Quench protection of the 16T dipoles for the FCC

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In collaboration with EuroCirCol wp 5 members (CERN, CEA, INFN, CIEMAT)

1st EuroCirCol review
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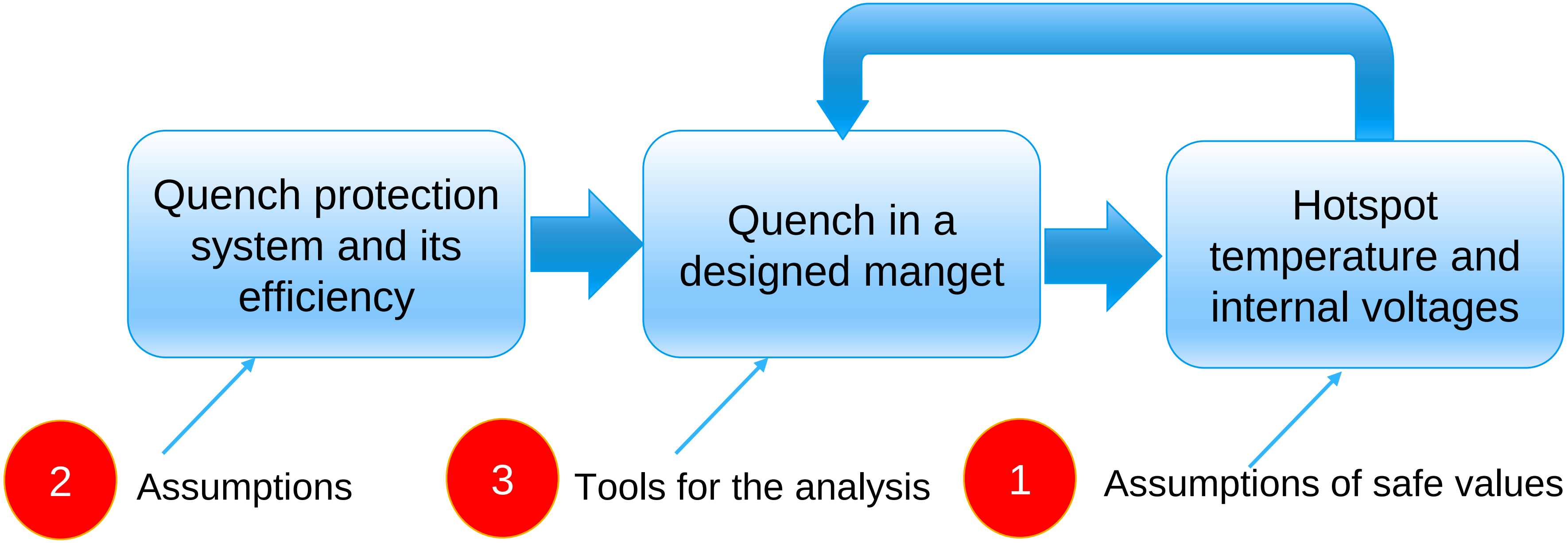
How to design 16 T dipoles that can be protected? And keep the magnets as compact as possible.

Quench protection analysis was integrated into the magnet design:



Quench protection system and its efficiency

Quench in a designed manget

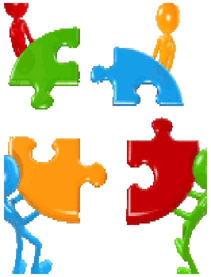
Hotspot temperature and internal voltages

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: Based on experiments with LARP Nb_3Sn magnets, and epoxy transition temperature (~380 K).

    Note: Need more experiments with cored cables to confirm this.

    (G. Ambrosio, WAMSDO 2013.)
  - ✦ Computed from MIITs (adiabatic)

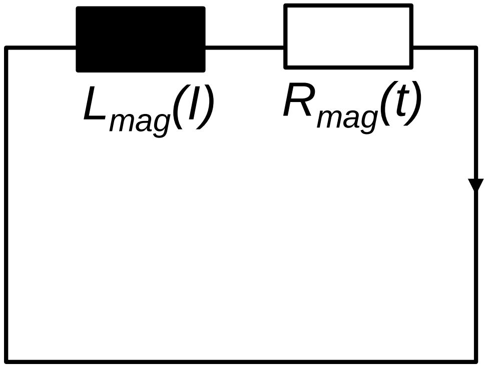
- **Maximum voltages inside the coil: 2 kV**
  - ✦ Design choice, based on insulation thickness .

Impact of thermal gradients still to be analyzed – for now no set limitations

2. Assumptions about the protection system

- **Quench detection by measuring the resistive voltage**
  - Assumed detection delay = 20 ms (includes validation + switches' delay)
  - Based on the LHC experience

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



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

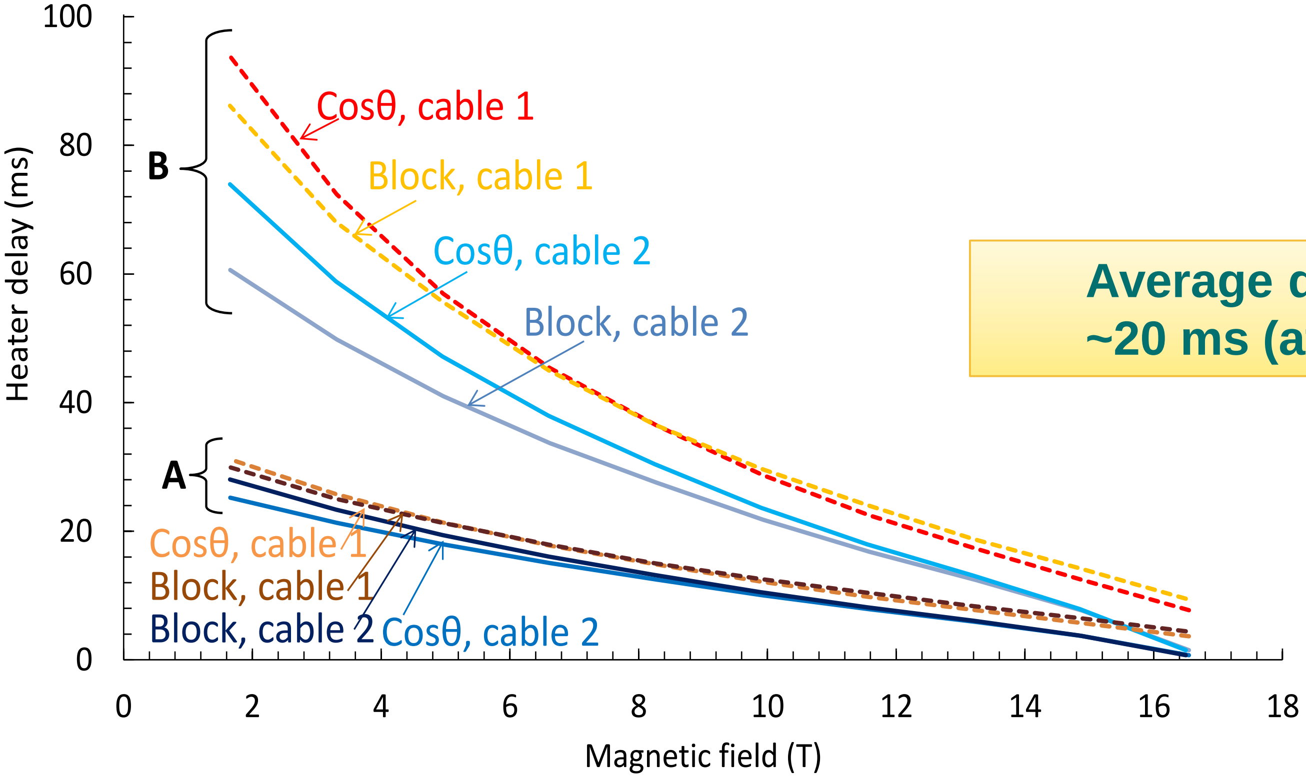
- **Protection by either quench heaters or/and CLIQ, which quench the coil and drive the current decay**
  - Quench delays were estimated based on improved HiLumi heater-technology (to get the first assumption for the protection efficiency)

2. Obtainable quench delay

- **Assuming HiLumi heater technology applied to FCC dipole**
  - Stainless steel strip heaters insulated from the coil by polyimide
  - Assumed improvement: All coil surface can be covered

Heater delay simulations using CoHDA

Case A: Optimistic: 150 W/cm^2 peak power, 50 µm polyimide
Case B: Less optimistic: 50 W/cm^2 peak power, 100 µm polyimide



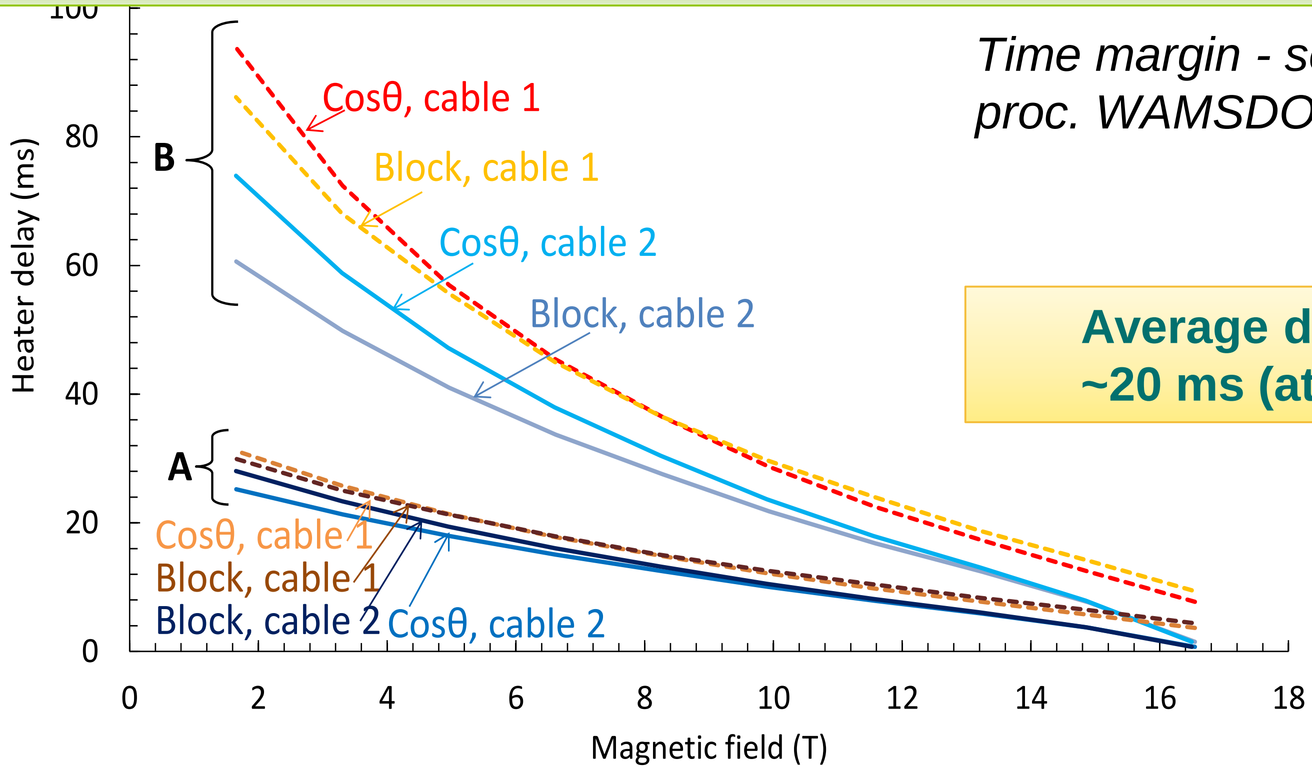
Average delay ~20 ms (at Inom)

2. Obtainable quench delay

- **Assuming HiLumi heater technology applied to FCC dipole**
  - ✦ Stainless steel strip heaters insulated from the coil by polyimide
  - ✦ Assumed improvement: All coil surface can be covered

Heater delay simulations using CoHDA

The design requirement: If the magnet is completely resistive 40 ms after the initial quench, the peak temperature must be below 350 K <u>at 105% of Iop</u>



Time margin - see E. Todesco, proc. WAMSDO 2013

Average delay ~20 ms (at Inom)

3. Methods and tools for quench analysis

Two new tools developed for fast feedback during the magnet design

- ”Temperature calculation work sheet” and ”Coodi”

Both use adiabatic temperature calculation

- In the spreadsheet discretization in block level, in Coodi cable level

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

$$\Delta T = \overbrace{\underbrace{\frac{I^2_{mag}\rho_{Cu}}{A^2{}_{cable}\, f_{Cu}}}_{\text{The heating power when all Imag flows in Cu}} \Delta t}^{\text{The heating energy during one time step (in J/m}^3\text{)}} \underbrace{\frac{1}{C_v}}_{\text{Cable specific heat (in J/(Km}^3\text{))}}$$

- Cable current from SC to Cu at *t* = total protection delay (input)
- Material propersties from NIST (*T* and *B* dependence accounted)
- Cable heat capacity includes the cable insulation and voids (G10)
- No heat diffusion
- Magnetic field map and inductance from ROXIE

3. Calculation of voltages (only in Coodi)

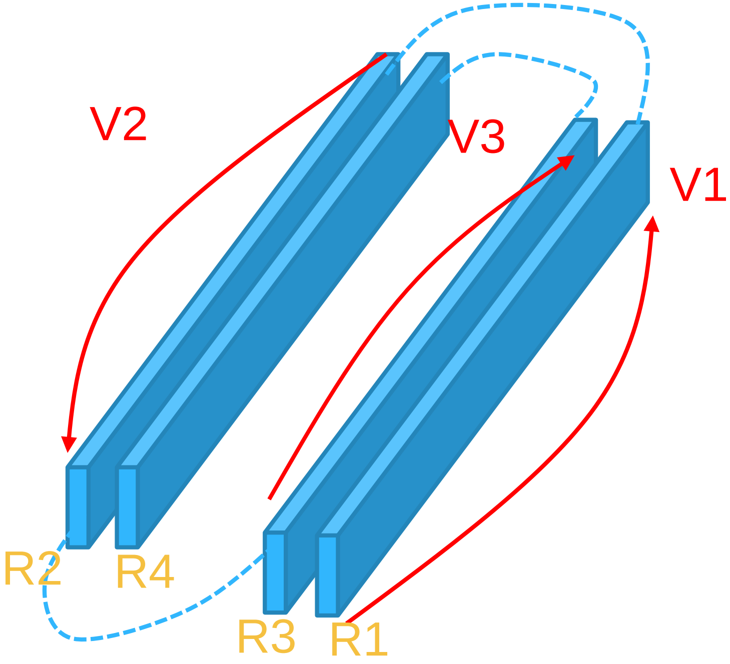
1. Total voltage computed is at each turn:

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.

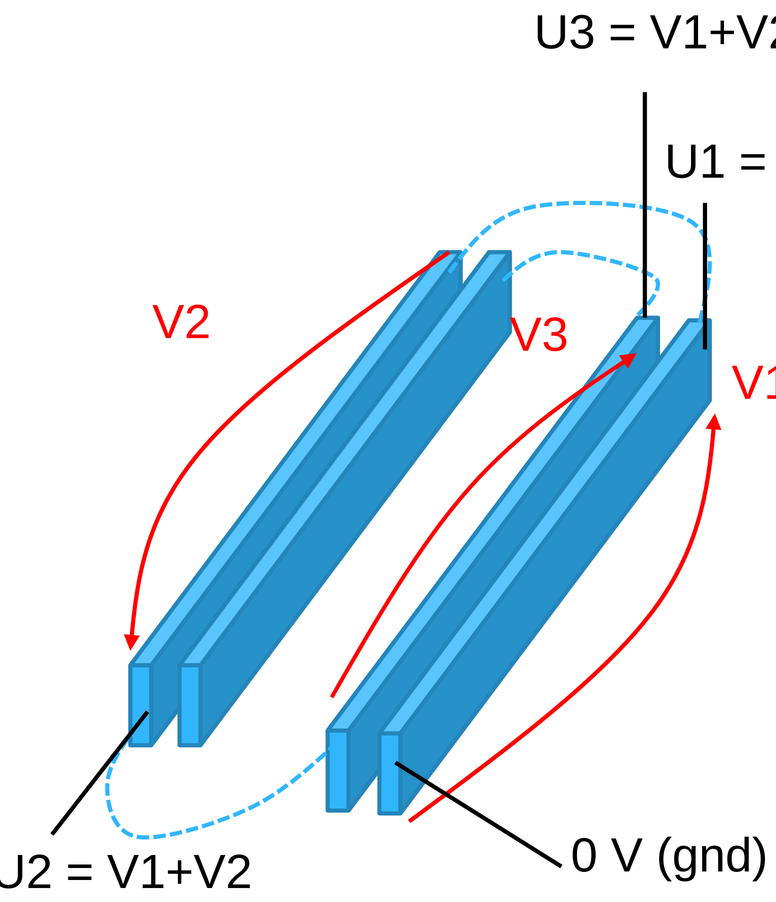


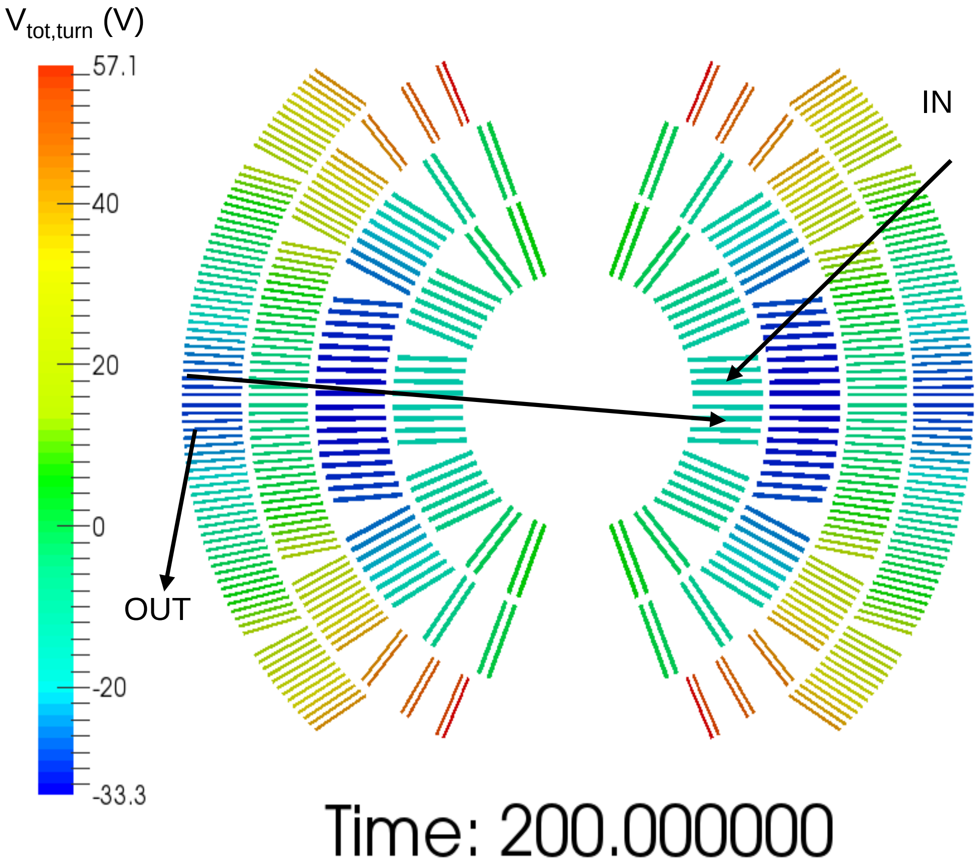
$$\boxed{V_{ind,i} = L_{eff,i} \frac{\Delta I_{mag}}{\Delta t}}$$

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

3. Calculation of voltages (only in Coodi)

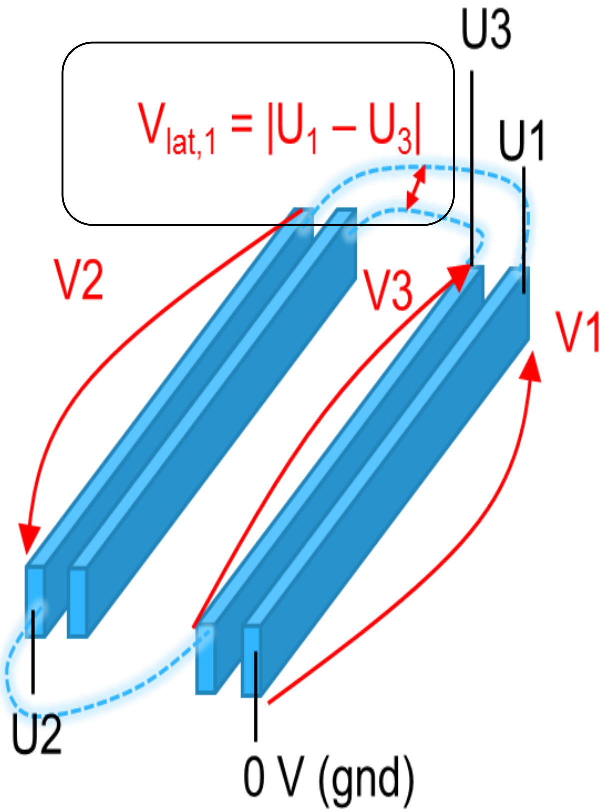
2. Potential to ground is obtained by summing the turn voltages (in the order of current flow).

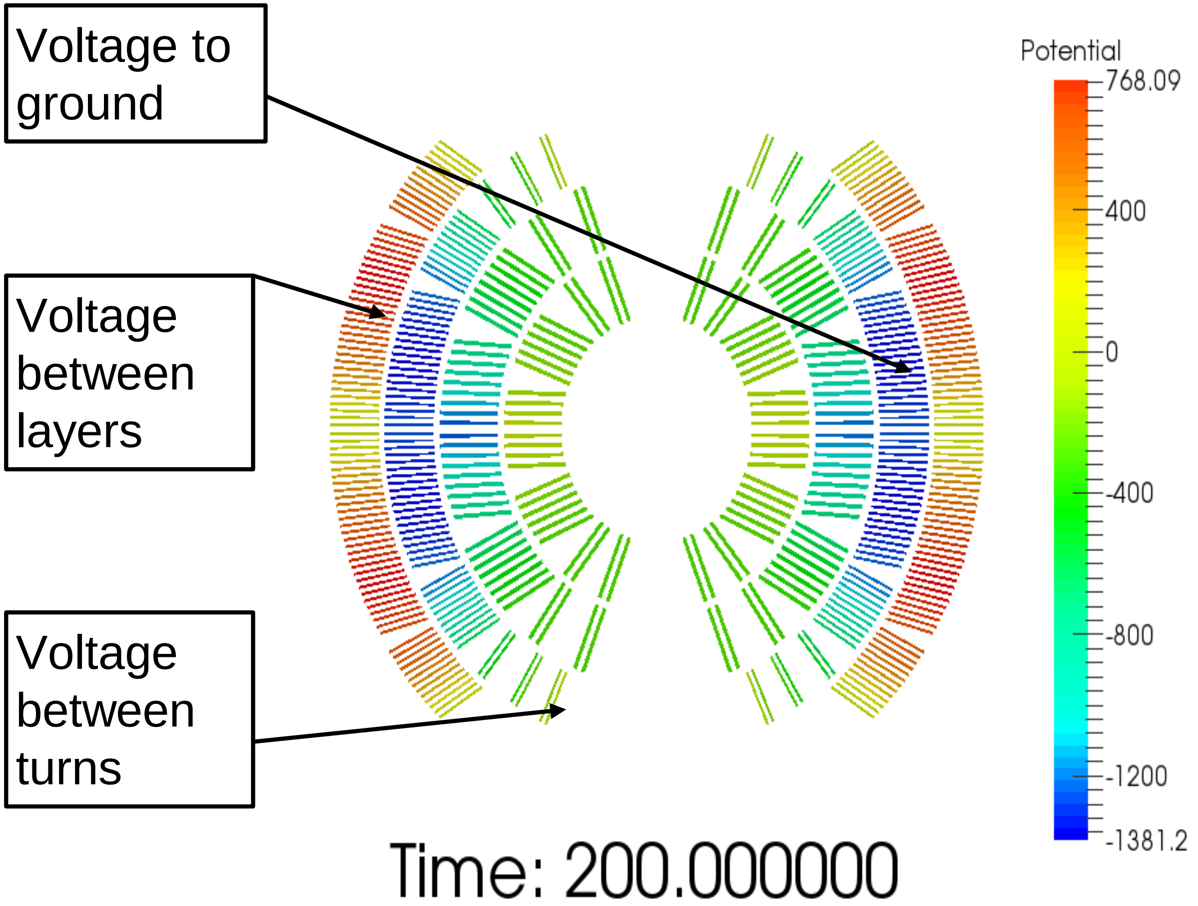




3. Calculation of voltages (only in coodi)

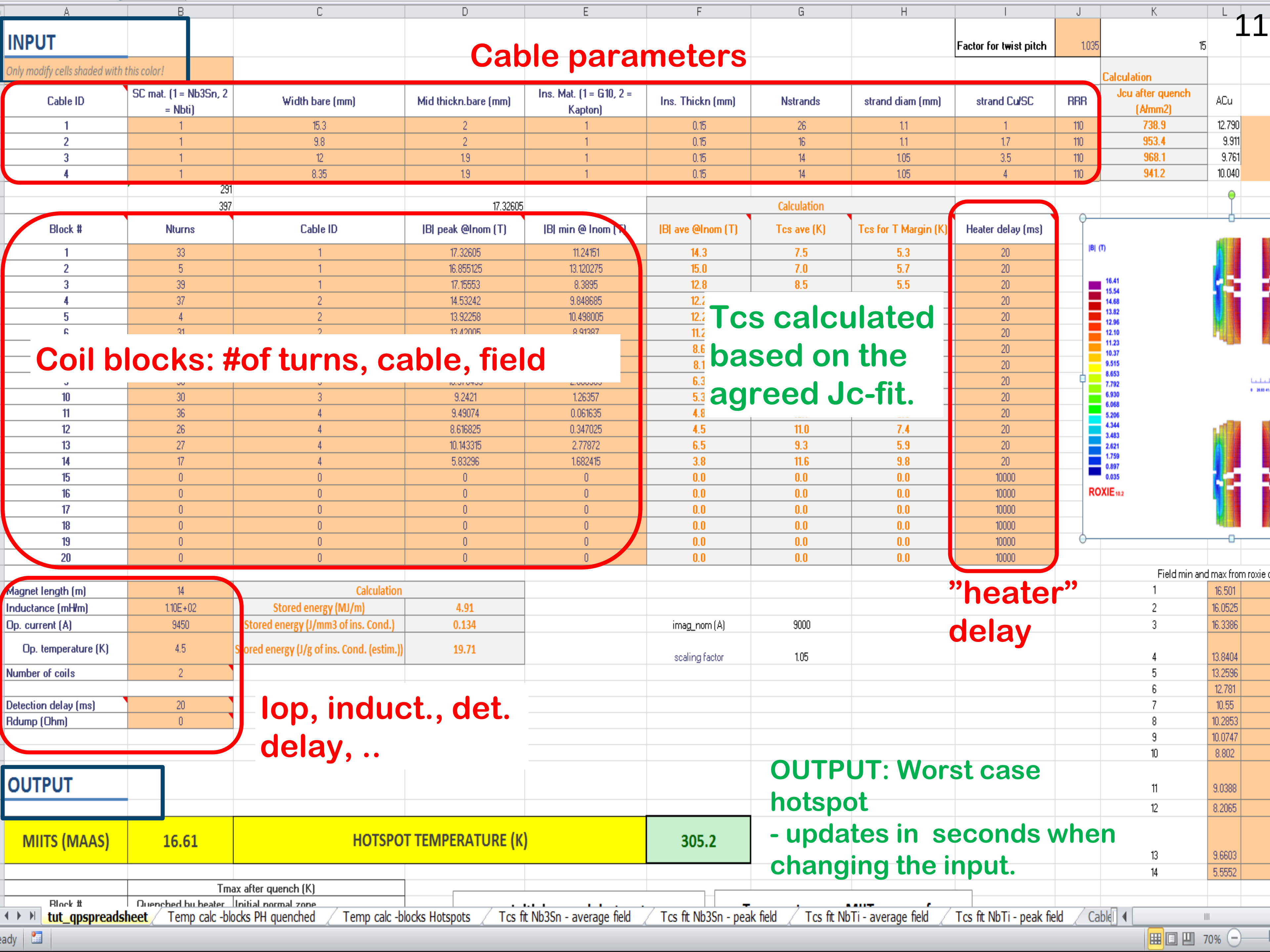
3. Critical peak values are defined from the potential:




Voltage to ground

Voltage between layers

Voltage between turns



INPUT

Only modify cells shaded with this color!

Cable parameters

					Factor for twist pitch	1.035	15

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								

Coil blocks: #of turns, cable, field

Tcs calculated based on the agreed Jc-fit.

"heater" delay

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	12.2			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

Iop, induct., det. 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

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

OUTPUT: Worst case hotspot
- updates in seconds when changing the input.

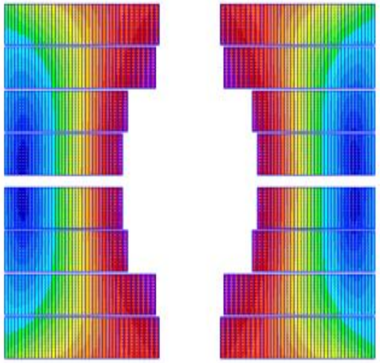
	Tmax after quench (K)	
Block #	Quenched by heater	Initial normal zone

4. Analysis of the designed magnets

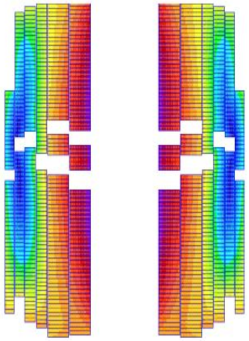
Design, cable	**$A_{ins.}$ (mm^2)**	**f_{Cu}**	**F_{Nb3Sn}**	**f_{G10}**
Block, 1 (HF)	32.5	0.36	0.36	0.27
Block, 2 (LF)	21.9	0.34	0.34	0.33
Cosθ, 1 (HF)	38.0	0.36	0.36	0.28
Cosθ, 2 (LF)	22.4	0.45	0.22	0.32
CC, 1 (HF)	33.9	0.36	0.36	0.29
CC, 2 (HMF)	23.2	0.43	0.25	0.32
CC, 3 (LMF)	19.0	0.51	0.15	0.34
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 x 2
CommonC	9000	110

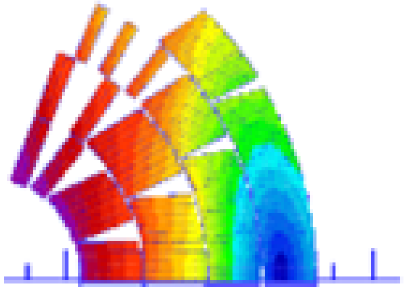
Block
(v26_b)

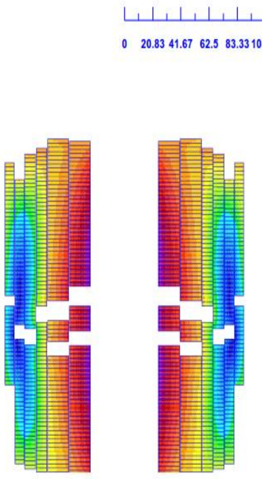


CommonC
(v1h_intragrad_t2)



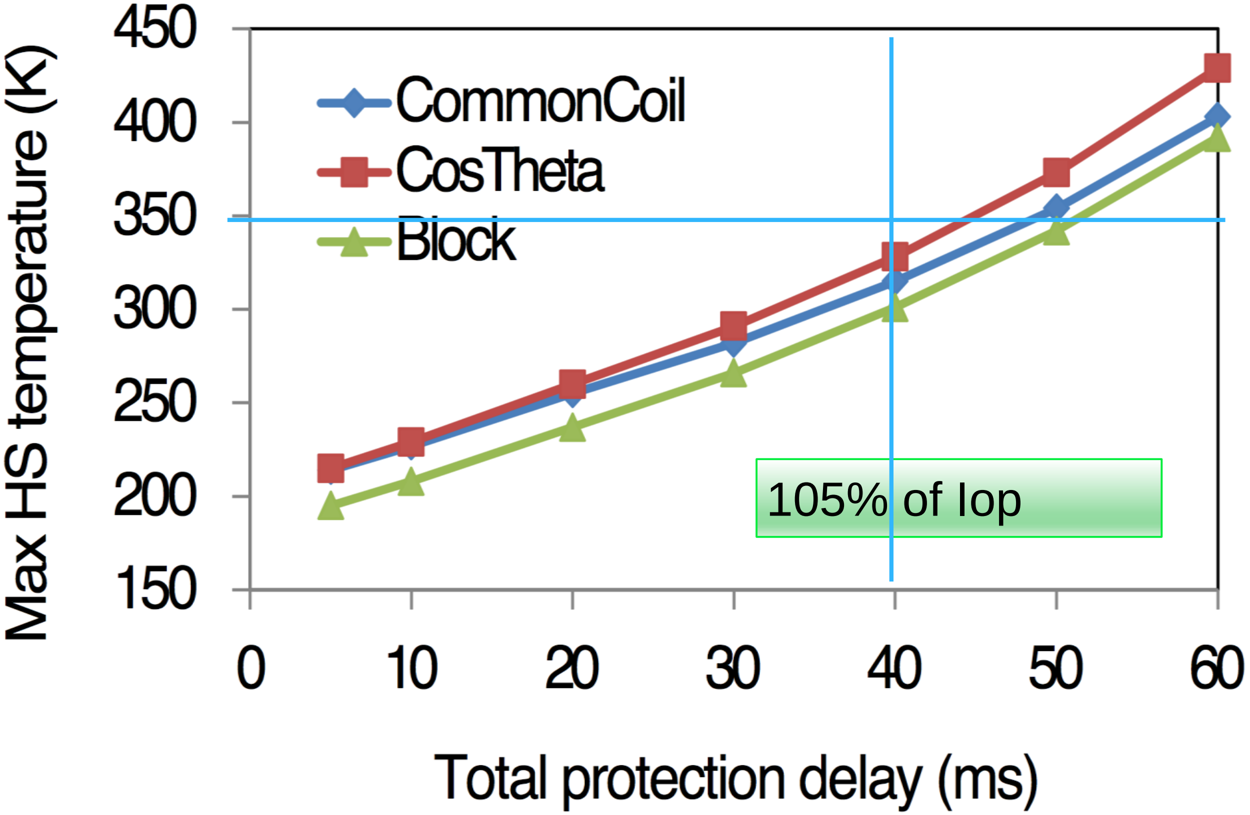
CosT
(16T_v28b-38-opt5d)





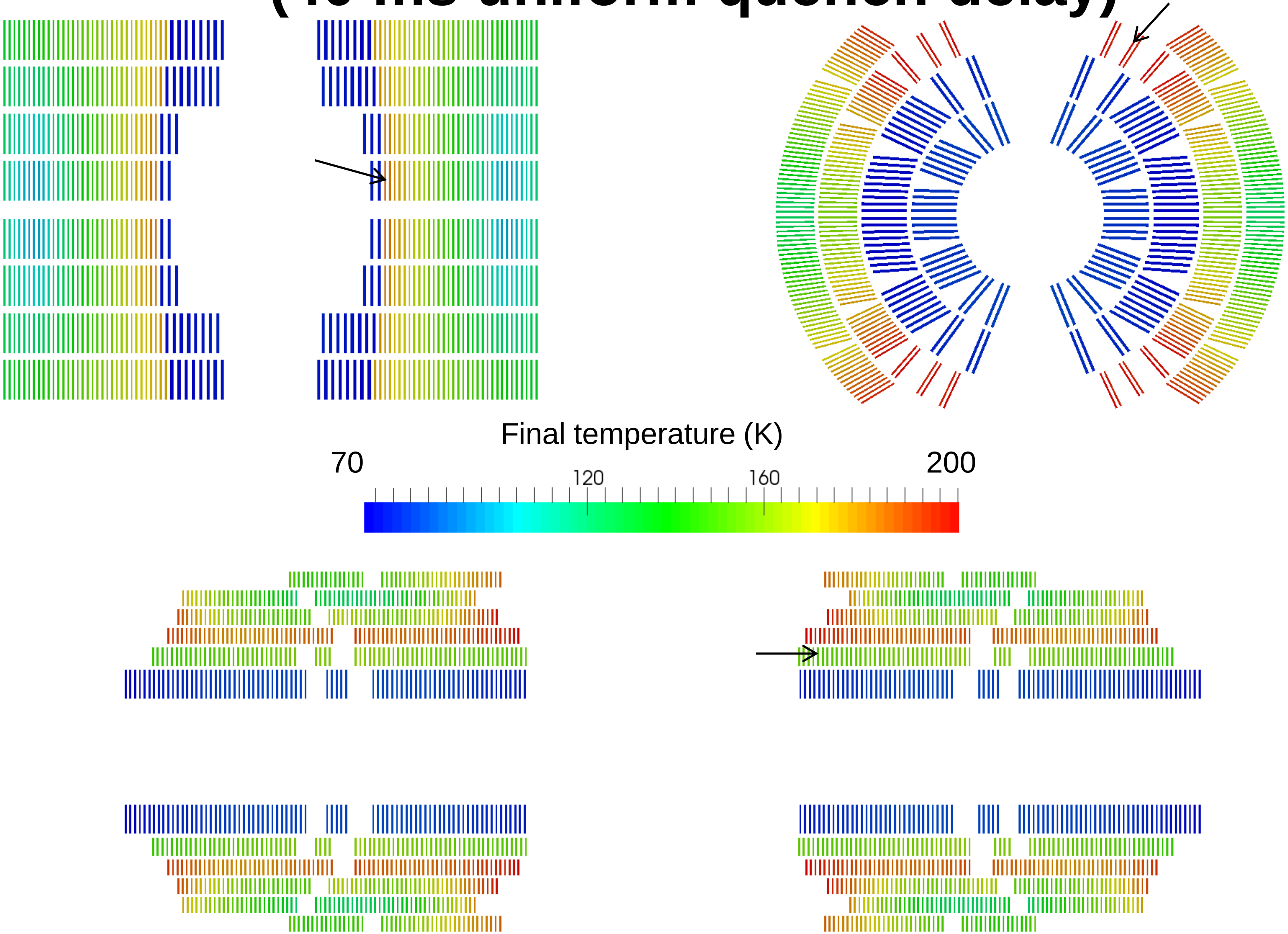
4. Simulated hotspot temperatures assuming uniform protection delay

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



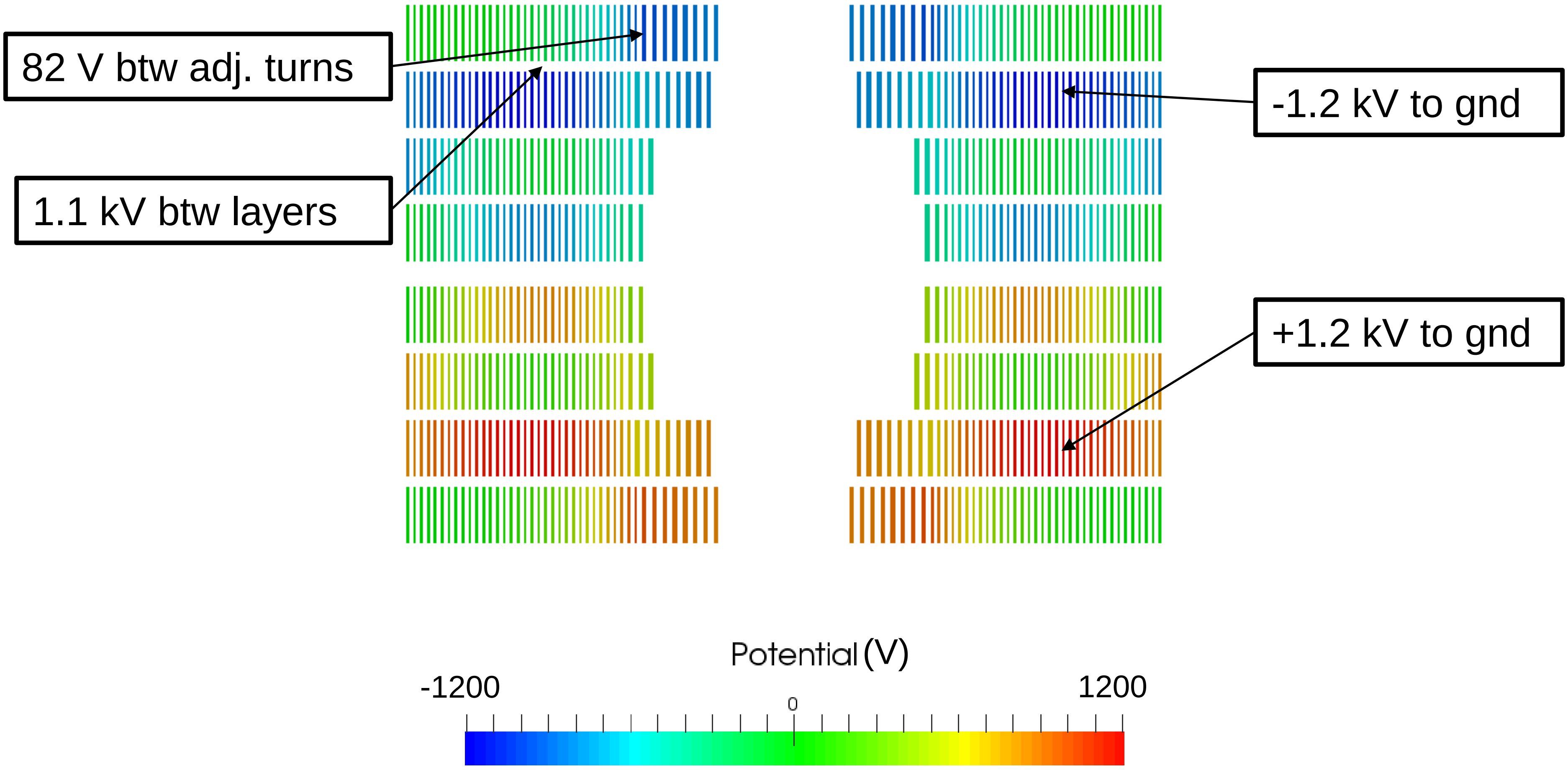
All designs valid from hotspot temperature point of view (< 350 K with 40 ms protection delay).

Simulated temperature distributions (40 ms uniform quench delay)



Simulated potential to ground

Peak potential to ground ~160 ms


82 V btw adj. turns

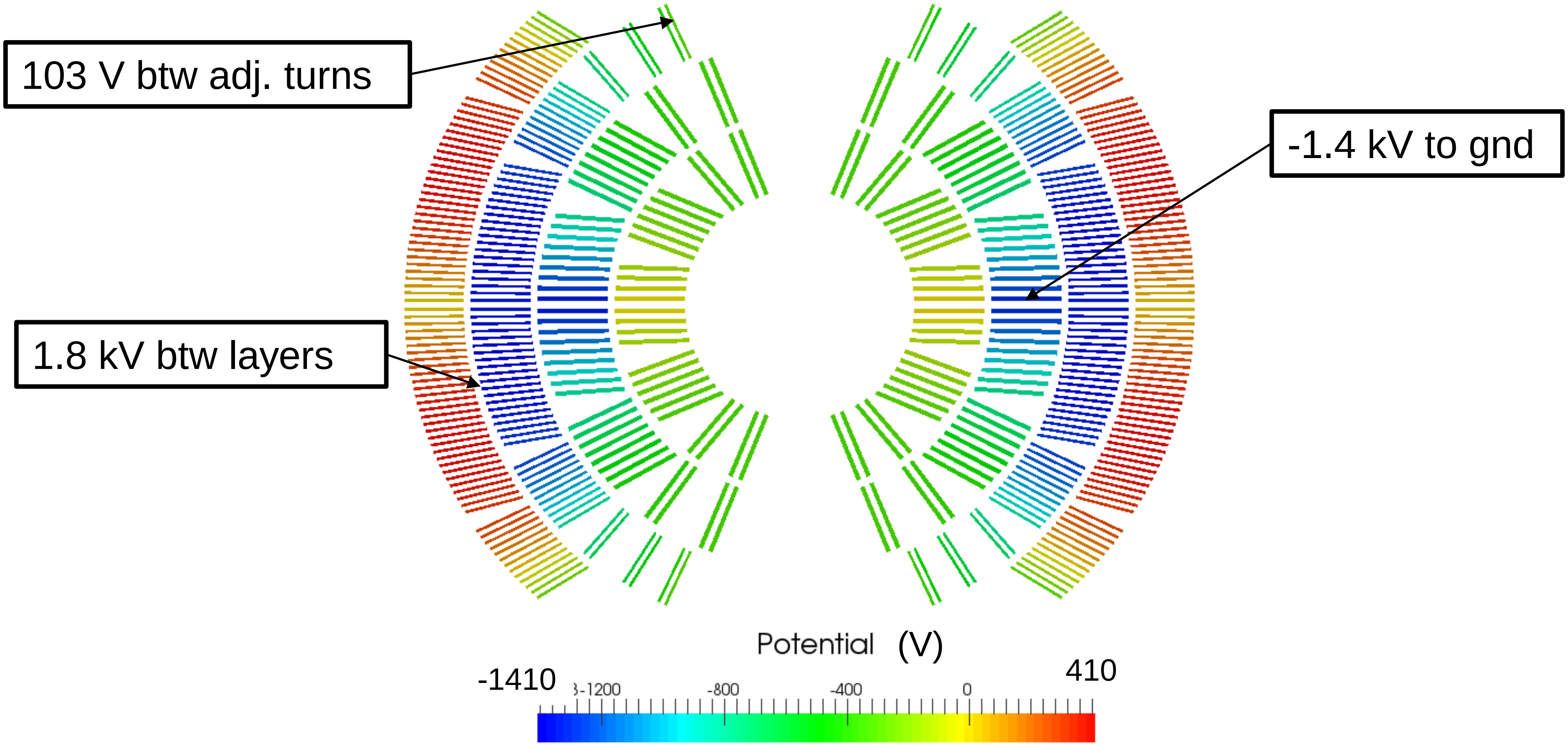
1.1 kV btw layers

-1.2 kV to gnd

+1.2 kV to gnd

Simulated potential to ground

Peak potential to ground ~190 ms



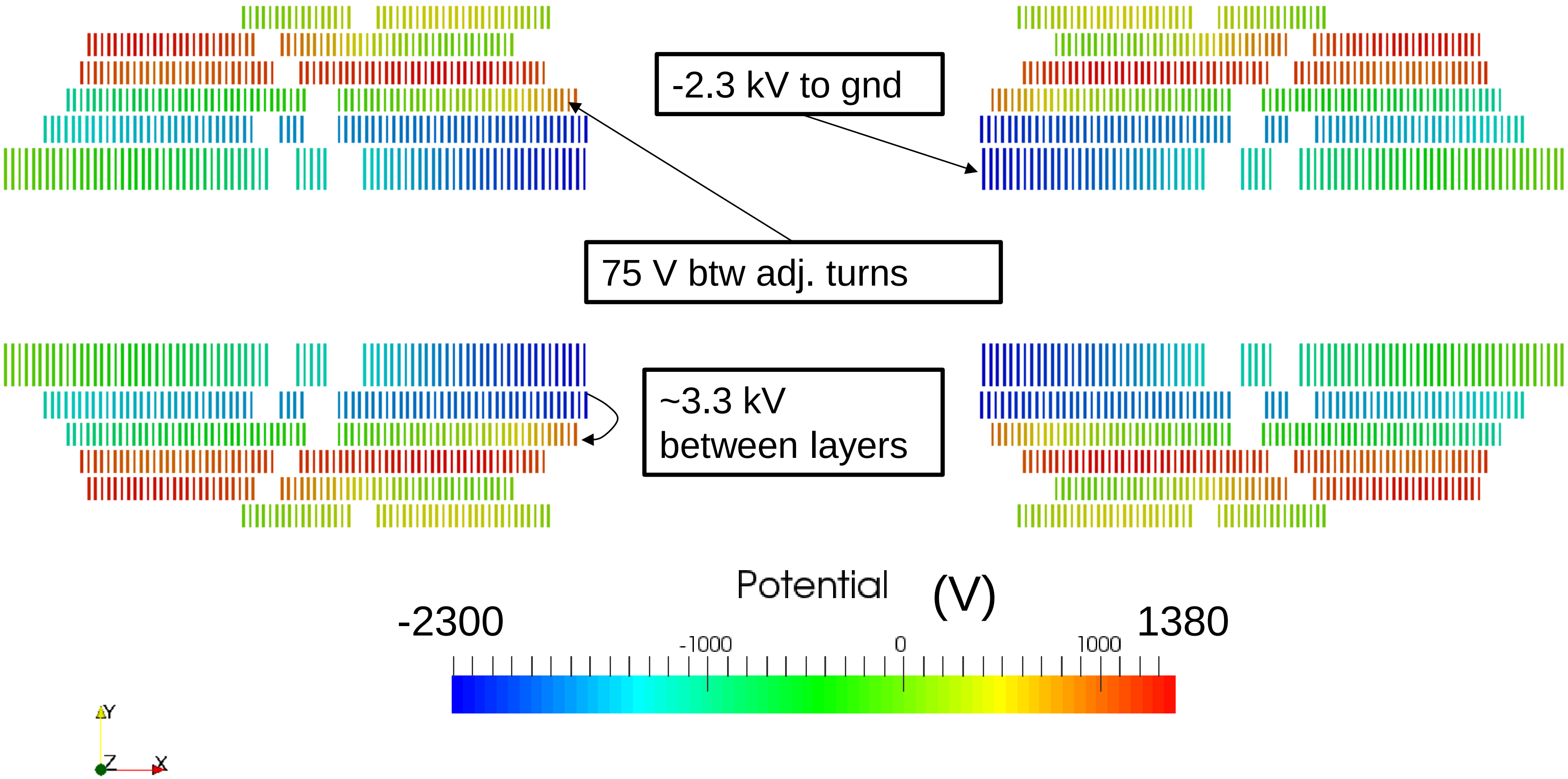
103 V btw adj. turns

-1.4 kV to gnd

1.8 kV btw layers

Simulated potential to ground

Potential to ground at ~200 ms



-2.3 kV to gnd

75 V btw adj. turns

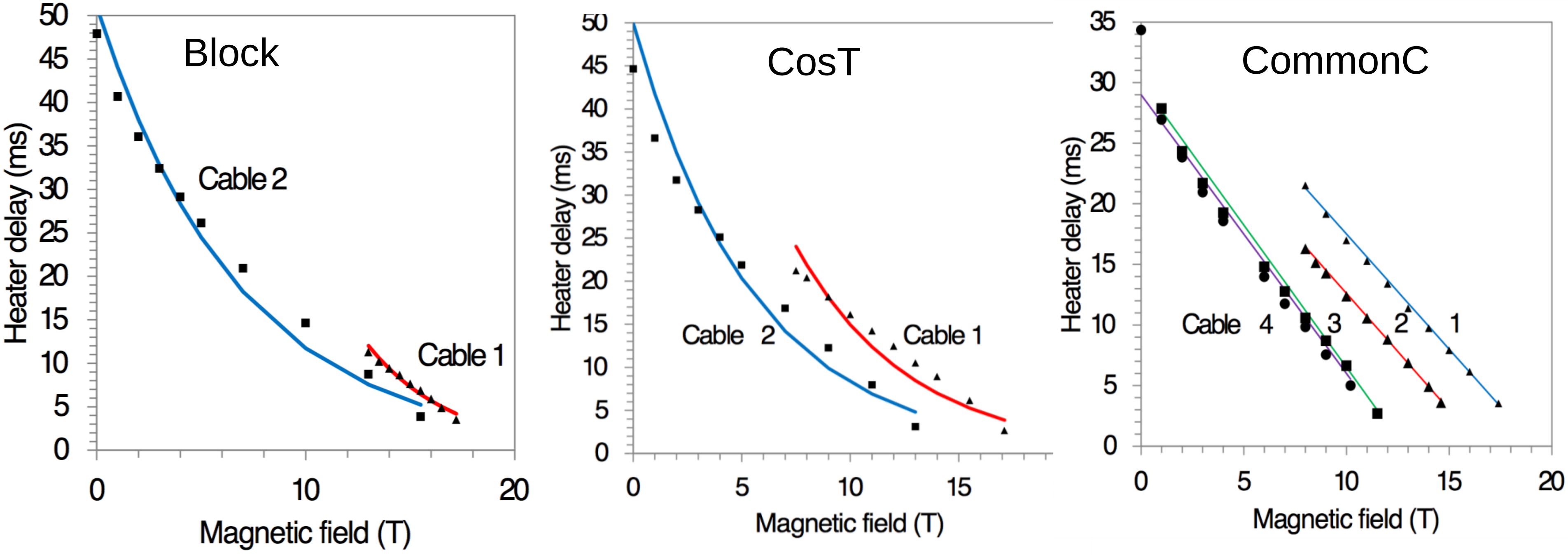
~3.3 kV
between layers

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

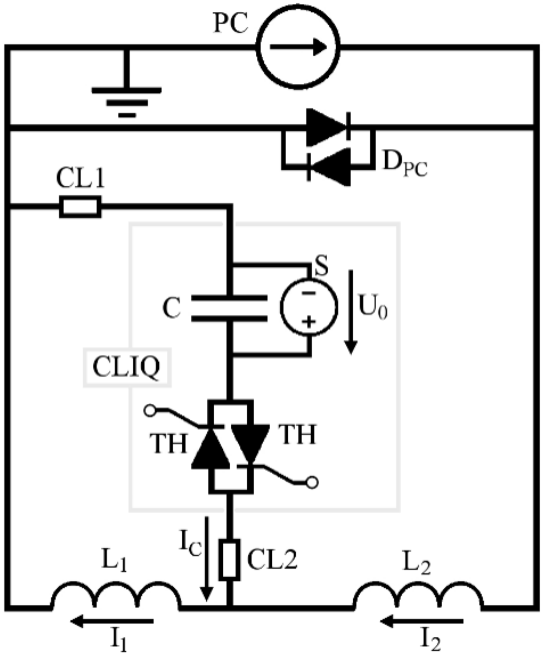
	T max (K)	V to gnd (kV)	V turn-to-turn (V)	V layer-to-layer (kV)
Block	308	-1.2 …+1.2	82	1.1
CosT	328	-1.4 … 0.4	103	1.8
CommonC	315	-2.3 … 1.4	75	3.3

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

Coupling-Loss Induced Quench protection system



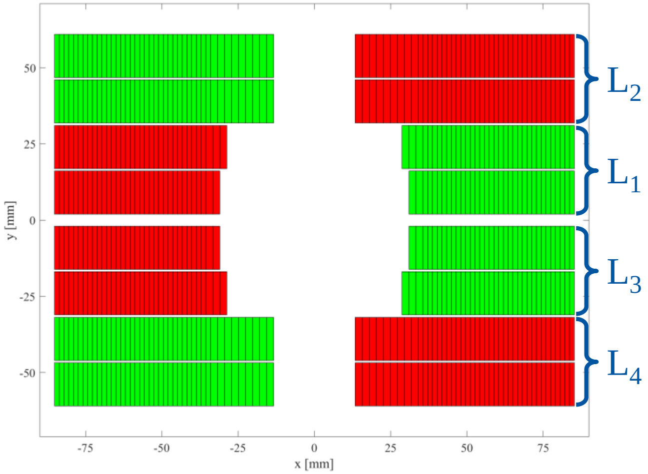
- CLIQ is a new technology for the protection of superconducting magnets. The core component is the capacitor bank that generates:
  - An alternated transport current in the magnet
  - A variable magnetic field in the coils
  - High inter-filament and inter-strand coupling losses
  - Heat on the superconductor
  - Quick spread of the normal zone after a quench

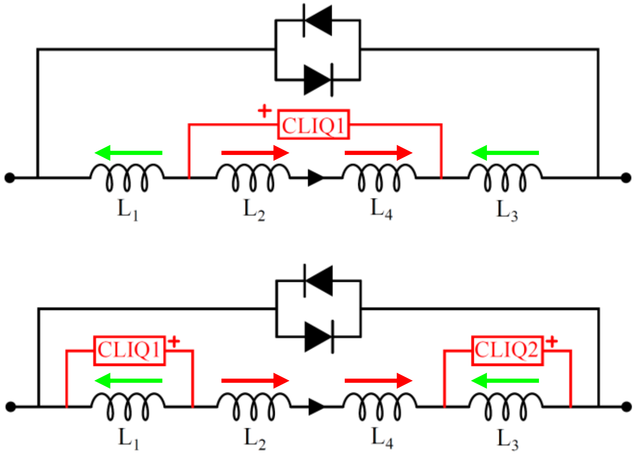
CLIQ starts quenching a magnet few milliseconds after it is fired

- 5 ms for the considered block coil

M. Prioli

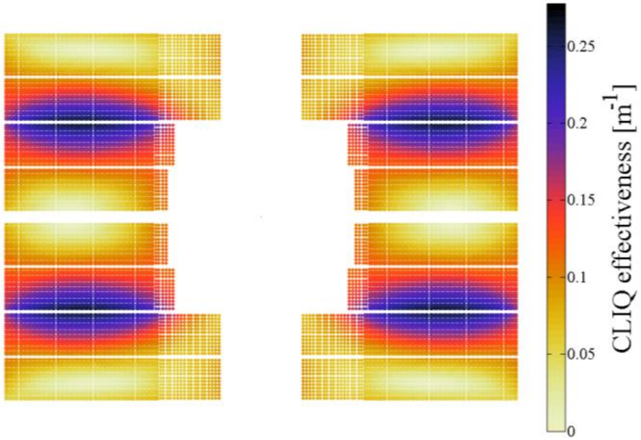
Connecting CLIQ to the magnet

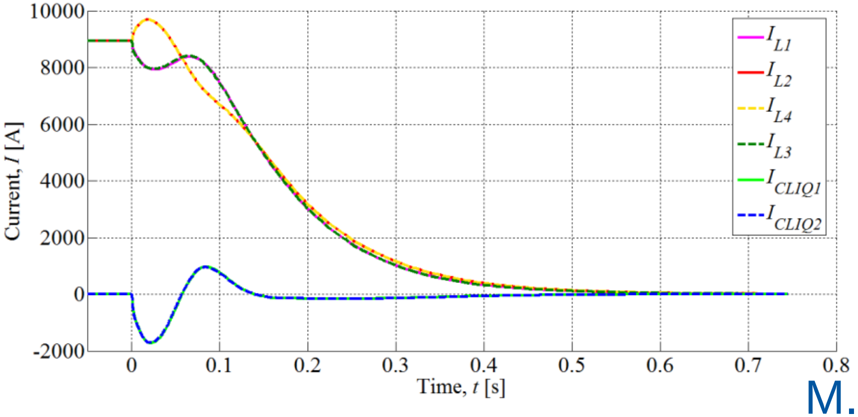




The two connections are electrically equivalent

The second is better for redundancy





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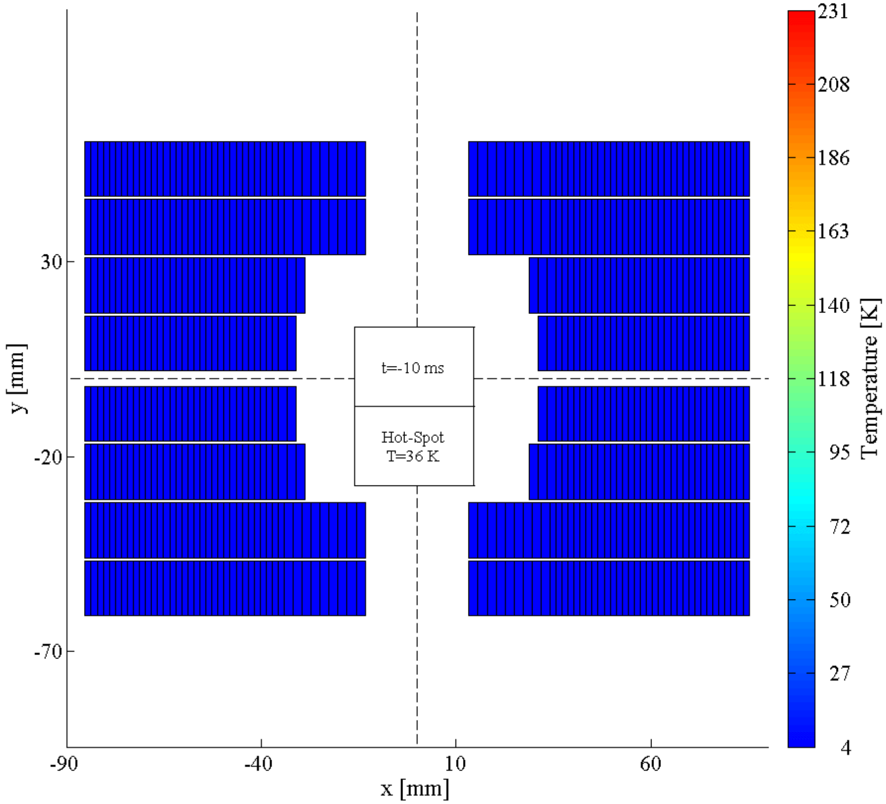
CLIQ temperatures



$C_{CLIQ1} = 40\ mF$
$V_{CLIQ1} = 1\ kV$

$C_{CLIQ2} = 40\ mF$
$V_{CLIQ2} = 1\ kV$

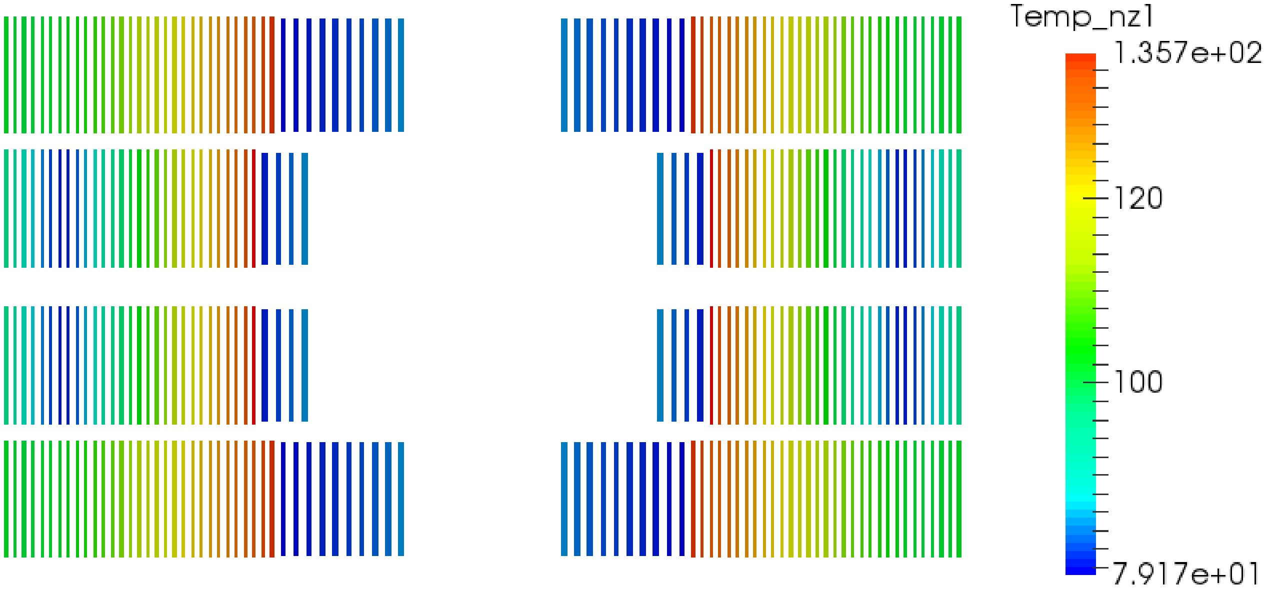
- Most of the coil turns are quenched by CLIQ (identified in red)
  - ~60% of turns quenched within 20 ms (~40% within 10 ms)
- $T_{HS} = 330K$ is below $350K$
- Temperature differences between low-field and high-filed cables are high ($110K$)
- Peak voltage to ground is about 1.3 kV (rough estimate)

M. Prioli

Decrease in voltages with larger cable (and operation at 1.9 K)

- Block V101: Iop = 15600 A, L = 11.5 mH/m/ap. Top = 1.9 K
- 38 / 60 strands, diam 1.1 / 0.7, Cu/Ncu 0.8 / 1.5

<u>At 105% of Iop with 40 ms protection delay:</u>
Tmax = 318 K
Vgnd = -570 V
Vlat = 55 V
Vvert = 510 V



Temperature distribution at t = 150 ms (hotspot not shown)

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

- **40 ms seems a good aproximation for heaters OR CLIQ separately. Probably we can get faster delays considering heating from BOTH.**

- **Voltages were above 1 kV even in the nominal case**
- **Designs with larger cable, smaller Cu/SC on HF cable and higher current (smaller inductance) at 1.9 K seem to help**

- **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

References

Maximum temperature: .G. Ambrosio, proc. WAMSDO 2013

Available online: https://arxiv.org/ftp/arxiv/papers/1401/1401.3955.pdf

Time margin: E. Todesco, proc. WAMSDO 2013

Available online: http://cds.cern.ch/record/1643430/files/p10.pdf

Heater delay modeling with CoHDA: T. Salmi, IEEE TAS, **24**(4), 2014

And T. Salmi, PhD Thesis

Available online: https://tutcris.tut.fi/portal/files/3827151/salmi_1311.pdf

Current decay with Coodi: T. Salmi, IEEE TAS, **26**(4), 2014

CLIQ: E. Ravaioli, PhD Thesis

Available onlline: https://cdsweb.cern.ch/record/2031159/files/Thesis-2015-Ravaioli.pdf

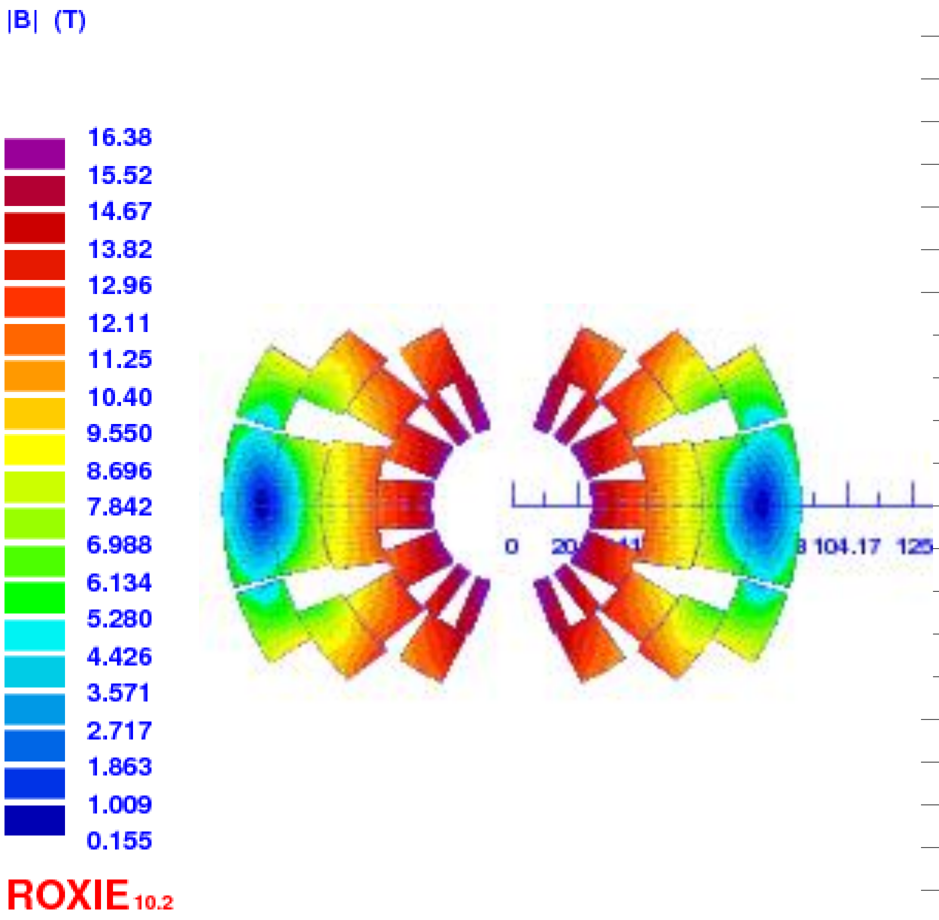
EXTRA MATERIAL

Calculated voltages with uniform quench delay

	% of Iop	Vmax gnd (V)	V turn-to-turn (V)	V layer-to-layer (V)	Tmax (K)
Block V101	105	-570	55	510	318
Daniel Slide 1	100	-501	71	654	321
Daniel Slide 1	105	572	80	734	352
Daniel Slide 2	105	530	72	513	366
Daniel Slide 3	105	426	76	633	354
Daniel Slide 4	105	526	73	516	360
Daniel Slide 5	105	390	72	632	392
Daniel Slide 6	105	389	68	402	390

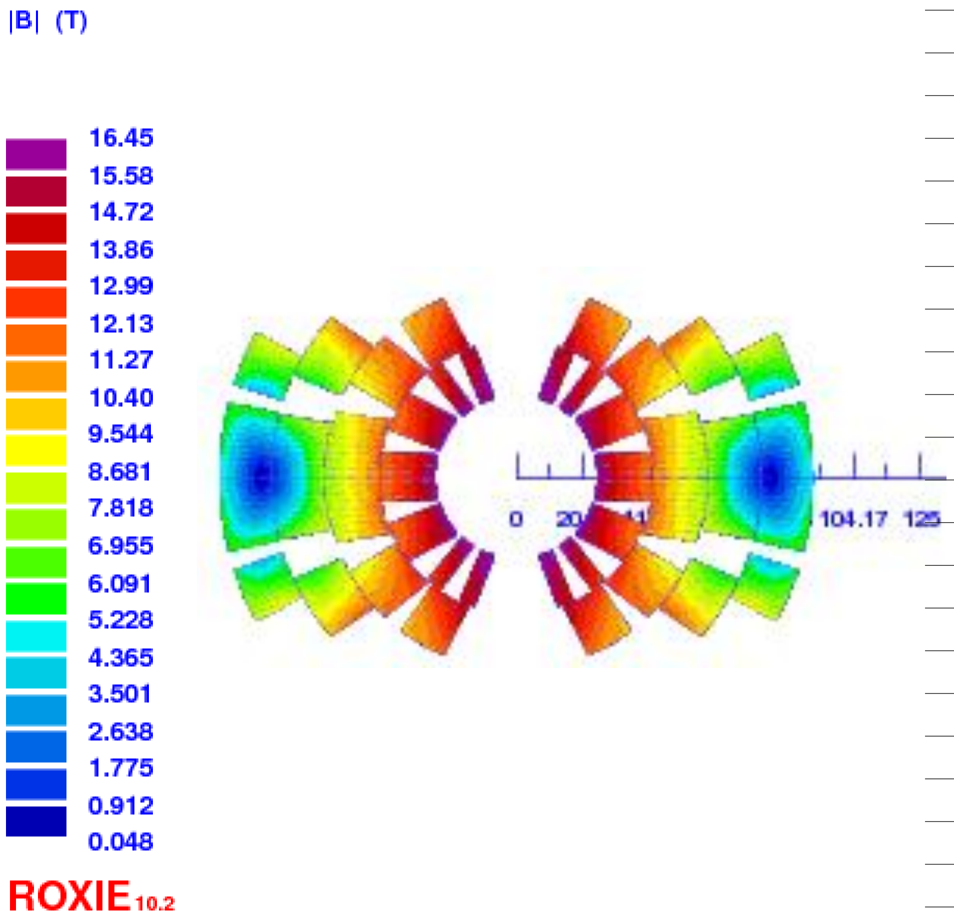
Delay time=40ms (uniform quench)

Cross-section, 13.5 kA, ϕ 1.1, Cu 1.0



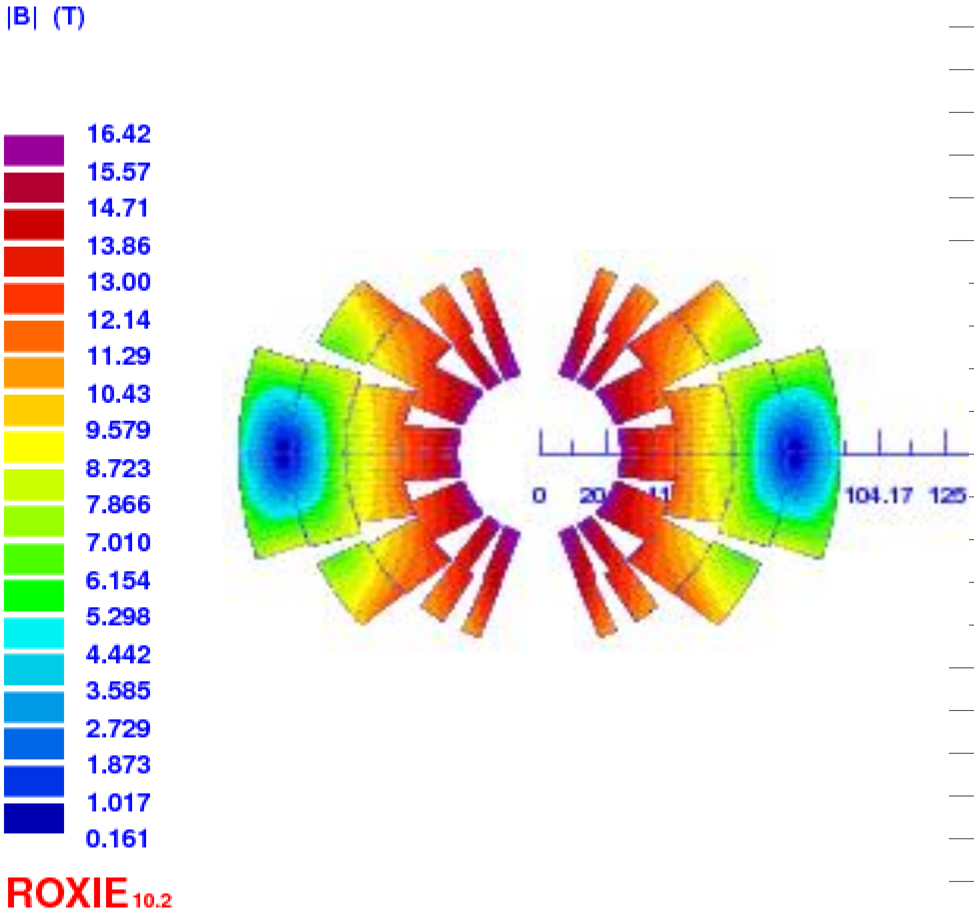
Operating current	(kA)	13.5 kA
Field in the aperture	(T)	16.0
Field in the aperture at SS current	(T)	18.5
Stored magnetic energy per unit length/ap	(MJ/m)	1.4
Inductance/aperture	(mH/m)	14.0
Diameter IL	(mm)	1.1
Strands/cable IL	-	28
Cu/Non-Cu IL	-	1.0
Diameter OL	(mm)	0.75
Strands/cable OL	-	38
Cu/Non-Cu OL	-	2.03
Total area of Cu/aperture	(mm^2)	4142
Total area of Sc/aperture	(mm^2)	2932
Total mass of Sc for FCC-hh	(t)	3340
Total mass of conductor for FCC-hh	(t)	8058
J_{eng} IL	(A/mm^2)	507
J_{eng} OL	(A/mm^2)	804
J_{overal} IL	(A/mm^2)	344
J_{overal} OL	(A/mm^2)	513
Average stress in Layer 1	(MPa)	74
Average stress in Layer 2	(MPa)	126
Average stress in Layer 3	(MPa)	142
Average stress in Layer 4	(MPa)	103

Cross-section, 15.1 kA, ϕ 1.1, Cu 0.8



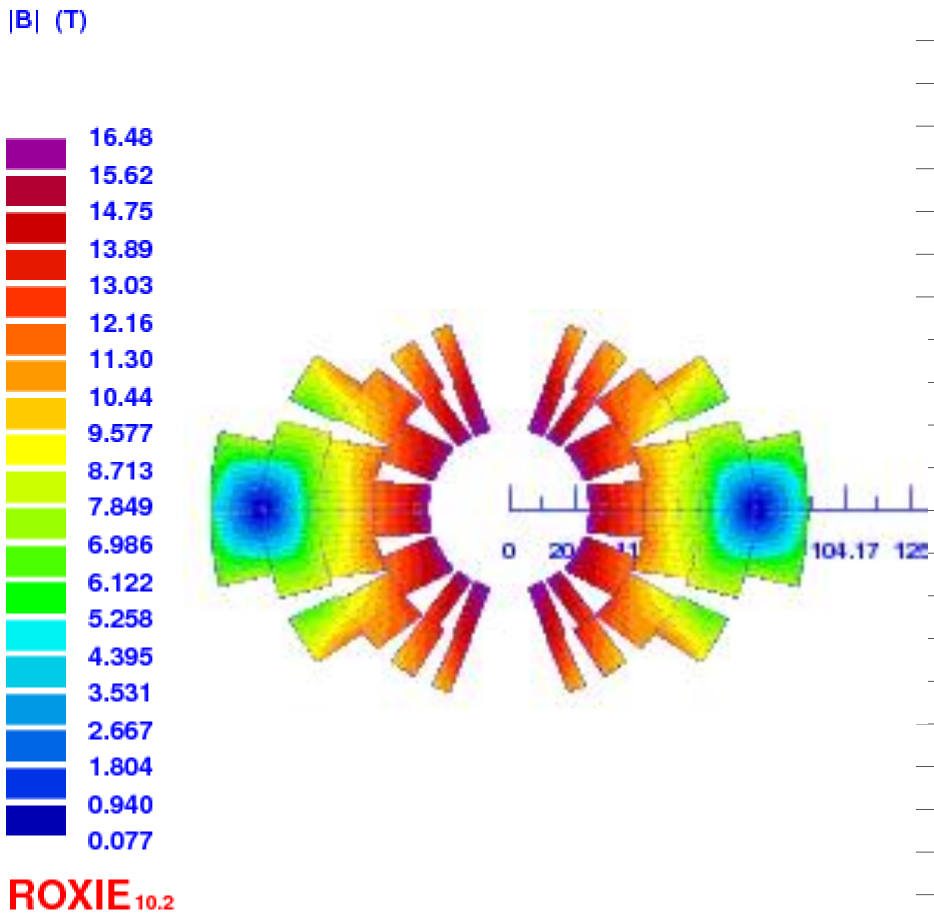
Operating current	(kA)	15.1
Field in the aperture	(T)	16.0
Field in the aperture at SS current	(T)	18.5
Stored magnetic energy per unit length/ap	(MJ/m)	1.3
Inductance/aperture	(mH/m)	10.6
Diameter IL	(mm)	1.1
Strands/cable IL	-	28
Cu/Non-Cu IL	-	0.8
Diameter OL	(mm)	0.77
Strands/cable OL	-	38
Cu/Non-Cu OL	-	2.44
Total area of Cu/aperture	(mm^2)	3671
Total area of Sc/aperture	(mm^2)	2816
Total mass of Sc for FCC-hh	(t)	3208
Total mass of conductor for FCC-hh	(t)	7389
J_{eng} IL	(A/mm^2)	566
J_{eng} OL	(A/mm^2)	852
J_{overal} IL	(A/mm^2)	384
J_{overal} OL	(A/mm^2)	546
Average stress in Layer 1	(MPa)	83
Average stress in Layer 2	(MPa)	142
Average stress in Layer 3	(MPa)	119
Average stress in Layer 4	(MPa)	84

Cross-section, 14.9 kA, ϕ 1.2, Cu 1.0



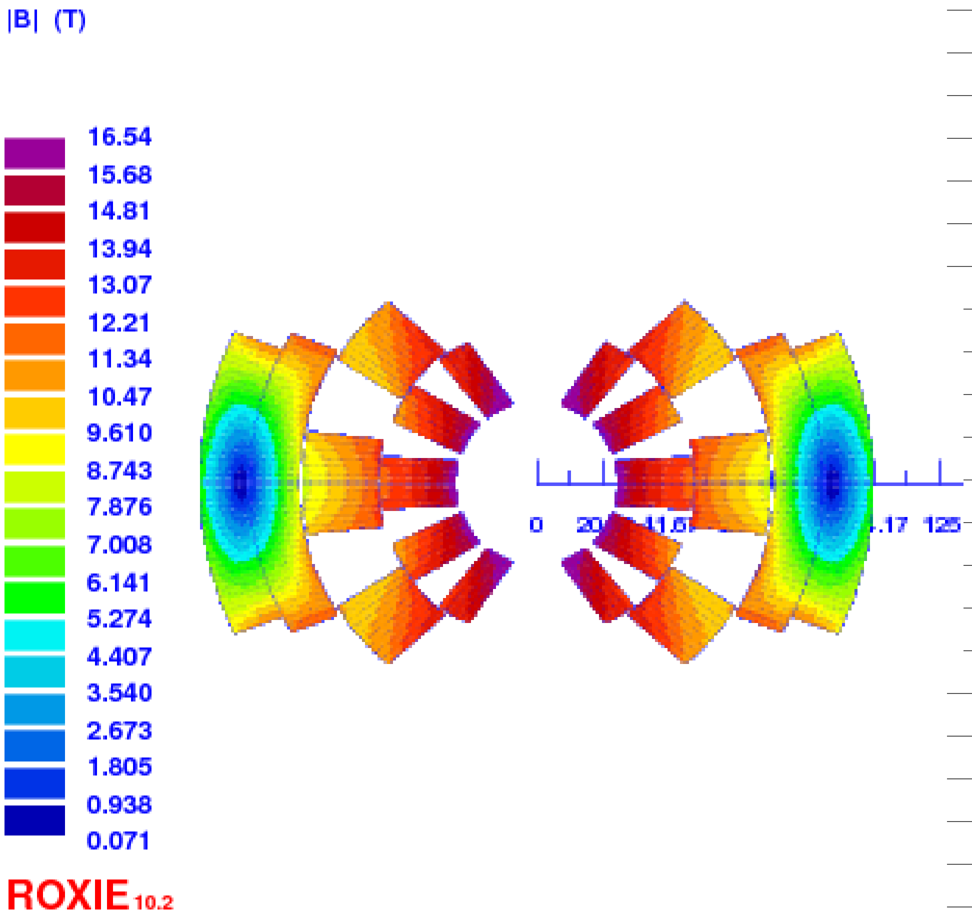
Operating current	(kA)	14.9
Field in the aperture	(T)	16.0
Field in the aperture at SS current	(T)	18.5
Stored magnetic energy per unit length/ap	(MJ/m)	1.4
Inductance/aperture	(mH/m)	11.1
Diameter IL	(mm)	1.2
Strands/cable IL	-	26
Cu/Non-Cu IL	-	1.0
Diameter OL	(mm)	0.78
Strands/cable OL	-	38
Cu/Non-Cu OL	-	2.16
Total area of Cu/aperture	(mm^2)	4067
Total area of Sc/aperture	(mm^2)	2894
Total mass of Sc for FCC-hh	(t)	3297
Total mass of conductor for FCC-hh	(t)	7929
J_{eng} IL	(A/mm^2)	507
J_{eng} OL	(A/mm^2)	821
J_{overal} IL	(A/mm^2)	347
J_{overal} OL	(A/mm^2)	527
Average stress in Layer 1	(MPa)	81
Average stress in Layer 2	(MPa)	127
Average stress in Layer 3	(MPa)	156
Average stress in Layer 4	(MPa)	60

Cross-section, 16.6 kA, ϕ 1.2, Cu 0.8



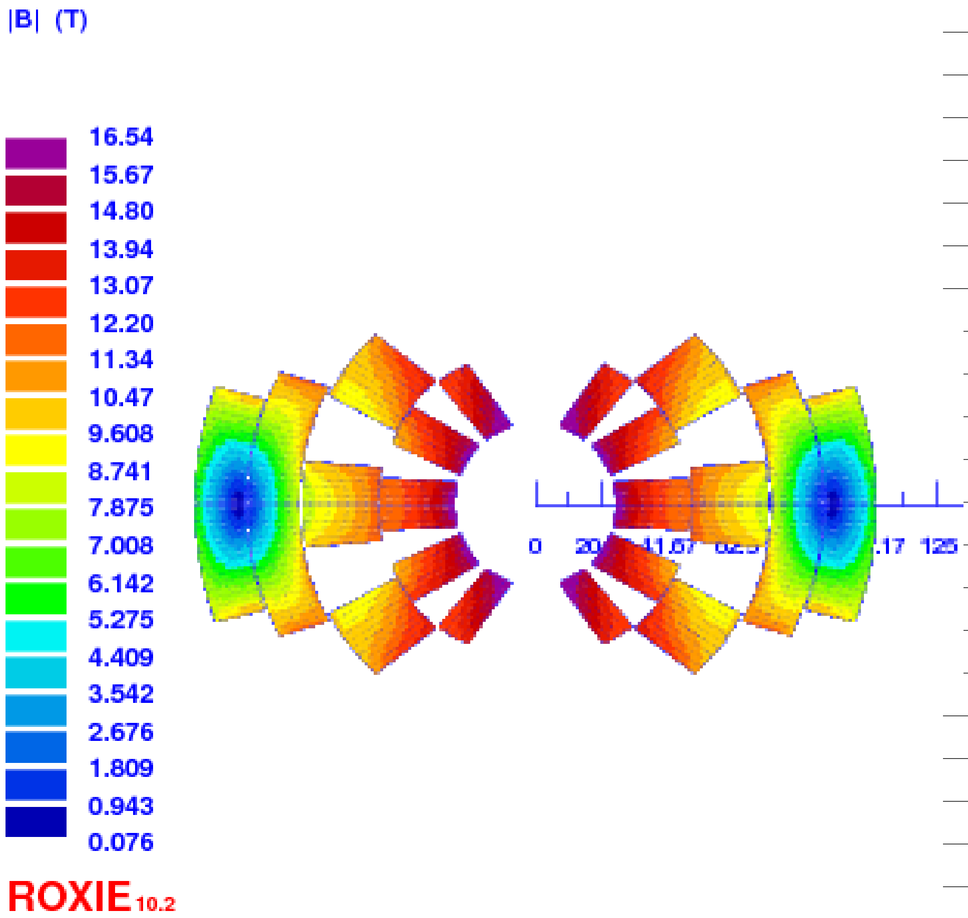
Operating current	(kA)	16.6 kA
Field in the aperture	(T)	16.0
Field in the aperture at SS current	(T)	18.5
Stored magnetic energy per unit length/ap	(MJ/m)	1.3
Inductance/aperture	(mH/m)	8.4
Diameter IL	(mm)	1.2
Strands/cable IL	-	26
Cu/Non-Cu IL	-	0.8
Diameter OL	(mm)	0.8
Strands/cable OL	-	38
Cu/Non-Cu OL	-	2.63
Total area of Cu/aperture	(mm^2)	3556
Total area of Sc/aperture	(mm^2)	2808
Total mass of Sc for FCC-hh	(t)	3199
Total mass of conductor for FCC-hh	(t)	7249
J_{eng} IL	(A/mm^2)	565
J_{eng} OL	(A/mm^2)	869
J_{overal} IL	(A/mm^2)	387
J_{overal} OL	(A/mm^2)	561
Average stress in Layer 1	(MPa)	91
Average stress in Layer 2	(MPa)	143
Average stress in Layer 3	(MPa)	132
Average stress in Layer 4	(MPa)	43

Large cable Cross-section, 18.8 kA



Operating current	(kA)	18.8
Field in the aperture	(T)	16.0
Field in the aperture at SS current	(T)	18.5
Stored magnetic energy per unit length/ap	(MJ/m)	1.8
Inductance/aperture	(mH/m)	9.3
Diameter IL	(mm)	1.1
Strands/cable IL	-	40
Cu/Non-Cu IL	-	1.0
Diameter OL	(mm)	1.06
Strands/cable OL	-	26
Cu/Non-Cu OL	-	2.15
Total area of Cu/aperture	(mm^2)	4547
Total area of Sc/aperture	(mm^2)	3162
Total mass of Sc for FCC-hh	(t)	3602
Total mass of conductor for FCC-hh	(t)	8781
J_{eng} IL	(A/mm^2)	495
J_{eng} OL	(A/mm^2)	819
J_{overal} IL	(A/mm^2)	336
J_{overal} OL	(A/mm^2)	551
Average stress in Layer 1	(MPa)	75
Average stress in Layer 2	(MPa)	85
Average stress in Layer 3	(MPa)	140
Average stress in Layer 4	(MPa)	120

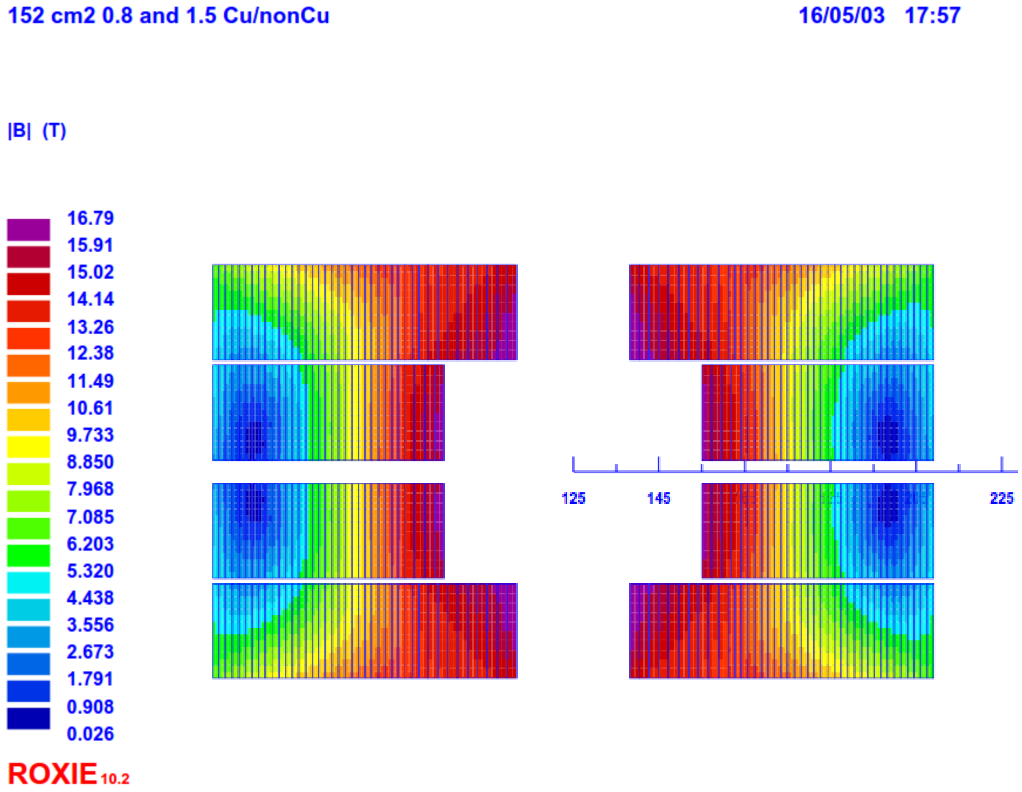
Cross-section, 20.9 kA



Operating current	(kA)	20.9 kA
Field in the aperture	(T)	16.0
Field in the aperture at SS current	(T)	18.5
Stored magnetic energy per unit length/ap	(MJ/m)	1.7
Inductance/aperture	(mH/m)	7.0
Diameter IL	(mm)	1.1
Strands/cable IL	-	40
Cu/Non-Cu IL	-	0.8
Diameter OL	(mm)	1.1
Strands/cable OL	-	26
Cu/Non-Cu OL	-	2.39
Total area of Cu/aperture	(mm^2)	3988
Total area of Sc/aperture	(mm^2)	3130
Total mass of Sc for FCC-hh	(t)	3565
Total mass of conductor for FCC-hh	(t)	8108
J_{eng} IL	(A/mm^2)	550
J_{eng} OL	(A/mm^2)	846
J_{overal} IL	(A/mm^2)	373
J_{overal} OL	(A/mm^2)	572
Average stress in Layer 1	(MPa)	83
Average stress in Layer 2	(MPa)	88
Average stress in Layer 3	(MPa)	128
Average stress in Layer 4	(MPa)	90

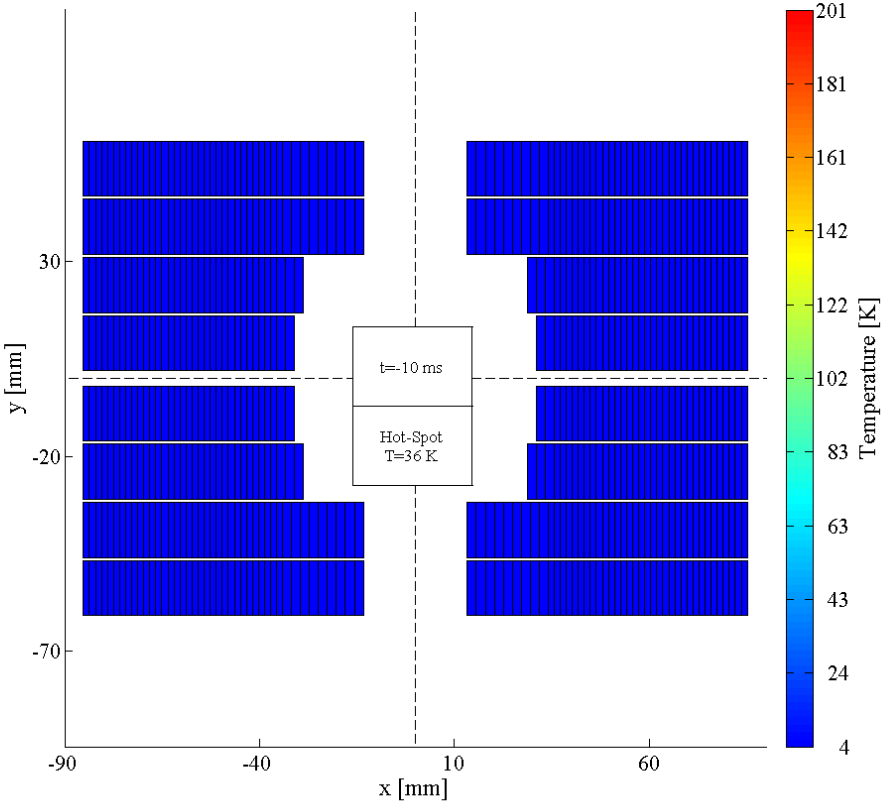
Block from Clement, V101

Cable ID	SC mat. (1 = Nb3Sn, 2 = Nbti)	Width bare (mm)	Mid thickn.bare (mm)	Nstrands	strand diam (mm)	strand Cu/SC	RRR
1	1	22	2	38	1.1	0.8	100
2	1	22	1.25	60	0.7	1.5	100



Magnet length (m)	14.3
Inductance (mH/m)	2 x 11.5
Op. current (A)	15600
Op. temperature (K)	1.9

CLIQ temperatures, case 2

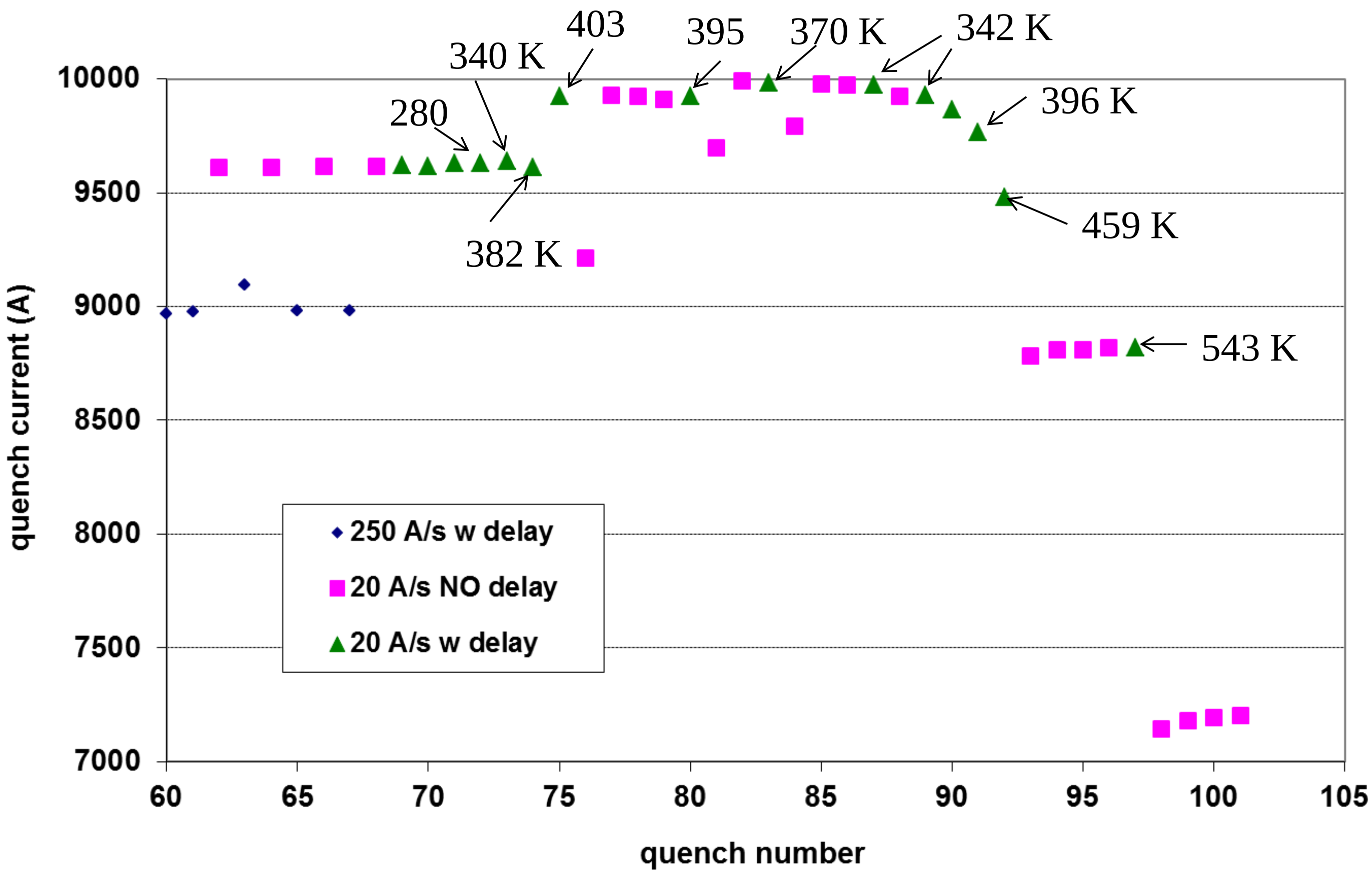


$C_{CLIQ1} = 40\ mF$
$V_{CLIQ1} = 1\ kV$

$C_{CLIQ2} = 40\ mF$
$V_{CLIQ2} = 1\ kV$

- All turns are quenched by assumption after 20 + 20 *ms* (identified in red)
- $T_{HS} = 290K$ is well below $350K$
- Temperature differences between low-field and high-filed cables are still high $(100K)$
- Peak voltage to ground is about 1 kV (rough estimate)

LARP experiment to find maximum hotspot temperature

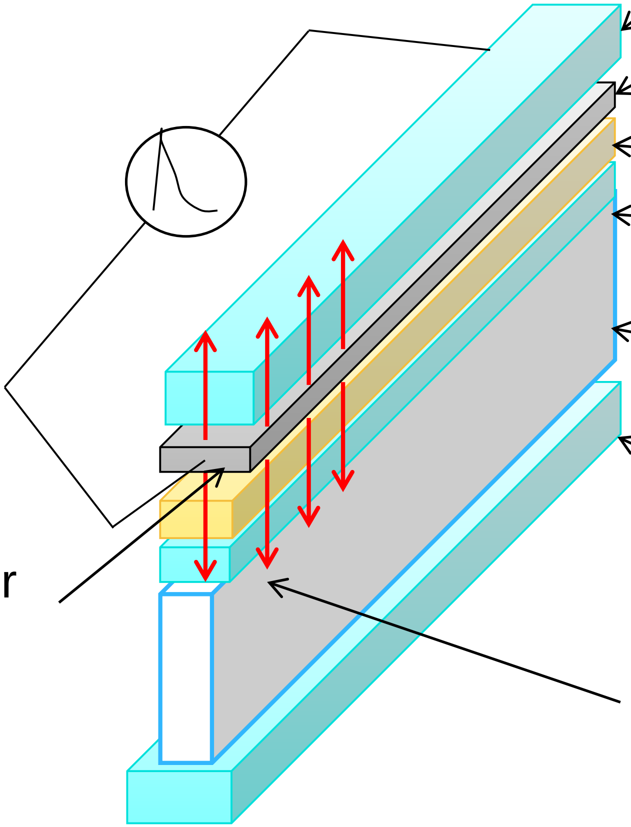


Quench history at TQS01c test, G. Ambrosio, WAMSDO 2013

2. Obtainable quench delay

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

Heater delay simulations using CoHDA



Insulation (G10, 0.8 mm)

Heater (stainless steel, 0.025 mm)

Heater insulation (polyimide, 0.05-0.1 mm)

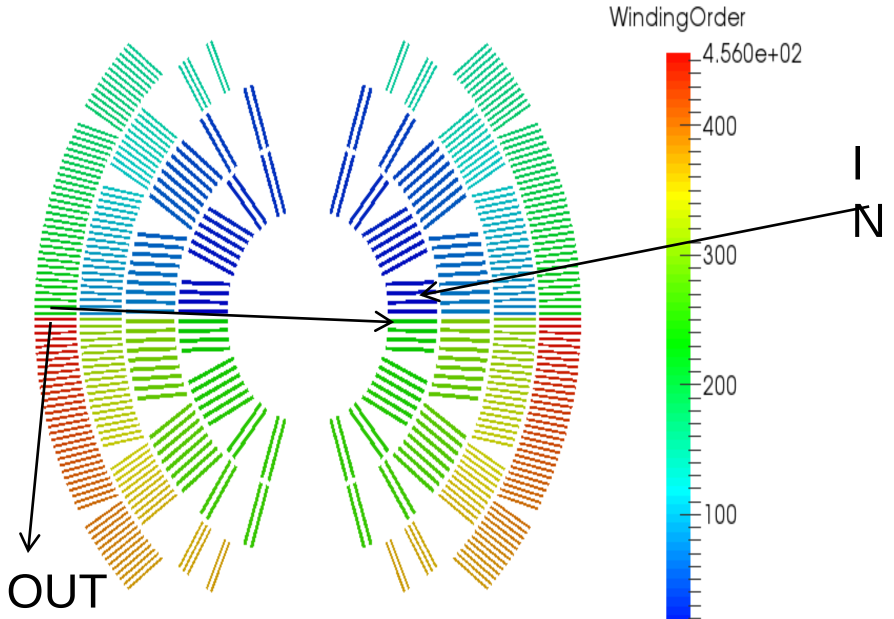
Cable insulation (G10, 0.15 mm)

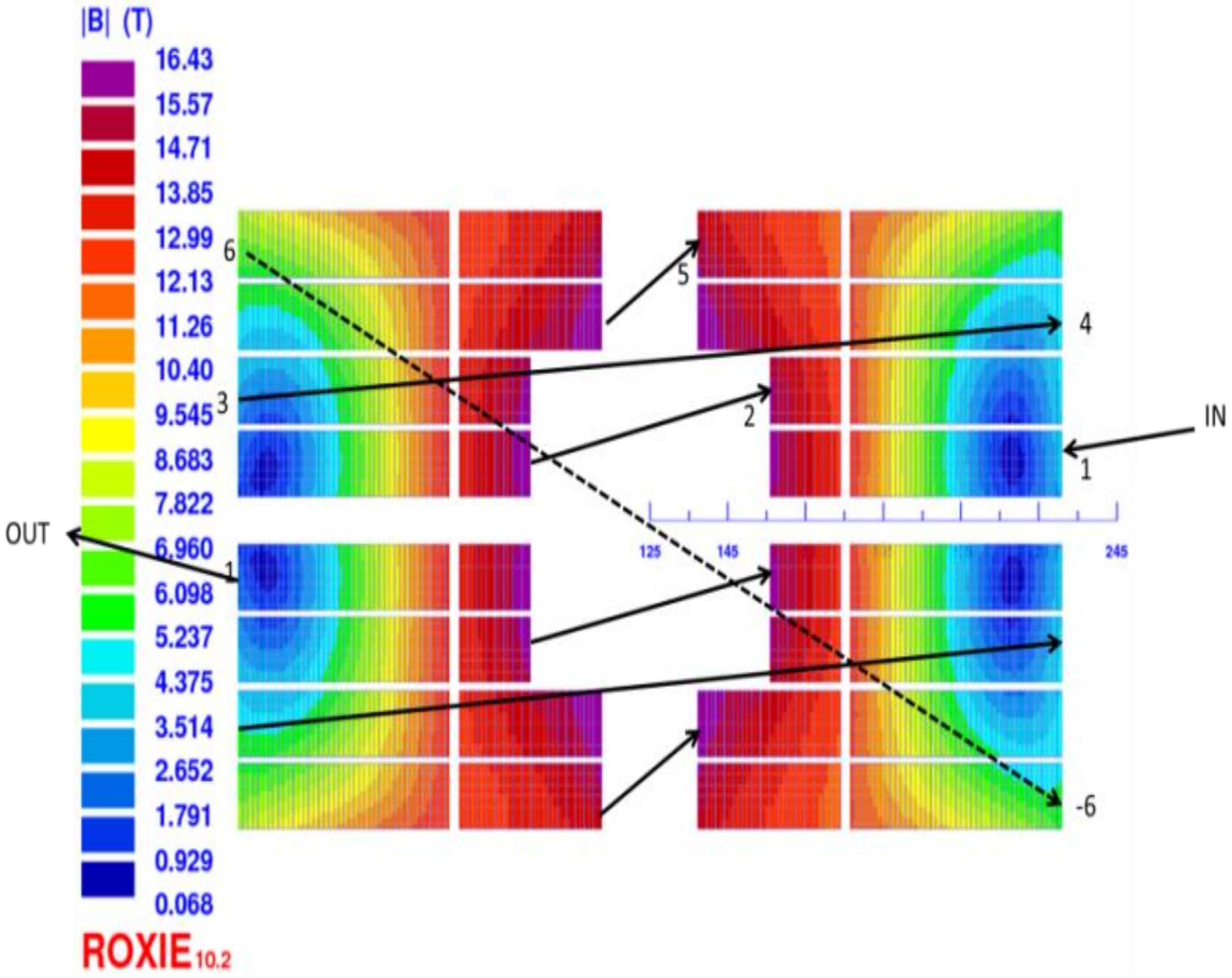
Cable (Cu + nb3Sn + epoxy in the strand voids)

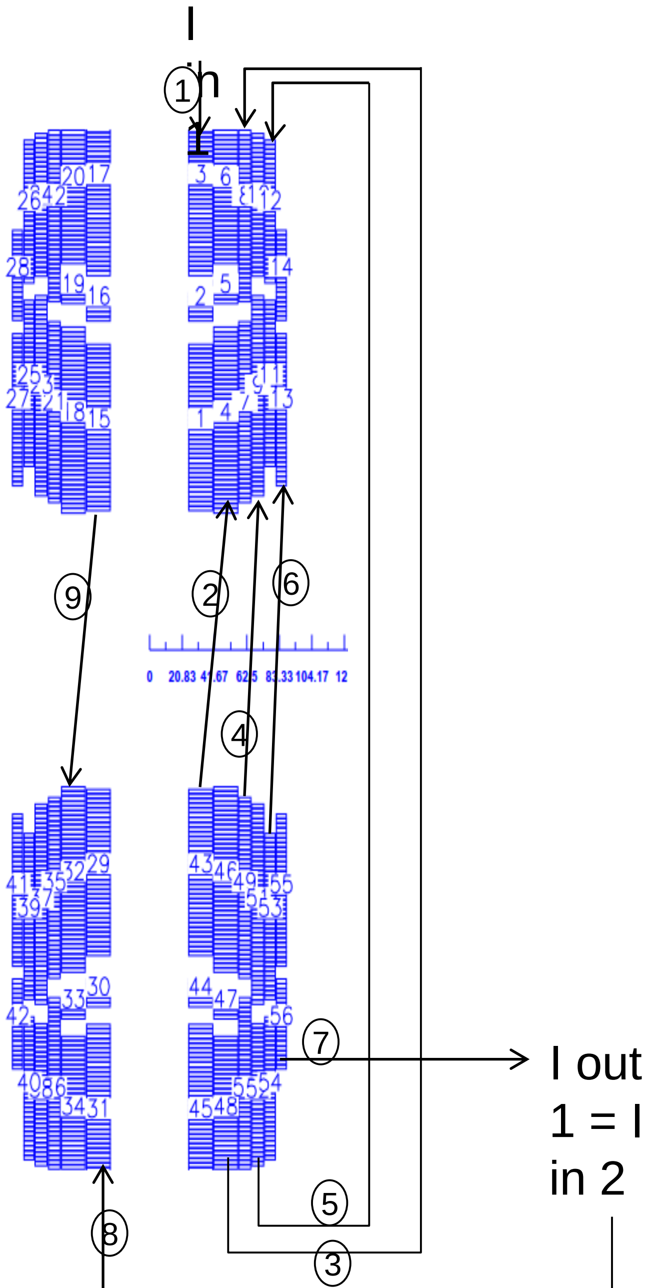
Insulation (G10, 0.8 mm)

PH power density (W/m^3): $J_{ss}^2 * \rho_{ss}$

Quench when cable (max) temperature reaches Tcs


WindingOrder
4.560e+02
400
300
200
100
1.000e+00
I
N
OUT


|B| (T)
16.43
15.57
14.71
13.85
12.99
12.13
11.26
10.40
9.545
8.683
7.822
6.960
6.098
5.237
4.375
3.514
2.652
1.791
0.929
0.068
ROXIE10.2
6
5
4
3
2
IN
1
OUT
1
125
145
245
-6



I in 1

I out 1 = I in 2

COMPUTATION OF EFFECTIVE INDUCTANCES

First computation of mutual inductances M_{ij} between cables C_i and C_j (note both sides of the coils considered)

$$M_{ij} = -\frac{\mu_0}{2\pi A_i A_j} \int_{C_i} \int_{C_j} \ln \|\mathbf{r} - \mathbf{r}'\| \, \mathbf{d}\mathbf{r}\mathbf{d}\mathbf{r}', \tag{1}$$

where A_k is the cross-section area of cable k.

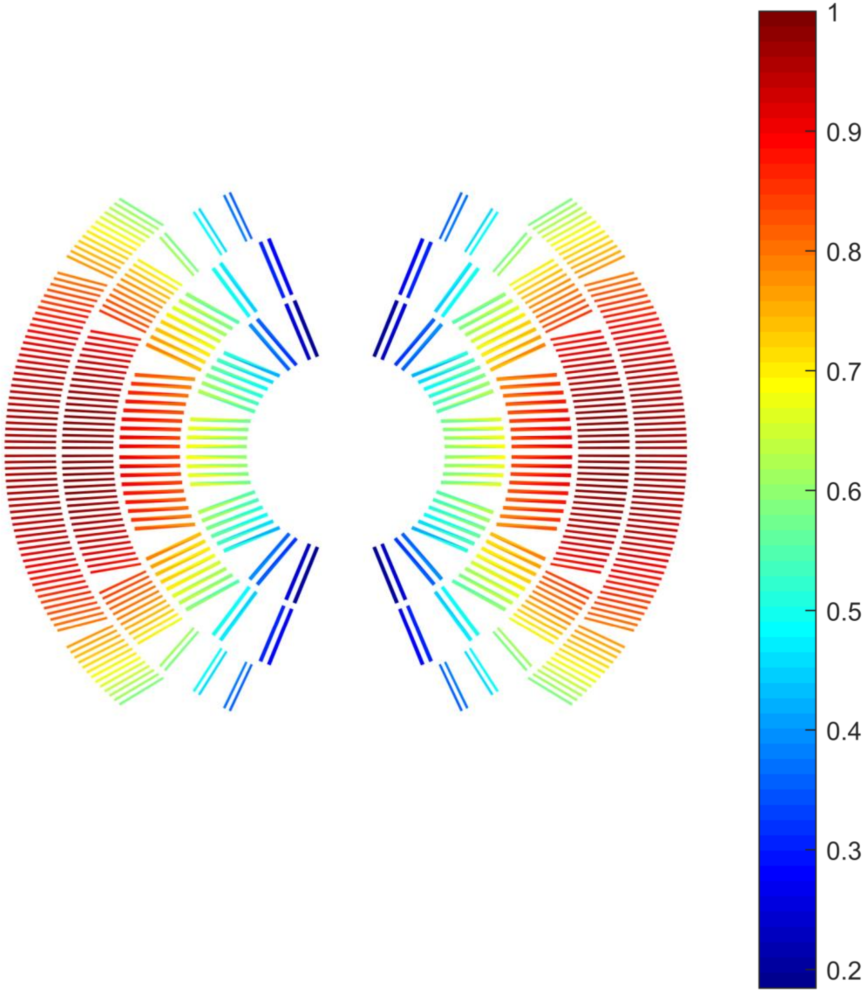
Then, computation of effective inductance L_{eff} for cable C_i when all the cables are in series

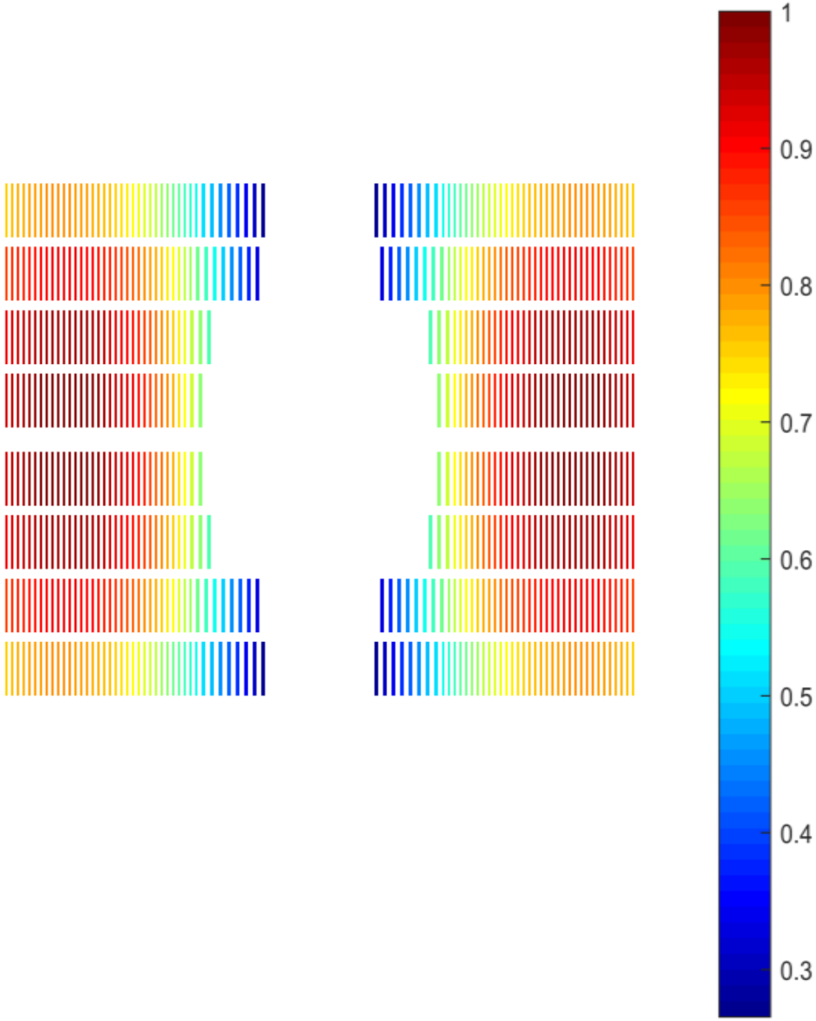
$$L_{eff,i} = \sum_j \text{sign}(I_i)\text{sign}(I_j) M_{ij}, \tag{2}$$

where $\text{sign}(I_k)$ is the direction of current ($+$ or $-$) of cable k.

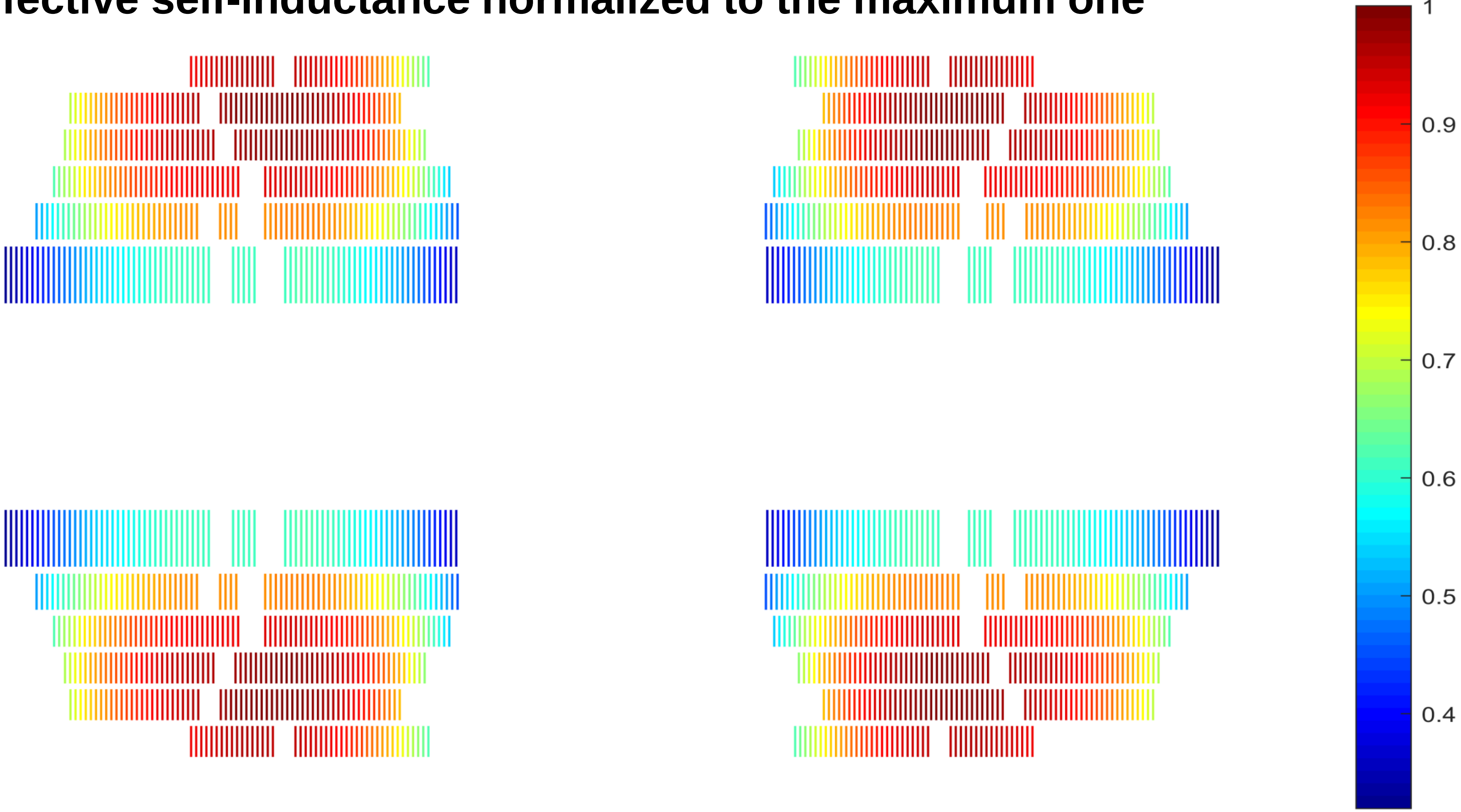
Computation of integrals is done analytically.

Effective self-inductance normalized to the maximum one



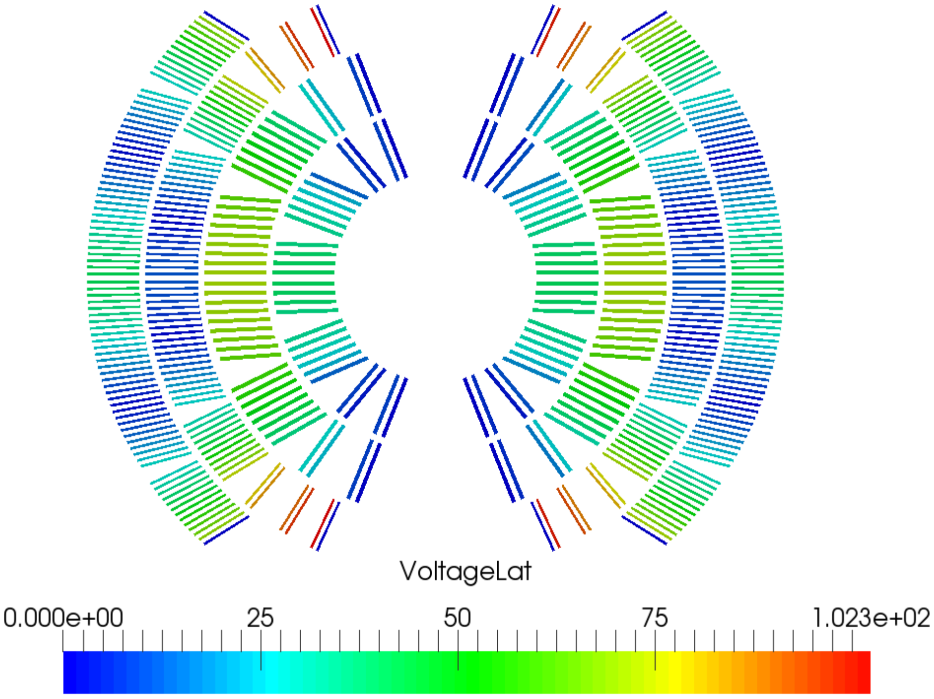


Effective self-inductance normalized to the maximum one

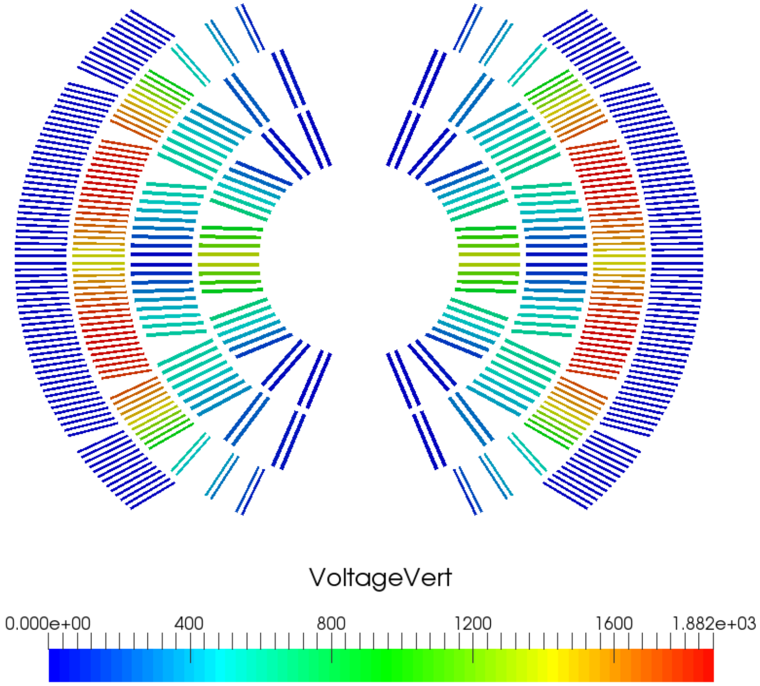


Costheta: Voltages between cables at 190 ms

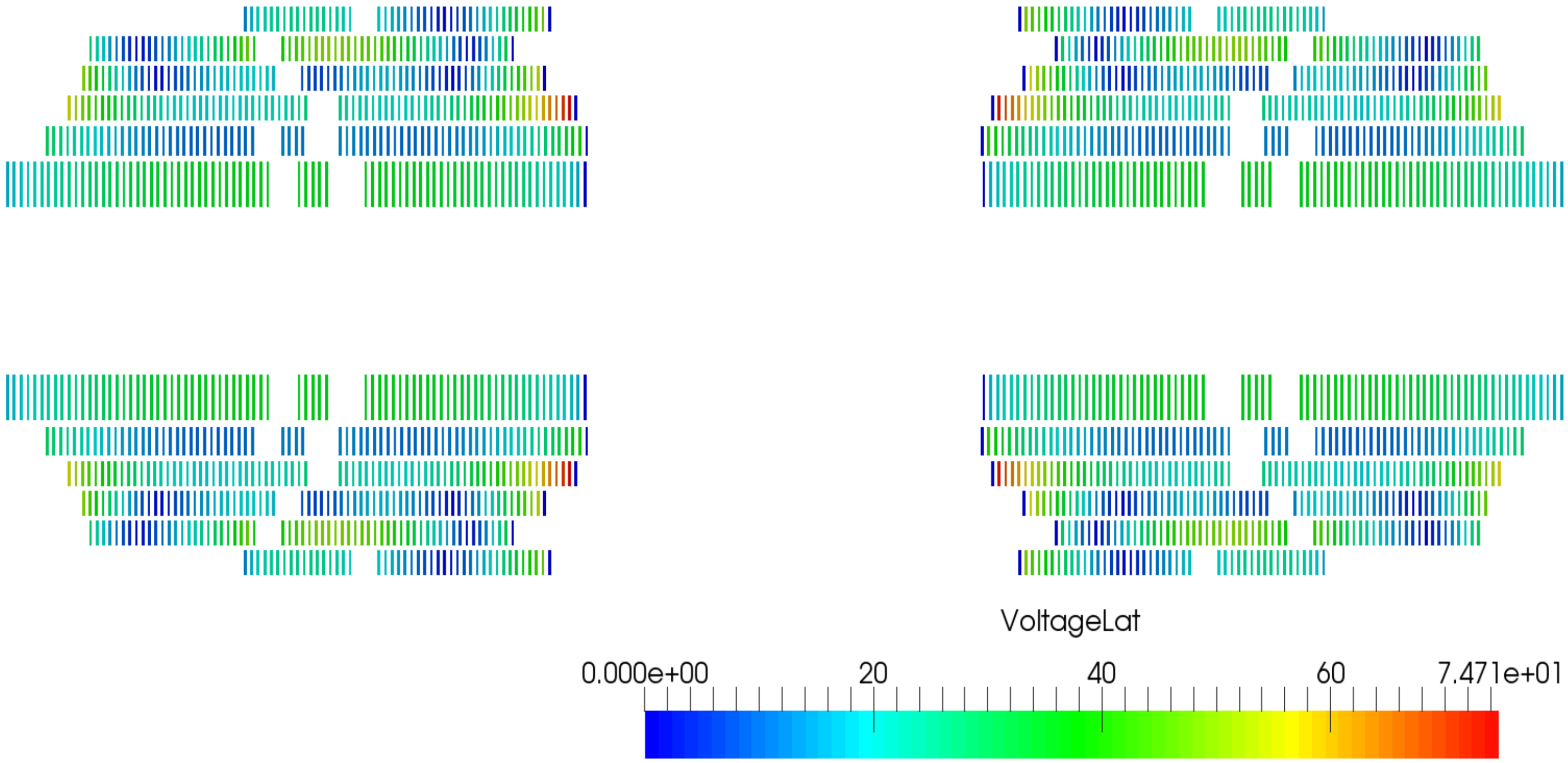
Turn-to-turn (Laterally adjacent turns)



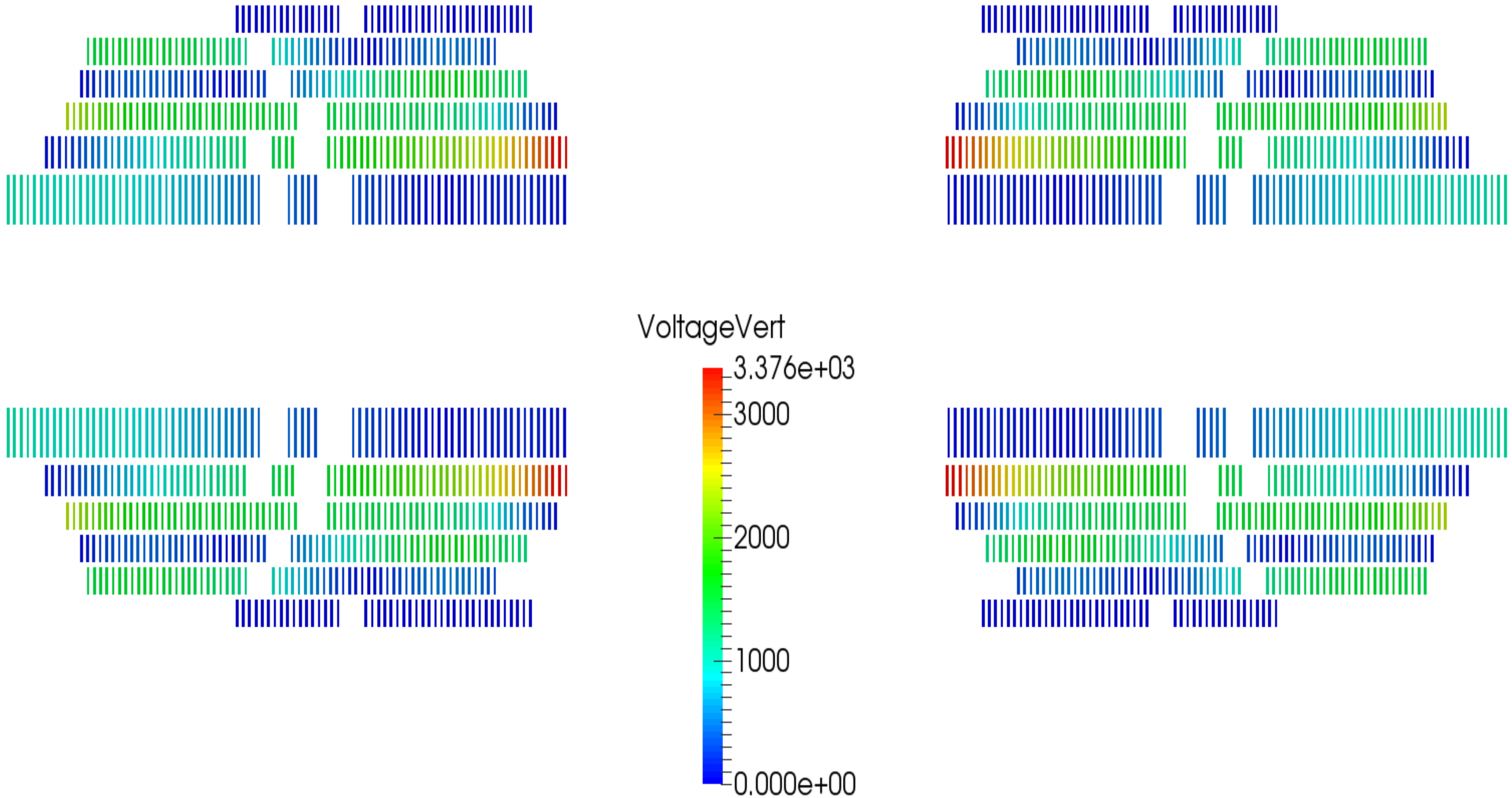
Layer-to-layer (vertically adjacent turns)



CommonCoil v1h_intragrad_t2: Turn-to-turn voltages at ~190 ms

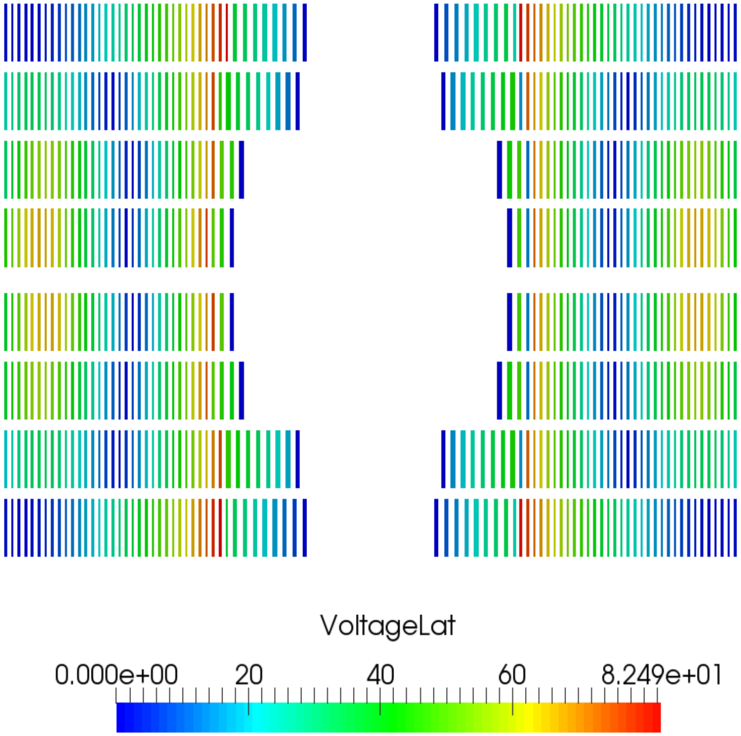


CommonCoil v1h_intragrad_t2: Layer-to-layer voltages at ~190 ms

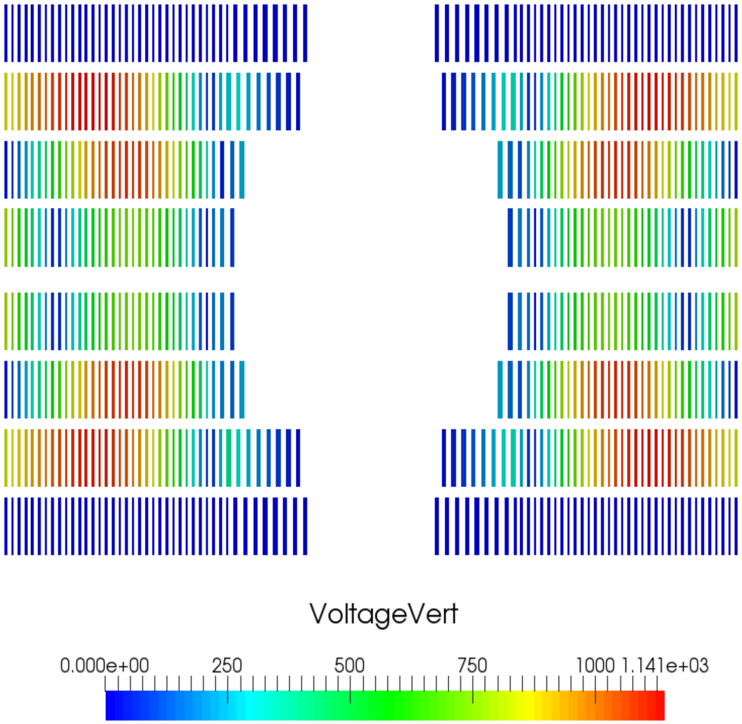


Block_v26b: Voltages between cables at ~160 ms

Turn-to-turn (Laterally adjacent turns)



Layer-to-layer (vertically adjacent turns)



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