PAUL SCHERRER INSTITUT

Swiss Accelerator Research and Technology

Michael Daly :: Paul Scherrer Institute, in collaboration with EMPA Dübendorf and UTwente

Using acoustic signals with post-mortem analysis for material research & development

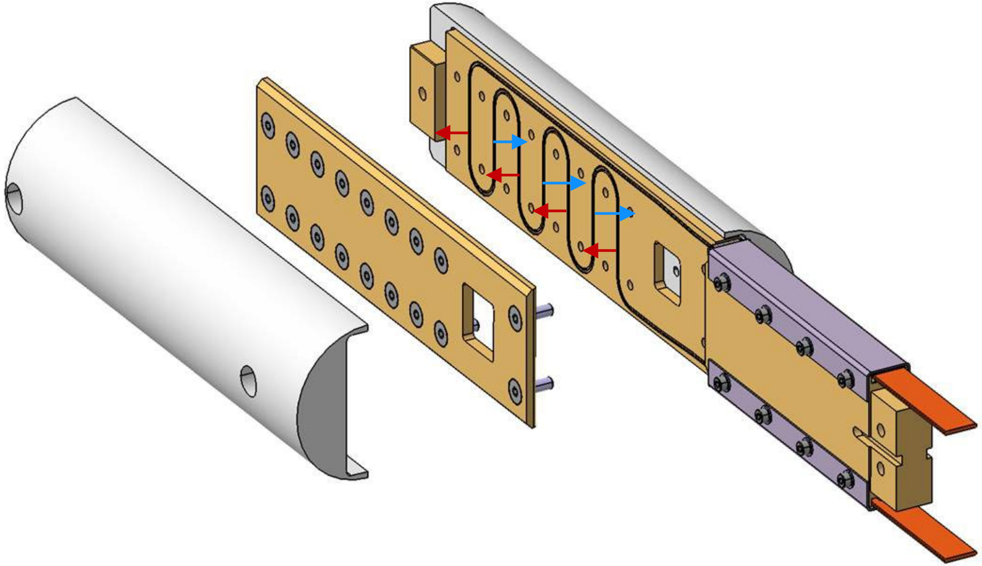
4th IDSM workshop 2023 - Paestum, Italy

Work supported by the Swiss State Secretariat for Education, Research and Innovation SERI.

Acknowledgements to USMDP and LBNL for supplying the Nb_3Sn cable

Content

- Context of work
- Experimental details
- Experimental results:
  - Post-mortem analysis
  - AE signals:
    - 1Mhz
    - 100kHz
- Concluding remarks

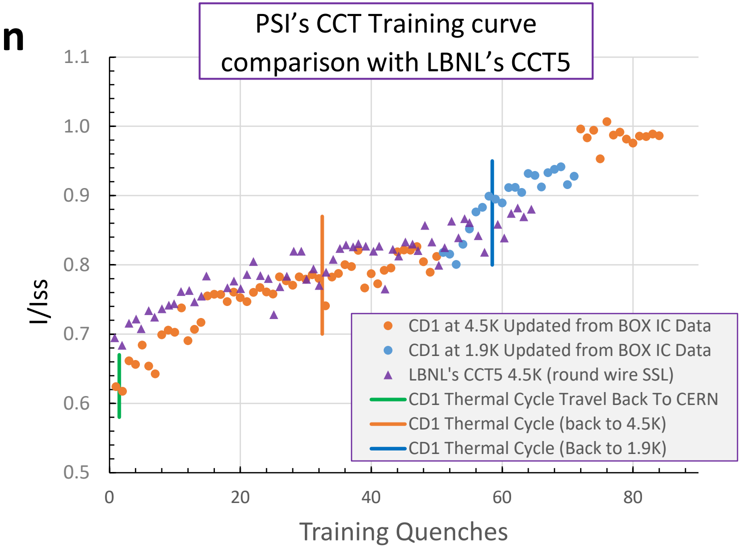


PSI's BOX Program

- **Reproduce conductor behaviour in High Field Magnets (Nb_3Sn, NbTi):**
  - High forces in strong magnetic field (7.5 T to 11 T) at 4.2 K and high currents
  - Failure modes: cracking, debonding, stick slip-motion, sliding

… to reduce magnet training and operational limitation

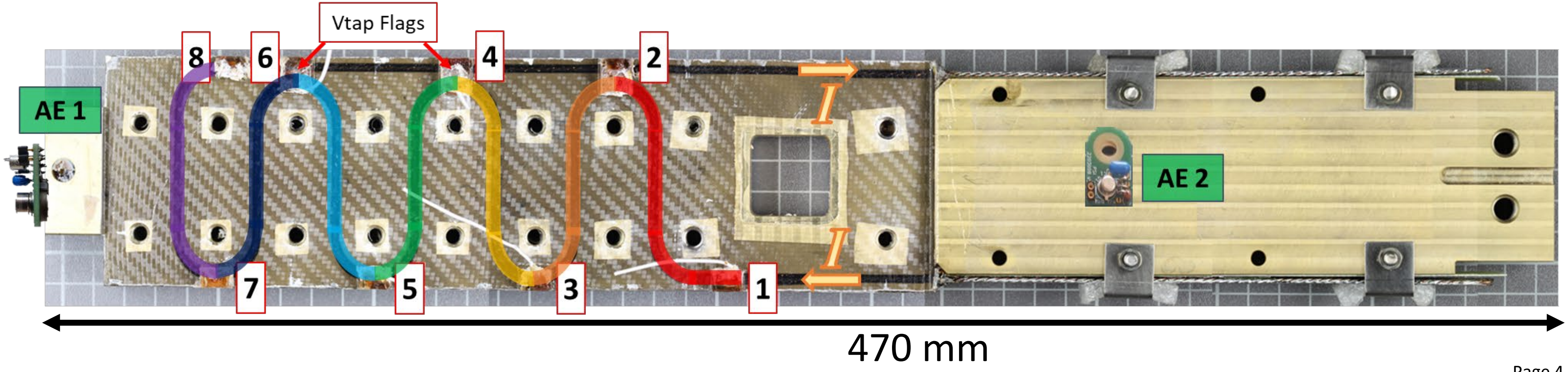
- Training quenches
- Fatigue (cyclic and thermal)
- Operational stability



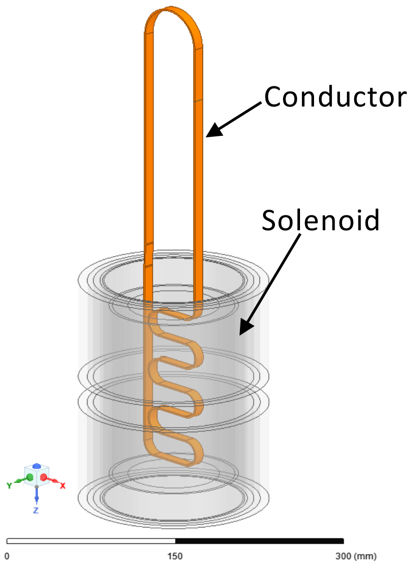
- **Requirements:**
  - Cost-effective (actual cost: 5k – 15k€ /test)
  - Fast turn-around (4 - 8 weeks)
  - Reproducible
  - **Assess various fabrication methods, tooling, materials and instrumentation**
  - Improve our understanding by "simplifying" behaviour

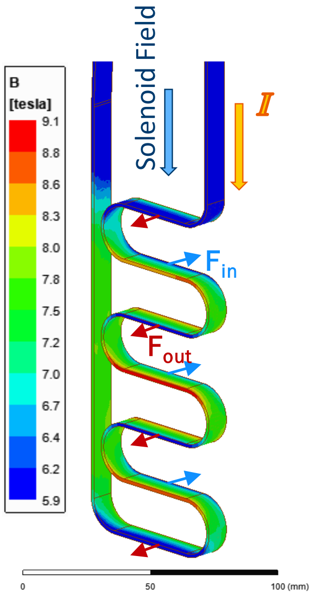
BOX Samples

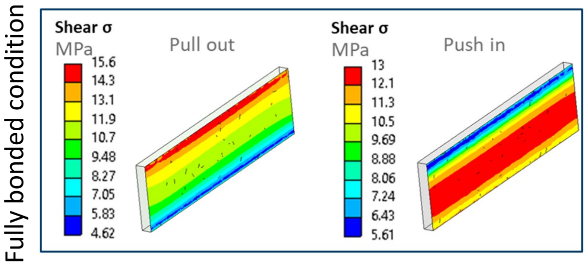
- **BOnding eXperiment Samples (UTwente: 7.5 T solenoidal field at 4.2 K)**
  - Conductor (Nb_3Sn: QXF 0.85mm RRP 108/127, 21 strand cable)
  - Aluminium bronze or Stainless steel former
  - Undergoes required heat treatment (max 665 C) and impregnation
  - Intrumentation:
    - Vtaps at each bend and on leads, x2 Acoustic Sensors, and current monitoring
  - Targeted NDE and destructive analysis



BOX Samples Results

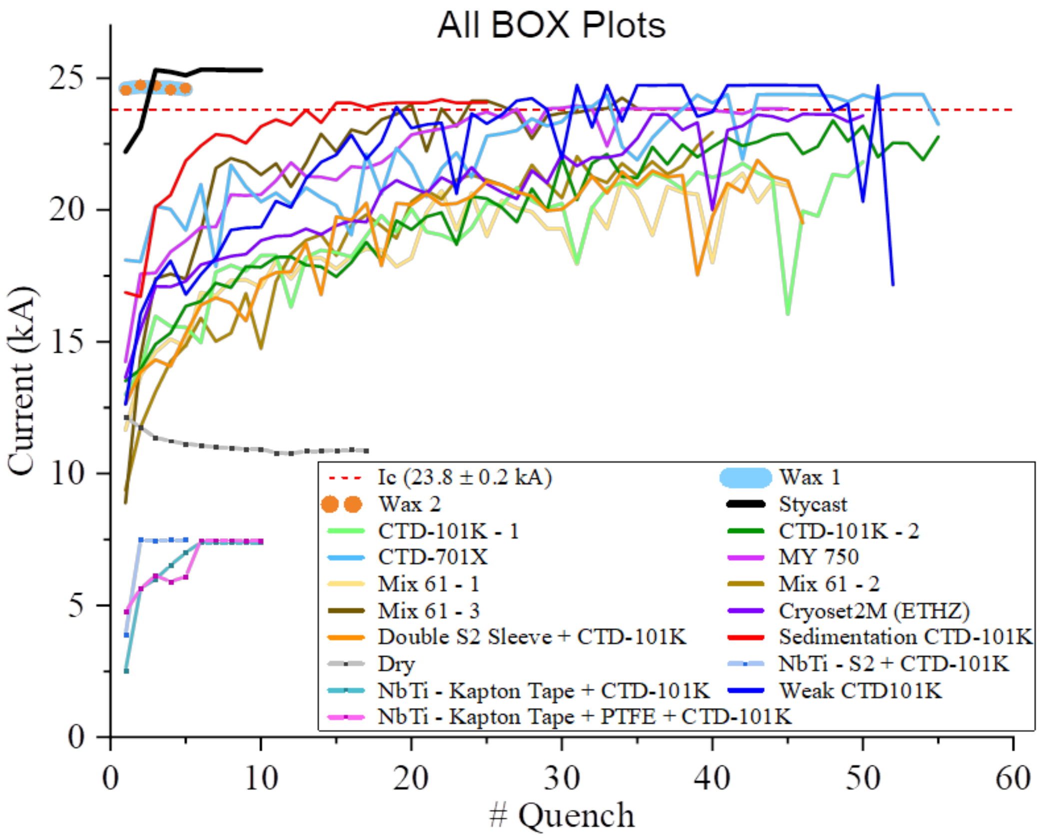






ID	Identifying feature	Conductor
BOX 1	Mix 61 with Mica	Nb_3Sn
BOX 2	Mix 61 - Rep CD1 mag	Nb_3Sn
BOX 3	Mix 61 Rep CD1 improved adhesion	Nb_3Sn
BOX 4	Non-impregnated	Nb_3Sn
BOX 5	“Kirby”/CERN CCT (“RED”)	Nb-Ti
BOX 6	Paraffin Wax 1	Nb_3Sn
BOX 7	CERN CCT Kapton ONLY (“PURPLE”)	Nb-Ti
BOX 8	MY750 (Baseline)	Nb_3Sn
BOX 9	Paraffin Wax 2	Nb_3Sn
BOX 10	CTD-701X	Nb_3Sn
BOX 11	CTD-101K (baseline)	Nb_3Sn
BOX 12	CTD-101K no 2 (Reproducibility)	Nb_3Sn
BOX 13	Teflon Coating “BLACK”	Nb-Ti
BOX 14	Ceramic Coating Stycast (Failed)	Nb_3Sn
BOX 15	Weakened CTD-101K	Nb_3Sn
BOX 16	Ceramic Coating Stycast	Nb_3Sn
BOX 17	Sedimented Particles with CTD-101K	Nb_3Sn
BOX 18	Double fibre glass with CTD-101K	Nb_3Sn
BOX 19	Higher toughness CryoSet2M	Nb_3Sn
COMP 1	Paraffin Wax 1	Nb_3Sn
COMP 2	Paraffin Wax 2	Nb_3Sn
COMP 3	CTD-101K - 01	Nb_3Sn
COMP 4	CTD-101K - 02	Nb_3Sn
COMP 5	Paraffin Wax (Improved filling)	Nb_3Sn

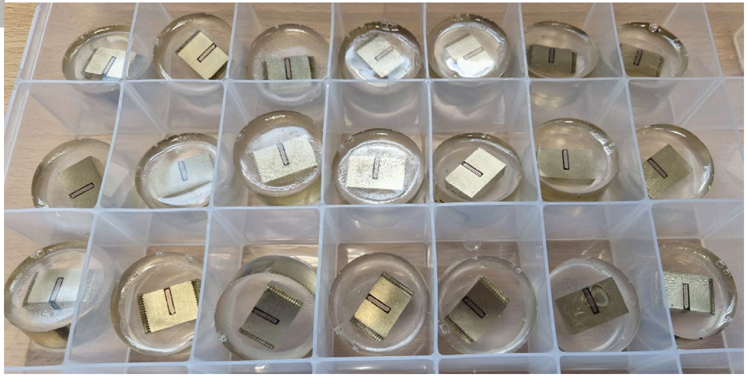
BOX Samples Results

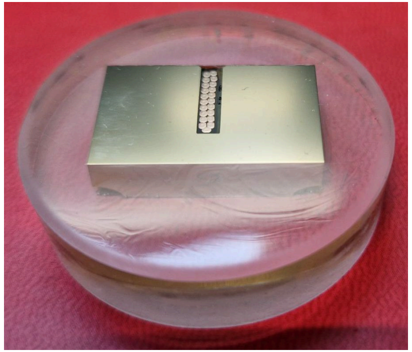


ID	Identifying feature	Conductor
BOX 1	Mix 61 with Mica	Nb_3Sn
BOX 2	Mix 61 - Rep CD1 mag	Nb_3Sn
BOX 3	Mix 61 Rep CD1 improved adhesion	Nb_3Sn
BOX 4	Non-impregnated	Nb_3Sn
BOX 5	"Kirby"/CERN CCT ("RED")	Nb-Ti
BOX 6	Paraffin Wax 1	Nb_3Sn
BOX 7	CERN CCT Kapton ONLY ("PURPLE")	Nb-Ti
BOX 8	MY750 (Baseline)	Nb_3Sn
BOX 9	Paraffin Wax 2	Nb_3Sn
BOX 10	CTD-701X	Nb_3Sn
BOX 11	CTD-101K (baseline)	Nb_3Sn
BOX 12	CTD-101K no 2 (Reproducibility)	Nb_3Sn
BOX 13	Teflon Coating "BLACK"	Nb-Ti
BOX 14	Ceramic Coating Stycast (Failed)	Nb_3Sn
BOX 15	Weakened CTD-101K	Nb_3Sn
BOX 16	Ceramic Coating Stycast	Nb_3Sn
BOX 17	Sedimented Particles with CTD-101K	Nb_3Sn
BOX 18	Double fibre glass with CTD-101K	Nb_3Sn
BOX 19	Higher toughness CryoSet2M	Nb_3Sn
COMP 1	Paraffin Wax 1	Nb_3Sn
COMP 2	Paraffin Wax 2	Nb_3Sn
COMP 3	CTD-101K - 01	Nb_3Sn
COMP 4	CTD-101K - 02	Nb_3Sn
COMP 5	Paraffin Wax (Improved filling)	Nb_3Sn

BOX Post-mortem

Destructive



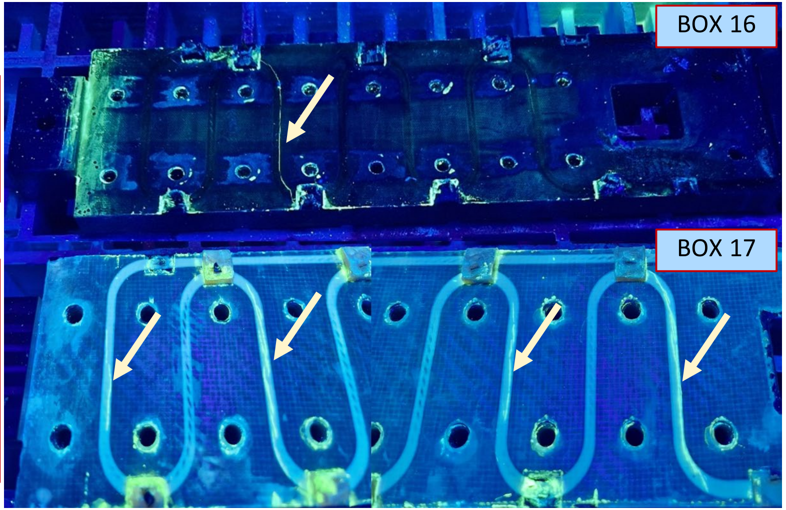


Non-Destructive

- Face imaging pre- and post-testing
- Dye penetrant on surface
  - Fluorescent and red dye

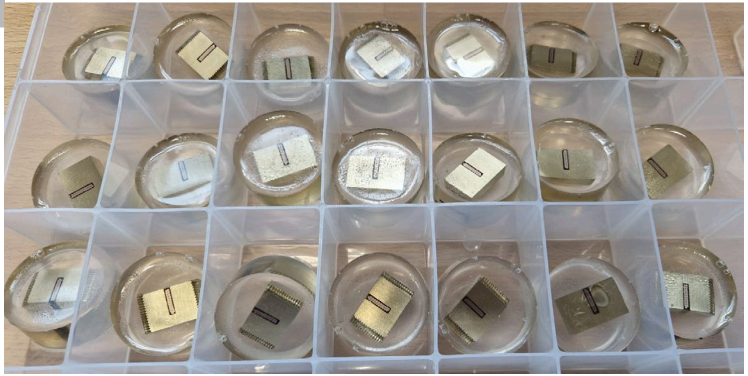
Stycast

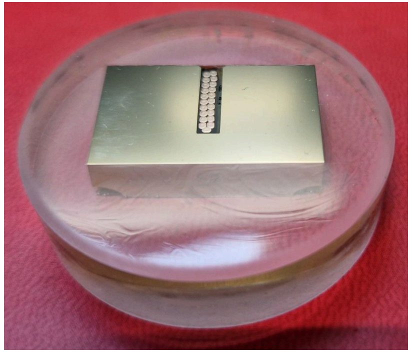
Sedimentation

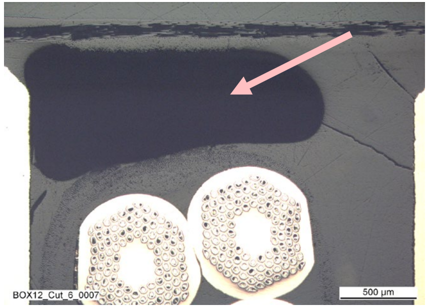


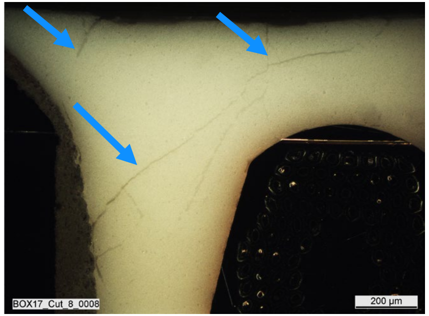
BOX Post-mortem

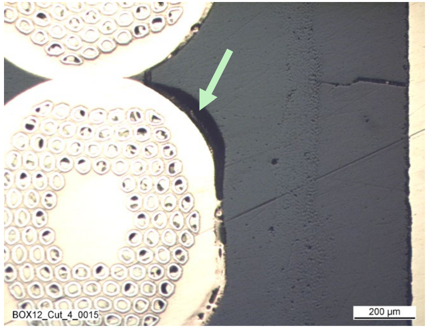
Defect characterization









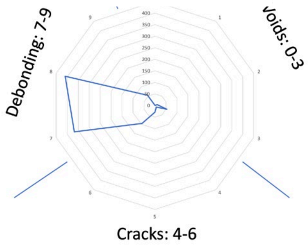


ID	Defect Type
0	Crack a > 2500 µm
1	1500 µm < a < 2500 µm
2	250 µm < a < 1500 µm
3	a < 250 µm
4	Void > 500 µm
5	150 µm < Void < 500 µm
6	Void < 150 µm
7	Crack-like gap w/ Wire
8	Void-like gap w/ Wire
9	Wall Debonding

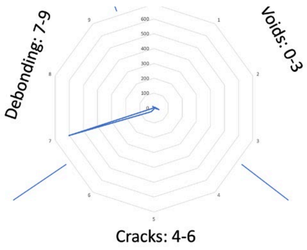
Courtesy of Oliver. Kirby

BOX sample “Fingerprinting”

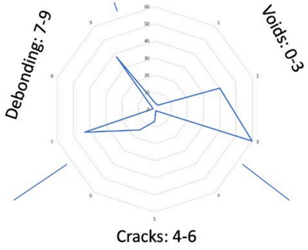
Mix61



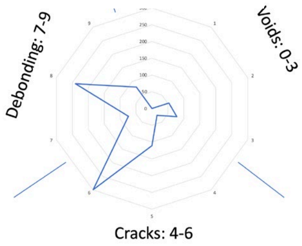
MY 750



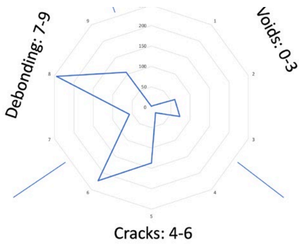
CTD701X



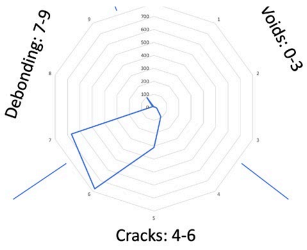
CTD101K - 1



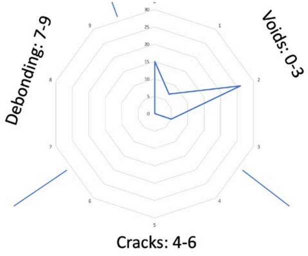
CTD101K - 2



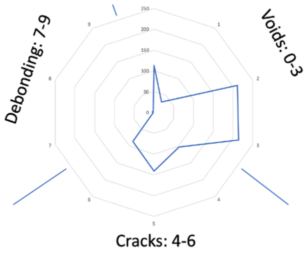
Weak CTD101K



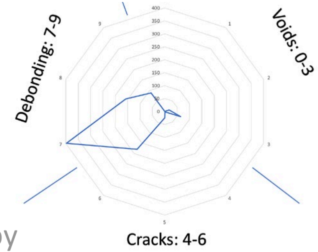
Stycast



Sedimentation

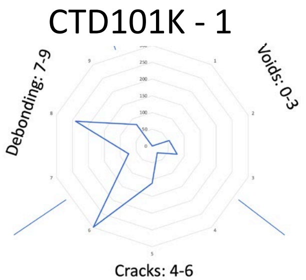


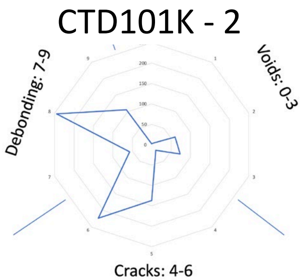
Cryoset 2M

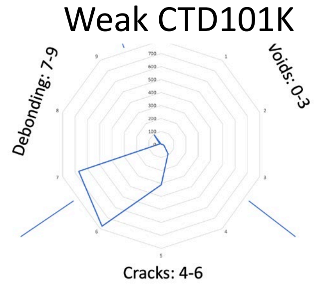


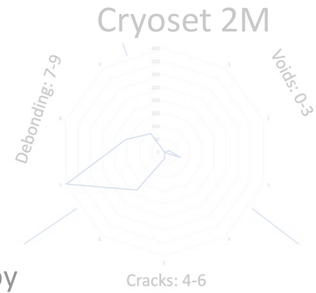
Courtesy of Oliver. Kirby

BOX sample CTD-101 K Series





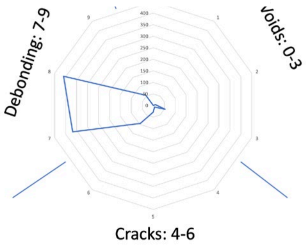




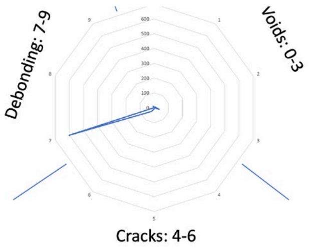
Courtesy of Oliver. Kirby

BOX sample "Tough" Resin Series

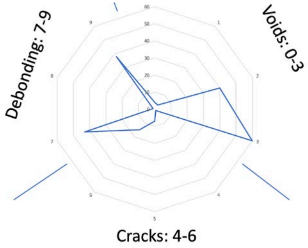
Mix61



MY 750



CTD701X



CTD101K - 1

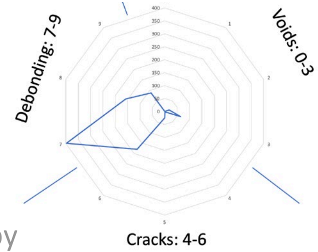
CTD101K - 2

Weak CTD101K

Stycast

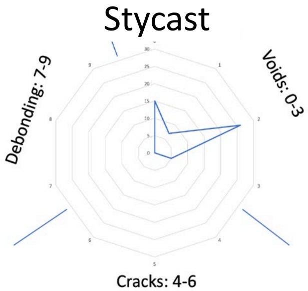
Sedimentation

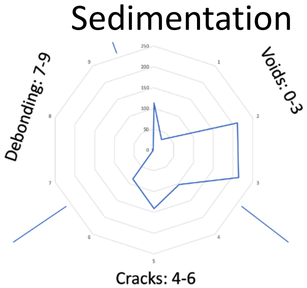
Cryoset 2M

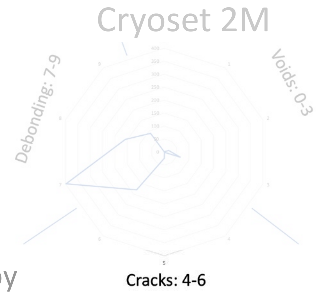


Courtesy of Oliver. Kirby

BOX sample Filled Systems Series



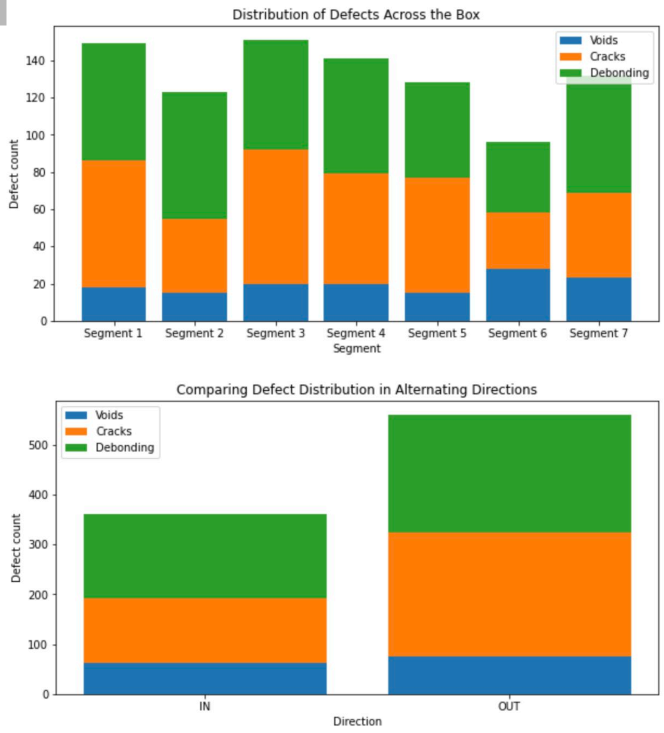


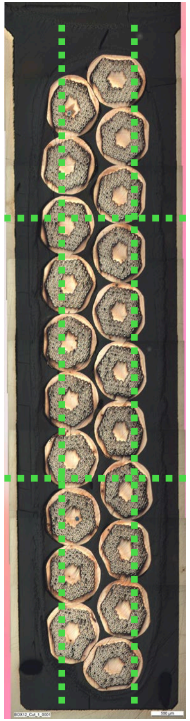


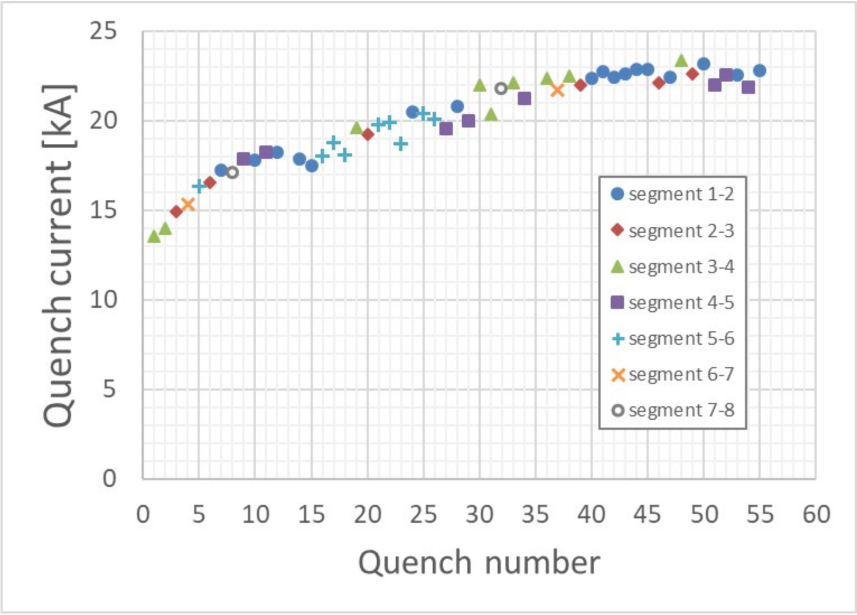
Courtesy of Oliver. Kirby

Single BOX data summary

- Post-mortem data specific to each BOX and each segment with location of defects and knowledge of quench segment.



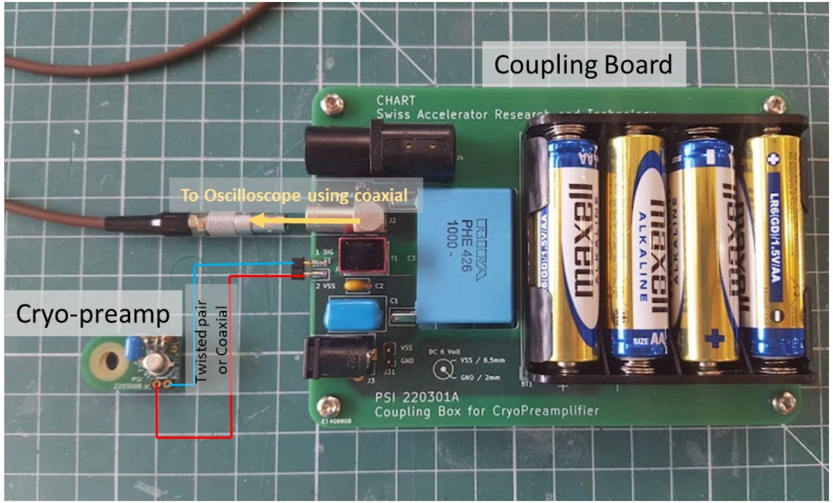




Courtesy of Oliver. Kirby

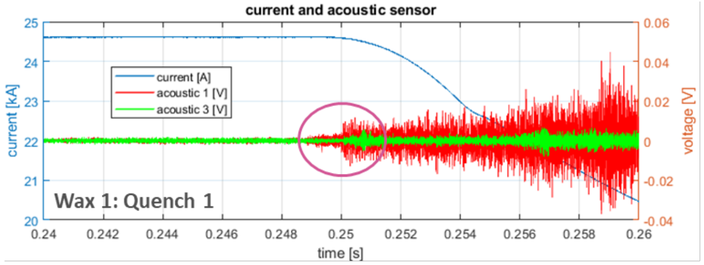
Acoustic Sensors

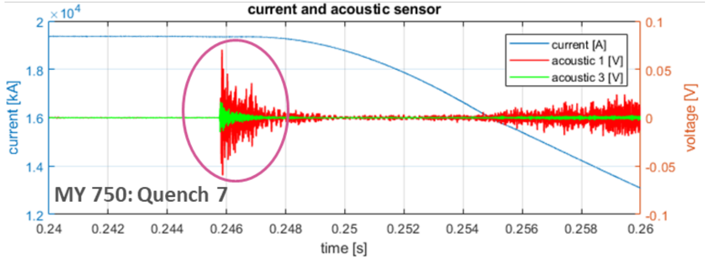
- **Aims:**
  - **Help assess BOXs as an R&D device (Failure analysis: Cracking, debonding, stick-slip)**
  - **To use as a monitoring and diagnostic device for magnets.**
- Design based on LBNL's Maxim Marchevsky's design
  - MOSFET (3N163) and Piezo rings purchased from Supplier in USA
- Screwed unto BOX using stainless steel screw
- Spring washer and copper washer interface with BOX
- Data recorded on Yokogawa DL850EV oscilloscope:
  - Full ramp approx. 2mins
  - Full ramp recorded at **100 kHz**
  - 250 ms before and after quench recorded at **1 MHz**

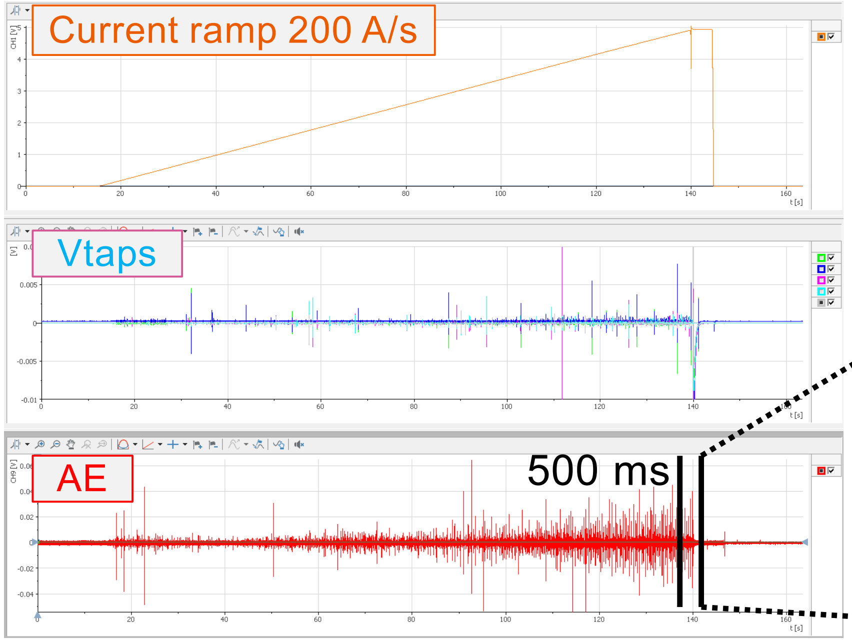


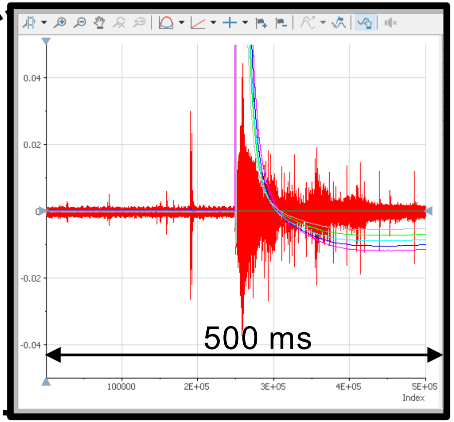
AE Acquired Data

- 1 MHz data ≈ 24MB; 100 kHz data ≈ 400MB
- 608 Quenches (QIDs)
- >1000 ramps (incl cyclic ramps)
- 360 GB of raw data



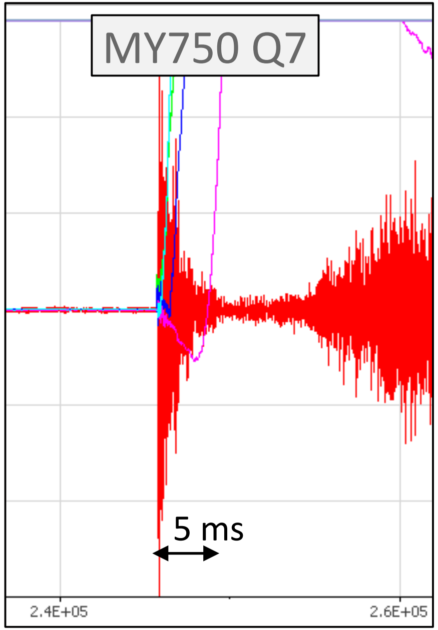


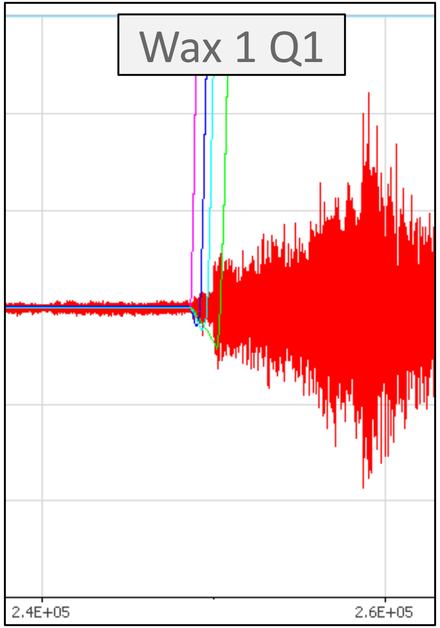


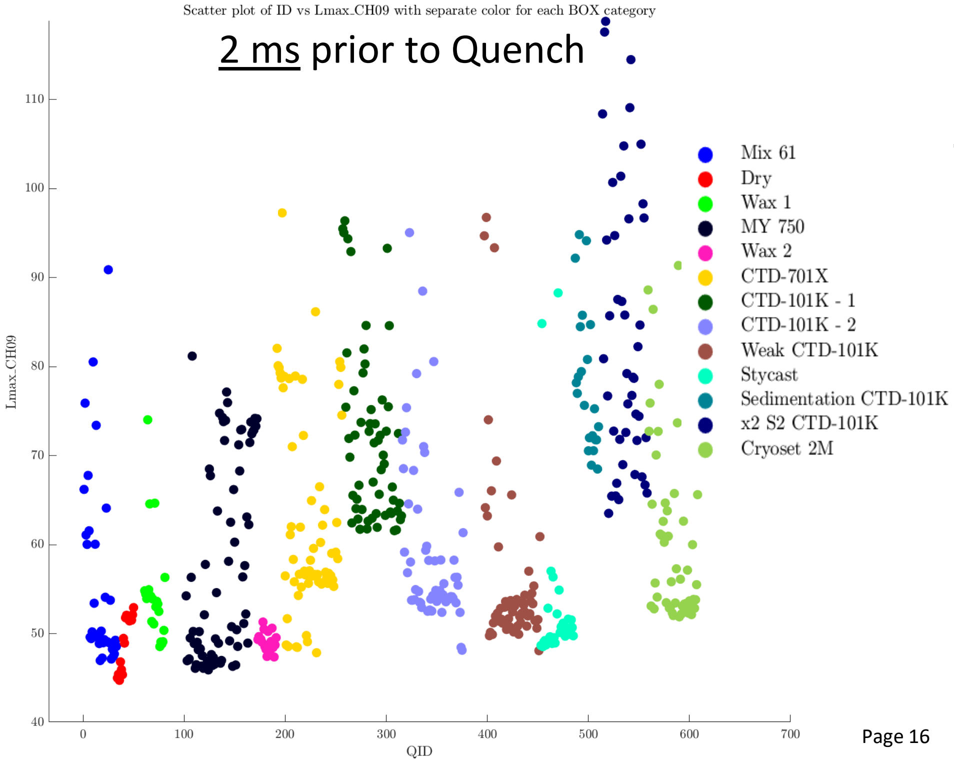


“Expectations vs Reality” (1 MHz data)

- Does an acoustic event precede or proceed a quench?
  - Did a crack or movement release sufficient energy to quench ?

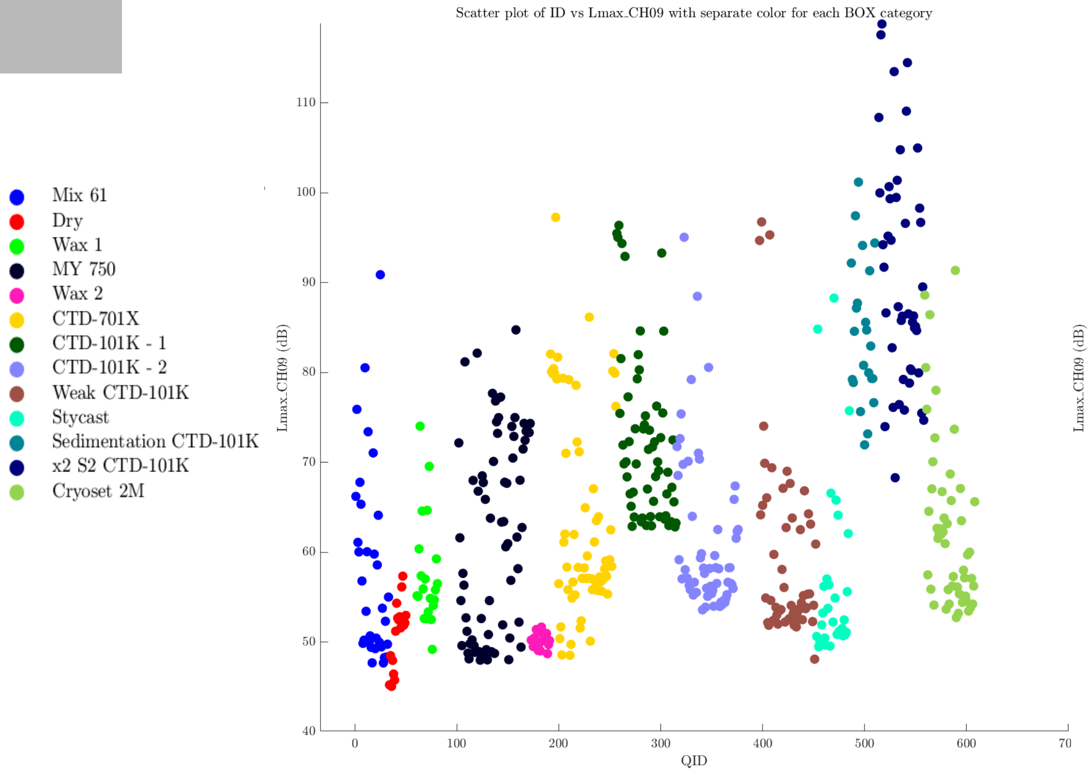




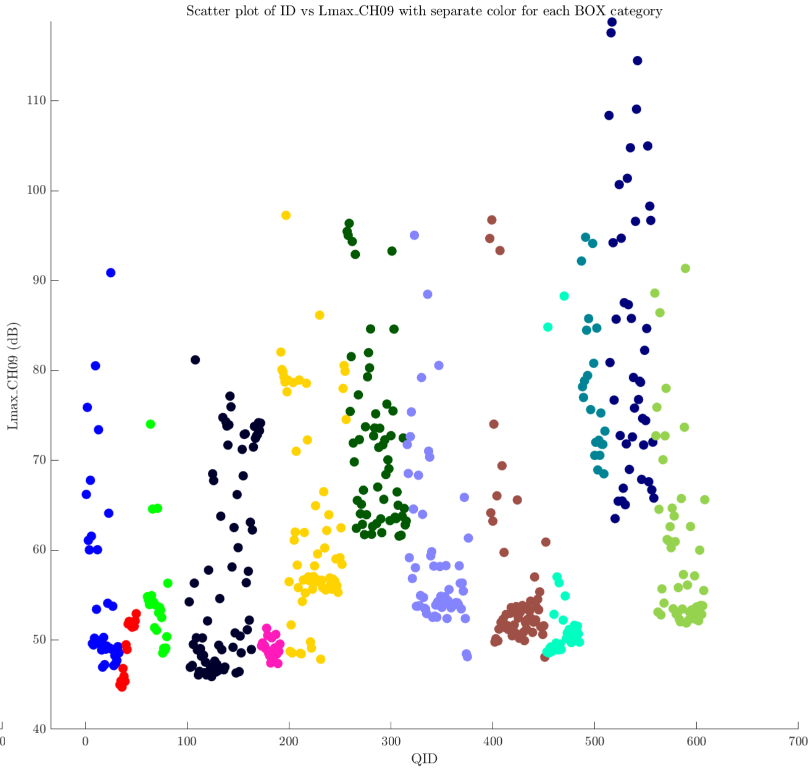


“Expectations vs Reality” (1 MHz data)

20 ms prior to Quench

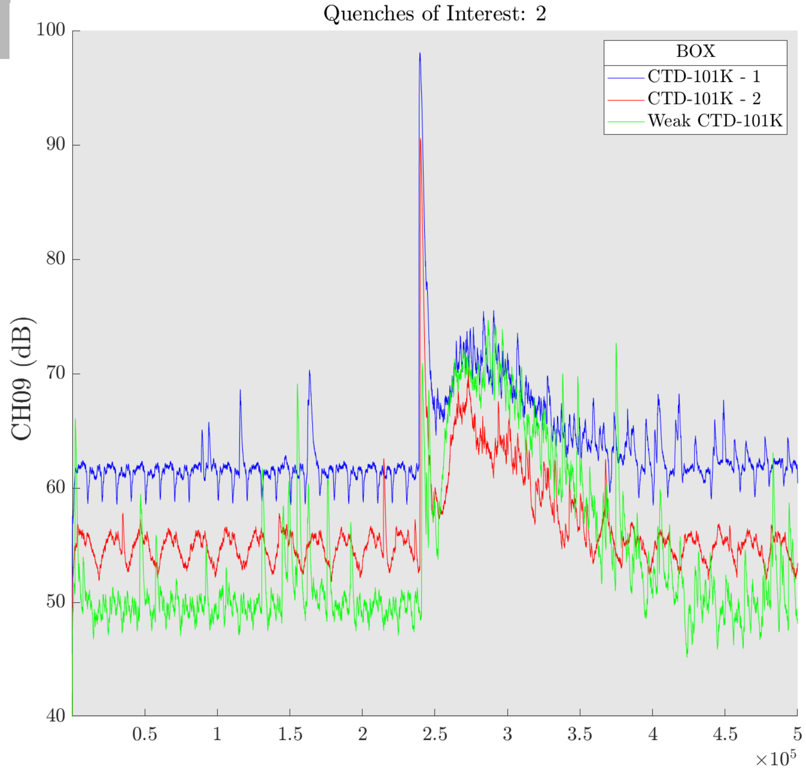


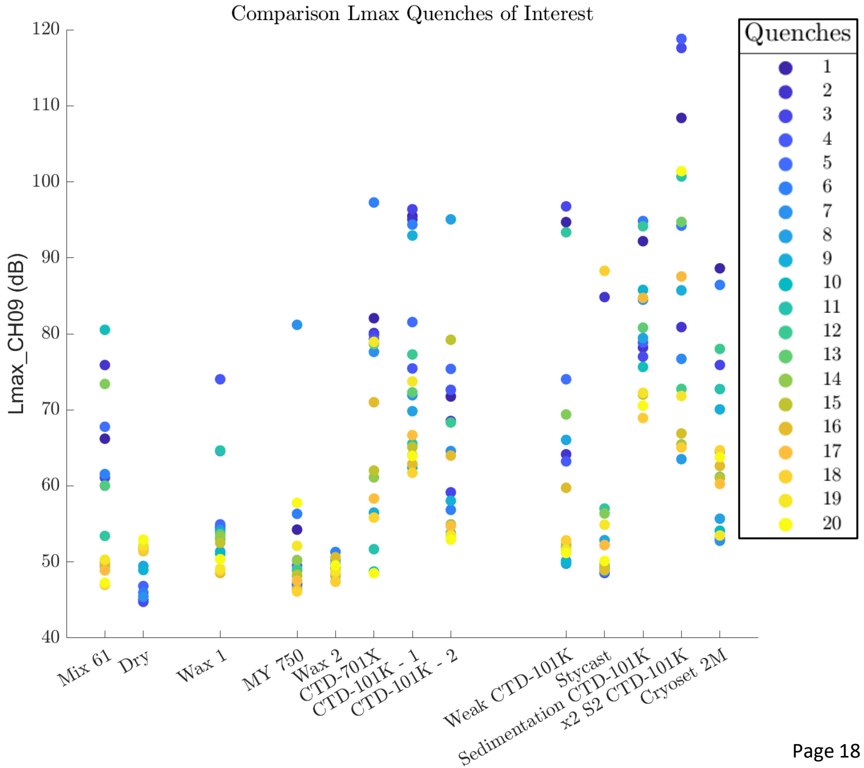
2 ms prior to Quench



Energy levels Comparisons (1 MHz data)

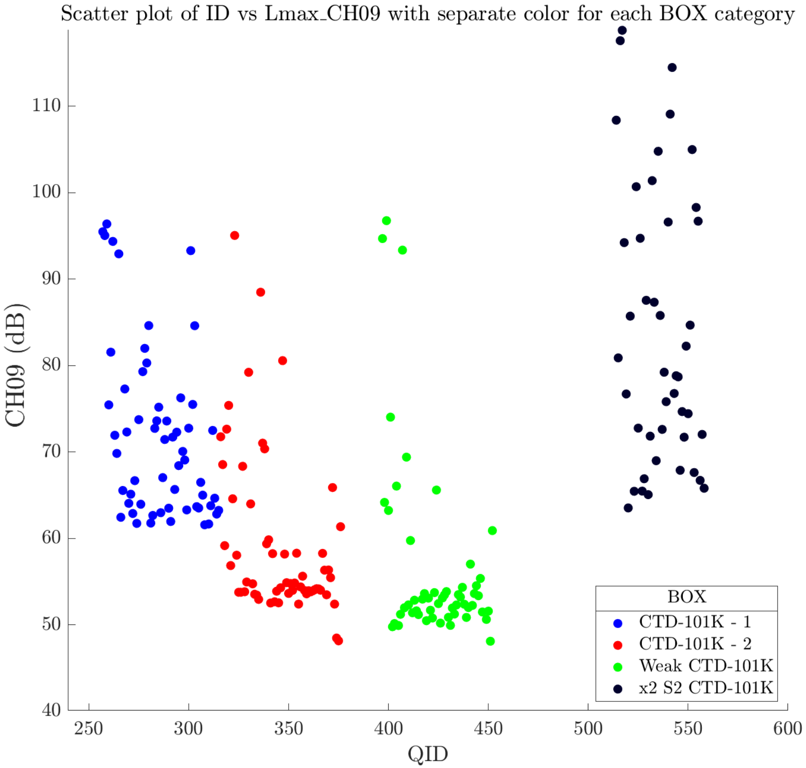
- Earlier events seem more energetic than later events.
- Background noise artificially increases energy levels

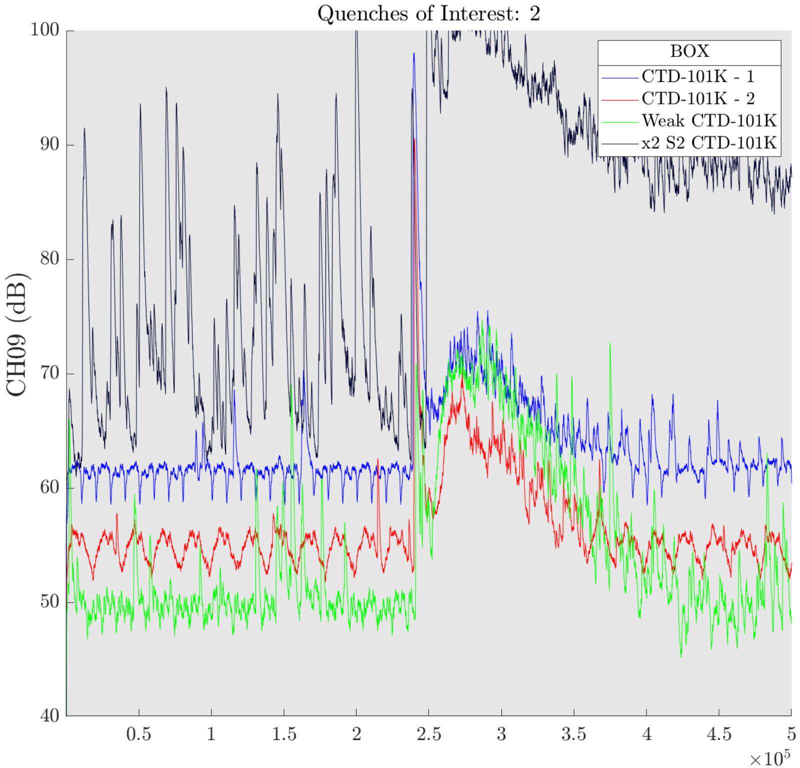




Energy levels Comparisons (1 MHz data)

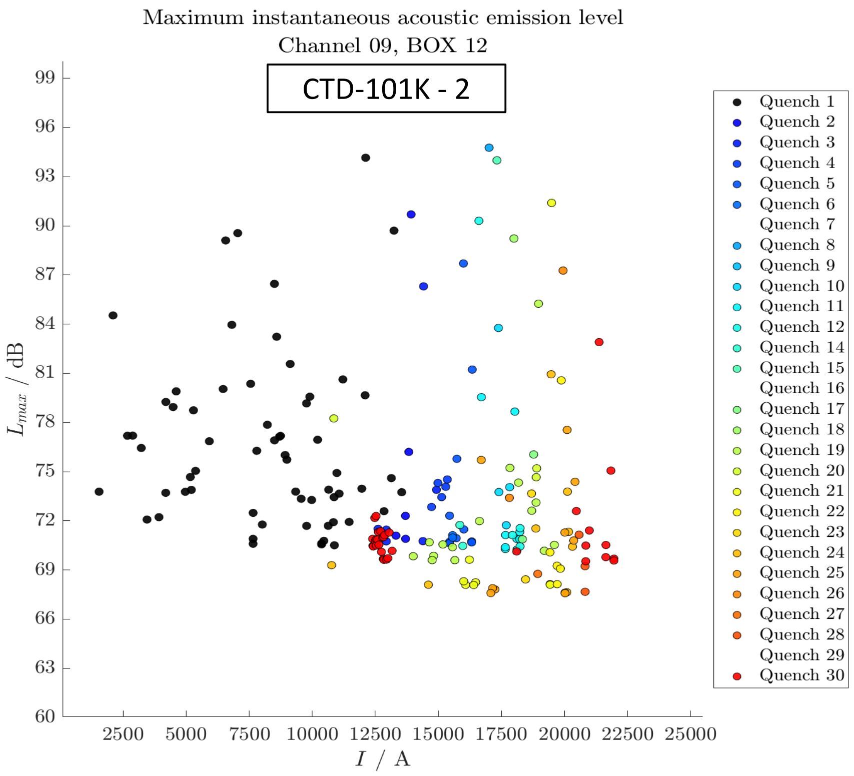
- In some cases, piezo sensors pick up excess background noise (increased sensitivity).
- Filters and offsets cannot always compensate.





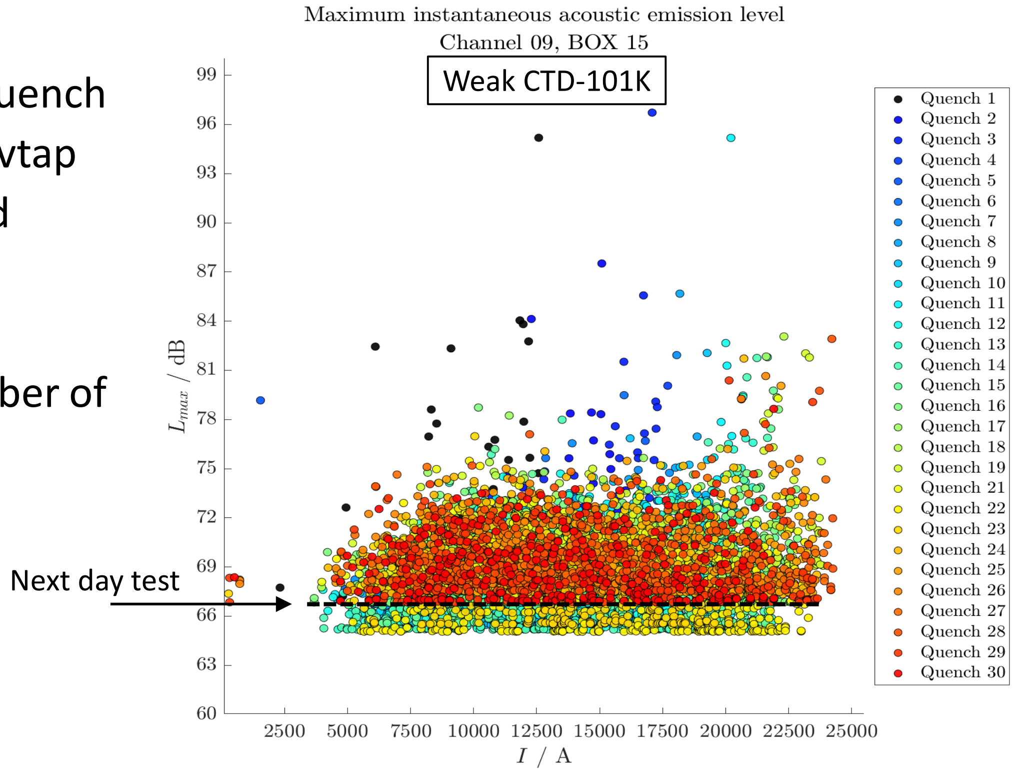
Energy levels Comparisons (100 kHz data)

- Energy levels for 100 kHz:
  – Captures the complete ramp to quench
- Uses a combination of AE data and vtap data to determine T0 of quench and thresholds
  – Threshold is specific to sample
- Scattered Results depend on a number of parameters:
  – Filters
  – Threshold
  – Offset
  – And, piezo sensitivity



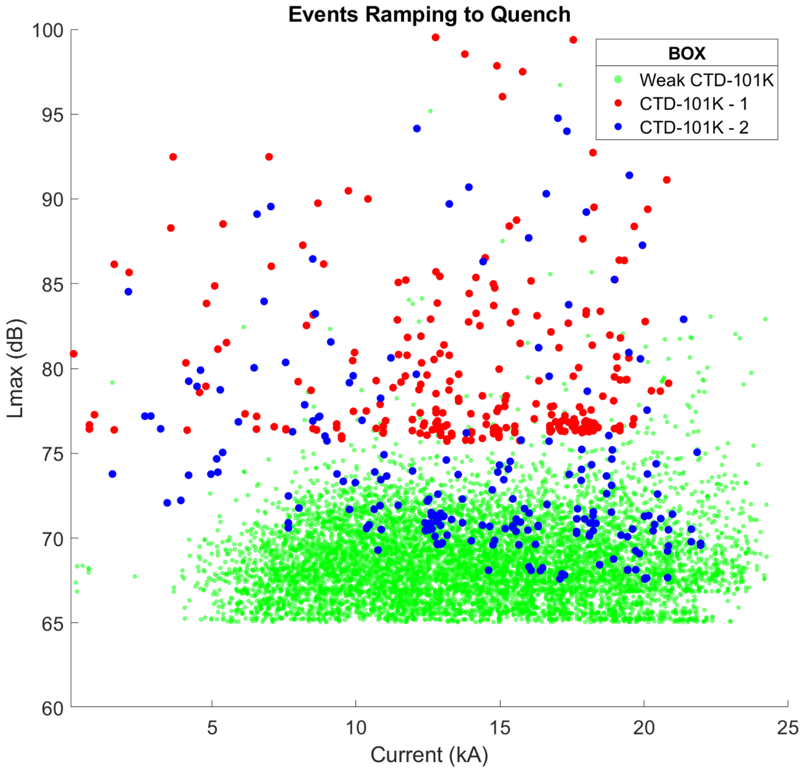
Energy levels Comparisons (100 kHz data)

- Energy levels for 100 kHz:
  - Captures the complete ramp to quench
- Uses a combination of AE data and vtap data to determine T0 of quench and thresholds
  - Threshold is specific to sample
- Scattered Results depend on a number of parameters:
  - Filters
  - Threshold
  - Offset
  - And, piezo sensitivity



Energy levels Comparisons (100 kHz data)

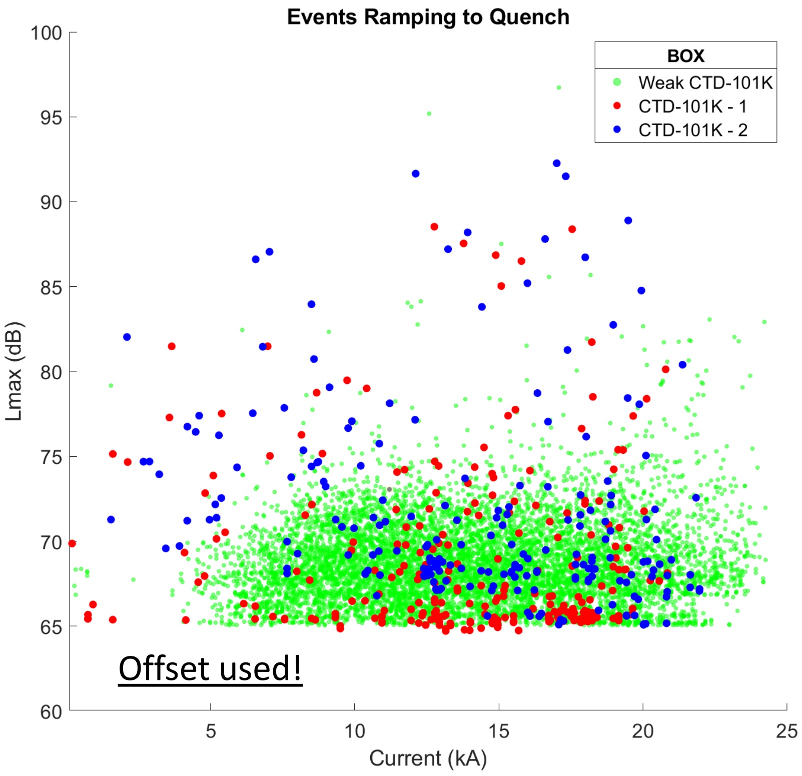
- Energy levels for 100 kHz:
  - Captures the complete ramp to quench
- Uses a combination of AE data and vtap data to determine T0 of quench and thresholds
  - Threshold is specific to sample
- Scattered Results depend on a number of parameters:
  - Filters
  - Threshold
  - Offset
  - And, piezo sensitivity



PAUL SCHERRER INSTITUT PSI

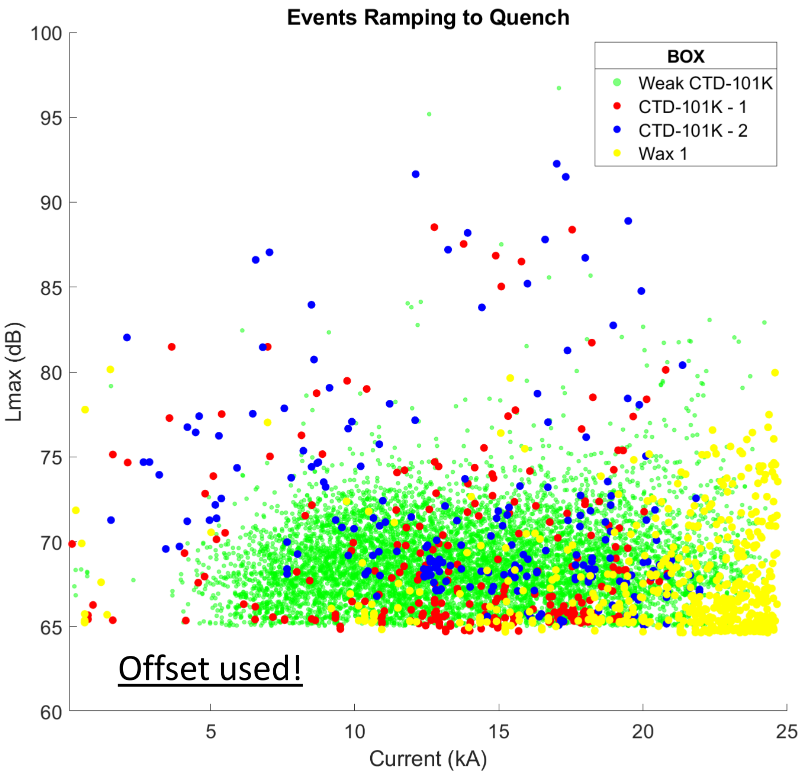
Energy levels Comparisons (100 kHz data)

- Energy levels for 100 kHz:
  - Captures the complete ramp to quench
- Uses a combination of AE data and vtap data to determine T0 of quench and thresholds
  - Threshold is specific to sample
- Scattered Results depend on a number of parameters:
  - Filters
  - Threshold
  - Offset
  - And, piezo sensitivity



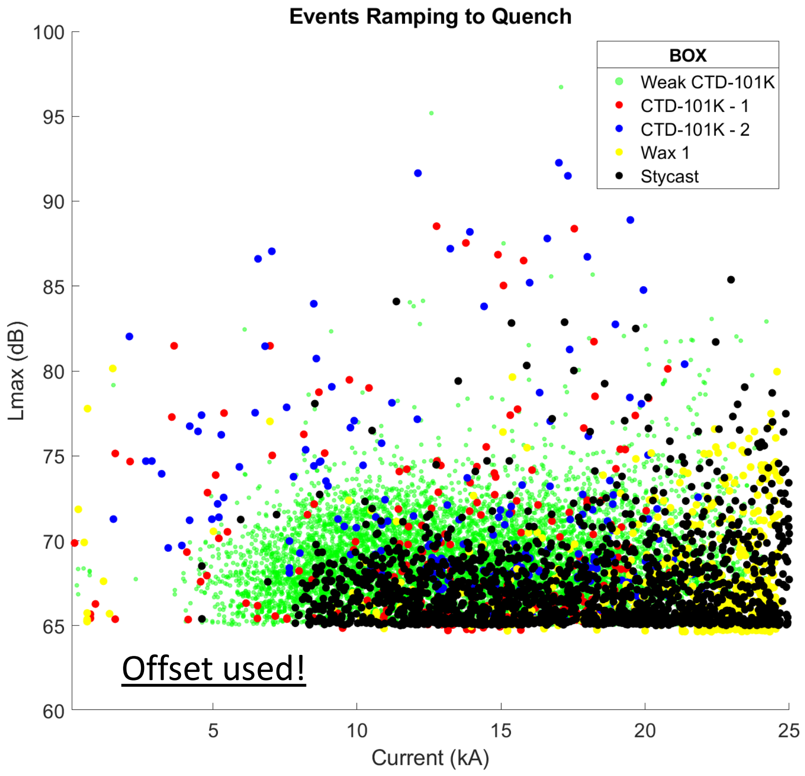
Energy levels Comparisons (100 kHz data)

- Energy levels for 100 kHz:
  - Captures the complete ramp to quench
- Uses a combination of AE data and vtap data to determine T0 of quench and thresholds
  - Threshold is specific to sample
- Scattered Results depend on a number of parameters:
  - Filters
  - Threshold
  - Offset
  - And, piezo sensitivity



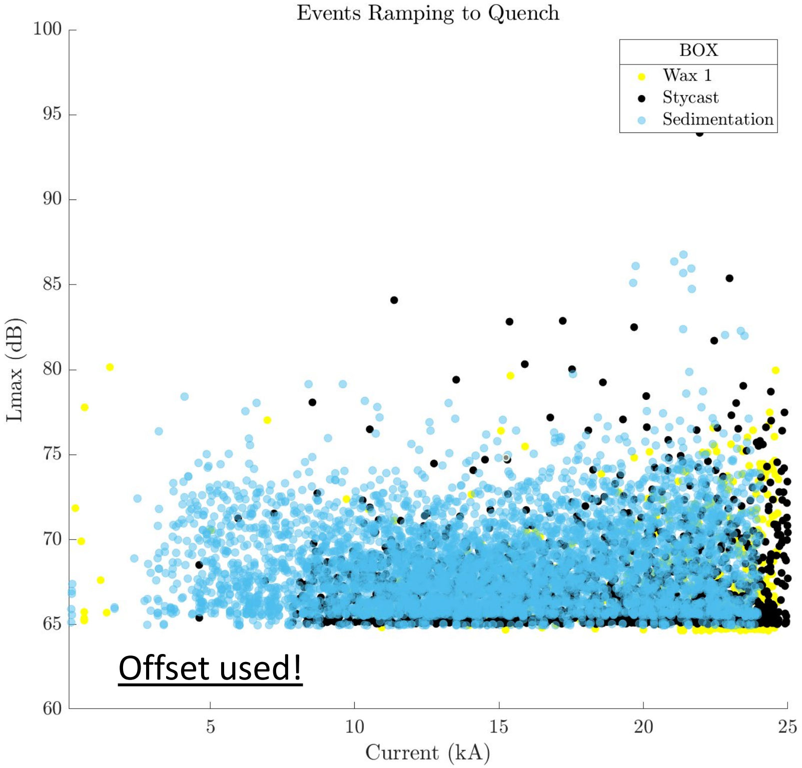
Energy levels Comparisons (100 kHz data)

- Energy levels for 100 kHz:
  - Captures the complete ramp to quench
- Uses a combination of AE data and vtap data to determine T0 of quench and thresholds
  - Threshold is specific to sample
- Scattered Results depend on a number of parameters:
  - Filters
  - Threshold
  - Offset
  - And, piezo sensitivity



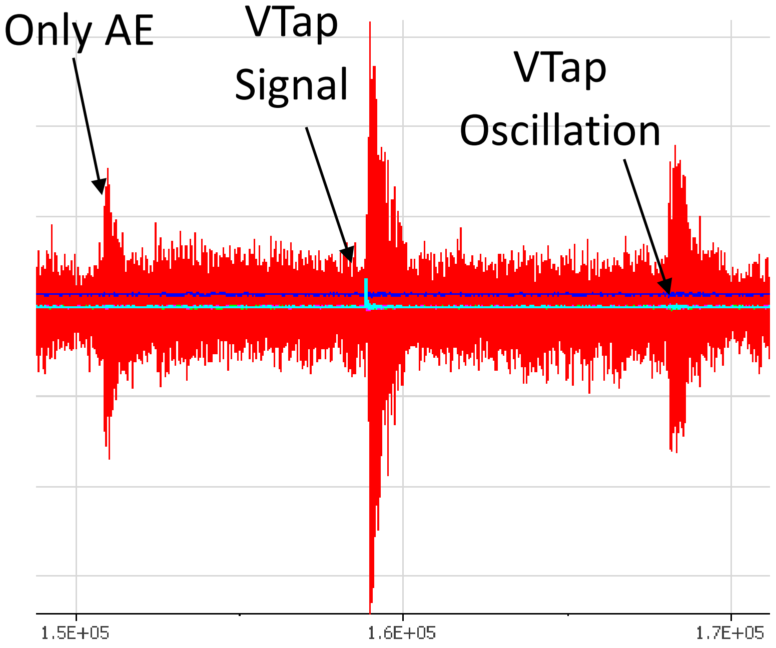
Energy levels Comparisons (100 kHz data)

- Energy levels for 100 kHz:
  – Captures the complete ramp to quench
- Uses a combination of AE data and vtap data to determine T0 of quench and thresholds
  – Threshold is specific to sample
- Scattered Results depend on a number of parameters:
  – Filters
  – Threshold
  – Offset
  – And, piezo sensitivity



Future plans

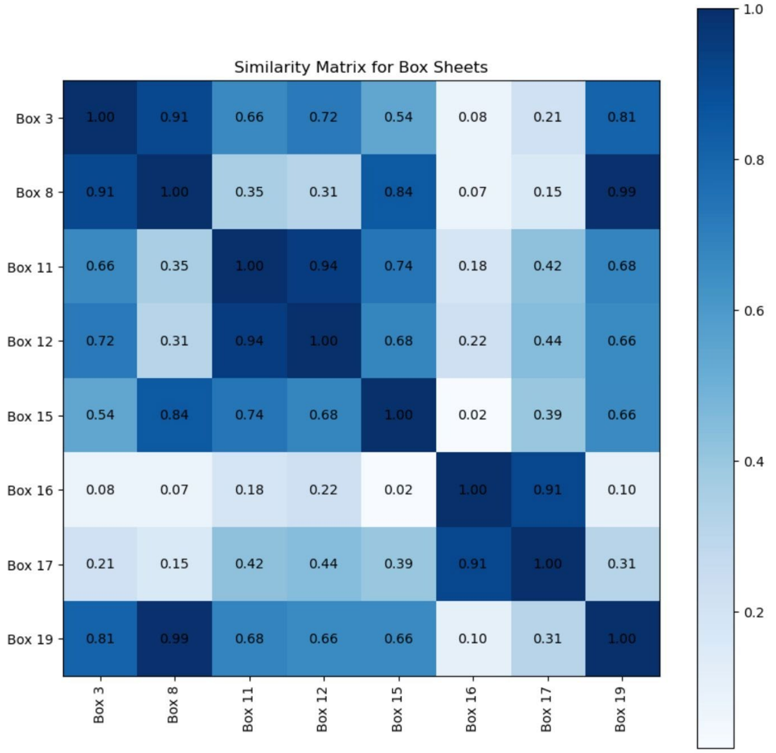
- More refined Analysis (Code improvements)
  - Adaptive thresholds
  - How to use both AE 1 and AE 2 to compensate
- Detection:
  - Do we have vtap signals with AE events?
- Correlate with experimental conditions & material properties:
  - Forces at quenching currents
  - MQE evaluation
  - Observed defects
  - Material Properties (CTE, K_{IC}…)
- Wavelet analysis
  - Early events and precursors
- In-situ calibration with inducers/waveform generator



PAUL SCHERRER INSTITUT

Future plans

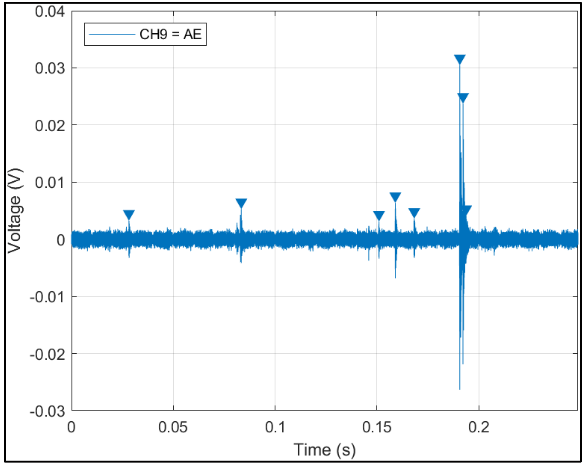
- More refined Analysis (Code improvements)
  - Adaptive thresholds
  - How to use both AE 1 and AE 2 to compensate
- Detection:
  - Do we have vtap signals with AE events?
- Correlate with experimental conditions & material properties:
  - Forces at quenching currents
  - MQE evaluation
  - Observed defects
  - Material Properties (CTE, K_{IC}…)
- Wavelet analysis
  - Early events and precursors
- In-situ calibration with inducers/waveform generator

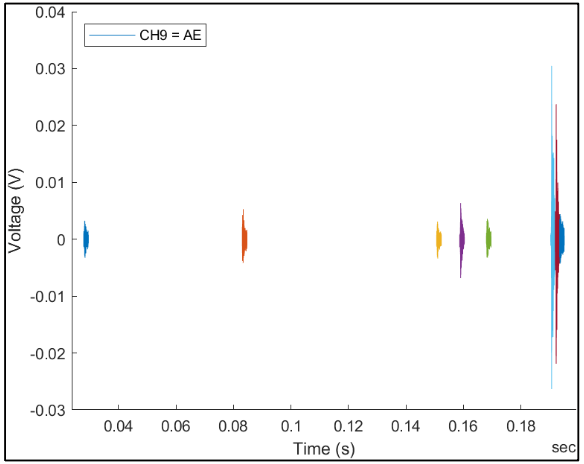


Courtesy of Oliver. Kirby

Future plans

- More refined Analysis (Code improvements)
  - Adaptive thresholds
  - How to use both AE 1 and AE 2 to compensate
- Detection:
  - Do we have vtap signals with AE events?
- Correlate with experimental conditions & material properties:
  - Forces at quenching currents
  - MQE evaluation
  - Observed defects
  - Material Properties (CTE, K_{IC}…)
- Wavelet analysis
  - Early events and precursors
- In-situ calibration with inducers/waveform generator





PAUL SCHERRER INSTITUT

Concluding remarks

- BOX is used to benchmark and assess:
  - Materials (resins, fillers, wax), coatings and processes
- Acoustic Sensors can complement diagnostics and analysis of samples
  - Energy levels:
    - ➢ Some Quenches show clear precursors
  - Noise of samples
    - ➢ Some indication that noise levels and quantity of events correlate to performance of BOXs
- Some correlation possible with post-mortem analysis and material properties.
- Nevertheless, further work required to better differentiate between acoustic phenomenons (normalising, offsets thresholding).

- **PSI Team:**

Michael Daly, Bernhard Auchmann, André Brem, Christoph Hug, Serguei Sidorov

- **UTwente Team:**

Anna Kario, Simon Otten, Herman Ten Kate, Marc Dhallé

- **EMPA Acoustic Analysis Support:**

Axel Heussel, Reto Pieren