MQXF Protection with Quench Heaters & LARP Experience

G. Ambrosio (FNAL)

on behalf of the MQXF team,
with special contributions by:
G. Chlachidze, V. Marinozzi, M. Marchevsky,
G. Sabbi, T. Salmi

Outline

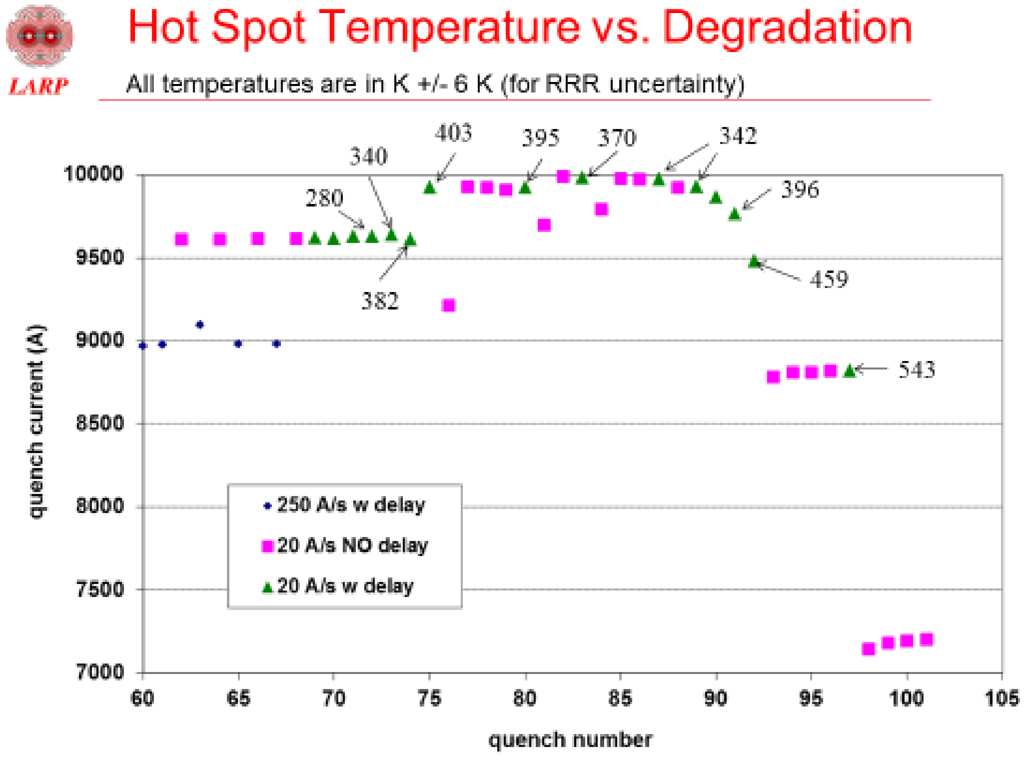
- Benchmarks (safe territory)
- Flux jumps & Detection Threshold
- Heater delays
- Heater “bubbles”
- Simulations Codes
- Simulation Results

Outline

- **Benchmarks (safe territory)**
  - **Hot-Spot Temperature**
  - **Voltages**
- Flux jumps & Detection Threshold
- Heater delays
- Heater “bubbles”
- Simulations Codes
- Simulation Results

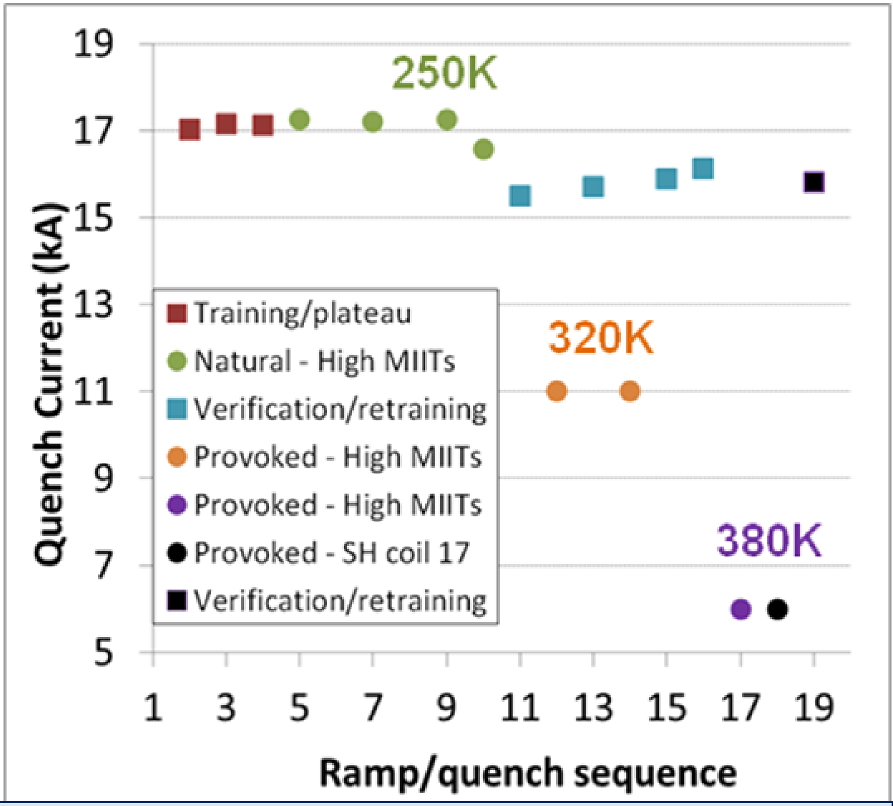
Hot Spot Temperature

- Tests on: cables, small racetracks, 90-mm short model (TQS01c), and 120-mm short model (HQ02)



Hot Spot Temperature vs. Degradation

All temperatures are in K +/- 6 K (for RRR uncertainty)



G. Ambrosio, “Maximum allowable temperature during quench in Nb3Sn accelerator magnets”, *Yellow Report CERN-2013-006*, pp. 43–46, WAMSDO 2013, CERN, Geneva, CH.

H. Bajas, et al., “Cold Test Results of the LARP HQ02b magnet at 1.9 K”, TASC.2014.2378375

Hot Spot Temperature

- Safe territory:
  - T_hot-spot < 350 K with full preload
  - T_hot-spot < 300 K with partial preload
    - For operation close to SSL

- Target: **T_hot-spot < 300 K nominal case**
- Target: **T_hot-spot < 350 K failure scenarios**

- *Error in temperature estimate (due to material property uncertainty and computation assumptions) is reduced by using the same properties and assumptions in these computation and in the MQXF simulations.*

Voltages (Work in Progress)

Voltage test values in LARP & CERN QXF coils/magnets

Units: all values are V (volt)	**LARP**	**LARP**	**LARP**	**CERN**	**CERN**	
in single coil	**V max at RT**	**MQXFS0 coils at RT**	**V standard at RT**	**V standard at RT**	**V max at RT**	comments
Coil - Heaters	5000	2500	2500	2500		
Turn - Turn	92	40	50	50	130	
Layer - Layer (midplane)	4600	2000	2500	2500	6500	QXFS01 impulse test failed at 4700 V

in magnet after pre-load	**MQXFS0 at RT**	**V standard at RT**	**V standard at RT**	**V standard at 1.9K**	comments
Coil - Ground	2500	3500	3500	1000	
Coil - Heaters	2500	2500	2500	1000	
Heaters - Ground	2500	2500		1000	
Turn - Turn	50	50	50	12	
Layer - Layer (midplane)	2500	2500	2500	577	Impulse test on individual coil up to 2500 V before splice box installation; V_dump in mirror = 577 V
Coil - Coil	1000	1000			Hipot between neighboring coils up to 1000 V

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- Heater delays
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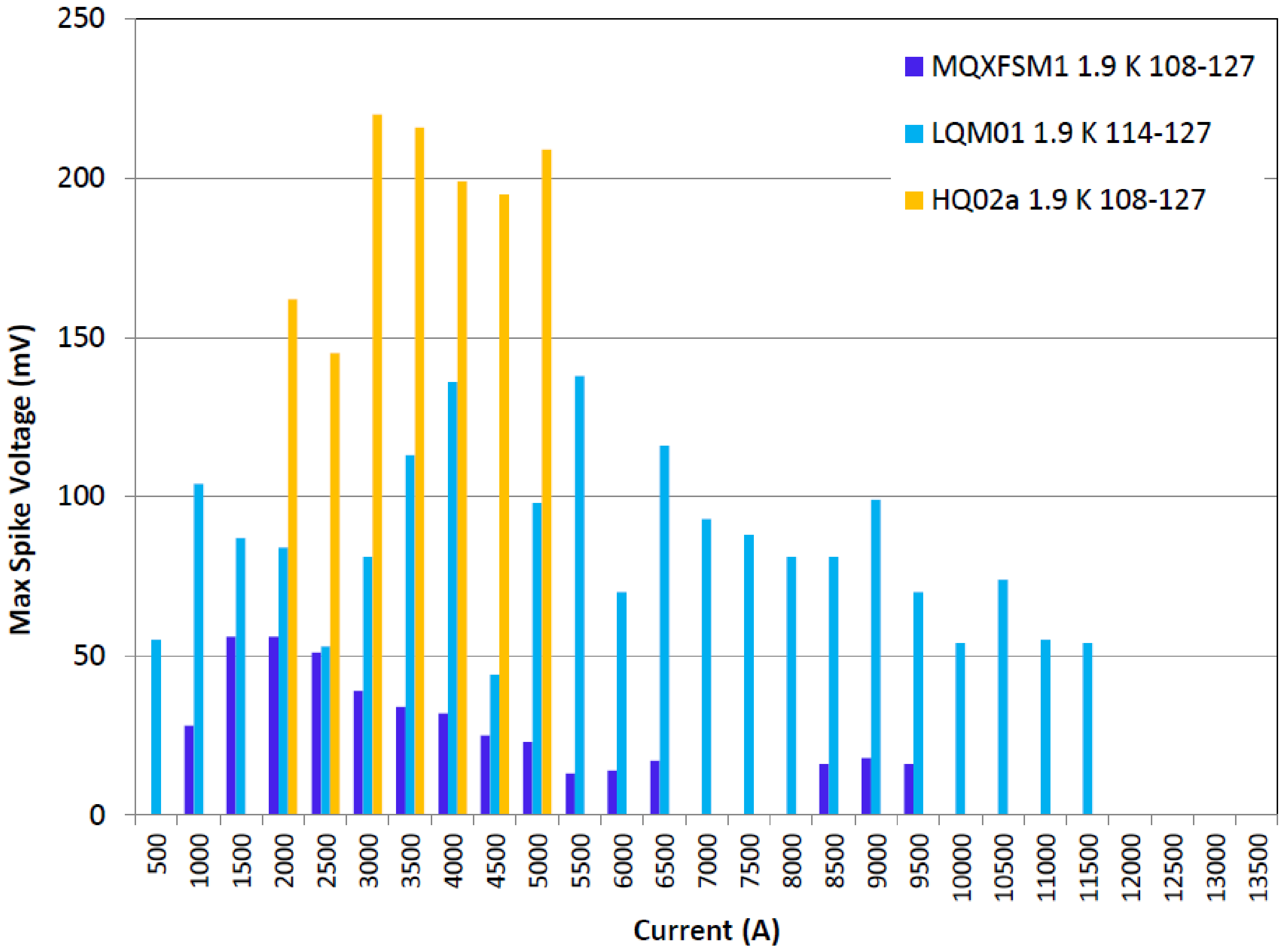
Voltage Spikes in MQXFSM1

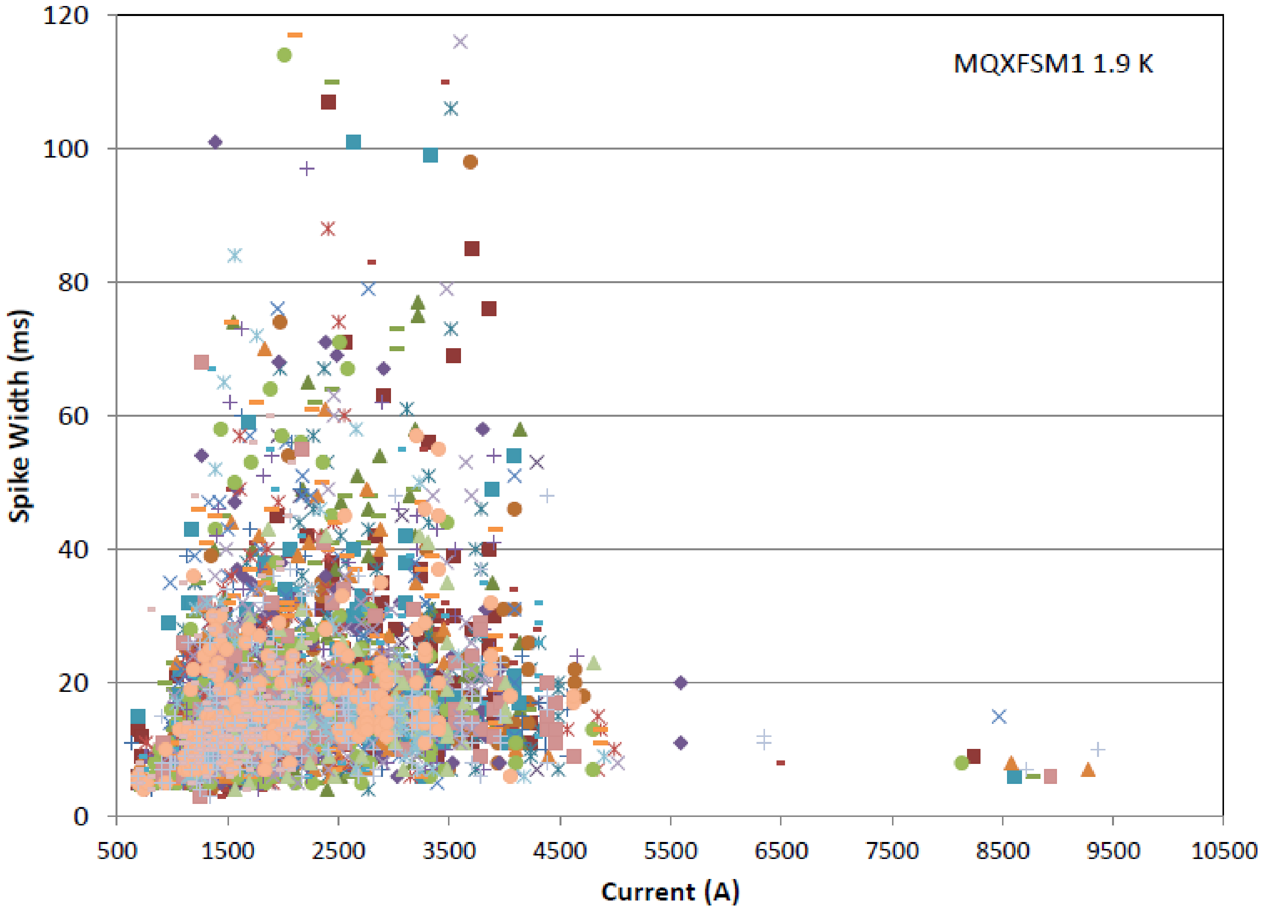
MQXFSM1 and LQM01 coils in a “mirror” structure, HQ02 quadrupole



Flux jump amplitude increases with # of coils and length

Voltage Spikes in MQXFSM1

Width of spike signals



Suggested Strategy

- Adaptive Quench Detection threshold is a robust solution against flux-jump induced trips
  - “Mid” threshold at low current
  - Low threshold at high current
    - 100 mV with 10 ms validation should be OK
- Demonstrated very effective in LQ and HQ magnets tested by LARP

Outline

- Benchmarks (safe territory)
- Flux jumps & Detection Threshold
- **Heater delays - slides by M. Marchevsky**
  - **Results from HQ02 and HQ03**
- Heater “bubbles”
- Simulations Codes
- Simulation Results

HQ03 Coil images

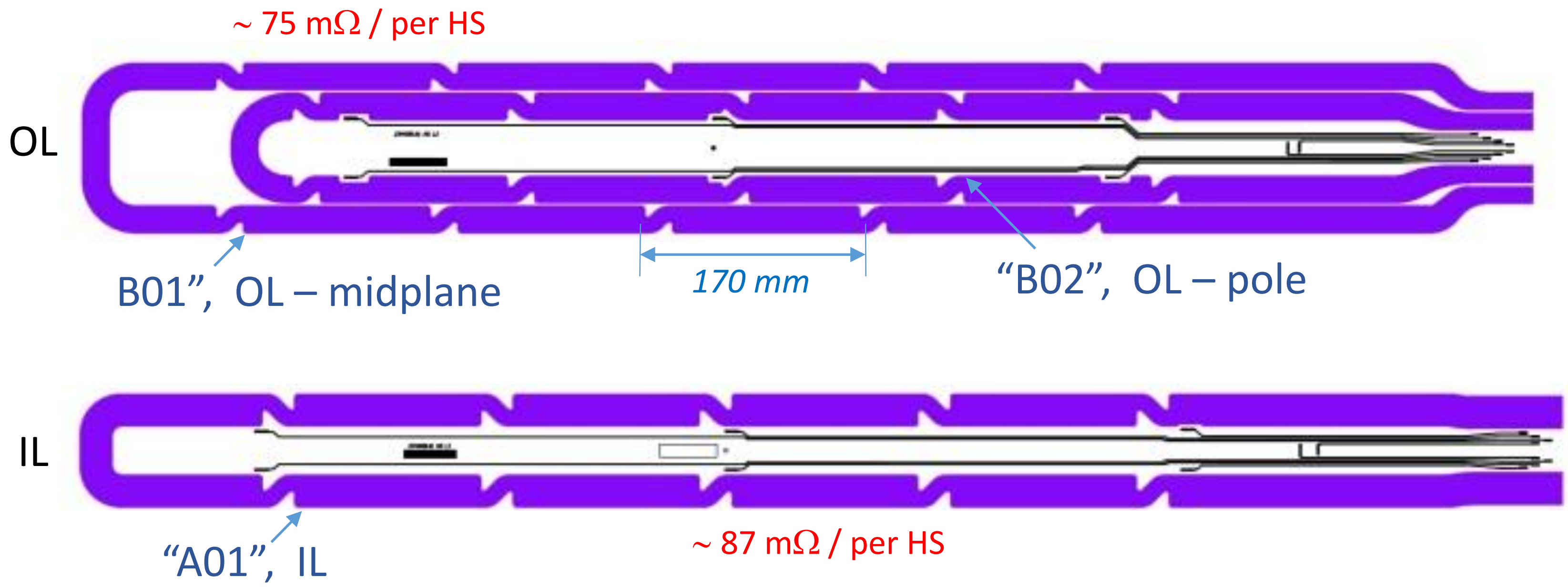
Regular HQ coil

OL IL

HQ Coil 26

OL IL

HQ 03 Coil 26 heaters

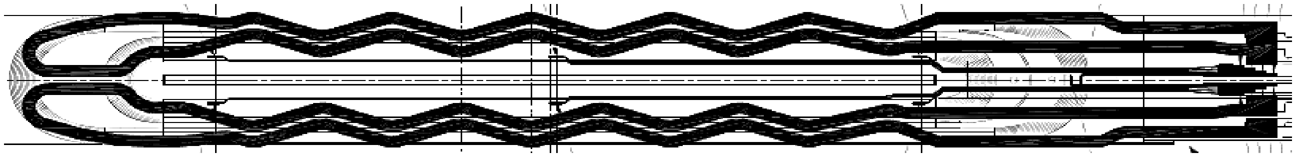


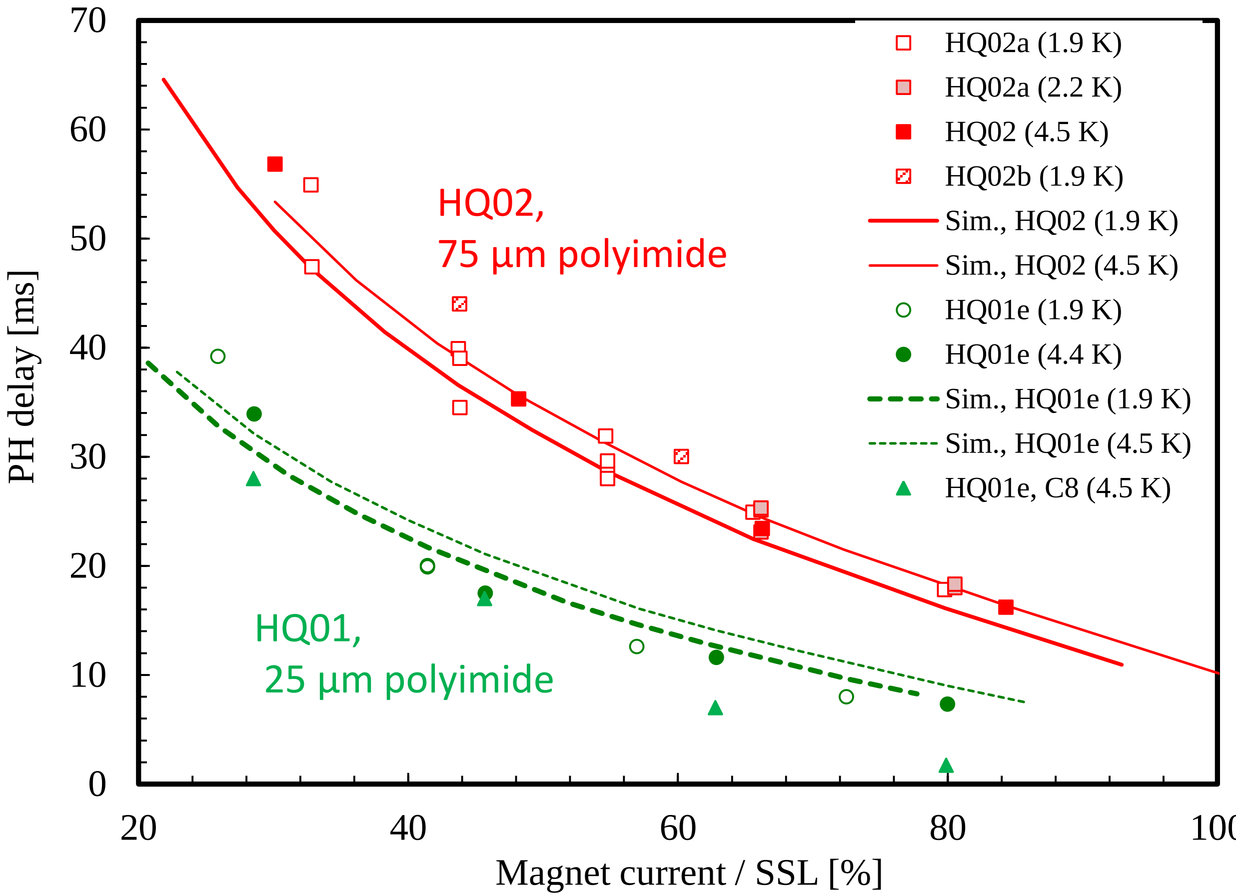
Coil 26 heaters have same main dimensional parameters of heating station (width, ends curvature) as the MQXF “stainless-only” design. Heating stations are separated by ~2x cable twist pitch of 170 mm. This layout can in principle be scaled (going end-to-end, without the loop) to 6.7 m of SQXF-L while keeping power density > 50 W/cm^2 and heater voltage under 450 V.

Heater	Full heater resistance	Full heater resistance incl. wiring	Heating station resistance	Heating station area
PHA01	2.33 Ω	3.285 Ω	58.4 mΩ	3.56 cm^2
PHB01	2.60 Ω	3.55 Ω	49.8 mΩ	2.91 cm^2
PHB02	2.40 Ω	3.35 Ω	50.7 mΩ	2.91 cm^2

Heaters are separated form the coil by 50 μm of polyimide insulation

HQ01 and HQ02 – Outer layer

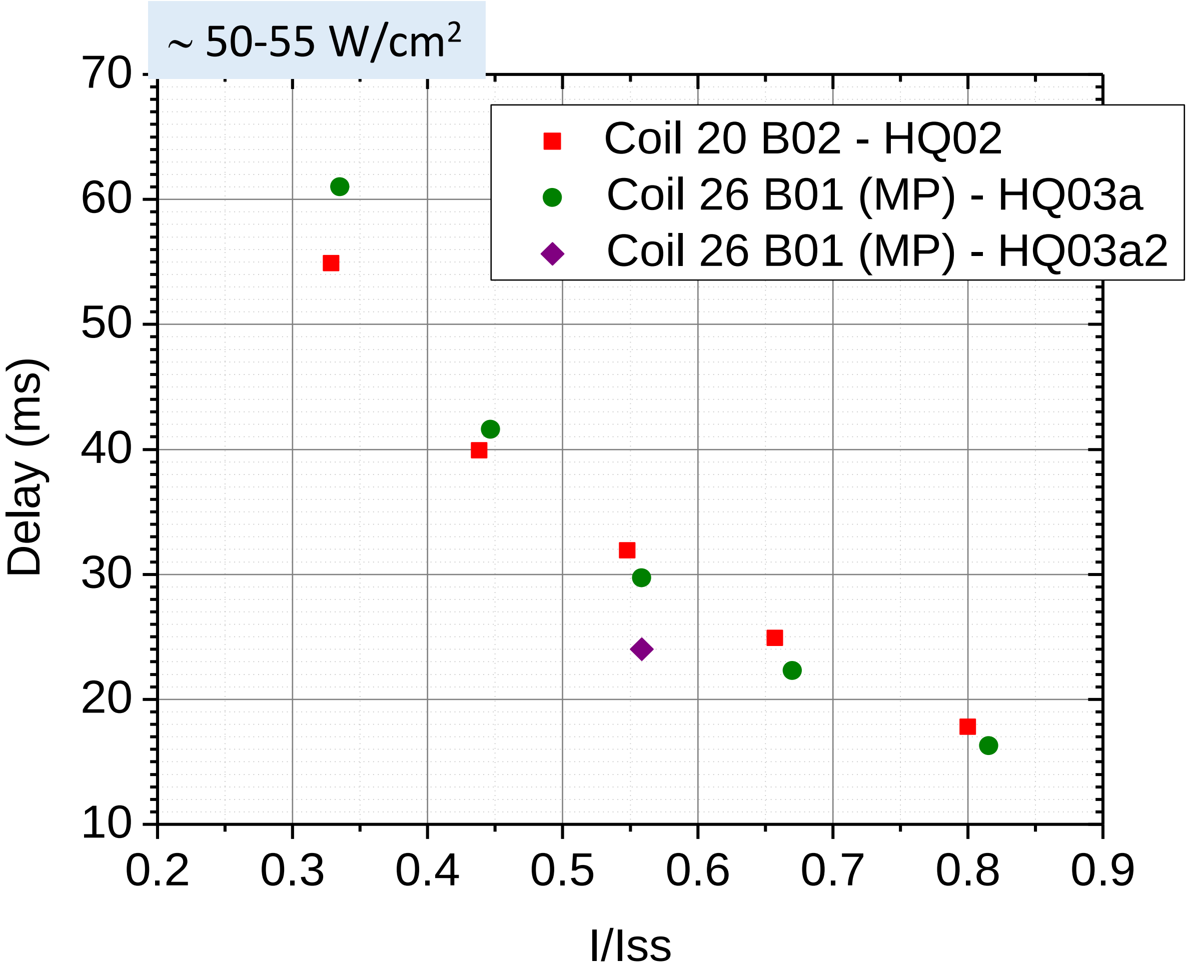




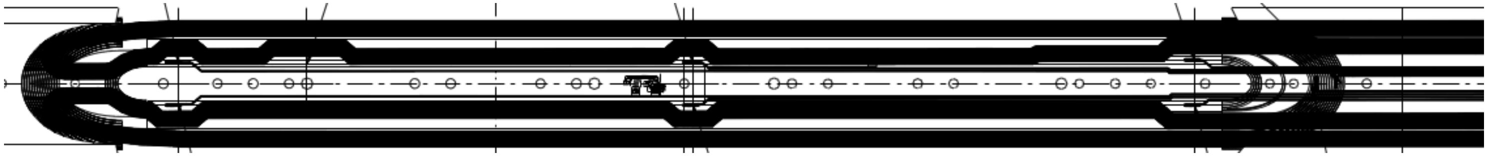
PH peak power
= 50-55 W/cm^2,
τ = 40-45 ms

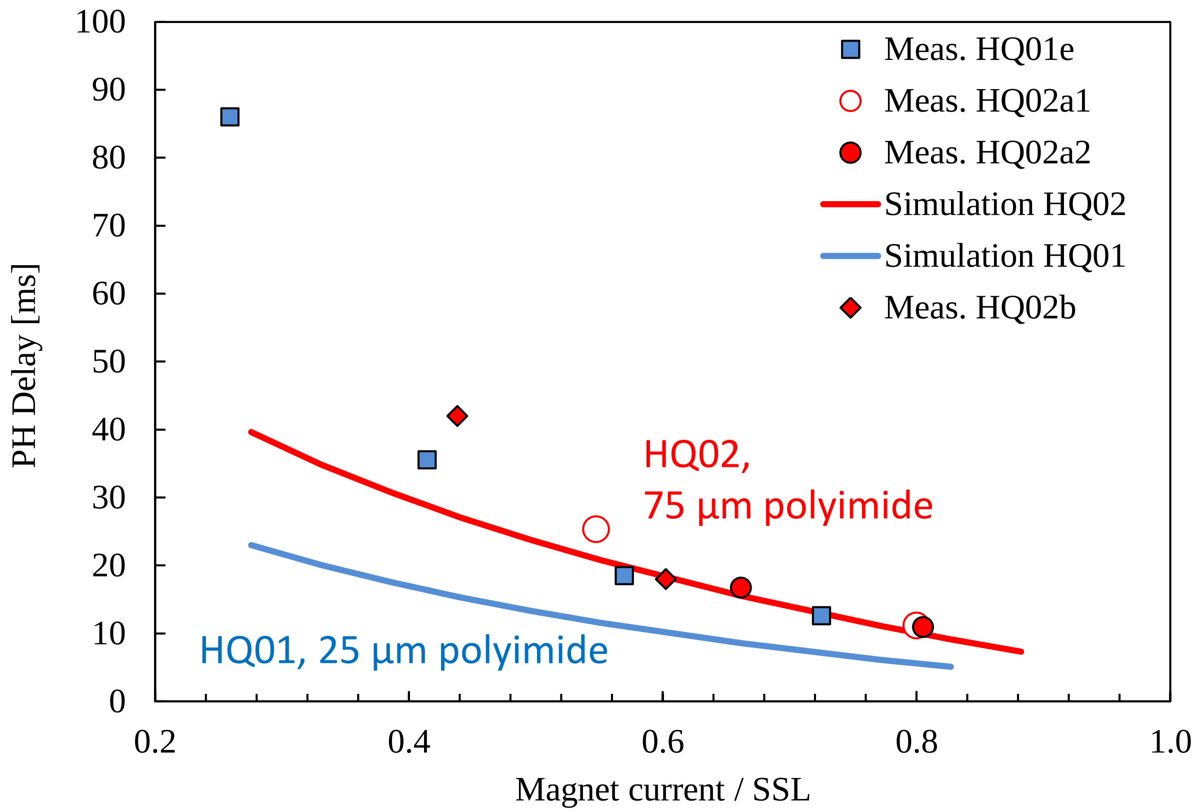
T. Salmi

Quench delay for the OL heaters



HQ01 and HQ02 – Inner layer



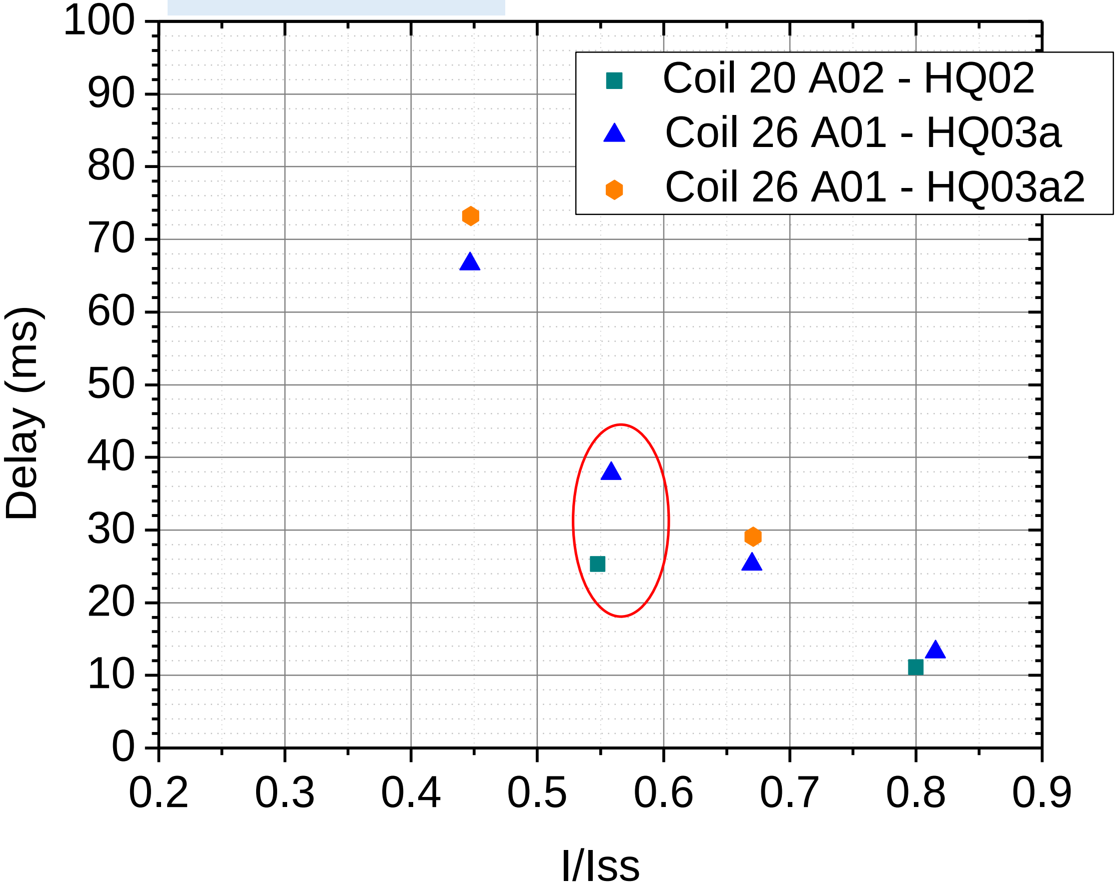


PH peak power
= 50-55 W/cm^2,
τ = 40-45 ms
Top = 1.9 K

T. Salmi

Quench delay for the IL heaters

~ 50-55 W/cm^2



Conclusions

- Heater delays for Coil 26 OL heater are very similar to those of a regular style HQ OL heater in the 0.3-0.8 range of I/ I_{ss}
- The IL heater of Coil 26 exhibits longer delays compared to the regular style IL HQ heater
- Quench delays are very well reproducible between the tests (HQ03a and HQ03a2)
- Delays for the Coil 26 OL heater measured at 12 kA magnet current in the 30-70 W/cm^2 power density range are longer than those for the regular style HQ OL heater

My Conclusions

- Comparison btw heaters with different designs is tricky
- However heaters with heating stations appear to be less efficient than heaters with large heating strips and copper plating (MQXF baseline)
- Heaters on the Inner Layer show larger differences in the delays, likely due to possible epoxy btw heater and coil (addressed in 2nd generation QXF coils)

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- **Heater “bubbles”**
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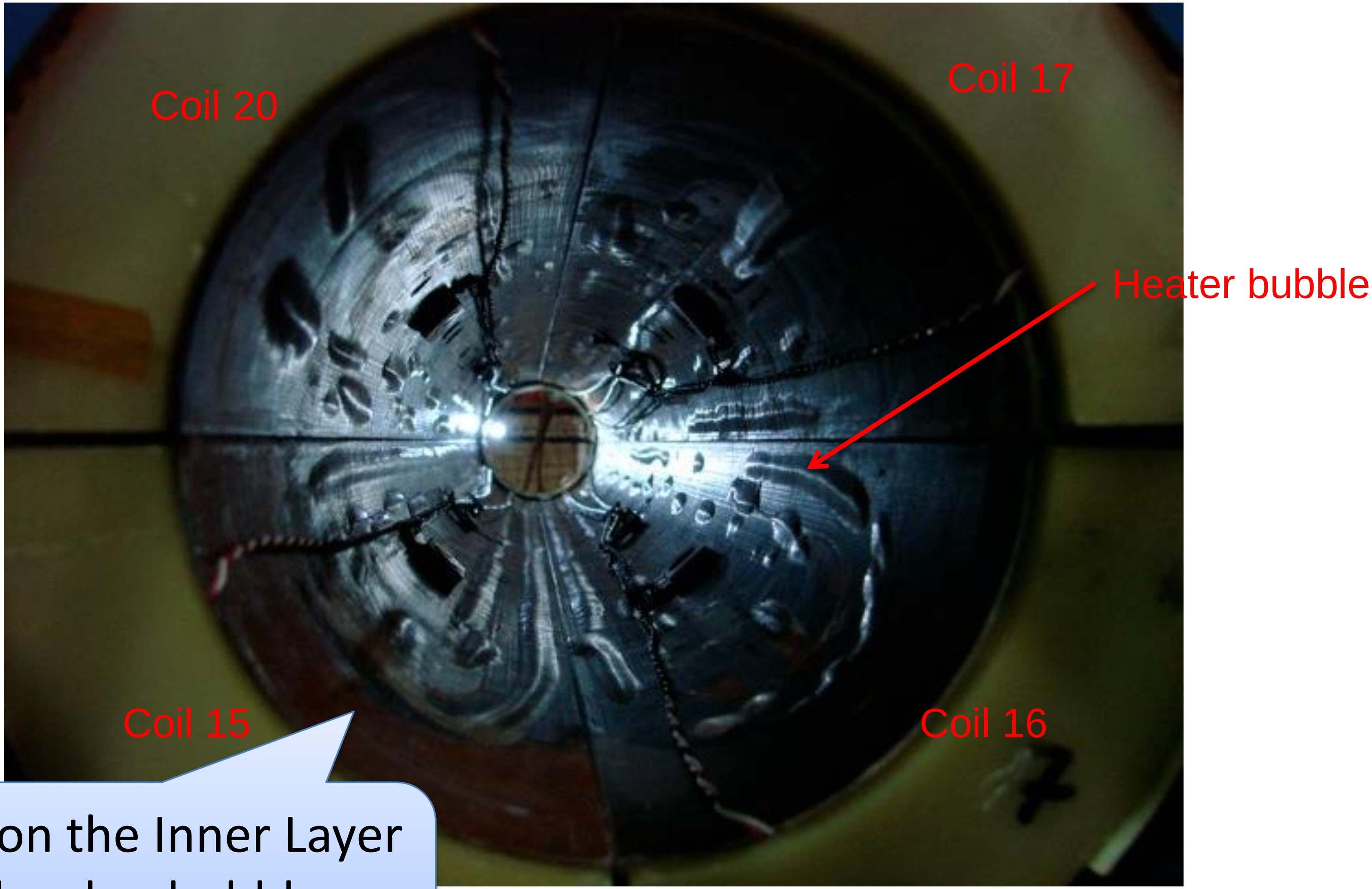
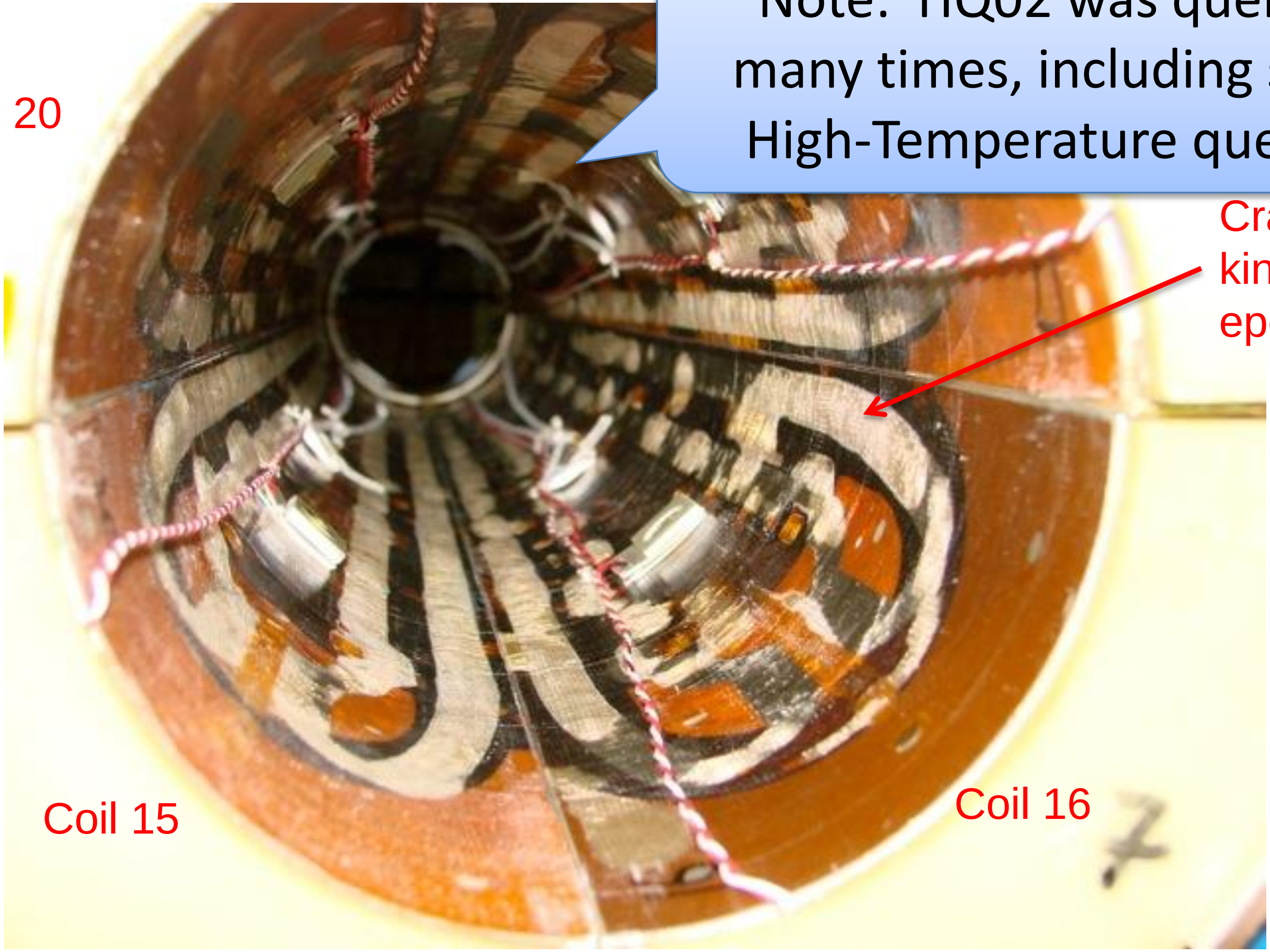
Post-HQ02b Test: Bore, viewed from RE



Heaters on the Inner Layer may develop bubbles during operation

Post-HQ02b Test: Bore, viewed from RE

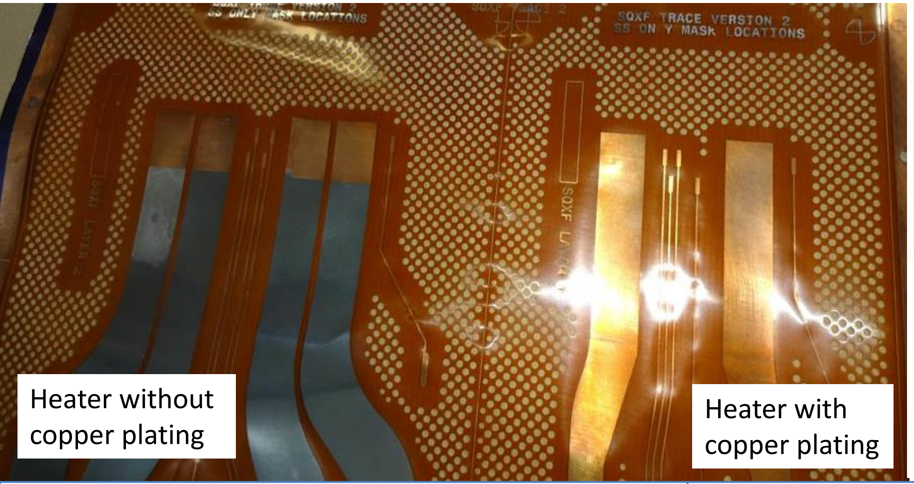


Note: HQ02 was quenched many times, including several High-Temperature quenches

Crazing/cracking of epoxy

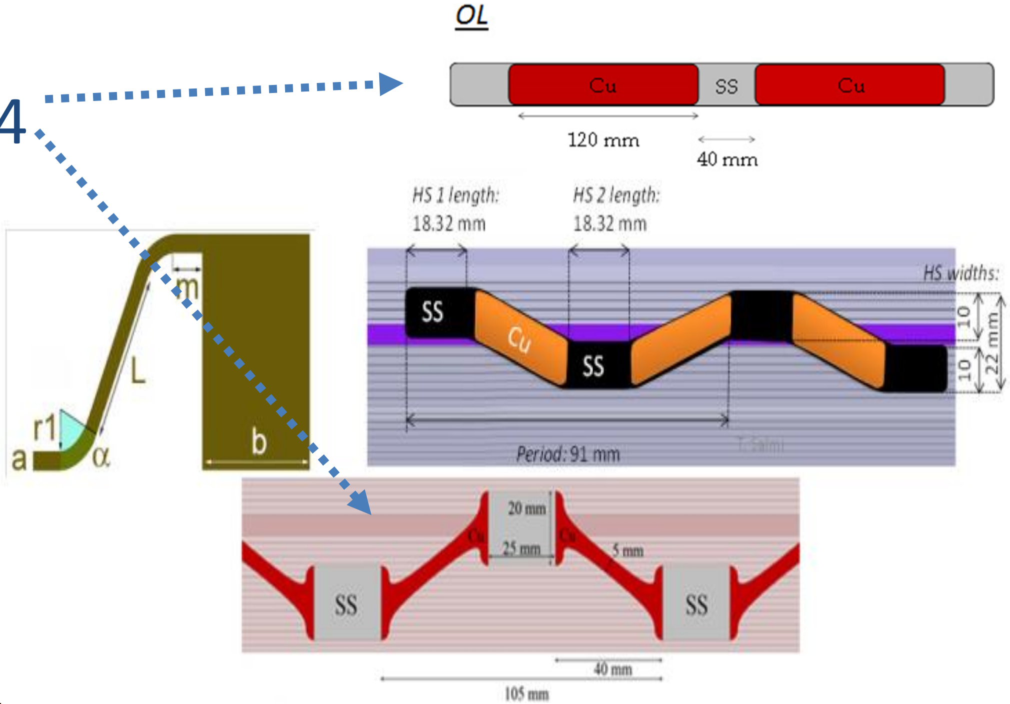
Heaters for MQXF

- With copper-cladding
- Trace with perforations, IL target: 40% polyimide free
- Several options
  - Baseline: heaters used on MQXFS1 coils 103 & 104



Heater without copper plating

Heater with copper plating

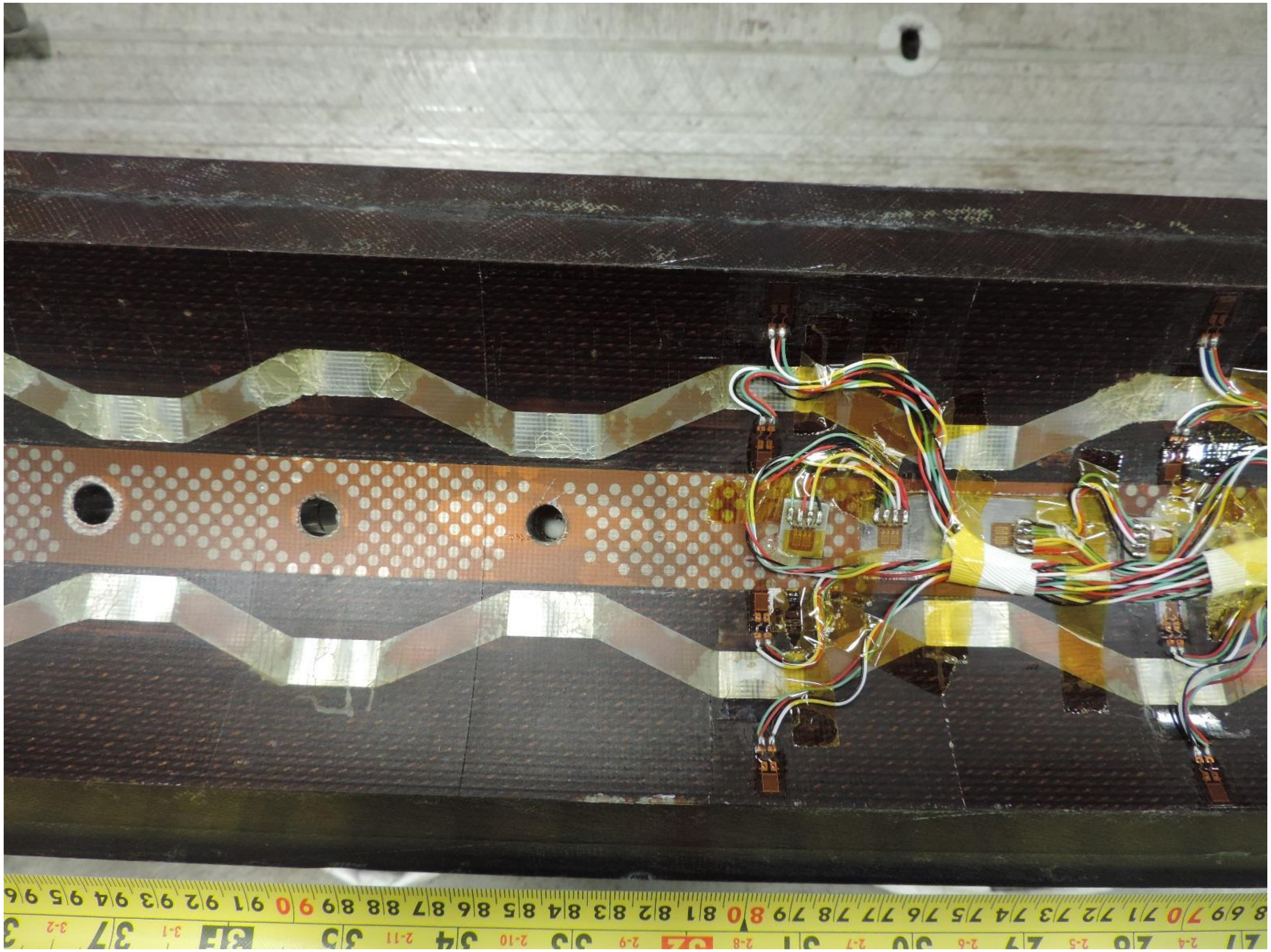


Courtesy J. C. Perez

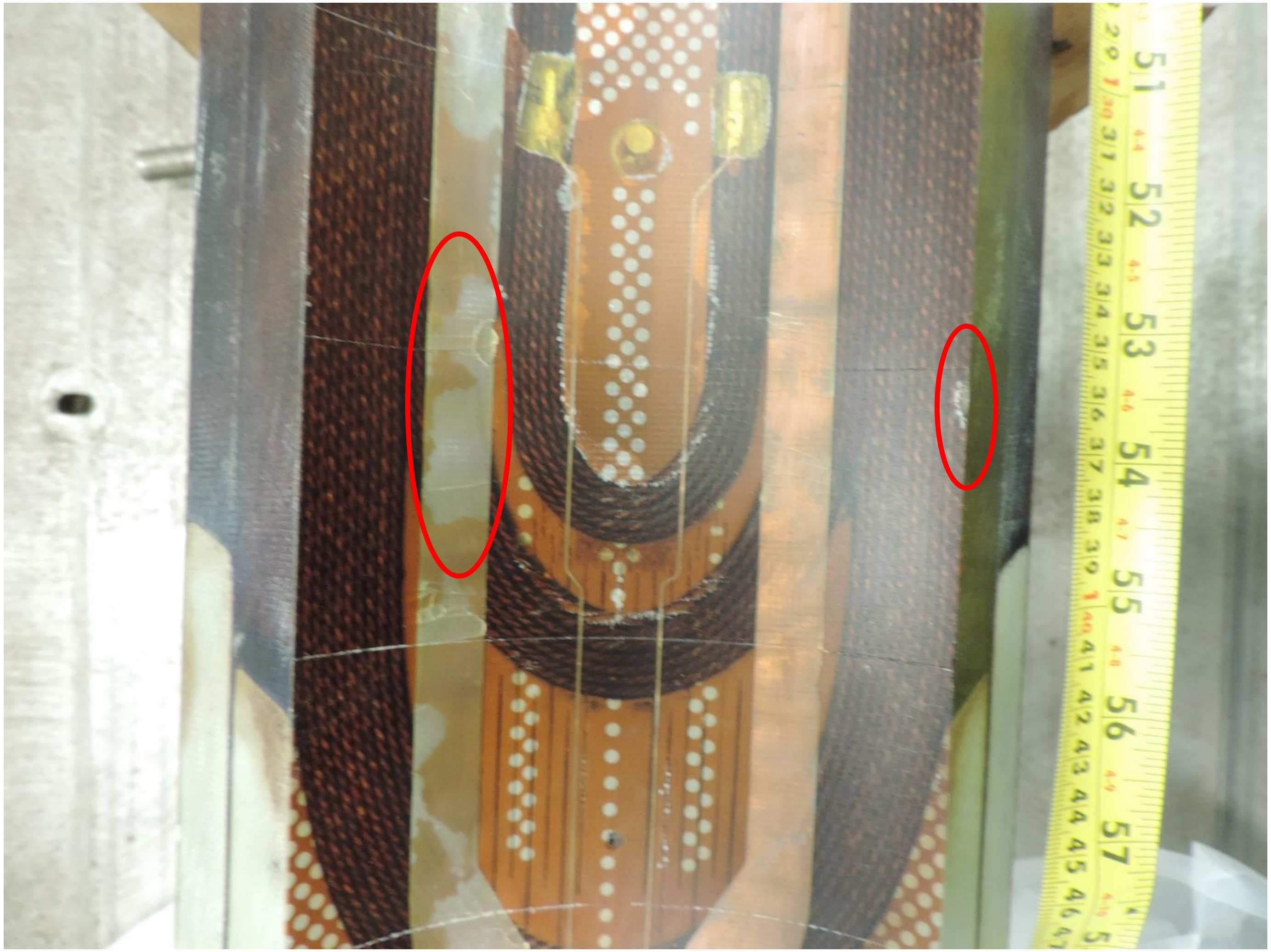
Courtesy M.Marchevsky, E.Todesco, D.Cheng, T.Salmi

M. Marchevsky, "Design optimization and testing of the protection heaters for the LARP high-field Nb3Sn quadrupoles", presented at ASC2014.

QXFS2 Coil After Mirror Test



QXFS2 Coil After Mirror Test



Preliminary Observations

- The inner surface of coil QXFS2 looks better than HQ02 coils after test
  - QXFS2 was tested in mirror structure, nonetheless I expect 1st short model to confirm this observation
- The trace perforations seems to help significantly
- MQXFS tests planned to understand if there is loss of efficiency on IL heaters

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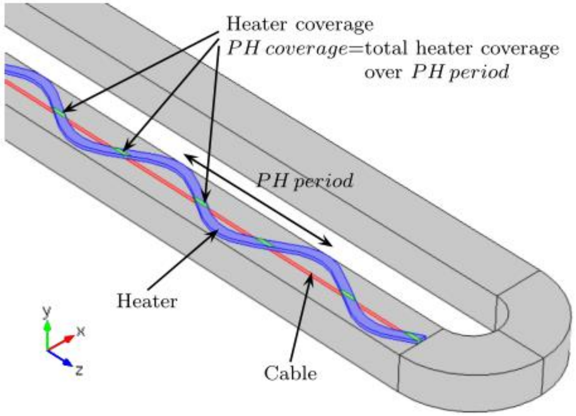
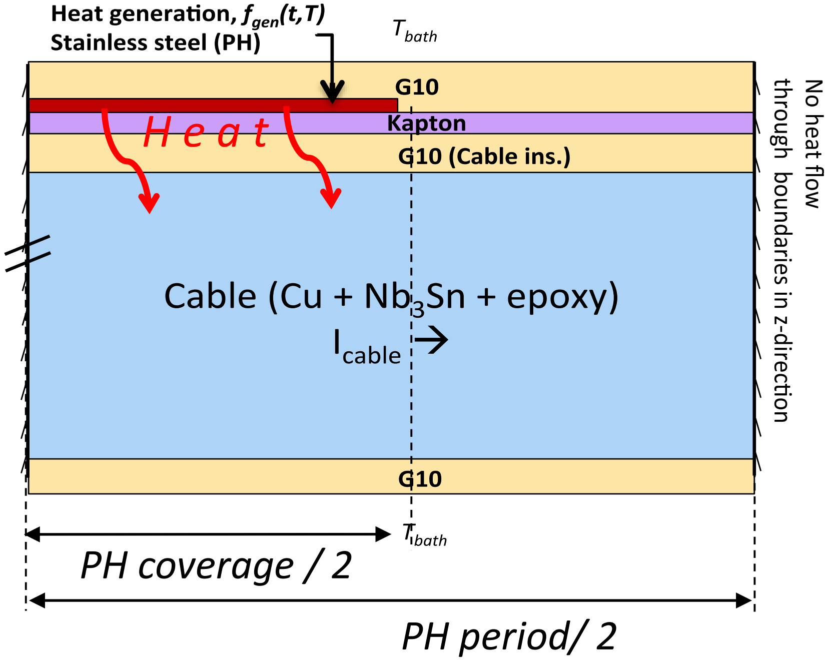
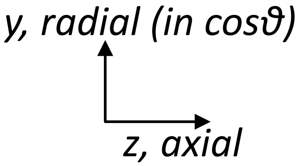
- Heater “bubbles”
- **Simulations Codes**
  - **“CoHDA” for heaters delay by T. Salmi**
  - **“QLASA” & “ROXIE” for T & V peak values by V. Marinozzi**
- Simulation Results

CoHDA: **Co**de for **H**eater **D**elay **A**nalysis

- **Heat conduction from heater to the superconducting cable**
- Quench when cable reaches $T_{cs}(I,B)$
- Each coil turn considered separately
    - Symmetric heater geometry: Model half of the heater period
    - 2-D model (neglect turn-to-turn)
    - Uniform magnetic field in the cable
- Thermal network method
- Model implementation verified in comparison with COMSOL (Thanks to Juho Rysti, CERN)



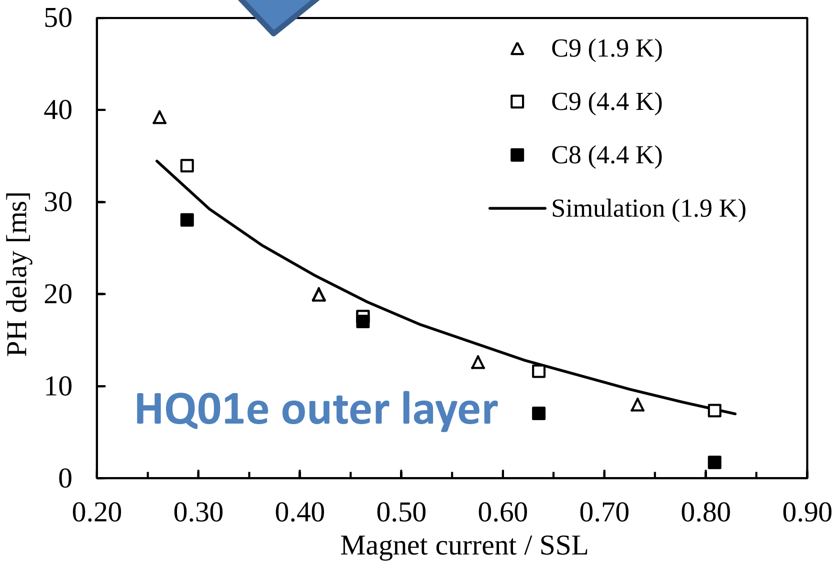




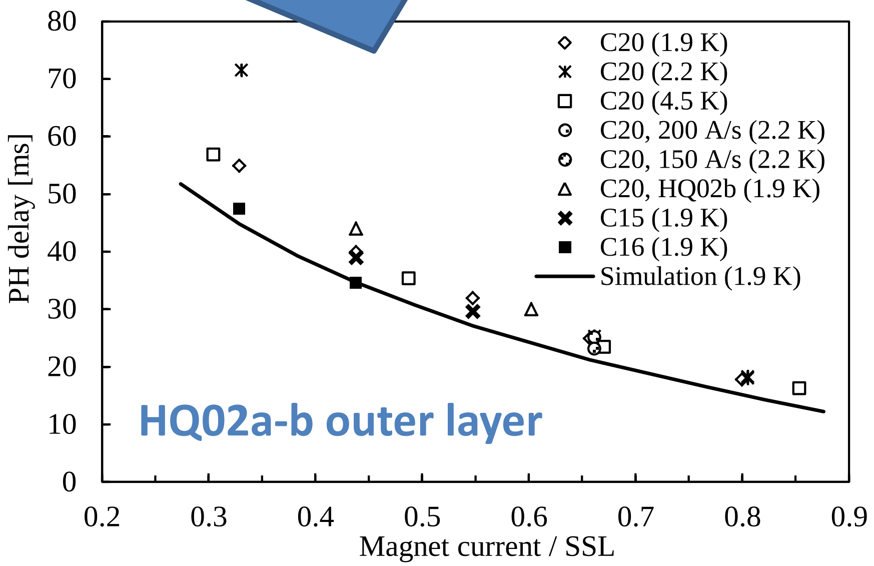
CoHDA comparison with experimental data - OL

1. **HQ01e, HQ02a-b, 11 T, HD3b: Outer layer (OL)**
    - Above 50% of SSL: Nominal simulations typically within 20% of measurement – **Good agreement**
    - Uncertainty larger at lower current
    - Comparable with experimental uncertainty

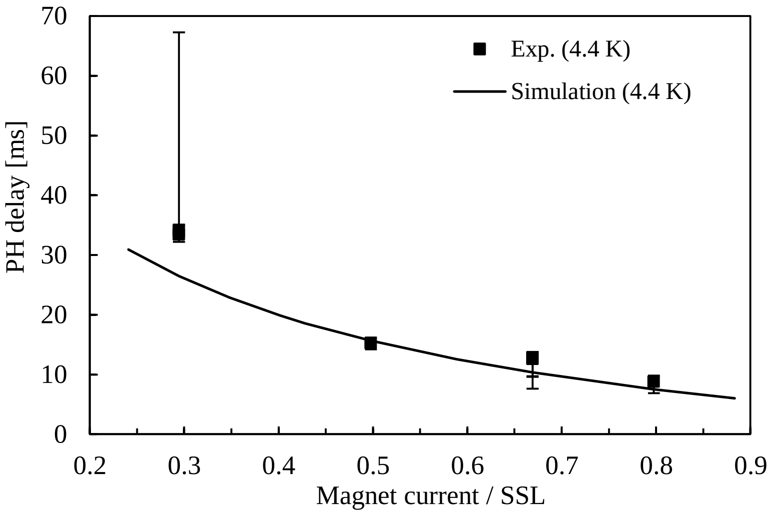
Large difference btw coils 8 and 9. Suspected a defect in coil 8.



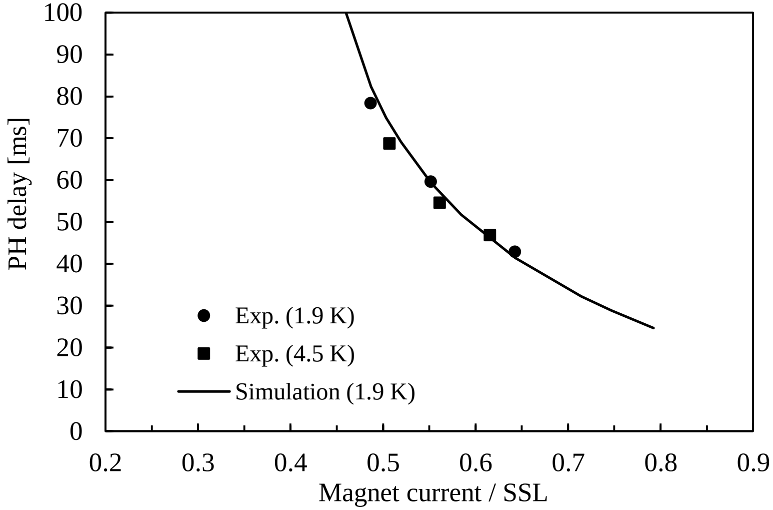
No signs of defects in HQ02 coils. The exp. variation suggests the *minimum exp. uncertainty.*.



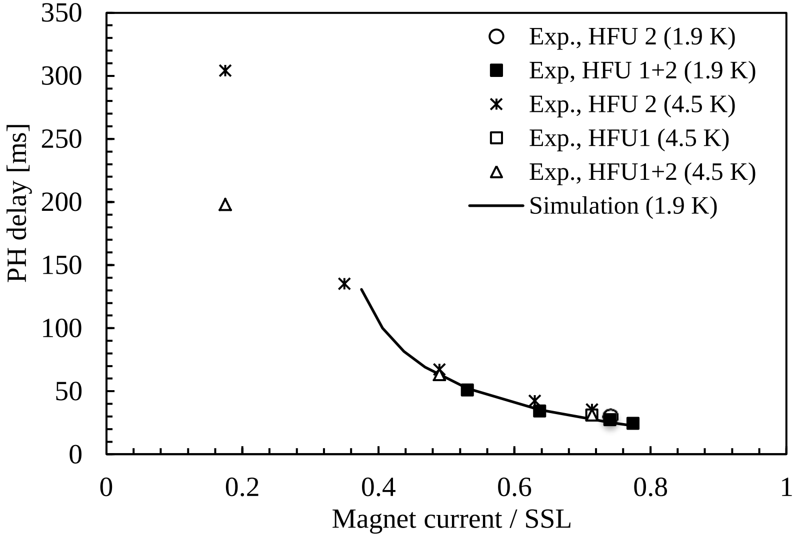
HD3 outer layer



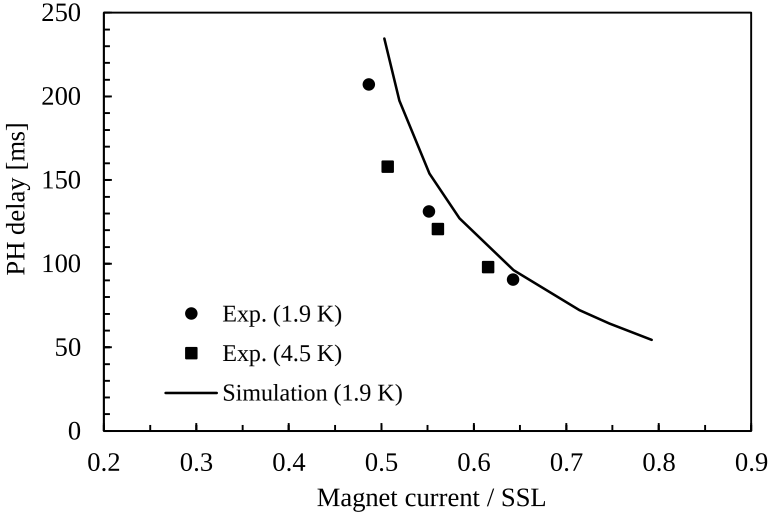
11 T MBHSP01, 76 µm Kapton



11 T MBHSP02

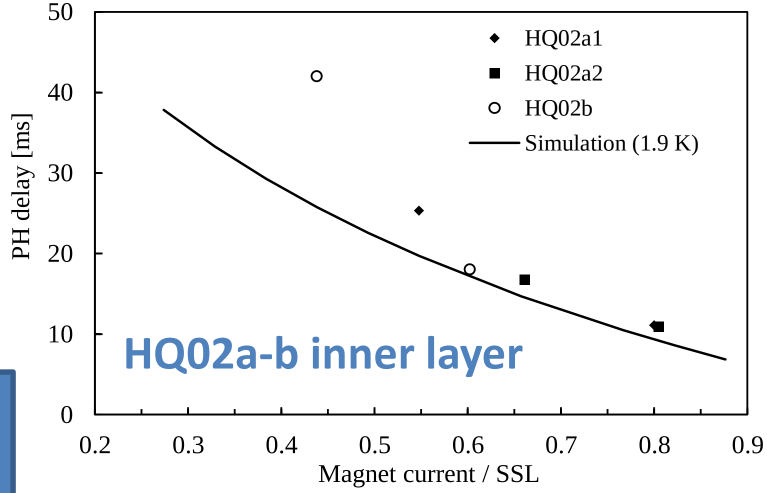


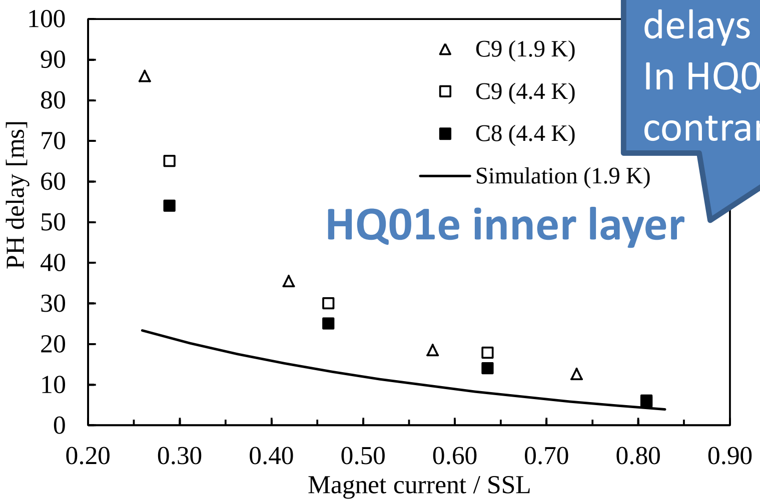
11 T MBHSP01, 203 µm Kapton



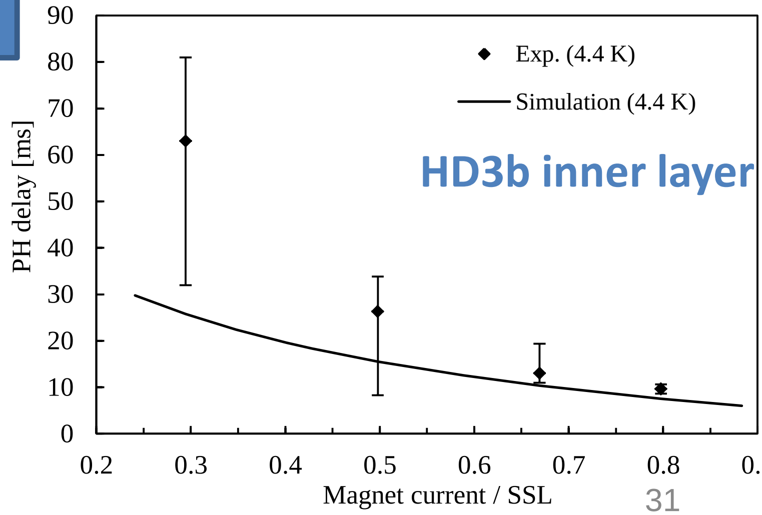
CoHDA comparison with experimental data - IL

2. **HQ01e, HQ02a-b, 11 T, HD3b: Inner layer (IL)**
   - Above 50% of SSL: Nominal simulations within 10 ms or 40% of measurement – **Not good agreement…**
   - At lower current simulation **underestimates** the delays
   - Experiment not fully understood either
     - He bubbles?

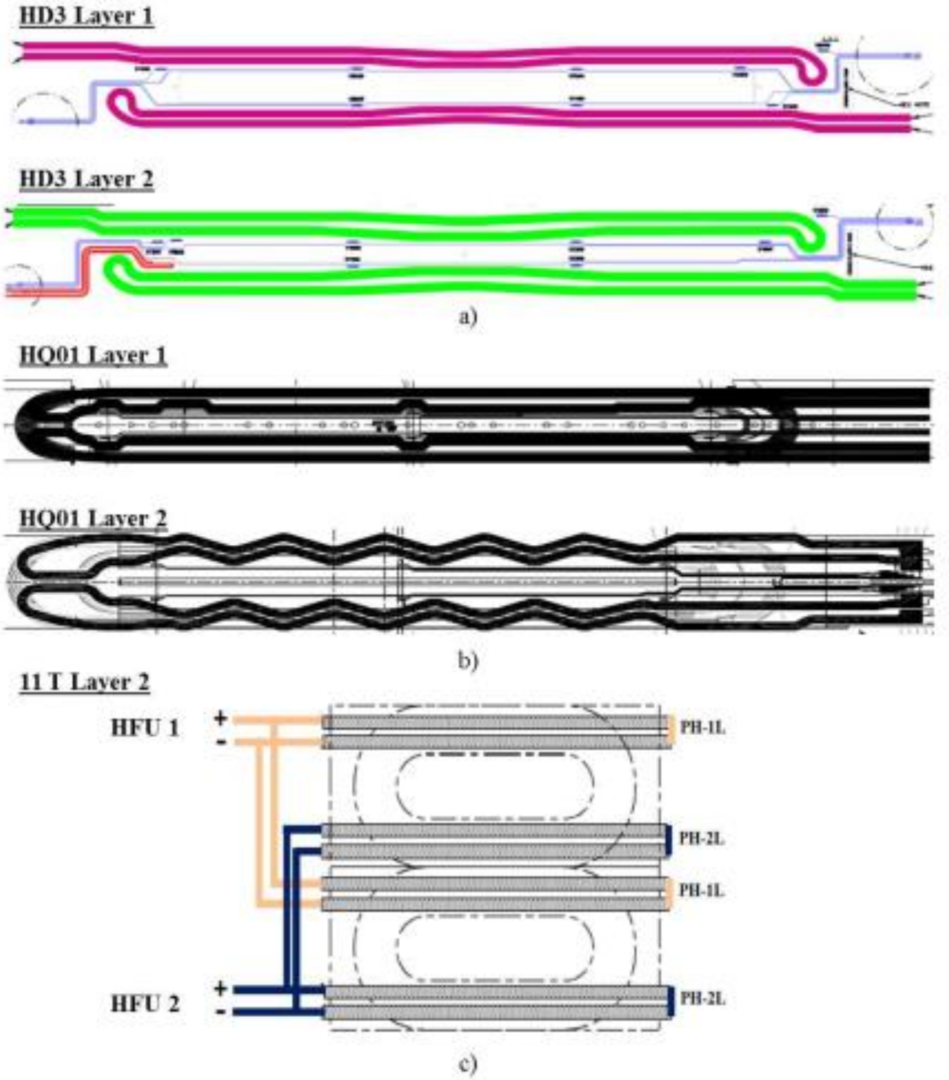




In HQ01 measured IL delays longer than OL. In HQ02 it was the contrary.



HD3, HQ, and 11 T dipole heaters are all of uniform width



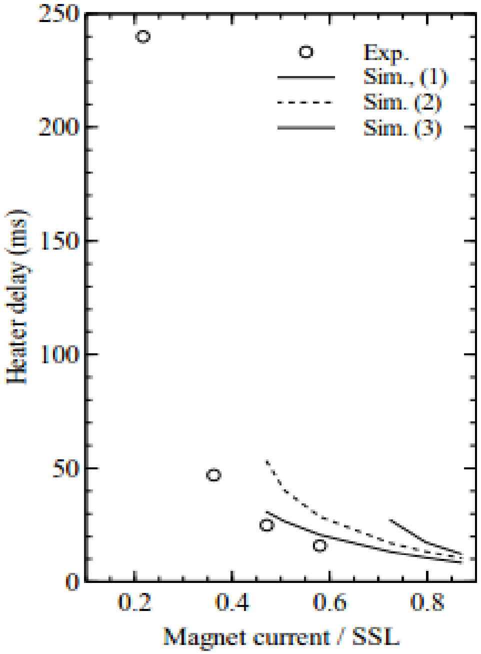
a)

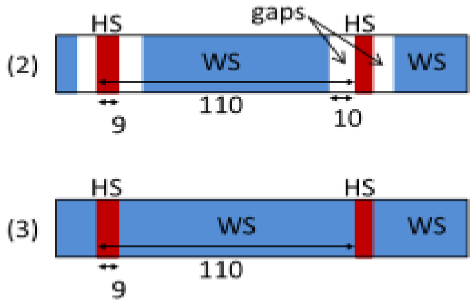
b)

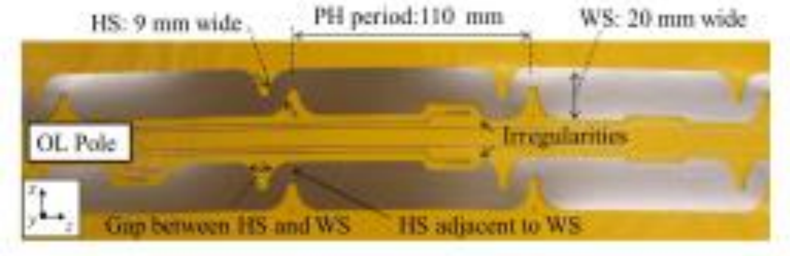
c)

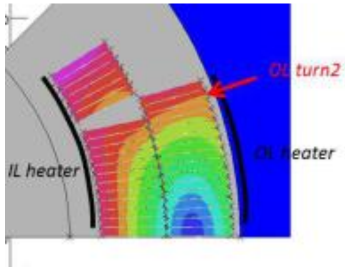
CoHDA comparison with experimental data - LQ

- In LQ also the wider segment participates in heating the cable
- LQ simulation was done for the high field turn (2nd from the pole). Due to asymmetry of heating station-wide segment connection 3 cases were simulated.
- The simulation predicted too long delays in all cases.
- Possible reasons why **model not suitable**: 1. short heating station requires more detailed model of the cable structure, 2. **non-uniform heating in the heater narrow segment must be simulated with more detail.**



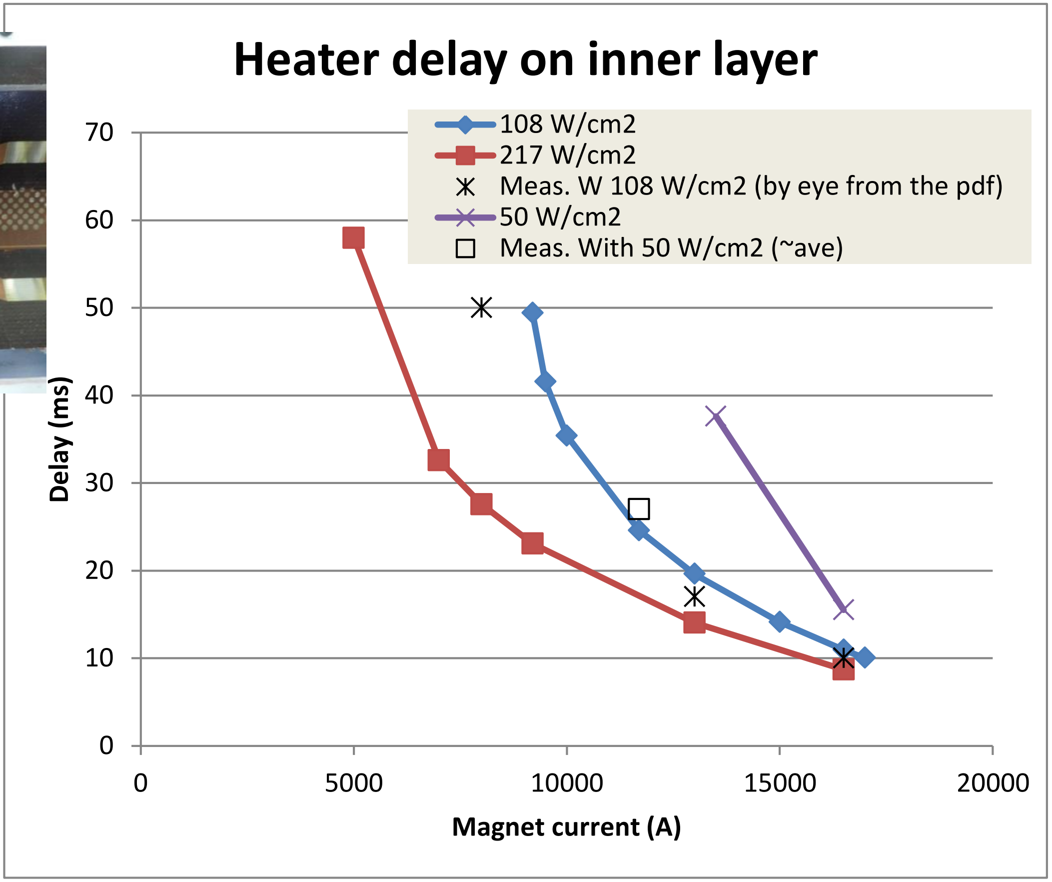






The SQXF-mirror, heaters in inner layer

- Measurement and simulation with 108 W/cm2 **agree reasonably** for $I_{mag} \geq 13$ kA
- The low current regime and low heater power **not captured in simulation.**
- Unlike in previous inner layer simulations, the simulation **overestimates** the delays



Summary of the heater delays

- Simulation of outer layer heater delays typically within 20% of measurements, above 50% of SSL
- Lower current has larger uncertainty
- Uncertainties comparable with experimental uncertainty
- Inner layer heater simulations have much larger uncertainty, typically giving too short delays – also the experiments less well undestood
- LQ-style heater with short and complex shaped heating station not well simulated wiht this model (simulation overestimates the delay)
- The above simulations were for the high field region
- Simulation of SQXF heaters is preliminary

- *Beginning of Dec. 2015: Extensive comparison with simulation with heater tests from RMC tested at CERN. (Analysis of heater delays on high field and low field, AC-losses, current decay and NZPV)*

QLASA*

Slides by V. Marinozzi

QLASA[1] is a program developed by the University of Milan and the INFN/LASA for the simulation of **quench evolution** in solenoids.

Main features:

- Pseudo-analytical: quench propagation is based on Wilson **analytical formulas**[2]; thermal calculations are made solving the heat equation in adiabatic approximation.
- Magnetic field is given as input
  - It is possible to simulate magnetic quadrupoles or other kind of magnets
- Magnet inductance is given as input
  - **Iron saturation** can be simulated
  - It is possible to simulate **dynamic effects** (reduction of the inductance[3])
- Protection circuit with external dump resistor
- It is possible to simulate **protection heaters** with heating stations[4]
- Material properties from MATPRO[5]

*

[1] "QLASA: a computer code for quench simulation in adiabatic multicoil superconducting windings", L. Rossi and M. Sorbi, 2004.

[2] "Superconducting magnets", M.N. Wilson, 1983.

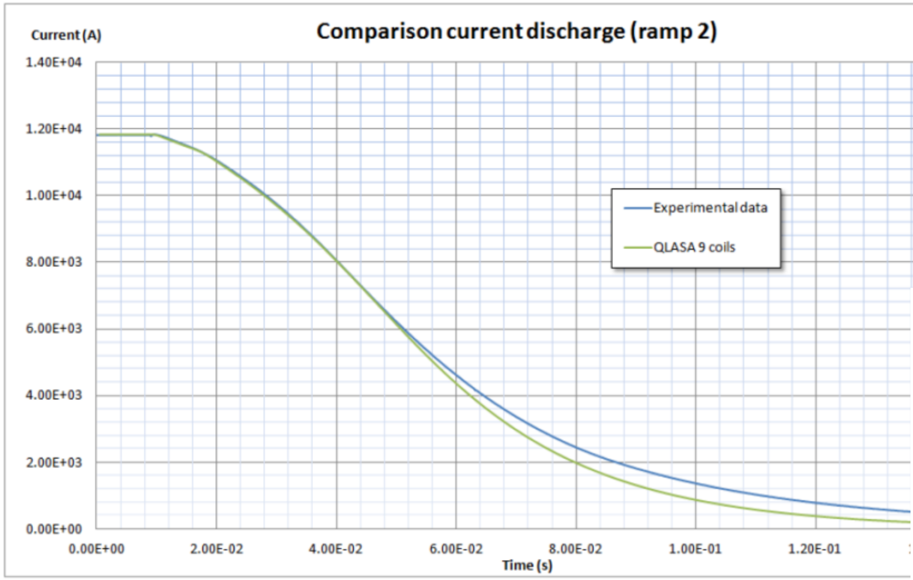
[3] "Effect of coupling currents on the dynamic inductance during fast transient in superconducting magnets", V. Marinozzi et al., 2015.

[4] "Guidelines for the quench analysis of Nb3Sn accelerator magnets using QLASA", V. Marinozzi, 2013.

[5] "MATPRO upgraded version 2012: a computer library of material property at cryogenic temperature," G.Manfreda et al., 2012

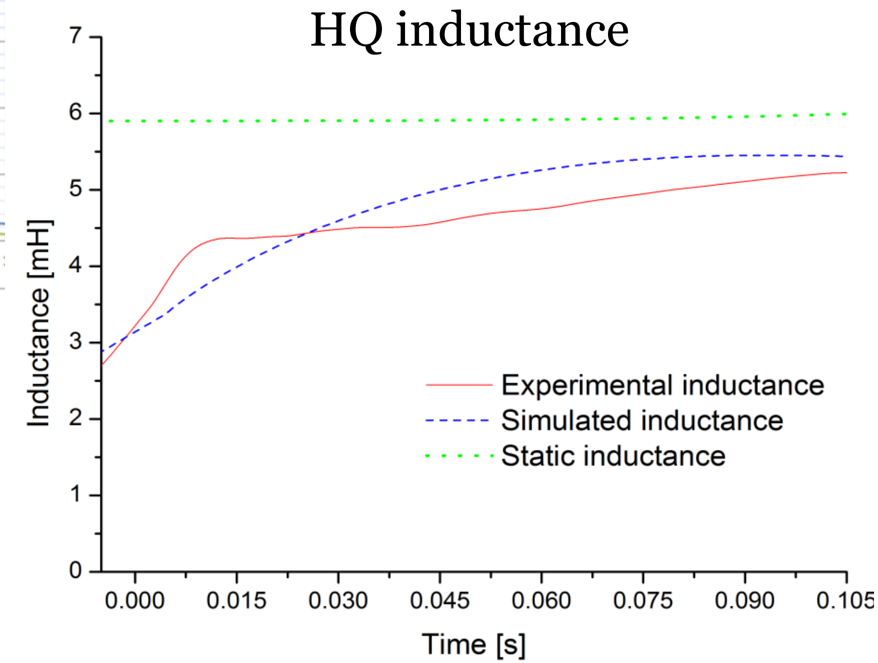
2. QLASA validation

- QLASA has been experimentally validated with several LARP prototypes test results
- It can predict dynamic effects on the inductance



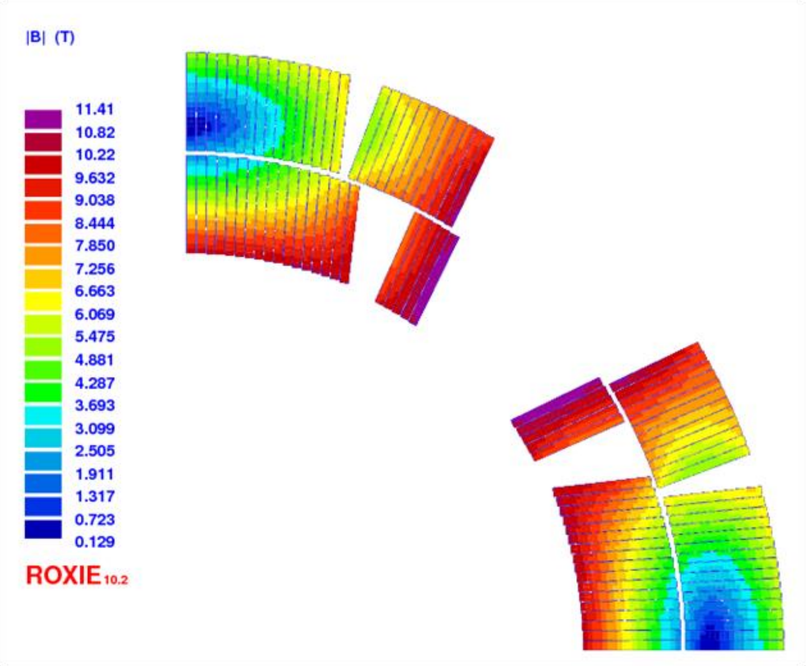
Validation on LQ data

- Right detection time
- Right resistance development simulation



1. Introduction

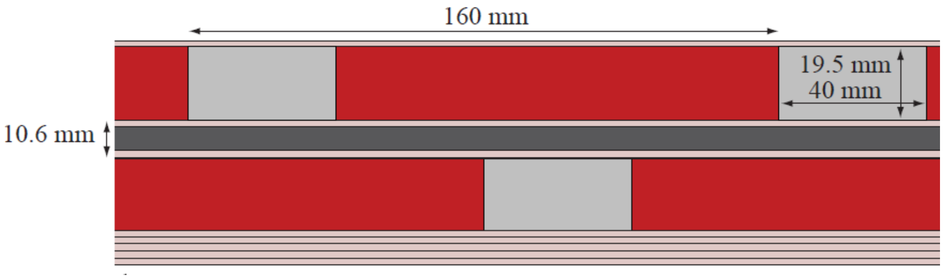
Aperture diameter	150 mm
Gradient	132.6 T/m
Nominal current	16470 A
Magnetic stored energy	1.17 MJ/m
Inductance	8.3 mH/m
Magnetic length Q1/Q3	2 x 4.2 m
Magnetic length Q2a/Q2b	7.15 m
Conductor peak field	11.4 T
Operating temperature	1.9 K
Strand diameter	0.850 mm
Bare cable width	17.86 mm
Bare cable thin/thick edge thickness	1.462/1.588 mm
Insulation thickness	0.145 mm
Number of strands	40
Copper/non-copper ratio	1.2
Copper RRR	100

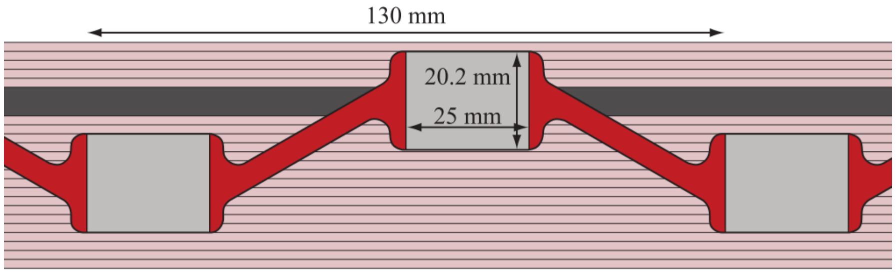


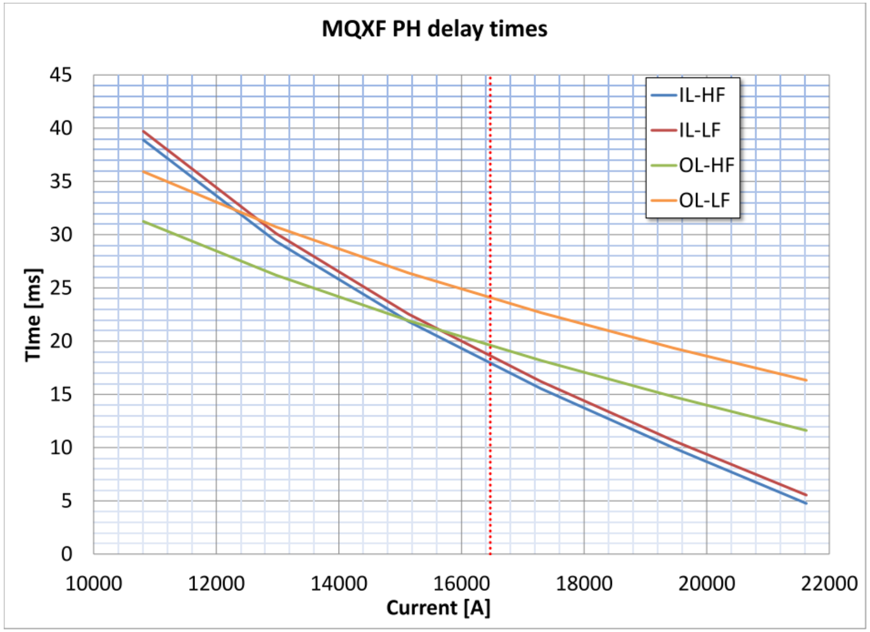
- ➢ High stored energy
- ➢ High peak field

➢ <u>Protection challenging!</u>

3. Quench heaters design







Quench heaters have been designed using copper plating for **inner** and **outer** layer:

- Two strips on each side of the outer layer (“High Field” and “Low Field”)
- One strip on each side on the inner layer
    - Inner layer 40% polyimide free

4. Assumptions in simulations

- The initial quench is a point (initial size equal to 0) located in the peak field zone (pole turn);
- The detection time is computed according to the propagation velocities computed by QLASA (~7 ms)
- Heaters-induced quench occurs at a different average time in the high-field and in the low-field blocks of each layer. The heating stations are simulated, but pre-heat from the copper-bridges is not considered;
- Heat exchange between layers is neglected;
- Dynamic effects on the magnet inductance due to the inter-filament coupling currents are taken into account. These effects have been experimentally observed in the latest LARP magnets;
- Quench-back is neglected.

Main protection parameters

Dump resistor (maximum voltage between ends)	46 mΩ (800 V)
Voltage threshold	100 mV
Validation time	10 ms
Switch opening delay time	5 ms

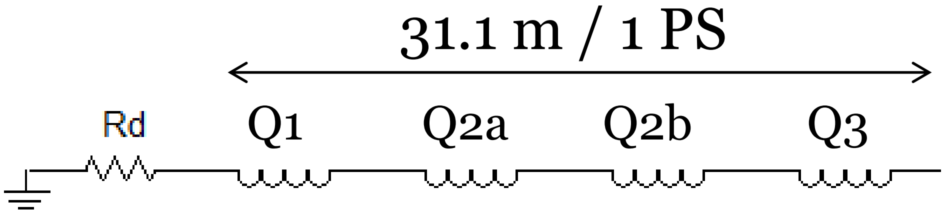
Outline

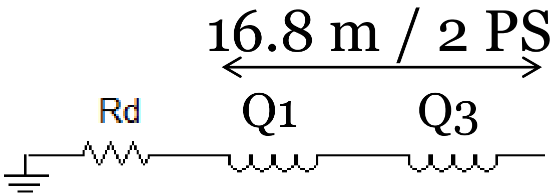
- Benchmarks (safe territory)
- Flux jumps & Detection Threshold
- Heater delays
- Heater “bubbles”
- Simulations Codes
- **Simulation Results**

5. Hot spot temperature

31.1 m (**1 PS**)	Hot spot temperature [K]	MIITs [MA²s]
Nominal	**261**	28.3
Only outer layer PH	346	33.6
Failure HF OL-PH (20 % less resistance)	299	30.7
16.8 m (**2 PS**)	Hot spot temperature [K]	MIITs [MA²s]
Nominal	**257**	28.1
Only outer layer PH	341	33.3
Failure HF OL-PH (20 % less resistance)	299	30.7

- ➢ Protection and redundancy are **ensured** only with both IL & OL heaters
- ➢ The 1 and 2 PS scenarios have very similar hot spot temperatures





6. Peak voltages

Voltages simulations made using **ROXIE**

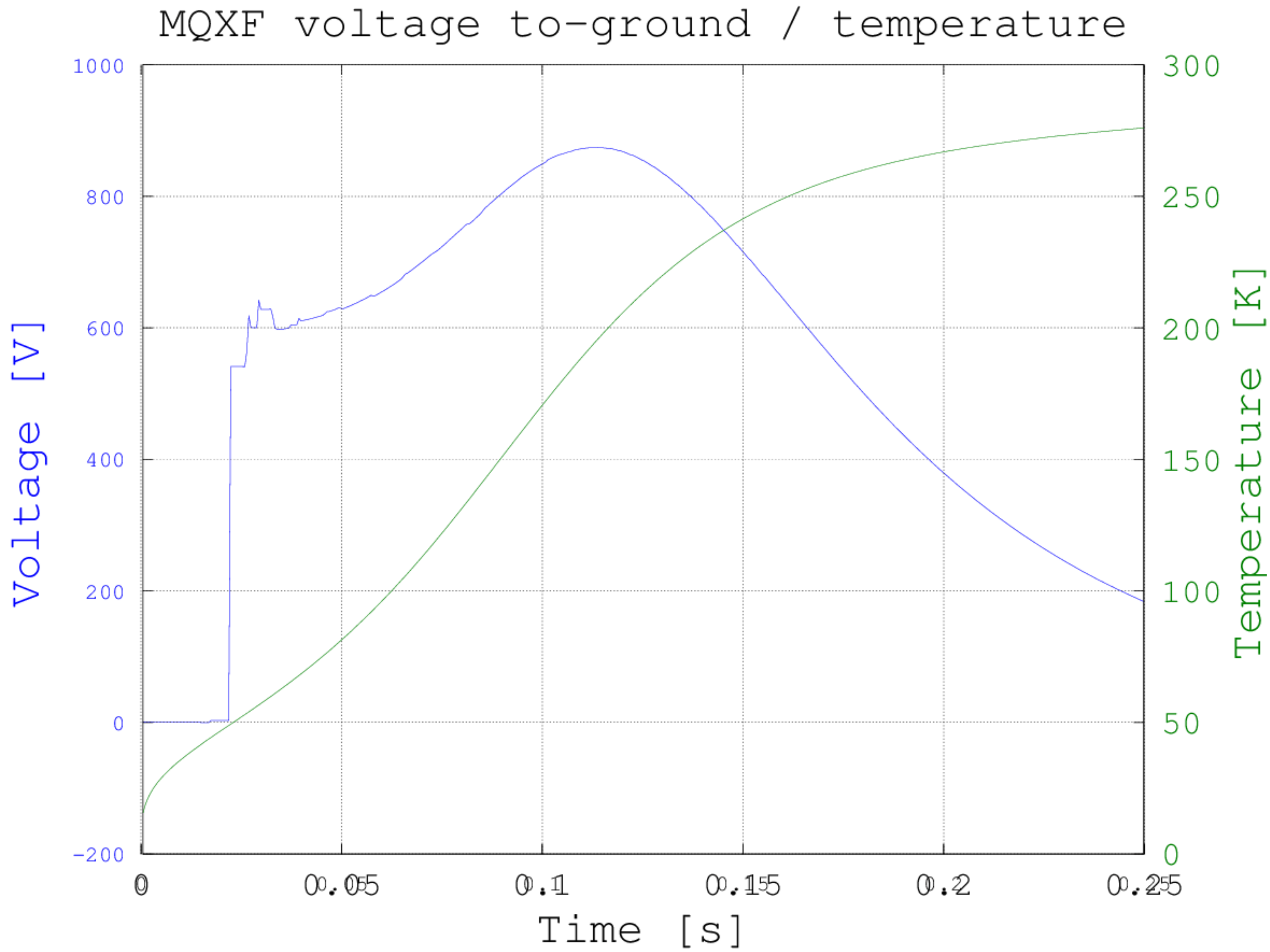
2 PS

	C-G [V]	C-G (short) [V]	T-T [V]	L-L [V]	M-M [V]
Nominal	**638**	838	**46**	**454**	**148**
Coil 1 IL fail	662	872	49	522	356
Coil 3 IL fail	663	873	50	527	482
Coil 1 OL-HF fail 1 side	608	813	48	487	159
Coil 3 OL-HF fail 1 side	608	813	47	490	275
Coil 1 OL-LF fail 1 side	597	802	47	472	147
Coil 3 OL-LF fail 1 side	582	787	47	472	176
Coil 1 fail	1862	2092	62	1734	1701
Coil 3 fail	1463	1693	63	1747	1832
OL-HF fail	738	958	66	239	148
OL-QH only	385	635	60	516	146

1 PS

	C-G [V]	C-G (short) [V]	T-T [V]	L-L [V]	M-M [V]
Nominal	**659**	859	**44**	**421**	**313**
Coil 1 IL fail	754	964	47	486	342
Coil 3 IL fail	755	965	47	490	494
Coil 1 OL-HF fail 1 side	704	909	45	452	314
Coil 3 OL-HF fail 1 side	704	909	45	455	314
Coil 1 OL-LF fail 1 side	680	885	45	439	312
Coil 3 OL-LF fail 1 side	681	886	45	439	313
Coil 1 fail	1810	2020	59	1674	1513
Coil 3 fail	1335	1565	59	1686	1769
OL-HF fail	833	1053	62	223	312
OL-QH only	494	744	56	478	311

- Peak voltage to ground is < 1kV in the most realistic failure scenarios
  - Worst scenarios (grey numbers) should be prevented by number of HFU & connection scheme
- The 1 and 2 PS scenarios have very similar peak voltages
  - Only midplane-midplane voltage doubles in the 1 PS scenario, in some cases



- Voltage to Ground and Temperature versus Time in case of Coil 1 IL heater failure

Heater-Coil Voltages

- Nominal condition (symmetric grounding of PS and HFUs): V_max < 650 V
- Double failure scenario (short in PS circuit and in HFU circuit): V_max < 1300 V

Work in Progress

- Understanding criteria for Electrical Qualification and Acceptance of MQXF magnets and components
  - Nb_3Sn coils/magnets are different from NbTi
- Developing plans for maximizing feedback from testing short models and prototypes

Conclusions

- MQXF protection with IL and OL heaters provides acceptable Hot-Spot temperature also in case of reasonable failure scenarios
- From the voltage point of view: worst failure scenarios should be prevented by design
  - Number of HFU and connections
- Work in progress for understanding ELQA
  - Finalization of QP system should take into account ELQA requirements and impact on MQXF design/risk

Back up Slides

7. Assumptions for voltage to ground

- Roxie allows simulating only one magnet, and not the whole chain
  - This affects the voltage to ground computation

- The computation has been performed as following:

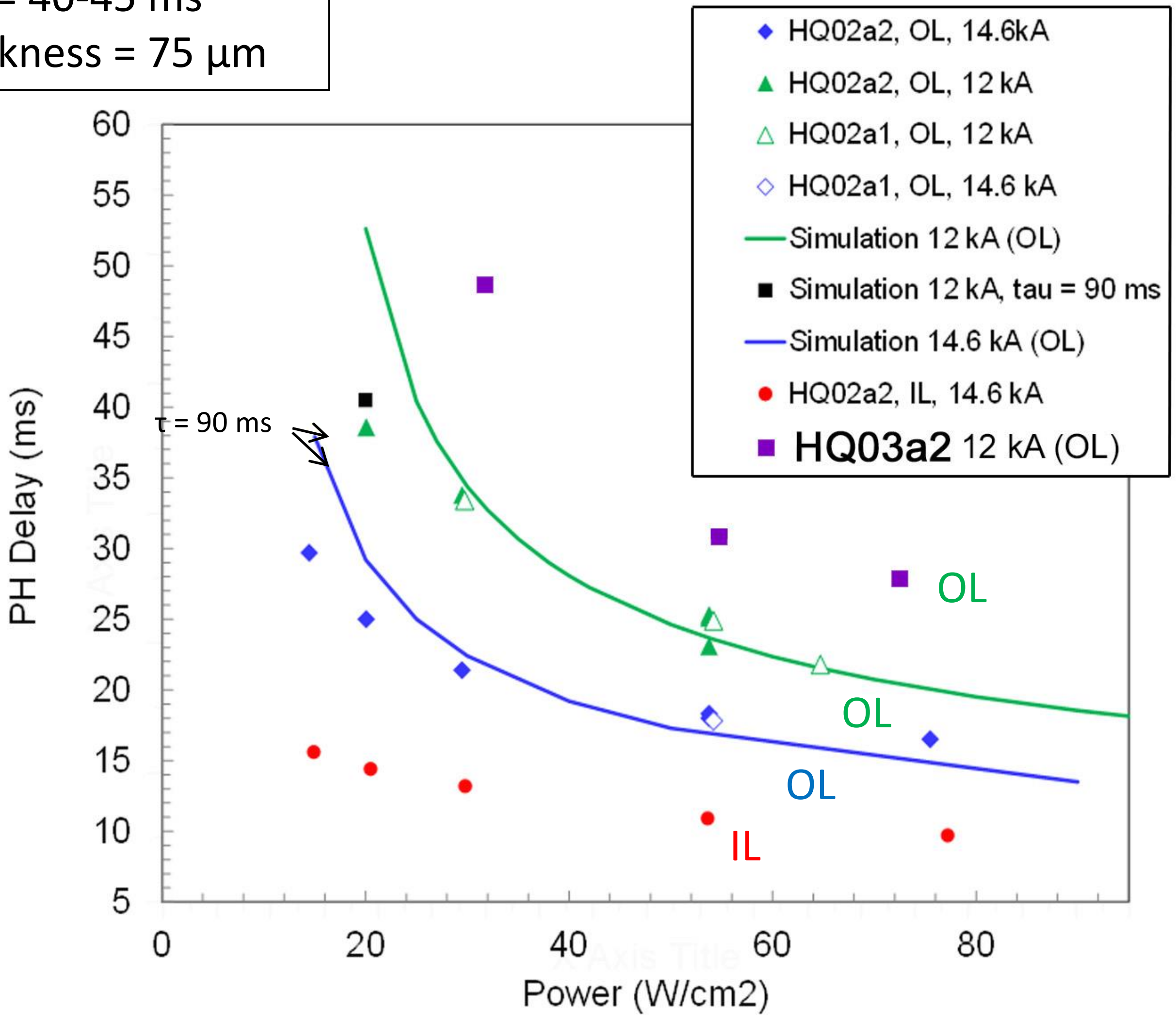
  1. Simulation of only one magnet, with a dump resistor dimensioned in order to obtain a voltage drop between the ends the same as the voltage across the magnet inserted in the chain.
     - It is assumed that all the protection heaters in the chain work well. This causes an error on the voltage to ground evaluation, on the order of the resistance difference.

  2. The input voltage of the magnet inserted in the chain is added to the obtained voltage to ground.
     - In this case too it is assumed that for the calculation of the input voltage all the protection heaters in the chain work well. This causes another error on the voltage to ground on the order of the resistance difference.

- In most of the failure scenarios, resistance difference is few %, therefore the voltages to ground are sufficiently reliable.

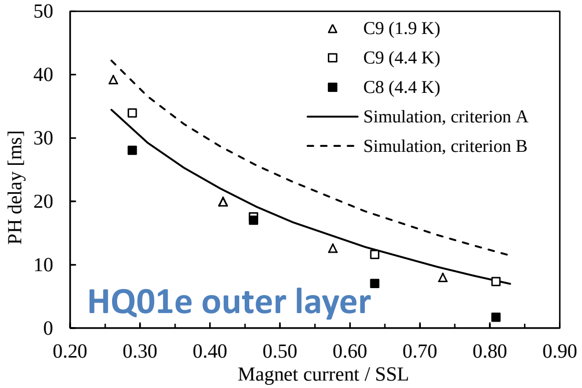
HQ02 – Delay vs. power

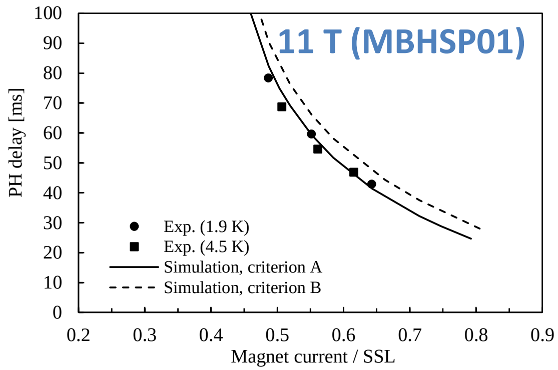
T = 1.9 K, τ = 40-45 ms
Kapton thickness = 75 µm

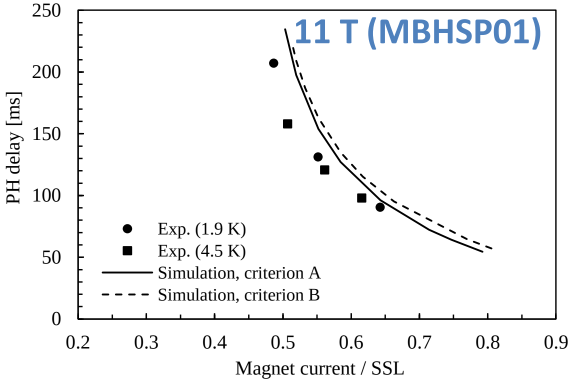


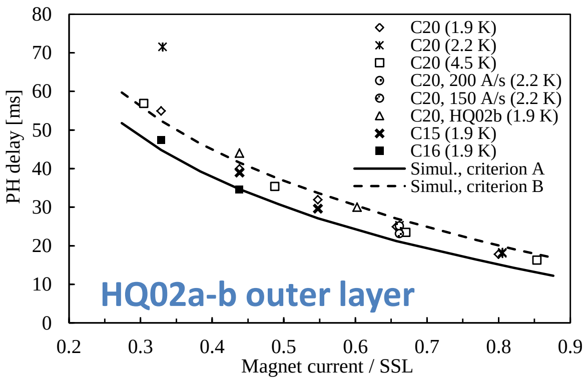
A possible conservative delay simulation criterion

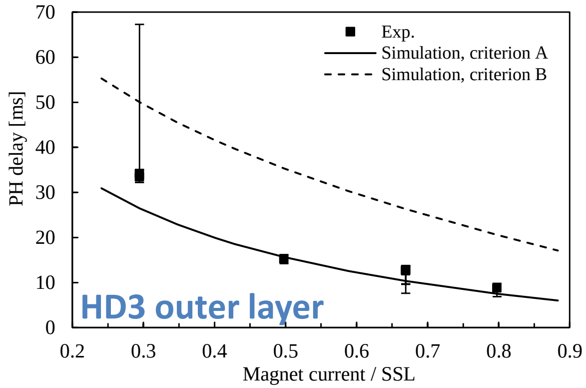
- We need to add margin to the simulated heater delays for quench simulations
- One option: Simulate delay time to the moment when cable I_c equals I_{mag}. This accounts for the temperature gradient in the cable cross-section.
  - Most of the measured delays on outer layer below this upper bound:

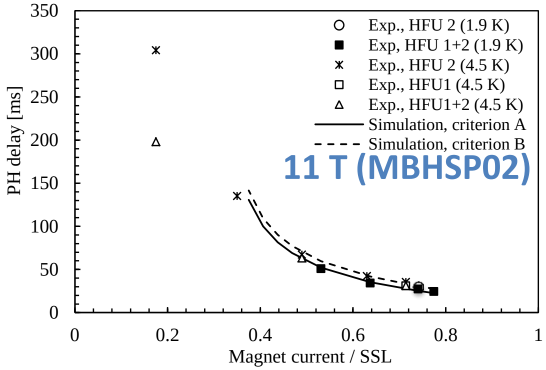










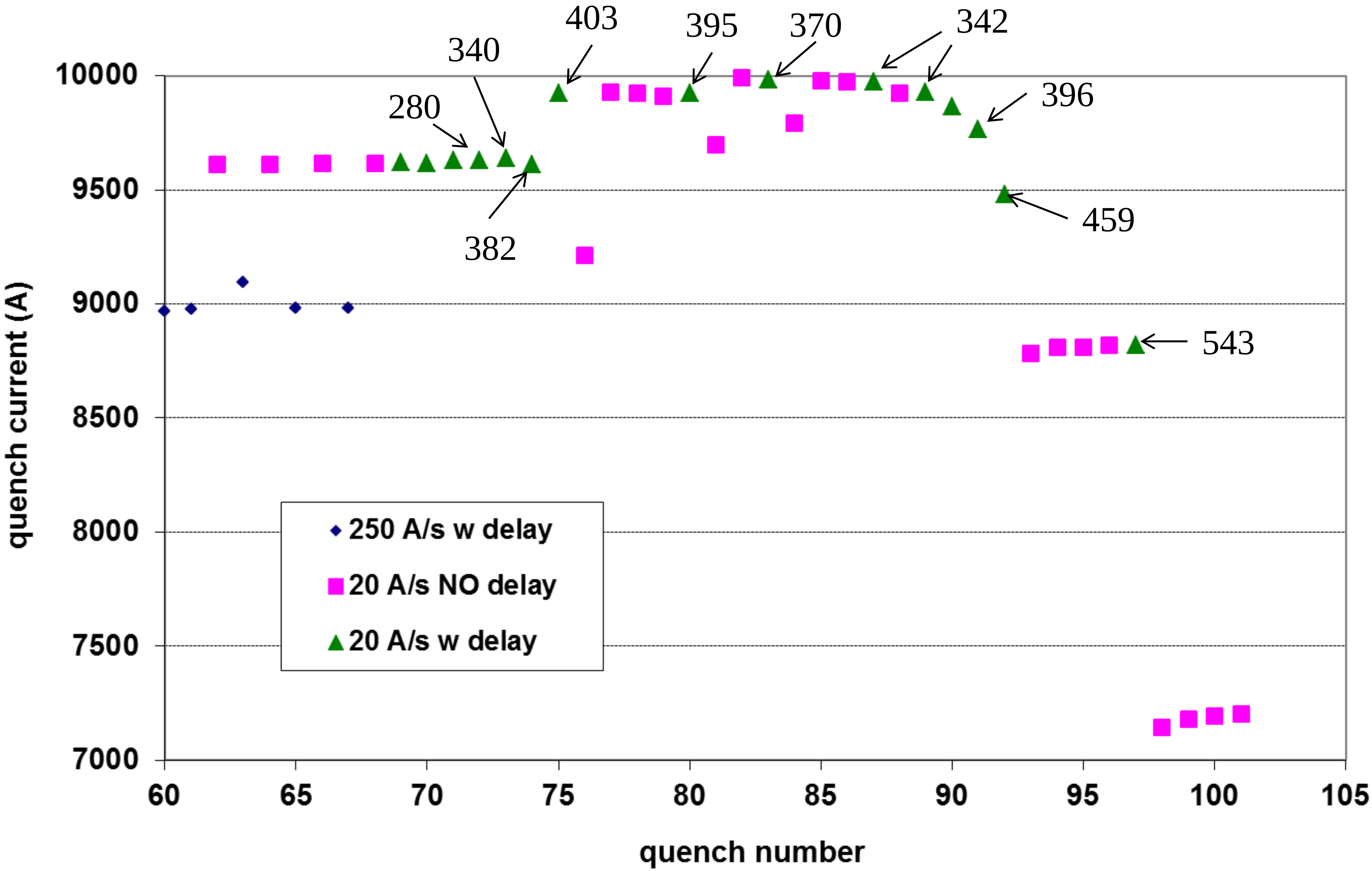


Criterion A: Nominal simulaion, quench when cable $T_{max} = T_{cs}$;
Criterion B: Conservative criterion, quench when cable $I_c = I_{mag}$.

Hot Spot Temperature vs. Degradation

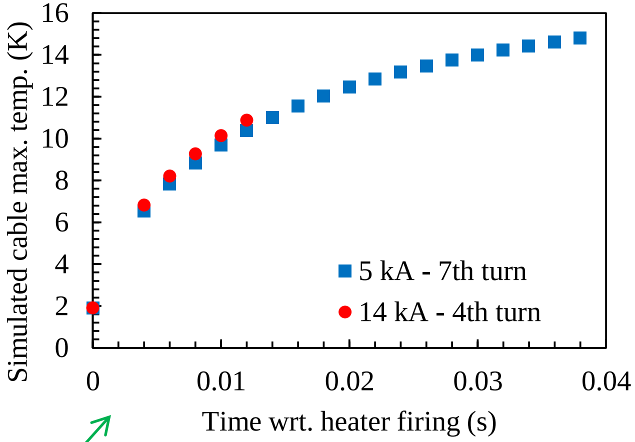
LARP

All temperatures are in K +/- 6 K (for RRR uncertainty)

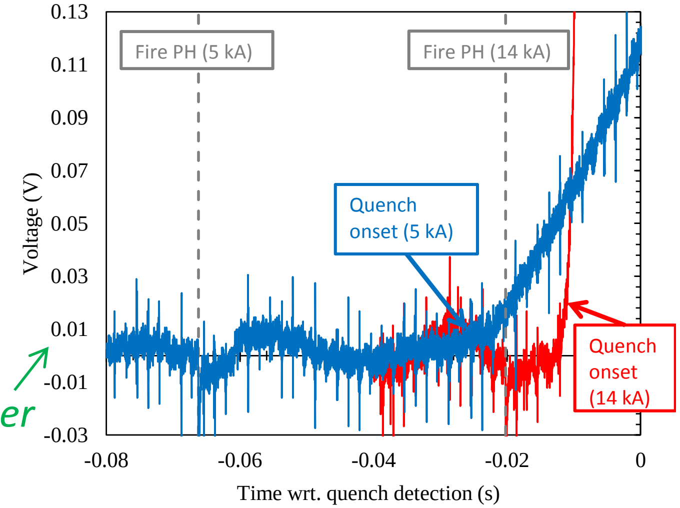


Possible reasons for uncertainties with low current, low field, or low heater power

- **Cable temperature increase slows down** as heater power decreases and cable specific heat increases:
  - **Small variations of T_{cs} have larger impact**
  - Details of cooling and heat conduction become more significant
  - Quench onset from voltage signals less clear at low current
  - Current redistribution and heat generation due to slow heating can occur (not modeled)
- Magnetic field simulation important for T_{cs} – Which field to use for each conductor?
  - I have used the field on coil surface (closest to the protection heater), except for 11 T the maximum field because the field was significantly higher deeper in the cable
- Luckily, low current regime less critical for quench protection



Simulated temperature rise after heater activation.



HQ01e voltage tap signals for a heater provoked quench at 5 kA and 14 kA.