Modeling of QXF protection

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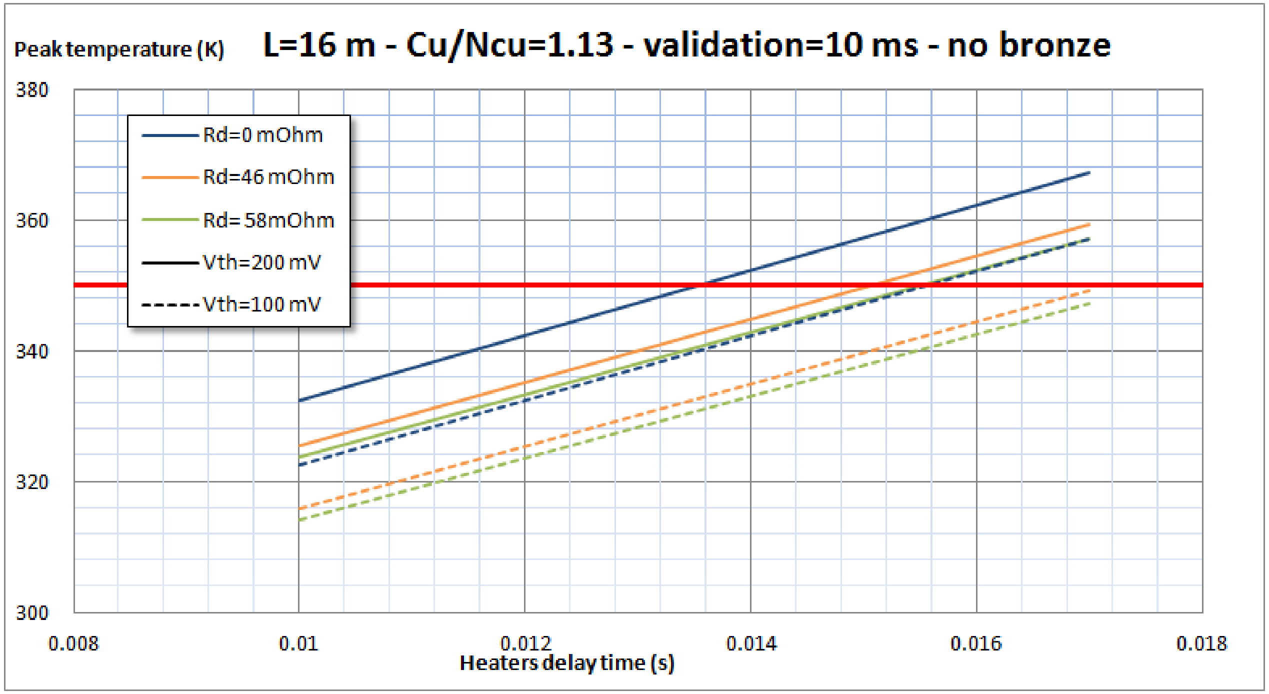
Summary:

- MQXF state of protection presented at MT-23
- Dynamic effects on the inductance
- Magnet coupling with external circuits
- MQXF inner layer quench heaters
- MQXF protection at 90 % of SSL
- MQXF protection redundancy
- CLIQ and MQXF

0.1 MQXF protection state at MT-23



MT-23: MQXF hot spot temperature is **very close** to the conventional maximum of 350 K

- Simulations have been performed making conservative assumptions on quench heaters and **magnet inductance**
- <u>How much conservative are the simulations?</u>

1.1 Dynamic effects

MIITS comparison between experimental data-simulations on HQ02a tests

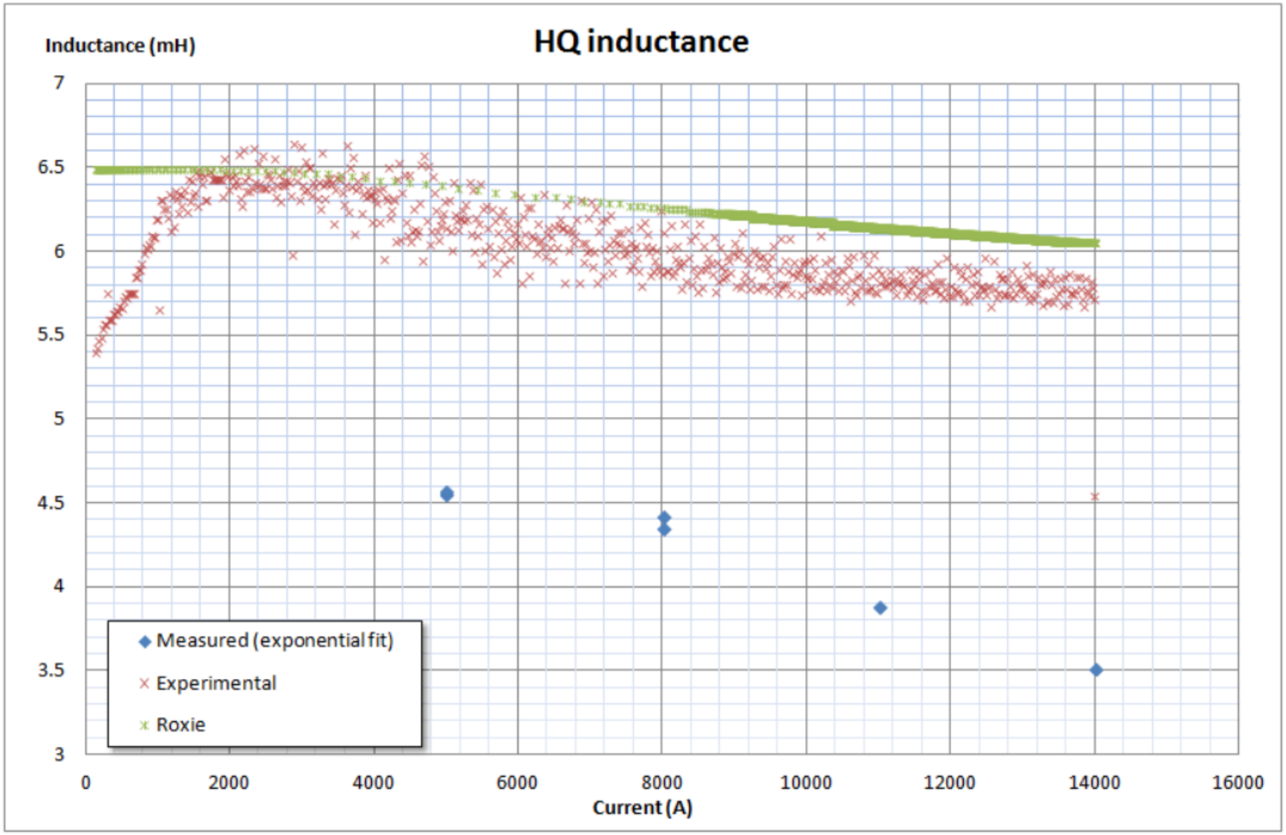
Current/SSL	0.8	0.7	0.6	0.5
MIITs difference %	16.5	13.3	4.8	2.4

Dumping resistance 5 mΩ
dI/dt similar to MQXF

Most significant case for MQXF

- HQ02a tests: considering the assumptions made for MQXF, there is a MIITs overestimations between experimental data and simulations of **16 %**, which is **80 K less** in hot spot temperature.
- This is due to **dynamic effects** on the inductance (plus other conservative assumptions)

1.2 Dynamic effects



After a quench, during a discharge, magnets inductance appears **lower** than expected

Probably due to additional energy extraction (besides dumping resistance)

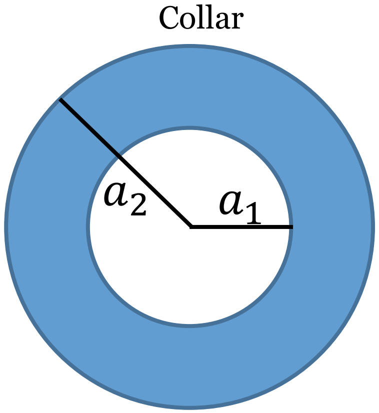
Possible explanations:

1. Coupling with shell, yoke, or any metallic part surrounding the magnet
2. Inter-filament **eddy currents**

2.1 Coupling – external ring

It can be proved that a cylinder external to the coils is interested by **cos(2θ) currents**

The collar can be described as a coupled, filamentary circuit



$$R_2 = \frac{\pi}{2}\frac{\rho}{a_2^2 - a_1^2}$$

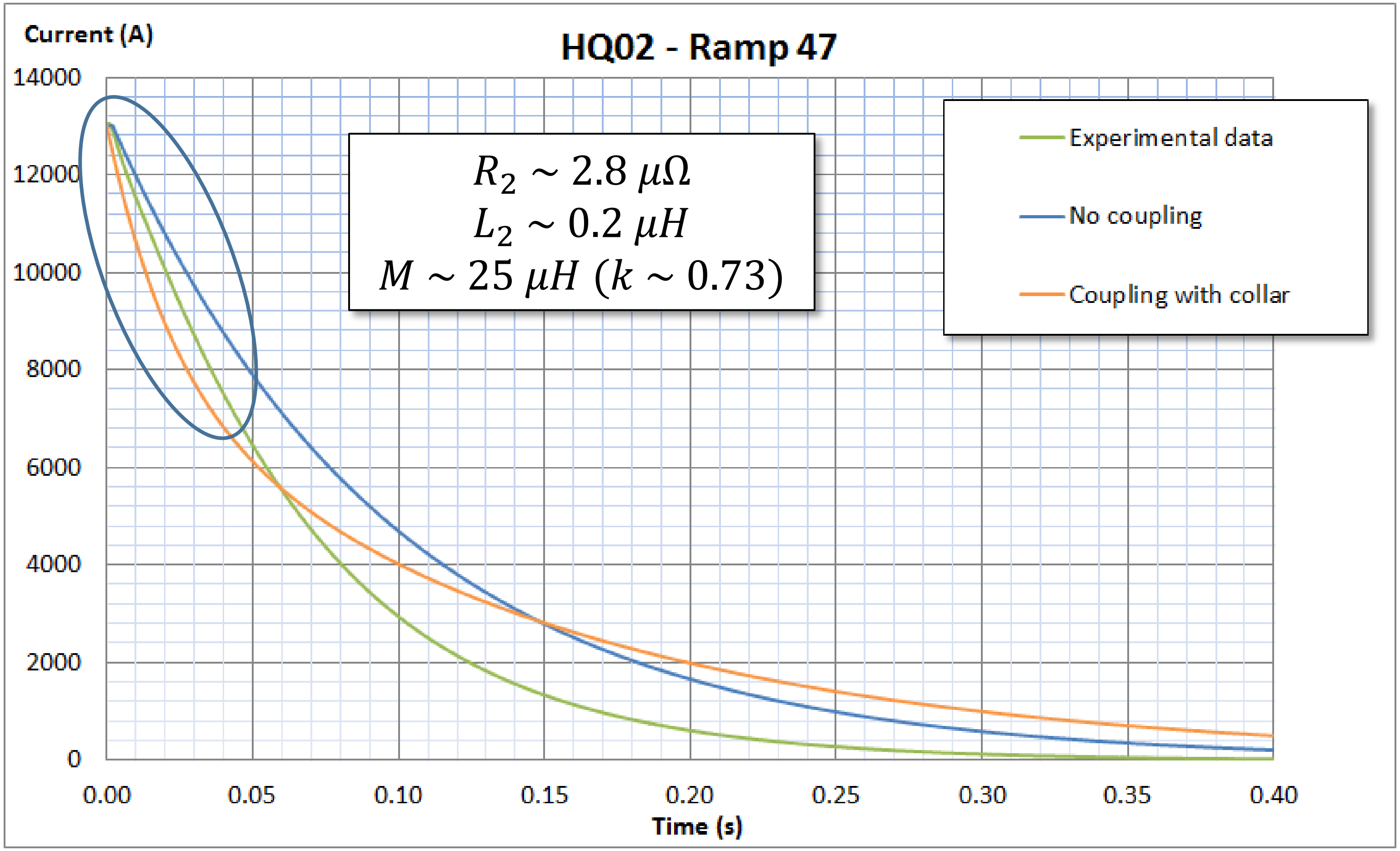
$$L_2 = \frac{\pi}{32}\mu_0 \frac{a_2^4 - a_1^4\left(1 + \ln\frac{a_2^4}{a_1^4}\right)}{(a_2^2 - a_1^2)^2}$$

$$M = \frac{\pi}{16}\mu_0 \ln\left(\frac{a_2}{a_1}\right)\frac{c_2^2 + c_1^2}{a_2^2 - a_1^2}N_1$$

You can solve the equation of two coupled circuits

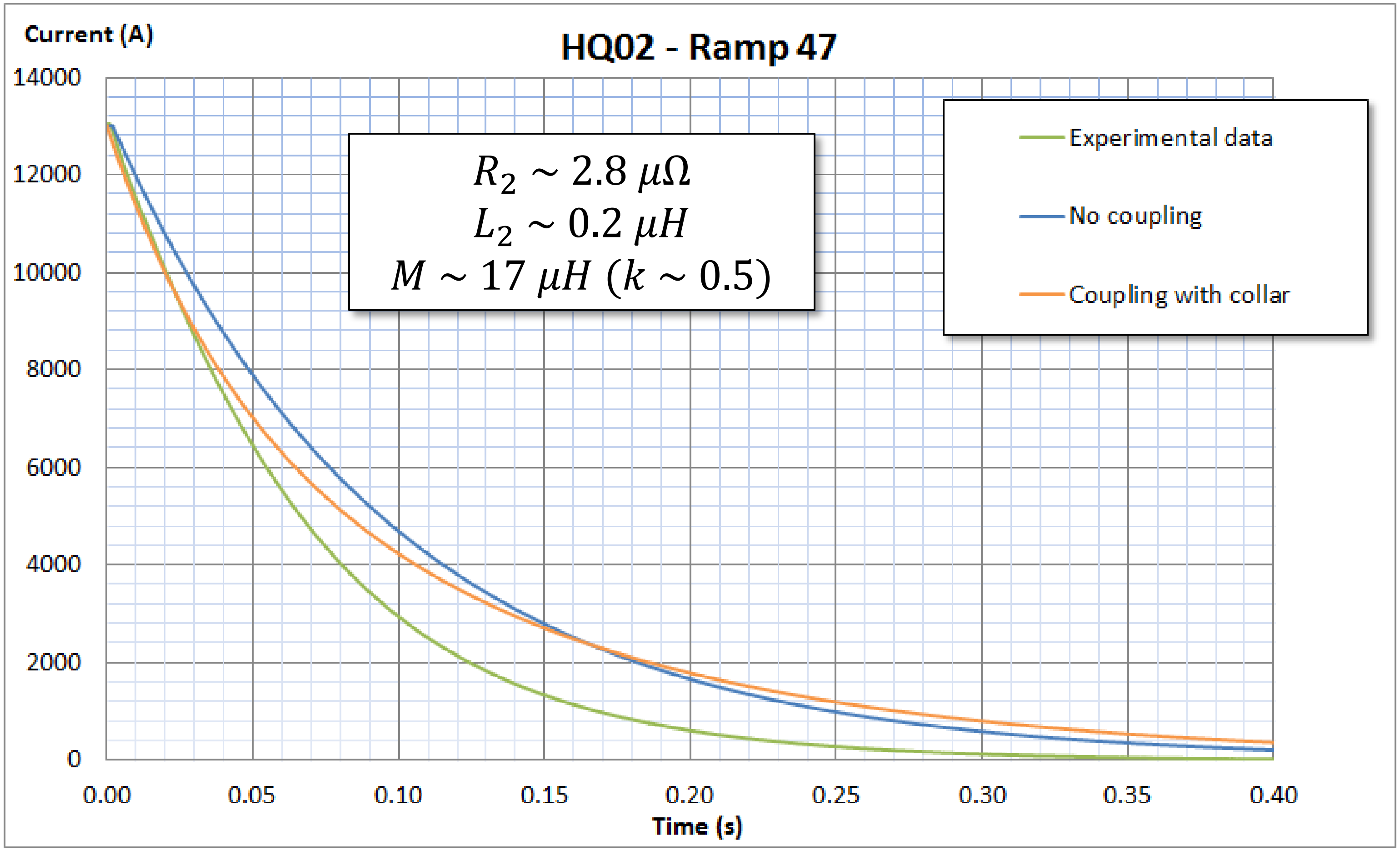
$$\begin{cases} L_1\dot{I}_1 + R_1 I_1 + M\dot{I}_2 = 0 \\ L_2\dot{I}_2 + R_2 I_2 + M\dot{I}_1 = 0 \end{cases}$$

2.2 Coupling – external ring



- The coupling **strongly affects** the current decay
- The mutual inductance is **too much high**

2.3 Coupling – external ring



- The fitting at the **start** of the decay is good
- At the end of the decay, the inductance comes back to the **nominal value**

2.4 Coupling – inter-filament eddy currents

- Calculation based on "*Superconducting magnets*", M.N. Wilson - 1983
- The inter-filament currents induced during an exponential current decay with time constant $\tau_{ext} = \frac{L}{R}$ produces a magnetization with a time-dependent permeability

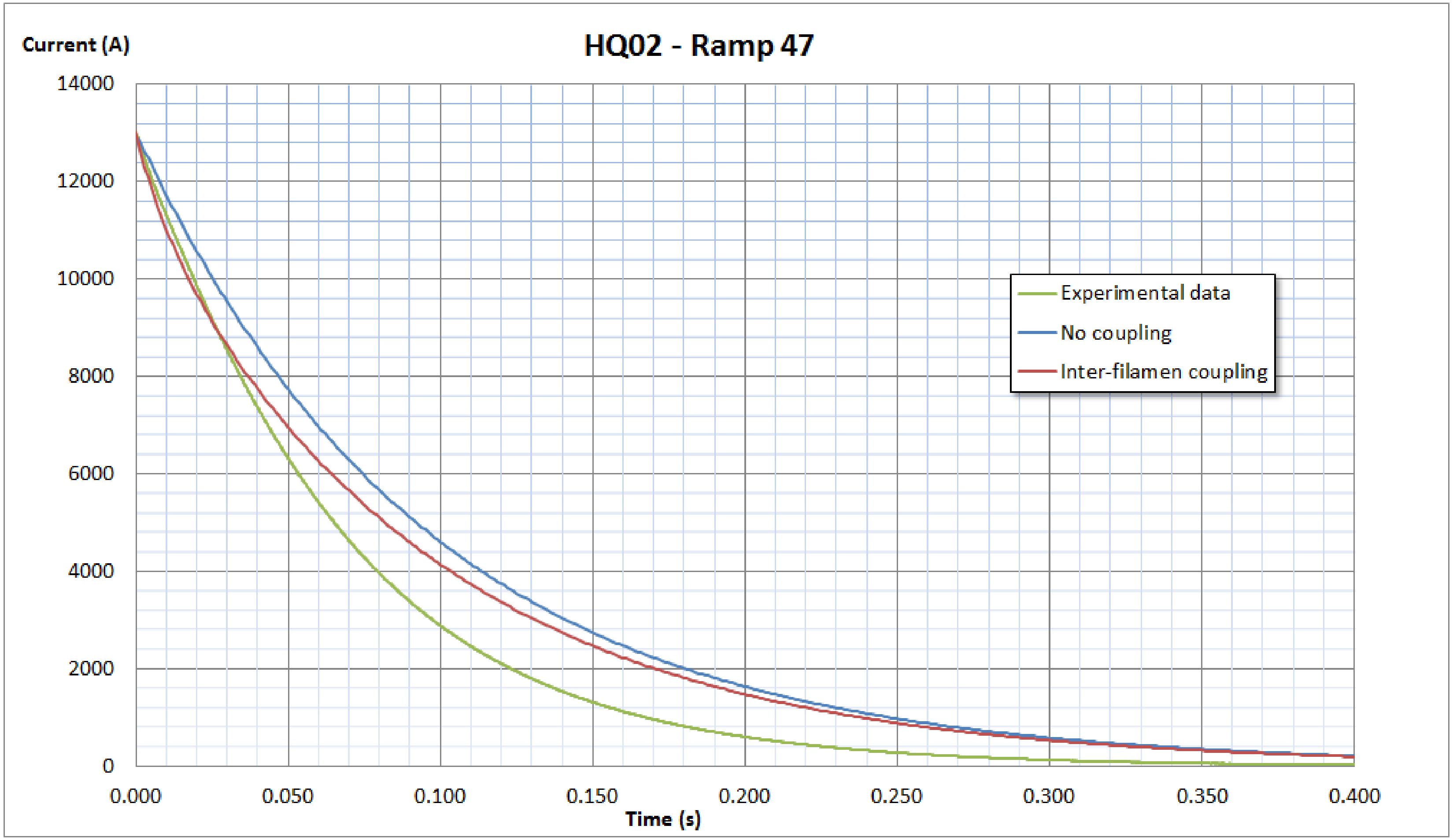
$$\chi(t) = 2\tau\left[\frac{e^{-\frac{t}{\tau}}}{\tau - \tau_{ext}} - \frac{\tau e^{-\frac{t}{\tau_{ext}}}}{\tau_{ext}(\tau - \tau_{ext})^2}\right]$$

- The inter-filament currents constant time is $\tau = \frac{\mu_0}{2\varrho_t}\left(\frac{L_{pitch}}{2\pi}\right)^2$

- The consequential dynamic inductance can be obtained as

$$L_d = \frac{1}{I}\frac{dU}{dI} = \mu_0\frac{dH^2}{dI} + \chi\mu_0\frac{dH^2}{dI} + \frac{\mu_0 H^2}{\dot{I}}\frac{d\chi}{dt}$$

2.5 Coupling – inter-filament eddy currents



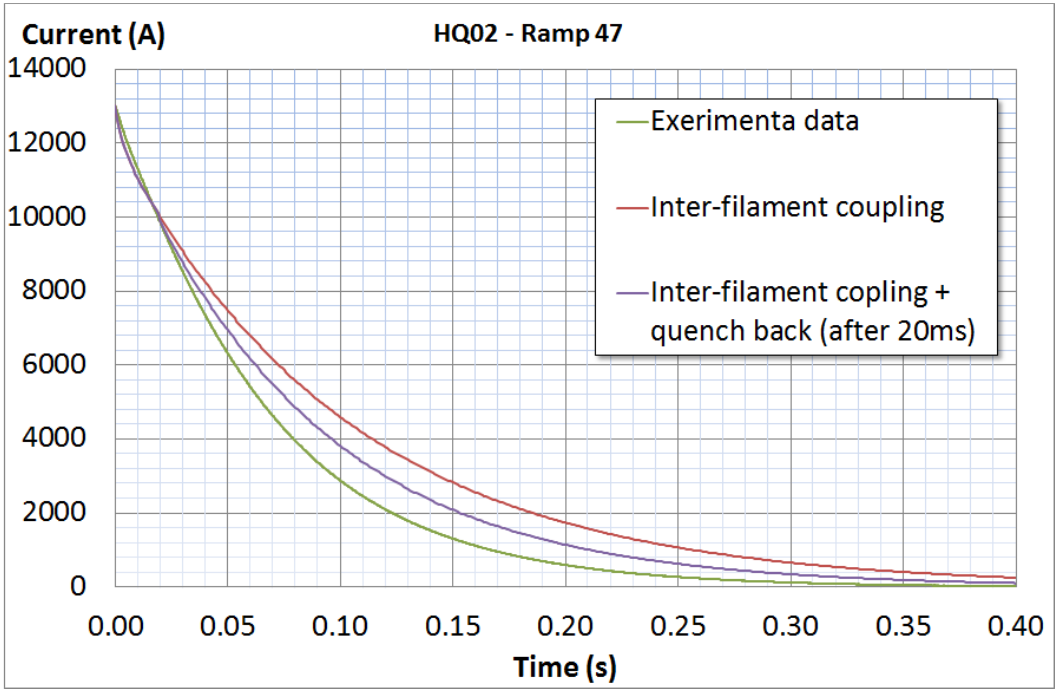
- Again, a **better according** can be seen at the start of the decay
- Then, the inductance gets back to the **nominal value**

2.6 Coupling – conclusions

- Both the coupling with an external ring and the inter-filament eddy currents could explain the magnet reduced inductance at the **start of the discharge**

- In both the models, after few tens of ms, the inductance gets back to the **nominal value**.
  - Possible explanation: quench back?

- Next step: FE simulation for a better description of the **magnet geometry**

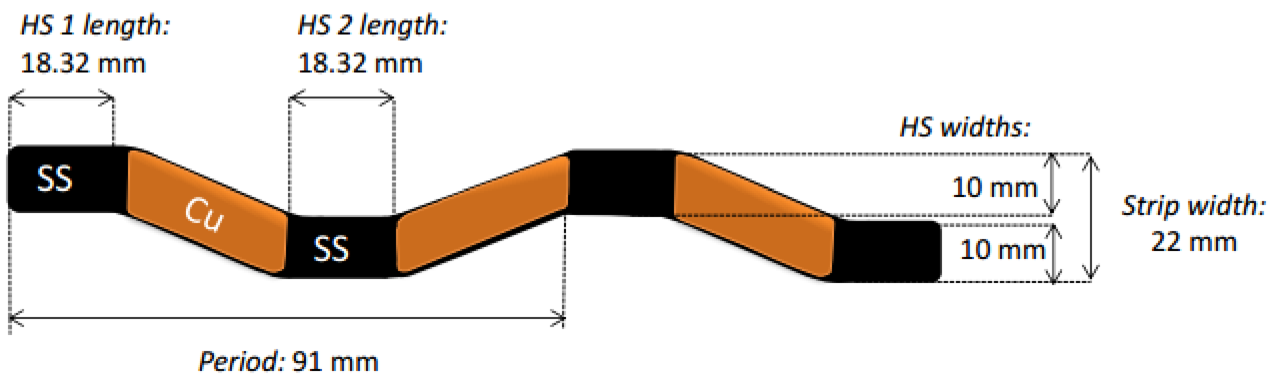


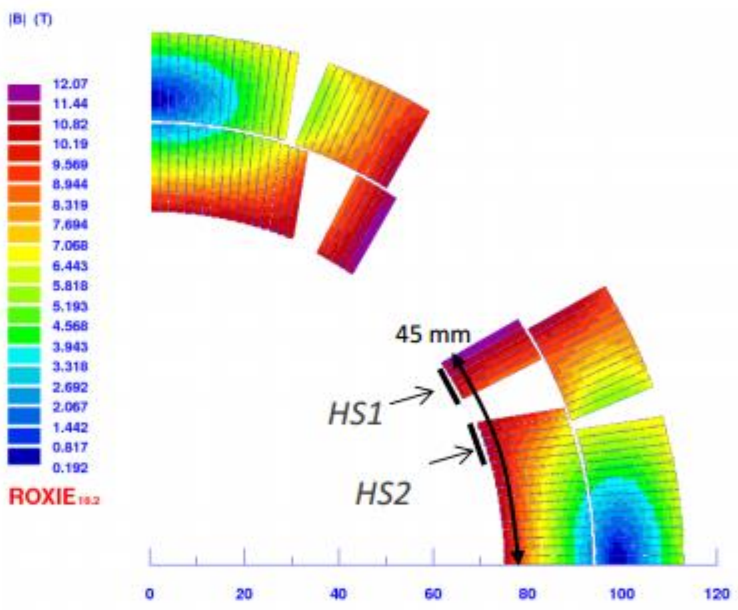
3.1 MQXF IL protection heaters

- MQXF protection with **only outer-layer** heaters is not sufficient
- Inner-layer protection heaters were not considered because of the bubbling issue; anyway, they are needed for reaching a **margin of safety**
- Two possible designs of inner-layer protection heaters have been proposed

3.2 MQXF IL protection heaters – proposal 1

Proposal 1 (Tiina Salmi)





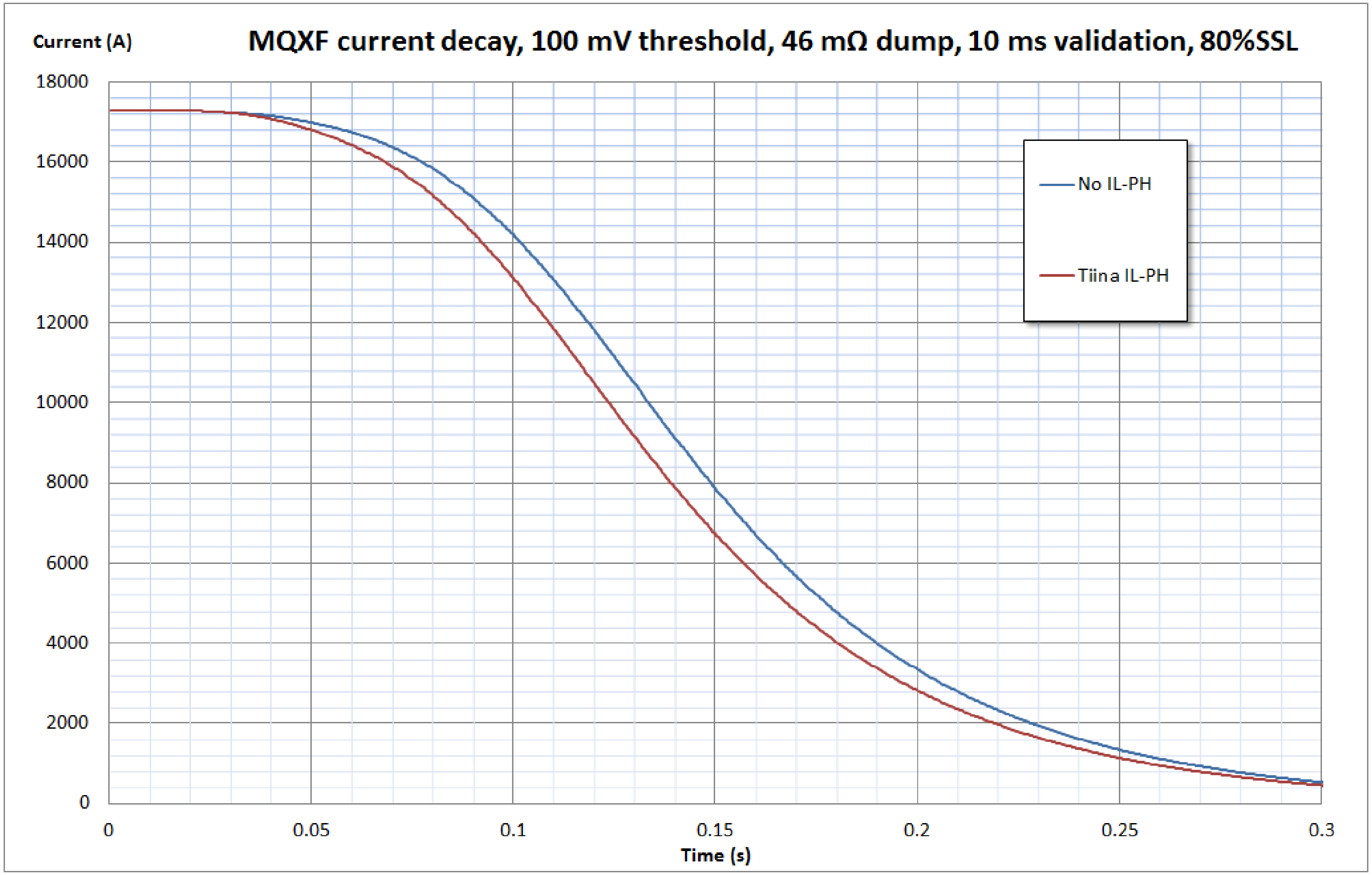
- S-type
- It covers **only HF** zone
- 13 ms average heaters delay time (from CoHDA - Tiina Salmi)

3.3 MQXF IL protection heaters – proposal 1

Assumptions made in QLASA simulations:

- 46 mΩ dumping resistance – 800 V maximum voltage (nominal value)
- 10 ms validation time (nominal value)
- 100 mV voltage threshold (nominal value)
- 16 ms outer layer PH delay time (from CoHDA – Tiina Salmi) -> **old design!**
- 13 ms inner layer PH delay time (from CoHDA – Tiina Salmi)
- No quench in the LF zone (transversal propagation neglected)
- Quench length 17 mm under each HS -> longitudinal propagation
- Material properties from MATPRO
- Nominal cable dimensions after reaction
- Dynamic effects neglected (nominal inductance)

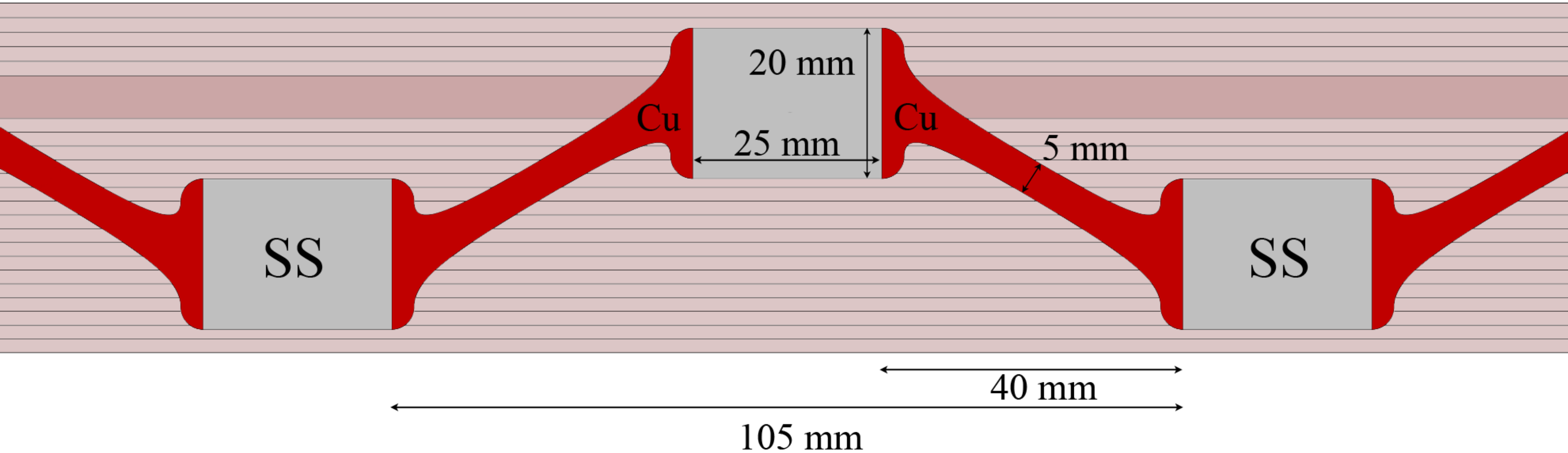
3.4 MQXF IL protection heaters – proposal 1



	No IL-PH	Tiina IL-PH
MIITs (MA^2s)	35.5	32.8
Hot spot temperature (K)	330	290

3.5 MQXF IL protection heaters – proposal 2

Proposal 2 (Ezio Todesco)



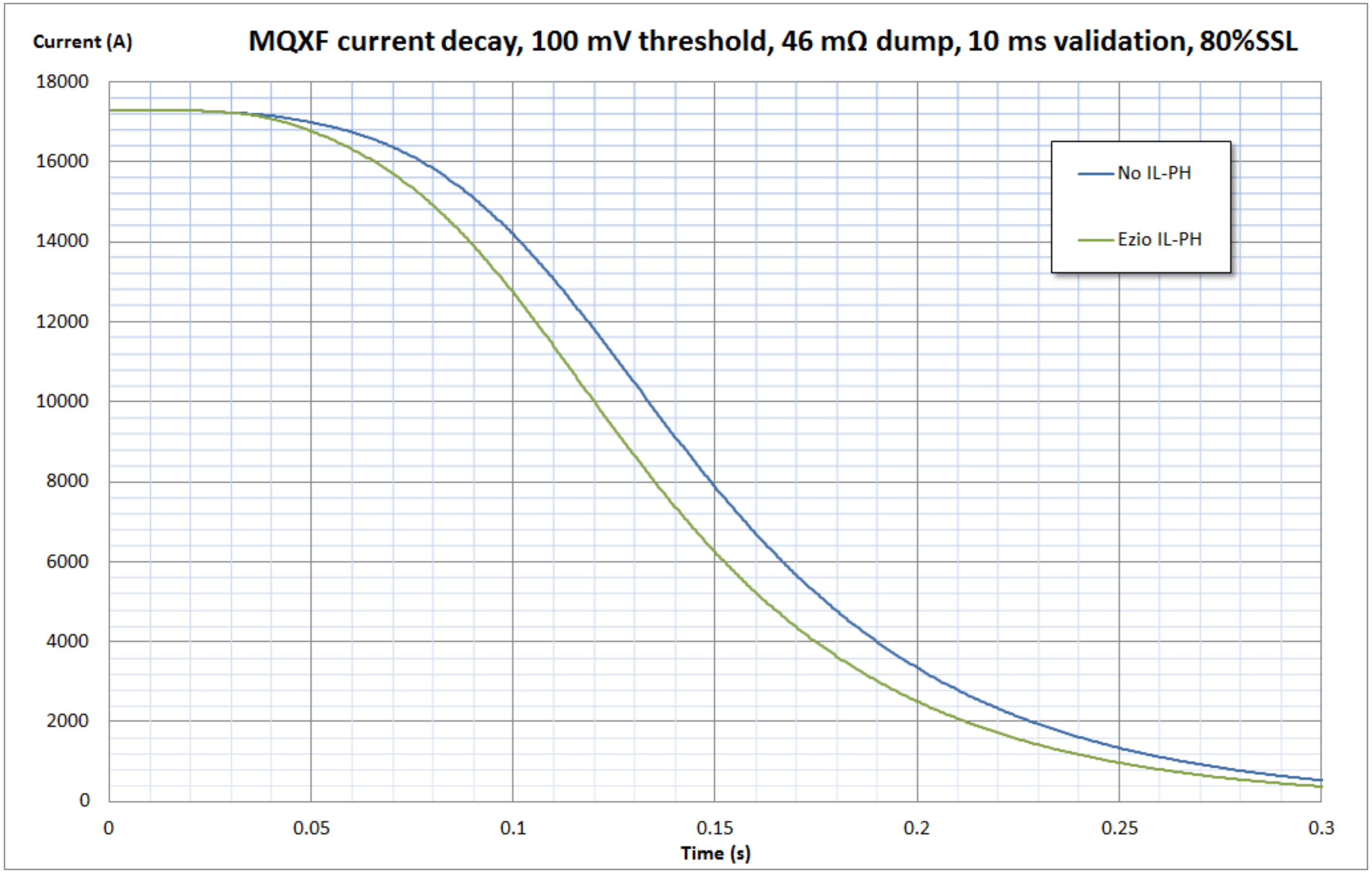
- S-type
- It covers **both** HF and LF zone
- Heaters delay time **not** available for this computation

3.6 MQXF IL protection heaters – proposal 2

Assumptions made in QLASA simulations:

- 46 mΩ dumping resistance – 800 V maximum voltage (nominal value)
- 10 ms validation time (nominal value)
- 100 mV voltage threshold (nominal value)
- 16 ms outer layer delay time (from CoHDA – Tiina Salmi) -> **old design!**
- 13 ms HF PH inner layer delay time (assumed equal to proposal 1, to be improved)
- 17 ms LF PH inner layer delay time (my assumption, to be improved)
- Quench length 23 mm under each HS -> longitudinal propagation
- Material properties from MATPRO
- Nominal cable dimensions after reaction
- Dynamic effects neglected (nominal inductance)

3.7 MQXF IL protection heaters – proposal 2



	No IL-PH	Tiina IL-PH	Ezio IL-PH
MIITs (MA^2s)	35.5	32.8	31.7
Hot spot temperature (K)	330	290	275

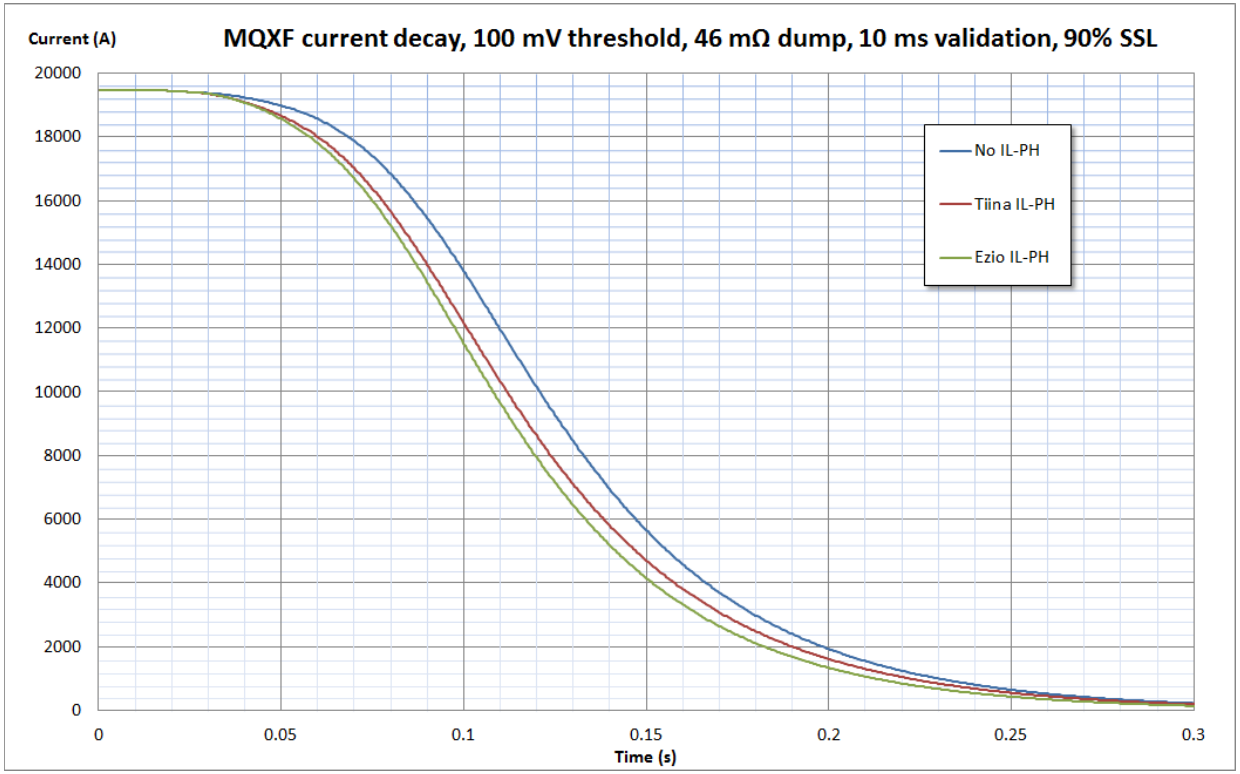
3.8 MQXF IL protection heaters – conclusions

- Inner layer protection heaters **significantly affect** the quench protection:
  - Tiina Salmi design -> 40 K less
  - Ezio Todesco design -> 55 K less

- Next steps:
  - Improve **heaters delay time** using CoHDA in Ezio's design
  - Consider the **transversal propagation** in the LF zone in Tiina's design
  - Use **unreacted** cable dimensions (void in cables issue)
  - Consider dynamic effects?

4.1 Protection at 90% of SSL

- MQXF will be tested at current higher than the **nominal** one (80 % of SSL)
- It could be needed to reach current higher than the nominal one in the machine, too
- Protection study at 90% of SSL is needed



4.2 Protection at 90% of SSL

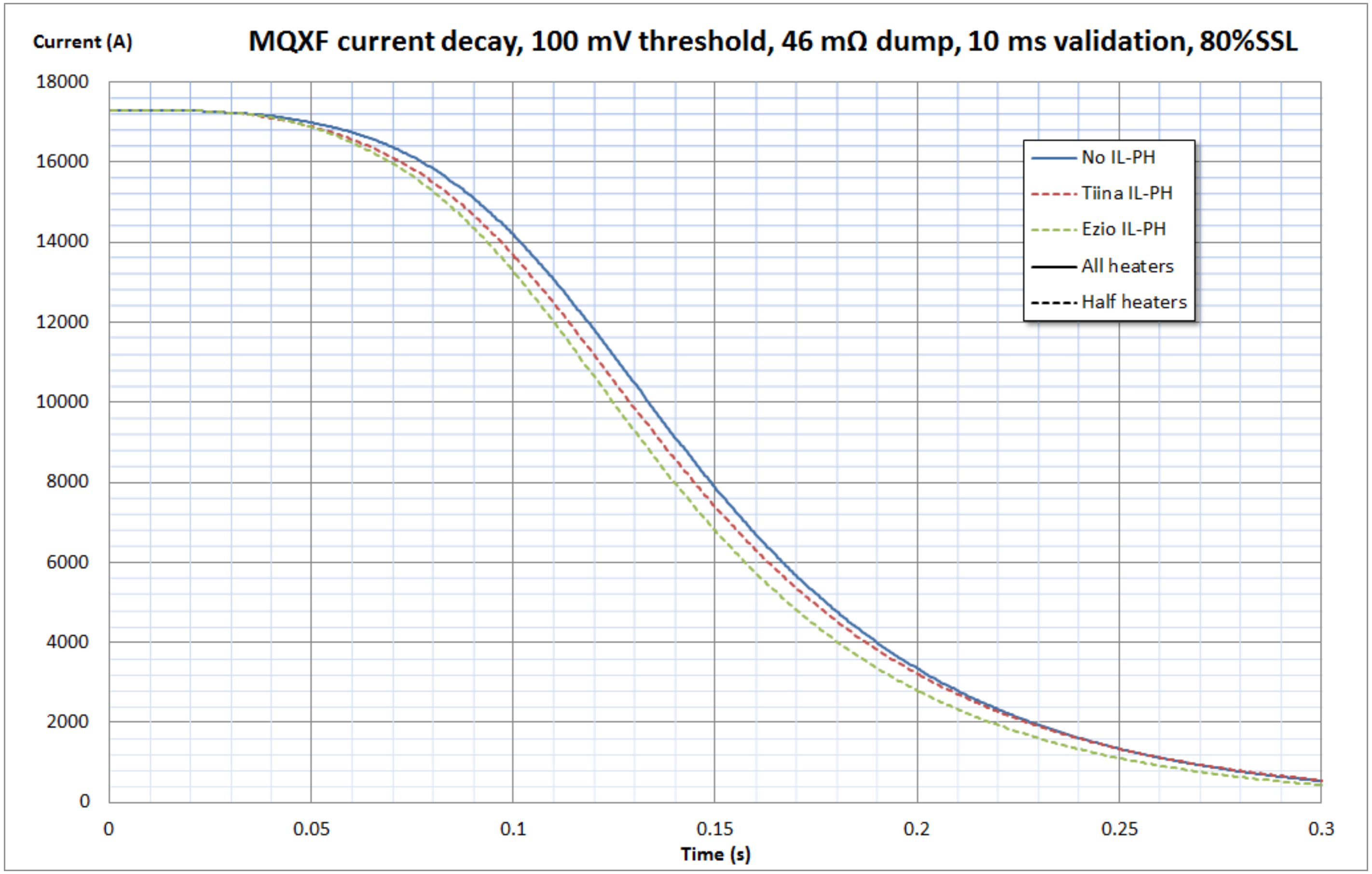
	No IL-PH	Tiina IL-PH	Ezio IL-PH
MIITs (MA^2s)	38.6	35.3	34.1
Hot spot temperature (K)	388	339	320

- **No safety** without inner layer heaters
- **Marginal protection** with both the IL-PH designs
- Dynamic effects neglected

5.1 Redundancy

<u>What if some protection heaters fail?</u>

➢ Simulations repeated considering only half of the magnet protected by quench heaters

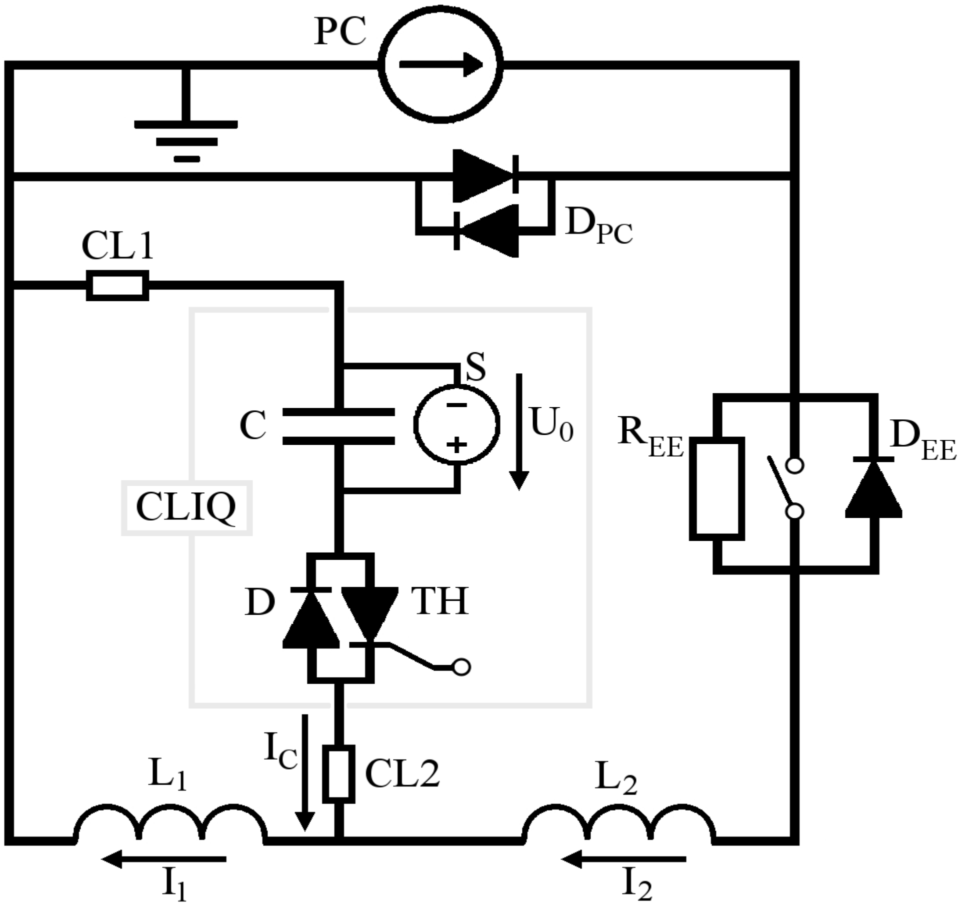


5.2 Redundancy

	No IL-PH All heaters	Tiina IL-PH Half heaters	Ezio IL-PH Half heaters
MIITs (MA^2s)	35.5	34.2	33.1
Hot spot temperature (K)	330	311	294

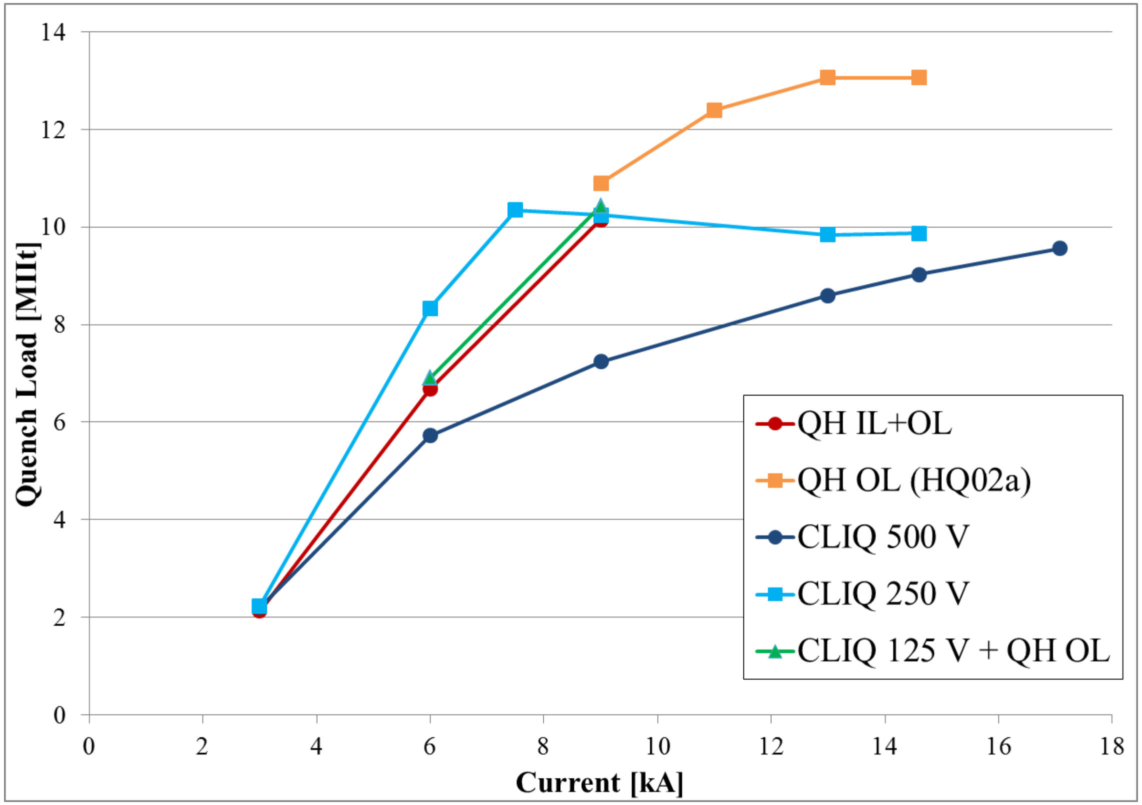
- Protection with IL and OL heaters covering only half magnet is easier than protection with only OL heaters covering the whole magnet
- Failure of half heaters in all coils is a **pessimistic** case, so redundancy is provided

6.1 CLIQ



- "CLIQ" is a new method for protecting magnets, based on a capacitor discharge when a quench is detected
- LC current oscillations are generated, and the subsequent AC losses induce the quench
- It can be used alternatively or together with protection heaters

6.2 CLIQ

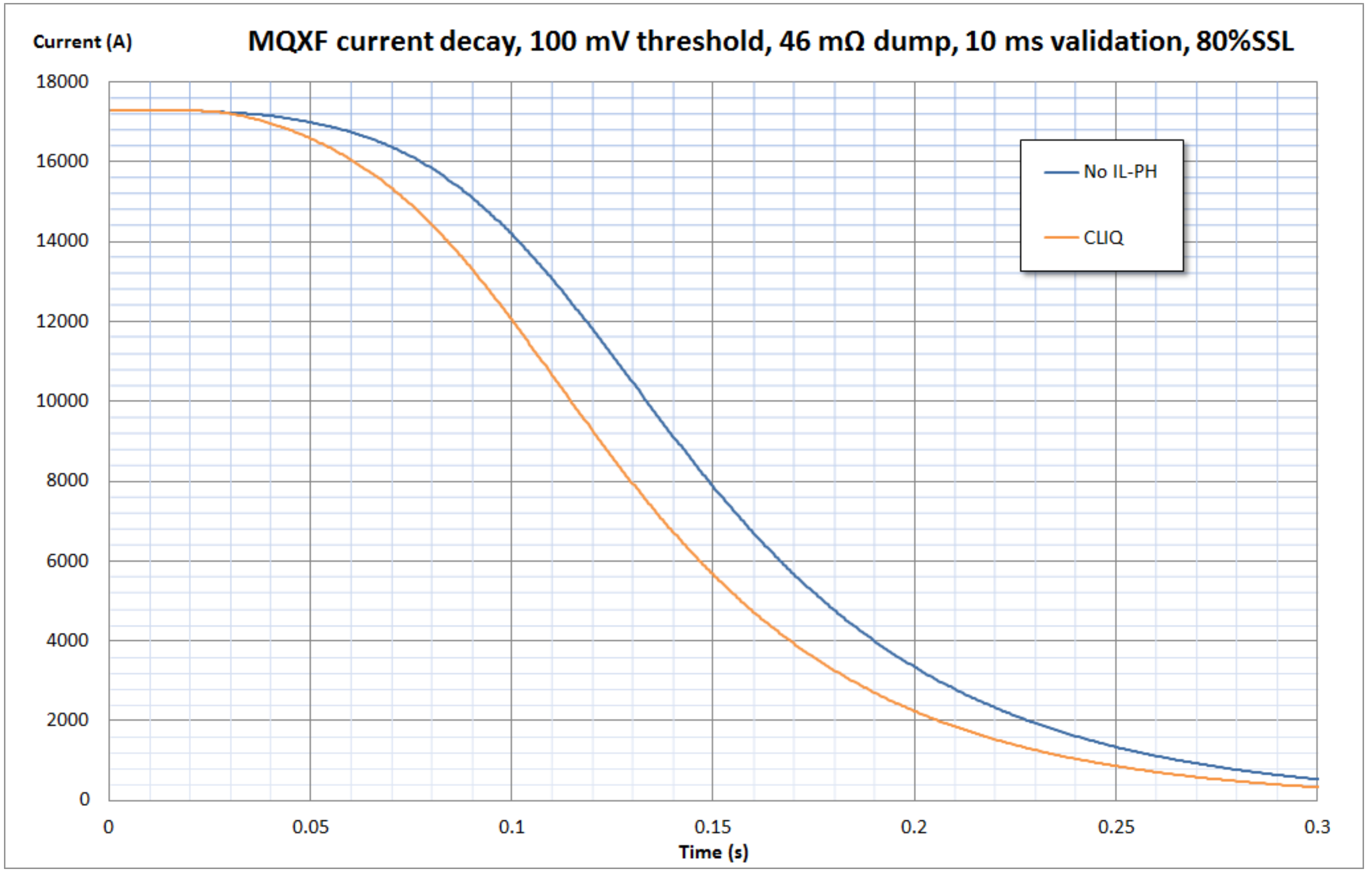


CLIQ performance during HQ02b tests are impressive:
the whole magnet is almost totally quenched in less than 5-10 ms

I assumed a similar behavior of CLIQ in MQXF:

- whole magnet quenched 10 ms after validation

6.3 CLIQ



	No IL-PH	Tiina IL-PH	Ezio IL-PH	CLIQ
MIITs (MA^2s)	35.5	32.8	31.7	30.2
Hot spot temperature (K)	330	290	275	253

6.4 CLIQ

- CLIQ provides a **better** protection than both IL and OL protection heaters
- Anyway, it’s not obvious how CLIQ performances scale with magnet dimensions (MQXF has an inductance **much bigger** than HQ)

7.1 Conclusions and future plans

- The MQXF protection presented at MT-23 can be considered **very conservative**, because comparisons with HQ02 experimental data showed a **large difference** (~16 %) with the simulations.
- The difference is probably due to **dynamic effects** on the inductance (together with other conservative assumptions).
- The inductance lowering can be explained by **coupling** with metallic components surrounding the magnet, or by inter-filament eddy currents, but only at the **start** of the decay. Quench back is under investigation as additional factor.
- **Finite elements** calculations will be performed for a better understanding of these phenomena.
- Two **inner-layer** protection heaters designs have been investigated, for providing a better magnet protection. Both the designs **significantly improve** the protection.
- Ezio's design study has to be improved with **heaters delay time** by CoHDA.
- Simulations have to be improved with the **new outer layer PH design**
- Protection at 90 % of SSL is **challenging** also with IL-PH
- **Redundancy** is provided by the IL-PH
- If **CLIQ** performance will be confirmed for the MQXF, several options will be available for MQXF protection.