MQXF quench protection

E. Ravaioli

with inputs from

GL. Sabbi (LBNL), G. Ambrosio, G. Chlachidze, S. Stoynev (FNAL),

H. Bajas, S. Izquierdo-Bermudez, F. Rodriguez-Mateos, D. Wollmann (CERN),

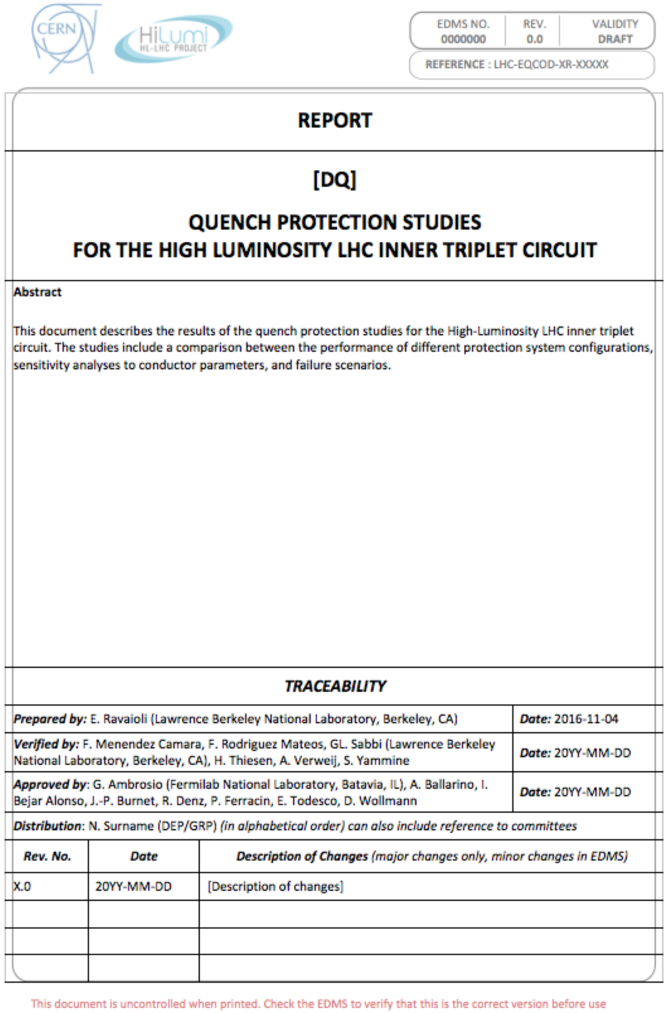
and many other CERN and LARP colleagues

6th HL-LHC Collaboration Meeting

15 November 2016

Outline

- Summary of the MQXF quench protection report
  - Circuit analysis
  - Quench heater configuration
  - CLIQ configuration
  - Effect of strand parameters
  - Worst-case analysis
- MQXFS01 and MQXFS03 quench protection tests
  - Quench heater delays
  - Quench integral studies
  - CLIQ performance
- Conclusions & next steps



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REFERENCE : LHC-EQCOD-XR-XXXXX

REPORT

[DQ]

QUENCH PROTECTION STUDIES
FOR THE HIGH LUMINOSITY LHC INNER TRIPLET CIRCUIT

Abstract

This document describes the results of the quench protection studies for the High-Luminosity LHC inner triplet circuit. The studies include a comparison between the performance of different protection system configurations, sensitivity analyses to conductor parameters, and failure scenarios.

TRACEABILITY

Prepared by: E. Ravaioli (Lawrence Berkeley National Laboratory, Berkeley, CA)	***Date:*** 2016-11-04
Verified by: F. Menendez Camara, F. Rodriguez Mateos, GL. Sabbi (Lawrence Berkeley National Laboratory, Berkeley, CA), H. Thiesen, A. Verweij, S. Yammine	***Date:*** 20YY-MM-DD
Approved by: G. Ambrosio (Fermilab National Laboratory, Batavia, IL), A. Ballarino, I. Bejar Alonso, J.-P. Burnet, R. Denz, P. Ferracin, E. Todesco, D. Wollmann	***Date:*** 20YY-MM-DD
Distribution: N. Surname (DEP/GRP) *(in alphabetical order) can also include reference to committees*	

Rev. No.	***Date***	***Description of Changes*** *(major changes only, minor changes in EDMS)*
X.0	20YY-MM-DD	[Description of changes]

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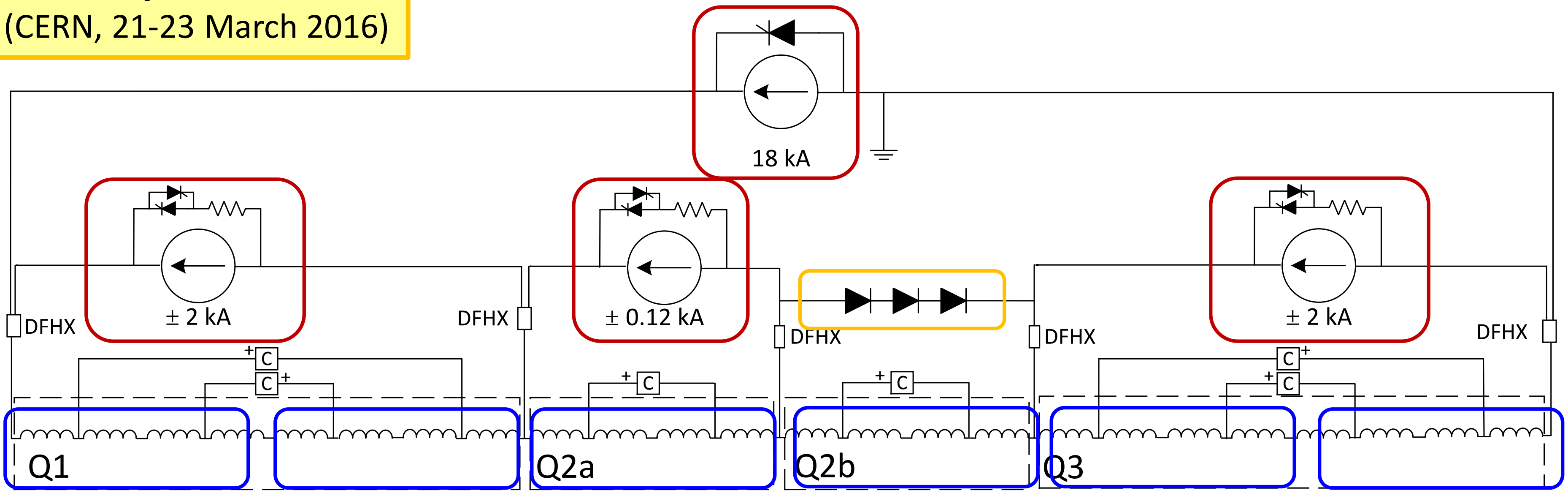
Powering and Quench protection system

Following the
Conceptual Design Review of the Magnet Circuits for the HL-LHC
(CERN, 21-23 March 2016)

<u>POWERING SYSTEM</u>
1 main power supply (2-quadrant)
3 trim power supplies

Parallel Diodes



<u>MAGNETS</u>
4x 4.2 m QXF (LARP)
2x 7.15 m QXF (CERN)

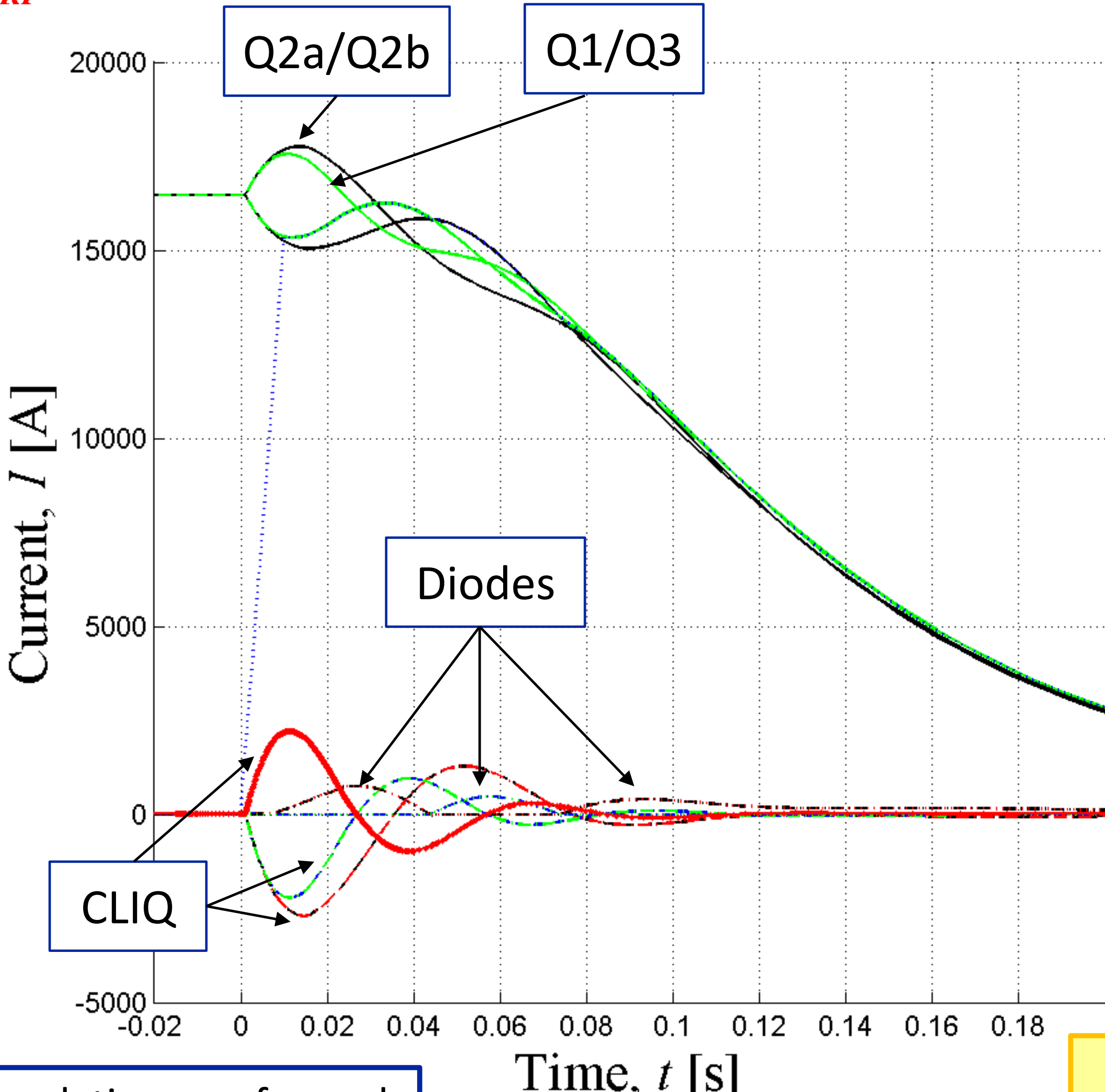
<u>PROTECTION SYSTEM</u>
Quench Heater system + CLIQ system

<u>Present baseline includes</u>
- Quench heaters attached to the outer layer
- Quench heaters attached to the inner layer
- CLIQ

Simulated currents in the circuit

LARP

High Luminosity LHC



Simulations performed with TALES

<u>CLIQ units for Q2a/Q2b</u>
Charging voltage: 1000 V
Capacitance: 40 mF

<u>CLIQ units for Q1/Q3</u>
Charging voltage: 600 V
Capacitance: 40 mF

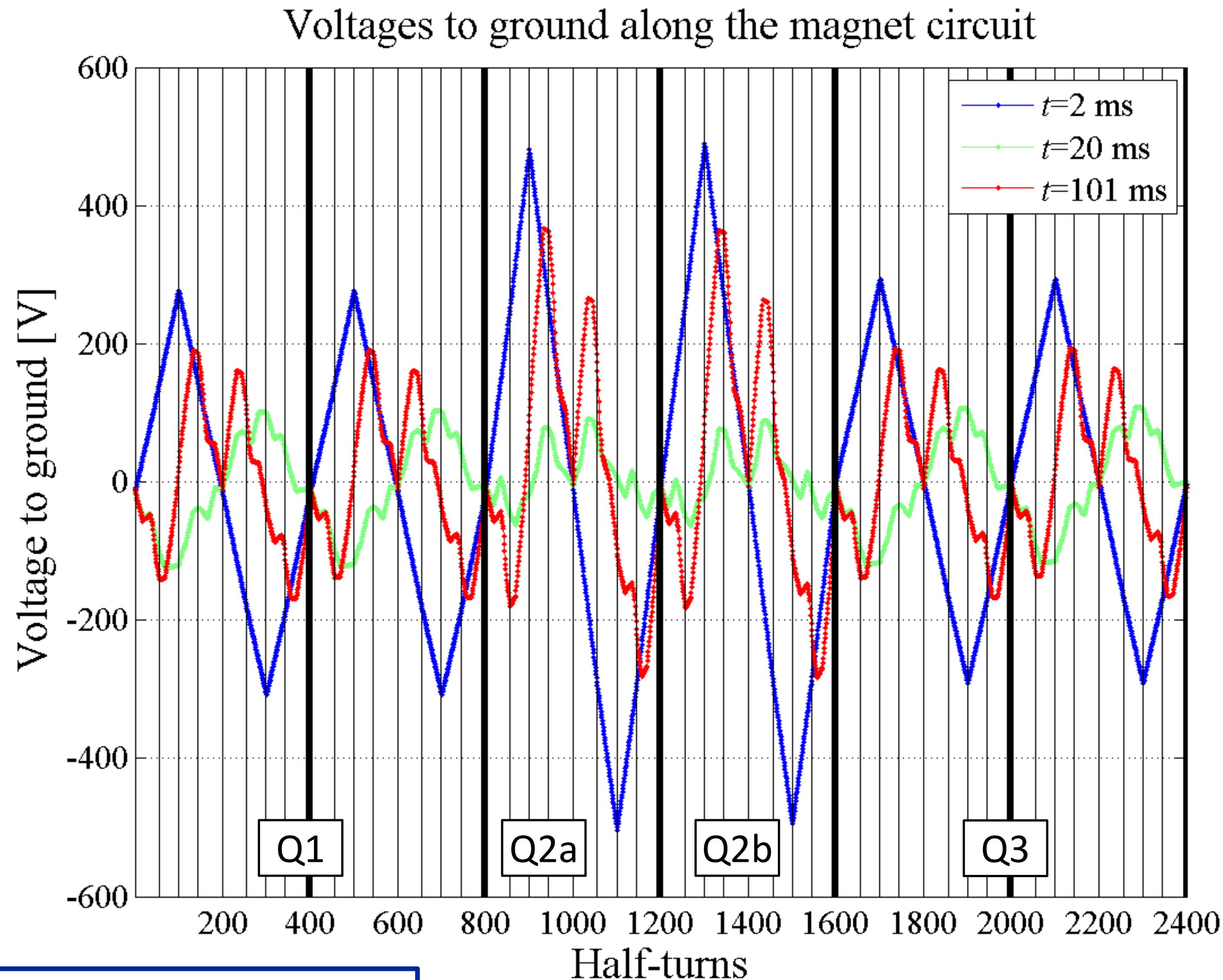
Hot-spot temperature
T_{hot}~230 K

<u>Currents through the SC Link</u> (no fault case)

- Main leads: Magnet current ± AC oscillations, 1.5 kA, 12 Hz
- Trim leads: Their initial current + AC pulse, 500 A, 12 Hz

More simulations in talks by F. Rodriguez Mateos and H. Thiesen

Simulated voltages to ground



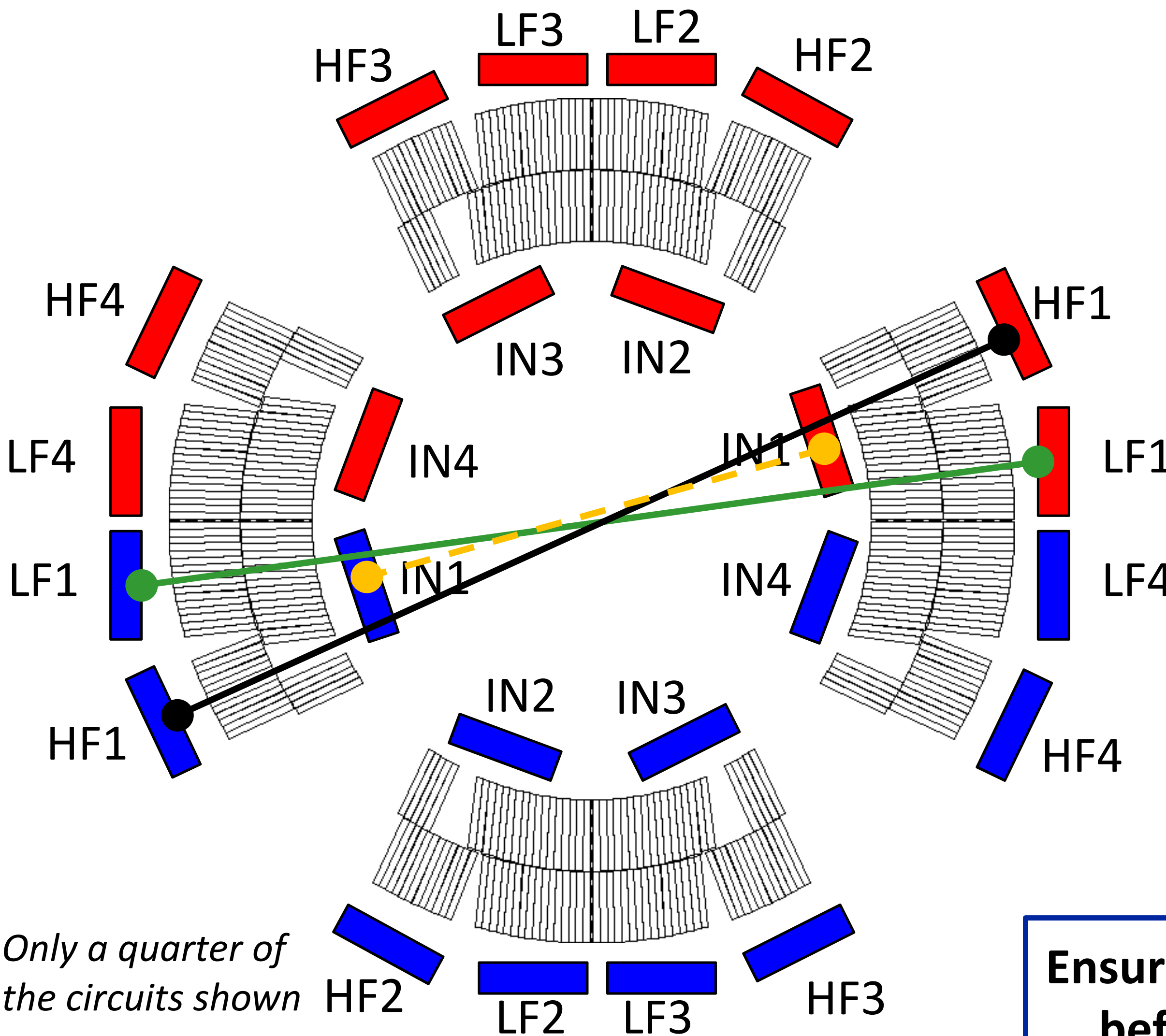
Voltages to ground and between coil sections in Q1/Q3 are 40% lower than Q2a/Q2b

Simulations performed with TALES

QH connection scheme

Each QH supply is connected to 2 strips in series

Connection scheme that compensates the voltages induced by CLIQ and QH



Only a quarter of the circuits shown

<u>Standard LHC quench heater power supply</u>

Charging voltage: 900 V

Voltage to ground: ±450 V

Capacitance: 7.05 mF

Note: 2x 450 V, 14.1 mF modules in series

<u>O-QH</u>

Peak power density: 213 W/cm^2

Peak energy density: 3.42 J/cm^2

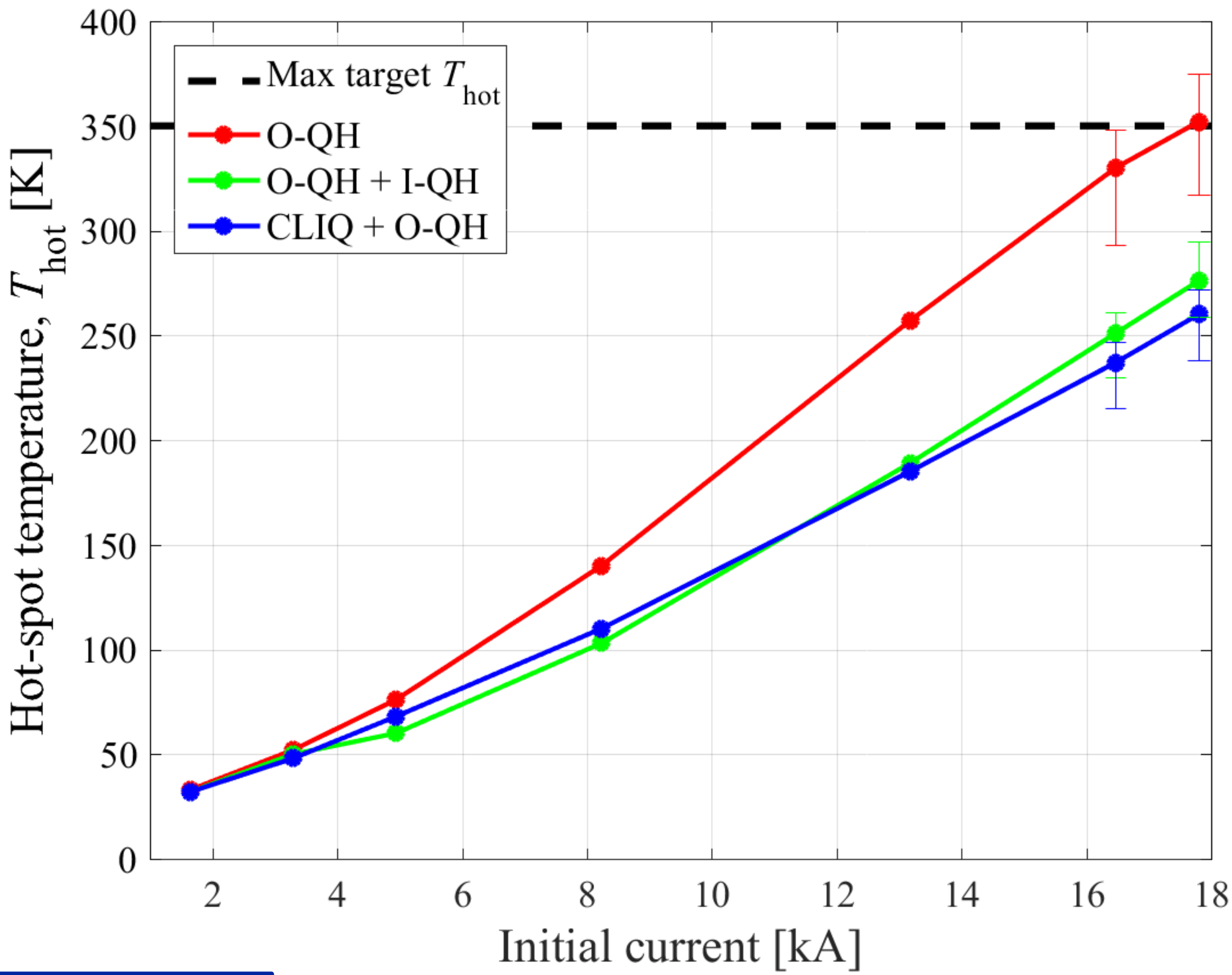
<u>I-QH</u>

Peak power density: 98 W/cm^2

Peak energy density: 2.32 J/cm^2

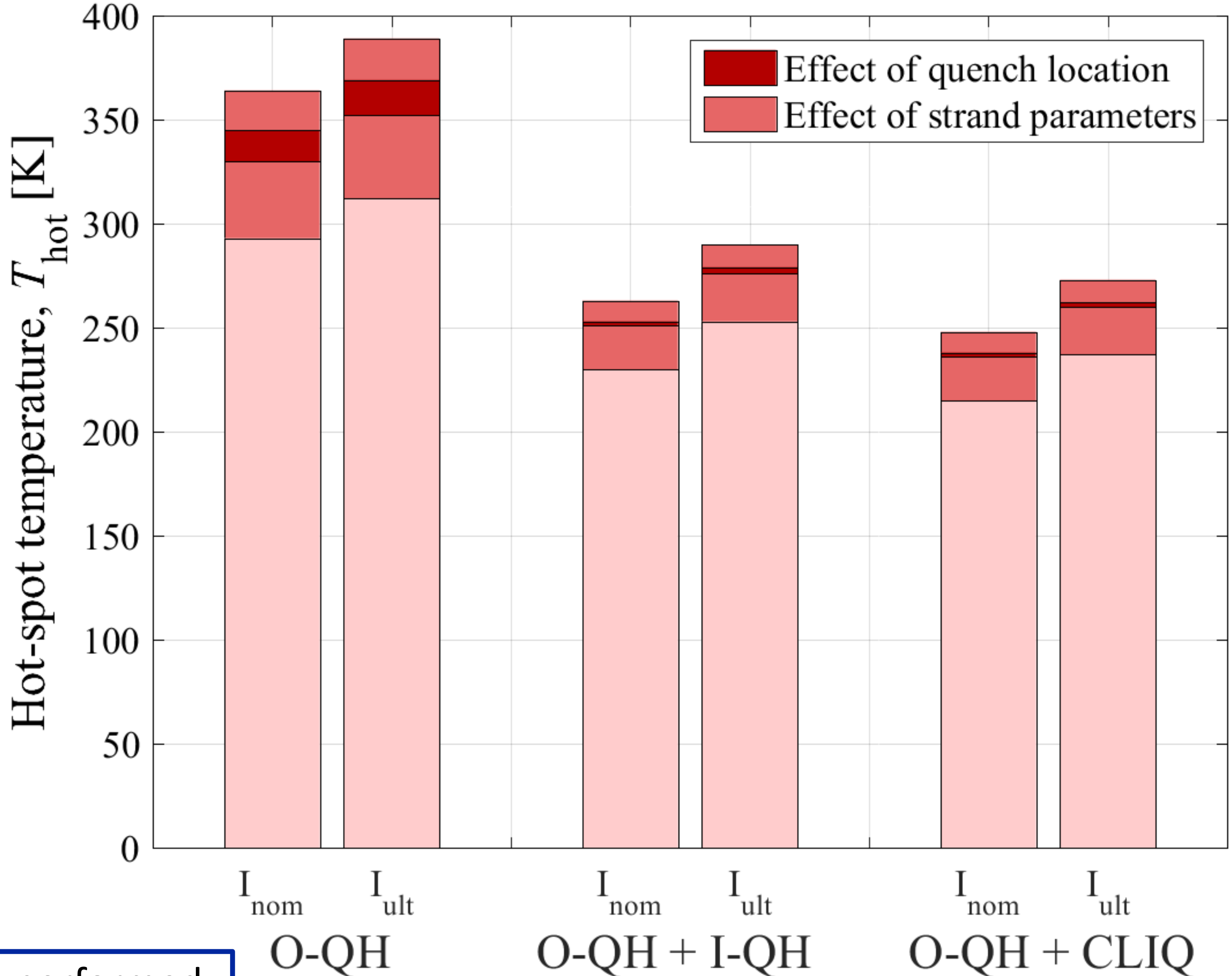
Ensure that beams are dumped before quench heater fire!

Options for the quench protection



Simulations performed with LEDET

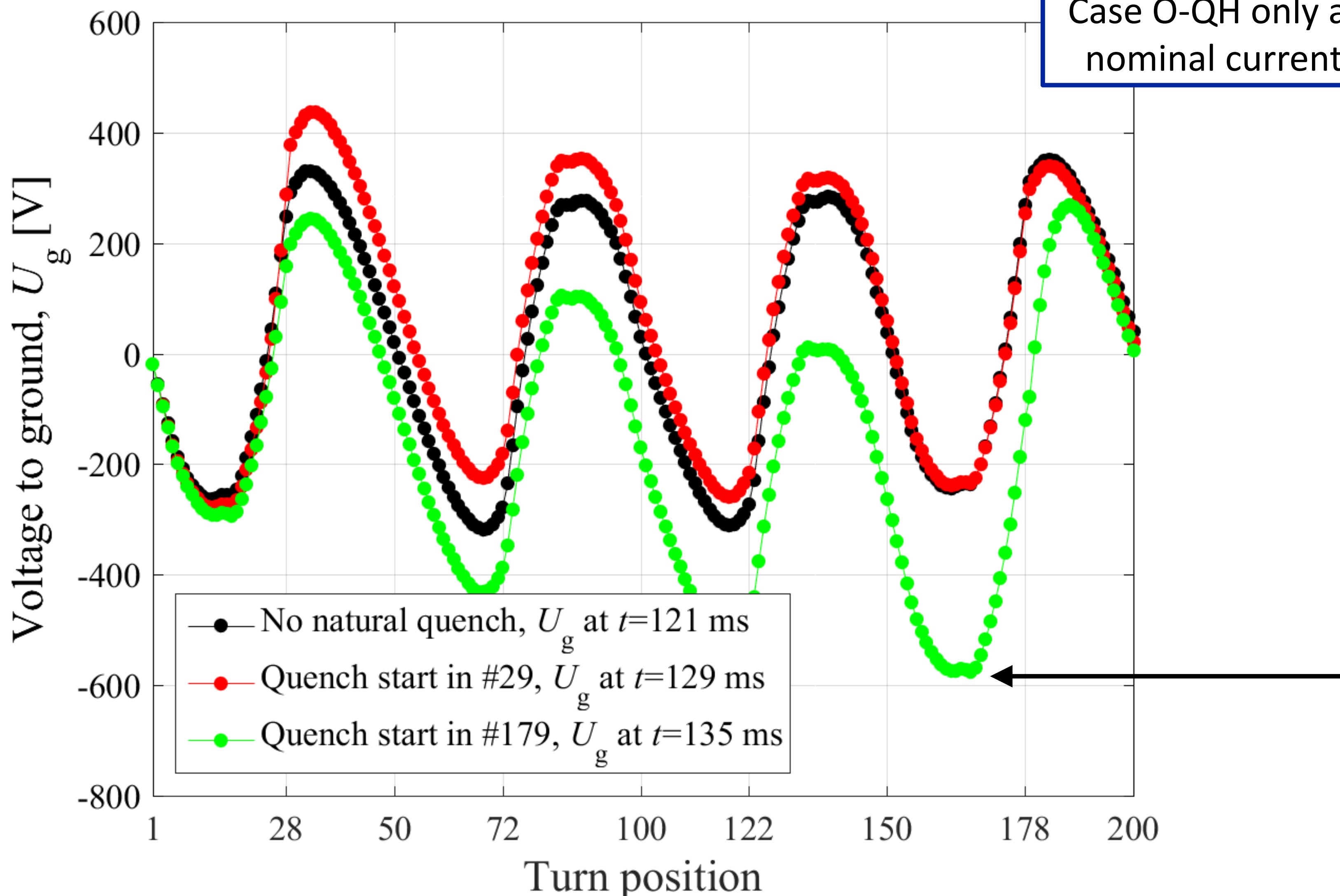
Effect of strand parameters and quench location



Simulations performed with LEDET

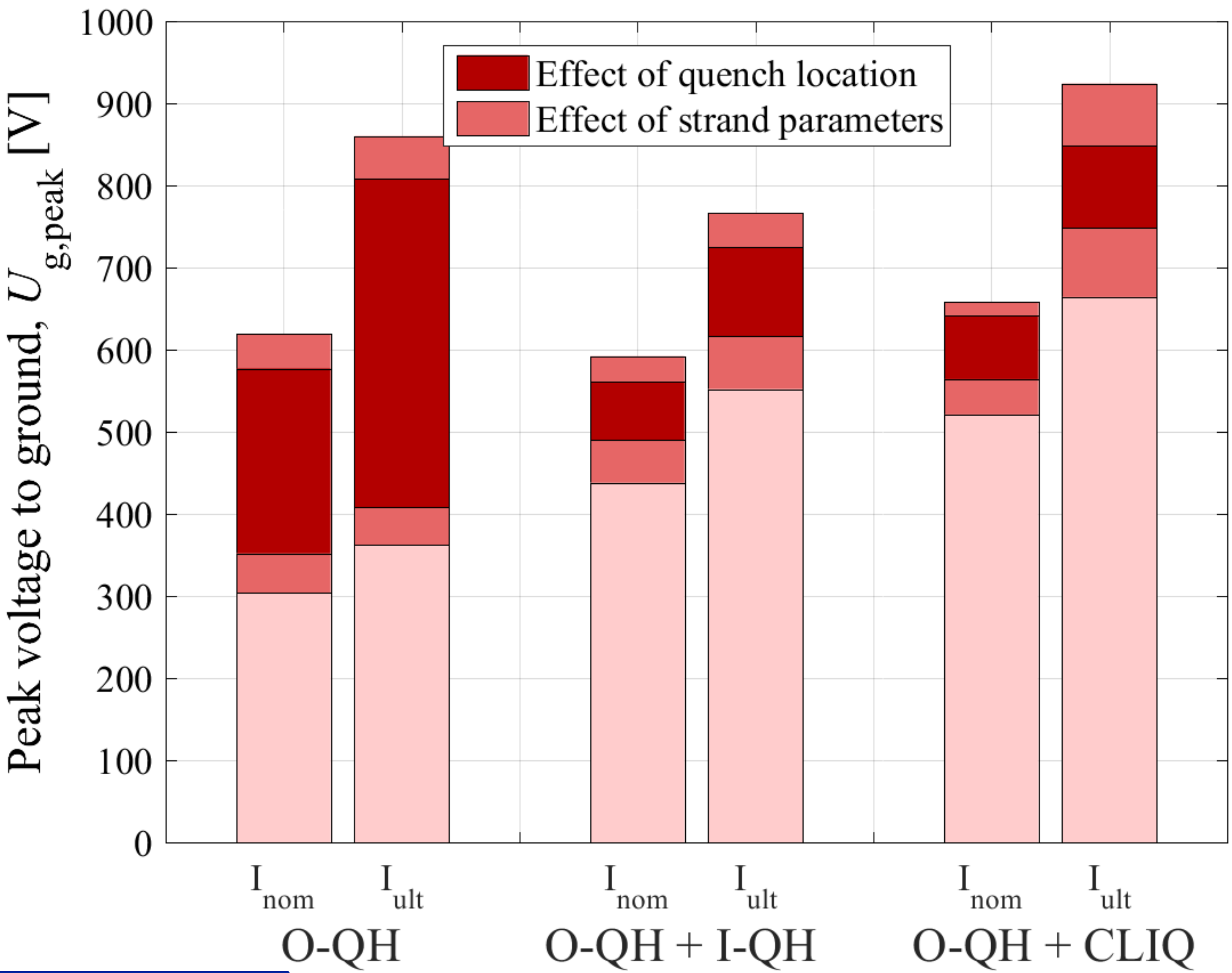
Simulated voltages to ground

Case O-QH only at nominal current



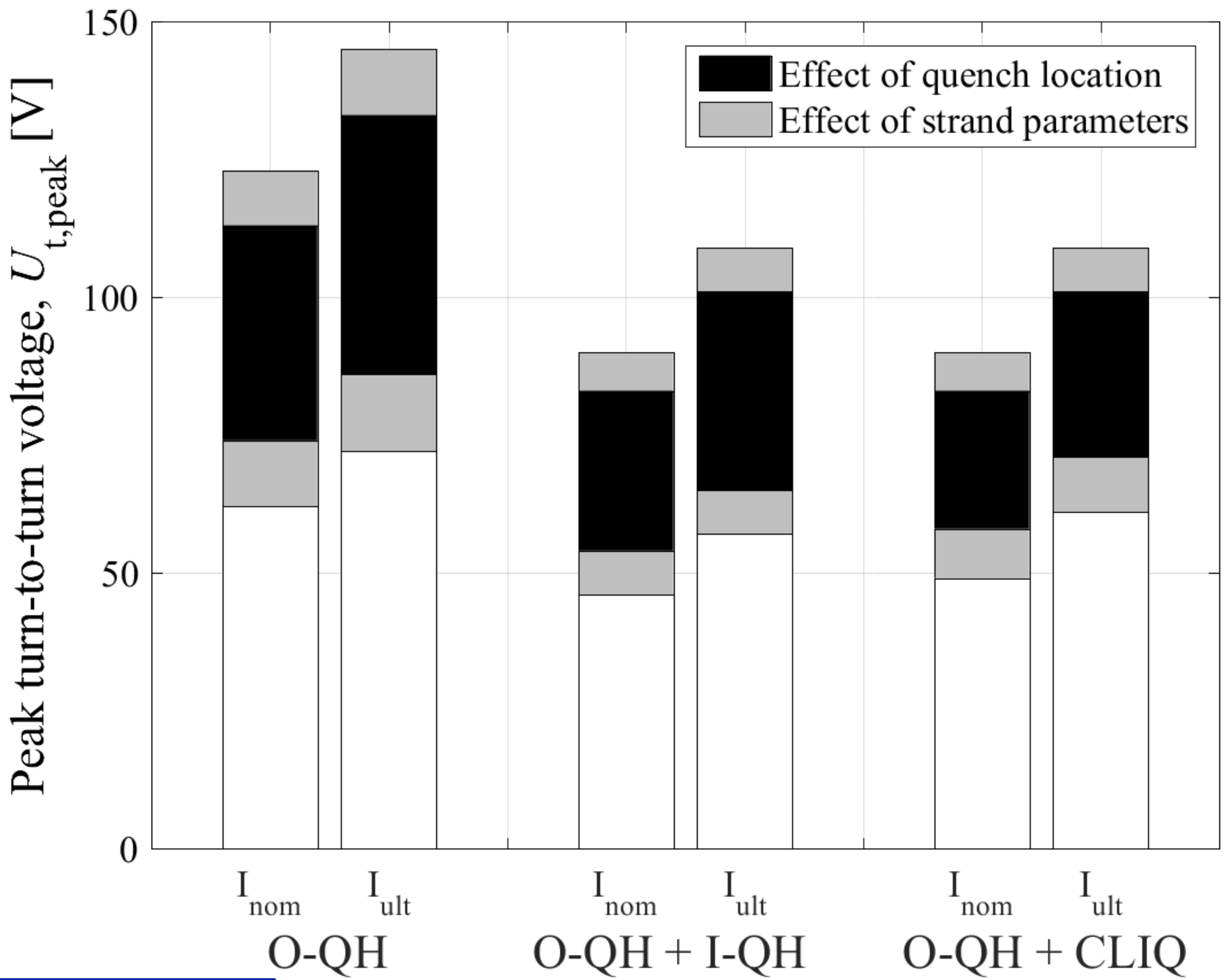
Simulations performed with LEDET

Simulated voltages to ground



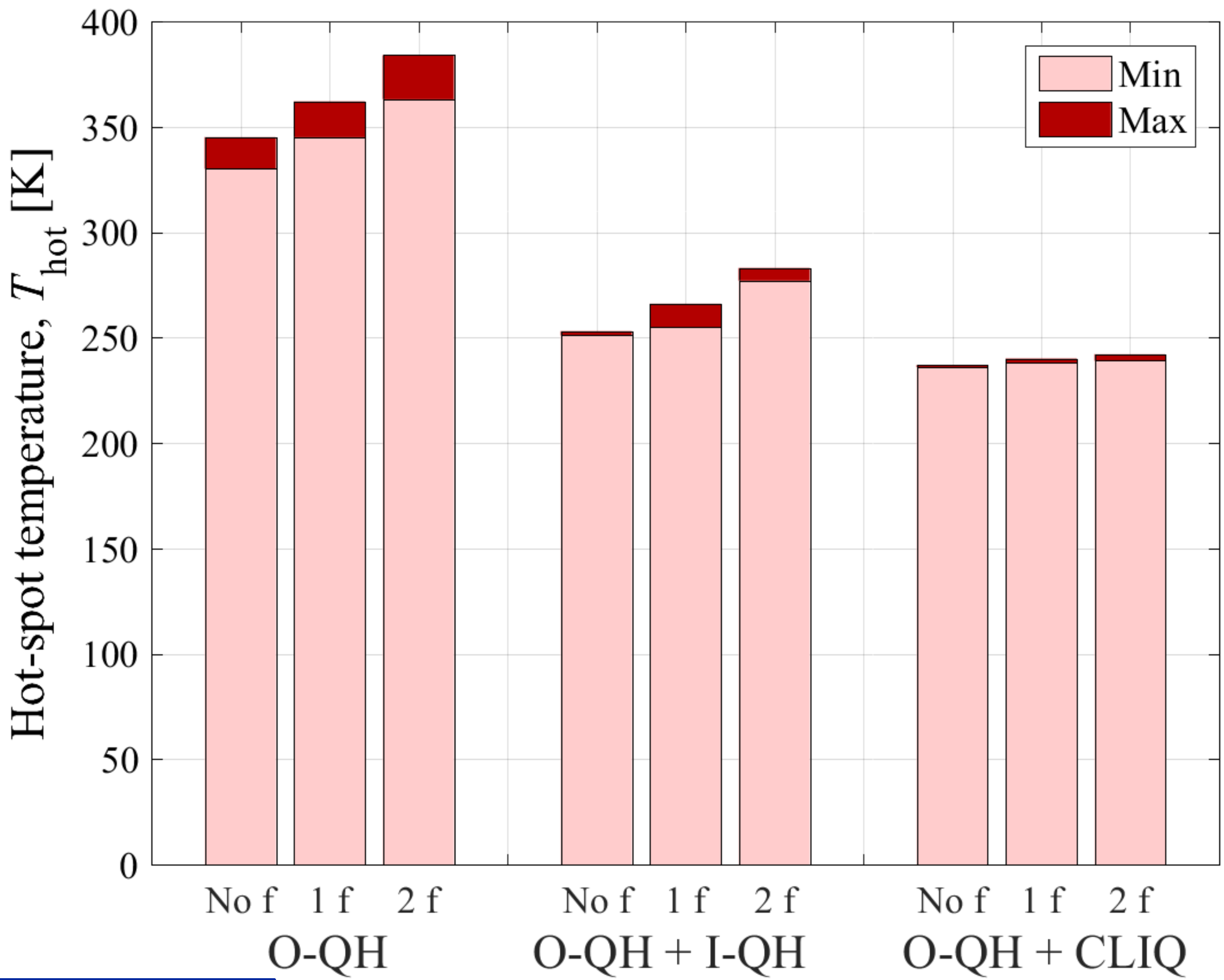
Simulations performed with LEDET

Simulated turn-to-turn voltages



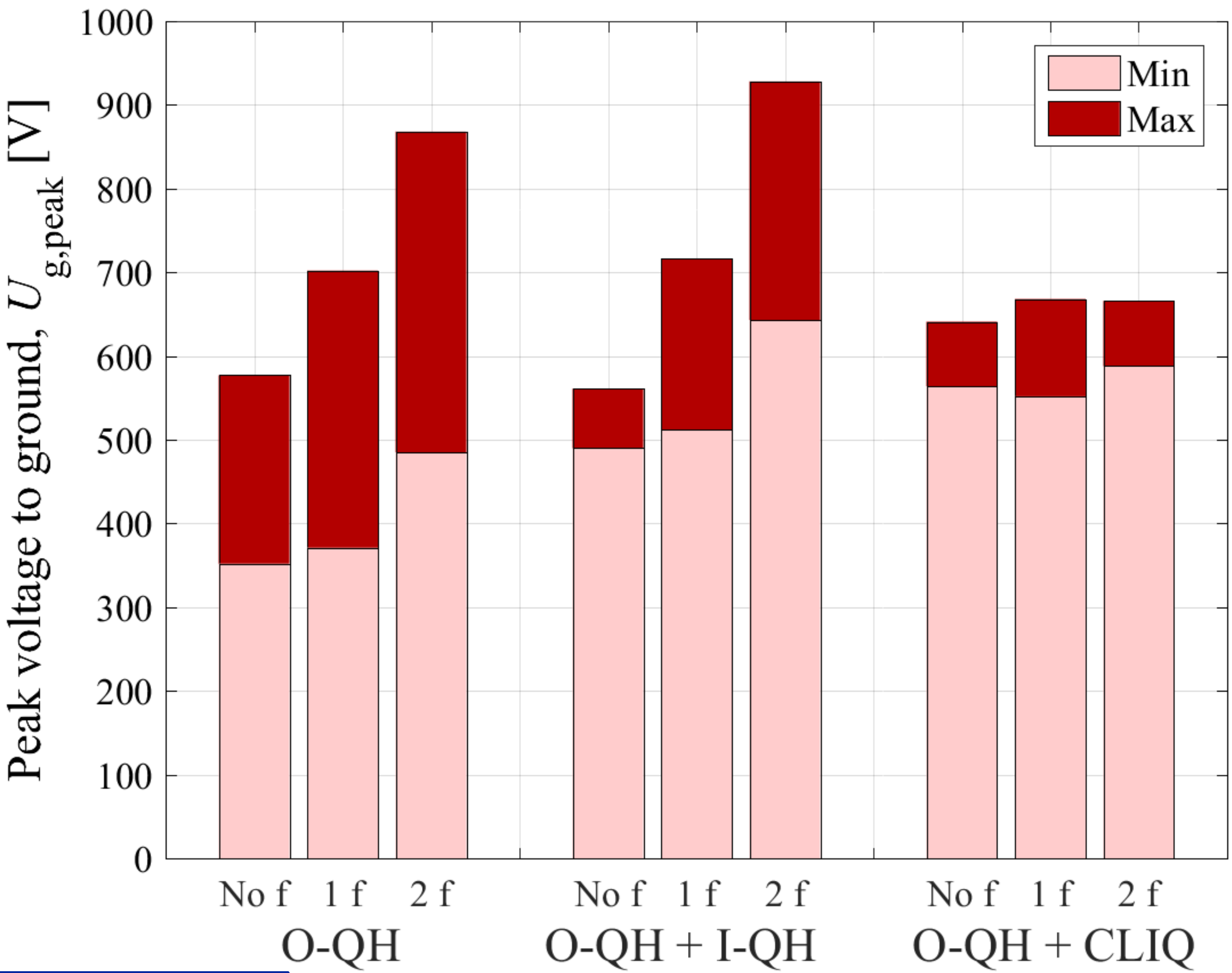
Simulations performed with LEDET, preliminary

Effect of QH strip failures – Hot-spot T



Simulations performed with LEDET

Effect of QH strip failures – U to ground



Simulations performed with LEDET

Revision of the worst-case peak U_{ground}

Guidelines followed to define the reference worst-case peak voltages to ground

- Values at nominal current (not at ultimate current) are chosen
- Worst-case failure includes 2 QH circuit failing simultaneously
- Influence of strand parameters studied, but corrective measures can be taken to avoid reaching the worst conditions. Hence, the reference values will not consider the influence of strand parameters.

Following these guidelines, the voltage to ground reference values are:

- O-QH: 868 V
- O-QH+I-QH: 928 V
- O-QH+CLIQ: 667 V

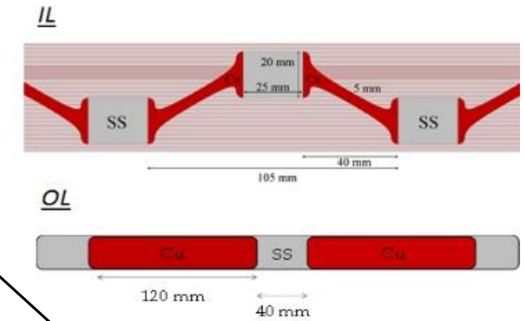
The previous reference value was 520 V, calculated in the case of O-QH+CLIQ.
The increase with respect to this value comes from the improvement in the model accuracy and from the detailed analysis of the effect of the initial hot-spot position.

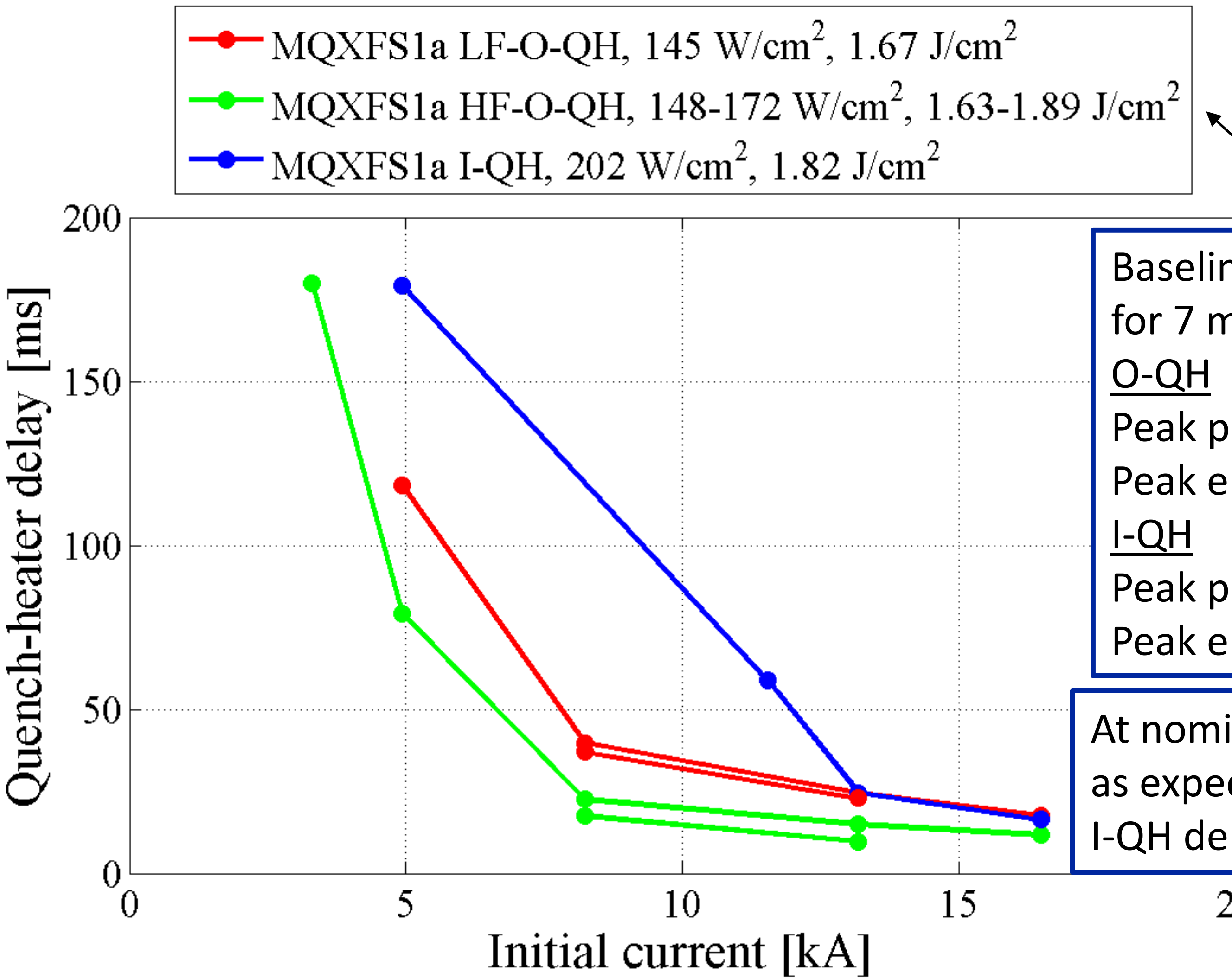
However, it is recommended that no correction of the test values during electrical quality be asked, considering that prudent safety margins were applied ($2xU_{ground,peak}$ +500 V).

Outline

- Summary of the MQXF quench protection report
  - Circuit analysis
  - Quench heater configuration
  - CLIQ configuration
  - Effect of strand parameters
  - Worst-case analysis
- MQXFS01 and MQXFS03 quench protection tests
  - Quench heater delays
  - CLIQ performance
  - Quench integral studies
- Conclusions & next steps

Quench heater delays – MQXFS1a





Baseline parameters for 7 m long MQXF magnet

<u>O-QH</u>

Peak power density: 213 W/cm²

Peak energy density: 3.42 J/cm²

<u>I-QH</u>

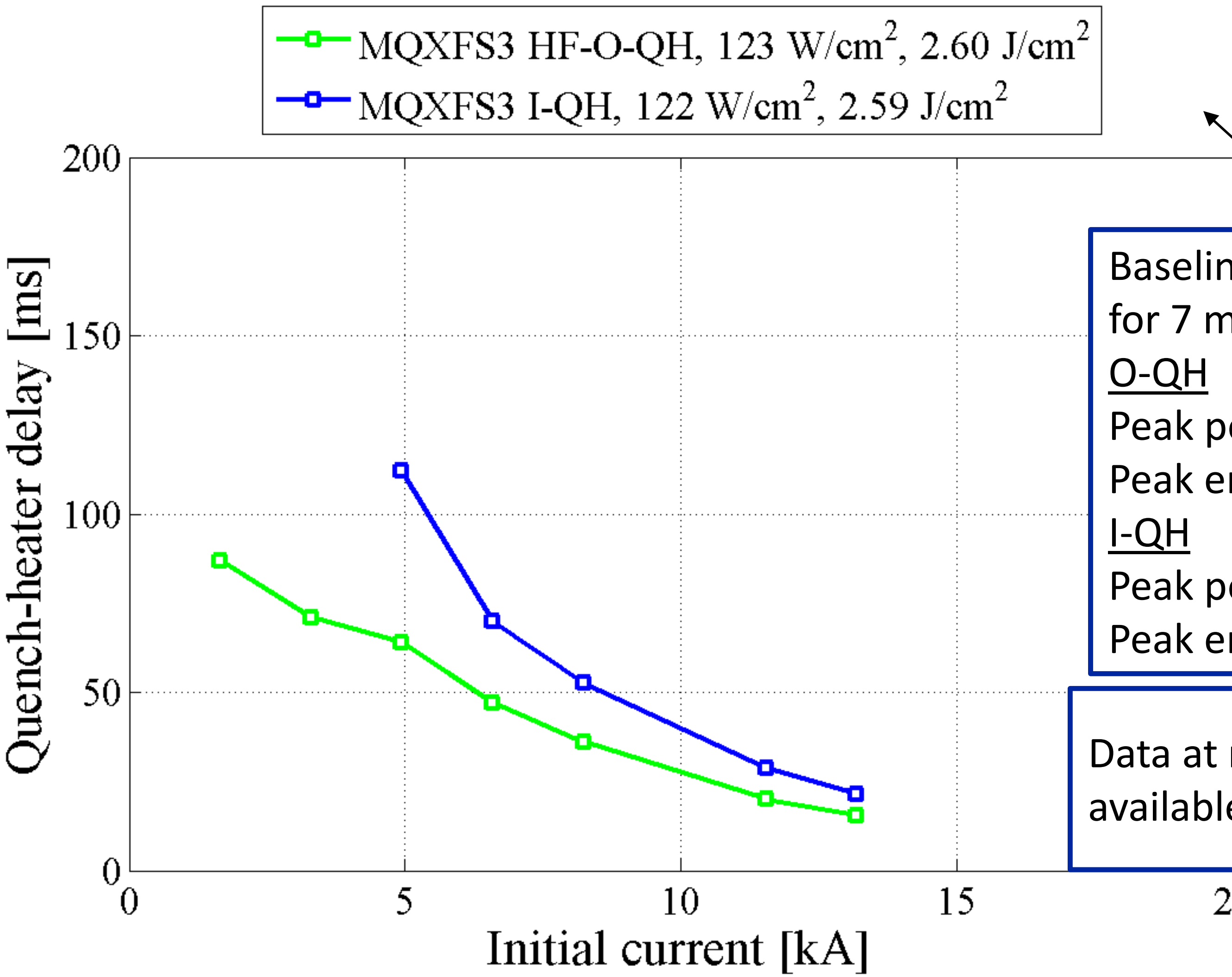
Peak power density: 98 W/cm²

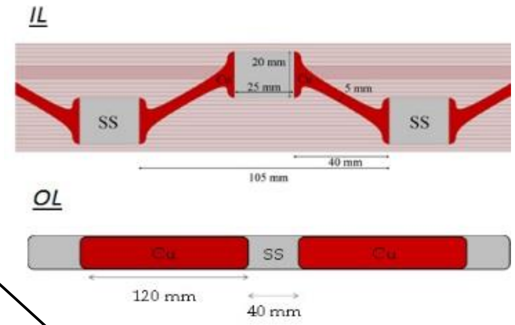
Peak energy density: 2.32 J/cm²

At nominal current, O-QH delays as expected from simulations, I-QH delays longer than expected

G. Chlachidze, S. Stoynev (FNAL)

Quench heater delays – MQXFS3a





Baseline parameters
for 7 m long MQXF magnet

<u>O-QH</u>

Peak power density: 213 W/cm²

Peak energy density: 3.42 J/cm²

<u>I-QH</u>

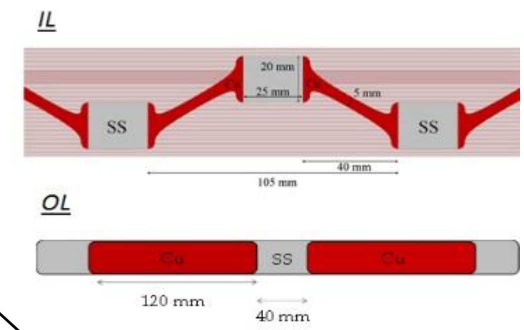
Peak power density: 98 W/cm²

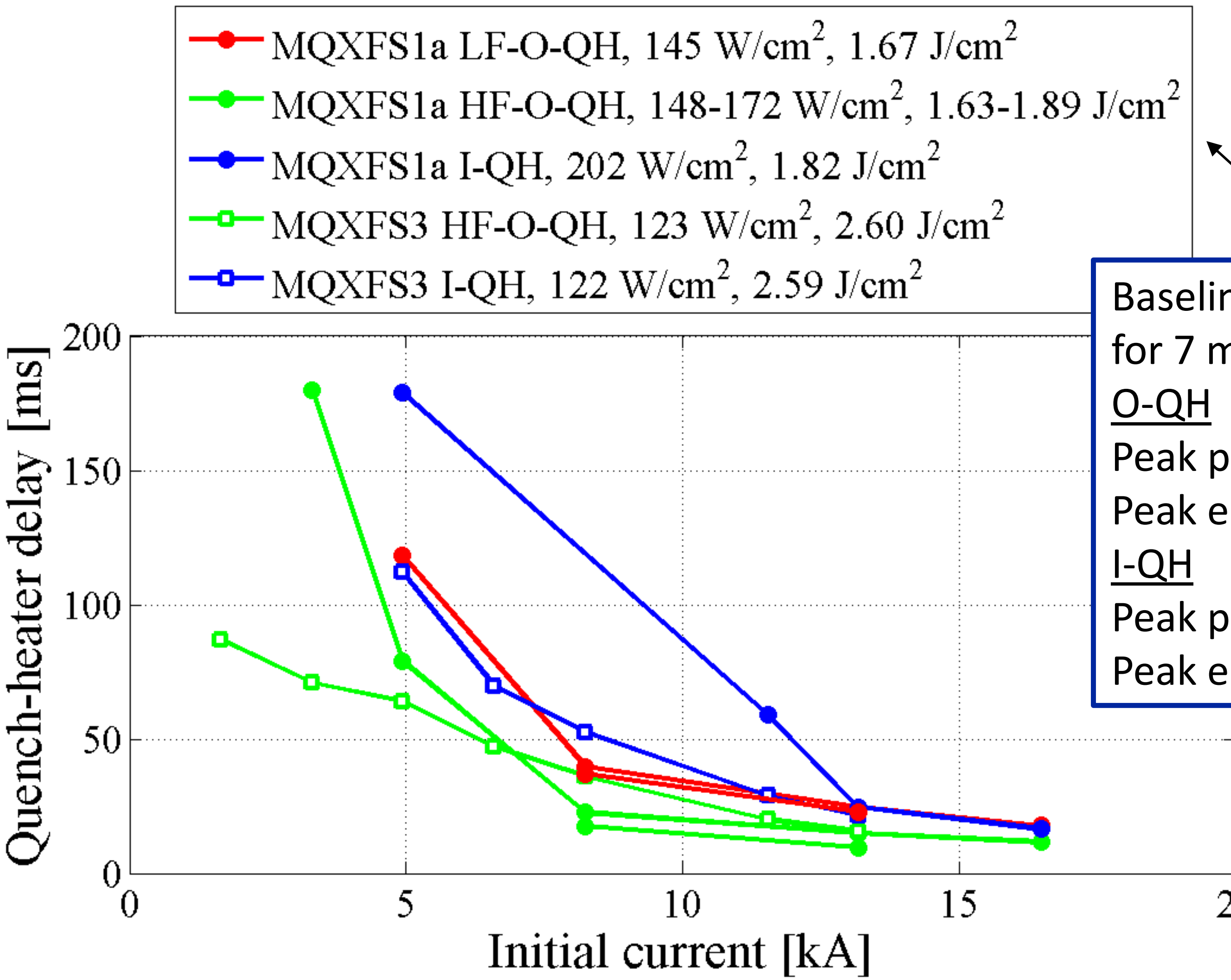
Peak energy density: 2.32 J/cm²

Data at nominal current not available yet (waiting MQXFS3b)

H. Bajas, S. Izquierdo Bermudez (CERN)

QH delays – MQXFS1a cpr MQXFS3a





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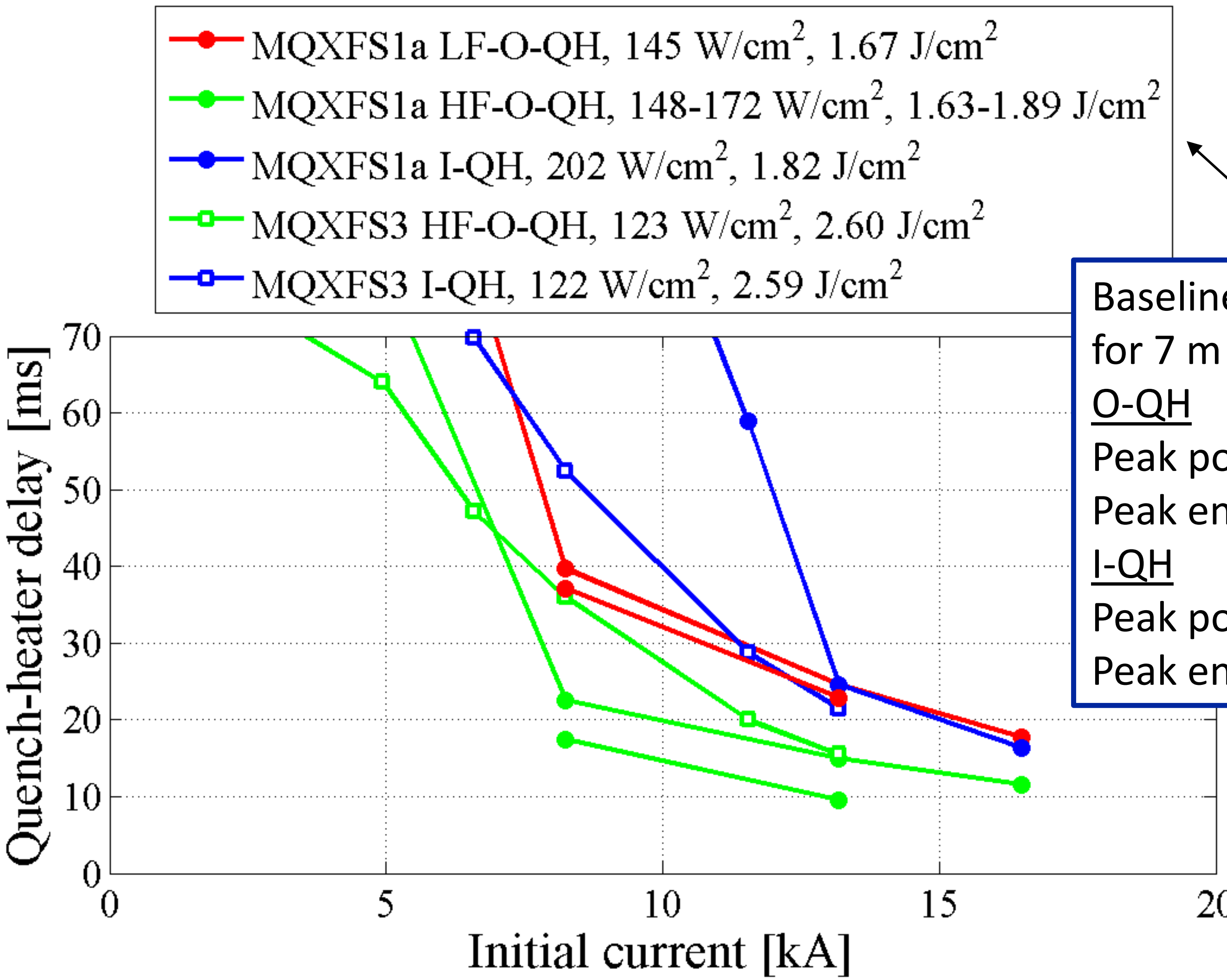
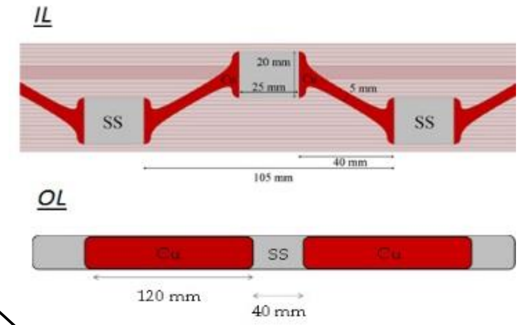
G. Chlachidze, S. Stoynev (FNAL)

H. Bajas, S. Izquierdo Bermudez (CERN)

QH delays – MQXFS1a cpr MQXFS3a

Zoom





Baseline parameters
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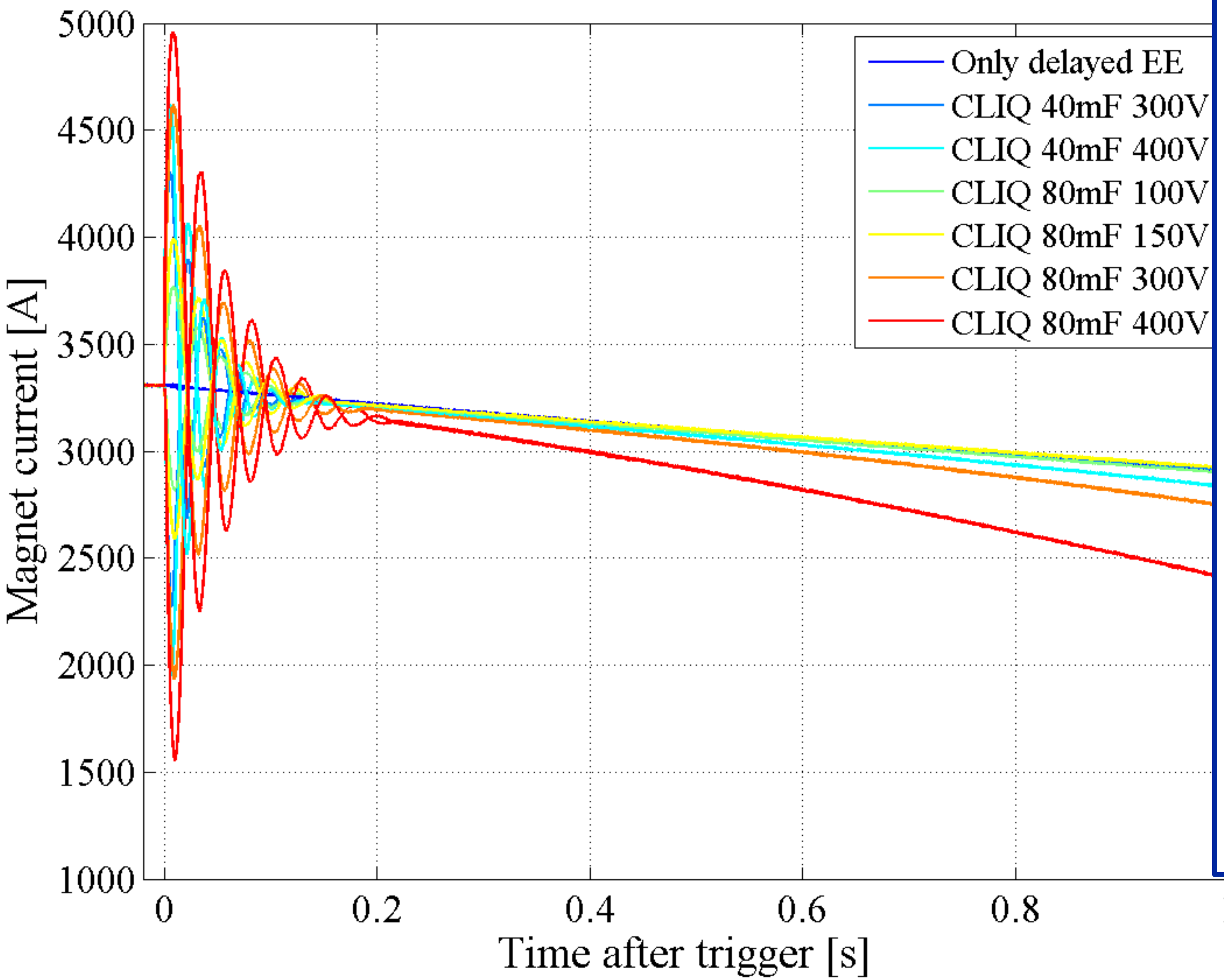
G. Chlachidze, S. Stoynev (FNAL)

H. Bajas, S. Izquierdo Bermudez (CERN)

CLIQ performance – MQXFS1b – 3 kA



Tests at low current triggering only CLIQ (+ delayed EE) to study impact of CLIQ parameters

Capacitance: 40, 80 mF

Charging U: 100-400 V

Wrt 7m MQXF

80mF, 200 V

144% power density

48% energy density

(relevant at high current)

80mF, 300 V

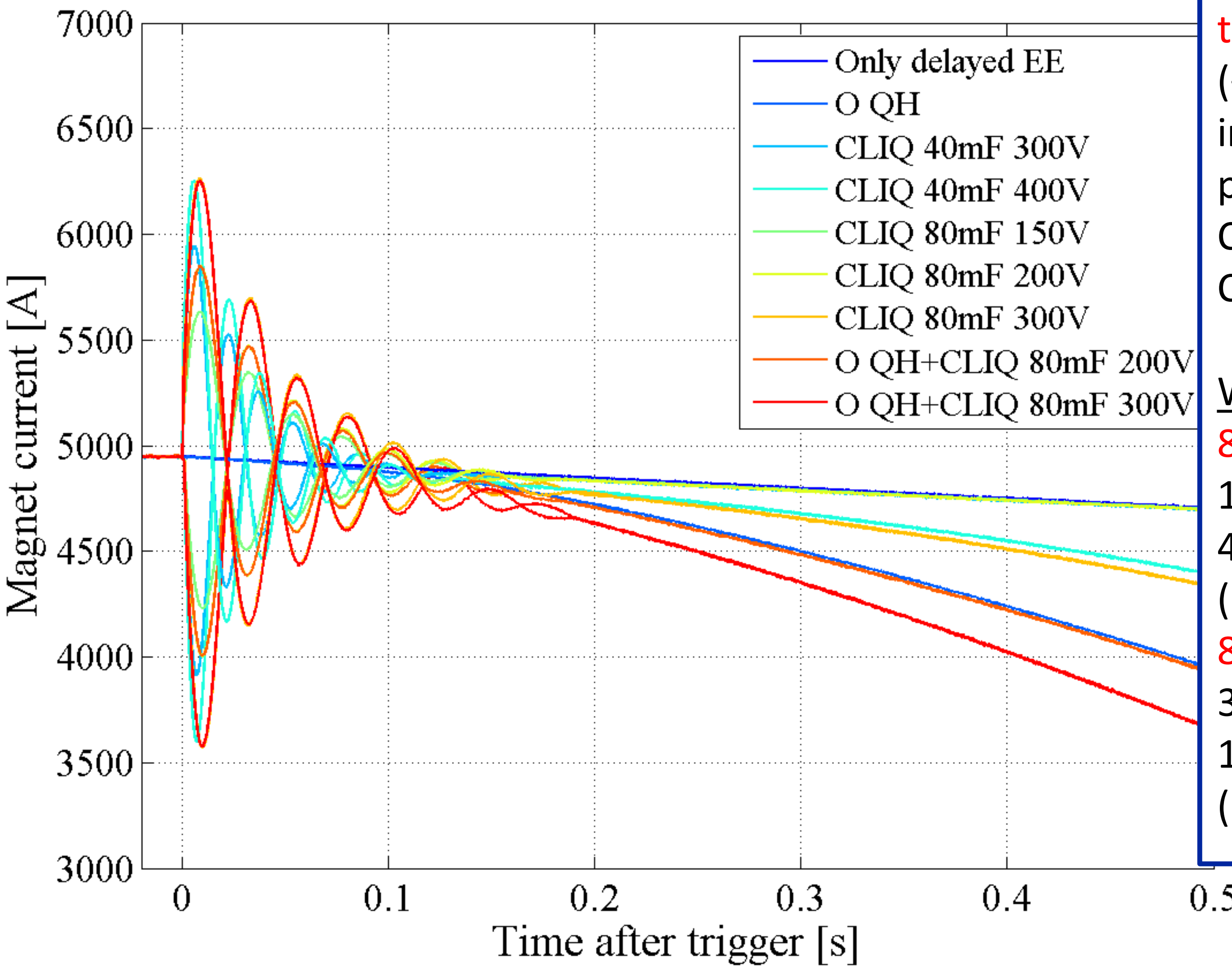
324% power density

104% energy density

(relevant at low current)

G. Chlachidze, S. Stoynev (FNAL)

CLIQ performance – MQXFS1b – 5 kA



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(relevant at high current)

80mF, 300 V

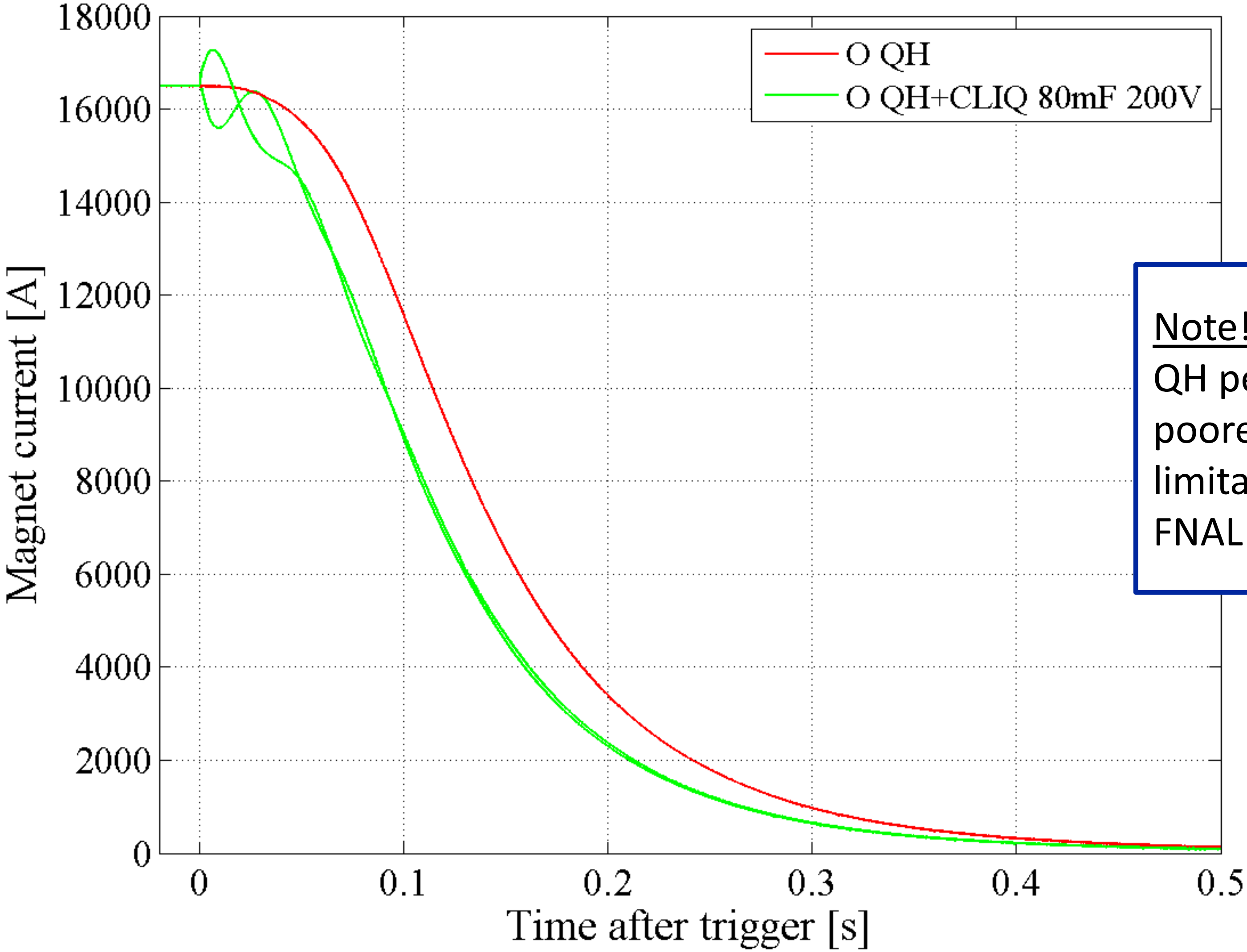
324% power density

104% energy density

(relevant at low current)

G. Chlachidze, S. Stoynev (FNAL)

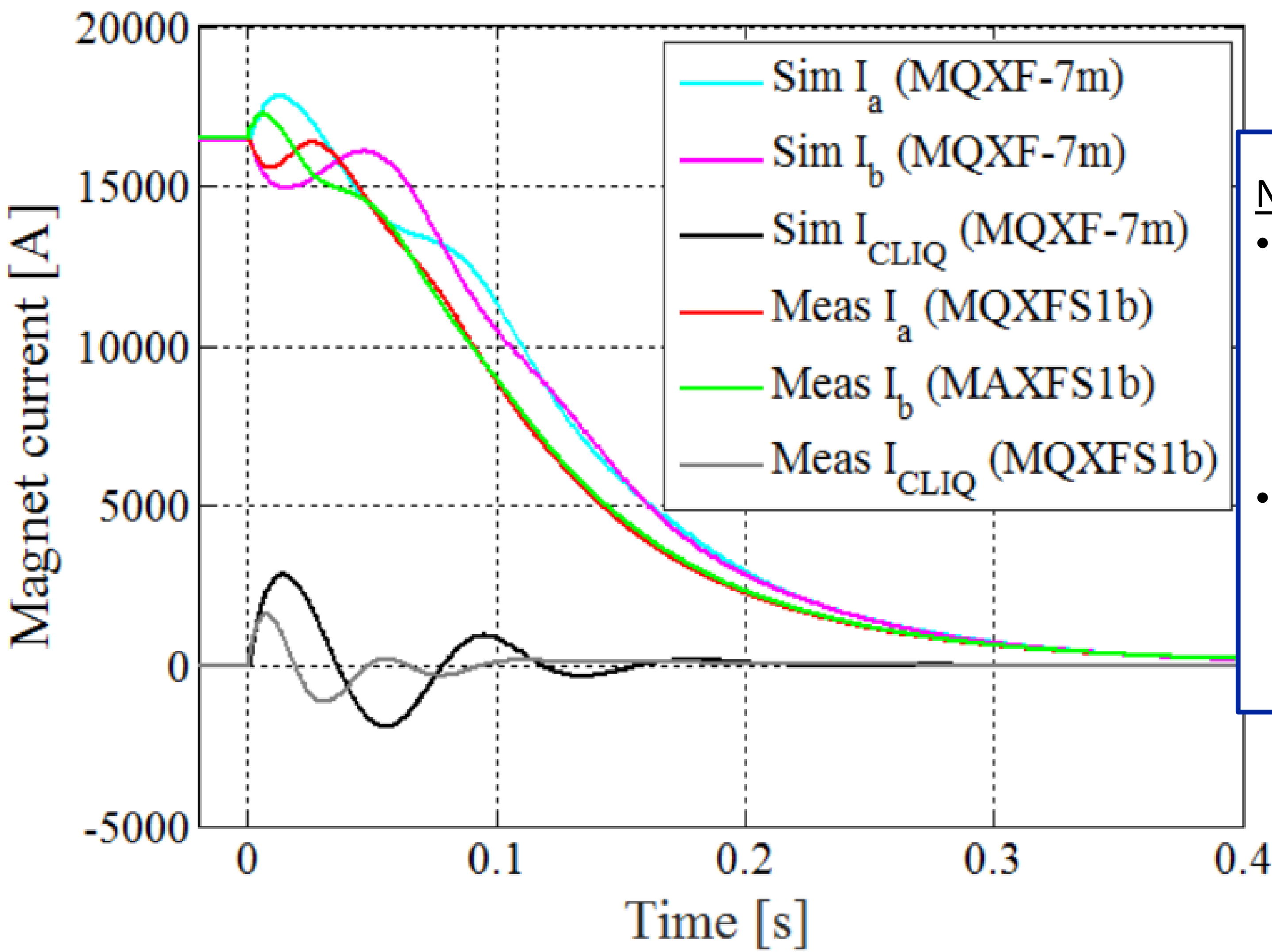
Quench integrals at I_{nom} – MQXFS1b



<u>Note!</u>
QH performance are slightly poorer than baseline due to limitations of QH units at FNAL

G. Chlachidze, S. Stoynev (FNAL)

Cpr with simulated 7m MQXF baseline



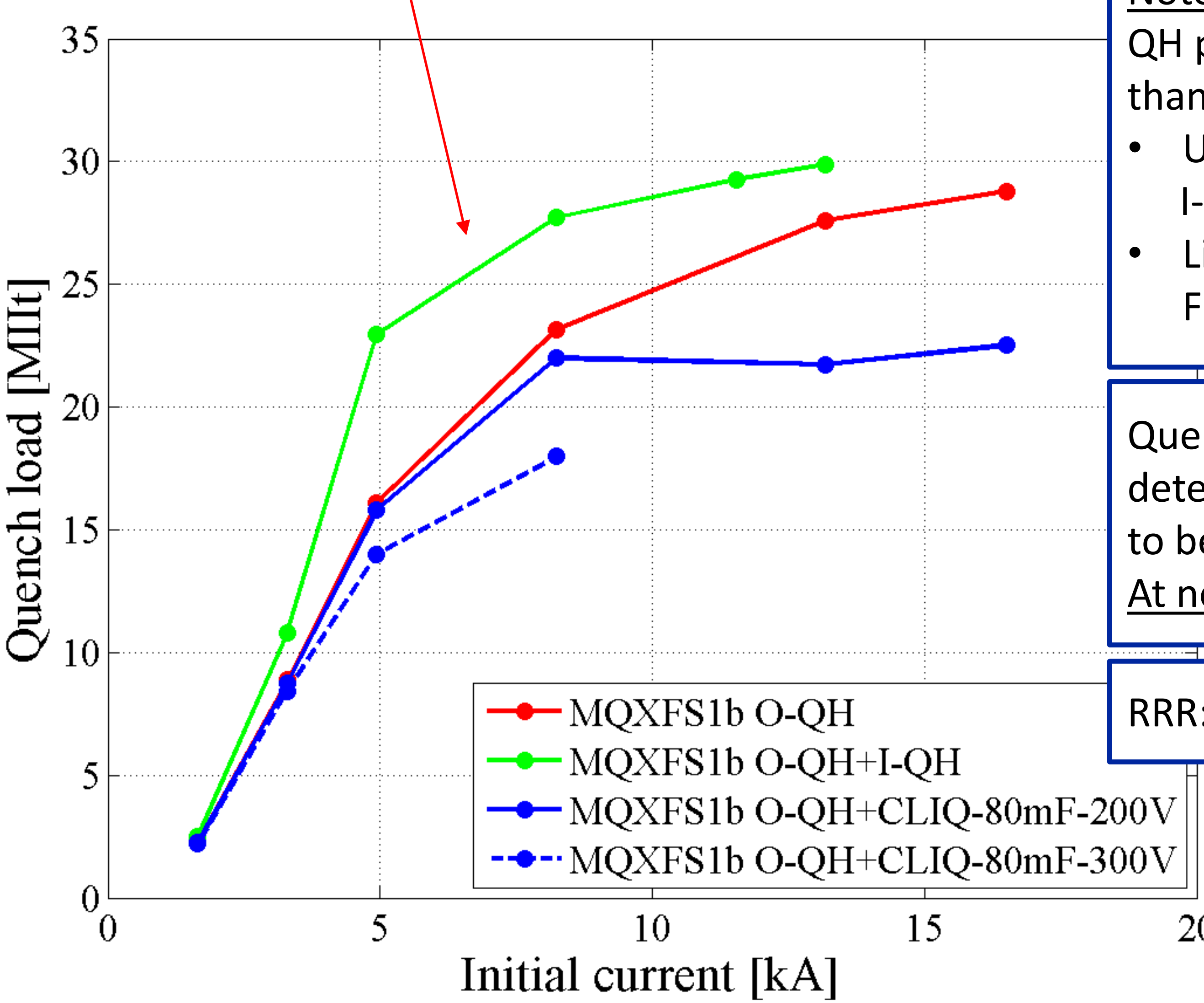
Note!

- QH performance are slightly poorer than baseline due to limitations of QH units at FNAL
- RRR of this magnet is different from the reference simulation

G. Chlachidze, S. Stoynev (FNAL)

Quench integral studies – MQXFS1b

not representative



Note!

QH performance are poorer than baseline due to

- Unavailability of some I-QH strips (4oo8)
- Limitations of QH units at FNAL

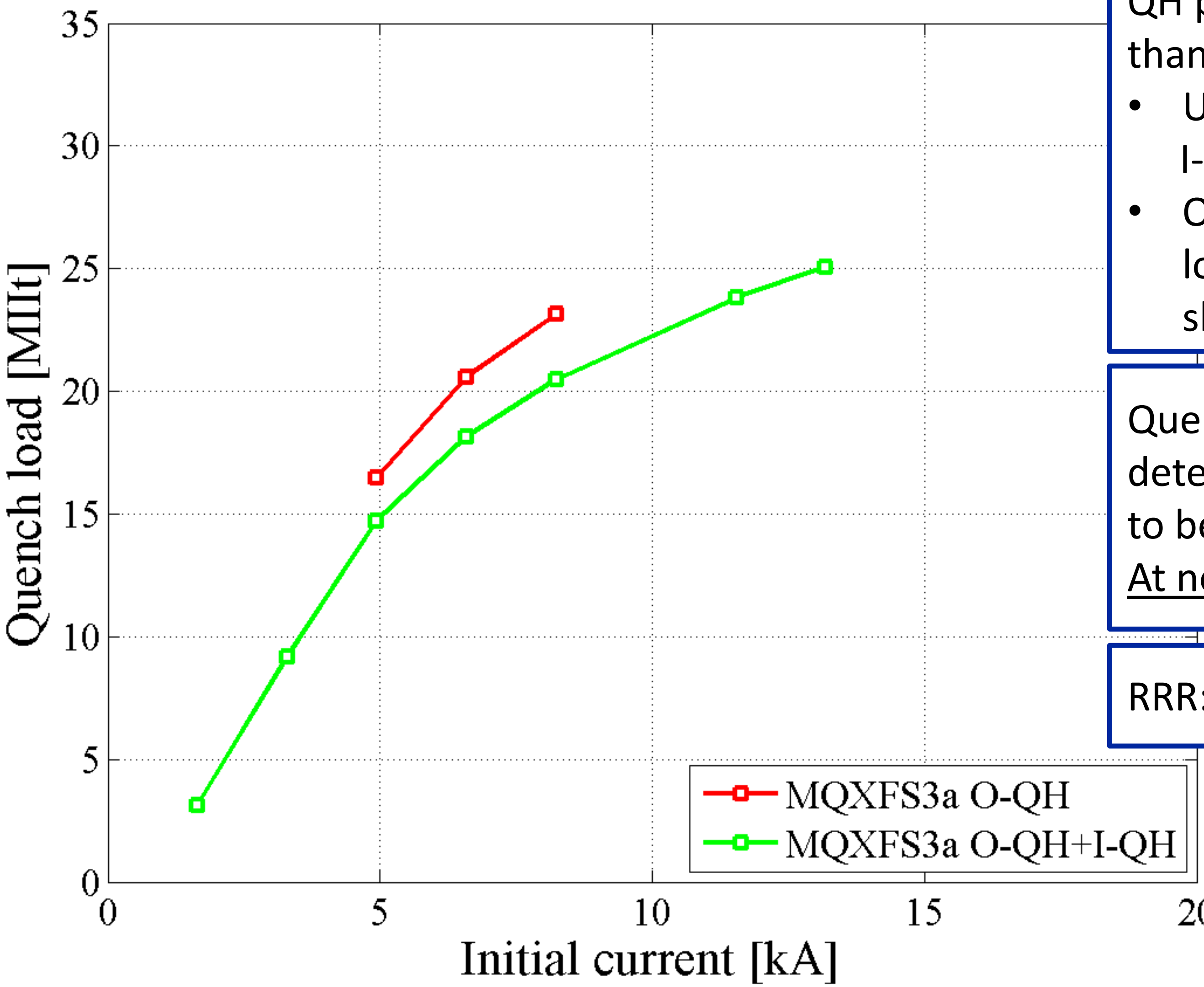
Quench load due to detection + validation time to be added

At nominal current ~4 MIIt

RRR: 250, 105, 255, 135

G. Chlachidze, S. Stoynev (FNAL)

Quench integral studies – MQXFS3a



Note!
QH performance are poorer than baseline due to

- Unavailability of some I-QH strips (2oo8)
- O-QH powered with lower power density, I-QH slightly higher

Quench load due to detection + validation time to be added
At nominal current ~4 MIIt

RRR: 140, 140, 140, 170

H. Bajas, S. Izquierdo Bermudez (CERN)

Conclusions & next steps

LARP

High Luminosity LHC

Quench protection report prepared

- Extensive simulation work aimed at identifying
  - Performances of various quench protection options
  - Effect of strand parameters and quench location
  - Effect of QH failures
  - Peak currents in all circuit elements
- Option with only O-QH does not offer enough protection, either I-QH or CLIQ (or both) are needed as well. Combination of protection elements guarantees great redundancy.

Test results

- Quench protection up to nominal current successfully demonstrated
- CLIQ tested for the first time on an MQXF model. As expected, a significant reduction of the quench load is achieved with respect to O-QH only. Direct comparison with O-QH+I-QH not available from experimental results yet.
- Quench protection at low current assured by O-QH, baseline parameters ok

Next steps

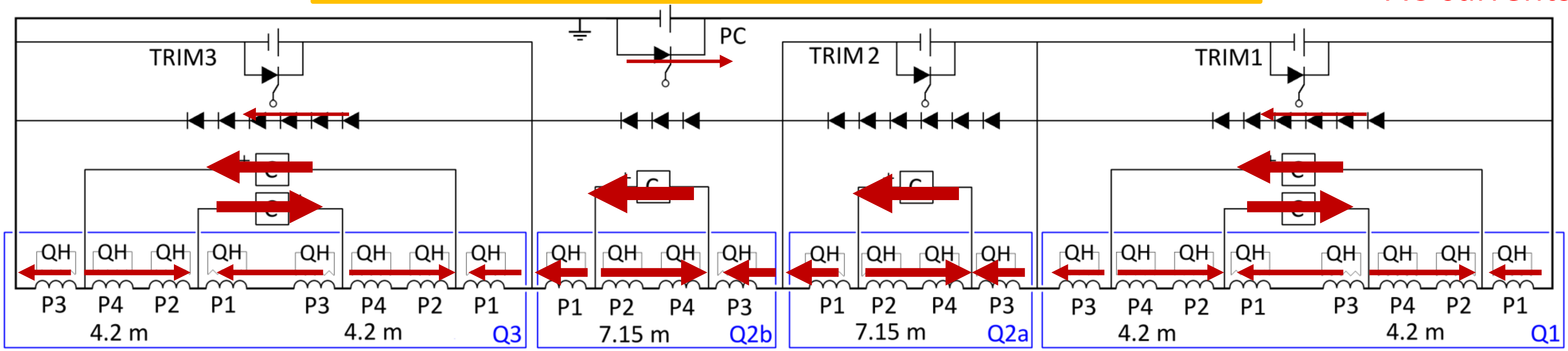
- Test response time of inner-layer quench heaters at nominal current on MQXFS3
- Test CLIQ performance on MQXFS3
- Quench integral studies at nominal/ultimate current
- Compare test results with simulations with the same RRR and QH conditions

Annex

Circuit analysis

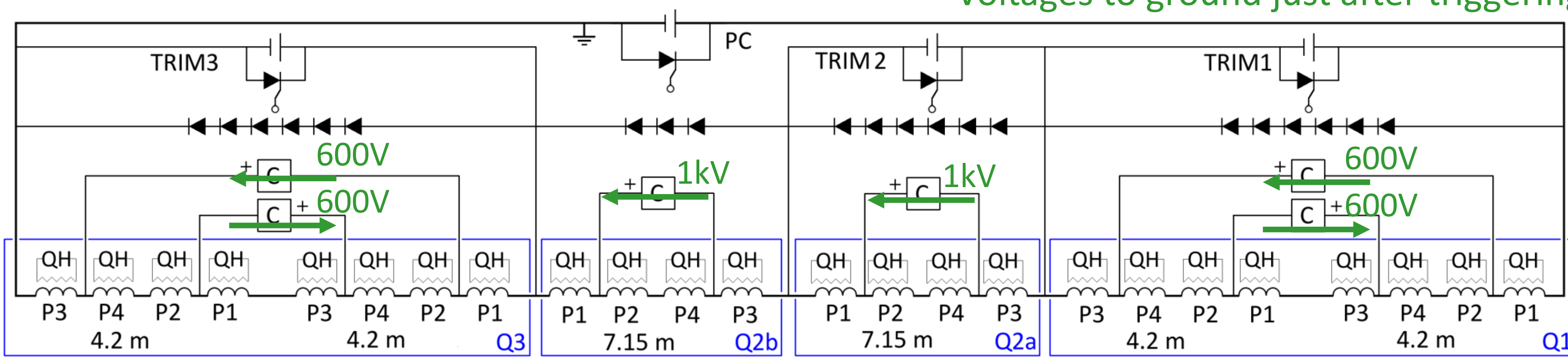
6 CLIQ units and 4 warm diode strings per triplet

AC currents



Parallel diodes only carry small current differences between magnets during the discharge

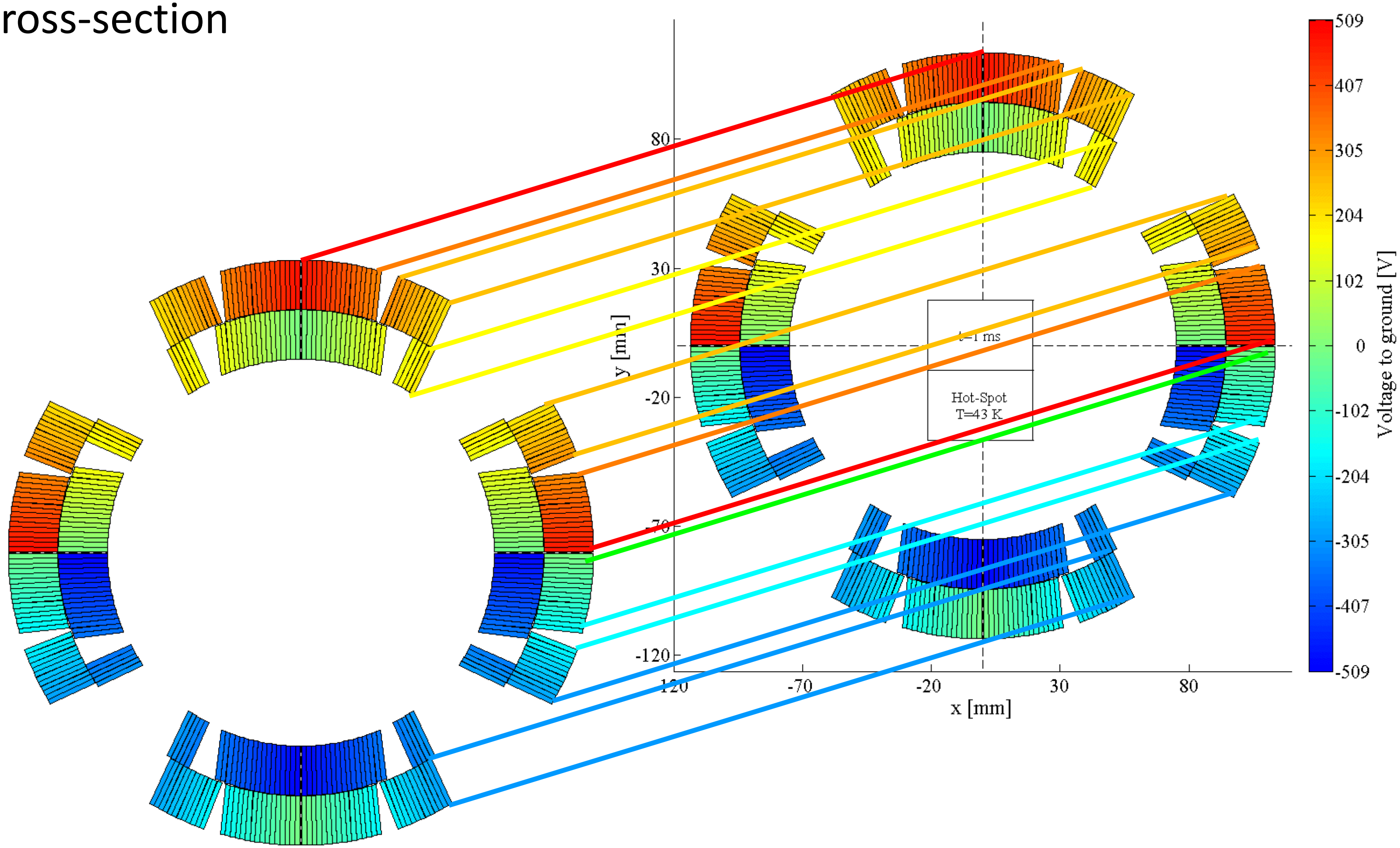
Voltages to ground just after triggering



~0 +300V -300V +300V -300V ~0 +500V -500V ~0 +500V -500V ~0 +300V -300V +300V -300V ~0

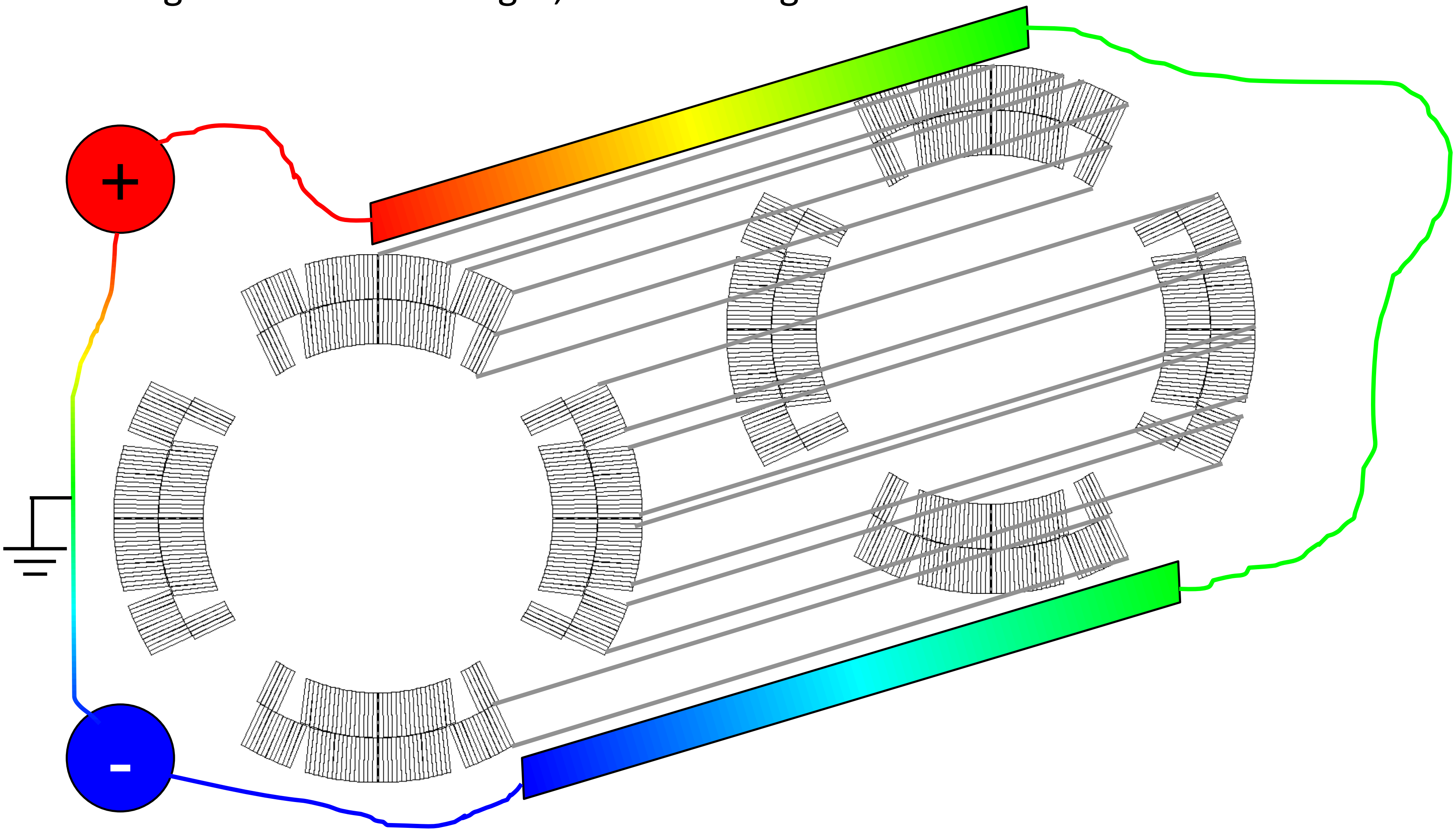
CLIQ-induced voltage distribution

- The voltage distribution in the windings just after triggering CLIQ remains almost constant along the magnet length, but is inhomogeneous in the magnet cross-section



QH-induced voltage distribution

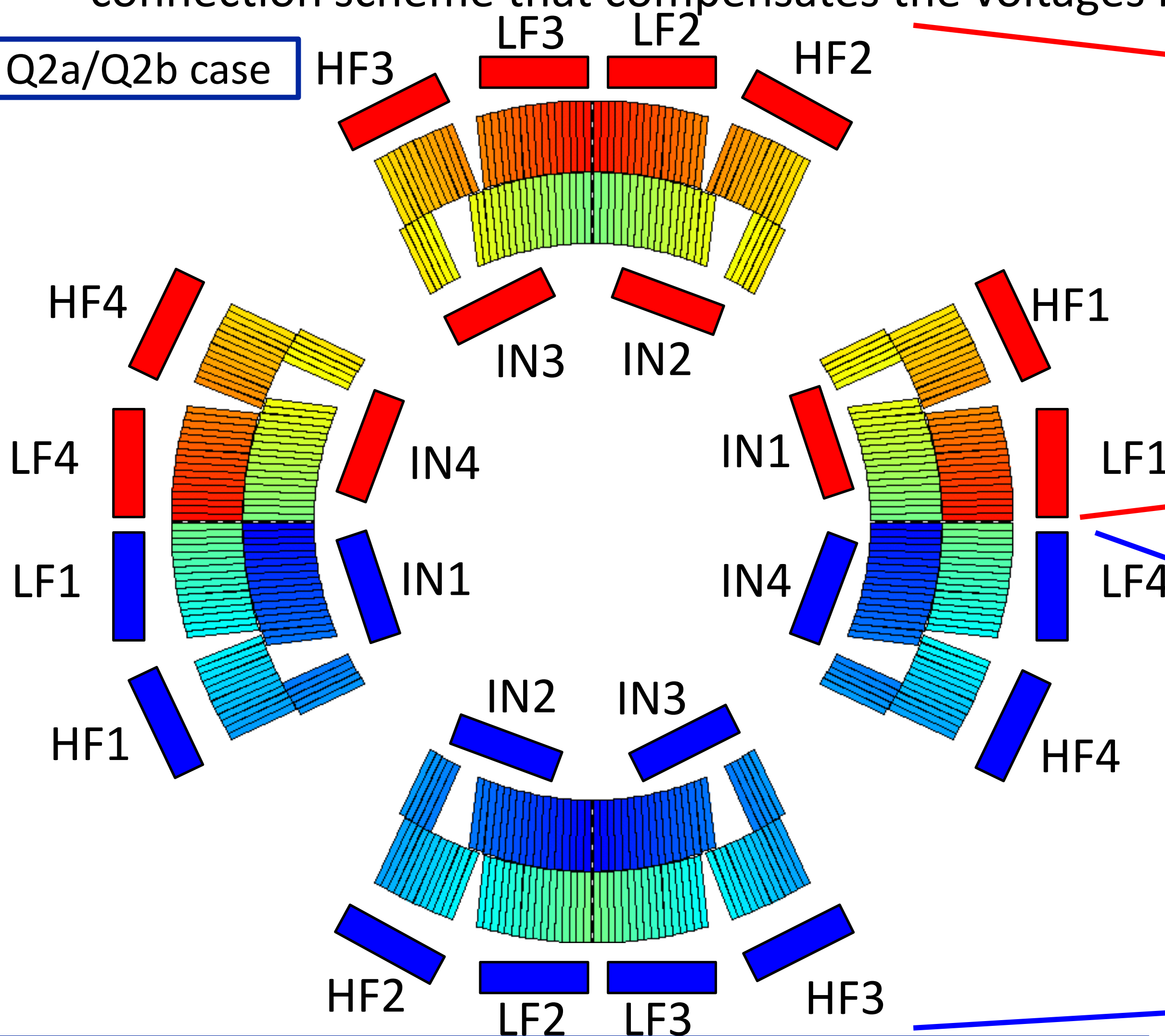
- The voltage distribution in the QH strips just after triggering varies linearly along the conductor length, but is homogeneous in the cross-section

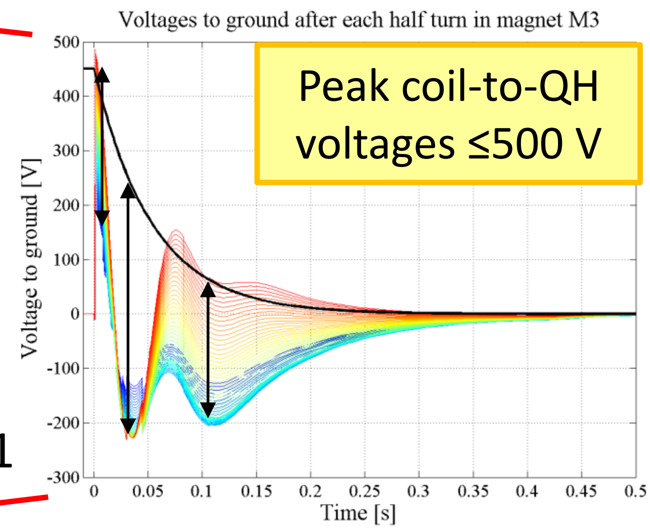


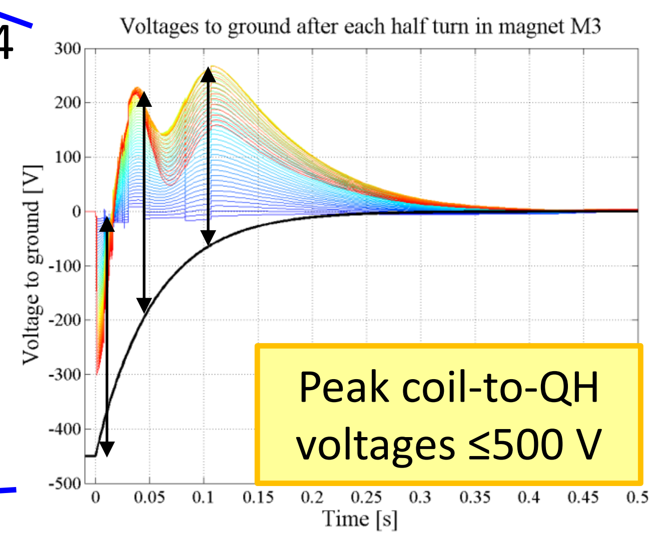
Coil to heater voltage optimization

- CLIQ and QH are triggered simultaneously. It is important to choose a QH connection scheme that compensates the voltages induced by CLIQ and QH

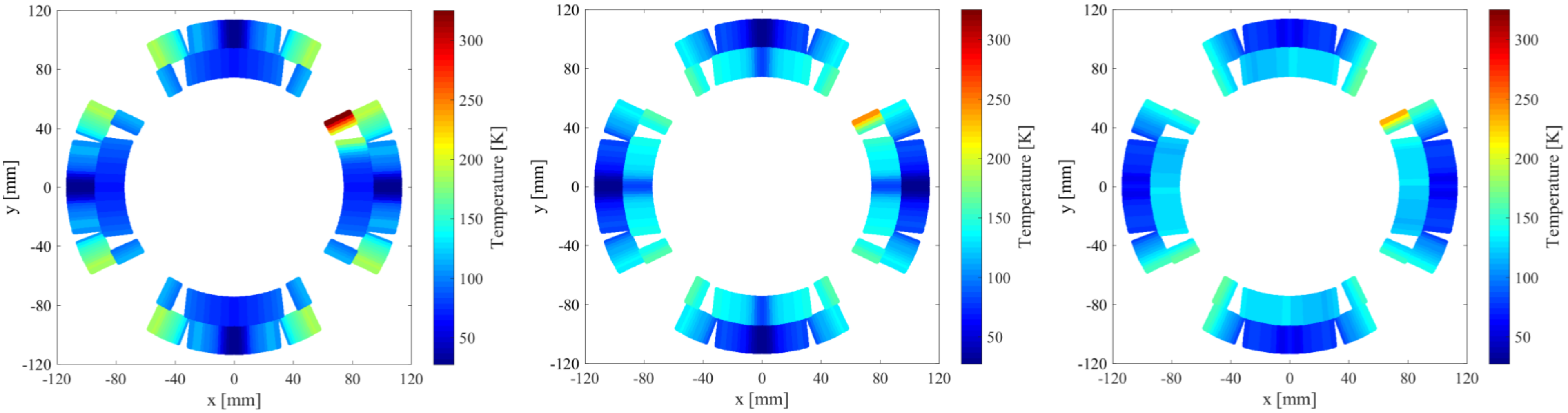
Q2a/Q2b case





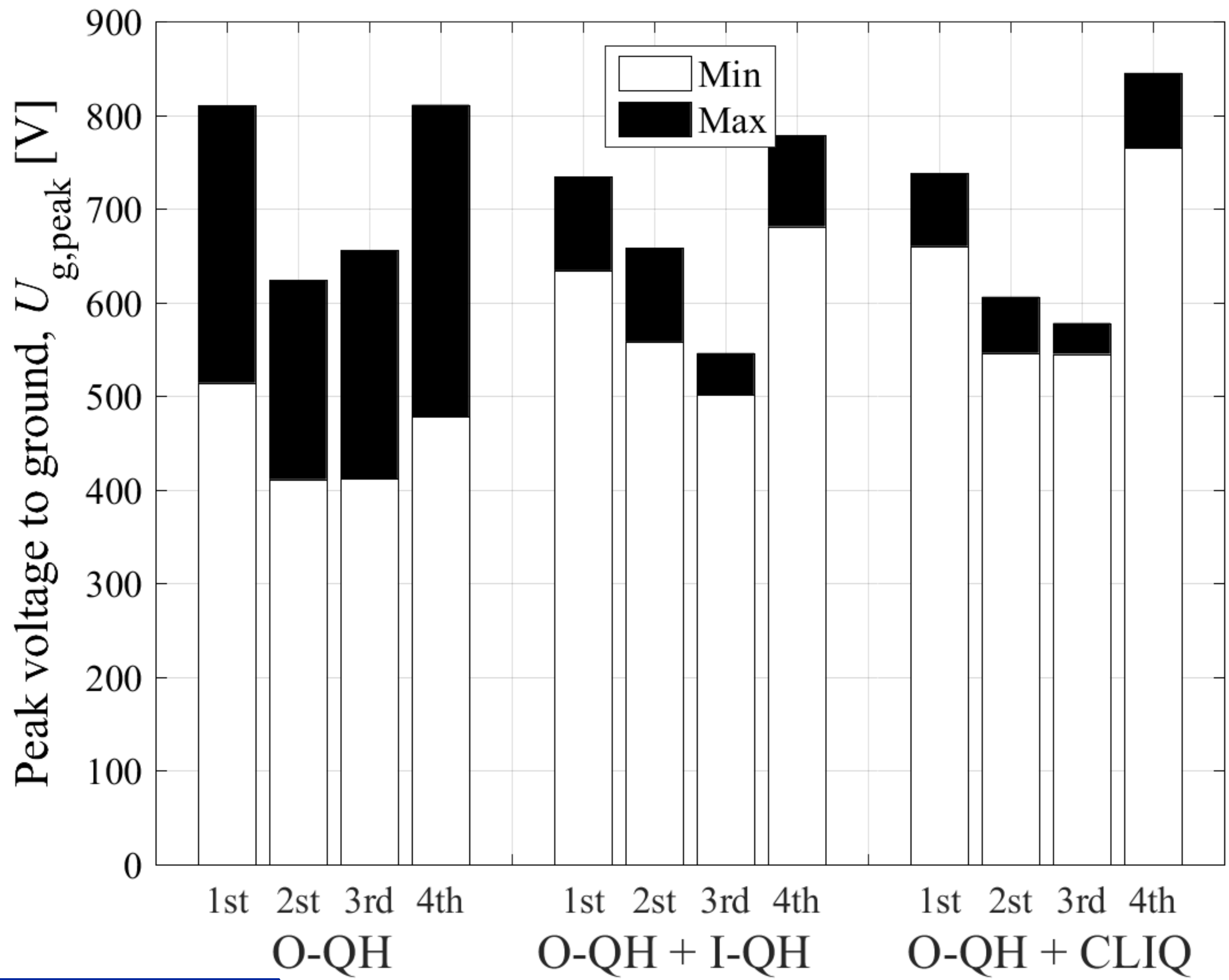


Simulated temperature profiles



Simulations performed with LEDET

Simulated voltages to ground



Simulations performed with LEDET

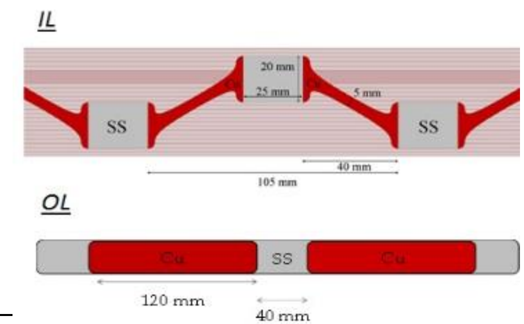
Minimum QH power density to quench

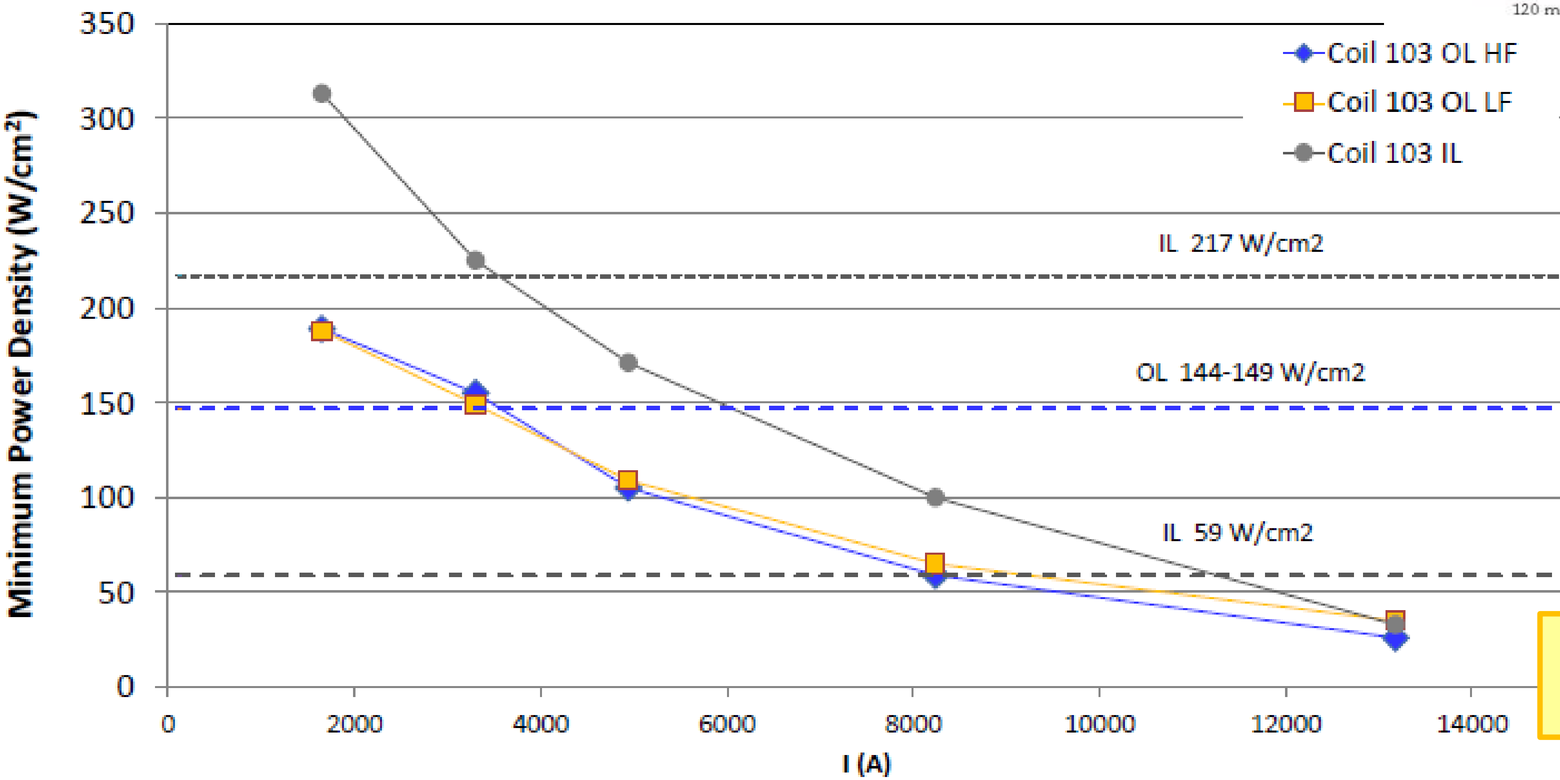
<u>CERN style heaters only</u>

Baseline power density in 7 m long MQXF:

OL – 213 W/cm2 (2-strips in series per HFU)

IL – 98 W/cm2 (2-strips in series per HFU)





C=19.2 mF

τ_{OL-LF}=23 ms

τ_{OL-HF}=21 ms

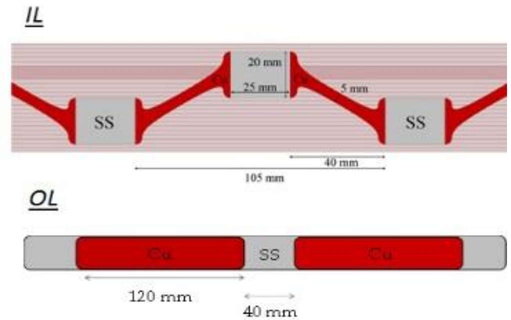
τ_{IL}=18 ms

G. Chlachidze (FNAL)

LARP

Minimum QH energy density to quench

High Luminosity LHC

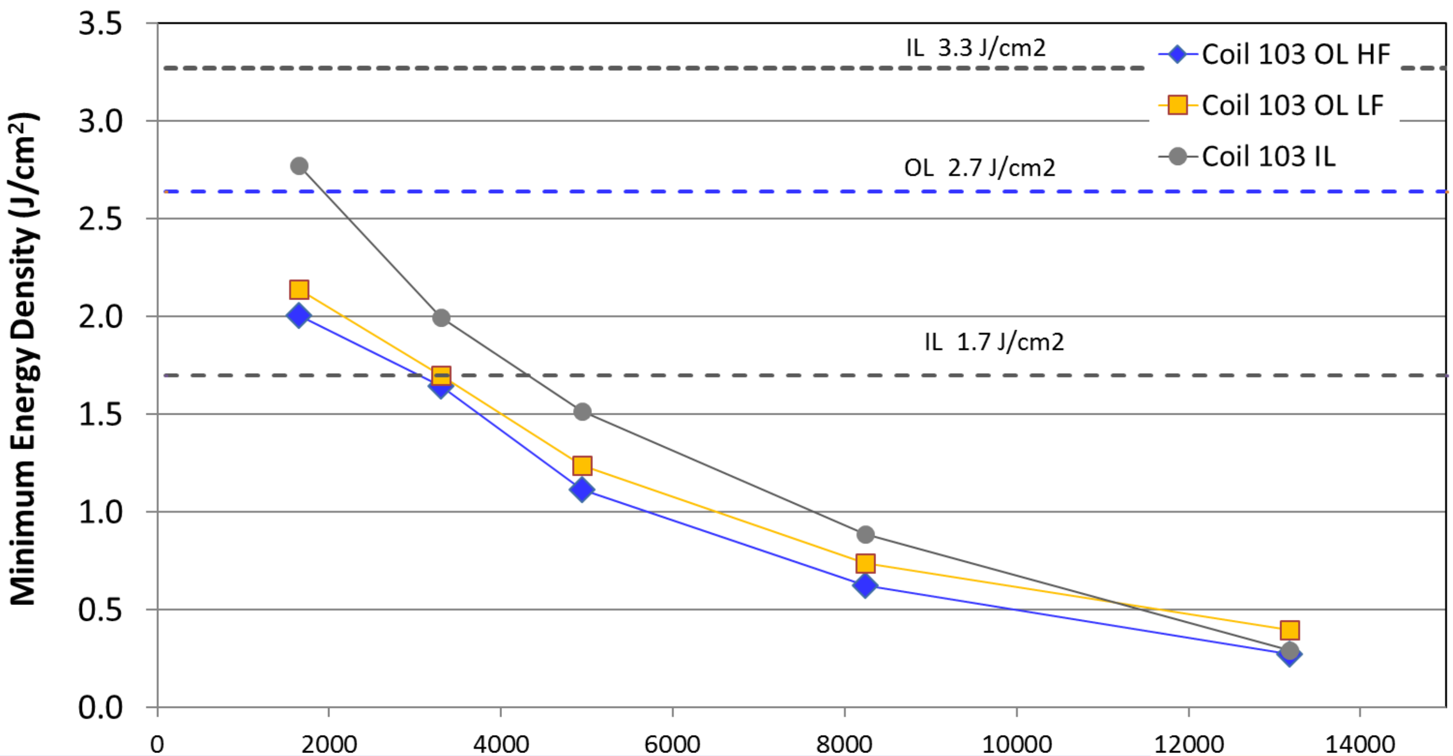


<u>CERN style heaters only</u>

Baseline energy density in 7 m long MQXF:

OL – 2.43 J/cm2 (2-strips in series per HFU)

IL – 2.32 J/cm2 (2-strips in series per HFU)



C=19.2 mF

τ_{OL-LF}=23 ms

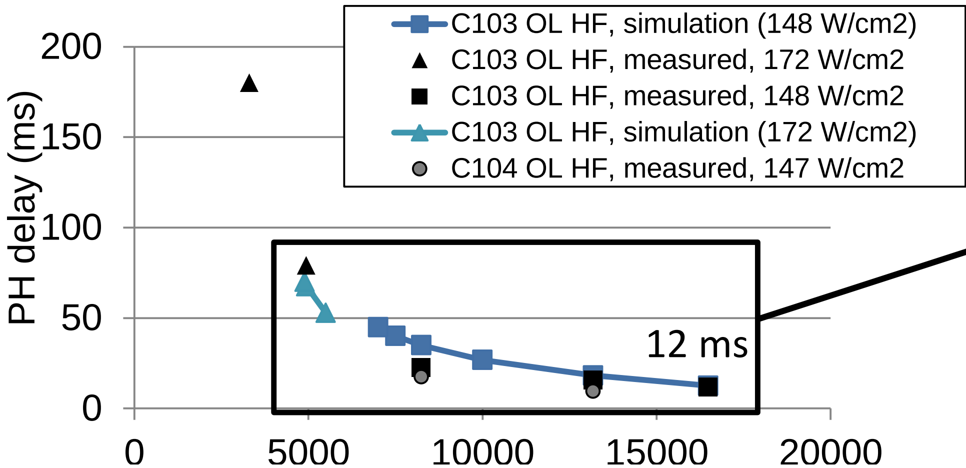
τ_{OL-HF}=21 ms

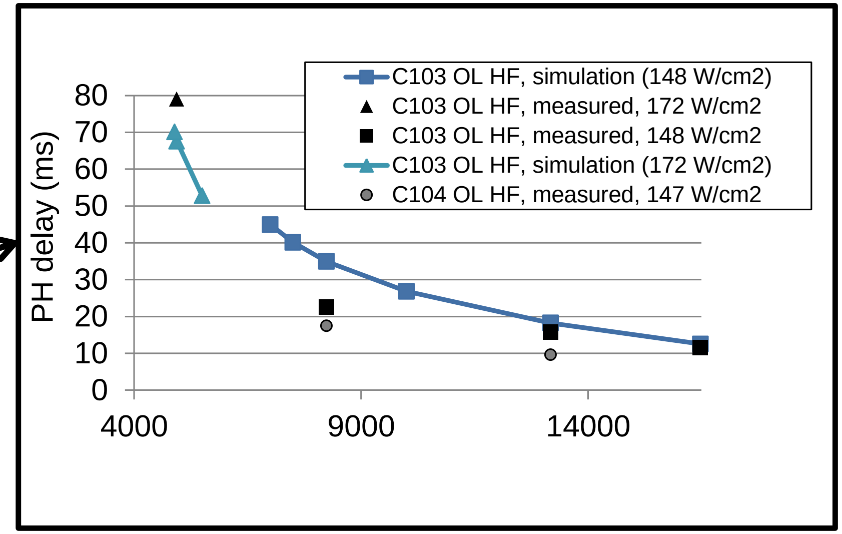
τ_{IL}=18 ms

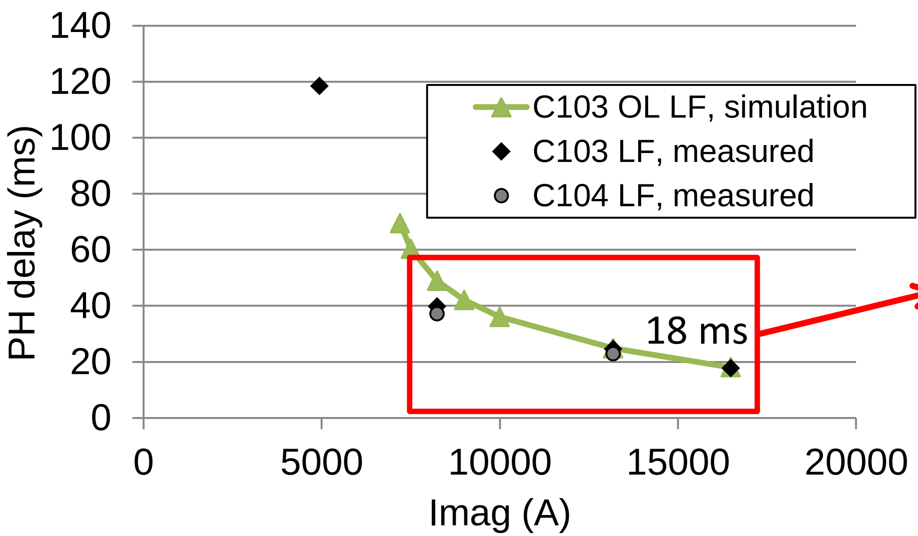
To further improve low-current performance, consider changing the QH strip design (longer heating stations) or use QH supplies with higher energy

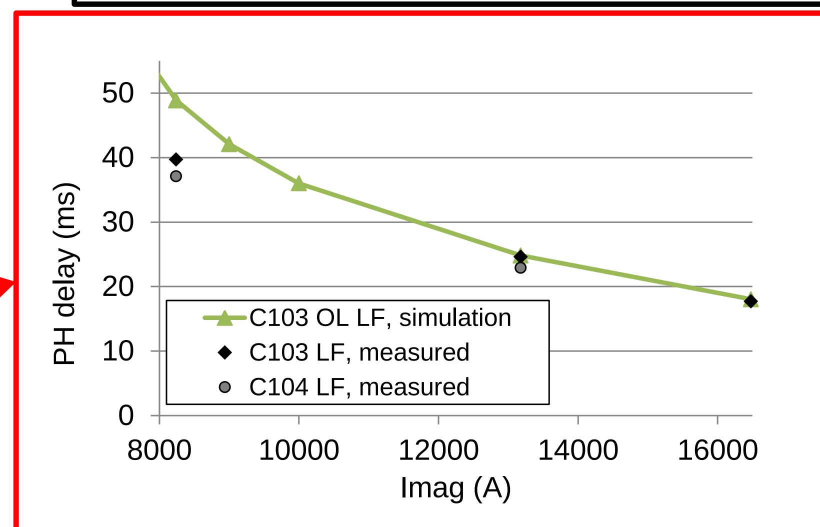
Data: G. Chlachidze
Analysis: S. Izquierdo-Bermudez, E. Ravaioli, J. Rysti

Measured and simulated heater delays – Outer layer







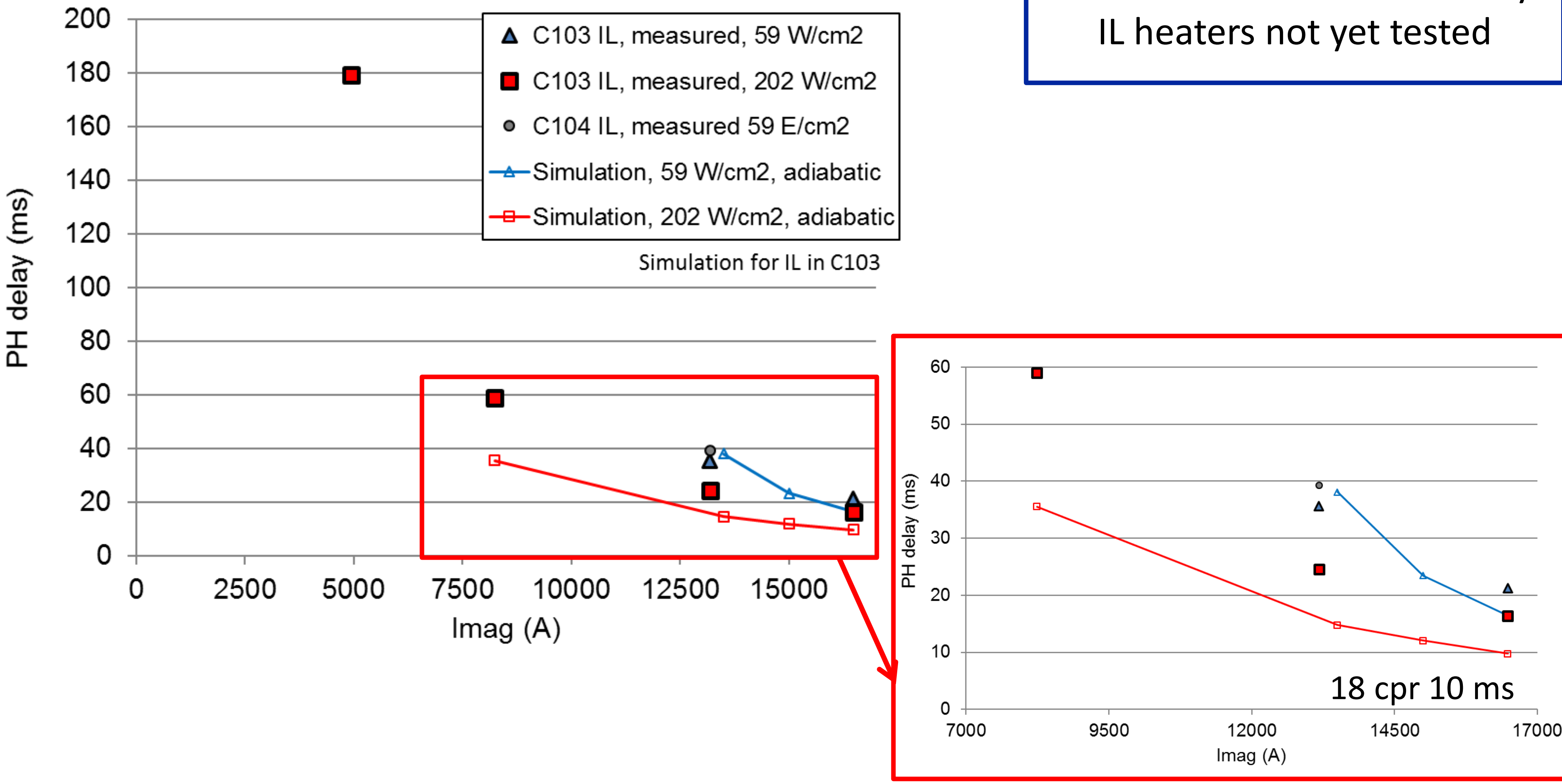


Data: G. Chlachidze (FNAL)
Simulations: T. Salmi (TUT)

Simulations performed with CoHDA

Measured and simulated heater delays – Inner layer

MQXFS01 stainless-steel only IL heaters not yet tested



Data: G. Chlachidze (FNAL)
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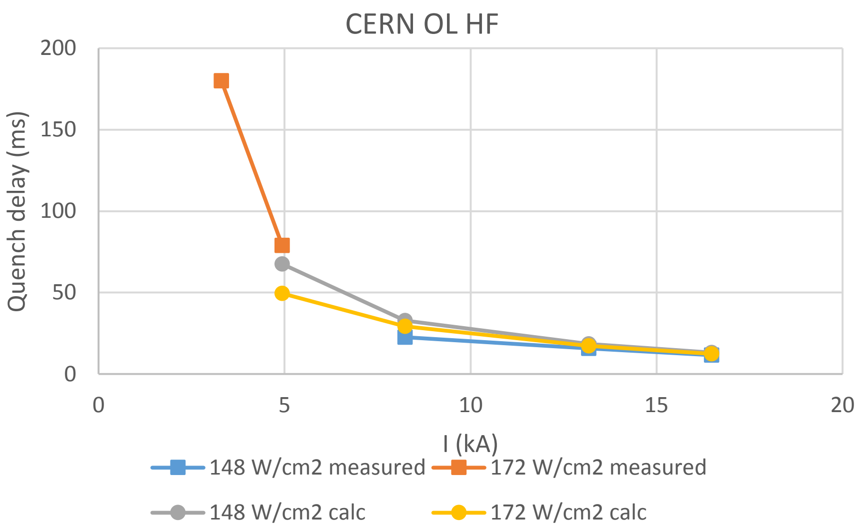
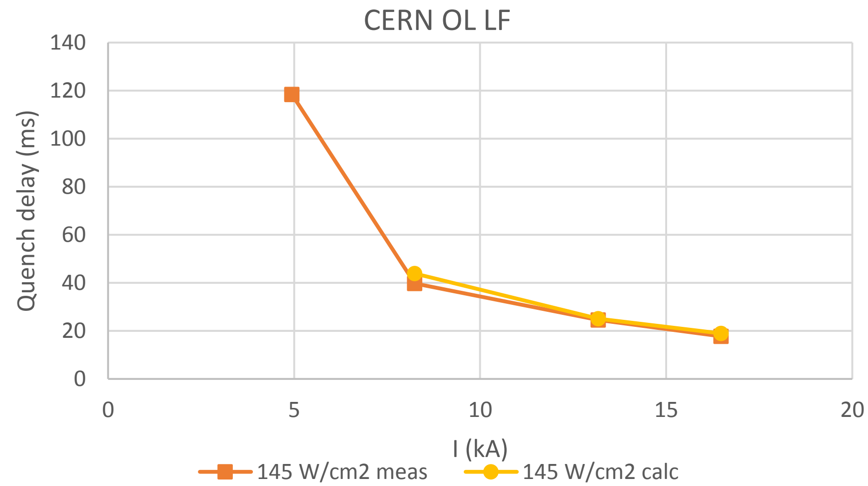
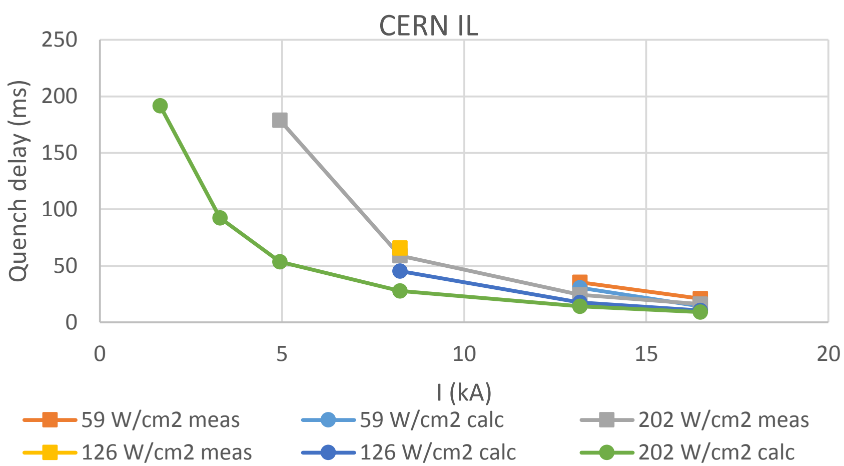
Measured and simulated heater delays – Outer and inner layers







OL heaters: Very nice agreement between measurements and simulations from two independent models

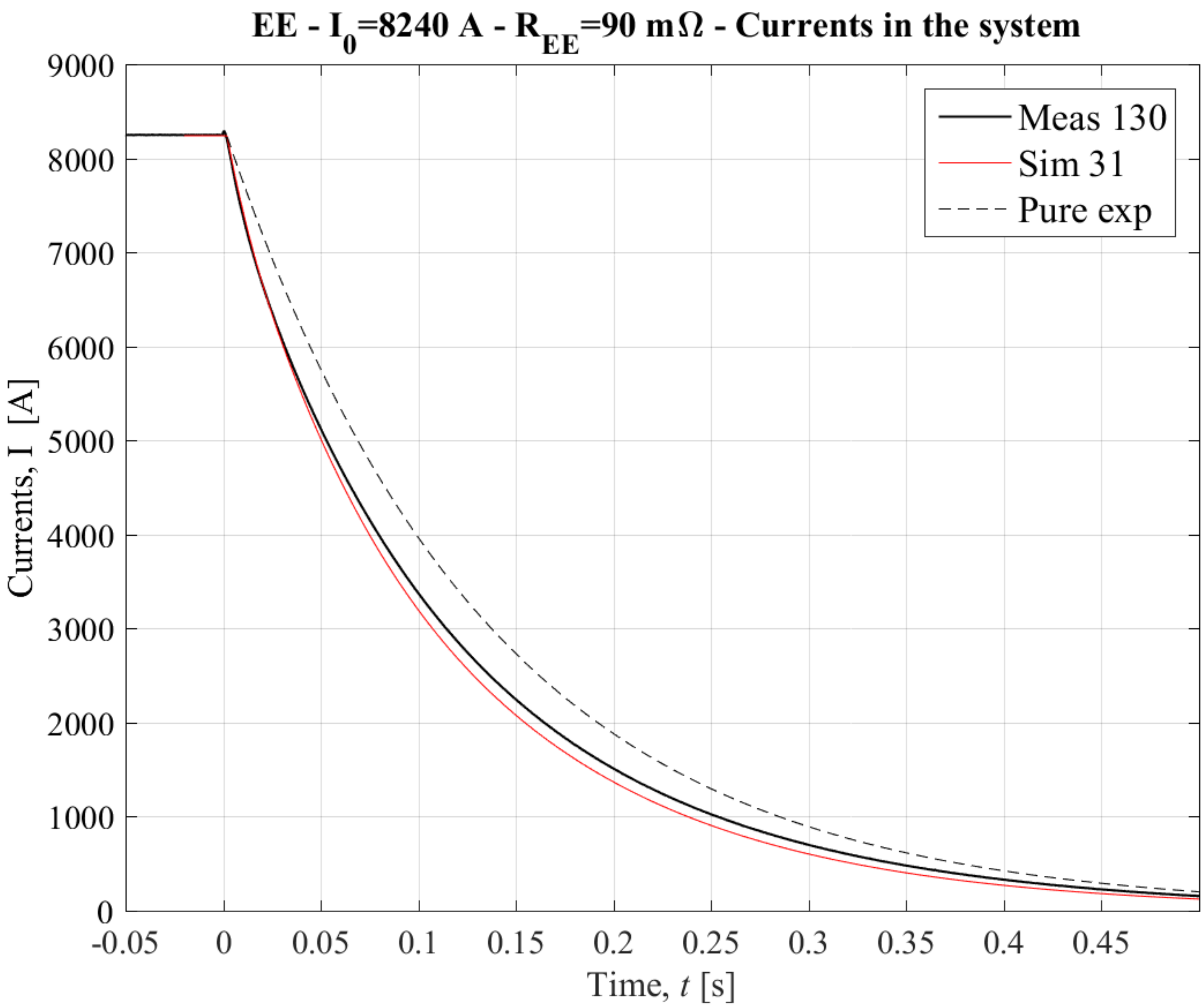
IL heaters: Both independent models predict shorter delays at nominal current.
Further analysis required

Additional heater delay tests with added warm resistance foreseen in the coming weeks

Data: G. Chlachidze (FNAL)
Simulations: J. Rysti (CERN)

Simulations performed with Comsol

Energy extraction decays (no heaters)



I_0=8.24 kA
R_{EE}=90 mΩ

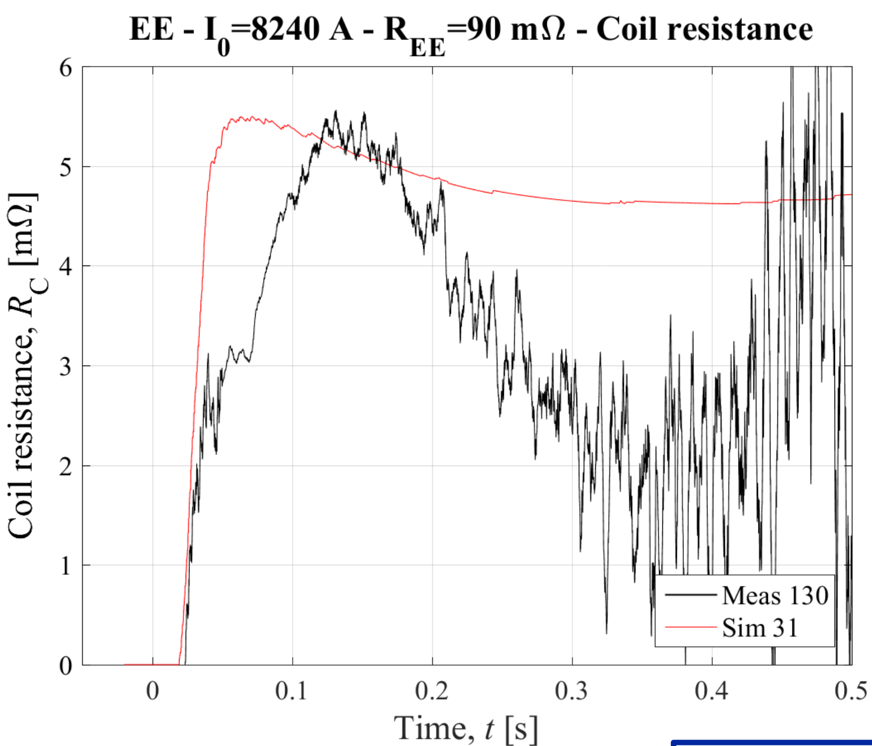
Data: G. Chlachidze (FNAL)

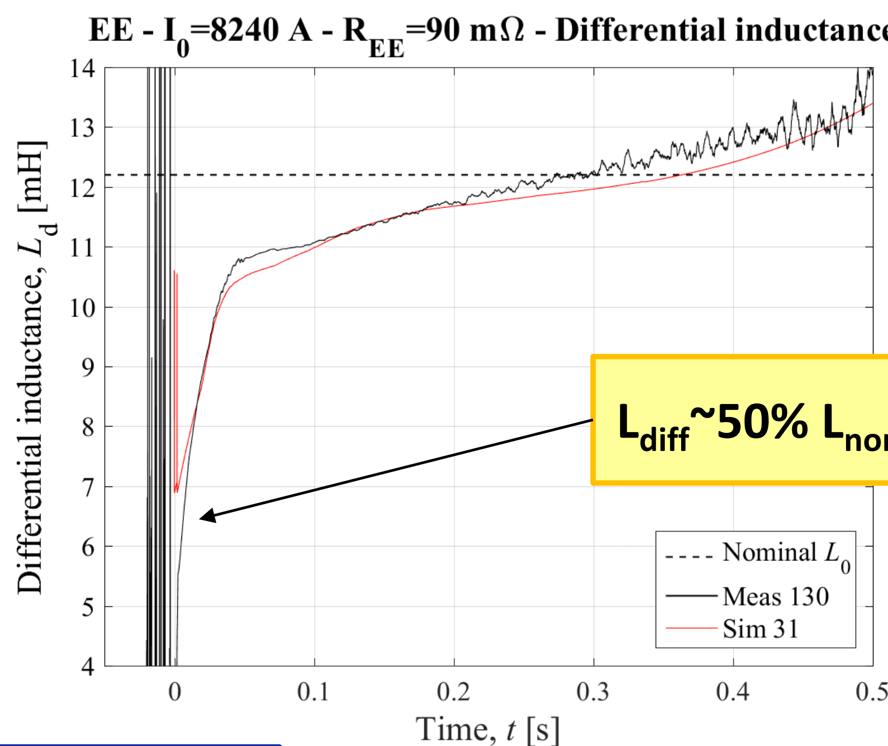
Simulations performed with LEDET

Energy extraction decays (no heaters) Quench back and inductance reduction

I_0=8.24 kA
R_{EE}=90 mΩ

L_{diff}~50% L_{nom} R_{coil}~5 mΩ → The faster decay observed in this discharge is mainly due to a reduction of the inductance, not due to quench-back





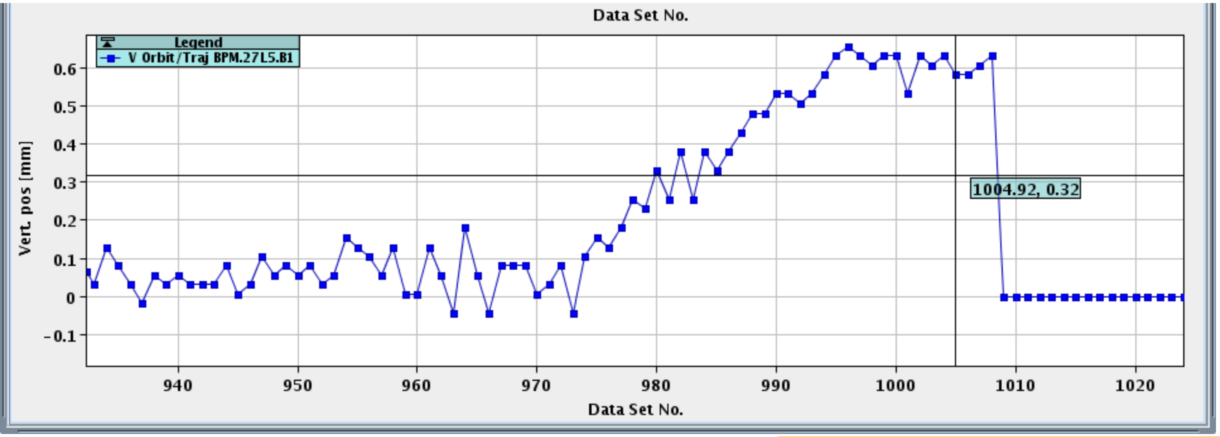
L_{diff}~50% L_{nom}

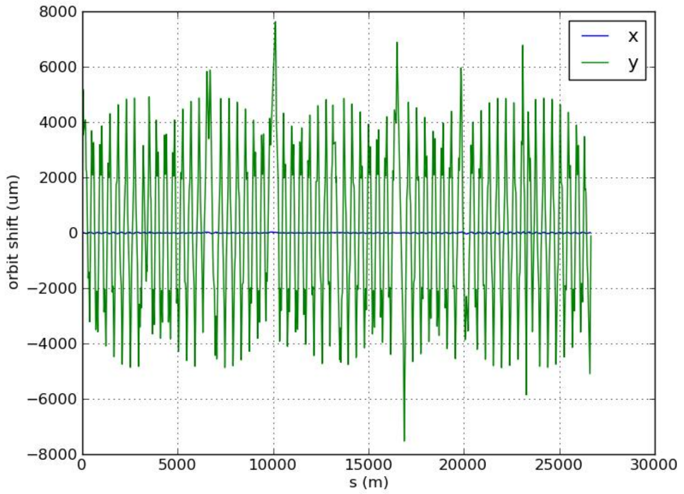
Data: G. Chlachidze (FNAL)

Simulations performed with LEDET

Fast kick due to quench heater firing

- Delay of ~3 ms (33 turns) observed (training & beam induced quenches, MD) between quench heater firing and beam dump in LHC main dipoles.
- Field from quench heater rises within 20 - 30 us.
- Max expected orbit excursions:
  - Main dipoles , 11 T dipole: ~ 0.13 σ
  - HL-LHC triplet (OL + IL): ~ 0.5 σ → ~150 um (@ 7 TeV); ~ 6 mm (@ 450 GeV)
- Minimize skew dipole fields from quench heaters.
- Ensure, that beams are dumped before quench heater fire.





By Daniel Wollmann