TAMPERE UNIVERSITY OF TECHNOLOGY

EuCARD²

Modeling quench propagation in a protection heater covered YBCO coil

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(WAMHTS-2)

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Outline

- Purpose of protection heaters and important parameters
- Simulation tool
- Analyzed cases
- Simulated heater delays and quench propagation velocities
- Ideas for future heater concepts and conclusion

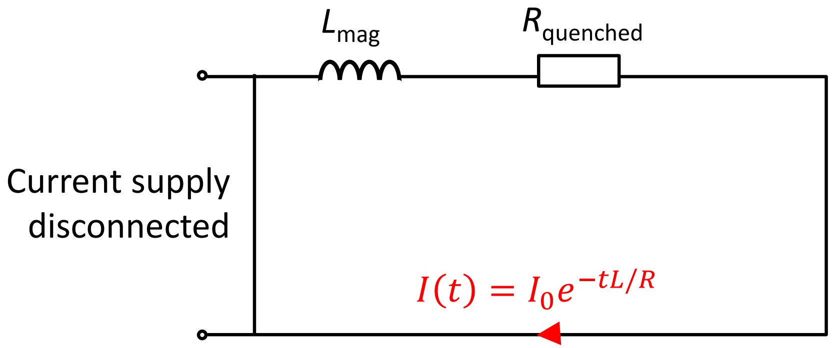
IMPORTANT HEATER PARAMETERS

Quench protection heaters

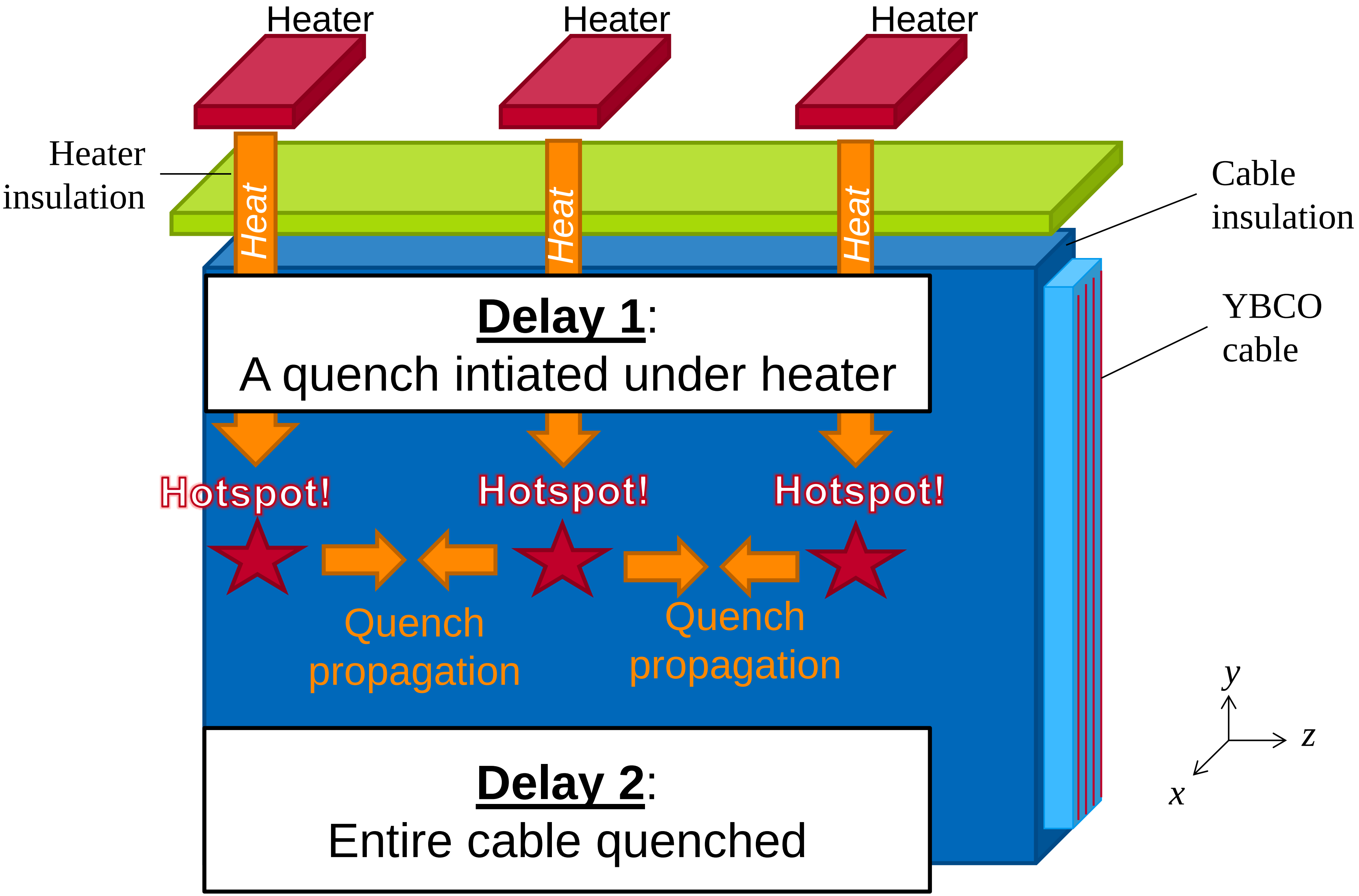
- After quench detection the magnetic energy ($E = I^2 L_{mag}/2$) must be safely discharged
  - Option 1: Extraction via external dump resitor
  - Option 2: Internal dissipation via Joule heating in resistive coil segments

R_{dump} limited by V:
Large I_0, large E → Extract
only a small fraction

(LTS) Heaters to quench large fraction of winding for fast I decay and uniform E dissipation



- Important parameters: Delay time to induce a quench, and the amount of quenched winding



Delay 1:
A quench intiated under heater

Delay 2:
Entire cable quenched

SIMULATION MODEL

CoHDA: Code for Heater Delay Analysis

- Computes **heat diffusion from heater to a cable** in 2-D (neglect transv.)

Heat balance eq. to be solved:

$$\gamma\, c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + f_{gen}(t,T)$$

Heat generation in heater:

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

T. Salmi et al., Trans. IEEE Trans. Appl. Supercond. 24(4), 2014

T. Salmi et al., Trans. IEEE Trans. Appl. Supercond. 25(3), 2015

- **Quench when $I_c == I_{op}$ → Delay 1**
  - Account for current redistribution
- **Heat generation due to current in Cu**
  - Current sharing model with critical surface

Heat generation in cable:

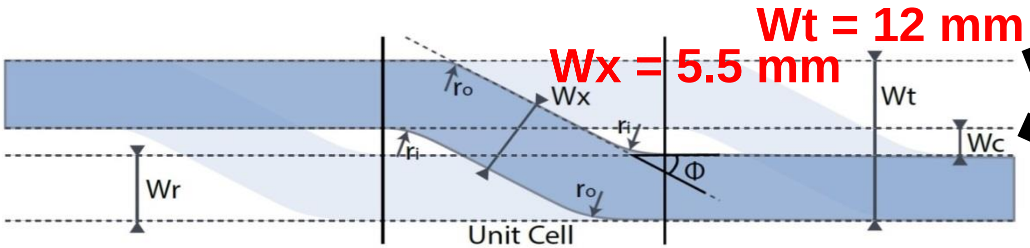
$$f_{gen,cable}(t,T) = \frac{I_{mag} V_{\Delta x}}{A_{cable}\Delta x} = \frac{I_{mag} I_{Cu}(t)\,\rho_{Cu}(T)\, f_{Cu}}{A_{Cu}^2}$$

- **Quench propagation between heating stations → Delay 2**

ANALYZED CASES

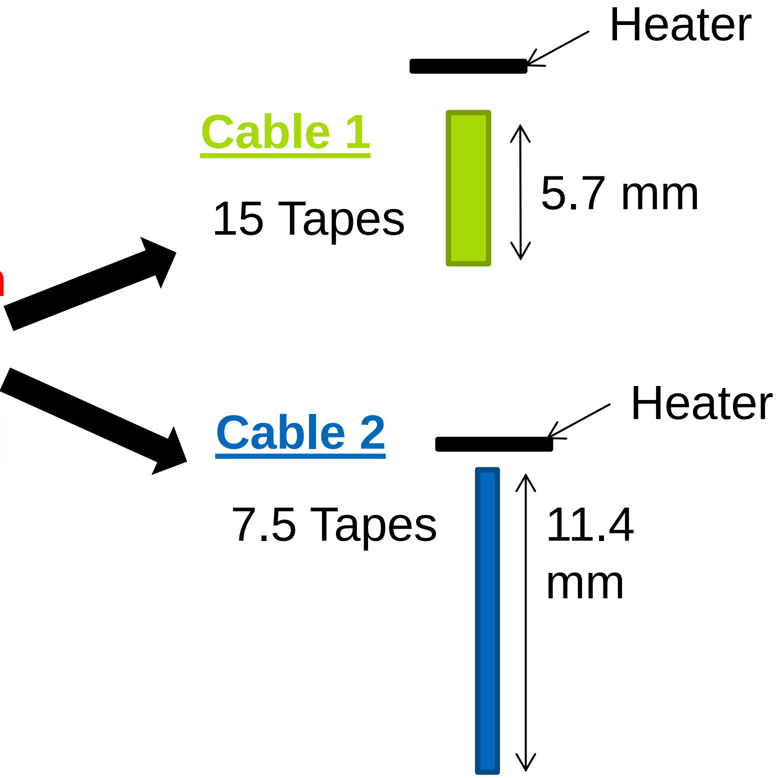
Analyzed cables based on EuCard-2 FM0

15-tape Roebel cable modeled as stacked tape cable



Wt = 12 mm

Wx = 5.5 mm



Heater

Cable 1

15 Tapes

5.7 mm

Heater

Cable 2

7.5 Tapes

11.4 mm

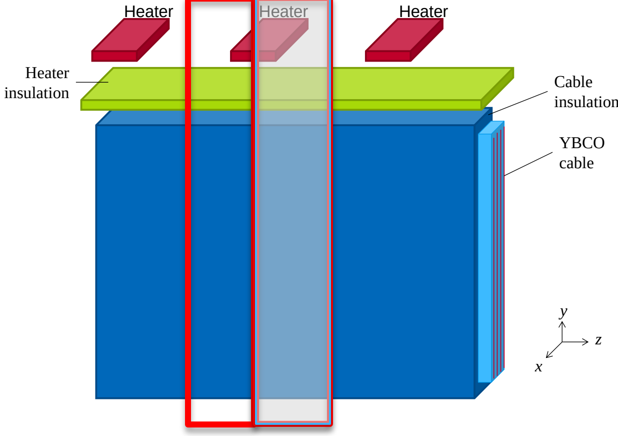
Conserving A_{cable} and material fractions

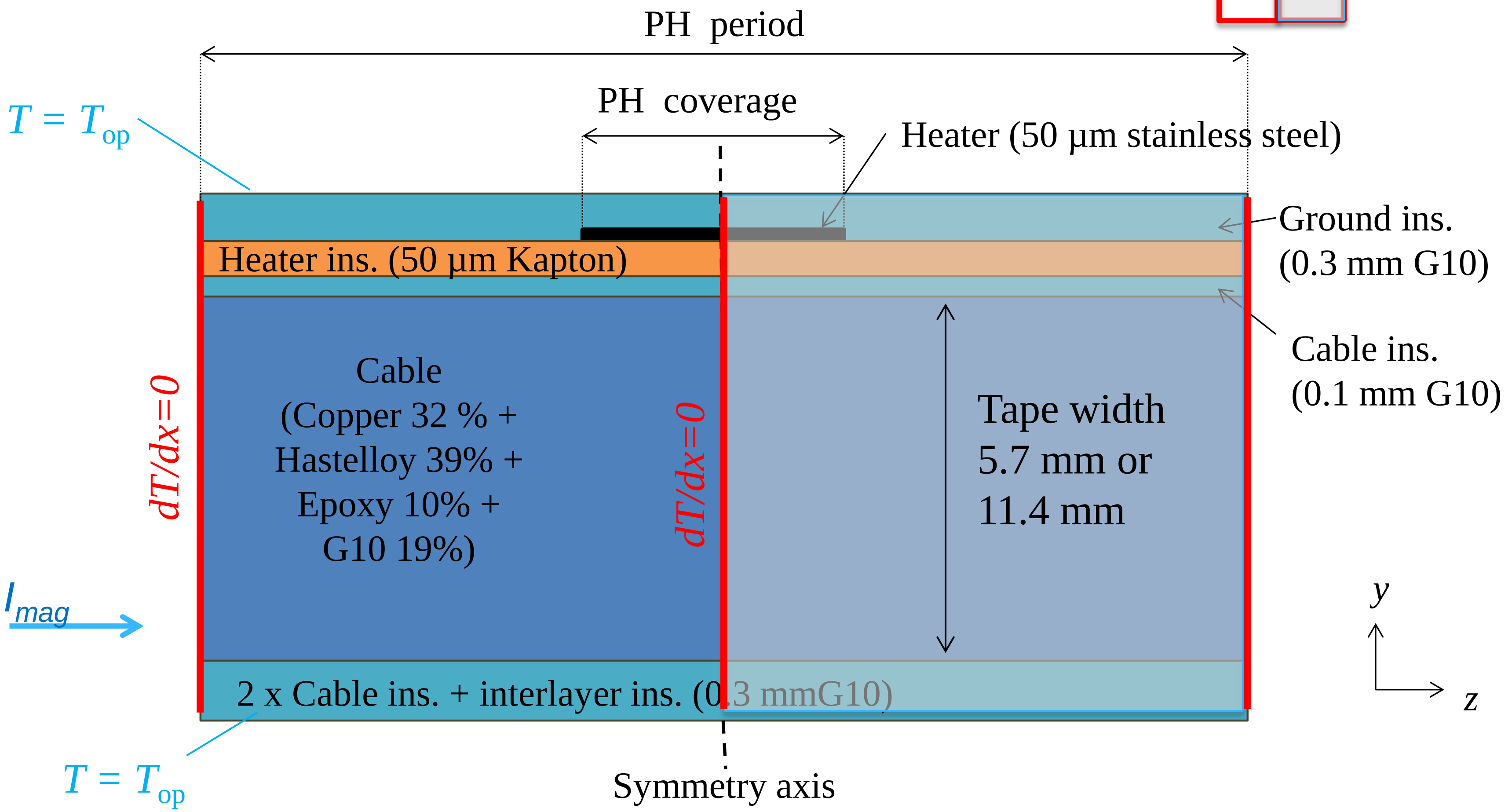
$A_{cable,ins} = 12.2\ mm^2$
$A_{YBCO} = 0.171\ mm^2$

$f_{Cu} = 0.315$
$f_{Hastelloy} = 0.385$
$f_{Voids\ (epoxy)} = 0.1$
$f_{Cable\ ins.} = 0.2$

G. Kirby and M. Durante, EuCARD2 Milestone report, MS64, 2014

Simulation domain





PH period

PH coverage

Heater (50 µm stainless steel)

$T = T_{op}$

Ground ins. (0.3 mm G10)

Heater ins. (50 µm Kapton)

Cable ins. (0.1 mm G10)

Cable (Copper 32 % + Hastelloy 39% + Epoxy 10% + G10 19%)

$dT/dx=0$

$dT/dx=0$

Tape width 5.7 mm or 11.4 mm

I_{mag}

y

z

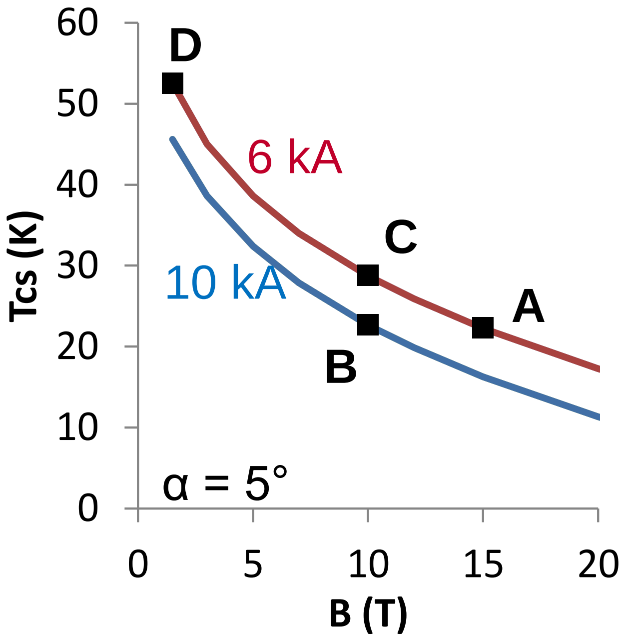
2 x Cable ins. + interlayer ins. (0.3 mmG10)

$T = T_{op}$

Symmetry axis

Analyzed operation points

CASE	Top (K)	Imag (kA)	B (T)	B angle (α) to ab-plane (°)	Tcs (K)
A	4.5	6	15	5	22.3
B	4.5	10	10	5	22.7
C	4.5	6	10	5	28.8
D	35	6	1.5	5	52.5



$J_c(B,T,\alpha)$: J. Fleiter (see talk by Glyn yesterday)

Analyzed heater

- State-of-the-art in LTS, typical values:
  - **25 µm** thick stainless steel
  - 50 µm Kapton
  - 50 W/cm^2 **(20 W/mm^3)** (min.)
  - τ_{RC} 50 ms (capacitor powered)

H. Felice et al., IEEE TAS 19(3), 2009
T. Salmi et al., IEEE TAS 24(3), 2014

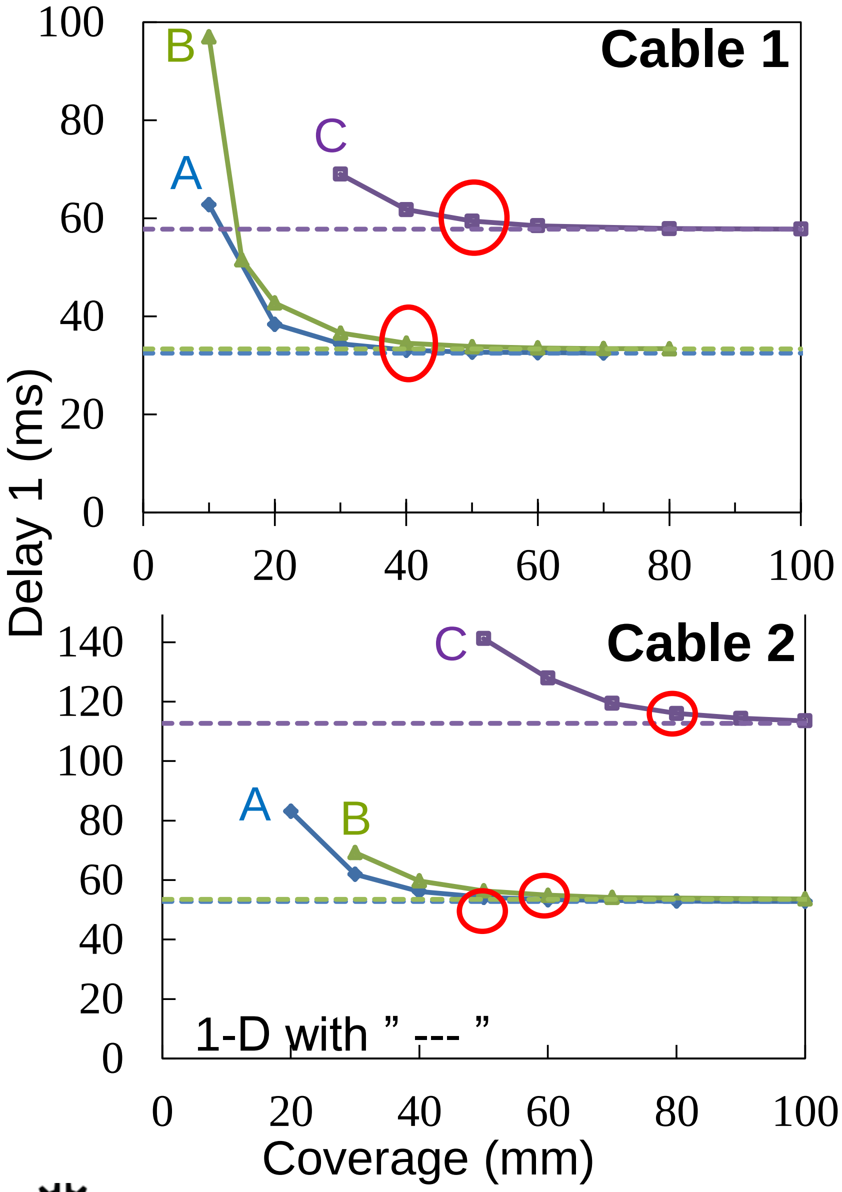
- Result presented at ASC-2014: In HTS heater like this does not have enough energy to quench for T_{cs} > ~20 K

T. Salmi and A. Stenvall, IEEE TAS 25(3), 2015

- Here is analyzed heater with 4 x more E
  - **50 µm** thick stainless steel
  - 50 µm Kapton
  - **200 W/cm^2 (40 W/mm^3)**
  - τ_{RC} 50 ms

SIMULATION RESULTS

Delay 1 vs. heater coverage



- Need 40 – 80 mm long heating stations (roebel?)
- Cable geom. impacts the delay 40-60% !
- Heater energy must be related to the **cable energy margin**
  - See extra slides

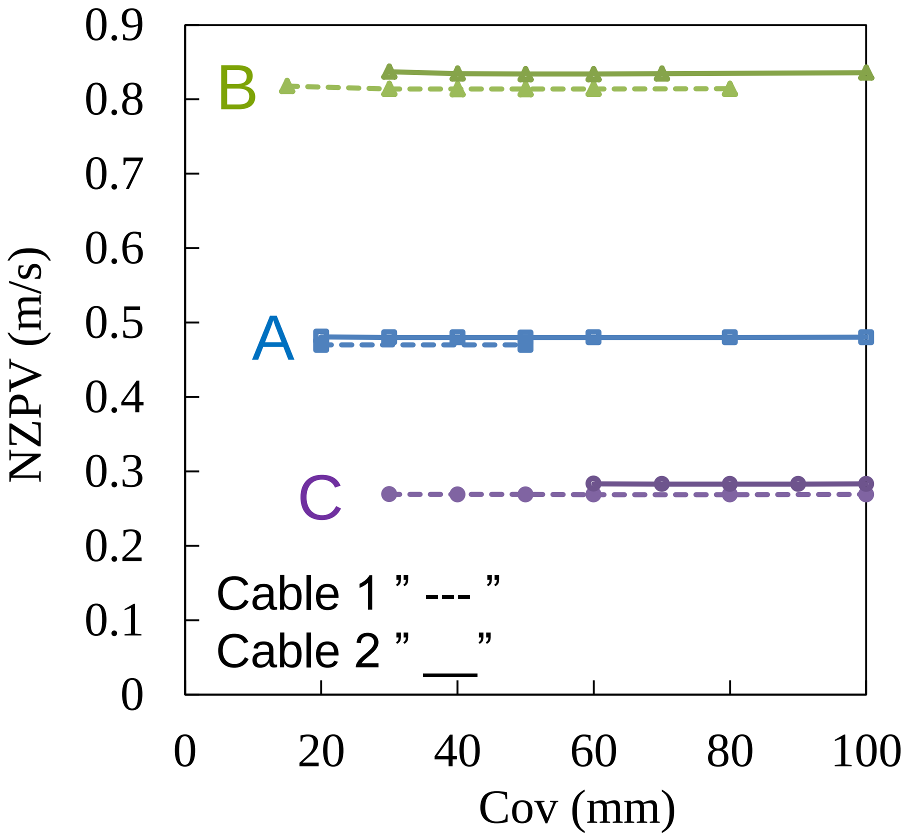
A: 4.5 K, 6 kA, 15 T (5°): Tcs = 22.3 K

B: 4.5 K, 10 kA, 10 T (5°): Tcs = 22.7 K

C: 4.5 K, 6 kA, 10 T (5°): Tcs = 28.8 K

D: 35 K, 6 kA, 1.5 T (5°) : Tcs = 52.5 K

Normal Zone Propagation Velocity



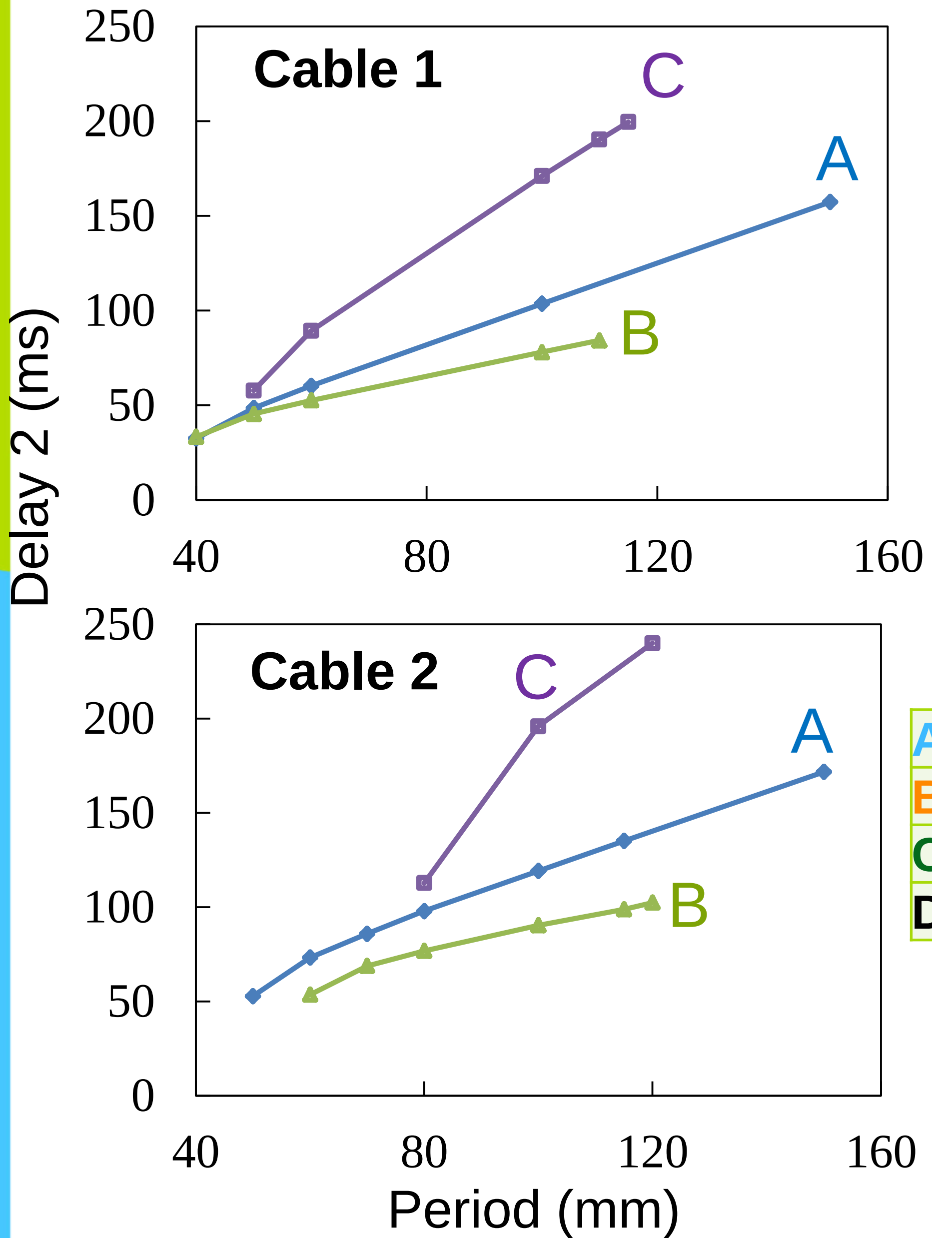
- I = 6 kA (4.5 K)
  B = 10 → 15 T
  NZPV = 0.3 → 0.5 m/s

- B = 10 T (4.5 K)
  I = 6 → 10 kA
  NZPV = 0.3 → 0.8 m/s

- **Geometry does not matter**
- Consistent with other studies

A: 4.5 K, 6 kA, 15 T (5°): Tcs = 22.3 K
B: 4.5 K, 10 kA, 10 T (5°): Tcs = 22.7 K
C: 4.5 K, 6 kA, 10 T (5°): Tcs = 28.8 K
D: 35 K, 6 kA, 1.5 T (5°) : Tcs = 52.5 K

Delay 2 vs. heater period



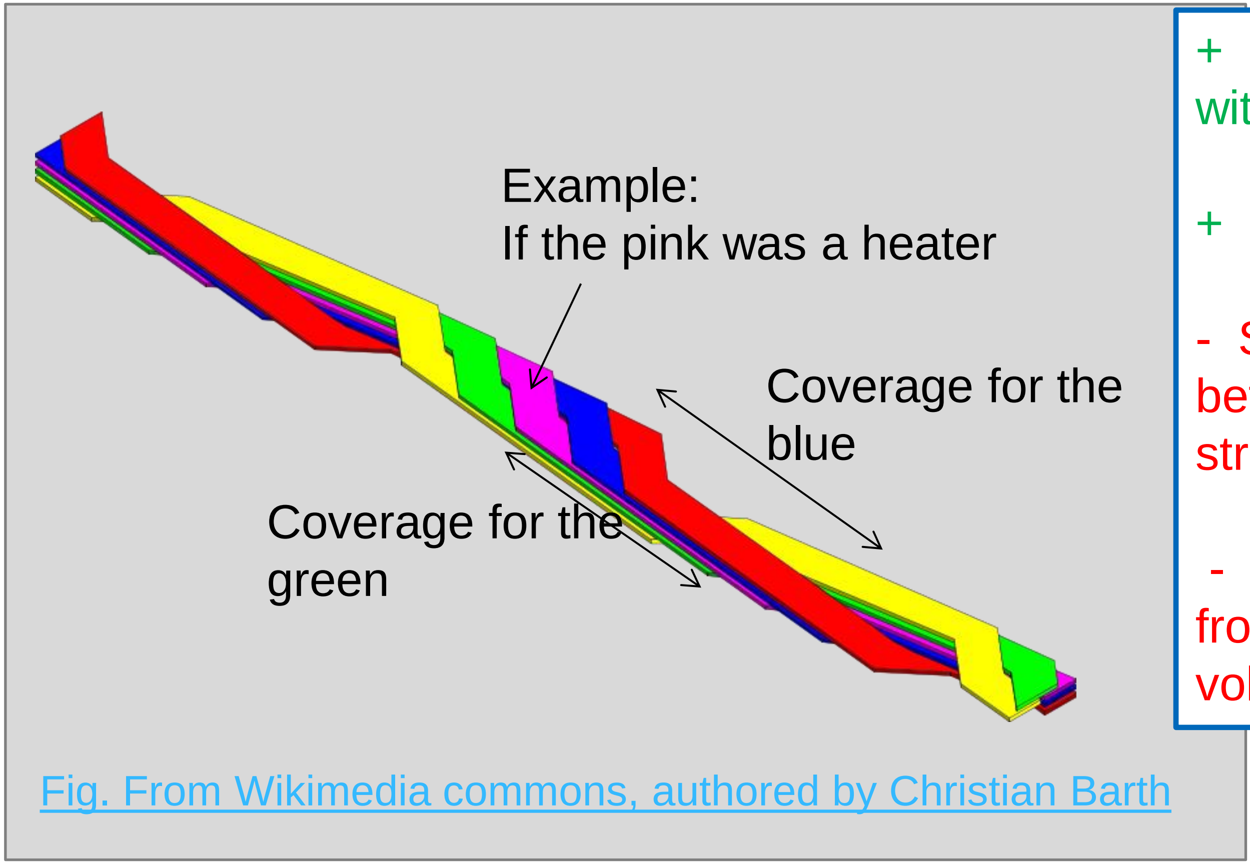
- Max 120 – 150 mm period
  - Or > 300 K under heater
  - Coverage <u>min</u> 30-50% (compare to 10-30% in LTS)
- **If protected with heaters, better to find a way to cover all with the heater!**

A: 4.5 K, 6 kA, 15 T (5°): Tcs = 22.3 K
B: 4.5 K, 10 kA, 10 T (5°): Tcs = 22.7 K
C: 4.5 K, 6 kA, 10 T (5°): Tcs = 28.8 K
D: 35 K, 6 kA, 1.5 T (5°) : Tcs = 52.5 K

IDEAS FOR FUTURE HEATERS AND CONCLUSIONS

Ideas for alternative heaters 1/2

1. Heater co-wound as one of the strands, or as a wider strip on the cable wide side



Example:
If the pink was a heater

Fig. From Wikimedia commons, authored by Christian Barth

- \+ Good heater contact with cable
- \+ Need less heater power
- \- Still need insulation between heater and other strands
- \- May require ”take-outs” from the middle to limit the voltage

Ideas for alternative heaters 2/2

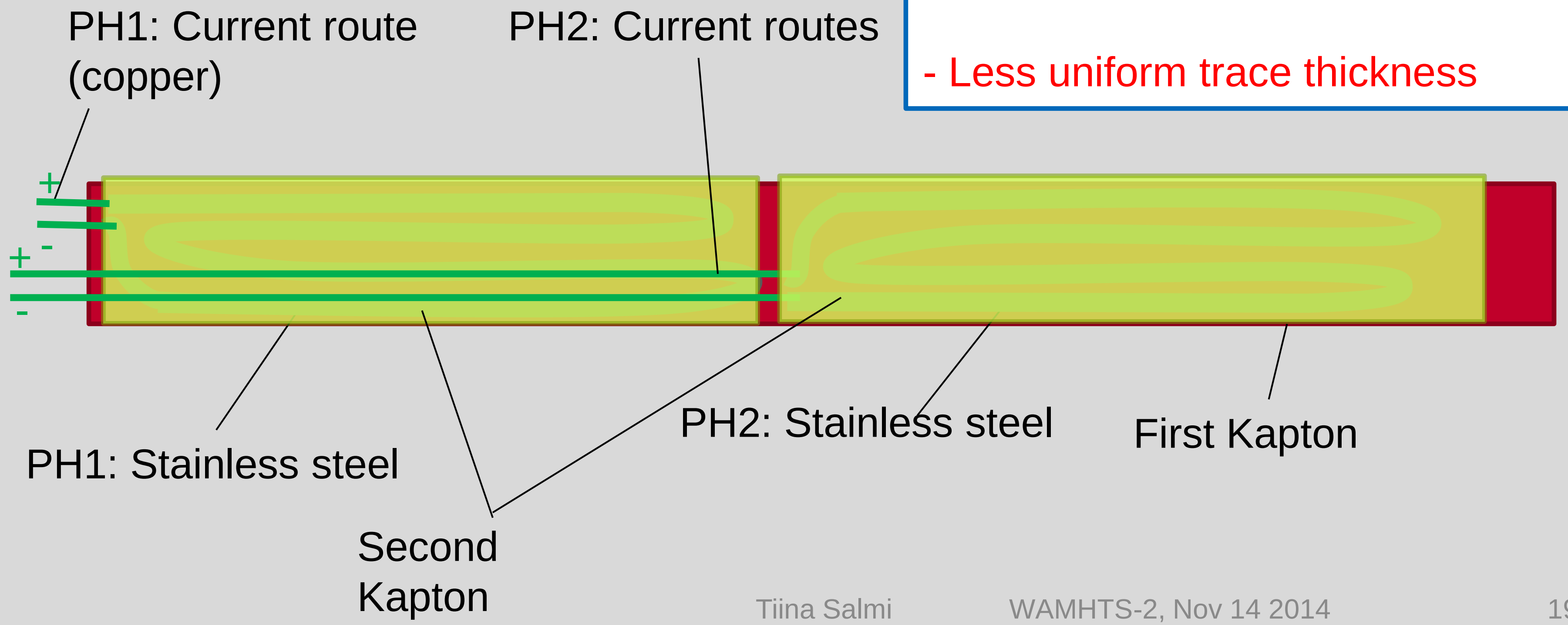
2. Several shorter ”layered” heaters on top of the coil

+ Can make several short heaters with high power (and low voltage) to cover a long coil

+ PH current leads only at coil ends

- Need many HFU’s

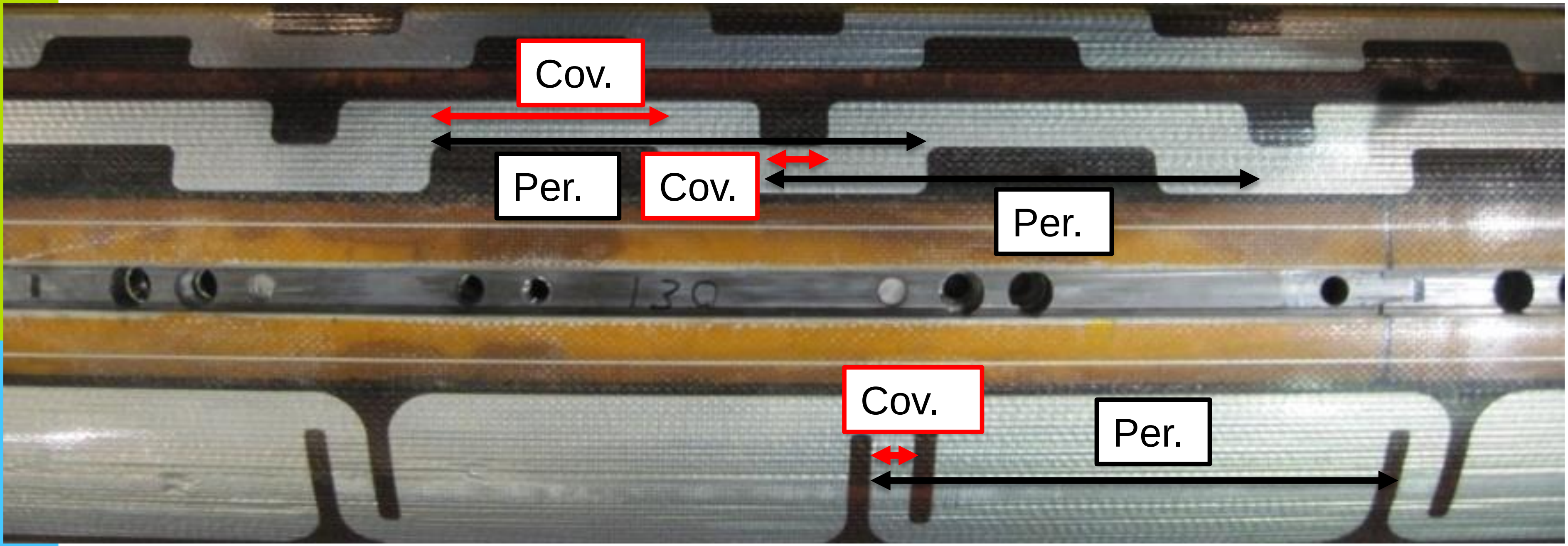
- Less uniform trace thickness



Conclusion

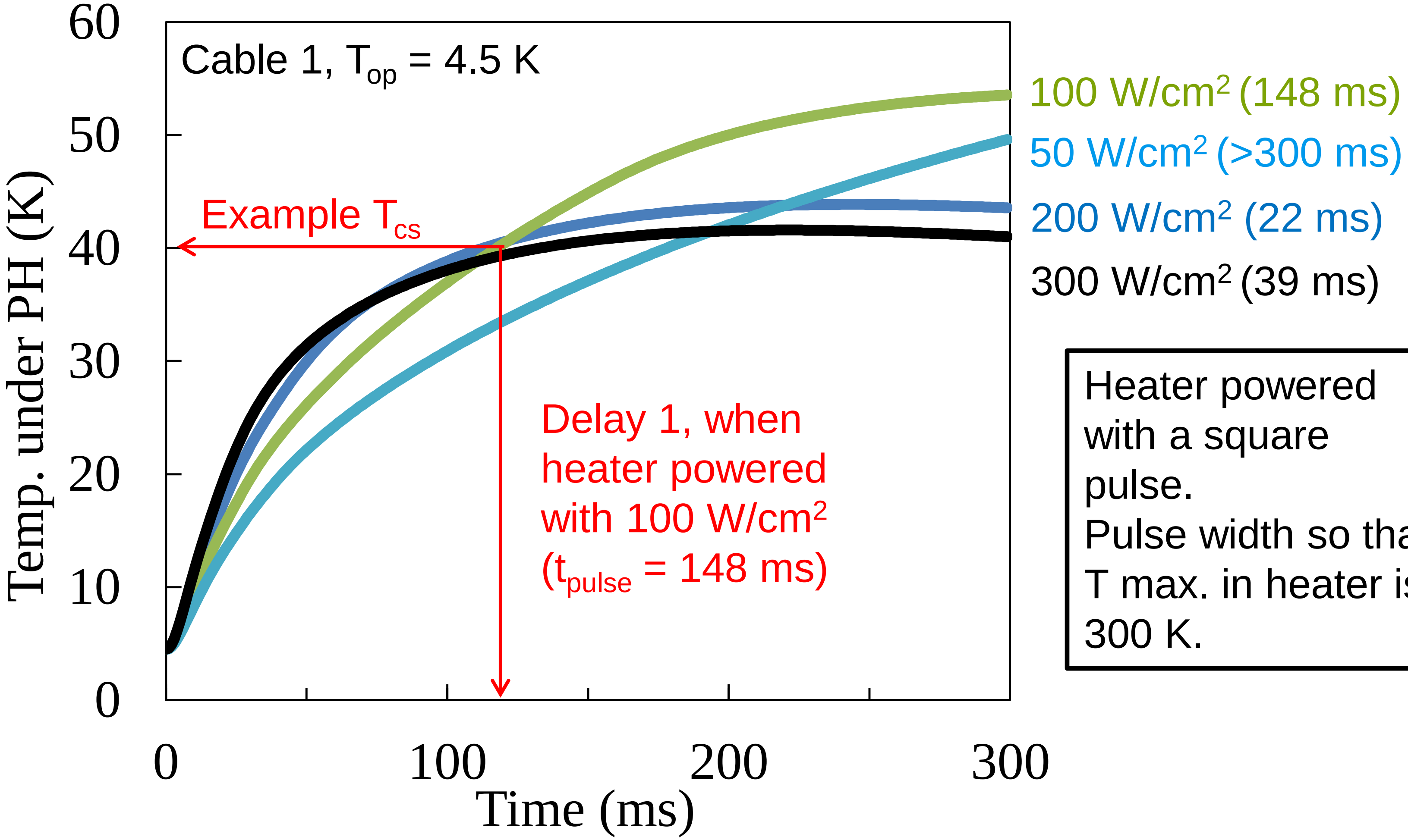
- The CoHDA simulation tool now includes also quench propagation in a YBCO cable
- Analysed heater delays in FM0 cable
  - Modeling roebel cable as stacked tape
    - Dimensions impact on heater delay time but not on NZPV
- Seems that with a powerful heater cables can be quenched, but the quench propagation is so slow that it is better to try to cover the entire cable with heater and not rely on heating stations
  - Needed delays depend on *J*, *L* and detection time
- **Must investigate also other protection options than heaters**
- Future work will consists of interfacing the heater model to a current decay model for a comprehensive quench protection analysis

Examples of heater geometries



Two geometries tested in 3.3 m long LARP LHQ 15 T Nb_3Sn quadrupole coil.

Design plot to estimate delay 1 vs. T_{cs}

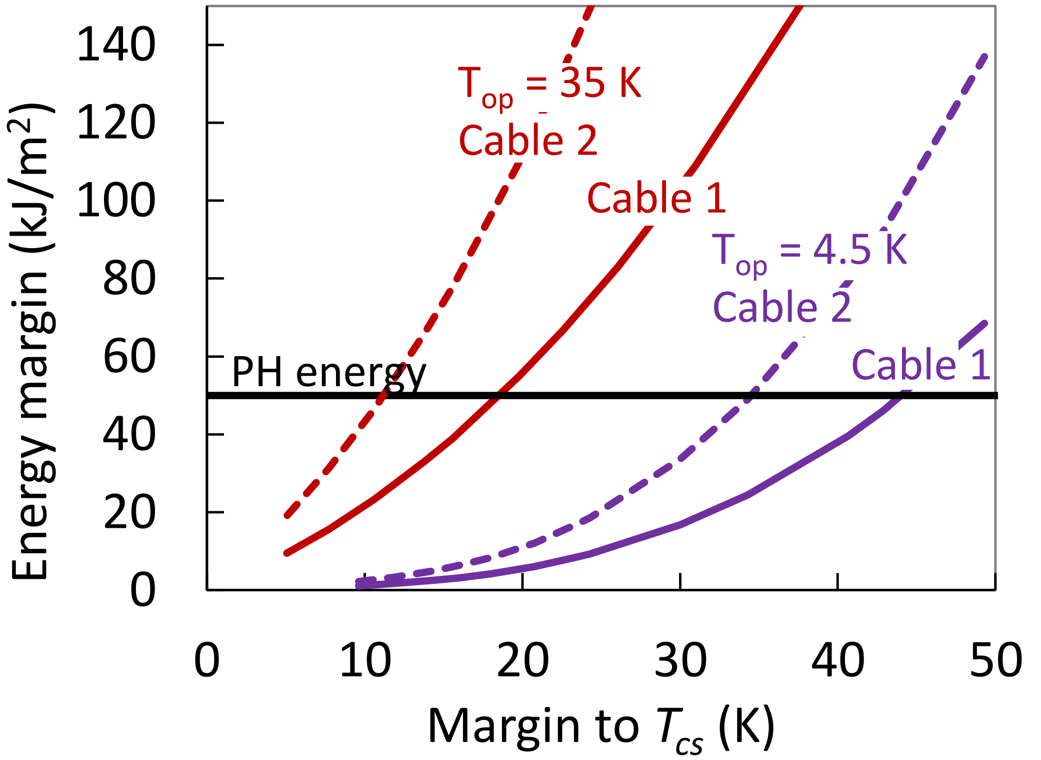


Delay 1, when heater powered with 100 W/cm² (t_{pulse} = 148 ms)

Heater powered with a square pulse.
Pulse width so that T max. in heater is 300 K.

Enthalpy vs. Temperature margin

- Heater energy must be related to the **cable energy margin**

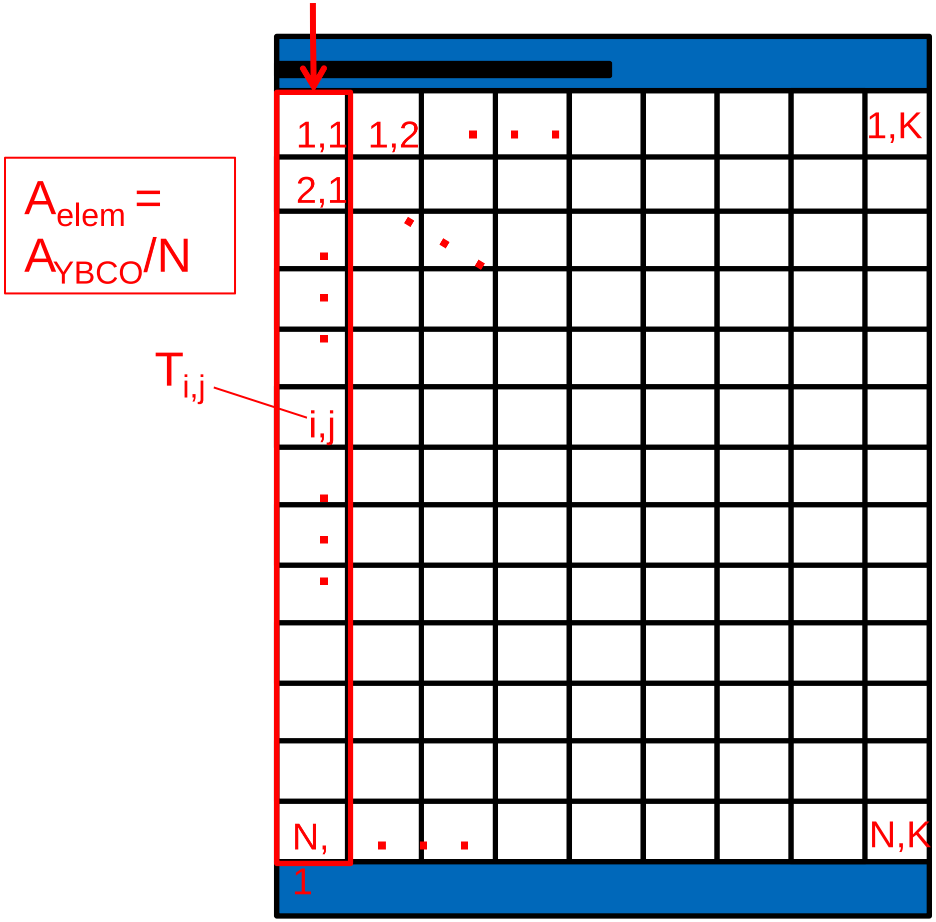


$$E_{PH} = P_{PH}(0)\frac{\tau}{2}$$

$$E_{margin} = w_{tape}\int_{T_{op}}^{T_{cs}} \gamma c_p dT$$

Current "redistribution"

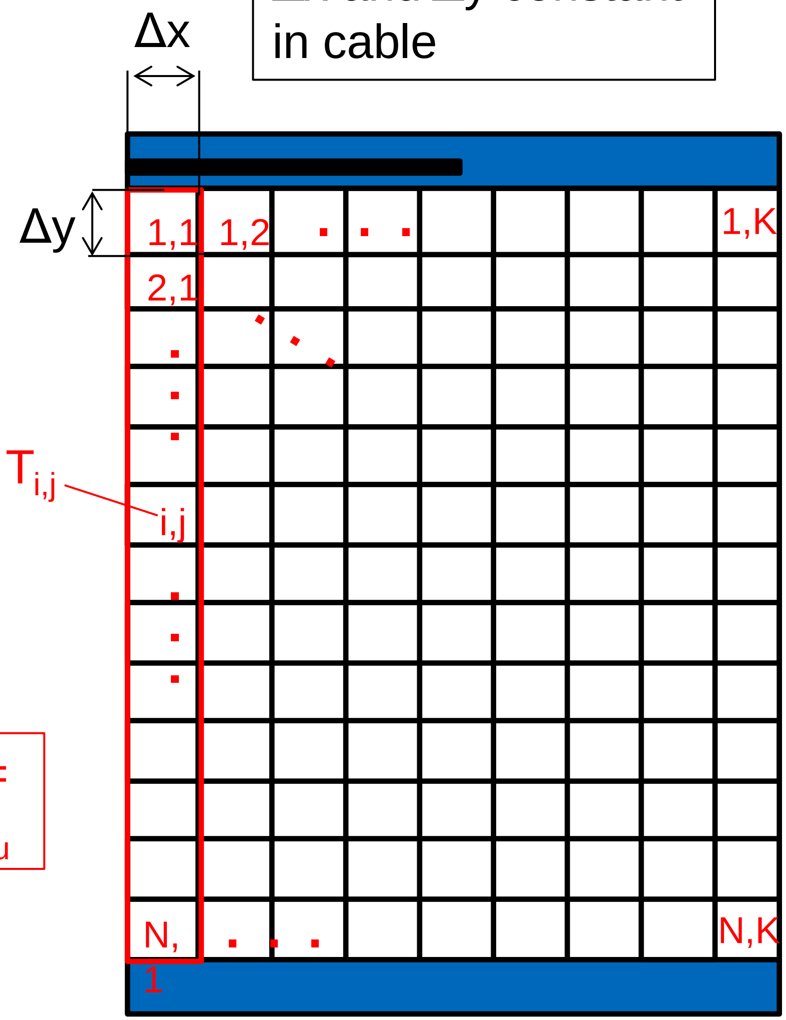
We go through cable segments column by column



```
QUENCH = 0
$t_{delay1}$ = -1

DO j = 1, K
    $I_{SC,j}$ = 0

    DO i = 1, N
        $I_{SC,j} = I_{SC,j} + J_C (B, T_{i,j}) * A_{elem}$

        IF ($I_{SC,j} \leq I_{op}$) $QUENCH_j = 1$
    END DO

    IF ($t_{delay1} = 0$) $t_{delay1}$ = time

    $I_{Cu,j} = Max (0, I_{op} - I_{SC,j})$

END DO
```

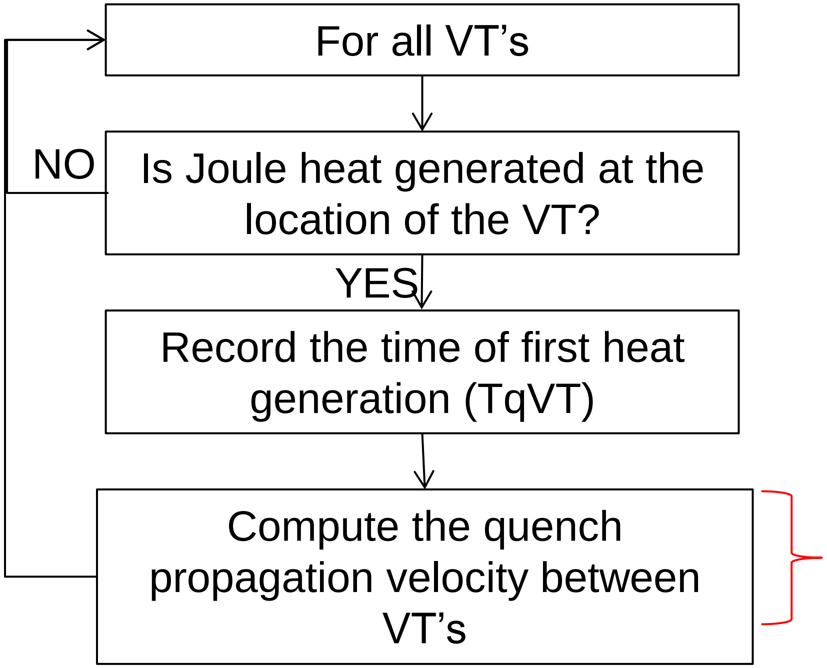
Heat generation

Δx and Δy constant in cable



$A_{cable} = A_{cu} / f_{Cu}$

```
$V_{tot} = 0$

DO j = 1, K
    $J_{Cu,j} = I_{Cu,j} / A_{cu}$
    $V_k = J_{Cu,j} * \rho_{Cu,i=N/2,j} * \Delta x$
    $f_{gen} = I_{op} * V_{ku} / (A_{Cable} * \Delta x)$
    $V_{tot} = V_{tot} + V_k$
END DO
```



Do all combinations of VT's (Consider only VT's where heat generation)