CERN

Multiphysics modelling of the LHC main quadrupole superconducting circuit
- Progress presentation

D. Pracht

On behalf of the **STEAM team** (Emmanuele Ravaioli, Matthias Mentink, Michał Maciejewski, Lorenzo Bortot, Akrivi Liakopoulou, Bernhard Auchmann, Arjan Verweij)

Thanks a lot for your help!

Thanks a lot for the great help using the PM Browser: Zinur Charifoulline (CERN)

Thanks a lot for the SM18 test data: Gerard Willering (CERN)

Thanks a lot for the great help regarding the LHC MQ circuit: Valérie Montabonnet (CERN)

Geneva, 11.04.2019

Checklist for this presentation

1. Goals and Motivation for the project
2. Validation of the magnet model (LEDET, COMSOL) at $I_{test,1}$ = 11.69 kA
3. Validation of the magnet model (LEDET, COMSOL) at $I_{test,2}$ = 7.554 kA
4. Discussing the influence parameters within the model
5. Validation of the circuit model (PSPICE)
6. Progress checklist for this project

Motivation

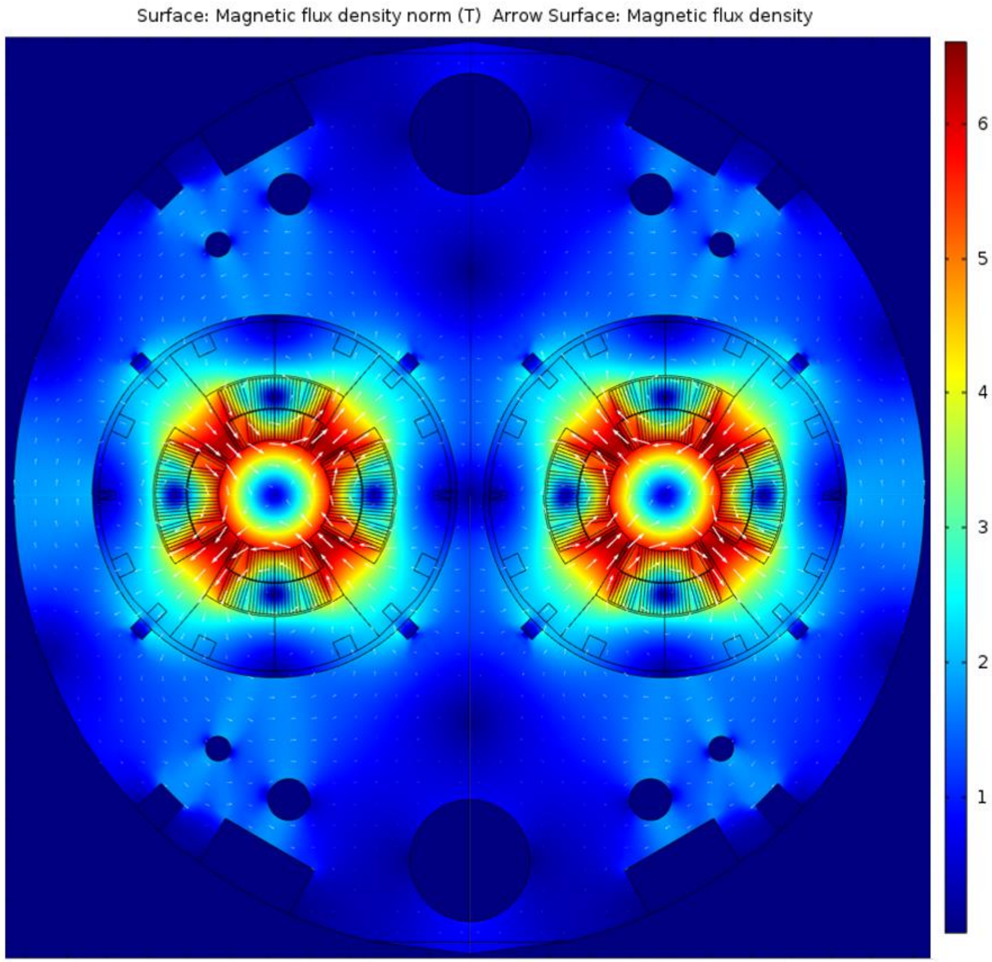
What is the final goal?

- To have a circuit library for all LHC circuits (RB, RQX, RQF/RQD,...)
- To have more magnet models within STEAM
- To constantly optimize STEAM-SIGMA for semi-automatic model generation

My task within the STEAM team

1. Develop the MQ magnet model
    1. SIGMA-COMSOL
    2. LEDET
2. Develop the RQD/RQF circuit model in PSPICE
3. Combine point (1) and (2) within COSIM
4. Validate points (1), (2) and (3)
5. Document the models and the results

LHC Main Quadrupole magnet



Main Quadrupole:

- The quadrupole magnets focus the particle beams, controlling their width and height
- Nominal current: 11870 A
- Operating at 1.9 K
- Length: 3.1 m
- Quench protection based on quench heaters (QHs) and cold by-pass diodes

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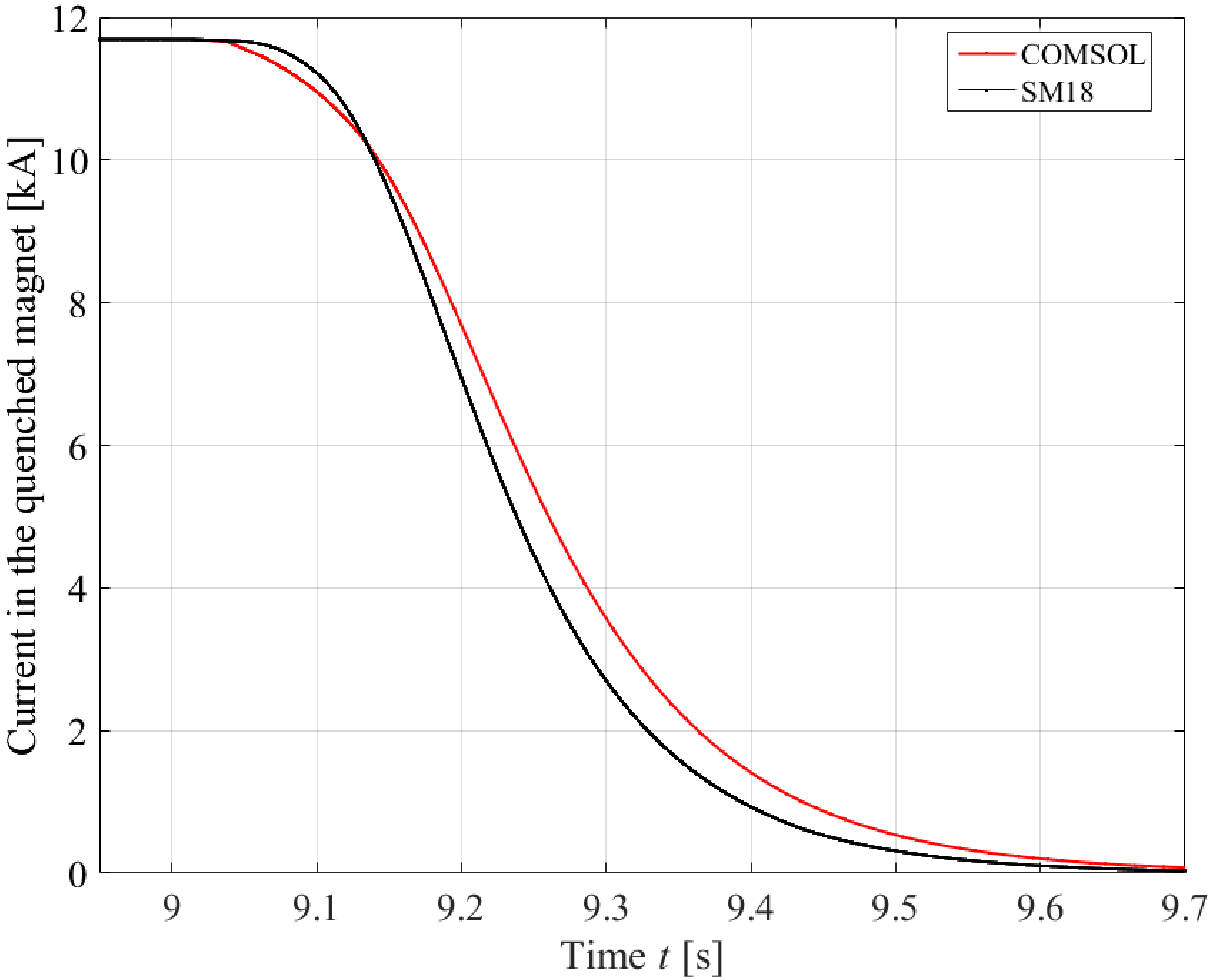


Bad agreement with measurement data

Parameters from the measurement:

$I_{test,1}$ = **11.69 kA**

$I_{test,2}$ = 7.554 kA

COMSOL® Parameters:

- Quenching 1 HT at $t_{quench,HT}$ = 0 s

frac_He = 5.5 %

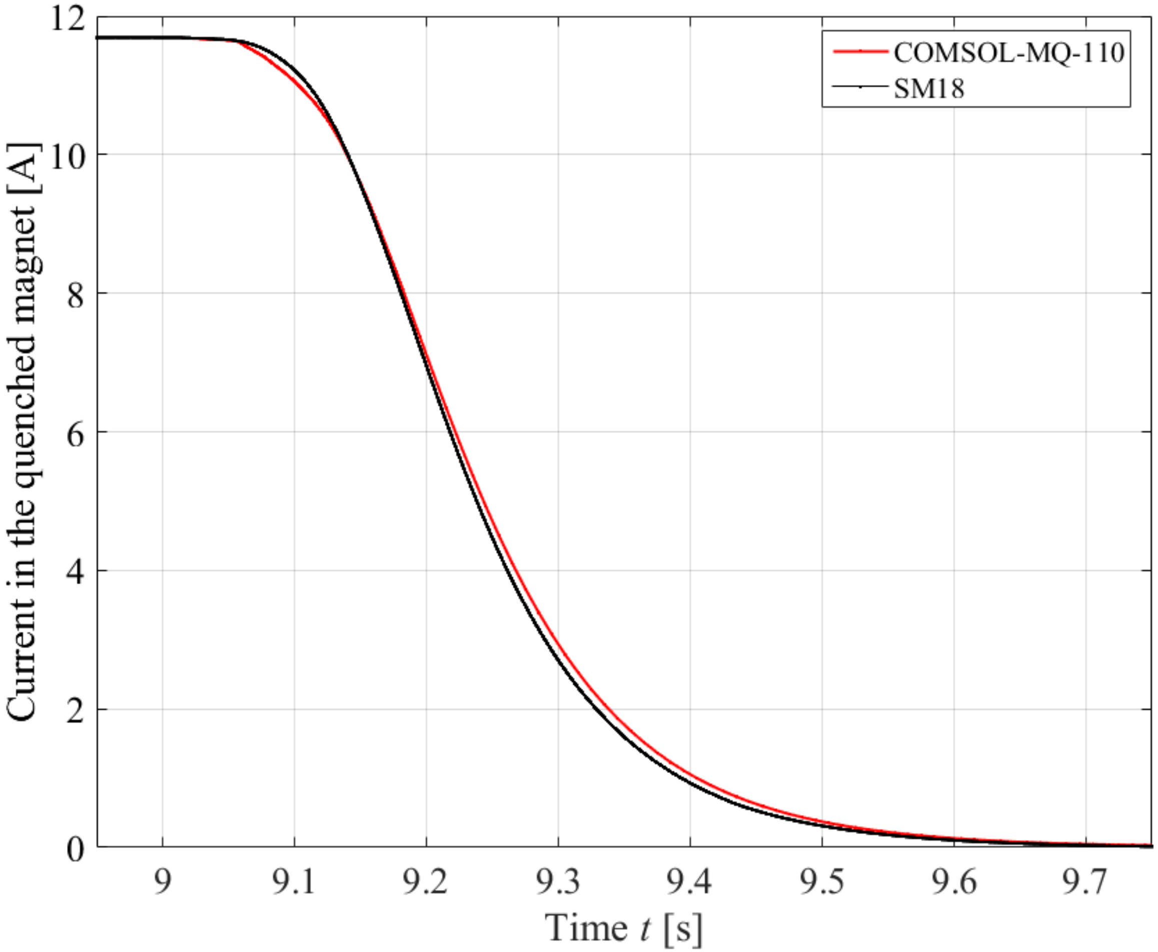
RRR = 209

v_{QP} → infinite

- Quench Heaters implemented

Heat exchange between layers and poles implemented

LHC Main Quadrupole magnet



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RRR = 100
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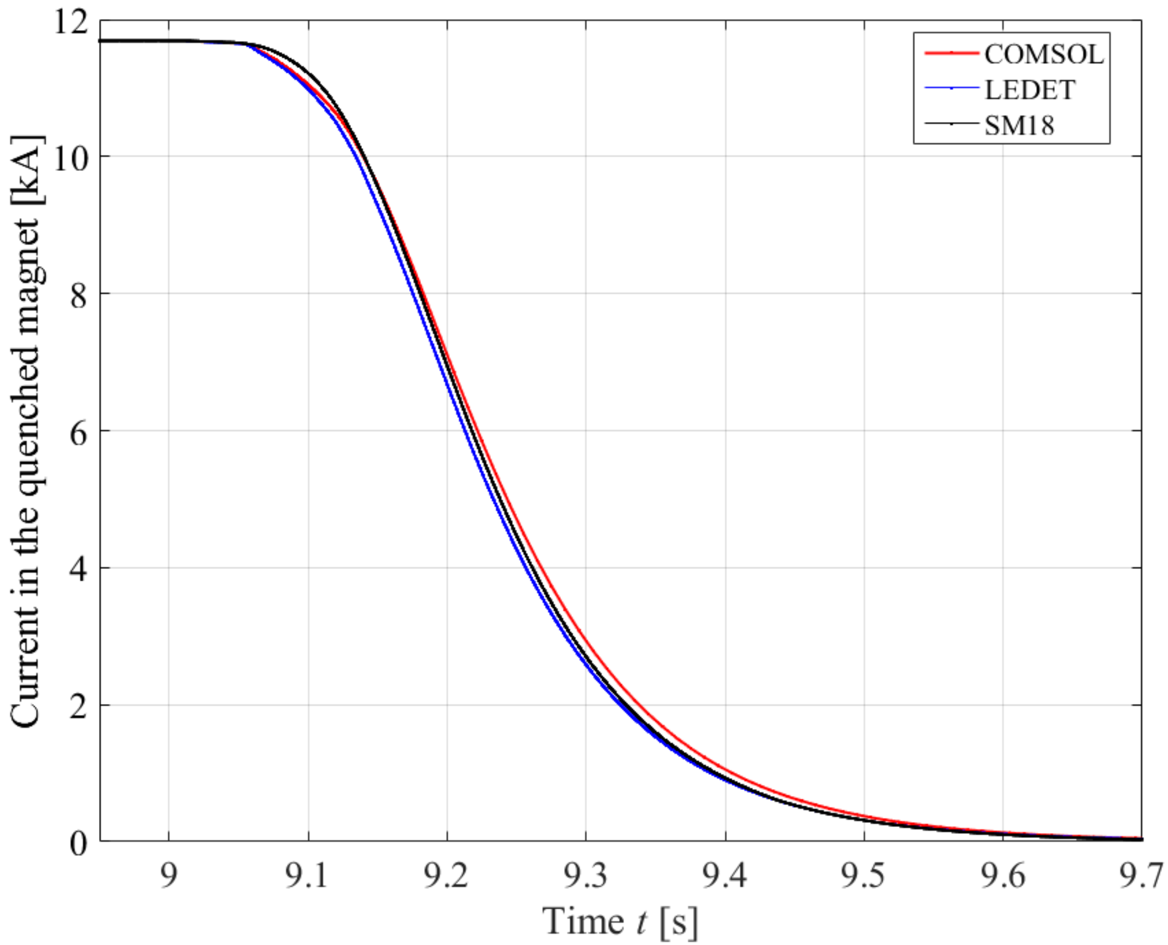
- Simplified (adiabatic) velocity of quench propagation used from the first timestep
v_{QP} = 25 m/s

LHC Main Quadrupole magnet



Good agreement with measurement data*

* Thanks to Emmanuele for implementing all these changes in LEDET within 1 (!) day

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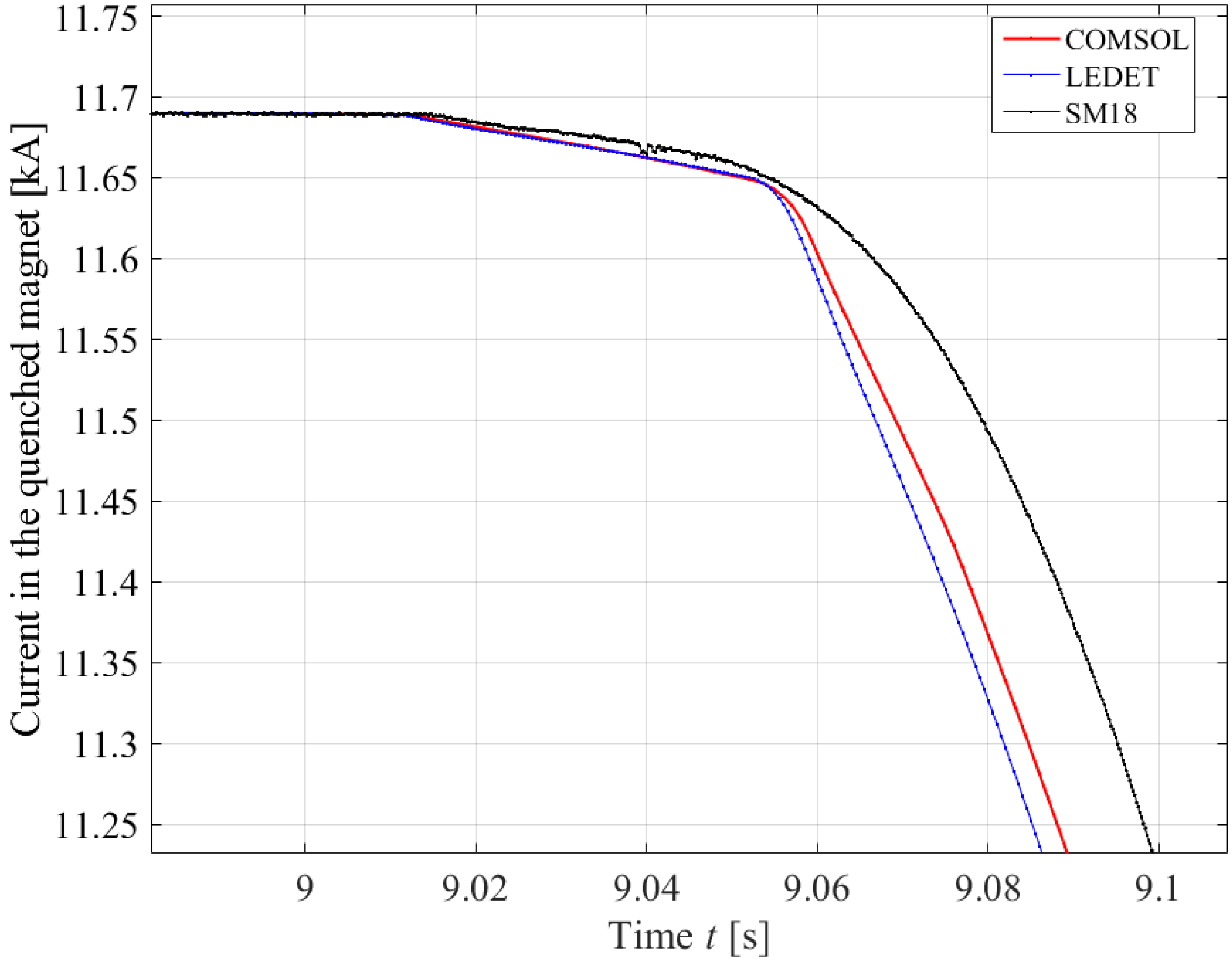
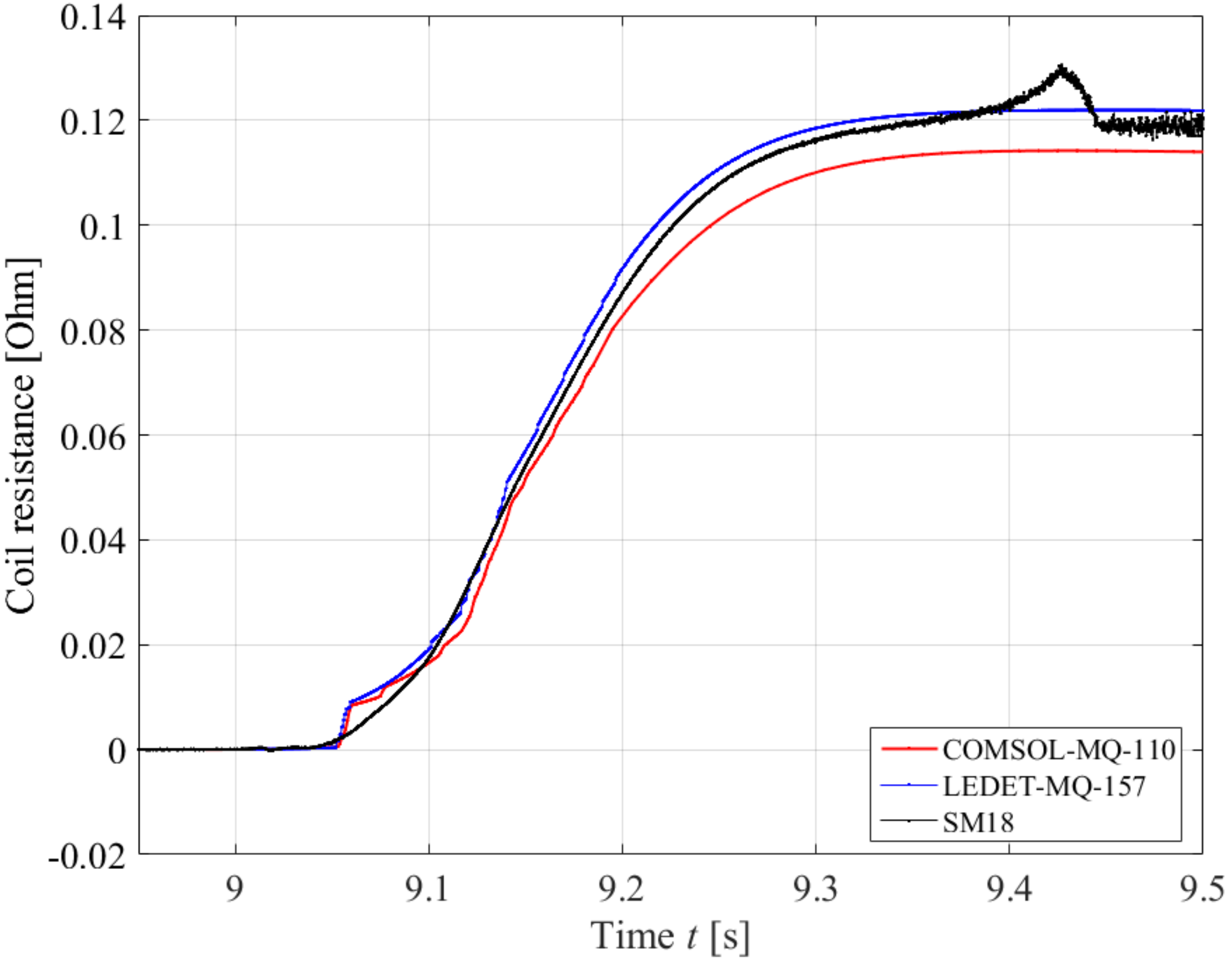


Fair agreement with measurement data

LHC Main Quadrupole magnet



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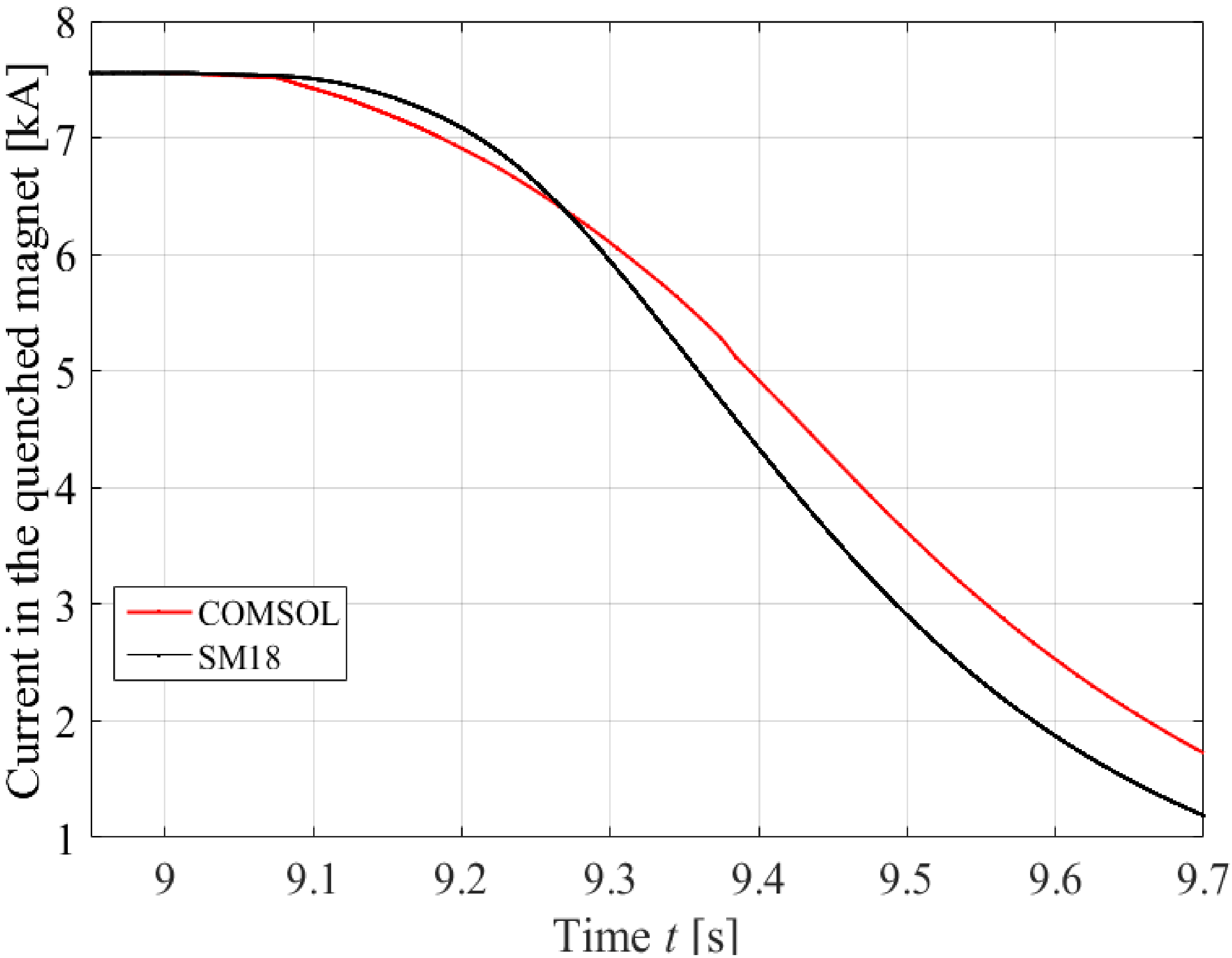

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COMSOL® Parameters:

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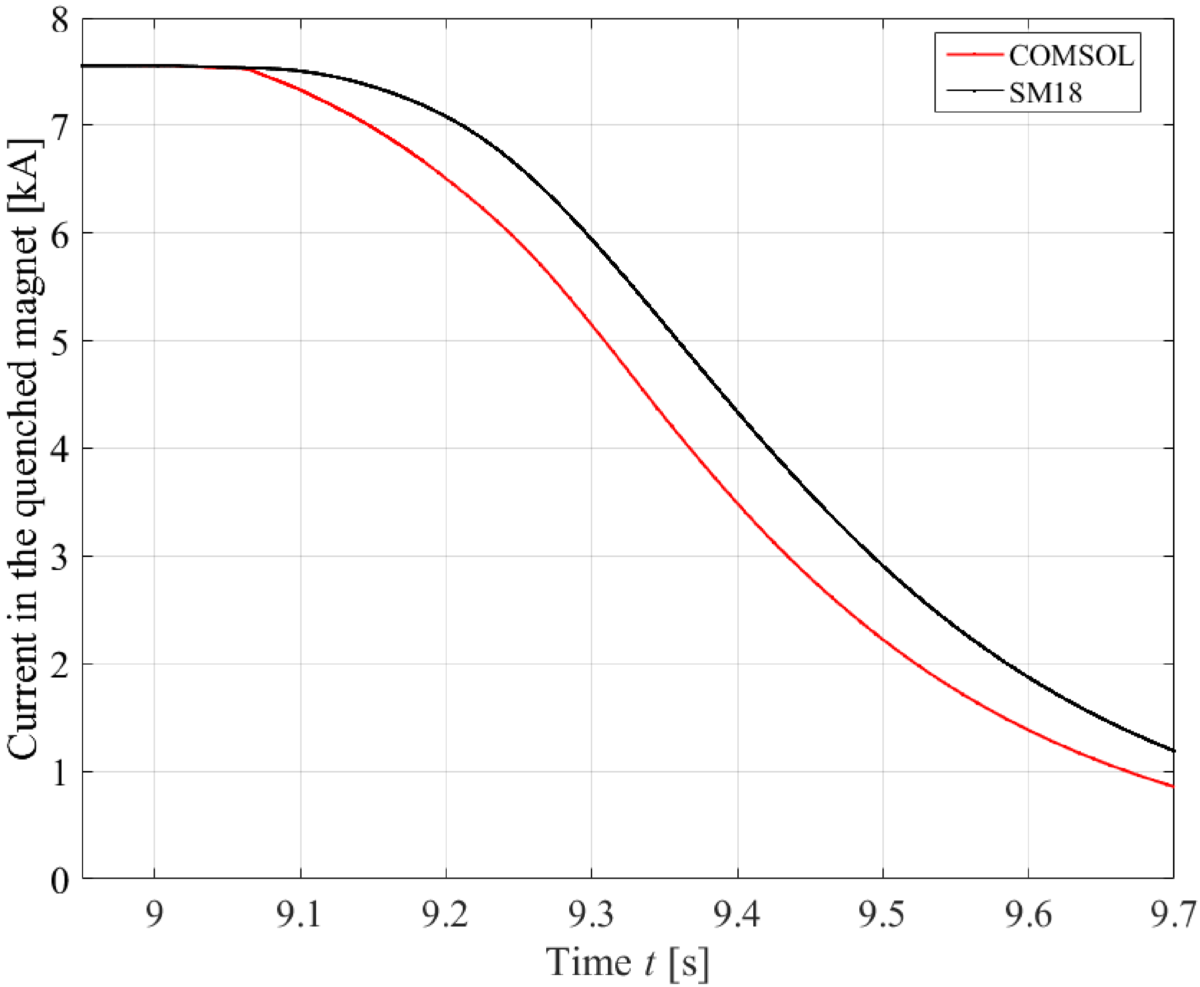
frac_He = 5.5 %
RRR = 209

- Quench Heaters implemented

Heat exchange between layers and poles implemented

$v_{QP} \rightarrow$ infinite

LHC Main Quadrupole magnet



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Parameters from the measurement:

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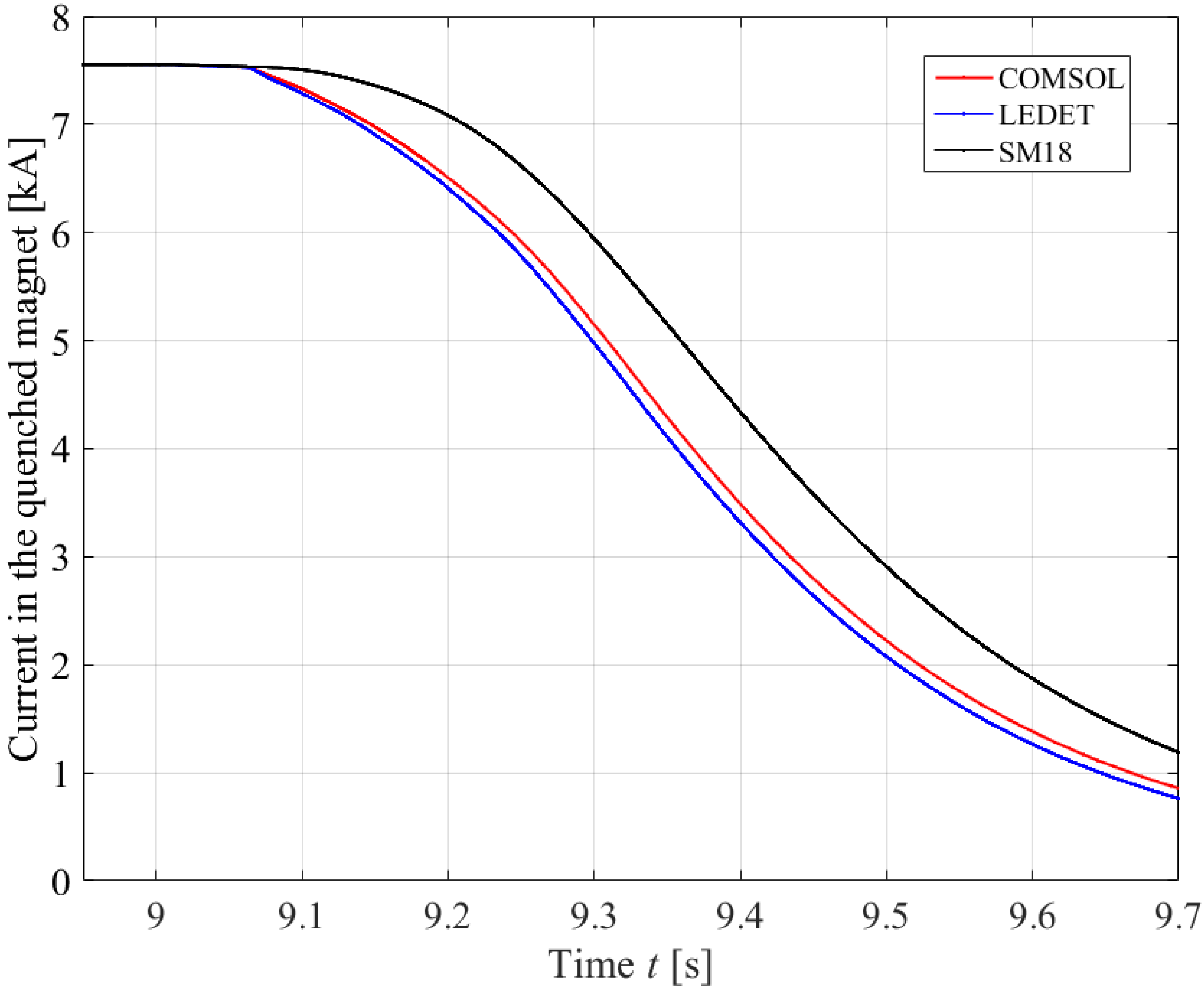
COMSOL® Parameters:

- Quenching 1 HT at
$t_{quench,HT}$ = 0 s
frac_He = 3.5 %
RRR = 100
v_{QP} → 11.45 m/s

- Quench Heaters implemented

Heat exchange between layers and poles implemented

LHC Main Quadrupole magnet



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LEDET® Parameters:

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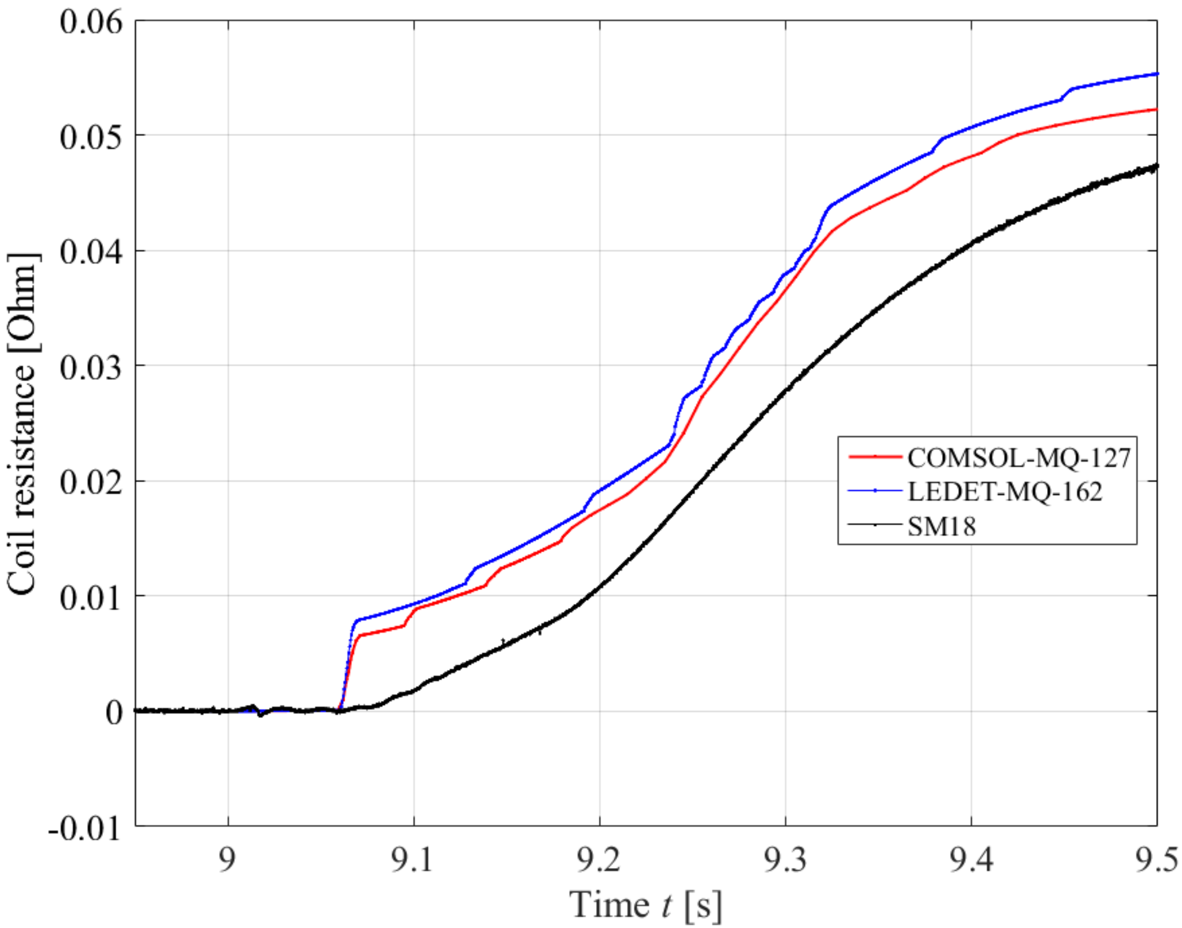
RRR = 100

v_{QP} → 11.45 m/s

- Quench Heaters implemented

- Heat exchange between layers and poles implemented

LHC Main Quadrupole magnet



Parameters from the measurement:

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- Quenching 1 HT at $t_{quench,HT}$ = 0 s
  frac_He = 3.5 %
  RRR = 100
  v_{QP} → 11.45 m/s

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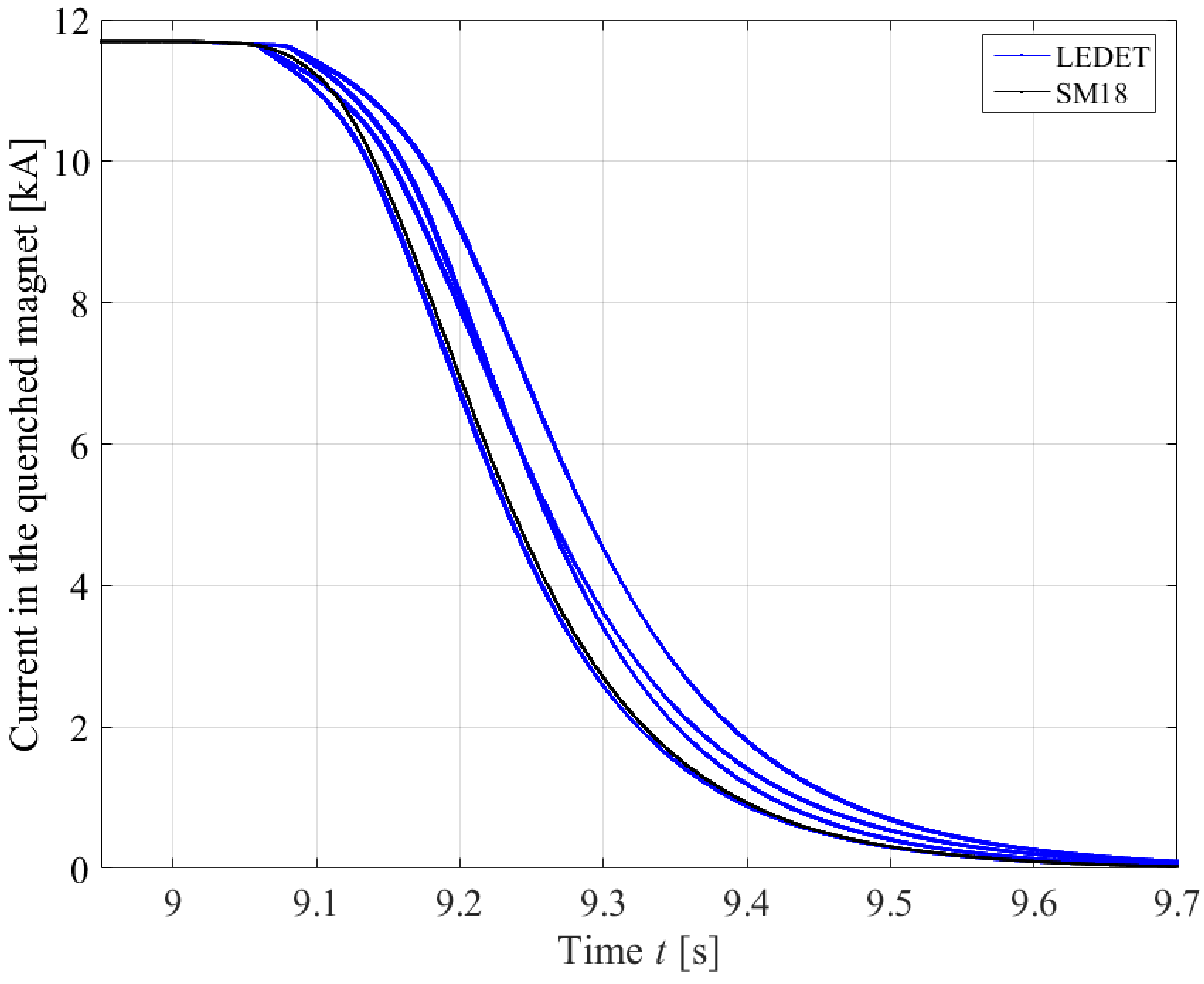
LHC Main Quadrupole magnet

Fist guess

1. v_{QP} → infinite → Halfturn is quenched immediately over the complete length
2. RRR = 209
3. Fraction of helium (frac_He) = 5.5 %

1. Changing RRR
2. Changing frac_He
3. Changing v_{QP}

LHC Main Quadrupole magnet



Parameters from the measurement:

$I_{test,1}$ = **11.69 kA**

RRR Variation:

- RRR = 100
- RRR = 209

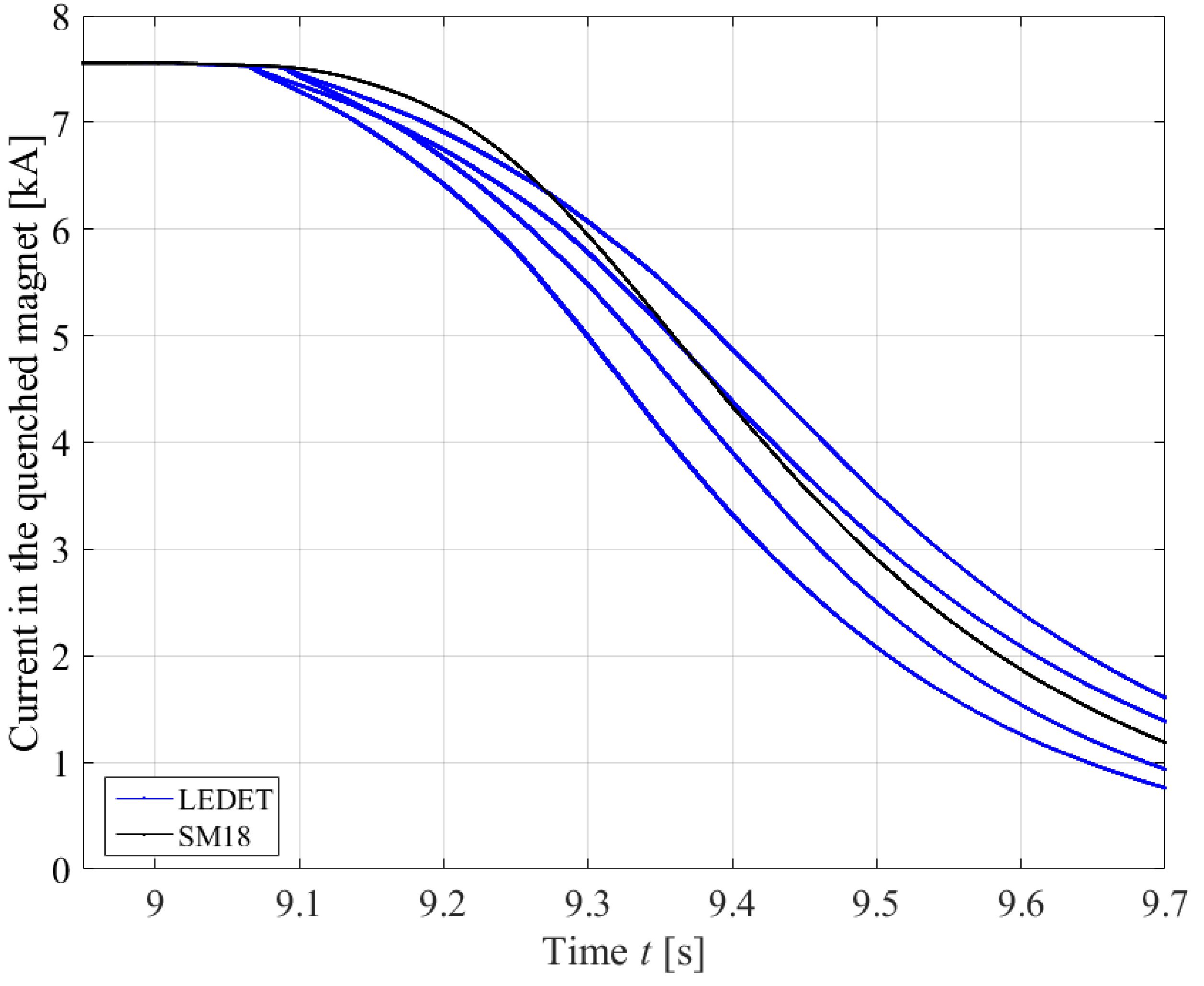
frac_He Variation:

- frac_He = 3.5 %,
- frac_He = 5.5 %

V_QP (adiabatic) Variation:

- 25 m/s
- 0.5 x 25 m/s

LHC Main Quadrupole magnet



Parameters from the measurement:

$I_{test,2}$ = **7.554 kA**

RRR Variation:

- RRR = 100
- RRR = 209

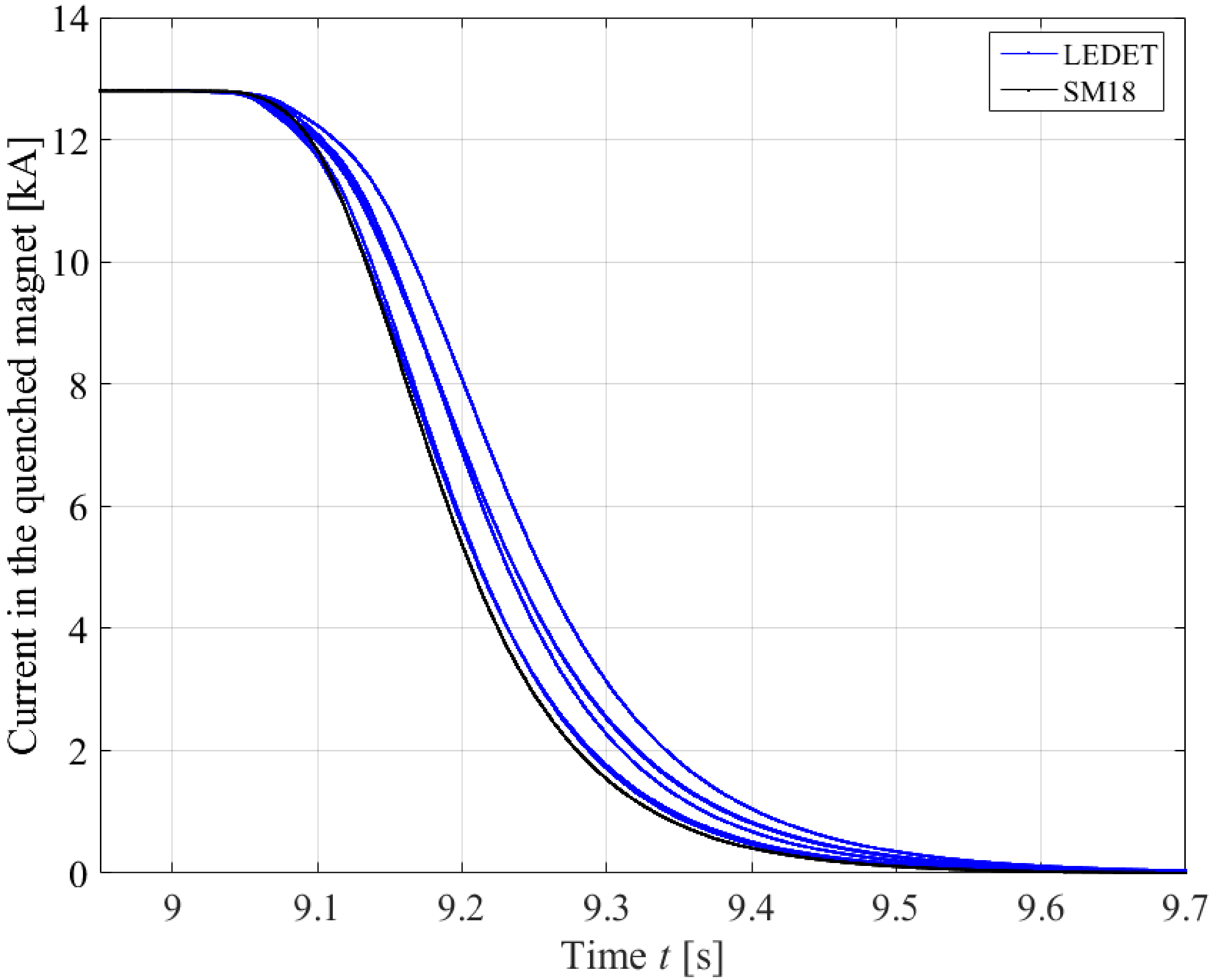
frac_He Variation:

- frac_He = 3.5 %,
- frac_He = 5.5 %

V_QP (adiabatic) Variation:

- 11.45 m/s
- 0.5 x 11.45 m/s

LHC Main Quadrupole magnet



Parameters from the measurement:

$I_{test,3}$ = **12.80 kA**

RRR Variation:

- RRR = 100
- RRR = 209

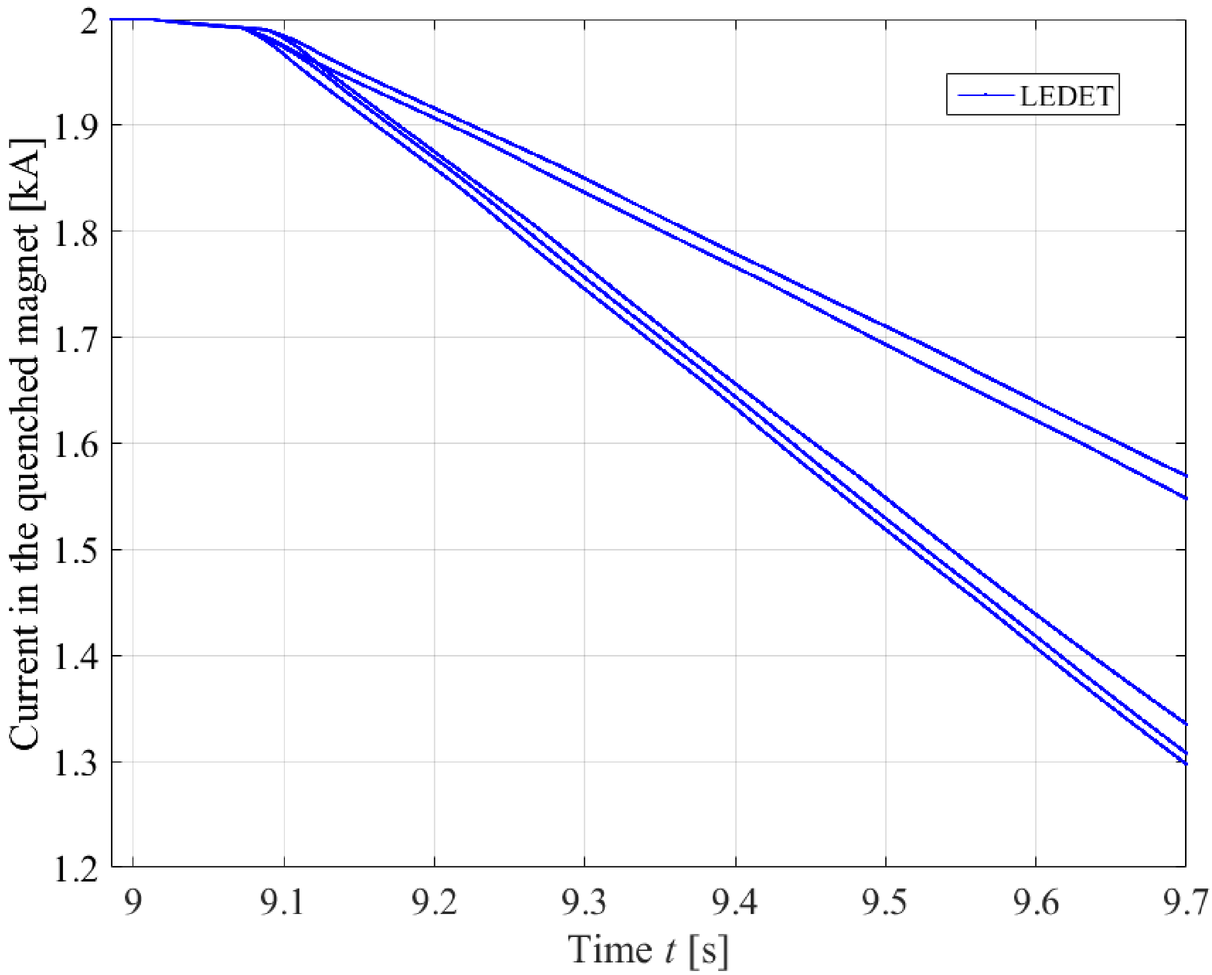
frac_He Variation:

- frac_He = 3.5 %,
- frac_He = 5.5 %

V_QP (adiabatic) Variation:

- 45 m/s
- 0.5 x 45 m/s

LHC Main Quadrupole magnet



Parameters from the measurement:

$I_{test,4}$ = **2.0 kA**

RRR Variation:

- RRR = 100
- RRR = 209

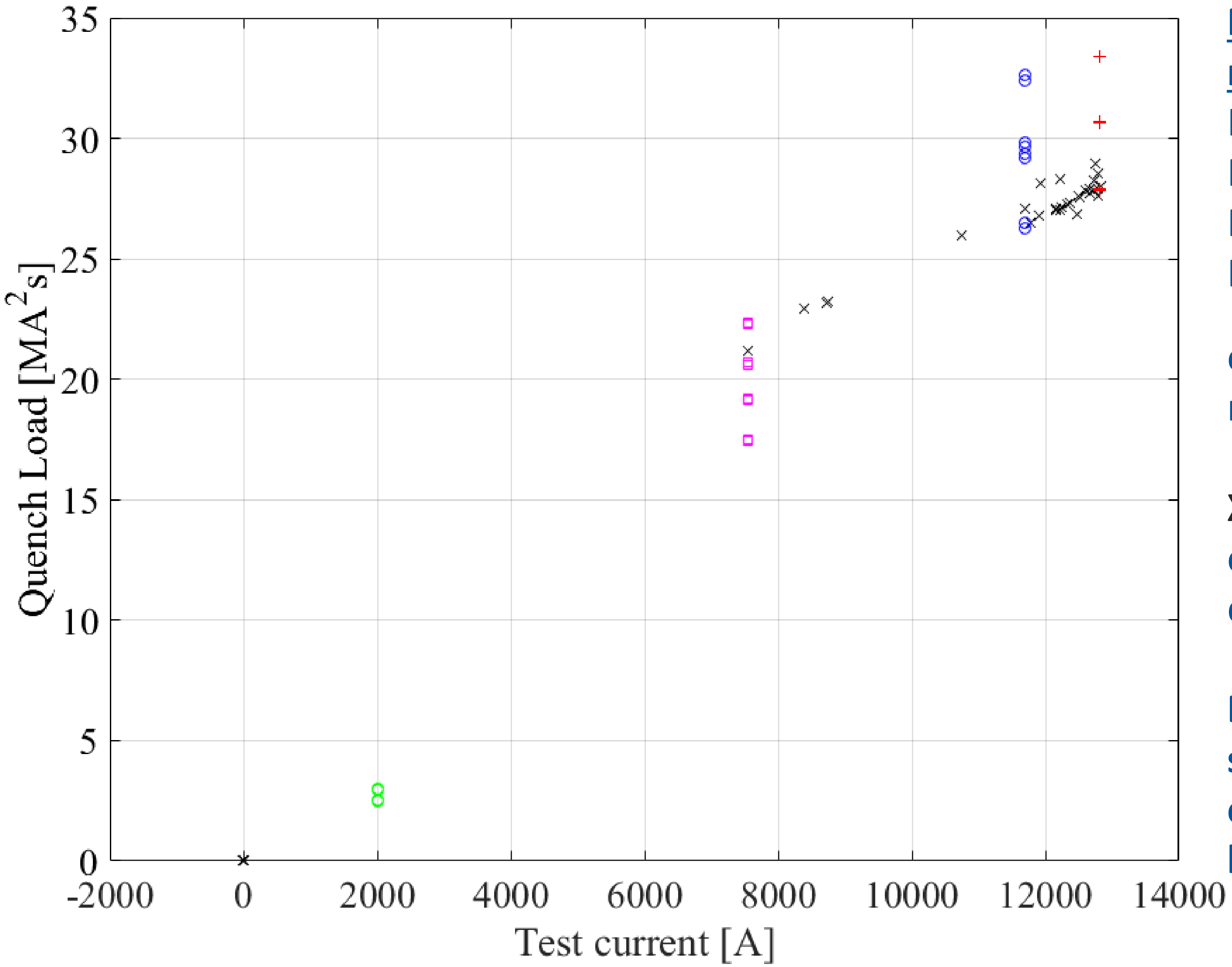
frac_He Variation:

- frac_He = 3.5 %,
- frac_He = 5.5 %

V_QP (adiabatic) Variation:

- 1.8 m/s
- 0.5 x 1.8 m/s

LHC Main Quadrupole magnet



Parameters from the measurement:

$I_{test,1}$ = 11.69 kA
$I_{test,2}$ = 7.554 kA
$I_{test,3}$ = 12.80 kA
$I_{test,4}$ = 2.0 kA

colors => simulation results

X => quench load calculated from SM18 data

Distribution of test signals from in SM18 even at identical current level

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Main quadrupole circuit

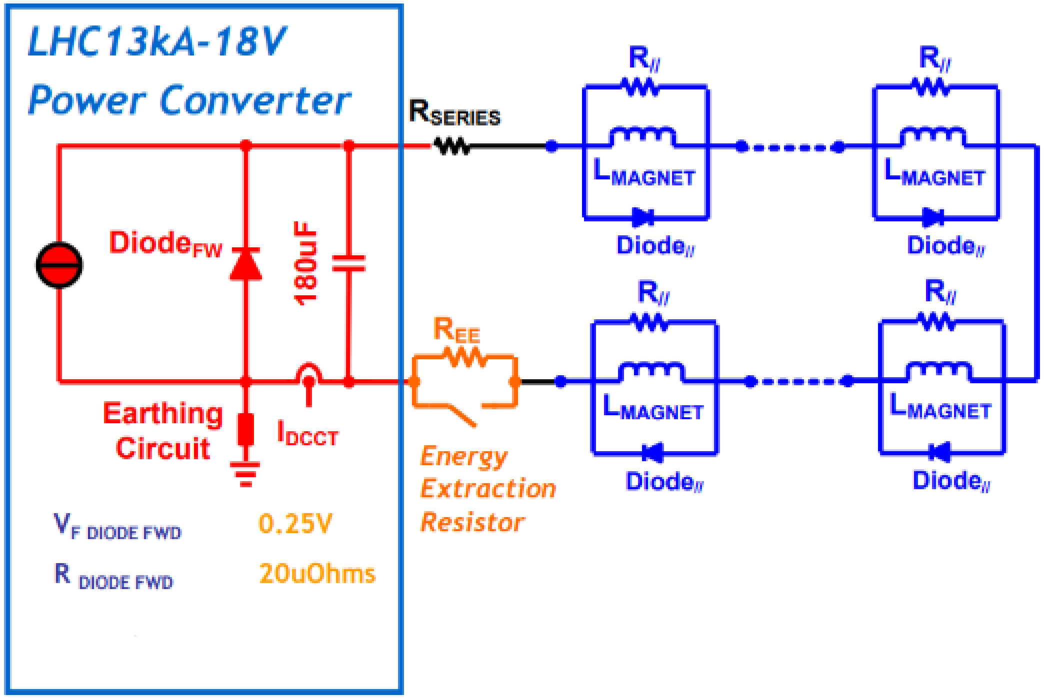


Fig. 7: LHC main quadrupole circuit – simplified schematic [1]

The LHC main quadrupole circuit:

- power converter (PC)
- energy-extraction (EE)
- main quadrupole magnets (MQ) and their protection system
- earthing circuits (EC)
- redundant system of sub-modules within the power converter

Main quadrupole circuit

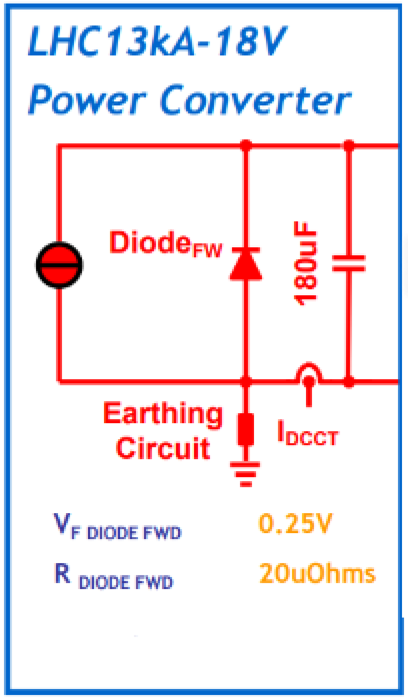
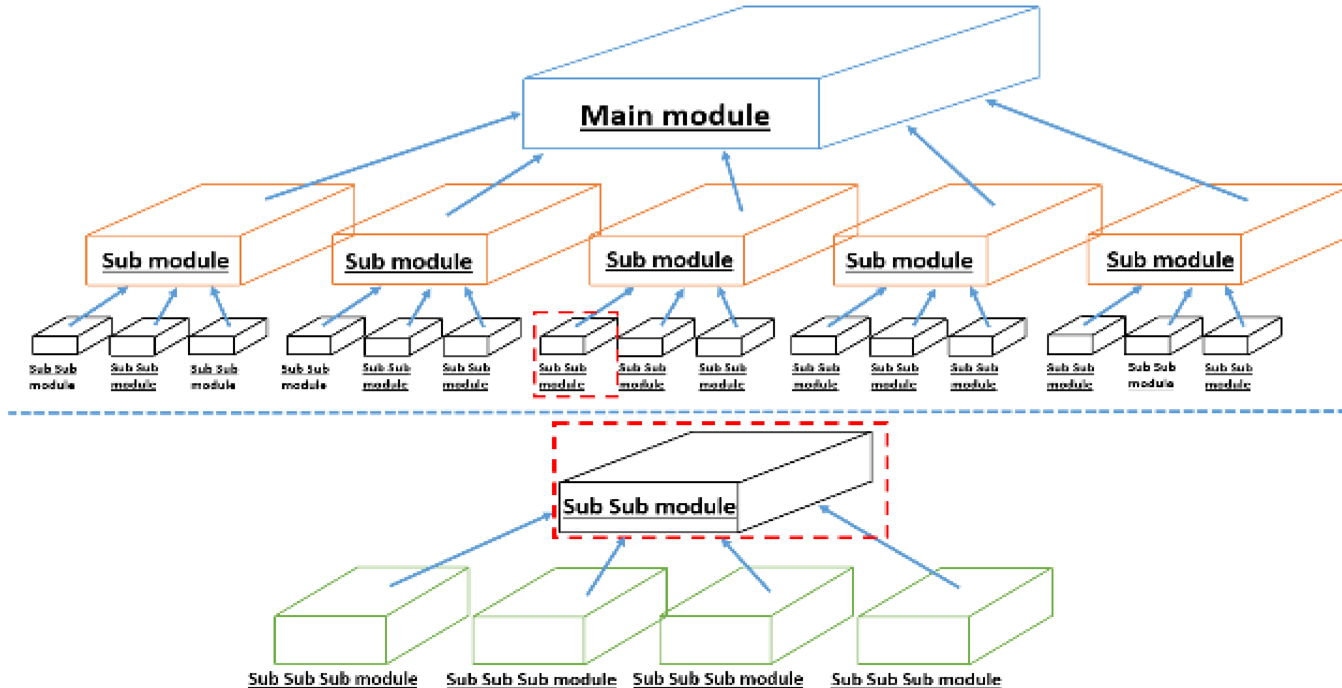


Fig. 7: LHC main quadrupole circuit – simplified schematic [1]



+ earthing circuit
+ filters
+ magnets
+ energy extraction

Main quadrupole circuit

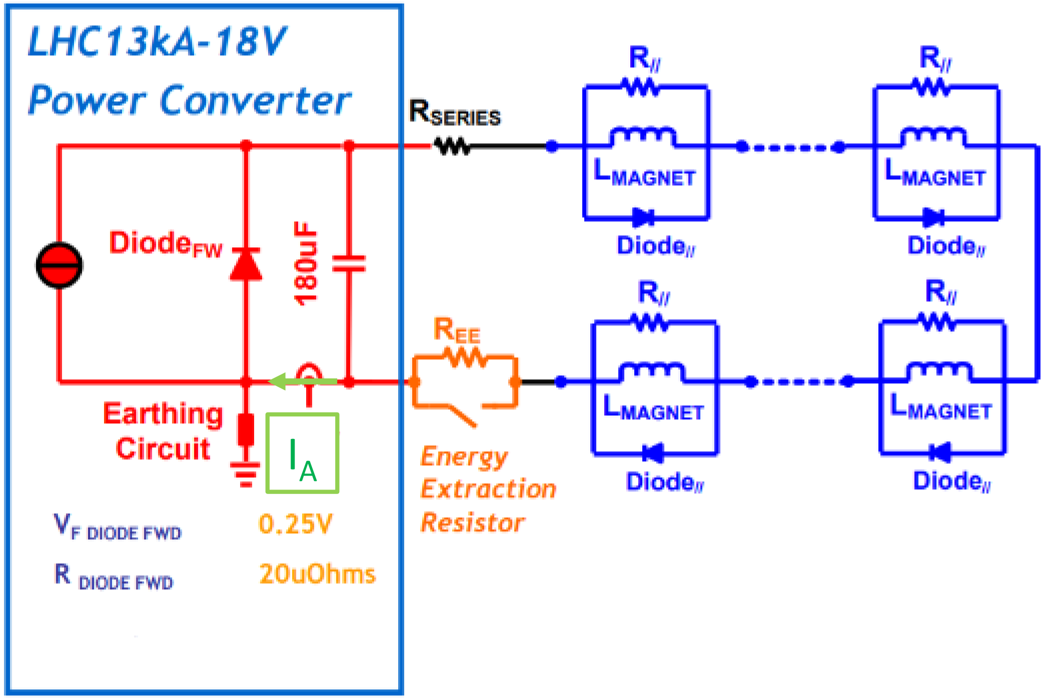
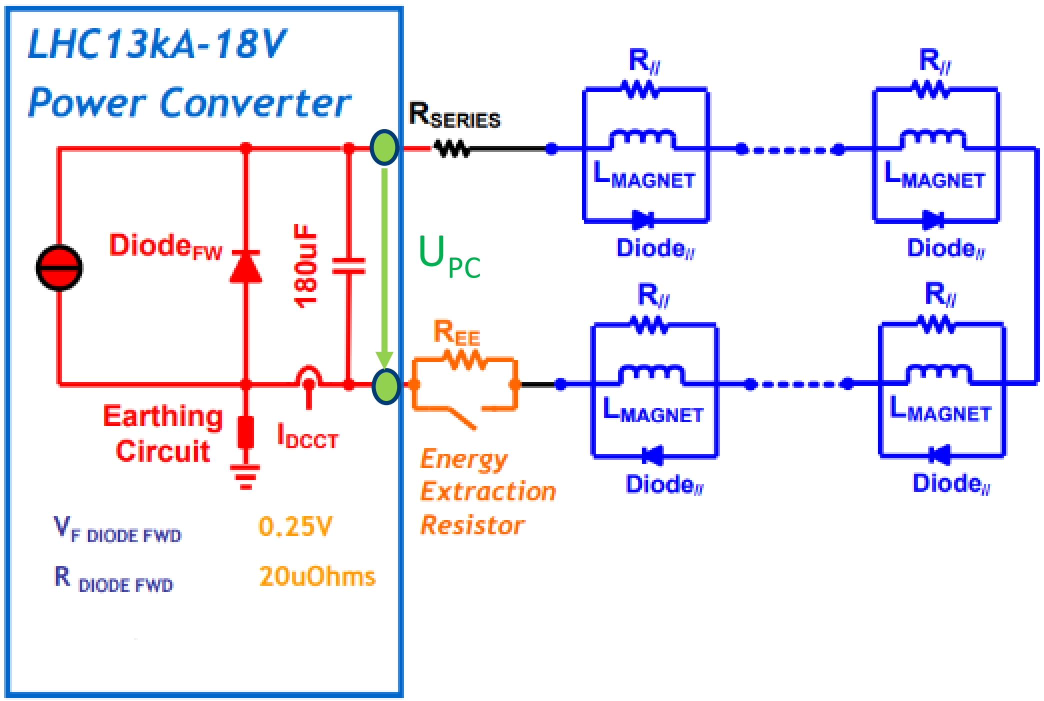


Fig. 7: LHC main quadrupole circuit – simplified schematic [1]

Signals for the validation:

- **Circuit current** **(I_{Meas}, I_A)**
- Voltage across the power converter output (U_{PC})
- Voltage across the energy extraction resistor (U_{EE})
- Current to ground (I_{EC})

Main quadrupole circuit



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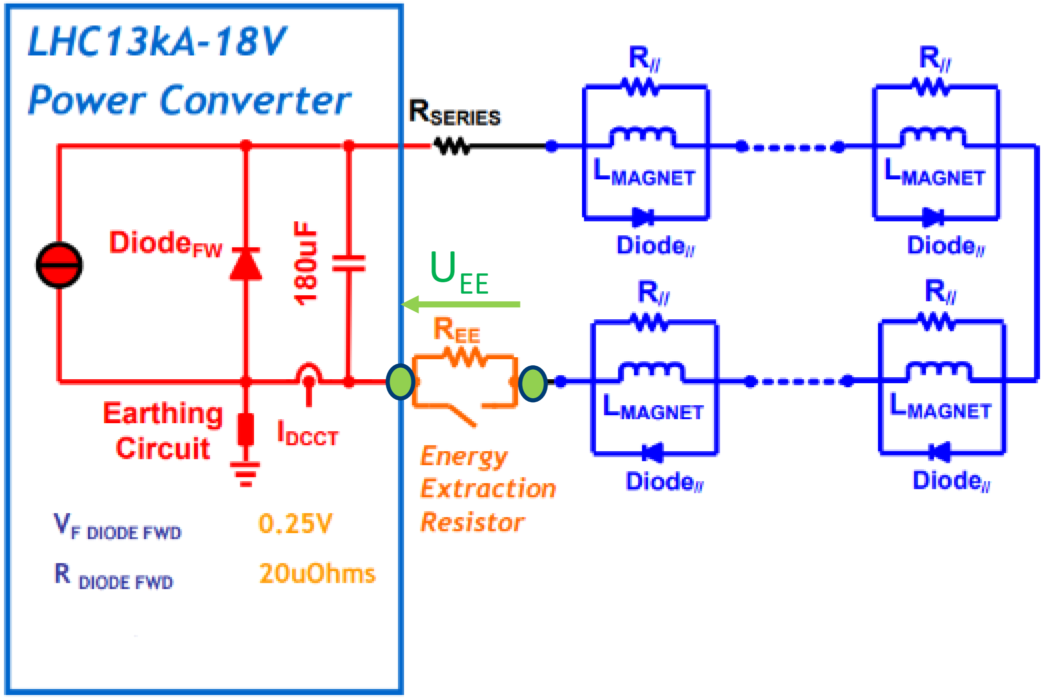
Main quadrupole circuit



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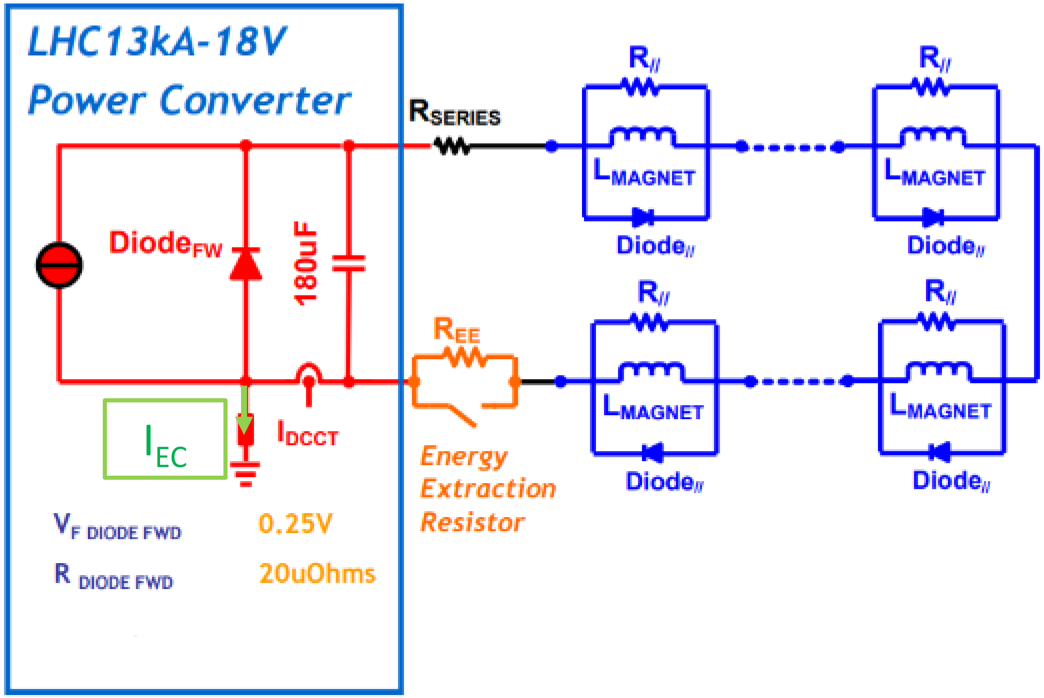

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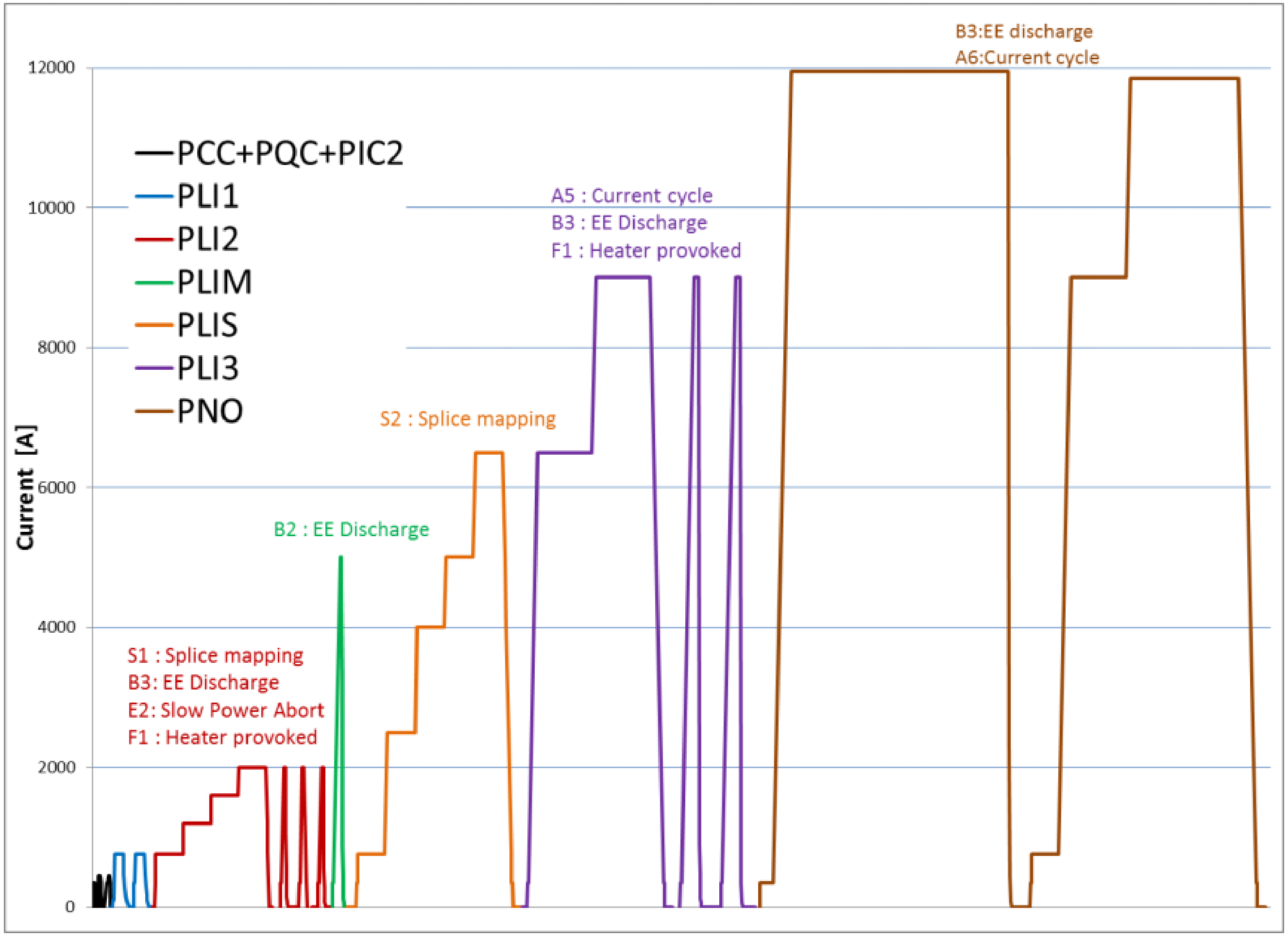


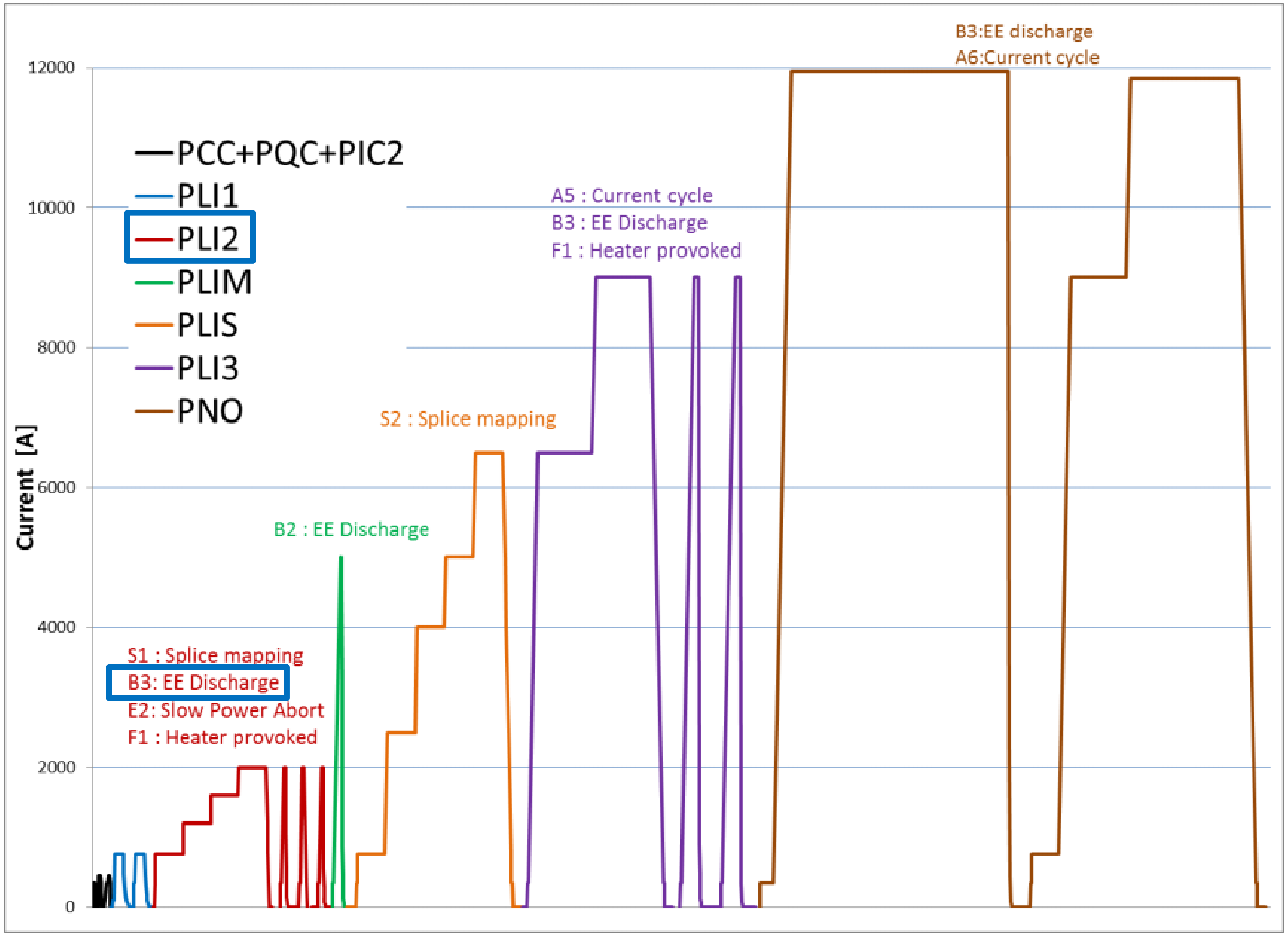
Hardware Commissioning Tests :

- Circuit has to pass several tests with different criteria
- For the circuit validation:

Simulating the tests [2]:

  - PLI2-B3 (2 kA)
  - PLIM-B2 (5 kA)
  - PNO-B3 (10.35 kA)

Main quadrupole circuit



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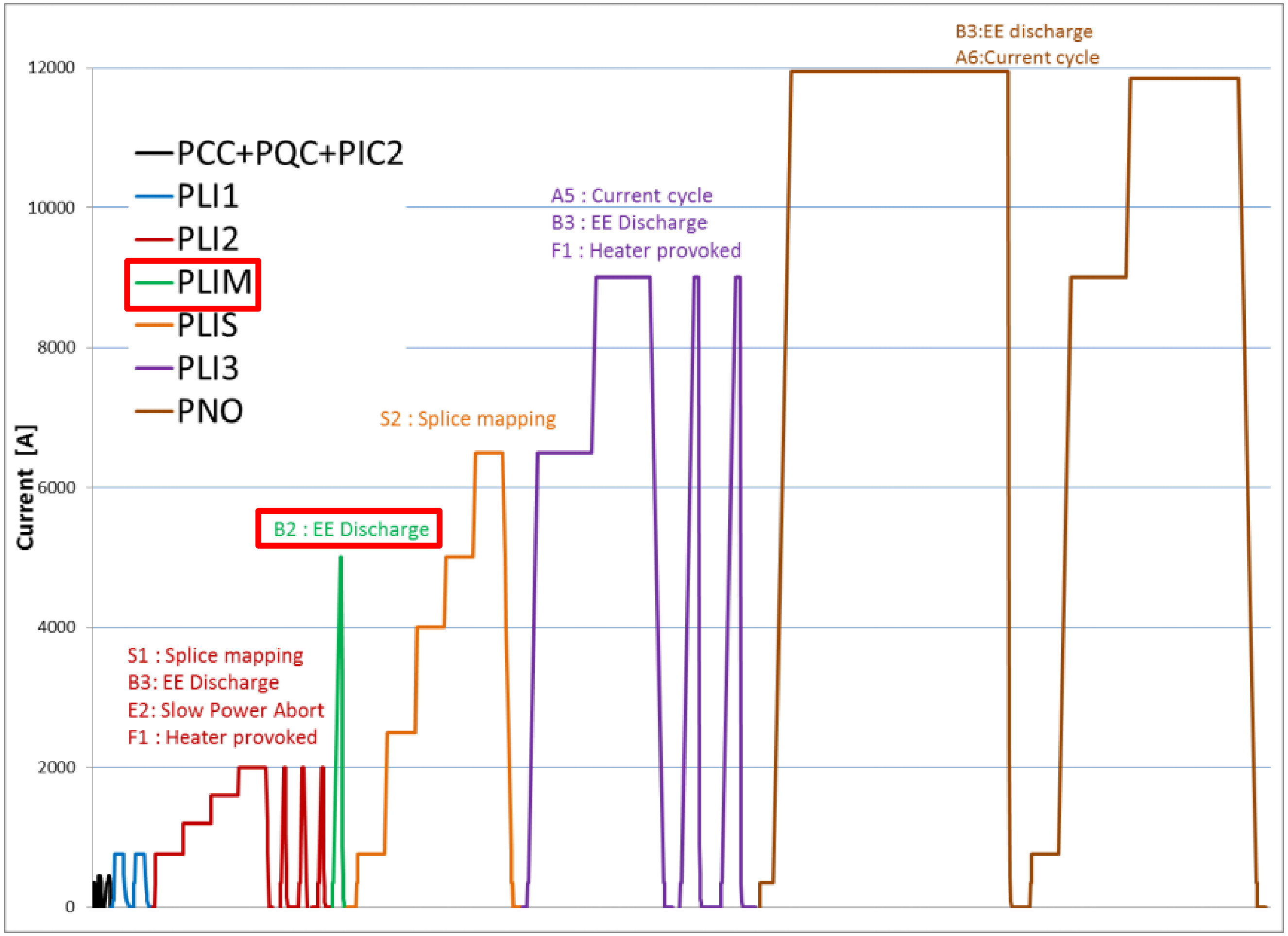

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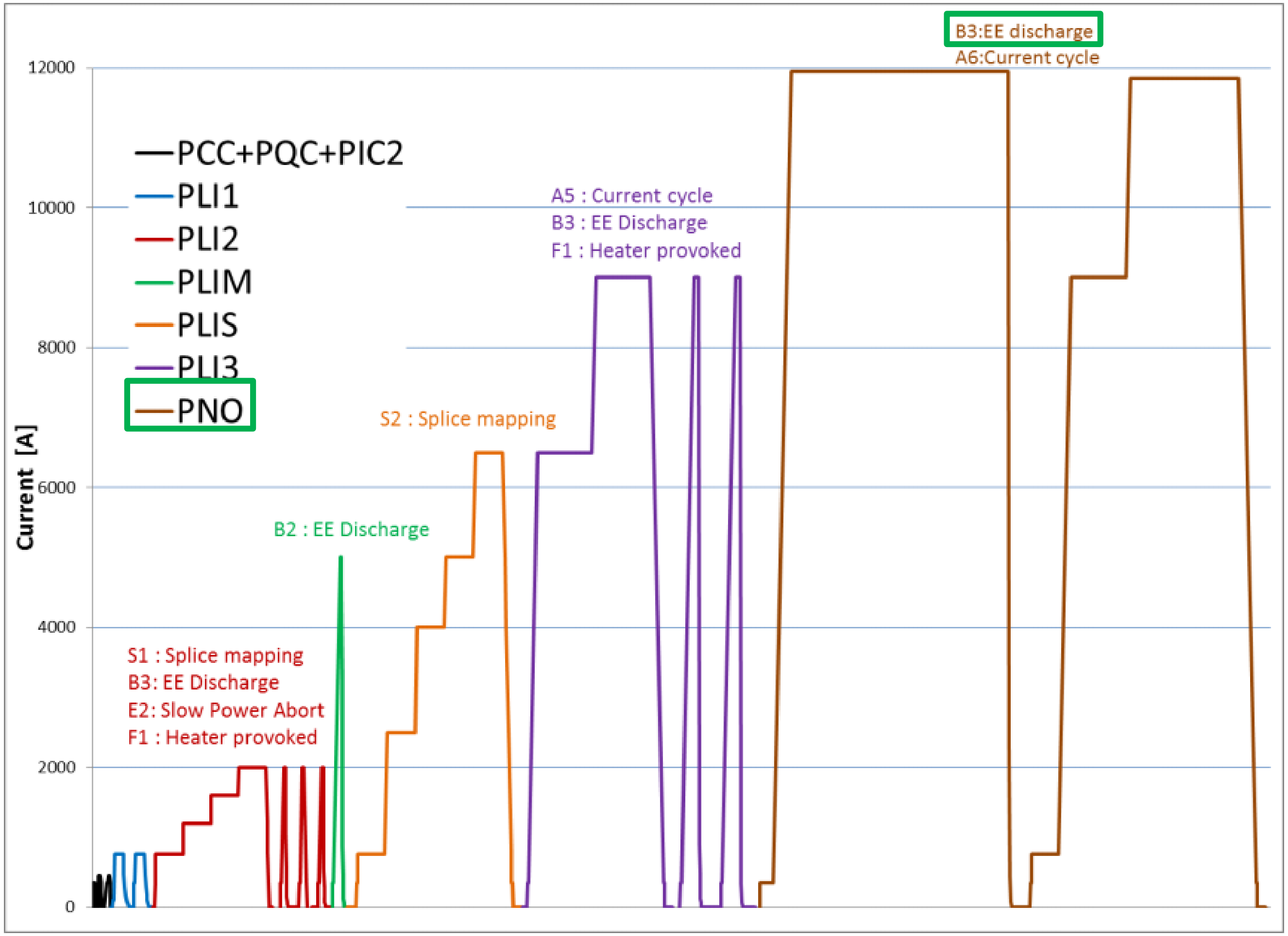

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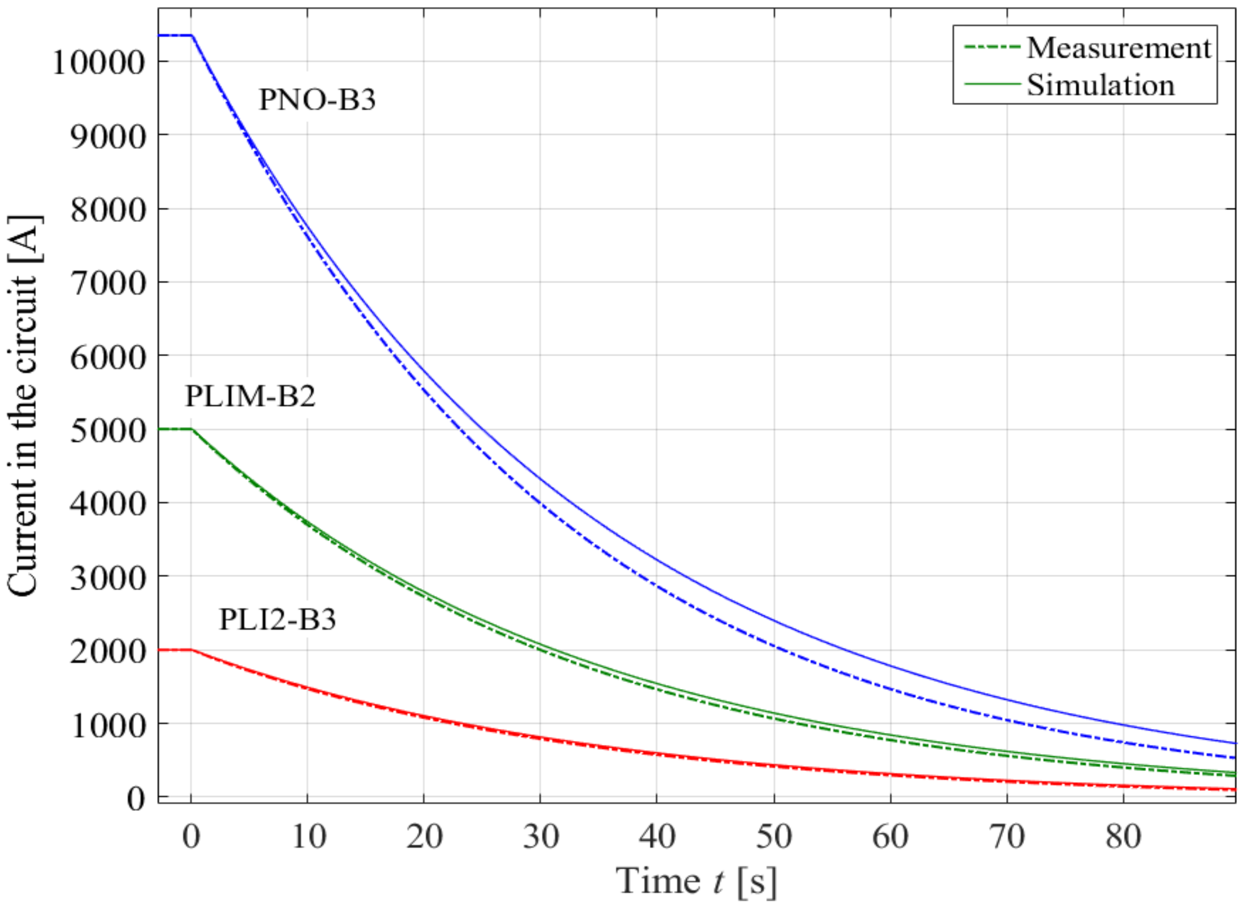


Parameters from the measurement:

t_{FPA} = -20 ms

t_{EE} = 82 ms

PSpice® Parameters:

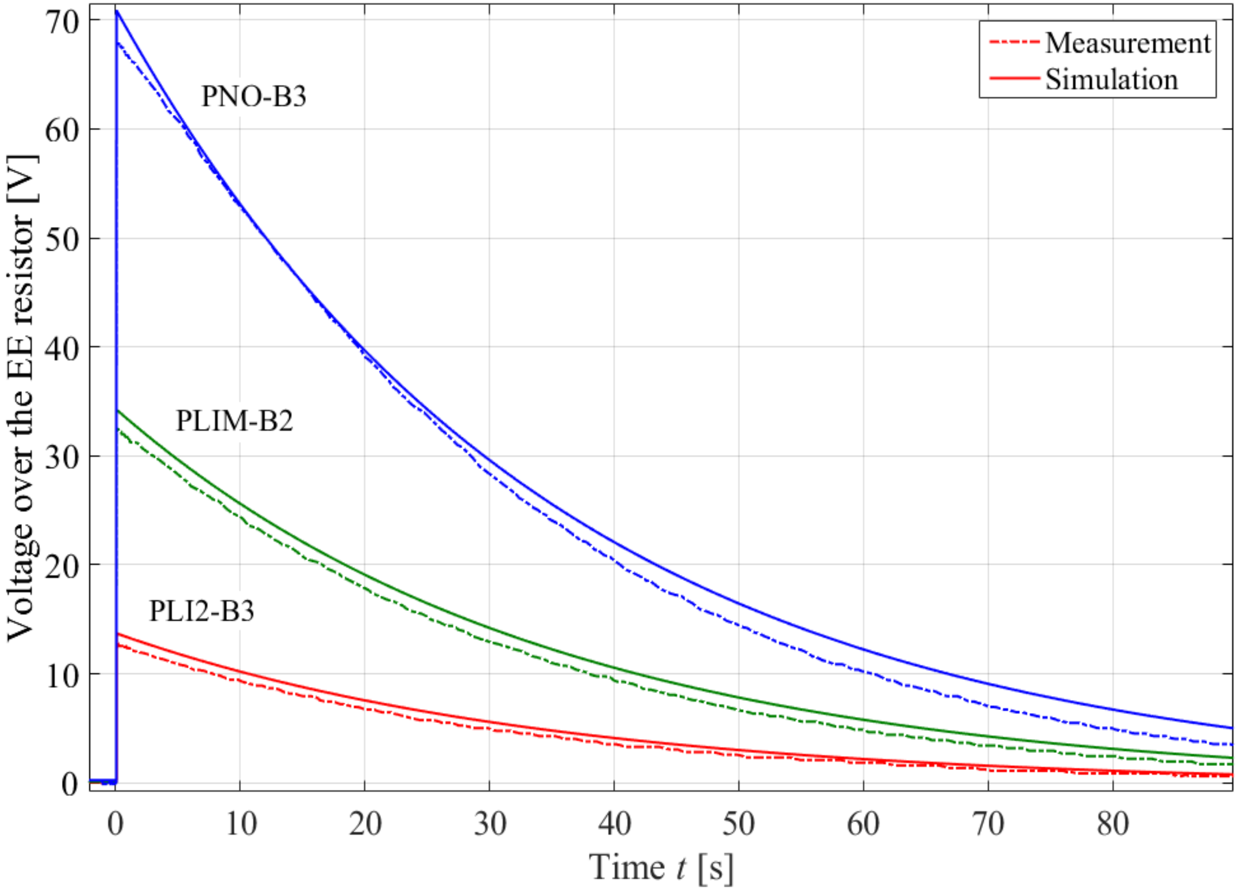
R_{warm} = 0.664404 mΩ

R_{EE} = 6.85 mΩ

Maximum difference within the test PNO-B3 is 300 A

Fair agreement with measurement data

Main quadrupole circuit



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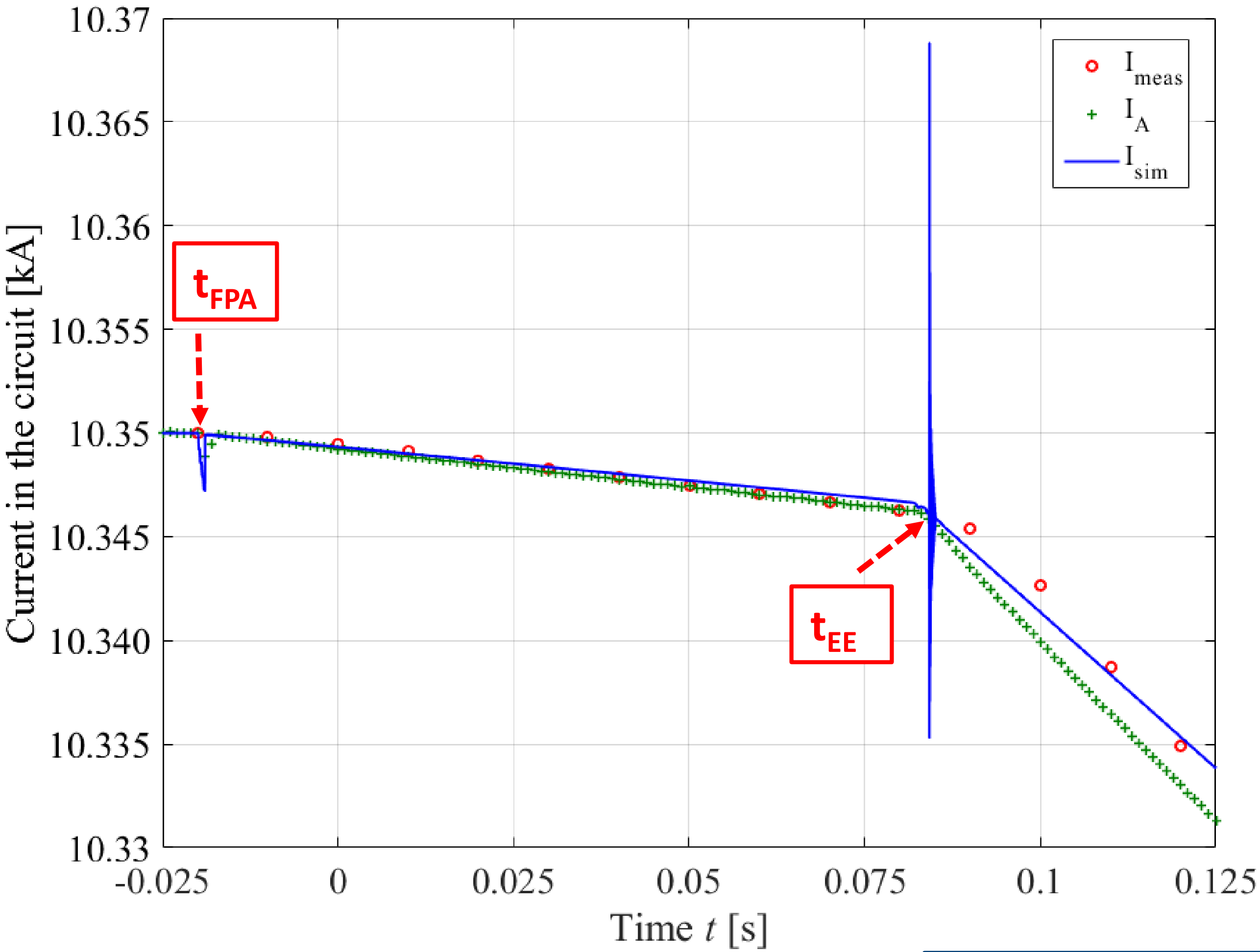


Closer look at the test data of PNO-B3 (10.35 kA test):

I_{meas} => Current measured with 100 Hz

I_A => Current measured with 1 kHz

I_{Sim} => Simulated current

- Acquisition frequency of 1 kHz is maybe not “enough”

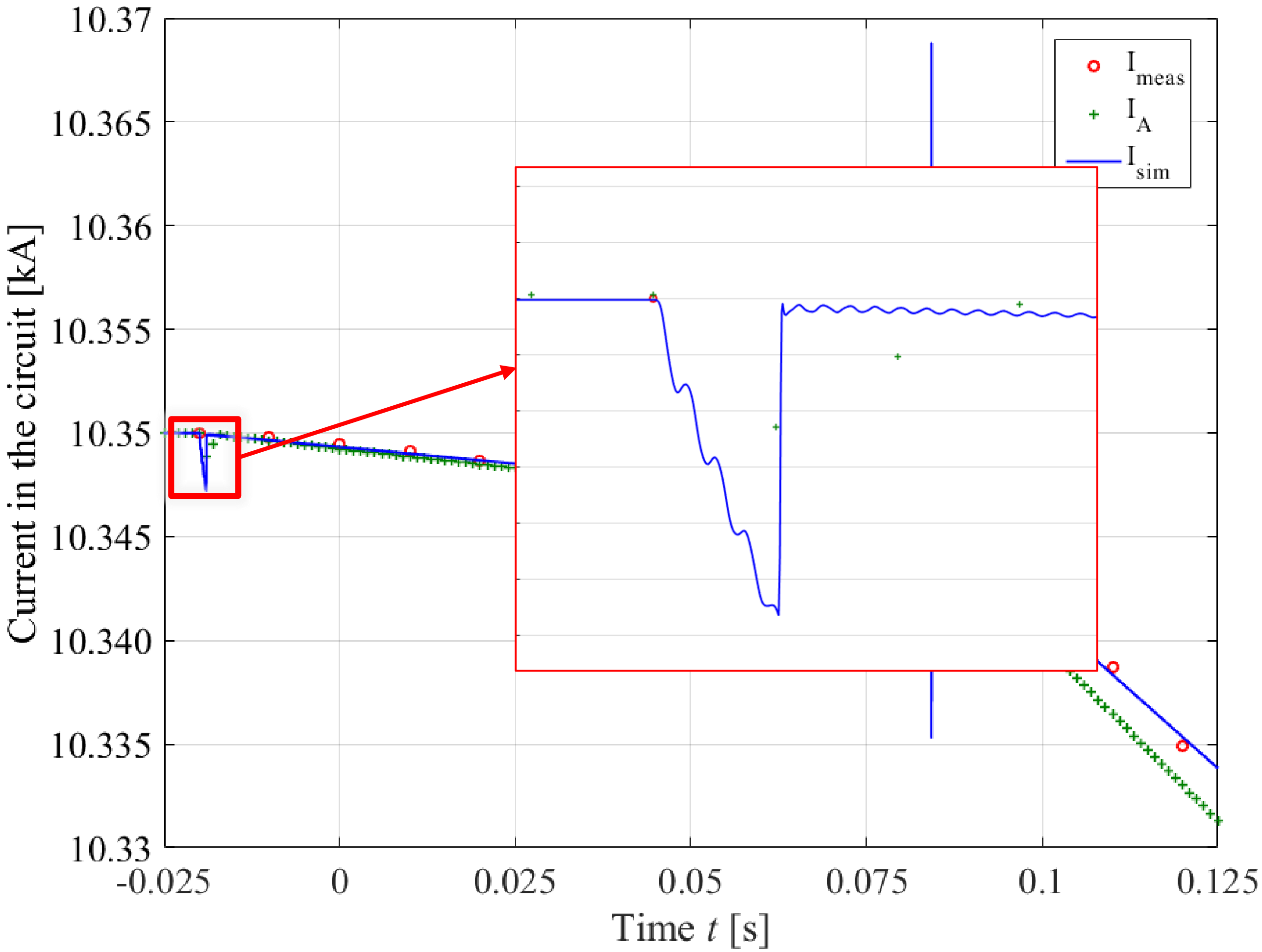
Time constants at the events:

$\tau_{FPA} = L_M \cdot N_M / R_{warm} = 792.28$ s

$\tau_{EE} = L_M \cdot N_M / (R_{warm} + R_{EE}) = 72.66$ s

Good agreement with measurement data

Main quadrupole circuit



Closer look at the test data of PNO-B3 (10.35 kA test):

I_{meas} => Current measured with 100 Hz

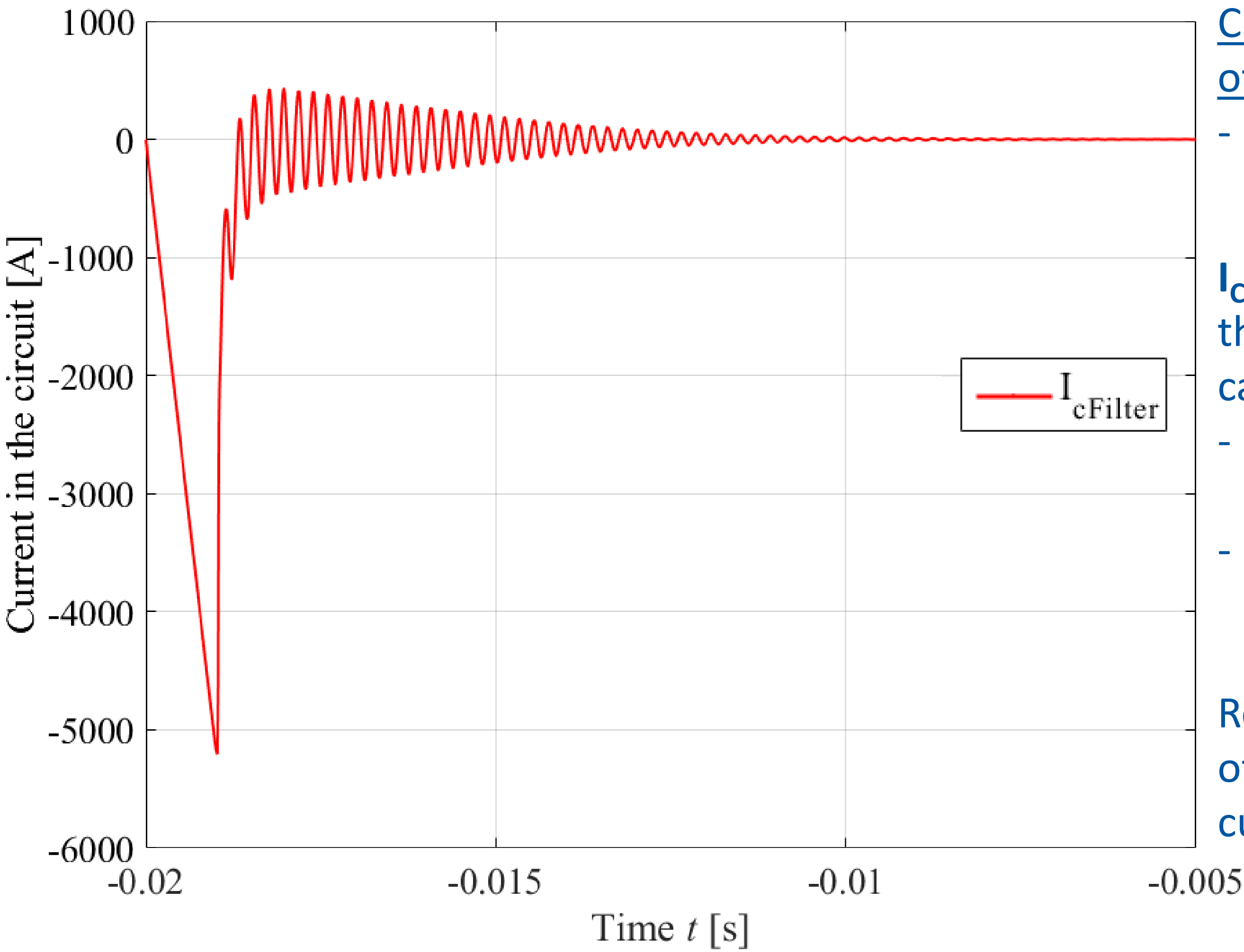
I_A => Current measured with 1 kHz

I_{Sim} => Simulated current

- Acquisition frequency of 1 kHz is maybe not "enough"
- Oscillation with ~4.4 kHz (comes close to the frequency of the output filter transfer function)
- Searching for the peak at t_{FPA}

Good agreement with measurement data

Main quadrupole circuit



Closer look at the test data of PNO-B3 (10.35 kA test):

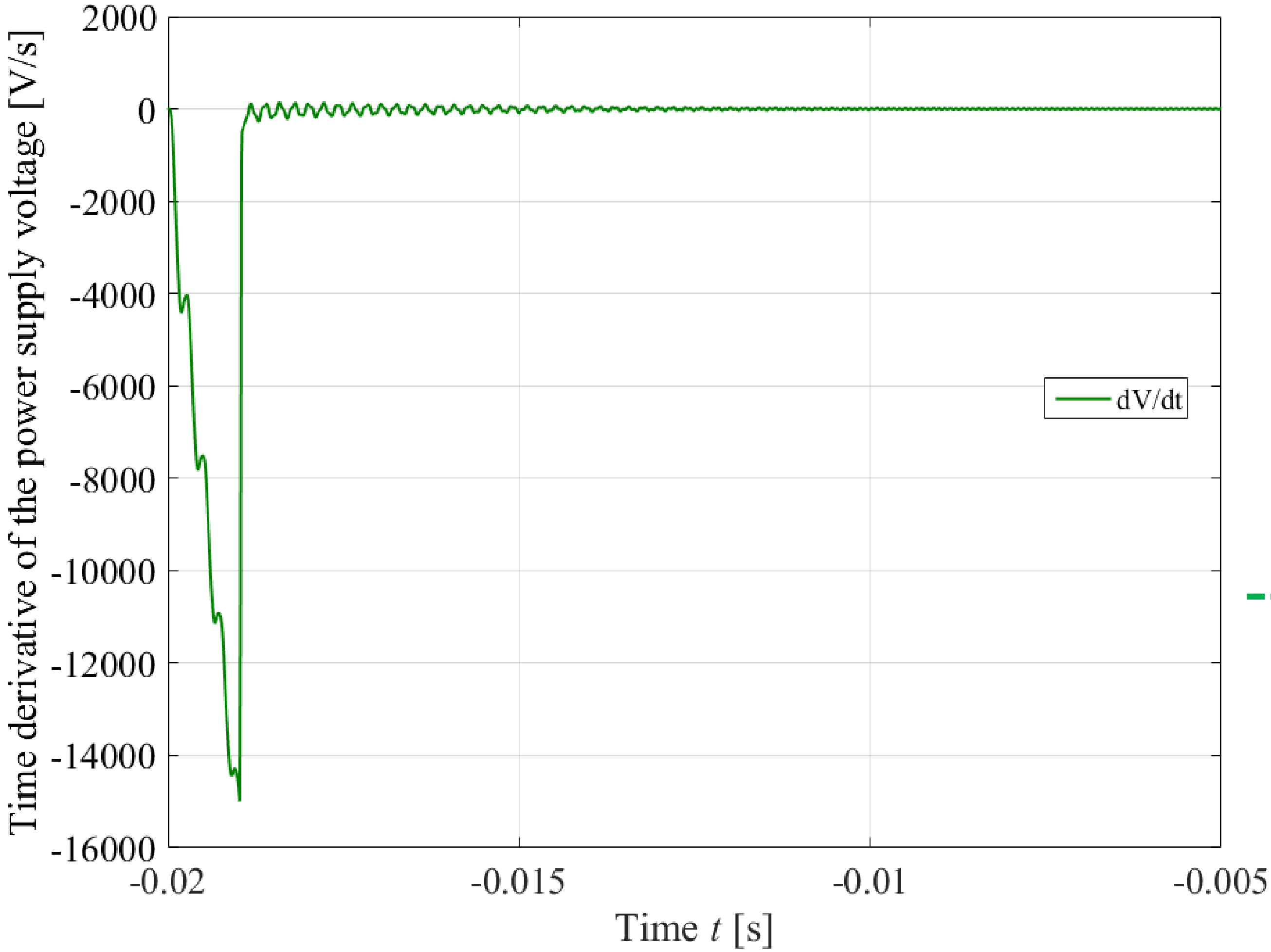
- Searching for the peak at t_{FPA}

I_C => Sum of all currents through all parallel capacitors in:

- filter of the Sub Sub module
- Main filter of the power converter

Results in the peak value of the simulated circuit current

Main quadrupole circuit



Closer look at the test data of PNO-B3 (10.35 kA test):

- Searching for the peak at t_{FPA}

Double check:

$I_C = C \times dU_C / dt$

- dU_C / dt = 14987 V/s
- C = 5202 A /14987 V/s

C = 0.347 F

In the main diode module:

2 x 18 uF + 18 x 10 uF

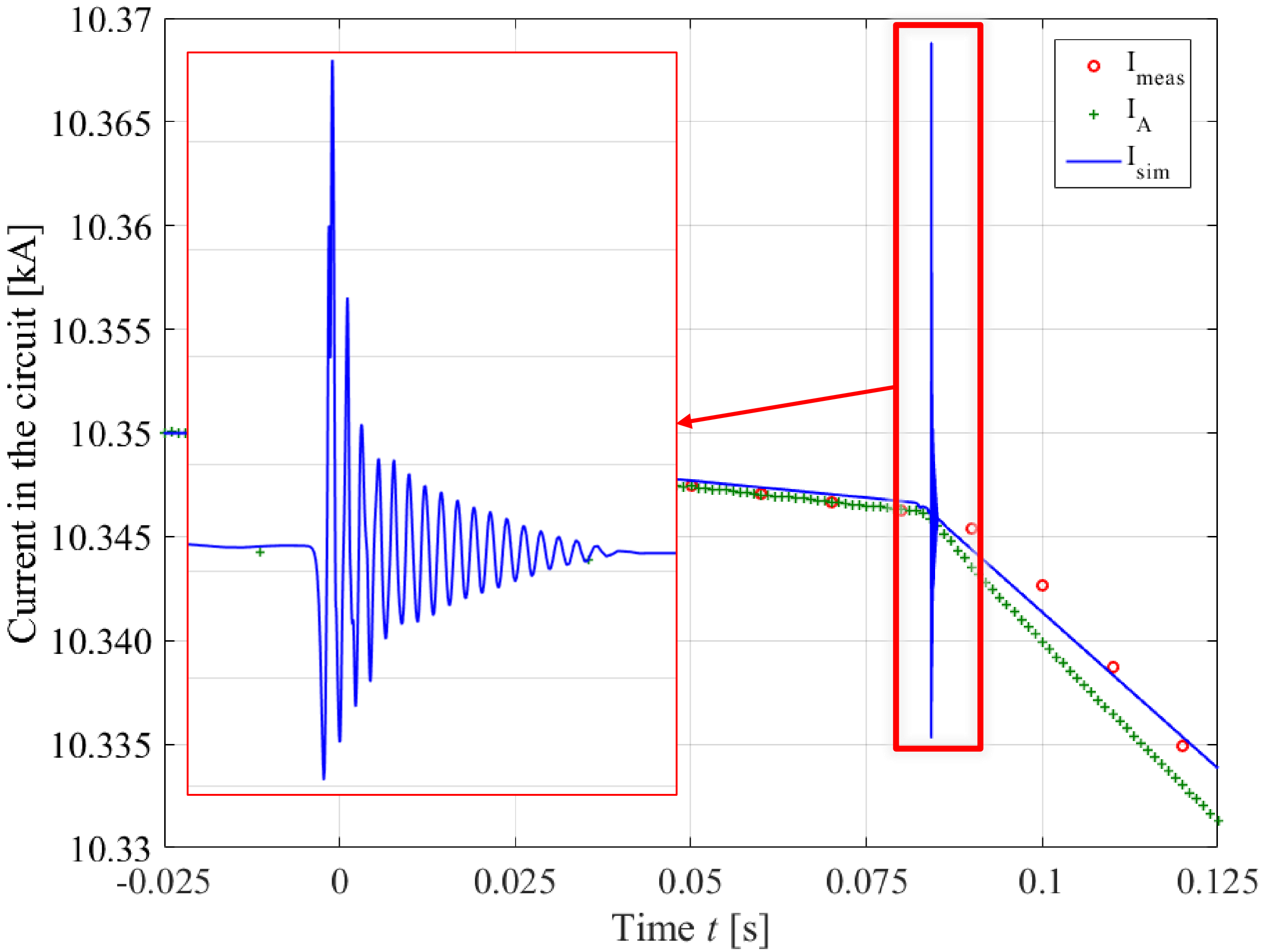
In the sub sub module filter:

15 x 10 mF + 15 x 10 mF + 15 x 9 x 470 uF

In total => **C = 0.364 F**

→ r.E [%]= -4.67 %

Main quadrupole circuit



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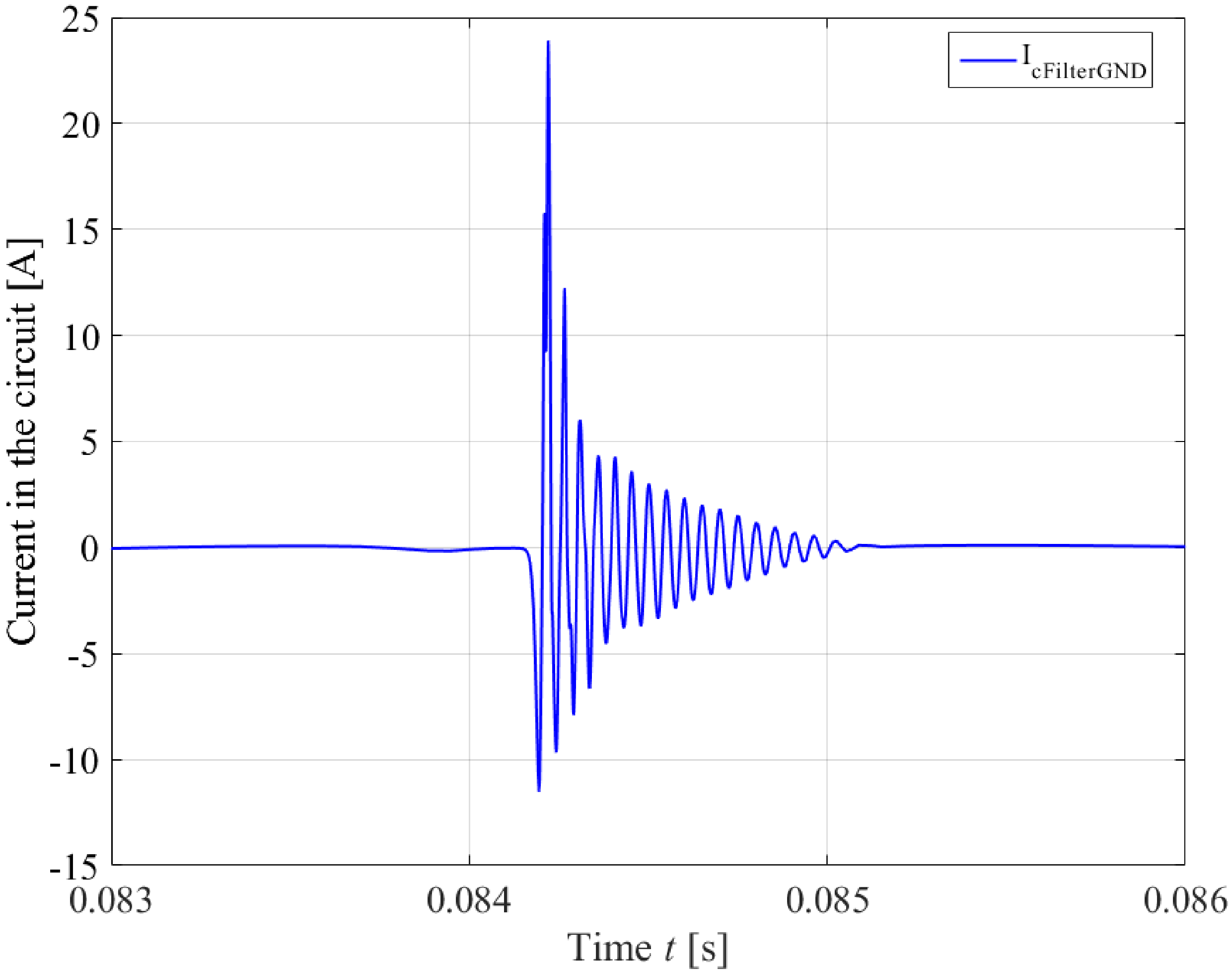
I_{meas} => Current measured with 100 Hz

I_A => Current measured with 1 kHz

I_{Sim} => Simulated current

- Acquisition frequency of 1 kHz is maybe not “enough”
- Searching for the peak at **t_{EE}**

Main quadrupole circuit

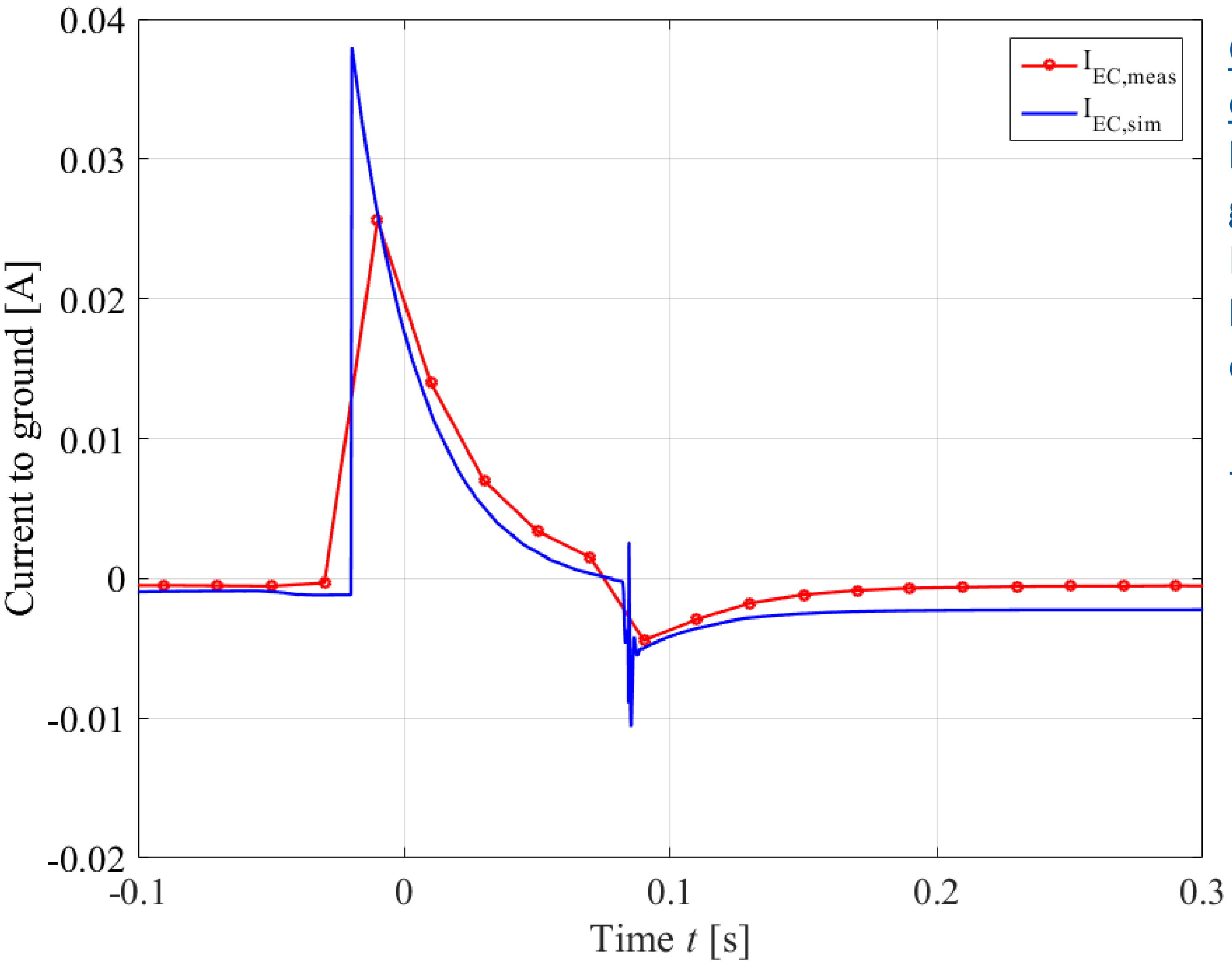


Closer look at the test data of PNO-B3 (10.35 kA test):
- Searching for the peak at $\mathbf{t_{EE}}$

$\mathbf{I_{C,gnd}}$ => Sum of all currents through all capacitors to ground in:
- filter of the Sub Sub module
- Main filter of the power converter
- Capacitors to ground in the magnet models

Results in the peak value of the simulated circuit current

Main quadrupole circuit



<u>Closer look at the test data of PNO-B3 (10.35 kA test):</u>

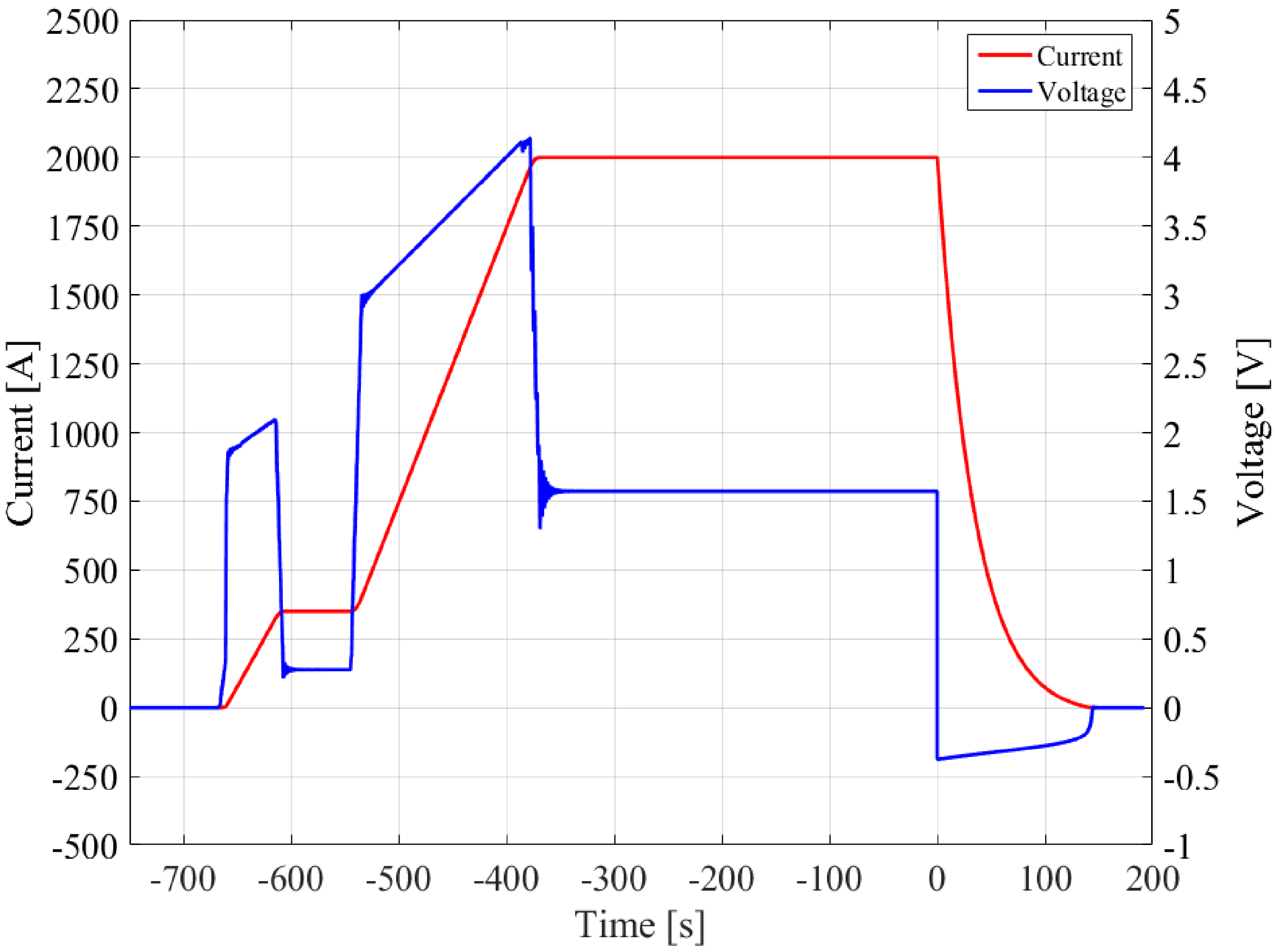
$\mathbf{I_{EC,meas}}$ => Current to ground measured with 50 Hz

$\mathbf{I_{EC,Sim}}$ => Simulated current to ground

- Acquisition frequency of 50 Hz is too low, to see all the oscillations

Good agreement with measurement data

Main quadrupole circuit

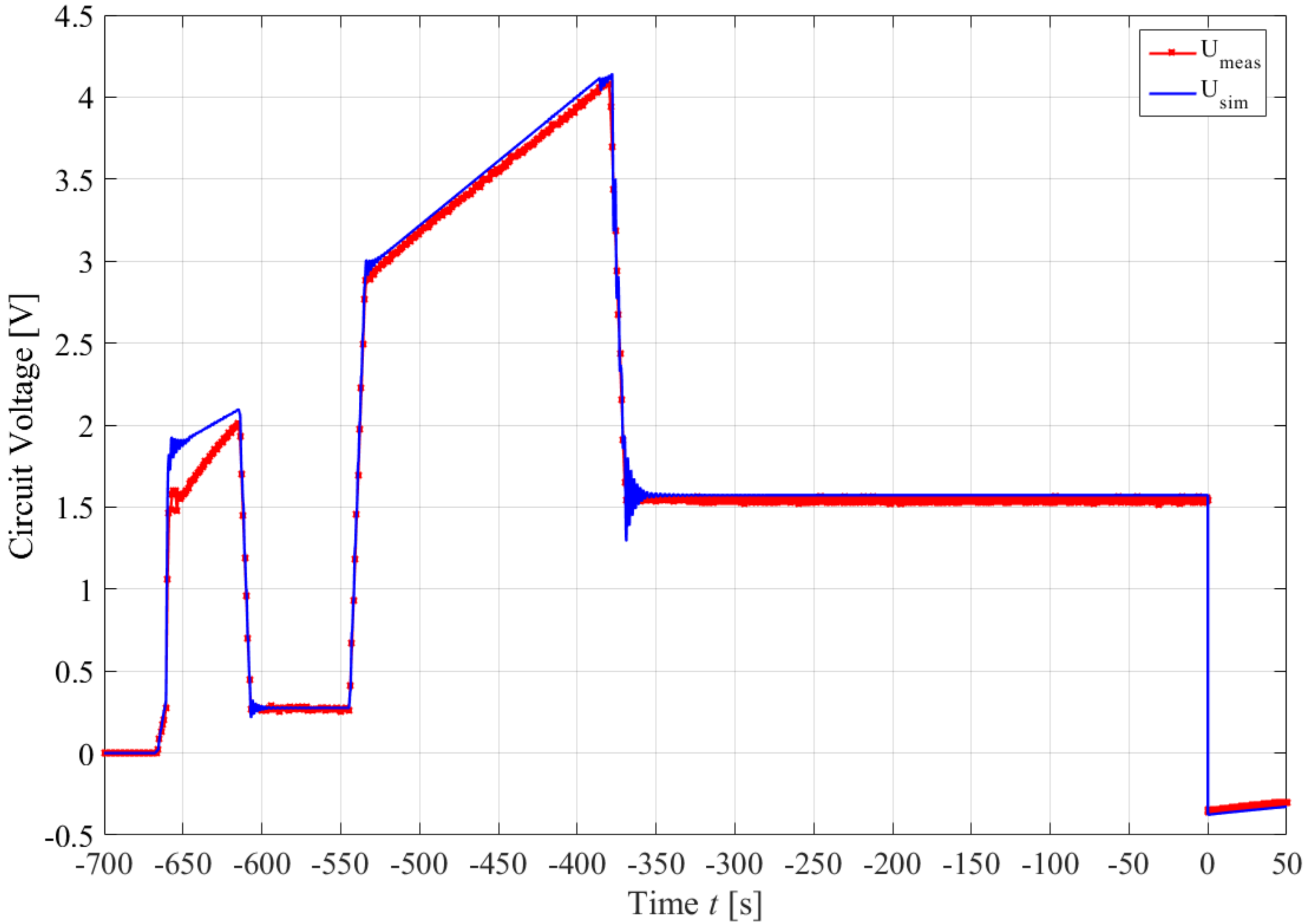


Closer look at the test data of PLI2-B3 (2 kA test):

$U_{PC,sim}$ => Voltage across the PC

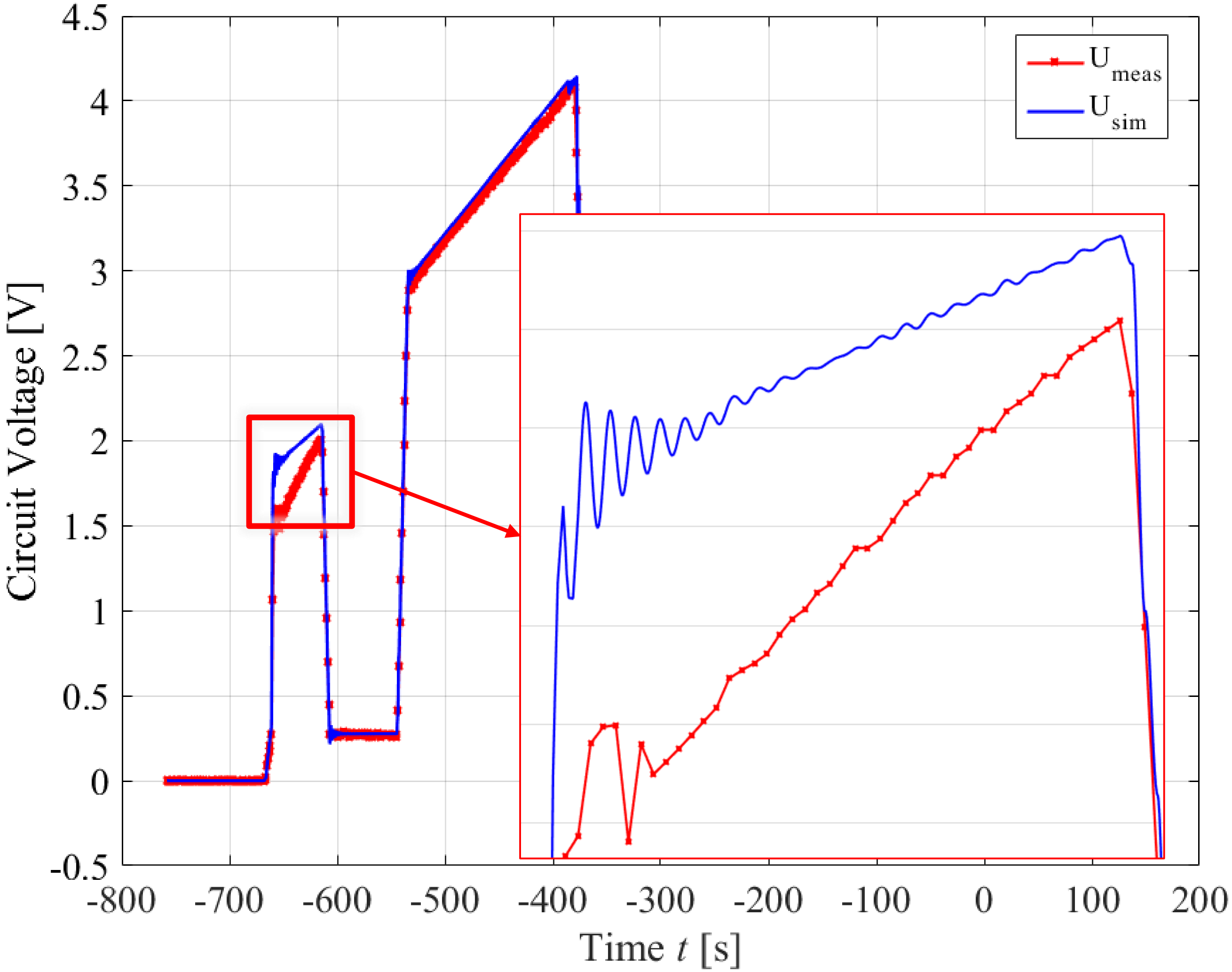
I_{Sim} => Simulated circuit current

Main quadrupole circuit



Good agreement with measurement data

Main quadrupole circuit



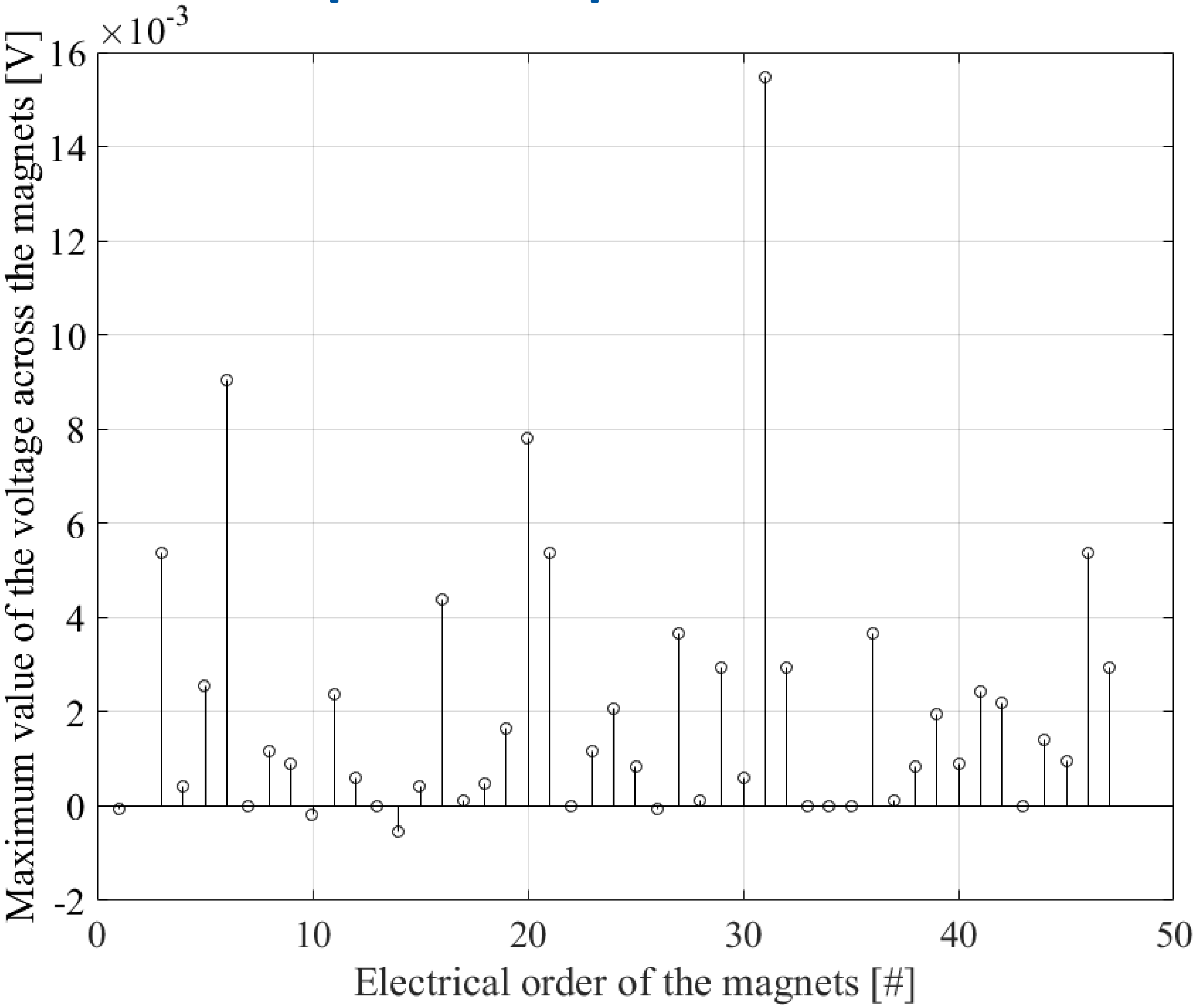
Closer look at the test data of PLI2-B3 (2 kA test):

Discrepancy between measurement and simulation (~20%):

- due to magnetization effects in the superconductor [3]
  - Which is not present in the simulation
- effect observed during measurements in the LHC main dipole circuit [3]

Good agreement with measurement data

Main quadrupole circuit



FPA* tests done 12.2018 at 2 kA and 6 kA [5]:

Within this test all nQPS and iQPS data storage is read:

- Sector 2-3
- **Sector 4-5**
- Sector 7-8

Data is stored as U_QDS0 in the PM Browser**

⇒ unbalanced quadrupoles in those circuits

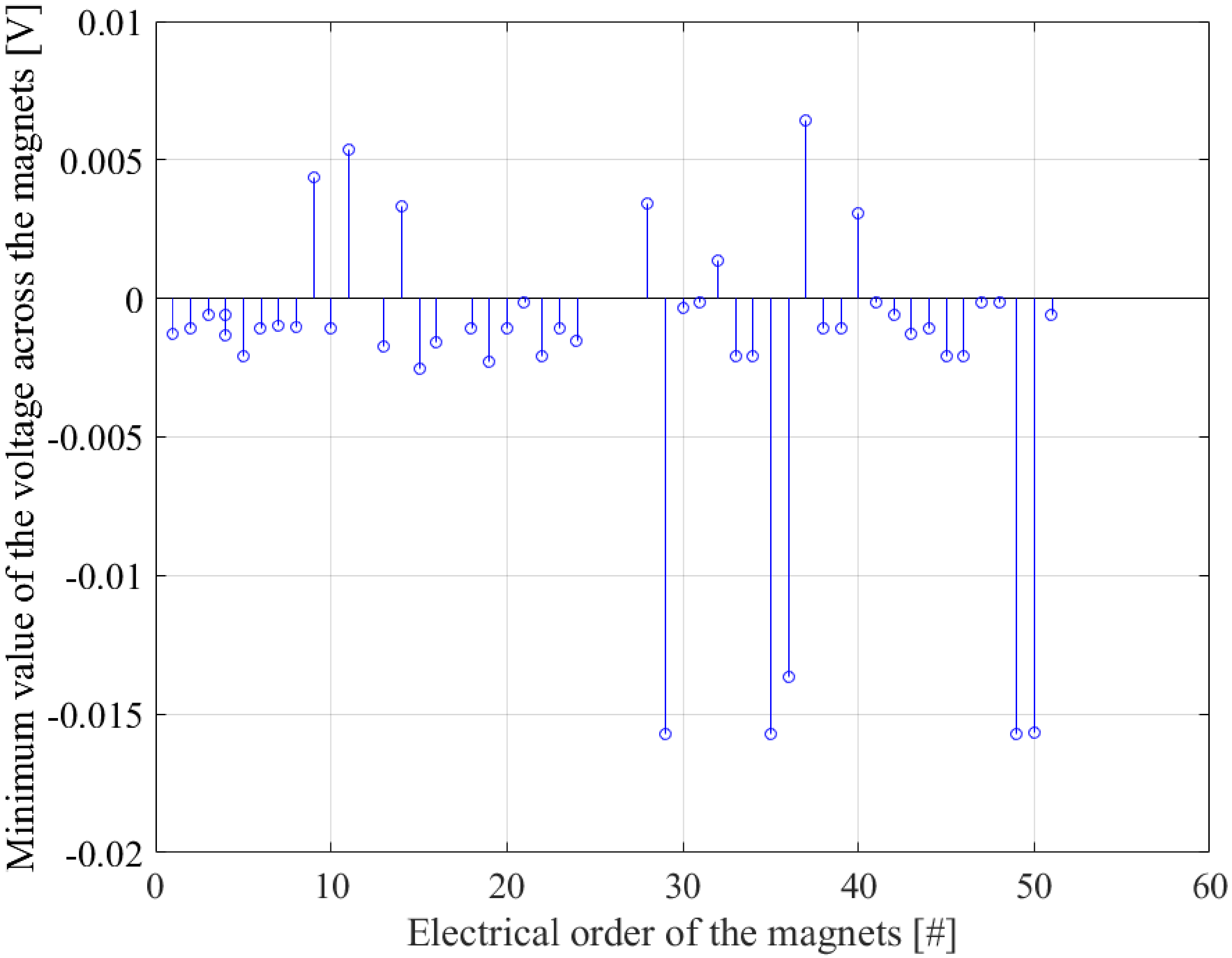
⇒ But: the transients don't have a critical effects on the LHC quench detection system (signals below threshold = 100 mV)

⇒ Different from LHC RB circuit

* Fast Power Abort

** Thanks to Zinur for helping me with the QPS data!

Main quadrupole circuit



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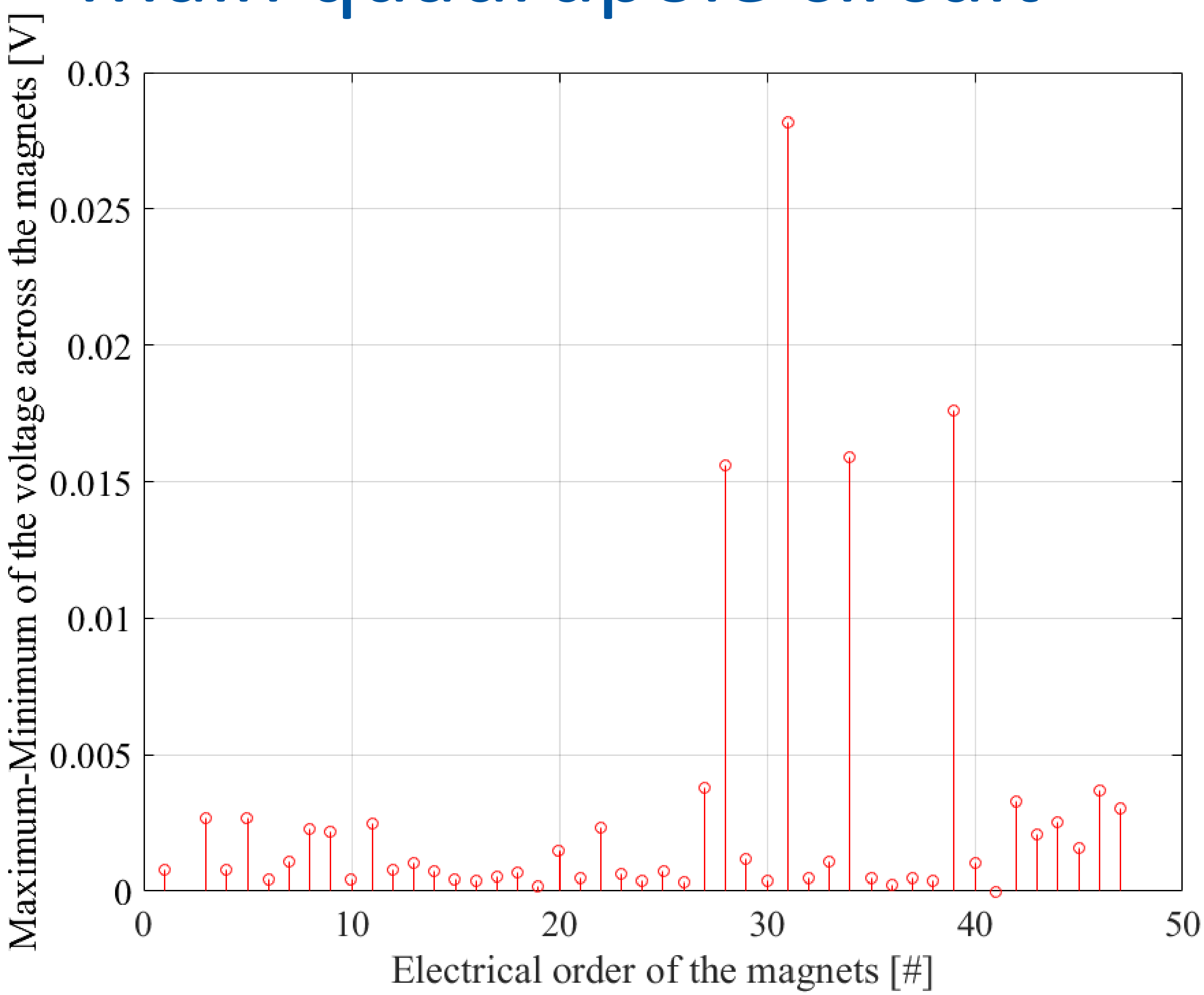

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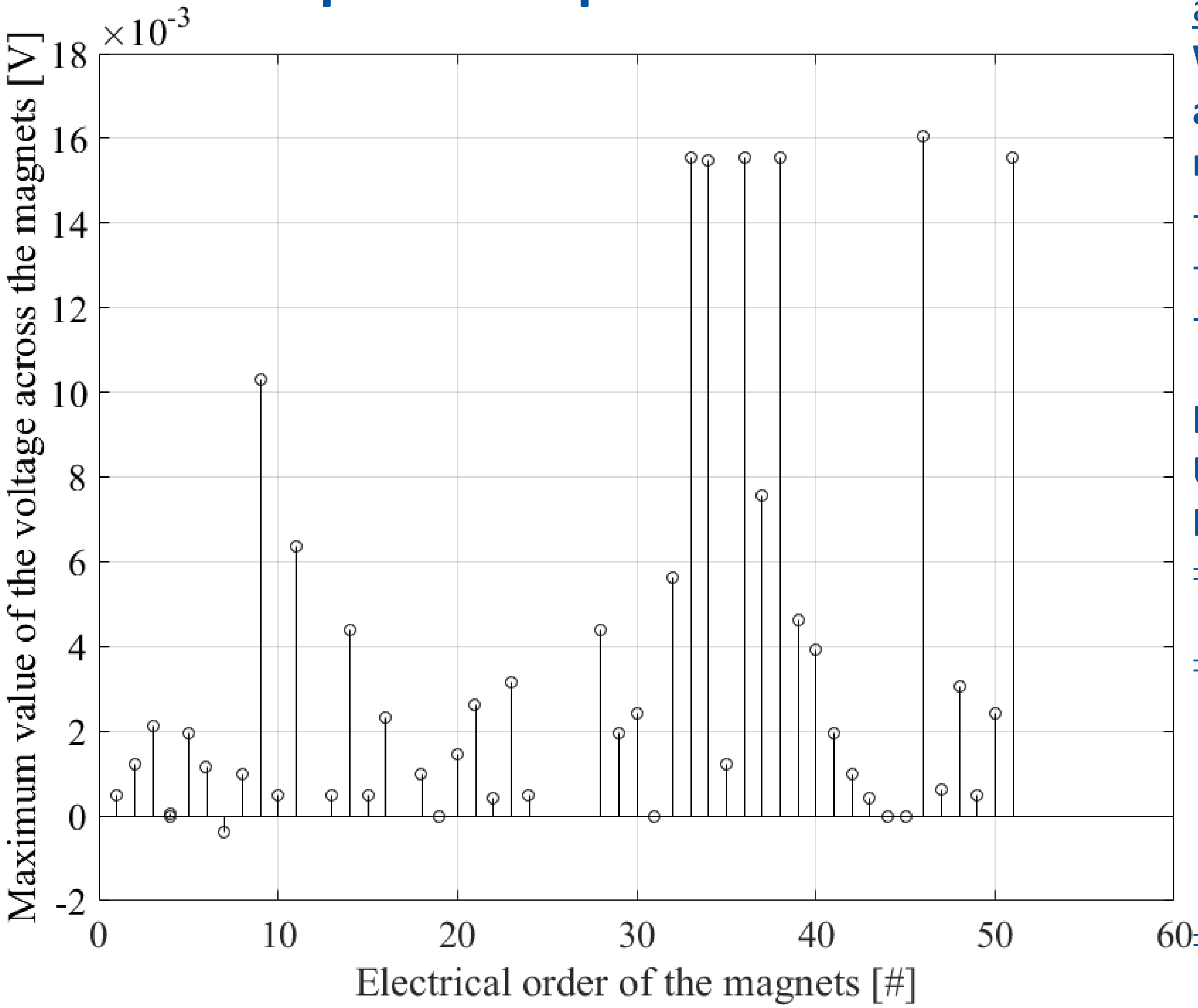
Main quadrupole circuit



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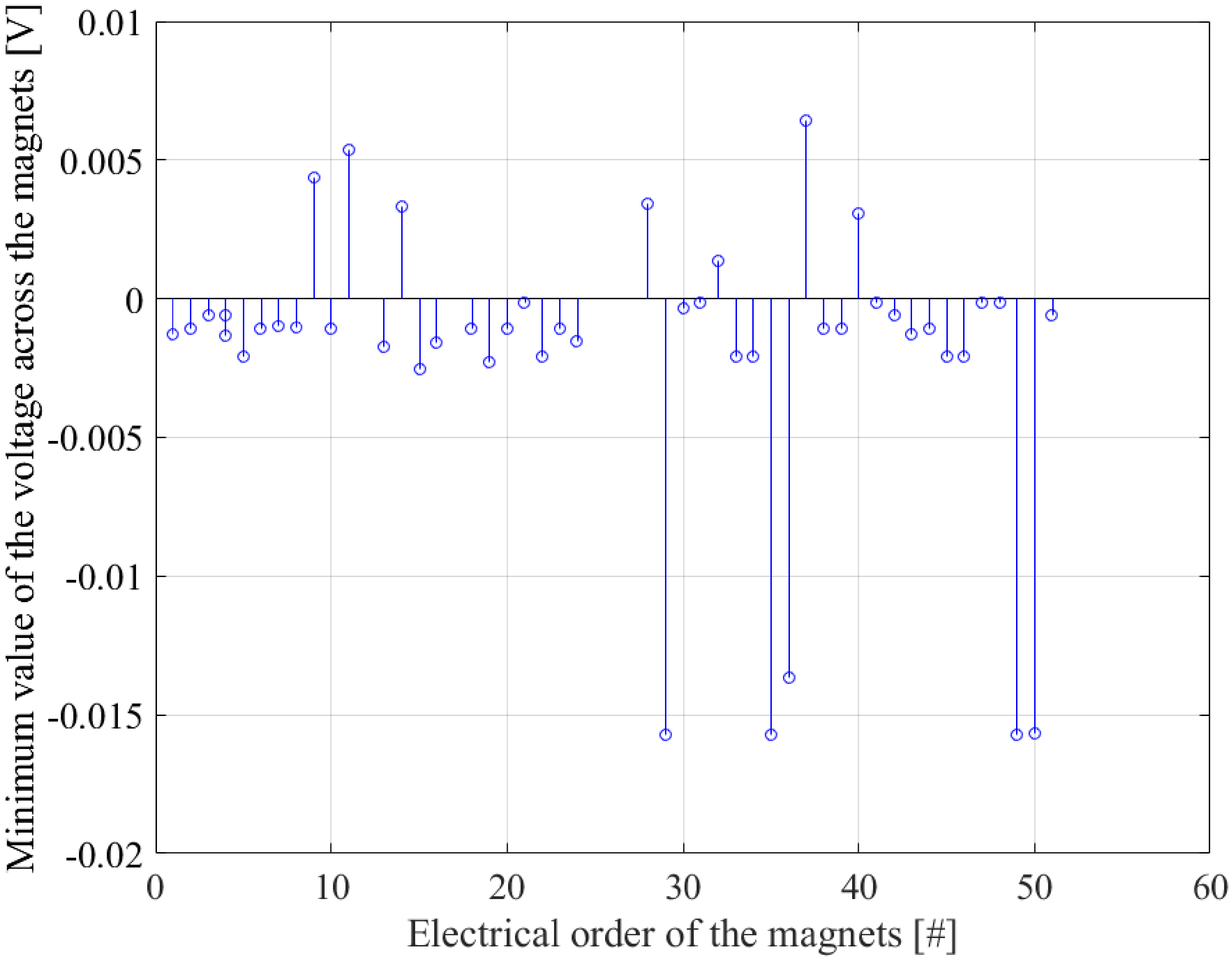

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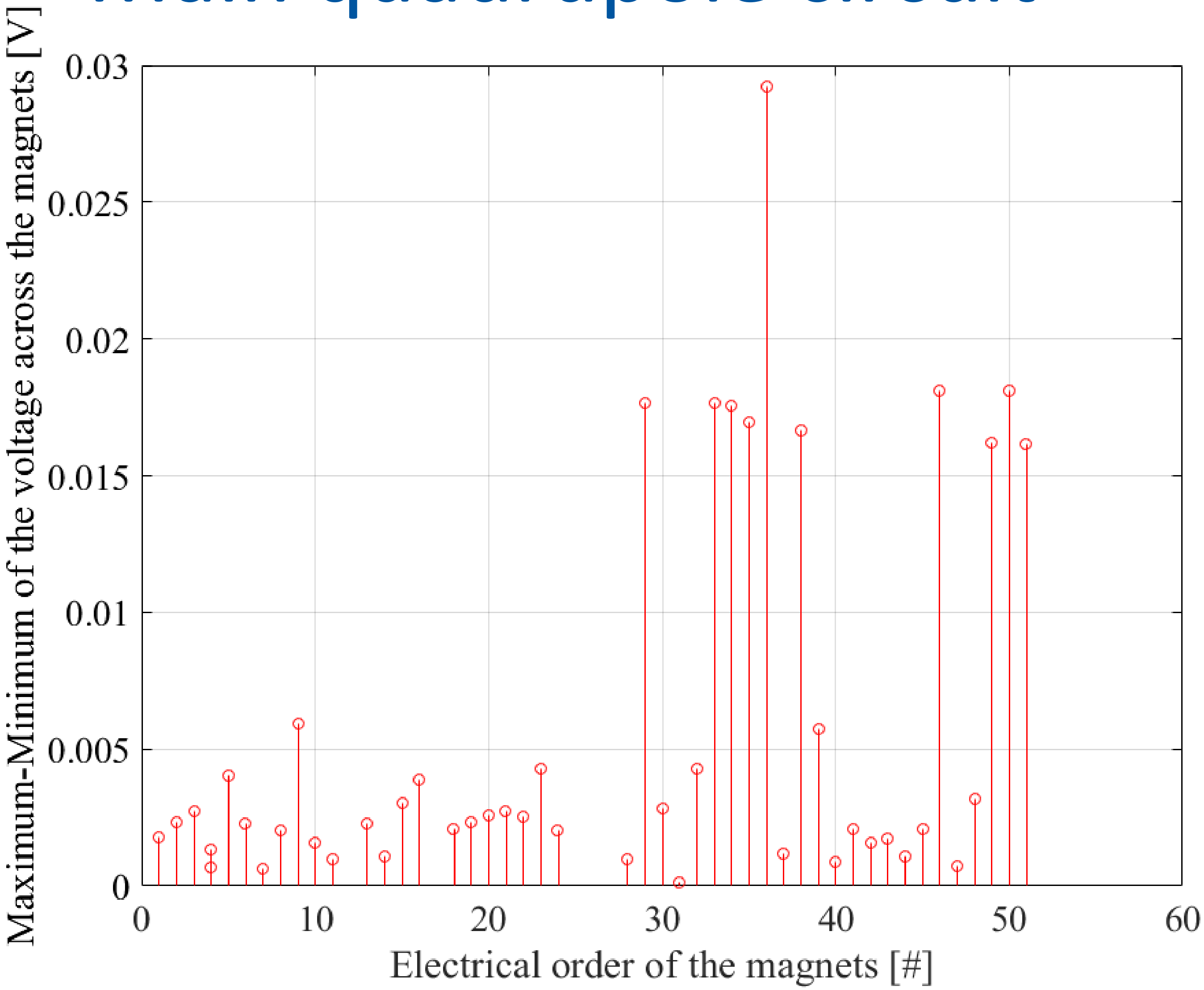

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Checklist for this presentation

1. Goals and Motivation for the project
2. Validation of the magnet model (LEDET, COMSOL) at $I_{test,1}$ = 11.69 kA
3. Validation of the magnet model (LEDET, COMSOL) at $I_{test,2}$ = 7.554 kA
4. Discussing the influence parameters within the model
5. Validation of the circuit model (PSPICE)
6. Progress checklist for this project

Progress checklist – outlook

Working Packages	Status
Validation of the LHC main quadrupole magnet model (COMSOL®) using the test data from SM18 at 11.69 kA	✓
Validation of the LHC main quadrupole magnet model (COMSOL®) using the test data from SM18 at 7.554 kA	⚡
Validation of the LHC main quadrupole magnet model (LEDET®) using the test data from SM18 at 11.69 kA	✓
Validation of the LHC main quadrupole magnet model (LEDET®) using the test data from SM18 at 7.554 kA	⚡
Validation of the LHC main quadrupole circuit model (PSpice®) using the test data from HWC	✓
Co-simulation of both models (LEDET, PSPICE) using COSIM	✗

Thesis – progress checklist – outlook

What we want to have in the end?

1. Validated LHC main quadrupole circuit model within PSPICE
2. Validated LHC main quadrupole magnet model within COMSOL
3. Validated LHC main quadrupole magnet model within LEDET
4. Validated Co-Simulation of circuit and magnet model within COSIM
5. Everything documented within the thesis

Future Improvement for the LHC main quadrupole circuit model:

1. R_{EE} as a function of quench load, not a constant anymore
2. Cold diodes as a function of temperature [4]

Thank you for your attention!

References

[1] “LHC13kA-18V LHC Main Quadrupole Circuit Power Converter”. Presentation. L. Charnay, V. Montabonnet. Geneva, 2010. EDMS-Nr.: 973221

[2] “Test Procedure and Acceptance Criteria for the 13 kA Quadrupole (RQD-RQF) Circuits”. MP3-Procedure. EDMS-Nr.: 874714

[3] “Fast Method to Quantify the Collective Magnetization in Superconducting Magnets”. Emmanuele Ravaioli, Bernhard Auchmann, and Arjan P. Verweij. IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013

[4] “HL-LHC Inner Triplets 18kA cold bypass diodes - Summary of diode irradiation campaign”. Arnaud Monteuuis for TE-MPE-EE. 23rd MPE-PE section meeting, 6th December 2018

[5] “FPA tests at 10 A/s performed in Dec 2018”. MP3-webpage, 10th December 2018. Last visit: 10.04.2019, https://twiki.cern.ch/twiki/bin/viewauth/MP3/FPAinRQ

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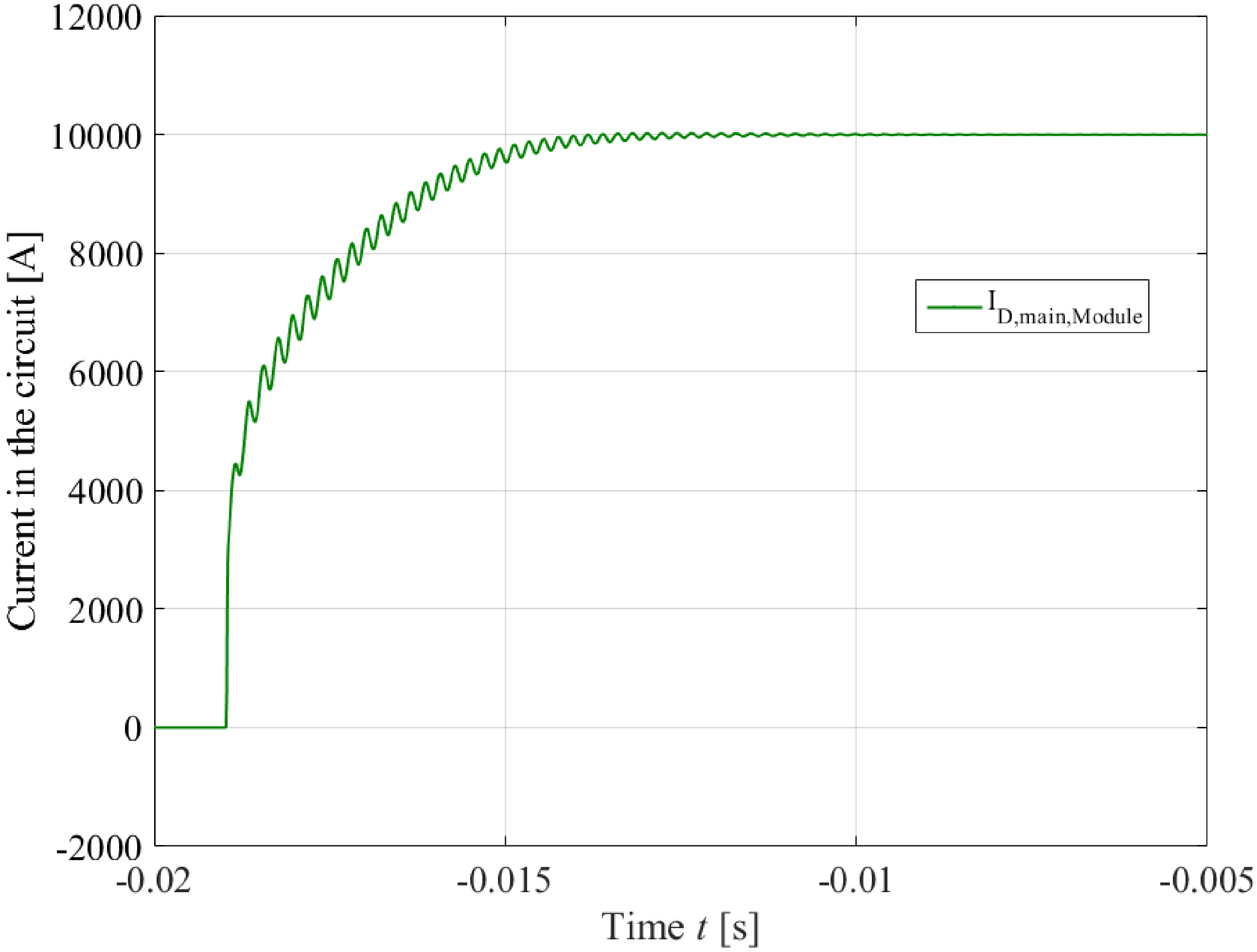
Main quadrupole circuit



Closer look at the test data of PNO-B3 (10.35 kA test):

- Current through the diodes in at $\mathbf{t_{FPA}}$

The 3rd diode branch doesn't get any current

The 1st diode branch gets ~90 % of the test current
→ $I_{D,1branch}$ = 9.315 kA

After the simulation:
- 10.0 kA (= 96.6 %)