Susana Izquierdo Bermudez. 29-04-2014

11T Quench Heater Design

OUTLINE

1. Quench Heater Design Guidelines
2. Modelling Quench Heater Delays
3. Definition of main Quench Heater Parameters
   1. Insulation from Heater to Coil
   2. Quench Heater Geometry
   3. Quench Heater Circuit
4. Trace manufacturing and characterization
5. Conclusions and final remarks

1. QH Design Guidelines

1. Design should be suitable for a 5.5 m length magnet
2. The distance between heating stations should be such that the heat has to propagate between stations in less than 5 ms.
   - For longitudinal propagation ≈ 10 m/s, distance ≈ **100 mm**
3. Kapton insulation thickness from heater to coil should be minimized, but guarantee a good electrical insulation from heater to coil.
   - **50 μm** seems to be minimum reliable Kapton thickness
4. Heat power density in the heating station should be as high as possible, but the temperature in the heater under adiabatic conditions should not increase above 350K.
   - Experimental data from LARP magnets and 11T FNAL show that **P_O ≈ 50-80 W/cm²** heater delay starts saturating, but first short models P_O up to **150 W/cm²** to find the optimal power density.
5. Heat as many turns as possible in the azimuthal direction.
6. Power density in the low field region should be higher than in the high field region to quench the magnet in a more uniform way.
7. No sharp edges, keeping the geometry of the heaters as simple and robust as possible.
8. If possible, use standard LHC QH power supply.
   - Total capacitance **7.05 mF** , maximum voltage **± 500V**.
   - Maximum current for continuous operation = 135 A
   - Peak current at 25 ˚C for 10 ms =1700 A (it will probably destroy the PCB of the power supply)
   - Can be safely operated up to **300 A**
9. At least two independent circuits per aperture (for redundancy)

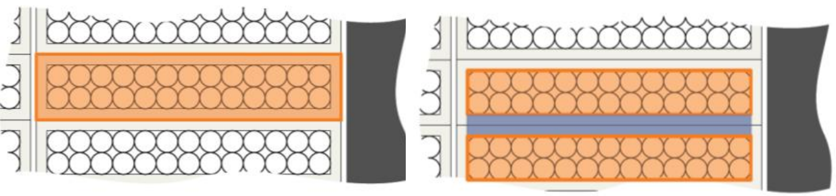
2. Modelling Quench Heater Delays

ROXIE quench heater model

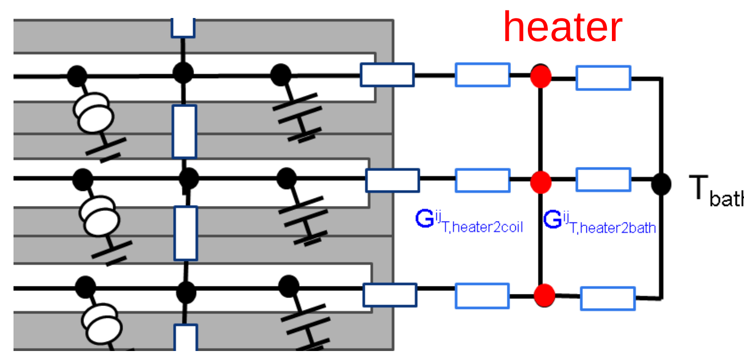
First Order Thermal Coupling as implemented in ROXIE

Heat capacity includes conductor + insulation

Thermal conductance and heat fluxes: Conductor without insulation. Uniform temperature in the conductor and linear temperature distribution in between them

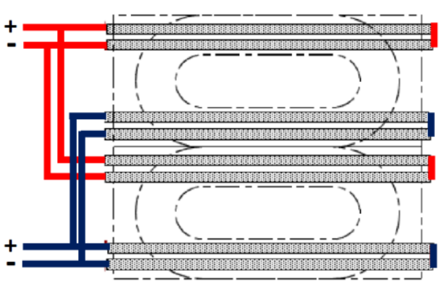


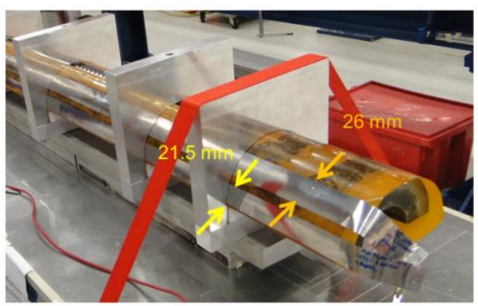
Extension for QH modelling →



Tuning factor (k) on $G^{ij}_{T,heater2coil/bath}$ to fit experimental and computed heater delays

Model validation

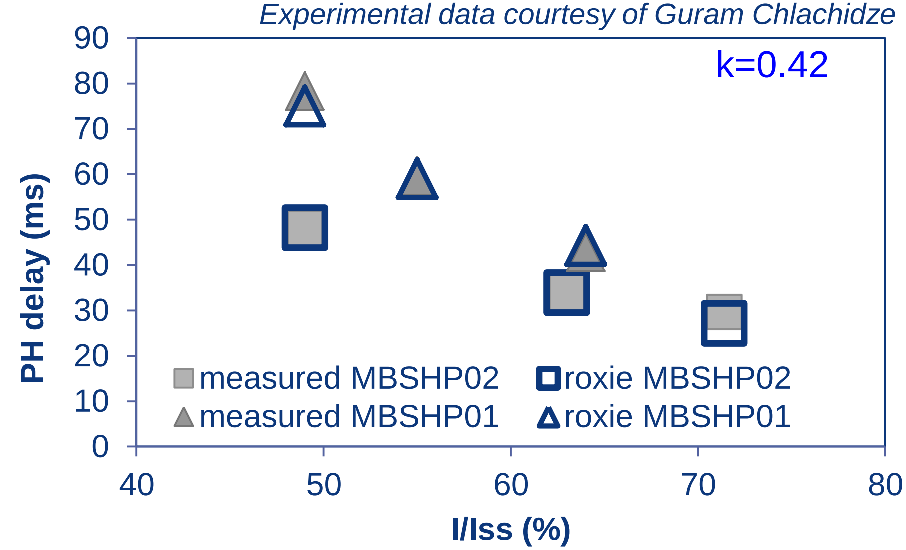




Insulation heater2coil = 114 µm kapton + 125 µm G10

Insulation heater2bath = 508 µm kapton

Experimental data courtesy of Guram Chlachidze

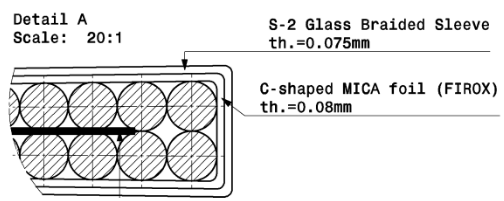


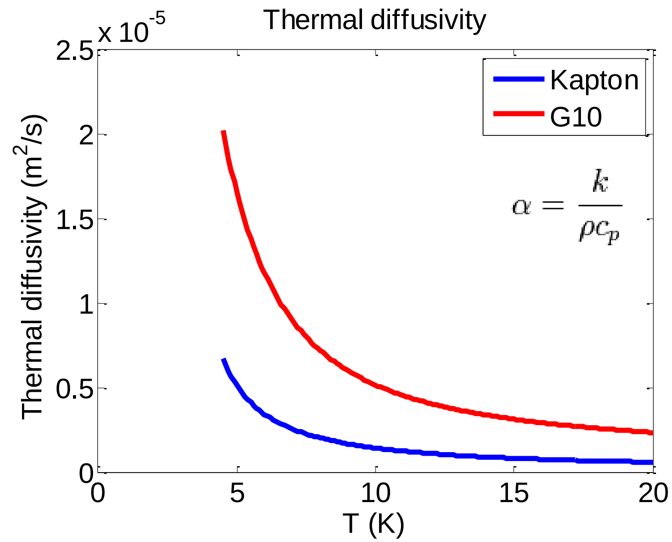
MBSHP02: $P_{o\ LF}$ = 65 W/cm^2 $P_{o\ HF}$=39 W/cm^2 2τ =31 ms

3.1 Insulation from heater to coil

Impact of insulation thickness on heater delay

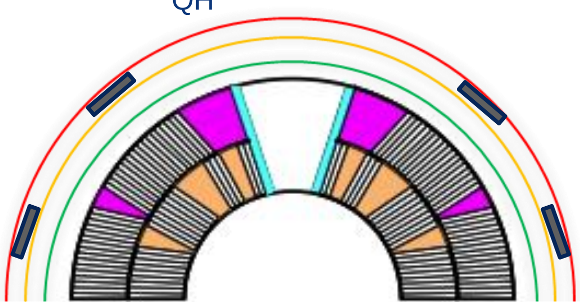
- P_o =50 W/cm^2 2t=15 ms and I/I_{ss}=80 %
- Assumptions
  - Quench heaters are a continuous strip (no heating stations)
  - Identical cable insulation scheme (CERN 11T insulation combines S-2 glass and Mica)





FNAL 11T coils

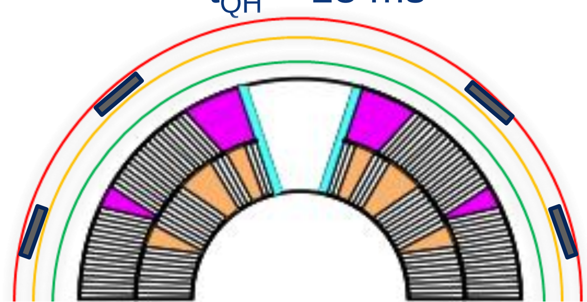
QH glued after impregnation
Measured QH delay
$t_{QH} \approx 25$ ms



0.125 mm S2 glass
0.025 mm glue + **0.114** mm kapton
QUENCH HEATERS
0.5 mm kapton (ground insulation)

CERN 11T coils

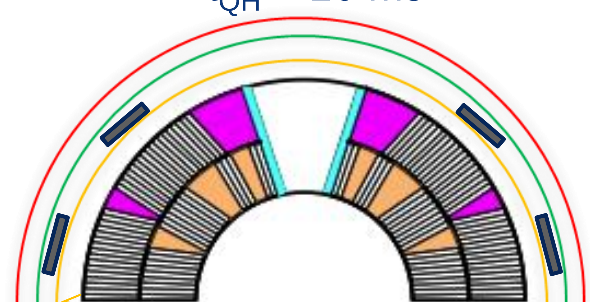
Trace glued after impregnation
Expected QH delay
$t_{QH} \approx 18$ ms



0.2 mm S2 glass
0.025$^+$ mm glue + **0.050** mm kapton
QUENCH HEATERS
0.5 mm kapton (ground insulation)

LARP approach

Trace impregnated with the coil
Expected QH delay
$t_{QH} \approx 16$ ms

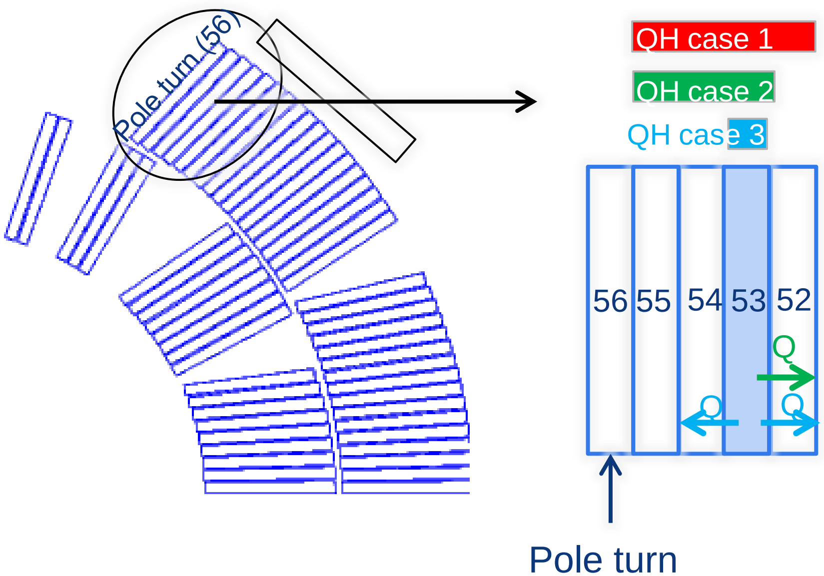


0.025 mm glue+ **0.050** mm kapton (trace)
QUENCH HEATERS
0.2 mm S2 glass
0.5 mm kapton (ground insulation)

3.2 Quench heater geometry (1)

Design objective:

Heat as many turns as possible in the same longitudinal section.



Increase in QH delay in conductor 53:	Δ Heater Delay (%) for a constant QH power density
CASE 1: adjacent conductors covered by QH	0
CASE 2: only one of the two adjacent conductors covered by QH	+ 18
CASE 3: none of the adjacent conductors covered by QH	+ 36

Simulated turn to turn propagation time:
3 ms in the inner layer pole turn, 22 ms in the outer layer mid-plane

Design Objective:

Design suitable for a 5.5 m length magnet

Design Objective:

Distance between heating stations ≈ 100 mm

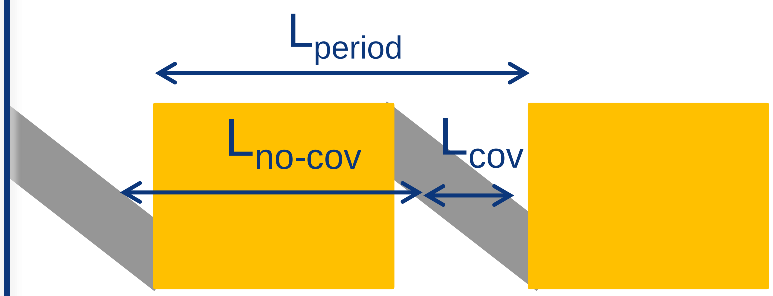
Design Objective:

Maximum voltage ± 450V

Copper plating is a must to reduce the overall strip resistance

3.2 Quench heater geometry (2)

OPTION 1



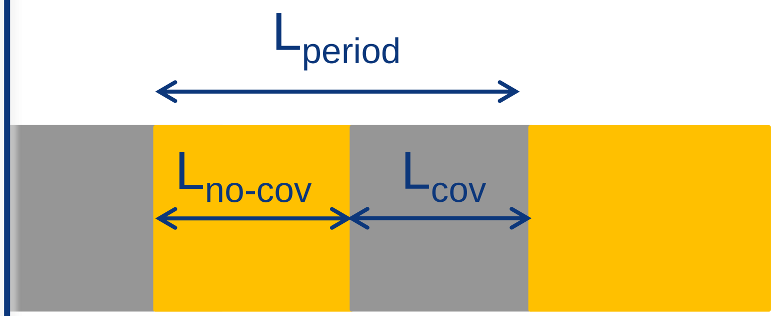
For the same power density and voltage drop[1]:

- Less current
- Less conductor can be covered longitudinally
- Stations are further

Reliability of copper cladding technology?

1: More details in “Additional Slides”

OPTION 2



For the same power density and voltage drop:

- More current
- More conductor can be covered longitudinally
- Stations can be closer

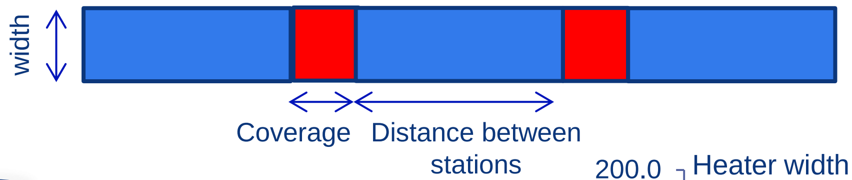
All turns (azimuthally) are heated in the same longitudinal section

Issues of current re-distribution? (talk from Juho)

Reliability of copper cladding technology?

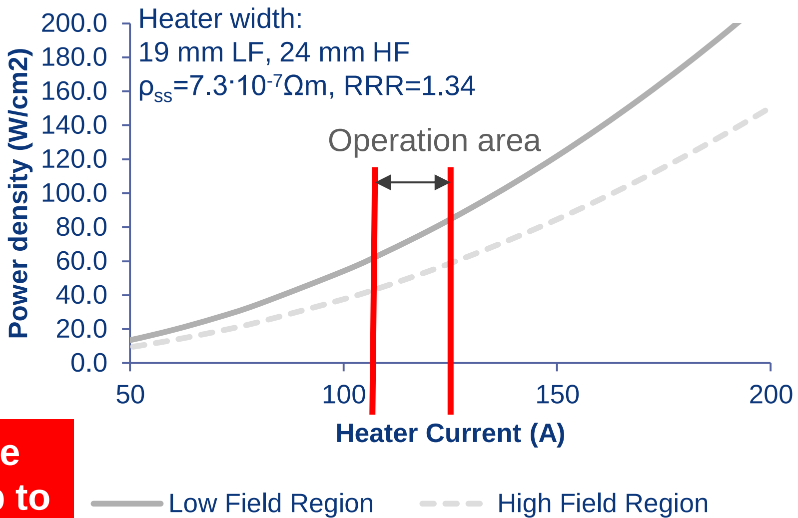
Baseline solution for 11T: OPTION 2

3.2 Quench heater geometry (3)



- **Width -> Cover as many turns as possible**
  - LF: 19 mm
  - HF: 24 mm
- **Power density**
  - LF ≈ 75 W/cm²
  - HF≈ 55 W/cm²

$$P_d = \frac{I^2 R}{wL}, \quad R = \frac{\rho L}{wt} \quad \Rightarrow \quad P_d = \frac{I^2 \rho}{w^2 t}$$

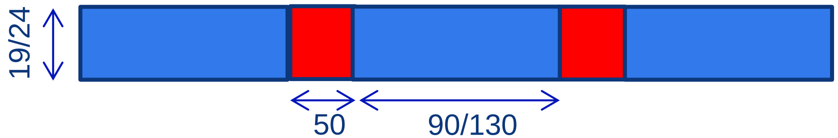


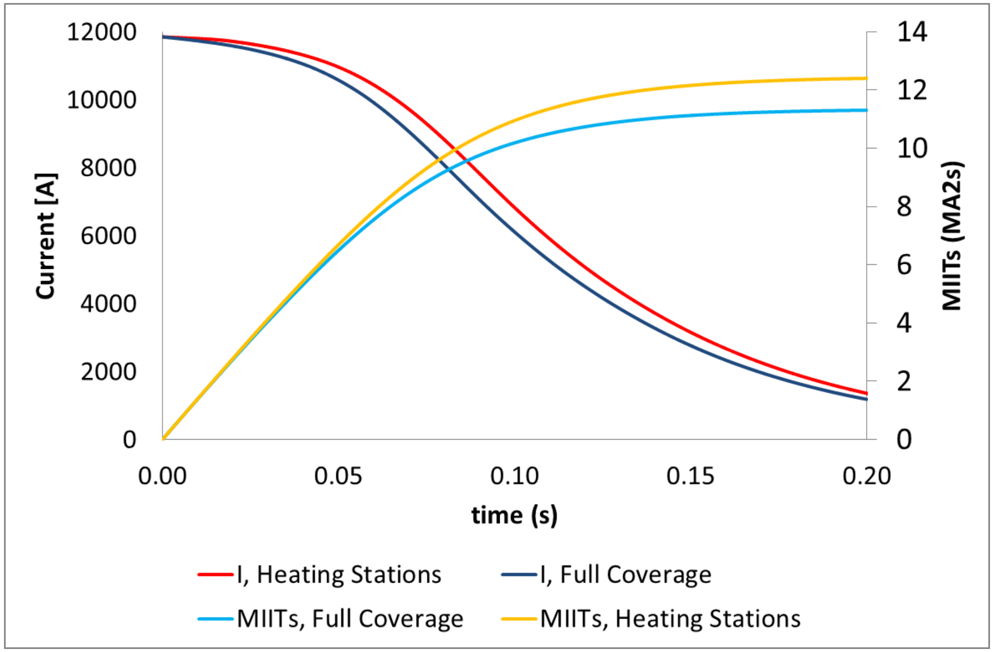
Even if the operational current is expected to be in the range 100-120 A, it would be good to have the possibility to go up to 150 A – 200 A during short model tests to check the saturation of the system in terms of heater delays.

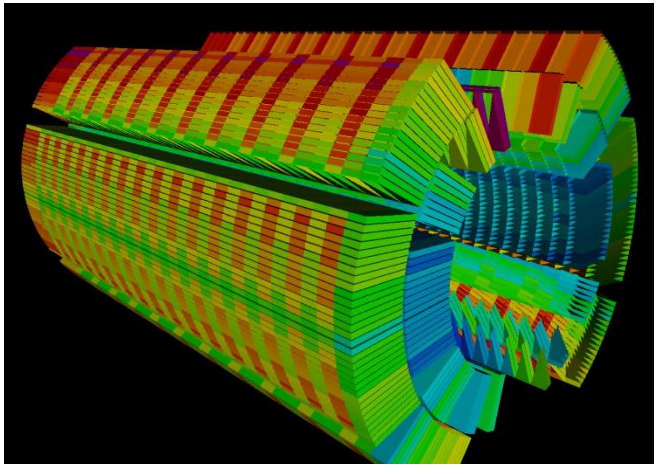
- **Distance between heater stations -> quench propagation in between stations ≈ 5 ms**
  - LF: 90 mm
  - HF: 130 mm
- **Coverage: maximum coverage keeping the resistance within the allowable limits for a 5.5m magnet (depends on the number of power supplies/heater circuits)**

3.2 Quench heater geometry (4)

3D simulation with heater stations







Full coverage vs heating stations:

1 MIITs difference

⬍

Time budget 7 ms higher in case of full coverage

Remarks: ROXIE thermal network has limitations that we try to overcome via fitting factors

More detailed quench heaters model show better agreement with experimental results without any free parameters [Tiina Salmi]

Inter-layer quench propagation computed in ROXIE is a factor 2.5 slower than experimental results

Adaptive mesh tracking is a must for efficient quench simulation [Luca Bottura, MT23]. ROXIE computed longitudinal propagation when using a coarse mesh is slower than expected (and computed when using a very fine mesh)

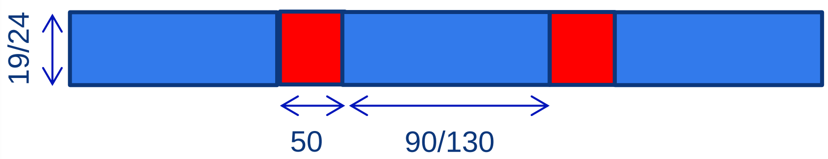
3.3 Quench heater circuit

Design Objective: Stay within LHC standard quench heater supply limits

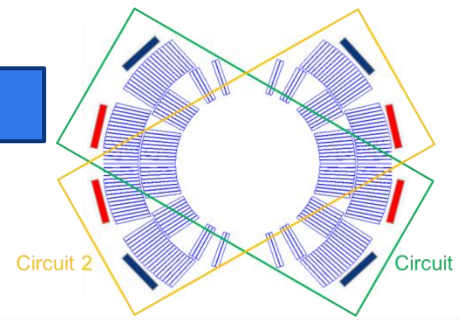
($V = \pm$ 450 V, C=7.05 mF, $I_p \approx$ 85 A but it can safely operate up to 300 A)

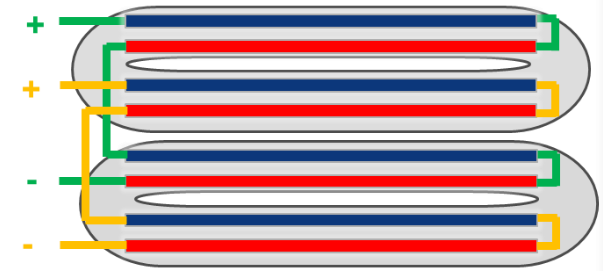
Baseline solution:

Heater strip



Heater circuit

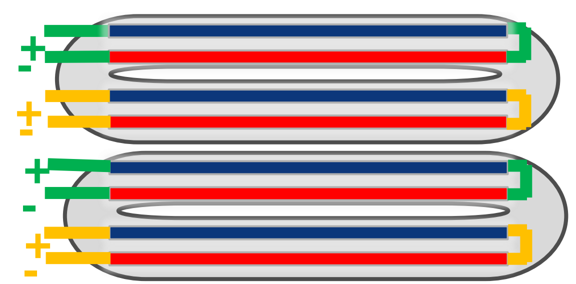




For a 5.5 m magnet:

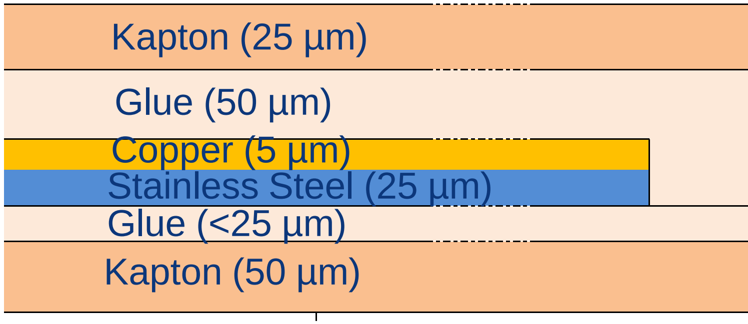
V (V)	I (A)	C (mF)	Tau (ms)	Max. Energy (kJ)	Power density (W/cm²)
900	122	7.05	55	2.8	80 (LF) 56 (HF)
850	115			2.5	72 (LF) 50 (HF)

Remark: each heater circuit can be divided in two if V=450 is preferred than $V = \pm$ 450 V

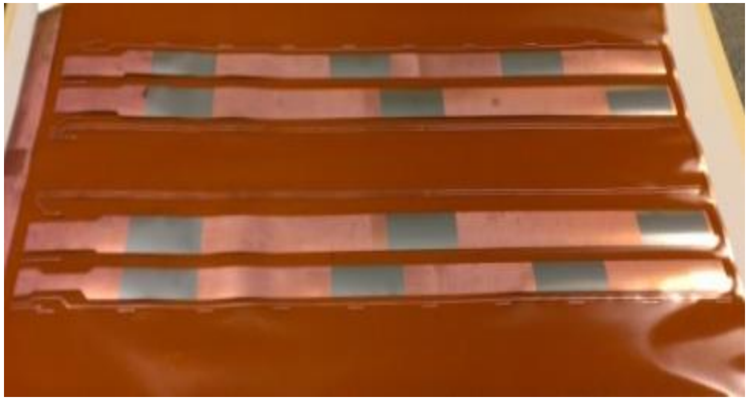


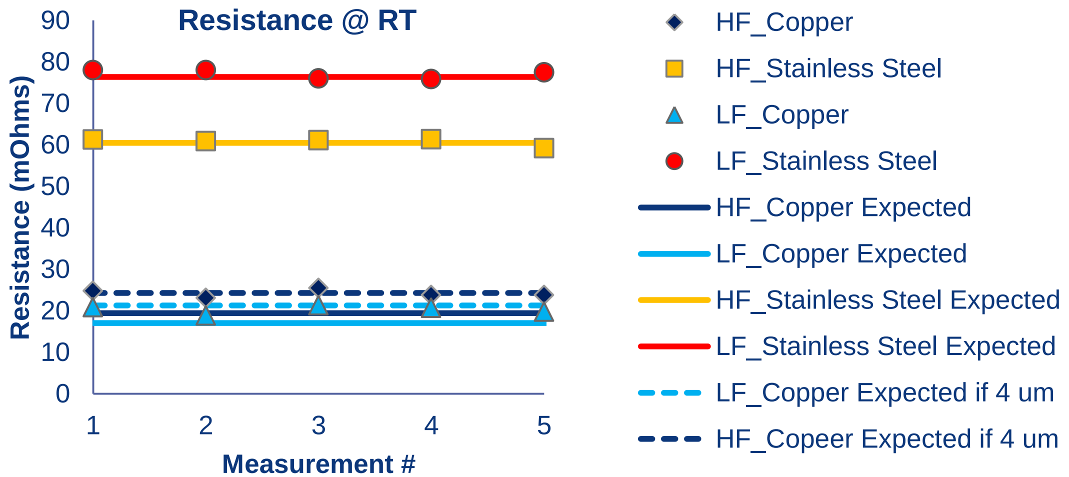
4. Trace manufacturing and characterization

- Resistance measurements at RT and 77 K
  - Stainless steel stations: Measured resistance close to expected values
    - 3% difference at RT
    - 8 % difference at 77K
  - Copper regions: Measured resistance higher than expected value
    - 20% difference at RT
    - 25 % difference at 77K
- High current test
  - No degradation was observed in the bonding
- Temperature cycling at 77 K
  - No degradation



Trace stack for 11T





$\rho_{SS}=7.3 \cdot 10^{-7}\Omega m$, $RRR_{SS}=1.34$ $\rho_{SS}=1.8 \cdot 10^{-8}\Omega m$, $RRR_{SS}=30$

7. Conclusions and final remarks

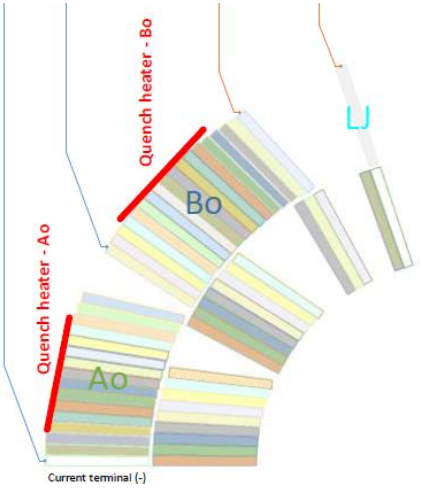
Main differences in between QXF and CERN 11T:

- CERN11T uses mica-glass insulation (lower thermal conductivity than G10).
- Trace is glued in the coil after impregnation → additional layer of 0.2 mm of S2 glass between heaters and coil

We should be careful when drawing conclusions from 11T to QXF

Redundancy with only outer layer heaters seems to be more than challenging

- Lower margin in the inner layer → heaters in the IL will provoke faster quench and more uniform heat propagation within the coil
- Could AC losses trigger a quench? how would it impact the rest of the RB circuit?



References

- Quench heater experiments on the LHC main superconducting magnets. F. Rodriguez-Mateos, P. Pugnat,S. Sanfilippo, R. Schmidt, A. Siemko, F. Sonnemann
- LQ Protection Heater Test at Liquid Nitrogen Temperature. G. Chlachidze, G. Ambrosio, H. Felice1, F. Lewis, F.Nobrega, D. Orris. TD-09-007
- Experimental Results and Analysis from the 11T Nb3Sn DS Dipole. G. Chlachidze, I. Novitski, A.V. Zlobin (Fermilab) B. Auchmann, M. Karppinen (CERN)
- EDMS1257407. 11-T protection studies at CERN. B. Auchmann
- Challenges in the Thermal Modeling of Quenches with ROXIE. Nikolai Schwerg, Bernhard Auchmann, and Stephan Russenschuck
- Quench Simulation in an Integrated Design Environment for Superconducting Magnets. Nikolai Schwerg, Bernhard Auchmann, and Stephan Russenschuck
- Numerical Calculation of Transient Field Effects in Quenching Superconducting Magnets. PhD Thesis. Juljan Nikolai Schwerg
- Thermal Conductivity of Mica/glass Insulation for Impregnated Nb3Sn Windings in Accelerator Magnets*. Andries den Ouden and Herman H.J. ten Kate
- Electrodynamics of superconducting cables in accelerator magnets, Arjan Peter Verweij
- Rossi, L. et al. "MATPRO: a computer library of material property at cryogenic temperature." Tech. Report, INFN, 2006.
- http://te-epc-lpc.web.cern.ch/te-epc-lpc/converters/qhps/general.stm

Additional slides

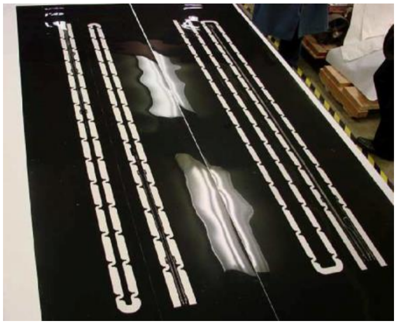
MB vs. 11T

	Parameter	MB	11T
Magnet	MIITs to reach 400 K @ 8T MA^2s	52	18
	Temperature margin LF	4	8-9
	Temperature margin HF	3-4	5-9
	Differential Inductance, mH/m	6.9	11.7
	Stored energy, kJ/m	567	897
Quench heater circuit	Operational voltage, V	$\pm$ 450	$\pm$ 450
	Peak Current, A	85	110-120
	Maximum stored energy, kJ	2.86	2.5 - 3.5
	Time constant, ms	75	55-72
	Quench Heater Pattern	400 mm plated 120 mm un-plated	90-140 mm plated 50 mm un-plated

Minimize heaters delay: heater design optimization

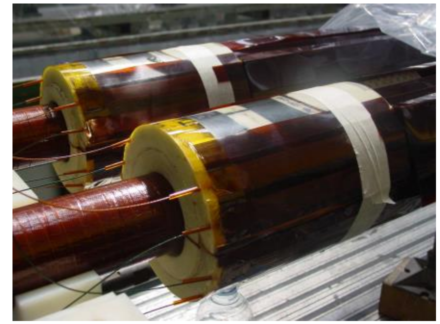
For long magnets, the total heater resistance becomes too high → Heating stations

2 possible options:



Heating stations LARP

LQ example: wide section = 23 mm, narrow section 9 mm, distance between stations 100mm



LHC copper plated solution

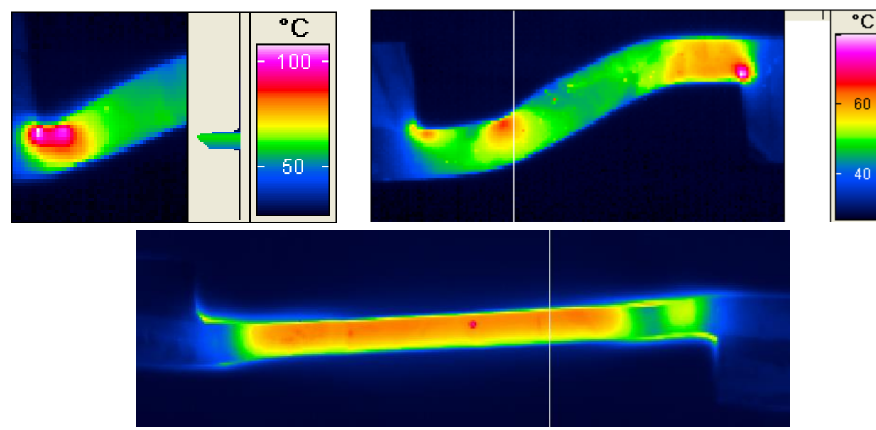
MB example: 15 mm width, 400 mm plated, 120 mm un-plated

Qualitative tests at CERN to understand how smooth the transition between narrow and wide section should be in order to avoid high spot temperatures.

More development required to find a solution which combines smooth transition, enough coverage and distance in between heater stations small enough to allow fast quench propagation in the longitudinal direction

↓

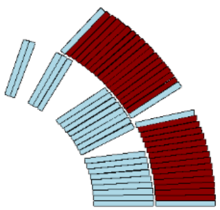
BASELINE SOLUTION FOR THE FIRST MODEL = COPPER PLATED SOLUTION



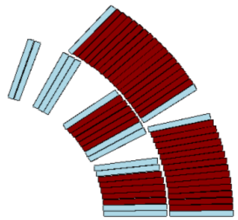
Thanks to Vladimir Datskov & Glyn Kirby

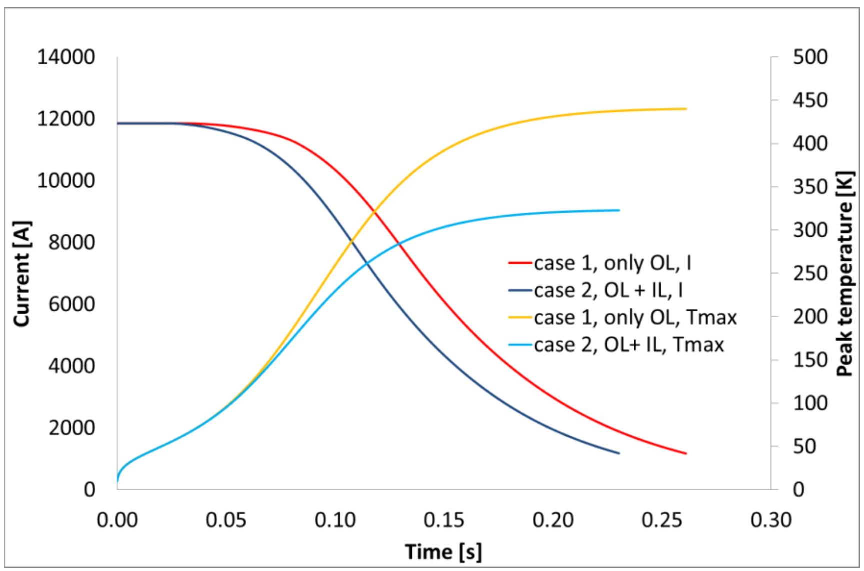
Minimize heaters delay: inter-layer heaters

CASE 1: Only Outer Layer Heaters



CASE 2: Outer Layer + Inter Layer Heaters





Heater parameters:

- Insulation heater2coil = 114 µm kapton + 125 µm G10 + conductor insulation
- Insulation heater2bath = 508 µm kapton
- P_o = 70 W/cm^2 , 2τ =74 ms, $\Delta t_{QHdelay}$=5 ms
- Non-redundant configuration

Parameter	Case 1 (only OL)	Case 6 (OL+IL)
OL HF heater delay, ms	14.6	10.1
OL LF heater delay, ms	27.7	19.5
IL delay, ms	56.5	**7.0**
MIITs total, MA^{2}s	18.2	**15.2**
MIITs after heater effective, MA^{2}s	13.6	11.7
MIITs heater fired until effective, MA^{2}s	2.1	1.0
Peak temperature in coil, K	440	322
Peak temperature in heater, K	292	260

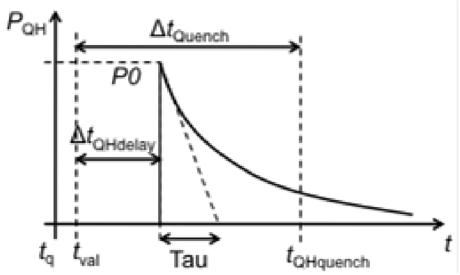
Δ OL HF QH_{delay} = - 31 %
Δ IL QH_{delay} = - 88 %
ΔT_{max} = - 27 %

Remarks:
Thermal contact resistances (e.g. between insulation layers) not included, the same scaling factor as the one used to fit the FNAL test data is kept for this simulation.
The insulation is a combination of glass fiber and Mica. At the moment in the model we use G10.

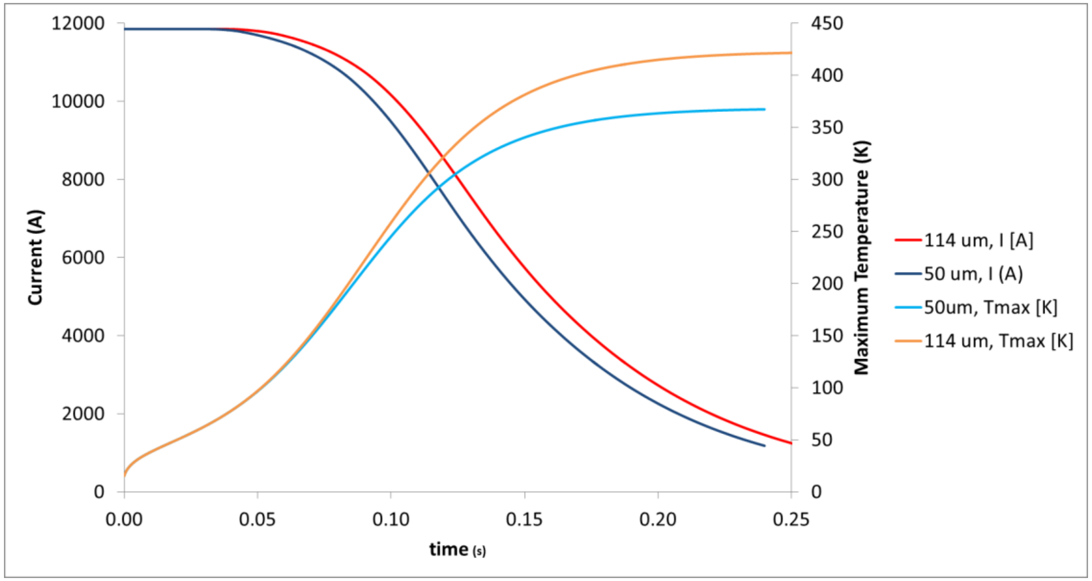
Some technical development required before inter-layer heaters become a feasible option

Minimize heaters delay: reduce kapton thickness

CASE 1:
Insulation heater2coil = 114 µm kapton + 125 µm G10 + conductor insulation
Insulation heater2bath = 508 µm kapton
CASE 2:
Insulation heater2coil = 50 µm kapton + 125 µm G10 + conductor insulation
Insulation heater2bath = 508 µm kapton



P_o = 64 W/cm^2 (LF), 39 W/cm^2 (HF)
2τ =31 ms, $\Delta t_{QHdelay}$ =5ms
Non-redundant configuration
Quench validation: 100mV, 10ms



Parameter	Case 1 114µm k.	Case 2 50µm k.
OL HF heater delay, ms	21	14
OL LF heater delay, ms	33.5	24
IL delay, ms	71	63
MIITs total, MA²s	17.6	16.3
MIITs after heater effective, MA²s	12.2	12
MIITs heater fired until effective, MA²s	4.6	4
Peak temperature in coil, K	422	367
Peak temperature in heater, K	208	196

Δ OL HF QHdelay = - 33 %
ΔTmax = - 13 %

Cable Parameters

Parameter	Value
Cable width, mm	14.847
Cable mid thickness, mm	1.307
Strand diameter, mm	0.7
No of strands	40
Cu/Sc ratio	1.106
Insulation thickness,mm	0.1
Total cable area, mm^2	22.676
Total strand area, mm^2	15.394
Cu area, mm^2	8.084
SC area, Nb_3Sn, mm^2	7.310
Insulation area, G10, mm^2	3.271
Void area filled with epoxy, mm^2	4.011
Cu RRR	100

Protection System LHC Magnets

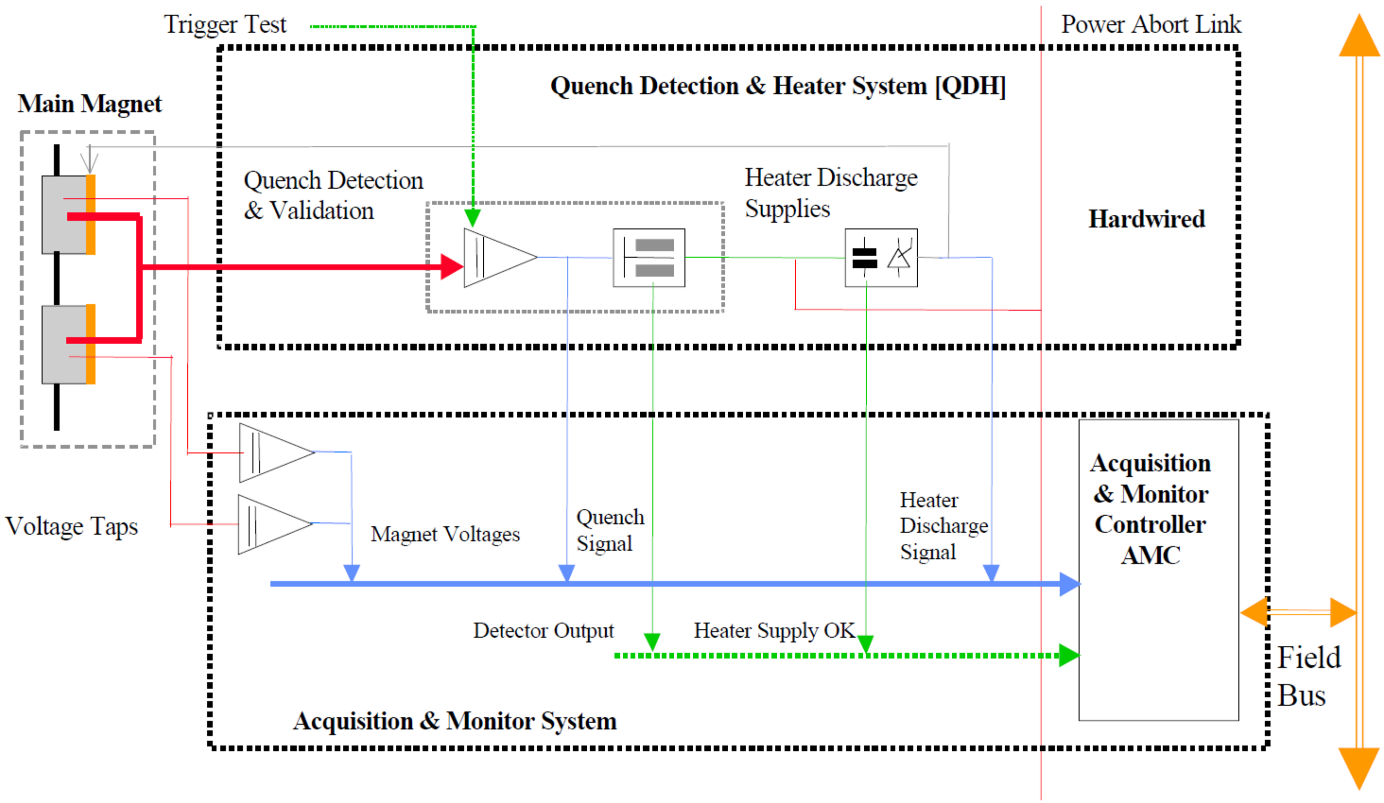


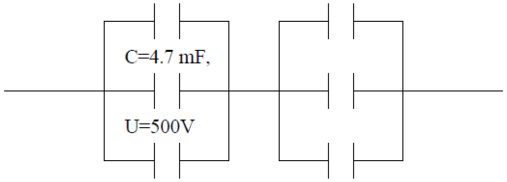
Figure 1: Block diagram for the protection system of the LHC main magnets.

The Protection System for the Superconducting Elements of the Large Hadron Collider at CERN

K. Dahlerup-Petersen1, R. Denz1, J.L. Gomez-Costa1, D. Hagedorn1, P. Proudlock1, F. Rodriguez-Mateos1, R. Schmidt1 and F. Sonnemann2

STANDARD LHC HEATER POWER SUPPLIES

- Supply based on the thyristor-triggered discharge of aluminium electrolytic capacitors.
- Each power supply contains a bank with 6 capacitors (4.7 mF/500V) where two sets of 3 parallel capacitors are connected in series → total capacitance 7.05 mF



$C_{tot} = 7.05\text{mF}, \; U_{max} = 1000 \text{ V}$

- Nominal operating voltage ± 450 V (90 % of the maximum voltage)
- **OPERATION**: Peak current about 85 A, giving a maximum stored energy of 2.86 kJ

QUENCH HEATER EXPERIMENTS ON THE LHC MAIN SUPERCONDUCTING MAGNETS
F. Rodriguez-Mateos, P. Pugnat,S. Sanfilippo, R. Schmidt, A. Siemko, F. Sonnemann

Actual limitations in terms of current

- Power supply equipped with two SKT80/18E type thyristors rated for 80 A at 85 ˚C.
- Maximum current for continuous operation = 135 A
- Peak current at 25 ˚C for 10 ms =1700 A (it will probably destroy the PCB of the power supply)
- Can be safely operated up to 300 A (resistive load in LHC from 12Ω in most of the circuits to 3.1 Ω in some systems such as D1 protection)

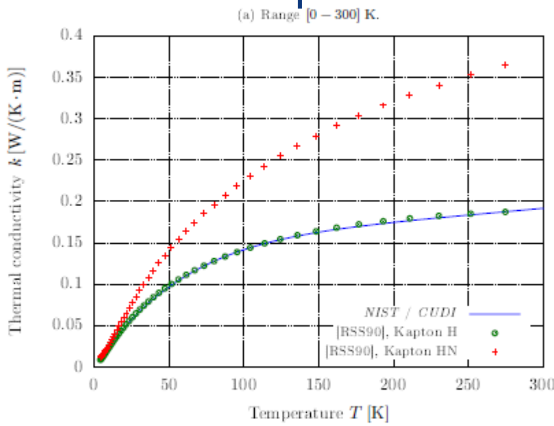
Impact of insulation material/thickness

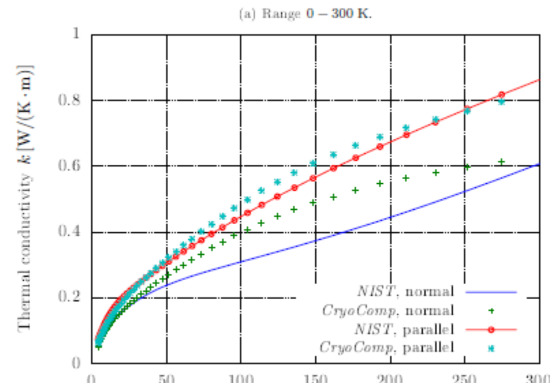
kapton thickness	G10 thickness	OL HF heater delay (ms)	Δ OL HF heater delay (ms)	Δ OL HF heater delay (%)
0.075	**0**	11	0	0.0
0.075	**0.2**	13.5	2.5	22.7
0.275	**0**	26	15	136.4

Kapton

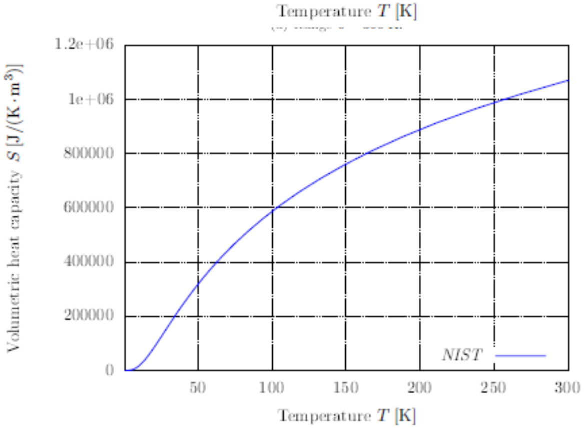
G10

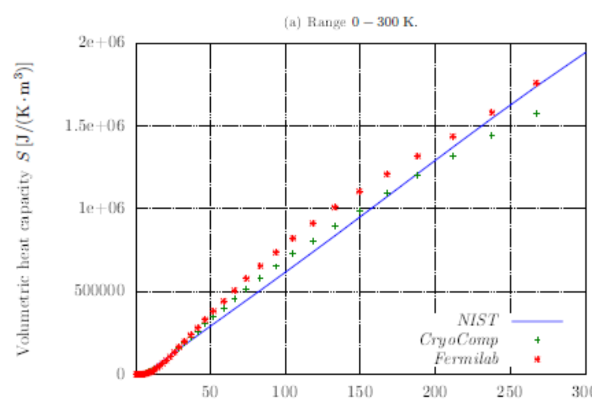
Thermal conductivity





Heat capacity

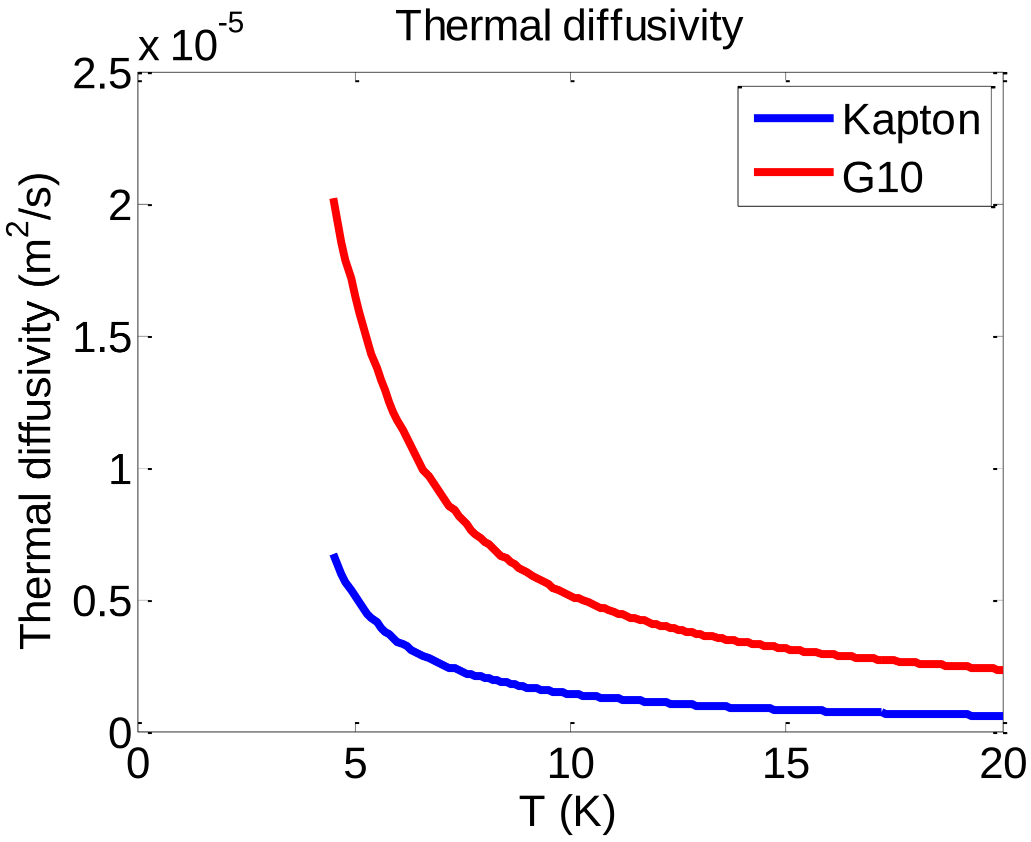




https://espace.cern.ch/roxie/Documentation/Materials.pdf

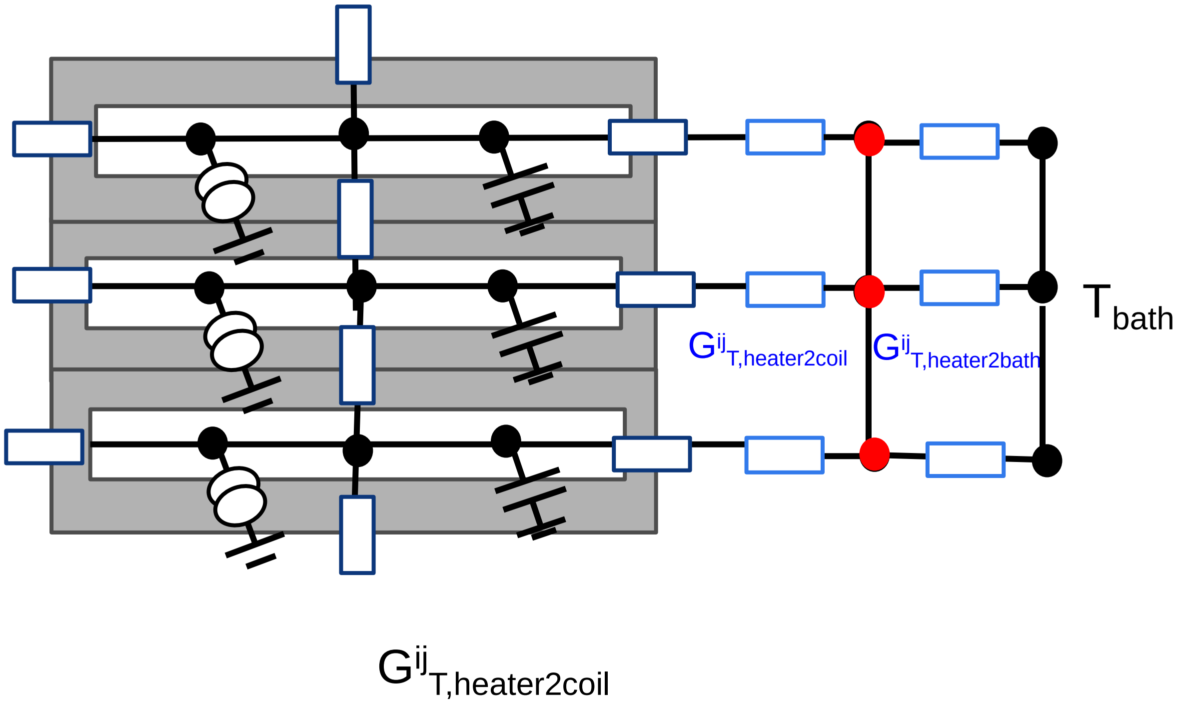
Impact of insulation material/thickness

$$\alpha = \frac{k}{\rho c_p}$$



ROXIE Thermal Network

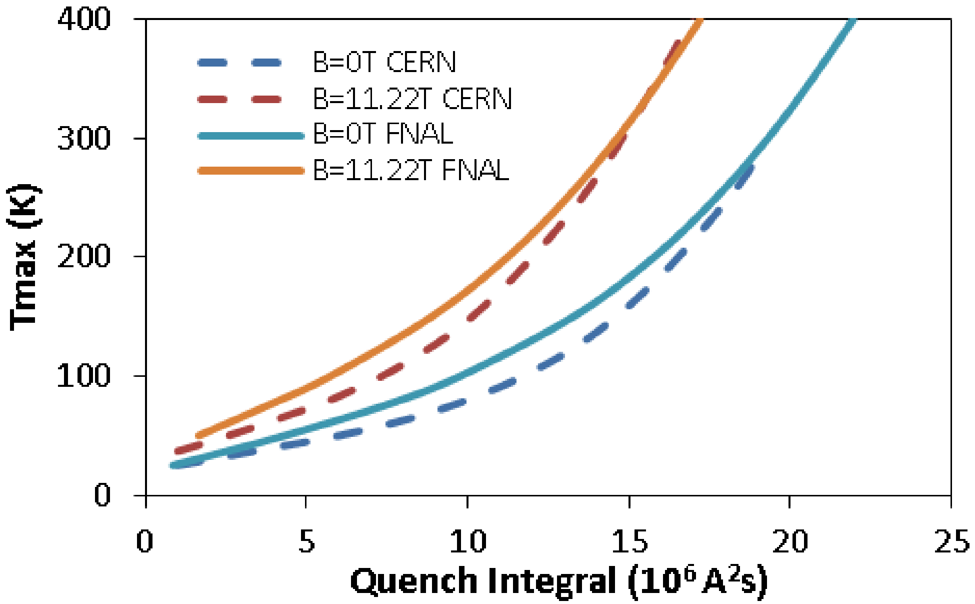
Lumped thermal network model in comparison to the coil/conductor geometry

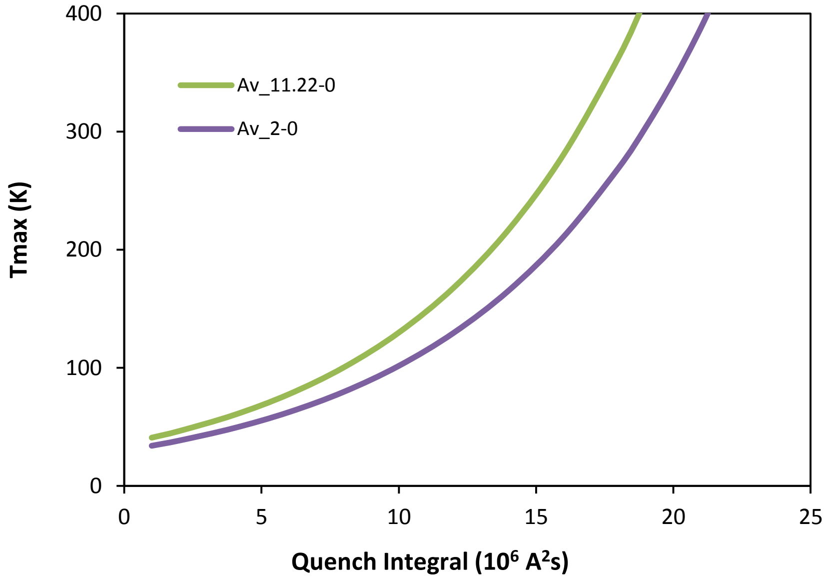


T_{max} vs MIITs

Experimental Results and Analysis from the 11T Nb3Sn DS Dipole

G. Chlachidze, I. Novitski, A.V. Zlobin (Fermilab)
B. Auchmann, M. Karppinen (CERN)

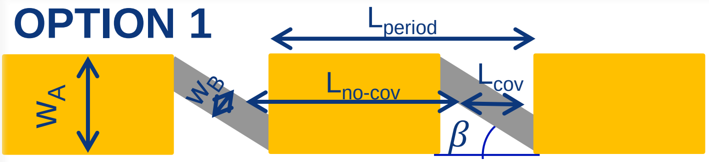




"To keep the cable temperature during a quench below 400 K, the quench integral has to be less than 19-21 MIITs"

Quench heater geometry

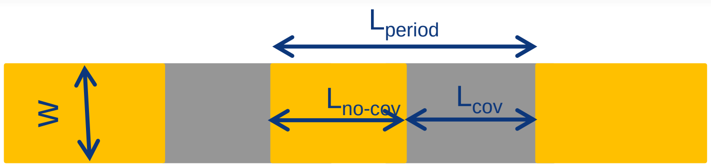
OPTION 1



$$L_{cov} = \frac{\frac{w}{3}}{sin(\beta)} = \frac{2w}{3\sqrt{3}} \quad L_{res} = \frac{\frac{2w}{3}}{sin(\beta)} = \frac{4w}{3\sqrt{3}} \quad L_{no\_cov} = Lpe_{riod}$$

$\beta = 60°$ $w_A = w$ $w_B = 1/3w$

OPTION 2



$$L_{cov} = Lre_s \qquad L_{no\_cov} = Lpe_{riod} - Lco_v$$

For the same power density and voltage drop:

$$P_{d1} = P_{d2} \xrightarrow{P_d = \frac{I^2\rho}{w^2 t}} \frac{{I_1}^2\rho}{{w_B}^2 t} = \frac{{I_2}^2\rho}{w^2 t} \rightarrow I_2 = 3I_1$$

$$V_1 = V_2 \xrightarrow{V=IR} I_1R_1 = I_2R_2 \xrightarrow{I_2=3I_1} R_2 = \frac{1}{3}R_1 \xrightarrow{R=\frac{\rho L}{wt}} L_{res2} = L_{res1}$$

$$L_{cov2} = 2Lcov_1$$
$$L_{non\_cov2} = Ln_{on\_cov1} - 2L_{cov1}$$

Example: For w = 20 mm	OPTION 1	OPTION 2
Distance covered by the quench heater(L_{cov}), mm	7.5	15
Distance in between heating stations ($L_{non-cov}$), mm	100	85

Trace manufacturing and characterization

Before trace installation

- Resistance measurements at RT

Expected value: R1=R2=1.65 Ω
Measured value ≈ 1.7 Ω

- High voltage test to ground under 20-30 MPa pressure (2kV).

After trace installation, every step of the manufacturing process

- Resistance
- QH to ground and QH to coil (1 kV)
- Discharge test (pulse). Low thermal load to the heaters (under adiabatic conditions and assuming constant material properties, peak current defined to limit the temperature increase to 50 K) (only in the manufacturing steps after collaring)