Magnet protection

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Merge of the two masterclasses given during Covid-19 pandemic:
Protection principles https://indico.cern.ch/event/926967/
Protection systems https://indico.cern.ch/event/940961/
… and based on the USPAS units of Helene Felice, LNBL, now at CEA, Saclay France
… plus Chapter 9 of M. Wilson book "Superconducting magnets"
Thanks to T. Salmi, S. Izquierdo Bermudez for contributions

All the units will use International System (meter, kilo, second, ampere) unless specified

These slides made with a Mac, if you do not see the equations properly use the pdf

PROLOGUE

- When a local transition of the superconductor to normal state has a set of parameters (current density, conductivity, resistivity, temperature margin) that exceeds the minimum propagating zone, the heat cannot be removed via conduction, and the transition to normal conducting state propagates to the whole conductor in an irreversible way (this is what we call a quench)
  - k: conductibility
  - T_c: current sharing temperature
  - T_{op}: operational temeprature
  - j: current density
  - ρ: resistivity

$$l_{mpz} = \frac{1}{j}\sqrt{\frac{2k(T_c - T_{op})}{r}}$$

- Two aspects that can endanger the magnet integrity
  - Temperature induced by Joule heating (hotspot temperature)
  - Voltages induced by normal/superconducting states in the coil, and by unbalance between inductive and resistive load in the coil

PROLOGUE

- The conductor that has crossed the critical surface is heated by the Joule effect, and reaches a temperature called hotspot
  - In the adiabatic approximation one has

$$r\, j^2(t)dt = C_p(T)dT$$

ρ: resistivity

t: time

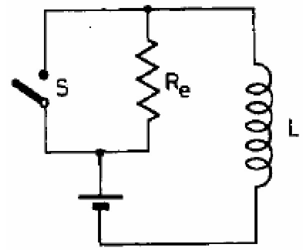
C_p: volumetric specific heat of the conductor

T: temperature

  - The circuit is a RL circuit
    - with the magnet inductance L (constant at first order, if one neglects the nonlinearities induced by non saturated iron)
    - and a highly variable resistance $R(t)$, growing with time
    - the current only flows in copper, the heat goes in the whole conductor
  - Higher resistance → faster current dump → lower hotspot

PROLOGUE

- Higher resistance → faster current dump → lower hotspot
- A solution is to add an external dump resistor
  - But this creates a voltage at the magnet leads: Maximum resistor size is determined by magnet insulation (typically 1 kV) and by the magnet current
  - This strategy works for "short" models, but not for long dipoles in accelerators



- Another solution is to decrease the overall current density, or to have more copper in the conductor
  - This makes the magnet larger, and/or less effective
  - For instance this is what can be done in HEP for experimental magnets or for corrector magnets, and in fusion …

PROLOGUE

- In superconducting magnets for particle accelerators overall current density is very large, every 0.1 mm / 0.1 s counts …
  - For these devices the protection aspects are pushed to the limits, in terms of hotspot and insulation: this is what we will discuss here

	Overall j (A/mm^2)	j in the SC (A/mm^2)	Ramp	Field
Tevatron dipole	360	1550	static	4.7
LHC dipole	360/440	1260/1820	static	8.6
ATLAS BCT	30	950	static	3.9
ITER (TF & CS)	20 to 40	150	static	5 to 13

- For these magnets, the only strategy is to dump the energy in the insulated coil
  - To get rid of the current one has to increase the resistance, transforming the local transition in a global transition to normal conducting state in the whole coil
  - This corresponds to rapidly heating the whole coil above the current sharing temperature (critical surface of the superconductor)

PROLOGUE

- Higher resistance → faster current dump → lower hotspot

- Two more solution are possible and used for standalone magnets, but not viable for main accelerator magnets
  - Couple the circuit via a mutual inductance to extract the energy (see M. Wilson, chapter 9.7)
  - Segment the circuit and apply energy extraction to each part (see M. Wilson, chapter 9.8)

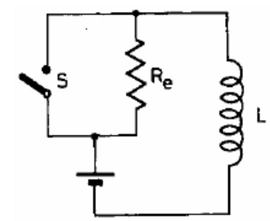
- Both cases will not be treated here

CONTENTS

- Hotspot temperature in adiabatic case
  - A digression on stored energy
- Time margin
- Quench detection
- Protection systems: quench heaters and CLIQ
- Appendix

HOTSPOT TEMPERATURE

- After quench, one has Joule heating – we have RL circuit
  - Power converter is switched off
  - Magnet has growing resistance depending on quench propagation/protection system
  - It can be assumed that current flows only in the Cu
  - (an external resistor can be included in the circuit)



- Resistance and heat capacity strongly depend on the coil temperature, highly nonlinear problem

$$k_{Cu} r_{Cu}(T) j_{Cu}^2(t)dt = C_p(T)dT$$

$$k_{Cu} j_{Cu}^2(t)dt = \frac{C_p(T)}{r_{Cu}(T)} dT$$

- j_{Cu}: current density in the copper
- ρ: resistivity of copper
- C_p: volumetric specific heat of the insulated conductor
- κ_{Cu}: volumetric fraction of copper in the insulated conductor

HOTSPOT TEMPERATURE

- Assuming that the heat stays locally, and just increases the temperature (adiabatic approximation) one can integrate

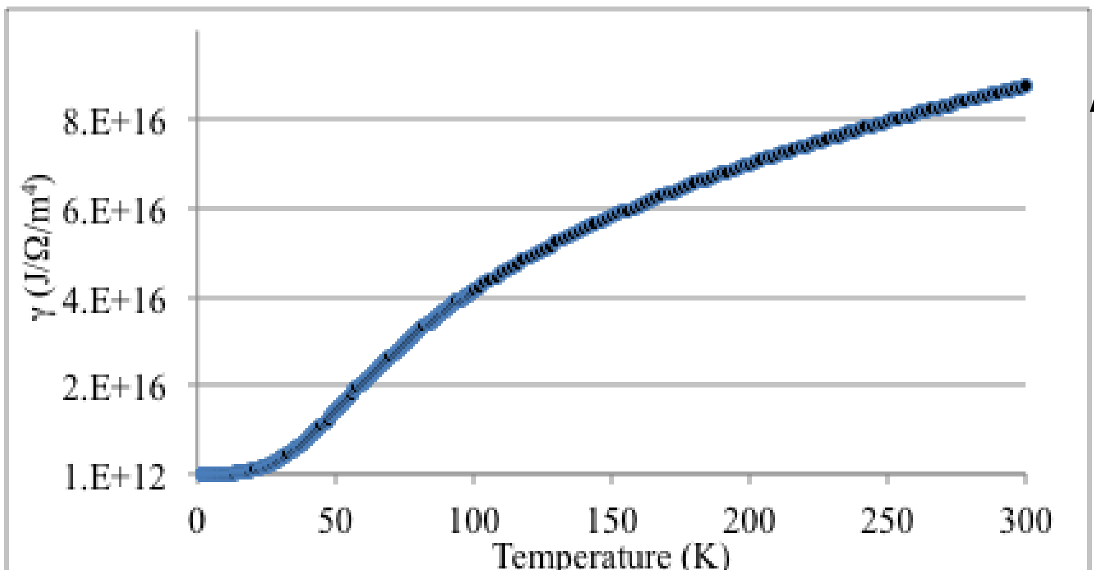
$$\kappa_{Cu} j_{Cu}^2(t)\,dt = \frac{C_p(T)}{\rho_{Cu}(T)}\,dT \qquad \kappa_{Cu}\int_0^{\infty} j_{Cu}^2(t)\,dt = \int_{T_0}^{T_{max}} \frac{C_p(T)}{\rho_{Cu}(T)}\,dT$$

- and compute numerically $j_{Cu}(t)$
  - This is a one dimensional integration, but with non trivial features due to the wide range of ρ and C_p: and adaptive step has to be used
  - This means that you must use very small time step at the beginning (much less than 1 ms), where the specific heats around the operational temperature of few K are varying a lot
  - More refined models: accounting for quench propagation, and exchange to He bath (1D-2D or 3D model meshes, plus time)
  - The adiabatic model is conservative on the hotspot, since part of the Joule heating goes away or is removed

HOTSPOT TEMPERATURE

- What is a safe T_{max} that can be reached in the coil?
    - Usually one does not want to go much beyond room temperature 30 C (300 K), at most 80 C (350 K)
  - Main reasons
    - For Nb-Ti damaging of insulation above 250 C (melts)
    - For Nb_3Sn glass transition of impregnation resin (120 C)
    - For all cases this very rapid (in fraction of second) heating induces local thermal stresses that can damage the cable
  - 350 K may be a reasonable maximum limit for high performance magnets (main magnets), including failures
    - Some experiments prove that degradation is negligible until 400 K
  - 270 K is a reasonable maximum limit for high performance magnets with standard protection (no failures)
  - 200 K to 250 K is used for correctors, where margin is much less expensive, and therefore lower current densities / more copper can be used

- Let us compute some orders of magnitude
  - First computation: the ability of the cable to absorb Joule heating
  - Below you see a typical plot of the right hand side integral for a typical Nb-Ti cable with half of copper in the cross-section
    - The integral is the order of 10^{17} J/Ω/m^4 for T_{max} =300 K



$$\kappa_{Cu} \int_0^{\infty} j_{Cu}^2(t)\, dt = \int_{T_0}^{T_{\max}} \frac{C_p(T)}{\rho_{Cu}(T)} dT$$

$$\gamma(T_{\max}) \equiv \int_{T_0}^{T_{\max}} \frac{C_p(T)}{\rho_{Cu}(T)} dT$$

Integral of the ratio between volumetric specific heat and Cu resistivity

HOTSPOT TEMPERATURE

- Let us consider some orders of magnitude
  - Second computation: how long can the magnet can stay at current density $j_{Cu,0}$

$$\kappa_{Cu}\int_0^{\infty} j_{Cu}^2(t)\,dt \approx \kappa_{Cu} j_{Cu,0}^2 t_0 = \gamma(T_{\max}) \qquad t_0 = \frac{\gamma(T_{\max})}{\kappa_{Cu} j_{Cu,0}^2}$$

  - Considering a magnet working at j overall 400 A/mm^2 and κ_{Cu}=0.4, $j_{Cu,0}$=1000 A/mm^2, we can stay a time $10^{17}/(10^9)^2/0.4$ = 0.25 s at that current before reaching 300 K
  - Therefore the time required to dump the current is of the order of tenths of seconds
  - If a device works at 40 A/mm^2, we can wait 25 s !

HOTSPOT TEMPERATURE

- The equation is given for intensive properties

$$k_{Cu}\int_0^{\infty} j_{Cu}^2(t)\,dt = \int_{T_0}^{T_{\max}} \frac{C_p(T)}{\rho_{Cu}(T)}\,dT$$

- We now write it in the extensive form
  - I: current in the cable
  - ρ_{cu}: copper resistivity C_p: volumetric specific heat
  - ν: fraction of copper in the insulated cable
  - A: insulated cable surface
- Since $I = k_{Cu} A j_{Cu}$ → $$\int_0^{\infty} I^2(t)\,dt = k_{Cu} A^2 \int_{T_0}^{T_{\max}} \frac{C_p(T)}{\rho_{Cu}(T)}\,dT$$
  - Right hand side: we define Γ

$$\Gamma(T_{\max}) = k_{Cu} A^2 \int_{T_0}^{T_{\max}} \frac{C_p(T)}{\rho(T)}\,dT = k_{Cu} A^2 \gamma(T_{\max})$$

  - Γ is the capital we can spend to protect the magnet
  - This has a physical dimension of a square of current times time (A^2 s)

HOTSPOT TEMPERATURE

- Left-hand side:

$$\int_0^\infty I^2(t)\,dt = k_{Cu} A^2 \int_{T_0}^{T_{max}} \frac{C_p(T)}{\rho_{Cu}(T)}\,dT$$

- The integral of the square of the current Γ_q is an observable during test

$$\Gamma_q \equiv \int_0^\infty I^2(t)\,dt$$

  - Usually the left hand is expressed using kA, and integral of square of kA is called MIITs

$$\Gamma\left(T_{hot}\right) = \Gamma_q$$

  - Then using the curve Γ versus T we can estimate the hotspot reached T_{hot}

$$\Gamma_q < \Gamma\left(T_{\max}\right)$$

- This is the condition for not exceeding T_{max}

HOTSPOT TEMPERATURE

- Let us compute some orders of magnitude
  - Third computation: MIITs of a cable (right hand side)

$$\Gamma(T_{\max})\left[\mathrm{A}^2\mathrm{s}\right] = k_{Cu}A^2\gamma(T_{\max}) = k_{Cu}A^2 \times 10^{17} \qquad \Gamma(T_{\max})\left[\mathrm{MA}^2\mathrm{s}\right] \approx \frac{k_{Cu}A^2\left[\mathrm{mm}^2\right]}{10}$$

- Let us compute some orders of magnitude
  - Fourth computation: quench integral when dominated by dump resistor (left-hand side)

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

$$\Gamma_q = \int_0^\infty I^2(t)dt = I_0^2 \int_0^\infty \exp\left(-\frac{2tR_d}{L}\right)dt = \frac{LI_0^2}{2R_d} = \frac{U}{R_d}$$

LIMITS OF ENERGY EXTRACTION

- Dump resistor R_d is limited by the maximum voltage

$$R_d I_0 < V_{max} \qquad R_d < \frac{V_{max}}{I_0}$$

- The condition for protection with energy extraction is

$$\Gamma_q = \frac{U}{R_d} < \Gamma(T_{max}) \qquad \frac{U}{\Gamma(T_{max})} < R_d < \frac{V_{max}}{I_o}$$

- Example: LHC dipole cannot be protected with a dump
  - Cable surface is 30 mm^2, ν~0.40 (fraction of copper in insulated cable)
  - Therefore $\Gamma(T_{max})$~ $(30\times10^{-6})^2\times0.40\times10^{17}=36\times10^6$ J/Ω/m^2 (these are 36 MIITs)
  - I_0=12 kA, U = 7 MJ

$$\frac{U}{\Gamma(T_{max})} = \frac{7\times10^6}{36\times10^6} = 0.2\ \text{W} \qquad \frac{V_{max}}{I_o} = \frac{600}{12000} = 0.05\ \text{W}$$

CONTENTS

A DIGRESSION ON STORED ENERGY

- The stored energy in magnetic field is given by the volumetric integration of the magnetic pressure (that is also the energy density)

$$U = \int \frac{B^2}{2\mu_0} dV$$

- Back of the envelope estimate:

$$U \approx \frac{B^2}{2\mu_0} \pi \left(r + w\right)^2 l$$

- Where *r* is the aperture radius and *w* the coil width, and *l* is the magnet length

A DIGRESSION ON STORED ENERGY

- A typical example done for giving an idea of the large size of the stored energy in the magnetic field of the LHC dipoles (7 MJ) is close to the kinetic energy of a 20 tons lorry at 100 km/h
  - $U=mv^2/2 = 20\,000 \times 28^2 / 2 = 7.7$ MJ
  - m=20 tons
  - v=100 km/h = 28 m/s

A 7 MJ lorry (S. Spielberg, "Duel" Universal Pictures, 1971)

A DIGRESSION ON STORED ENERGY

- Or the potential energy of 700 tons of water falling by one meter
  - $U=mgh$ = 700 000 × 10 × 1 = 7 MJ
- On the other hand I can also convince you that the stored energy is small …
  - A glass of gasoline
  - Gasoline has stored energy of about 35 MJ/liter

  - 10 T magnetic field has stored energy of 0.04 MJ/liter

A DIGRESSION ON STORED ENERGY

- How many dipoles can you eat?
  - BigMac has 550 cal
  - Please note that this means 550 kcal

- 1 cal = 4.18 J
  - 1 Big Mac = 2 MJ
  - 3 Big Mac + 1 French fries = 1 LHC dipole

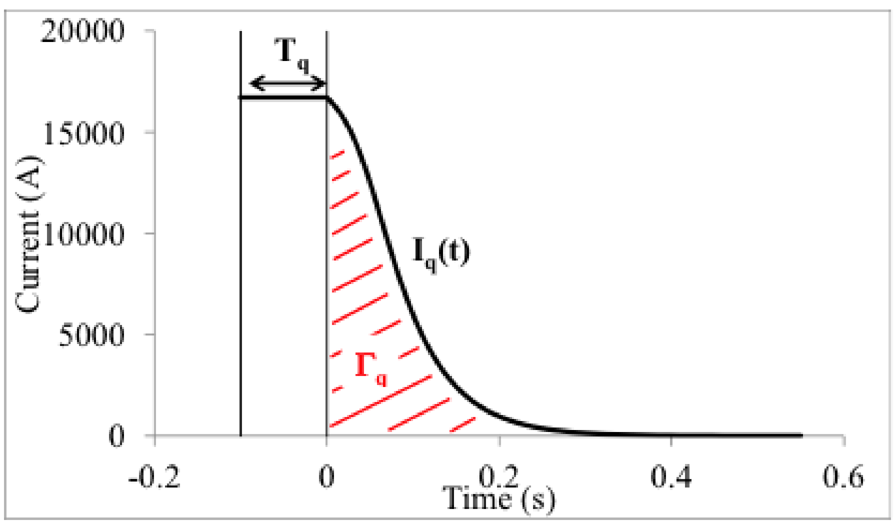
CONTENTS

TIME MARGIN

- The best protection system we can imagine is a system that in 0 s makes all the coil resistive
  - And let us assume that $I_q(t)$ is the current decay in a magnet totally resistive, and operational temperature
    - This can be estimated through numerical codes, and the quench integral can be computed
      - It is a property of the magnet design, independent of the protection system

$$\Gamma_{q,m} \equiv \int_0^{\infty} I_q^2(t)\,dt$$

  - How long we can survive at maximal current ?



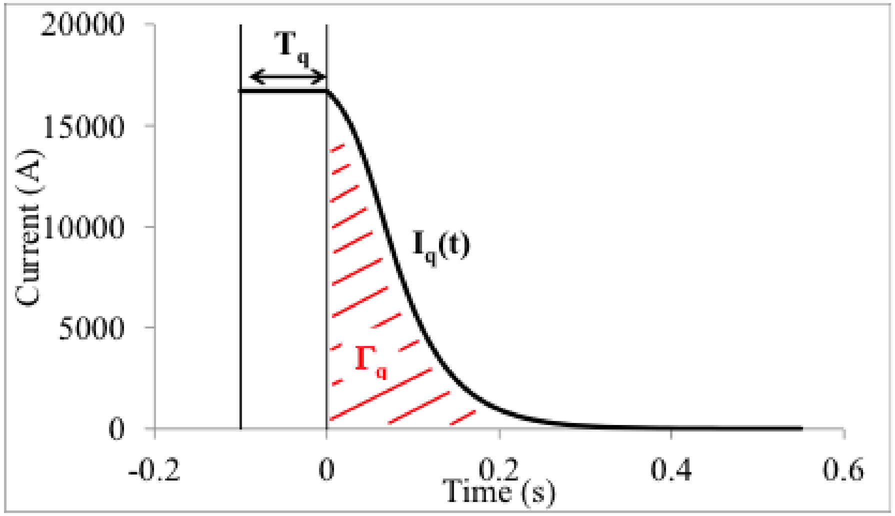
$$I_0^2 T_q + \Gamma_{q,m} = \Gamma(T_{max})$$

$$T_q \equiv \frac{\Gamma(T_{max}) - \Gamma_{q,m}}{I_0^2}$$

TIME MARGIN

- T_q is the time margin for protection
  - This gives the time required to react to the quench and to spread all the quench through the quench heaters before the magnet reaches T_{max}
  - Order of magnitude:
    - For Nb-Ti high field magnets the magnet design aims at having around 100 ms
    - For Nb_3Sn high field magnets we try to go towards 50 ms
      - Less becomes impossible ..
      - I will show why

$$T_q = \frac{G(T_{max}) - G_q}{I_0^2}$$



TIME MARGIN

- Typical order of magnitudes
  - Energy density in Nb-Ti magnets is order of 0.05 J/mm^3 , that is 1/10 of C_p^{ave} at 300 K
    - The corresponding time margin is of the order of 100 to 200 ms for high field dipoles or quadrupoles as LHC main dipole, LHC IR quadrupoles
  - For Nb_3Sn magnets, the energy density increases to 0.10-0.15 J/mm^3 (that is up to 1/4 of C_p^{ave})
    - The corresponding time margin is of the order of 50 ms
  - In the next unit we will see why we need order of 50 ms for the protection system to react

CONTENTS

QUENCH DETECTION

- The detection of a quench is based on the measurement of the resistive voltage growth
  - The quench propagates along the cable with a velocity, that can be estimated according to

$$v_q = \frac{j}{C_p(T_{op})}\sqrt{\frac{k\rho}{\Delta T}}f$$

(see M. Wilson book)

- j: overall current density
- C_p: volumetric specific heat at operational temperature
- k: thermal conductivity
- ρ: copper resistivity
- ΔT= temperature margin (current sharing temperature minus operational temperature)

  - With the factor *f* is equal to 1 for the adiabatic case, and accounts for the heat exchange with helium bath or on the surface of the strand

QUENCH PROPAGATION

- Typical quench velocities (along the cable) of the order 10 m/s for high field LTS magnets at operational current
  - The equation for quench velocity is

$$v_q = \frac{j}{C_p(T_{op})}\sqrt{\frac{k\rho}{\Delta T}}f$$

  - Parametric dependence:
    - proportional to current density in copper
    - Inverse proportional to square root of temperature margin
  - Can also be written as
    - L_0 Lorentz number 2.45×10^{-8} W Ω /K^2

$$v_q \approx \frac{j}{C_p(T_{op})}\sqrt{\frac{L_0 T_{cs}}{T_{cs} - T_{op}}}$$

  - Example
    - j: 400 A/mm^2 = 4×10^8 A/m^2
    - C_p: 5×10^3 J/K/m^3 (considering at 4 K)
    - T_{cs}: 4 K T_{op}: 2 K
    - One finds $v_q=4\times10^8 / 5\times10^3 \times \sqrt{(2.5\times10^{-8}\times 4/2)} =$ 18 m/s

QUENCH DETECTION

- How to translate the quench velocity in a resistance growth ?
  - Equation for resistance growth $$\frac{dV}{dt} = \frac{dR}{dt} I = \frac{r_{Cu}}{A_{Cu}} \frac{dl}{dt} I = \frac{r_{Cu}}{A_{Cu}} I v_q$$
  - For example, LHC dipole
    - I = 12 000 A
    - A_{Cu}= 15 mm^2 = 15×10^{-6} m^2
    - ρ = 5×10^{-10} Ω m
    - Scaling factor from velocity to voltage increase: 5×10^{-10} / 15×10^{-6} × 12000 = 0.4 V/m
    - Therefore for a 17 m/s quench velocity, the voltage increase of of the order of 7 V/s
    - So for a 100 mV threshold, reached after 15 ms
  - Note: this is once more an estimate of order of magnitudes, more precise values require to know the quench location (high field or low field) and the related temperature margin, and many other details

QUENCH DETECTION

- Detection thresholds
  - The detection threshold are defined through two parameters
    - A voltage level (above the noise level) – typically 100 mV
    - 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
  - For Nb_3Sn magnets flux jumps generate voltages of order of 1 V at low and intermediate currents
    - Variable thresholds are being implemented for the HL-LHC Nb3Sn magnets: larger at low currents, they progressively diminish towards nominal current
  - Therefore on the time needed to detect the voltage, one has to add the validation time

CONTENTS

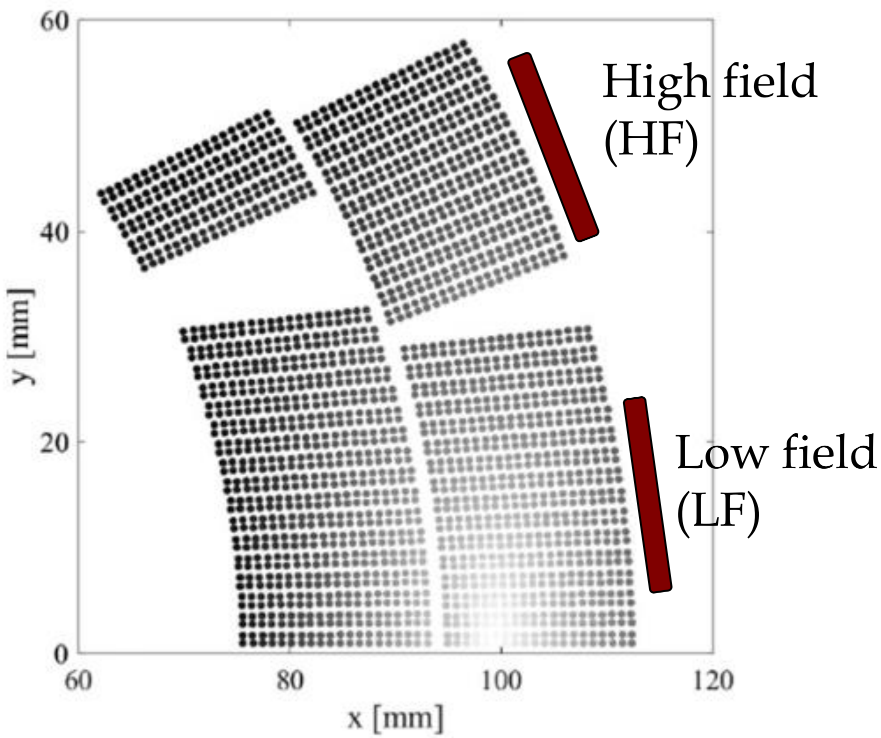
QUENCH HEATERS PRINCIPLE

- The idea of quench heaters is to heat the coil to bring the whole superconducting coil above the critical surface
  - Quench heaters are strips of stainless steel where an impulse of current is put as soon as the quench is detected
    - Capacitor discharge
  - Strips heat thanks to Joule heating, and give heat power to the coil
  - The reaction time that can be obtained is of the order of 10-50 ms

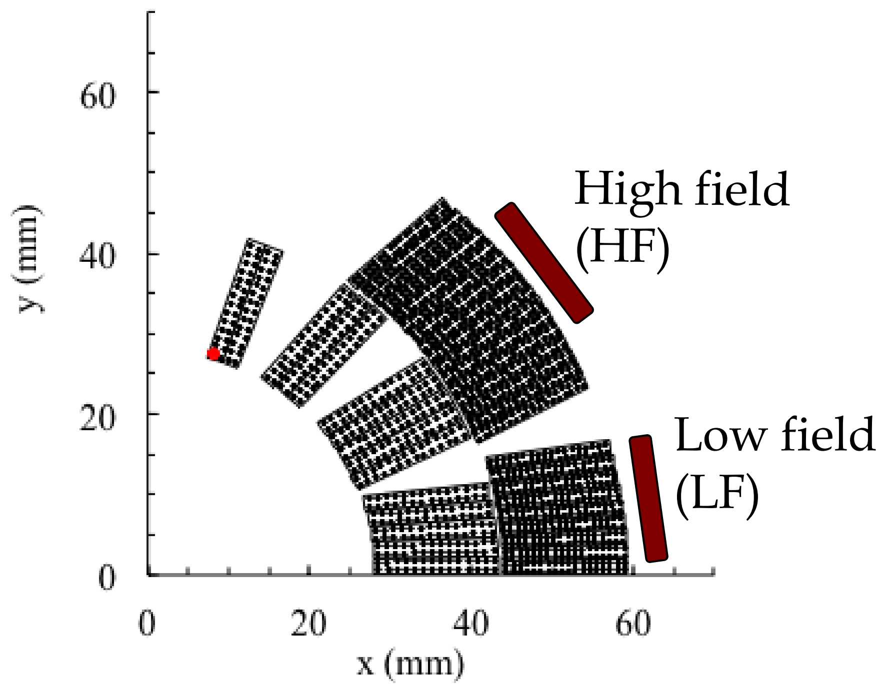
Quench heaters in HQ (courtesy of H. Felice and LARP teams)

QUENCH HEATERS DESIGN

- Quench heater design
  - Usually two strips to cover several turns of the outer layer, one in the high field region and one in the low field region



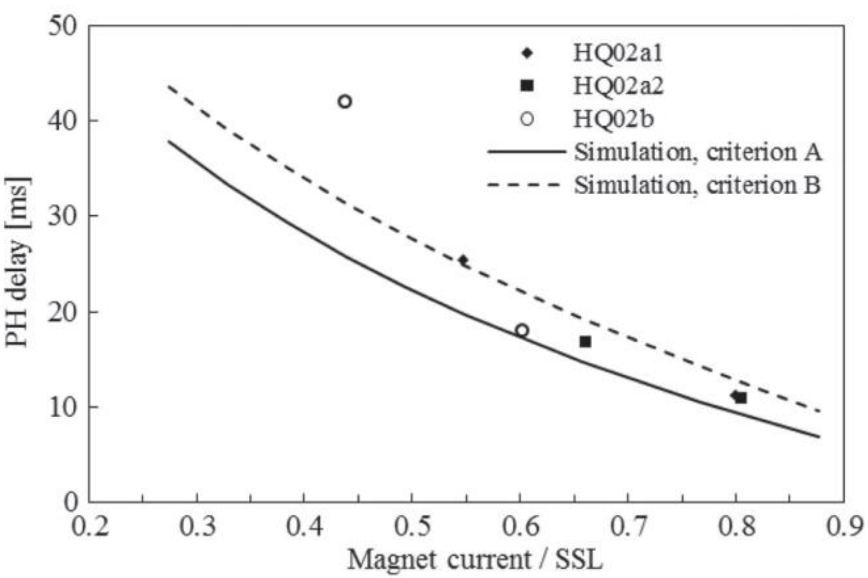
Quench heater strips in MQXF

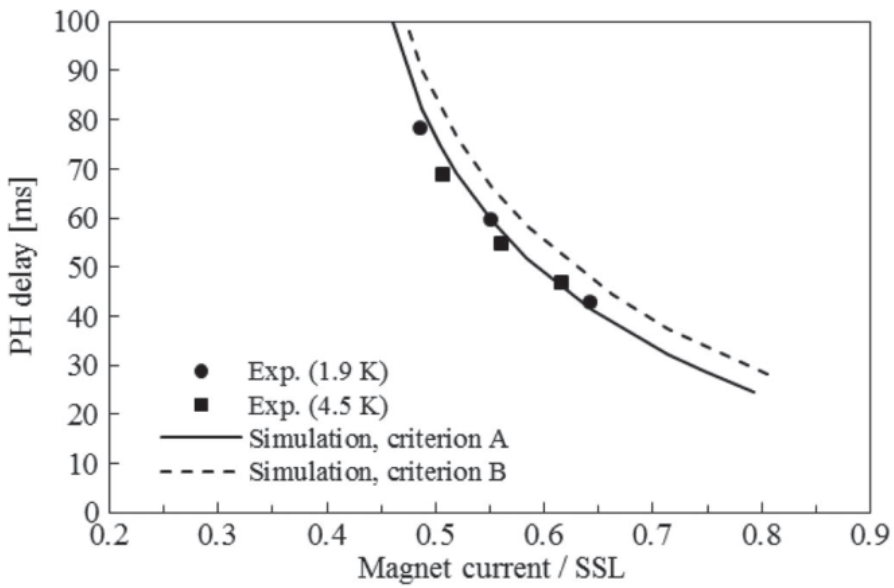


Quench heater strips in the main LHC dipole

QUENCH HEATERS DELAY

- Time delay: time between heater activation and transition to resistive state of the coil
  - For high current density, main magnets is of the order of 10 ms
  - Scales with the thickness of the insulation between the heater and the coil: this is a very important design parameter
  - It can be measured during test, and it can be modeled via numerical codes

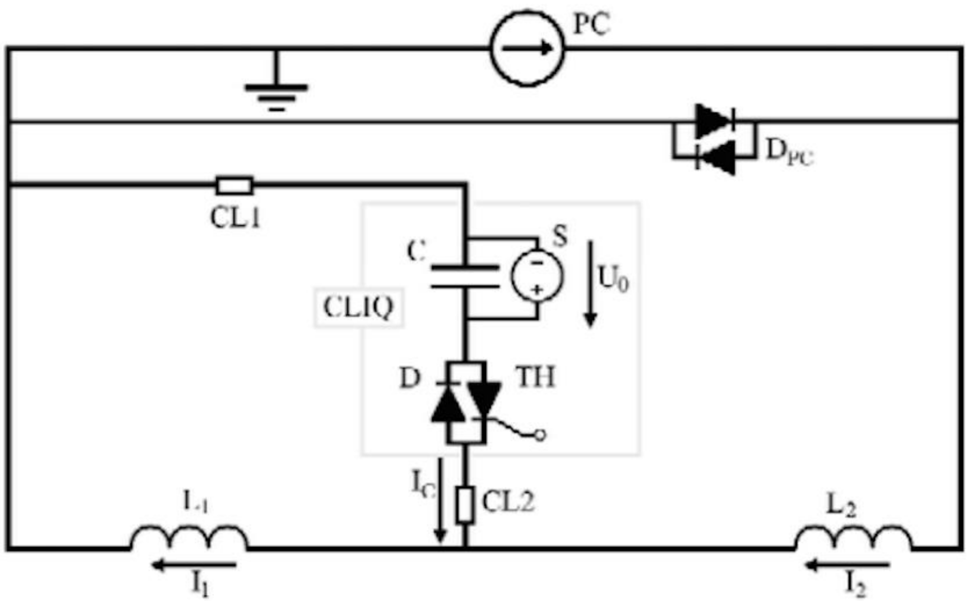




Heaters delay measured vs model in HQ, 25 μm polymide (left) and 11 T 75 μm polyimide (right)
[T. Salmi, et al, IEEE TAS 25 (2015) 4004212]

CLIQ PRINCIPLE

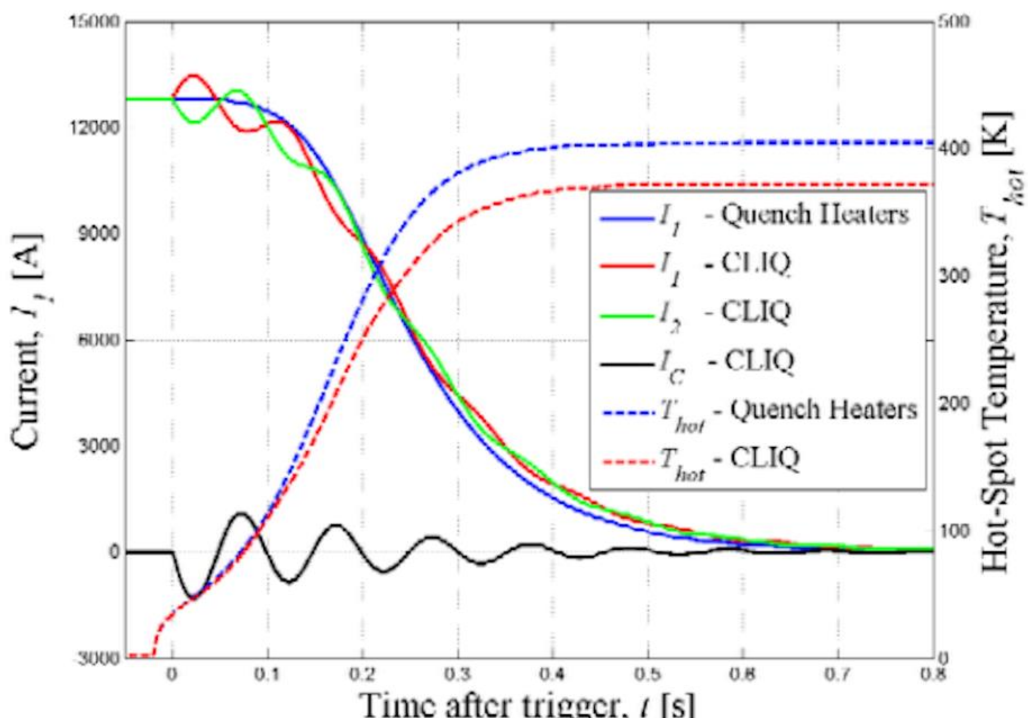
- CLIQ (Coupling Losses Induced Quench)
  - This system is based on injecting in the magnet coils two opposite impulses of current via a capacitor
  - The mechanism is the heating due to interfilament coupling losses induced by the variation of the field
    - It has been developed at CERN and patented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

- For a magnet with a 10 kA current, the pulse is of the order of 1 kA, with a period of 0.1 s
- The heat induces a quench in the coil within order of 10 ms
- It is the baseline protection scheme for the HL LHC inner triplet
- E. Ravaioli, et al. IEEE TAS 28 (2018) 4701606



CLIQ discharge in an LHC dipole (G. Kirby, et al. IEEE TAS)

CONCLUSIONS

- Magnet protection concerns two different phenomena
  - Increase of temperature due to Joule effect
  - Increase of voltage due to a transition to resistive state only in a limited section of the conductor
- We focussed on the hotspot temperature
  - During a quench, it should not go above room temperature

$$n j_{Cu}^2(t)dt = \frac{C_p(T)}{\rho_{Cu}(T)} dT \qquad \int_0^\infty I^2(t)\,dt = nA^2 \int_{T_0}^{T_{max}} \frac{C_p(T)}{\rho_{Cu}(T)} dT$$

  - Right hand side is the ability of the cable of « taking » the current (combination of enthalpy and resistivity)
  - Left hand side is the load due to the current decay, that should be made as fast as possible and is an observable

CONCLUSIONS

- Having a resistor in series with the magnet after the quench allows to rapidly get rid of the current (energy extraction)
  - This strategy is limited by the voltage, and for long magnets is not effective
- For long and high current density magnets, the only way of protection is to induce a rapid transition to resistive state in the whole magnet
  - In this case the cable enthalpy takes the magnet stored energy
  - A limit for protection is an energy density on the coil much smaller than 0.5 J/mm^3 : the LHC dipoles had about 0.05 J/mm^3, the new generation of Nb_3Sn magnets have about 0.10 J/mm^3

CONCLUSIONS

- We defined a protection time margin, that gives the challenge of protection related to the magnet design
  - This is the time allowed to the protection system to react
  - It is order of 100 ms for Nb-Ti main magnets, and has been reduced to 40 ms for Nb_3Sn magnets
    - This because the coil energy density is higher (higher field, and similar or higher current densities)
  - If your magnet design has less than 40 ms, increase the copper quantity in the strand or (the most effective) decrease the current density
- Quench heaters and CLIQ are two systems that can make the work in order of 20 ms
- Another order of 20 ms are needed to detect the quench

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  - QLASA (L. Rossi, et al. INFN 2004)
  - LEDET (E. Ravaioli et al. *Cryogenics* **80** (2016))
  - STEAM framework (A. Verweij, et al., www.cern.ch/steam)

APPENDIX

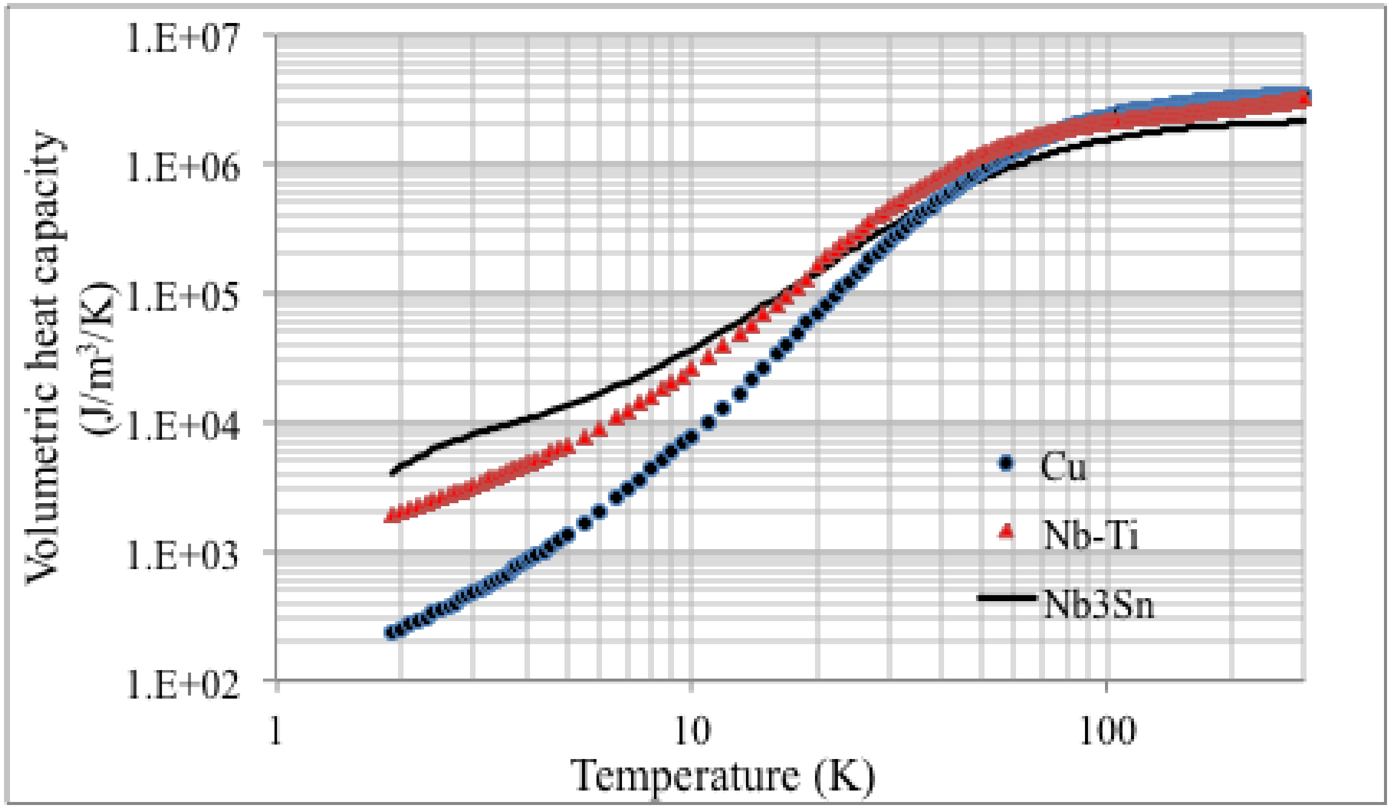
- Material properties
- Nonlinear inductance
- More about quench propagation and detection thresholds
- More about quench heaters

MATERIAL PROPERTIES

- Material properties are varying on several orders of magnitude
- Two main ingredients
  - Specific heats (for superconductor, copper, and insulation)
  - Resistivity (for copper, since the superconductor and insulation have such high resistivity that can be ignored)
    - Note the copper resistivity at low temperatures depends on RRR
    - Copper resistivity also has a dependence on magnetic field
- Due to the wide range, integration is not trivial and has to be done with an adaptive step
  - This means you use smaller steps over certain ranges, and larger over other ranges

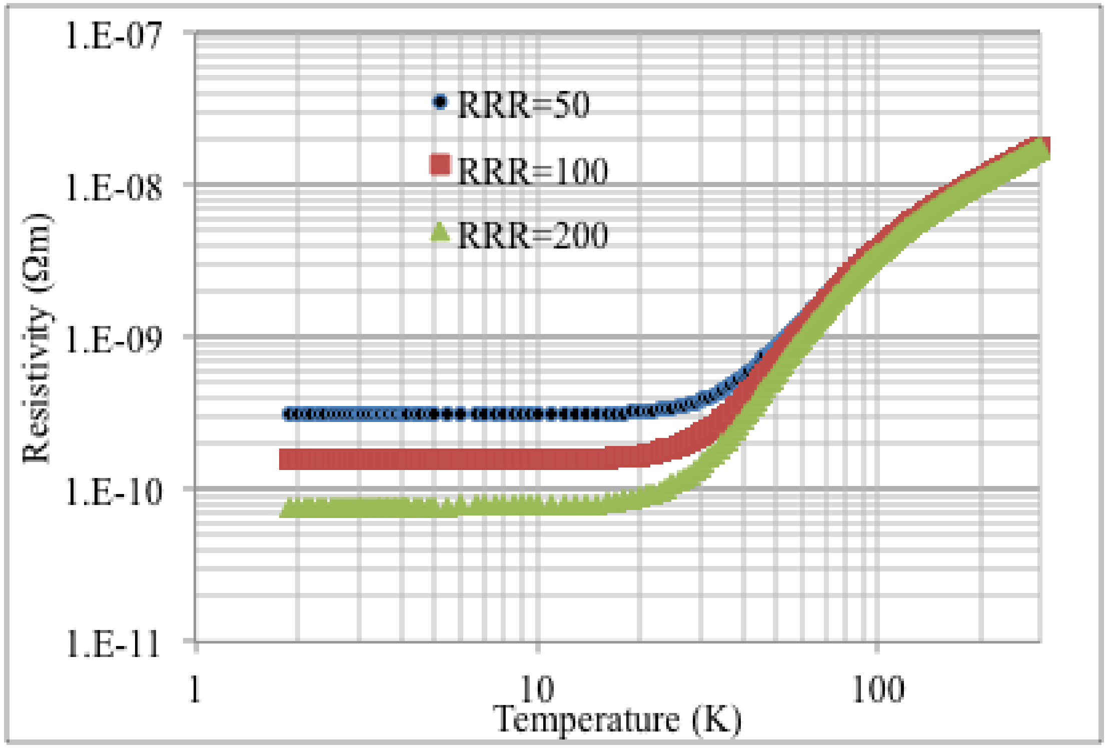
MATERIAL PROPERTIES: SPECIFIC HEATS

- Volumetric specific heats are fit with polynomials
  - They vary over 5 orders of magnitude
    - Note: Nb_3Sn and Nb-Ti data for resistive state



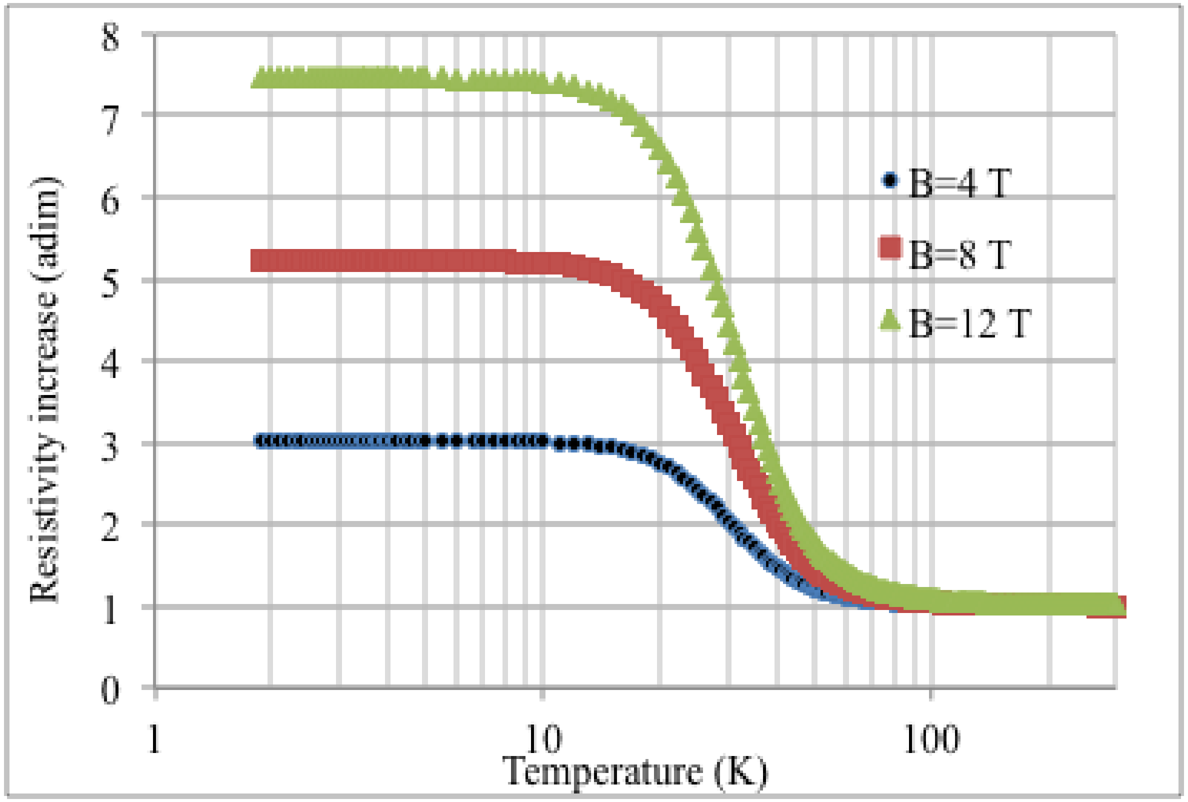
MATERIAL PROPERTIES: RESISTIVITY

- Copper resistivity is the physical quantity with the most complex dependence
  - At low temperatures, the value is dominated by the presence of impurities (measured by the so called RRR, residual resistivity ratio)



MATERIAL PROPERTIES: RESISTIVITY

- On the top of this, there is a dependence on the magnetic field
  - Larger magnetic field increases the resistivity



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NONLINEAR INDUCTANCE

- Definition of inductance in the linear case

$$U = \frac{1}{2} L I^2 \qquad\qquad L = \frac{2U}{I^2}$$

- Definition of inductance in the nonlinear case
  - Energy is not anymore proportional to square of current
  - In these cases, inductance decreases for higher currents
  - Therefore one defines the differential inductance as

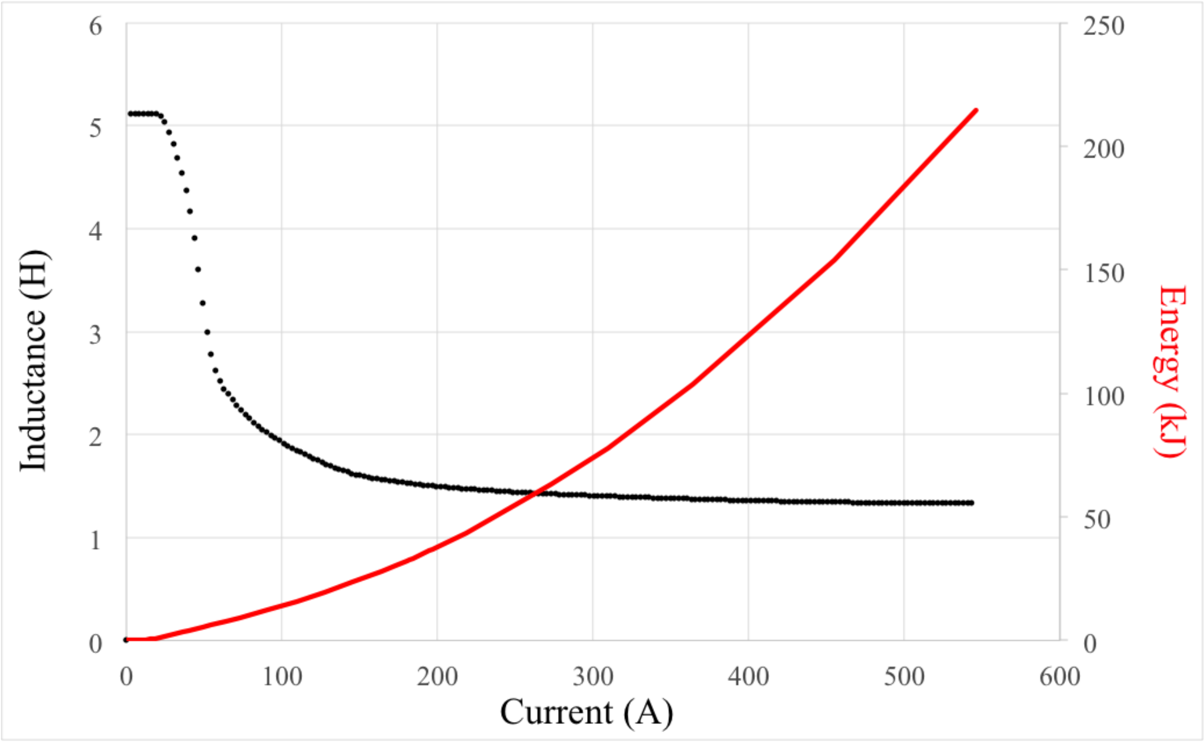
$$\frac{1}{I}\frac{dU}{dI} = L(I)$$

  - And one has

$$U(I) = \int_0^I L(i)\,i\,di$$

NONLINEAR INDUCTANCE

- Example of superferric skew quadrupole for HL-LHC
  - Highly nonlinear due to iron saturation



$$U(I) = \int_0^I L(i)\, i\, di$$

$$\frac{1}{I}\frac{dU}{dI} = L(I)$$

Stored energy and inductance in the skew quadrupole for HL LHC
(M. Statera et al.)

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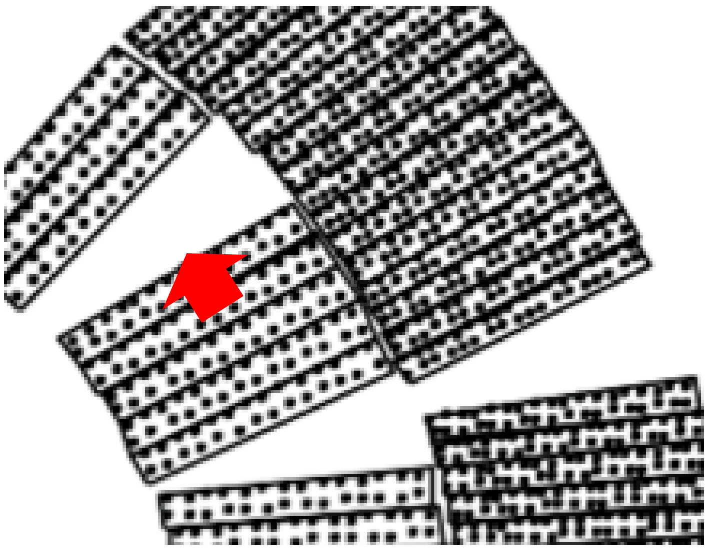
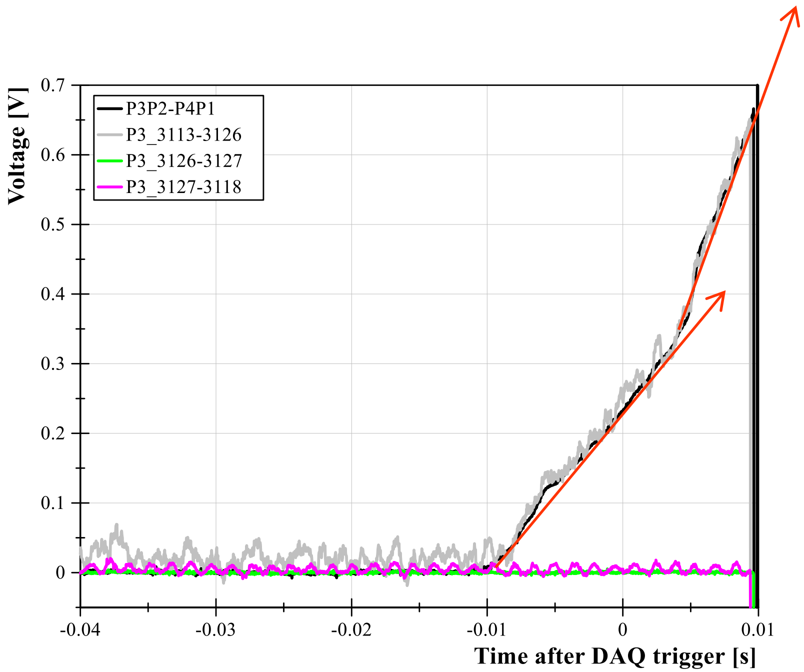
QUENCH PROPAGATION

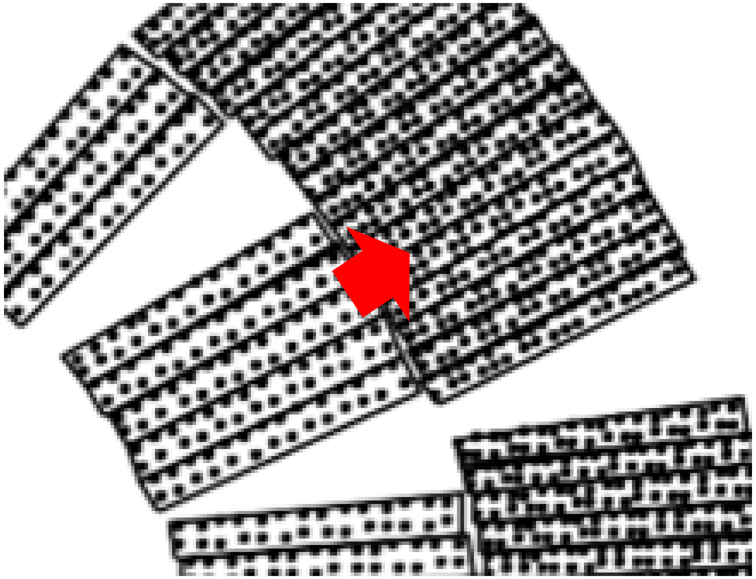
- Order of magnitude of propagation time from one cable to the adjacent one for high field main magnets is ~ 10 ms
  - Clearly, this depends on temperature margin and insulation scheme
  - This is sometimes clearly visible in successive increase of the slope of the voltage

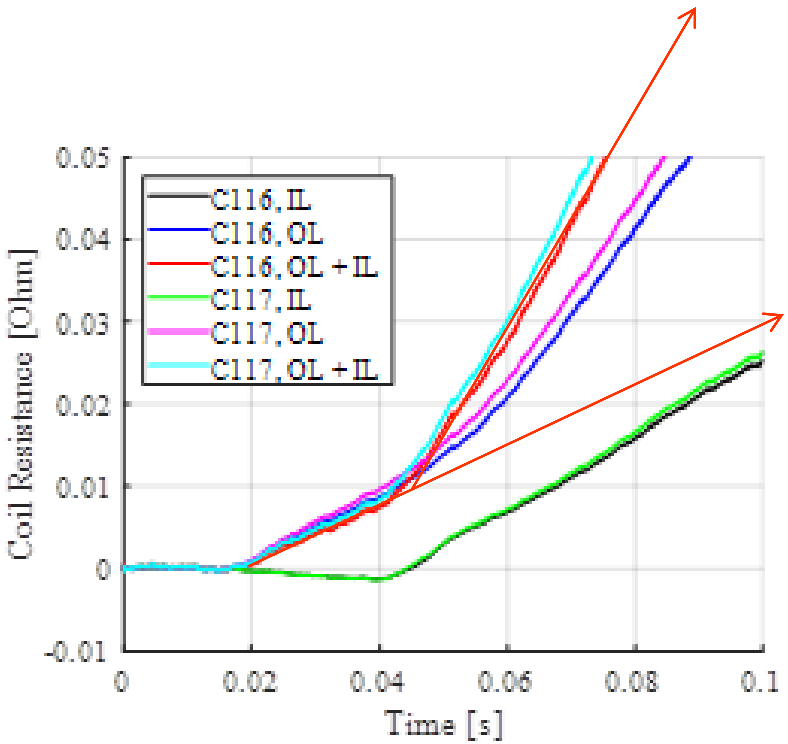




Propagation from one cable to the adjacent one (left), and signals in the voltage in MQXF (courtesy of G. Willering and SM18 teams)

- Order of magnitude of propagation time from inner layer to outer layer (or viceversa) high field main magnets is ~ 20 ms
  - Clearly, this depends on temperature margin and insulation scheme between the two layers





Propagation from inner to outer layer in 11 T dipole
(courtesy of S. Izquierdo Bermudez and SM18 team)

QUENCH DETECTION

- Other sources of voltage
  - During the ramp, the magnet has an inductive voltage $V_i = L\frac{dI}{dt}$
    - Example of LHC dipole: ramp at 10 A/s, inductance of 100 mH, voltage during ramp is 1 V
    - Example of MQXF quadrupole: ramp at 14 A/s, inductance of 50 mH, voltage during ramp is 0.8 V
  - The inductive voltage is removed by subtracting signals from two coils, or from two apertures (if the magnet has two apertures)
    - The assumption is that only one coil is quenching, so that subtracting the two voltages the inductive part is removed and the resistive is left
    - This is not working in the case of quench developing in the two coils at the same time (symmetric quench), where a second level of control is added
  - For corrector magnets, the inductive part can be also removed by software (based on model) to reduce the voltage taps

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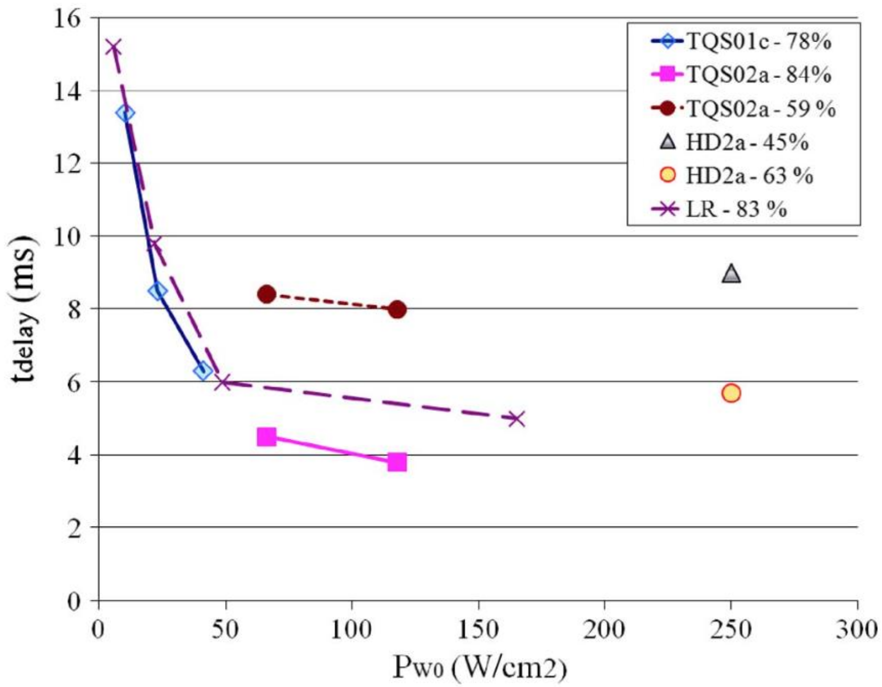
QUENCH HEATERS DESIGN

- Quench heater design
  - The strip is made by stainless steel – ususally 25 μm
  - One has to guarantee two conflicting conditions:
    - a good electrical insulation between heater and coil
    - a good thermal conductivity between heater and coil
  - This is achieved with a polyimide strip of 25-75 μm thickness
    - The thicker the polyimide, the longer the time to heat the coil
    - The thinner the polyimide, the higher the risk of electrical short between heater and coil
  - LARP R&D magnets: 25 μm
    - Effective, but danger of pinholes – ok for R&D, not suitable for magnets to be installed
  - LHC dipoles: 75 μm
  - HL-LHC magnets: 50 μm

QUENCH HEATERS POWER DENSITY

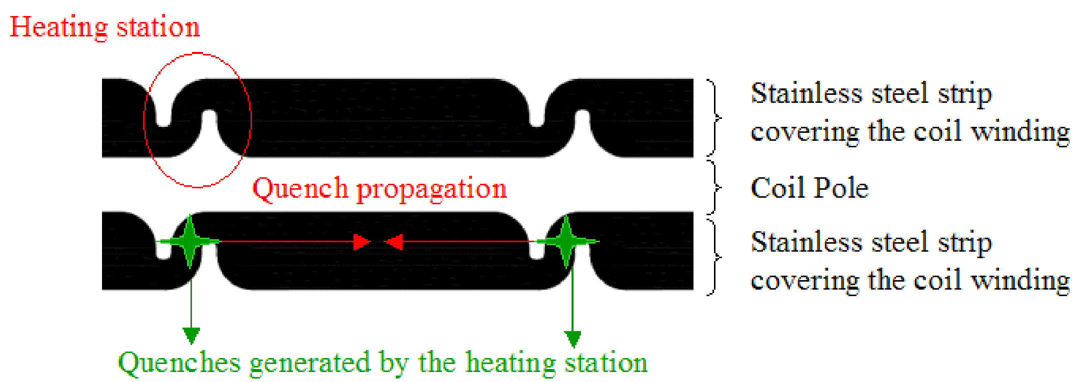
- Typical power densities are limited by the maximum temperature in the heaters after the discharge
  - Typically one needs 100 W/cm^2 - Power becomes relevant at low current, where the temperature margin is larger and can be difficult to quench the coil



Quench heater delay versus power density [H. Felice, et al. IEEE TAS 19 (2019) 2458]

QUENCH HEATERS STATIONS

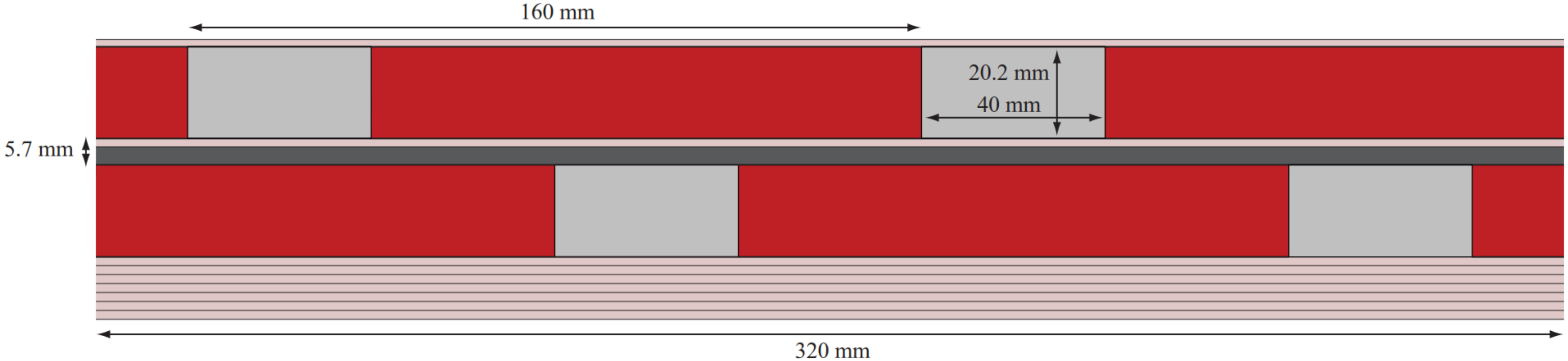
- Another constraint is the voltage at the quench heaters
  - For long magnet, voltage needed to have power density is too high
    - For this reason, the resistance is reduced by alternating the resistance zones with conductive zones (Cu plating) or decreasing the strip size
    - The resistive zone called heating stations (20-50 mm long)
  - The quench is initiated below these stations, and then propagates through the coil
    - Station distance is of the order of 100 mm (0.1 m)
    - Since quench velocity is of the order of 10 m/s, the whole coils quenches after 5 ms = 0.1/2/10



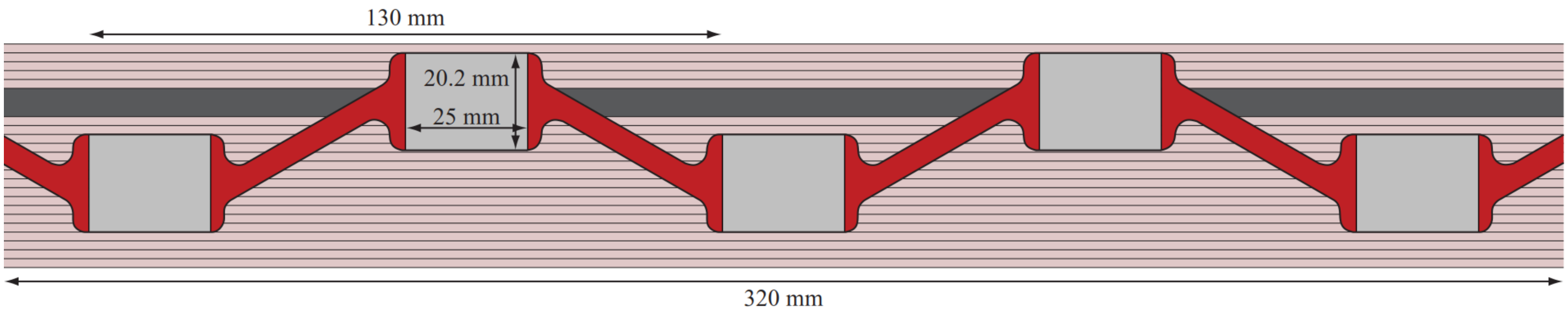
Heating stations in LQ magnet (courtesy of H. Felice)

QUENCH HEATERS STATIONS

- Different topologies for heating stations can be used
  - Based on copper plating, as in the LHC, or on the topology of the stainless steel strip, or on both



Heating stations in MQXF magnet, outer layer, based on LHC dipole design (courtesy of S. Izquierdo Bermudez)



Heating stations in the initial phase of MQXF magnet development, inner layer, (courtesy of S. Izquierdo Bermudez)