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EASISchool 3

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Superconducting dipoles and quadrupoles for accelerators

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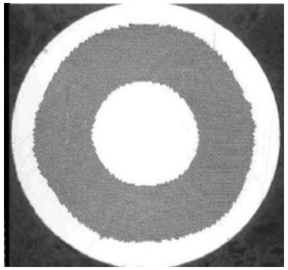
Based on USPAS lecturers from Paolo Ferracin, Soren Prestemon,
Ezio Todesco and Helene Felice

Goal of the course

- Overview of superconducting magnets for particle accelerators (dipoles and quadrupoles)
  - Conductor
  - Magnetic design
  - Mechanical design
  - **Quench protection**

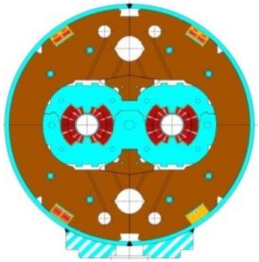
Conductor, Magnetic design: Stefania Farinon

Mechanical design, Quench protection: Susana Izquierdo Bermudez


Superconducting strand


Superconducting cable


Superconducting coil


Superconducting magnet

Outline

- Quench definition and protection strategies (self dump vs external dump)
- Heat balance equation, hot spot temperature and time margin
- Quench propagation
- Protection systems in accelerator dipoles/quadrupoles: quench heaters and CLIQ

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Quench Definition

Quench = irreversible transition to normal state

- **Heat generation > cooling**

Why do magnets quench?

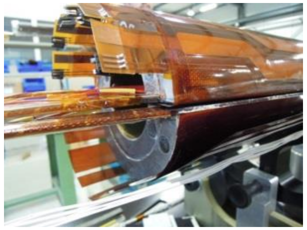
Thermal energy released by

- **Mechanical events**
  - Frictional motion
  - Epoxy cracking
- **Electromagnetic events**
  - Flux-jumps ,AC loss
- **Thermal events**
  - Degraded cooling
- **Nuclear events**
  - Particle showers

What do we do when a magnet quenches?

Conversion **magnetic energy** → **thermal energy** (redistribute the energy in the whole coil volume, joule heating)

$$E_m = \int_V \frac{B^2}{2\mu_0} dv = \frac{1}{2} L I^2 \longrightarrow J^2 \eta$$



Why is it a problem ?

- Quench is the result of the resistive transition, leading to appearance of voltage, temperature increase, thermal and electro-magnetic forces, and cryogen expulsion
- If the process does not happen uniformly: as little as 1 % of the magnet mass may absorb the total energy – large damage potential !

Result of the chain of events triggered by a quench in an LHC bus-bar

Result of degradation due to local heating in a NbTi coil

Result of electrical short circuit quench heater to coil in a Nb_3Sn coil

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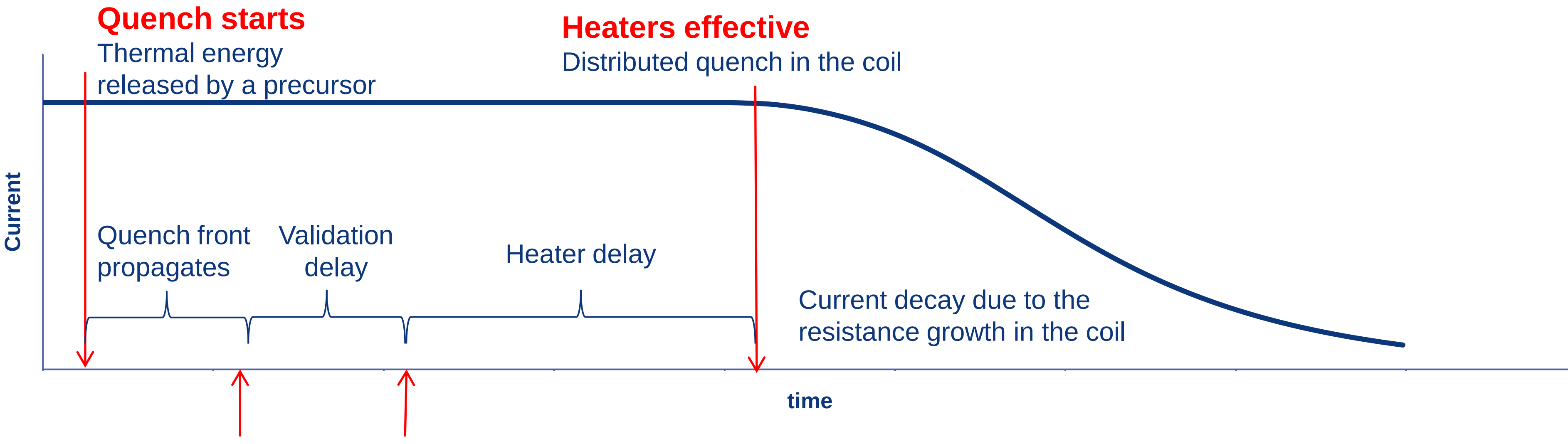
The quench event: summary



Quench starts
Thermal energy released by a precursor

Heaters effective
Distributed quench in the coil

Current decay due to the resistance growth in the coil

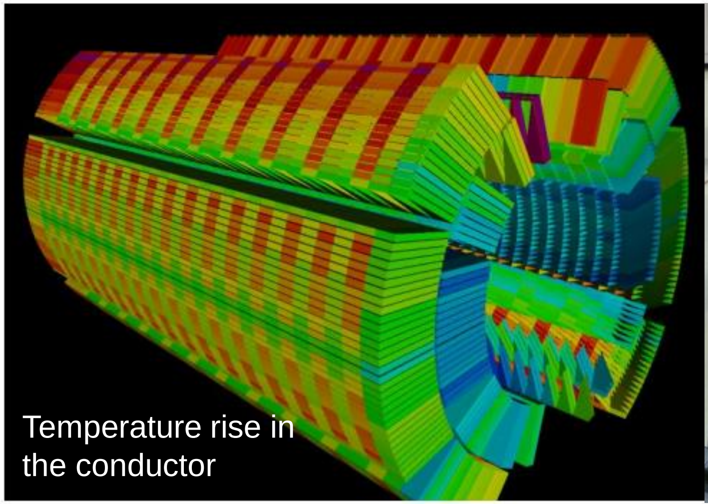
Quench detected

Quench validated
(power supply off, protection system fired)

Typical time scale:

- From quench start to quench detected ~ 5 ms
- Validation delay ~ 10 ms
- Heater delay ~ 20 ms
- Current decay ~ 100-200 ms

Maximum acceptable temperature: **350K**



Temperature rise in the conductor

Protection strategies

Two limiting cases in terms of magnet protection strategy:

1. **External-dump**: The magnet is dumped externally on a large resistance ($R_{dump} >> R_{quench}$) as soon as the quench is detected (e.g. ITER)

2. **Self-dump:** The circuit is on a short circuit and is dumped on its internal resistance ($R_{dump} = 0$) (e.g. LHC). Actually, external dump is not an option for a chain of accelerator magnets.
   Typical $J_{Cu} \approx 1000 \ldots 1250$ (A/mm^2)
      Meaning $dT/dt \approx 1000 \ldots 2000$ (K/s)
      We need to dump quickly! $\tau(300\text{ K}) \approx 0.15 \ldots 0.3$ (s)
   $I_{op} \approx 15$ (kA)
   $E/l \approx 1000$ (kJ/m)

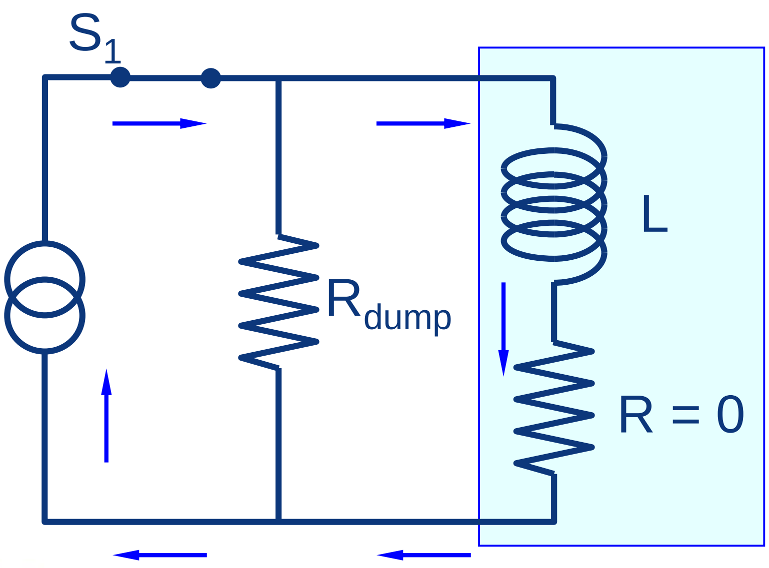
$$\frac{\mathbf{V}}{\mathbf{l}} \approx \frac{\mathbf{2E}/\mathbf{l}}{\boldsymbol{\tau}\mathbf{I_{op}}} = \mathbf{500 \ldots 1000\ V/m}$$

Protection strategy – External dump

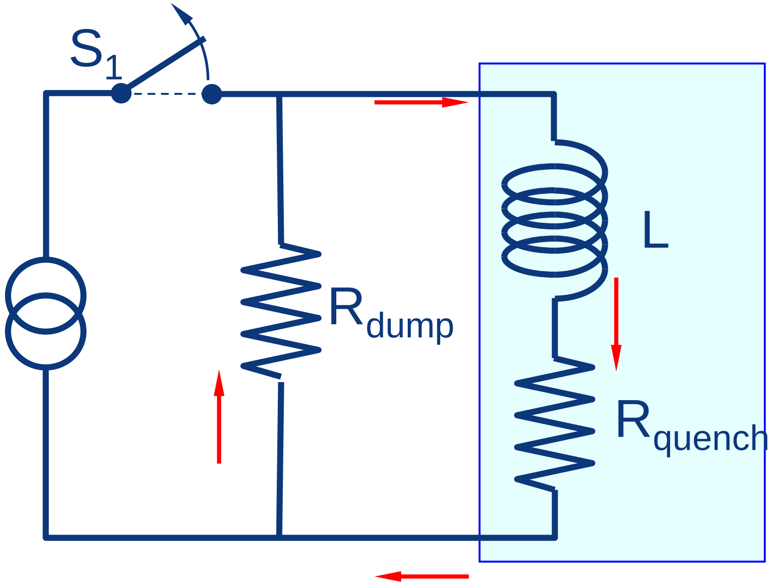
- The magnetic energy is extracted from the magnet and dissipated in an external resistor:

$$I(t) = I_0 \exp\left(-\frac{t}{L}R(t)\right) \approx I_0 \exp\left(-\frac{tR_d}{L}\right)$$

normal operation



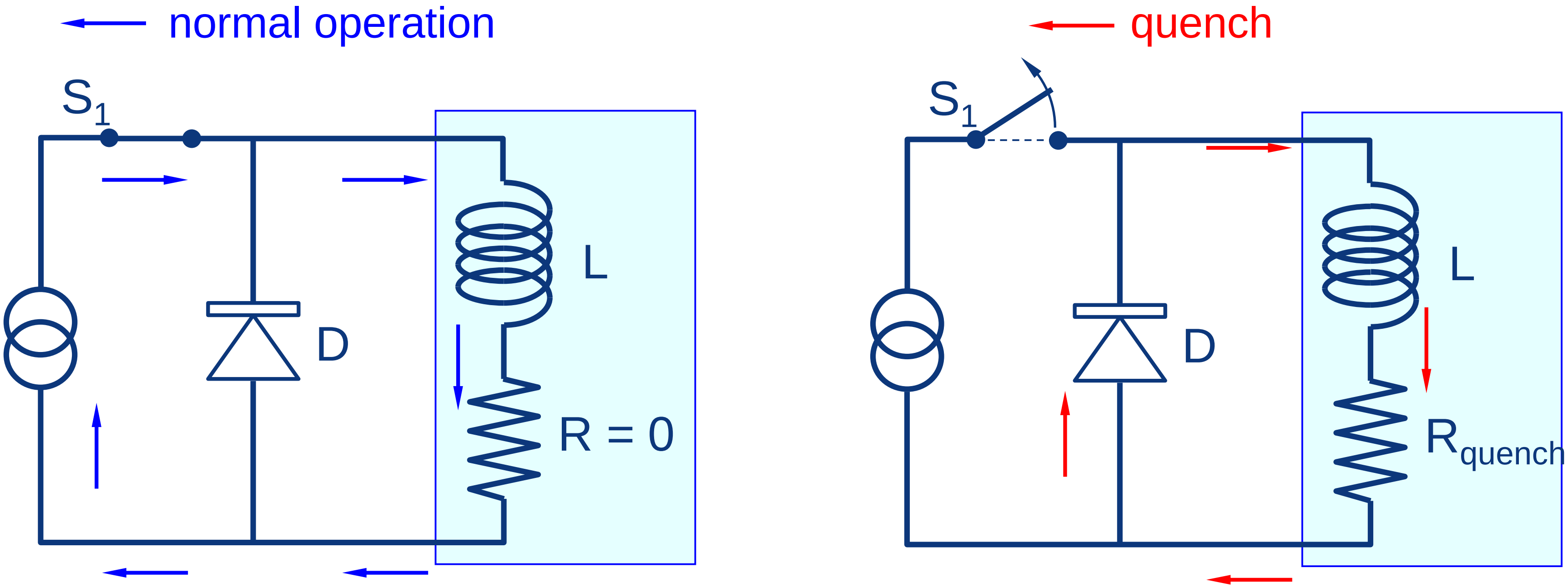
quench



Protection strategy – Self dump

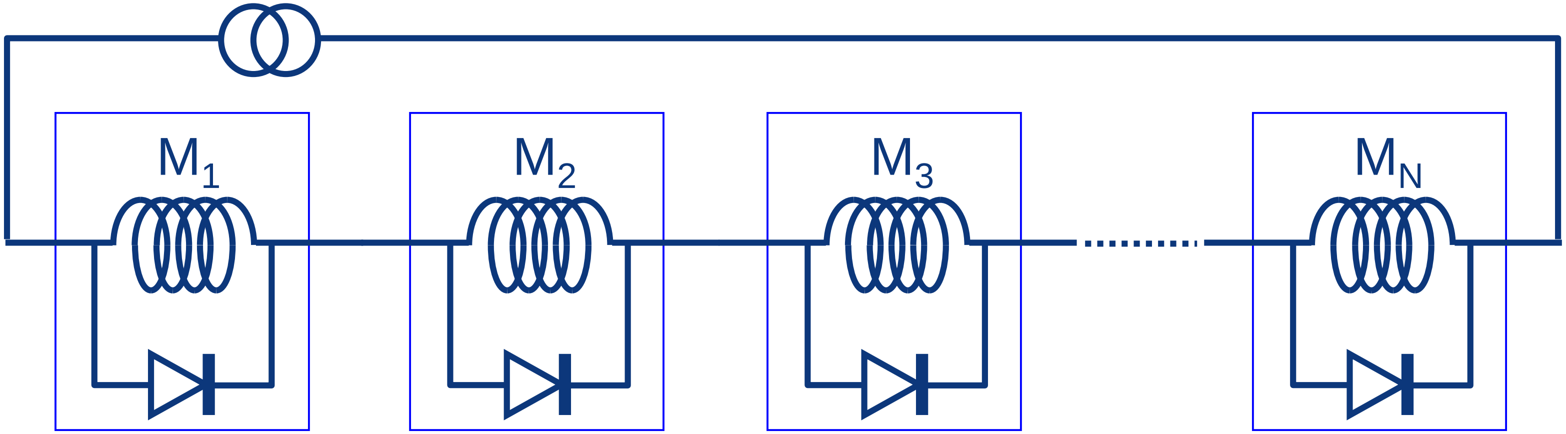
In the case of the LHC, the magnetic energy is completely dissipated in the internal resistance, which depends on the temperature and volume of the normal zone

(when increasing the temperature the material becomes resistive→ resistance increase→ current decrease (fix voltage))



Protecting a magnet string

- Magnet strings (e.g. accelerator magnets, fusion magnetic systems) have exceedingly large stored energy (10’s of GJ):
  - energy dump takes very long time (10…100 s)
  - the magnet string is *subdivided* and each magnet is by-passed by a diode (or thyristor)
  - the diode acts as a shunt during the discharge



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Adiabatic heat balance

- The simplest (and conservative) approximation for the evolution of the maximum temperature during a quench is to assume adiabatic behavior at the location of the hot-spot:

$$\boxed{A\overline{C}\frac{\partial T_{cond}}{\partial t} = A q''_{joule} \rightarrow \overline{C}\frac{\partial T_{cond}}{\partial t} = \eta_{Cu} J^2}$$

Average heat capacity: $\overline{C}(T) = \sum_i f_i \rho_i c_i$

Electrical resistivity of the stabilizer (Cu): $\eta_{Cu}(B, RRR, T)$

- The circuit is a RL circuit
  - with the magnet inductance L
  - and a highly variable resistance R(t), growing with time
  - the higher the resistance, the faster the current dump, the lower hotspot

$$\boxed{L\frac{\partial I}{\partial t} + RI = 0}$$

Hot spot temperature

- Adiabatic conditions at the hot spot:

$$\overline{C}\frac{\partial T_{cond}}{\partial t} = \eta_{Cu} J^2$$

- Can be integrated

$$\boxed{\int_{T_{op}}^{T_{max}} \frac{\overline{C}}{\eta_{Cu}}\, dT} = \boxed{\int_0^{\infty} J^2\, dt}$$

Ability of the cable of « taking » the current (combination of enthalpy and resistivity): **Quench capital (Γ)**

Load due to the current decay, that should be made as fast as possible and is an observable: **Quench tax**

Protection limit

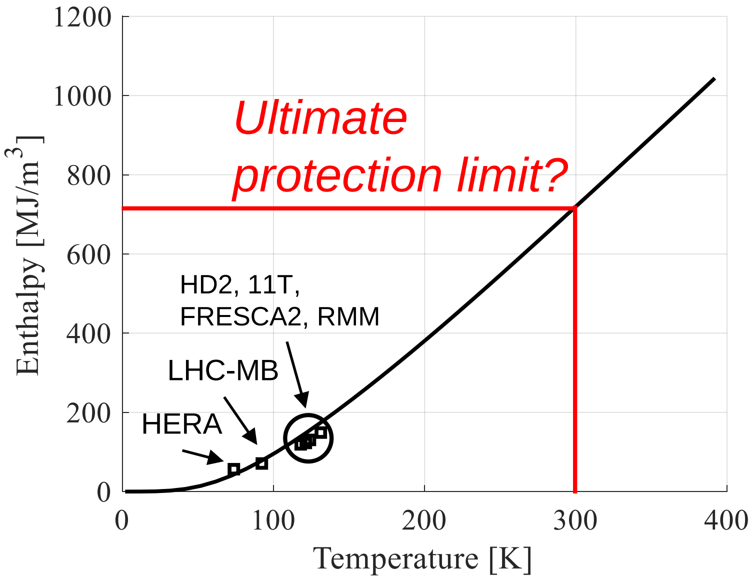
- Ideal case: all magnet is quenched at the quench start

Assuming adiabatic conditions

$$\frac{E}{V} = \int_{T_{op}}^{T} \overline{C}(T)\,dT$$

$\frac{E}{V}$	Magnet stored energy per unit volume.
$\overline{C}(T) = \sum_i f_i \rho_i c_i$	Volumetric heat capacity of the cable

i = copper, superconductor and insulation.



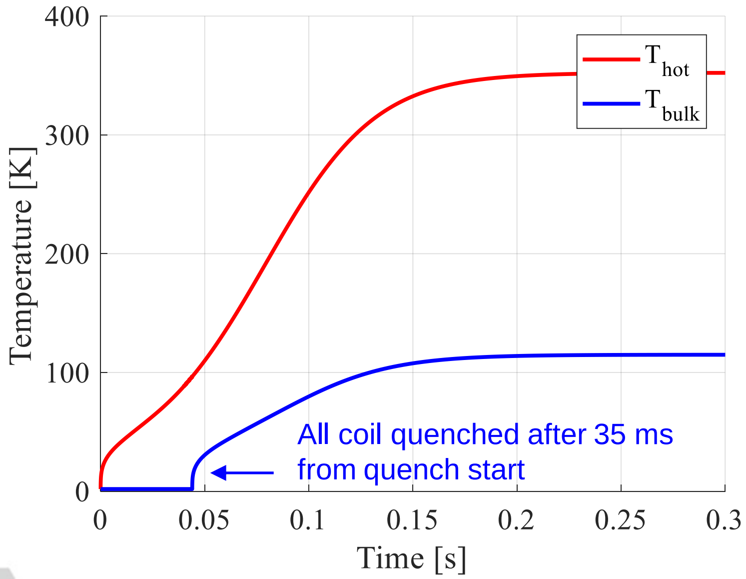
Enthalpy of the strand volume (neglecting the insulation)

- Reality: we need time to detect, validate and quench the magnet.

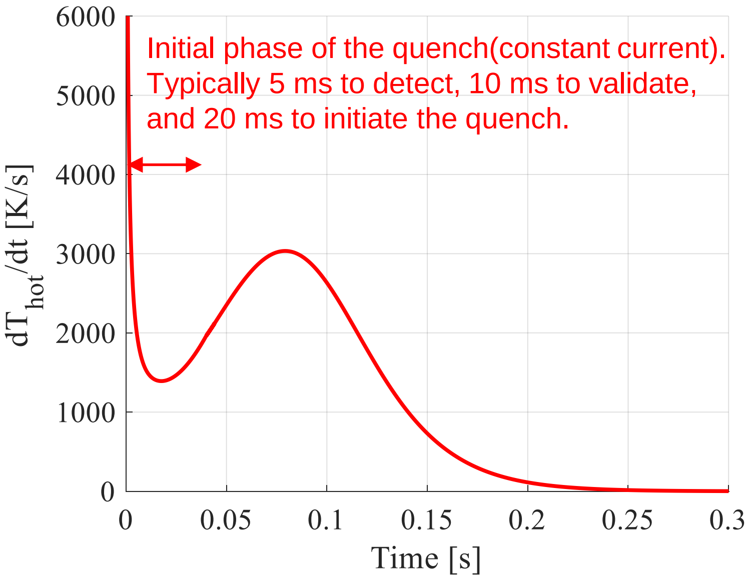
Detection and quench initiation

- The time needed to detect, validate and quench the coil is very expensive in terms of temperature rise. And here is where current density become critical!
- This is what we typically call ‘time margin’ (≈ 40 ms in HL-LHC Nb_3Sn magnets, ≈ 100 ms in LHC MB dipoles)

$$\frac{dT_{hot}}{dt} = \frac{I^2}{(A_{Cu} + A_{SC} + A_{ins}) \cdot A_{Cu} \cdot \Gamma(T,B)} \qquad \Gamma(T,B) = \frac{\overline{C}(T)}{\eta_{Cu}(T,B)}$$



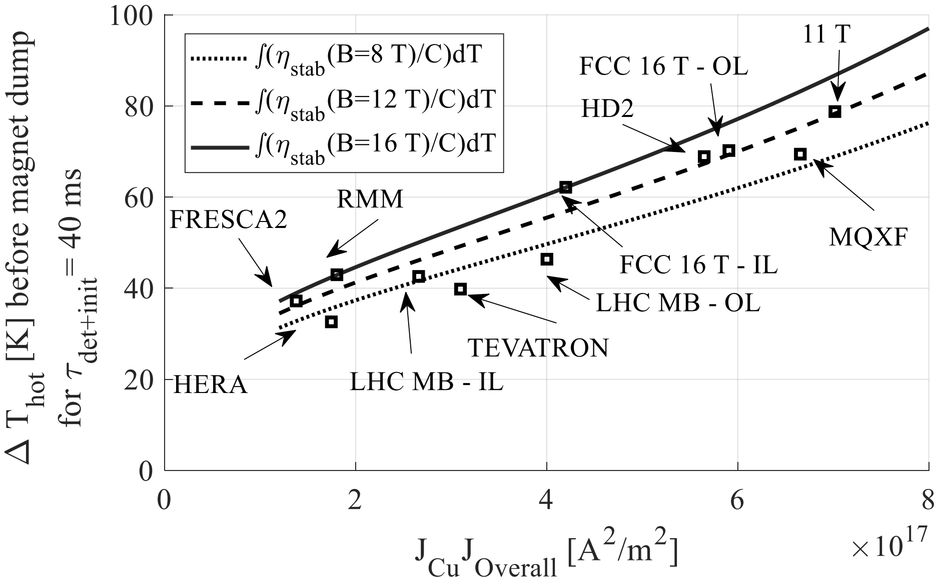
All coil quenched after 35 ms from quench start

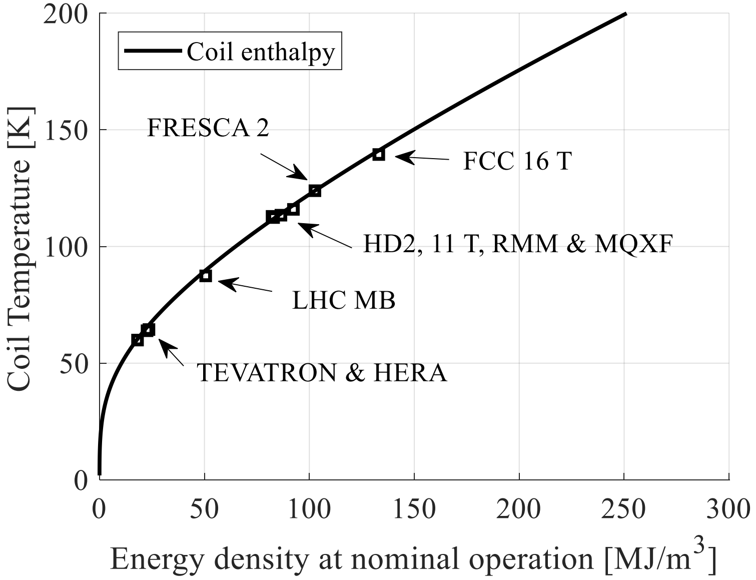


Initial phase of the quench(constant current). Typically 5 ms to detect, 10 ms to validate, and 20 ms to initiate the quench.

‘Basic’ ingredients for protection

- Thus, the two key parameters for the protection of a magnet are:
  - Current density in the copper (heating rate)
  - Energy density in the coil (needs to be dissipated in the coil enthalpy)
- Compact high field magnets require both!





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Quench propagation - longitudinal

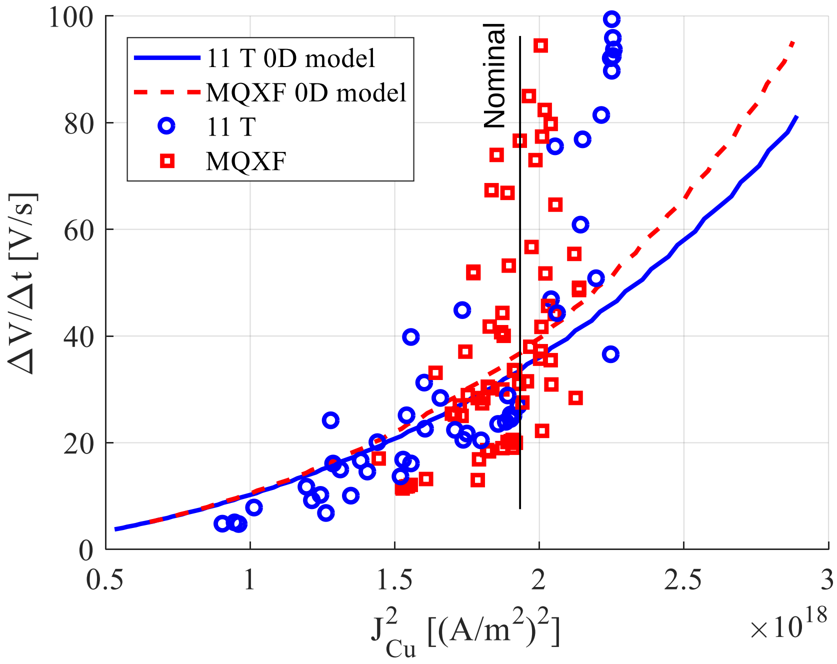
- Voltage growth $(V(t))$:

$$V(t) = 2J_{op} \int_0^{v_Q t} \bar{\eta}\,(T(x,t))dx$$

- Quench propagation in the initial phase

$$v_Q = \frac{J_{op}}{\bar{C}} \sqrt{\frac{\bar{\eta}\bar{k}}{(T_{joule} - T_{op})}} = \beta J_{op}$$

Typical velocity in the HL-LHC Nb$_3$Sn magnets is 10-20 m/s

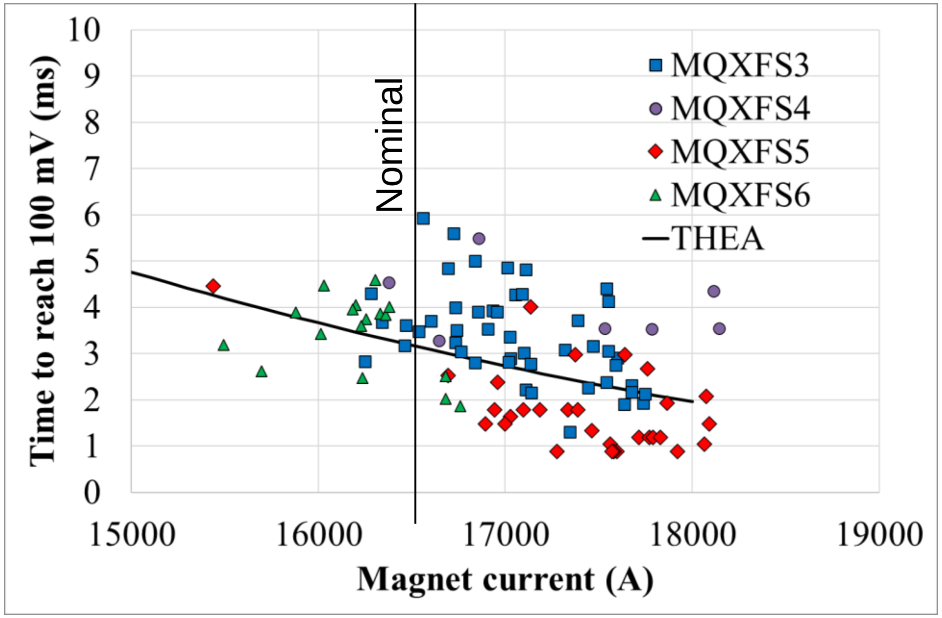


- The resistivity of the stabilizer is approximately constant for T < 20 K (η_{low}) → constant voltage rise with time.

$$V(t) = 2J_{op} \int_0^{v_Q t} \eta_{low}\,dx = 2\eta_{low}\beta J_{op}^2 t$$

Quench propagation - longitudinal

- The detection threshold are defined through two parameters:
  - A voltage level (above the noise level) – typically 100 mV → 3-5 ms at nominal
  - A validation time (to reject spurious spikes in voltages) – typically 10 ms



- Voltages staying above voltage level for a time longer than validation time are interpreted as a magnet quench, and activate the protection system
  - Therefore on the time needed to detect the voltage, one has to add the validation time ~ 15 ms

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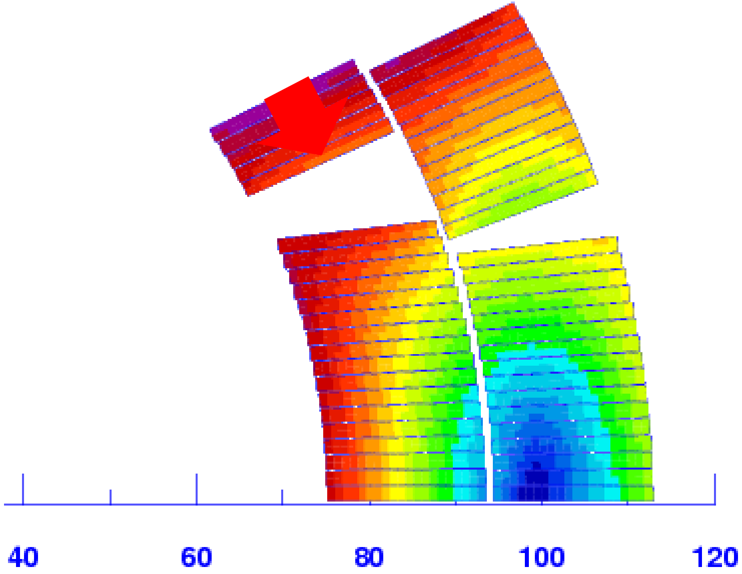
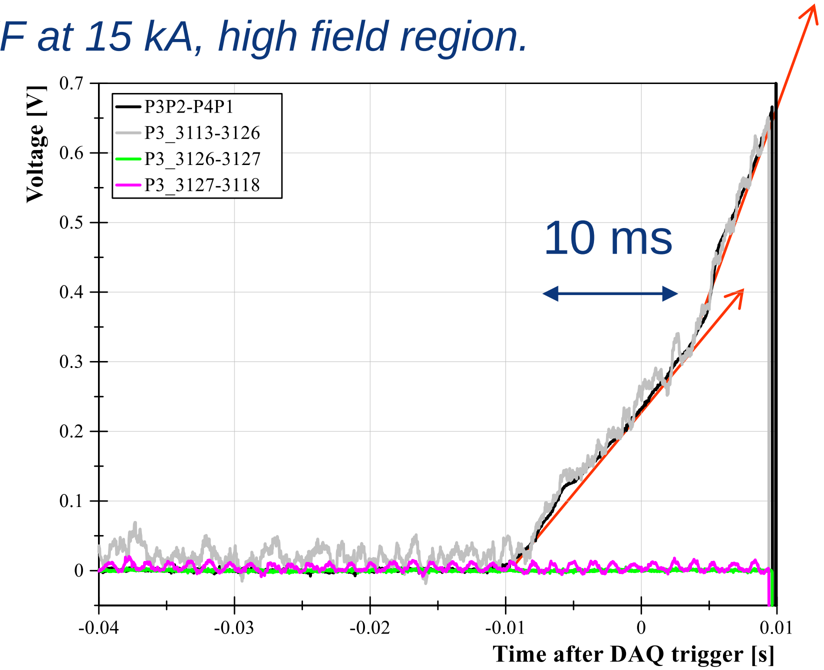
Quench propagation – transversal

- Order of magnitude of propagation time from turn to turn in the high field area of HL-LHC Nb_3Sn magnets is ~ 10 ms
  - It depends on the temperature margin and insulation scheme between layers.

Turn to turn propagation in MQXF at 15 kA, high field region.



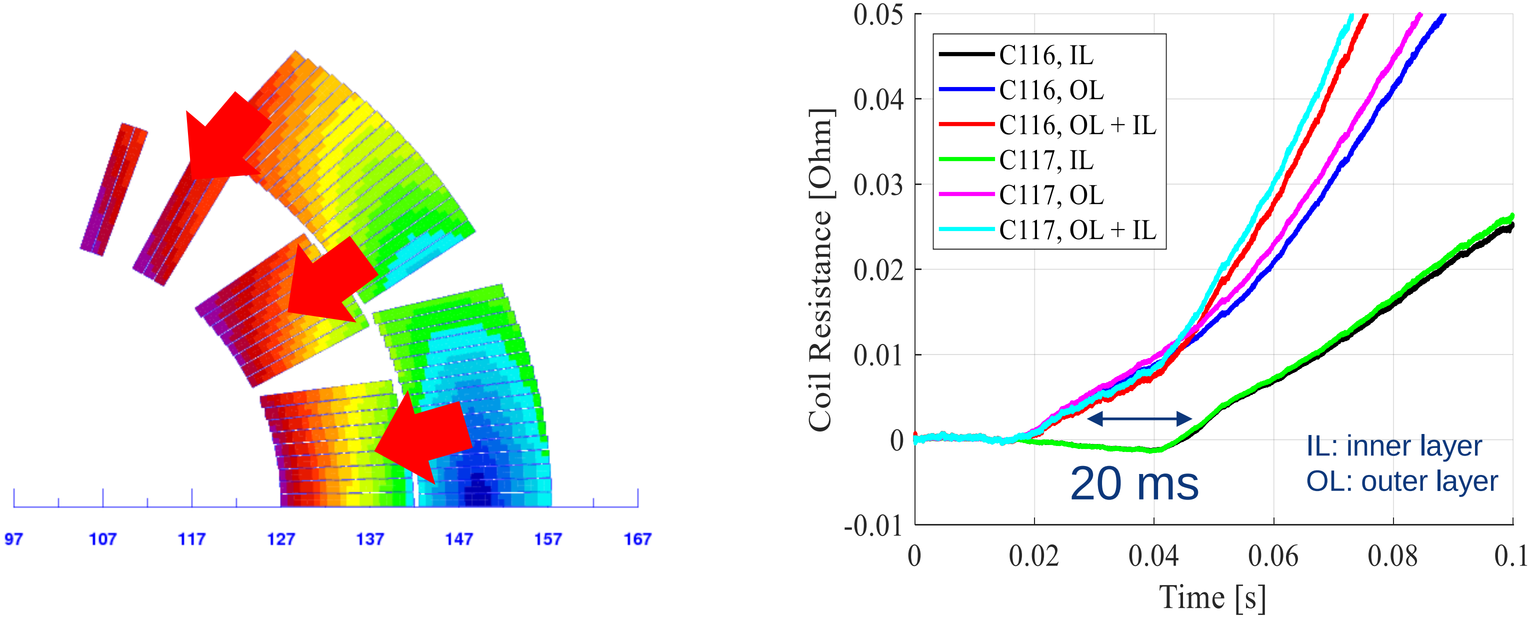


(courtesy of SM18 team at CERN)

Quench propagation – transversal

- Order of magnitude of propagation time from inner layer to outer layer in HL-LHC Nb_3Sn magnets is ~ 20 ms
  - It depends on the temperature margin and insulation scheme between layers.

Layer to layer propagation in the 11 T dipole at nominal current



(courtesy of SM18 team at CERN)

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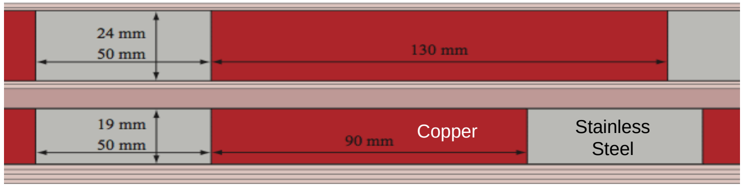
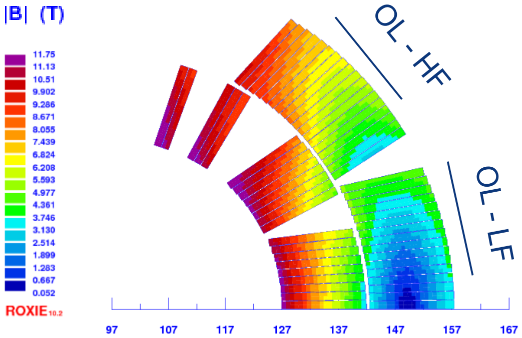
Quench heaters

- Principle: temperature rise in the conductor through the heating of metal strips attached to the coil.
- They are typically installed in the outer surface of the coil

11 T Heater Lay-Out (only outer layer heaters)

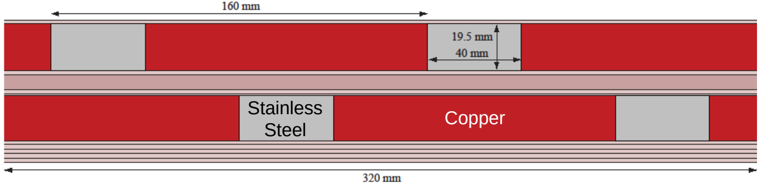
Outer layer heater design



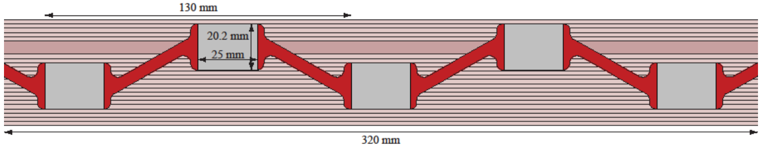


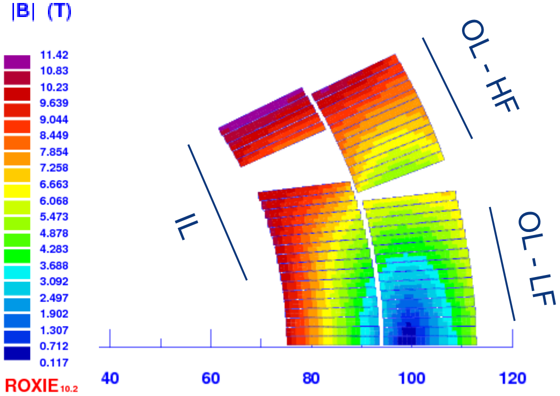
MQXF Heater Lay-Out (heater in the inner and outer layers)

Outer layer heater design



Inner layer heater design

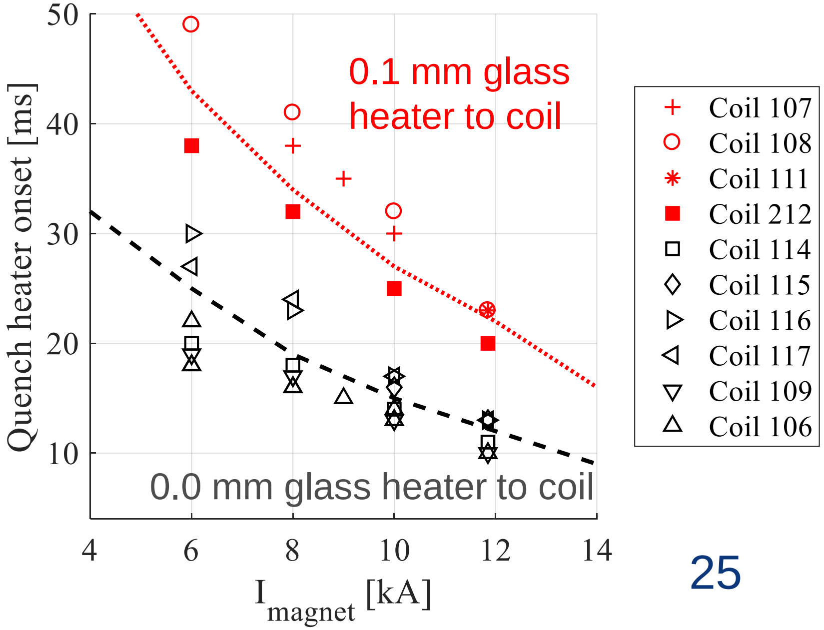




Quench heaters

- The quench heater strip is made by stainless steel, usually 25 µm thick, bonded to layer of polyimide (75 µm thick in the LHC dipoles, 50 µm thick in the HL-LHC magnets)
  - Copper plating of the stainless steel needed to reduce the strip resistance and limit the quench heater to coil voltage.
- One has to guarantee two conflicting conditions:
  - A good electrical insulation between heater and coil
  - A good thermal conductivity between heater and coil
- In Nb_3Sn magnets, quench heaters are sometimes impregnated with the coil → polyimide in direct contact with the conductor insulation.
- If heaters are installed after impregnation, additional layer of S2 glass (typically 0.1 mm thick) between heater and conductor increases the heater delay by ≈ 10 ms

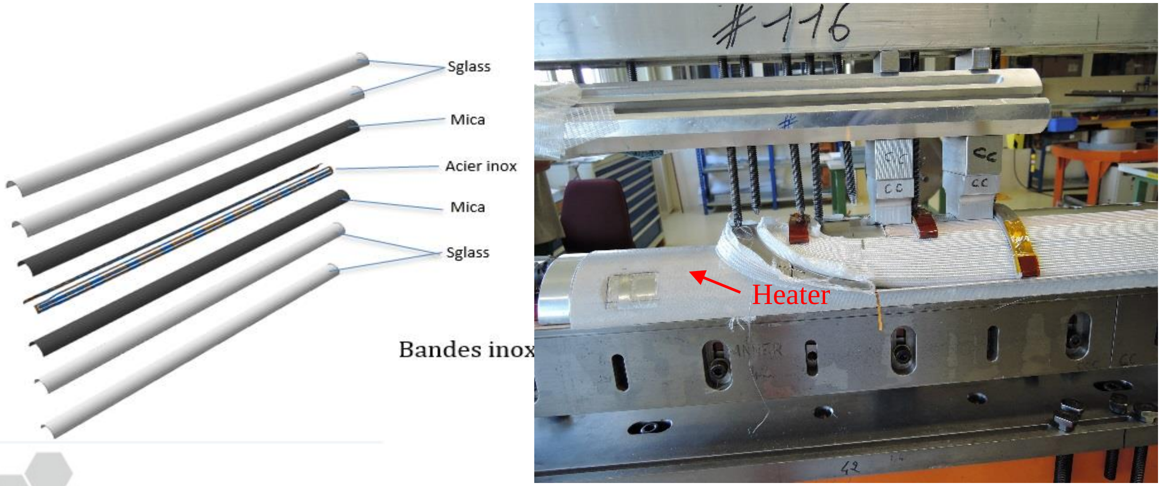
Quench heater delay in the 11 T dipole



Quench heaters

- Attempts have been done in the 11 T and MQXF Nb_3Sn magnets for the HiLumi upgrade to quench faster the inner layer:
    - An interlayer heater must be reacted with the coil
        - Main critical point is integration
        - Two heaters were lost in the first test, and this option has still to be explored
    - Inner layer heaters showed a non negligible rate of heater circuits lost, and evidence of detachment of the heaters from the coil (bubbles)

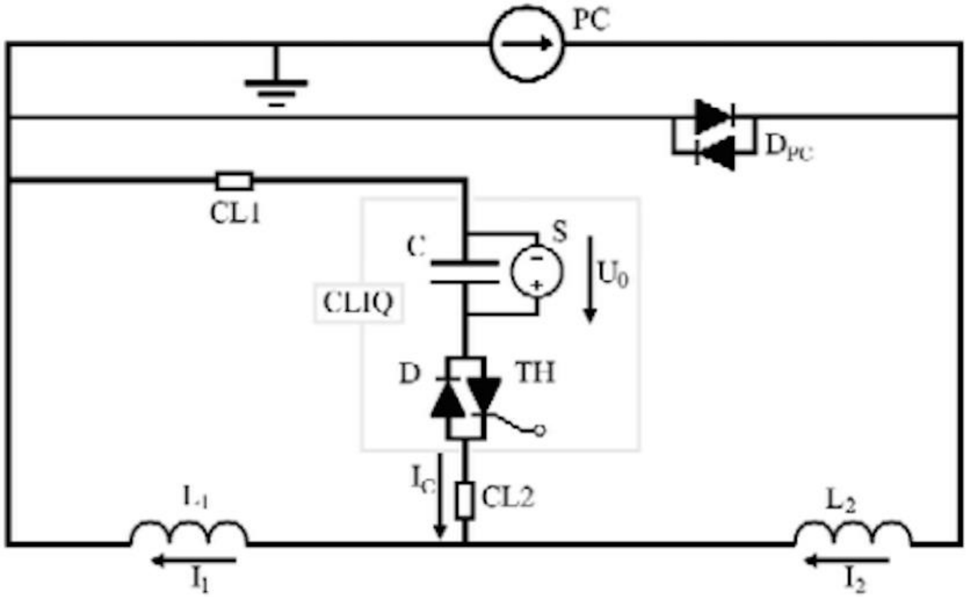
Inter-layer heater in a 11 T coil



Inner layer heater in a MQXF coil after coil powering

CLIQ

- CLIQ (Coupling Losses Induced Quench)
  - This system is based on injecting in the magnet coils two opposite impulses of current via a capacitor
  - The mechanism is the heating due to interfilament coupling losses induced by the variation of the field
    - It has been developed at CERN and patented in 2014 (EP13174323.9)

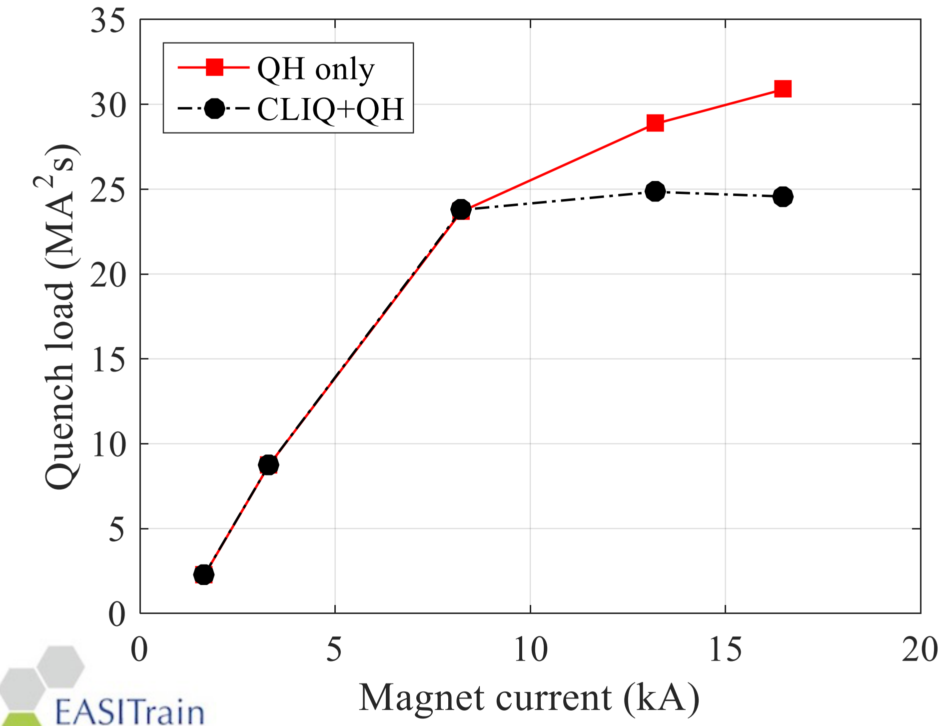


Electrical scheme of CLIQ implementation in a dipole
G. Kirby, V. Datskov, E. Ravaioli et al. IEEE TAS 24 (2014) 0500905

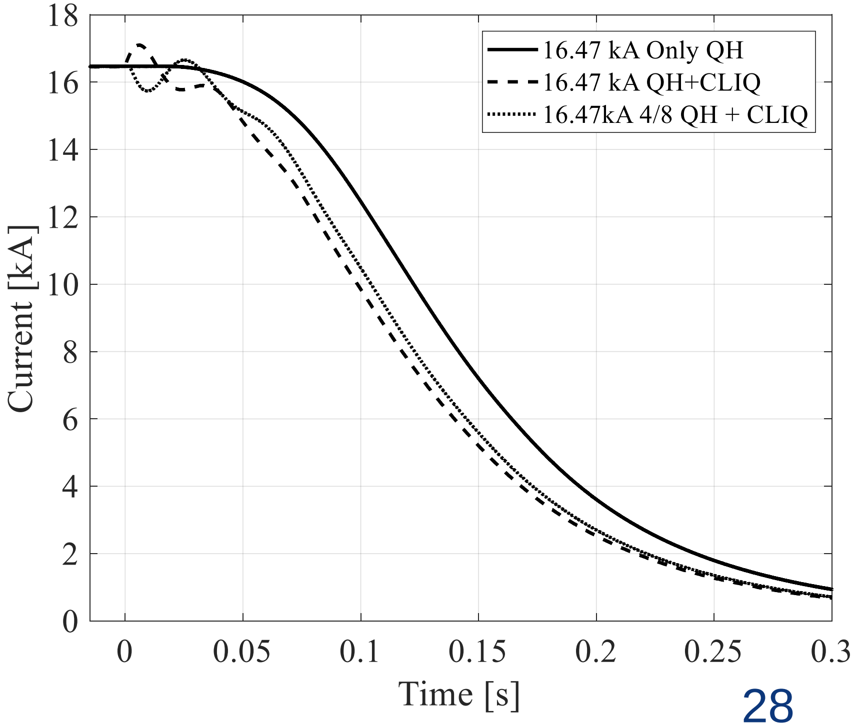
CLIQ

- In combination with QH, provides a redundant protection system. In the case of MQXF, it reduces the quench load by 20 % at high current, decreasing the hot spot temperature by~ 100 K.
- The baseline protection scheme of the HL-LHC MQXF quadrupole relays on CLIQ + QH, a prima for accelerator magnets.

Comparison of quench load in MQXF magnets when protected only with QH and QH+CLIQ



Current decay in MQXF for CLIQ + QH or QH only protection



Summary

- Magnet protection concerns two different phenomena: increase of temperature (joule heating) and increase of voltage (transition to resistive state).
- The two key parameters for the protection of a magnet are:
  - Current density in the copper (heating rate)
  - Energy density in the coil (needs to be dissipated in the coil enthalpy)
- A resistor in series with the magnet allows to dump part of the energy, but it is not effective for long magnets or magnets in a string due to the voltage limitation.
- For long and high current density, the protection relies on the induction of a rapid transition to resistive state in the full coil.
  - In the LHC-MB NbTi magnets, the time margin is ≈ 100 ms.
  - In the HL-LHC Nb_3Sn magnets, the time margin is ≈ 40 ms.

Summary

- The typical time needed to detect and validate a quench is 15 ms.

- Two systems to induce a resistive transition in the full coil:
  - Quench heaters: temperature rise in the conductor through the heating of metal strips attached to the coil.
  - CLIQ: temperature rise in the conductor through the inter-filament coupling losses induced by the variation of the field.

- Today a total of 40 ms for quench detection, validation and delay of heater or CLIQ is the minimal value for the magnets to be installed in the HL-LHC. It is also the target for FCC magnets.

- R&D magnets explored the possibility of further reducing the time margin to 20 ms, but with features that look problematic for an accelerator magnet (robustness, redundancy, failure…)

References

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- More on quench propagation and scaling :
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- U.S. Particle Accelerator School, lectures from Ezio Todesco, http://etodesco.web.cern.ch/etodesco/
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    - H. Felice, et al., “Instrumentation and quench protection for LARP Nb3Sn magnets” IEEE Trans. Appl. Supercond. 19 (2009) 2458-2462
    - S. Izquierdo Bermudez, et al., "Overview of the quench heater performance for MQXF, the Nb$_3$Sn low-beta quadrupole for the high-luminosity LHC" IEEE Trans. Appl. Supercond. 28 (2018) 4008406
    - T. Salmi, et al., “Quench protection analysis integrated in the design of dipoles for the Future Circular Collider” Phys. Rev. STAB 20 (2017)