# *Quench protection of the 16T dipoles for the FCC*

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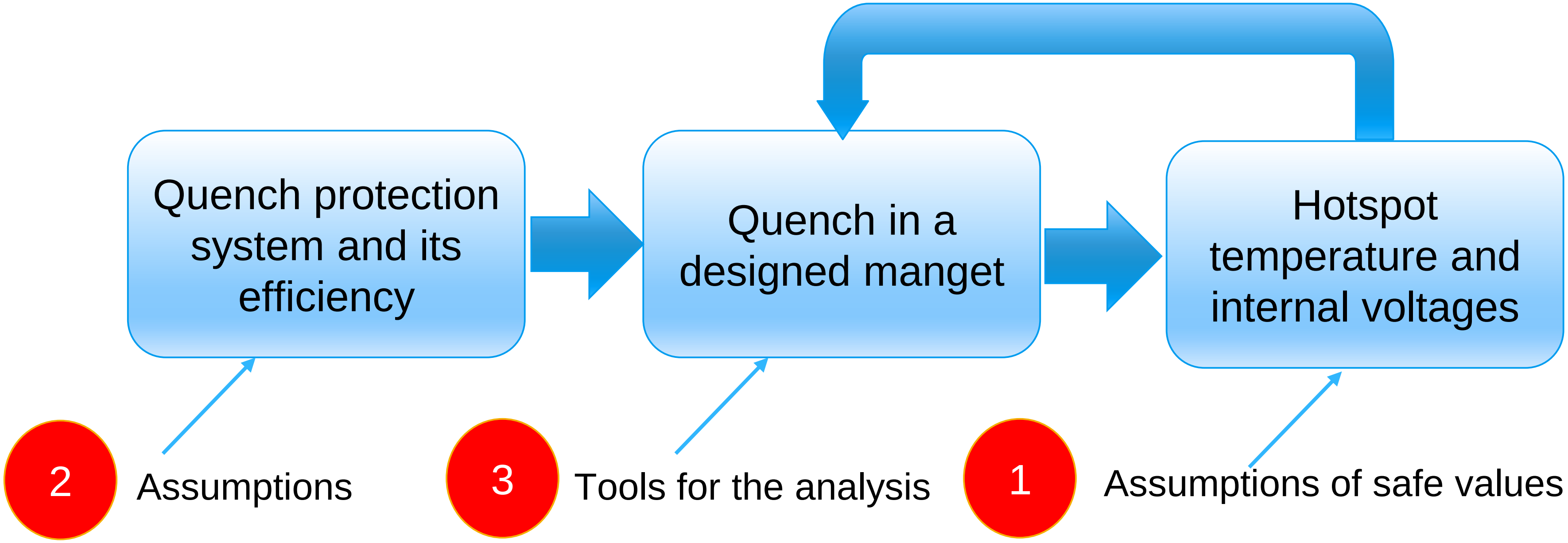
# How to design 16 T dipoles that can be protected? And keep the magnets as compact as possible.

## Quench protection analysis was integrated into the magnet design:



Quench protection system and its efficiency

Quench in a designed manget

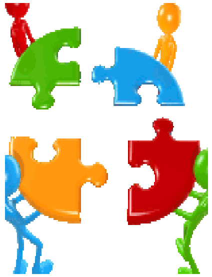
Hotspot temperature and internal voltages

2 Assumptions

3 Tools for the analysis

1 Assumptions of safe values

**The designed magnet is not impossible to protect** 4



# 1. Assumptions about the safe temperatures and voltages

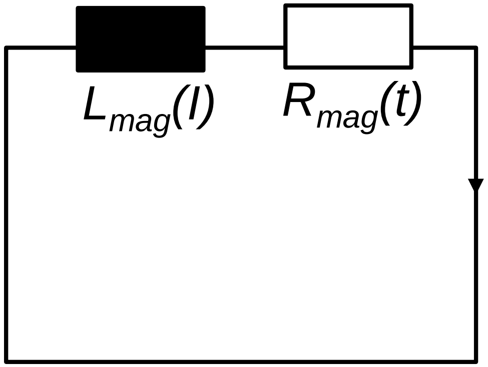
- **Maximum allowed hotspot temperature: 350 K**
  - Same reference than HiLumi
  - For justification, see G. Ambrosio, WAMSDO 2013

- **Maximum voltages inside the coil: 2 kV**
  - Design choice, based on insulation thickness .

# 2. Assumptions about the protection system

- **Quench detection by measurement the resistive voltage**
    - Assumed detection delay = 20 ms (based on the LHC)

- **Quenching magnet by-passed using a diode, like in LHC:**



$$I_{mag}(t) = I_0 e^{-\frac{t}{\tau}}$$

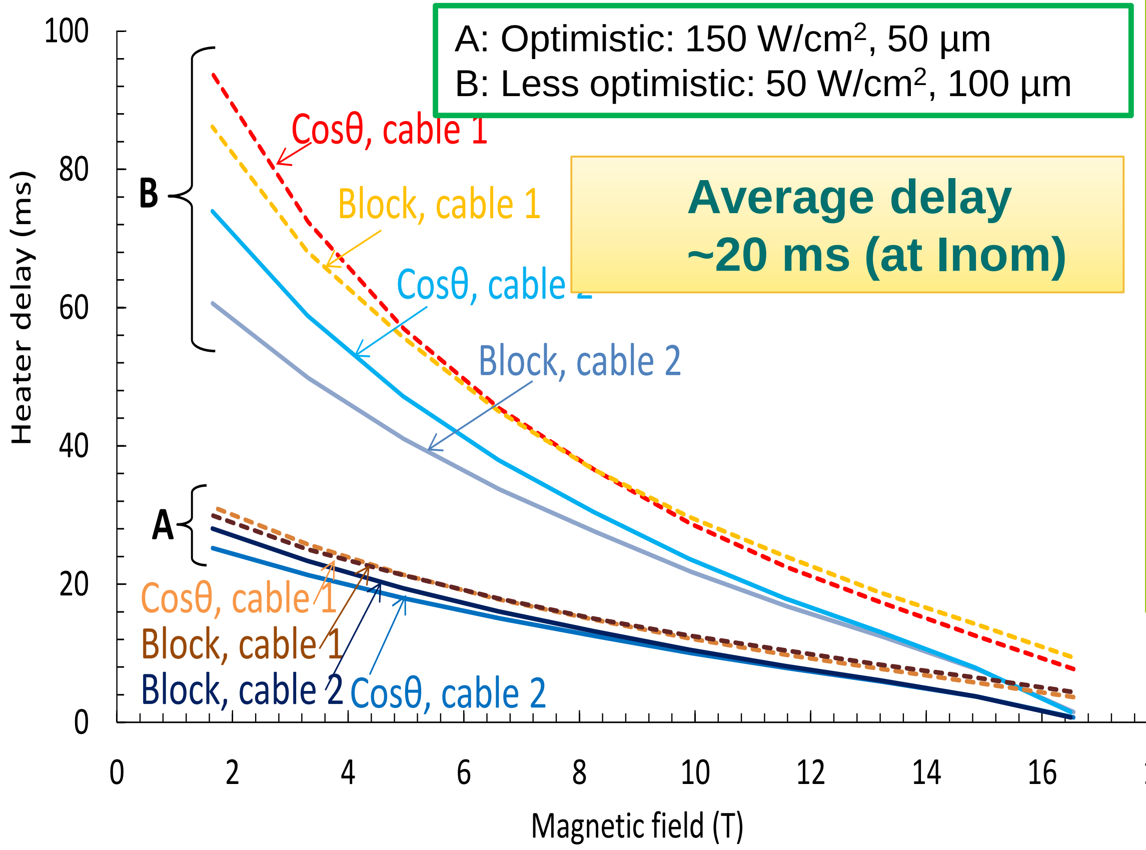
$$\tau(t) = R_{mag}(t)/L_{mag}$$

- **Protection by either quench heaters or/and CLIQ, which quench the coil and drive the current decay**
    - Quench delay estimated based on HiLumi technologies

# 2. Obtainable quench delay

- **Assuming HiLumi heater technology applied to FCC dipole**
    - ✦ Assumed improvement: All coil surface can be covered

*Example of heater delay simulations using CoHDA*



A: Optimistic: 150 W/cm$^2$, 50 µm
B: Less optimistic: 50 W/cm$^2$, 100 µm

**Average delay ~20 ms (at Inom)**

**The design requirement: If the magnet is completely resistive 40 ms after the initial quench, the peak temperature must stay below 350 K at 105% of Iop**

Preliminary analysis of CLIQ suggests ~similar value (Marco Prioli)

# 3. Methods and tools for quench analysis

## Two new tools developed for fast feedback during the magnet design

- ”Temperature calculation work sheet” and ”Coodi”

## Adiabatic temperature calculation:

Cable temp. Increase during a time step (in K)

The heating energy during one time step (in J/m$^3$)

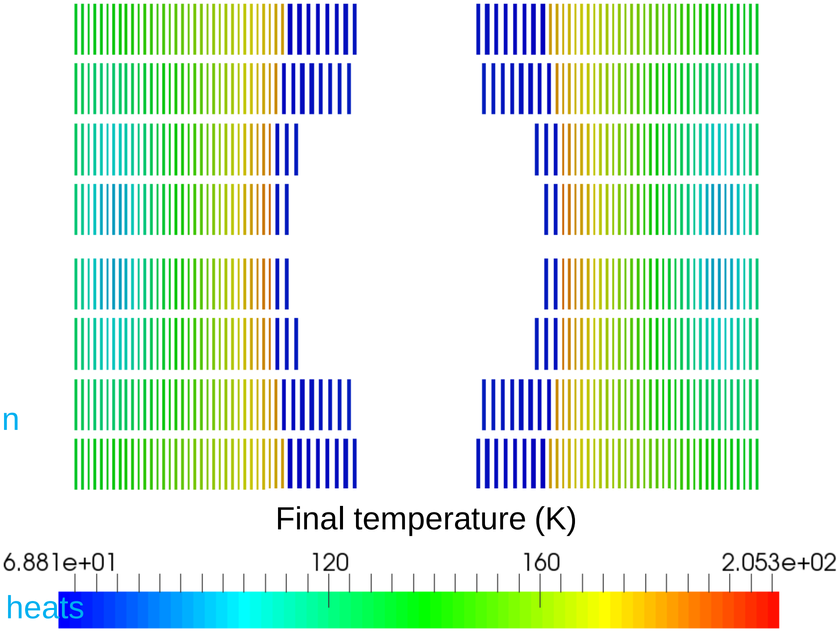
$$\Delta T = \overbrace{\underbrace{\frac{I_{mag}^2 \rho_{Cu}}{A^2{}_{cable} \, f_{Cu}}} \Delta t} \underbrace{\frac{1}{C_v}}$$

The heating power when all Imag flows in Cu

Cable specific heat (in J/(Km$^3$))

Cable current moves from SC to Cu at the time instant of ”det + protection delay” (input)

Cu resistivity and specific heats depend on cable temperature and field.



# 3. Calculation of voltages

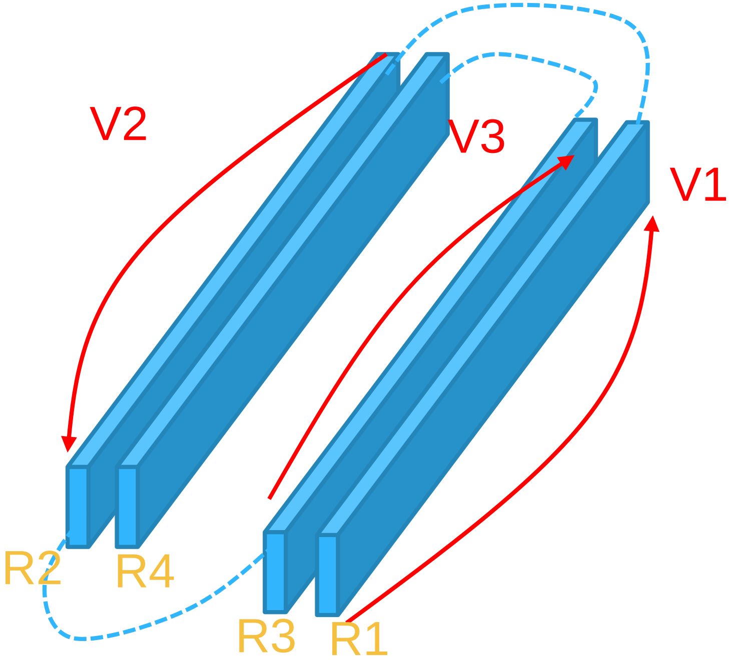
## 1. Total voltage computed is at each turn:

A sum of resistive and inductive component.

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

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

The turn resistance is based on the Cu resistivity and area and turn length.

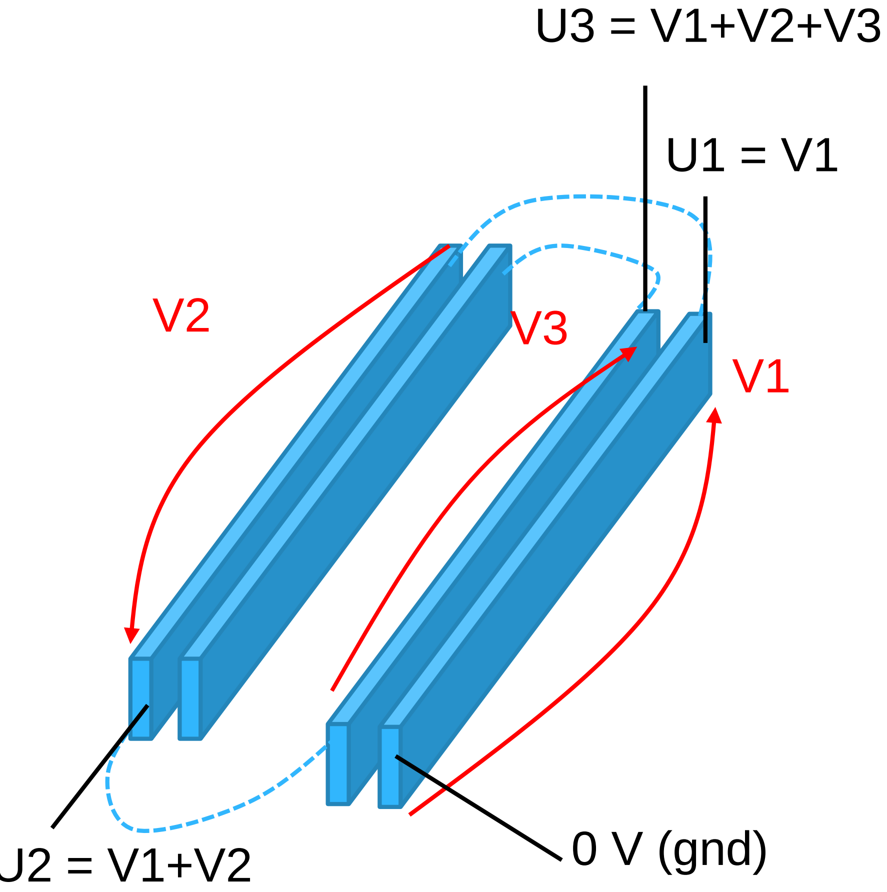


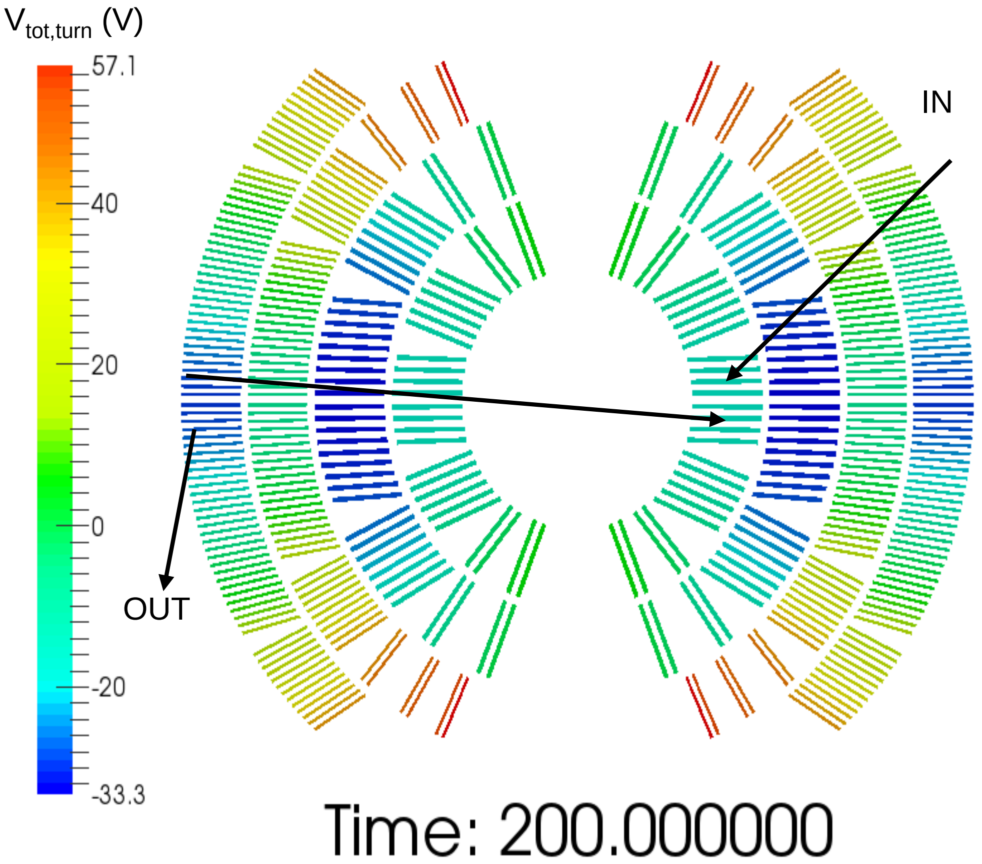
$$\boxed{V_{ind,i} = L_{eff,i} \frac{\Delta I_{mag}}{\Delta t}}$$

The ”effective inductance” accounts the turn self inductance and the mutual inductances with the other turns.

# 3. Calculation of voltages

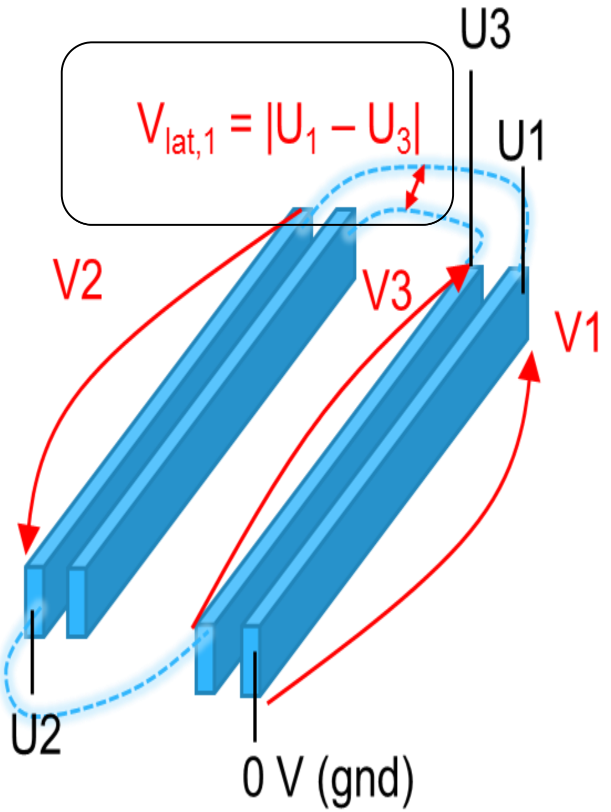
**2. Potential to ground is obtained by summing the turn voltages (in the order of current flow).**

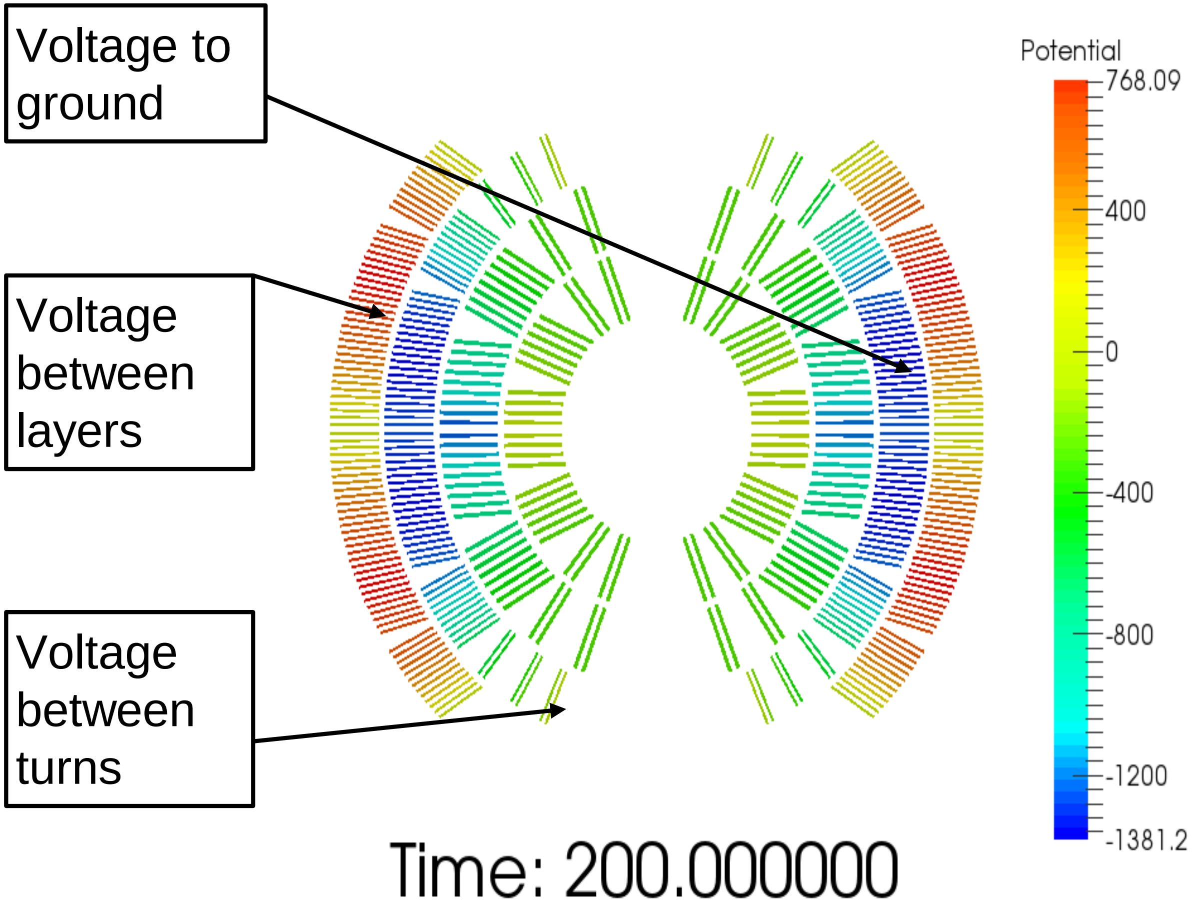




# 3. Calculation of voltages

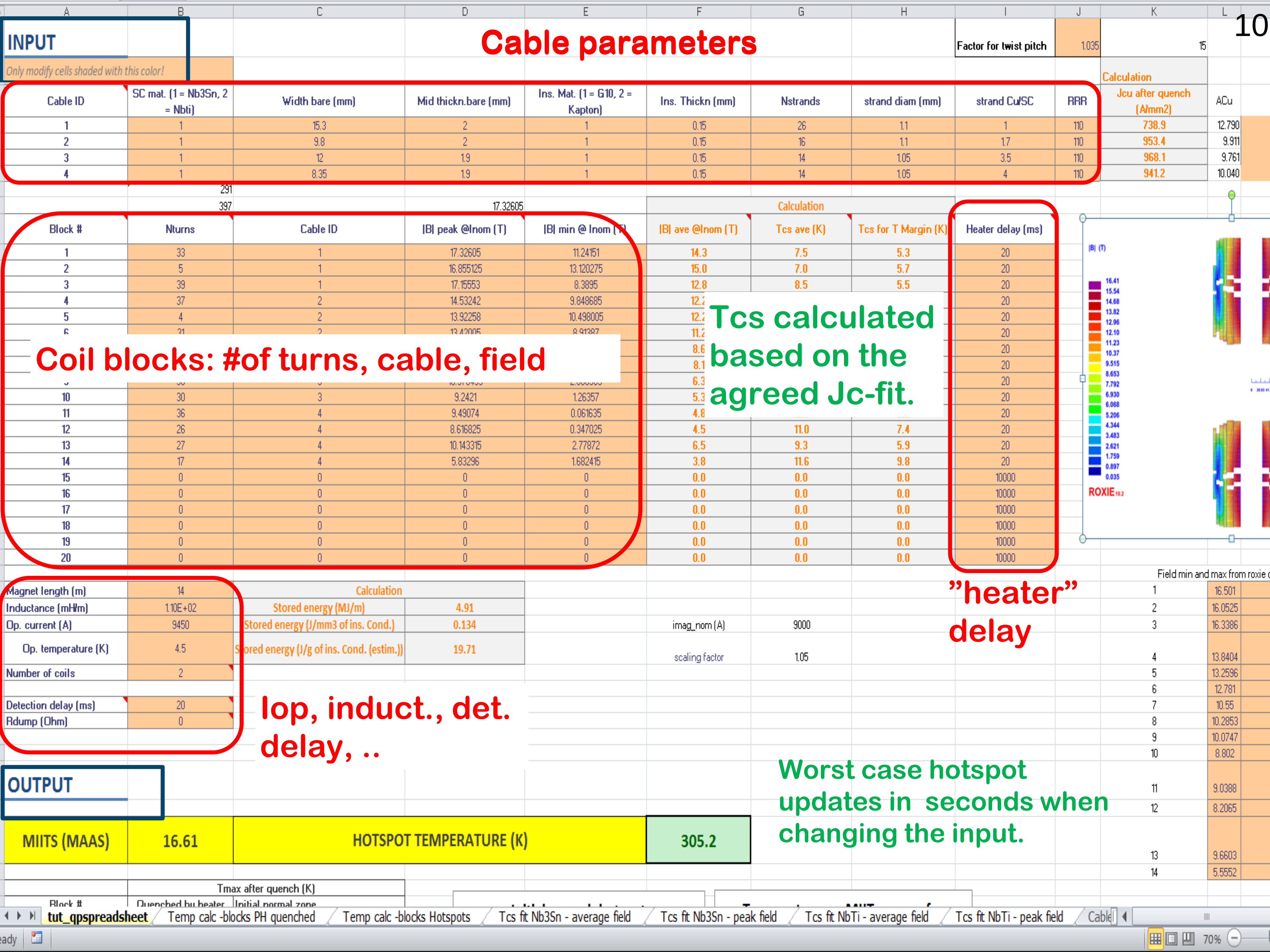
## 3. Critical peak values are defined from the potential:




Voltage to ground

Voltage between layers

Voltage between turns



## Cable parameters

**INPUT**

*Only modify cells shaded with this color!*

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Factor for twist pitch | 1.035 |

| 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 | 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 |

Calculation

15

291

397 17.32605

Coil blocks: #of turns, cable, field

Tcs calculated based on the agreed Jc-fit.

| Block # | Nturns | Cable ID | \|B\| peak @Inom (T) | \|B\| min @ Inom (T) | \|B\| ave @Inom (T) | Tcs ave (K) | Tcs for T Margin (K) | Heater delay (ms) |
|---|---|---|---|---|---|---|---|---|
| | | | | | Calculation | | | |
| 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 | 12.2 | | | 20 |
| 5 | 4 | 2 | 13.92258 | 10.498005 | 12.2 | | | 20 |
| 6 | 31 | 2 | 13.42005 | 8.91387 | 11.2 | | | 20 |
| | | | | | 8.6 | | | 20 |
| | | | | | 8.1 | | | 20 |
| | | | | | 6.3 | | | 20 |
| 10 | 30 | 3 | 9.2421 | 1.26357 | 5.3 | | | 20 |
| 11 | 36 | 4 | 9.49074 | 0.061635 | 4.8 | | | 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 |

"heater" delay

| | | Calculation | |
|---|---|---|---|
| Magnet length (m) | 14 | | |
| Inductance (mH/m) | 1.10E+02 | Stored energy (MJ/m) | 4.91 |
| Op. current (A) | 9450 | Stored energy (J/mm3 of ins. Cond.) | 0.134 |
| Op. temperature (K) | 4.5 | Stored energy (J/g of ins. Cond. (estim.)) | 19.71 |
| Number of coils | 2 | | |
| Detection delay (ms) | 20 | | |
| Rdump (Ohm) | 0 | | |

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.

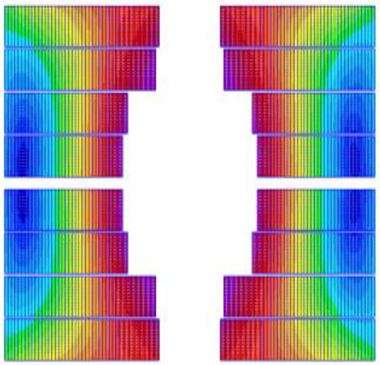
| Block # | Tmax after quench (K) | |
|---|---|---|
| | Quenched by heater | Initial normal zone |

# 4. Analysis of the designed magnets

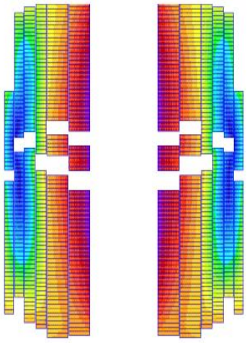
| **Design, cable** | **$A_{ins.}$ ($mm^2$)** | **$f_{Cu}$** | **$F_{Nb3Sn}$** | **$f_{G10}$** |
|---|---|---|---|---|
| Block, 1 (HF) | 32.5 | 0.36 | 0.36 | 0.27 |
| Block, 2 (LF) | 21.9 | 0.34 | 0.34 | 0.33 |
| Cosθ, 1 (HF) | 38.0 | 0.36 | 0.36 | 0.28 |
| Cosθ, 2 (LF) | 22.4 | 0.45 | 0.22 | 0.32 |
| CC, 1 (HF) | 33.9 | 0.36 | 0.36 | 0.29 |
| CC, 2 (HMF) | 23.2 | 0.43 | 0.25 | 0.32 |
| CC, 3 (LMF) | 19.0 | 0.51 | 0.15 | 0.34 |
| CC, 4 (LF) | 19.0 | 0.53 | 0.13 | 0.34 |

|  | **$I_{mag,nom}$ (A)** | **L (mH/m)** |
|---|---|---|
| Block | 8440 | 42.5 x 2 |
| Cosθ | 10275 | 26.0 |
| CommonC | 9000 | 110 |

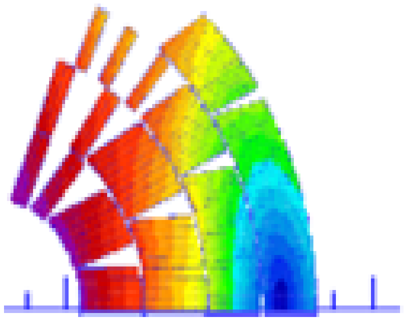
Block
(v26_b)

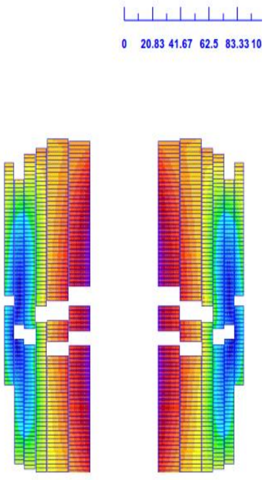


CommonC
(v1h_intragrad_t2)



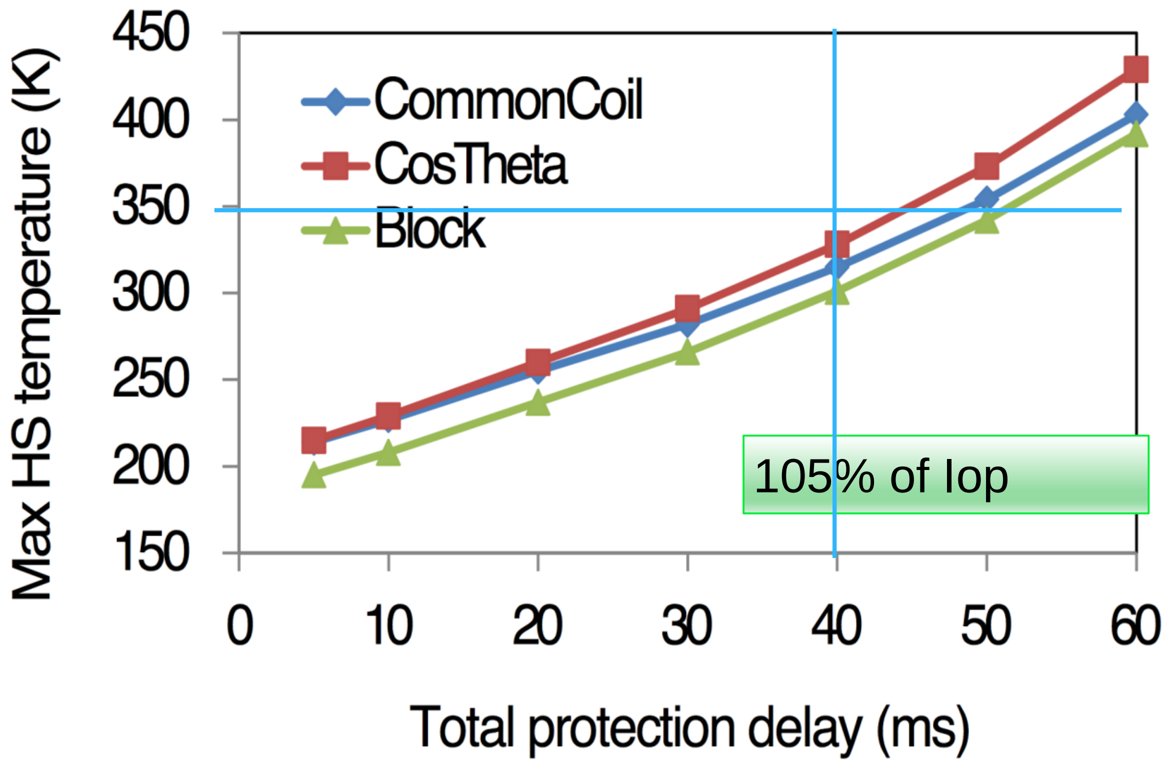
CosT
(16T_v28b-38-opt5d)





# 4. Simulated hotspot temperatures assuming uniform protection delay

- **All the coil resistive after the protection delay**
  - Assume worst-case location for hotspot



105% of Iop

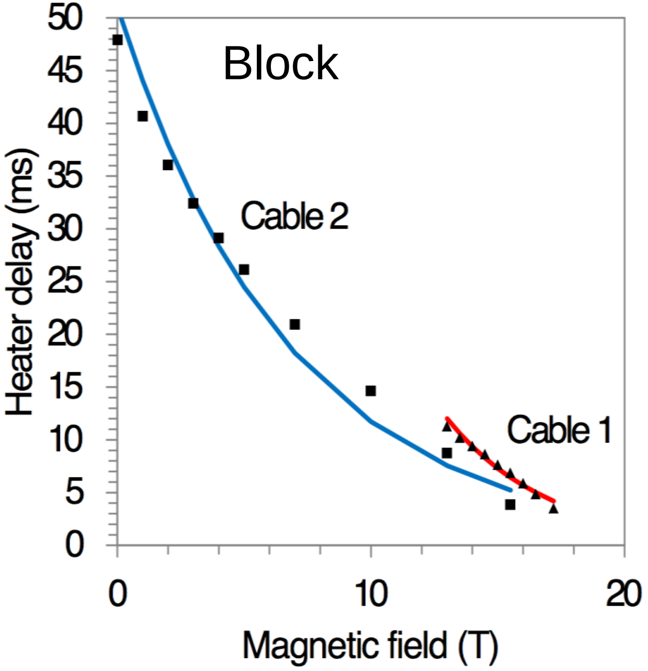
All designs valid from hotspot temperature point of view (< 350 K with 40 ms protection delay).

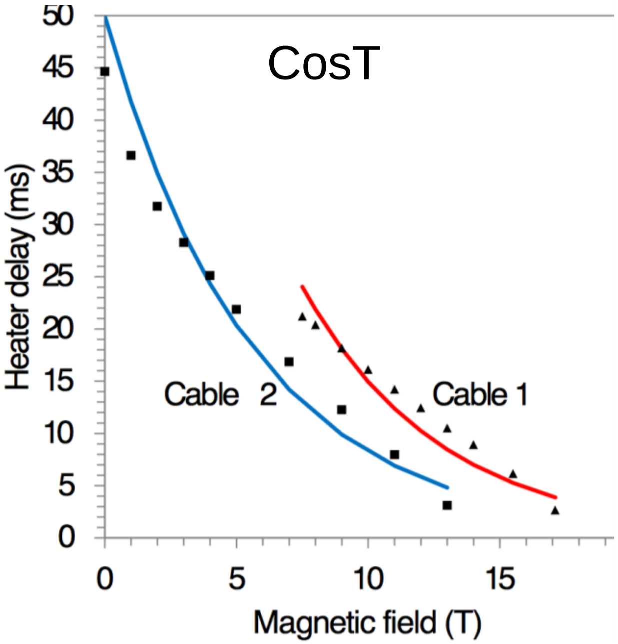
# 4. Simulation with distributed heater delays

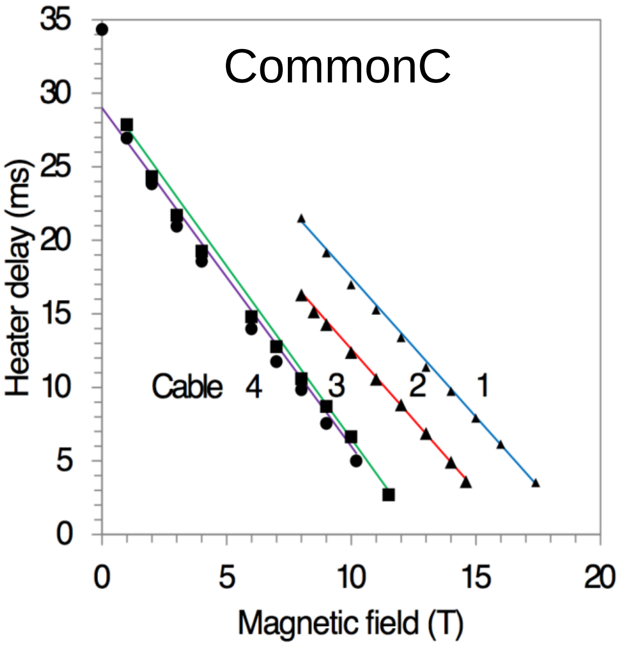
- **Heater delay simulation assuming**
  - ✦ 25 um thick stainless steel heaters with 75 um polyimide insulation to coil
  - ✦ Peak power 100 W/cm$^2$, circuit time constant 50 ms
  - ✦ Heaters cover all the coil turns entirely

105% of Iop (4.5 K)

First heater delays 3-4 ms in all magnets







# 4. Results at 105% of Iop

Temperatures OK!

Tdelay = 40 ms

| | T max (K) | V to gnd (kV) | V turn-to-turn (V) | V layer-to-layer (kV) |
|---|---|---|---|---|
| Block | 308 | -1.2 …+1.2 | 82 | 1.1 |
| CosT | 328 | -1.4 … 0.4 | 103 | 1.8 |
| CommonC | 315 | -2.3 … 1.4 | 75 | 3.3 |

But voltages are large… Analysis ongoing.

Distributed heater delays (+ detection 20 ms)

| | T max (K) | \|V\| to gnd (kV) | V turn-to-turn (V) | V layer-to-layer (V) |
|---|---|---|---|---|
| Block | 291 | 1.6 | 107 | 1.6 |
| CosT | 305 | 1.4 | 123 | 2.2 |
| CommonC | 293 | 2.7 | 93 | 4.1 |

# Conclusion

- **Integrated quench protection analysis applied to 16 T dipole design**
  - ✦ Goal was to ensure temperatures stay < 350 K
  - ✦ The protection efficiency, 40 ms delay, was based on LHC and HiLumi experience and foreseeable improvements in the technology
  - ✦ Goal was obtained by fast feedback loop and team work

- **Voltages need more analysis**

- **During the magnet design phase focus was on nominal cases to ensure it is not impossible to protect**
  - ✦ Future analysis includes more details and failure scenarios

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