QXF Quench Protection

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With contributions from a lot of people including:

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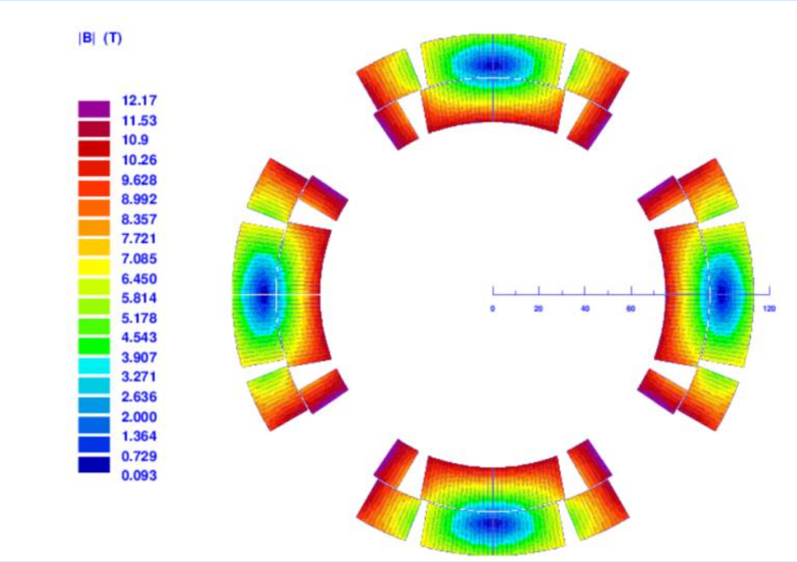
Outline

1. Status of MQXF QP at Magnet Technology 23
2. Improvements so far
3. Options and plans going forward

Design Parameters



MQXF parameters	
Aperture	150 mm
Peak field	12.2 T
Magnetic gradient	140 T/m
Operational current	17300 A
Inductance	8.27 mH/m
MQXF cable	
Material	Nb_3Sn
Average thikness	1.5675 mm
Width	18.638 mm
Insulation thickness	0.15 mm
Strands number	40
Strand diameter	0.85 mm

Requirements

- *Max hot spot temperature < 350 K*
- *Max Voltage in magnet 800 V*
- *Redundancy (TBD)*

The goal is quite challenging because:

- *The conductor is Nb_3Sn (lower quench velocity, less experience on material properties)*
- *Large energy/conductor ratio (120 MJ/m^3, to be compared to 52 MJ/m^3 for the actual NbTi MQXA on LHC)*
- *Long magnet (2 x 4 m), so the extracted energy by means of dump resistance is very low.*

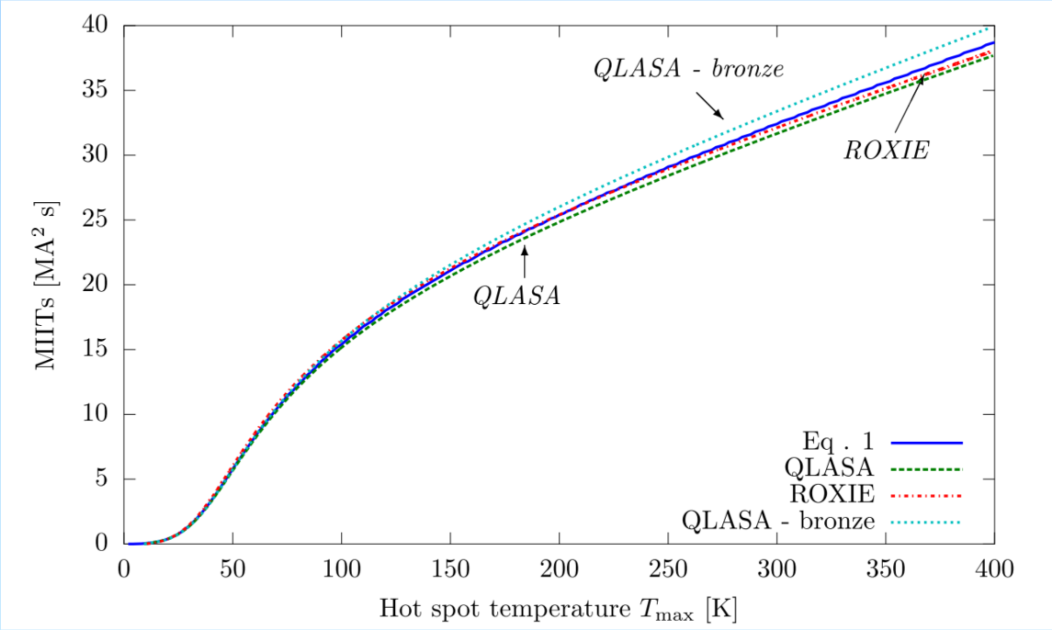
The first study (presented at MT23) was done with two codes:

- ***QLASA** (pseudo-analytical model, adiabatic assumptions, analytical formulas for propagation velocities)*
- ***Roxie** (quench routine based on a weak coupling between thermal and magnetic models)*

*Both codes used the material property database **MATPRO***

- *There is good agreement between codes: 32 MIITs @300 K & 34 MIITs @ 350 K*
- *The residual bronze (~1/3 of non-Cu) gives additional margin in MIITs*

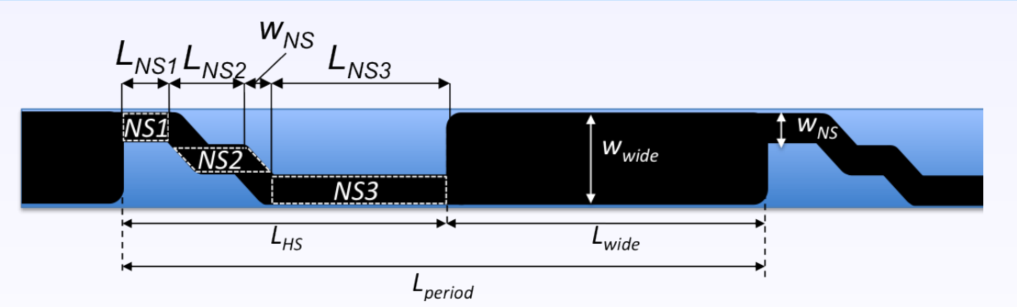
$$\text{MIITs} = \int_{t_q}^{\infty} i^2(t)dt = A_t^2 \int_{T_{He}}^{T_{max}} \frac{\gamma c_p(T)}{\rho_{El}(T, B, \text{RRR})} dT \quad (1)$$



Quench heaters

They are resistive stainless steel strips on the coil outer surface insulated by 50 μm polyimide foil;

- *Four heater strips for each MQXF outer layer coil:*
- *4 m long, two for each high (HF) and low field (LF) blocks.*
- *"Steps-like" shape, three narrow segments;*



- *Narrow segments optimized with 2D heat transfer model by T. Salmi*

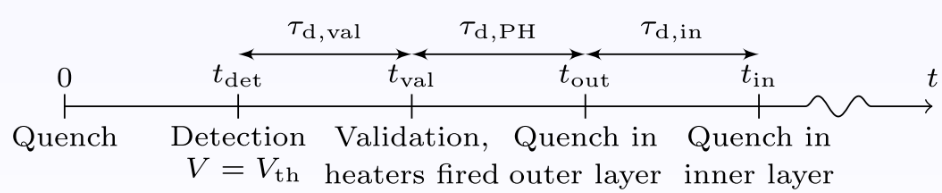
Quench heater activation

The simulation of heater diffusion time gives the following results to induce quench in the blocks

$\tau_{d,\ PH}$ = 17 ms in High Field block,

$\tau_{d,\ PH}$ = 25 ms in Low Field block.

Quench simulation timeline:



V_{th} [mV]	$\tau_{\mathrm{d,val}}$ [ms]	$\tau_{\mathrm{d,PH}}$ (HF) [ms]	$\tau_{\mathrm{d,in}}$ [ms]
100-200	10	10-17	20

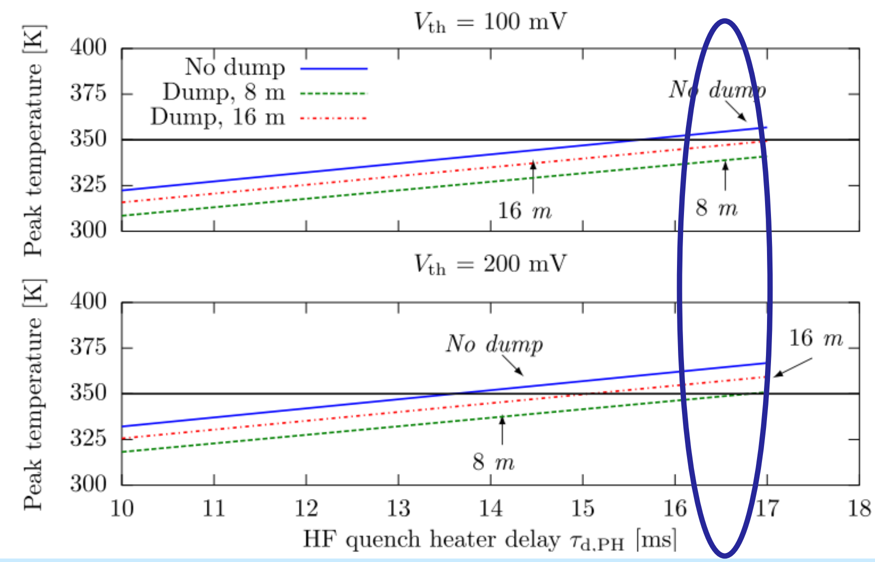
The time delay for quench activation is an input parameter in the quench codes

Protection scenarios considered:

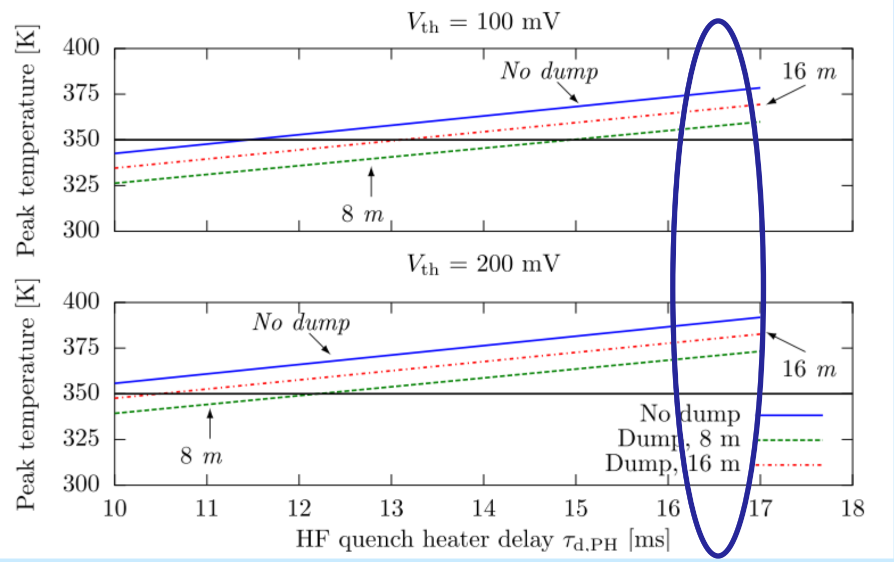
- *No dump resistor, results almost indepedent on magnet length;*
- *46 mΩ dump resistor, Vpeak≈ 800 V;*
- *Single quadrupole (8 m long);*
- *Two quadrupoles connected in series (16 m overall)*
- *100 mV or 200 mV threshold voltage for QDS.*

The simulation with ROXIE are more conservative than QLASA, because the propagation from outer to inner layer is much slower

QLASA simulation



ROXIE simulation



Issues after MT23 study

- With present assumptions $T_{hot\text{-}spot}$ is too high
- We need to have redundancy
- We need to protect these magnets at 90% of ssl for training

2 - IMPROVEMENTS SO FAR

Open question

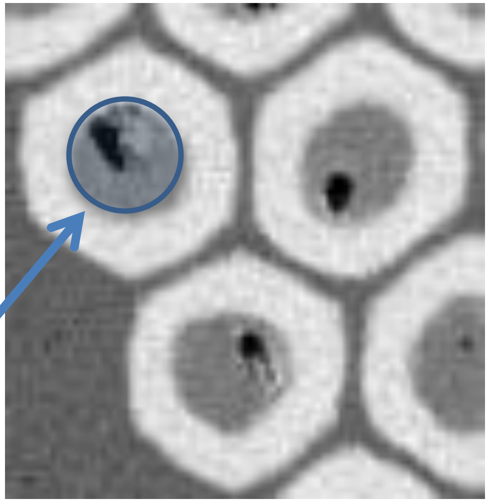
- Conductor:
  - $T_{hot\text{-}spot}$ is lower if bronze is included in the computation

    → measure impact of bronze on strand electrical conductivity at 300 K (after HT)

R_{293K} of Reacted Ti-Ternary RRP strand
LARP-CERN Video-Mtg.
2013-09-23

Arup K. Ghosh

Evaluating resistance contribution from Bronze

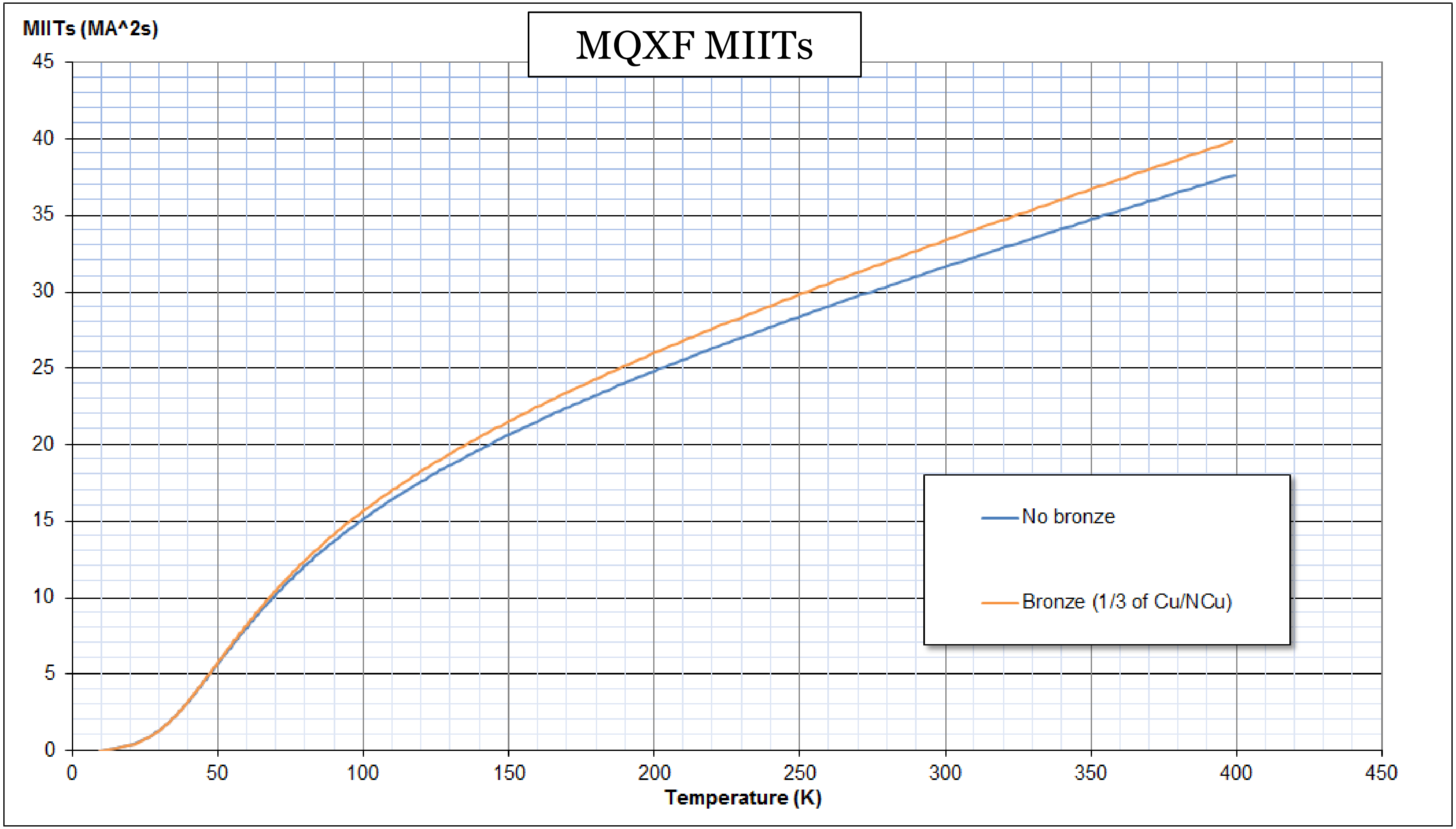


- R_w (293K)= $R_i + R_0$
- RRR = R_w / R_0
- $R_{Calc} = [1/R_{Cu} + 1/R_{Bz}]^{-1}$
- $R_{Cu} = 1.695\ (\mu\Omega\text{-cm}) / (A_w * Cu\%)$
- $R_{Bz} = \rho_{Bz} / (0.3 * A_w * \%\text{Non-Cu})$
  - Bronze area is ~ 30% of non-Cu area
- For A_w use un-reacted wire diameter (measured at BNL); and non-Cu fraction as reported by OST
- Compare R_{Calc} and R_i and minimize by varying ρ_{Bz}

Summary

- The difference between the measured RT resistance and that calculated using just the copper fraction is ~ 5%.
- Difference can be accounted by the parallel resistance of the bronze left in the sub-elements.
- With 30% area fraction of bronze in the sub-element, the bronze resistivity is ~ 7.5 μΩ-cm for the reduced-Sn content wire and ~ 13.5 for the standard-Sn content wire.
- At high reaction temperatures, the bronze resistivity decreases
- Bronze resistivity is commensurate with 2-4 at% Sn in the bronze. ($\Delta\rho/\Delta c$ for Sn in Copper is 3.1 μΩ-cm/at%).

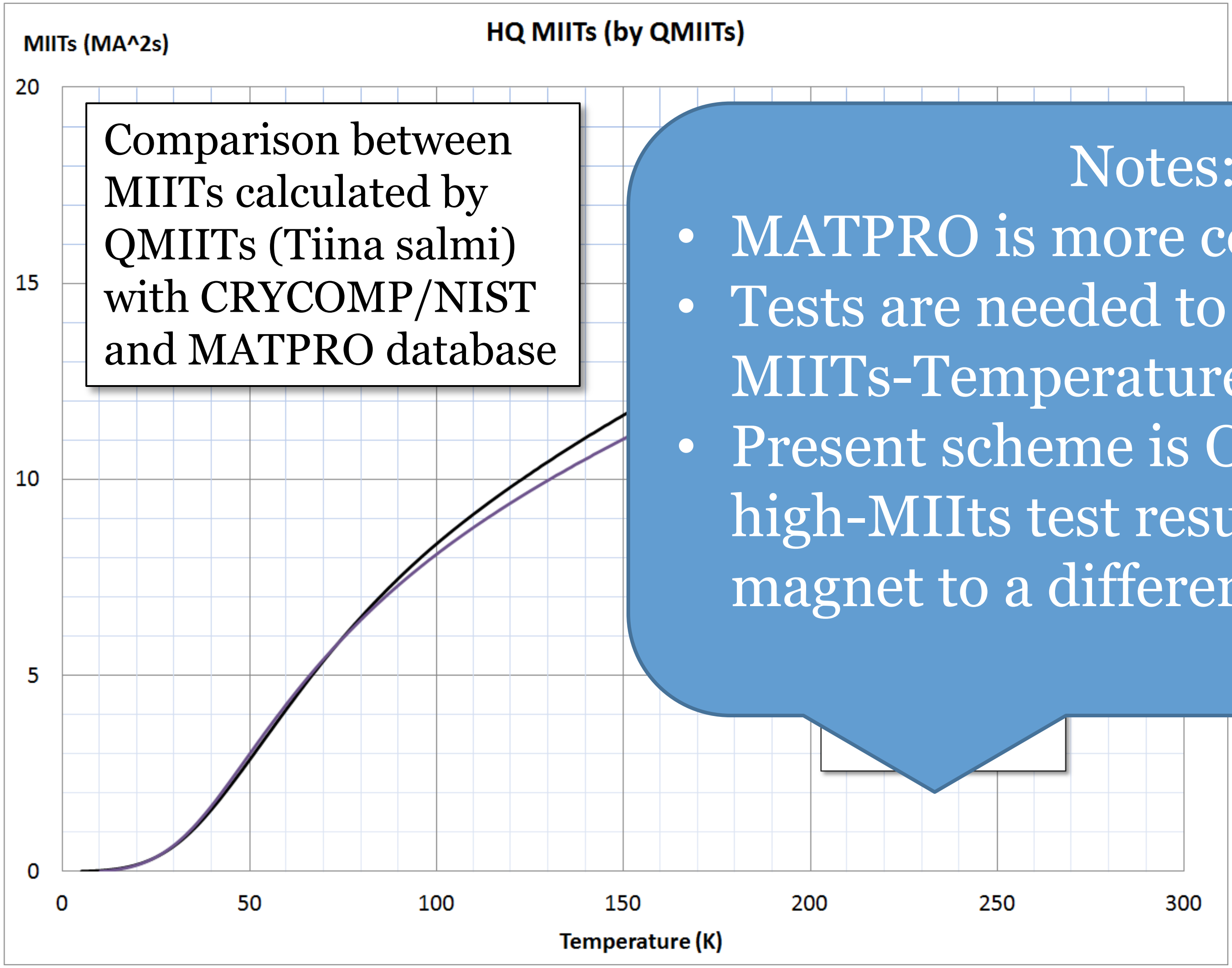
1.3 Residual bronze after reaction



Considering bronze, at given MIITS we have **~30 K less** in hot spot temperature

Impact of the material properties uncertainty on the MIITs-T curve

2.1 Material properties impact



• At given

Question: what are the **right** material properties? **Temperature measurement** needed to answer

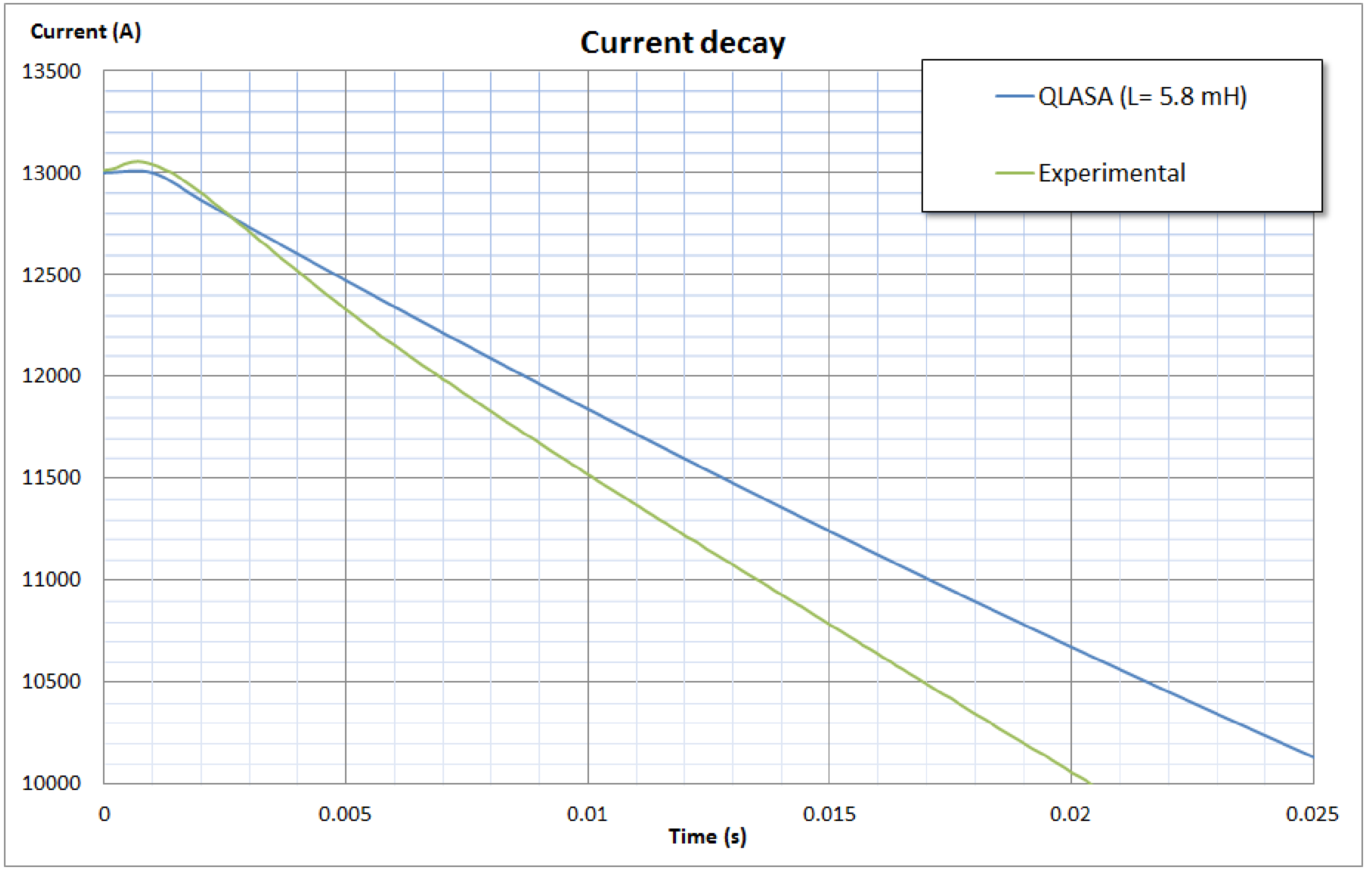
Open questions

- Simulations:
  - Are simulations conservative? How much?
  - ➔ Compare HQ simulations with HQ02 test results

    Improve simulation of inner layer quench; …
  - Do we have dynamic effects with a small dump?
  - ➔ Do HQ02 tests and simulations with small dump
  - ➔ Start analysis of dynamic effects (if present w small dump)

  ➔ Rerun QXF analysis after the previous points have been addressed

1.2 dI/dt effects

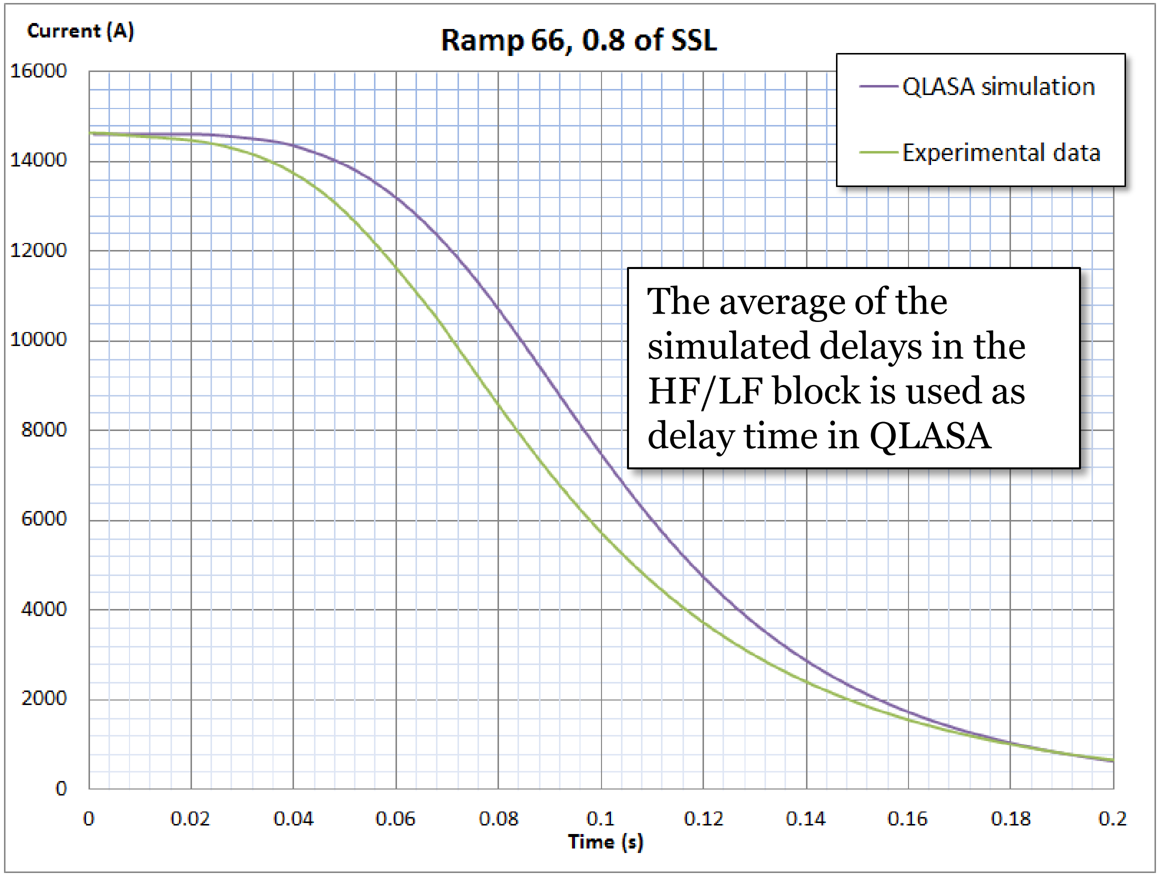


- 13 kA @ 1.9 K (0.7 of SSL)
- 60 mΩ dumping resistance
- No PH

✓ Dynamic effects confirmed with the **cored cable**, too.

With 60 mΩ dumping resistance, dI/dt is very higher than MQXF one.
Question: do dynamic effects affect the decay with smaller dumping resistance? If yes, how much conservative have we been?

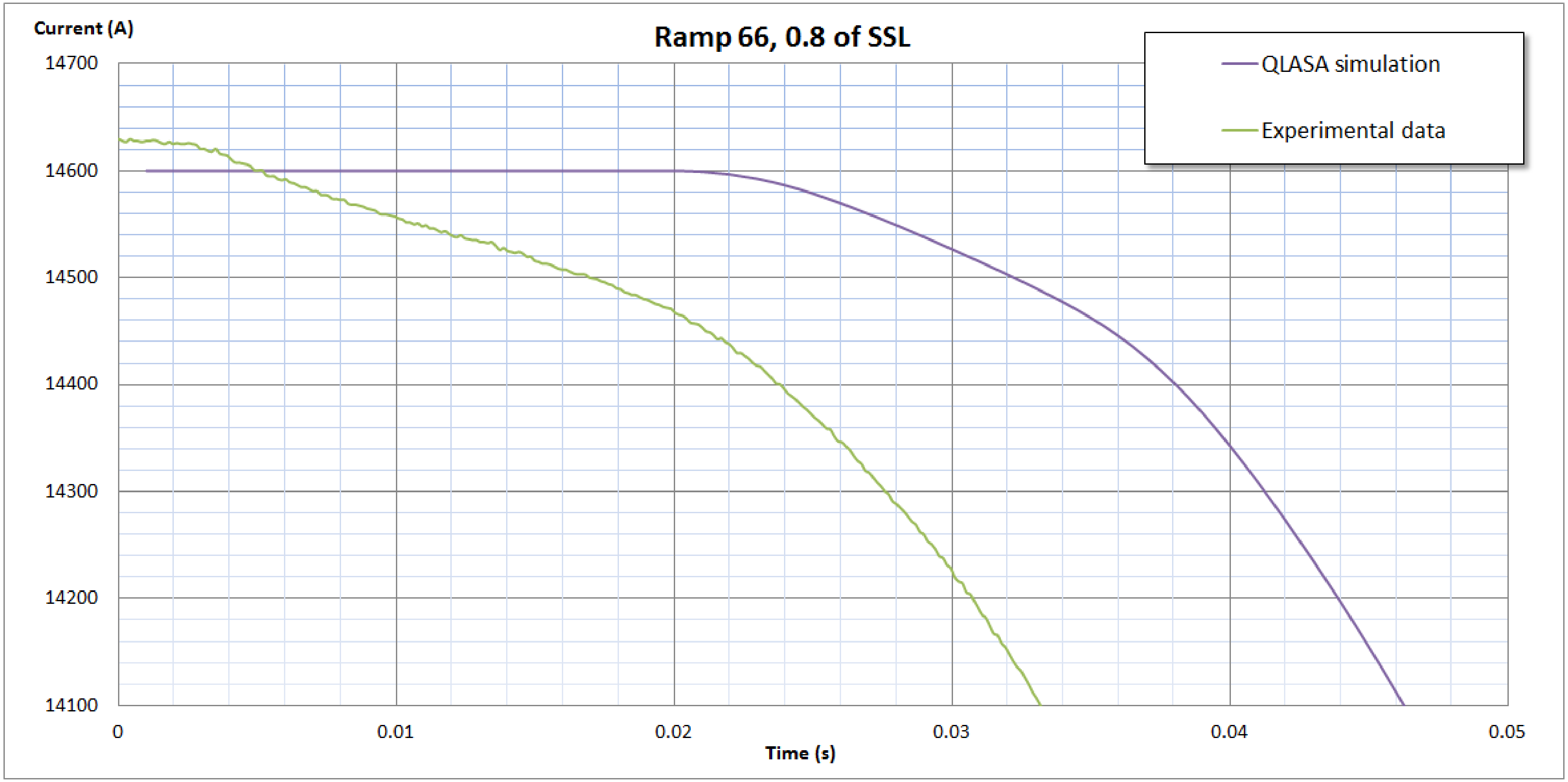
3.2 Current decay comparison



- 14.6 kA @ 1.9 K (0.8 of SSL)
- OL-PH firing at 0 ms
- No dump resistance
- Heaters delay time from Tiina Salmi simulations by CoHDA (Code for Heater Delay Analysis) (heat equation solving)
- Heaters-induced quench covers all the turns, except the top and the bottom ones
- Simulation using nominal inductance (5.8 mH)

- The simulated decay is very **slower**. MIITs are surely overestimated
- At the start of the decay, the experimental curve is **faster than expected**

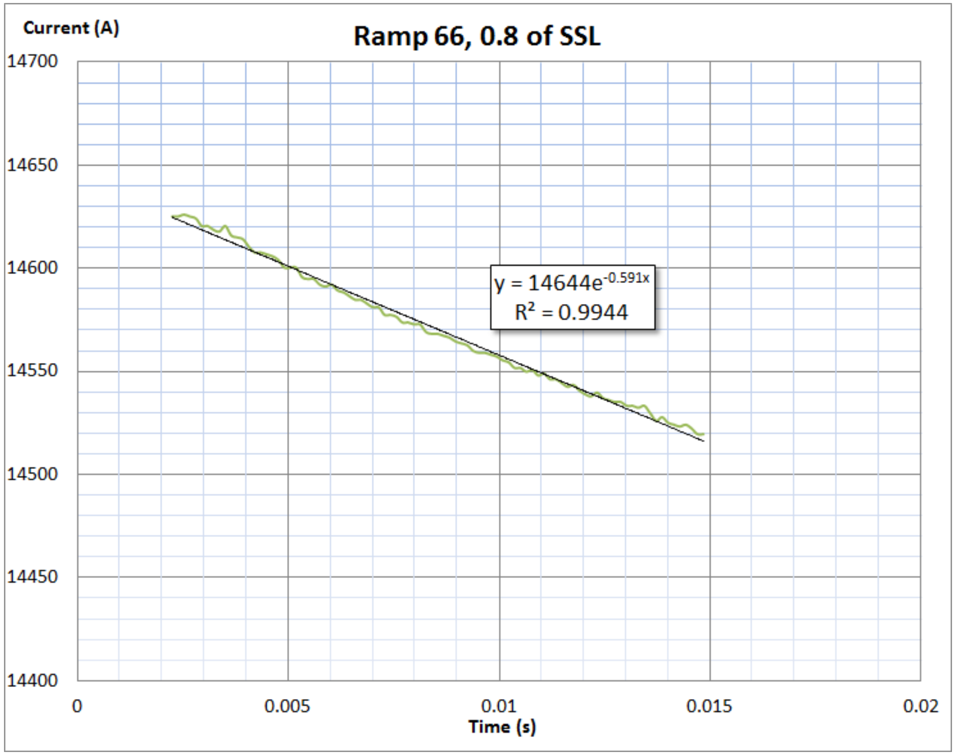
3.2 Current decay comparison



Current starts to decay **after few ms**. Heaters **do not** induce quench so quickly (checked on voltage taps)

Evidence of a **"dark" resistance**

3.2 Current decay comparison



$$\tau = \frac{1}{0.591} \sim 1.69 \text{ ms}$$

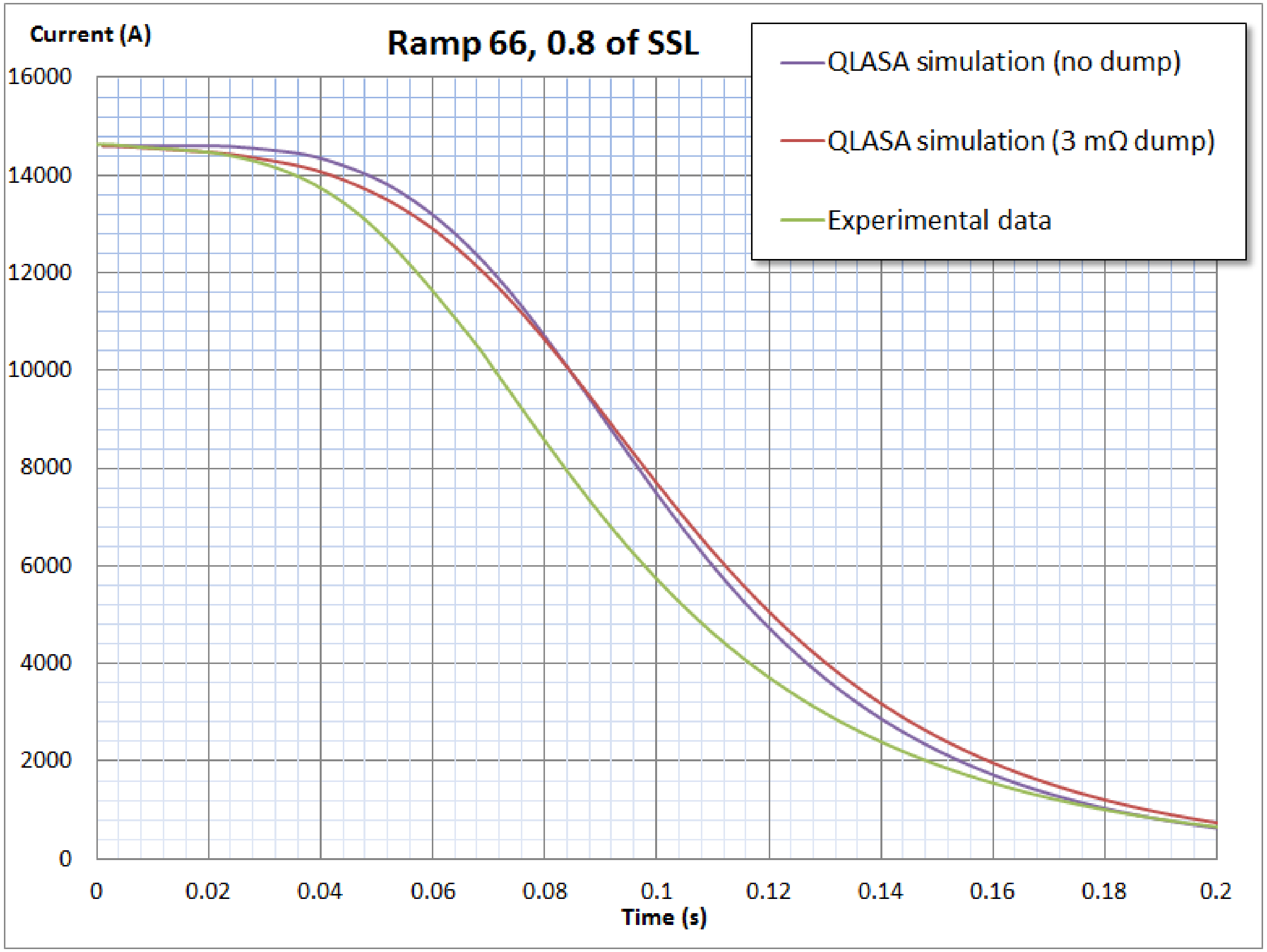
$$R = \frac{L}{\tau}$$

Inductance (mH)	Resistance (mΩ)
4	2.4
5	2.9
6	3.5

- Decay is compatible with a resistance between **2.5 and 3.5** mΩ
- **Expected** resistance coming from bus, diodes, connections is < **1 mΩ**
- There is an **unexplained resistance** of 1.5/2.5 mΩ

Could it be that this is the reason of the similarity between the MIITs developed during 5 mΩ dumping resistance and no dumping resistance tests?

3.2 Current decay comparison



Simulation repeated with a 3 mΩ dumping resistance, in order to simulate the “dark” resistance

Ideal for giving a more accurate MIITs estimation

- Simulation with dumping resistance fits better at the start of the decay
- Nonetheless, simulated current decay is still slower than experimental one

3.3 MIITs comparison and conclusions

Current/SSL	0.8	0.7	0.6	0.5	0.4
MIITs difference % (no dump case)	14.5	13.2	9.6	10.7	8.1
MIITs difference % (3 mΩ dump case)	13.4	11.1	6.4	5.3	0.9

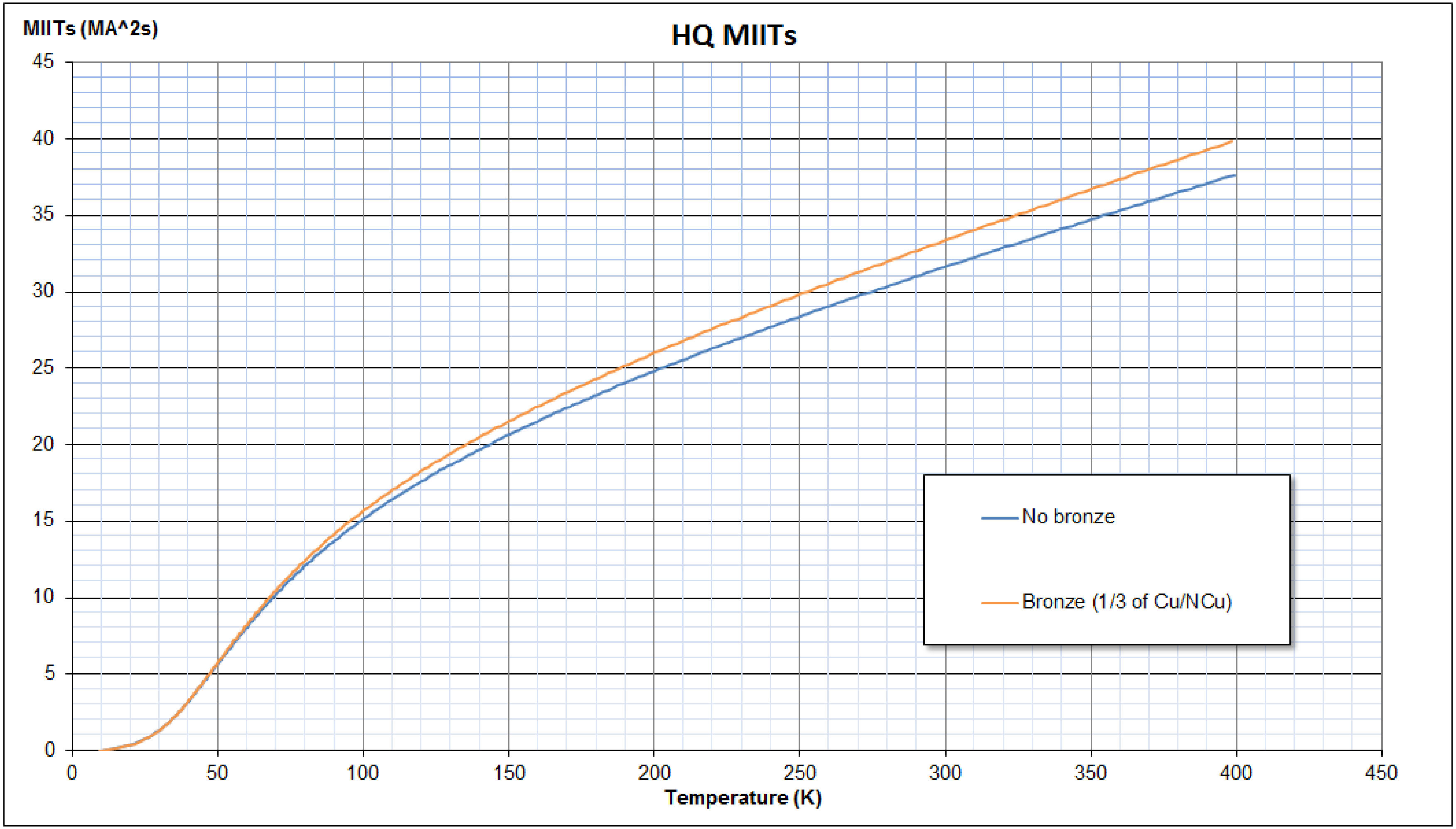
Most significant case for MQXF

- Under the assumptions used for MQXF, the heaters-induced quench simulation is **conservative**.
- At the current of interest (0.8 of SSL), the MIITs are **overestimated of about 13 %**. The overestimation is lower at lower currents.
- An **unexpla**
  dumping resis
  MIITs develope
  a 5 mΩ resistanc

Margin is due to:

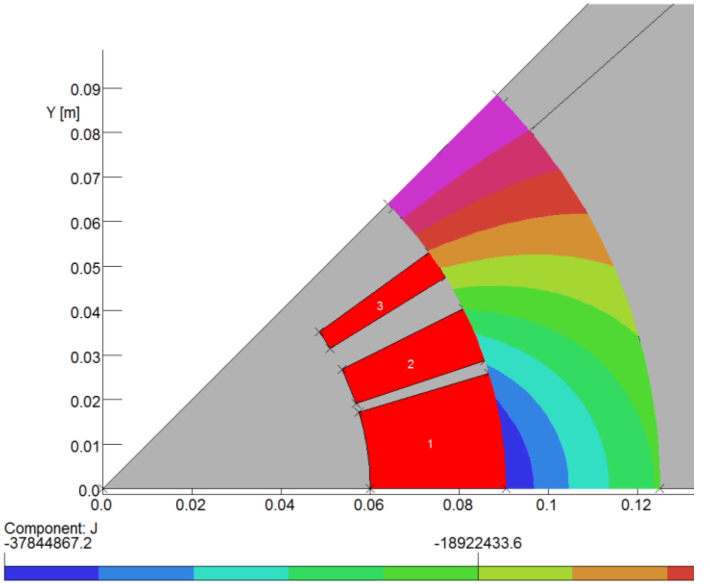
- dI/dt effects;
- Conservative assumptions in modeling of heaters and propagation from OL to IL

3.3 MIITs comparison and conclusions



In MQXF, a MIITs overestimation of 13% at 350 K corresponds to about **60-70 K less** in hot spot temperature!

The dI/dt effects:



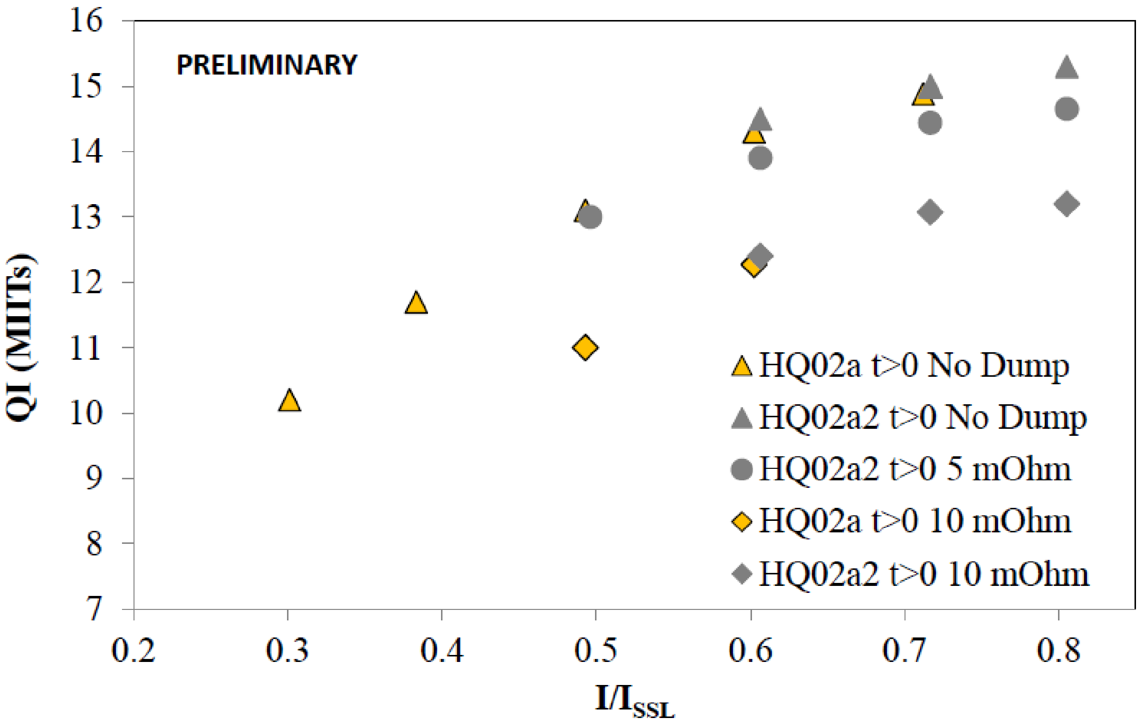
- *They may due to coupled currents induced in the metallic part of the magnet (collars, yoke, beam tube, external cylinder, rods, etc.). The energy transferred to these secondary circuits has the benefic effect to decrease the current in the coils (the primary circuit). The apparent inductance of the coils seems lower because the current decreases faster.*
- *They may due to coupled current in the Rutherford cable (inter-strand of inter-filament). In this case the enhanced heating of the conductor or the transition due to large current in some strands, would induce back quench in large part of the coils, before the effect of quench heater.*

These effects are clearly evident in the LARP model coil, and they give a consisten margin in the real accumulated MITTs during the discharge.

Models and studies have began in order to well understand ad foresee these important and beneficial effects.

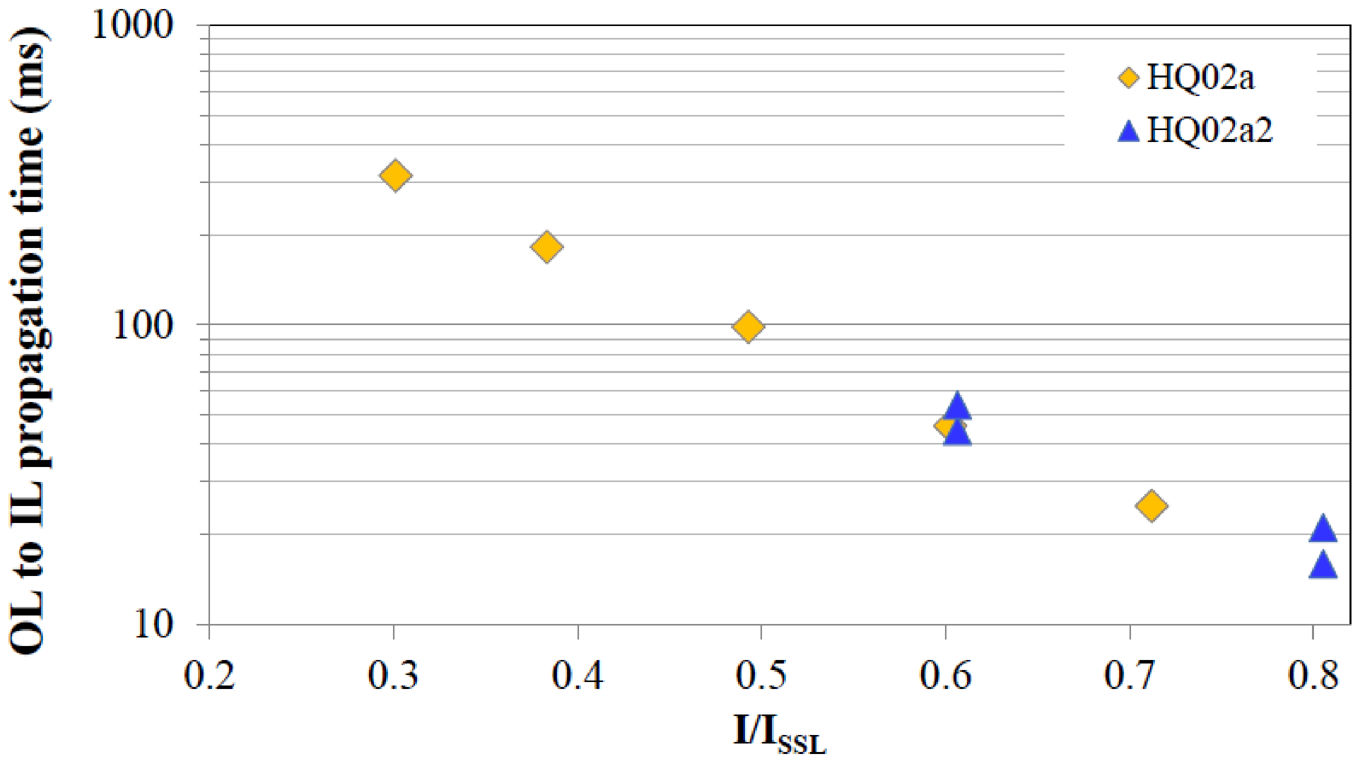
QI study on HQ02 with different dump resistors

- Tests performed with 5 mΩ and 10 mΩ dump resistors, as well as without the dump at 2.2 K. Only OL heaters used for the magnet protection
- Very good reproducibility of the QI measurements in the current range of (60-70)% of SSL
- Data analysis in progress



OL to IL quench propagation

- OL protection heater induced quenches w/o dump
- OL to IL quench propagation time ***t = t(IL quench) – t(OL quench)***
- OL to IL quench propagation time spread between coils shown for HQ02a2



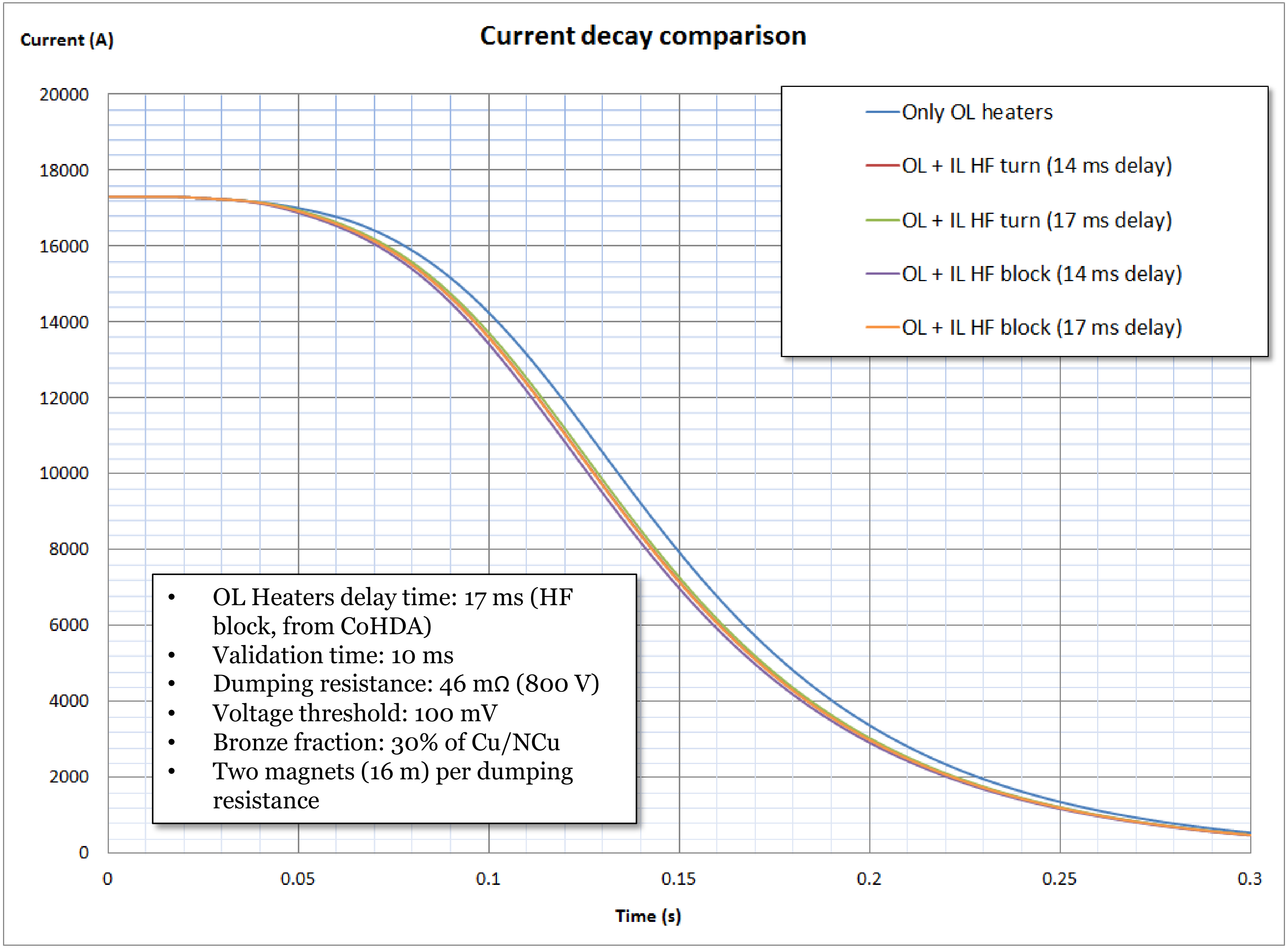
3 - OPTIONS AND PLANS

Options for further improvements

- Heaters on Inner Layer
- Different materials for heaters and traces
- CLIQ
- Other options…

MQXF protection with IL-HF block PH

6.1 PH in the IL – HF zone



6.2 PH in the IL – HF zone

What's the impact of protection heaters in the inner layer (only high-field zone) on the hot spot temperature?

Only OL PH case
332.7 K

Four cases considered:

- Quench induced in the **IL high-field block** at the same time of the OL high-field block (average from CoHDA) → **305.6 K** 8.9 % less
- Quench induced in the **IL high-field block** 3 ms before the OL high-field block (average from CoHDA) → **299.5 K** 11.1 % less
- Quench induced in the **IL high-field turn** at the same time of the OL high-field block (average from CoHDA) → **310.4 K** 7.2 % less
- Quench induced in the **IL high-field turn** 3 ms before the OL high-field block (average from CoHDA) → **306.1 K** 8.7 % less

Open questions

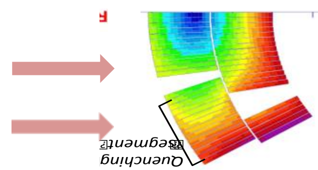
- Heaters optimization:
  - What is the "best design" with present technology?
  - What is the correct heater delay time with best design?
  - What is the correct time to quench the whole OL?
  - ➔Test LHQ coil with different heaters and compare with simulations

LARP magnet heater options

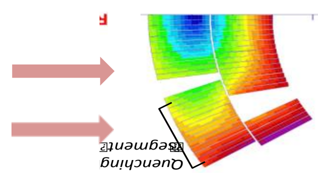
a) HQ-style heater – a single strip meandering along the coil inner and outer surfaces

b) LQ/LHQ style" – a meandering strip with varying cross-section – "heating station" concept

c) Straight strips separately covering the high field and low filed zones and separately powered



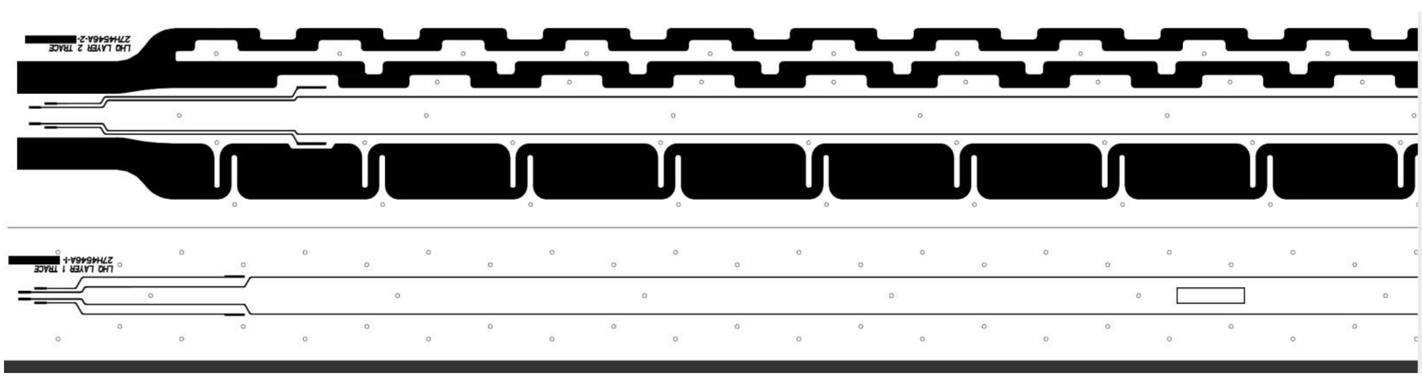
d) A modification of c) with sections lengths optimized according to the superconducting margin of each section



Choosing the layout

The only layout that was successfully tested in long magnets if the “LQ-style” one (“b”). It allows extension over large distances by spacing the “heating stations” further apart

Its first alternative is the pattern “c” that is planned to be checked against the pattern “b” in the upcoming test of the LHQ. The trace containing both patterns is being fabricated :



Open questions and Action Items

- Heaters optimization:
  - Can we reduce heat diffusion time and/or increase dielectric strength?
    - Minimize polyimide and add layer of different material
    - Use doped polyimide
    - Use alternative material btw trace and coil
  - Can we have heaters btw layers?
  - Can we have heaters on IL w/o bubbles?

➔ How can we test options faster than in a mirror?

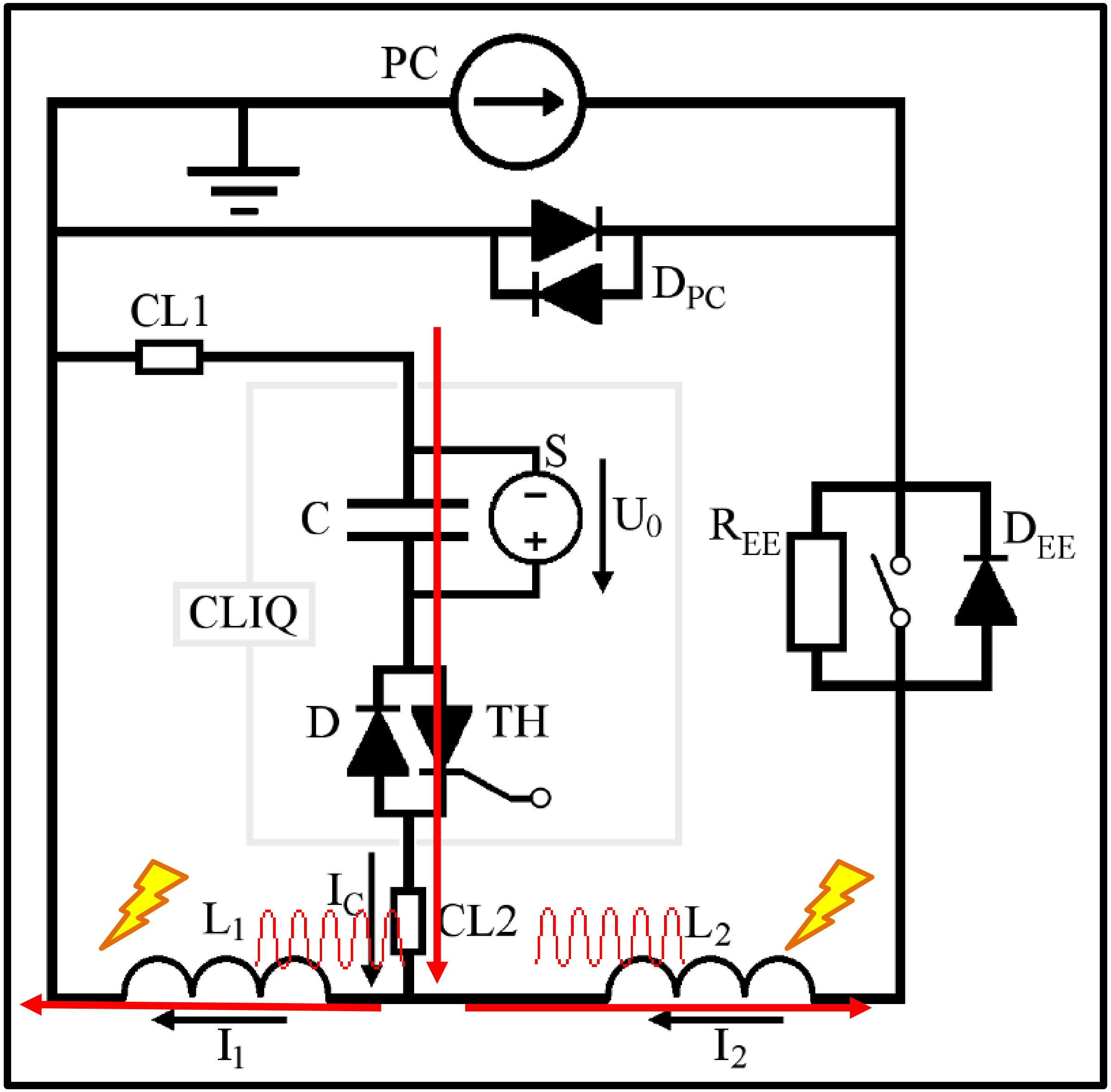
- Copper trace option discarded
- Copper laminate on stainless steel trace to be studied
- Other materials may be considered if trace is turned upside-down

25 µm thick polyimide trace materials	Additi… polyimide protects against material flaws	Entire laminate may not impregnate well; Unknown epoxy layer thickness after impregnation	Requires additional 25 µm layer of polyimide
50 µm thick polyimide trace materials	Improved impregnation due to single layer of material	Does not inherently provide protection from material flaws	Does not require additional layer of polyimide
Copper trace materials (Pyralux AP)	One less layer between heater and conductor; polyimide is 0.26 W/mK @ ~RT	Unknown performance (SS only has been used in LARP)	No adhesive layer between copper and polyimide (directly bonded)
Kapton MT	0.37 W/mK (3x Kapton HN equiv. at ~RT)	Unknown performance (has not been tested)	Same laminate bonding process as SS materials

Open questions

- Redundancy
  - Can we use CLIQ to have a redundant QP system?
  - ➔ Do analysis of CLIQ on MQXF
  - ➔ Test is on HQ02/03?
  - If not, what is the best lay-out for providing enough redundancy?

Concept of CLIQ – Coupling Loss Induced Quench



Current Change

Magnetic Field Change

Coupling Losses (Heat)

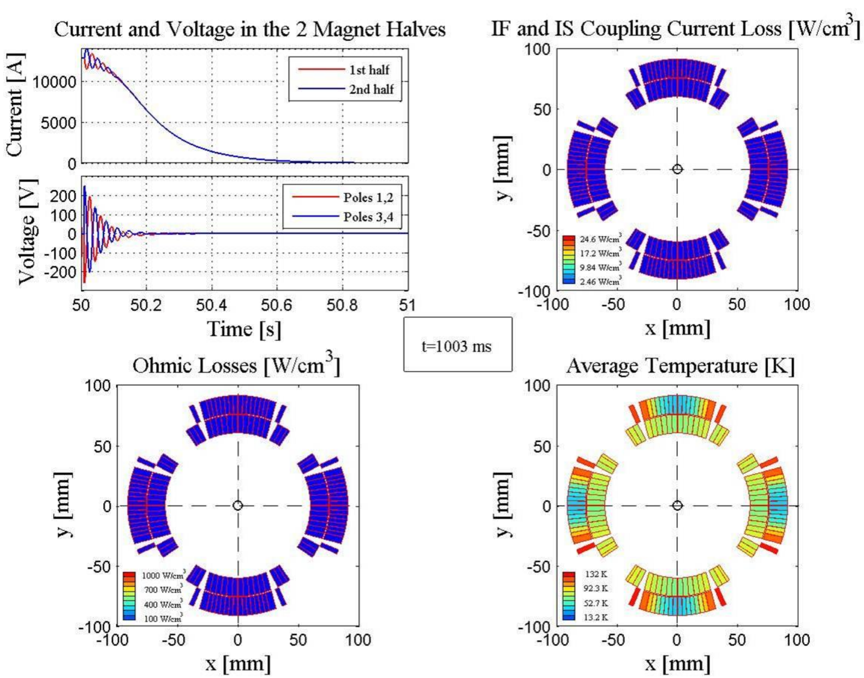
Temperature Rise

QUENCH

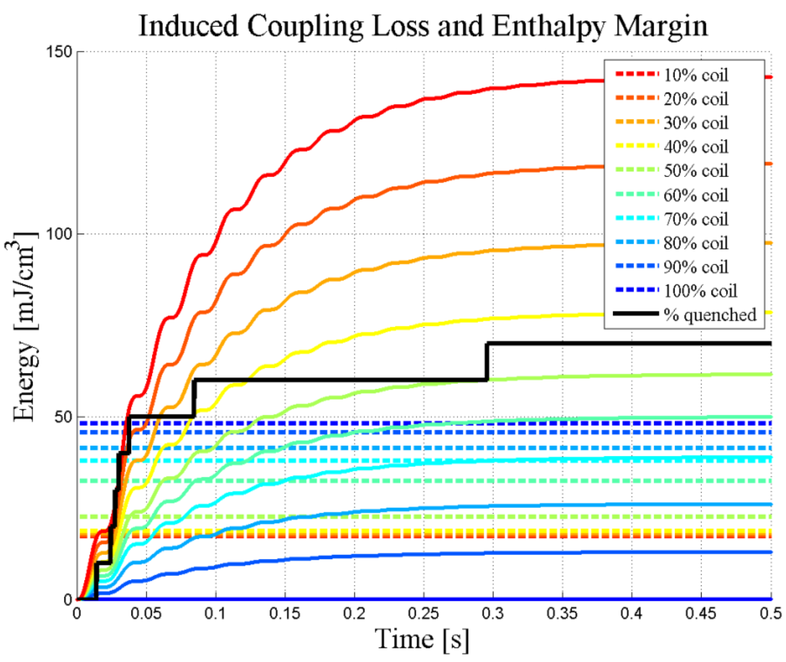
CLIQ for MQXF

- CLIQ will be tested on HQ02b at CERN
- Goal: test its efficiency in MQXF-like conditions

CLIQ on MQXC



CLIQ on MQXF



Open question

- What is the maximum acceptable $T_{hot\text{-}spot}$?
  - ➔ High-MIITs test on HQ02b

MARGIN VS COPPER

- Estimate of the gain in time margin and temperature vs copper fraction

Cu-Non_Cu (adim)	ss gradient (T/m)	Margin (adim)	Time margin (ms)	Hotspot ΔT (K)
1.2	172	0.814	33.3	-
1.3	169	0.828	34.6	-10
1.4	167	0.838	36.2	-20
1.5	165	0.848	37.7	-29

- Estimate of the gain in time margin and temperature vs operational gradient

Cu-Non_Cu (adim)	Op. gradient (T/m)	Margin (adim)	Time margin (ms)	Hotspot ΔT (K)
1.2	140	0.819	33.3	-
1.2	135	0.789	37.5	-27
1.2	130	0.760	47.7	-58
1.2	125	0.731	67.6	-95

Summary

- The first complete QP analysis of MQXF showed no margin
  - With some conservative assumption
- Benchmarking codes with HQ02 data has shown that we have some margin
- HQ02b should give us more answers
  - High-MIITs; CLIQ
- Optimization of traces/heaters in progress
- Extreme solution: lower gradient…