# QXF quench heater delay simulations

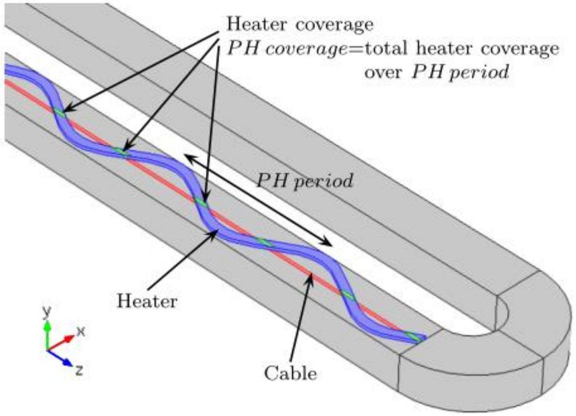
Tiina Salmi, 27.10.2015

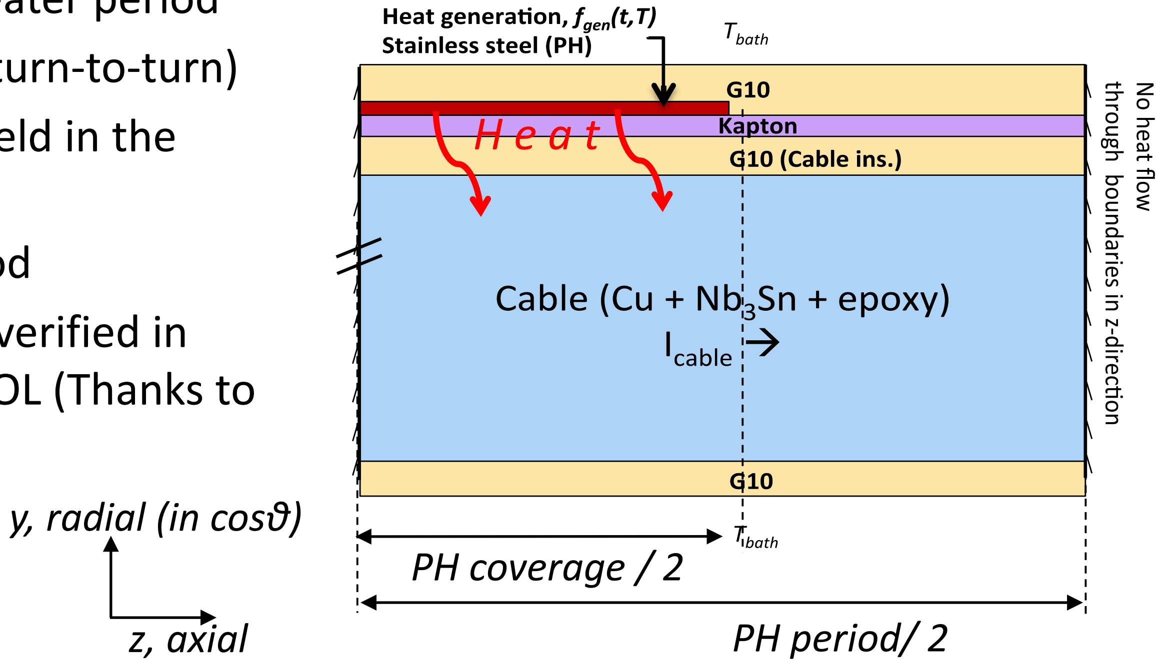
# Outline

- The main principles of the heater delay simulation code: CoHDA
- CoHDA validation by comparison of simulated delays to measurements
  - HQ01e, HQ02a-b, 11 T, HD3, LQ
- Simulation of LHQ and SQXF delays
- Possible reasons for the simulation uncertainties
- Summary of the heater delays agreement with simulation
- Description of a new code for computing current decay after a known distribution of heater delays and propagation velocity
- A case study for MQXF: The impact of heater delays distribution on hotspot temperature
- Summary of heater simulation status
- References for more detailed information

# CoHDA: **Co**de for **H**eater **D**elay **A**nalysis

- **Heat conduction from heater to the superconducting cable**
- Quench when cable reaches $T_{cs}(I,B)$
- Each coil turn considered separately
    - Symmetric heater geometry: Model half of the heater period
    - 2-D model (neglect turn-to-turn)
    - Uniform magnetic field in the cable
- Thermal network method
- Model implementation verified in comparison with COMSOL (Thanks to Juho Rysti, CERN)

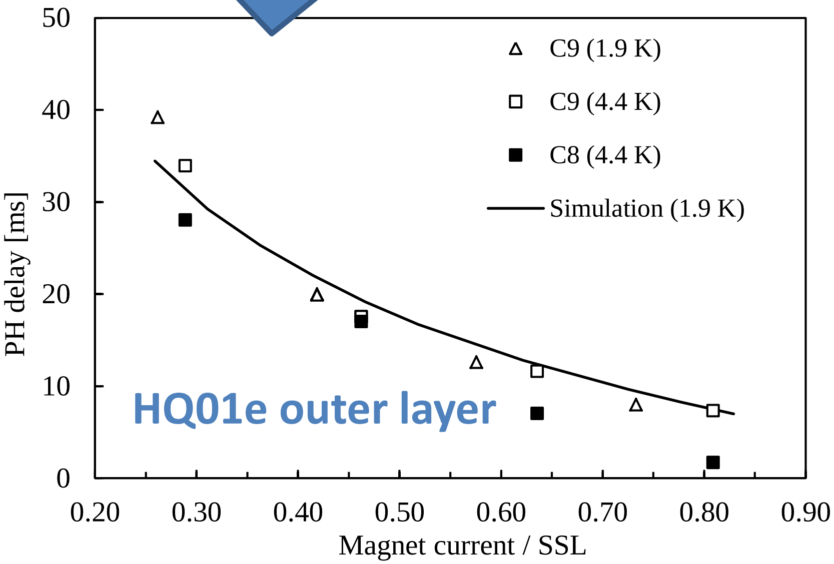




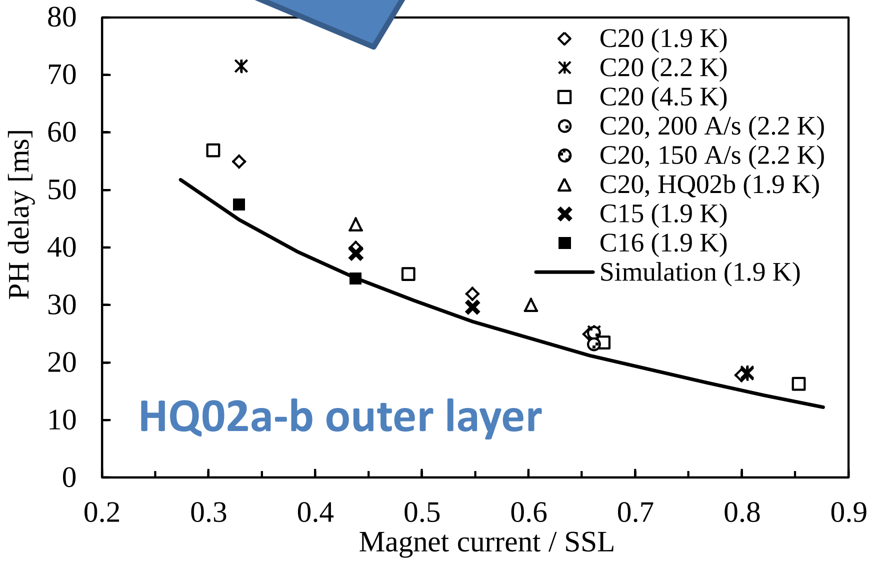
# CoHDA comparison with experimental data - OL

1. **HQ01e, HQ02a-b, 11 T, HD3b: Outer layer (OL)**
   - Above 50% of SSL: Nominal simulations typically within 20% of measurement – **Good agreement**
   - Uncertainty larger at lower current
   - Comparable with experimental uncertainty

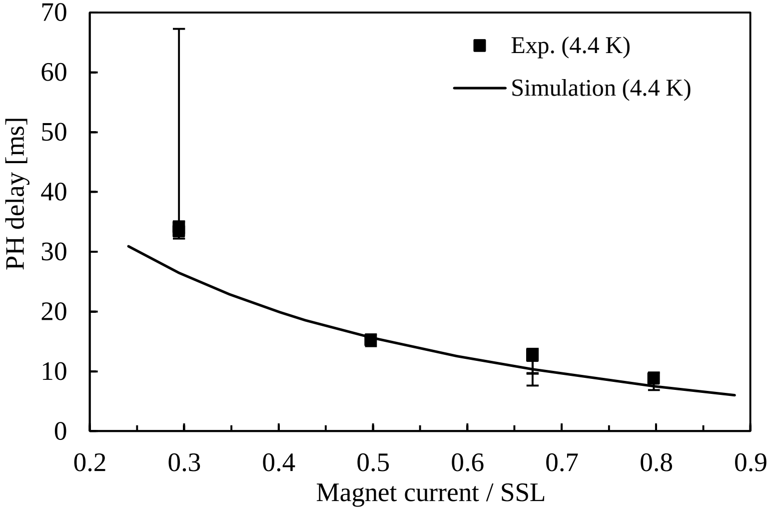
Large difference btw coils 8 and 9. Suspected a defect in coil 8.



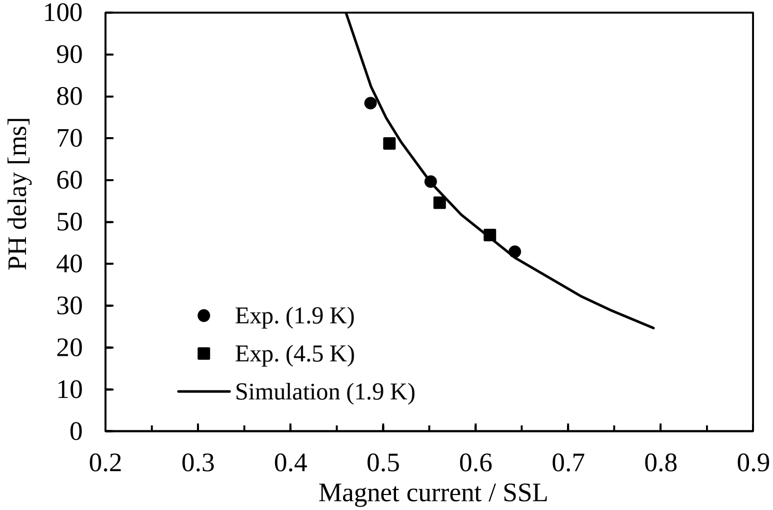
No signs of defects in HQ02 coils. The exp. variation suggests the *minimum exp. uncertainty..*



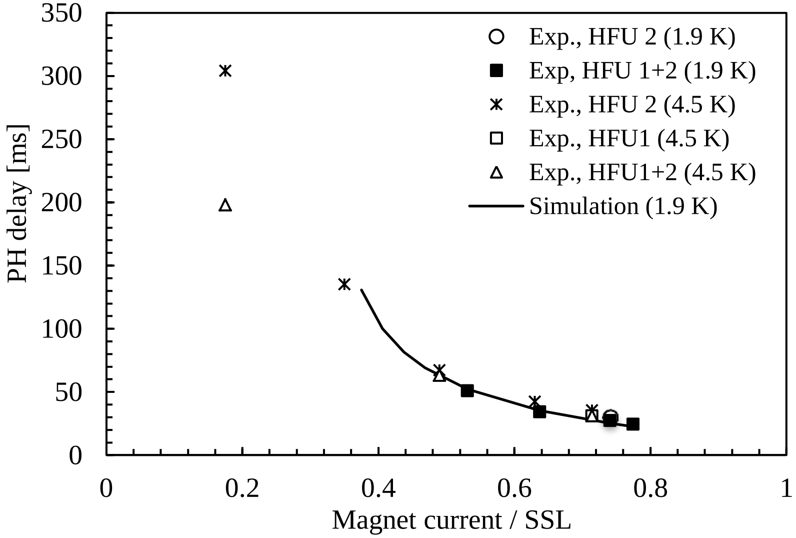
## HD3 outer layer



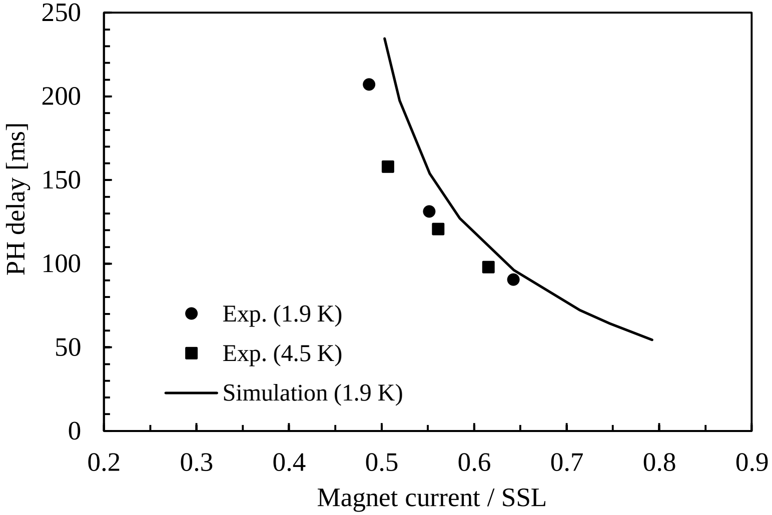
## 11 T MBHSP01, 76 µm Kapton



## 11 T MBHSP02

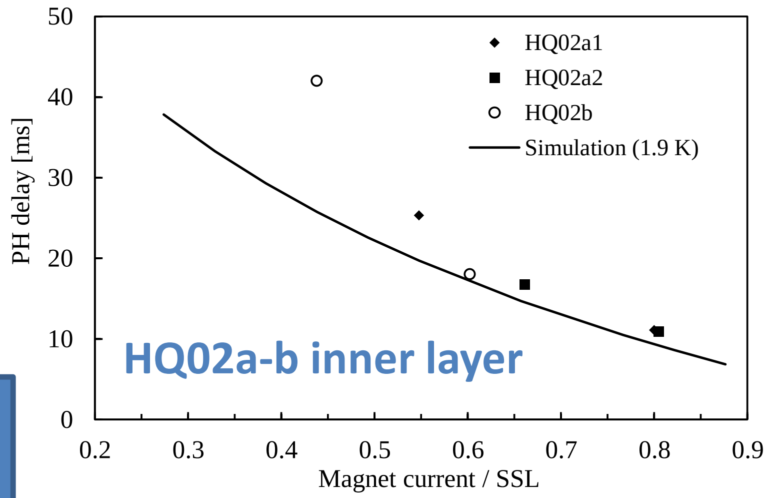


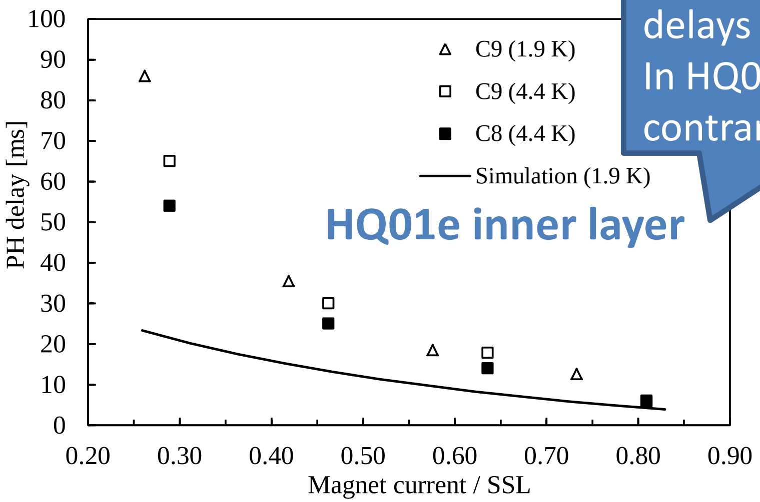
## 11 T MBHSP01, 203 µm Kapton



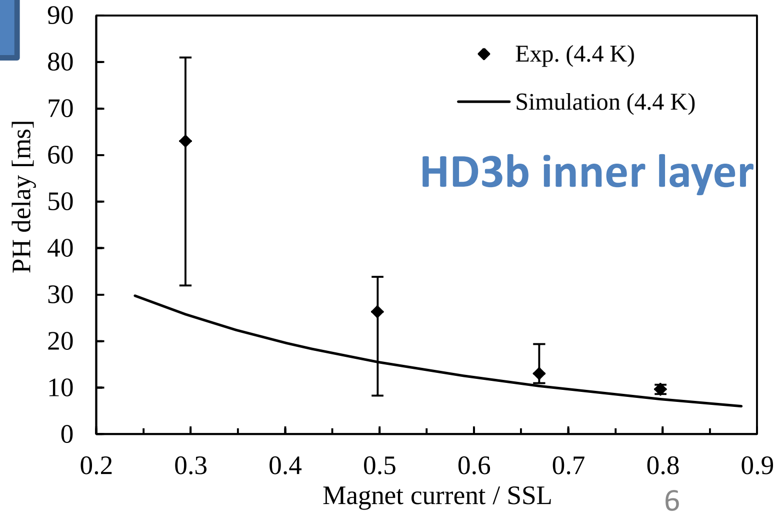
# CoHDA comparison with experimental data - IL

2. **HQ01e, HQ02a-b, 11 T, HD3b: Inner layer (IL)**
   - Above 50% of SSL: Nominal simulations within 10 ms or 40% of measurement – **Not good agreement…**
   - At lower current simulation **underestimates** the delays
   - Experiment not fully understood either
     - He bubbles?

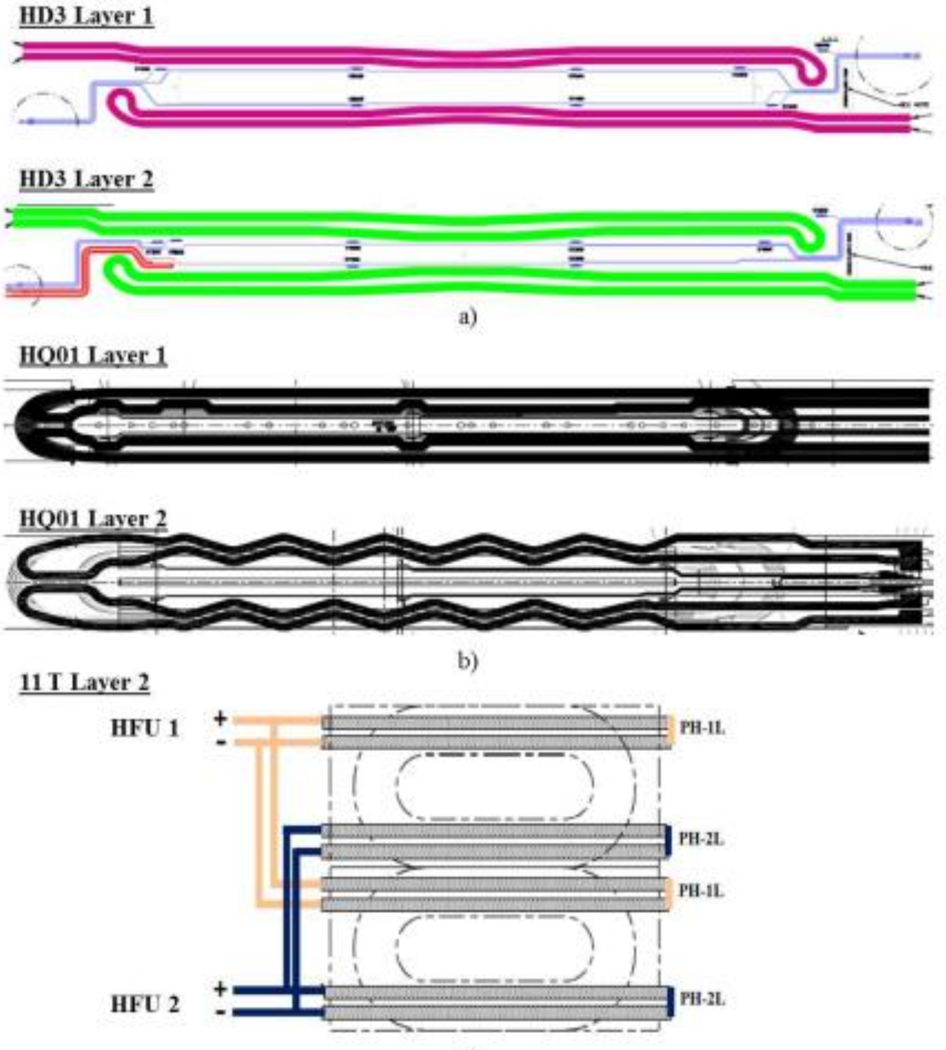




In HQ01 measured IL delays longer than OL. In HQ02 it was the contrary.



# HD3, HQ, and 11 T dipole heaters are all of uniform width



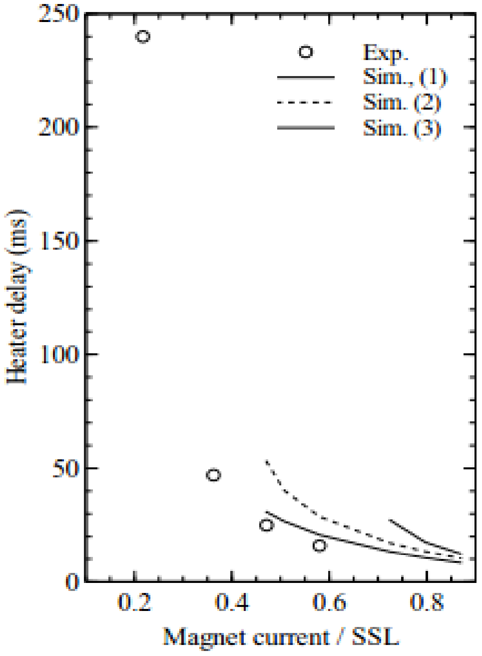
a)

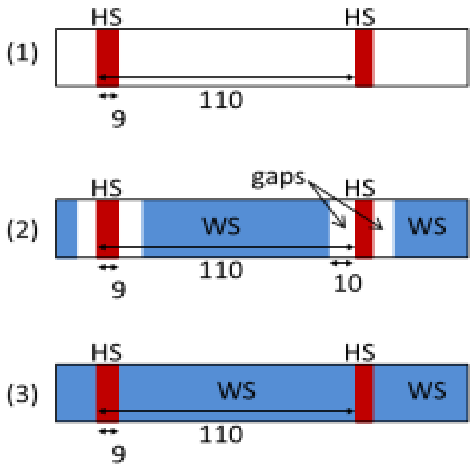
b)

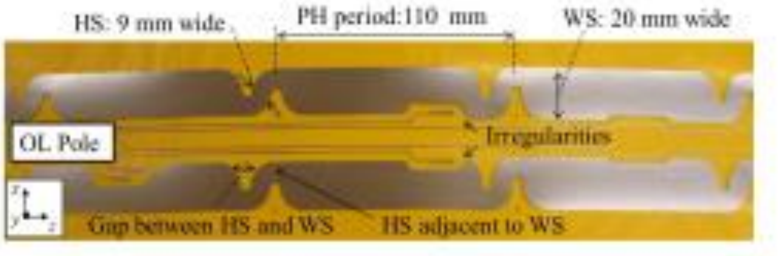
c)

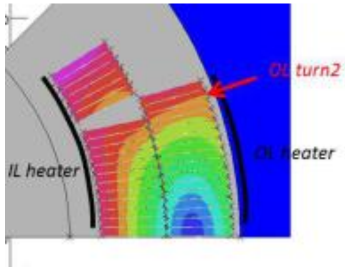
# CoHDA comparison with experimental data - LQ

- In LQ also the wider segment participates in heating the cable
- LQ simulation was done for the high field turn (2nd from the pole). Due to asymmetry of heating station-wide segment connection 3 cases were simulated.
- The simulation predicted too long delays in all cases.
- Possible reasons why **model not suitable**: 1. short heating station requires more detailed model of the cable structure, 2. **non-uniform heating in the heater narrow segment must be simulated with more detail.**



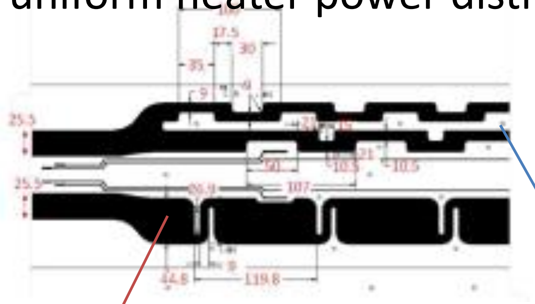


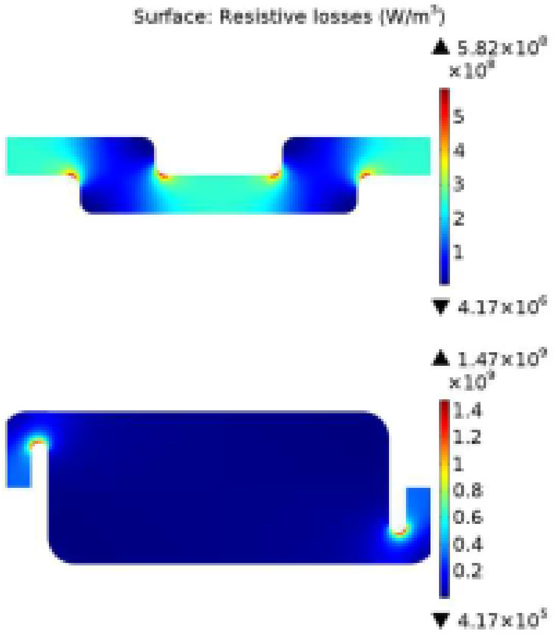


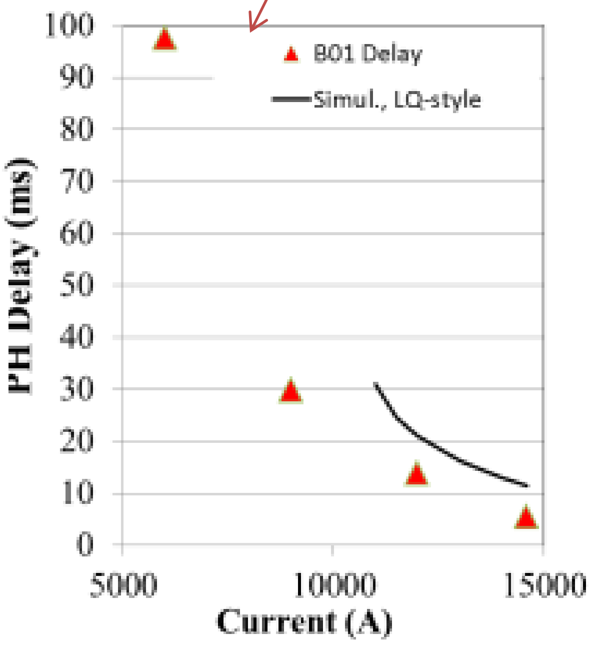


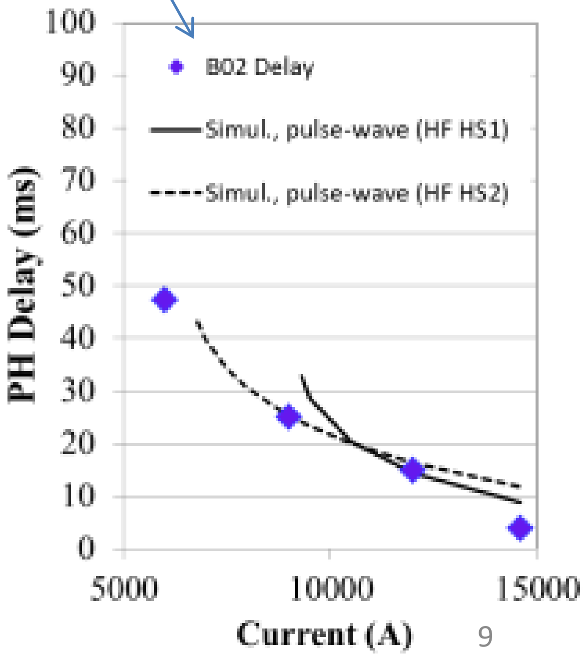
# The LHQ heaters

- Two different heater layouts tested (only OL): ”pulse-wave” and ”LQ-style”
- The measured delays with pulse-wave **agree well** with simulation
- Simulation again **overestimates** the delay with ”LQ-style”.
- Comsol simulations shows the non-uniform heater power distribution on the heating segments.



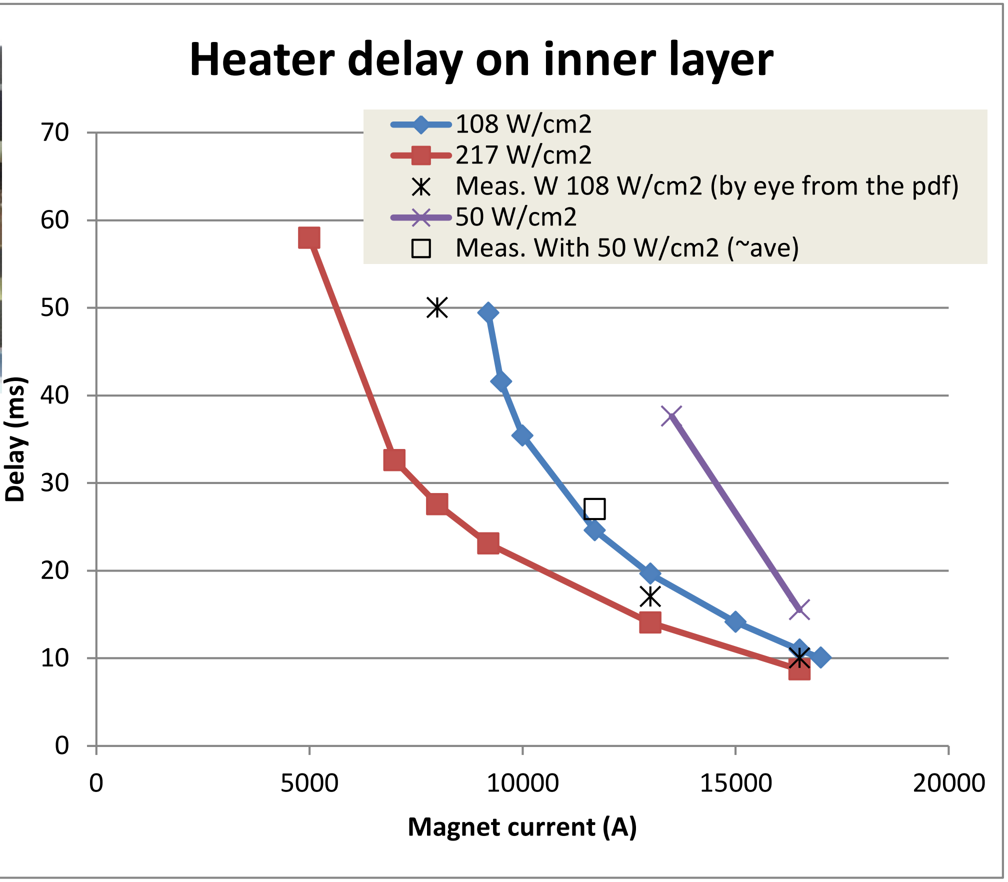






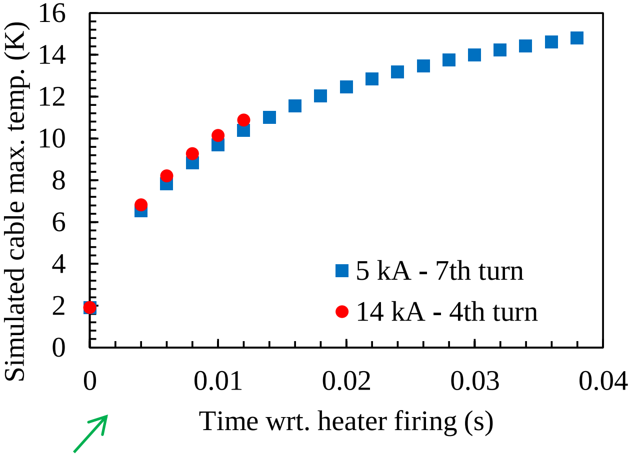
# The SQXF-mirror, heaters in inner layer

- Measurement and simulation with 108 W/cm2 **agree reasonably** for $I_{mag} \geq 13$ kA
- The low current regime and low heater power **not captured in simulation.**
- Unlike in previous inner layer simulations, the simulation **overestimates** the delays

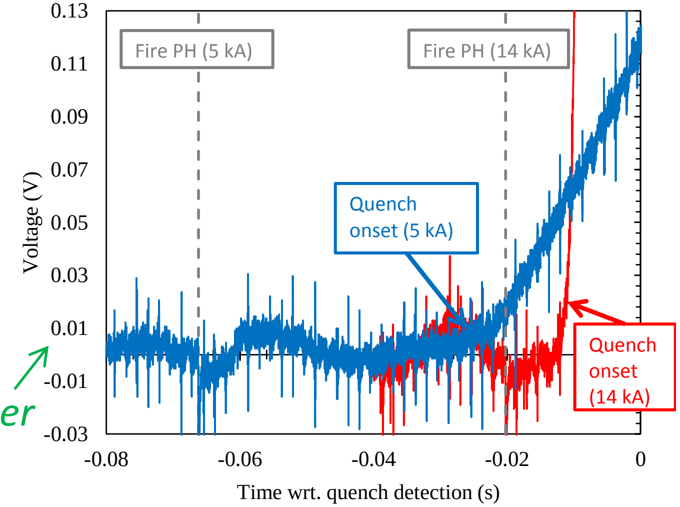


# Possible reasons for uncertainties with low current, low field, or low heater power

- **Cable temperature increase slows down** as heater power decreases and cable specific heat increases:
  - **Small variations of $T_{cs}$ have larger impact**
  - Details of cooling and heat conduction become more significant
  - Quench onset from voltage signals less clear at low current
  - Current redistribution and heat generation due to slow heating can occur (not modeled)
- Magnetic field simulation important for $T_{cs}$ – Which field to use for each conductor?
  - I have used the field on coil surface (closest to the protection heater), except for 11 T the maximum field because the field was significantly higher deeper in the cable
- Luckily, low current regime less critical for quench protection



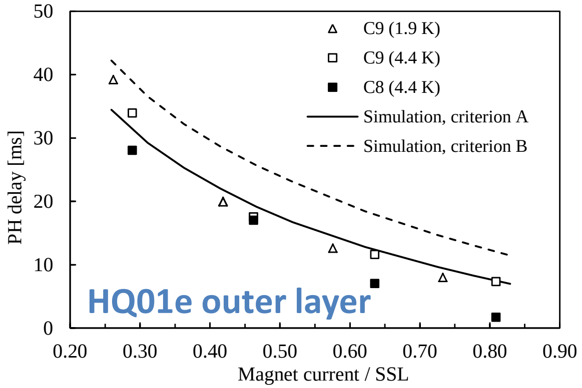
*Simulated temperature rise after heater activation.*

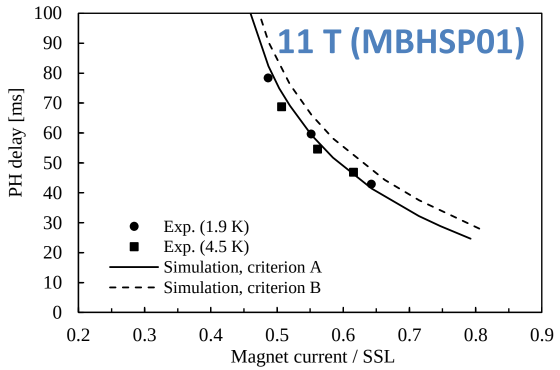


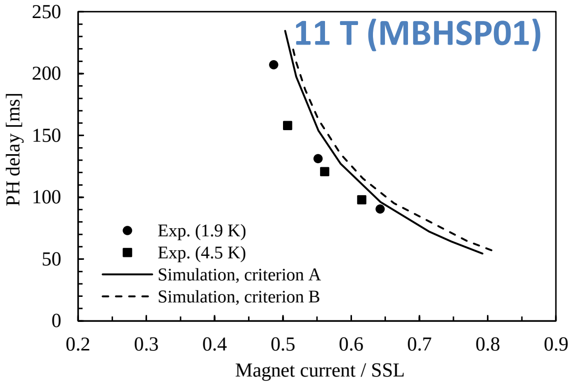
*HQ01e voltage tap signals for a heater provoked quench at 5 kA and 14 kA.*

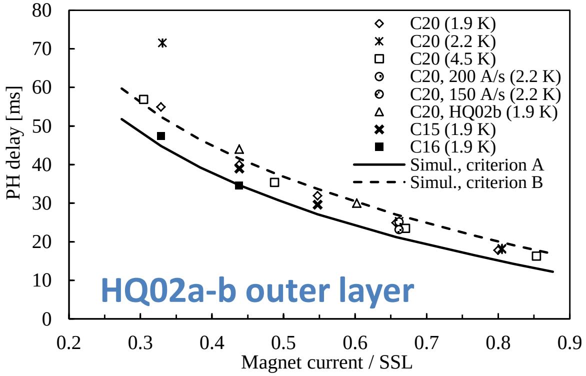
# A possible conservative delay simulation criterion

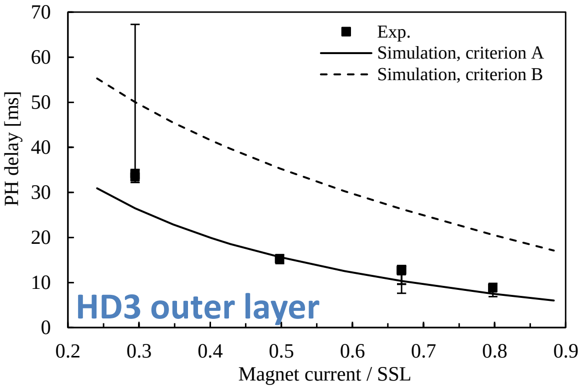
- We need to add margin to the simulated heater delays for quench simulations
- One option: Simulate delay time to the moment when cable $I_c$ equals $I_{mag}$. This accounts for the temperature gradient in the cable cross-section.
  - Most of the measured delays on outer layer below this upper bound:

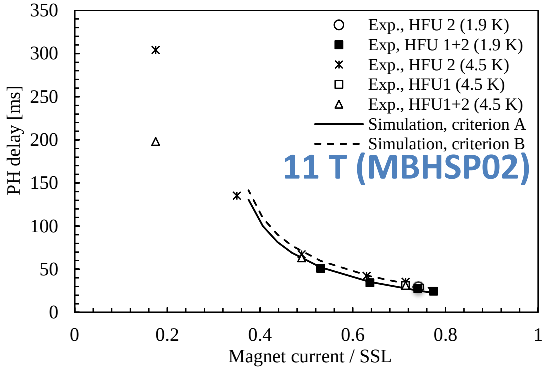












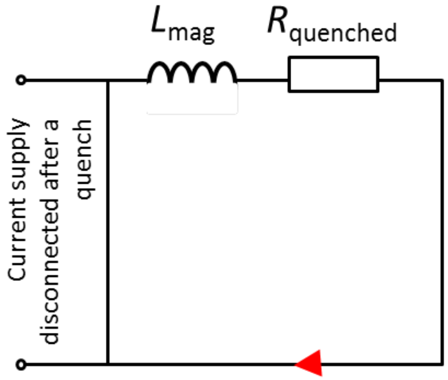
Criterion A: Nominal simulaion, quench when cable $T_{max} = T_{cs}$;
Criterion B: Conservative criterion, quench when cable $I_c = I_{mag}$.

# Summary of the heater delays

- Outer layer heater delays typically within 20% of measurements, when above 50% of SSL
- Lower current has larger uncertainty
- Uncertainties comparable with experimental uncertainty
- Inner layer heater simulations have much larger uncertainty – but also the experiments less well understood
- LQ-style heater with short and complex shaped heating station not well simulated with this model (simulation overestimates the delay)
- The above simulations were for the high field region

- More analysis coming soon from comparison with the RMC tested at CERN (heater delays on high field and low field, AC-losses, current decay and NZPV)

# Coodi: **Co**de for current decay computation based on known protection efficiency



**Input:**

- For each turn:
  - Heater delay, heating station length and period
  - Normal zone propagation velocity (between heating stations)
  - Magnetic field, $T_{cs}$
  - Cable parametetrs
- Magnet length, inductance vs. current, operating temperature, initial current
- Initial normal zone length and location
- Detection time, switches delays and external dump resistor

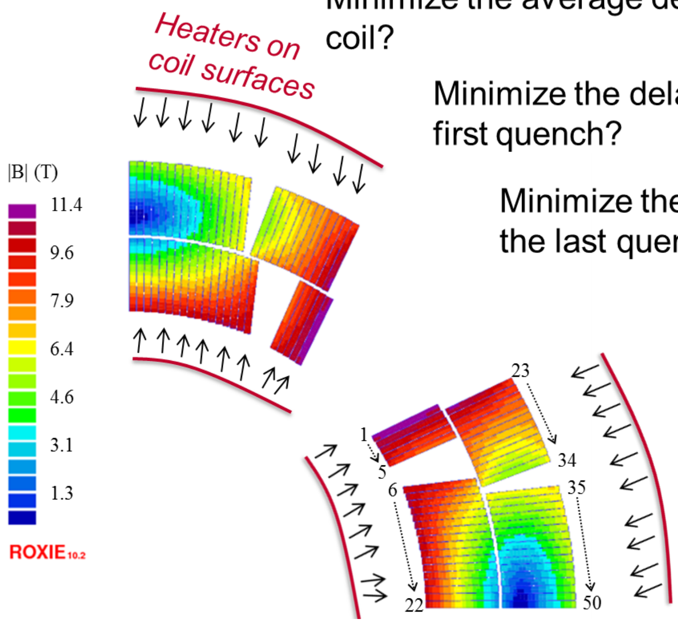
**Each coil turn can have different heater delay and geometry** (allows analysis of real heater geometres and delay distributions), **different cables can be used to simulate graded coils.**

The input delays and NZPV define the coil resistance development *a priori*. **The code calculates the resistance at each time step, accounting for the different quenching times of the coil turns. The resistance drives the current decay.** Temperature at the resistive coil turns and in the hotspot is calculated using the **MIITs-concept** at each time step. For each turn the heater covered segmentes and not-covered are treated separately.

# A case study: What is the impact of different heater delay distributions?

The available heater energy is limited. The heater geometry defines the heater delay distribution in the coil turns.

What is the best criterion for the heater geometry design?



Minimize the average delay in the coil?

Minimize the delay to the first quench?

Minimize the delay to the last quench?

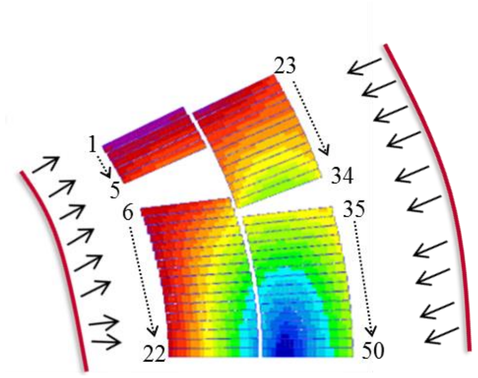
*Thanks to S. Izquierdo-Bermudez and V. Marinozzi for the field map.*

## Coil parameters*

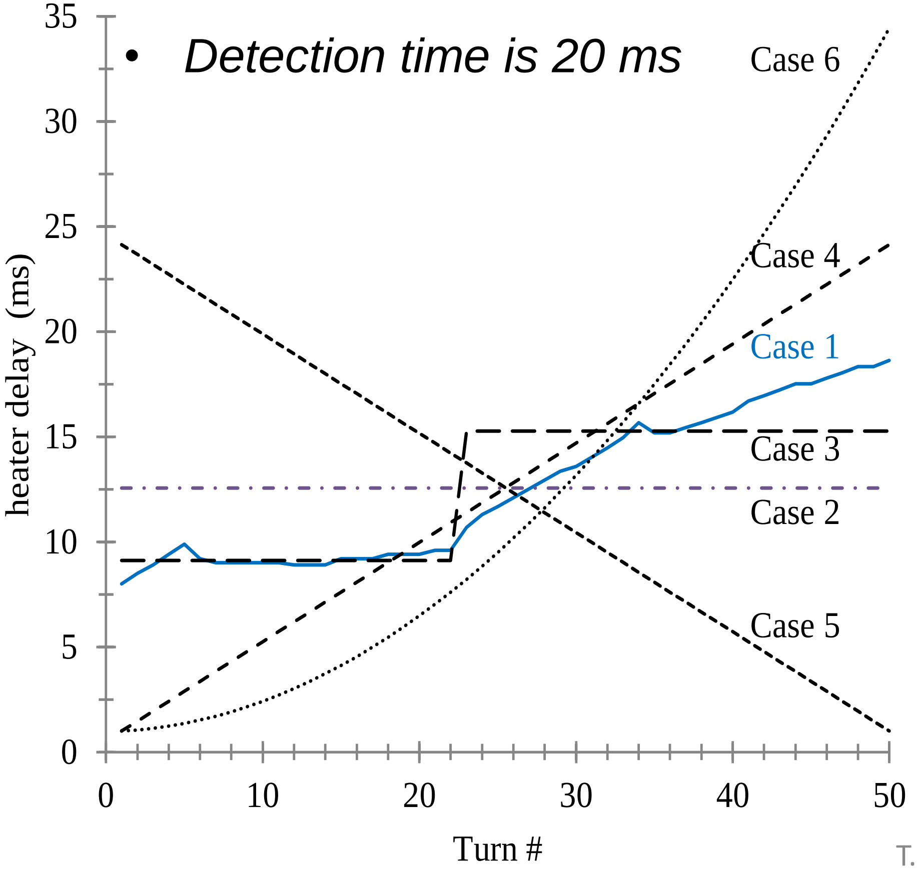
| | |
|---|---|
| Area of insulated cable | 35.61 mm$^2$ |
| Strand Cu /Nb$_3$Sn ratio | 1.15 |
| Voids fraction of bare cable | 0.2 |
| Cable insulation thickness | 0.145 mm |
| Width of cable | 18.383 mm |
| Mid-thickness of cable | 1.594 mm |
| RRR | 140 mm |
| Inter-layer insulation (G10) | 0.5 mm |
| Insulation between outer layer heater and collar | 0.8 mm |
| Insulation between inner layer heater and bore | 0.15 mm |
| Magnet length | 7.2 m |

* May not represent the latest design

# Simulated heater delay distributions, average delay in all cases 12.6 ms



Case 1: CoHDA simulation with 150 W/cm$^2$ peak power ($\tau$ = 50 ms), heater covers entire turn.
Case 2: The average delay in every turn (12.6 ms).
Case 3: The average delay for inner and outer layer.
Case 4: A linear increase from 1 ms at turn #1 to 24 ms at turn #50.
Case 5: A linear decrease from 24 ms at turn #1 to 1 ms at turn #50.
Case 6: An exponential increase from 1 ms at turn #1 to 34 ms at turn #50.



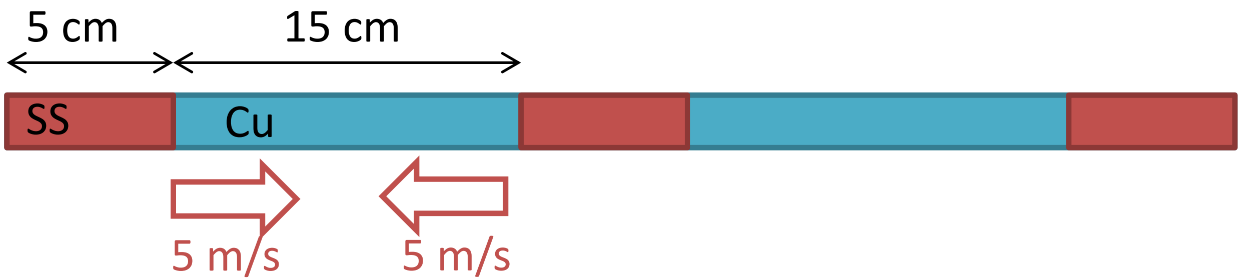
- *Detection time is 20 ms*

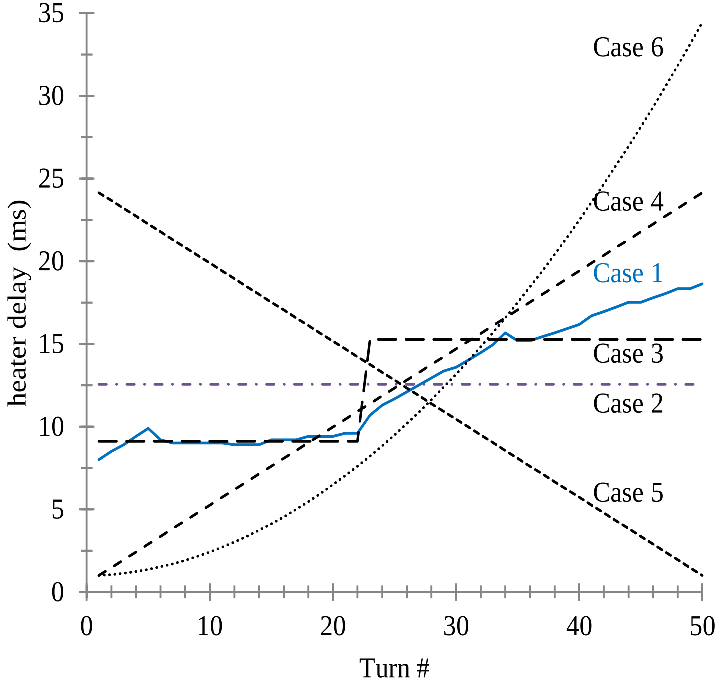
**Entire turn quenches at the given delay time**

| Case | Hotspot temperature (K) |
|---|---|
| 1 | 238 |
| 2 | 241 |
| 3 | 239 |
| 4 | 233 |
| 5 | 244 |
| 6 | 228 |

Lower hotspot temperature when the quench starts faster in the high field region, even it means longer delay for low field region.

# With 5 cm heating stations, 20 cm period





Heating station quenches at the given delay time, propagation between them at each time step

Entire turn quenches instantaneously, delay = heater delay + propagation time/2 (7.5 ms)

| Case | Hotspot temperature with HS (K) | Hotspot temperature with HS and average delay (K) |
|---|---|---|
| 1 | 258 | 268 |
| 2 | 261 | 271 |
| 3 | 259 | 269 |
| 4 | 253 | 262 |
| 5 | 264 | 273 |
| 6 | 247 | 257 |

~ 20 K higher compared to covering entire turn

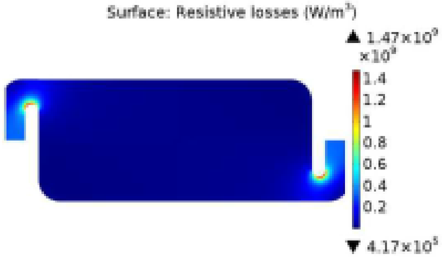
~ 10 K higher compared with simulation with HS.

Faster first delay, lower hotspot temperature…

-> **Better aim for short delay under HS.**

# Summary of the heater modeling status

- Heater delays for coil outer layers typically modeled well above 50% of SSL
  - Uncertainty ~20% is comparable with experimental uncertainty
- Lower currents and inner layer simulations have larger uncertainty
  - Also the experimental uncertainty is larger
- LQ-style heating stations require improvement to the model, because of non-uniform heating in the heating station



- More comparison with experiment foreseen in near future, and model development continues
- A code for computing magnet current decay and temperatures for different heater delay distributions was presented.
- A study was done to define what is a good criterion for heater layout optimization design
  - The result showed, that it is the best to aim at minimizing the delays to first quenches, and to start the quenches in high field region
    - More detailed optimization needed, but in principle, better to put more heating stations on high field region than low field.

# References for the details

- T. Salmi et al., ”A novel computer code for modeling quench protection heaters in high-field $Nb_3Sn$ accelerator magnets”, IEEE TAS 24(4), 2014
- T. Salmi et al., ”Analysis of uncertainties in protection heater delay time measurements and simulations in $Nb_3Sn$ high-field accelerator magnets”,
- T. Salmi, ”Optimization of Quench Protection Heater Performance in High-Field Accelerator Magnets Through Computational and Experimental Analysis”, PhD Thesis, Tampere University of Technology, Finland
- T. Salmi et al., ”The impact of protection heaters delay distribution on the hotspot temperature”, Presented at MT-24.