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Introduction to quench detection

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SMTS and IDSM workshops

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Outline

- Magnet quenching and protection
- Standard quench detection techniques
- Typical quench detection signals
- Quench detection systems - implementation
- Novel methods of quench detection - brief

The base for discussions here are LTS accelerator magnets but most of the logic applies elsewhere

I used material from:

https://indico.cern.ch/event/440690/
https://uspas.fnal.gov/materials/18MSU/MSU-Super-Accel-Mag.shtml
http://cdsweb.cern.ch/record/1158462/files/cern-2010-004.pdf

along with sources I refer to later

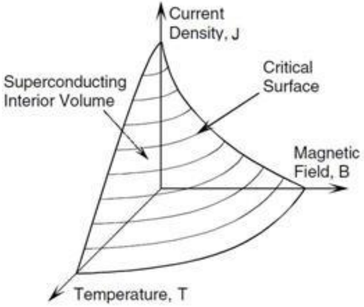
Superconducting magnet quenching

- A magnet can store large energy: $E = \dfrac{LI^2}{2}$

  For a HL-LHC quadrupole: inductance L = 35 mH, I = 16.5 kA => 4.8 MJ

https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.superconductivity_in_short

- A superconductor retains its properties withing a "critical surface" only:



- Very small heat energy, of the order of 1 mJ or less, may be enough to shift, locally, the conductor beyond its "critical surface" and then superconductivity is lost; Joule heating may be self-sustaining

- The process of irreversible transition from superconducting to normal state is called **quench**

- A quenching magnet will end up fully quenched (normal state) and its stored (magnetic field) energy will have to go somewhere if current decreases fast

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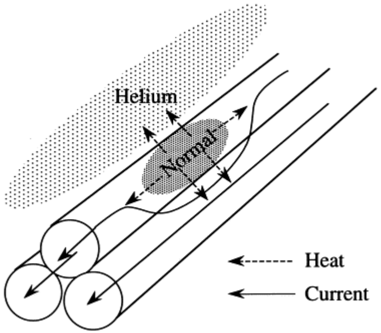
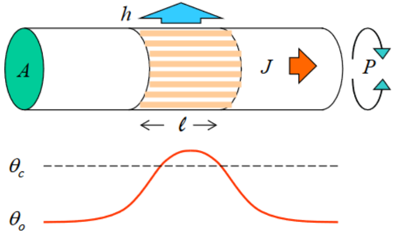
Quench initiation

- A “disturbance” can cause a quench (irreversible process) depending on circumstances
- Current can get “redistributed”, to non-superconductor or another strand/wire, heat can get removed fast enough by cooling



N. Amemiya et al., Cryogenics, vol. 38, Issue 5, May 1998, Pages 559-568

- The initial resistive zone can fully shrink or can continue expanding – the line between the two is called Minimum Propagation Zone (**MPZ**)
- There is some Minimum Quench Energy (**MQE**) associated to MPZ and both can be calculated, they depend on conductor and conditions



energy volume [J kg K^{-1}] [kg m^{-3}]

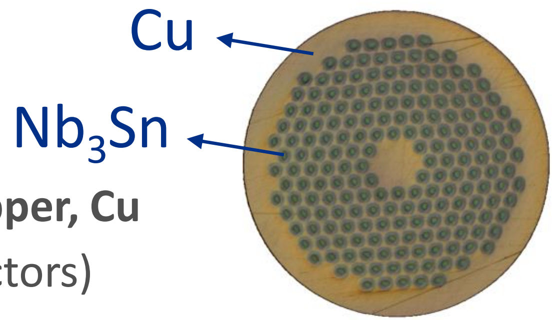
$$E_{MQE} = V_{MPV} \int_{\theta_0}^{\theta_C} \gamma C(\theta) d\theta$$

Martin Wilson Lecture 2, Superconducting Accelerators: Cockroft Institute June 2006

- Heat energy can come from various sources – wire vibration, friction/sliding, insulation cracking, eddy-currents, etc.

Hot spot

Example of a strand/wire



- In the zone ("spot") where quenching starts all the current flows through resistive conductor called "stabilizer"; **often copper, Cu** (because superconductors are usually very bad normal conductors)

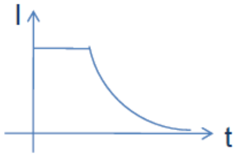
- From energy conservation it follows that Joule heating must be equal to heat absorption: (adiabatic approximation)

$$\gamma C_p(T)dT = \rho J(t)^2 dt$$

- Then one arrives at an expression like this: $10^6 MIITs \equiv \int_0^\infty I(t)^2 dt = A_{tot} A_{Cu} \int_{T_0}^{T_{max}} \frac{\sum_k \gamma_k v_k C_{p,k}}{\rho_{Cu}(T,B)} dT$

"Mega I I t"

From quench start



It means that the time integral of magnet current squared,
a.k.a. **MIITs** /another term is "quench integral"/,
is directly related to the **hot-spot temperature (T_{max})** and can be parametrized.

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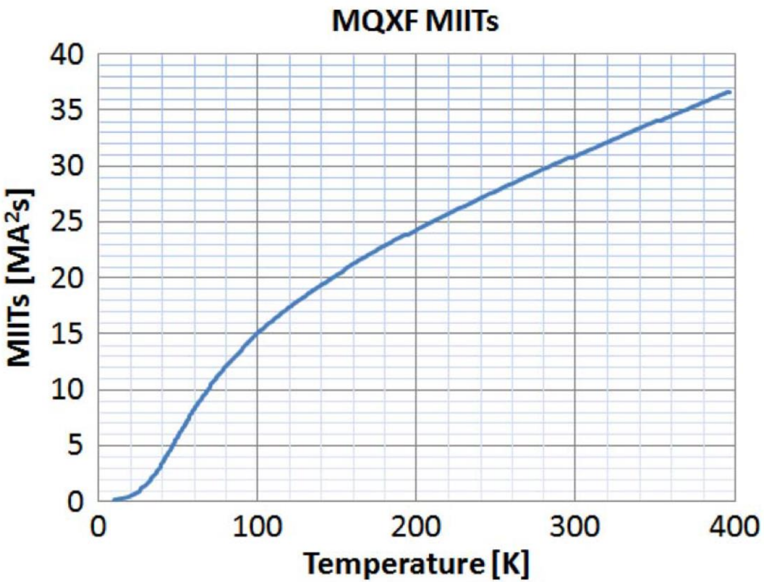
MIITs-hot-spot-temperature relation

V. Marinozzi *et al.*, "Quench Protection Study of the Updated MQXF for the LHC Luminosity Upgrade (HiLumi LHC)," in *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 4, pp. 1-5, June 2016, Art no. 4001805, doi: 10.1109/TASC.2016.2523548.

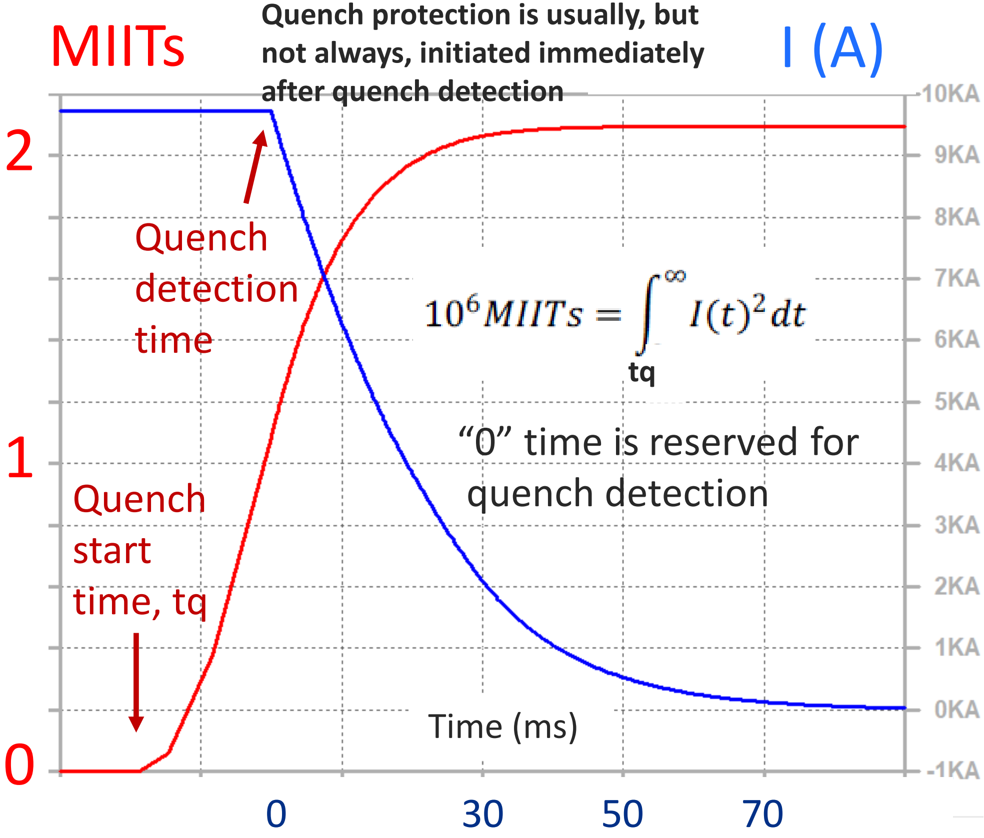
- MIITs-temperature relation depends on the concrete case (magnet design including conductor properties, conditions)

- The maximum MIITs (or temperature) allowable is also debatable, higher temperatures are associated with higher risks
  - Fast thermal expansion of materials (temperature gradient) creates large stresses
  - Coil interfaces are particularly vulnerable

- For accelerator magnets the range 250-300 K for the hot spot is considered safe, for larger and "unique" magnets this may be 100-120 K (it also depends on design considerations)



MIITs accumulation



To calculate MIITs one needs to know what the quench start time is and the current as a function of time

There are two parts of the quench integral – **before quench detection/protection and after it**. The former is characterized by nearly constant current (ms scale usually) and the latter sees sudden current decrease.

Quench detection delays are easy to account for: current at 10 kA will lead to 1 MIITs for each 10 ms quench detection delay, current at 20 kA – 4 MIITs for each 10 ms

Quench protection chain

Quench

Normal zone growth

Detection

Power supply switched off

Trigger protection options

Protection heaters | Extraction | Quenchback

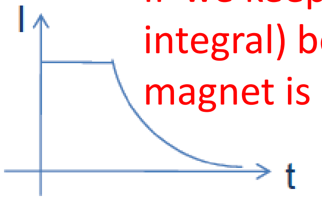
Current decay in the magnet

Something, likely some energy dissipation, causes a quench

If energy is enough, i.e. above MQE, a MPZ is created and the normal zone continues to expand (quench propagation)

We detect the quench – this is the main topic of the present lecture

We do something about it (magnet protection)



IF we keep MIITs (the quench integral) below limits the magnet is safe

Quench protection methods – popular choices

To protect a magnet from reaching high hot-spot temperature after quenching there are multiple measures that can be taken, in addition to proper conductor and magnet design

- Joule heating on large part of the coil and creating large normal, i.e. non-superconducting, volume to mitigate point-like energy dissipation in the coil
- Inducing electrical oscillations (or high current gradients) to create large normal, i.e. non-superconducting, volume by coupling losses in the conductor stabilizer
- Extracting part of the energy through an external “dump” resistor
- Extracting part of the energy through a coupled magnet (circuit)

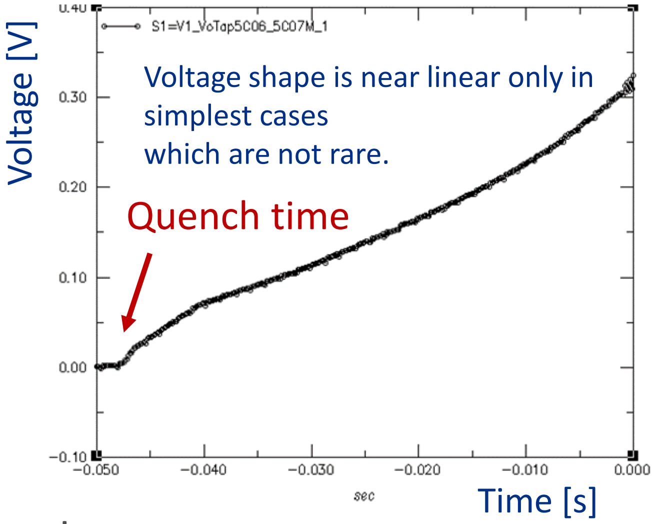
You will hear much more about quench protection* in separate lectures

*Quench protection and magnet protection have the same meaning

How do we know a quench occurs

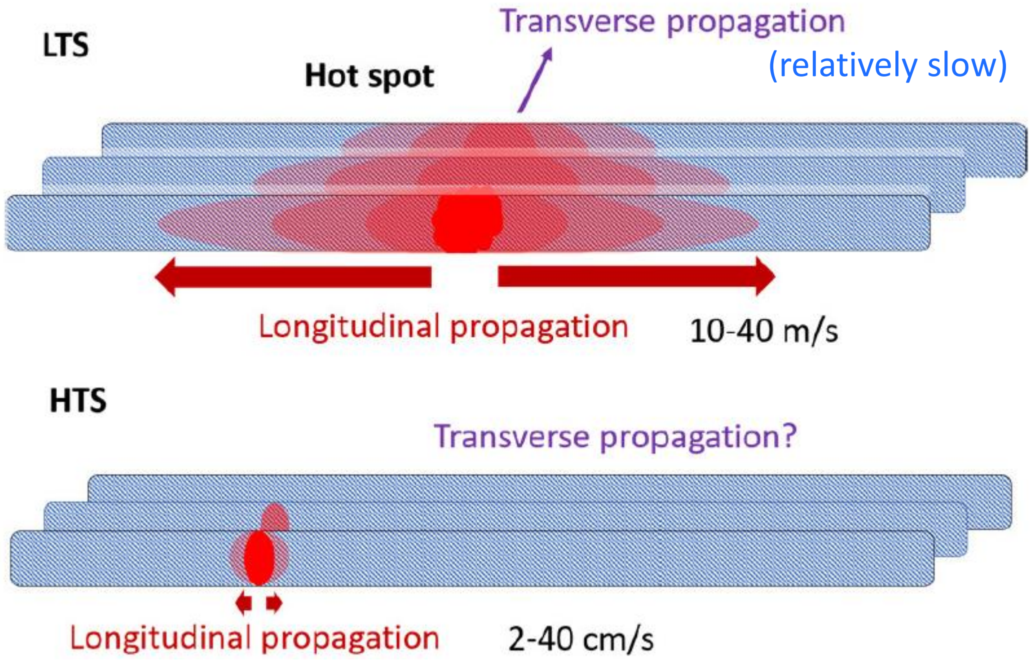
- By definition, a quench requires some part of the magnet/coil to become normal
- As current still flows through the magnet some non-zero voltage starts to develop
- Due to the nature of quenching, the normal zone expands, and more cable length becomes resistive, i.e., **resistance grows**
- Due to Joule heating **resistance also grows** per unit of conductor (Cu resistivity between 20 and 300 K grows typically by 100-200 times, depending on Cu purity/quality)
- Ultimately, **voltage** across the expanding normal zone also grows and can be measured
- "How fast" is what makes this very reliable quench detection method not entirely universal, but quite dominating for LTS (low temperature superconductors) at least

Voltage across the resistive part of the SC coil



Resistance grow during quench

Marchevsky, Maxim. (2021). Quench Detection and Protection for High-Temperature Superconductor Accelerator Magnets. Instruments. 5. 27. 10.3390/instruments5030027.



(relatively slow)

Resistance develops mainly due to quench propagation: **normal zone grows in size**

Voltage will increase fast

Resistance develops mainly due to heating of a hot spot: **normal zone heats up**

Voltage will increase <u>not so</u> fast

You will learn more about "HTS" specifically in other lectures

Quench propagation velocity

The velocity by which quench propagates can be calculated and it is approximately (adiabatic approximation):

Current density

$$v_{long} \approx v_{adia} \approx \frac{J_e}{\gamma C_{p,av}} \left(\frac{\rho_{Cu} k_{av}}{\Delta T} \right)^{1/2}$$

Transverse quench propagation is much slower than longitudinal propagation (10-100 times) because of insulation. Other than that, the same formula for propagation velocity applies (with different parameters accounting for insulation).

where $C_{p,av}$ and k_{av} include only copper
where $\Delta T = T_s - T_0$ with T_s average temperature between critical temperature and current sharing temperature

Note that the important practical variable is current density.
Still, if the conductor is “pre-heated” (any resistance developed or present along the path, eddy currents, …) ΔT gets lower than nominal, and the velocity also increases that way.

Higher the velocity, faster the resistance development, faster the quench detection.

Detection is typically faster at higher currents

Importance of fast quench detection

- It is obvious that we want to detect a quench as soon as possible
- Sometimes we have very stringent limits on MIITs (hot spot temperature) – every ms matters; this is often the case
- In other times (different magnet designs, conductor, conditions) we are more relaxed MIITs-wise but then we could explore protection options
  - the current decay shape depends on quench protection parameters chosen
- All magnets also have a “self-protection” regime in which MIITs are below limits even if no protection action is taken (current decays due to normal zone resistance)
  - this is usually the case at low currents but in many cases, it is for really very-very low currents – away from any operationally significant ones
  - in fact, fast detection at low-to-mid current has limitations due to “instabilities”
  - also, slower quench propagation at low current means “adiabatic approximation” eventually stops being a good approximation for MIITs

What quenches? (everything that can)

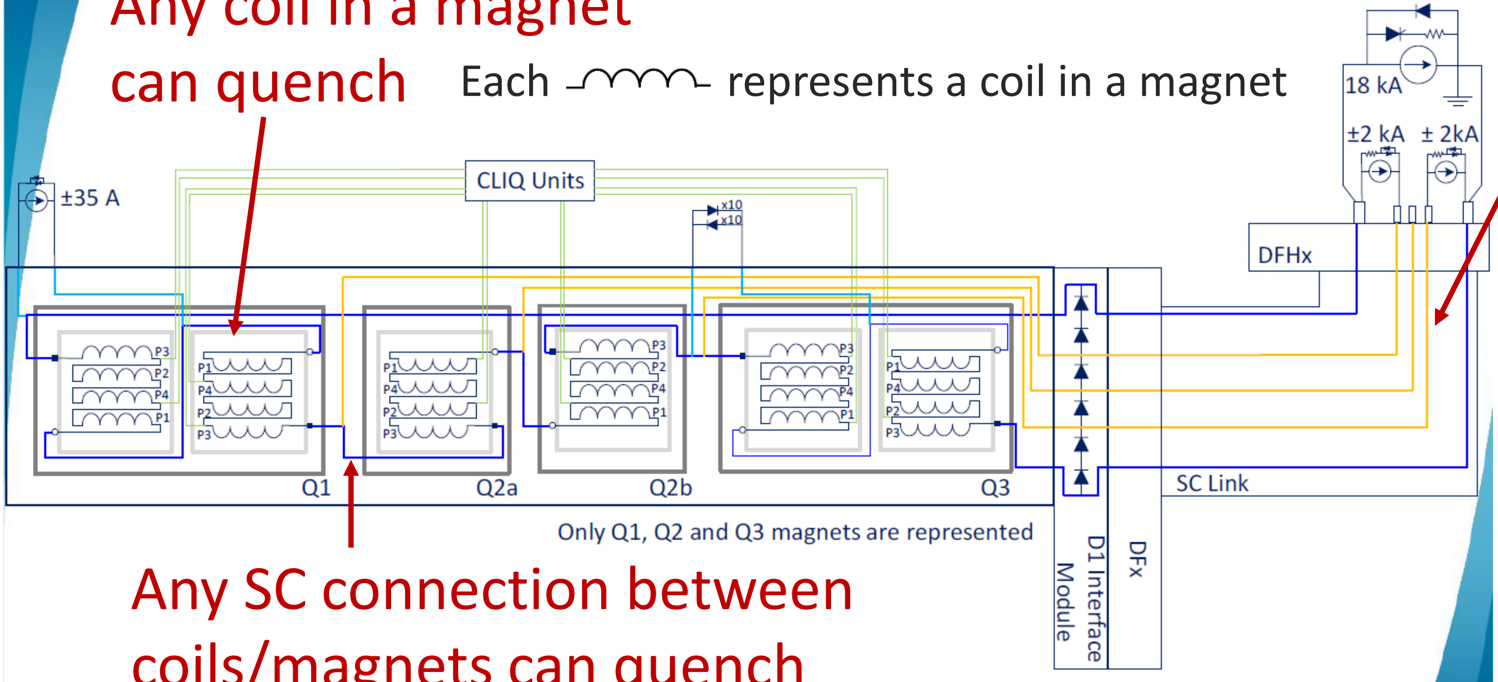
https://indico.cern.ch/event/835702/contributions/3503949/attachments/1903781/3143546/Intro_FRM_v1_1.pdf

An example multi-magnet setting

Any coil in a magnet can quench

Each represents a coil in a magnet

Any SC lead (connection) to the PS can quench



Any SC connection between coils/magnets can quench

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Areas of interest for quench detection/protection

Remember that the critical surface is governed by T, B and I. The current is the same through the whole magnet circuit but the temperature and magnetic field are not!

- Magnet (coils) – in magnetic field, in cooling liquid (usually; they could be conduction cooled, or forced flow cooled) inductive
- Superconducting leads – not in (strong) magnetic field, in cooling liquid (usually)
  - Cable connections between magnet and non-superconducting leads
  - Cable connections between superconducting coils
  - All of those are often NbTi or some of them could be HTS

not inductive

- Splices/joints between leads above - can be of special interests (they are not fully superconducting)
- Non-superconducting leads - partially in liquid (usually)
  - our power supplies are at room temperature and eventually we have to transition to conventional conductors (thick copper able to carry high current)

Quench detection requirements

- A quench must be detected 100% of the times (>0.9999 fraction of cases?)
  - if it is not, a detailed investigation will be launched to find reasons and make corrections
  - each quench has the potential to destroy an expensive object (magnet) and the infrastructure may need repairments too
  - a lot of time and resources are wasted
- False triggering should be minimized if not eliminated (<0.01 fraction of cases?)
  - it is still expensive to recover from a false quench/trip
  - multiple use of protection devices could damage integrity (temperature, voltage)
  - the magnet itself may get degraded after multiple “false” or real quenches

“Bucking” (cancellation of one signal or part of a signal by another signal)

- Relative measurements are typically much more precise and “clean” than absolute measurements
- Measured voltage signals in magnets are often noisy (long cables, inductive) but noise* in different parts of the circuit is usually in the same phase (correlated)

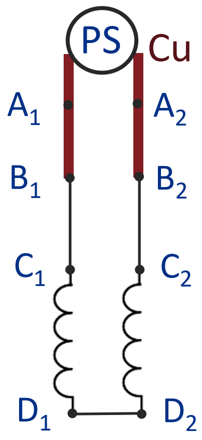
- Thus, subtracting of signals, or “**bucking**” is by far the most important type of quench detecting signal: $det = X - aY$ with a being a balancing parameter
  - the alternative is to have a lot of false triggers due to noise (often spikes)

- Bucking is also used to link a signal to “expected” values: $det = X - aE$ with E – expected signal (if we know it)

*In any case – using “twisted pairs” for signal wires is the norm

Typical quench detection signals (conceptually)

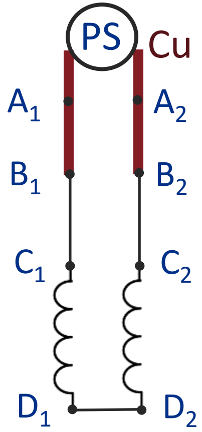
Oversimplified magnet circuit



- Let coils between D's and C's are from a dipole magnet
- The line between D's is a superconducting connection between the coils
- The lines between C's and B's is a superconducting connection between the magnet and copper leads
- The line between B's and A's is some "cold" part of the conventional connections to the power supply (PS)
- A's, B's, C's, D's are voltage taps (we can measure voltage)

Typical quench detection signals (conceptually)

Oversimplified magnet circuit



- **When the magnet is superconducting and current increases**:

  Voltage between A's and B's, i.e. $V(A_i,B_i)$, increases (Ohm's law)

  $V(B_i,C_i) = 0$, superconducting cable, non-inductive

  $V(C_i,D_i)$ increases due to magnet/coil inductance ($V = L_i\ dI/dt$),

  $V(C_1,C_2)$ increases as well

  However, $det(idot) \equiv V(C_1,C_2) - a\ L_{mag}\ dI/dt = 0$ (for proper $a \sim 1$)

- **When the magnet quenches in coil** C_1-D_1

  $V(C_1,D_1)$ increases while $V(C_2,D_2)$ will react inductively (smaller -V);

$det(half\text{-}coil) \equiv V(C_1,D_1) - b\ V(C_2,D_1)$ increases as well and is less noisy

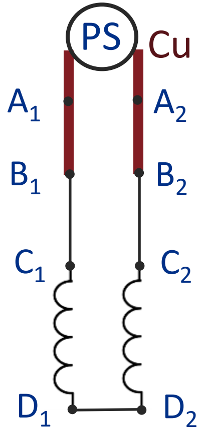
- **When a quench occurs in cable** B_1-C_1

  $V(B_1,C_1)$ increases: $det(SC\ lead) \equiv V(B_1,C_1)$

- **When the copper is over-heated** resistance will grow well above nominal values (resistivity is T-dependent): $det(Cu\ lead) \equiv V(A_1,B_1)$

Typical quench detection signals (conceptually)

Oversimplified magnet circuit



$$det(\textbf{half-coil}) \equiv V(C_1,D_1) - b\ V(C_2,D_1)$$

In multi-coil systems one could use many similar combinations

$$det(\textbf{idot}) \equiv V(C_1,C_2) - a\ L_{mag}\ dI/dt$$

One could use individual coils too (similarly)

If a quench is exactly "in the middle" of the magnet (a.k.a. "symmetric quench") ***det(half-coil) = 0;*** usually a single "mid-point" (D_1) is used to define the signal

a and *b* above are tunable parameters and are not current-dependent (but L usually are…)

$$det(SC\ \textbf{lead}) \equiv V(B_i,C_i)$$

$$det(Cu\ \textbf{lead}) \equiv V(A_i,B_i)$$

Lead signals

$V(D_1,D_2)$ could be a separate "lead" signal

Noise, instabilities, flux-jumps and other treats

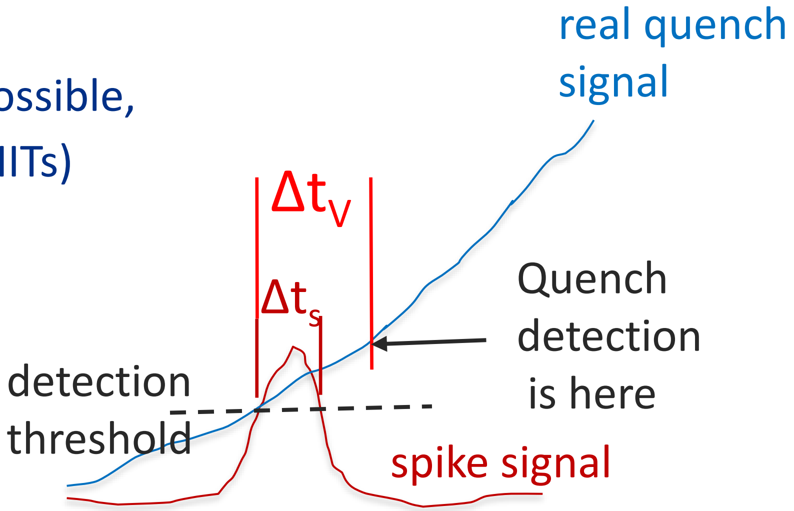
- It is difficult to get rid of all noise (often voltage spikes) in the system
  - Especially if the system is an old one
  - It may be random or permanent (modulated?) noise
  - Some events may cause it (PS switch ON, power tools ON/OFF, …)

- At low currents (mostly at few kA) there are “flux jumps”
  - Fluxoids through the superconductor (type II) tend to move and it is more difficult to “pin” them at low current due to conductor instabilities
  - The result is a lot of real current-dependent voltage spikes (the opposing electric field induced by the fluxoids motion can be represented as resistance to the current flow)

- Some signals may be particularly sensitive to noise (bad shielding, electrical loops) or not well balanced (“bucked”) which may look like noise

Main considerations for detection algorithms

- Current dependent thresholds for some signals
  - it is more difficult to fight low current “noise”
  - it is important that our thresholds are lowest possible, especially at high current (fast accumulating MIITs)
- Avoiding spikes
  - ”signal” rises fast but then drops fast – it is only above a threshold for some time
  - introducing “validation time” for detection:



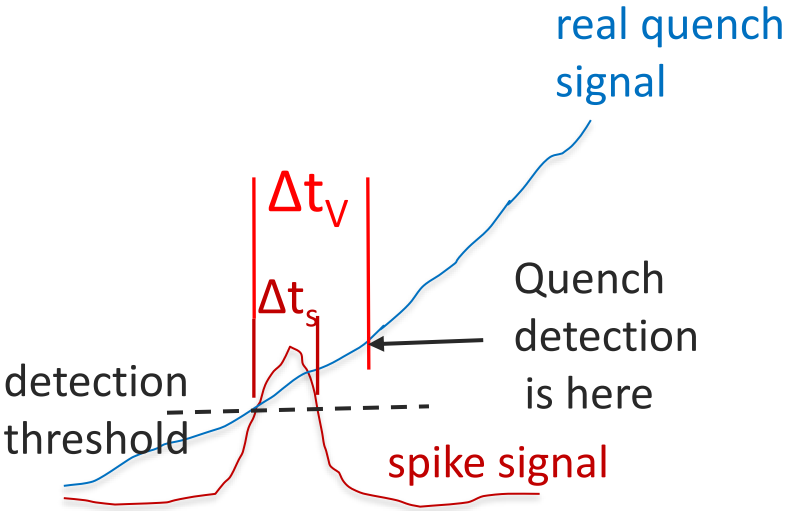
If the detection signal drops below threshold within a specified time window, Δt_V (validation time), detection trigger is not issued

- Validation time can also be current dependent
- Each detection signal will have its own thresholds and validation times

More details…

Validation times cause an obvious delay for quench detection but avoid false triggers. Depending on the type of spikes and the rise of real quench signals you may find you are better off increasing the threshold and not using validation time at all. But then you rule out possibility of very large narrow spikes…

In the arbitrary example on the right just raising the threshold above the spike peak will give me the same or better (shorter) detection time for the real quench.



How well can we know expected spike characteristics (flux jumps? others?) and the expected voltage increase rate during quench?

Quench protection is usually, but not always, initiated immediately after quench detection (ASAP).

Tuning of thresholds and validation times is typical.

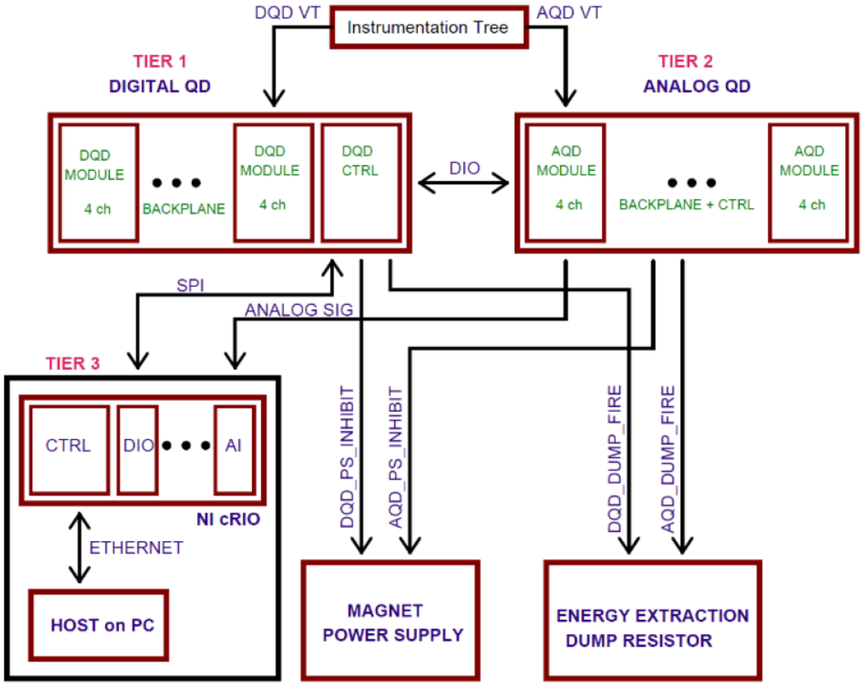
Risk management

- A detection system can rely on just few "important" detection channels as long as all quench regions are covered by it
  - Simplicity means less opportunities for encountering issues
- Alternatively, especially for multi-coil systems, one can have a lot of detection channels, some possibly redundant
  - More channels already suggests higher efficiency to detect a quench
  - More complicated detection logic guarantees more troubles and more false detections
- Usually there are two independent detection systems in case one malfunctions
  - the whole logic can be covered in an alternative way – like using DQD (digital quench detection) and AQD (analog quench detection); in OR condition
  - or if you are "sure" in the logic performance/reliability – two DQD systems (in OR condition)
- Consider also duplicating the source of "important" detection signals
  - voltage taps and signal wires can be duplicated or triplicated for independent processing

Typical actions from a quench detection system

Signal	Action	Comment
Magnet quench signal	When threshold is reached, quench detection triggers after validation time	Those are often "bucked" signals
SC or Cu Lead quench signal	When threshold is reached, quench detection triggers after validation time (protection delays, if any, are often by-passed here)	Those are usually absolute signals – they are not too noisy, voltage rise is predictable and meaningful constant thresholds can be set; Cu leads are a relevant marker
Ground fault, equipment malfunctioning detection, external fault detection	Issues a "slow ramp down" signal for the current to be reduced to 0; no quench detection trigger is issued but the system is "armed" and can still detect and react to a quench	Any "fault" condition will cause "safe" current reduction but this is different than "quench detection" – no quench protection is initiated (there is no quench to protect from).

Quench detection/protection systems – implementations



A. Galt *et al.*, "A Quench Detection and Monitoring System for Superconducting Magnets at Fermilab," in *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 6, pp. 1-4, Sept. 2022, Art no. 9500404, doi: 10.1109/TASC.2022.3155492.

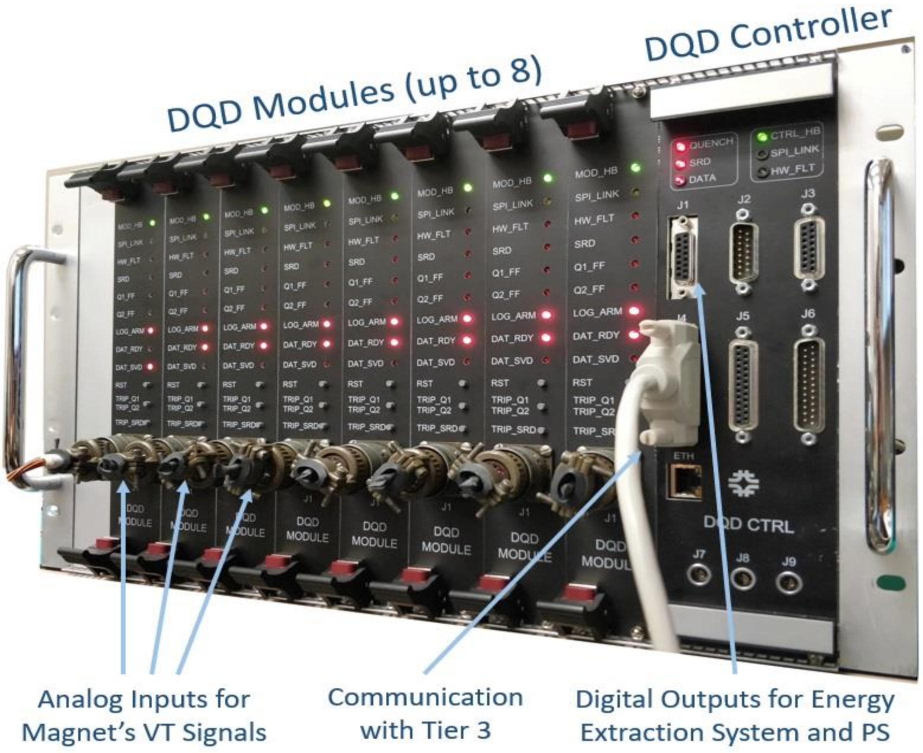
Quench Detectors & Management

FNAL developed for the Mu2e experiment, replicated for HL-LHC support at FNAL

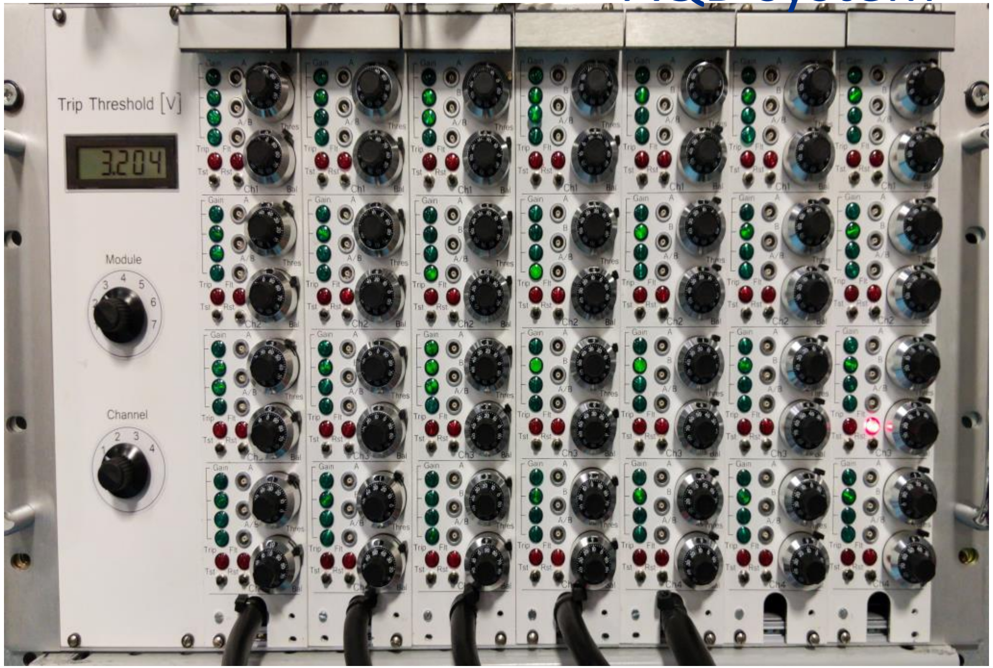
- **Primary Digital Quench Detection (DQD) hardware system**
- **Redundant Analog Quench Detection (AQD) hardware system**
- **Tier 3 Quench management system, based on National Instruments C-RIO. The quench management system provides quench configuration, control and monitoring, and quench data management.**

Quench detection/protection systems – implementations

FNAL developed for Mu2e



AQD system



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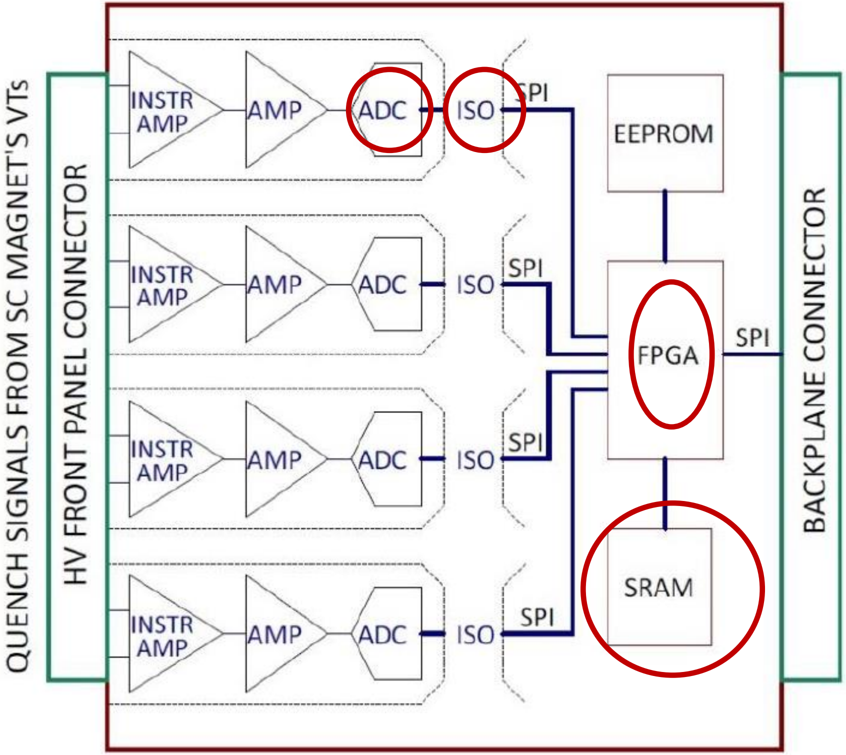
Quench detection/protection systems – implementations

FNAL developed for Mu2e

DQD Module Block-Scheme



external SRAM memory

circular buffer size is 60 kS/channel (480 kS/module)

inputs have 2 kV channel-to-channel and 2 kV channel-to-ground galvanic isolation

16-bit ADC

signal is sent to FPGA via the digitally isolated SPI interface

Quench detection/protection systems – implementations

FNAL developed for Mu2e

Integration

Quench Logic & Protection

A hardware quench logic module (QLM) carries out the critical hardware-based quench logic, such as:

- Various protection circuits control logic

- Energy extraction system enable and discharge control

- Power system enable and phase back, and slow ramp down.

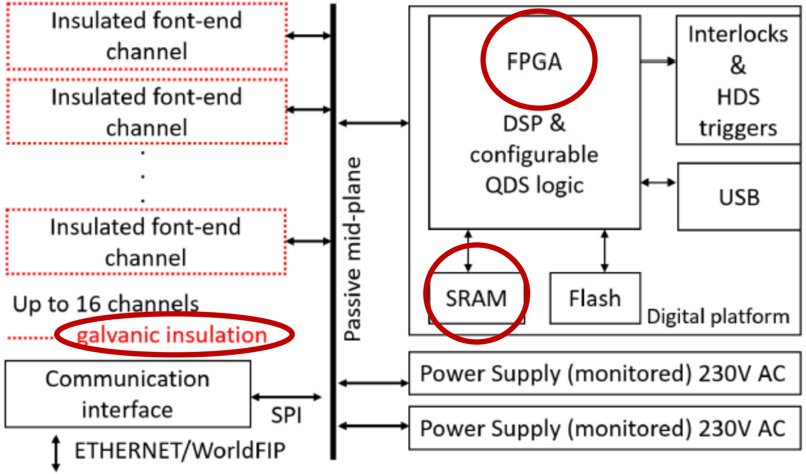
PS Control and Monitoring

- **Subordinate PLC to monitor temp, water pressure, DCCTs and Dump Switches status**
- **2x Active Ground Fault Detectors**
- **PS consists of Switching Power Supply modules and I-regulator**
- **NI c-RIO based I-control produces open loop Current set-point (Custom profile or periodic waves)**
- **PS Ethernet monitoring for Fast Trip Module and Imbalanced Current protection**
- **Optical fiber based Current readout and distribution**

Quench detection/protection systems – implementations

CERN developed for HL-LHC

Front-side view and block-diagram of UQDS (universal quench detection system)



R. Dentz et al., “Quench detection and diagnostic systems for the superconducting circuits for the HL-LHC”, 10th International Particle Accelerator Conference, Melbourne, Australia, 19 - 24 May 2019, pp.THPTS036

J. Steckert et al., "Application of the Universal Quench Detection System to the Protection of the High-Luminosity LHC Magnets at CERN," in IEEE Transactions on Applied Superconductivity, vol. 32, no. 6, pp. 1-5, Sept. 2022, Art no. 4006305, doi: 10.1109/TASC.2022.3152125.

UQDS units are always deployed as a set of two independent units reading signals from two redundant sets of instrumentation voltage taps

Quench detection/protection systems – implementations

CERN developed for HL-LHC

UQDS:

- FPGA of type M2GL150 and high-resolution ADCs of type LTC2378
- The front-end channels can sample up to 700 kHz
- Separating the inputs from local ground using digital isolators
- Differential voltages up to 1 kV can be tolerated for a short time
- Digital logic device executing the quench detection algorithm
- Interlocks which activate protection devices
- Communications module to connect to controls system

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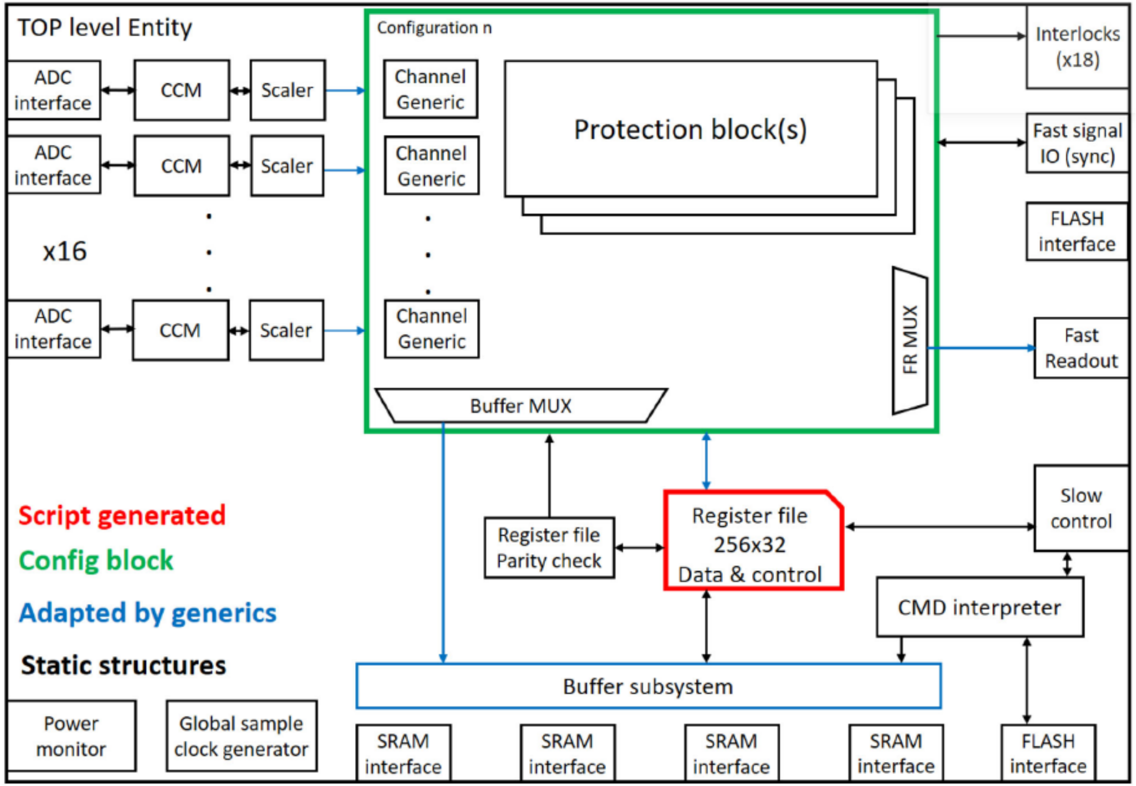
Quench detection/protection systems – implementations

CERN developed for HL-LHC

Block diagram of the UQDS firmware structure



This structure and the usage of verified code blocks allows to generate a new application specific firmware within days.

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Novel quench detection methods

- Voltage development is mostly sufficient quench detection method for LTS

- For HTS, at least, anything else is on the table
  - Quench antenna signals, acoustic signals (passive and active approaches), optical-fiber based info (stress/temperature), stray capacitance, "second sound" , RF-based signals, etc.
  - You can compliment all this by Machine Learning techniques combining the above (possibly including voltage development too)
- The two main requirements remain, and this is the non-trivial part

  High efficiency of detecting quenches (~100%) and fast (safe)

  Low probability of false triggers (<0.01? <0.001?)
- Using a single sensor-type method alone assumes full superconductor coverage and enough sensitivity; it may be more reasonable to combine several methods for better detection

Summary

- Superconducting magnets quench and they need to be protected
- Standard methods for quench detection are based on voltage measurements, and they work well and are reliable for LTS
- Quench detection systems have, in essence, two requirements

  Very high efficiency of detecting quenches

  Low probability of false triggers

- Redundancy is an important way of risk mitigation, but sometimes this leads to more false triggers (often needs retuning)
- Large labs typically have developed “standard” quench detection systems which can be used in different experimental settings
- For HTS, especially/at least, new quench detection methods are being developed