PROTECTION ISSUES IN MAGNET DESIGN

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Acknowedgements
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FOREWORD

- Protection is considered a critical issue in the 120 mm aperture Nb_3Sn quadrupole HQ, built by the LARP
- Since the beginning of High Luminosity LHC project, it appears evident that aperture means performance and that 120 mm is not aiming at maximum performance
- But larger apertures mean larger stored energies, so in principle the situation becomes worse
- In March I started to explore protection issues related to the choice of the strand and of the cable for a 150 mm aperture quadrupole

CONTENTS

- Recall of adiabatic approximation, MIITS
  - Parametric analysis: material, Cu/NoCu ratio, magnetic field
- Dumping on resistor
- Quality factors
  - Time at maximum current
  - Time needed to quench
- Detection time
- Application to 150 mm aperture

RECALL OF ADIABATIC APPROXIMATION

- Balance between Joule heating and heat capacity (adiabatic approximation)

$$\rho(T)\left[j(t)\right]^2 dt = c_p(T)dT$$

ρ: resistivity [Ω m]

j: current density [A/m^2]

c_p: volumetric heat capacity [J/K/m^3]

- Integrating from t=0 to infinity, temperature increases from T_{op} to T_{max}

$$\int_0^{\infty}\left[j(t)\right]^2 dt = \int_{T_0}^{T_{\max}} \frac{c_p(T)}{\rho(T)} dT$$

RECALL OF ADIABATIC APPROXIMATION

- We now express in terms of current

  j: current density [A/m^2]

$$\int_0^{\infty} [j(t)]^2 dt = \int_{T_0}^{T_{\max}} \frac{c_p(T)}{\rho(T)} dT$$

  A: cable cross-sectional surface

  A_{Cu}: copper cable cross-sectional surface

  ρ: resistivity [Ω m]

  c_p^{ave}: average volumetric heat capacity [J/K/m^3]

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

- Assuming: conductivity only through copper

RECALL OF ADIABATIC APPROXIMATION

- Balance between Joule heating and heat capacity

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

- Right side: property of the cable
  - The capital we have to spend (some dependence on magnet design)

$$\Gamma(T_{\max}) \equiv A_{Cu} A \int_{T_0}^{T_{\max}} \frac{c_p^{ave}(T)}{\rho_{Cu}(T)} dT = A_{Cu} A \int_{T_o}^{T_{\max}} \gamma(T) dT$$

- Left side: measured during quench
  - High current dumped rapidly equivalent to low current for long time, what counts is integral of I square
  - This is what is usually called MIITS

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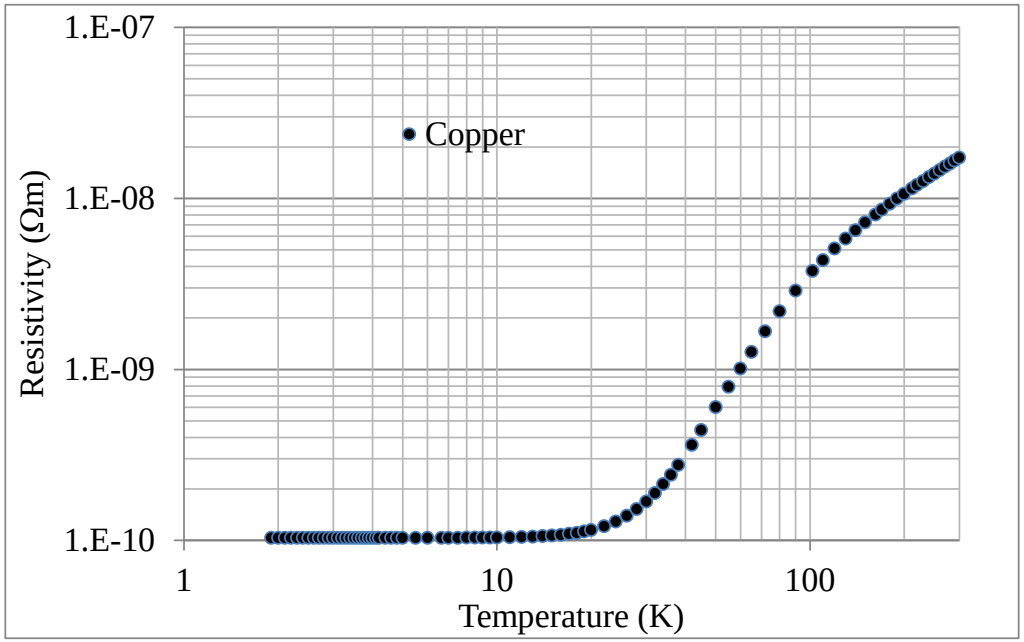
PARAMETRIC ANALYSIS

$$\Gamma(T_{\max}) \equiv A_{Cu} A \int_{T_0}^{T_{\max}} \frac{c_p^{ave}(T)}{\rho_{Cu}(T)} dT = A_{Cu} A \int_{T_o}^{T_{\max}} \gamma(T) dT$$

- Copper resistivity:
  - Important dependence on RRR and on magnetic field B
  - Dependence on B gives a dependence of Γ on the magnet design and not only on cable geometry

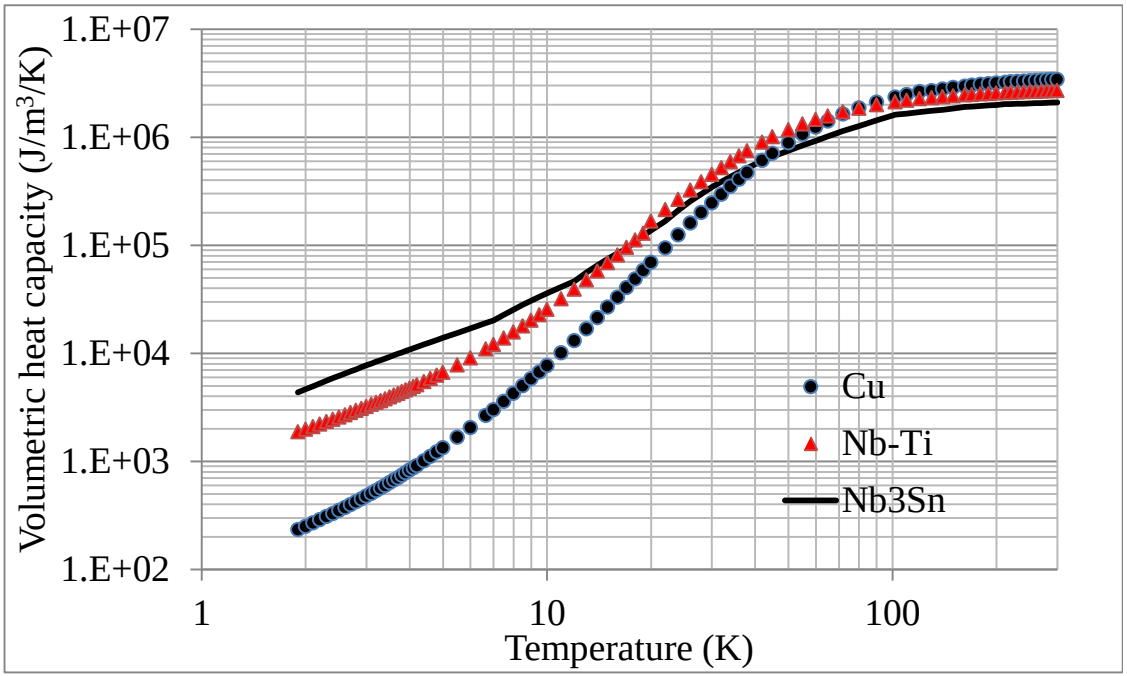


Copper resistivity in B=8 T and RRR = 100

PARAMETRIC ANALYSIS

$$\Gamma(T_{\max}) \equiv A_{Cu} A \int_{T_0}^{T_{\max}} \frac{c_p^{ave}(T)}{\rho_{Cu}(T)} dT = A_{Cu} A \int_{T_o}^{T_{\max}} \gamma(T) dT$$

- Heat capacity:
  - Some differences between Cu, Nb-Ti, Nb_3Sn
  - In this analysis I neglect epoxy, insulation, and I fix $T_{\max}$=300 K

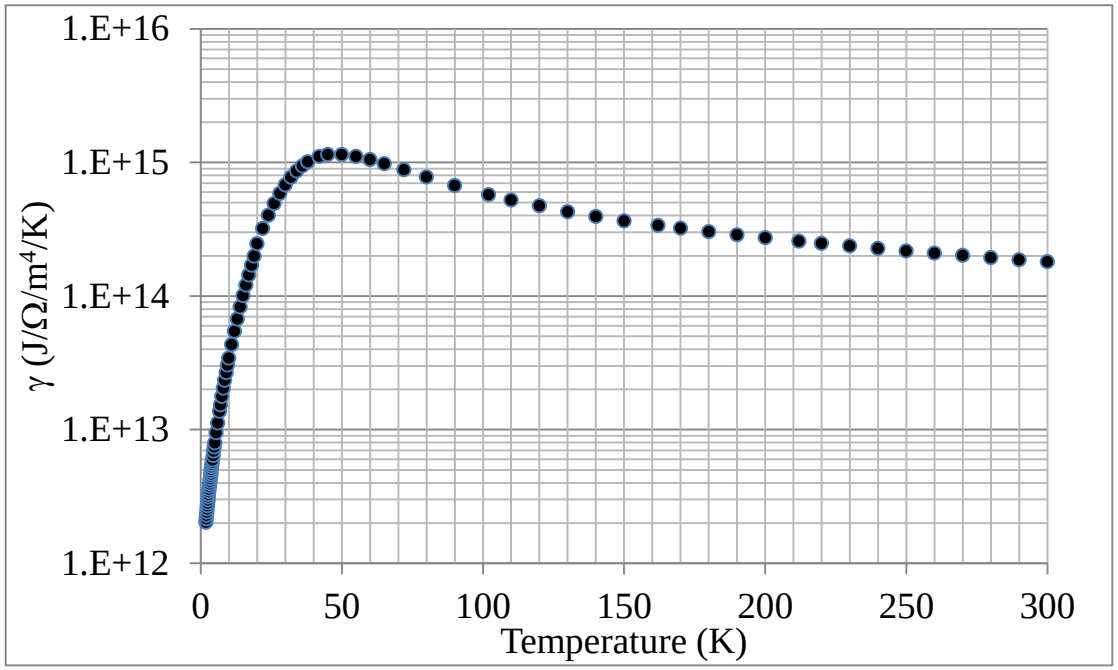


Volumetric heat capacity for Cu, Nb-Ti, Nb_3Sn

PARAMETRIC ANALYSIS

$$\Gamma(T_{\max}) \equiv A_{Cu} A \int_{T_0}^{T_{\max}} \frac{c_p^{ave}(T)}{\rho_{Cu}(T)} dT = A_{Cu} A \int_{T_o}^{T_{\max}} \gamma(T) dT$$

- Integrand γ:
  - Part below 20 K is small



Factor γ for the LHC dipole inner cable

PARAMETRIC ANALYSIS

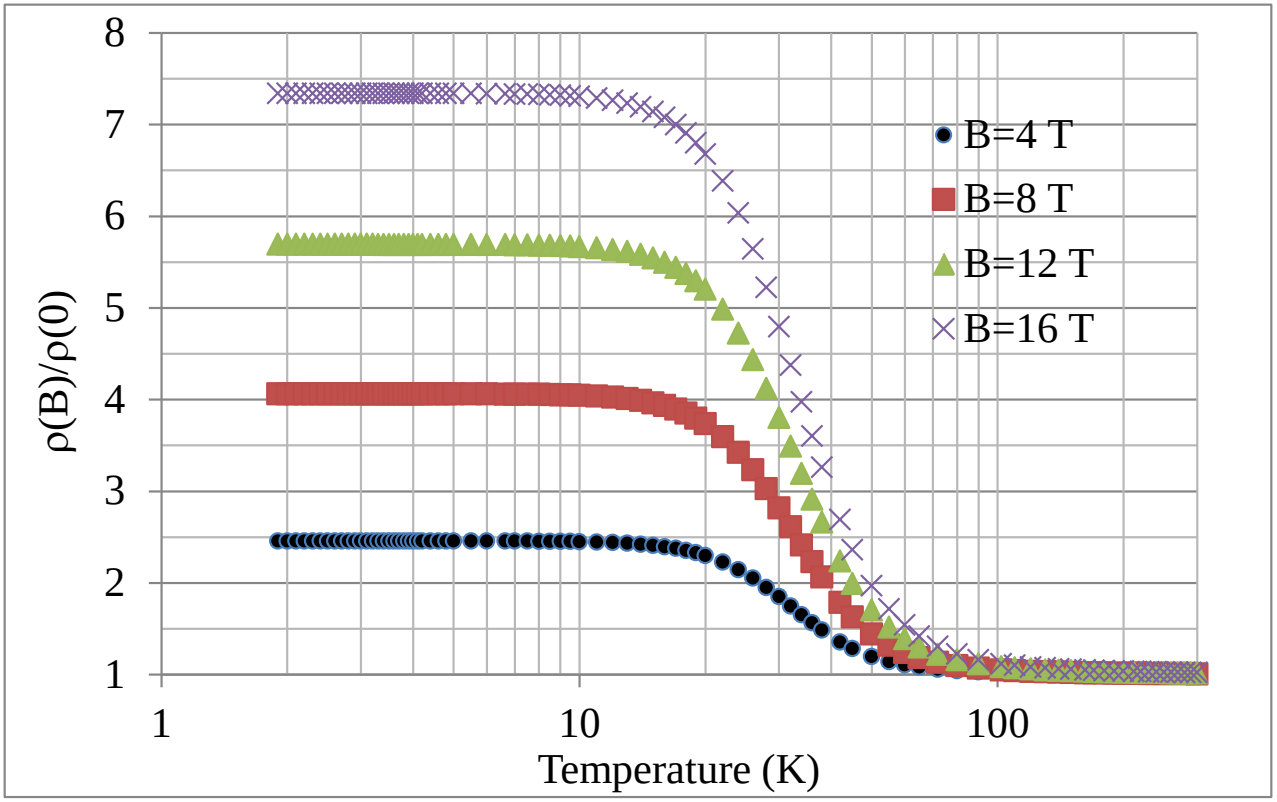
- First trivial remarks:
  - Γ scales with square of the area of the cable
    - Double cable size, four times Γ

$$\Gamma(T_{\max}) \equiv A_{Cu} A \int_{T_0}^{T_{\max}} \frac{c_p^{ave}(T)}{\rho_{Cu}(T)} dT = A_{Cu} A \int_{T_o}^{T_{\max}} \gamma(T) dT$$

  - Linear with the percentage of copper
    - Please note: doubling the Cu/NoCu from 1 to 2 → fraction of copper from 50% to 67% → increase of Γ of 33% (1/3)
    - So, this has some effect but not so large as one would expect

PARAMETRIC ANALYSIS: MAGNETIC FIELD

- Dependence on magnetic field
  - Enters through copper resistivity
  - Disappears at 100 K



Impact of magnetic field on copper resistivity

PARAMETRIC ANALYSIS: MAGNETIC FIELD

- Dependence on magnetic field
  - ☹ Higher fields, less Γ
  - From 8 to 12 T, 8% difference
    - Not huge, but not negligible

	B (T)			
	4	8	12	16
LHC inner	11%	0%	-8%	-13%
HQ	21%	9%	0%	-6%

Impact of magnetic field on Γ for two cases

PARAMETRIC ANALYSIS: RRR

- Dependence on RRR
  - ☺ Higher RRR, larger Γ
  - From RRR=100 to 150, small difference (3%)
  - From RRR=50 to 150, 10% difference

	RRR			
	50	100	150	200
LHC inner	-12%	-3%	0%	2%
HQ	-7%	0%	3%	5%

Impact of RRR on Γ factor for two cases

CONTENTS

- Recall of adiabatic approximation, MIITS
- Parametric analysis: material, Cu ratio, magnetic field
- Dumping on resistor
- Quality factors
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DUMPING ON RESISTOR

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

- How to reduce I as fast as possible ?
  - Once the switch is opened, one has a RL circuit, current decreases exponentially with time constant τ
- We first neglect magnet resistance and add a resistor R_d

$$\tau = \frac{L_m}{R_d} \qquad \int [I(t)]^2 dt = I_o^2 \int e^{-2t/\tau} dt = \frac{\tau}{2} I_o^2 = \frac{L_m}{2R_d} I_o^2 \sim \frac{U_m}{R_d}$$

- A large enough resistor protects magnets with any energy
- But …

DUMPING ON RESISTOR

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

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

$$\int [I(t)]^2 dt = \frac{U_m}{R_d} = \frac{U_m I_o}{V_{\max}}$$

- As far as I understand V_{max} is a kind of constant for accelerator magnets (independent of the design ?)

- 600-1000 V looks as a typical value

DUMPING ON RESISTOR

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

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

- Typical case of MQXC, outer cable has Γ=30 MIITS

  I_o=13 kA $\rightarrow R_d$ = 70 mΩ , V_{max}=910 V

  L_m=5.0-4.8 mH/m, for 2 m long L_m=10 mH

  τ=10/70=140 ms $\rightarrow$ 12 MIITS < Γ=30 MIITS
- At short sample:

  I_o=16 kA $\rightarrow R_d$ = 55 mΩ , V_{max}=880 V

  τ=10/55=180 ms $\rightarrow$ 24 MIITS < Γ=30 MIITS safe

DUMPING ON RESISTOR

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

$$\int [I(t)]^2 dt = \frac{\tau}{2} I_o^2 = \frac{U_m I_o}{V_{\max}}$$

- Case of HQ, cable has Γ~17 MIITS

  I_o=15 kA $\rightarrow R_d$ = 60 mΩ , V_{max}=900 V

  L_m=7-8 mH/m, for 0.8 m long L_m=6 mH

  τ=6/60=100 ms $\rightarrow$ 11 MIITS < Γ=17 MIITS

- At short sample:

  I_o=19 kA $\rightarrow R_d$ = 50 mΩ , V_{max}=950 V

  τ=6/50=120 ms $\rightarrow$ 22 MIITS

too much ☹

DUMPING ON RESISTOR

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

$$\int [I(t)]^2 dt = \frac{\tau}{2} I_o^2 = \frac{U_m I_o}{V_{\max}}$$

- Long MQXC (for HL LHC):

  I_o=13 kA $\rightarrow R_d$ = 70 mΩ , V_{max}=910 V

  L_m=5.0-4.8 mH/m, for 10 m long L_m=50 mH

  τ=50/70=700 ms $\rightarrow$ 60 MIITS < Γ=30 MIITS too much

- Our long magnets in general cannot be protected only by dump
  - If magnets insulation could withstand 100 kV we could protect everything with dump …
  - Protection could be solved by insulation ?

DUMPING ON RESISTOR: WHY LARGER CABLE HELPS

- We consider two magnets with the same coil surface, but the second with a cable with double surface
  - Example, a double layer versus a single layer with double width

$$\Gamma > \frac{U_m I_o}{V_{\max}}$$

- Γ scales with square of cable area → we gain a factor 4
- If we are dominated by dump resistor, MIITS scale with current, i.e., a factor 2
  - In this case, protection becomes easier by a factor 2

- Larger cable helps when there is a dump resistor

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FIRST QUALITY FACTOR
SURVIVAL TIME AT NOMINAL CURRENT

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

- Dump resistor effect becomes negligible for long magnets

- How long the magnet can stay at nominal current having a resistive part?
  - We ignore dump resistor, and quench propagation
  - This is just a battle between Γ and the operational current

  - LHC MB, MQXC, Fresca2: 200-300 ms
  - HQ, 11T: 80-90 ms

QUALITY FACTOR Q2: TIME LEFT TO QUENCH ALL THE MAGNET

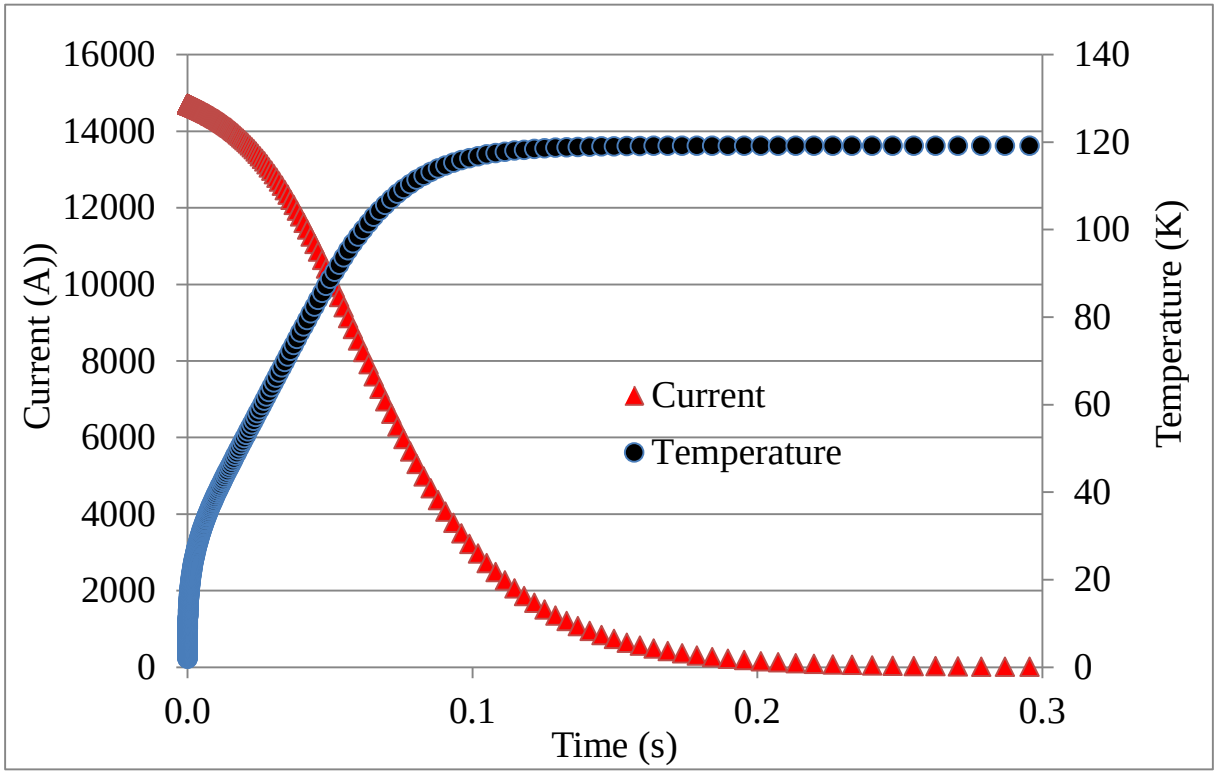
- More realistic case: no dump resistor, a magnet at operational current totally quenched at operational temperature
  - What happens? Joule heating increases temperature, that increases resistance

$$R_m(T,B) = \frac{\rho(T,B)}{A_{Cu}} l_c \qquad R_d = 0 \qquad \tau(t) = \frac{L_m}{R_m(T(t),B(t))}$$

  - Current versus time is gaussian-like shape rather then exponential
    - This is the best case we can imagine for a long magnet: protection system so effective that instantaneously quenches all the magnet
    - If we do not survive here, we are dead
  - Must be solved by numerical integration
  - This case does not depend on magnet length

QUALITY FACTOR Q2: TIME LEFT TO QUENCH ALL THE MAGNET

- Case of HQ at nominal current
  - Reaches 120 K, i.e. consumes ~11 MIITS over ~ 17 available
  - 6 MIITS left, at 15 kA you can resist 6/(15*15)~30 ms



QUALITY FACTOR Q2: TIME LEFT TO QUENCH ALL THE MAGNET

- Subtilities of the computations
  - Also inductance varies with field due to saturation – starts from 5.6 mH and ends at 6.4 mH
    - Not very large – gives a variation of 10 K, 5% in MIITS
    - Not taken into account in most codes (except ROXIE)
  - Field decreases with current and this induces a variation of resistivity
  - Total resistance of the magnet has to take into account that field is not the same in the coil
  - Integration is delicate since parameters have a wide range of variation – time step either adaptive or very small (<<1 ms)

QUALITY FACTOR Q2: TIME LEFT TO QUENCH ALL THE MAGNET

- We define Γ_q: MIITS consumed by the fully quenched magnet at operational current and temperature, dumped on itself
  - Does not depend on magnet length!

$$t_2 \equiv \frac{\Gamma - \Gamma_q}{I_o^2}$$

- We define as quality factor t_2: max time available to quench all magnet
- (Fresca2: 300 ms)
- LHC MB, MQXC: 80-90 ms
- 11 T: 50 ms
- HQ: 30 ms

Scaling of MIITS consumed by fully quenched magnet

- Two scaling of this max time to quench all magnet I would like to discuss (cross-checks needed)
- Case 1: doubling the cable size, same coil, same field, same energy
  - Available MIITS $\rightarrow$ 4 times
  - $\Gamma_q \rightarrow$ 4 times
  - $I_0 \rightarrow$ 4 times neutral action: larger cable does not help

$$t_2 \equiv \frac{\Gamma - \Gamma_q}{I_o^2}$$

- Case 2: doubling Cu/NoCu ratio from 1 to 2, keeping same field (academic case, since you change the margin)
  - Available MIITS scale linearly $\rightarrow$ +33%
  - $\Gamma_q \rightarrow$ +33% (same linear scaling)
  - I_0 constant
  - There is a 33% gain in time available to quench (not so impressive)
    - We gain if the time needed to quench the magnet does not scale as well!

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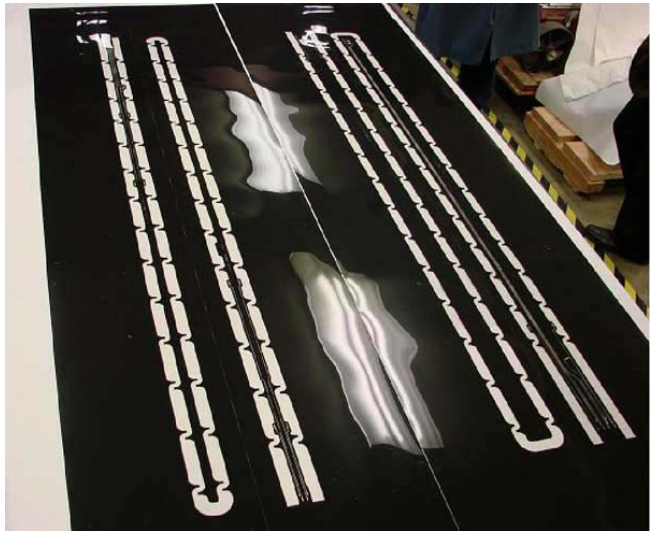
  - Time needed to quench
- Time needed to quench

How to quench all the magnet

- For long magnets protection strategy is to make them resistive, so the time constant of the circuit goes down and current is dumped
- Quench propagation velocities (longitudinal) are of the order of 10 m/s in Nb-Ti and Nb_3Sn
  - So for a 10-m-long magnet it takes one second for the quench to cover the whole magnet – too long

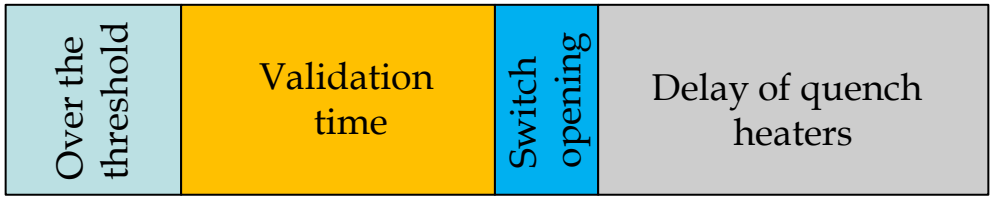
- Heaters: stripes of metal close to the coil, heated through a current pulse, to quench all magnet



TIME TO QUENCH ALL THE MAGNET

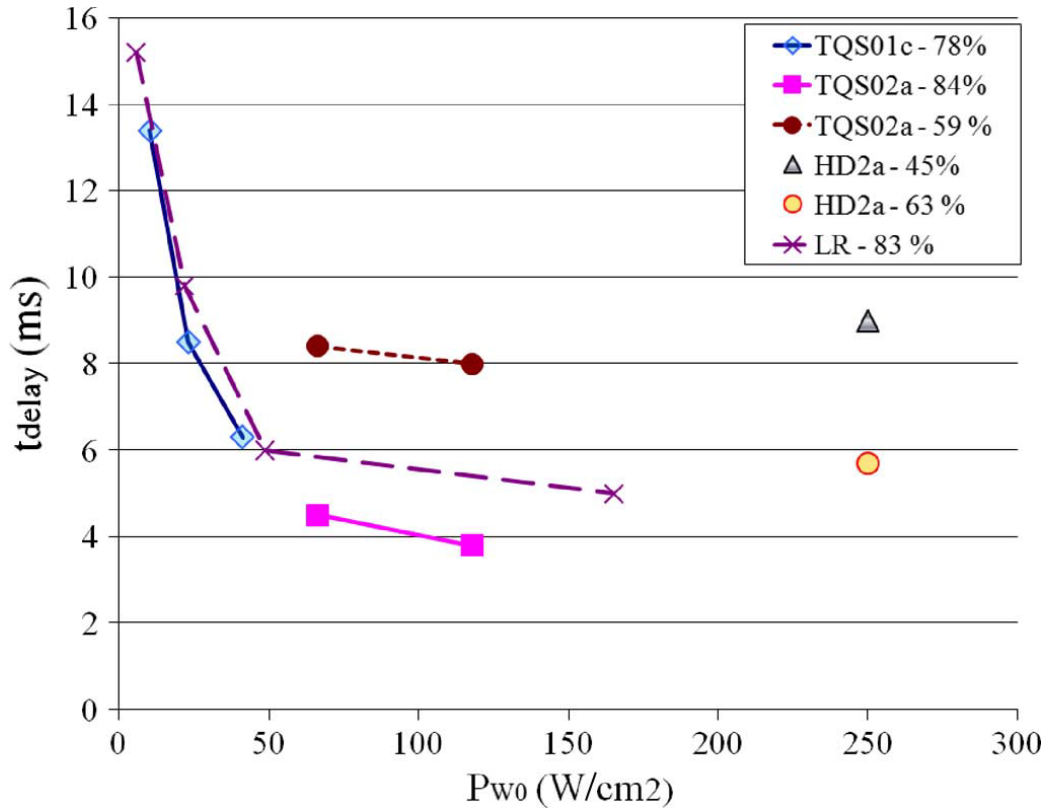
- Detection time
  - Time to get over the threshold (a few ms)
  - Validation time 10 ms
  - Switch opening 2 ms
- Time for the quench heaters to quench
  - Depends on the margin: lower margin, lower time
  - Of the order of 10 ms
- Budget for HQ 3+10+2+10=25 ms, so we are at the limit

$$t_2 \equiv \frac{\Gamma - \Gamma_q}{I_o^2}$$



TIME FOR HEATERS TO QUENCH THE MAGNET

- Study of quench delay induced by quench heaters is an important tool



Time needed to quench the magnet [H. Felice, et al, IEEE Trans. Appl. Supercond. **19** (2009) 2460]

TIME TO DETECT THE QUENCH

- Time to get over the threshold depends on

$$V_{th} = R(t_d) I_0$$

  - Voltage threshold, typically 100 mV – a constant ?

$$R(t) = \frac{\rho_{1.9}}{A_{Cu}} v_q t_d$$

  - Quench propagation velocity – typically 10 to 20 m/s
  - Cable cross section, quantity of copper and current
    - Here larger cable, more copper, and lower RRR all go in the wrong direction of reducing resistance and increasing time

$$t_d = \frac{V_{th}}{\rho_{1.9} v_q} \frac{A_{Cu}}{I_o} = \frac{RRR}{\rho_{300}} \frac{V_{th}}{v_q} \frac{A_{Cu}}{I_o}$$

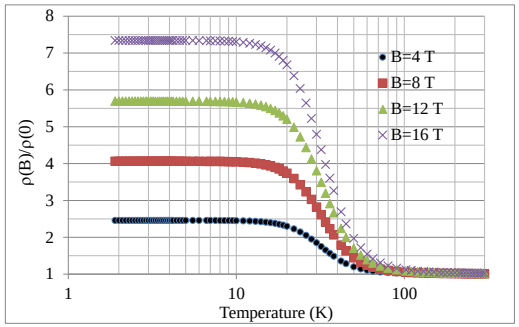
TIME TO DETECT THE QUENCH

- Time to get over the threshold: HQ case

$$t_d = \frac{V_{th}}{\rho_{1.9} v_q} \frac{A_{Cu}}{I_o} = \frac{RRR}{\rho_{300}} \frac{V_{th}}{v_q} \frac{A_{Cu}}{I_o}$$

RRR=100 V_{th}=0.1 V A_{Cu}= 9 mm^2 = 9×10^{-6} m^2

R_{300}=17×10^{-9} Ω m v_q=20 m/s I_o=15 kA



- Result: t_d=17 ms (too much)
  - But this is at B=0, at 12 T we have about 6 times larger resistance ☺☺☺
  - So this gives about 3 ms – not totally negligible
  - Quenches at low field can be very slow … also because there is more margin
  - 11 T case: current is 20% lower, A_{Cu} 14% lower – similar result

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APPLICATION TO 150 MM APERTURE CASE

- Guideline: keep the same ratio coil width/aperture *w/r*
  - 15 mm cable for 120 mm, 19 mm for 150 mm
  - Since the gradient *G* goes down from 170 to 140 T/m, the current density *j* scales accordingly (-18%)

$$G = j\gamma \log\left(1+\frac{w}{r}\right)$$

- Larger coil width comes from two sources
  - Strands from 35 to 40 (+14%)
  - Strand diameter from 0.8 to 0.85 (+6%)
  - Keep same copper content to avoid losing gradient

- Good side effect: more coil to compensate the stress increase due to larger aperture
  - So coil stress variation is negligible

APPLICATION TO 150 MM APERTURE CASE

- Larger coil width comes from two sources
  - Strands from 35 to 40 (+14%)
  - Strand diameter from 0.778 to 0.85 (+9%)
  - Keep same copper content to avoid losing gradient
- Cable properties:
  - Cable cross-section $\rightarrow$ +36%
  - $\Gamma \rightarrow$ +86% = $(+36\%)^2$
- Current
  - Current density -18%
  - Increase of current +12%
- $\Gamma_q \rightarrow$ +86%
- Time needed to quench increases from ~30 to ~45 ms
  - Small impact on detection time: 60% more, i.e. from 3 to 5 ms

TENTATIVE CONCLUSIONS

- Dump resistor strategy:
  - Viable for short magnets
  - Larger cable make protection easier, scales linearly with surface
  - Strategy is not independent of length – for «long» magnets is not viable due to limits in insulation
- Magnets without dump resistor
  - Heaters are used to quench the magnets
  - The problem becomes independent of length
  - Complex interplay between inductance, current, and resistance of the coil – need numerical integration
  - Estimating the time available for quenching the magnet can be a good indicator
    - Increasing Cu/NoCu one has more time – but performance goes down
    - Large or small cables, it is the same

TENTATIVE CONCLUSIONS

- Time needed to quench the magnet by detection system+quench heaters
  - I would judge it independent of magnet length
  - Only one part depends on the cable: time to go over the threshold – it is not a dominant factor in our cases
  - Time needed for quench heaters has a strong dependence on margin (in the right sense, lower margin smaller times)
  - Time needed for quench heaters depends on insulation layers – and if heaters reach directly every layer or not
- HQ case seems very tight, with ~30 ms only available to quench all magnet
  - It looks that the 150 mm case can be made easier, even if the stored energy is nearly twice HQ, by choosing a lower current density
  - Verification on a full model is needed

QUESTIONS ?