# Predicting the behavior of insulated REBCO coils up to their operation limit to identify safe operation domain

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# Outline

- Motivation
- Thermal runaway modelling
  - Agreement with experiment data
  - Influence of defect size
- Transient effects on coil voltage
- Practical protection implantation :
  Case of 20 Pancake insert @ HFLSM, Tohoku

# REBCO HTS coils have large margin : why study “quench” ?

**Example : Ongoing 33 T REBCO insert design @ HFLSM, Tohoku Univ.**

- Nominal field reached at :
  **278, 358 and 438 A**
  using different conductor options

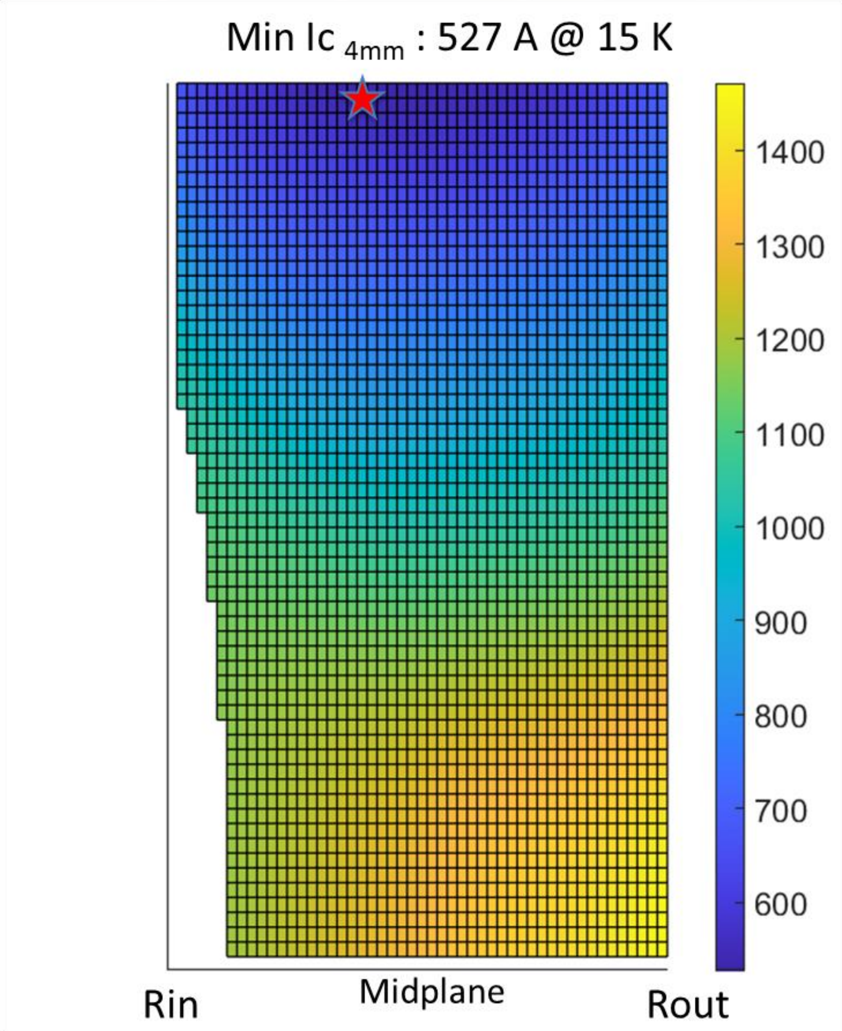
- Margin estimation based on short sample data for Fujikura tape. Operation at

  **26 %, 34 %, and 42 % of Ic** respectively

  At 15 K !

**Robustness against defect : 2 tape co-wound for redundancy**

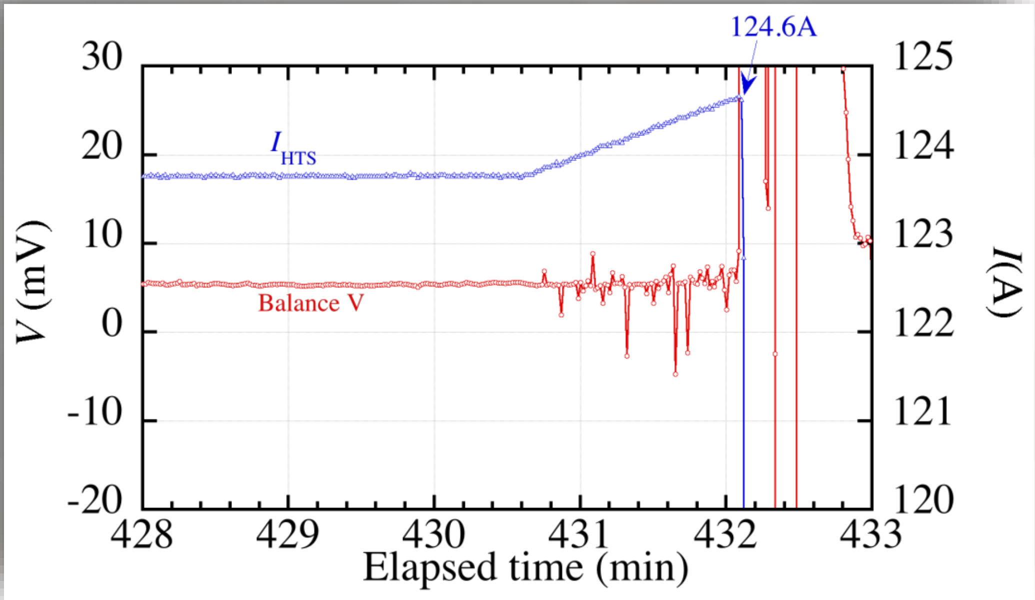
⇒ A local loss of critical current on 1 tape is “acceptable” for all cases at 15 K




Badel 2024, doi: 10.1109/TASC.2024.3367620

# REBCO HTS coils have large margin : why study “quench” ?

- **In Sendai, 25 T CSM installed in 2015** but failure of 1st REBCO insert




Failure occurred at 86 % of $I_{nom}$

but less than 30 % of Ic

- Why only 30 % of Ic ?
- The damage occurred 6 s after quench detection : why that long ?
- Could it be seen in advance ?

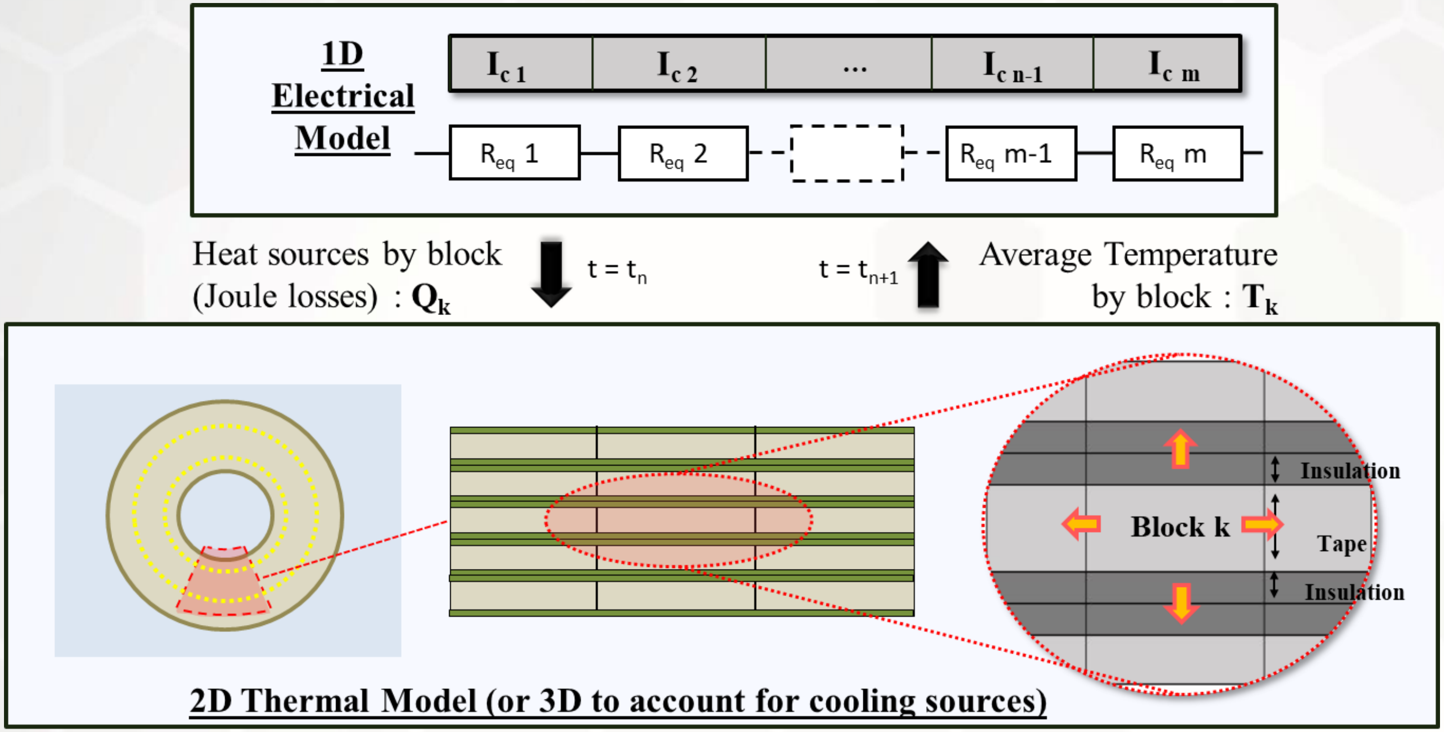
$\Rightarrow$ **Need for understanding / modelling !**

# Thermal runaway : Modelling for REBCO HTS Magnets

Understand local phenomena coming from statistical distribution

⇒ **FAST** modelling to study **many scenarios of possible inhomogeneity distribution**

⇒ Simplify to thermo – electrical model only




Badel 2019 *SuST: DOI* 10.1088/1361-6668/ab181f

# Thermal runaway : Modelling for REBCO HTS Magnets

- Include  the system point of view :
  - If an LTS outsert exist, REBCO insert discharge speed is constrained !
  - ⇒ No energy should be transferred from HTS to LTS
  - Local dissipation in REBCO insert negligible compared to dump resistor
  - ⇒ Discharge profile defined by Voltage considerations, LTS quench dynamics, LTS/HTS coupling…

- Knowing the current discharge profile:

  **Simulation of local thermal runaway with various hypothesis**

  - « Usual » statistical distribution of local critical current: unavoidable
  - Local sharp defect (delamination, winding damage…):

  **BUT how severe a defect should we « cover » ?**

- Detailed thermo-electric analysis… of where ?

  **Min Ic zone derived from margin estimation work**

# REBCO (isolated) magnet : Thermal runaway modelling

**"Final" study of 25 T CSM**
**(the one that burned)**
**w/ single 2 cm defect**

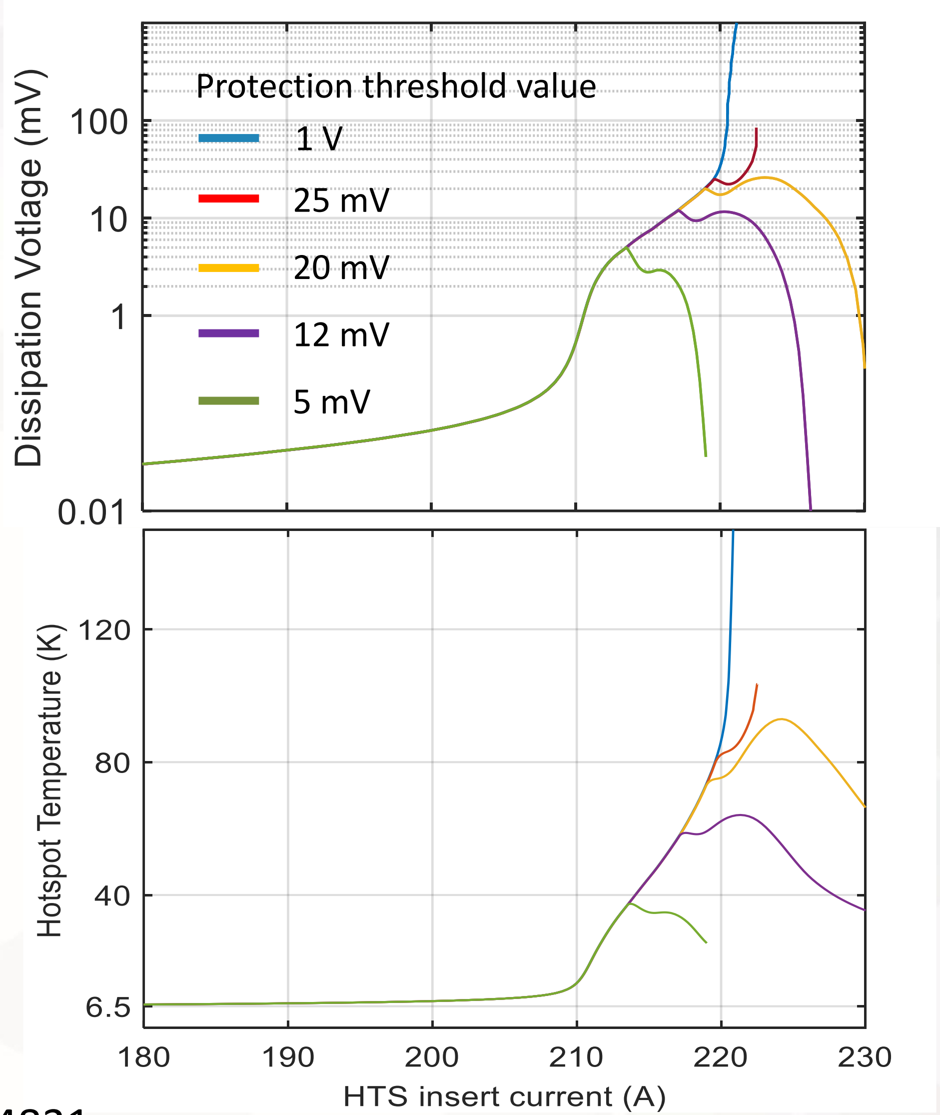
- Threshold set at 1V (experiment)

Thermal runaway takes several seconds

- If < 10 mV several seconds of reaction time are acceptable

⇒ **Move on to next magnets with "Early detection/protection concept"**

*For 33 T project @HFLSM*
*For standalone solenoids and*
*large splits in Grenoble*




Badel 2019 doi: 10.1109/TASC.2019.2894831

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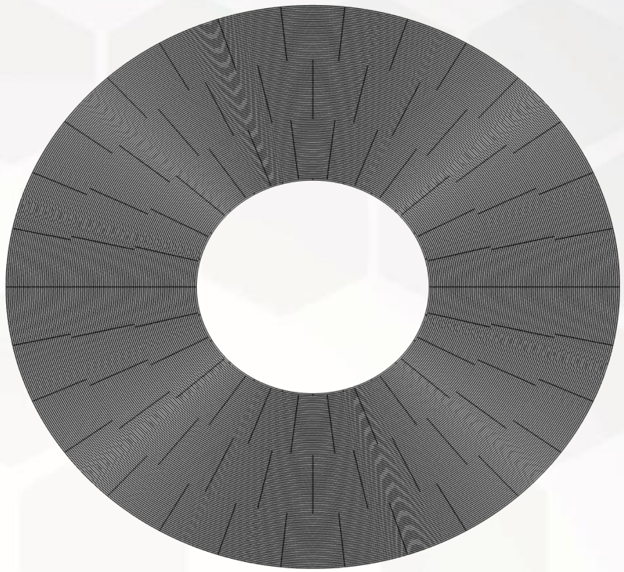
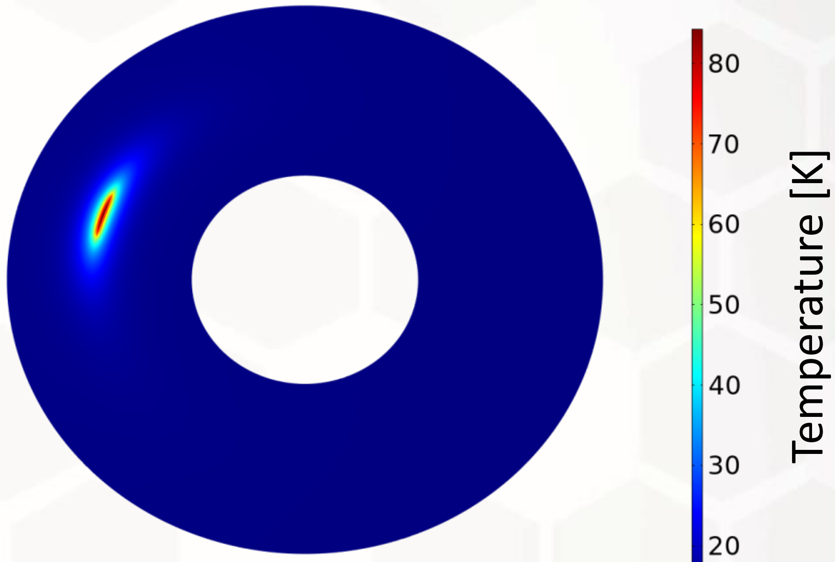




# Thermal runaway detection : influence of current density

## Study for REBCO insert of 33 T magnet project @ HLFSM

Assumption : 50 % Ic reduction over 1.6 cm

- Operation at 278 A (w/o reinforcement)

⇒ Jtape = 230 A / mm²

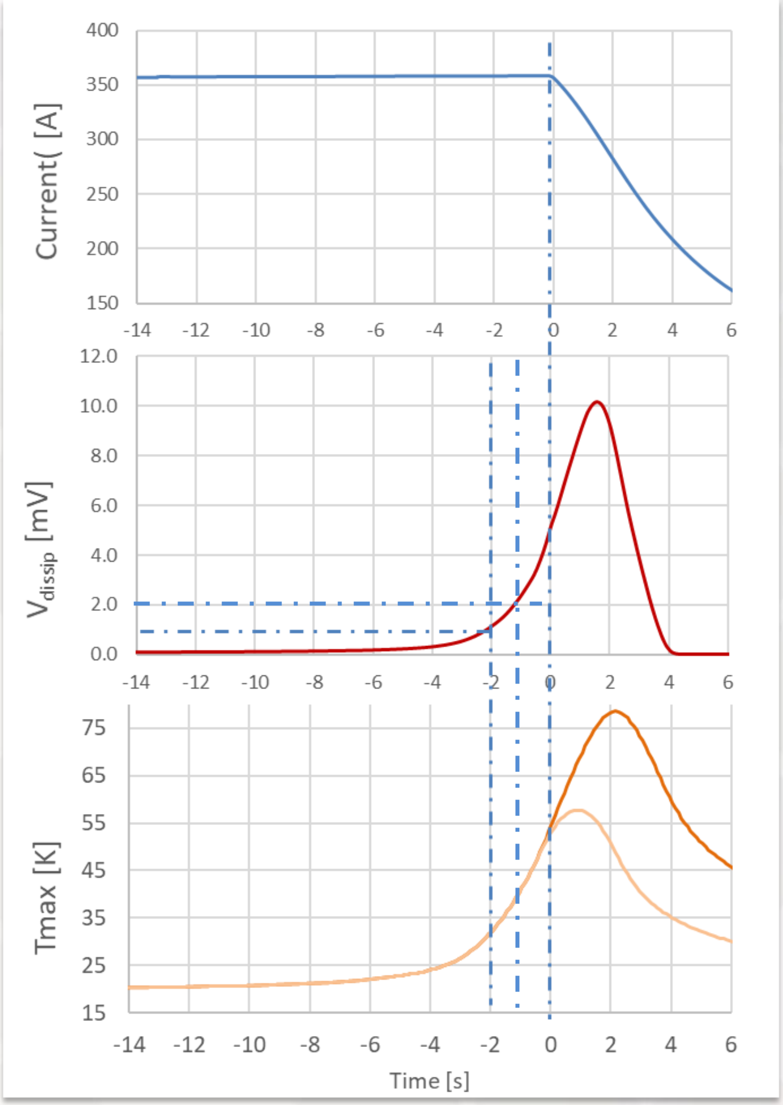
**1s delay achieved with 8 mV threshold**

- Operation at 358 A (0.1 thick reinforcement)

⇒ Jtape = 290 A / mm²

**1 s delay achieved with 2 mV threshold**

**Sensitive thermal runaway detection still feasible**



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⇒ Jtape = 290 A / mm²

**1 s delay achieved with 2 mV threshold**

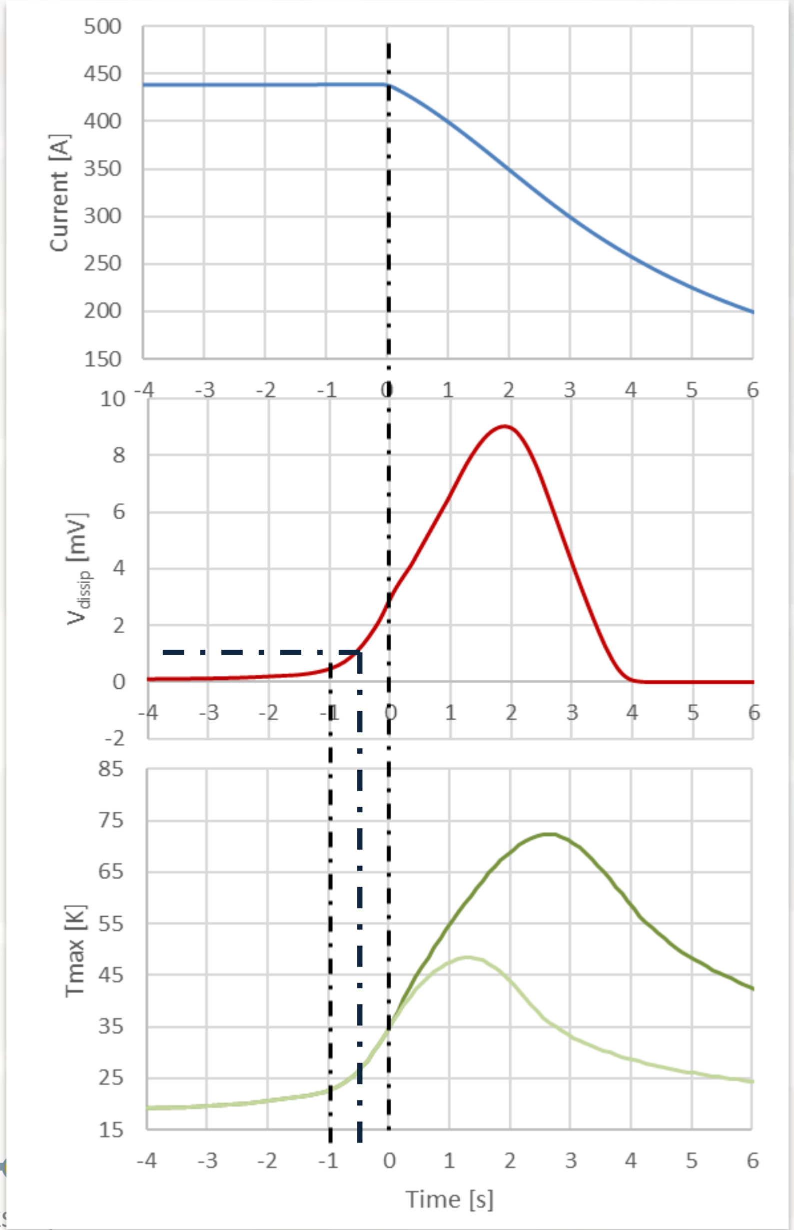
**Sensitive thermal runaway detection still feasible**

- Operation at 438 A (0.2 thick reinforcement)

⇒ Jtape = 356 A / mm²

**1 s delay achieved with 0.5 mV threshold,**
**0.55 s with 1 mV threshold**
**0.2 s with 2 mV threshold**

Very demanding target



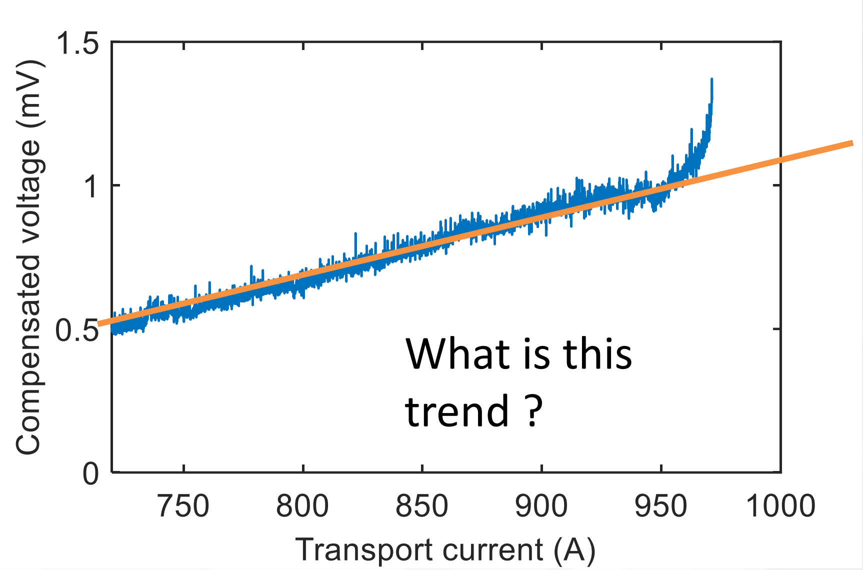

Badel 2024, doi: 10.1109/TASC.2024.3367620

# Early detection: Experimental cases

- On SMES pancake @ 4.2 K

under 900 A/mm²

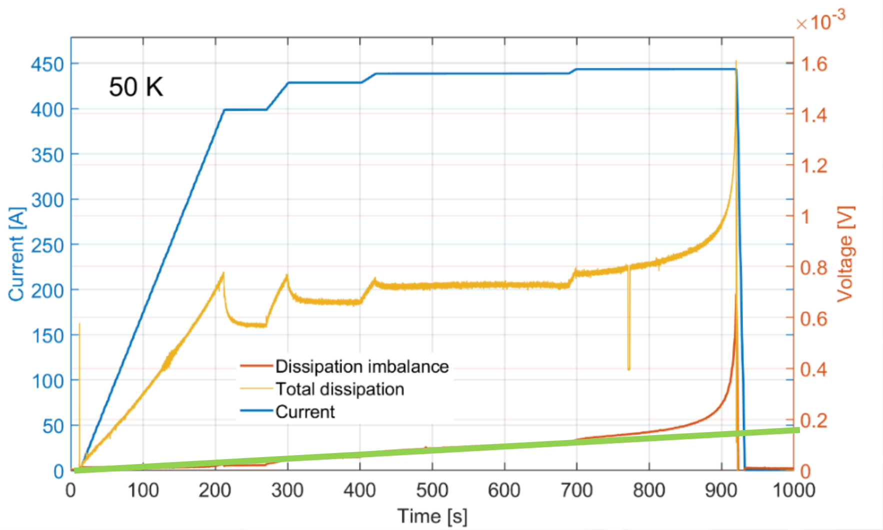
On very slow ramp (0.2 A/s),
clear change of trend over 10 s +




- On Fujikura pancake @ 30 – 77 K

**Under 500 A/mm², with**
**50 % Ic local degradation on 1 cm**
**(artificially added)**

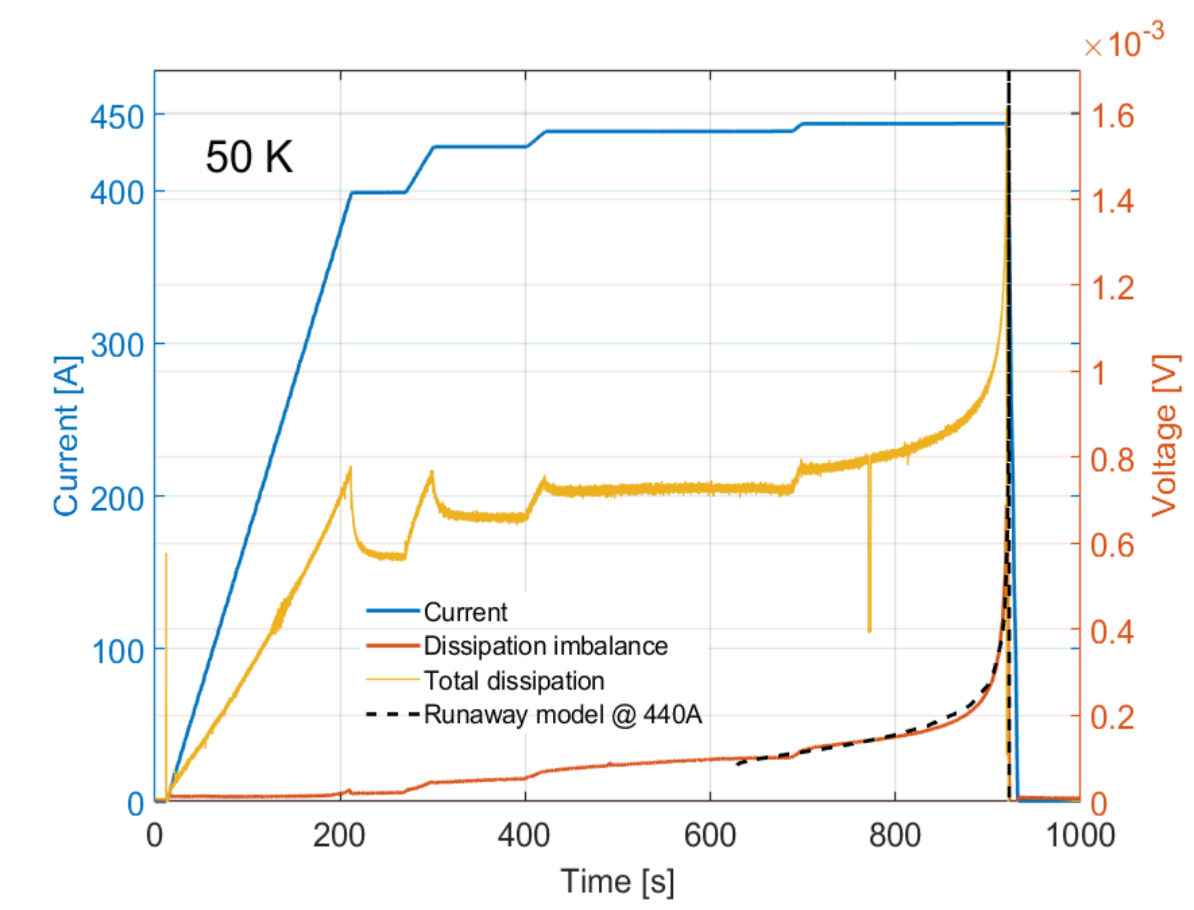
- – Thermal balance is possible around a defect above Ic
- – Loss of balance clearly visible




Abe 2022, DOI : 10.1109/TASC.2022.3163690

# Modelling agreement

- Only one case available with known defect and controlled conditions : very weak conduction cooling power = close to adiabatic simulation




The dynamic at the **onset of thermal runaway** is well represented

# Influence of defect size

33T insert scenario (see above)

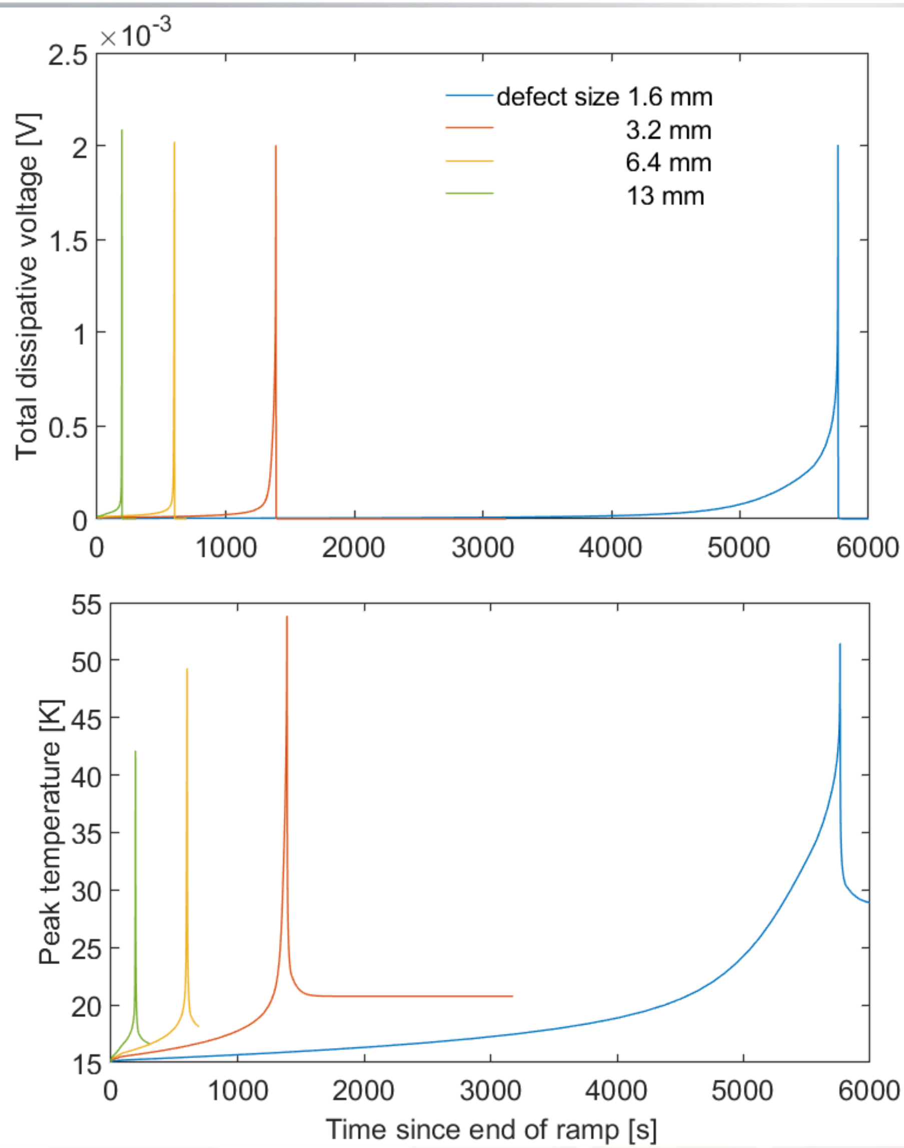
- Single 1.6 cm defect at 50 % I
- Discharge when Voltage reaches 2 mV

What if the defect is smaller ?

⇒ Study at constant current 350 A

- The thermal runaway appears very late, even in adiabatic case
- Tmax increase a bit, then saturates

- Harder to protect ?



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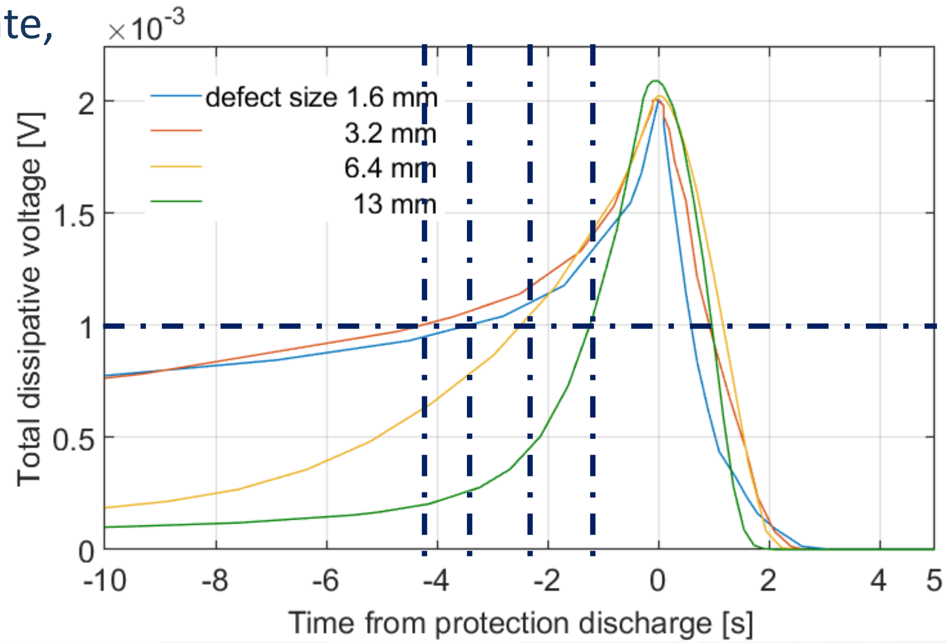
Not really !

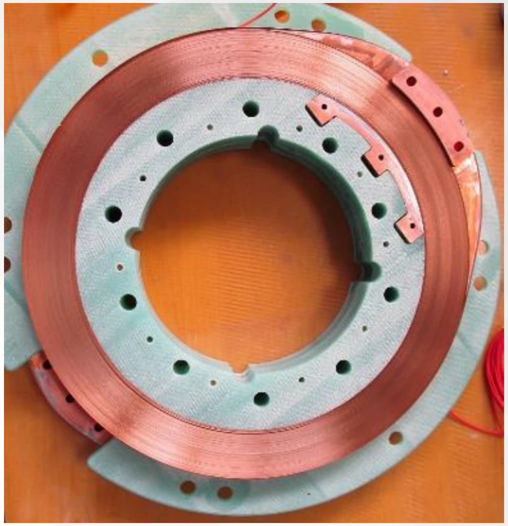


# Observed voltage transient behavior

- 2D Axisymmetrical model, thin sheet hypothesis
- Integral method : mesh only active regions
- E(J) relationship : power law with Jc(B,Theta,T)
- External field due to outsert and /or other coil elements applied as source term
- Circuit solver => the coil voltage is an output

cf A. Zampa's Poster yesterday

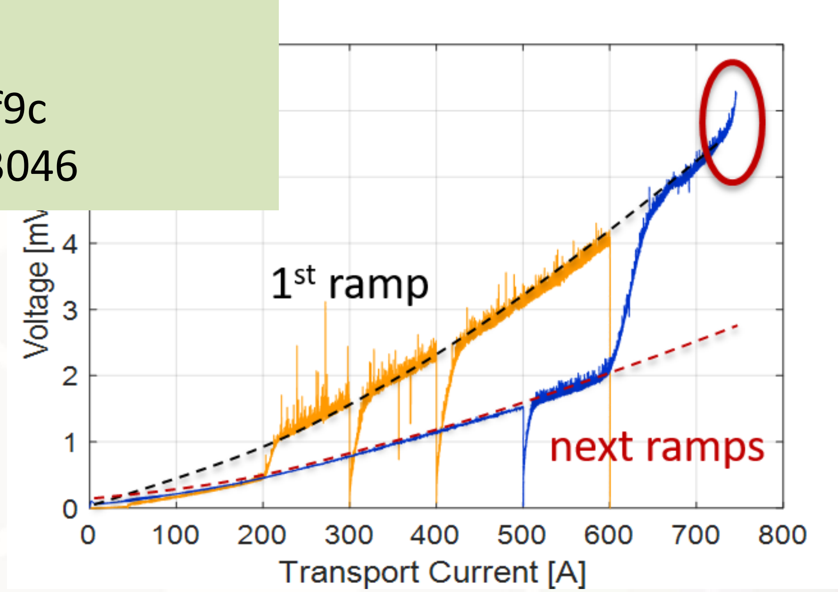
Rozier 2019 SuST: DOI 10.1088/1361-6668/aaff9c
Rozier 2019 TAS: DOI 10.1109/TASC.2019.2903046



higher in magnitude
than detection threshold !

⇒ detect **change of trend**

⇒ **predict trend** with transient EM model
for us: **G2Elab integral method approach**

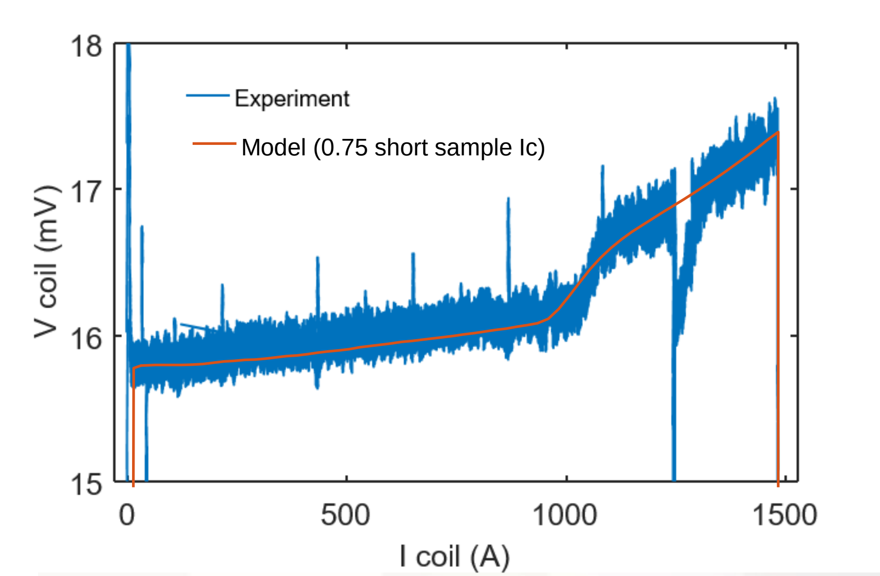


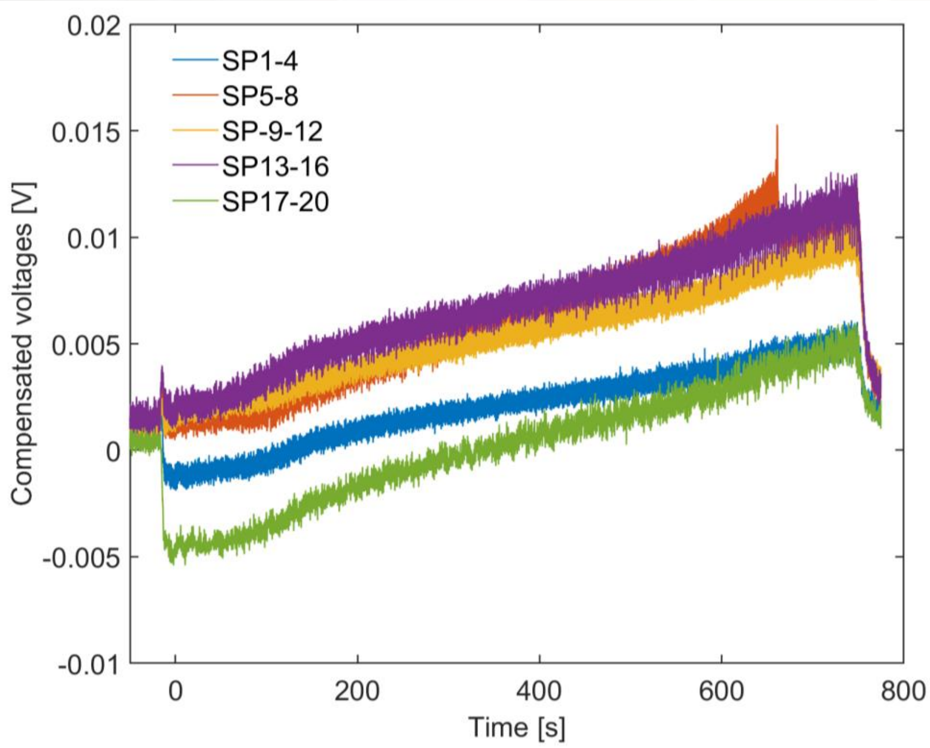
# Transient voltage trend in REBCO coils

- On prototype pancake @ 4 K

We can predict "history" influence in measured voltage

- **What about much larger coils ?**




Case of 20 Pancake coil @ 4 K
(Half size prototype of 33 T insert)

**Transient voltage amplitude is challenging for thermal runaway detection**

# Sensitive detection: application to practical full size coil

| REBCO prototype insert: Characteristics | |
|---|---|
| REBCO Tape | 4 mm Fujikura |
| Tape thickness | 0.15 mm |
| **Number of tapes per turn** | 2 (Face-to-back) |
| **Number of turns per pancake** | 271-294 |
| **Inner diameter** | 68 mm |
| **Outer Diameter** | 266 mm |
| **Number of pancakes** | 20 |
| **Self-Inductance** | 2.63 H |
| **Nominal Current** | 300 A |
| **Nominal Axial Magnetic Field** | 11 T |

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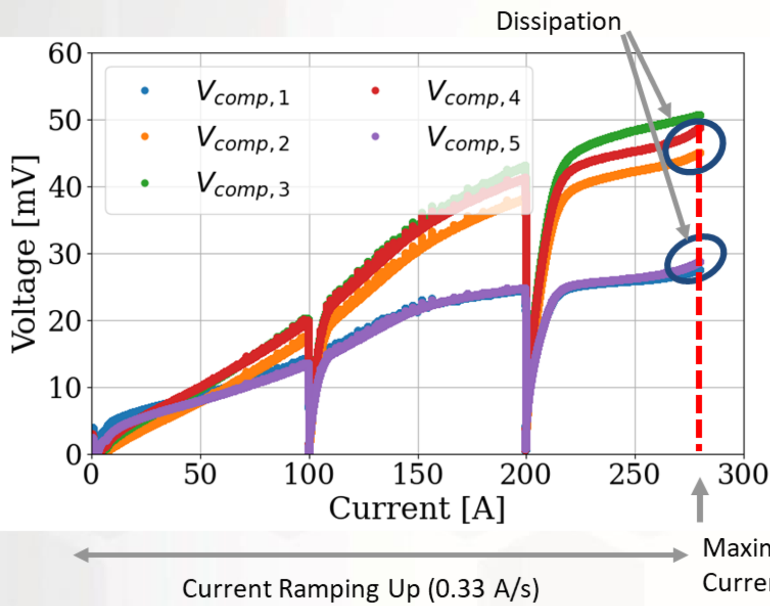
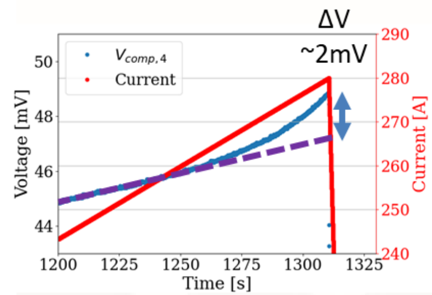
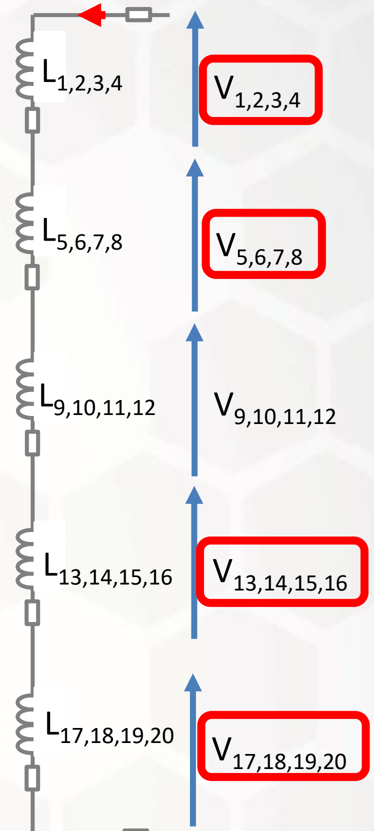
$$V_{comp}(t) = V_{losses}(t) + \boldsymbol{V_{dissip\ sc}(t)}$$




Limits reached safely dozens of time @ various Temp. and $J_{eng}$ up to 250 A/mm²



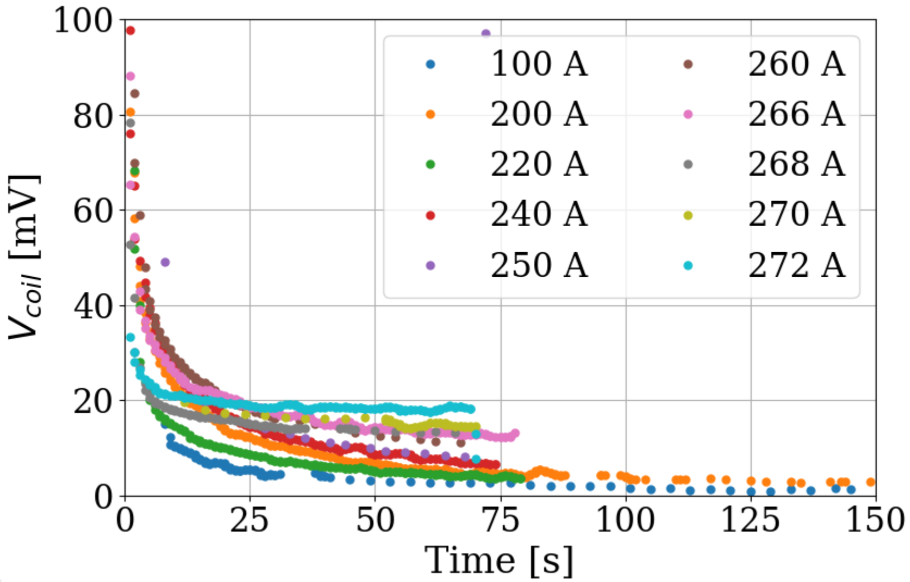

Zampa 2024 @ MT 28

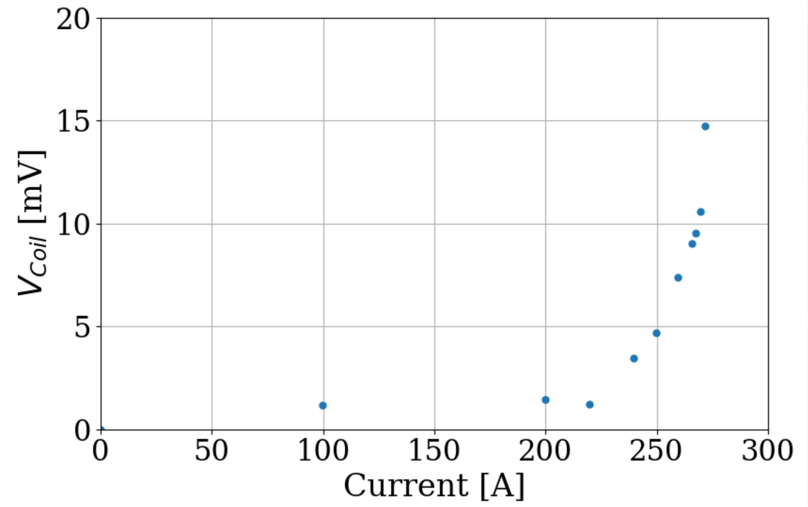


# Practical full size coil : What if there is no defect ?

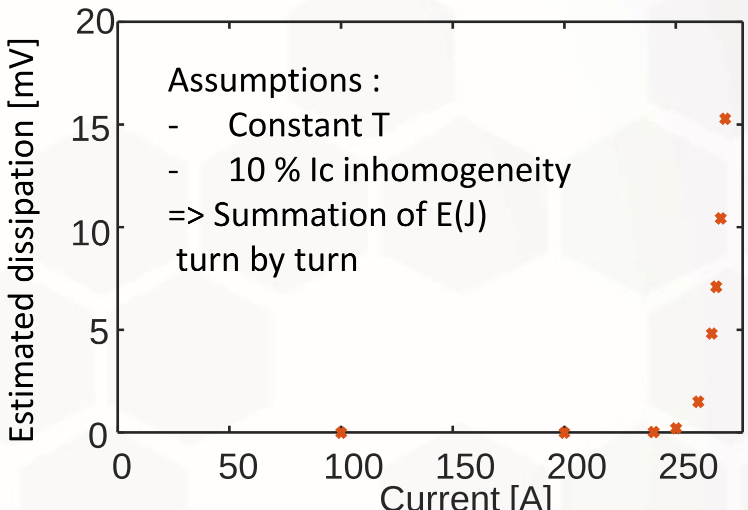
- Dissipation measured on plateau to reduced transient component @ 47 K

$$V_{coil}(t) = V_{joints} + V_{losses,transient}(t) + \boldsymbol{V_{dissip,sc}(t)}$$




Stable operation in dissipation (at least for the time of observation)

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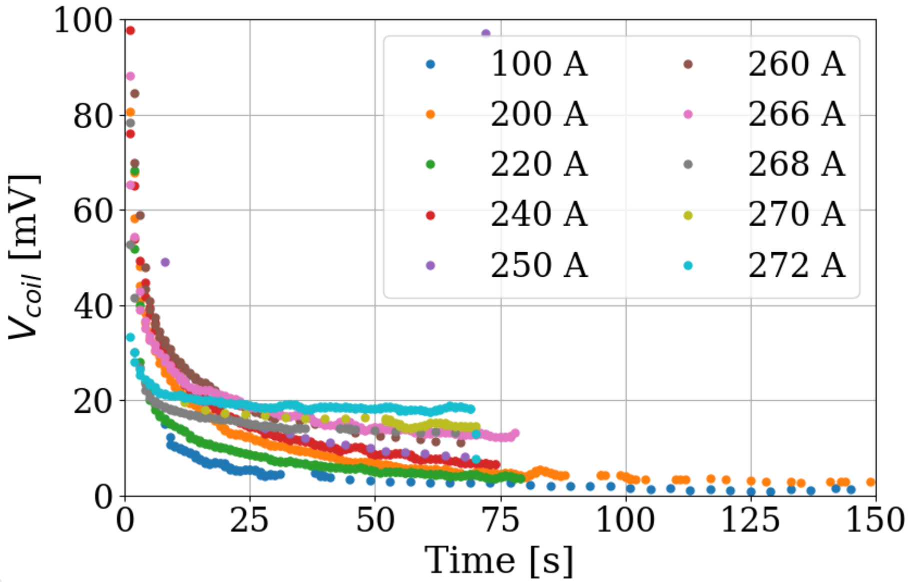


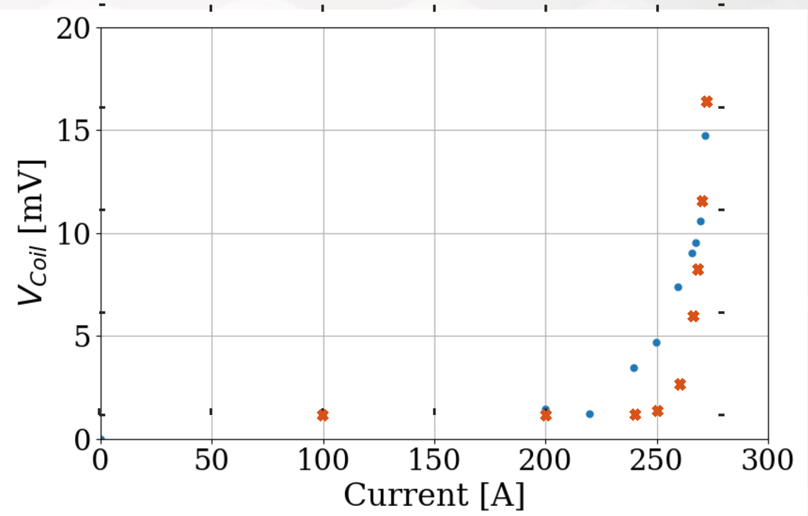


Stable operation in dissipation (at least for the time of observation)

Assumptions :
- Constant T
- 10 % Ic inhomogeneity

=> Summation of E(J) turn by turn

## Summary

- Thermal runaway study showed that isolated REBCO magnet can be protected … How to make it happen ?
  - Threshold on dissipation voltage
  - Trend of Transient voltage : analysis and prediction
  - Many pancake tests to accumulate experience

- Even coils with "obvious defect" can operate : what should be the limit ?

No need to protect a magnet that is not working !

- Gradually the size of REBCO windings increase, next step is multi-tape conductors ?
  - Model requirements are more severe (3D unavoidable)
  - Multiscale is also required
  - How to validate the concepts ? Need for "realistic" modelling benchmarks

Thanks !