# The margin of safety of quench protection of high temperature superconducting magnets

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**With inputs from Dan Wang and Xiaorong Wang**

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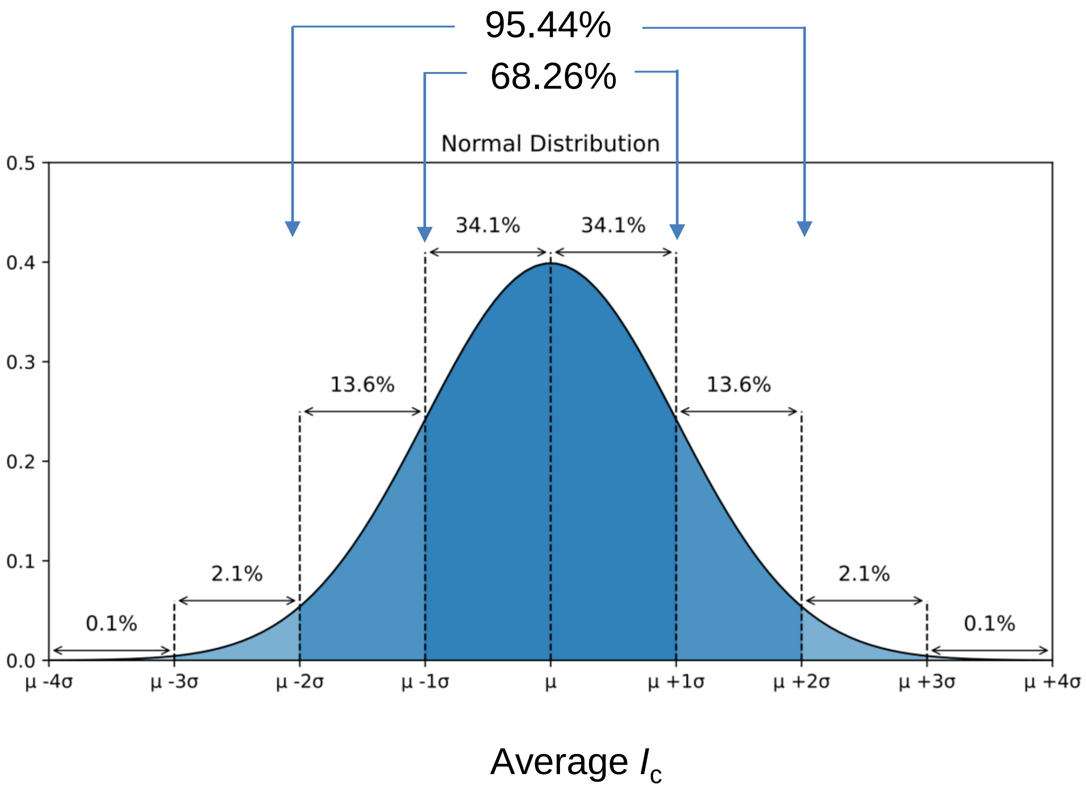
We thank our colleagues at LBNL and collaborators at the National High Magnetic Field Lab who help construct magnets used in this study, in particularly Daniel Davis and Laura Garcia Fajardo.

# Where do your superconducting magnets quench?

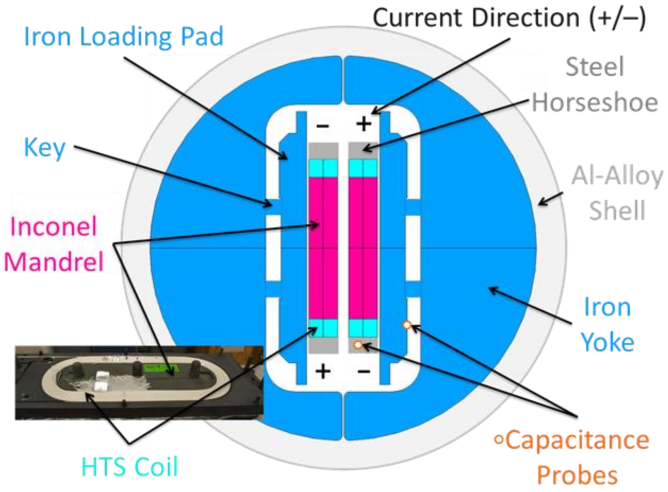
**Normal distribution of superconductor $I_c$.**



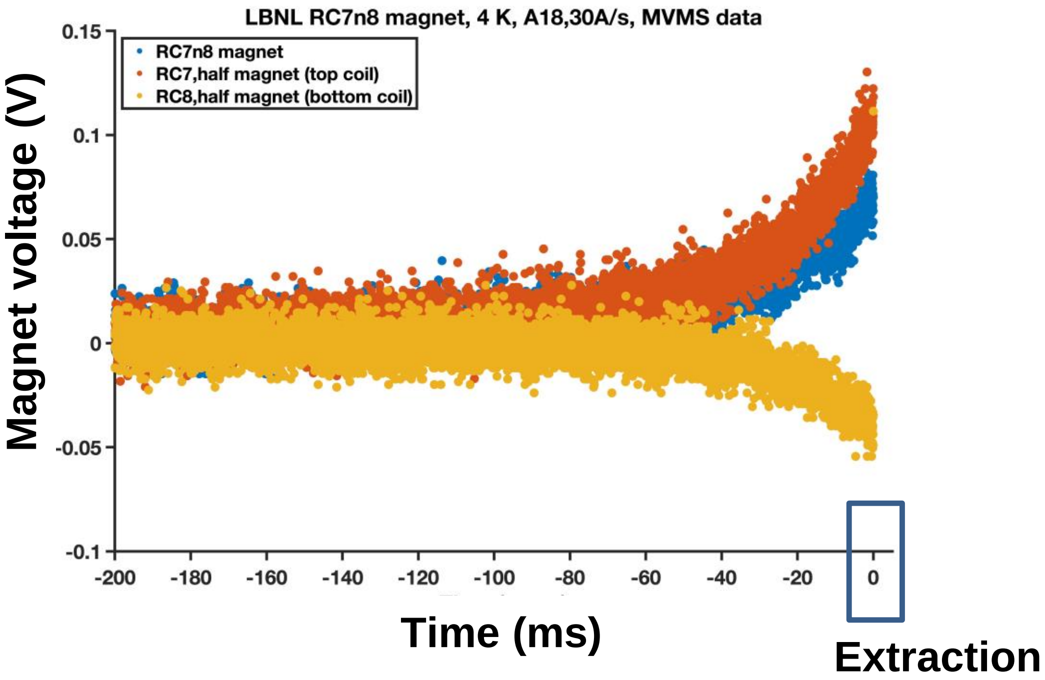
# Two magnets, their quench protection, what is the margin of safety for them, how to further improve?

- **Known and existing: cRIO + FPGA/PXI, LBNL MTF developed for LTS magnets**

**RC7n8 is a common-coil HTS (Bi-2212) dipole magnet**
**I = 5700 A, 4.7 T**



(Graph by Daniel Davis)

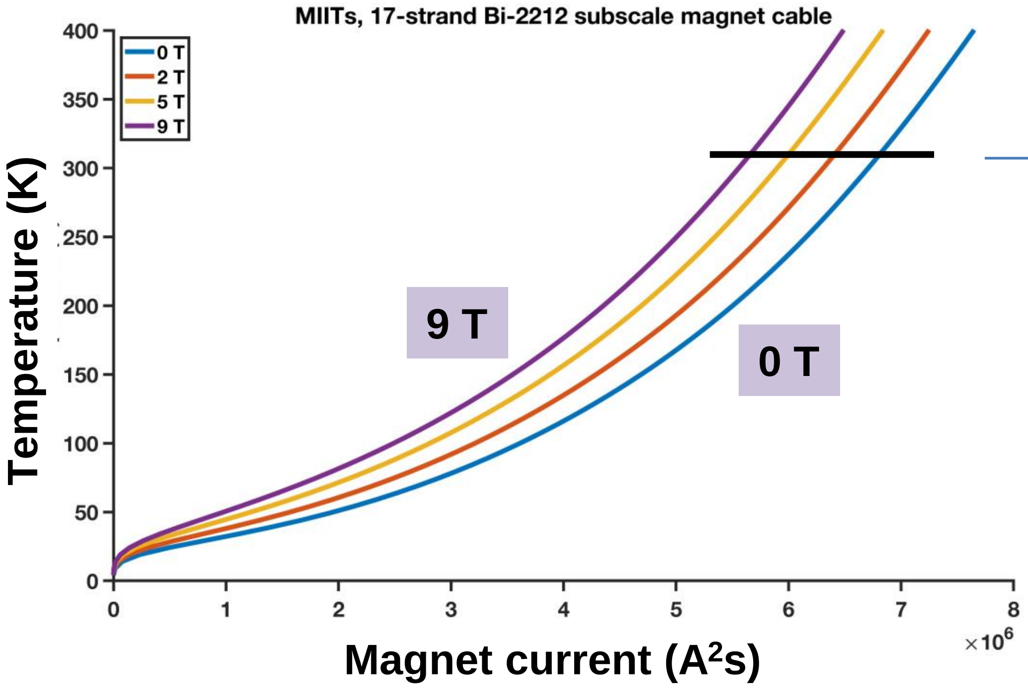


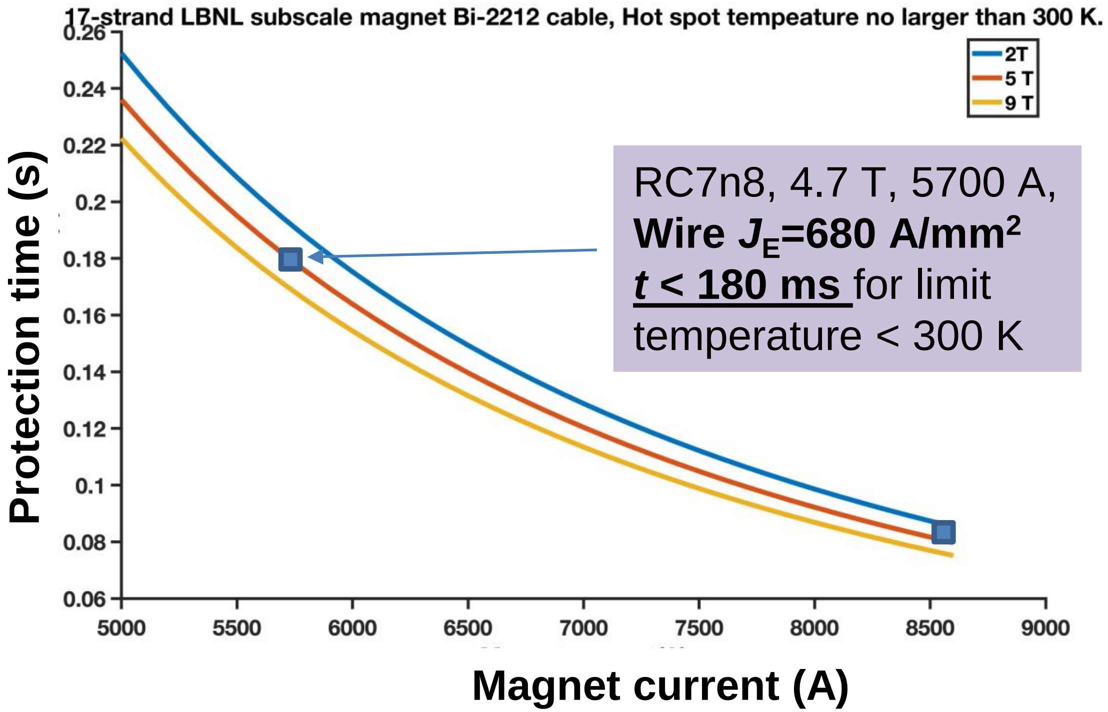
**BIN5c1 is a canted-cosine-theta HTS (Bi-2212) dipole magnet.**
**I = 3600 A, 1.64 T, 3**

(Graph by Ray Hafalia)

- **RMS noises in $10^{-2}$ V.**
- **Quench detection at 50 – 100 mV.**

# Quench protection and the MIITS method for estimating the margin of safety, applied as if it was a LTS magnet





RC7n8, 4.7 T, 5700 A,
**Wire $J_E$=680 A/mm$^2$**
***t* < 180 ms** for limit
temperature < 300 K

**Heat balance in a unit volume**

$$J_m^2\rho(T)dt = C(T)dT$$

$$\int_0^\infty J_m^2(t)dt = \int_{T_0}^{T_{max}} \frac{C(\theta)}{\rho(\theta)}d\theta$$

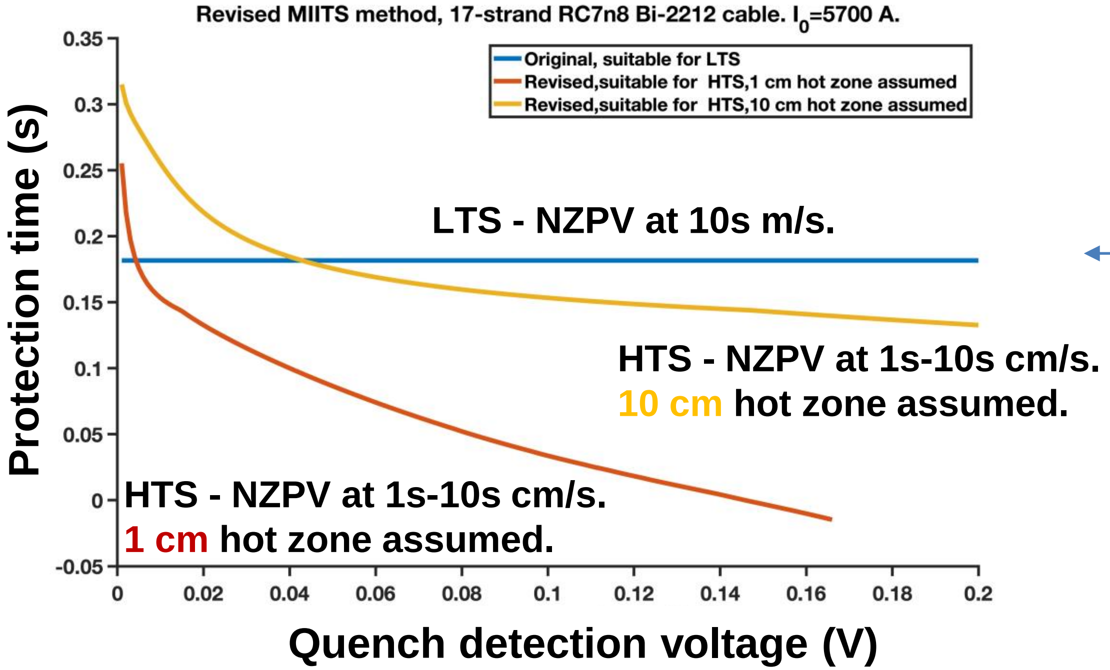
$$T_{max} \propto MIITS = \int I_{mag}^2(t)dt$$

Manuscript in preparation.

# A revised MIITS method for HTS magnets and implications

**Revised** $MIITS = \int((I_{mag}(t) - I_c(t))^2\,dt + MIITS(t = t_D, T = T_D).$

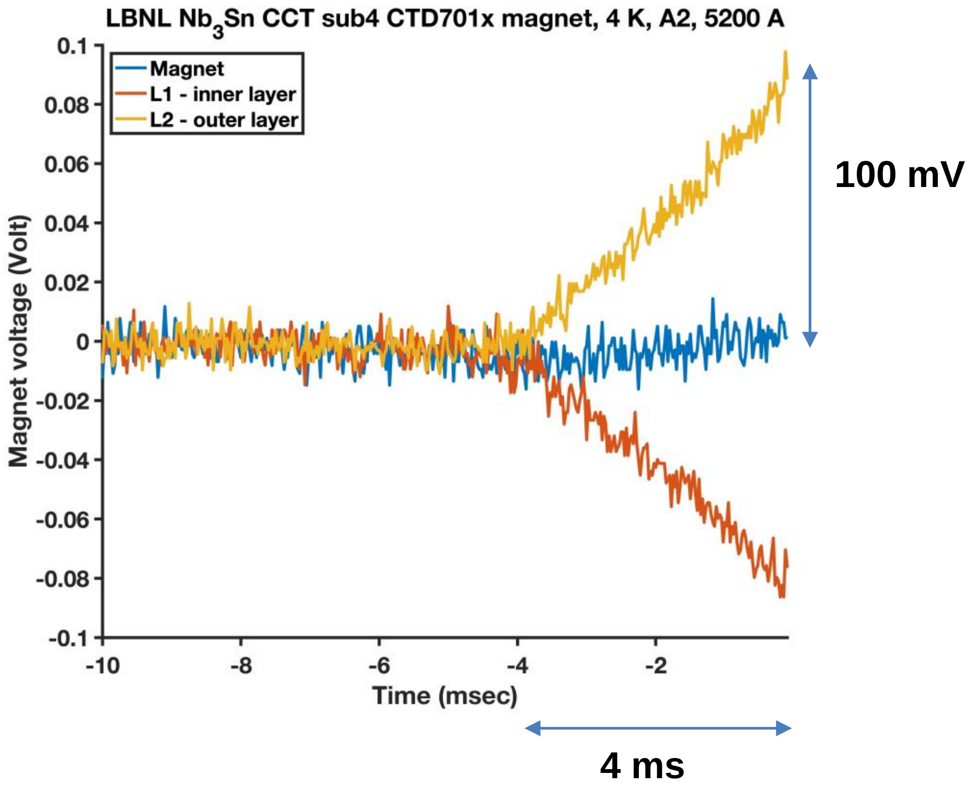
**Use Revised MIITS to find $T_{max}$ from T(MIITS) plot.**



**LTS - NZPV at 10s m/s.**

**HTS - NZPV at 1s-10s cm/s.**
**10 cm hot zone assumed.**

**HTS - NZPV at 1s-10s cm/s.**
**1 cm hot zone assumed.**



**100 mV**

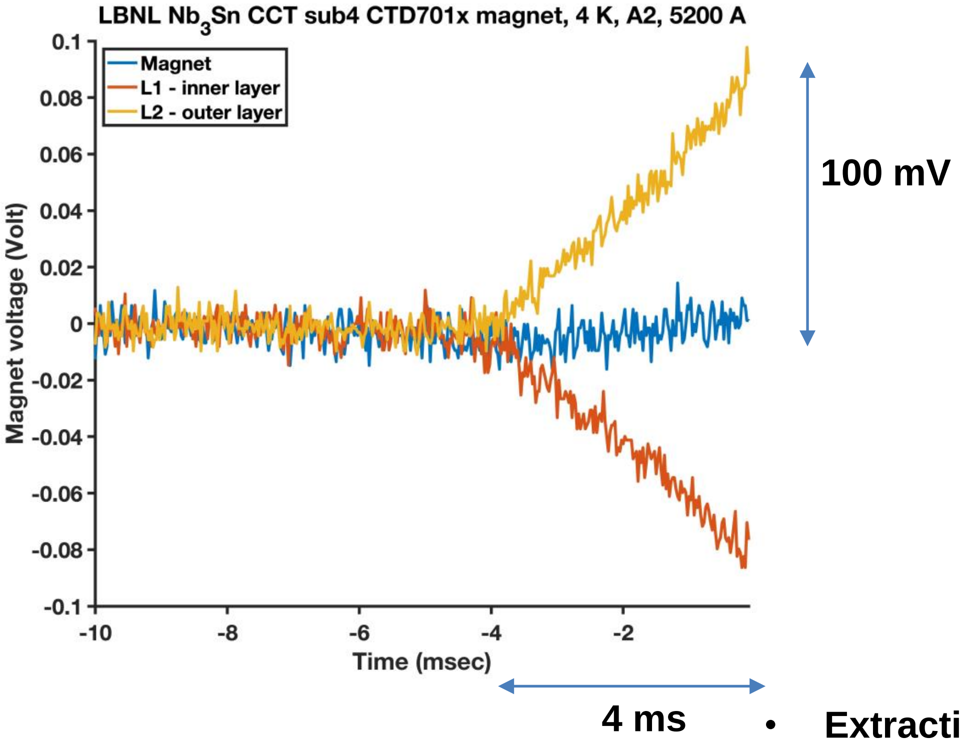
**4 ms**

**NZPV = normal zone propagation velocity.**

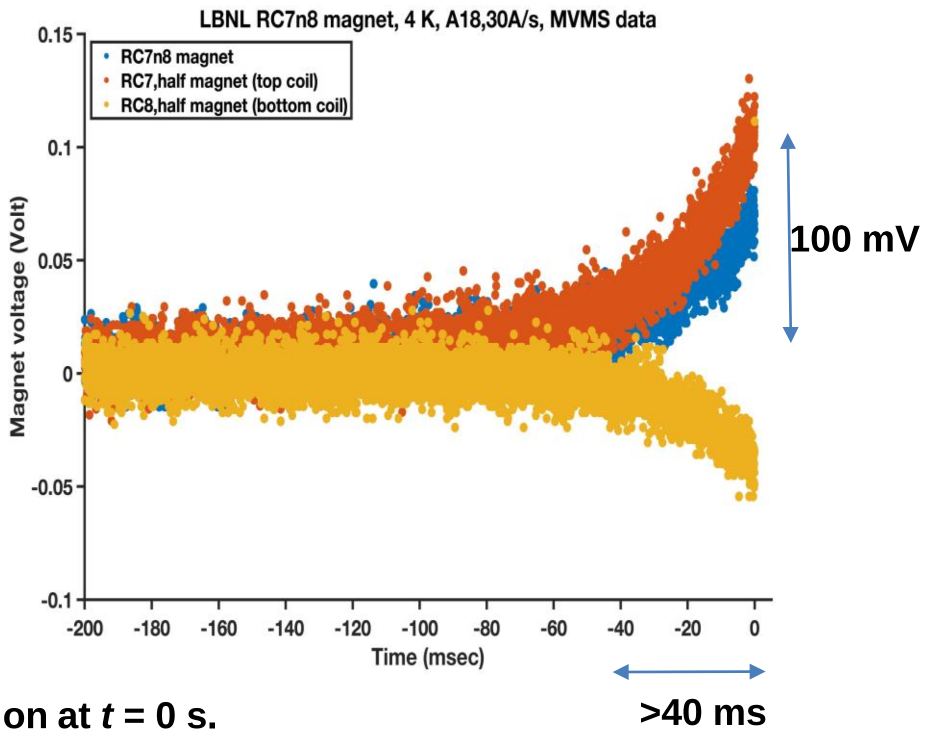
Manuscript in preparation.

# Back to the margin of safety question

- **LTS – $Nb_3Sn$ CCT in this case.**



- **HTS – Bi-2212 RC7n8 in this case.**



- **Extraction at *t* = 0 s.**

$$Stability \propto (T_c - T_o)$$

$$NZPV \propto 1/(T_c - T_o)$$

$$V = \rho(T)\frac{L}{s} = \rho(T)\frac{2 \cdot NZPV \cdot t}{s}$$

$$dV/dt \propto NZPV$$

**The <u>lack of speed</u> is compensated by a higher quench detection temperature and a reduced time for protection and margin of safety.**

**MIITS/time budget:**

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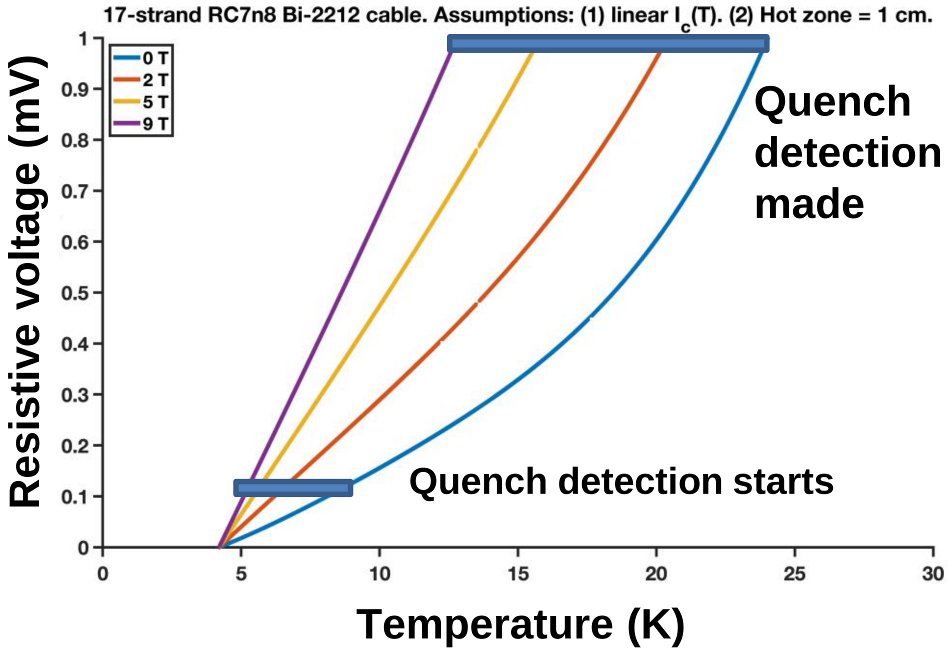
# Benefit of early detection – increased margin of safety – the question is how?

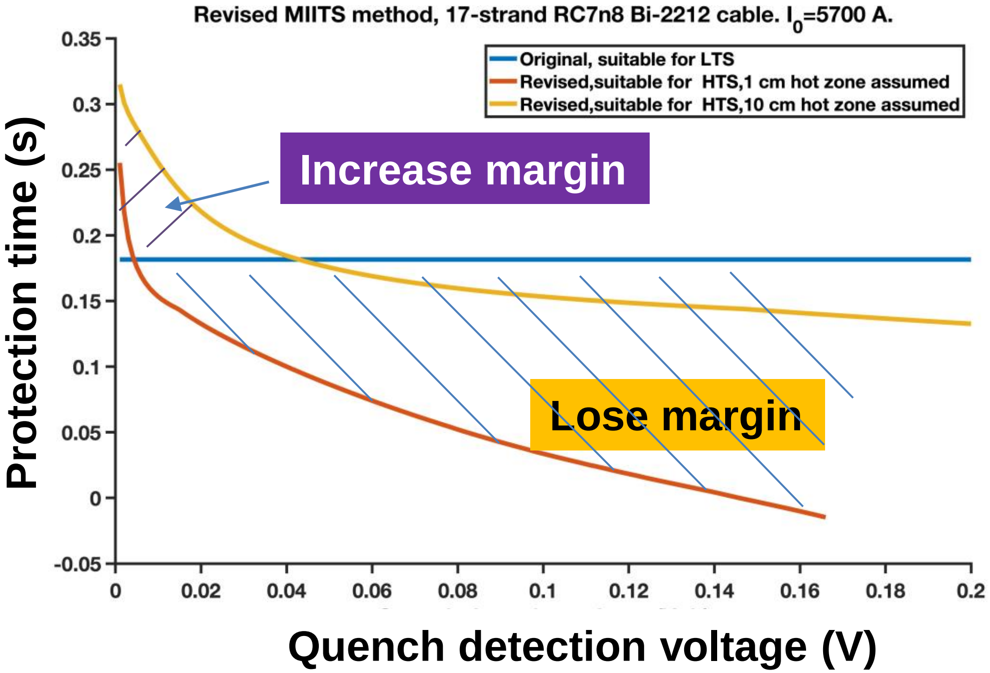
**Quench detection at current sharing region.**



**Quench detection made**

**Quench detection starts**

RC7n8, experimentally proved,
**as large as 2500 ms.**

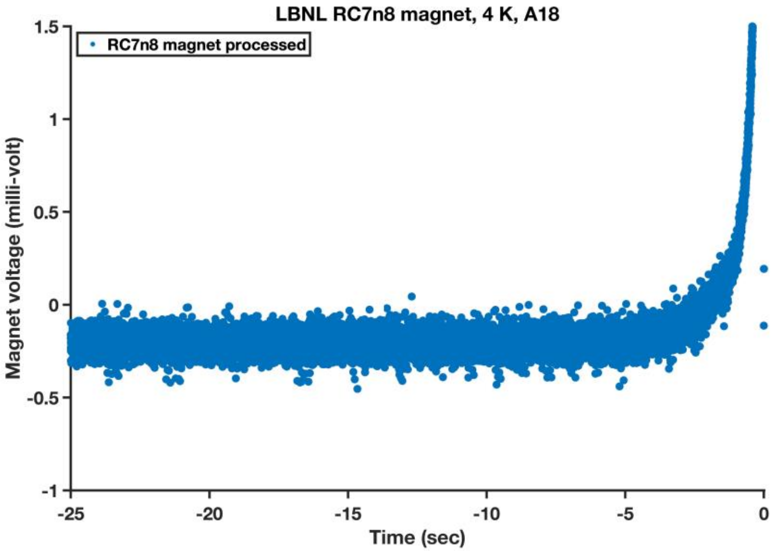


**Increase margin**

**Lose margin**

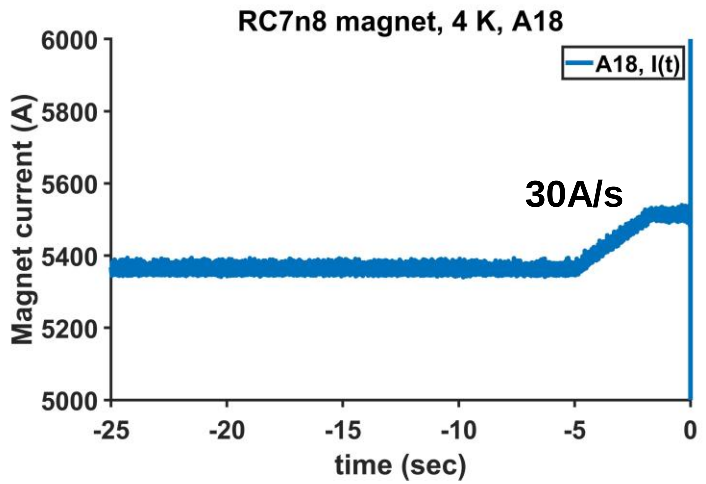
Manuscript in preparation.

# Quench detection of HTS magnets beyond the methods established for LTS magnets – what do we need?

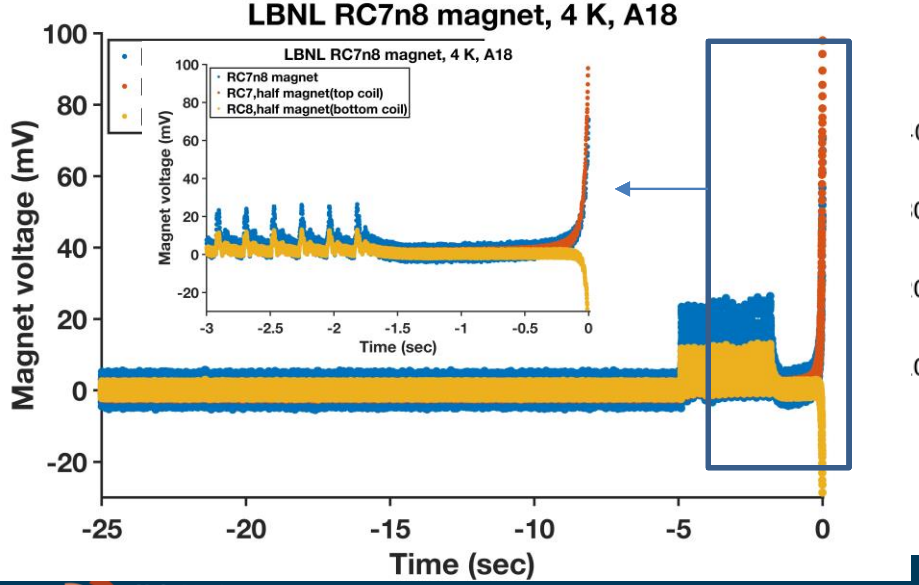


- **For HTS magnets, human brains can tell that a thermal runaway quench is coming if the magnet current continues to rise.**
- A **fast** (discrimination at every **1 ms or smaller**) quench detection method capable of **reducing the rms noise to 100 μV** or less based on real-time digital signal processing algorithms or others simple to implement.
- Such method should be **reliable** and can be implement on a hardware-in-the-loop platform like FPGA.
- Such method should **work with all magnet operating scenarios** including current ramps up and down and holds.
- Such method should have **a low rate of false alarms**.
- Such method should be able to raise the margin of safety for protecting HTS magnets against thermal runaway quenches above the dogma established for LTS magnets.
- Such method should be **verified with** practical HTS magnets with local voltage or temperature **measurements** at or near quench spots.

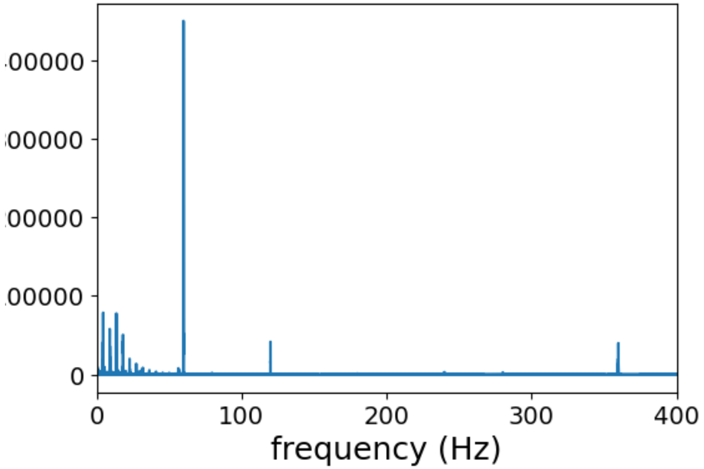
# Step #1: Noise spectrum and real time noise reduction applied to a test case A18 of the RC7n8 magnet

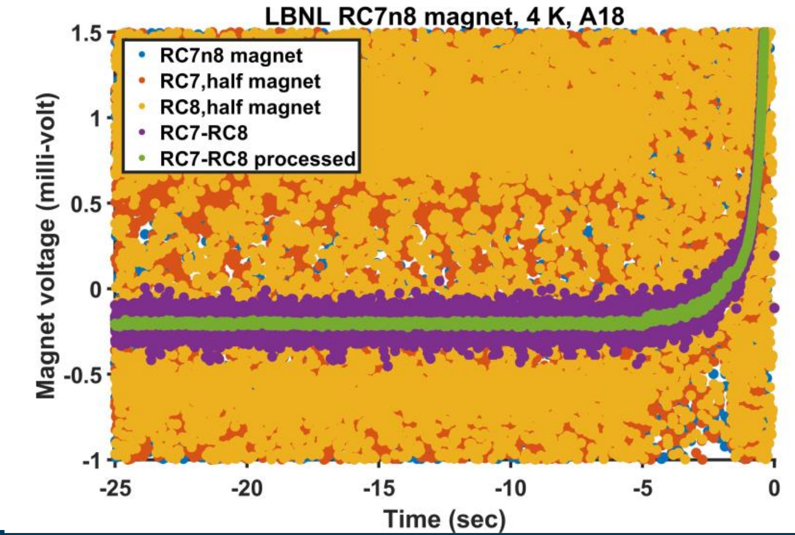


- <u>Front-end electronics</u>: Programmable gain amplifier and electronics for low-level measurements (signal conditioning) @ 1kHz
- <u>Followed by a smart unit</u>: real-time, fast digital signal processing + a simple detection algorithm, and machine learning blocks.
- <u>More than conventional QDS</u>: Monitoring and analyzing magnet behaviors, predicting and detecting quenches.

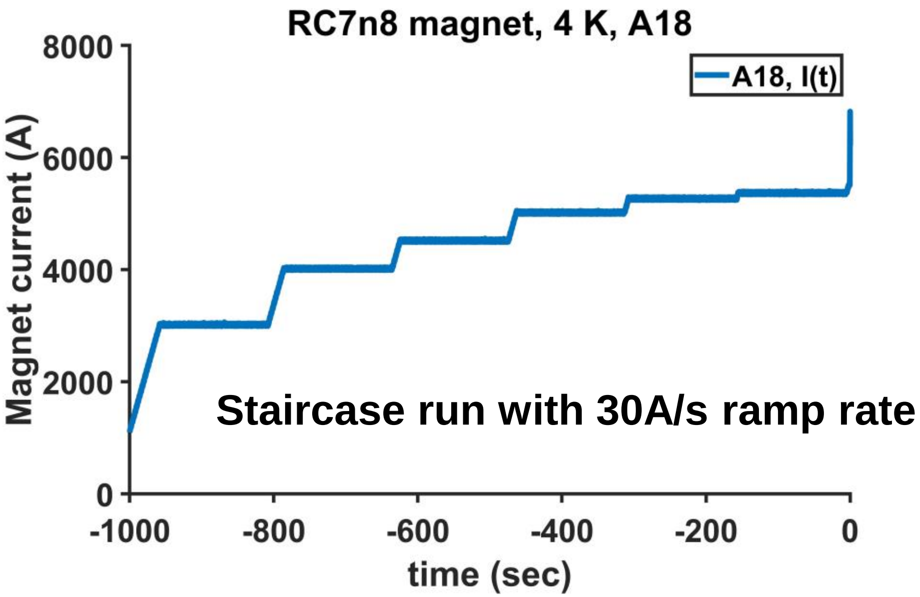


@1kHz





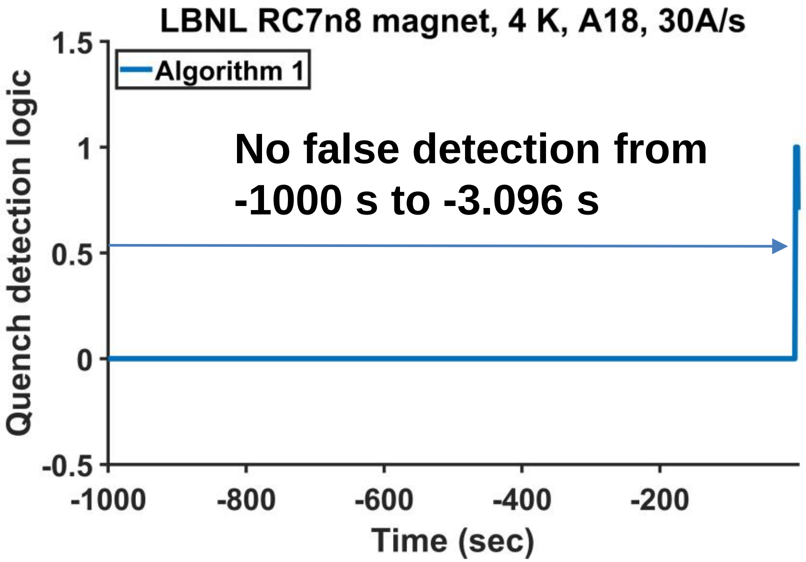
# Step #2: Generating quench detection logic with a simple algorithm operating real-time (per ms) on the processed data of A18



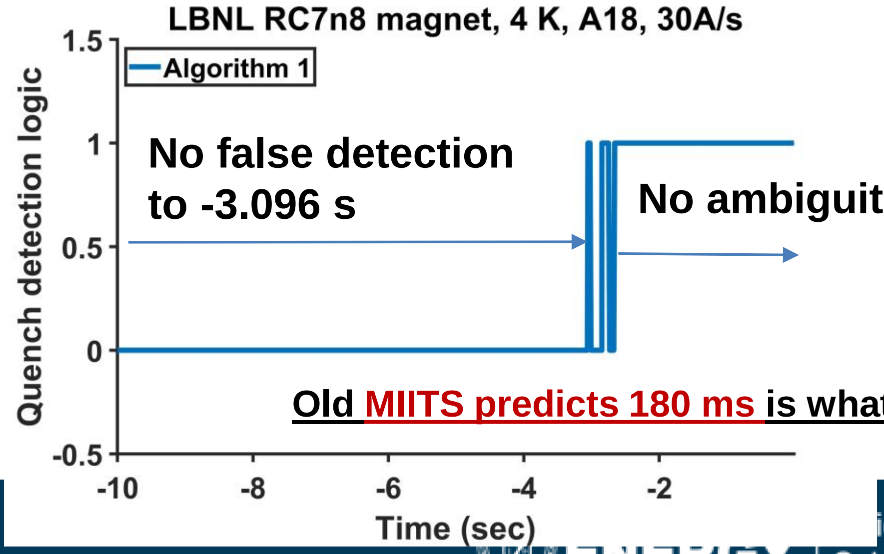
Staircase run with 30A/s ramp rate

↑

**Time = 0 s**
**SCR opened**



**No false detection from -1000 s to -3.096 s**

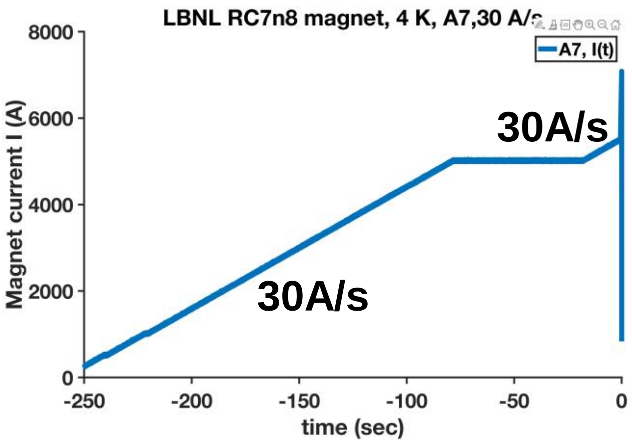


**No false detection to -3.096 s**

**No ambiguity after -2.652s**

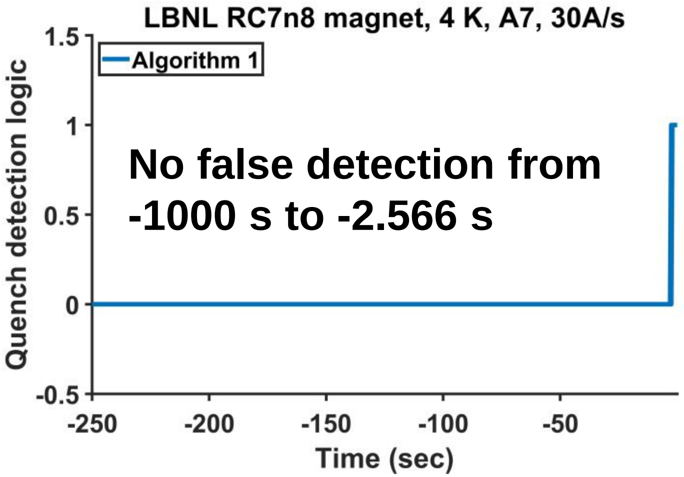
**Old MIITS predicts 180 ms is what we have.**

# Two other cases – ramp I at 30 A/s, ramp II at 200 A/s

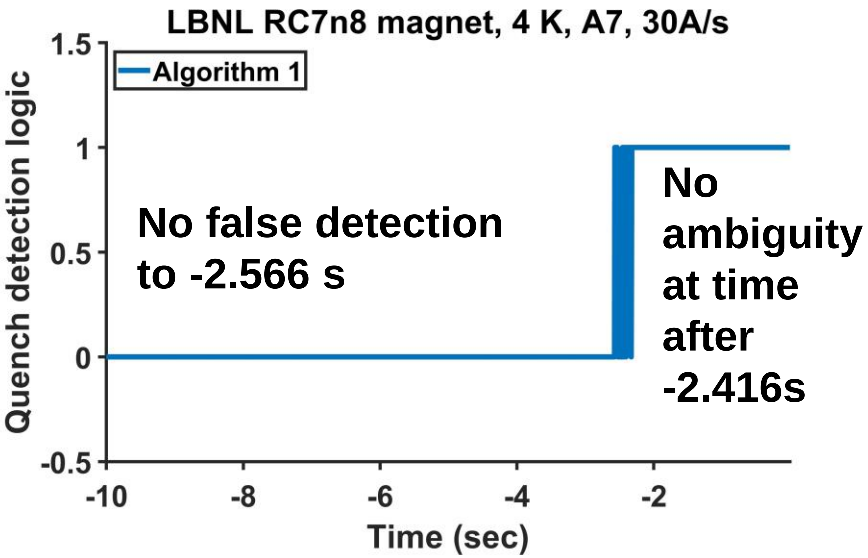


30A/s

30A/s

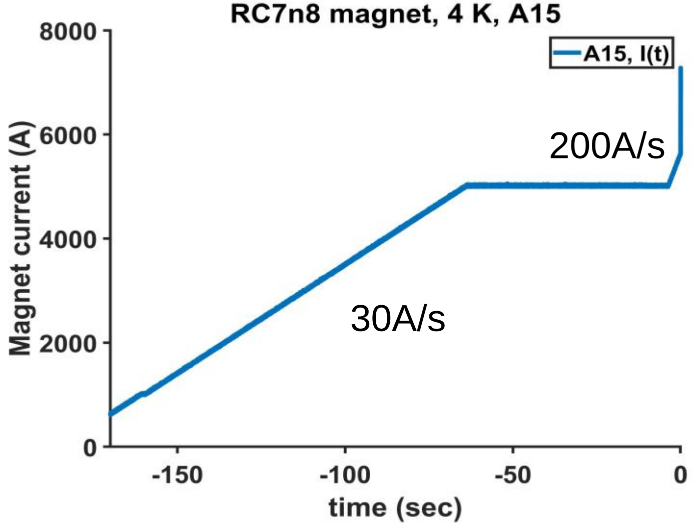


No false detection from -1000 s to -2.566 s



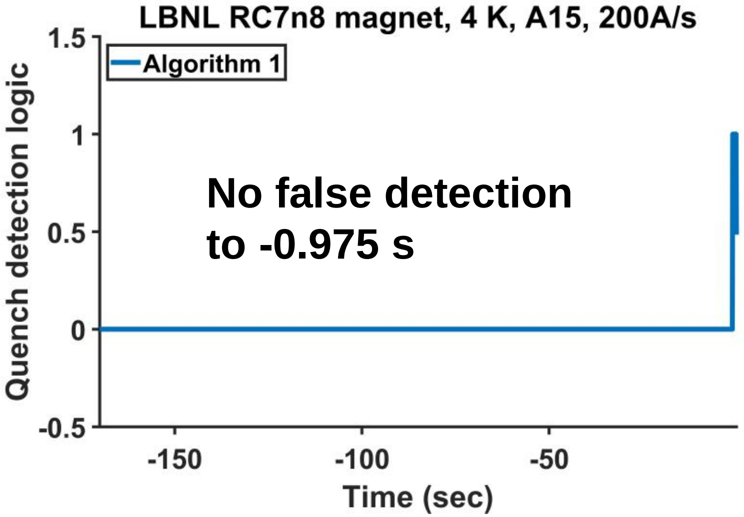
No false detection to -2.566 s

No ambiguity at time after -2.416s

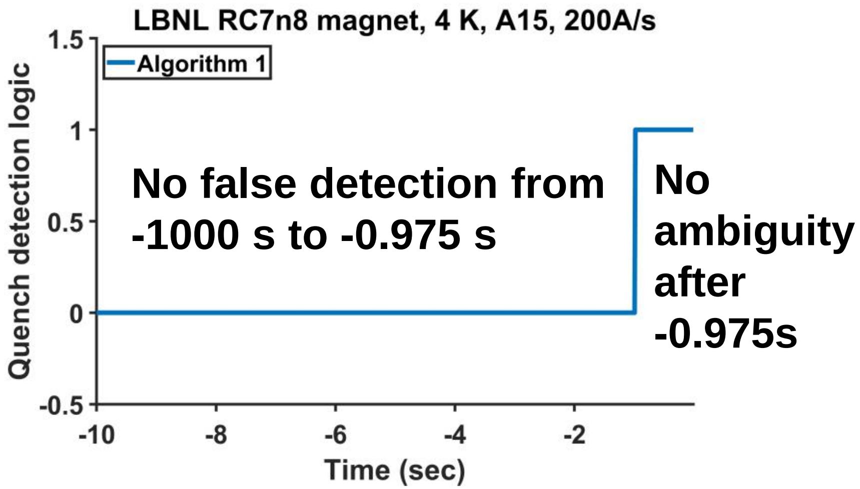


200A/s

30A/s



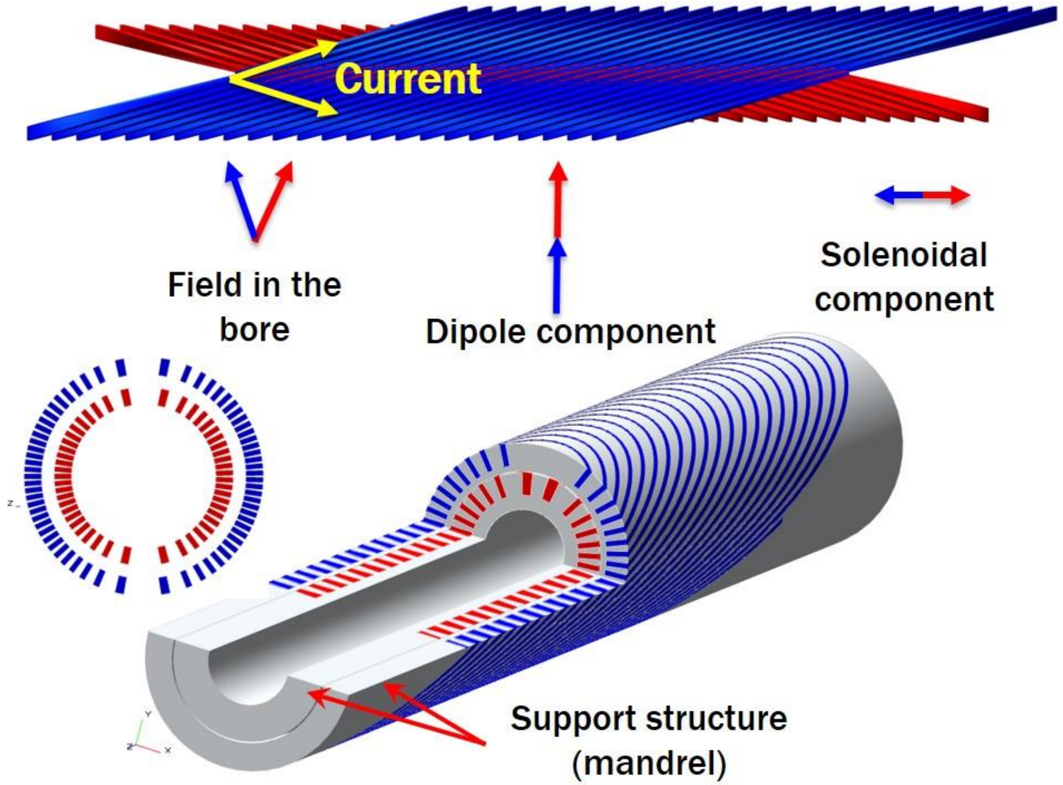
No false detection to -0.975 s



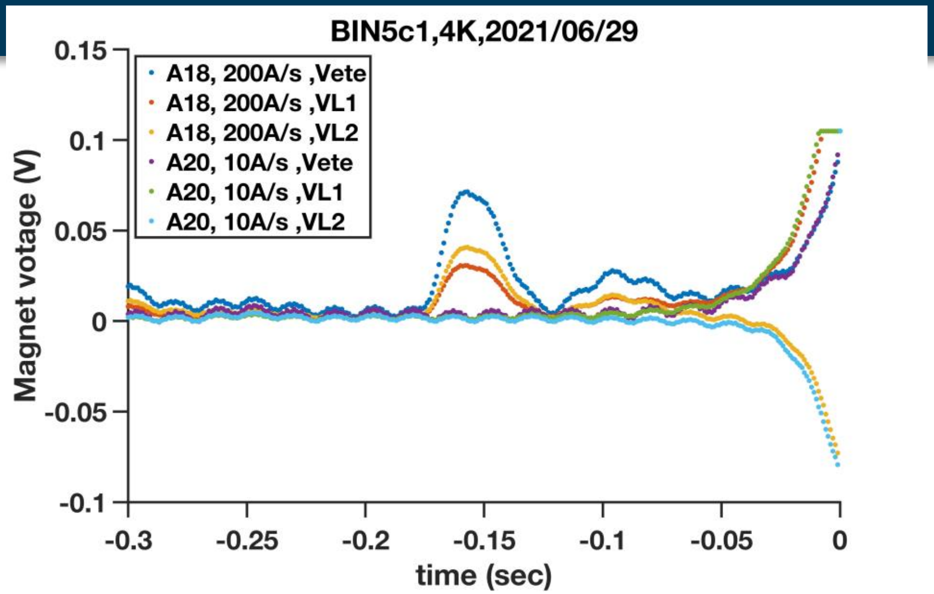
No false detection from -1000 s to -0.975 s

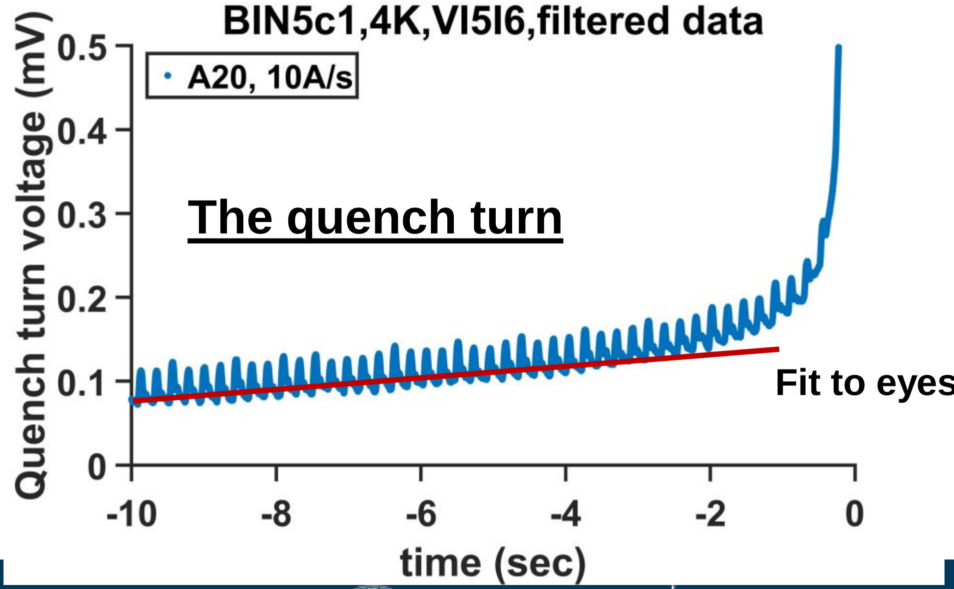
No ambiguity after -0.975s

# The case of CCT magnet BIN5c1, a more difficult to handle magnet



- Inherent stress management capability.
- Unique: Voltage of each turn was monitored.
- Inductance and magnetic environment of two coils are different, leading to large noise.



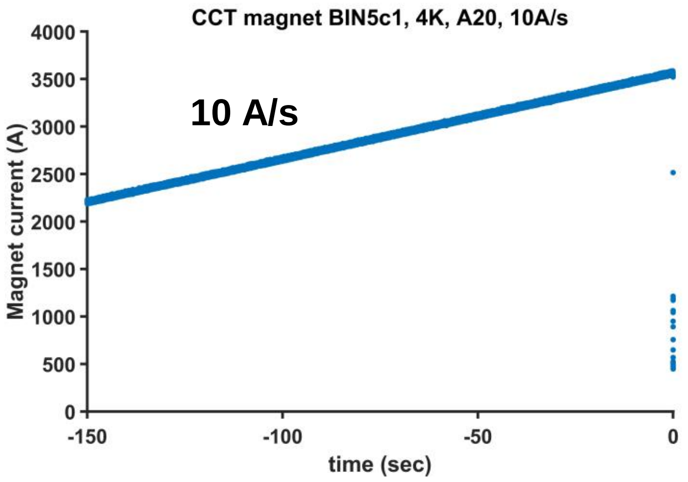


**The quench turn**

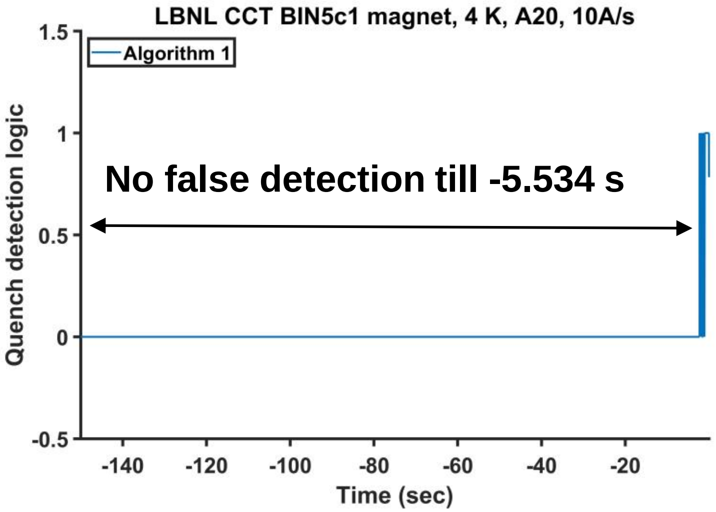
Fit to eyes

For fabrication and performance of this magnet, see
Shen et al., PRAB, https://journals.aps.org/prab/accepted/fc079Mf6Gc811d0311b39fe697a8ef84c27cafa4f

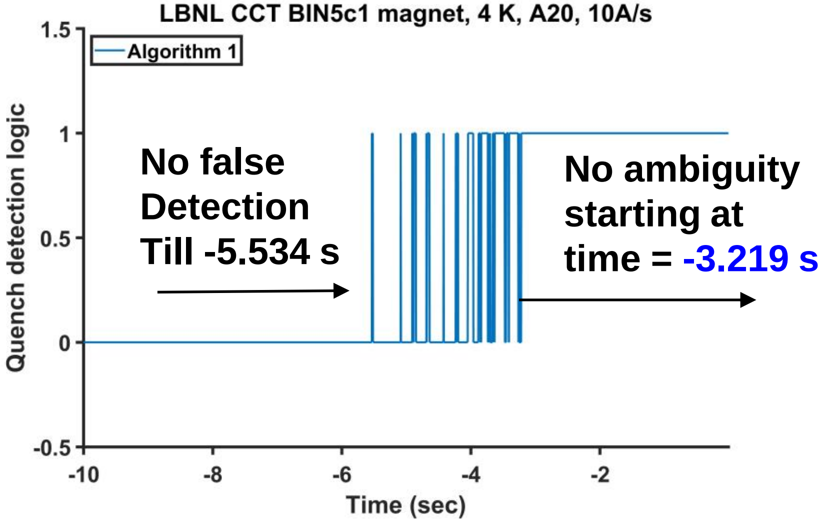
# Quench detection logic as the result of a simple algorithm operating real time on the processed signal on CCT BIN5c1 dipole magnet – 10A/s case



10 A/s



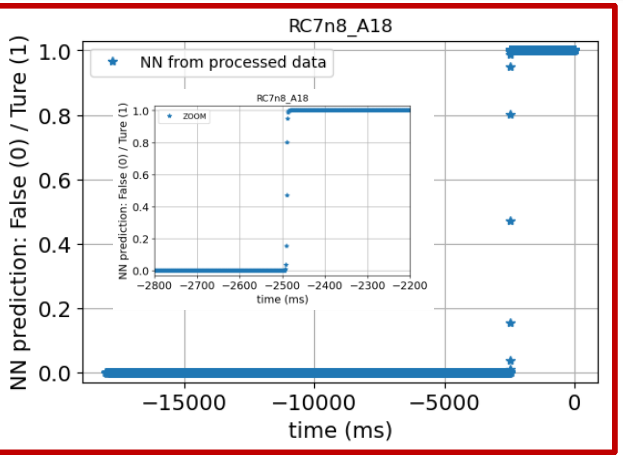
No false detection till -5.534 s

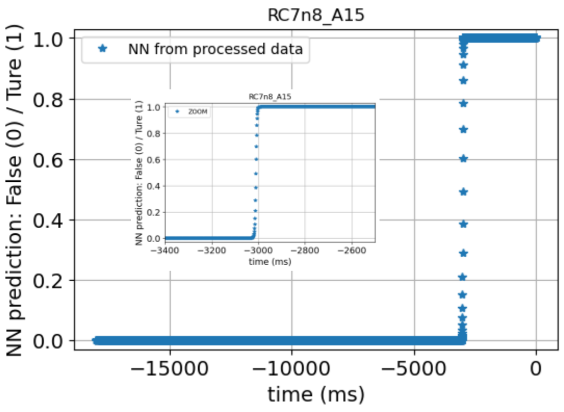


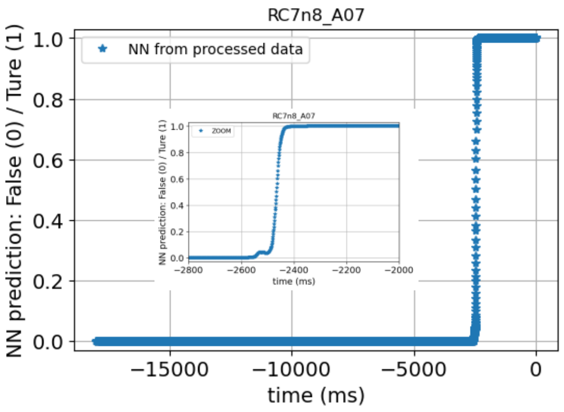
No false Detection Till -5.534 s

No ambiguity starting at time = -3.219 s

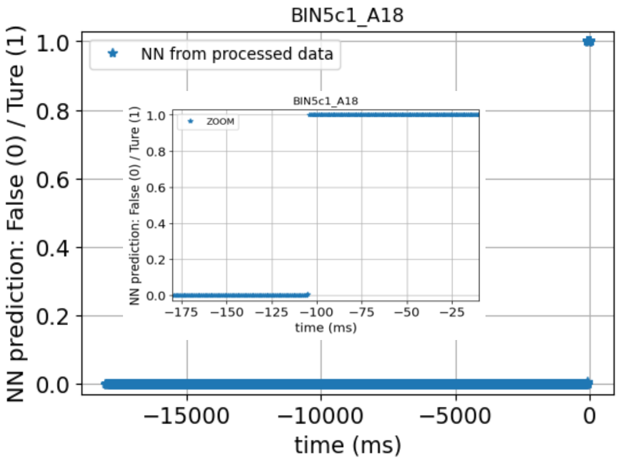
# Machine learning potentially enables automatic and smart learning

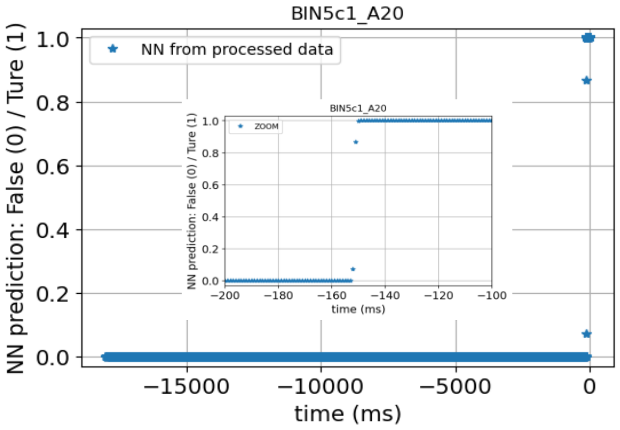


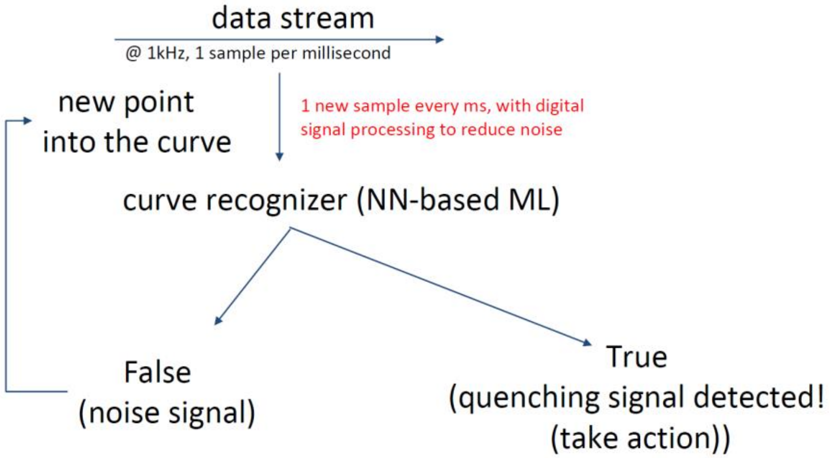




- **Supervised training.**
- **Trained on RC7n8_A18**
- **Apply to all other cases.**
- **Neutron network based.**







data stream

@ 1kHz, 1 sample per millisecond

new point into the curve

1 new sample every ms, with digital signal processing to reduce noise

curve recognizer (NN-based ML)

False (noise signal)

True (quenching signal detected! (take action))

By Dan Wang, LBNL

# Section summary

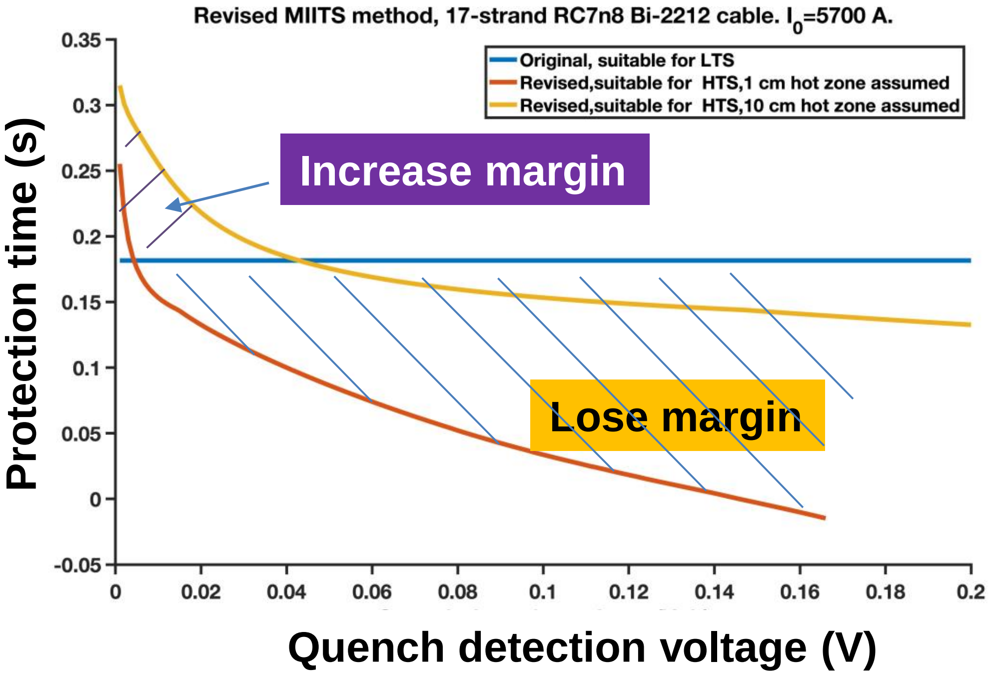
- **Introduced a revised MIITS method for HTS magnets.**
  - **The time budget for quench protection of HTS magnets can be either higher or lower than that predicted with the conventional MIITS method used for LTS magnets.**
  - **It shows the uncertainty with estimating the maximum hot spot temperature and thus the margin of safety.**

- **Provided a wish-list of quench detection for HTS magnets and verification of a quench detection method in two HTS HEP-type magnets.**
  - **2500 ms (experimental demonstrated) quench detection ahead of quenches possible.**
  - **Versus**
  - **180 ms predicted by old MIITS.**

- **Exploration of machine learning.**

# However, things do not entirely add up, do they? Then why?

RC7n8, experimentally proved,
**as large as 2500 ms.**

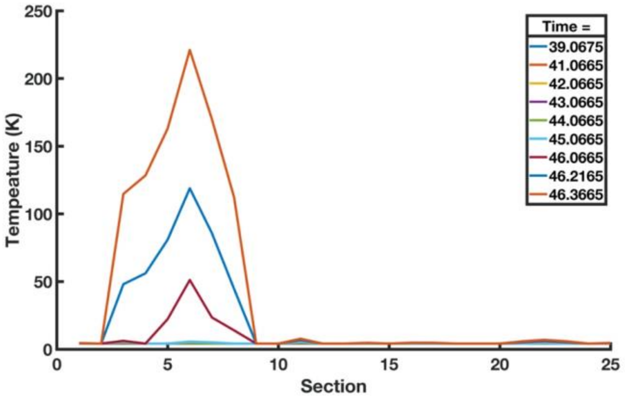

Revised MIITS method, 17-strand RC7n8 Bi-2212 cable. $I_0$=5700 A.

Increase margin

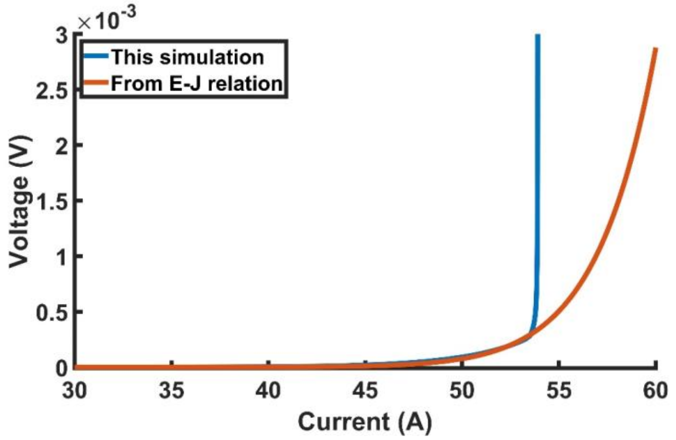
Lose margin

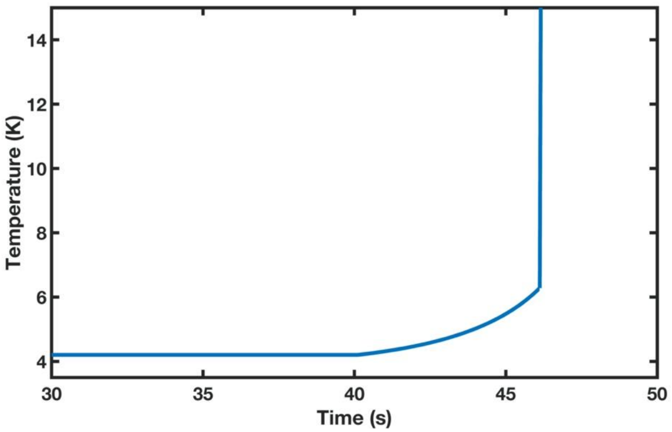
# Let’s examine an 1D superconductor quench simulation of an HTS conductor

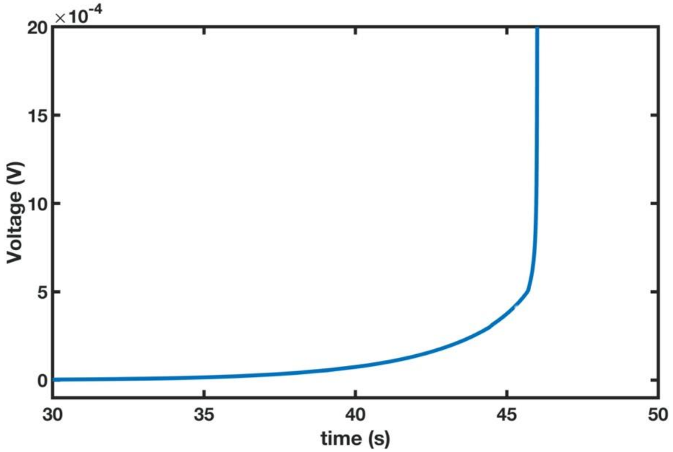
| $I_c$ (A) average | Variation in $I_c$ (A) | n-value average | Variation in N | No. of Section | Length of a section (cm) | Cooling power (kW/m$^2$) |
|---|---|---|---|---|---|---|
| 50 | 2 | 15 | 2 | 25 | 3 | 0.01 |

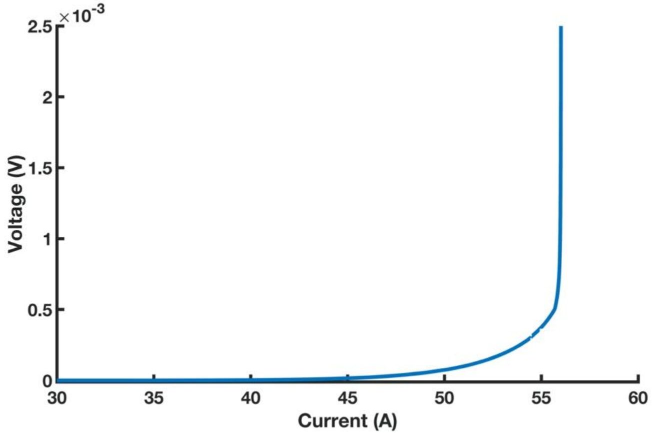


- **$T_o$ = 4.2 K.**
- **$T_c$ = 72 K.**
- **$I_c(T)$ is linear at a fixed B.**
- **d$I$/d$t$ = 1 A/s.**





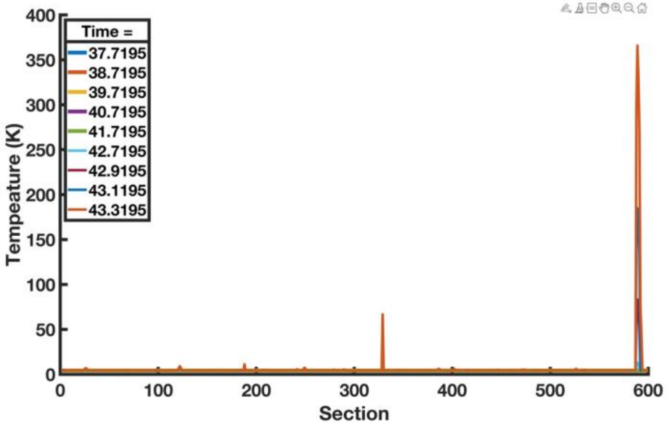


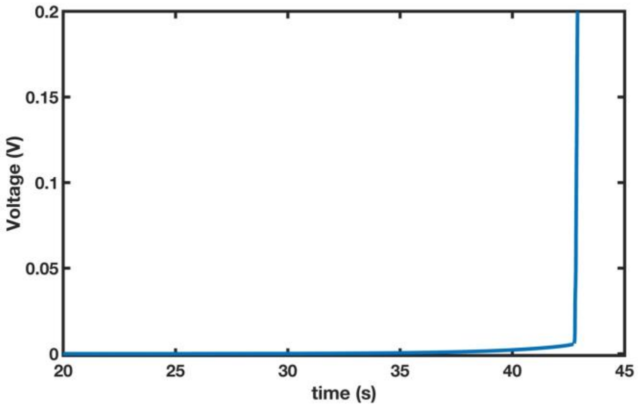


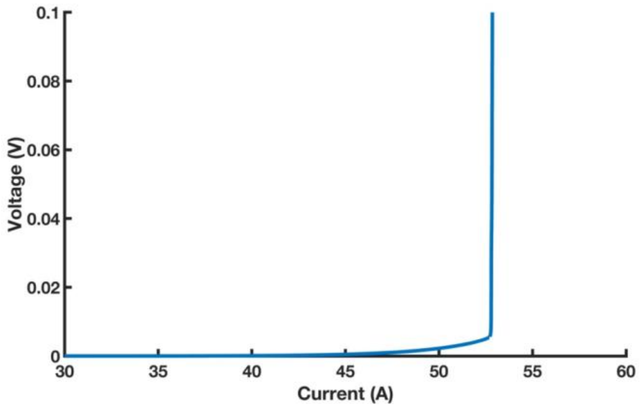
# Let’s look at a longer piece (18 m)

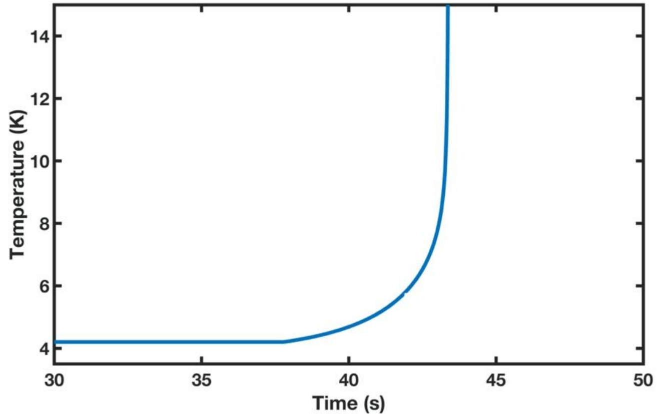
| $I_c$ (A) average | Variation in $I_c$ (A) | n-value average | Variation in n-value | No. of Section | Length of a section (cm) | Cooling power (kW/m$^2$) |
|---|---|---|---|---|---|---|
| 50 | 2 | 15 | 2 | 600 | 3 | 0.01 |

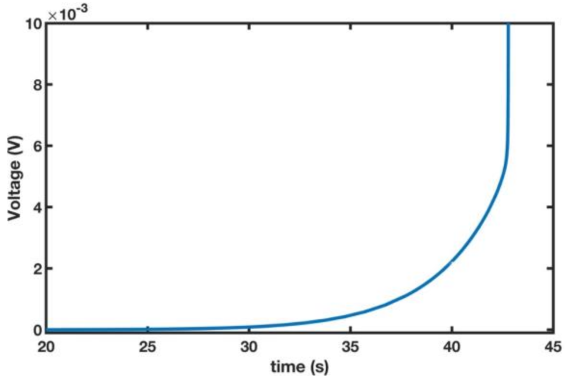
- **$T_o$ = 4.2 K.**
- **$T_c$ = 72 K.**
- **$I_c(T)$ is linear at a fixed B.**
- **d$I$/d$t$ = 1 A/s.**

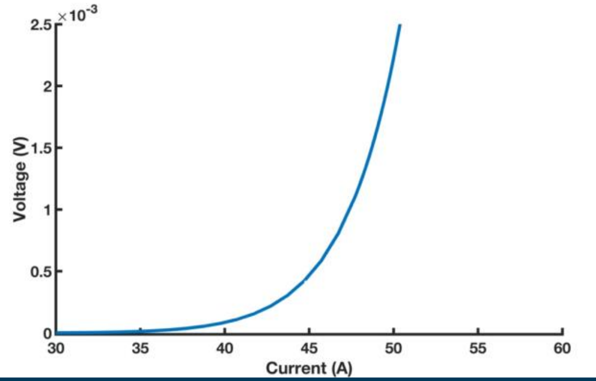




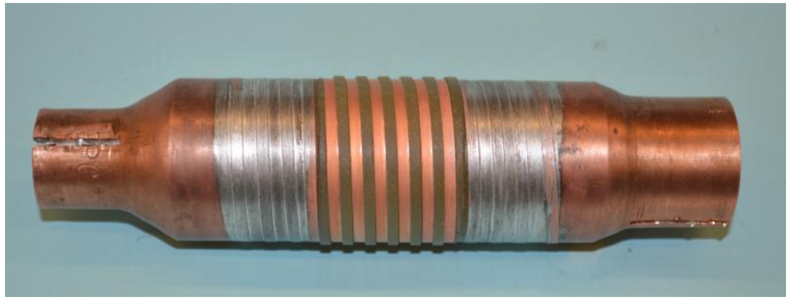


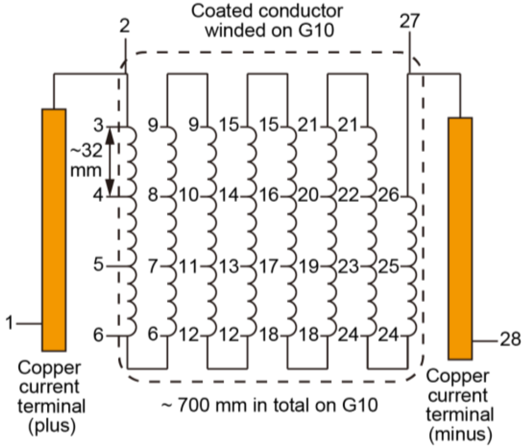


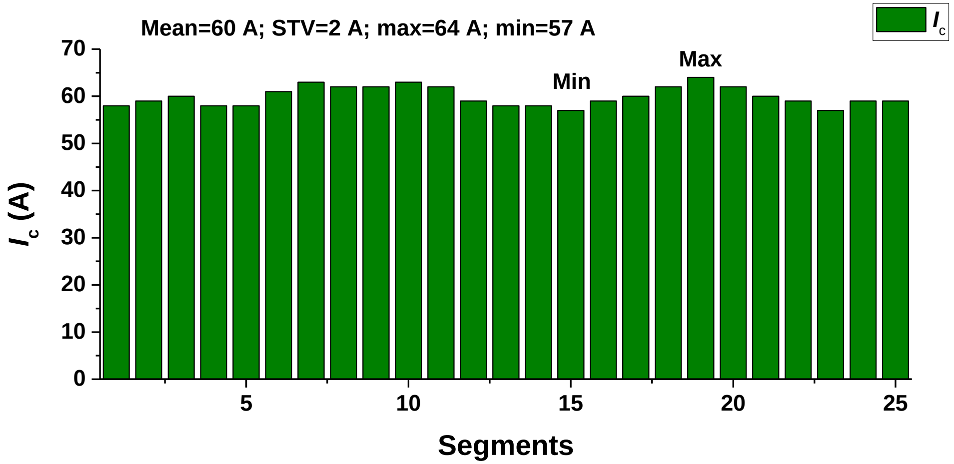


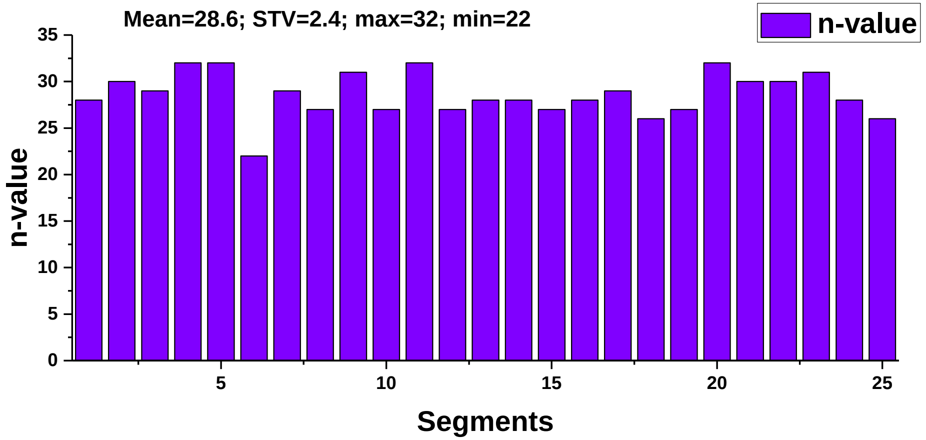


# Verification of the simulation provided by an experiment - sample



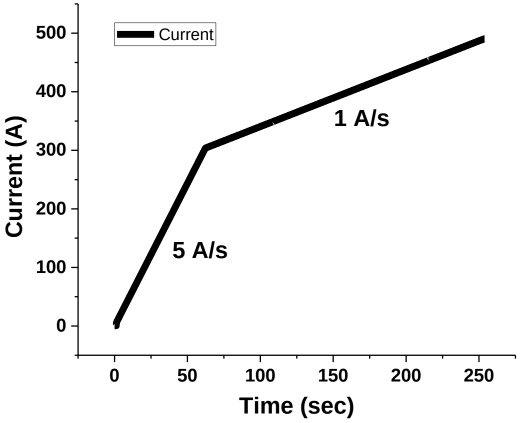


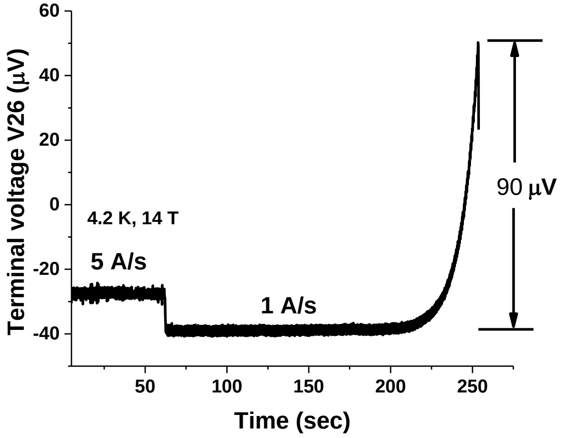


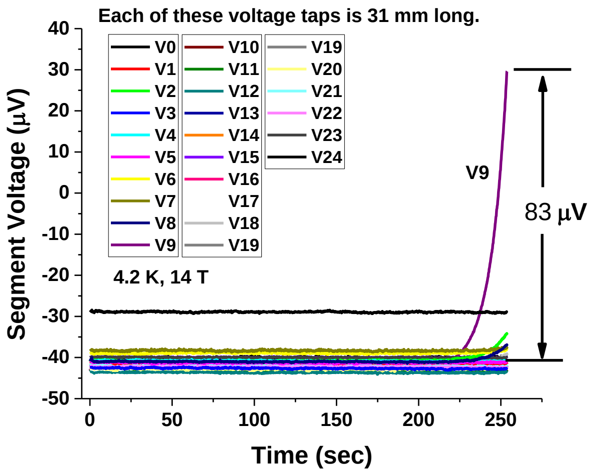


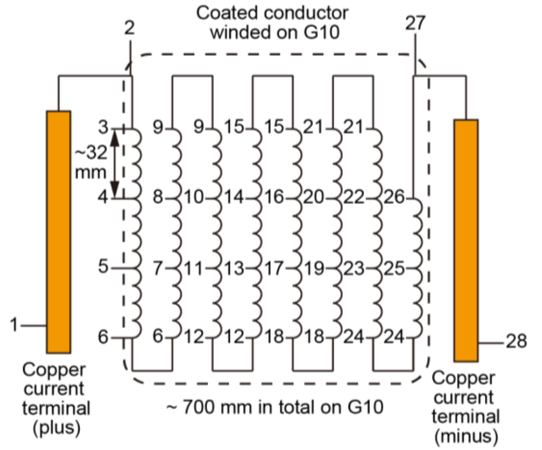
Xijie Luo from Kyoto Uni. contributed to this measurement. Support partially from the US-Japan HEP collaboration.

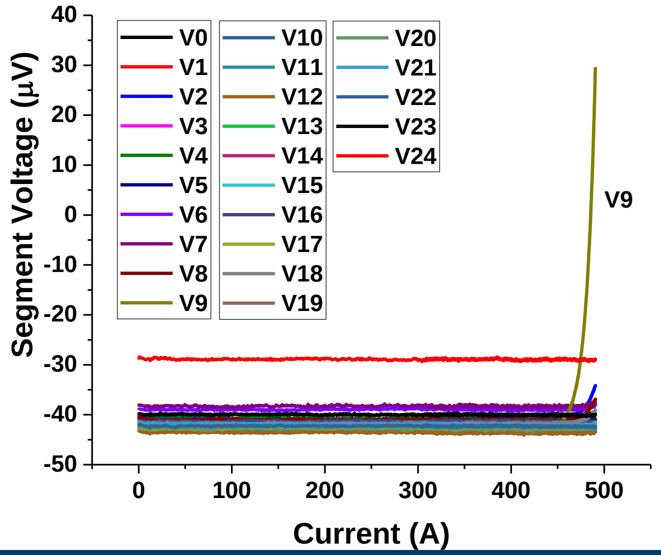
# Verification of the simulation provided by an experiment - results







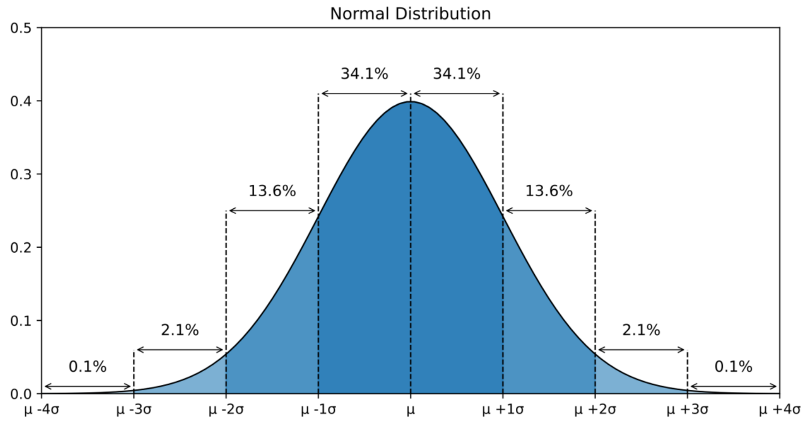


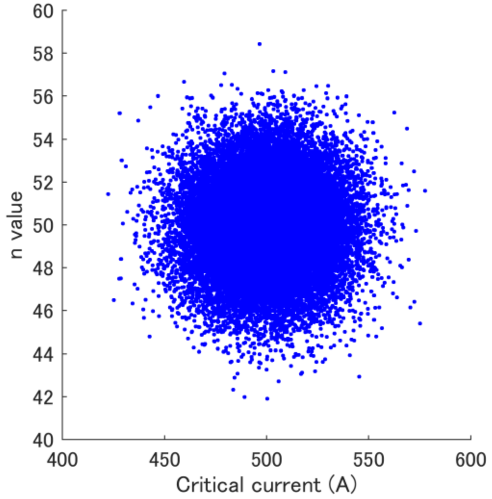


**V9 – $I_c$ – 464 A, n-value=51;**
**V8- $I_c$ – 490 A, n-value=43;**
**V2- $I_c$-486 A, n-value = 50;**
**Other sections all with $I_c$ > 490 A.**
**@4.2 K and 15 T.**

Xijie Luo from Kyoto Uni. contributed to this measurement. Support partially from the US-Japan HEP collaboration.

# Then back at this question and add a bit statistics in.

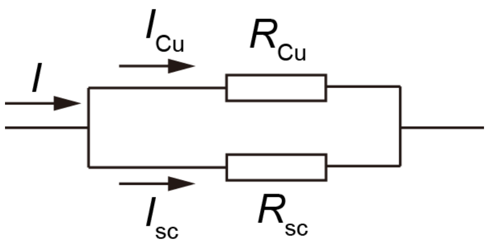




- ○ **Statistical model (Monte-Carlo Simulation, 1000 runs for each sample and operation conditions)**

$$f(I_c) = \frac{1}{\sqrt{2\pi I_{\text{c\_dev}}^2}} \exp\left[-\frac{\left(I_c - I_{\text{c\_aver}}\right)^2}{2I_{\text{c\_dev}}^2}\right]$$

$$f(n) = \frac{1}{\sqrt{2\pi n_{\text{dev}}^2}} \exp\left[-\frac{(I_c - n_{\text{aver}})^2}{2n_{\text{dev}}^2}\right]$$



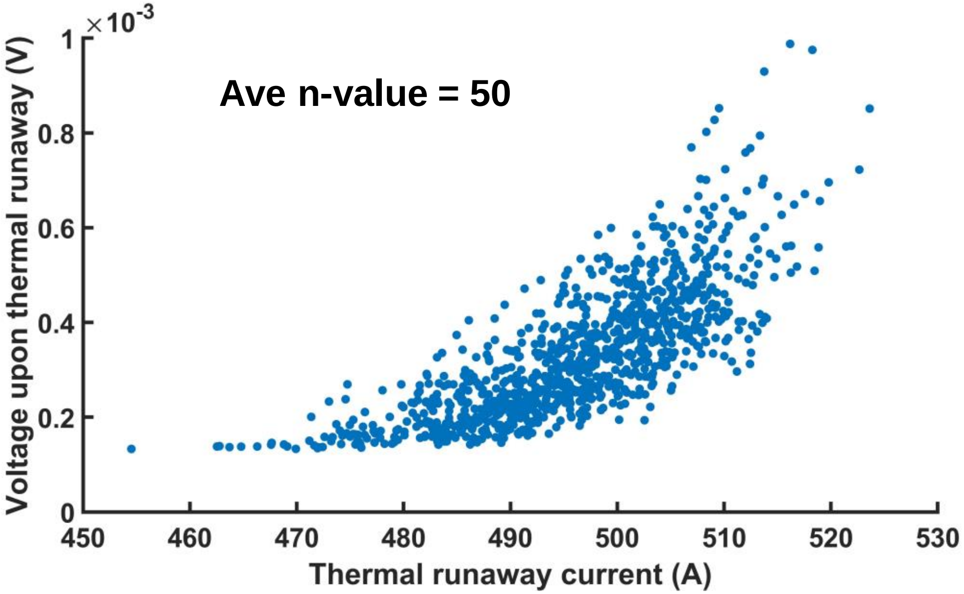
$$R_{\text{Cu}} = \rho_{\text{Cu}} L / w t_{\text{Cu}}$$

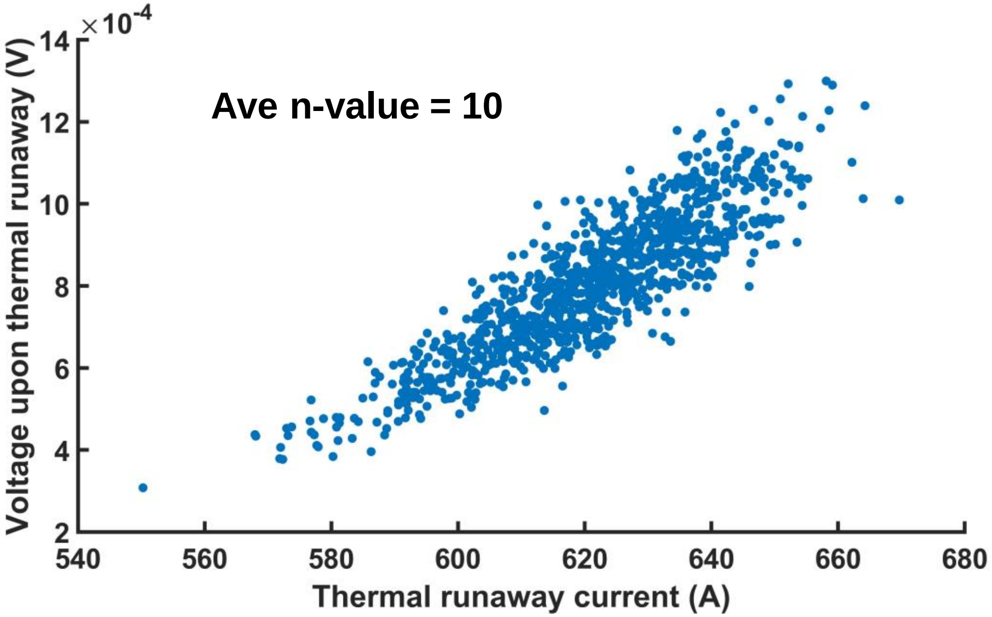
$$R_{\text{sc}} = E_0 L (I_{\text{sc}}/I_c)^n / I_{\text{sc}}$$

$$\int_{t_0}^{t} (I^2 R - cooling)dt = \int_{T_0}^{T} C dT$$

# Monte Carlo experiment:
# Screening and sensitivity analysis that shows the effect of n-value

| $I_c$ (A) | Variation in $I_c$ (A) | n-value | Variation in n-value | No. of Section | Length of a section (cm) | Cooling power (kW/m$^2$) |
|---|---|---|---|---|---|---|
| 500 | 20 | **50 (left); 10 (right)** | 2 | 25 | 3 | 1 |





# What have we learned?

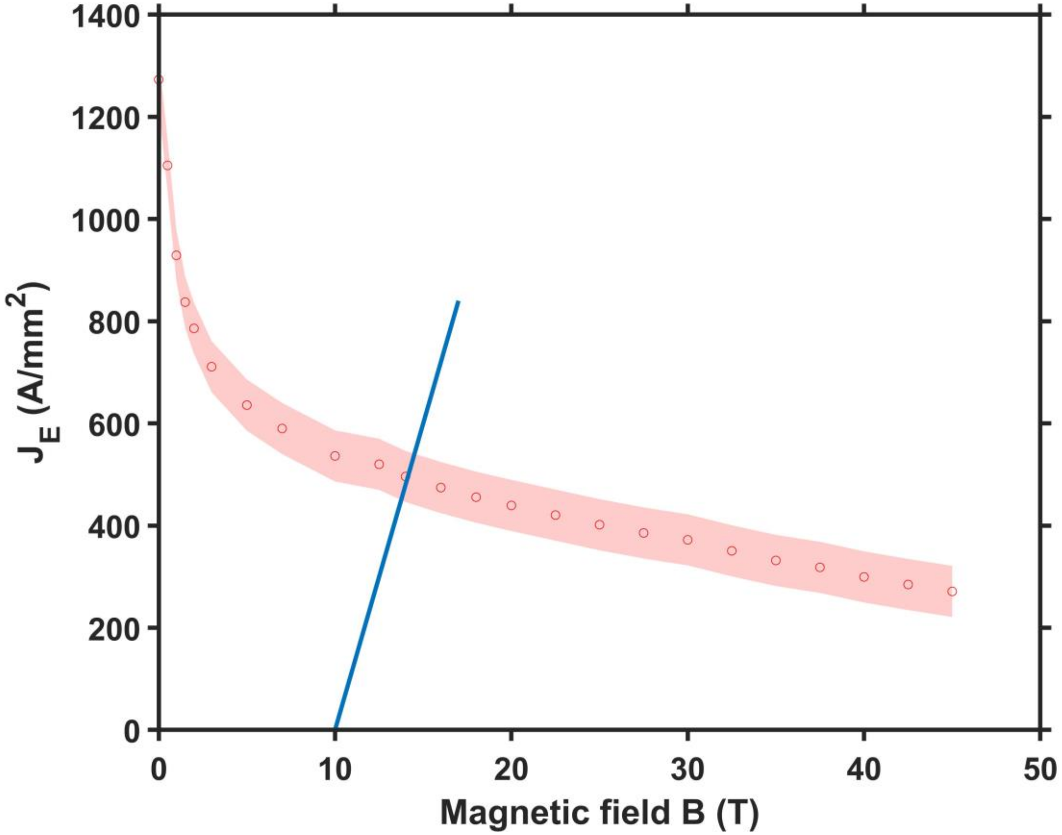
- Before entering into a thermal-runaway quench, HTS magnets/conductors have small but detectable voltages that last multiple even tens of seconds.

- They provide an opportunity with quench detection and perhaps even prevention.
  - Such opportunity rarely exists for LTS magnets.

- Missing this opportunity comes with a high cost: The margin of safety for quench protection drops to nearly zero, especially for large HTS magnets.

# Apply the same perspective with another angle – the short sample limit of your HTS magnets

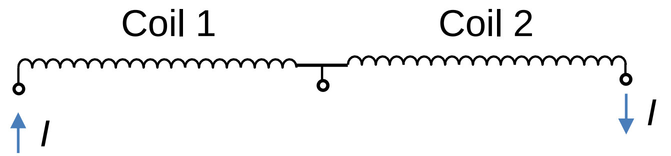
**A schematics for determining short sample limit (quench current) for a superconducting magnet.**
**Now it comes with an uncertainty band for HTS magnets.**



**The quench current of your HTS magnet doesn't come with an absolute value like LTS magnets.**

**It is modulated by $I_c$ distribution, primarily $I_{c_{dev}}$, cooling, and n-value, and comes with an uncertainty band.**

# Practical magnets – can you guess which coil quenched?



$$V_1 = L_1 \frac{di(t)}{dt} + \boxed{R_{sc,1} i(t) + R_{NZ,1} i(t)} + M_1 \frac{di_e(t)}{dt}$$

$$V_2 = L_2 \frac{di(t)}{dt} + \boxed{R_{sc,2} i(t) + R_{NZ,2} i(t)} + M_2 \frac{di_e(t)}{dt}$$

**Let's only look at these components. They can be measured.**

**The first component, index loss caused voltage, only shows occasionally for LTS magnets, e.g. $Nb_3Sn$ magnets with cable damages and low n-values.**

**REBCO CORC C2**
**Co-wound voltage taps**

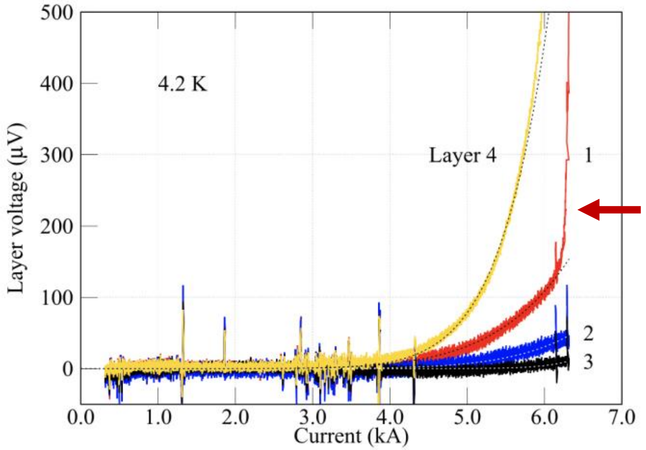


**Figure 16.** The $V(I)$ of each layer during a ramp at 4.2 K. The dashed lines are the exponential fits of the voltage data according to (1). The spikes were inductive voltages due to ramp-rate irregularities.

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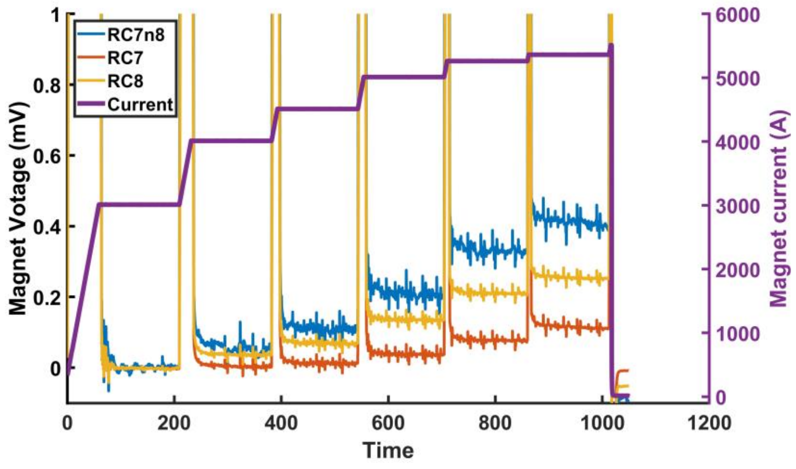
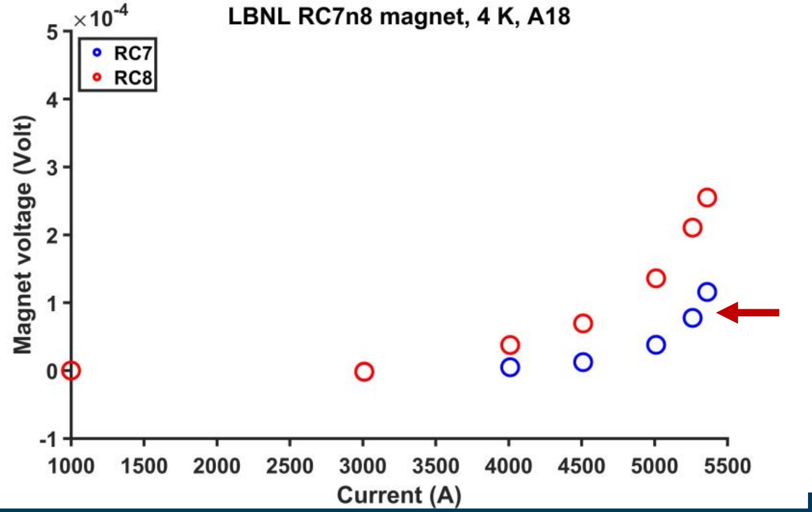
**Bi-2212 RC7n8, inductive signals removed by staircase run.**





# Summary

- A revised MIITS method – what it implies for margin of safety and uncertainty.
- A surprise shown by "experiments" – the protection time budget for quench protection is raised by ~10 and why.
- An opportunity window for quench detection for HTS magnets (which rarely exists for LTS magnets) and how the margin of safety of quench protection of HTS magnets drops to nearly zero if it were missed for large HTS magnets.
- SSL for HTS magnets – no longer a point.
- The resistive voltage limit of an HTS magnet – not so simple to call it – where statistics plays a role.

Thank you for your attention.