CERN, WAMSDO workshop
15th January 2012

PROTECTION IN MAGNET DESIGN

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With help from
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CONTENTS

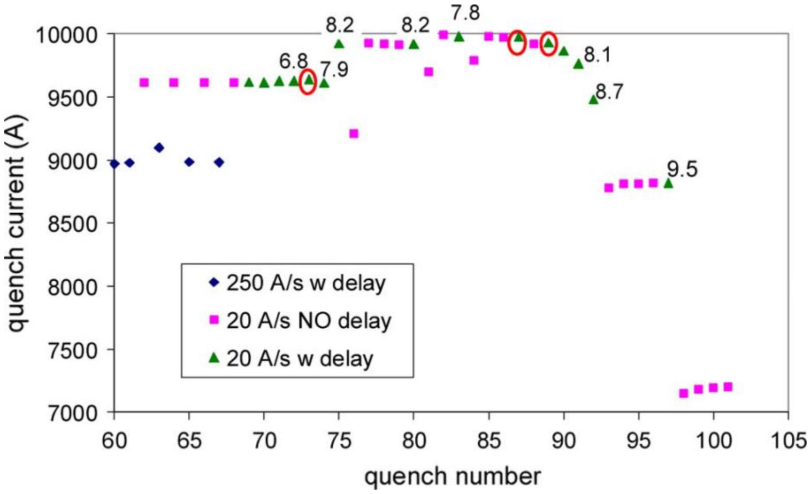
- Main physics given in previous talk [talk by L. Bottura]
- Hotspot temperature
  - Maximum temperature for Nb-Ti and Nb_3Sn
  - Time margin
    - Case with a dump resistor: scalings
    - No dump resistor: intrinsic limits, scalings, field dependence
- Budget for time margin: detection, heater delay, etc
  - Heaters
    - Delays vs operational current and vs field
    - How to quench the inner layer ?
  - Detection
    - Thresholds, scalings and the case of HTS
  - Other terms: quenchback, …
- Inductive voltages

LIMITS TO HOTSPOT TEMPERATURE

- What is the maximum acceptable hotspot temperature ?
  - Nb-Ti
    - Degradation of insulation at 500 K
    - Limit usually set at 300 K
  - Nb_3Sn
    - Weak point: avoid local stress that could damage the Nb_3Sn
    - Limits around 300 K, with some more conservative down to 200 K and more daring up to 400 K
    - That's a big difference … what to choose? Difficult to simulate, experiments should drive this choice

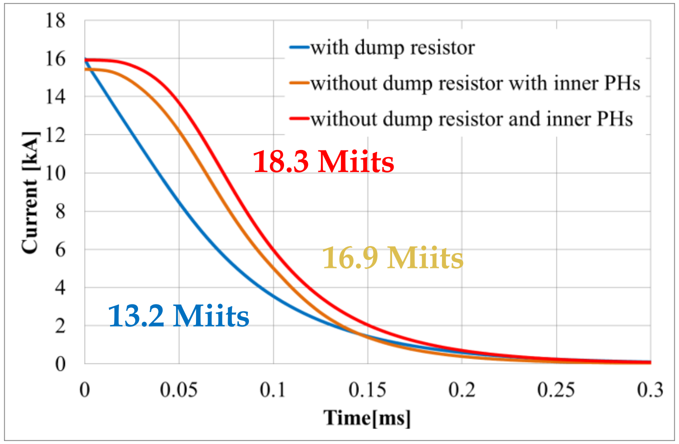
LIMITS TO HOTSPOT TEMPERATURE

- Data from TQ series
  - Degradation from 8 to 9 MIITS
  - Estimate hot spot of 370-390 K



[G. Ambrosio et al., *IEEE Trans. Appl. Supercond.* **18** (2008) 268]

- Data from HQ
  - High MIITs test, no degradation at 18 MIITS (300 K at 12 T)



- Some uncertainty due to ignorance of local field

[H. Bajas, et al., *IEEE Trans. Appl. Supercond.* **23** (2013) in press]

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  - Case with a dump resistor: scalings
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DUMPING ON RESISTOR

- We neglect magnet resitance

$$\int_0^\infty [I(t)]^2 dt = A_{Cu} A \int_{T_0}^{T_{\max}} \frac{c_p^{ave}(T)}{\rho_{Cu}(T)} dT$$

Quench capital

$$R_d = \frac{V_{\max}}{I_o} \qquad \tau = \frac{L_m}{R_d} = \frac{L_m I_o}{V_{\max}}$$

- Resistor is limited by the maximum voltage that the magnet can withstand

$$\Gamma_q = \int [I(t)]^2 dt = I_o^2 \int e^{-2t/\tau} dt = \frac{\tau}{2} I_o^2 = \frac{1}{2V_{\max}} L_m I_o^3 \sim \frac{U_m I_o}{V_{\max}}$$

Quench tax

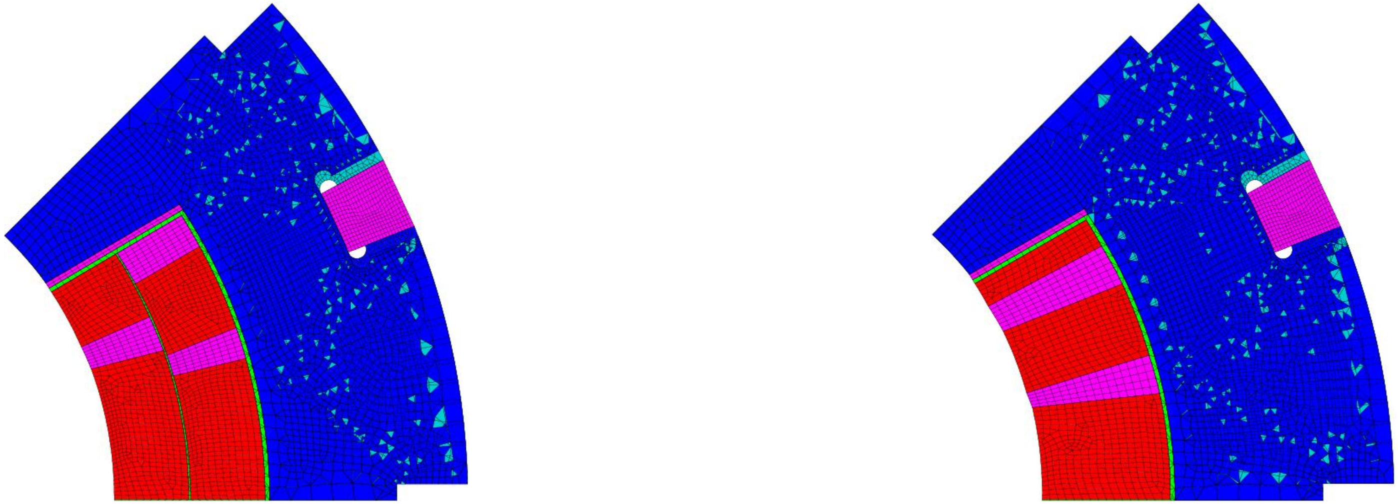
- Protection condition:
  - Balance between quench capital and tax

$$\Gamma(T_{\max}) > \Gamma_q$$

- So we conclude
  - **External dump strategy not invariant on the magnet length**
    - If it works for 1 m, it can be not viable for 10 m long magnets
  - **External dump strategy: larger cables allow to gain time margin**
    - Γ scales with square of cable area
    - Γ_q scales with the cable area

DUMPING ON RESISTOR

- Example of Q4 for the LHC upgrade [M. Segreti, J. M. Rifflet]
  - Two layers of 8.8 mm cable or one layer of 15.1 mm cable ?



  - Similar gradient 120-128 T/m and current density 700 A/mm^2
  - One layer design has a cable cross-section 3 times larger, 13 times lower inductance – no need of heaters
    - Γ=30 MIITs, Γ_q=18 MIITs for one layer
    - Γ=3.2 MIITs, Γ_q=6.2 MIITs for one layer

$$\Gamma(T_{max}) > \Gamma_q$$

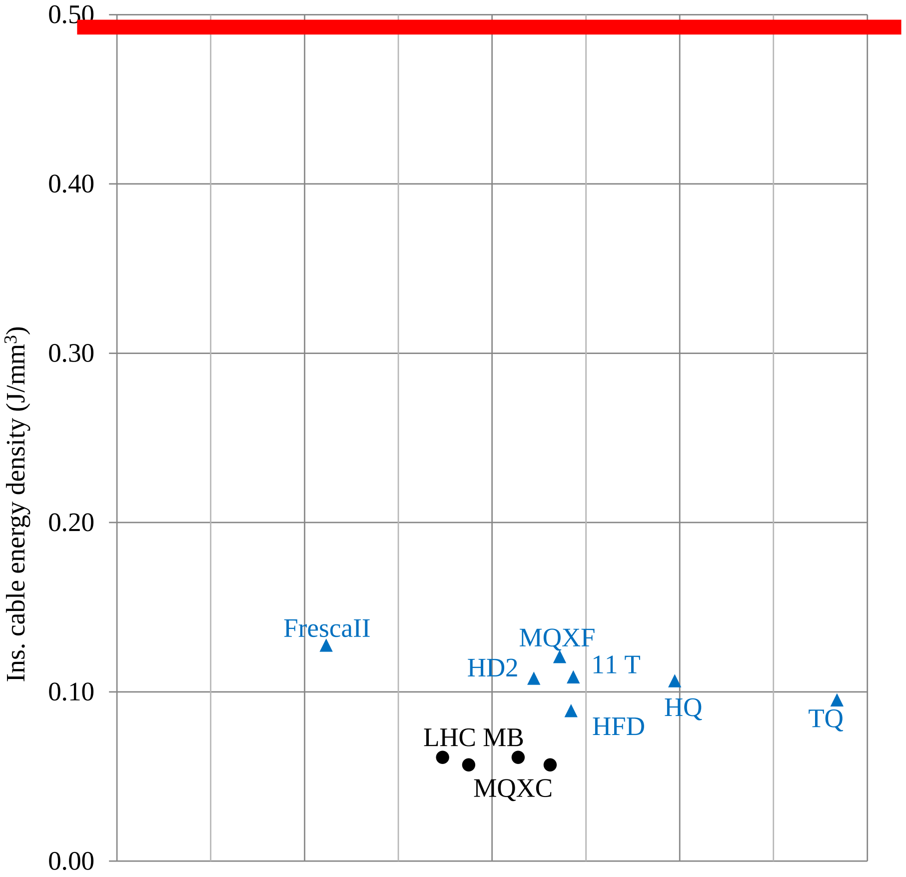
NO DUMP: INTRINSIC LIMIT TO PROTECTION

$$C_p^{ave} \equiv \int_{T_0}^{T_{\max}} c_p^{ave}(T)dT$$

- No external dump
  - Ideal is quenching all the magnet in zero time
  - An intrinsic limit to protection is the trivial balance between energy density and heat capacity
  - Nb-Ti
    - Typical enthalpy at 300 K is 0.65 J/mm^3 → with copper is 0.7 J/mm^3 → with 30% voids one has 0.5 J/mm^3 (helium neglected)
  - Nb_3Sn
    - Typical enthalpy at 300 K is 0.45 J/mm^3 → with copper is 0.6 J/mm^3 → with 30% insulation 0.5 J/mm^3
  - HTS:
    - YBCO: typical enthalpy at 300 K is 0.55 J/mm^3
- A limit is given by the enthalpy which looks rather similar for different coils – hard limit at ~0.5 J/mm^3

NO DUMP: INTRINSIC LIMIT TO PROTECTION

- Where are we with respect to these limits ?
  - Nb-Ti: 0.05 J/mm^3,
    we are a factor 10 below
    (factor 3 in current)
  - Nb_3Sn: =0.10-0.12 J/mm^3,
    we are a factor 4-5 below
    (factor 2 in current)



Energy density in the insulated cable, and limit given by enthalpy at 300 K

DEFINITION OF TIME MARGIN

- There are several concepts of margin for superconducting magnets
  - Current density margin
  - Loadline margin
  - Temperature margin
- We propose a margin for protection: the time margin
  - Hypothesis: adiabatic approximation (conservative)

$$\int_0^\infty [j(t)]^2 dt = \int_{T_0}^{T_{\max}} \frac{c_p(T)}{\rho(T)} dT \qquad \int_0^\infty [I(t)]^2 dt = \nu A^2 \int_{T_0}^{T_{\max}} \frac{c_p^{ave}(T)}{\rho_{Cu}(T)} dT$$

  - j: current density $\qquad$ I: current
  - ρ_{cu}: copper resistivity $\qquad$ c_p^{ave}: volumetric specific heat
  - ν: fraction of copper $\qquad$ A: cable surface

DEFINITION OF TIME MARGIN

- We define the MIITS of the cable (the capital we can spend)

$$\int_0^\infty [I(t)]^2 dt = \nu A^2 \int_{T_0}^{T_{\max}} \frac{c_p^{ave}(T)}{\rho_{Cu}(T)} dT \qquad \Gamma(T_{\max}) \equiv \nu A^2 \int_{T_0}^{T_{\max}} \frac{c_p^{ave}(T)}{\rho_{Cu}(T)} dT$$

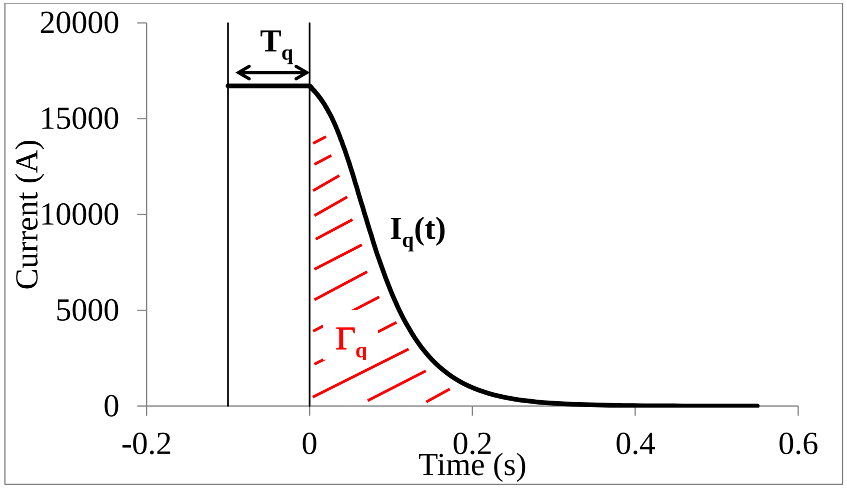
  - Γ_q are the MIITS of a quench where all magnet quenches at time 0

$$\Gamma_q \equiv \int_0^\infty [I_q(t)]^2 dt$$

- How long can we stay at nominal current I_0 ? We call this the protection time margin T_q

$$I_0^2 T_q(T_{\max}) + \Gamma_q = \Gamma(T_{\max})$$

$$T_q(T_{\max}) \equiv \frac{\Gamma(T_{\max}) - \Gamma_q}{I_0^2}$$



NO DUMP: SCALINGS - 1

- **No dump strategy is independent of the length**

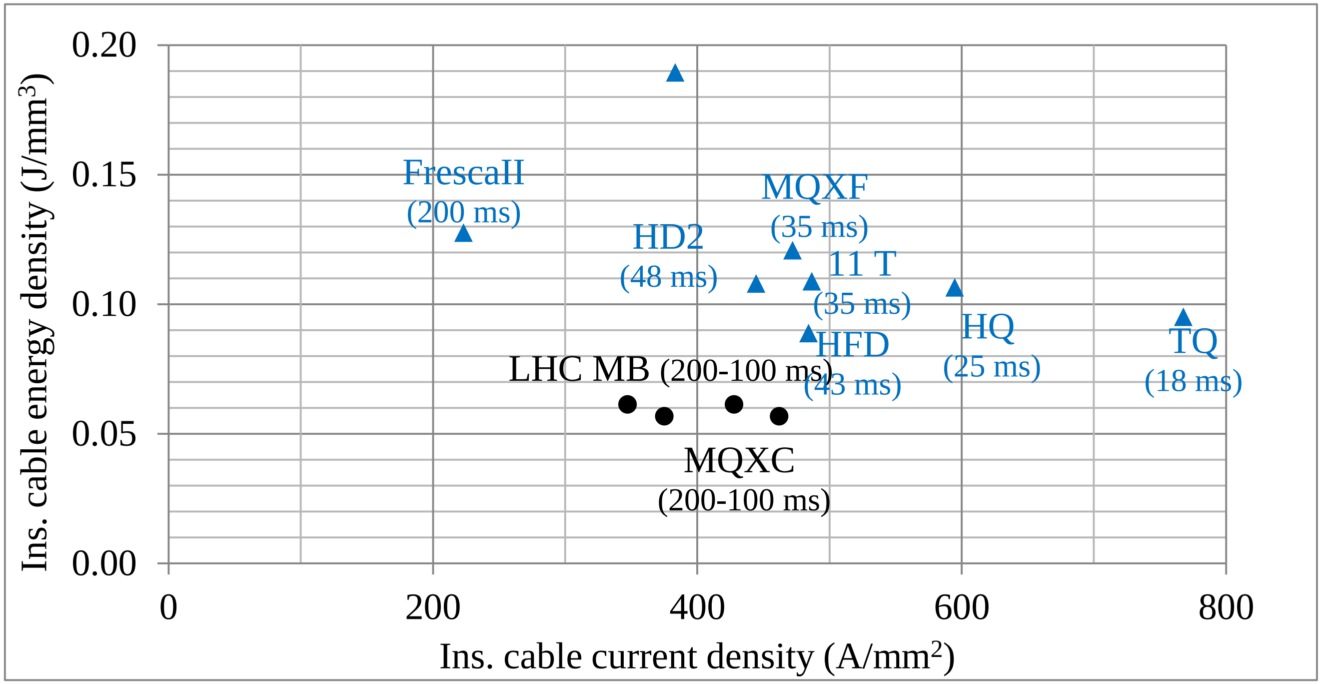
$$I_q(t) = I_0 \exp\left(-\frac{t}{\tau(t)}\right) = I_0 \exp\left(-\frac{tR(t)}{L}\right)$$

  - Both *R* and *L* scale with lenght so the problem in independent of magnet length
- **No dump strategy is independent of the size of the cable**
  - To be more precise: replacing a double layer coil with a single layer and double width, same *U* and *j* (see case Q4), has no impact
    - $w \rightarrow w'=2w$ $I_o \rightarrow I_o'=2I_o$ $U \rightarrow U'=U$
    - Same time constant: $L \rightarrow L'=L/4$ $R \rightarrow R'=R/4$
    - 4 times MIITS and Γ_q $\Gamma \rightarrow \Gamma'= 4\Gamma$ $\Gamma_q \rightarrow \Gamma_q'= 4\Gamma_q$
    - Same time margin $T_q'=T_q$
  - What is relevant?

$$T_q(T_{\max}) \equiv \frac{\Gamma(T_{\max}) - \Gamma_q}{I_0^2}$$

NO DUMP: SCALINGS - 2

- We are going from time margin of 100 ms (LHC NbTi) to 50 ms (Nb_3Sn) and even lower
  - Note that stored energy is not relevant: TQ worse than Fresca2
  - Note the role of current density (up to now neglected I think, whilst the role of copper has been overestimated)



Energy density versus current density in the insulated cable

NO DUMP: SCALINGS - 3

- So what is relevant ?
  - One can derive an equation with intensive properties

$$T_q(T_{\max}) \equiv \frac{\Gamma(T_{\max}) - \Gamma_q}{I_0^2}$$

Copper fraction

cable enthalpy

energy density

$$T_q = \frac{\nu}{\bar{\rho} j_0^2}\left[C_p^{ave} - \eta U_d\right]$$

Average resistivity

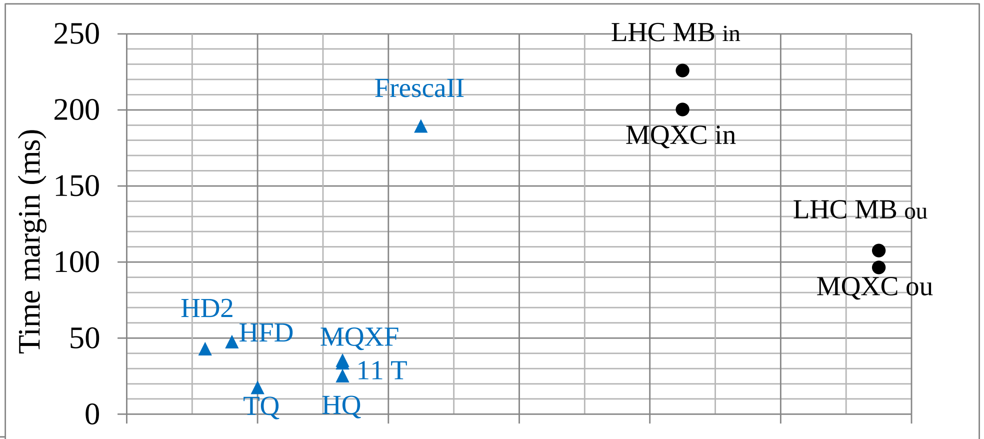
current density

where η is a parameter $\to 1$ for energy density approaching cable enthalpy

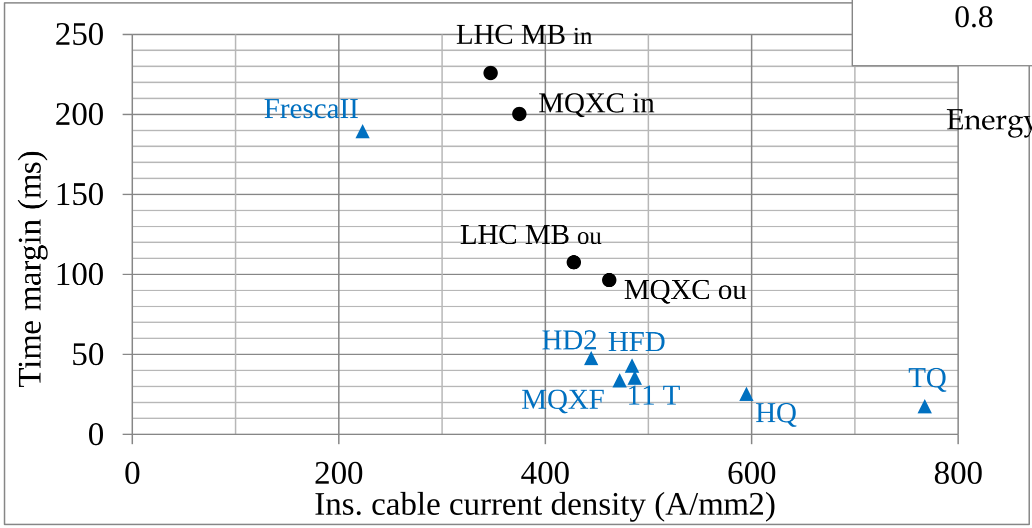
NO DUMP: SCALINGS - 4

- The role of current density is not less important than Cu fraction !

$$T_q = \frac{\nu}{\bar{\rho} j_0^2}\left[C_p^{ave} - \eta U_d\right]$$



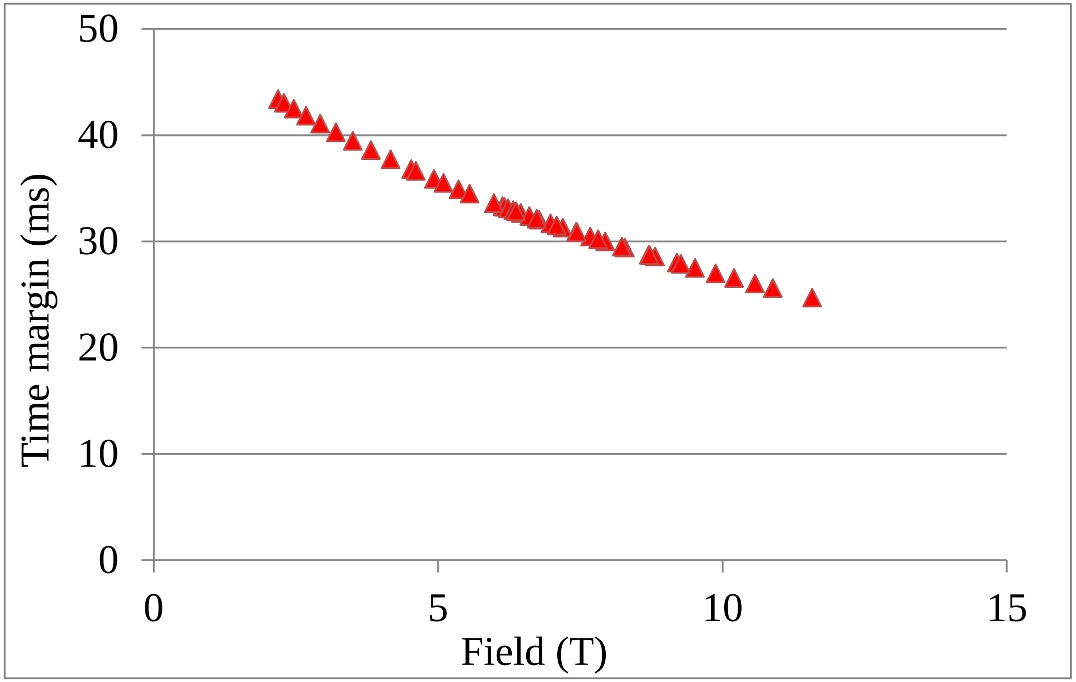
Energy density versus Cu no-Cu in the insulated cable



Time margin vs current density in the insulated cable

NO DUMP: DEPENDENCE ON FIELD

- Depending on the initial quench location one has a large variation of the budget for MIITs →large variation time margin
    - Example HQ: from 25 (12 T) to 45 ms (2 T)
        - This additional margin for low field will be needed

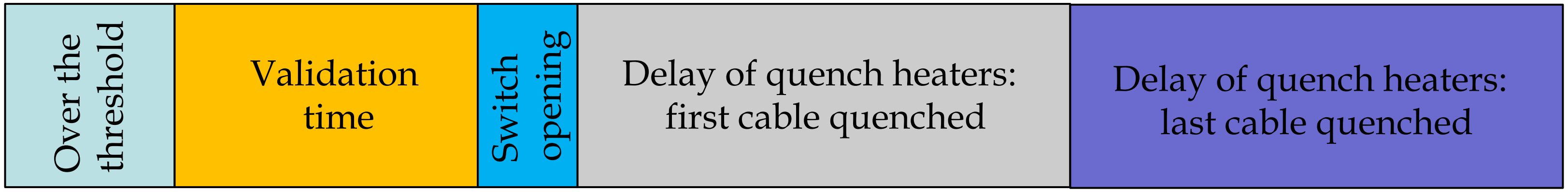


Time margin vs field in HQ (one marker per cable)

TIME TO QUENCH ALL THE MAGNET

- Detection time
  - Time to get over the threshold (a few ms → 10, 20 ms?)
    - Larger for lower fields !
  - Validation time 10 ms, possibly lowered to 5 ms
  - Switch opening 2 ms
- Quench heaters
  - Delay to quench the first cable (5-10 ms)
  - Delay to quench the last cable (10-20 ms)
- A time budget of 40 ms is at the limit

$$T_q \equiv \frac{\Gamma - \Gamma_q}{I_o^2}$$



Over the threshold

Validation time

Switch opening

Delay of quench heaters: first cable quenched

Delay of quench heaters: last cable quenched

The budget for the time margin

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- Hotspot temperature
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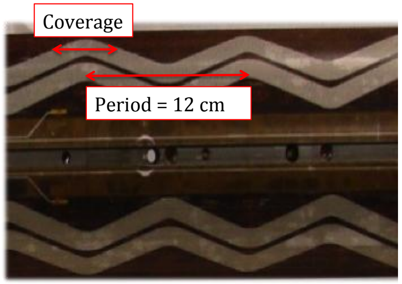
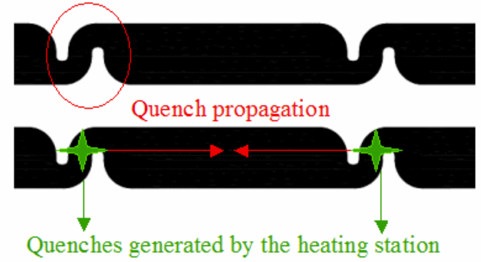
HEATERS: FIRST OBSERVATIONS

- Typical quench velocities
  - Along a cable ~10-20 m/s → 50-100 ms to make 1 m
  - From turn to turn ~10 ms From outer to inner ~50 ms
  - The build up of resistance due to quench propagation is negligible
  - Essential part of the modeling is the heat trasfer from the quench heaters to the coil
    - Interplay of heat transfer, temperature margin



- Heaters power is limited by voltage
  - The heater geometry is not indepedent of length !
  - For long magnet one has to make heating stations to preserve a large power (~50 W/cm^2 for 25 μm thick – or better say 20 W/mm^3?)
    - Distance of stations ~100 mm to have propagation in less than 5 ms
    - This also makes the problem more complex

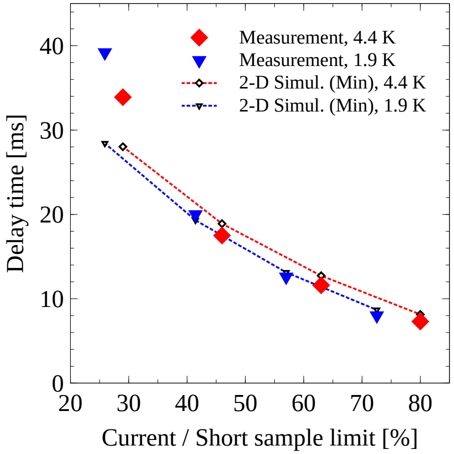


HEATERS: FIRST OBSERVATIONS

- Simple model
  - Estimate the temperature margin T_{cs} a
  - Integrate specific heat from T_{op} to T_{cs} to get the energy needed
  - Time proportional to energy (one free parameter)
  - The case 1.9 K vs 4.2 K
    - 1.9 K: T_{cs}=1.9 + 4.8 = 6.7
    - 4.2 K: T_{cs}=4.2 + 3.3 = 7.5
    - At the end «by chance» the two integrals are similar within 10-20% - so similar delays as found experimentally

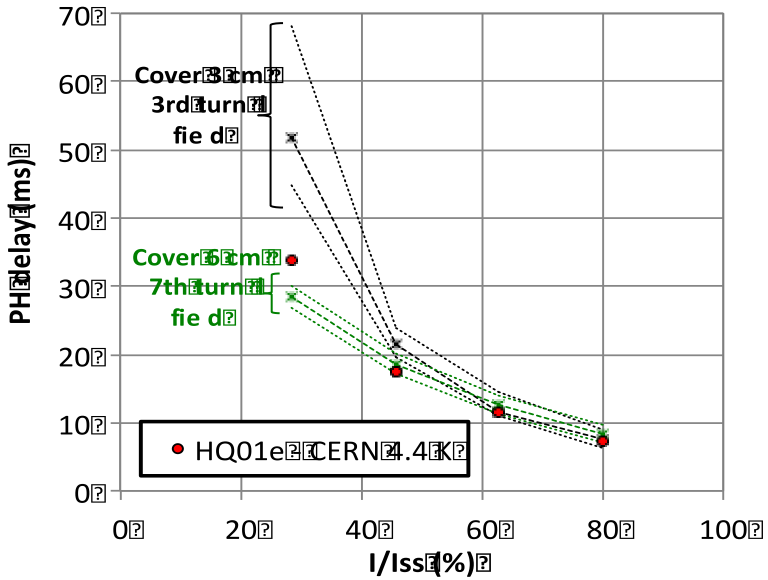
$$t_d \propto \int_{T_{op}}^{T_{cs}} c_p^{ave}(T)dT$$

- More refined models
  - Thermal network [talk by T. Salmi]

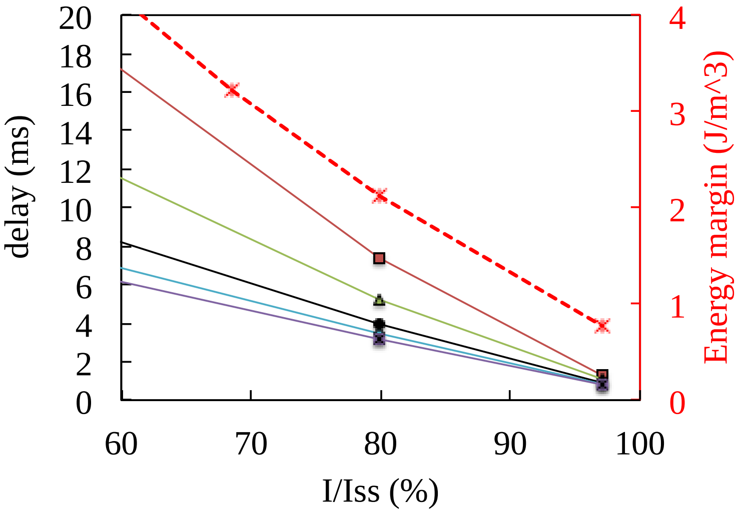


HEATERS DELAY

- Case of HQ [see G. Ambrosio talk]
  - 25 μm Kapton baseline, 50 μm and 75 μm analysed
  - 20-80% I/I_{ss} range less than 10 ms at 80%
  - Nominal power of 50 mW/cm^2
  - Very good modeling



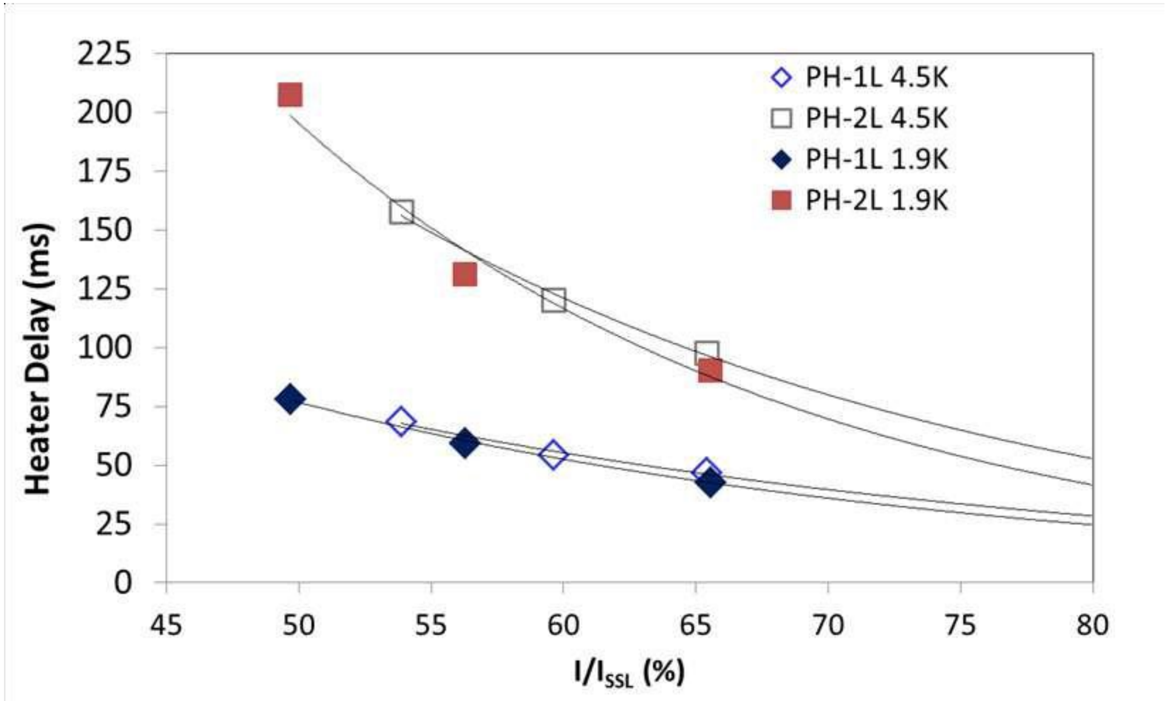
Heaters delay vs model [T. Salmi, H. Felice]



Heaters delay vs powering [T. Salmi, H. Felice]

HEATERS DELAY

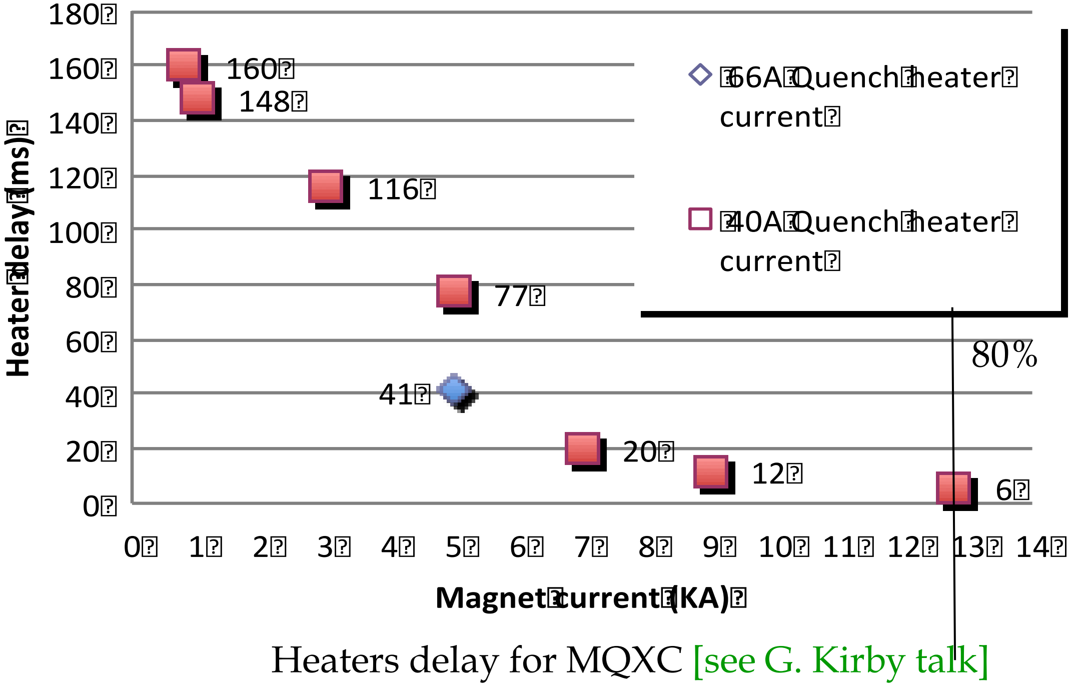
- Case of 11 T
  - 125 μm Kapton baseline, 250 μm also used
  - 20-60% I/I_{ss} range
  - Nominal power of 25 mW/cm^2



Heaters delay for 11 T [see G. Chalchdize]

HEATERS DELAY

- Case of MQXC (Nb-Ti coil, permeable to HeII)
  - QH between inner and outer layer
  - 50 μm Kapton baseline
  - 10-80% I/I_{ss} range
  - Nominal power of 15 mW/cm^2



Heaters delay for MQXC [see G. Kirby talk]

DELAY VS LOCAL FIELD

Over the threshold

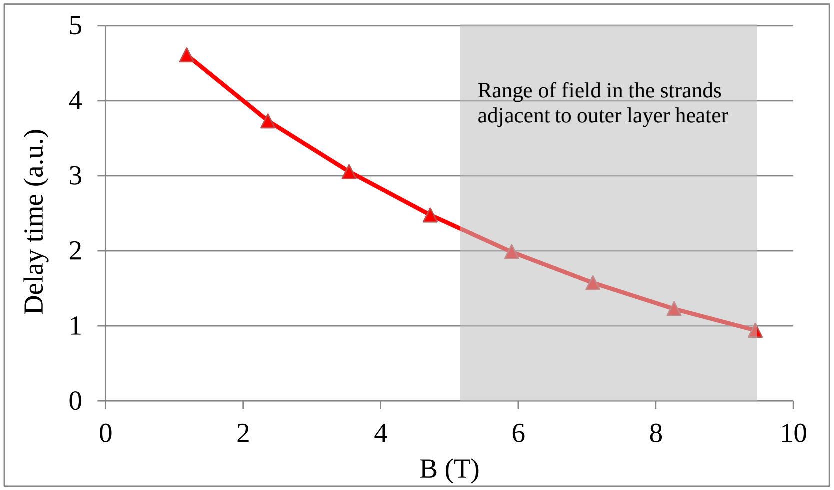
Validation time

Switch opening

Delay of quench heaters: first cable quenched

Delay of quench heaters: last cable quenched

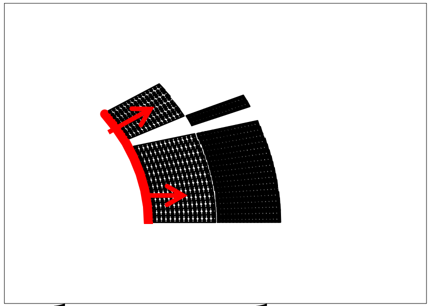
- Problem: the heater is on part of the coil with different field → different temperature margin
  - Typically (LARP quads) we find a factor 2-3 between the two delays
  - So if first quench is induced after 6 ms, last part of the outer quenches at 15-20 ms



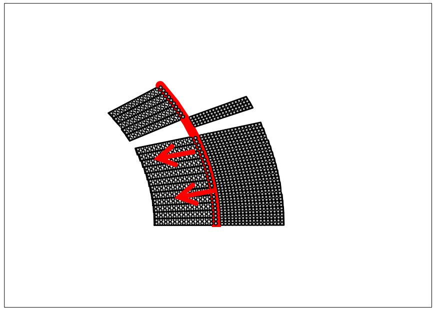
Delay estimated through energy margin versus field HQ

HOW TO QUENCH THE INNER LAYER ?

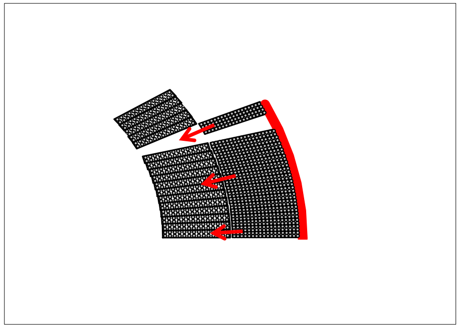
- 1st solution: quench heaters on the inner layer inner side
  - Done in HQ, they work but
    - Barrier to heat removal
    - Indications of detatchement (there is no support), i.e. efficiency could degrade with time



- 2nd solution: quench heaters between inner and outer layer
  - Done in MQXC (Nb-Ti)
  - For Nb_3Sn one has to find material resisting curing at 650 C (tried in HFD, abandoned) or make a splice



- 3rd solution: use the outer layer as heater
  - Is it fast enough ? 50 ms measured in 11 T very relevant number for protection (to be measured and simulated)



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DETECTION

- Time to go above the threshold

$$t_d = \frac{V_{th}}{v_{NPZ}\rho}\frac{1}{j_{o,Cu}}$$

$$V_{th} = R(t)I_o = \frac{v_{NPZ}t\rho}{A_{Cu}}I_o$$

  - Up to 40 K low dependence of resistivity on temperature

- Estimate for HQ, at 12 T
  - V_{th}=100 mV $j_{o,Cu}$=1400 A/mm^2
  - v_{NPZ}= 20 m/s ρ(12 T)=6 ×10^{-10} Ω m
- t_d=6 ms (reasonable)

DETECTION

- Time to go above the threshold

$$V_{th} = R(t)I_o = \frac{v_{NPZ}t\rho}{A_{Cu}} I_o$$

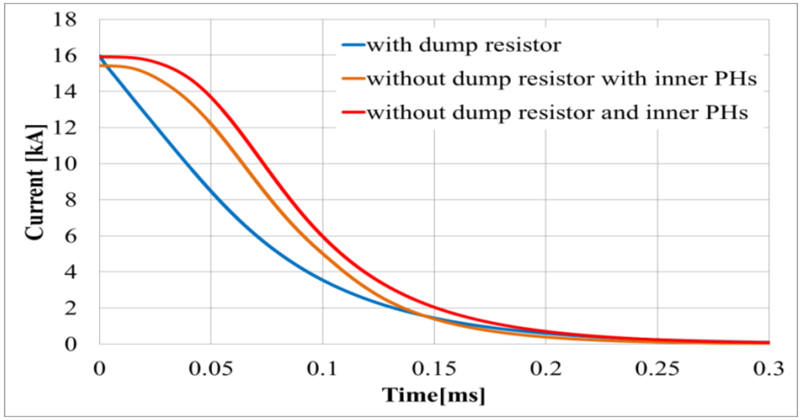
$$t = \frac{V_{th}}{v_{NPZ}\rho} \frac{1}{j_{o,Cu}}$$

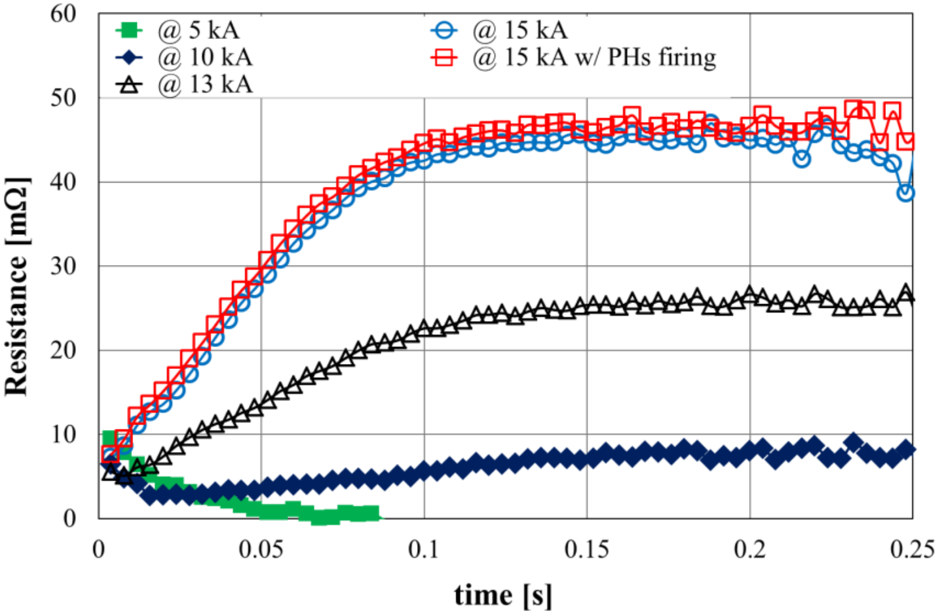
$$v_{NPZ} \propto \sqrt{\frac{\rho\kappa}{T_{cs} - T_{op}}}$$

  - Strong influence of field
    - ρκ(12 T) /ρκ(0 T) ~2 or 1
    - T_{cs}-T_{op}~5 K at 12 T, T_{cs}-T_{op}~15 K at 0 T
    - v_{NPZ}(12 T)/ v_{NPZ}(0 T) ~ 2.5 or 1.7
    - $v_{NPZ}\,\rho$(12 T)/ $v_{NPZ}\,\rho$(0 T) ~ 10 or 6
- So at 0 T NPZ can propagate 10 times slower …
  - Detection time can be much longer for low field
  - Larger budget (20 ms) partially compensates
    - Careful study of quench velocity needed [See H. ten Kate talk]
- For HTS the v_{NPZ} is a factor 100 less so the detection is the real bottleneck [See J. Schwartz talk]

QUENCHBACK

- For LARP quads we have evidence of strong quenchback
  - Method: open switch and dump current on resistor – estimate resistance from dI/dt





High MIITs test [H. Bajas, M. Bajko, H. Felice, G. L. Sabbi, T. Salmi, ASC 2012]

- This effect can be dominant! We can get wrong conclusions
- The initial ramp rate is huge! with I=15 kA, τ=1, dI/dt= 15000 A/s …

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INDUCTIVE VOLTAGES

- During the quench one has
  - a resistive voltage propto I (where the magnet is quenched)
  - an inductive voltage propto dI/dt (everywhere)
- The two compensate at the end of the magnet in case of no dump resistor

$$V_{in} = L_{in} \frac{dI}{dt} \qquad V_{ou} = L_{ou} \frac{dI}{dt} - R_{ou} I$$

- Worst estimate:
  - Outer layer quenched – inner layer not
  - Equal split of inductance

$$L_{in} \sim L_{ou} \sim \frac{L}{2}$$

  - So the highest voltage vs time is

$$V_{\max}(t) = \frac{1}{n_p} L_{in} \frac{dI(t)}{dt}$$

    - where the I(t) is computed for a fully quenched outer layer

INDUCTIVE VOLTAGES - SCALING

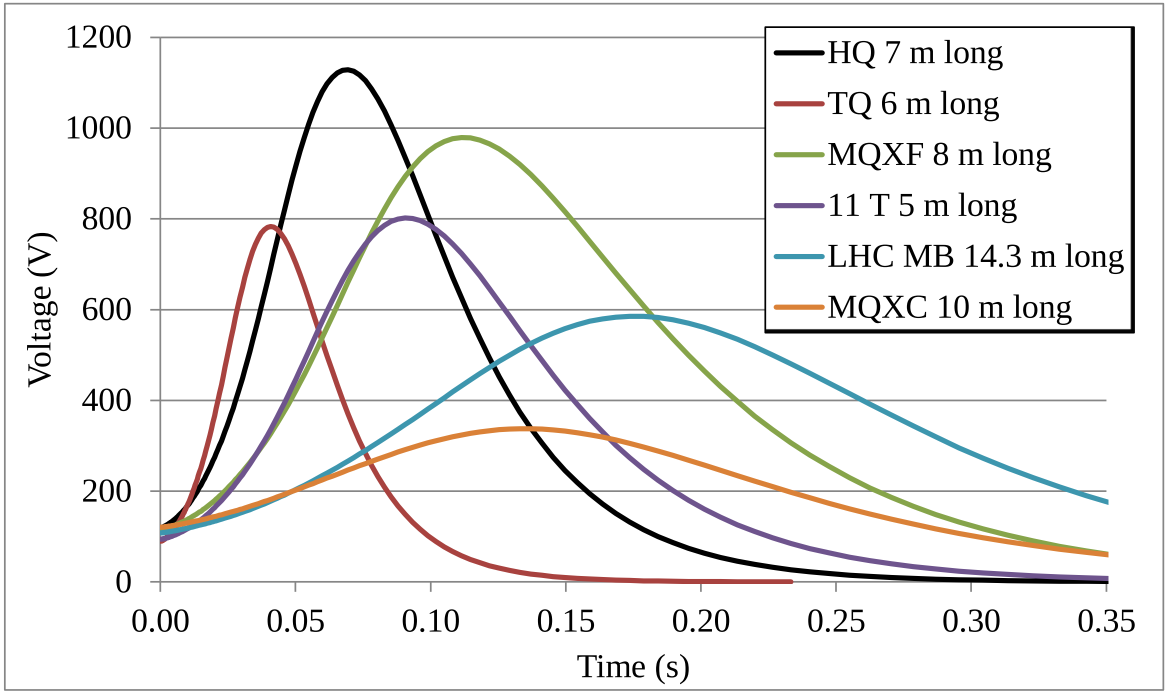
- **The inductive voltage is proportional to magnet length**
  - Current inpendendent of length, derivative as well
  - Inductance propto length

$$V_{\max}(t) = \frac{1}{n_p} L_{in} \frac{dI(t)}{dt}$$

- **The inductive voltage is reduced for larger cables**
  - Usual case two magnets same field and energy, one with two layers and width *w*, one with one layer and width 2*w*
  - $I \rightarrow I'=2I$ $w \rightarrow w'=2w$ $L \rightarrow L'=L/4$ $R \rightarrow R'=R/4$
  - $\tau \rightarrow \tau'=\tau$ $V_{\max} \rightarrow V_{\max}'=V_{\max}/2$
  - So small cables can be dangerous for long magnet

INDUCTIVE VOLTAGES - SCALING

- Where are we ?
  - For all magnets we are safe
    - also considering that anyway after 50 ms the inner has to quench (in this simulation inner never quenches)
  - But we are not so far from the limit



Estimate of maximum inductive voltage in some future magnets

CONCLUSIONS

- With Nb_3Sn magnets we are entering a new regime of protection
  - We are a factor 5 below energy density limit set by heat capacity
    - It was a factor 10 with Nb-Ti
  - The time margin needed to quench the magnet is of ~50 ms
    - It is a factor 2-4 larger for LHC MB and MQXC
  - Large current densities are challenging …
    - TQ was probably impossible to protect in long version
- How heaters work is a key point
  - Delays of 5-10 ms are acceptable
  - Optimize power, thickness of insulation, coverage
  - The question of the inner layer: what to do?
    - Measuring and modeling the delay between outer and inner quench

CONCLUSIONS

- Detection time
  - Is the main bottlenck for HTS
  - It can become critical for Nb_3Sn at low fields

- Quenchback can become the dominant mechanism for LARP Nb_3Sn magnets without cored cable
  - Measurements needed, with low dump resistor

- Inductive voltages are not a problem for the magnets being planned
  - They scale with magnet length
  - The inner triplet for the HL-LHC is just going close to this limit