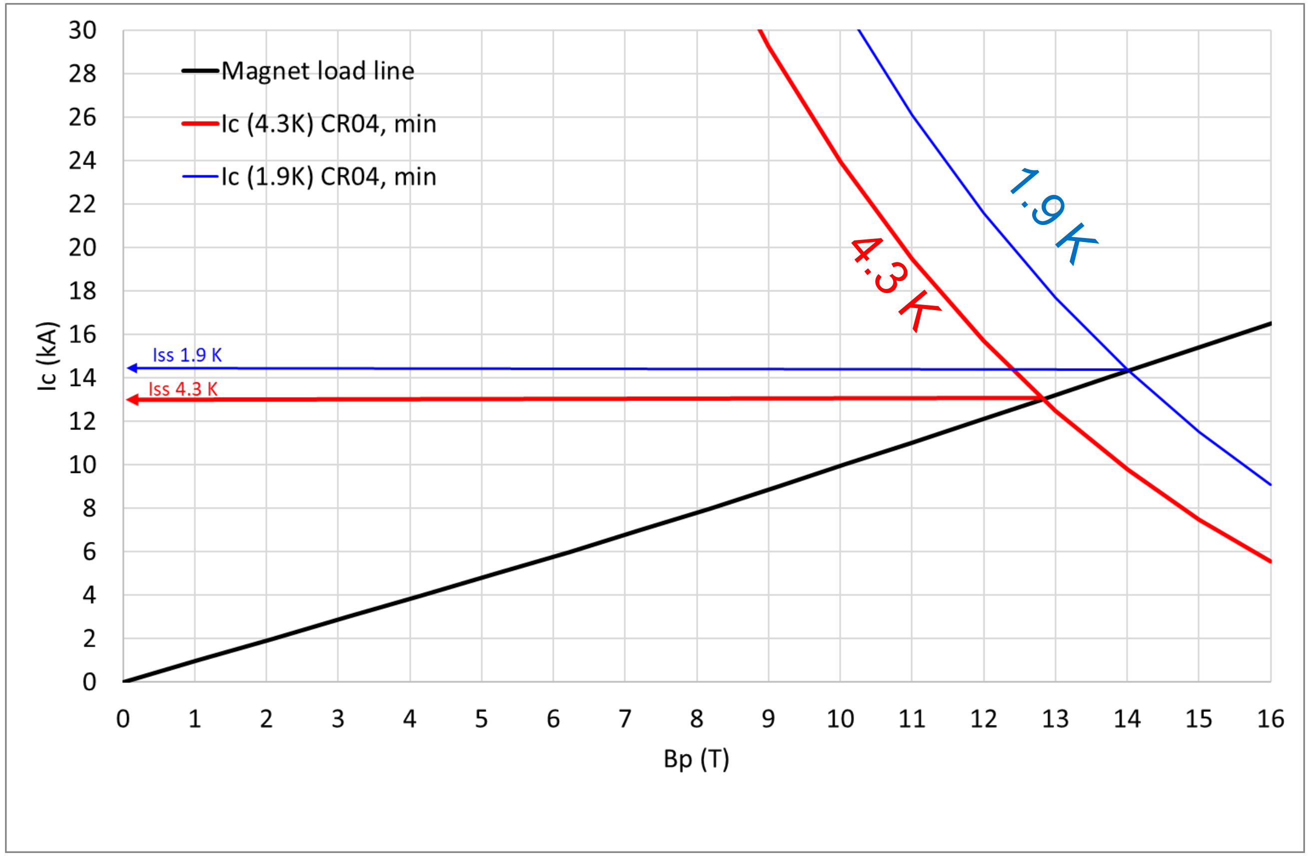
Perform deeper investigation

V-I curve on voltage segments
- Look for SC-NC transition
- Look for decay at flattop
- Look for negative voltages
- Look for high-field instability spikes

Look at possible ….. Etc.…

Other effects to verify
- Very fast longitudinal quench propagation
- Very slow training (seen in layer jump issues in 11T short models, explained as combination of some strands having small margin and more susceptible to mechanical transients).
- Variations in strain gages
- Look at variations in higher order field errors with rotating coils

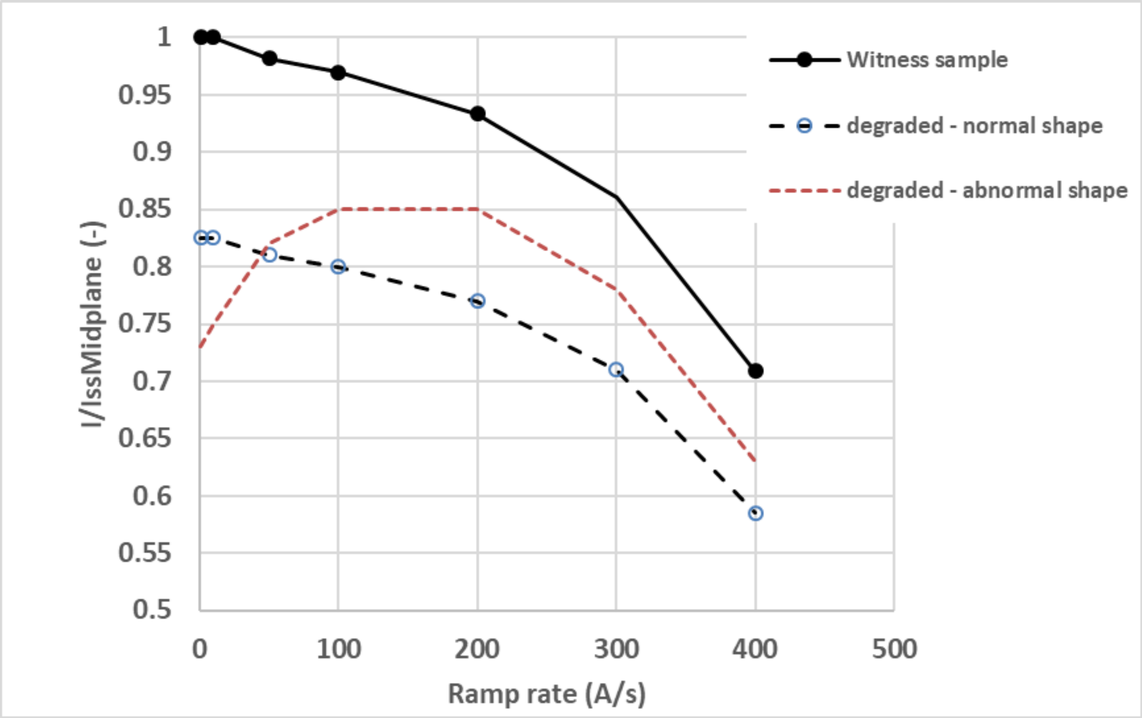
What is normal: Temperature dependency (Nb_3Sn)



Normal for Nb_3Sn:
From 1.9 K to 4.5 K about 8 to 10 % reduction of I_{SS}

$$I_{Q,1.9K}/I_{SS,1.9K} = I_{Q,4.5K}/I_{SS,4.5K}$$

What is normal: Ramp rate dependency



Expected in perfect case:

$I_Q = I_{ss}$ at low ramp rate

Homogeneous degradation:

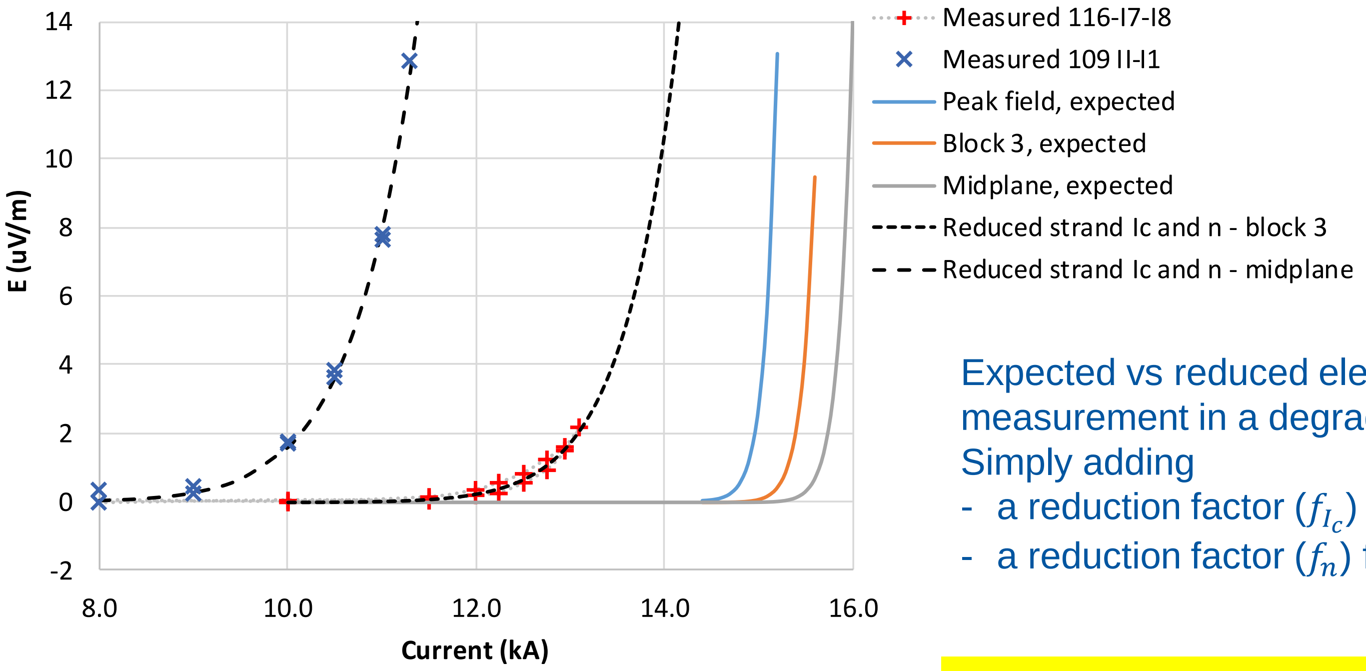
Expect similar curve shape, but at lower fraction.

Non-homogenous degradation/self field instabilities

Expect abnormal shape, for example highest I_q at intermediate current levels.

What is normal: V-I curves?

V-I curves



Expected vs reduced electric field measurement in a degraded conductor.
Simply adding

- a reduction factor (f_{I_c}) for I_c
- a reduction factor (f_n) for n

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

I_c(B) and n(B) characteristics measured in B163

Note:
A reduction of I_c by 10 % at fixed field (cable/strand test characterisation) corresponds to about 3 % of reduction on the load line for a magnet

Note 2: Generally two main causes of I_c variation are distinghuished

- Filament breakage: permanent degradation
- Strain state of the filament: can be reversible

It is difficult to separate the two in magnet measurements.