Models and experimental results from LQ, HQ (… and more) and QXF

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With contributions by:

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Giulio Manfreda (Univ. of Udine)

WAMSDO
CERN
January 16, 2013

Outline

- What is the **maximum acceptable temperature** at the hot spot in Nb_3Sn accelerator magnets?
- What **feedback from magnet test** to QP codes?
- Where does the **QXF** stand?

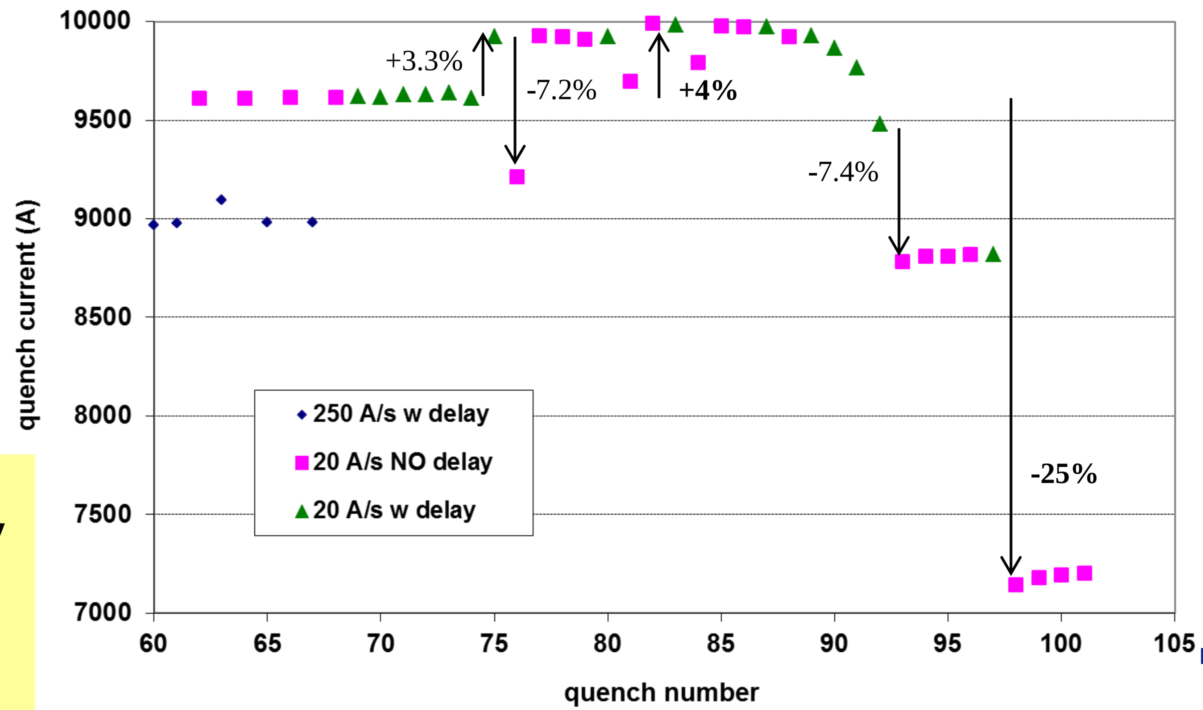
MAXIMUM ACCEPTABLE TEMPERATURE AT HOT SPOT?

In Nb_3Sn accelerator magnets

High Hot-Spot Temperature Test in Quad

Test performed on **TQS01c** (1m quad)

- with MJR conductor (47% copper)
- Spontaneous quenches (pole turn, inner layer)
  - same segment during all study;
- High MIITs (and Temp) by removing protection features
- Iq ~ 80% ssl at start
- Iq_max: + 4%
- Iq_min: - 25%



Fermilab TD Note: TD-07-007:

LARP TQS01c Test Summary

G. Ambrosio, R. Carcagno, S. Caspi, G. Chlachidze, F. Lewis, A. Lietzke, D. Orris, Y. Pischalnikov, G.L. Sabbi, D. Shpakov, C. Sylvester, M. Tartaglia, J.C. Tompkins, G. Velev, A.V. Zlobin

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 18, NO. 2, JUNE 2008 179

Test and Analysis of Technology Quadrupole Shell (TQS) Magnet Models for LARP

S. Caspi, G. Ambrosio, A. N. Andreev, E. Barzi, R. Bossert, D. R. Dietderich, P. Ferracin, A. Ghosh, A. R. Hafalia, V. V. Kashikhin, A. F. Lietzke, I. Novitski, G. L. Sabbi, and A. V. Zlobin

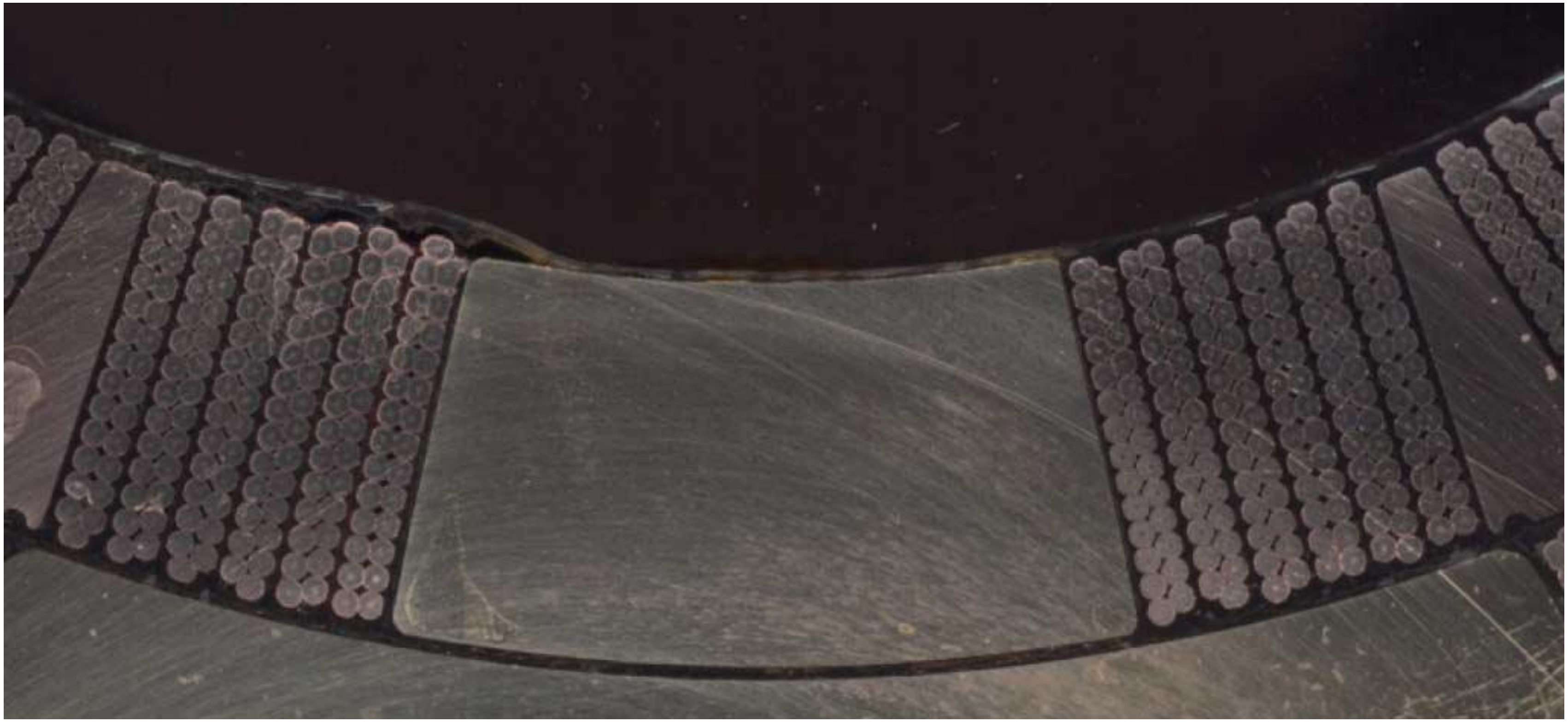


Fig. 9. Epoxy de-lamination and slight inward cable displacements on one side of coil-15’s inner-pole island after high-MIITs study.

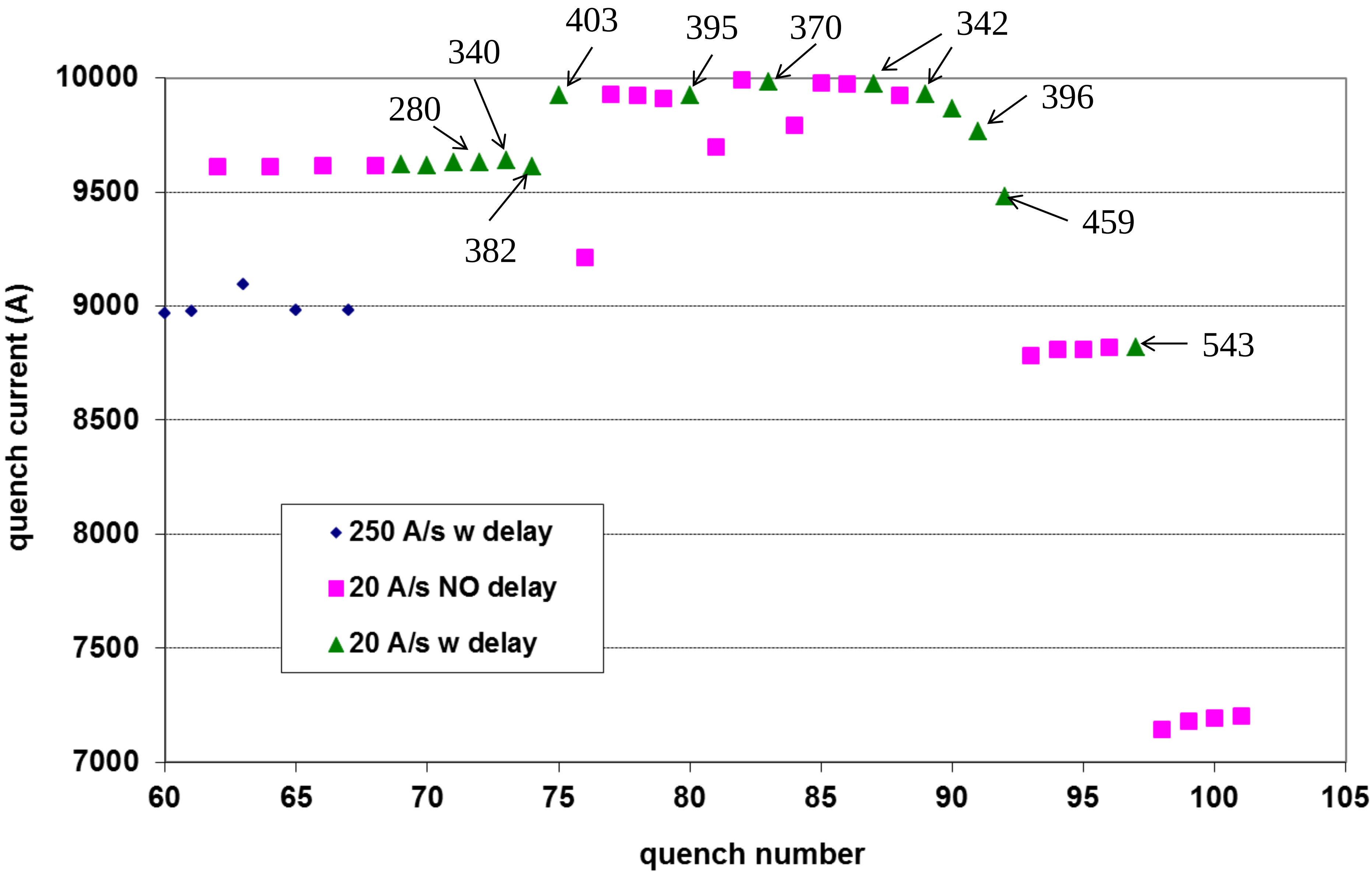
Hot Spot Temperature Computation

Hot spot temperature computed with QuenchPro:

- MIITs vs. Temperature including epoxy and insulation in enthalpy computation
- Adiabatic approximation
- Assuming peak field on cable (at quench current)
  - Constant in QuenchPro
- RRR: 130-170 (range of RRR in quenching coil)
  - RRR of quenching segment not available

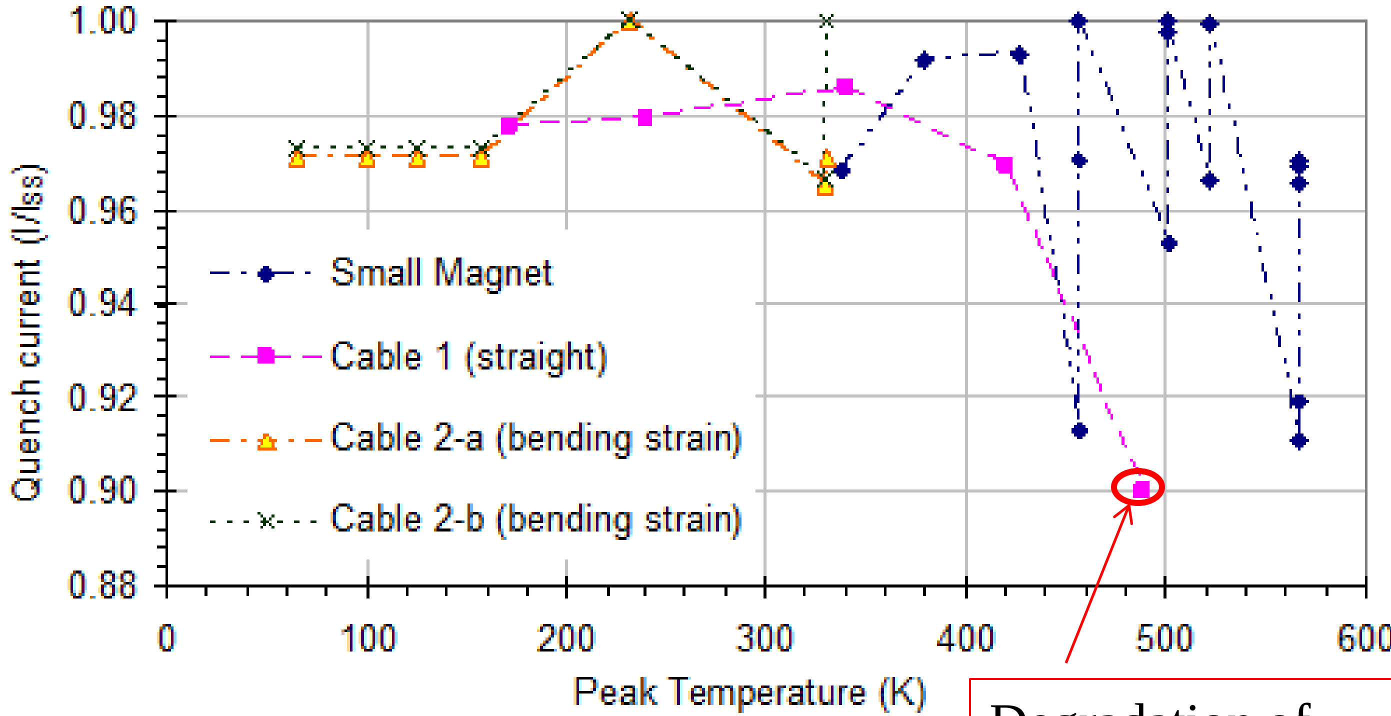
Hot Spot Temperature vs. Degradation

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



Tests on Cable Samples and Small Racetrack

Peak temperatures **measured** by resistance growth with voltage taps around hot spot



Degradation of electrical strength

Fig. 6.8: Summary of quench experiments: reduced current (quench current divided by maximum current) vs. peak temperatures reached during the preceding quench test. The lines represent the temporary sequence of the peak temperature events.

http://lss.fnal.gov/archive/thesis/2000/fermilab-thesis-2004-14.pdf

Quench Protection Issues of Nb3Sn Superconducting Magnets for Particle Accelerators

L. Imbasciati, PhD dissertation

Conclusions - I

- T_hot spot > T_1 ➔ “Active territory”:
  - Hot spot after quench is not in the same strain/stress state where it was before the quench
  - Magnet may train, detrain, … effect is reversible
- T_hot spot > T_2 > T_1 ➔ “Degradation territory”:
  - Degradation is irreversible and/or the magnet insulation failures
- T1 = 340-370 K based on TQS01C
- T1 > 400 K based on results in L. Imbasciati dissertation
- Glass Transition temperature of CTD101K = **386 K**

This may be the physical limit!

Max acceptable temperature = 386 K - margin

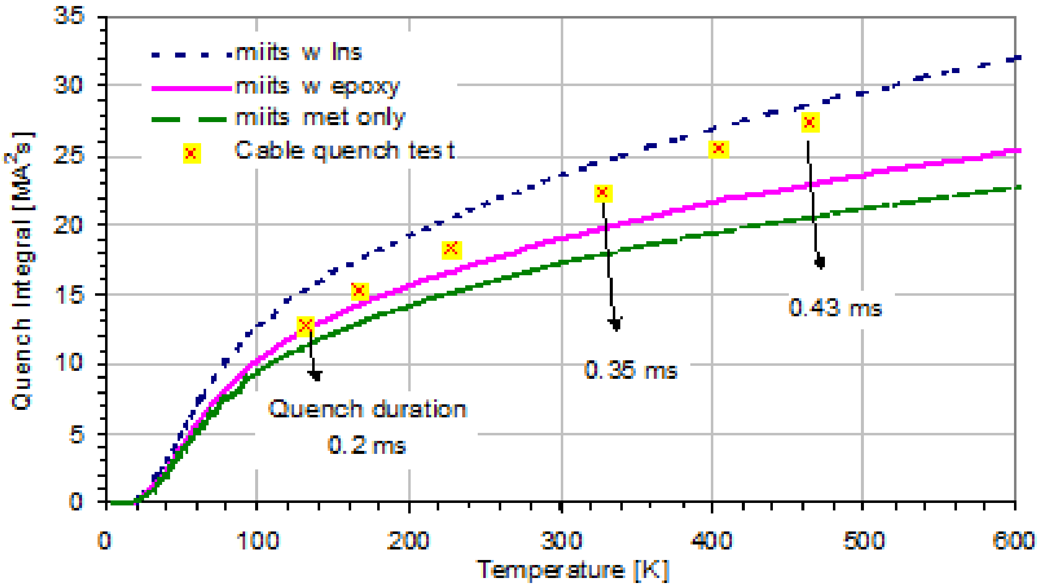
AIP Conf. Proc. 614, pp. 295-304;
Highly radiation-resistant vacuum impregnation resin systems for fusion magnet insulation
P. E. Fabian, N. A. Munshi, and R. J. Denis
and **CTD-101K Material datasheet**

Conclusions - II

Computations may slightly underestimate the hot spot temperature because:

- They include epoxy and insulation
- They compute “cable average temperature”
  - Local RRR may be higher (for instance at cable edge)
- Material prop. may not be “correct” (for instance G10)

with RRR = 70 the hot spot temperature changes 340 K ➔ 383 K



Quench Protection Issues of Nb3Sn Superconducting Magnets for Particle Accelerators
L. Imbasciati

Fig. 6.6: Quench integral accumulated during the quench experiments performed on cables (above), and during the small magnet experiment (below), compared to curves calculated using the heat balance equation including metal components only, with epoxy resin and with 0.15 mm insulation.

Conclusions - III

- This picture may change if **another material** is used for potting:
  - The glass transition temperature may change
  - Other mechanisms may cause detraining or degradation

- These tests should be repeated on magnet with **cored cable**
  - Core and cable may not come back to the same condition after quenches at high temperature, …

FEEDBACK FROM LQ TEST

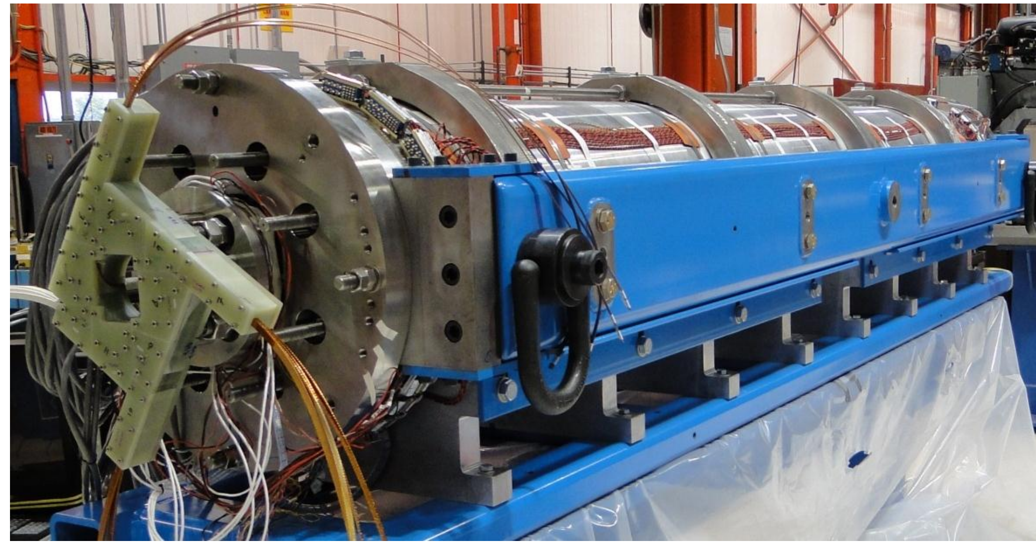
LARP

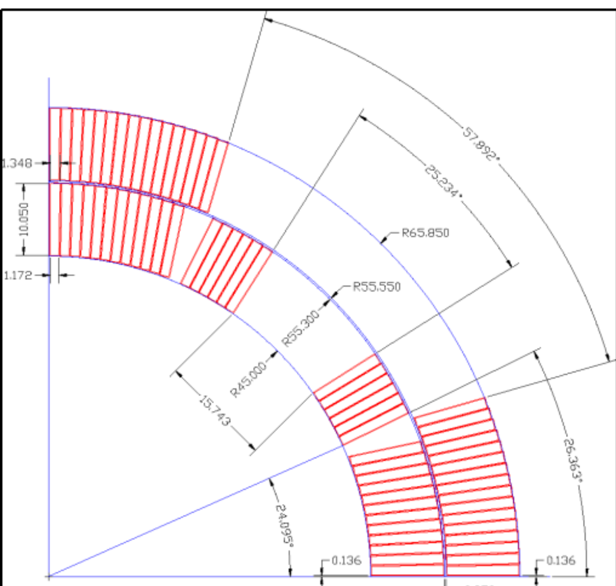
Long Quadrupole

Main Features:

- Aperture: 90 mm
- magnet length: 3.7 m

LQS01 SSL	4.5 K
Current	13.7 kA
Gradient	240 T/m
Peak Field	12.25 T
Stored Energy	460 kJ/m





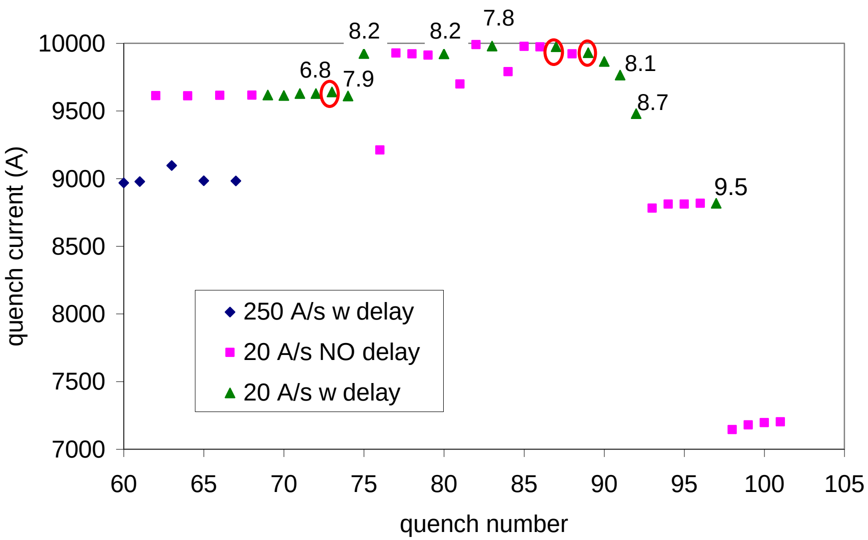
Parameter	Unit	LQ
N of layers	-	**2**
N of turns	-	**136**
Coil area (Cu + nonCu)	cm^2	**29.33**
Coil Length	m	**3.3**

LQ Design Report available online at:
https://plone4.fnal.gov/P1/USLARP/MagnetRD/longquad/LQ_DR.pdf

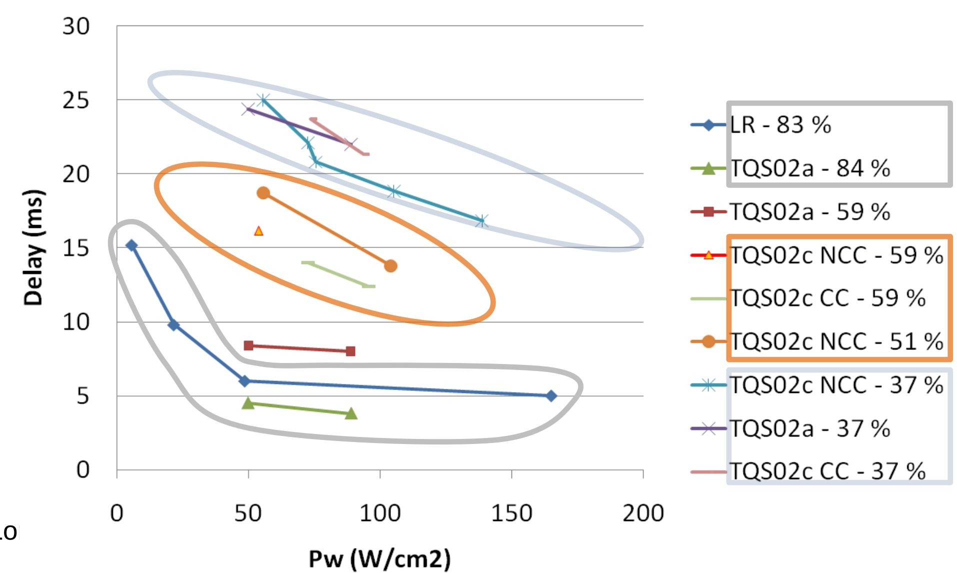
Quench Protection

Very challenging!
J in copper = 2900 A/mm²
at 13.9 kA (4.3 K SSL)

- **Goal: MIITs < 7.5 ⇔ Temp ~ 360-370 K (adiabatic approx)**
- **Quench protection param. (4.5 K) – conservative hypothesis**
  - Dump resistance: **60 mΩ** (extract ~1/3 of the energy; V_{leads} ~ 800 V)
  - **100%** heater coverage (➔ heaters also on the inner layer)
  - Detection time: **~5 ms** based on TQs with I > 80% ssl
  - Heater delay time: **12 ms** based on TQs with I > 80% ssl
    - 6 ms (transv. propagation through insul.) + 6 ms (long. propagation btw heating station)



Lo



Measurement vs. Computation

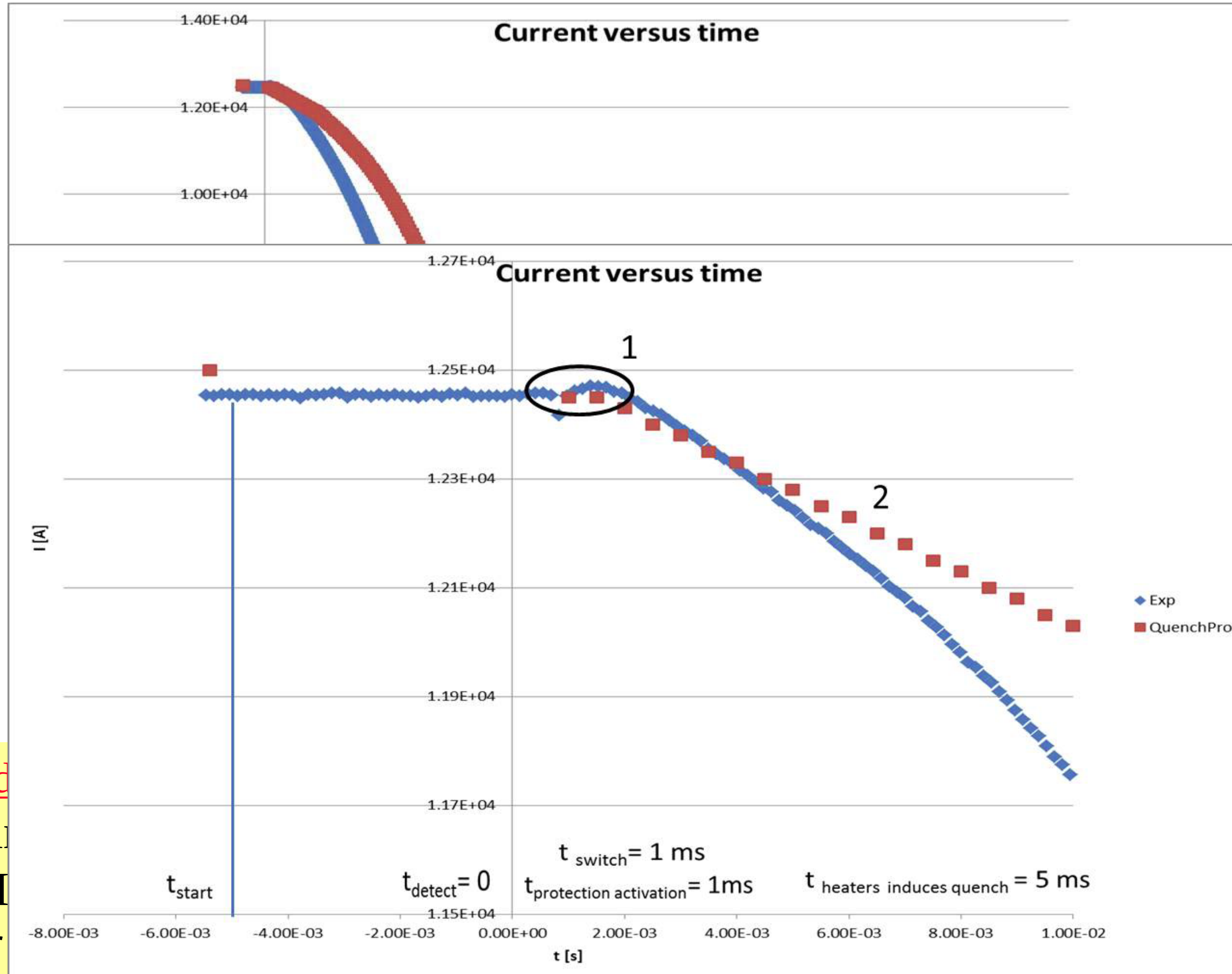
- Tests showed that there is margin:
  - MIITs lower than computed ➔ Faster current decay,
    - With one exception: quench in midplane block at 11.3 kA
  - RRR higher than value used in computations.
  - ➔ Hot spot temperature lower than computed values

	COMPUTED			MEASURED		
Current (A)	**MIITs**	RRR	**Temp (k)**	**MIITs**	RRR	**Temp (k)**
13500	**7.5**	100	**376**			
12590	**7.0**	100	**326**	**5.6**	270	**197**
11703	**6.4**	100	**268**	**6.5**	293	**< 247**

Feedback from LQ test

LARP

- Current decay faster than computed



- At very start!

  0 – 10 ms

http://tdserver1.fnal.gov/td

Study of Superconducti

Quadrupoles for the LH

Lidia Rossi, Bachelor

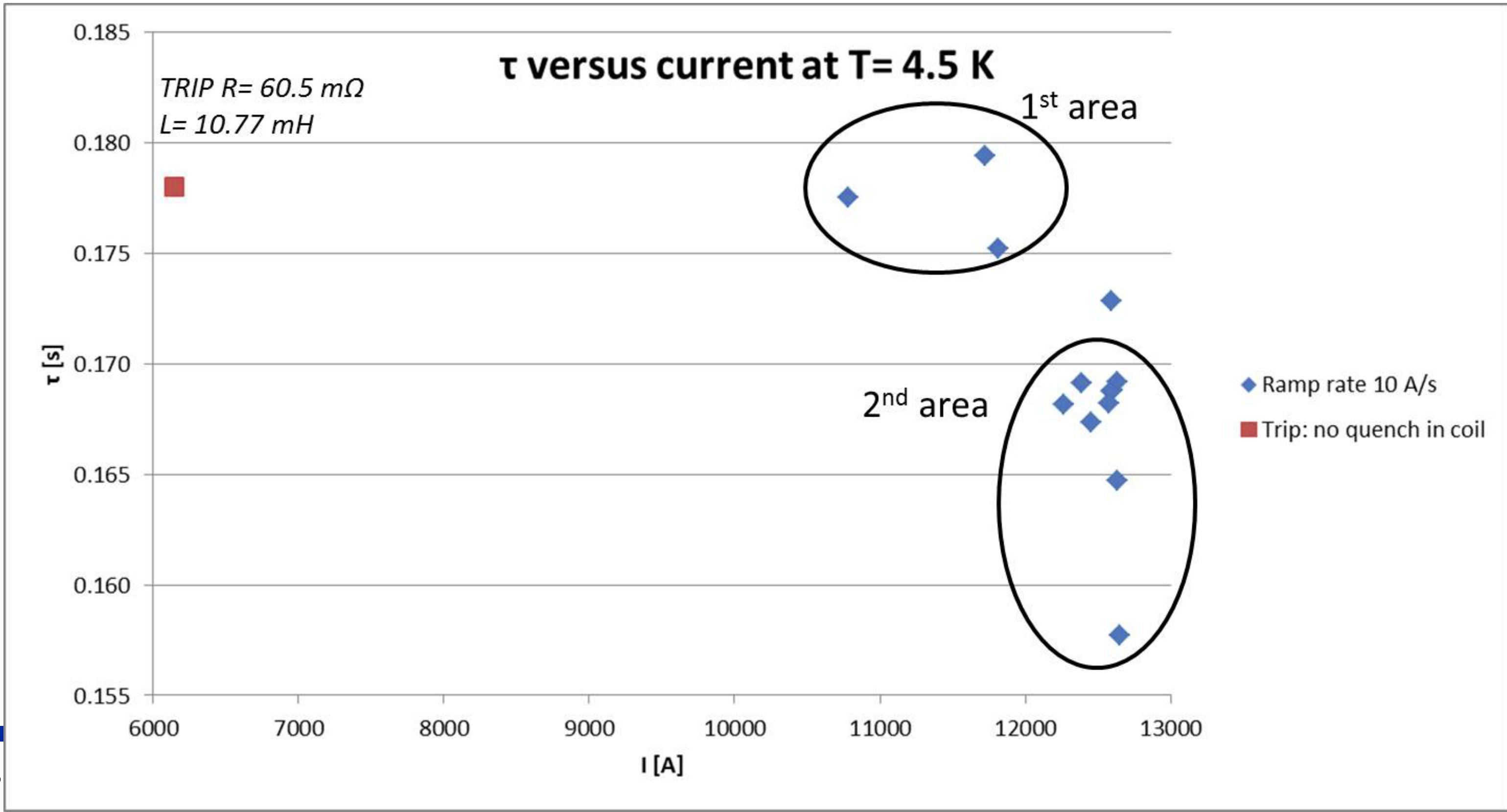
Time constant at current decay start

Time constant at decay start: $\tau = L / R$

with $R = R_{dump} + R_{busbars}$ (R_{coil} is negligeable)

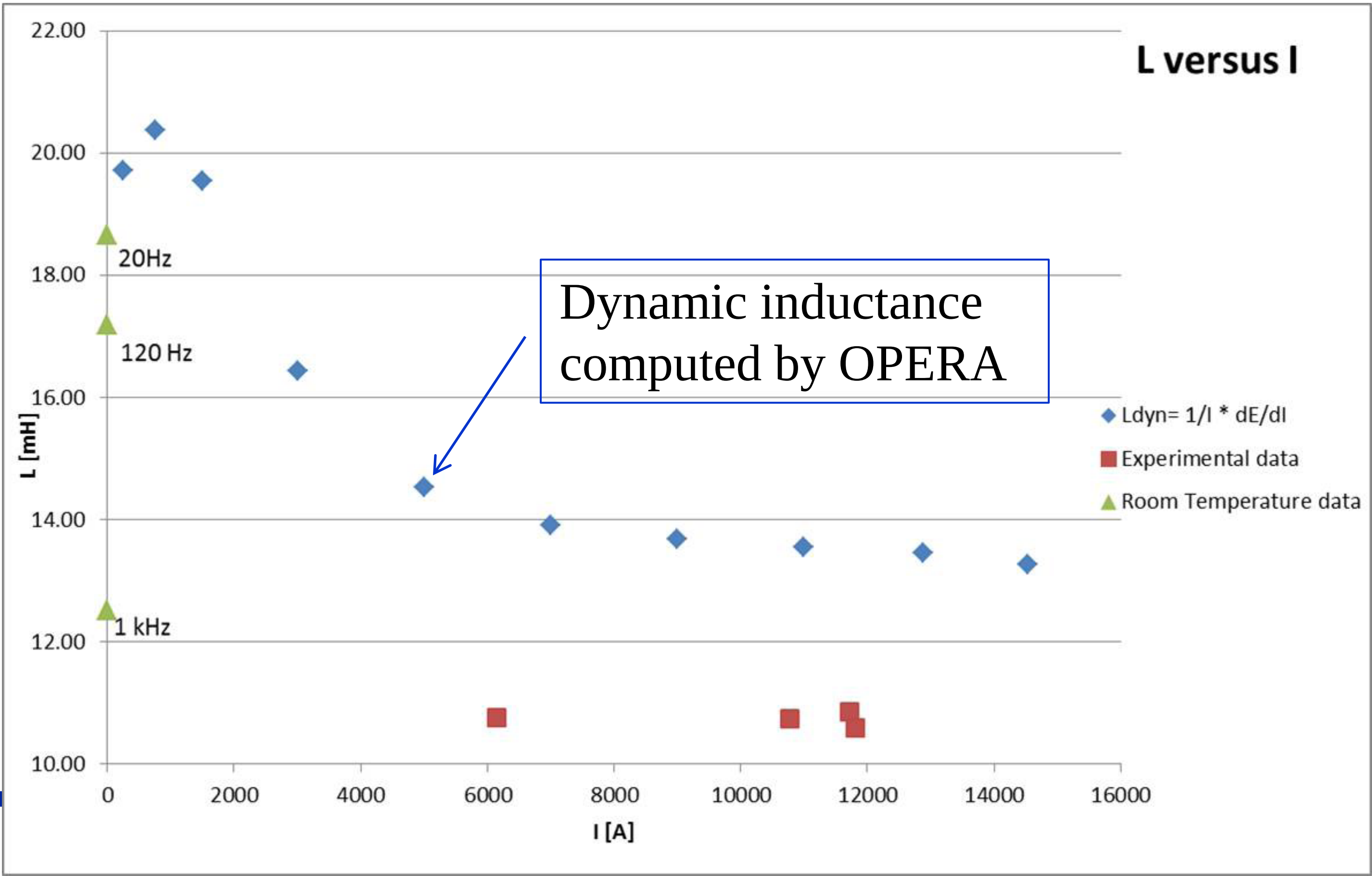
$\tau_{measured} < \tau_{estimated}$ (240 ms)

➔ $\tau_{measured}$ used to evaluate $L_{effective}$



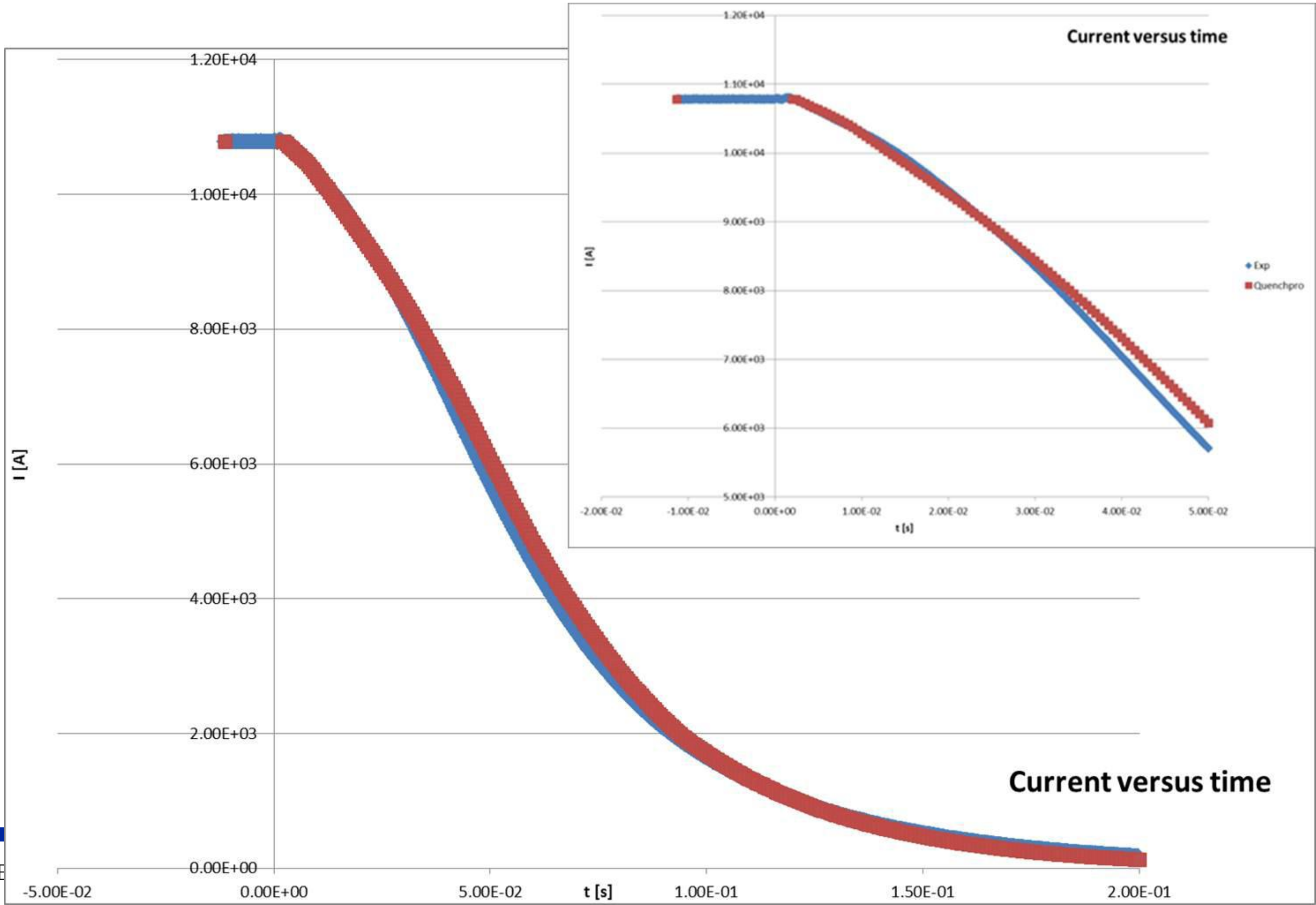
Dynamic Inductance vs. Measurements

- $L_{effective} < L_{dynamic}$
- Large variation of L with frequency at room temperature
- ➔ reduction of $L_{effective}$ due to **eddy currents** (cable, structure)



New Comparison

- Better modeling after including these and other improvements into QuenchPro



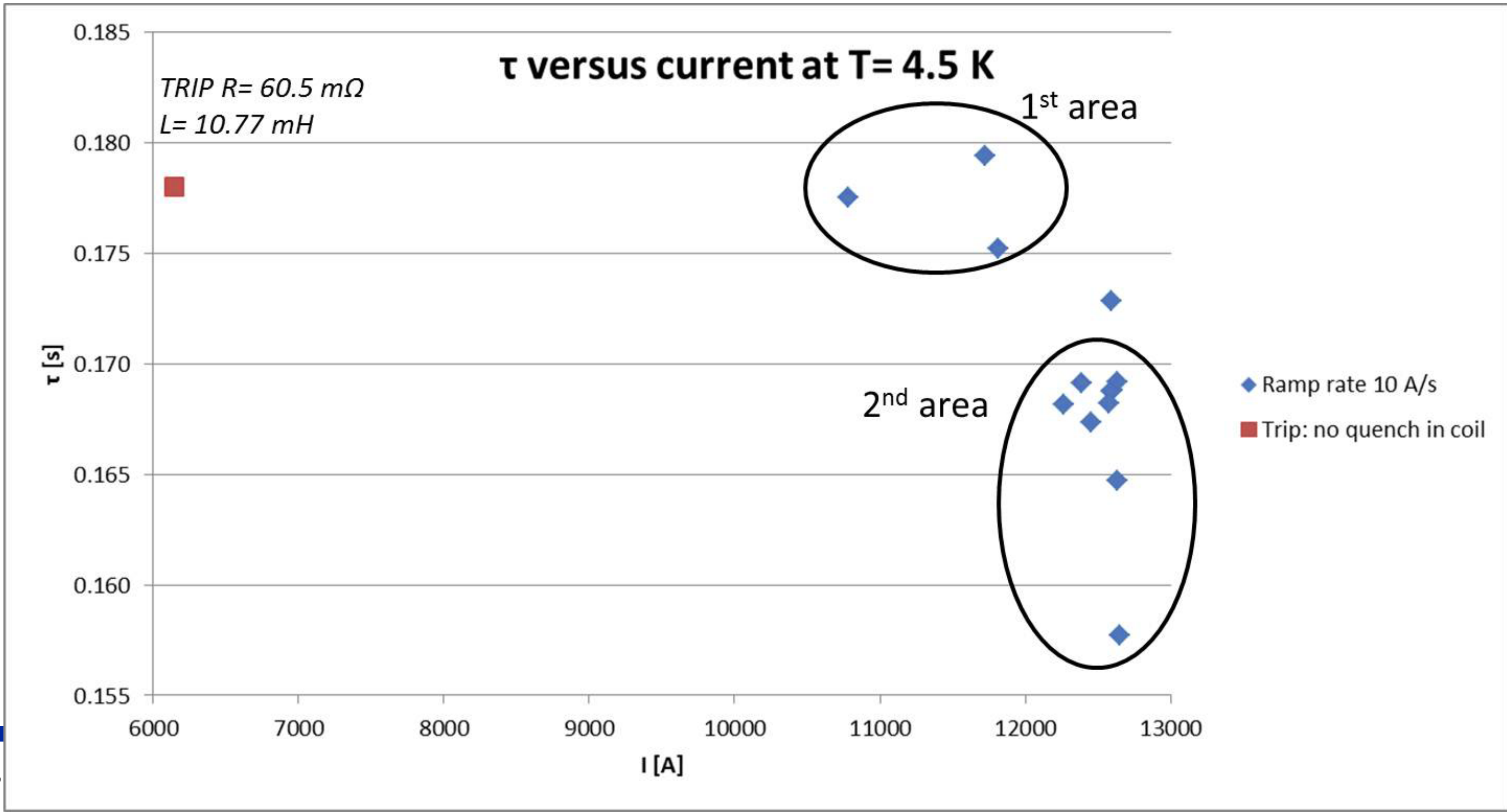
“Quench-back” at High Current?

Time constant at decay start: $\tau = L / R$

At I_q/I_{ssl} > 88% ➔ $\tau_{measured}$ becomes smaller

➔ Quench back?

➔ Multipole quenches due to current redistribution?



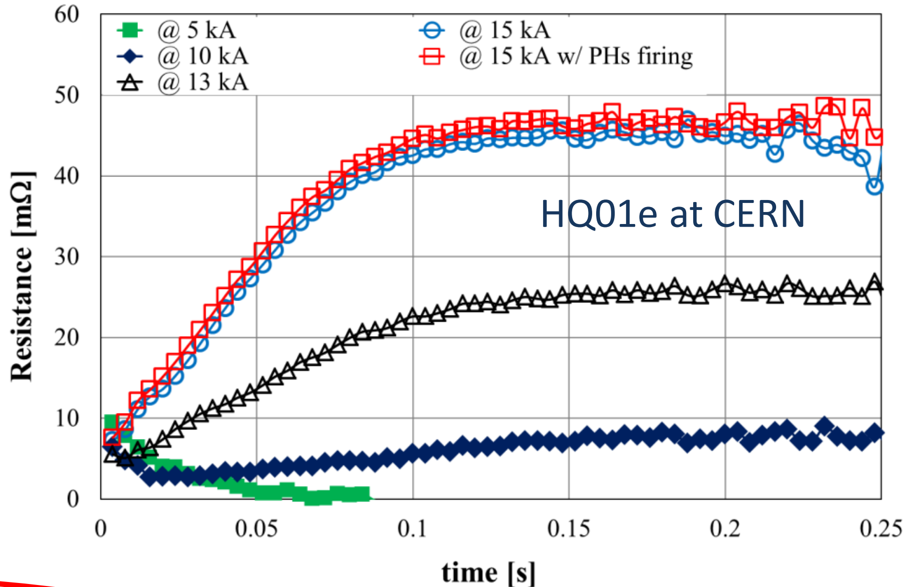
HQ01e – Quench-Back

- Magnet sitting at a constant current: from 5 to 13 kA – (NO quench)
- Discharge in the 40 mΩ dump resistor without PH

- Does the magnet quench from eddy current generation in the cable (form of quench-back)?
- From the current decay:

$$I(t) = I_0 e^{\frac{-R\,t}{L}}$$

$$R_{mag}(t) = -L\frac{d}{dt}\ln\left(\frac{I(t)}{I0}\right) - R_{dump}$$



H. Bajas et al., "Test Results of the LARP HQ01 Nb_3Sn quadrupole magnet at 1.9 K", presented at ASC2012

- At 5 and 10 kA: no sign of quench
- A 13 kA: signs of quench
- At 15 kA: fraction of the magnet is quenching
- Last 15 kA test with PH: no clear impact

Conclusions

- These features may help the protection, but should be well understood:
  - Above what I_q/I_{ssl} do they have a significant effect?
  - Effect of cored cable?

- Note: maybe a “dump resistor” may help to trigger them even if the energy extracted is no so significant…

- Generally speaking: do validation of QP codes with real data!

LQ Coils after Test

LARP

Delamination on Inner layer

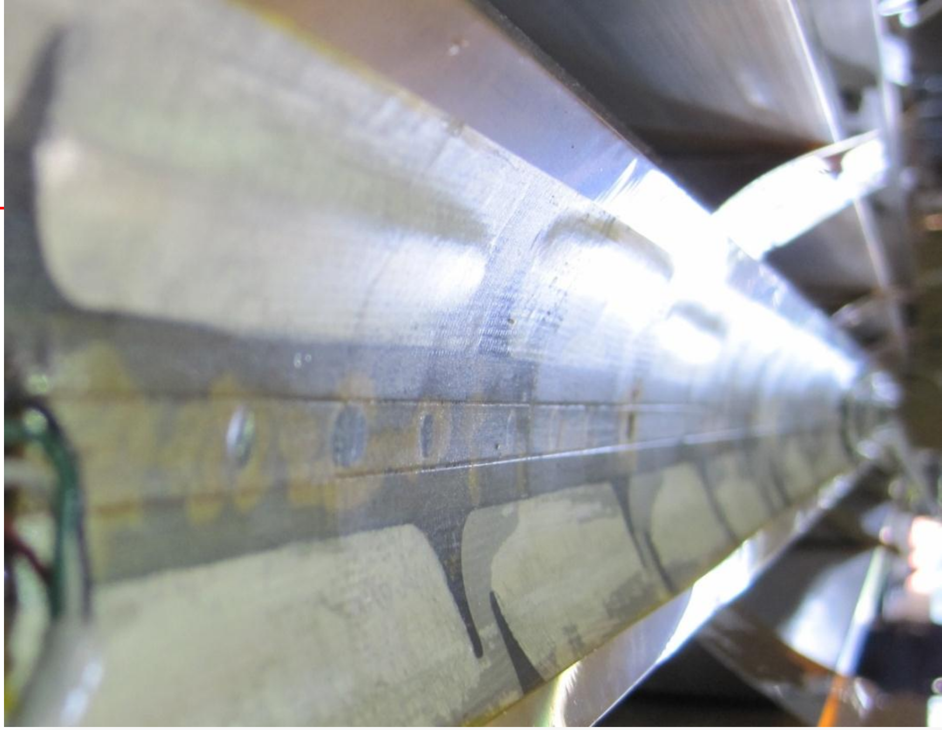
Heater – coil

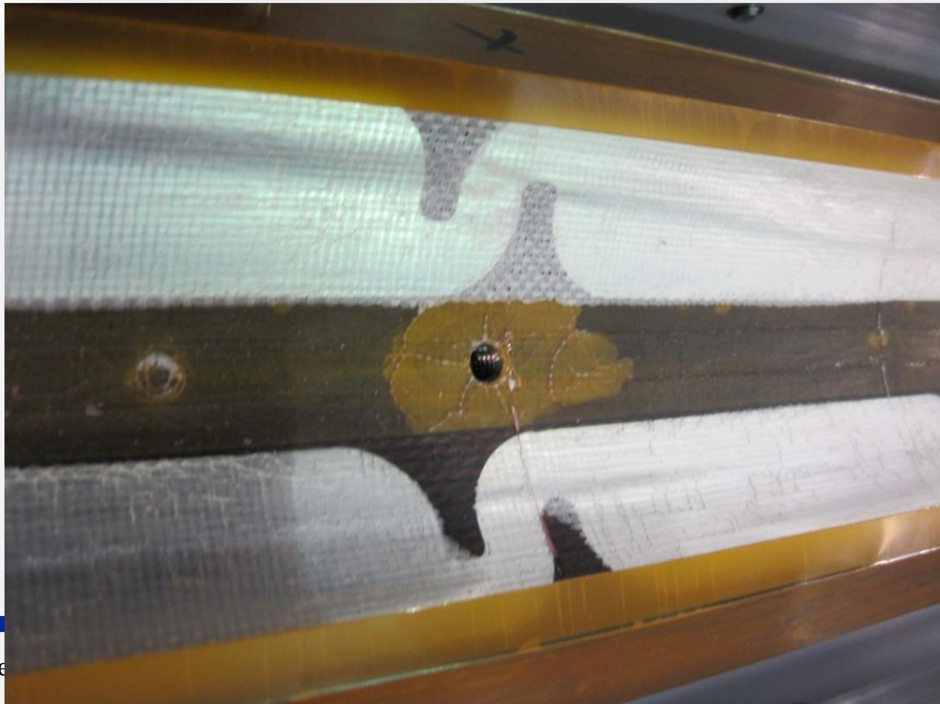
Insulation – heater

Insulation – coil

Also one heater-coil short

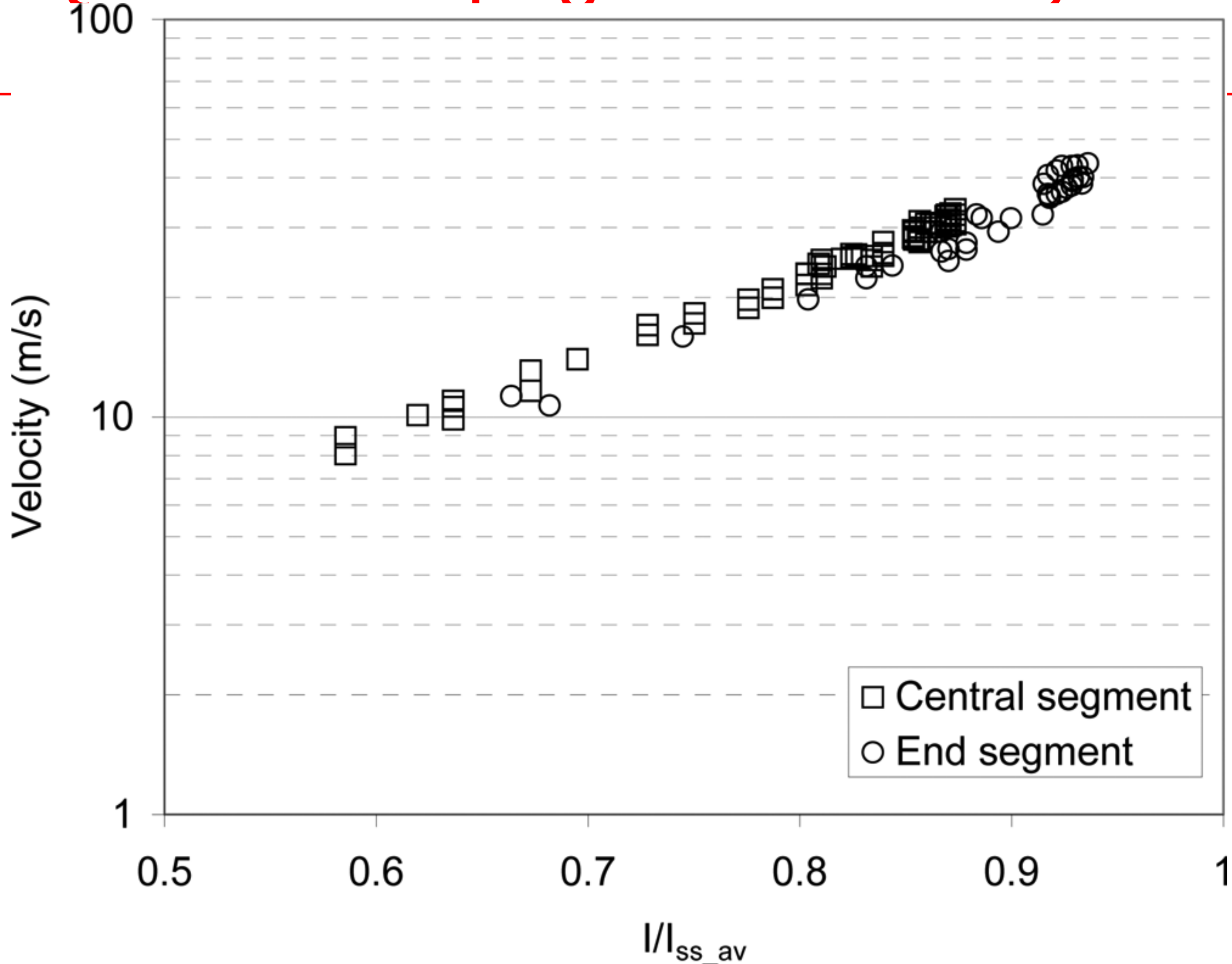
- Possible causes:
  - Superfluid helium + quench
    - Seen in TQ coils
  - Heat from heaters on ID
    - Not done in TQ coils
- Options:
  - Strengthen insulation
    - Not good for cooling
  - Change heater location
    - Best solution





Quench Propagation Velocity

Measurements at 4.3 K



IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 17, NO. 2, JUNE 2007

Assembly and Tests of SQ02, a Nb3Sn Racetrack Quadrupole Magnet for LARP

P. Ferracin, G. Ambrosio, E. Barzi, S. Caspi, D. R. Dietderich, S. Feher, S. A. Gourlay, A. R. Hafalia, C. R. Hannaford, J. Lizarazo, A. F. Lietzke, A. D. McInturff, G. L. Sabbi, and A. V. Zlobin

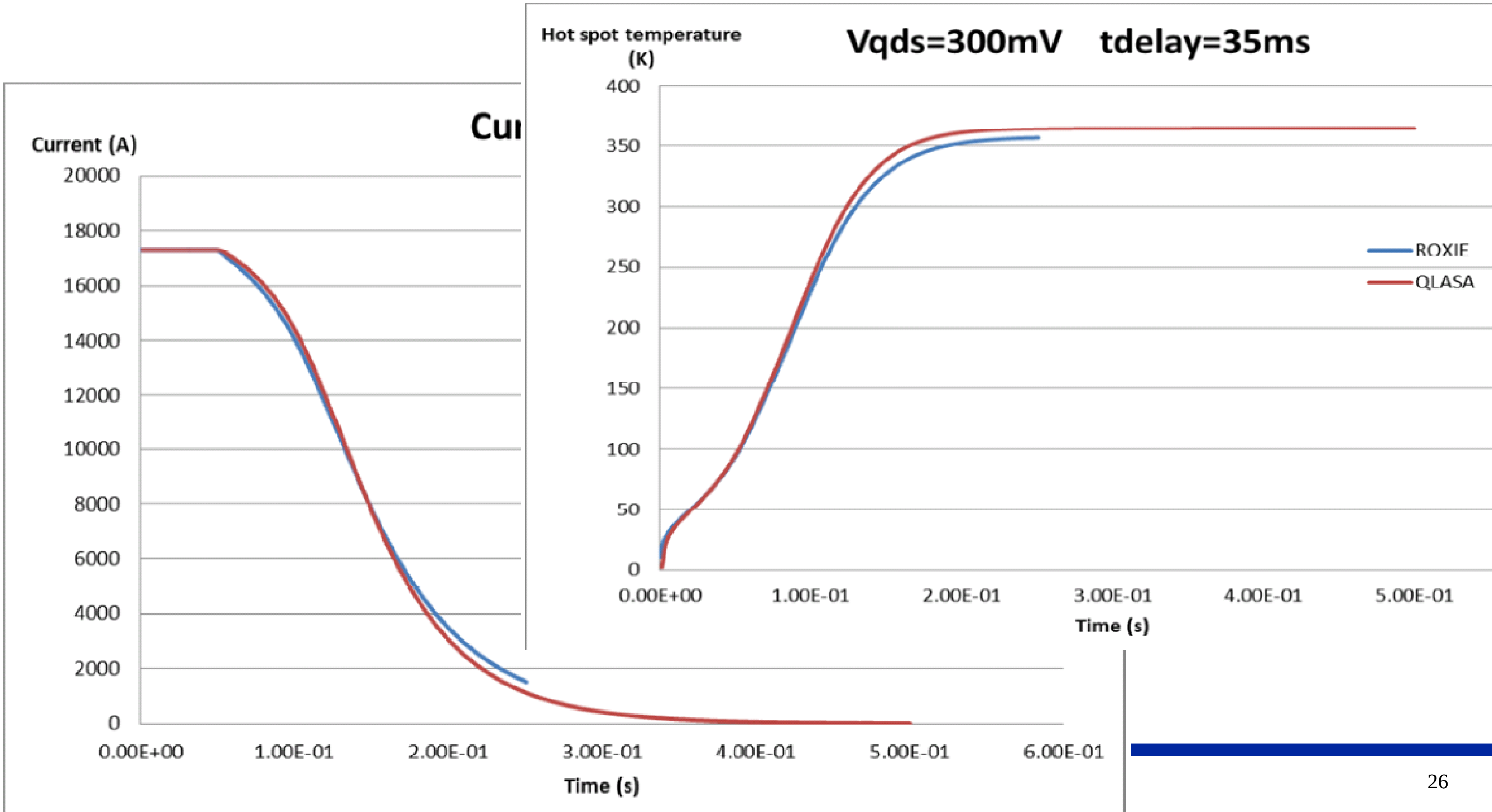
LARP

QXF PROTECTION
(preliminary results)

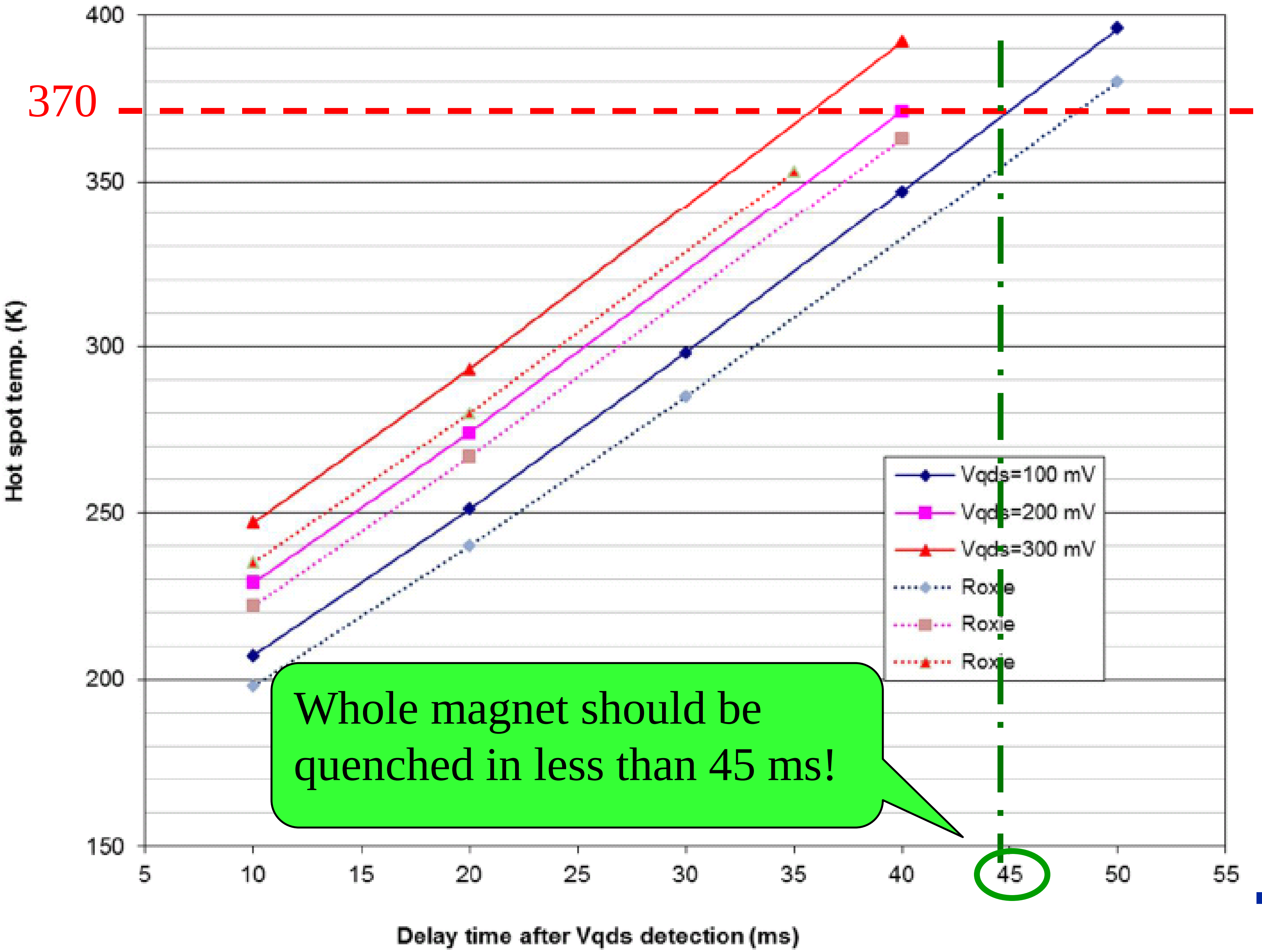
By Massimo Sorbi, Giulio Manfreda, Vittorio Marinozzi

ROXIE – QLASA Comparison

Comparison btw QLASA and ROXIE using same material properties (MATPRO library) and assumptions:



Hot Spot Temperature vs. Delay Time



Can we achieve this delay time with heaters only on outer layer?

LARP

	IL	OL
• Delay time after detection =		
▪ Validation time +	8	8
▪ Switch time +	2	2
▪ Heater-coil diffusion time +	15	15
▪ Longitudinal propagation btw heating stations	5	
• All Outer Layer quenched		
▪ Layer-layer diffusion +		15
▪ Longitudinal propagation		5
• Whole magnet quenched		
In order to have all magnet quenched in 45 ms:	30	45

Preliminary Conclusions

- We should **calibrate ROXIE and QLASA** with experimental results
- We should test Nb_3Sn magnets with **cored cables** at high hot spot temperatures
- **We have to fight for every ms** in the design of MQXF and its protection system

Together we will make it!