Quench protection models at TUT

For high-field Nb_3Sn accelerator magnets

1. Code for Heater Delay Analysis (CoHDA)
2. Code for Current decay analysis based on know protection efficiency (Coodi)
3. Adaptive Hybrid Code for The Study of Quench Protection of Superconducting Devices (HOSTED) – Under development
   - Heat diffusion in entire coil, using coupled 1-D FEM (and FD) models with adaptive meshing

Reference publications

CoHDA:

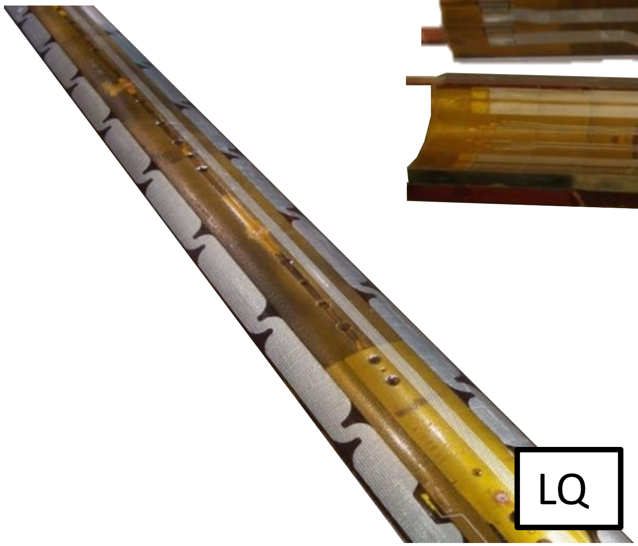
- T. Salmi et al., "A Novel Computer Code for Modeling Quench Protection Heaters in High-Field Nb_3Sn Accelerator Magnets", *IEEE TAS,* 24(4), 2014.
- T. Salmi et al., “Analysis of uncertainties in protection heater delay time measurements and simulations in Nb_3Sn high-field accelerator magnets” *IEEE TAS,* 25(4), 2015.
- T. Salmi et al., “Modeling quench protection heater delays in an HTS coil”, *IEEE TAS,* 25(3), 2015.

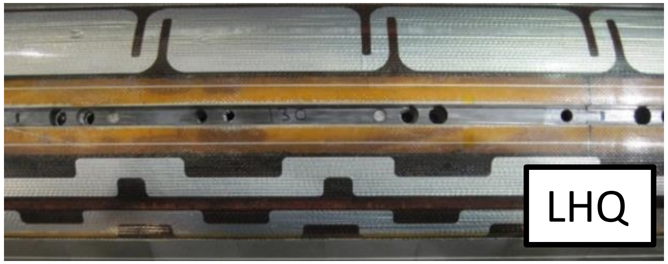
Coodi:

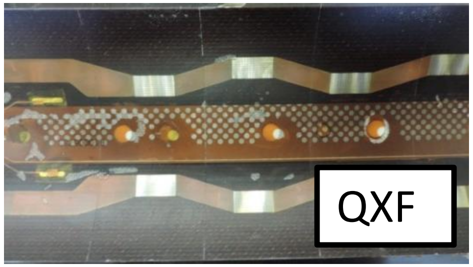
- T. Salmi et al., “Quench protection analysis integrated in the design of dipoles for the Future Circular Collider”, Phys. Rev. Accel. Beams 20, 032401
- T. Salmi et al., ”The Impact of Protection Heater Delays Distribution on the Hotspot Temperature in a High-Field Accelerator Magnet”, *IEEE TAS,* 26(4), 2016.

Figures: Protection heaters in LARP high-field Nb3SN quadrupoles.


HQ


LQ

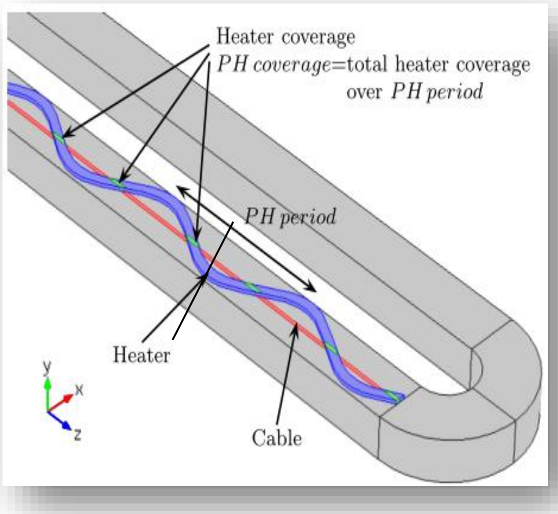

LHQ

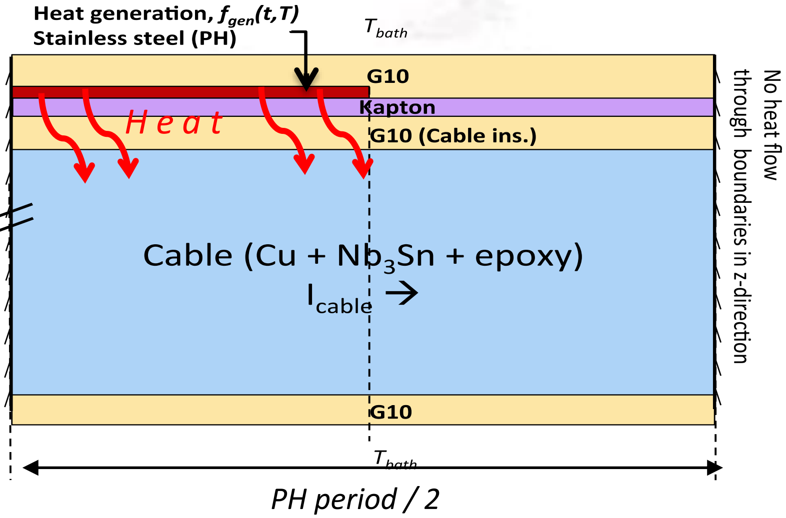

QXF

CoHDA: Code for Heater Delay Analysis

CoHDA: Idea

- Compute heat generation in heater and diffusion to cable
- Quench when cable temperature reaches a threshold value
- One coil turn is simulated independently:
  - <u>2D thermal model along the cable length</u>





Quench when $T_{max,cable}$ = T_{cs} (*I*, *B*)

CoHDA: Model

Input: Heater parameters, coil parameters, operation conditions, critical surface,…

Output: Temperature evolution, delay to reach T_{cs} in cable

Governing equations:

2-D heat balance eq.:

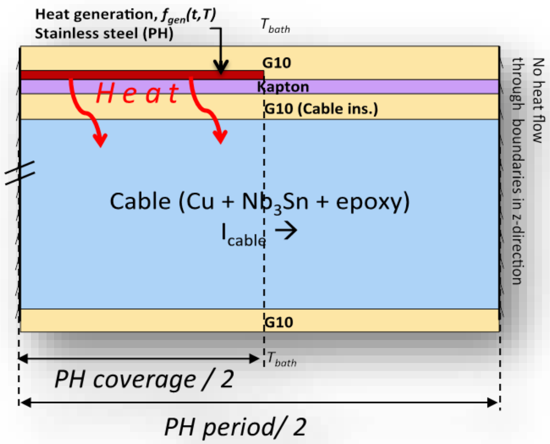
$$\gamma_m c_{p,m}(B,T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(k_m(B,T)\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_m(B,T)\frac{\partial T}{\partial z}\right) + f_{gen,m}(t,T)$$

With internal heat source (in heater*):

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

Boundary cond. and init. values:

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

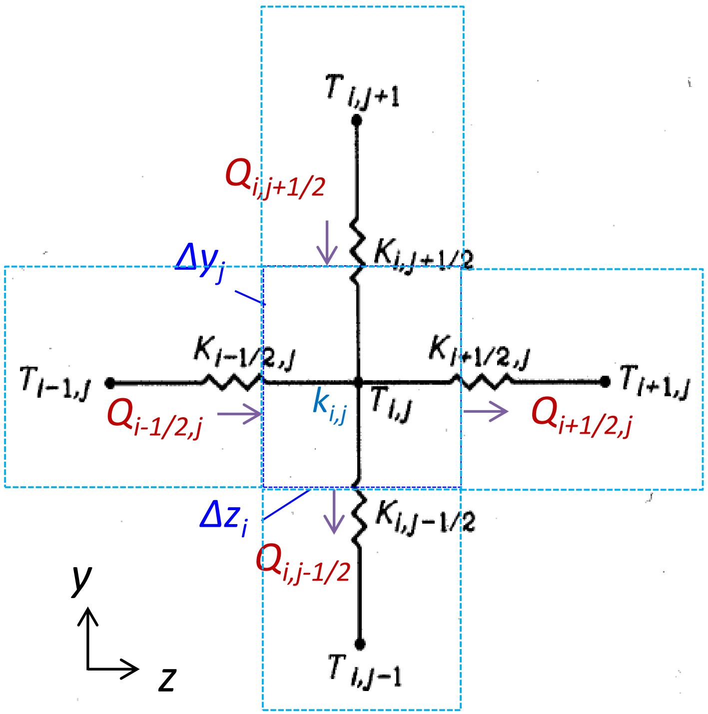


t = time [s], $T = T(t, y, z)$ = Temp. [K], $c_{p,m}(B,T)$ = Specific heat [J/K/kg],
γ = Mass density [kg/m^3], $k_m(B,T)$ = Thermal conductivity [W/K/m],
$f_{gen,m}$(t,T) = Internal heating [W/m^3], q'' = heat flux [W/m^2],
ρ_{ss} (T) = Electrical resistivity of ss in Ωm, J_{ss} = Current density in ss x-sect. in A/m^2

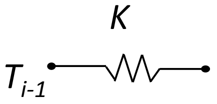
*Can be used also for Joule heating in cable

CoHDA: Implementation

- ”Home made” code with Fortran 90
- Thermal network method for numerical solution



Analogy with electrical network:



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

Conductance (W/m/K):

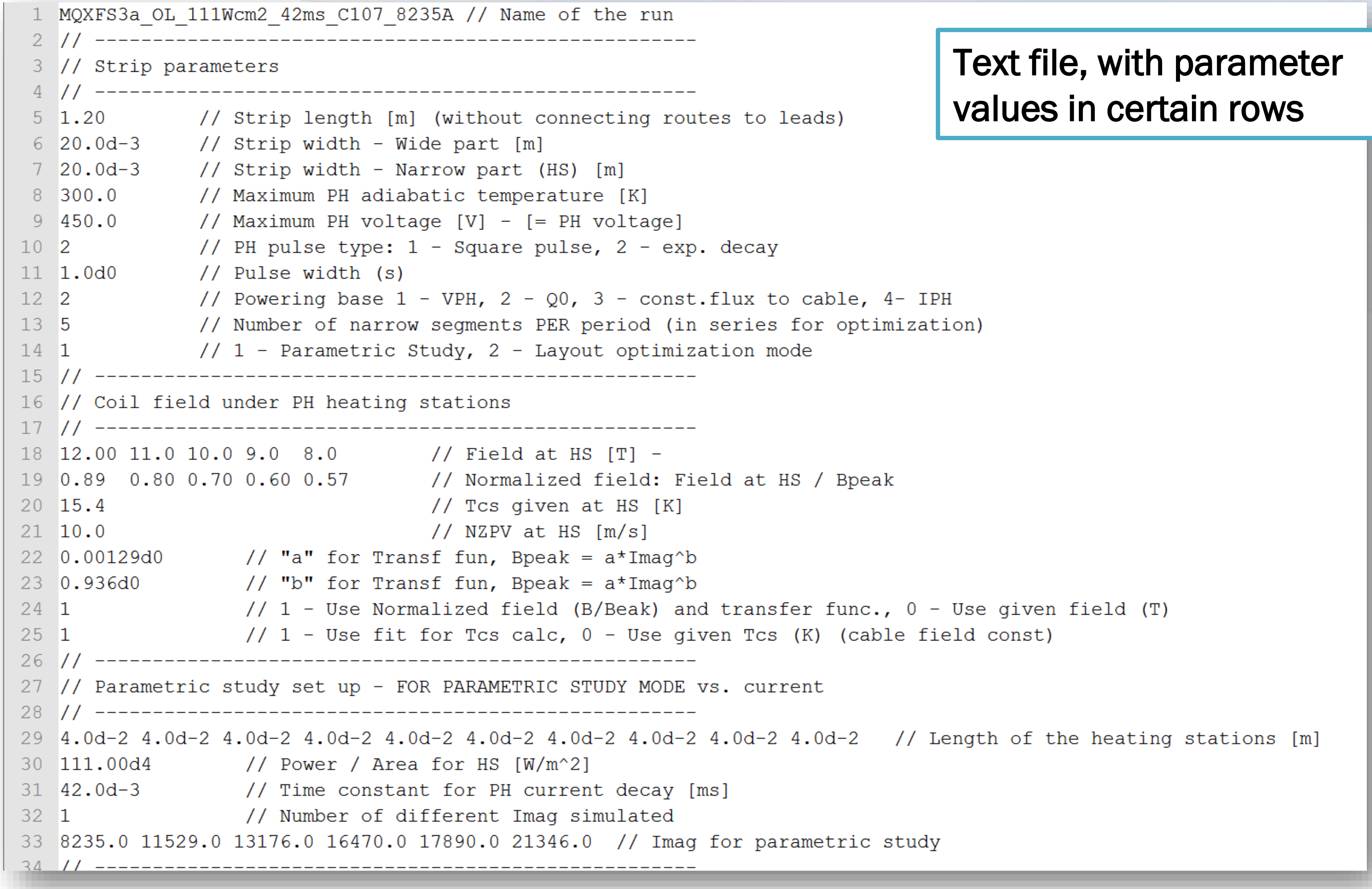
$$K_{i-\frac{1}{2},j} = \frac{\Delta y_j}{\Delta z_{i-1}/\left(2k_{i-1,j}\right) + \Delta z_i/\left(2k_{i,j}\right)}$$

New temperatures:

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

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

CoHDA: Input file 1/3

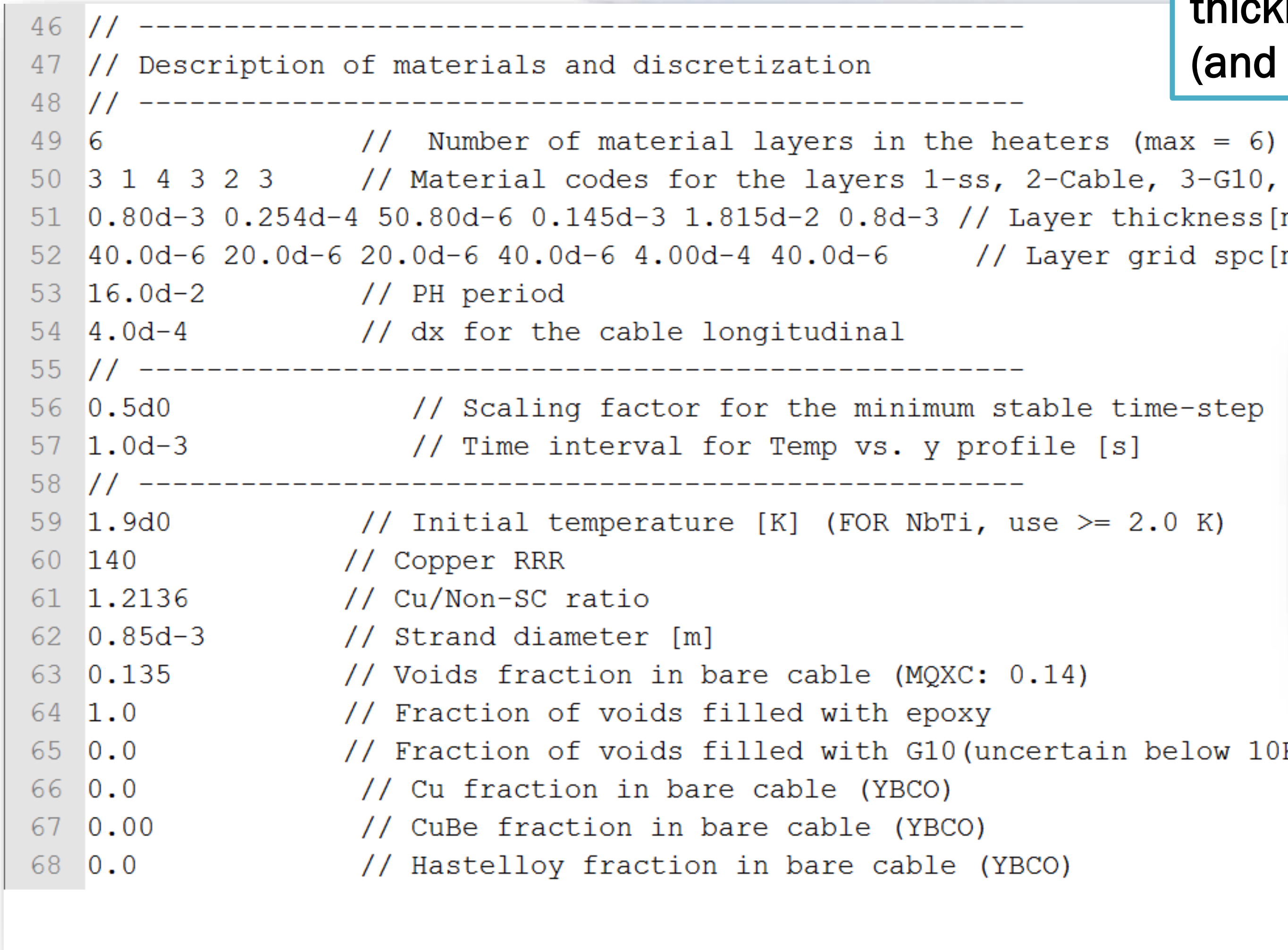


```
MQXFS3a_OL_111Wcm2_42ms_C107_8235A // Name of the run
// ----------------------------------------------------
// Strip parameters
// ----------------------------------------------------
1.20        // Strip length [m] (without connecting routes to leads)
20.0d-3     // Strip width - Wide part [m]
20.0d-3     // Strip width - Narrow part (HS) [m]
300.0       // Maximum PH adiabatic temperature [K]
450.0       // Maximum PH voltage [V] - [= PH voltage]
2           // PH pulse type: 1 - Square pulse, 2 - exp. decay
1.0d0       // Pulse width (s)
2           // Powering base 1 - VPH, 2 - Q0, 3 - const.flux to cable, 4- IPH
5           // Number of narrow segments PER period (in series for optimization)
1           // 1 - Parametric Study, 2 - Layout optimization mode
// ----------------------------------------------------
// Coil field under PH heating stations
// ----------------------------------------------------
12.00 11.0 10.0 9.0  8.0        // Field at HS [T] -
0.89  0.80 0.70 0.60 0.57       // Normalized field: Field at HS / Bpeak
15.4                            // Tcs given at HS [K]
10.0                            // NZPV at HS [m/s]
0.00129d0       // "a" for Transf fun, Bpeak = a*Imag^b
0.936d0         // "b" for Transf fun, Bpeak = a*Imag^b
1               // 1 - Use Normalized field (B/Beak) and transfer func., 0 - Use given field (T)
1               // 1 - Use fit for Tcs calc, 0 - Use given Tcs (K) (cable field const)
// ----------------------------------------------------
// Parametric study set up - FOR PARAMETRIC STUDY MODE vs. current
// ----------------------------------------------------
4.0d-2 4.0d-2 4.0d-2 4.0d-2 4.0d-2 4.0d-2 4.0d-2 4.0d-2 4.0d-2 4.0d-2   // Length of the heating stations [m]
111.00d4        // Power / Area for HS [W/m^2]
42.0d-3         // Time constant for PH current decay [ms]
1               // Number of different Imag simulated
8235.0 11529.0 13176.0 16470.0 17890.0 21346.0  // Imag for parametric study
// ----------------------------------------------------
```

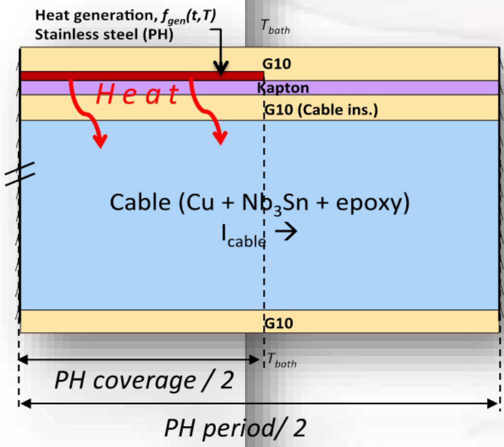
Text file, with parameter values in certain rows

CoHDA: Input file 2/3

Geometry is defined as thicknesses of the layers (and heating station length(s))



```
// ---------------------------------------------------------
// Description of materials and discretization
// ---------------------------------------------------------
6               //  Number of material layers in the heaters (max = 6)
3 1 4 3 2 3     // Material codes for the layers 1-ss, 2-Cable, 3-G10, 4-Kapton
0.80d-3 0.254d-4 50.80d-6 0.145d-3 1.815d-2 0.8d-3 // Layer thickness[m]
40.0d-6 20.0d-6 20.0d-6 40.0d-6 4.00d-4 40.0d-6     // Layer grid spc[m]
16.0d-2         // PH period
4.0d-4          // dx for the cable longitudinal
// ---------------------------------------------------------
0.5d0              // Scaling factor for the minimum stable time-step
1.0d-3             // Time interval for Temp vs. y profile [s]
// ---------------------------------------------------------
1.9d0           // Initial temperature [K] (FOR NbTi, use >= 2.0 K)
140            // Copper RRR
1.2136         // Cu/Non-SC ratio
0.85d-3        // Strand diameter [m]
0.135          // Voids fraction in bare cable (MQXC: 0.14)
1.0            // Fraction of voids filled with epoxy
0.0            // Fraction of voids filled with G10(uncertain below 10K)
0.0             // Cu fraction in bare cable (YBCO)
0.00            // CuBe fraction in bare cable (YBCO)
0.0             // Hastelloy fraction in bare cable (YBCO)
```



CoHDA: Input file 3/3

Other functions provided in CoHDA:

- 5 different Jc fits
- Different boundary conditions, and constant material properties
- Joule heating and quench propagation
- Automatized sensitivity analysis to mat. props.
- File for cable internal heat source (vs. time) to simulate AC-loss / CLIQ
- Varying field profile in cable cross-section
- Heater geometry optimization…
- Simulation of transversally cut coil block…

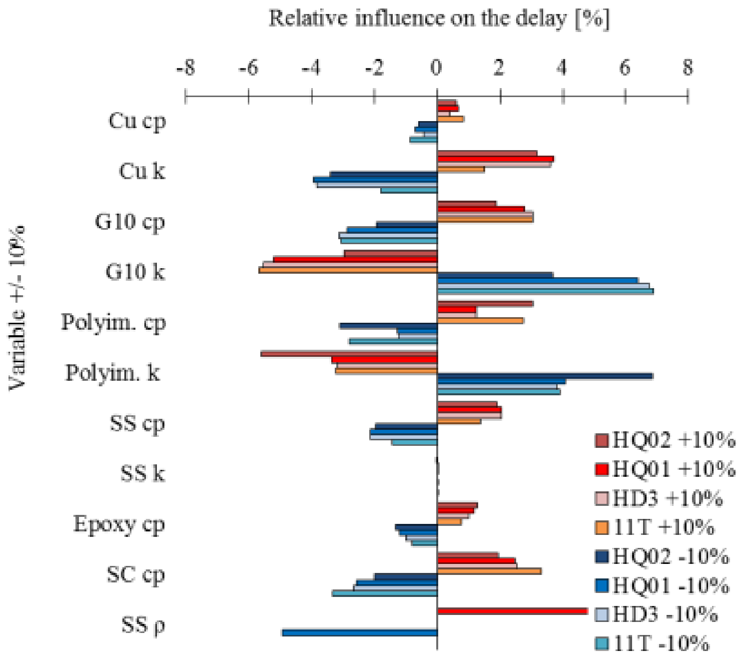


Fig. 17. Heater delay sensitivity to material properties variation of + or - 10%.

Changing the domain to be a transversal cut of coil block

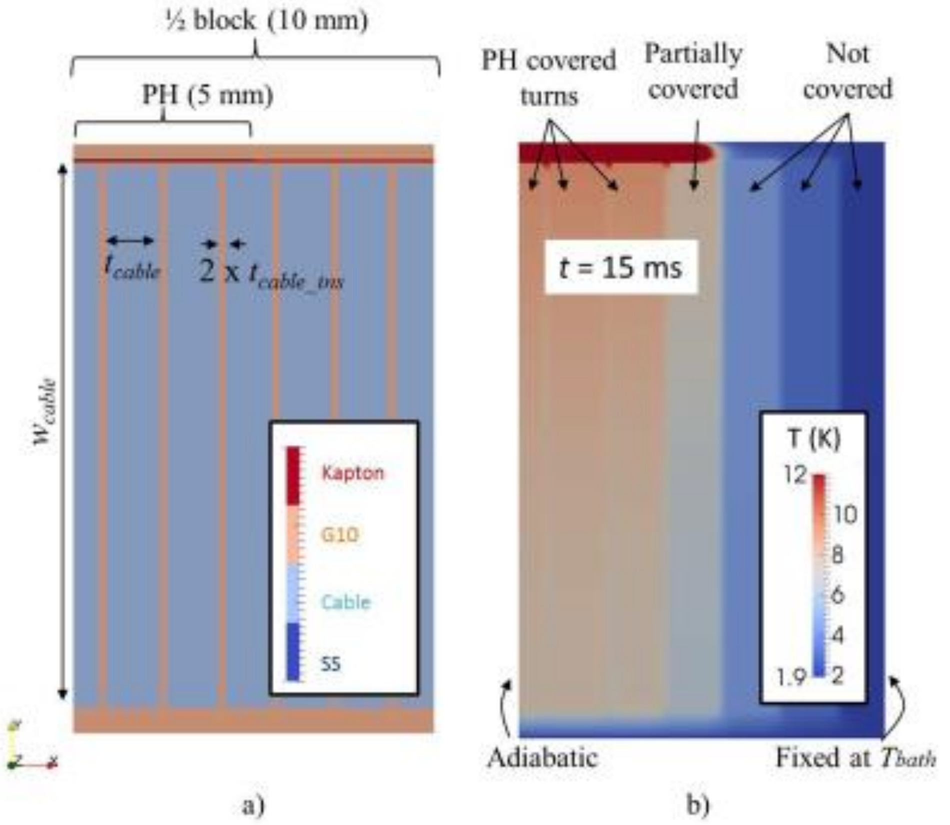
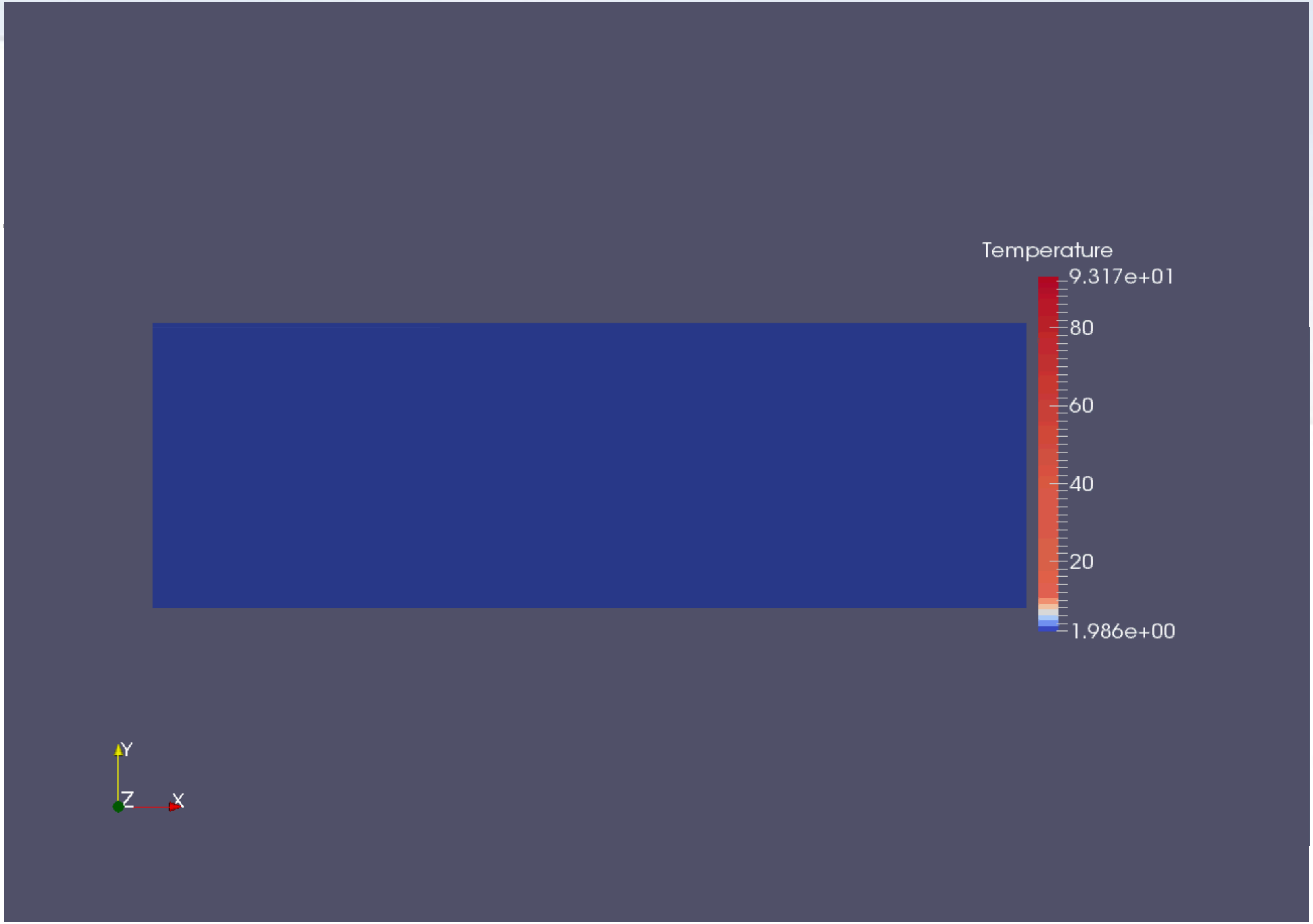


Fig. 19. Transversal heat diffusion simulation in HQ02: a) domain and materials, b) temperature distribution 15 ms after heater activation. The temperature scale is adjusted to show differences below 12 K. The maximum temperature in the heater at this moment is 90 K.

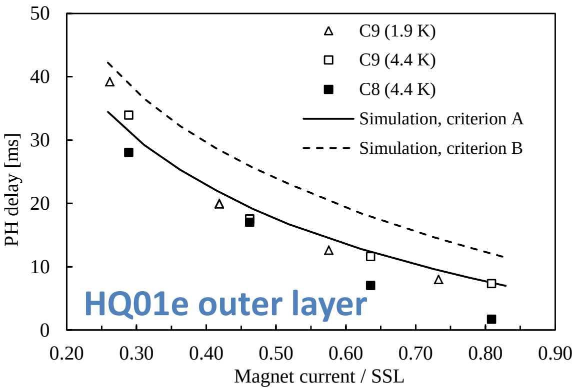
CoHDA: DEMO

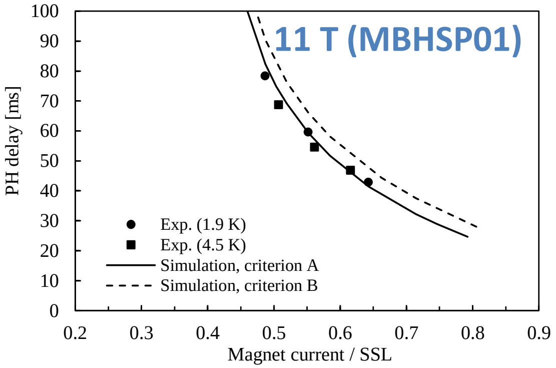

Heating Station (HS)

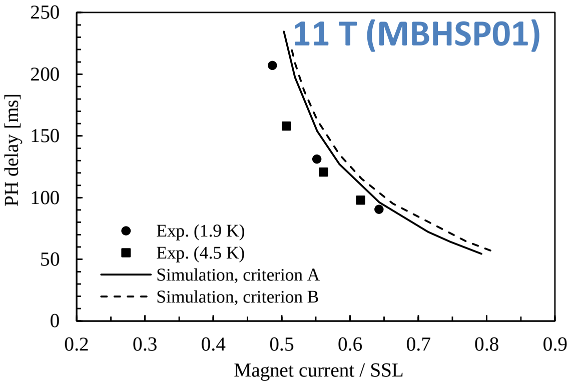

Temperature
9.317e+01
80
60
40
20
1.986e+00
Y
Z
X

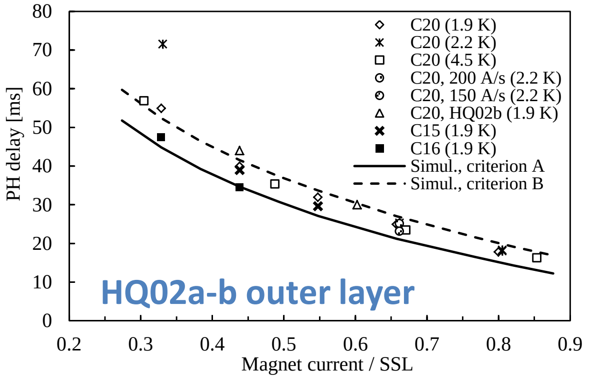
CoHDA: Validation

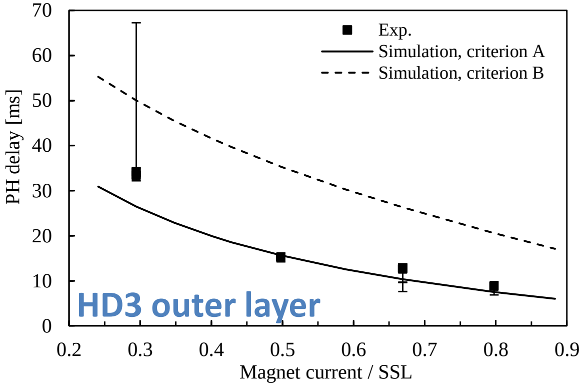
1. Checked with analytical and in comparison with Comsol (ok)
   - COMSOL model by J. Rysti, CERN, 2014
2. Validation with experimental data.. (reasonable for outer heaters)

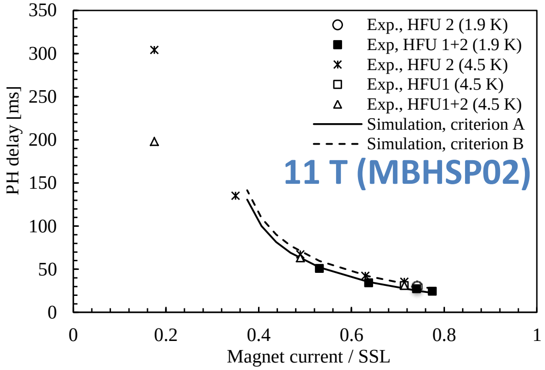












Criterion A: Nominal. Quench when cable $T_{max} = T_{cs}$.
Criterion B: quench when cable $I_c = I_{mag}$.

At high magnet current:
Accuracy is ~20%

CoHDA: Use

1. Analysis of experimental data

2. Heater design for MQXF magnet

3. Quench protection analysis for the FCC magnets

- Simulated delays have been used as input to other quench simulation software
    - Quench analysis for MQXF with QLASA (collaboration with INFN-Milan)
    - To *Coodi*
    - To STEAM??

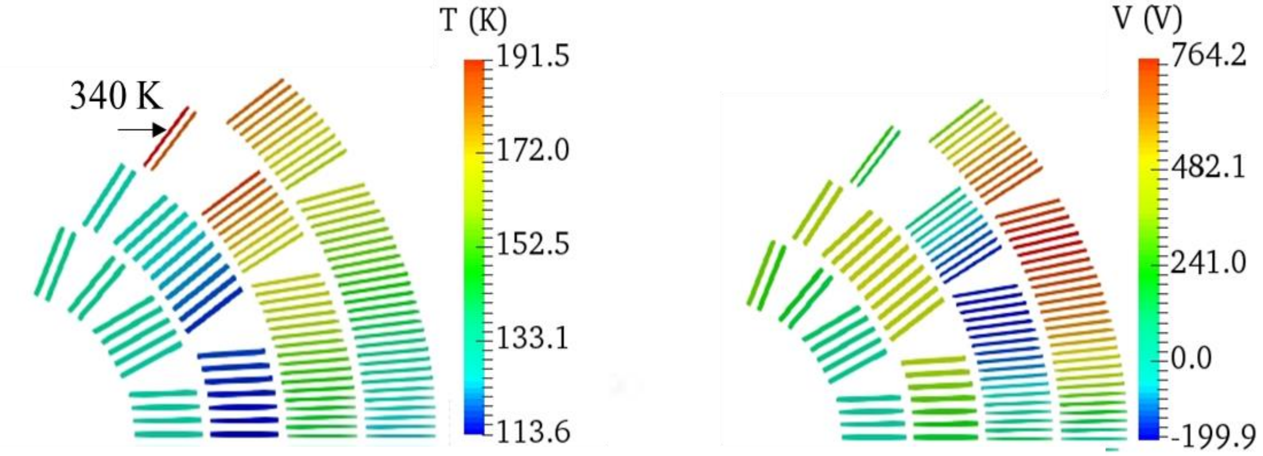


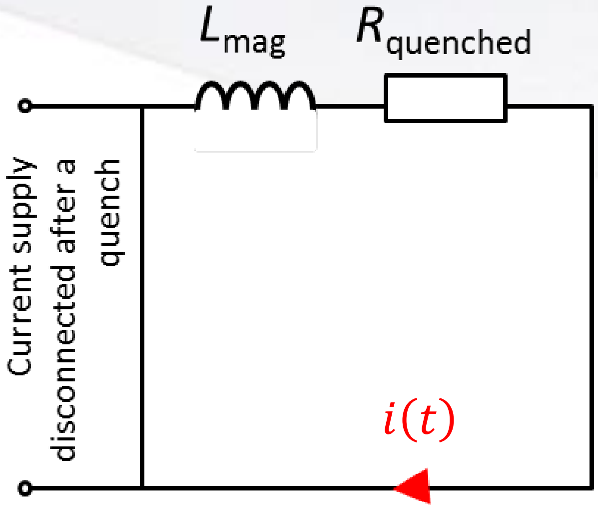
Figure: Simulation results in a EuroCirCol 16-T-dipole.

Coodi: Code for Current decay analysis based on know protection efficiency

Coodi: Idea

Compute the coil resistance development and current decay after heater activation

Assume a single magnet de-coupled from the circuit



The heater delays and quench propagation velocities are input.

Neglect AC-loss

→ No computation of heat diffusion, fast calculation, good for initial quench analysis

Coodi: Input

Input:

- For each turn:
  - Heater delay, heating station length and period
  - Normal zone propagation velocity (between heating stations)
  - Magnetic field (can read an output file from ROXIE)
  - Cable parameters
  - ”Mutual inductance matrix” for turns

- Magnet length, inductance vs. current (from roxie), operating conditions
- Coil geometry – (coordinates from Roxie field map)

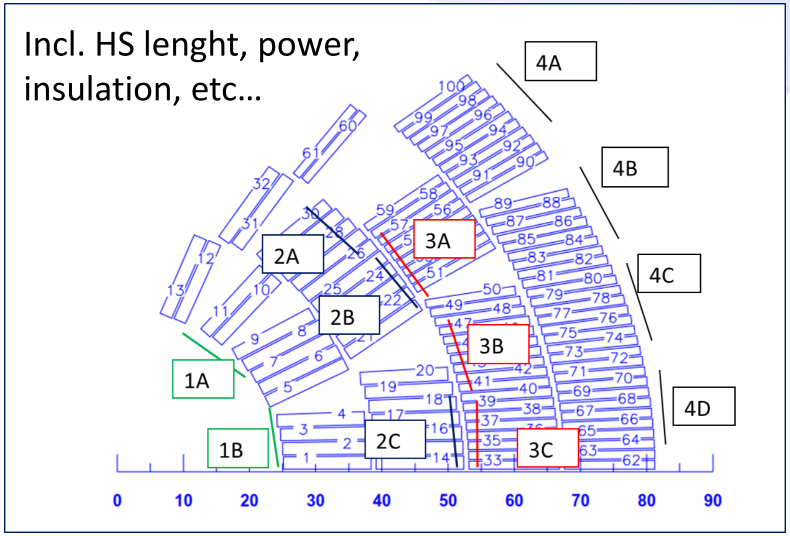
- Initial normal zone length and location
- Detection time, switches delays and external dump resistor

- Coils turns were heaters fail
  - (otherwise all coils are symmetric)

Text file with similar format than for CoHDA

CoHDA+Coodi: Work-flow

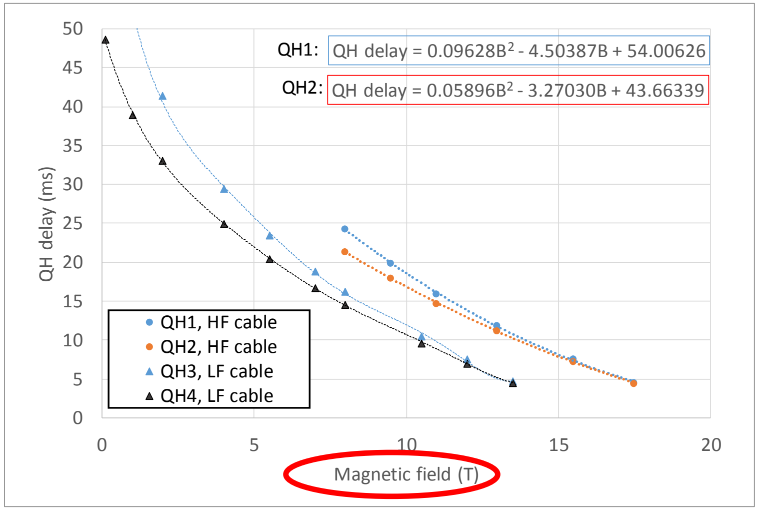
1. Heater design



Incl. HS lenght, power, insulation, etc…

Example of ECC Cosθ, at 105% I_{nom}, with 10 ms turn-to-turn propag., 20 ms det.

With heater delays with CoHDA



2. Heater delays preparation to Coodi

Turn#	QH	B (T)	QH delay (ms)
1	-	16.95	25.4
2	-	16.95	15.4
3	QH1	16.90	5.4
4	QH1	16.78	5.5
5	QH1	16.75	5.6
6	-	16.89	15.6
7	-	16.97	25.3
8	-	17.01	15.3
9	QH1	17.00	5.3
10	QH1	16.89	5.4
11	QH1	16.97	5.3
12	-	16.88	15.3

Note, these are delays under the heating station.

Coodi: Simulation

Input

At each time step, for each turn

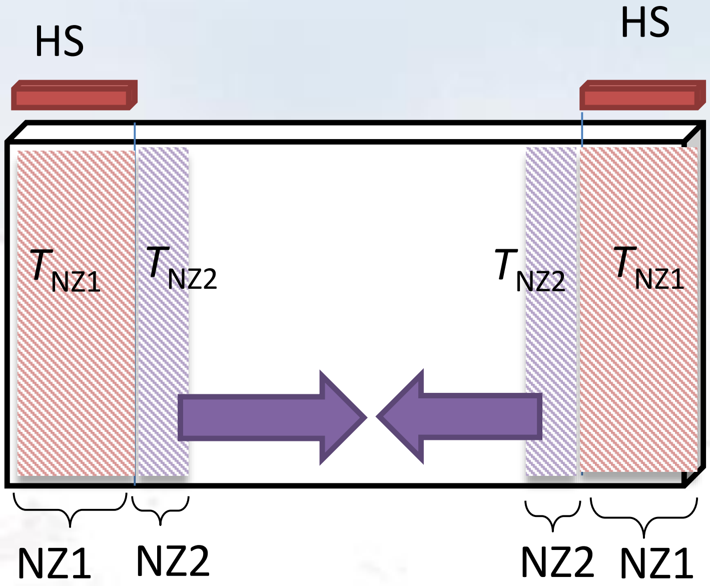
Turn#	B (T)	QH +det. delay (ms)	T (K) Nz1	T (K) Nz2	R (Ω) =R_{NZ1}+ R_{NZ2}	Vres (V)	Vind (V)
1	17.0	55.4					
2	17.0	40.4					
3	16.9	25.4					
4	16.8	25.5					
5	16.8	25.6					
6	16.9	40.6					
…							
INZ (61)	17.0	0.0		-			-

Resistance of the entire magnet:

$$R_{mag}(t) = \sum_{i=1}^{N_{turns}*2} R_i(t) + R_{ext} + R_{INZ}$$

Exponential current decay between each time step

$$I_{mag}(t+\Delta t) = I_{mag}(t) e^{-\Delta t R_{mag}(t)/L(I)}$$



Adiabatic temperature calculation*

$$\Delta T_{NZ} = \frac{I_{mag}^2 \rho_{Cu}}{A_{cable}^2 f_{Cu}} \Delta t \frac{1}{C_v}$$

*While normal front propagating:

$$T_{NZ2} = \frac{1}{2}(T_{NZ1} + T_{cs})$$

Coodi: Output

- Current decay
- Hotspot temperature
- Temperature distribution
- Voltage distribution (max V to gnd, btw turns, btw layers…)

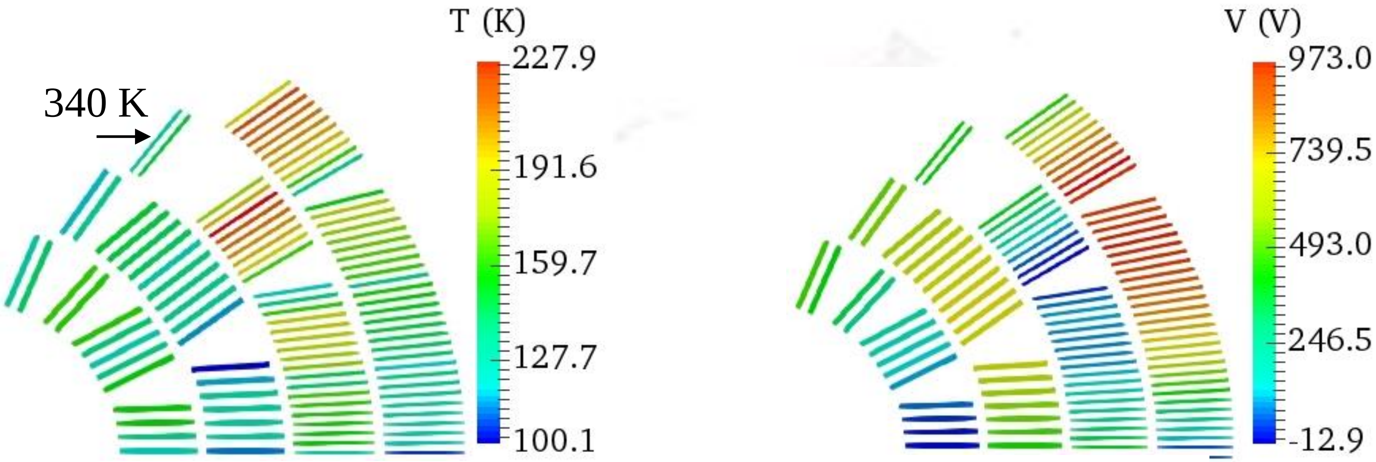
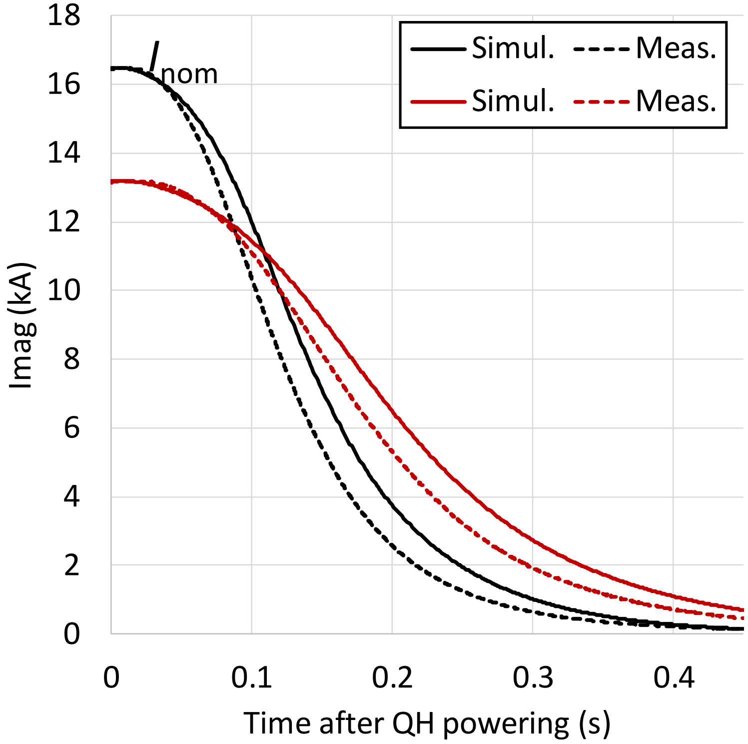


Figure: Simulation results in a EuroCirCol 16-T-dipole.

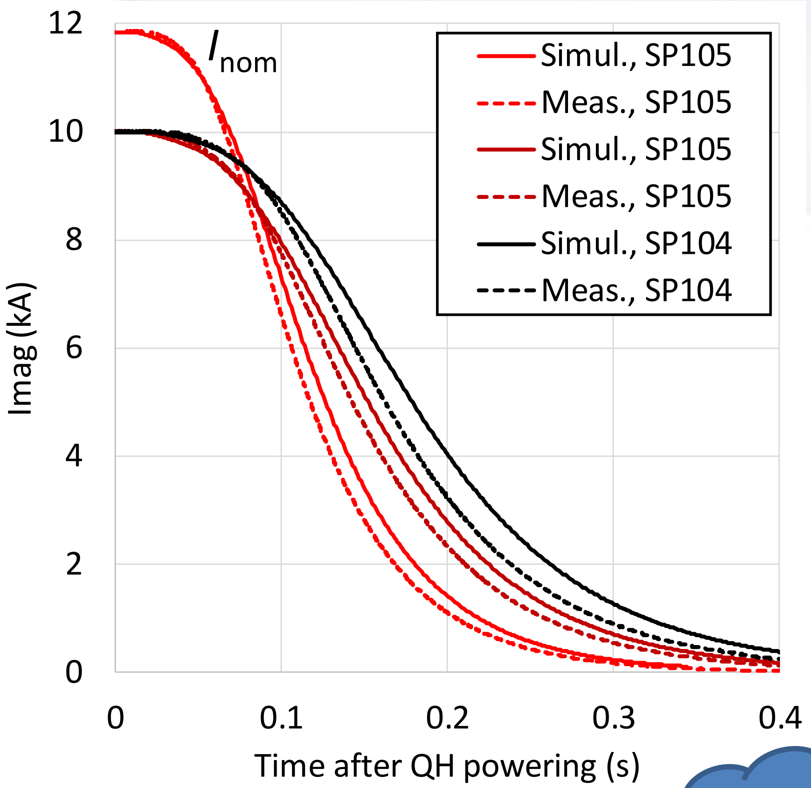
Coodi: Validation

Experimental data from tests at CERN, Thanks to H. Bajas, G. Willering, and S. Izquierdo-Bermudez
In the tests all heaters are fired to induce the current decay. No initial normal zone.

MQXFS03 quadrupole



11 T Dipole



At I_{nom} simulated **MIITs are larger by 7-15%**

In the adiabatic computation translates to 25-40 K

→ Simulated temperatures were 190-240 K

Analysis ongoing.

Coodi: Use

1. Study of the impact of different heater designs

2. Quench analysis for the EuroCirCol dipole option (conceptual design)

3. The computation method also applied into a spreadsheet for magnet designers to get fast-feedback on protectability
   - In the spreadsheet the coil is desicretized in block level, and voltage calculation is not included
   - Estimated average ”heater delay” is provided in advance

Summary

1. Codes for heater delays and current decay
2. Simple, seem to work ok, useful in the first phase of quench analysis
3. Need documentation
4. Missing component: Quench propagation and AC-losses

5. Gladly interface them to the STEAM environment

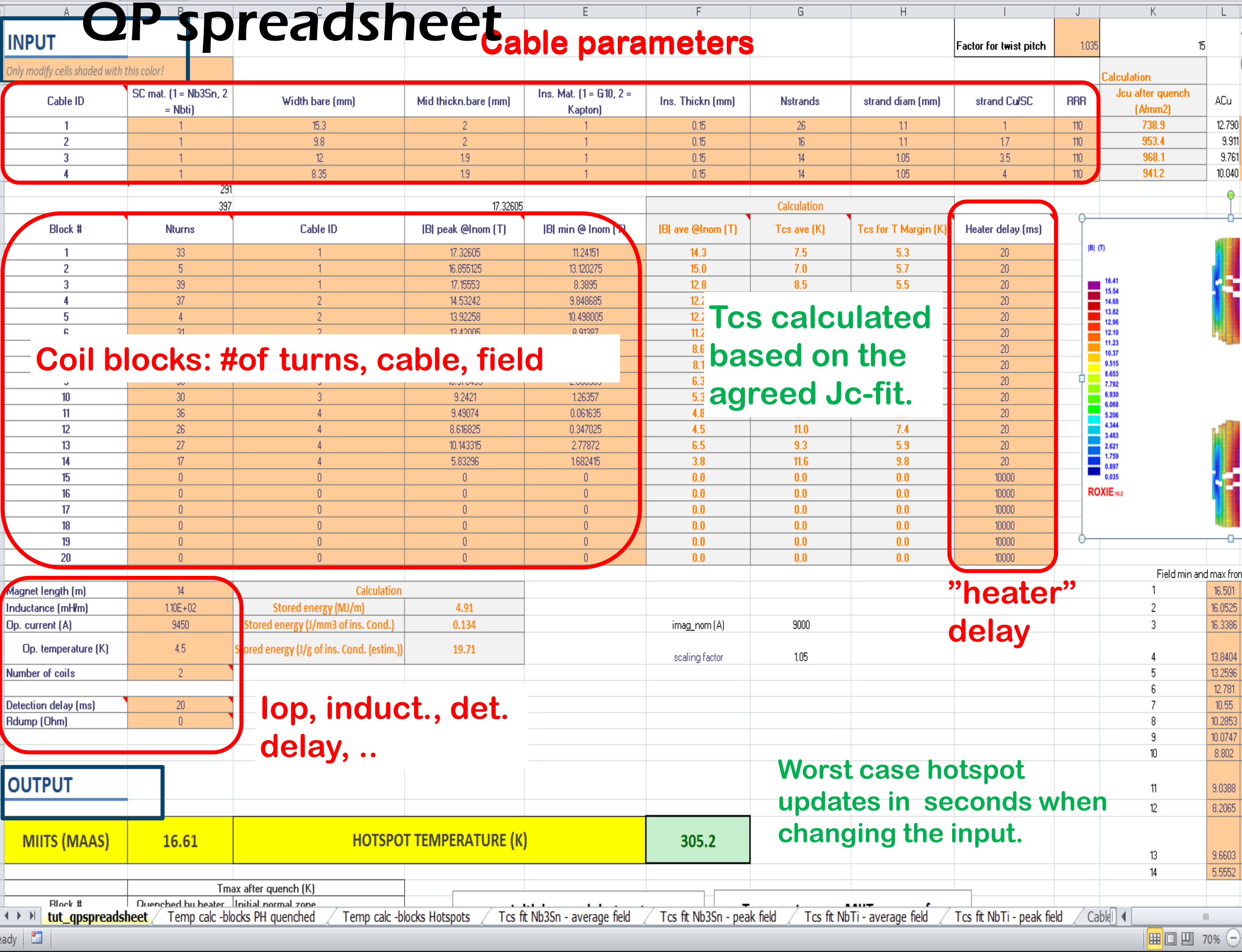
Note: At CERN the CoHDA heater delay model is built with COMSOL (Juho Rysti, Susana Izquierdo-Bermudez). Interesting collaboration?

Thank you.

– *Contact:*
Tiina.salmi@tut.fi

Appendix

QP spreadsheet



INPUT

Only modify cells shaded with this color!

Factor for twist pitch | 1.035 | 15

Cable parameters

Cable ID	SC mat. (1 = Nb3Sn, 2 = Nbti)	Width bare (mm)	Mid thickn.bare (mm)	Ins. Mat. (1 = G10, 2 = Kapton)	Ins. Thickn (mm)	Nstrands	strand diam (mm)	strand Cu/SC	RRR	Calculation Jcu after quench (A/mm2)	ACu
1	1	15.3	2	1	0.15	26	1.1	1	110	738.9	12.790
2	1	9.8	2	1	0.15	16	1.1	1.7	110	953.4	9.911
3	1	12	1.9	1	0.15	14	1.05	3.5	110	968.1	9.761
4	1	8.35	1.9	1	0.15	14	1.05	4	110	941.2	10.040

291

397 17.32605

Block #	Nturns	Cable ID	|B| peak @Inom (T)	|B| min @ Inom (T)	Calculation |B| ave @Inom (T)	Tcs ave (K)	Tcs for T Margin (K)	Heater delay (ms)
1	33	1	17.32605	11.24151	14.3	7.5	5.3	20
2	5	1	16.855125	13.120275	15.0	7.0	5.7	20
3	39	1	17.15553	8.3895	12.8	8.5	5.5	20
4	37	2	14.53242	9.848685	12.	[illegible]	[illegible]	20
5	4	2	13.92258	10.498005	12.	[illegible]	[illegible]	20
6	31	2	13.42005	8.91387	11.2	[illegible]	[illegible]	20
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.6	[illegible]	[illegible]	20
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.1	[illegible]	[illegible]	20
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.3	[illegible]	[illegible]	20
10	30	3	9.2421	1.26357	5.3	[illegible]	[illegible]	20
11	36	4	9.49074	0.061635	4.8	[illegible]	[illegible]	20
12	26	4	8.616825	0.347025	4.5	11.0	7.4	20
13	27	4	10.143315	2.77872	6.5	9.3	5.9	20
14	17	4	5.83296	1.682415	3.8	11.6	9.8	20
15	0	0	0	0	0.0	0.0	0.0	10000
16	0	0	0	0	0.0	0.0	0.0	10000
17	0	0	0	0	0.0	0.0	0.0	10000
18	0	0	0	0	0.0	0.0	0.0	10000
19	0	0	0	0	0.0	0.0	0.0	10000
20	0	0	0	0	0.0	0.0	0.0	10000

Coil blocks: #of turns, cable, field

Tcs calculated based on the agreed Jc-fit.

"heater" delay

Magnet length (m)	14
Inductance (mH/m)	1.10E+02
Op. current (A)	9450
Op. temperature (K)	4.5
Number of coils	2
Detection delay (ms)	20
Rdump (Ohm)	0

Calculation	
Stored energy (MJ/m)	4.91
Stored energy (J/mm3 of ins. Cond.)	0.134
Stored energy (J/g of ins. Cond. (estim.))	19.71

imag_nom (A) 9000

scaling factor 1.05

Iop, induct., det. delay, ..

Field min and max from roxie

1	16.501
2	16.0525
3	16.3386
4	13.8404
5	13.2596
6	12.781
7	10.55
8	10.2853
9	10.0747
10	8.802
11	9.0388
12	8.2065
13	9.6603
14	5.5552

OUTPUT

MIITS (MAAS)	16.61	HOTSPOT TEMPERATURE (K)	305.2

Worst case hotspot updates in seconds when changing the input.

Tmax after quench (K)

Block # | Quenched by heater | Initial normal zone

tut_qpspreadsheet / Temp calc -blocks PH quenched / Temp calc -blocks Hotspots / Tcs fit Nb3Sn - average field / Tcs fit Nb3Sn - peak field / Tcs fit NbTi - average field / Tcs fit NbTi - peak field / Cable

eady 70%

Coodi: Voltage calculation 1

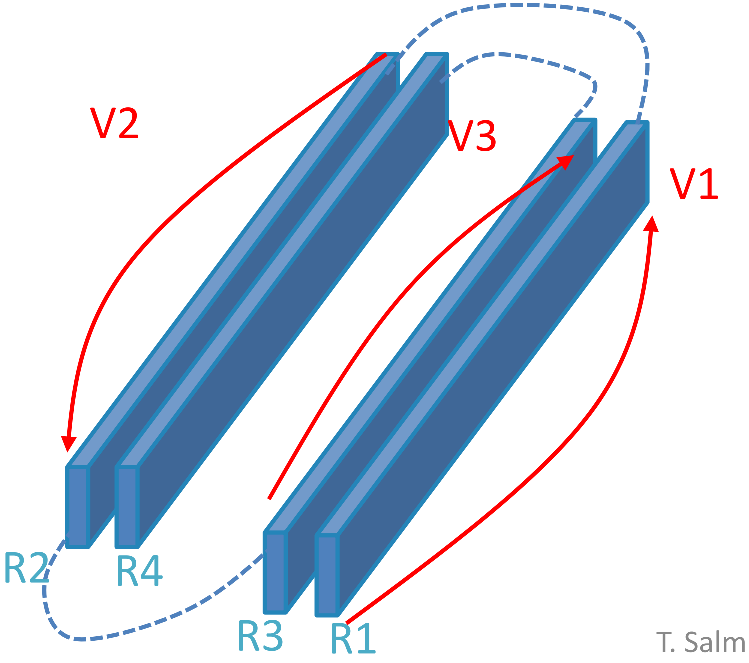
Turn voltages computed based on Ohms law.

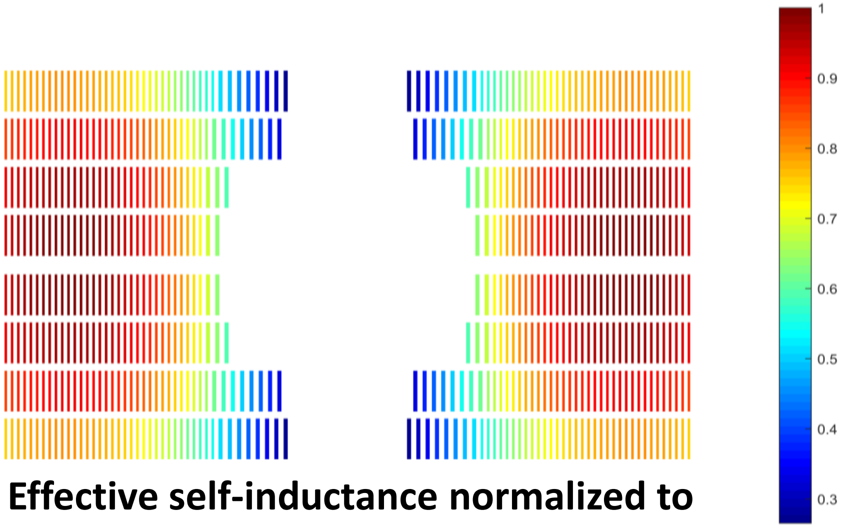
Distribution of the inductive voltage among turns based on ”mutual inductance matrix”.

$$V_i = V_{res,i} + V_{ind,i}$$

$$V_{res,i} = R_i I_{mag}$$

$$V_{ind,i} = L_{eff,i} \frac{\Delta I_{mag}}{\Delta t}$$

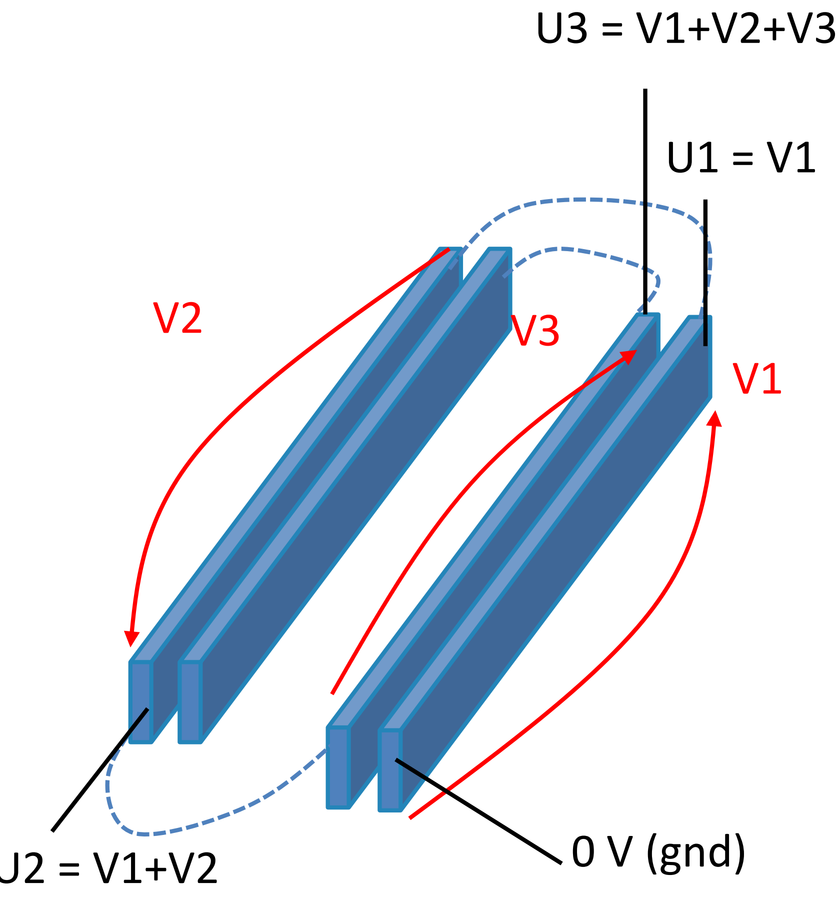


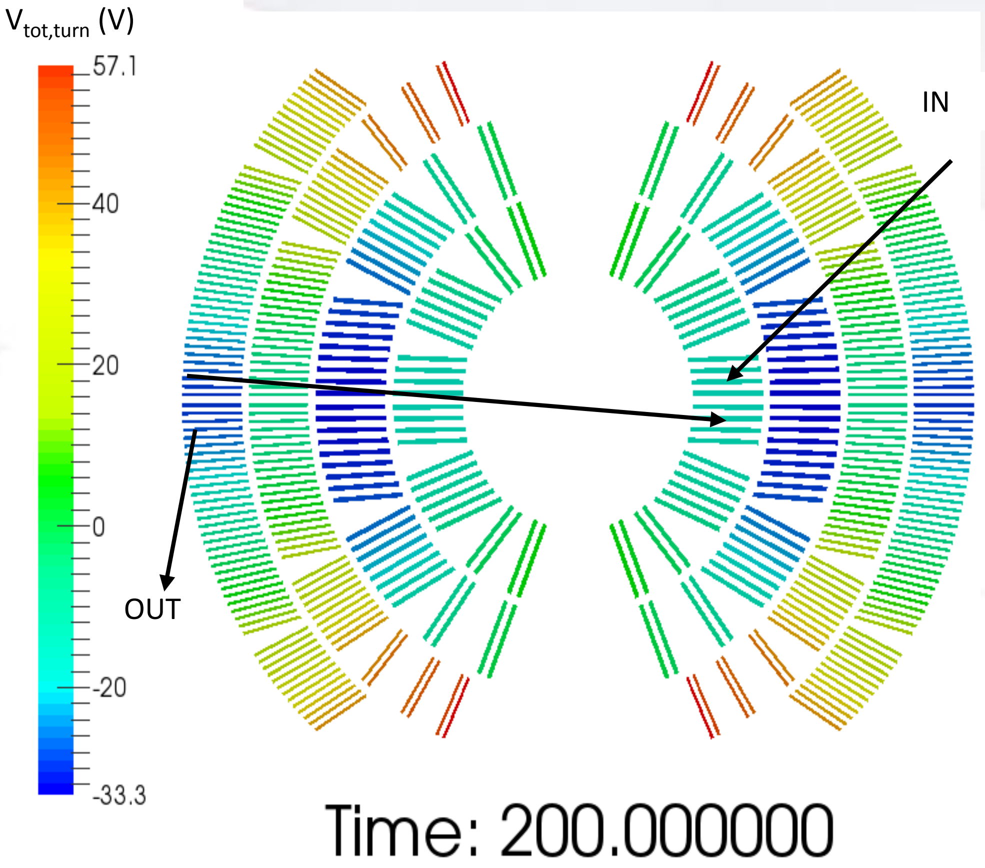


Effective self-inductance normalized to the maximum one

Coodi: Voltage calculation 2

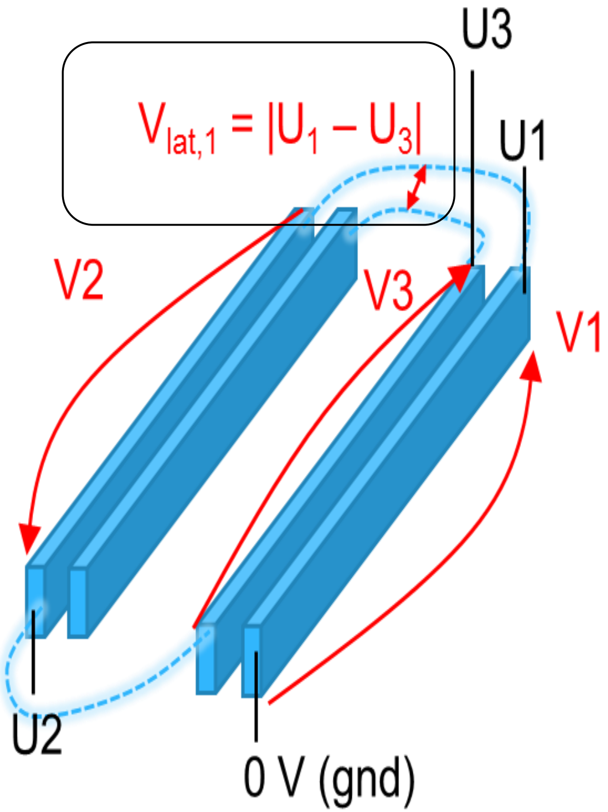
- Potential to ground is obtained by summing the turn voltages (in the order of current flow).



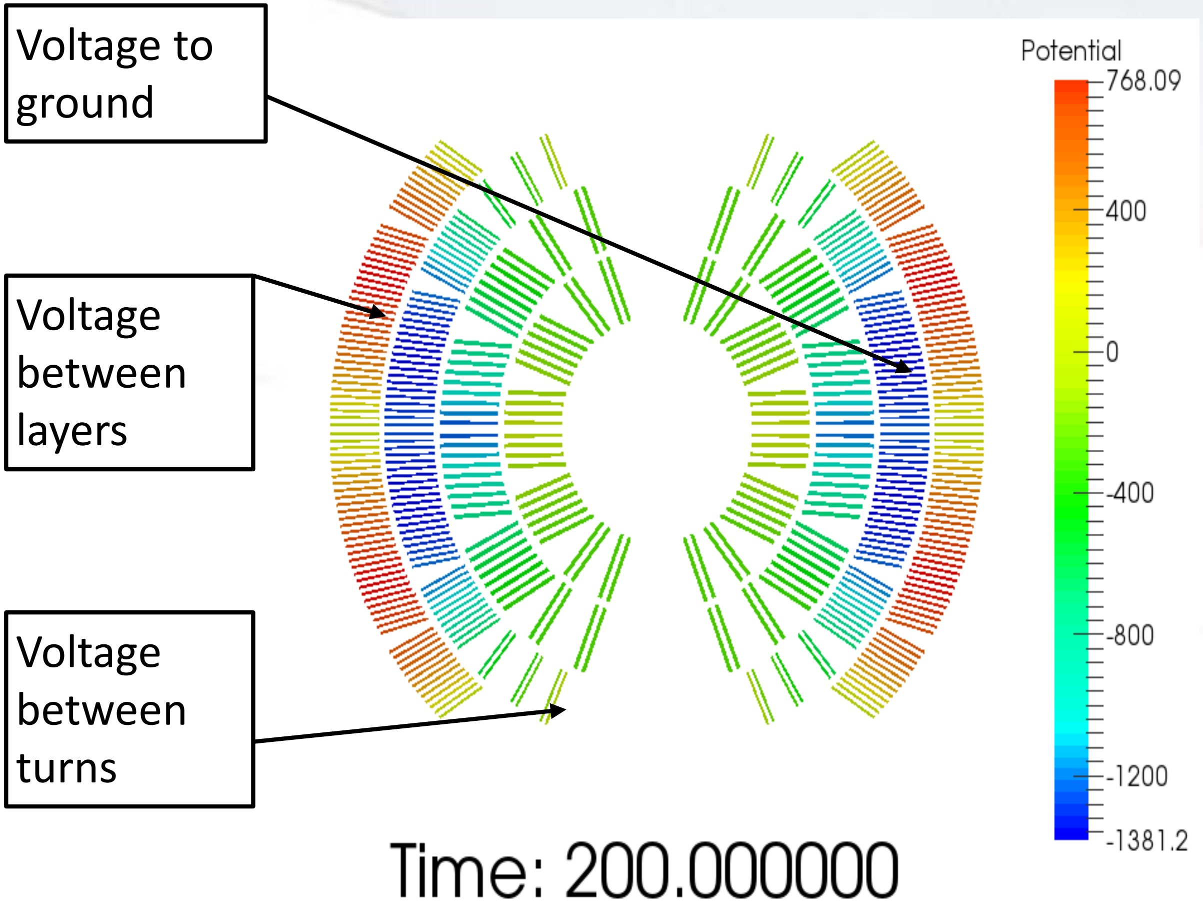


Coodi: Voltage calculation 3

- Critical peak values are defined from the potential:



$V_{lat,1} = |U_1 - U_3|$

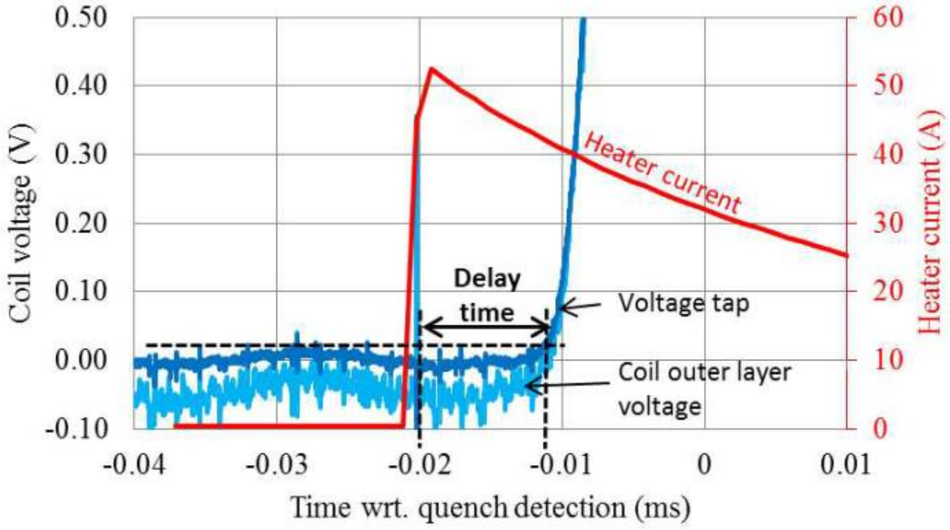


Voltage to ground

Voltage between layers

Voltage between turns

Experimental heater delay measurement



LARP HQ01 outer layer heater delay measurement at 14 kA, and 1.9 K (quench ID qh088)

1. Magnet current constant
2. Fire one heater strip
3. Wait for quench to initiate
4. Let the quench propagation trigger the protection (excluding the heater that is already fired)
5. Determine heater delay from voltage tap signals

- The quench onset usually clear at high current but at low current the rise is slower and the onset less clear

HOSTED: Adaptive Hybrid Code for The Study of Quench Protection of Superconducting Devices

- New, still evolving, code has resulted from our research on combining adaptive meshing to front-tracking
-
- Assumes isothermal cable cross-section
- Propagation along turns is modelled with finite element method (1-D)
- Turn-to-turn propagation is modelled with finite difference method (no need to represent complex modelling domains, only connections between points of lines)
- Adaptive meshing taking advantage of the front-tracking is under development
- Solves only for the heat diffusion equation and circuit model, magnet flux density distribution etc is input, AC-losses are not computed