Heat transfer and quench propagation from protection heaters

Tiina Salmi

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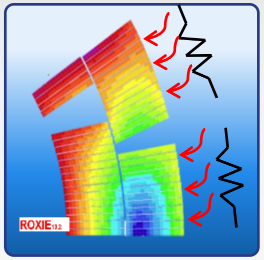
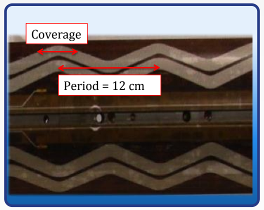
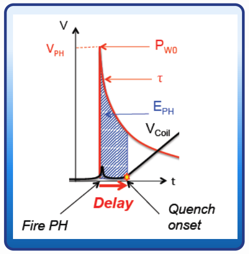
1. Protection heater purpose and design

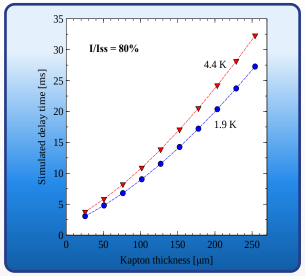




2. Modeling

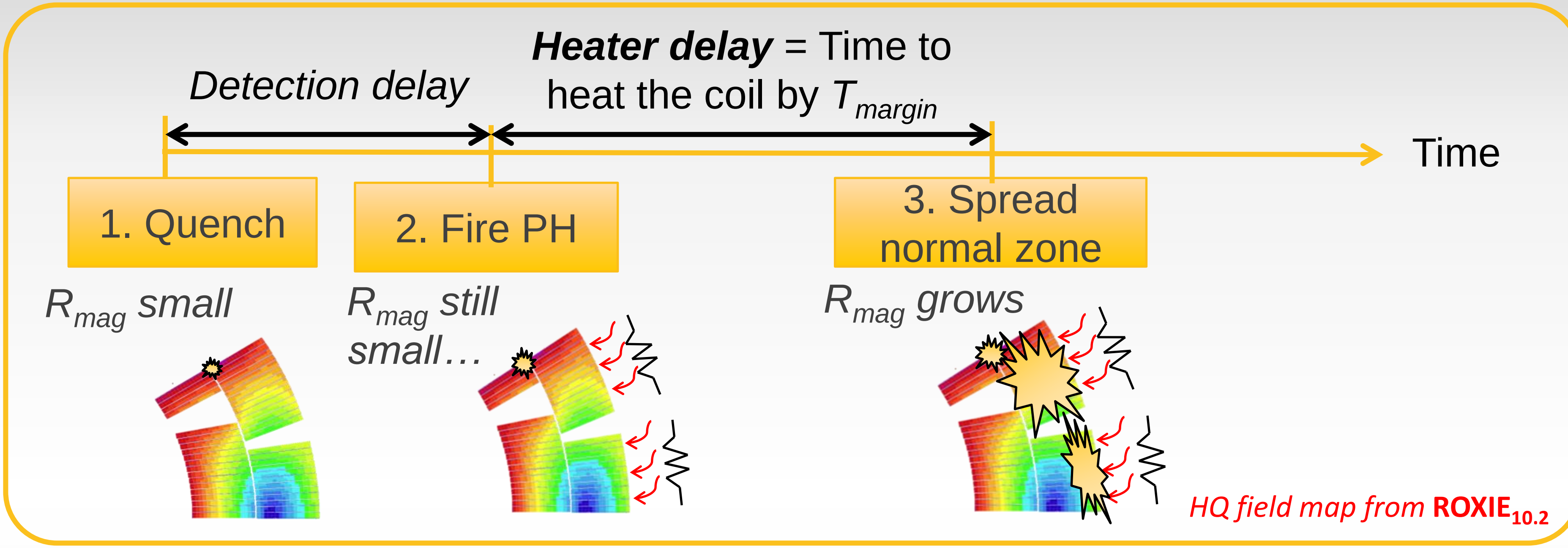


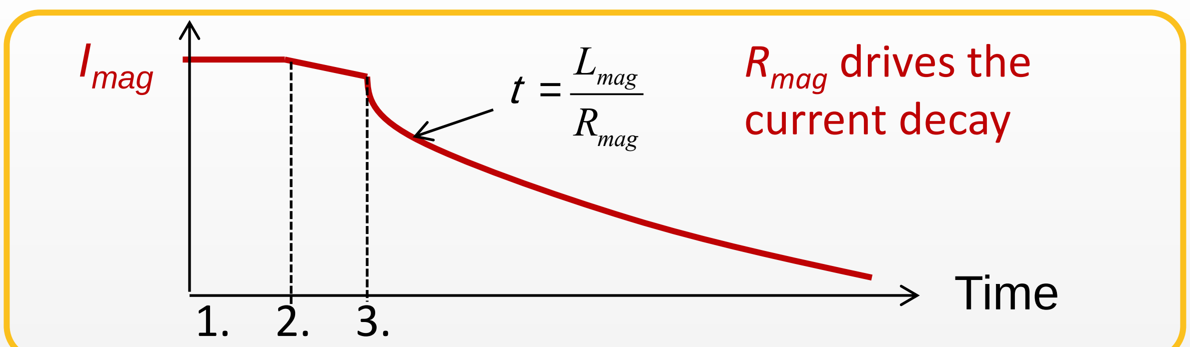
3. Analysis of design parameters and comparison to experiments



1. protection heater purpose and design

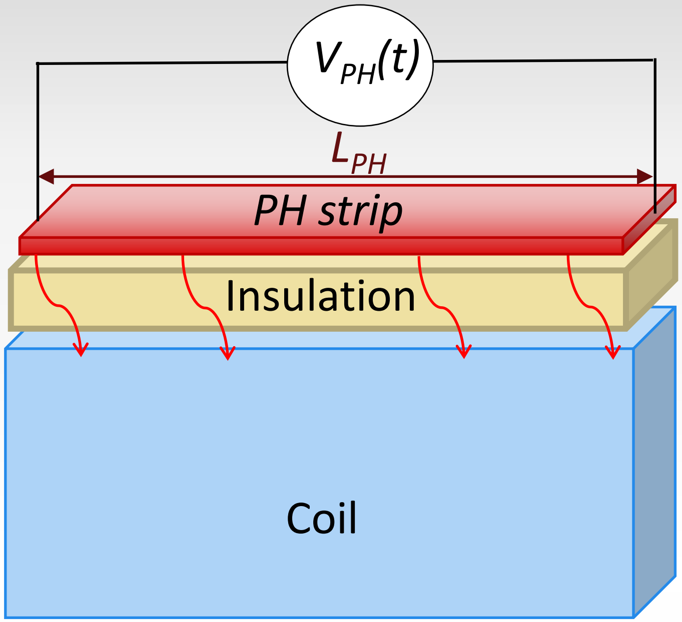
Why protection heaters (PH)?





Faster current decay and larger resistive volume to dissipate the stored energy
→ **Smaller quench temperatures and voltages**

Protection heater: Design parameters to optimize



1. Power / Surface

$$P_{PH} = \frac{V_{PH}^2(t)}{r_{ss} \times L_{PH}^2} \; \left(W / cm^2\right)$$

2. Insulation thickness

- Heat transfer vs. electrical integrity

→ $V_{PH,max}$ ~ 400 V is fixed, so for long L_{PH}, P_{PH} is smaller

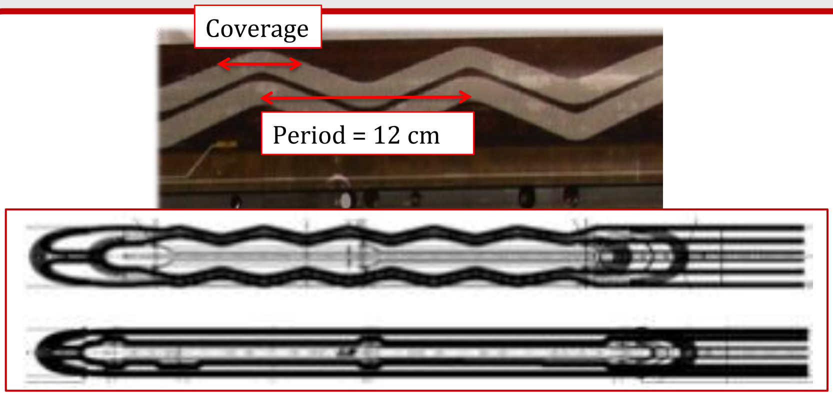
- Need certain P_{PH} *(e.g. 50 W/cm² for strip of 0.025 mm thickness)*

→ Long magnets need specific PH layout to distribute the available heating area

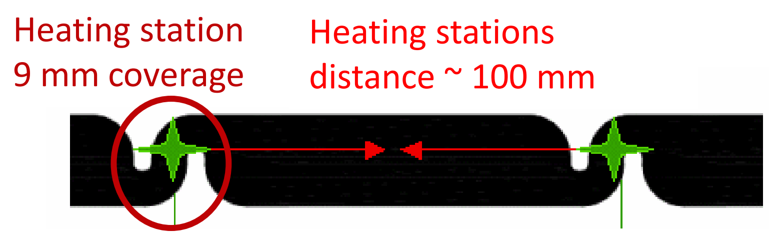
3. Heater layout

Heater design and experience in LARP Nb_3Sn quadrupoles

1-m-long HQ (1 MJ/m)



4-m-long LQ (0.5 MJ /m)



Kapton: 0.025 mm
(HQ some coils with 0.050 or 0.075 mm)
P_{PH} = 50 W/cm^2
(LQ margin up to 120 W/cm^2)

Delays:
HQ: 5 – 15 ms
LQ: 10 – 25 ms

Hypothesis: Longer delay than in HQ because shorter coverage
Issues: El. breakdowns (0.025 mm Kapton)
ID prone to detach during test

PH design analysis needed for the future Nb_3Sn magnets

- Future magnets (e.g. QXF - 150 mm aperture Nb_3Sn quad.):
  - Increase Kapton to 50 or 75 µm (under discussion) → Delays will be longer
  - Heater possibly only on OD
  - Magnet will be 8 m long or 2 * 4 m long so heating stations needed

→ Need to analyze the heater delays

→ Analysis in this talk focus in impregnated magnets, operating at 80% of short sample current and PH only on OL

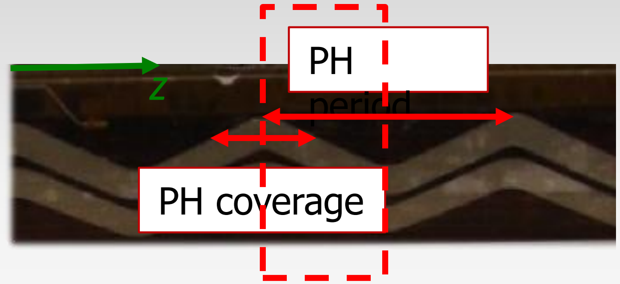
- Case of NbTi different because better contact with Helium (not analyzed)

2. Modeling

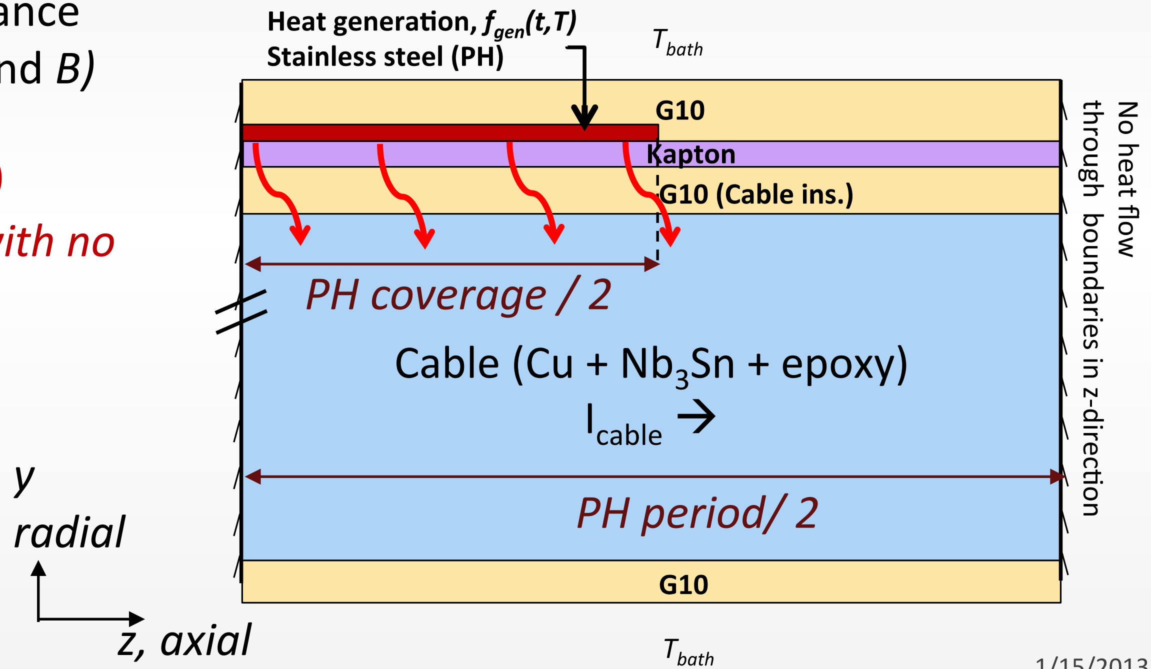
QPH: 2-D heat conduction model

<u>Assumptions</u>

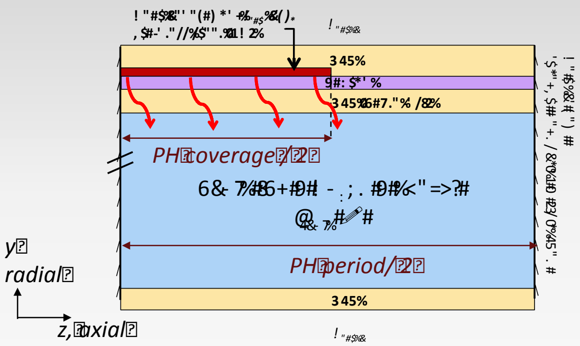
- Single turn with periodic PH coverage
- Heat generation in ss (PH)
- 2-D Heat conduction (neglect turn-to-turn)
- Adiab. boundary in z-dir., heat sink at y-dir.
- Perfect thermal contact conductance
- Mat. properties functions of *T* (and *B*)
- Uniformly SC cable
- Quench when cable reach $T_{cs}(I,B)$
- *Gives the time delay to quench with no free parameters*



1/2 period in HQ PH



Equations



Mathematical model:
Energy balance + boundary conditions

Discrete solution:
Thermal network method

Heat balance equation:

$$\gamma_m c_{p,m}(B,T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(k_m(B,T)\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_m(B,T)\frac{\partial T}{\partial z}\right) + f_{gen,m}(t,T)$$

Heat source term only in the stainless steel heater (W/m³) (Joule heating)

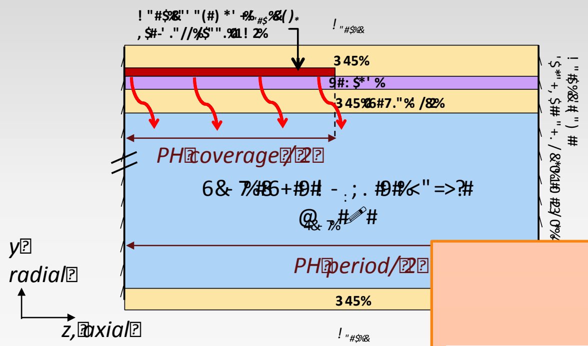
$$f_{gen}(t,T) = \rho_{ss}(T)J_{ss}^2(t)$$

Boundary conditions and intial values

$$T(z,H,t) = T(z,0,t) = T_{bath}$$
$$q''_z(y,0,t) = q''_z(y,Per_{PH}/2,t) = 0$$
$$T(z,y,0) = T_{bath}$$

t = time [s], $T = T(t, y, z)$ = Temp. [K], $c_{p,m}(B,T)$ = Specific heat [J/K/kg],
γ = Mass density [kg/m³], $k_m(B,T)$ = Thermal conductivity [W/K/m],
$f_{gen,m}$(t,T) = Internal heating [W/m³] (only in ss), q'' = heat flux [W/m²],
ρ_{ss} (T) = Electrical resistivity of ss in Ωm, J_{ss} = Current density in ss x-sect. in A/m²

Equations

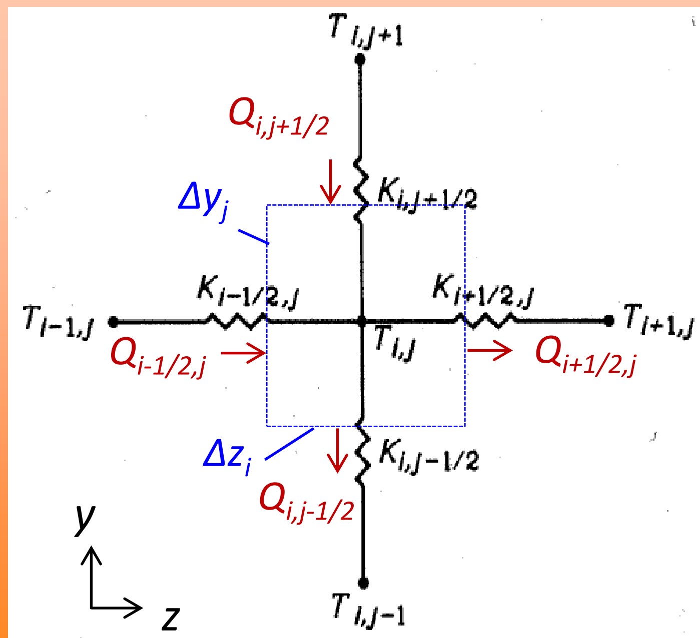


Heat balance equation:

$$\gamma_m c_{p,m}(B,T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(k_m(B,T)\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_m(B,T)\frac{\partial T}{\partial z}\right)+f_{gen,m}(t,T)$$

Mathematical model: Energy balance + boundary conditions

Discrete solution: Thermal network method



Analogy with electrical network:

T_{i-1} —K— T_i $\quad (T_i - T_{i-1})\,K = Q_i$ (W/m)

Conductance (W/m/K):

$$K_{i-\frac{1}{2},j} = \frac{\Delta y_j}{\Delta z_{i-1}/\left(2k_{i-1,j}\right)+\Delta z_i/\left(2k_{i,j}\right)}$$

New temperatures:

$$T^{new}_{i,j} = T_{i,j} + \frac{\Delta t}{\rho_{i,j}c_{p,i,j}\Delta z_i \Delta y_j}\cdot\left(Q_{i-\frac{1}{2},j} - Q_{i+\frac{1}{2},j} + Q_{i,j-\frac{1}{2}} - Q_{i,j+\frac{1}{2}} + f_{gen,i,j}\Delta z_i \Delta y_j\right)$$

T. Blomberg, *"Heat Conduction In Two And Three Dimensions", PhD Thesis*

Material properties (1.9 K to 300 K)

- **Cable properties weighted average over its components**
  - **Nb_3Sn $c_p(T, B)$**: A fit proposed by Manfreda in [1]
  - **Epoxy $c_p(T)$**: Ref. [2] for T ≥ 4.4 K. Below 4.4 K linear interp. to Cp = 0 at 0 K
  - **Copper $c_p(T)$ and $k(T, B)$**: Ref. [2] (Includes magnetoresistance)
    - *Cu dominates cable thermal conductivity*
- **Kapton $c_p(T)$**: Ref. [3]; **$k(T)$**: Ref. [3] for T ≥ 4.3 K. Below 4.3 K linear extrap. as in [1]
- **Impregnated glass-resin (G10) $c_p(T)$ and $k(T)$:** Ref. [3] (uncertainty several 10 % for *k* below 4 K)
- **Stainless steel $k(T)$**: Ref. [3]; **$c_p(T)$**: Ref. [3] for T ≥ 5 K. Below 5 K extrap. as in [4]
  - **El. resistivity(T)**: Fit to data from [5] and extrap.

Uncertainties at least 10 – 20 %

[1] G. Manfreda, CERN 2011-24, EDMS Nr: 1178007
[2] CRYOCOMP (© copyright Eckels Eng. Inc.)
[3] NIST - E.D. Marquardt et al., in Proc. 11th Int.
[4] A. Davies, "Material properties data for heat transfer modeling in Nb3Sn magnets"
[5] S. Prestemon, private communication

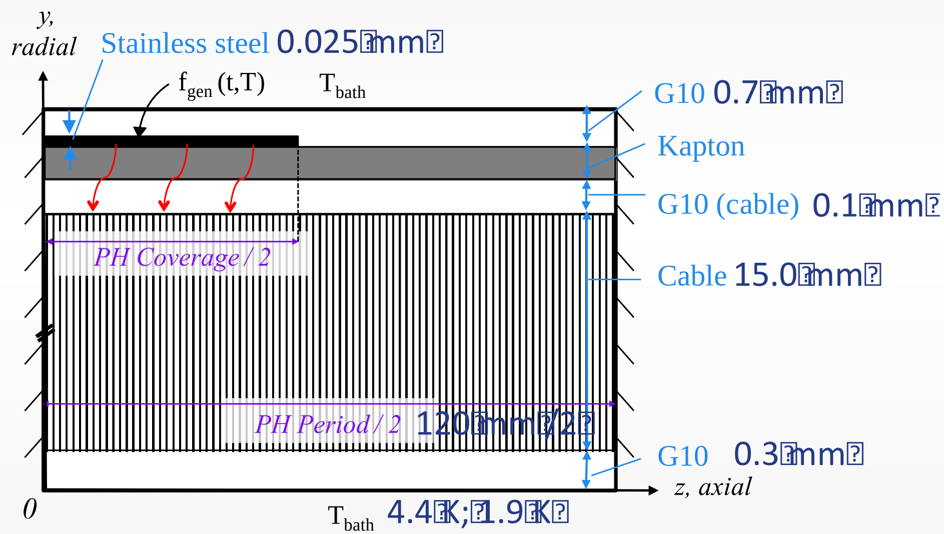
3. Analysis of heater design parameters and comparison with experiment

Parametric analysis of heater delay in LARP HQ

Studies of the delay time dependence on:

1. **Operation current**
2. **Operation temperature**
3. **Magnetic field, B**
4. **PH power, P_{PH}**
5. **PH coverage**
6. **Kapton thickness**

RRR	80
Cu/SC	1.1
Cable voids	12%
l_{PH}	220 mm
I_{ss} at 1.9 K	19.3 kA
I_{ss} at 4.4 K	17.5 kA



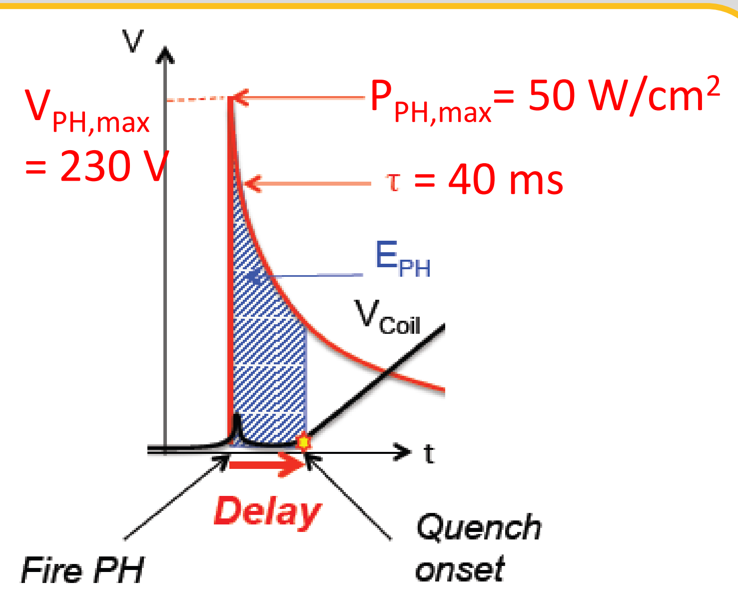
Delay vs. operational current: Experiment in HQ01e

T_{op}: 4.4 K, 1.9 K

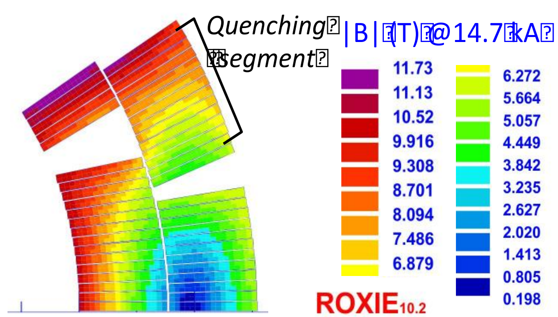
I_{mag}: 5 – 14 kA

B_{peak}: 4 – 11 T

OL PH strip C9B02 fired
25 µm Kapton



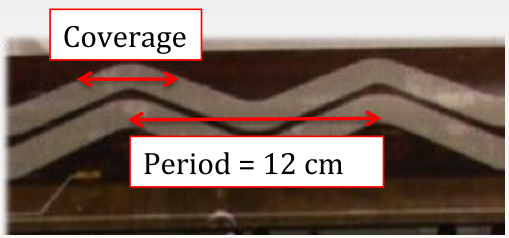
H. Bajas at al., ASC 2012

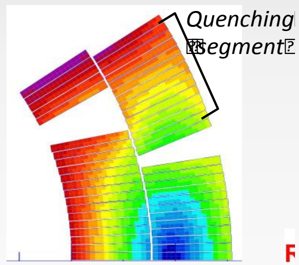


Coverage and field changes depending on the turn

Delay vs. operation current: QPH simulation vs. experiment

Simulated delay at 5 different turns:



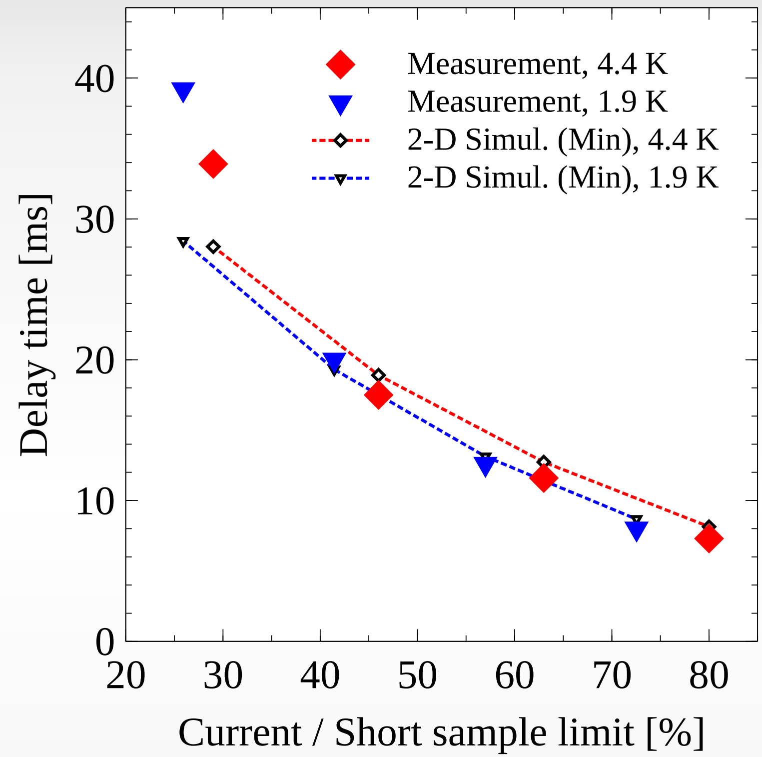


Turn # from OL Pole	Coverage	B/B_{peak}
3	30 mm	74%
4	40 mm	72%
5	50 mm	70%
6	60 mm	69%
7	70 mm	66%

Delay depends on quench location, the shortest delay predicts the measurement

*** No free parameters ***

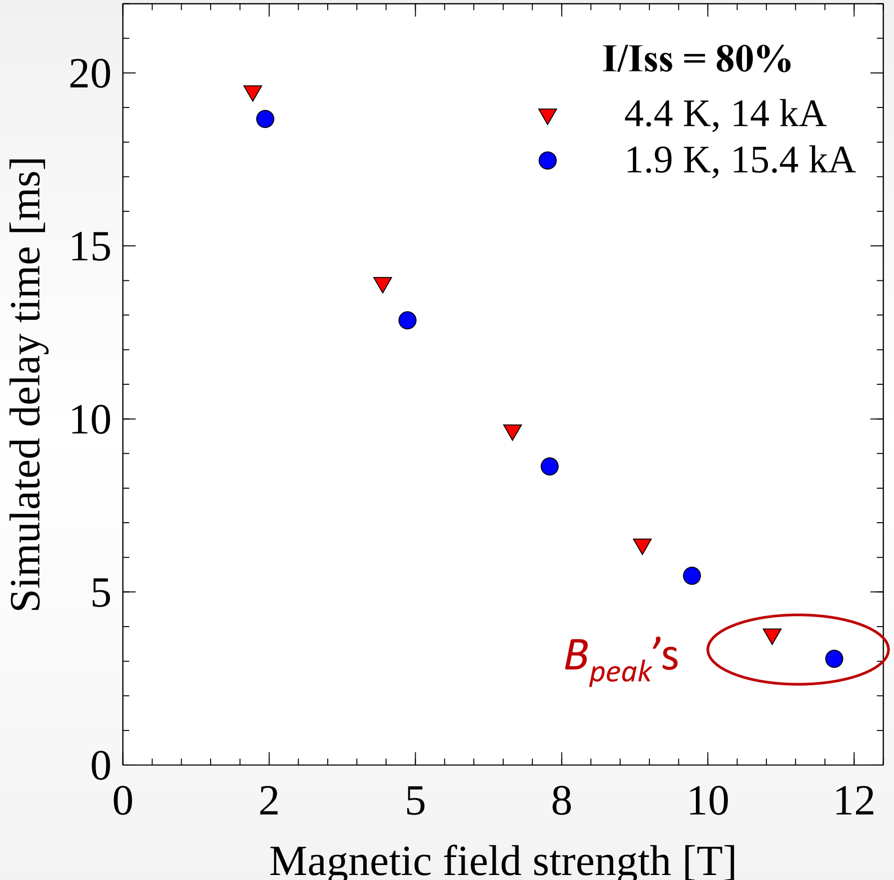
Shortest delays



Simulation and experiment agree very well at I/I_{ss} > 40% (difference is < 1 ms)

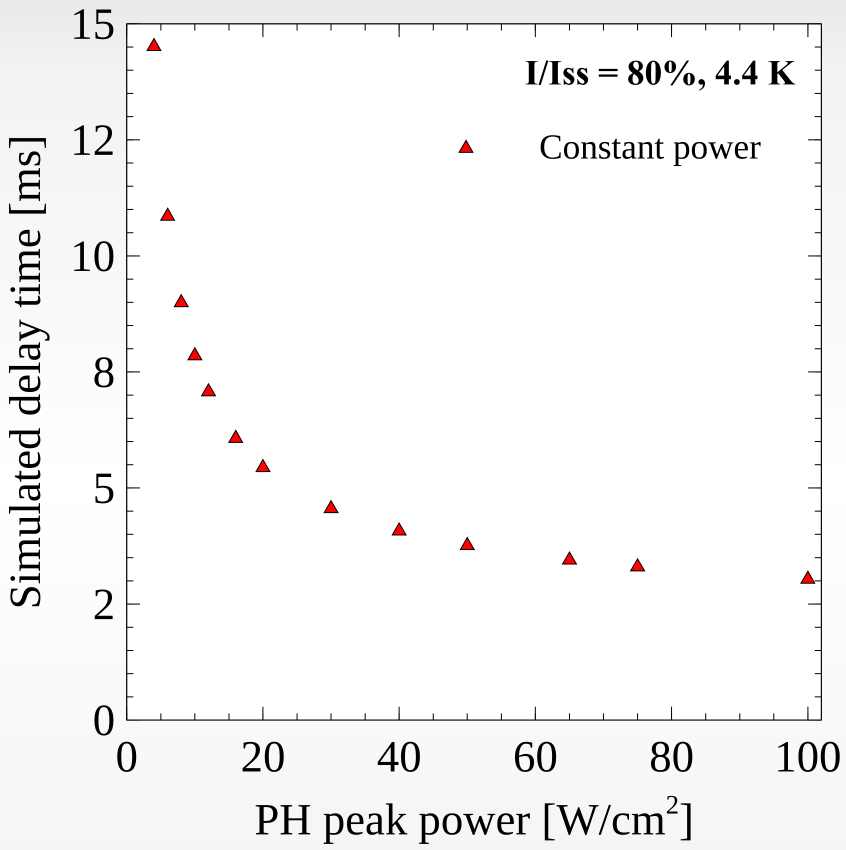
Heater delay vs. magnetic field region

Simulation using full coverage, moving inside the coil between turns



- Delays are similar at 1.9 and 4.4 K
- Delay 3 times longer at low field region
  - Whole coil quenched in 5 to 20 ms
  - Important for
    1. R_{mag} evolution
    2. Inductive voltages
  - Not accessible by measurement

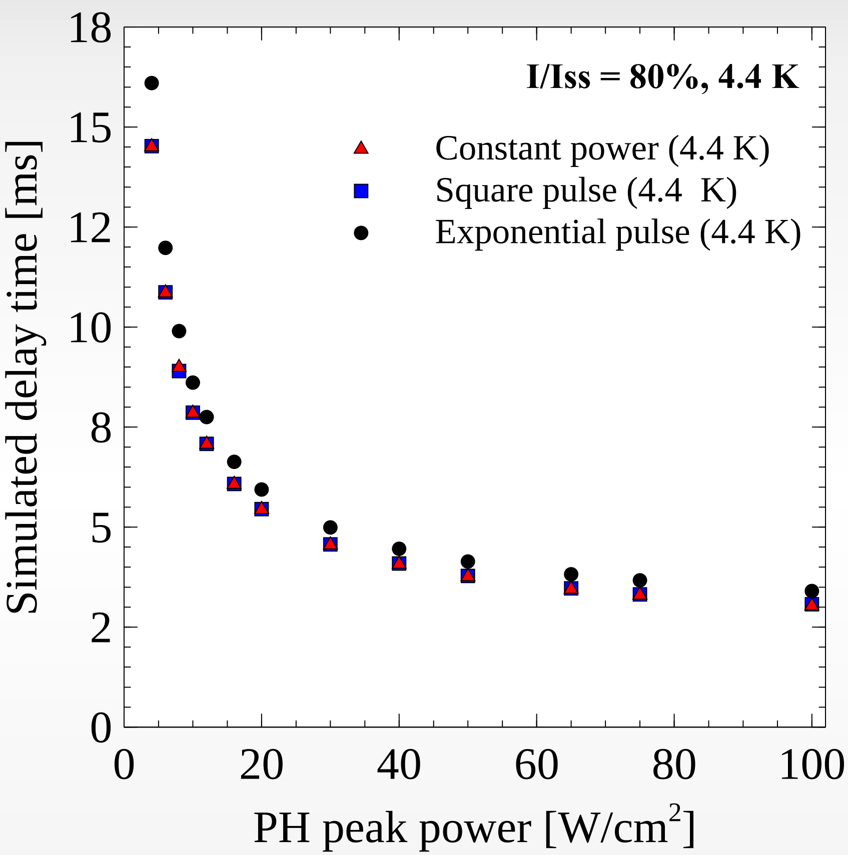
Heater delay vs. heater powering



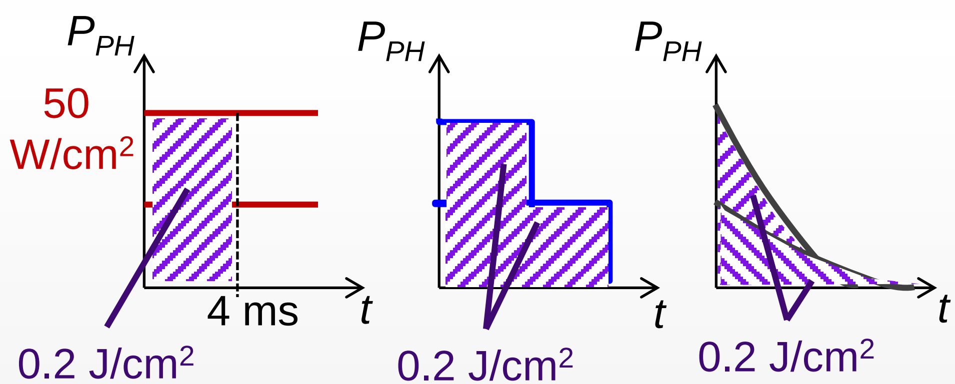
- Smaller delay with larger power
- Saturation at 50 W/cm^2
  - Consistent with experiments

H. Felice at al. IEEE Trans. Appl. Supercond. (2009)

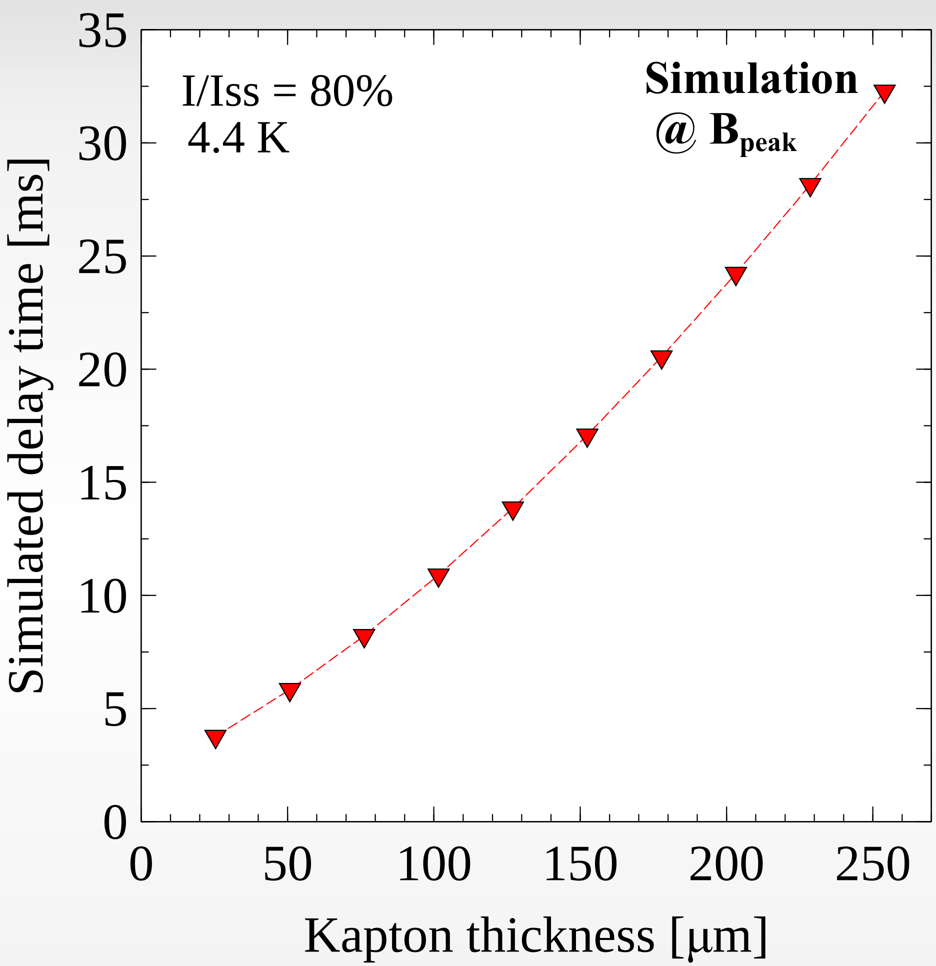
Heater delay vs. heater powering



- Smaller delay with larger power
- Saturation at 50 W/cm^2
  - Consistent with experiments
- Difference peak power, same pulse energy: Pulse shape does not matter

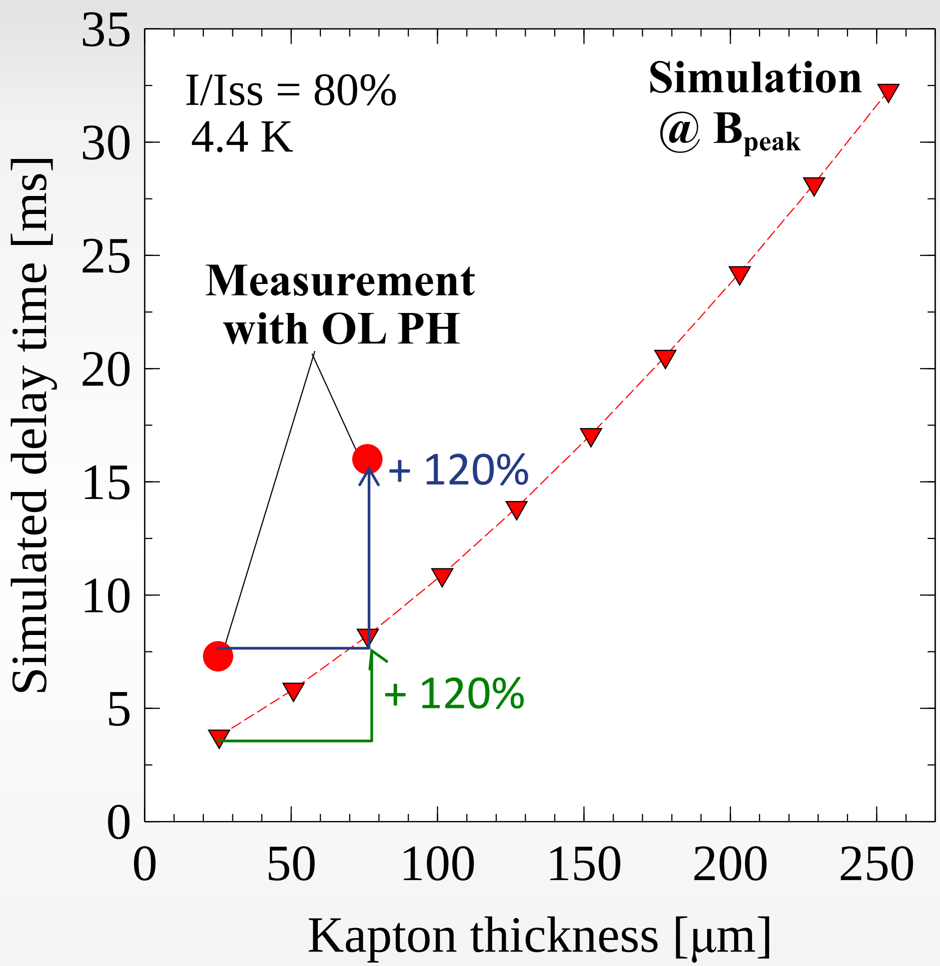


Heater delay roughly proportional to Kapton thickness



- Delay +15–60% (2–4 ms) per each added 25 μm Kapton layer

Heater delay roughly proportional to Kapton thickness



- Delay +15–60% (2–4 ms) per each added 25 µm Kapton layer
- Experiment and simulation consistent:

Delay increase 120% when increasing Kapton from 25 µm to 75 µm

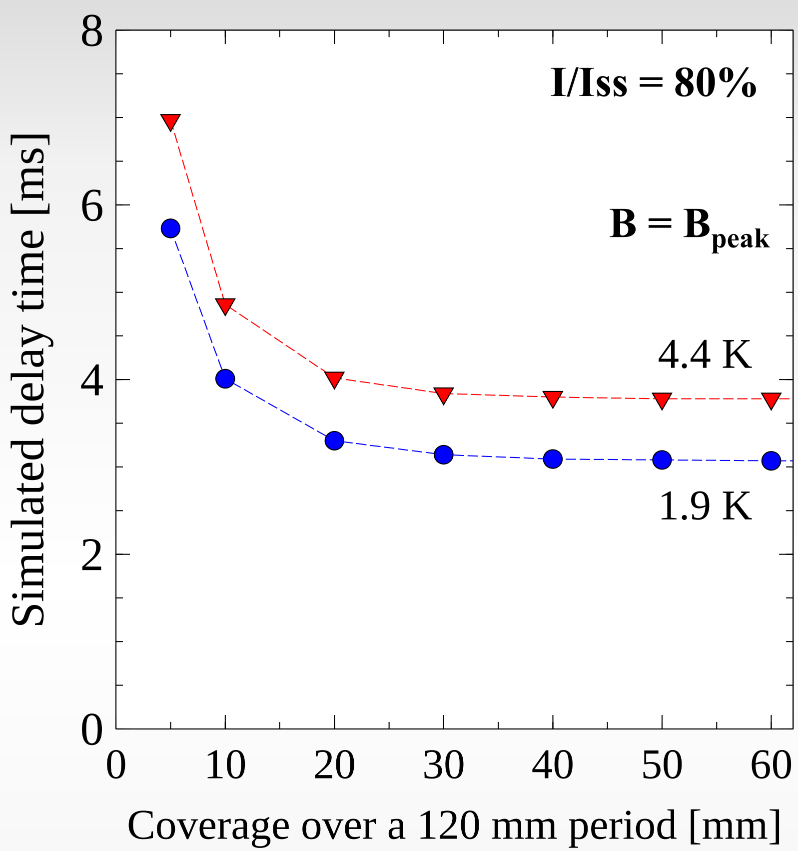
Measurement: P_{PH}(t=0) = 45-50 W/cm^2, tau 40-46 ms

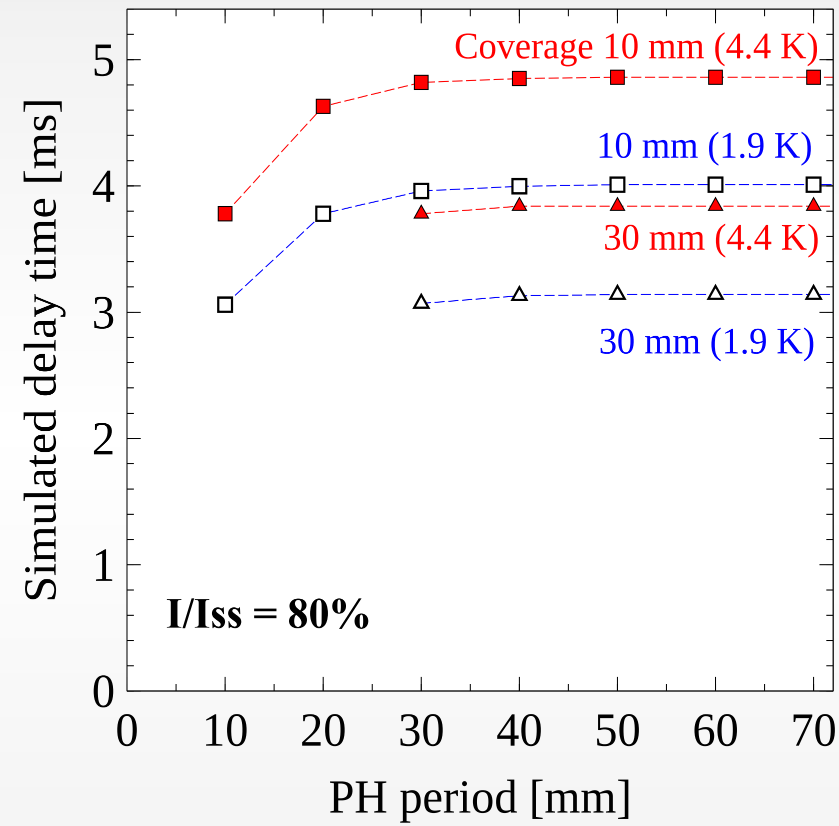
25 µm (HQ01e), 75 µm (HQM04)

Heater delay vs. heater coverage and period

Coverage = length of heated cable segment at a turn

Period = Distance between heated segments





Delays larger if coverage < 20 mm

Consistent with LQ / HQ heatre design

Delays shorter, if period < 50 mm

Conclusions

- Protection heaters for new high-field magnets need complex geometry and numerical models to analyze the delay

- New thermal simulation model QPH is developed for heater design

- The heater delays dependence on heater design was analyzed (HQ)
  - Delays up to 5 times longer at low I/Iss than at 80% Iss
  - Operating at 80% I/Iss, the heater quench all the coil in 5 to 20 ms
  - Delay shorter with larger heater power until saturation at 50 W/cm^2
  - Delay roughly proportional to Kapton thickness
  - Longer delays with small heater coverage up to saturation

    → Minimum heating station length of 20 mm recommended

- Simulation results are consistent with experiments

- The model can be used to design heaters in the LHC upgrade magnets

For more information:
T. Salmi et al., "Modeling protection heaters in high-field Nb_3Sn Magnets" Proc. of this workshop

Abbreviations

PH = Protection Heater

ID = Inner Diameter

OD = Outer Diameter

I_{mag} = Magnet current

R_{mag} = Magnet resistance

P_{PH} = PH power in W/cm^2

V_{PH} = PH voltage

…………

Numerical formulation for the boundary cells

$$K_{i,\frac{1}{2}} = \frac{\Delta z_i}{\Delta y_1 / \left(2k_{i,1}\right)}, \quad K_{i,Ny-\frac{1}{2}} = \frac{\Delta z_i}{\Delta y_{Ny} / \left(2k_{i,Ny}\right)}$$

$$Q_{i,\frac{1}{2}} = K_{i,\frac{1}{2}} \cdot \left(T_{bath} - T_{i,\frac{1}{2}}\right), \quad Q_{i,Ny-\frac{1}{2}} = K_{i,Ny-\frac{1}{2}} \cdot \left(T_{i,Ny-\frac{1}{2}} - T_{bath}\right)$$

$$Q_{\frac{1}{2},j} = Q_{Nx-\frac{1}{2},j} = 0$$

Governing differential equations

- 2-D heat balance equation: $\gamma_m c_{p,m}(B,T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(k_m(B,T)\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_m(B,T)\frac{\partial T}{\partial z}\right) + f_{gen,m}(t,T)$

- Heat generation, ONLY in the stainless steel: $f_{gen}(t,T) = \begin{cases} \rho_{ss}(T)J_{ss}^2(t) \\ P_{PH}(t)/t_{ss} \\ V_{PH}^2(t)/\rho_{ss}(T)/l_{PH}^2 \end{cases}$

- Boundary conditions and initial values:

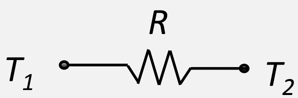
$$T(z,H,t) = T(z,0,t) = T_{bath}$$
$$q''_z(y,0,t) = q''_z(y, Per_{PH}/2, t) = 0$$
$$T(z,y,0) = T_{bath}$$

  - Internal boundaries btw. the materials: $k_1 \left.\frac{\partial T}{\partial n}\right|_1 = k_2 \left.\frac{\partial T}{\partial n}\right|_2$

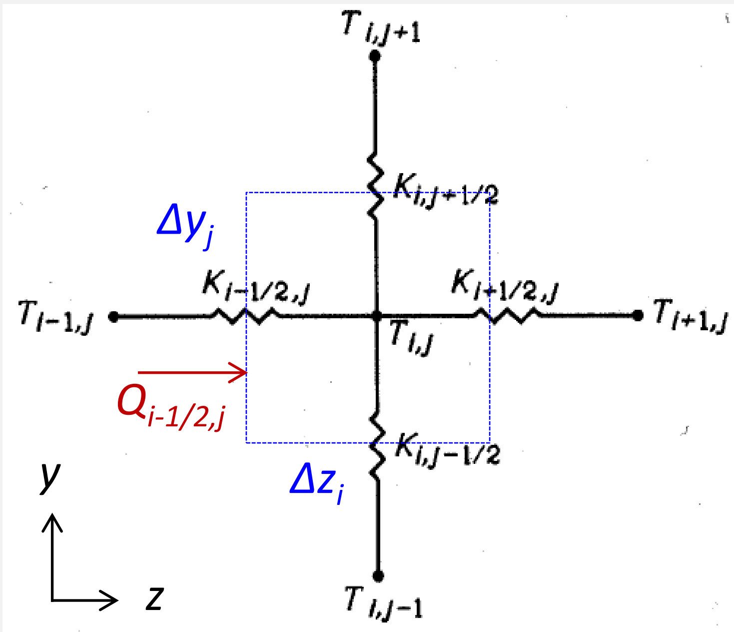
y, z : Space coordinate [m]; *t*: time [s]; *T = T(t, y, z)*: Temperature [K]; $c_{p,m}(B,T)$: Specific heat capacity of material *m* [J/K-kg] , γ – Density [kg/m³]; $k_m(B,T)$: Thermal conductivity of material *m* [W/(K-m)]; $f_{gen,m}$(t,T): Volumetric PH power (in ss) [W/m³]; P_{PH}(t) PH surface power [W/m²]; …

Numerical formulation

Analogy with electrical network:



$(T_2 - T_1) / R = Q$



T. Blomberg, *"Heat Conduction In Two And Three Dimensions", PhD Thesis*

Conductance and heat flow

between cells (*i*, *j*) and (*i-1*, *j*):

$$K_{i-\frac{1}{2},j} = \frac{\Delta y_j}{\Delta z_{i-1}/\left(2k_{i-1,j}\right) + \Delta z_i/\left(2k_{i,j}\right)} \qquad (W/m/K)$$

$$Q_{i-\frac{1}{2},j} = K_{i-\frac{1}{2},j} \cdot \left(T_{i-1,j} - T_{i,j}\right) \qquad (W/m)$$

(For boundary cells, see slide 28)

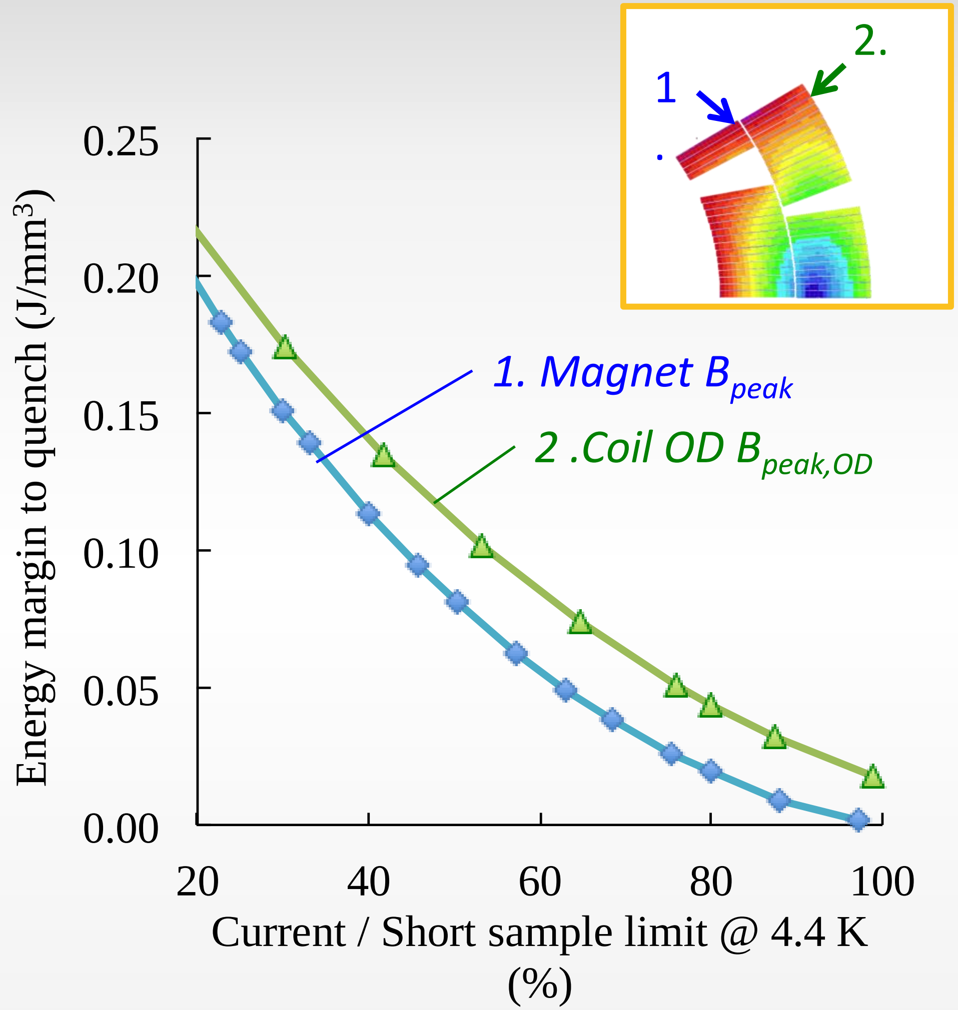
New temperatures:

$$T_{i,j}^{new} = T_{i,j} + \frac{\Delta t}{\rho_{i,j} c_{p,i,j} \Delta z_i \Delta y_j} \cdot \left(Q_{i-\frac{1}{2},j} - Q_{i+\frac{1}{2},j} + Q_{i,j-\frac{1}{2}} - Q_{i,j+\frac{1}{2}} + f_{gen,i,j} \Delta z_i \Delta y_j \right)$$

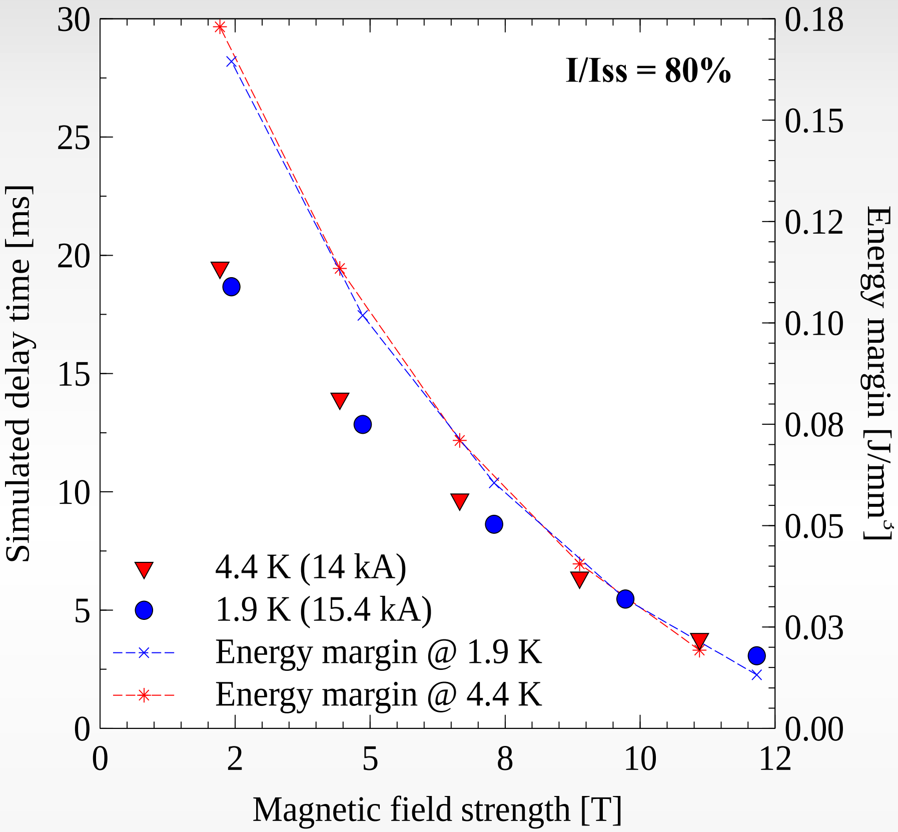
Energy margin

- Energy margin = Enthalpy from operating temperature to the current sharing temperature:

$$E_m(B,I) = \int_{T_{op}}^{Tcs(I,B)} c_{p,cable}(T,B)\,dT$$

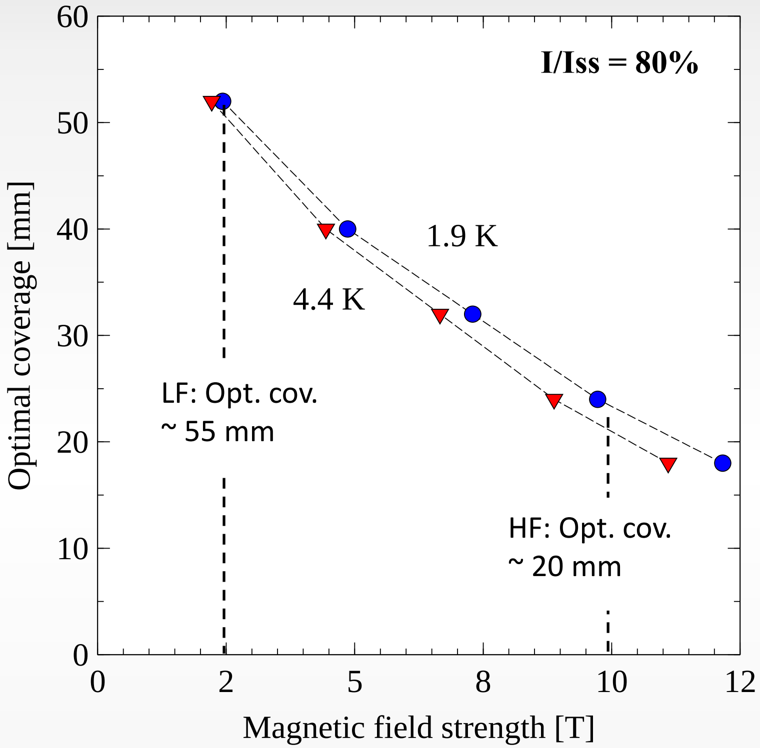


Heater at different field region



Quench the coil from 4 ms to 20 ms

Optimal coverage



To get delay within 10% of full cov., larger coverage needed at low field area