EuroCirCol 16 T Nb_3Sn dipoles: Quench protection

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With contributions from

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B. Auchmann (CERN, PSI), J. Ruuskanen (TUT),

and all the EuroCirCol WP5 members

2nd review of EuroCirCol WP5, 9 Oct 2017, CERN

Outline

- Introduction:
  - Quench protection integration in magnet design
  - EuroCirCol 16-T-dipole design options (Cosθ, Block, and Common-Coil)

- Used simulation tools

- The ”40 ms” case

- Protection with quench heaters

- Protection with CLIQ

- Summary and conclusions

- Appendix: More information about the simulation models and results

Introduction

Quench protection integration in magnet design

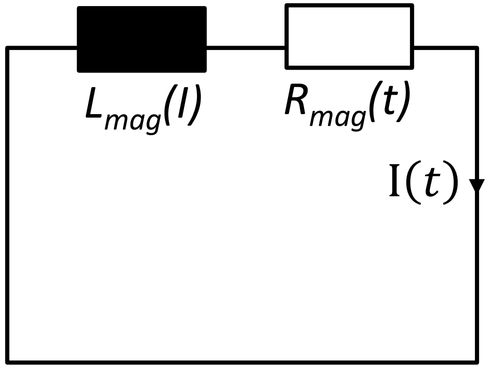
Protection goal:

For a quench at 105% of I_{nom},
T_{max} < 350 K and V_{max} < 1200 V (single magnet)

Magnet design criteria[1]: Protection goal obtainable, assuming

- **20 ms detection time** (incl. validation, etc.)
- **20 ms for the protection system to quench entire coil**
- No dump resistor
- No AC-loss, no heat diffusion
  - Simulation tools developed for fast-feed back analysis

The ”40 ms” criterion



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

Conceptual protection designs:

Protection schemes based on **quench protection heaters, or CLIQ**

❖ This presentation covers the protection of a single magnet. The circuit is perspective is given in the next talk by M. Prioli

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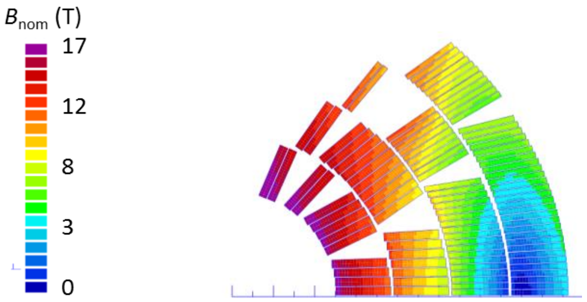
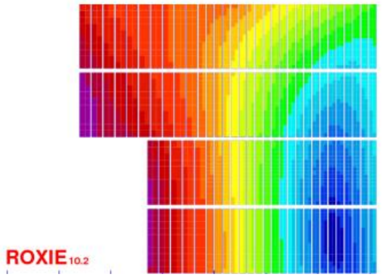
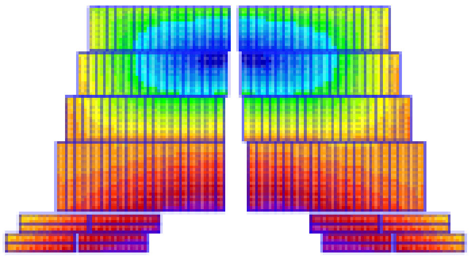
[1] T. Salmi et al., “Quench protection analysis integrated in the design of dipoles for the Future Circular Collider”, Phys. Rev. Accel. Beams 20, 032401

EuroCirCol 16-T-dipole design options







Magnet, version	Cosθ, 22b-37-optd7f8		Block, V2ari194		CommonCoil, vh12_2ac6	
Inom (A)	11240		10000		16400	
Ld,nom (mH/m)	2 x 19.8		2 x 24.8		21.1 (2-ap.)	
Cable	**HF-cable**	**LF-cable**	**HF-cable**	**LF-cable**	**HF-cable**	**LF-cable**
Cable *w* x *t* (bare) (mm)	13.2 x 1.950	13.65 x 1.264	12.6 x 2.0	12.6 x 1.27	19.2 x 2.2	12.0 x 2.2
Number of strands	22	37	21	34	30	18
Strand diam. (mm)	1.1	0.7	1.1	0.7	1.2	1.2
Cu/SC	0.85	2.2	0.8	2.0	1.0	2.5
Cable ins. (mm)	0.15					
RRR	100					
Fil. twist (mm)	14					
Jc-fit	From B. Bordini with T_{c0} = 16 K, B_{c20} = 29.38 T, α = 0.96, C_0 = 267845 A/mm^{2}T					

All 14.3 long

Used simulation tools

The used simulation tools

Coodi[1]

- Calculation of coil temperatures and voltages with heater based protection
  - Used for initial quench analysis
- 2-D cross section of coil
- Adiabatic, no AC-loss
- Inputs:
  - Magnetic field (ROXIE)
  - Turn mutual inductances
  - Heater delays
  - Detection time
  - Quench propag. velocity

Coodi was used for the intial quench analysis for all magnets. An Excel spreadsheet implementation for temperature calculation was provided for magnet designers.

CoHDA[2]

- Calculation of heater delay
- 2-D model for one coil turn, longitudinally
- Heat generation in heater and diffusion to cable
  - 2-D heat equation to solve

LEDET[3]

- Calculation of coil temperatures and voltages for CLIQ based protection
- 2-D cross section of coil
- Computes interfilament coupling loss
- Inputs:
  - Magnetic field (ROXIE)
  - Turn mutual induct. (ROXIE)
  - Detection time

STEAM[4]

- LEDET-Pspice co-simulation of multi-CLIQ configurations

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[2] 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.

[2] T. Salmi et al., “Quench protection analysis integrated in the design of dipoles for the Future Circular Collider”, Phys. Rev. Accel. Beams 20, 032401

[3] E. Ravaioli et al., “Lumped-Element Dynamic Electro-Thermal model of a superconducting magnet”, Cryogenics, 2016.

[4] L. Bortot, , “A consistent simulation of electrothermal transients in accelerator circuits,” *IEEE TAS,* 27(4), 2017.

The ”40 ms” case using Coodi

Coodi benchmark

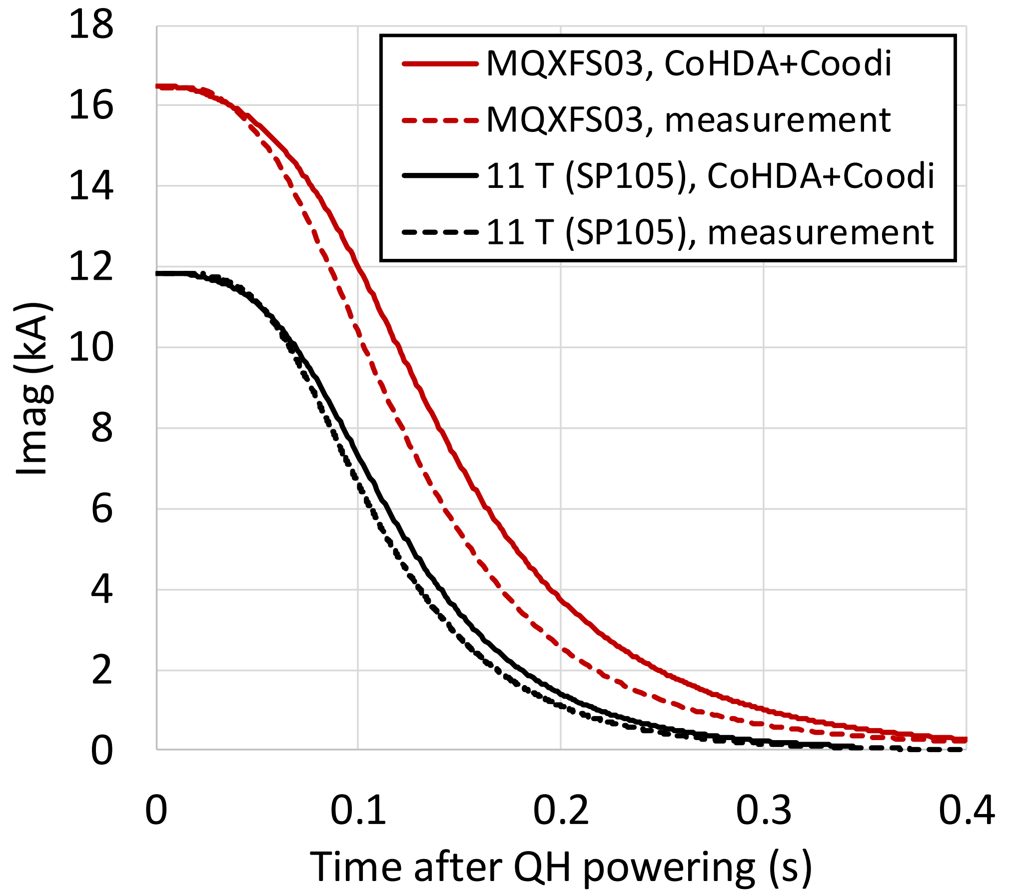
- Comparison with experimental data[1,2]: **At I_{nom}, simulated MIITs larger by 7-15%** (to 25-40 K in Coodi adiab. comput.)

HL-LHC magnets tested at CERN:
Experimental data thanks to
H. Bajas, G. Willering,
and S. Izquierdo-Bermudez

❖ Test procedure:
1. Magnet stable at I_{nom}
2. Fire all heaters

❖ Simul. with EuroCirCol assumptions

Recent work. Analysis is ongoing!



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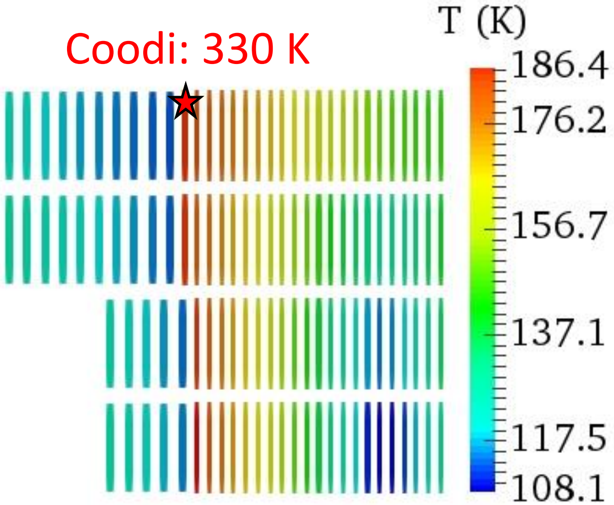
[1] S. Izquierdo-Bermudez et al., "Quench Protection of the 11 T Nb3Sn Dipole for the High Luminosity LHC", Submitted in MT-25

[2] S. Izquierdo-Bermudez et al., " Overview of the Quench Heater Performance for MQXF, the Nb3Sn low-β Quadrupole for the High Luminosity LHC", Submitted in Eucas 2017

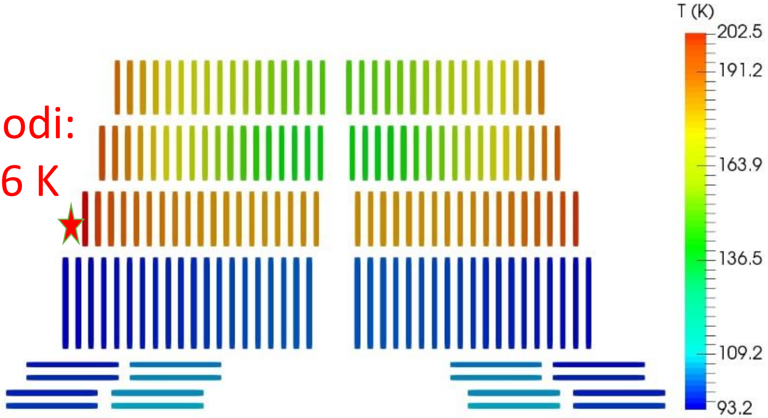
Simulated temperature and voltage after the 20+20=40 ms delay

Coodi: 340 K
(LEDET: 350 K)

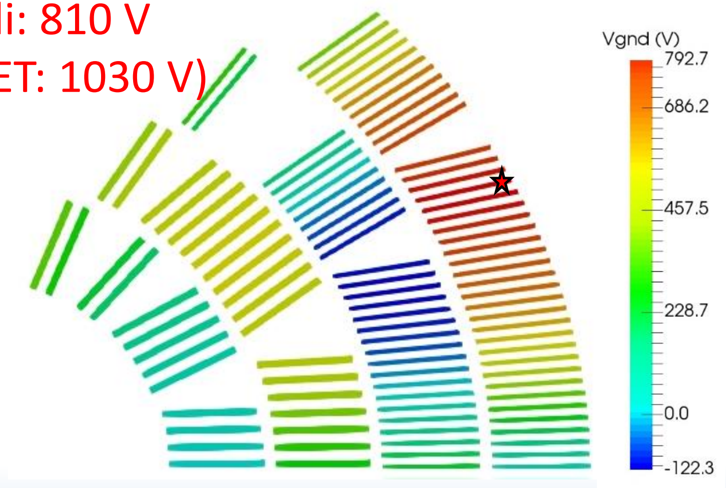
Coodi: 330 K



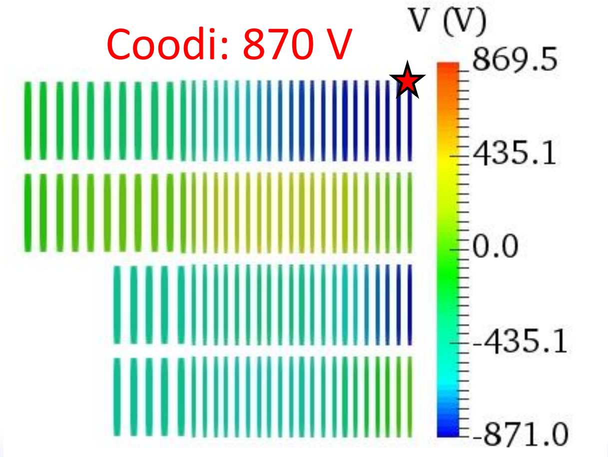
Coodi:
356 K



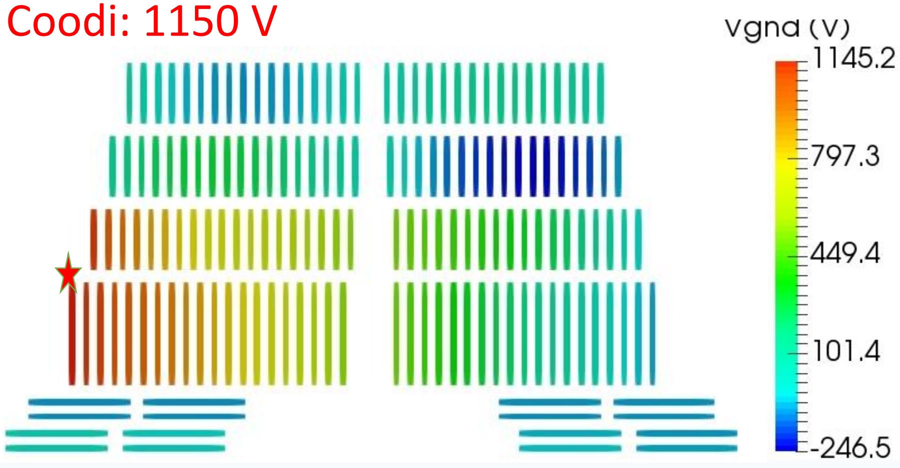
Coodi: 810 V
(LEDET: 1030 V)



Coodi: 870 V



Coodi: 1150 V



- With 20 ms delay the peak temperatures are ~250 – 270 K (Lower limit to temperatures after protection)

Protection with quench heaters (CoHDA + Coodi)

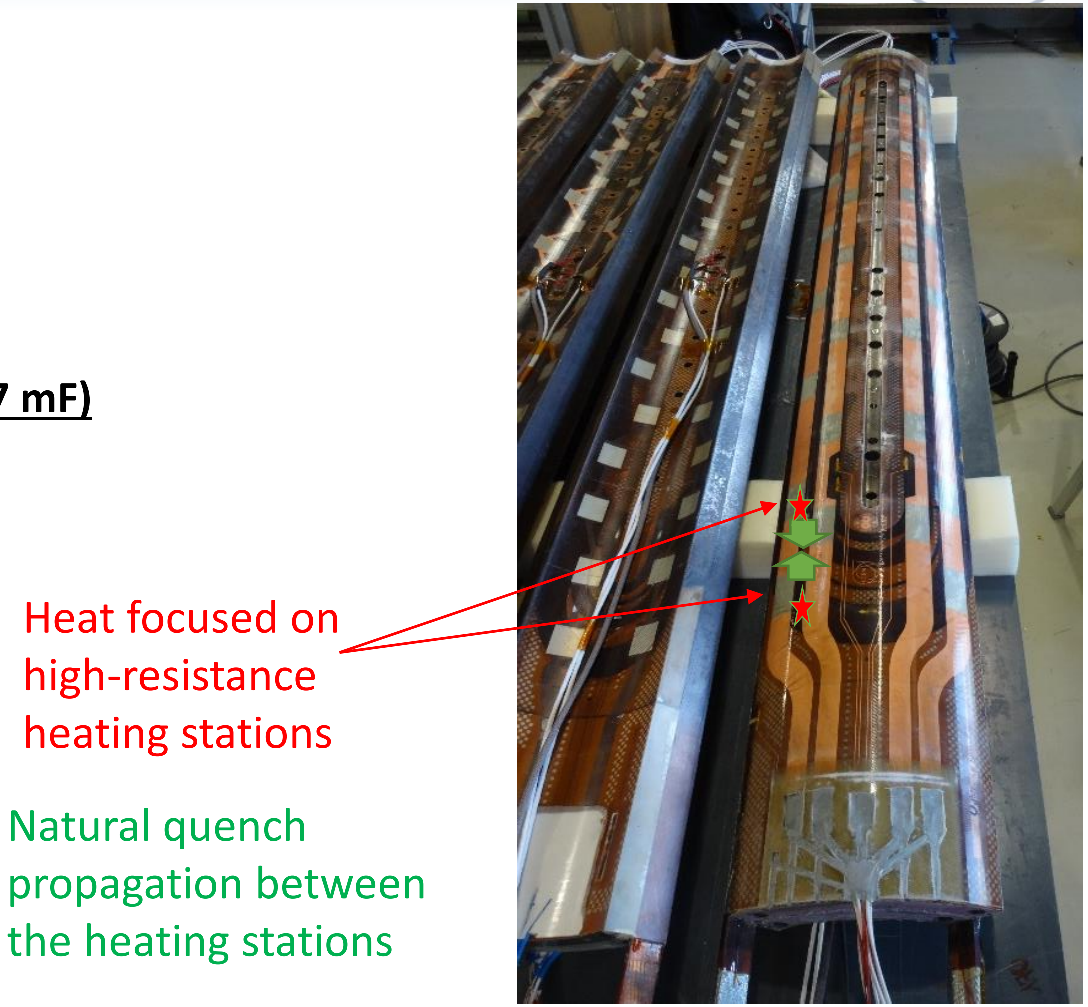
Design of quench heaters

- Heater technology similar than in LHC[1] and HL-LHC[2,3]:
  - Cu-plated stainless steel strips:
    - SS thickness 25 μm, Cu thickness 10 μm
  - **Insulation to coil: 75 μm polyimide**

- Powering with capacitor bank discharge:
  - Heater Firing Unit (HFU): **1000 V and 10 mF (LHC: 900 V and 7 mF)**
  - 1 Ω for wires etc. / circuit

- **Analysis at 105% of I_{nom}**
- Protection checked also at 1000 A

- Goal: Heater design satisfies the requirements and **minimizes the number of HFU's**
  - Further decerase of *T* and *V* possible byt adding more HFU's


Heat focused on high-resistance heating stations

Natural quench propagation between the heating stations

Heaters on HL-LHC quadrupole MQXFS03

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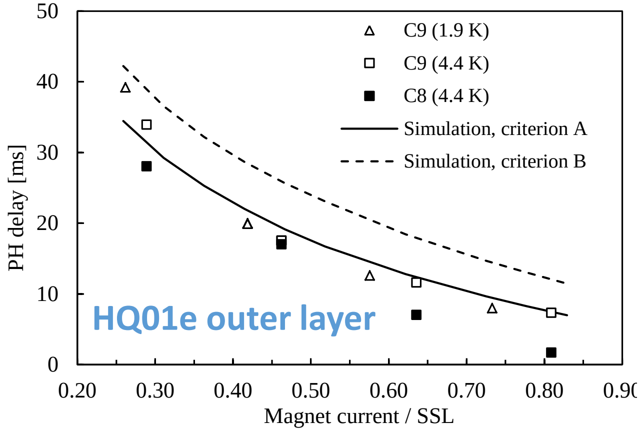
[1] F. Rodriquez-Mateos and F. Sonneman, "Quench heater studies for the LHC magnets", Proc. of PAC, 2001.

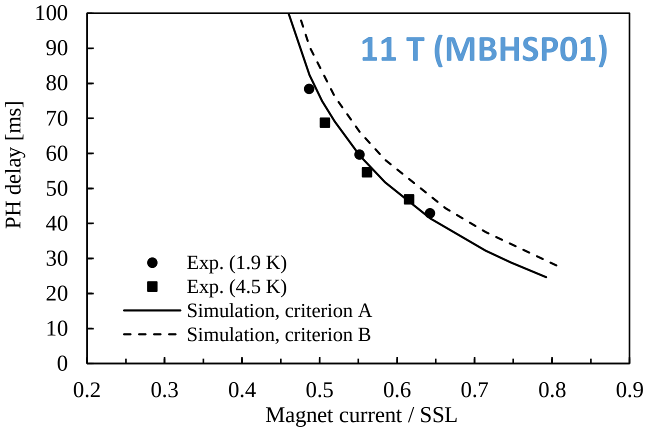
[2] H. Felice et al., "Instrumentation and Quench Protection for LARP Nb3Sn Magnets", *IEEE TAS,* 19(3), 2009.

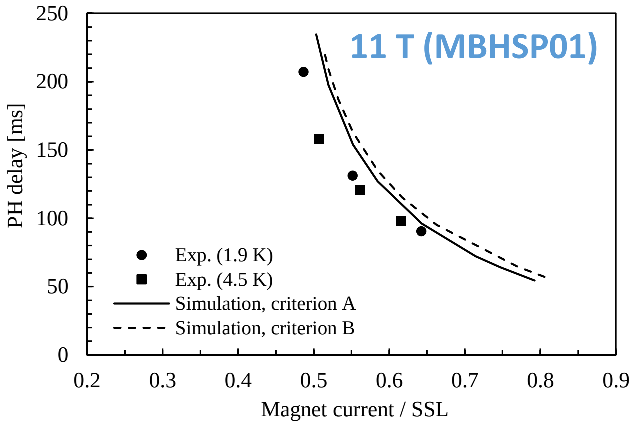
[3] P. Ferracin et al, "Development of MQXF, the Nb3Sn Low-β Quadrupole for the HiLumi LHC ", *IEEE TAS,* 26(4), 2016.

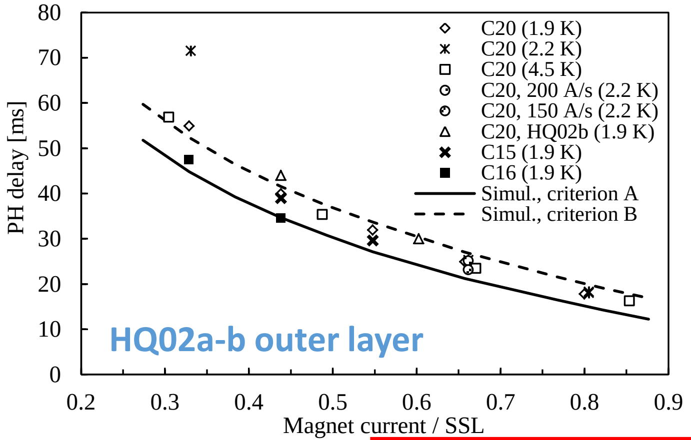
CoHDA benchmark

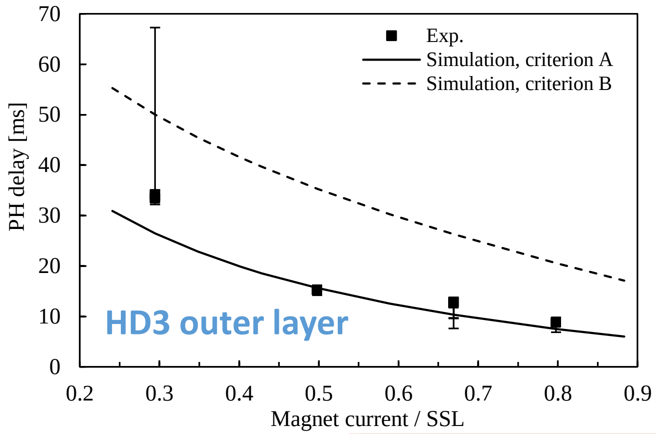
- Comparison with experimental data: **Accuracy 20% at high current** (outer heaters)[1]

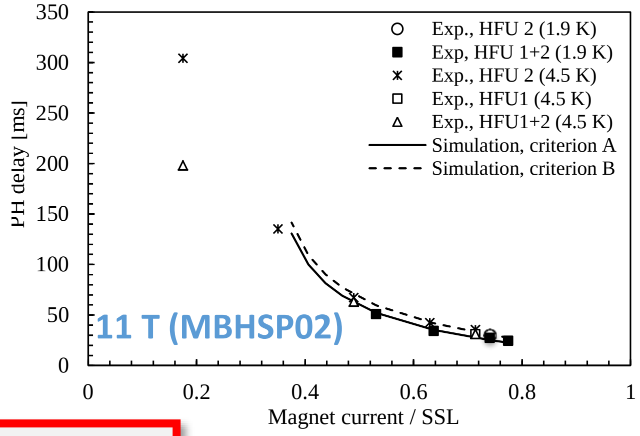












Criterion A: Quench when cable $T_{max} = T_{cs}$.

Criterion B: quench when cable $I_c = I_{mag}$.

”Default” criterion. Used for ECC simulations.

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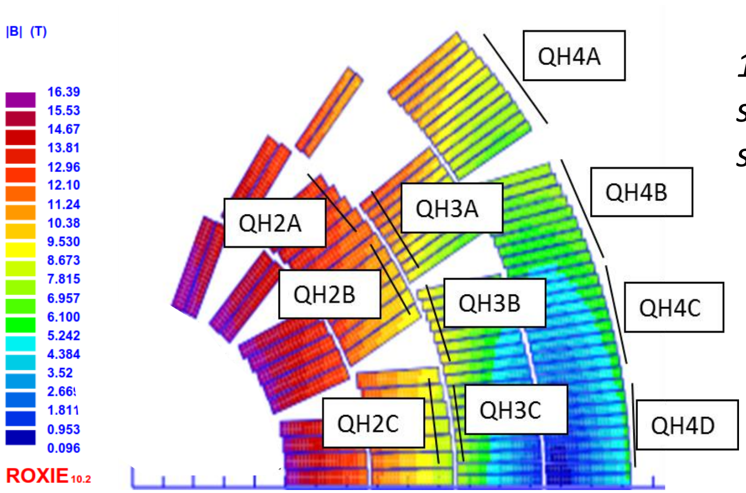
[1] T. Salmi, “Analysis of uncertainties in protection heater delay time measurements and simulations in Nb_3Sn high-field accelerator magnets” *IEEE TAS,* 25(4), 2015.

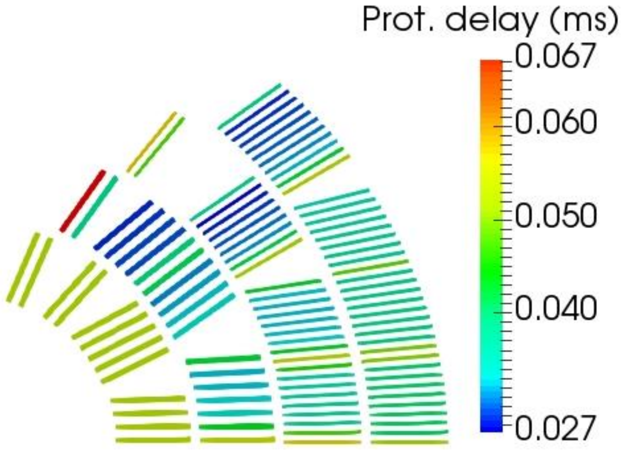
Quench protection with heaters: Cosθ

Location of heater strips:



Each strip is 2 x 14.3 m long: U-shape covering both sides of coil.

Simulated delays:



includes 20 ms det. delay

Heater geometry and powering circuits:

HFU	QH Strips	Strip width (cm)	HS/ period (cm)	$P_{QH}(0)$ (W/cm^2)	τ_{RC} (ms)
#1	2A || 2B || 2A* || 2B*	1.0	5/25	85	38
#2	2C || 3A || 3B || 3C	1.0	5/25	85	38
#3	4A || 4B	1.3	7/40	127	48
#4	4C || 4D	1.3	7/40	127	48

** Strips from the other coil*

→ 7 HFU's / aperture, total E_{stored} 35 kJ

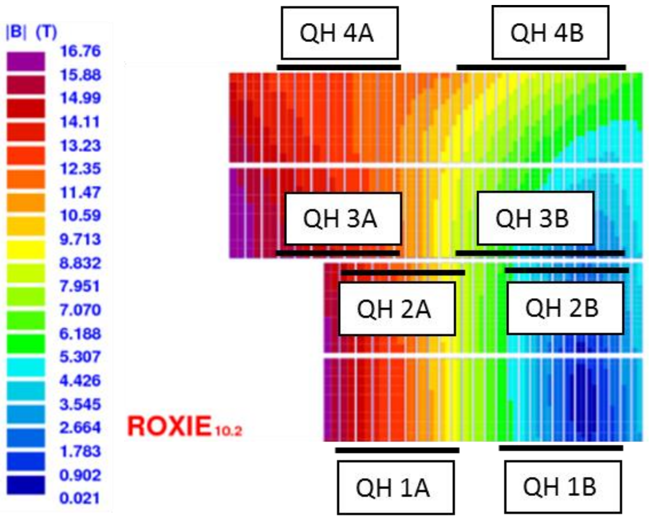
Result of quench simulation:

$$T_{max} = 345\ \mathrm{K},$$
$$V_{gnd} = 950\ \mathrm{V},$$
$$V_{t\text{-}t} = 90\ \mathrm{V},\ V_{l\text{-}l} = 1170\ \mathrm{V}$$

(CoHDA + LEDET: 330 V; 1180 V to gnd)

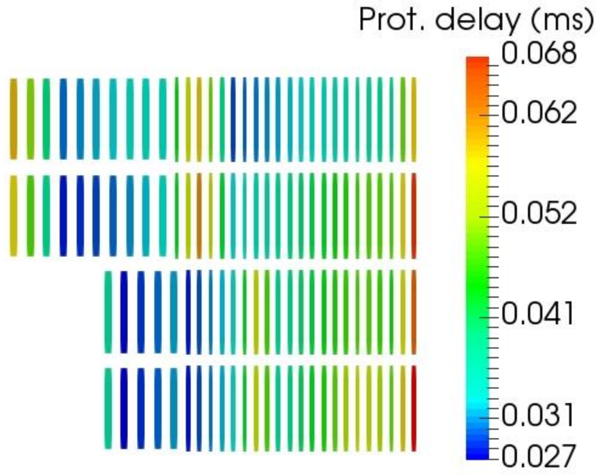
Quench protection with heaters: Block

Location of heater strips:



Each strip is 2 x 14.3 m long: U-shape covering both sides of coil.

Simulated delays:



includes 20 ms det. delay

Heater geometry and powering circuits:

HFU	QH Strips	Strip width (cm)	HS/ period (cm)	$P_{QH}(0)$ (W/cm^2)	τ_{RC} (ms)
#1	1A || 2A	1.8	5/25	90	40
#2	1B	1.8	7/20	145	65
#3	2B	1.8	7/20	145	65
#4	3B || 4B	2.5	7/40	90	30
#5	3A+4A || 3A*+4A* || 3A**+4A** || 3A** + 4A**	1.8	6/60	60	25

** Strips from the other coil., ** Strips from the other aperture*

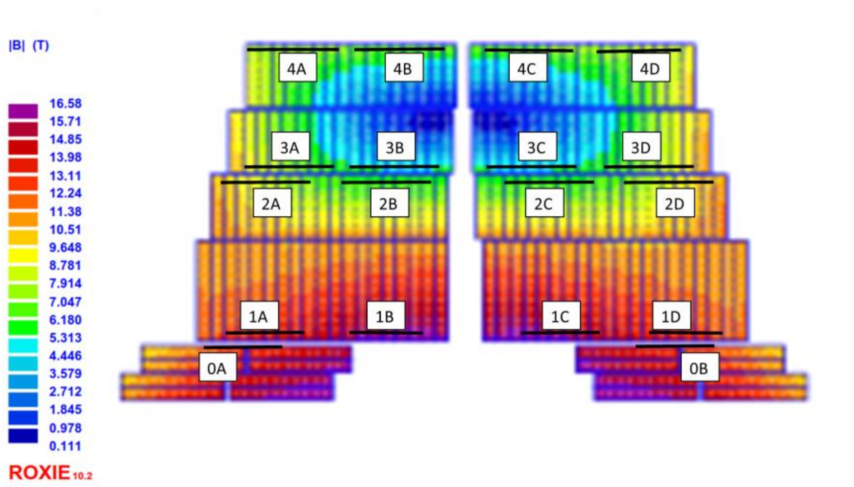
→ 8.5 HFU's / aperture, total E_{stored} 42.5 kJ

Result of quench simulation:

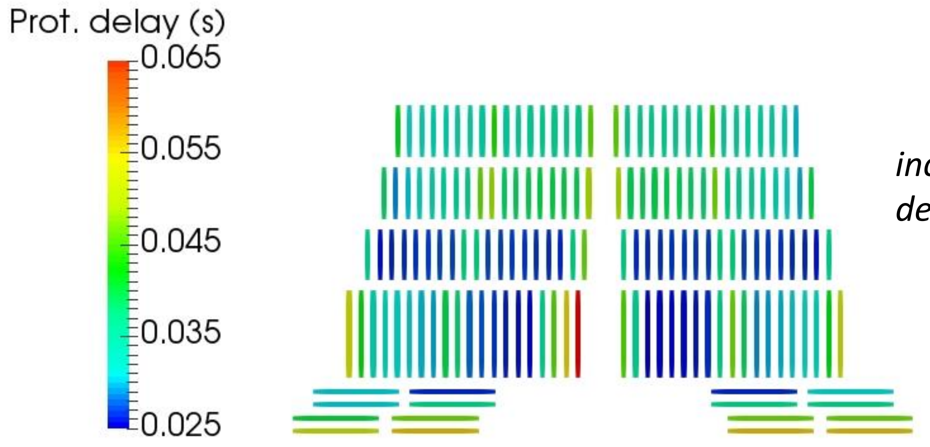
$$T_{max} = 346\text{ K},$$
$$V_{gnd} = 800\text{ V},$$
$$V_{t\text{-}t} = 100\text{ V},\ V_{l\text{-}l} = 990\text{ V}$$

Quench protection with heaters: Common coil

Location of heater strips:



Simulated delays:



includes 20 ms det. delay

Heater geometry and powering circuits:

Circuit	QH Strips	Strip width (cm)	HS/ period (cm)	$P_{QH}(0)$ (W/cm^2)	τ_{RC} (ms)
HFU#1	4A || 4B	1.75	6/40	138	34
HFU#2	4C || 4D	1.75	6/40	138	34
HFU#3	3A || 3B	1.75	6/40	138	34
HFU#4	3C || 3D	1.75	6/40	138	34
HFU#5	2A || 2B	1.75	6/40	138	34
HFU#6	2C || 2D	1.75	6/40	138	34
HFU#7	1A || 1B || 1C || 1D	1.5	4/25	87	26
HFU#8	0A || 0B || 0A* || 0B*	1.5	4/25	87	26

* *Strips from the other coil*

→ 7.5 HFU's / aperture, total E_{stored} 37.5 kJ

Result of quench simulation:

T_{max} = 350 K, V_{gnd} = 1170 V

Some sensitivity analyses for the Cosθ heater design

Heater design:

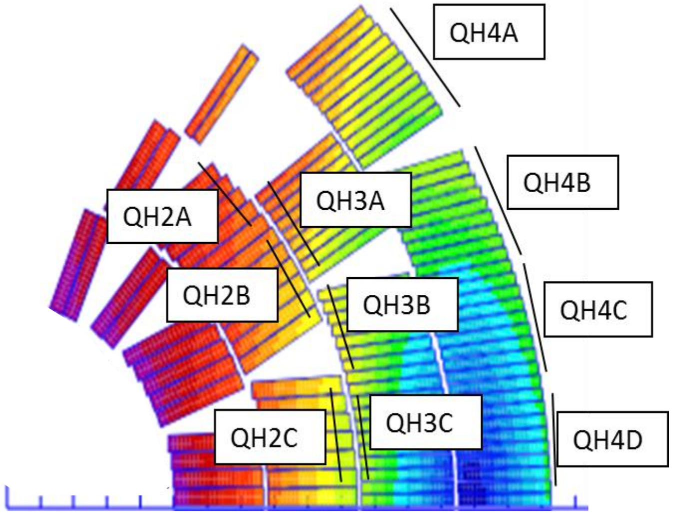
- Increase heater polyimide insulation from 0.075 mm to 0.1 mm
  → T_{max} + 15 K, V_{max} + 60 V

Reference at 105 % I_{nom}:
T_{max} = 345 K, V_{max} = 950 V

Material parameters and model assumptions:

- Heater delays uncertainty (20% increase of heater delay)
- Material properties (Coodi using MATPRO instead of NIST)
- Propagation velocities (reduction of 50%)

→For each: T_{max} + < 25 K, V_{max} + < 300 V

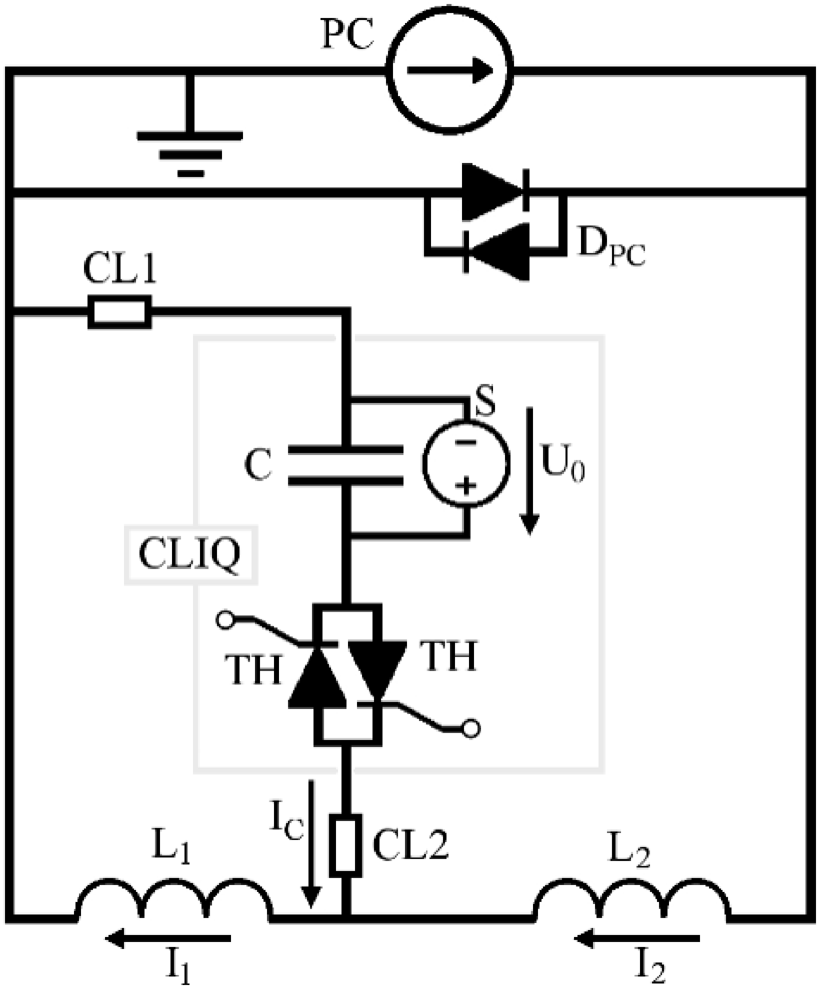


→**Uncertainty (25 K, 300 V) comparable to expected modeling uncertainty**

❖ **Adding inner layer heaters**: → T_{max} - 10 K, V_{max} + 130 V

Protection with CLIQ using LEDET and STEAM: LEDET+STEAM

Protection with CLIQ – Coupling-Loss Induced Quench



CLIQ is a new technology for the protection of superconducting magnets[1]. 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

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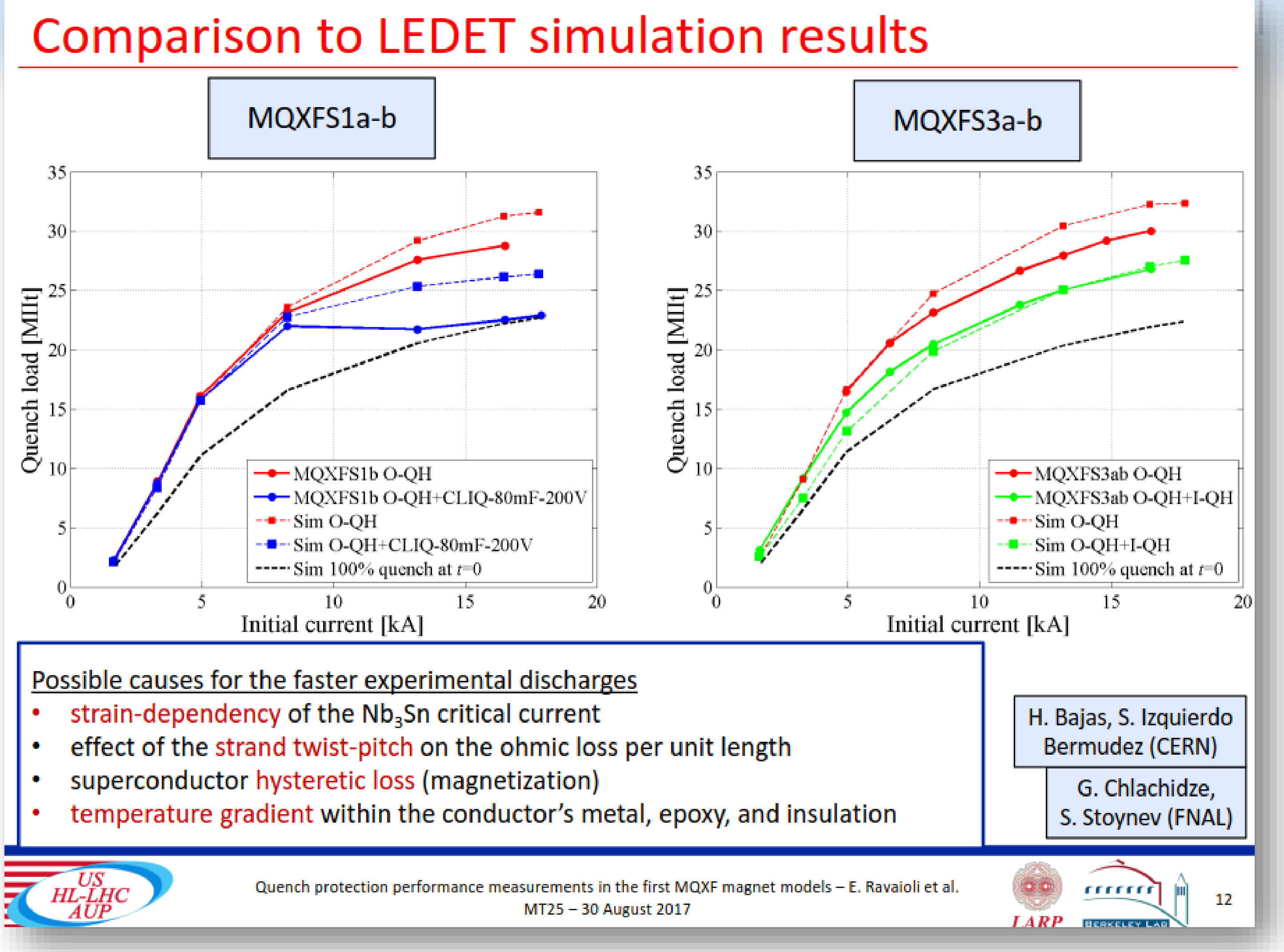
[1] E. Ravaioli, ”CLIQ – A new quench protection technology for superconducting magnets”, PhD thesis, 2015.

LEDET benchmark

Work of E. Ravaioli (LBNL)

- Similar lumped element model than in TALES[1], which was **validated with several magnets**[2,3,4,5]
- LEDET comparison with experimental data[6]: **MIITs are larger than measured at I_{nom}**, except of MQXFS3 with IL+OL heaters, where perfect agreement
- **Quench-back validation**[7]: Good agreement of current decay after fast extraction in MQXFS1 (tests at 20 - 50% of I_{nom})

Slide from E. Ravaioli (LBNL) talk at MT-25



Comparison to LEDET simulation results

Possible causes for the faster experimental discharges

- strain-dependency of the Nb_3Sn critical current
- effect of the strand twist-pitch on the ohmic loss per unit length
- superconductor hysteretic loss (magnetization)
- temperature gradient within the conductor's metal, epoxy, and insulation

H. Bajas, S. Izquierdo Bermudez (CERN)

G. Chlachidze, S. Stoynev (FNAL)

Quench protection performance measurements in the first MQXF magnet models – E. Ravaioli et al.
MT25 – 30 August 2017

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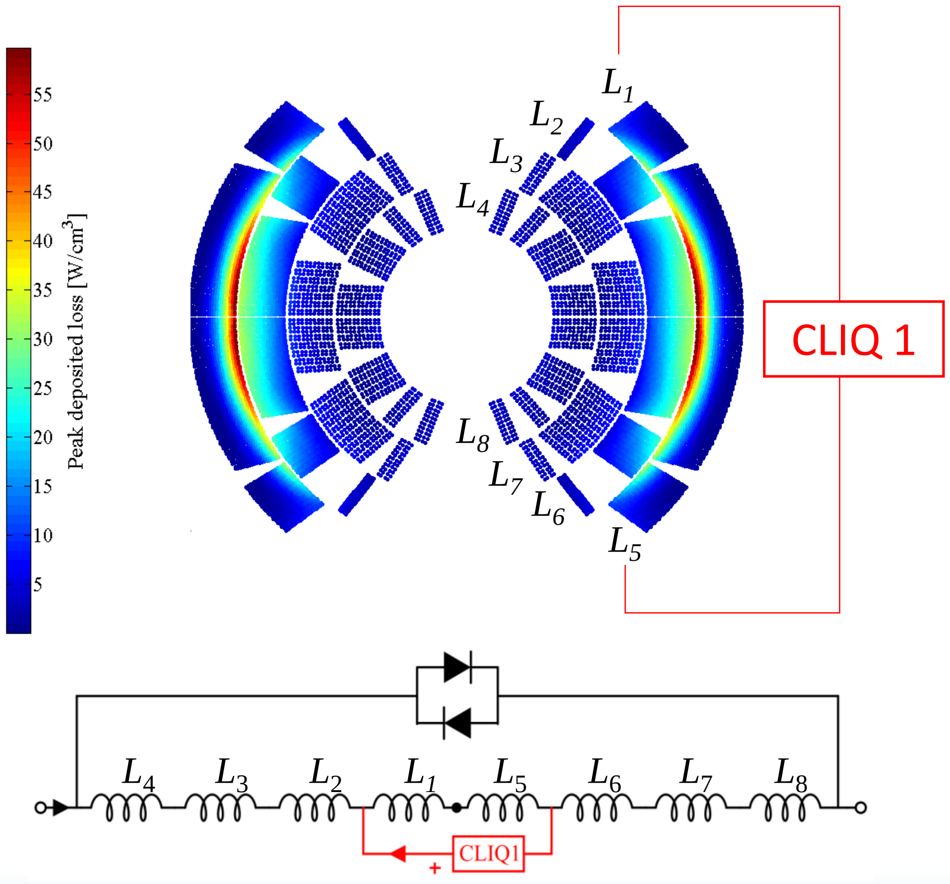
[1] TM. Maciejewski et al., "Automated lumped-element simulation framework for modelling of transient effects in superconducting magnets," MMAR 20, IEEE, 2015, pp. 840–845.
[2] E. Ravaioli et al., "New, Coupling Loss Induced, Quench Protection System for Superconducting Accelerator Magnets," *IEEE TAS,* 24, 2014.
[3] E. Ravaioli et al., "Protecting a Full-Scale Nb3Sn Magnet with CLIQ, the New Coupling-Loss Induced Quench System," *IEEE TAS,* 25, 2015.
[4] E. Ravaioli et al., "First implementation of the CLIQ quench protection system on a full-scale accelerator quadrupole magnet", *IEEE TAS,* 26, 2016.
[5] E. Ravaioli et al., "First implementation of the CLIQ quench protection system on a 14 m long full-scale LHC dipole magnet", *IEEE TAS,* 26, 2016.
[6] E. Ravaioli et al., "Quench protection performance measurements in the first MQXF magnet models", submitted for publication.
[7] E. Ravaioli et al., . "Modeling of Inter-Filament Coupling Currents and Their Effect on Magnet Quench Protection ", *IEEE TAS,* 2017.

Quench protection with CLIQ: Cosθ

Work of M. Prioli (CERN)

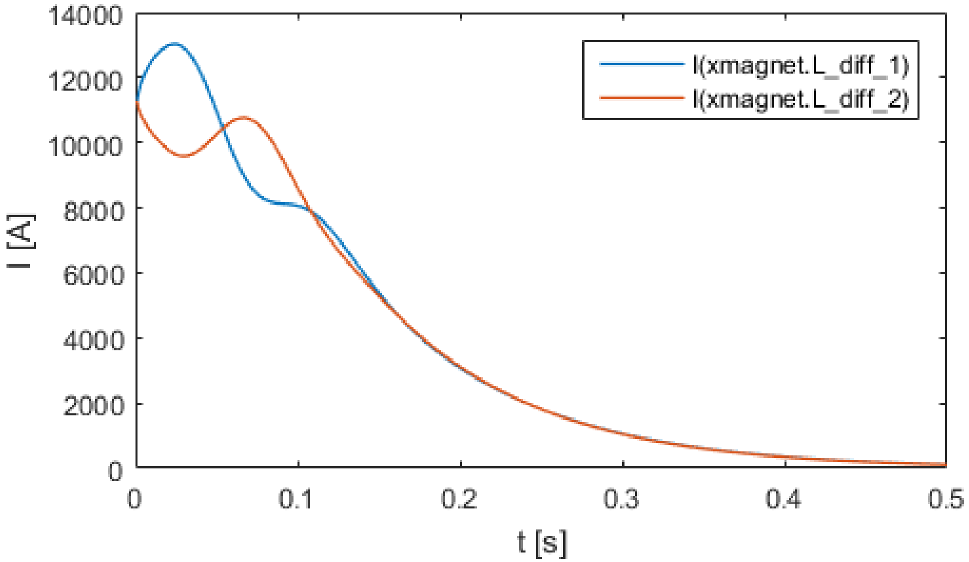
CLIQ configuration, and location of coupling losses:



CLIQ unit with 40 mF, charged to 1250 V

→ 1 CLIQ units / aperture, total E_{stored} 29 kJ

Current decay:



Result of quench simulation:

T_{max} = 315 K,

V_{gnd} = 1000 V

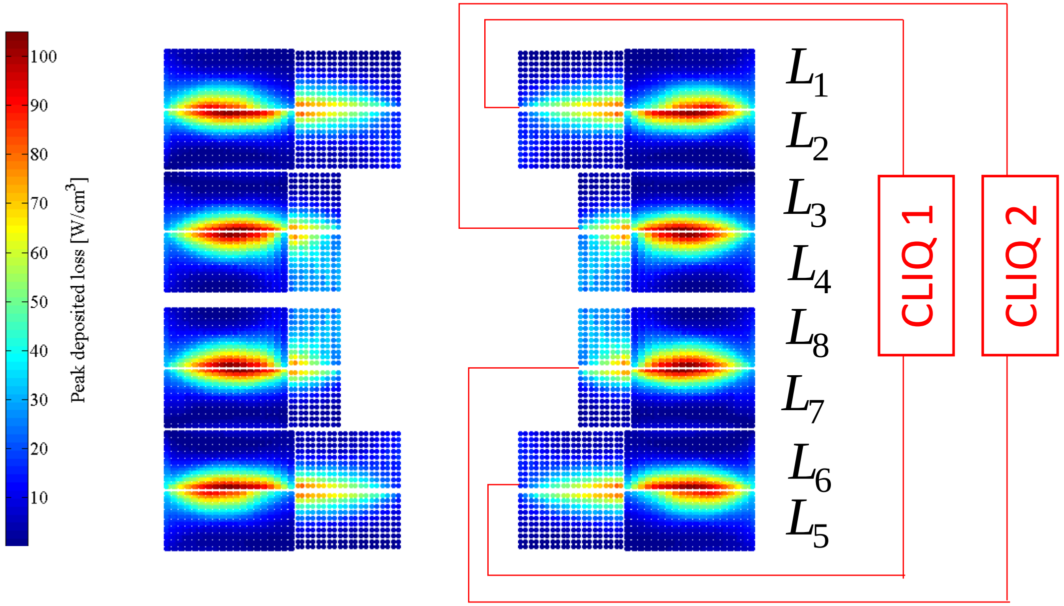
Simulation with LEDET

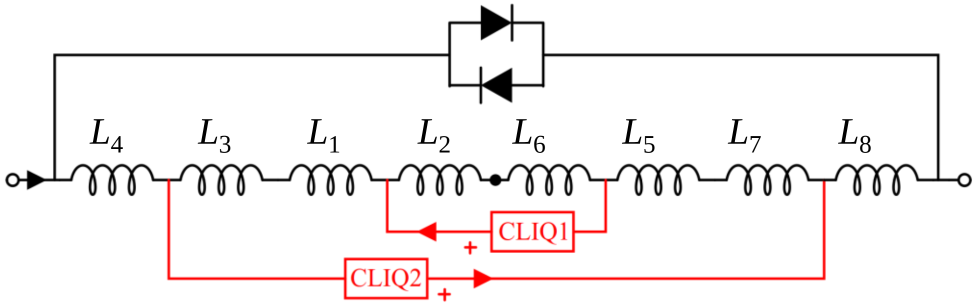
*Version V20ar, parameters in appendix

Quench protection with CLIQ: Block*

Work of M. Prioli (CERN)

CLIQ configuration, and location of coupling losses:

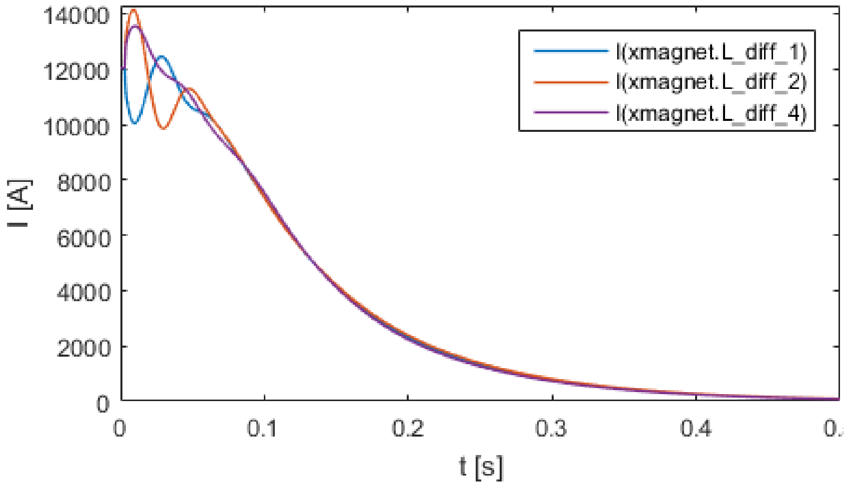




Each CLIQ has 40 mF, charged to 800 V

→ 2 CLIQ units / aperture, total E_{stored} 25.6 kJ

Current decay:



Result of quench simulation:

T_{max} = 300 K,

V_{gnd} = 900 V

Simulation with STEAM:
LEDET+PSPICE

Summary and conclusions

Summary of the protection performances @ 105% Inom

Protection with heaters

	Cosθ	Block	C-C	
T_{max} (K)	345	346	350	(limit 350 K)
V_{gnd} (V)	950	800	1170	(limit 1200 V)
$E_{QH\text{-}system,\ 1\text{-}ap}$ (kJ)	35	42.5	37.5	

CoHDA+Coodi

Protection with CLIQ

	Cosθ	Block* V20ar	C-C
T_{max} (K)	315	300	(To be added)
V_{gnd} (V)	1000	900	
$E_{QH\text{-}system,\ 1\text{-}ap}$ (kJ)	29.0	25.6	

LEDET

LEDET+PSPICE

- At I_{nom} hotspot temperature and voltage are smaller by ~15-25 K, and ~100 V (with heaters)

Summary of the models cross-check

- **Peak temperatures from Coodi and LEDET are within 20 K, voltages within 300 V**

EuroCirCol Cosθ at 105% of I_{nom}, 40 ms delay

	Coodi	LEDET
T_{max} (K)	340	350
MIITs (10^6A^2s)	19.7	19.1
V_{gnd} (V)	810	1030

EuroCirCol Cosθ at 105% of I_{nom} , with heaters

	CoHDA+Coodi	CoHDA+LEDET
T_{max} (K)	345	333
MIITs (10^6A^2s)	20.0	18.6
V_{gnd} (V)	950	1180

❖ In the ”40 ms” case different way to model strand accounts for the difference in T_{max} and MIITs (but not for the voltages)

❖ In the case with heaters, the association of heater delays to entire turn (no heating stations) and faster quenching of IL turns due to quench-back, accounts for the lower T_{max} and MIITs in LEDET

❖ V_{gnd} is very sensitive to the coil resistance distribution, and mutual inductance computation

Conclusions

- **Quench protection integrated in the 16 T dipole magnets design from beginning**
  - At 105% of I_{nom} assumed protection efficiency 40 ms, and required T_{max} < 350 K, V_{max} < 1200 V

↓

- **Two technical systems available for magnet protection:**
  - Quench heaters: T_{max} 340 – 350 K and V_{max} 1000 – 1200 V
  - CLIQ: T_{max} 300 - 320 K, 900 – 1000 kV (demonstrated for Block and Cosθ)

- At the moment the main safety margin comes from neglecting the AC-loss **– Simulation seems conservative by 20-40 K based on comparison with HL-LHC magnets – This is comparable to the simulation uncertainty.**
  - Voltage calculaton is very sensitive to simulation assumptions, and uncertainty is several hundreds of V

- Experimental validation, iteration of assumptions, and further software development is ongoing

Appendix

List of simulation assumptions

- Material properties based on NIST data (exception Nb3SN specific heat)
- The cable voids are filled with G10 in Coodi and LEDET, and with Epoxy (CryoComp) in CoHDA
- After quenching, magnet current goes straight in the cable (does not follow the wavy strand path)
- Strand twist (elliptical shape of strand cross-section) is accounted in computing the material fractions (not for Jc) in Coodi and CoHDA, and not accounted in LEDET

- Heater delays associated to the cable maximum field
- Hotspot associated to the cable maximum field
- Cable thermal properties associated with cable average field

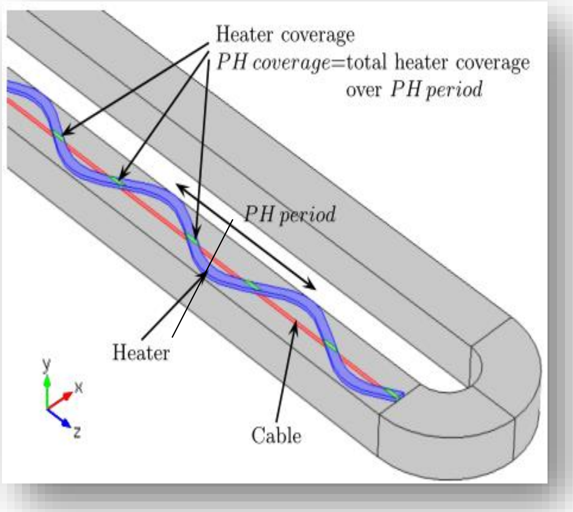
- Quench propagation velocity set in Coodi
    - 20 m/s longit., 10 ms turn-to-turn, 20 ms from second to first layer

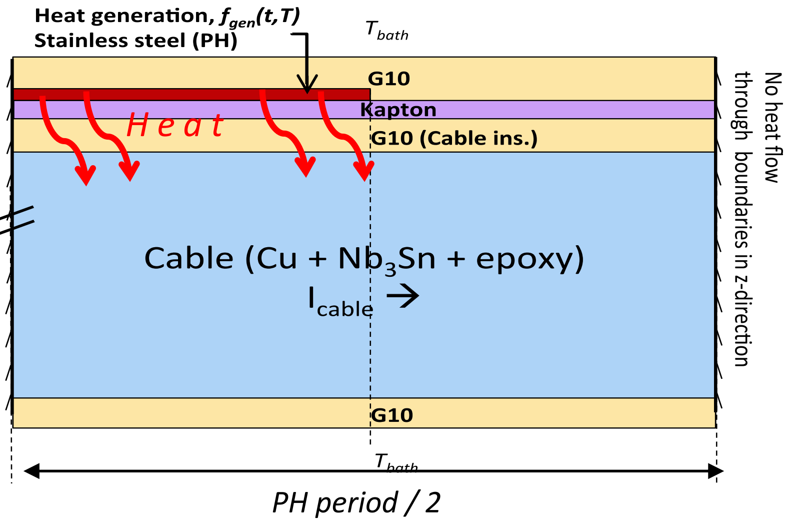
CoHDA: Code for Heater Delay Analysis

IDEA:

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

Photo: Protection heaters in LARP Nb3SN HQ quadrupole.





Heat generation, $f_{gen}(t,T)$
Stainless steel (PH)
T_{bath}
G10
Kapton
Heat
G10 (Cable ins.)
Cable (Cu + Nb_3Sn + epoxy)
I_{cable} →
G10
T_{bath}
No heat flow through boundaries in z-direction
PH period / 2

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*):

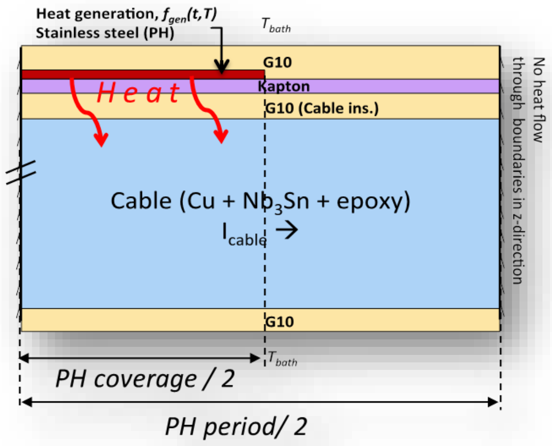
$$f_{gen,ss}(t,T) = \rho_{ss}(T)J_{ss}^2(t)$$

Boundary cond. and init. values:

$$T(z,H,t) = T(z,0,t) = T_{bath}$$

$$q''_z(y,0,t) = q''_z(y,Per_{PH}/2,t) = 0$$

$$T(z,y,0) = T_{bath}$$

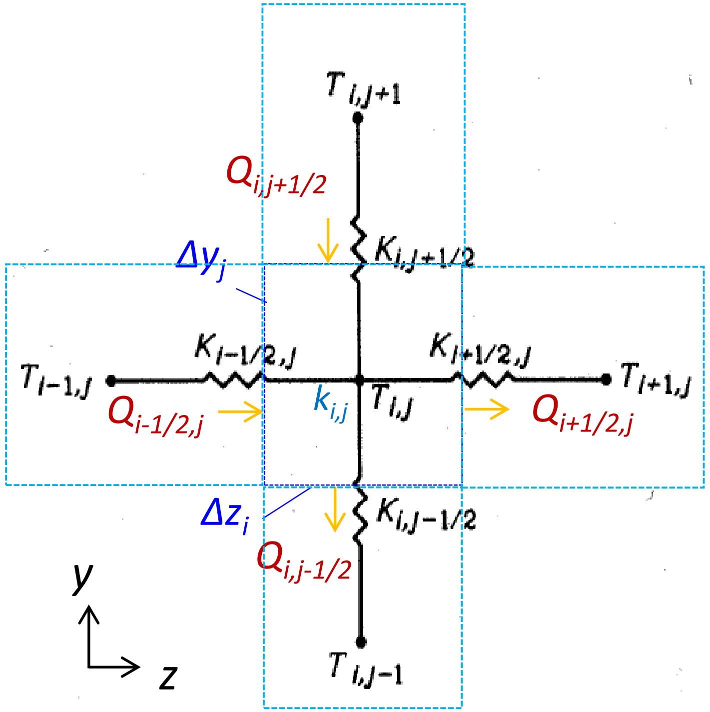


t = time [s], $T = T(t, y, z)$ = Temp. [K], $c_{p,m}(B,T)$ = Specific heat [J/K/kg],
γ = Mass density [kg/m^3], $k_m(B,T)$ = Thermal conductivity [W/K/m],
$f_{gen,m}(t,T)$ = Internal heating [W/m^3], q'' = heat flux [W/m^2],
$\rho_{ss}(T)$ = Electrical resistivity of ss in Ωm, J_{ss} = Current density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

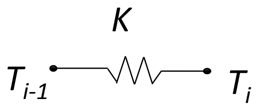
*Can be used also for Joule heating in cable

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:

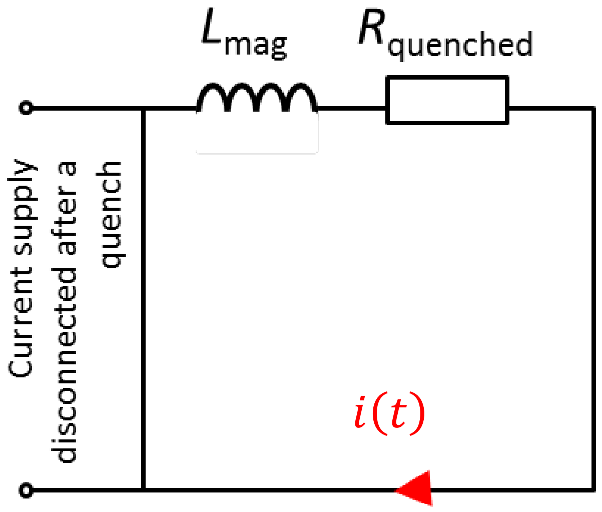
$$T_{i,j}^{new} = T_{i,j} + \frac{\Delta t}{\rho_{i,j}\, c_{p,i,j}\, \Delta z_i \Delta y_j} \cdot \left(Q_{i-\frac{1}{2},j} - Q_{i+\frac{1}{2},j} + Q_{i,j-\frac{1}{2}} - Q_{i,j+\frac{1}{2}} + f_{gen,i,j}\,\Delta z_i \Delta y_j \right)$$

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

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

IDEA:

- Compute 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

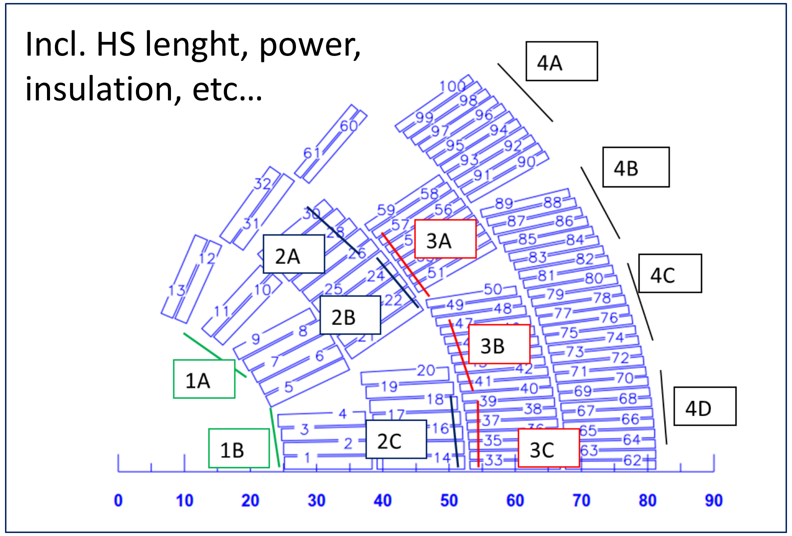
- Magnet length, inductance vs. current (from roxie), operating conditions
- Coil geometry – (coordinates from Roxie field map)

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

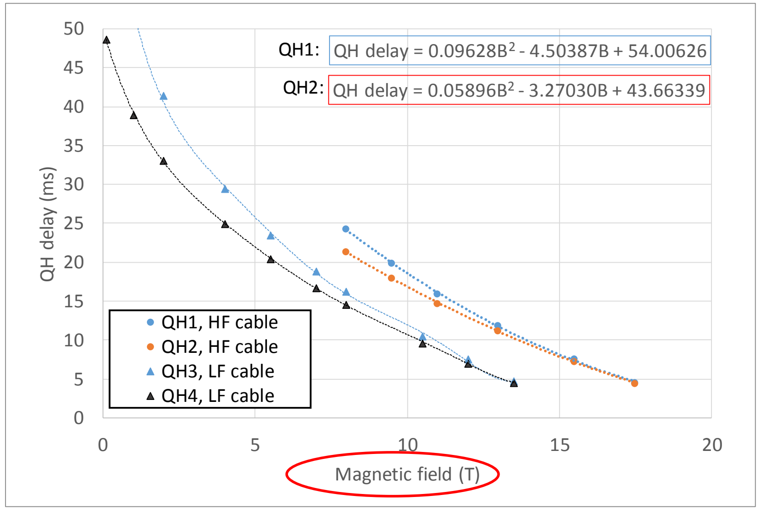
- Coils turns were heaters fail
  - (otherwise all coils are symmetric)

CoHDA+Coodi: Work-flow

1. Heater design


Incl. HS lenght, power, insulation, etc…

With heater delays with CoHDA



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

2. Heater delays preparation to Coodi

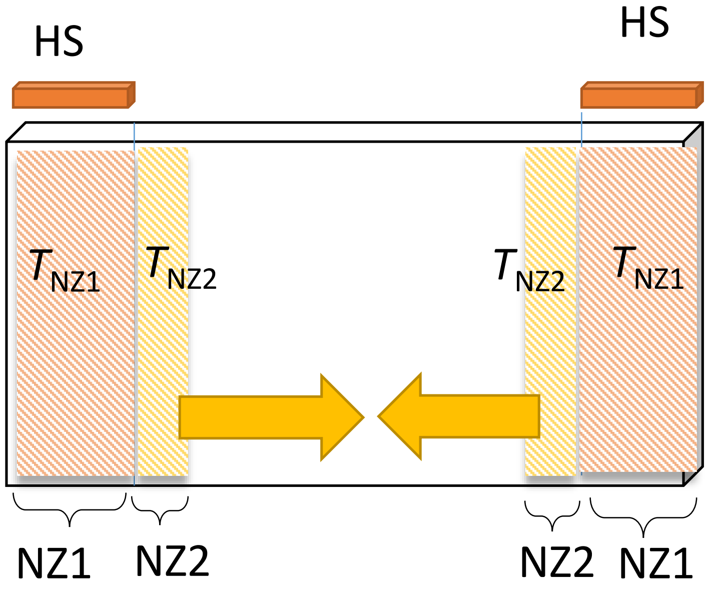
Turn#	QH	B (T)	QH delay (ms)
1	-	16.95	25.4
2	-	16.95	15.4
3	QH1	16.90	5.4
4	QH1	16.78	5.5
5	QH1	16.75	5.6
6	-	16.89	15.6
7	-	16.97	25.3
8	-	17.01	15.3
9	QH1	17.00	5.3
10	QH1	16.89	5.4
11	QH1	16.97	5.3
12	-	16.88	15.3

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*

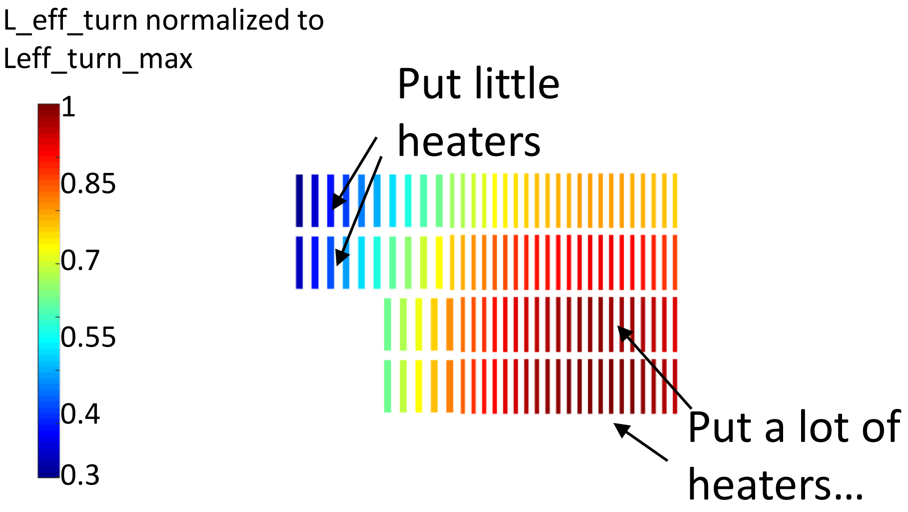
$$\Delta T_{NZ} = \frac{I_{mag}^2 \rho_{Cu}}{A_{cable}^2 f_{Cu}} \Delta t \frac{1}{C_v}$$

*While normal front propagating:

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

About heater design

Heater design for voltage mitigation:

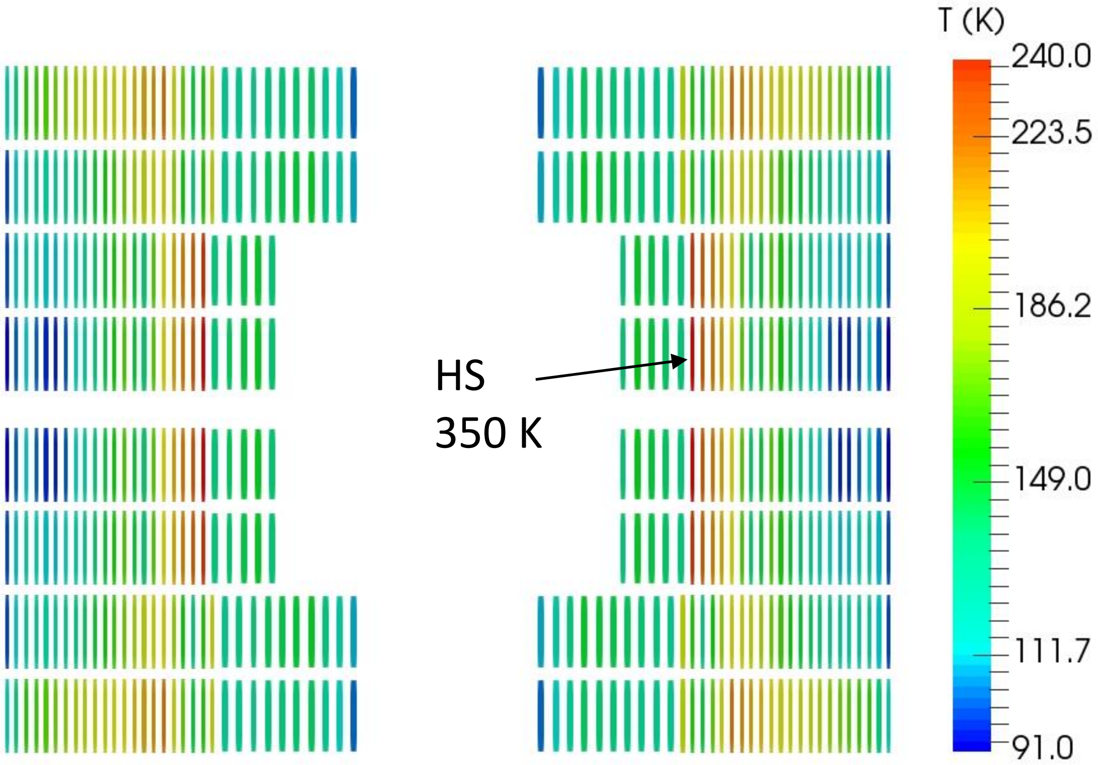


Put little heaters

Put a lot of heaters…

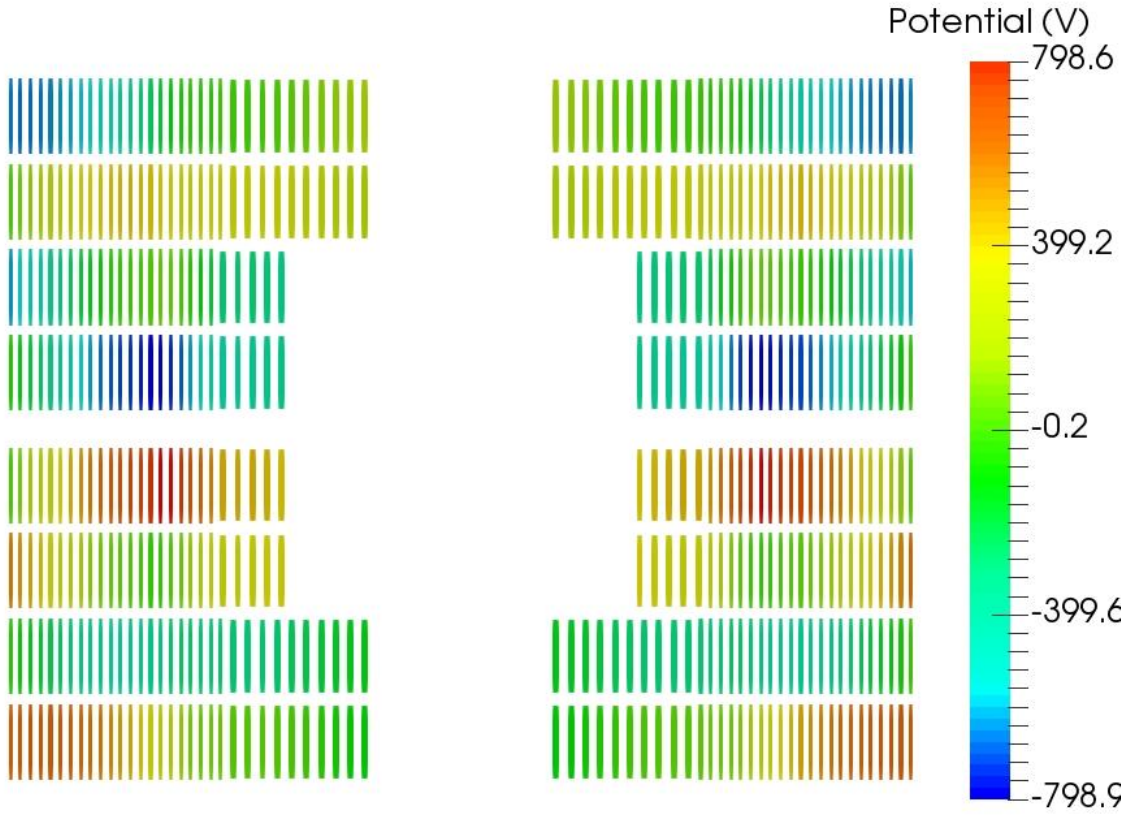
Protection with heaters: Block

Final temperature distribution



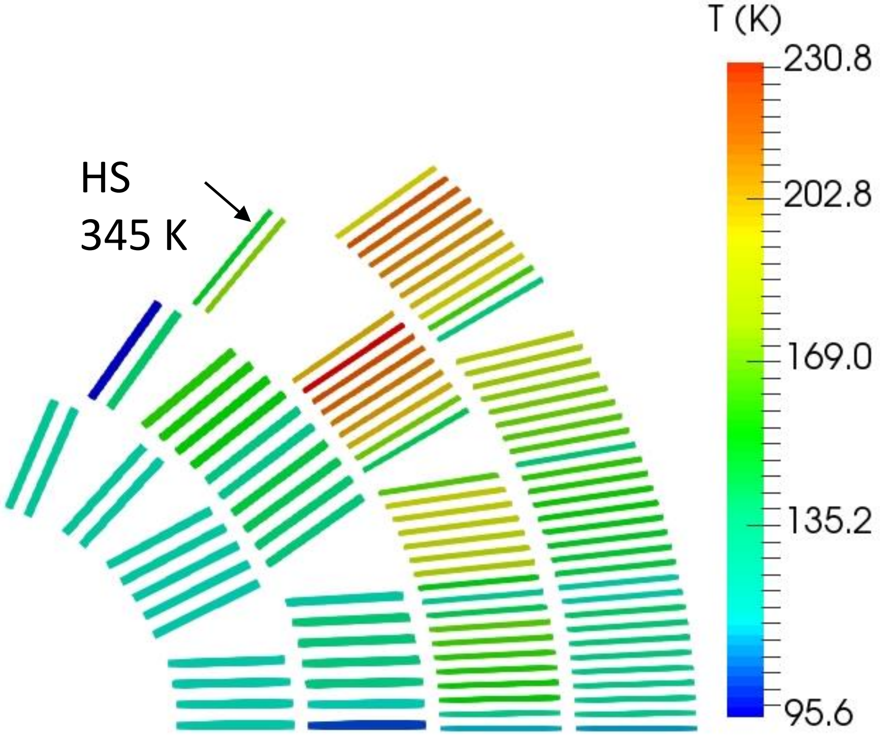
HS
350 K

Voltage to ground distribution (t = 150 ms)

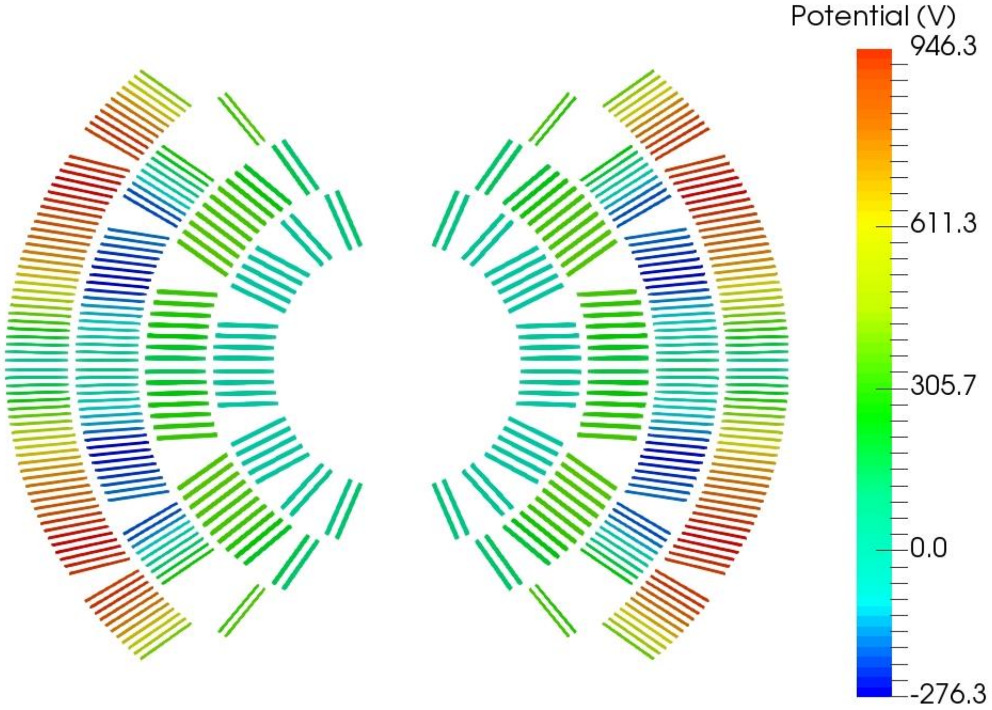


Protection with heaters: Cosθ

Final temperature distribution

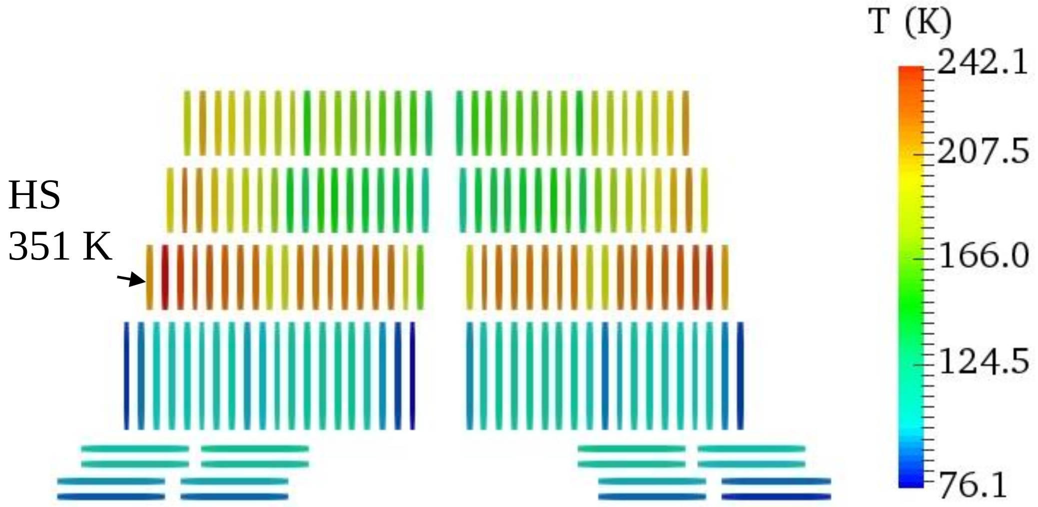


Voltage to ground distribution

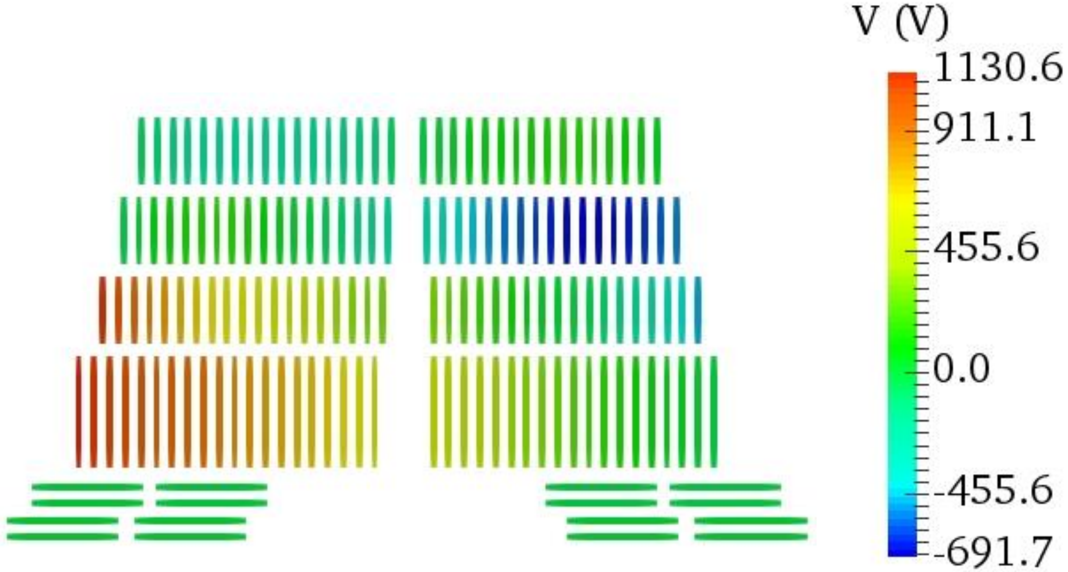


Protection with heaters: Common-Coil

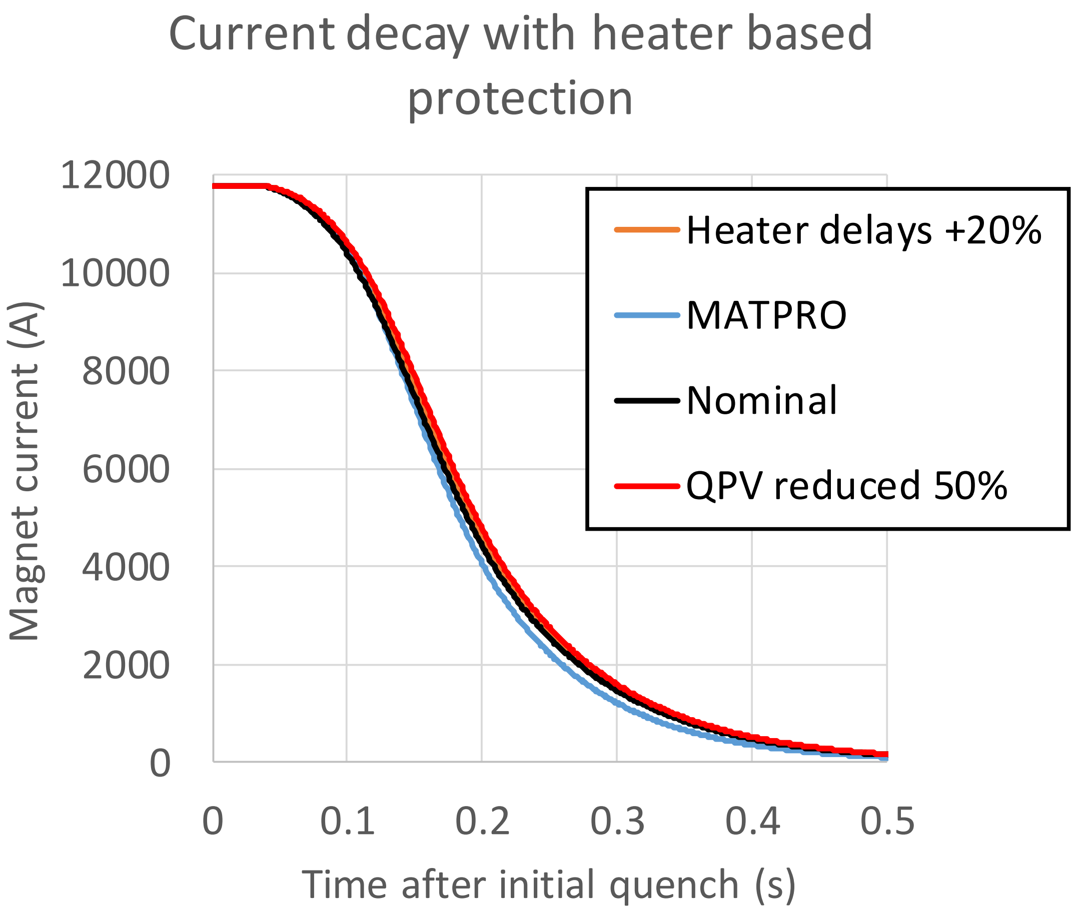
Final temperature distribution

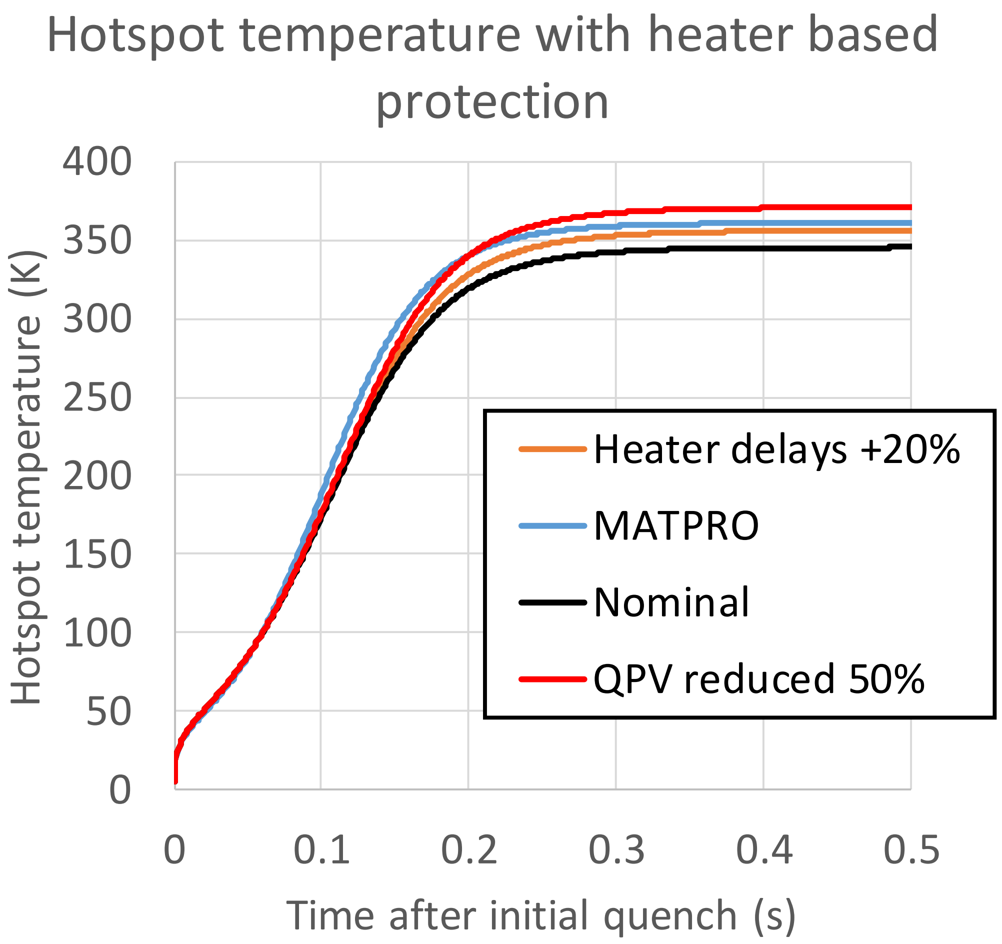


Voltage to ground distribution

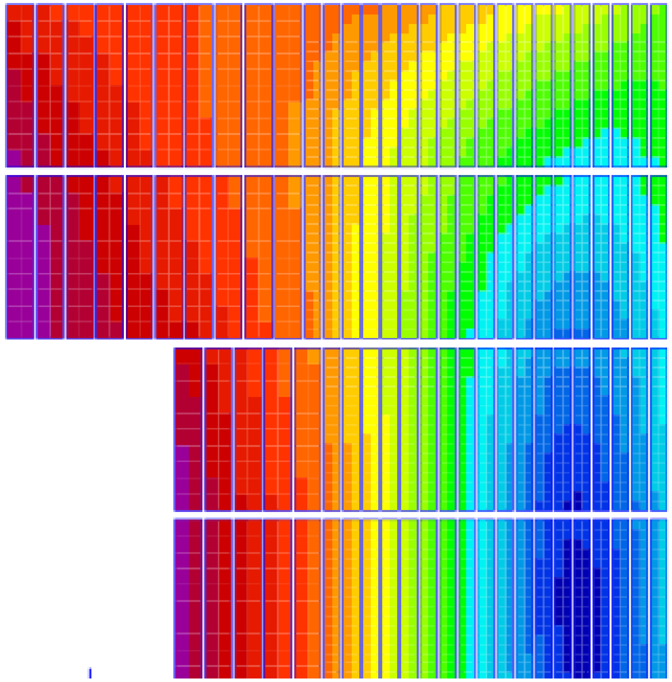


Example current decays for Cosθ: Heater based protection





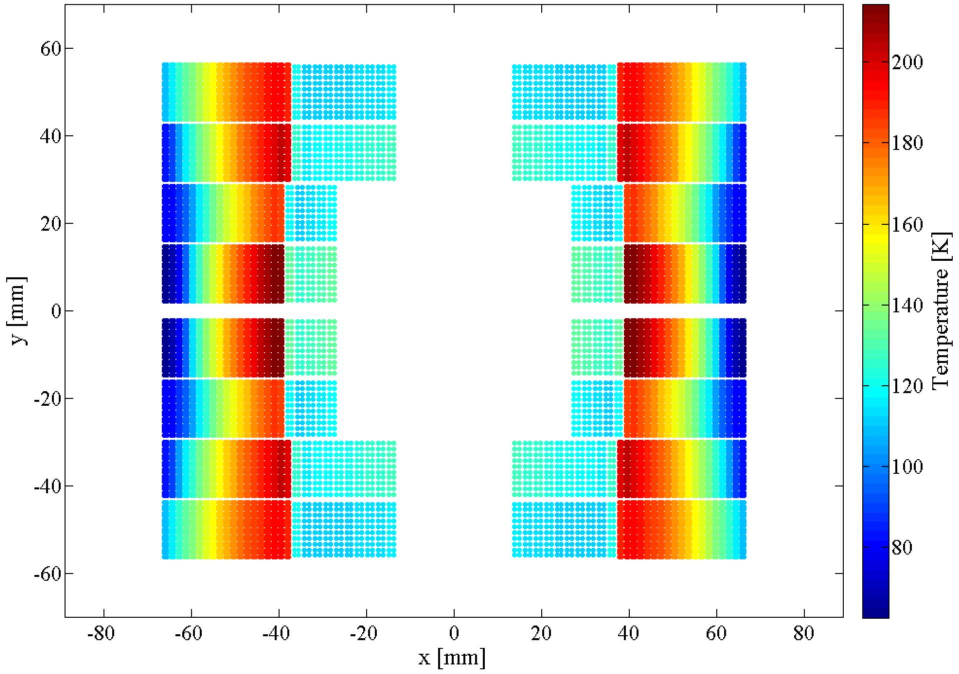
Parameters of Block V20ar, used in CLIQ simulation



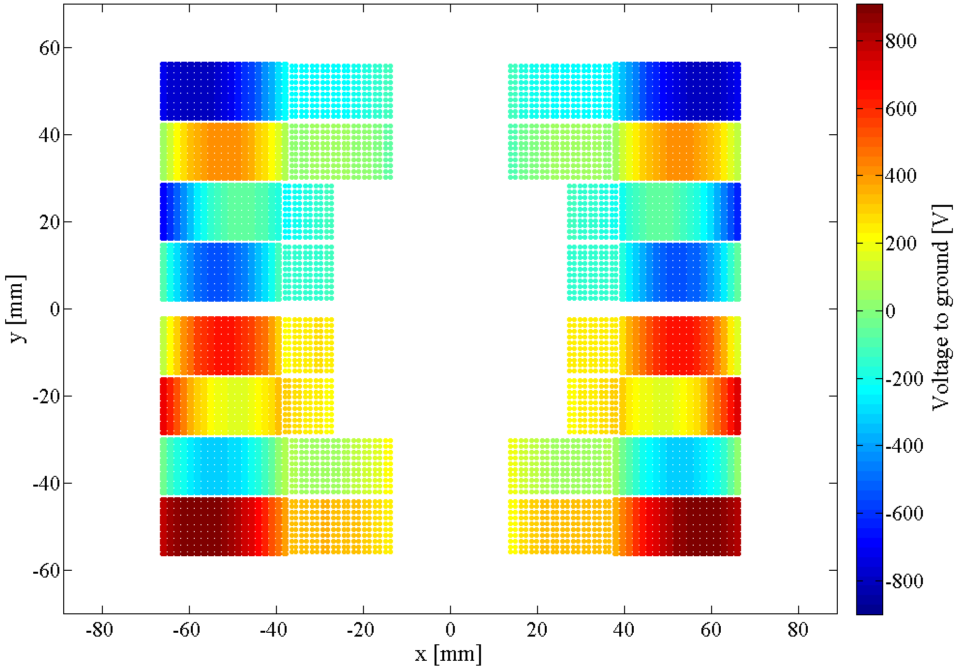
	Block, V20ar, single aperture	
Inom / 105% Inom (A)	11470 / 12040	
Ld,nom (mH/m)	17.57	
Cable	**HF-cable**	**LF-cable**
Cable *w* x *t* (bare) (mm)	13.05 x 2.1	13.05 x 1.25
Number of strands	21	35
Strand diam. (mm)	1.155	0.705
Cu/SC	0.8	2.3
Cable ins. (mm)	0.15	
RRR	100	
Fil. twist (mm)	14	
Jc-fit	From B. Bordini with T_{c0} = 16 K, B_{c20} = 29.38 T, α = 0.96, C_0 = 267845 A/mm^{2}T	

Protection with CLIQ: Block

Final temperature distribution

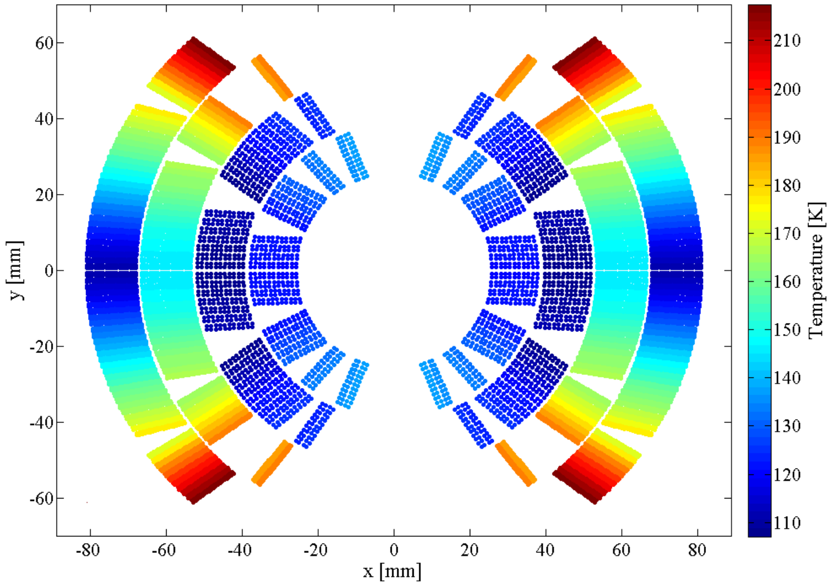


Voltage to ground distribution



Protection with CLIQ: Cos-theta

Final temperature distribution



Voltage to ground distribution