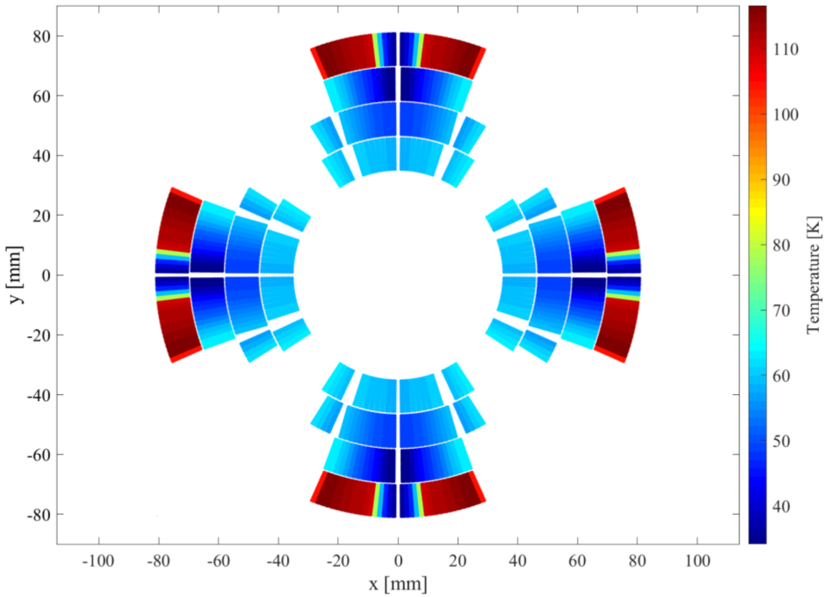
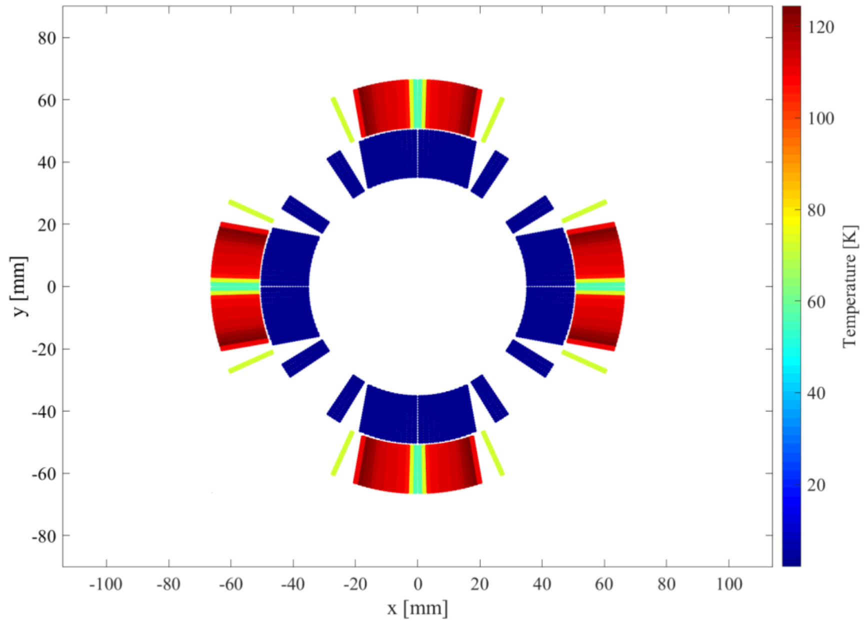
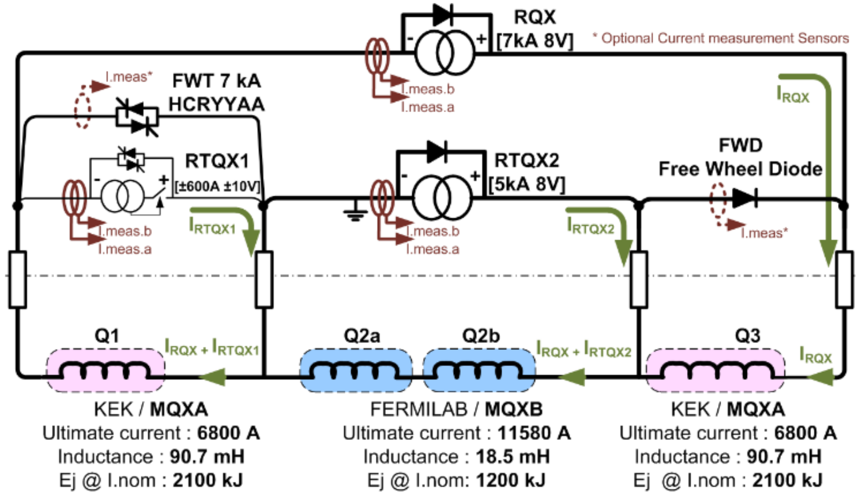




Simulation of transients in the RQX circuit

Federica Murgia
On behalf of the STEAM team
Section Meeting
27/08/2020



A special thanks to Emmanuele Ravaioli, and all the STEAM and SIGMON teams

Motivation:

Final goal:

A **complete multi-physics library** of the LHC superconducting circuits

(RB, RQX, RQF/RQD, RQ4, …)

Analyse unexpected events occurring in the circuits.

Assess the impact of proposed circuit modification.

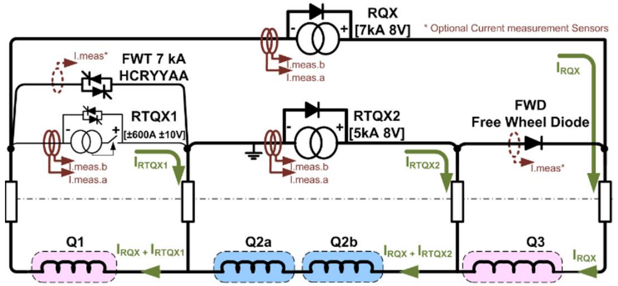
Reduce risks and downtime during operation.

Constantly optimize STEAM[1] for automated model generation.

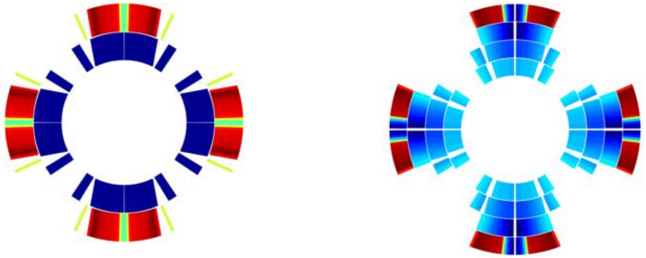
Framework composed by a variety of tools to simulate
transient effects *in the superconducting circuit and magnet*

My main tasks:

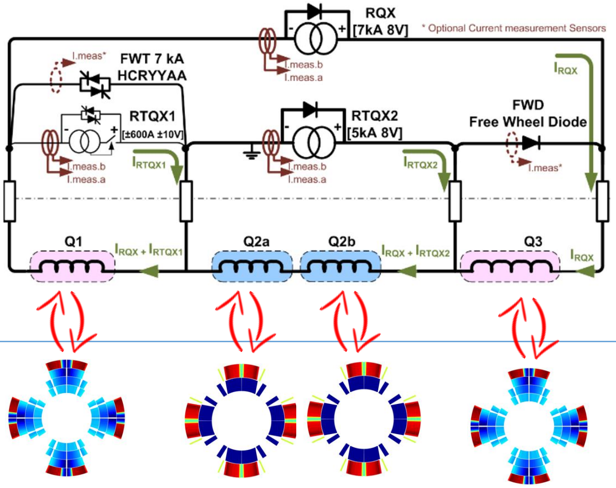
- Develop the superconducting **electrical circuit** using STEAM-SING[2]
  - Validate the model with experimental data



- Develop the superconducting **magnet model** using STEAM-LEDET[3]
  - Validate the model with experimental data



- **Combine** both models (LEDET and PSpice) using STEAM-COSIM[4]
  - Validate the model with experimental data

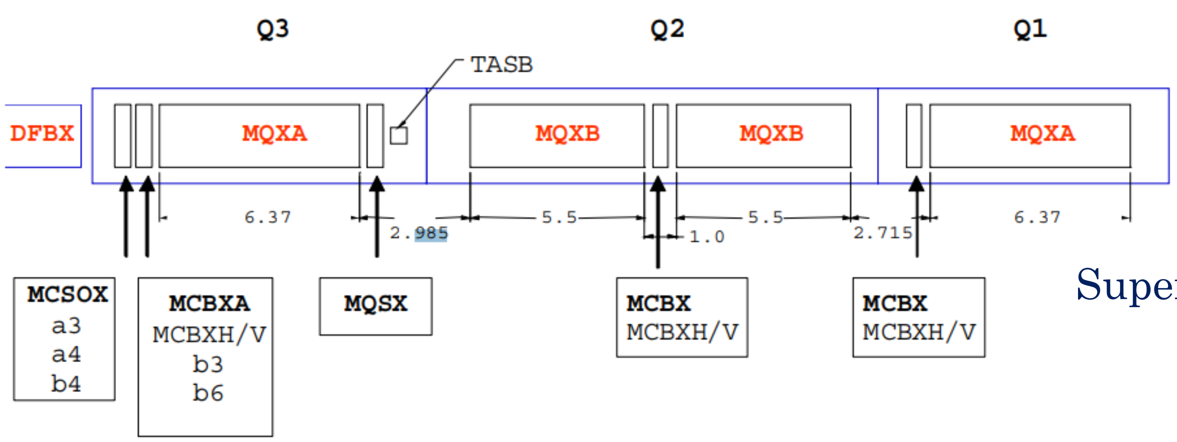


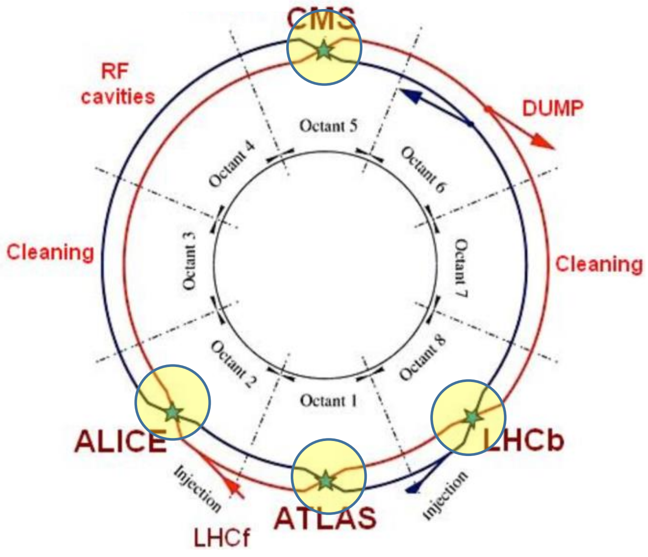
RQX superconducting circuit:

Designed and built in 1996 during a collaboration between CERN, KEK, and FermiLab

Located on either side of the four interaction points

The RQX superconducting circuit are 8 in total and operate at 1.9 K





Superconducting quadrupole

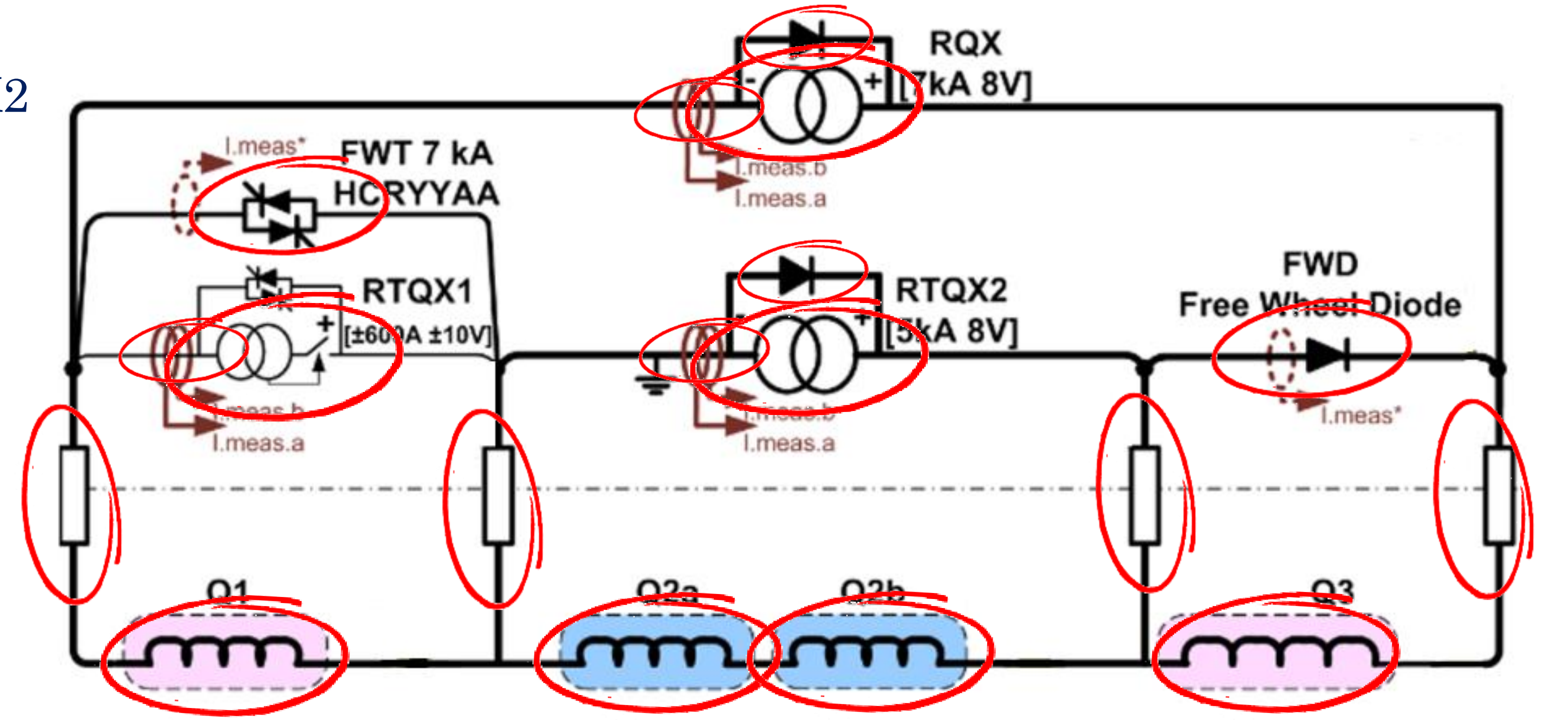
- 2x MQXA 6.6 m long, developed at KEK
- 2x MQXB 5.7 m long, developed in Fermilab

Corrector Magnet

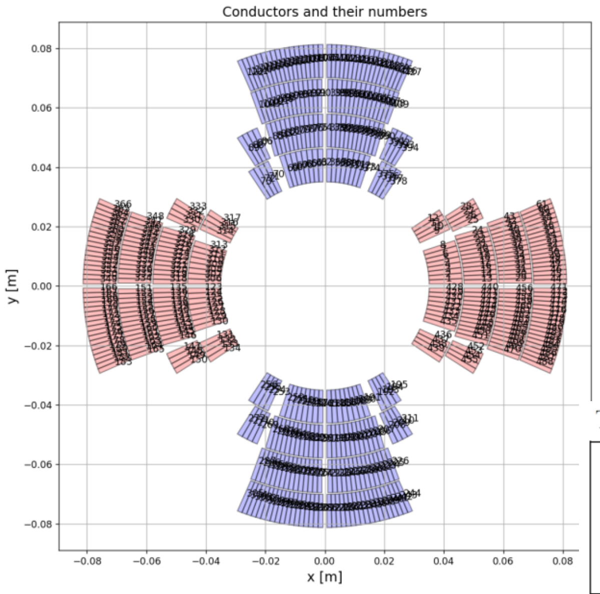
- MCSOX nested skew sextuple, octupole, skew octupole
- 2x MCBX orbit correctors
- MCBXA MCBX with a nested 6-pole, 12-pole
- MQSX skew quadrupole

RQX superconducting circuit:

- 3 Power converters   RQX, RTQX1, RTQX2
- 3 Direct Current Transducer
- 40 Diodes in parallel with RQX pc
- 20 Diodes in parallel with RTQX2 pc
- 1 Free Wheel Diode
- 1 Free Wheel Thyristor
- 4 Warm current leads
- 4 Superconducting quadrupole magnets



MQXA and MQXB, superconducting quadruple magnets:



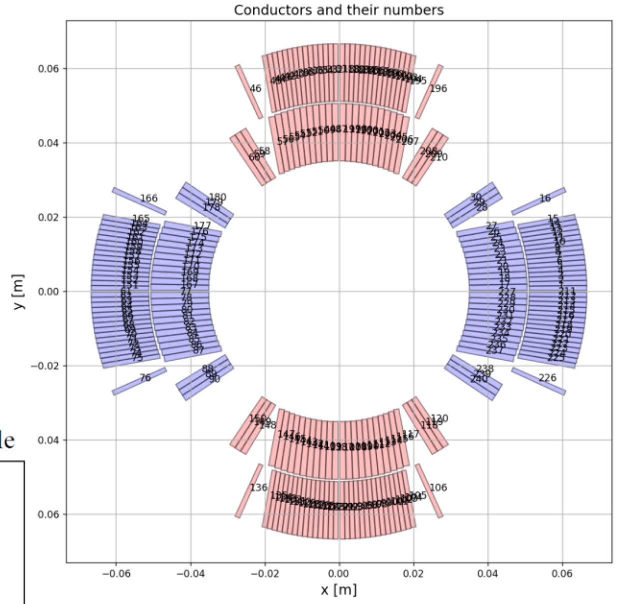
MQXA
KEK

Table 8.12: Main parameters of the MQXA low-β quadrupole

Coil inner diameter	70 mm
Magnetic length	6.37 m
Operating temperature	1.9 K
Nominal gradient	215 T/m
Nominal current	7149 A
Cold bore diameter OD/ID	66.5/62.9 mm
Peak field in coil	8.6 T
Quench field	10.7 T
Stored energy	2300 kJ
Inductance	90.1 mH
Quench protection	Quench heaters, two independent circuits
Cable width, cable 1/2	11/11 mm
Mid-thickness, cable 1/2	1.487/1.340 mm
Keystone angle, cable 1/2	2.309/1.319 deg.
No of strands, cable 1/2	27/30
Strand diameter, cable 1/2	0.815/0.735 mm
Cu/SC Ratio, cable 1/2	1.2/1.9
Filament diameter, cable 1/2	10/10 μm
j_c, cable1/2, (4.2 K and 6 T)	2200/2160 A/mm^2
Mass	9600 kg

Table 8.14: Main parameters of the MQXB low-β quadrupole

Coil inner diameter	70 mm
Magnetic length	5.5 m
Operating temperature	1.9 K
Nominal gradient	215 T/m
Nominal current	11950 A
Cold bore diameter OD/ID	66.5/62.9 mm
Peak field in coil	7.7 T
Quench field	9.2 T
Stored energy	1360 kJ
Inductance	19.1 mH
Quench protection	Quench heaters, two independent circuits
Cable width, cable 1/2	15.4/15.4 mm
Mid-thickness, cable 1/2	1.456/1.146 mm
Keystone angle, cable 1/2	1.079/0.707 deg.
No of strands, cable 1/2	37/46
Strand diameter, cable 1/2	0.808/0.650 mm
Cu/SC Ratio, cable 1/2	1.3/1.8
Filament diameter, cable 1/2	6/6 μm
j_c, cable 1/2 (4.2 K and 5 T)	2750/2750 A/mm2
Mass	5700 kg

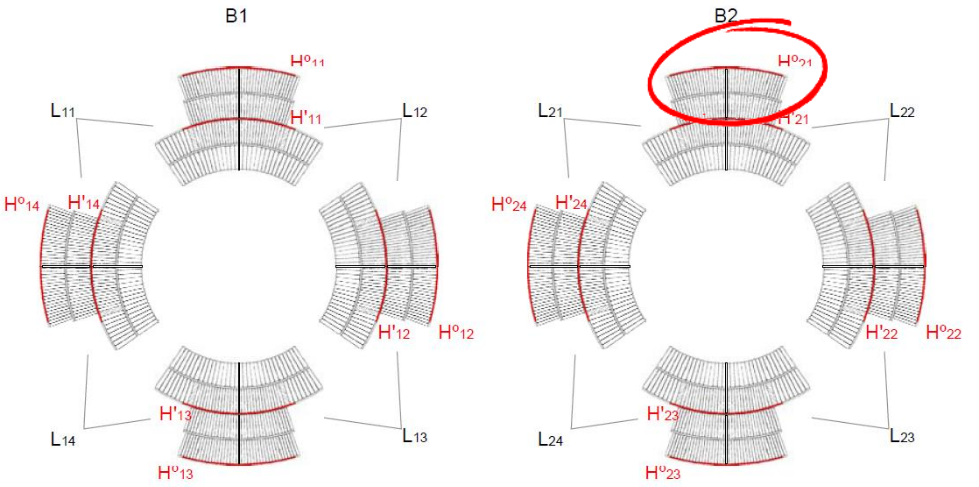


MQXA
Fermilab

MQXA and MQXB, quench protection:

By design, the protection of both magnets is guarantee by Quench Heaters (QHs)

The QHs are μm-thin strips glued to the coil, which heat the turns by thermal diffusion



Quench appears

↓

Quench is detected

↓

Quench heaters are triggered

↓

Heat transfer by thermal diffusion

↓

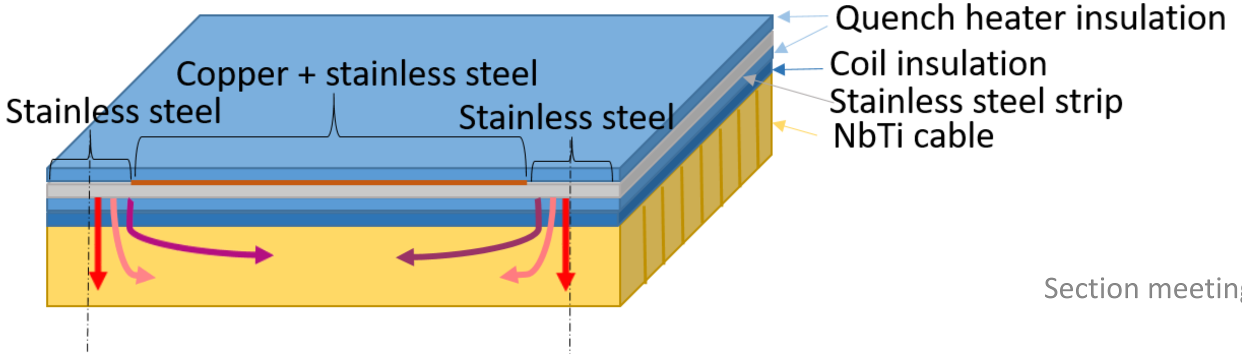
Part of the coil is transferred from SC to NC state

↓

The resistance of the coil increases

↓

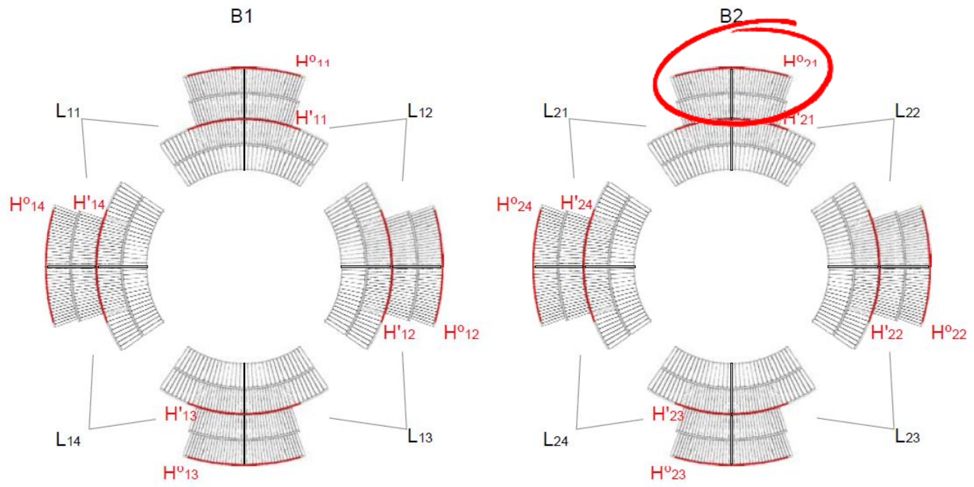
The magnet current discharges quickly

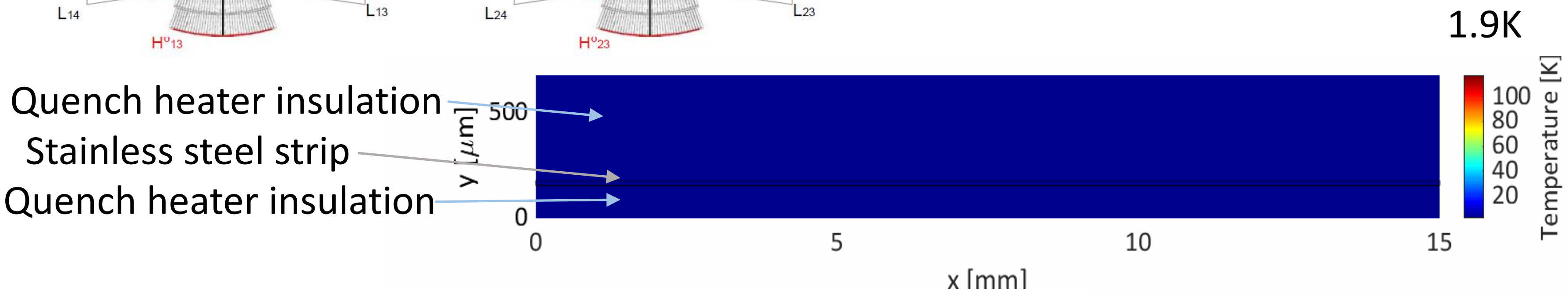


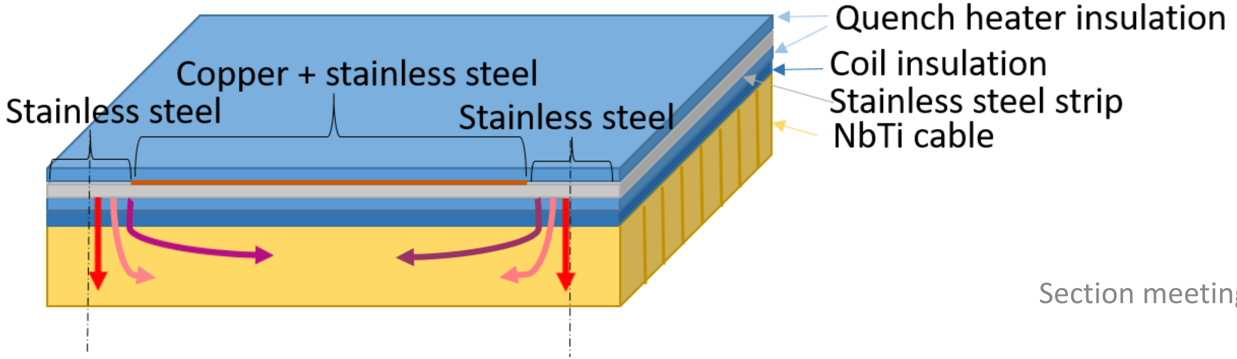
MQY quench protection system:

By design, the protection the MQY magnets are protected with Quench Heaters (QHs)

The QHs are µm-thin strips glued to the coil, which heat the turns by thermal diffusion







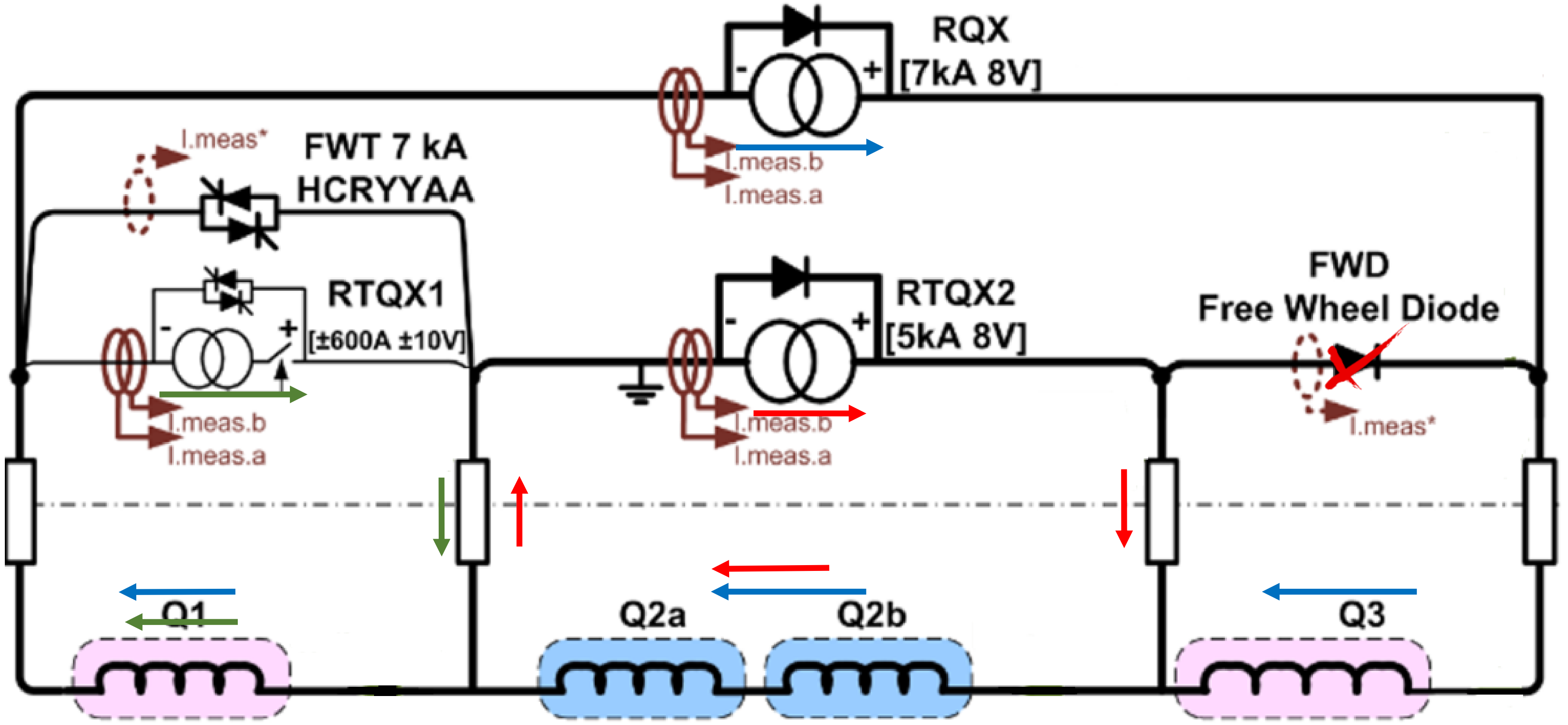
- Quench appears
- Quench is detected
- Quench heaters are triggered
- Heat transfer by thermal diffusion
- Part of the coil is transferred from SC to NC state
- The resistance of the coil increases
- The magnet current discharges quickly

Transient in the circuit:

Powering

PCs ON
QHs not triggered

RQX ~ 7000A
RTQX1 ~200 A
RTQX2 ~4700A

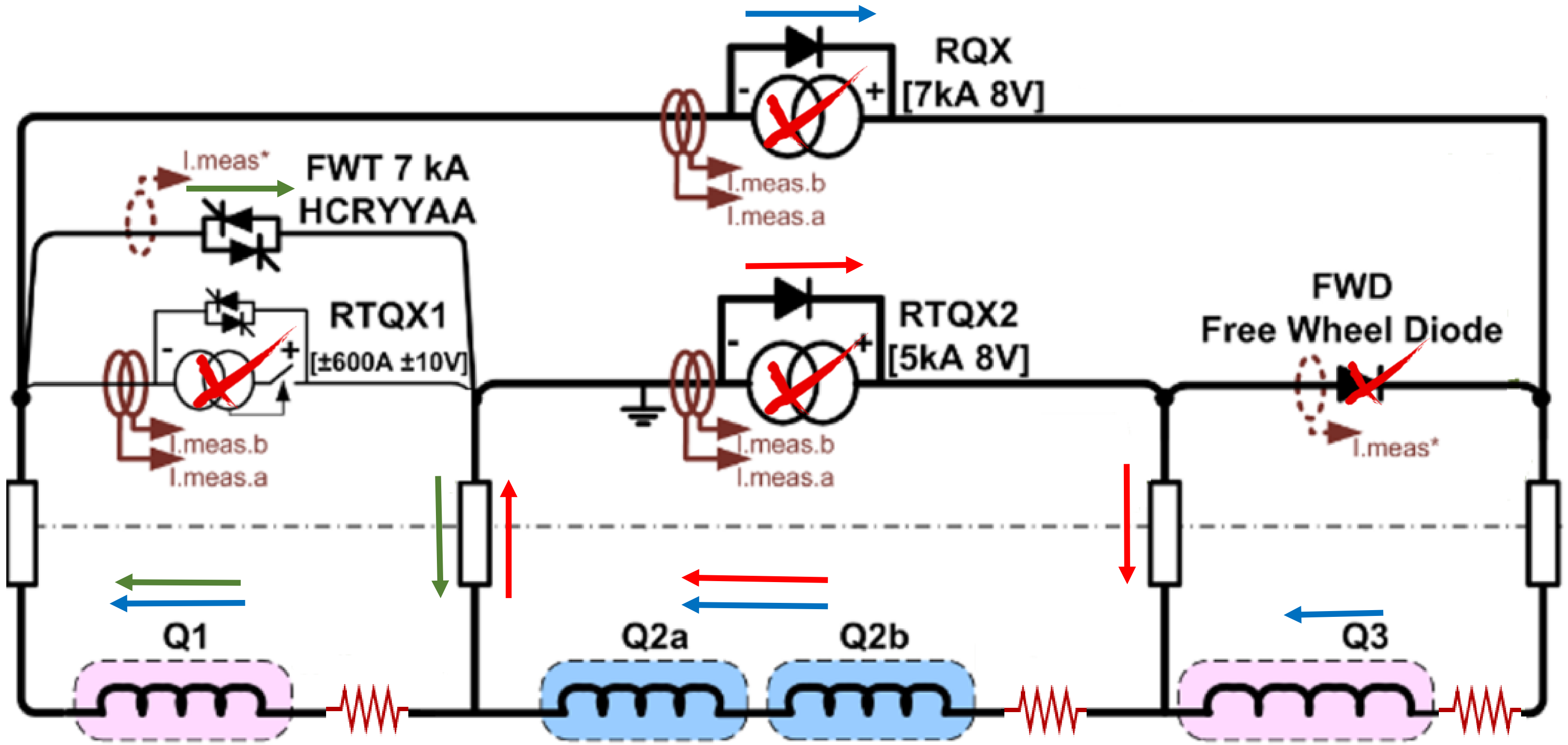


Transient in the circuit:

t<~130ms

Fast Power Abort

PCs OFF
QHs triggered

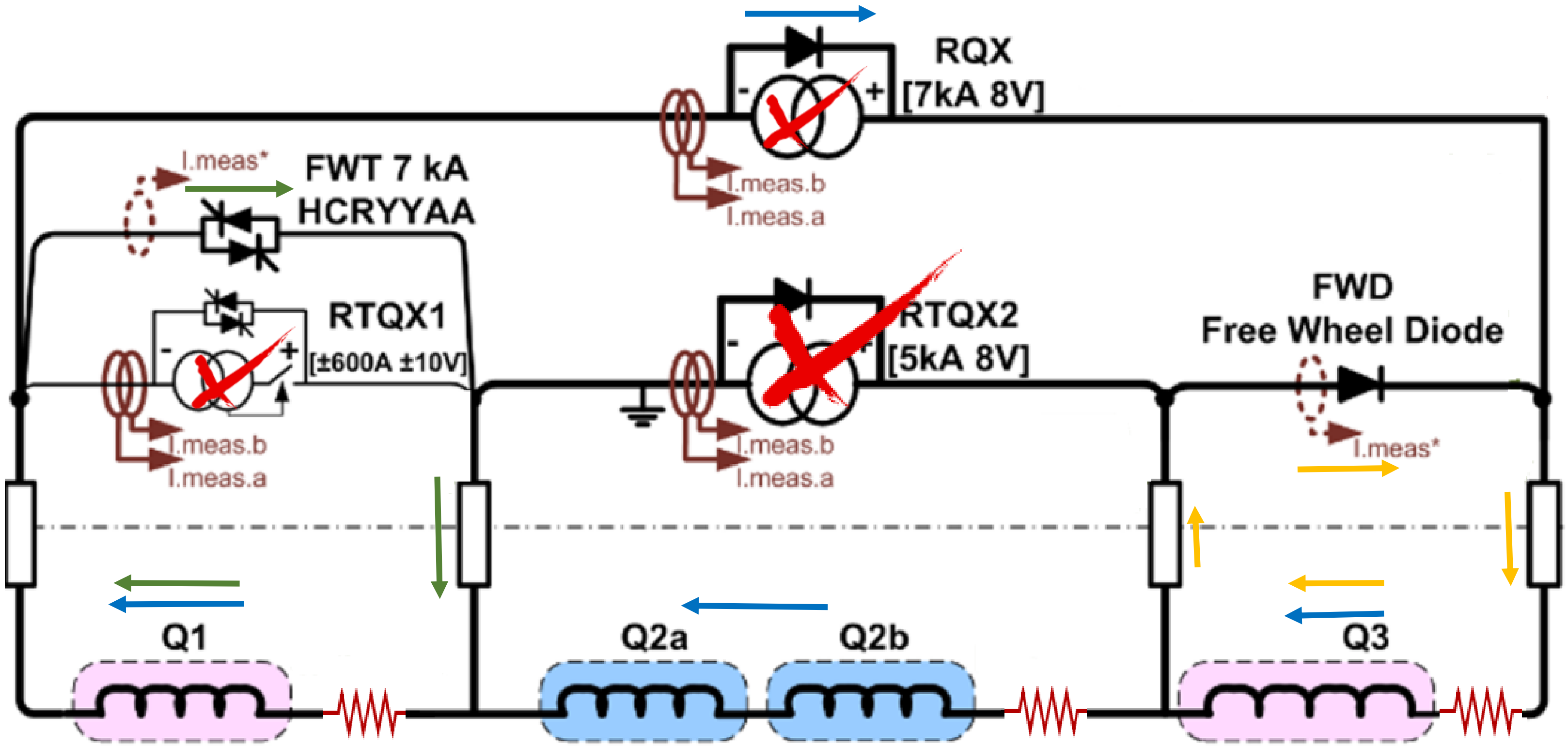


Transient in the circuit:

t>~130ms

Fast Power Abort

PCs OFF
QHs triggered

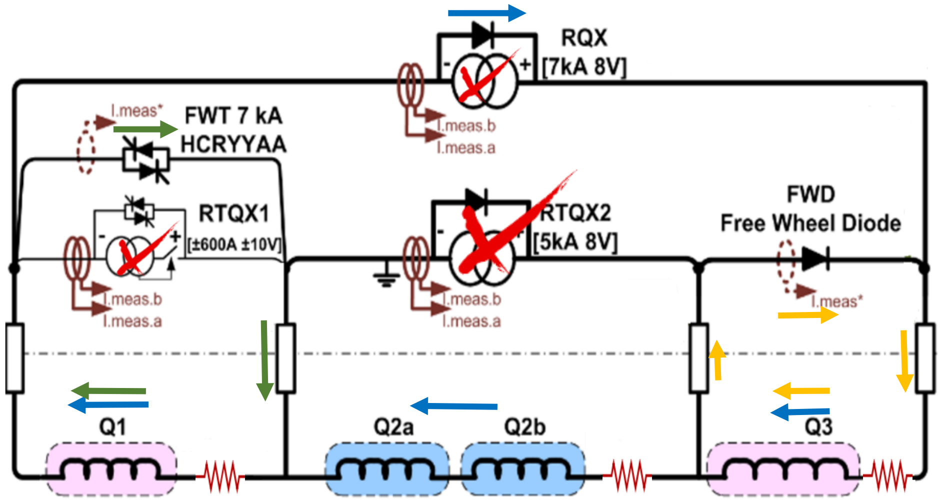


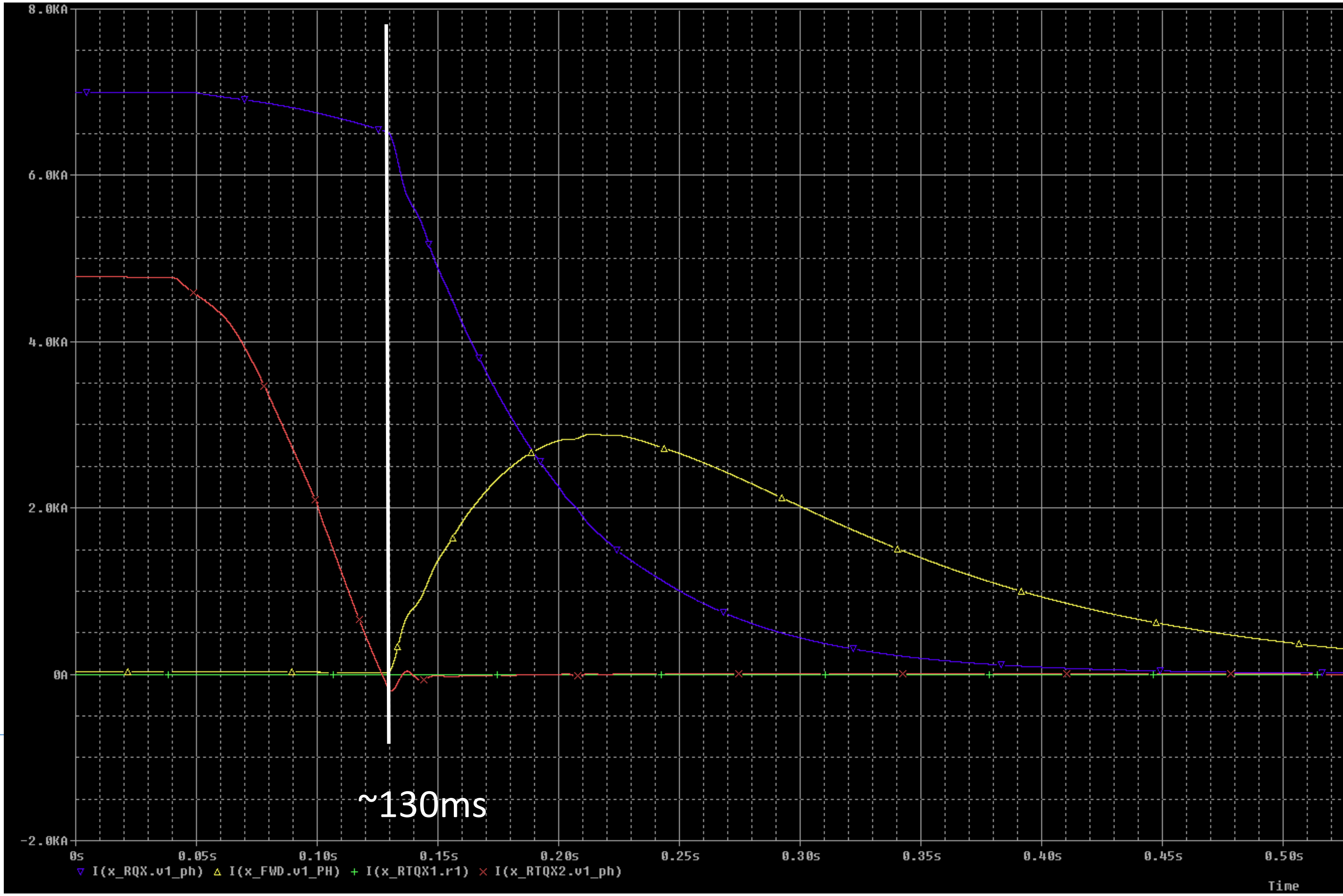
Transient in the circuit:

t>~130ms

Fast Power Abort

PCs OFF
QHs triggered

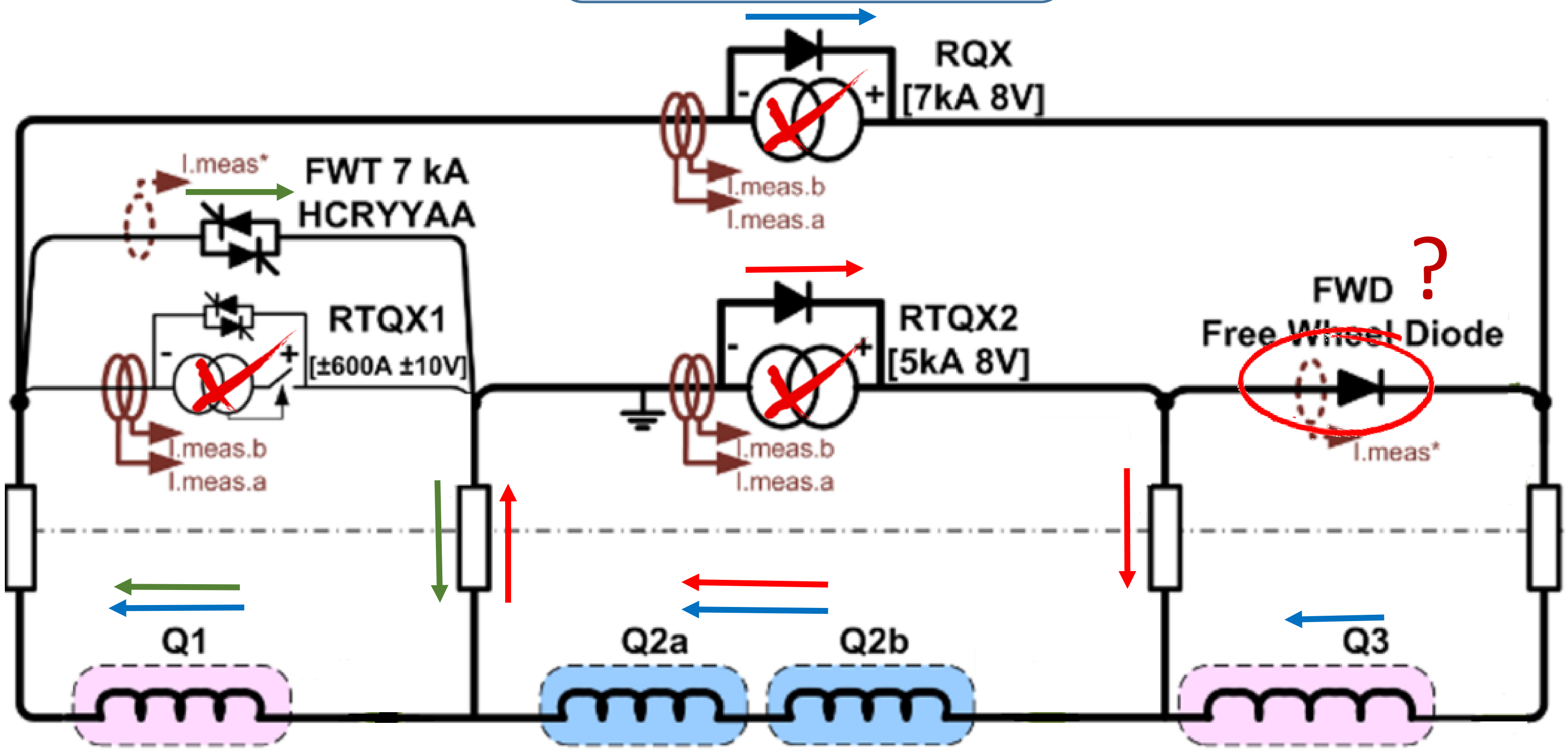




Transient in the circuit:

Slow Power Abort

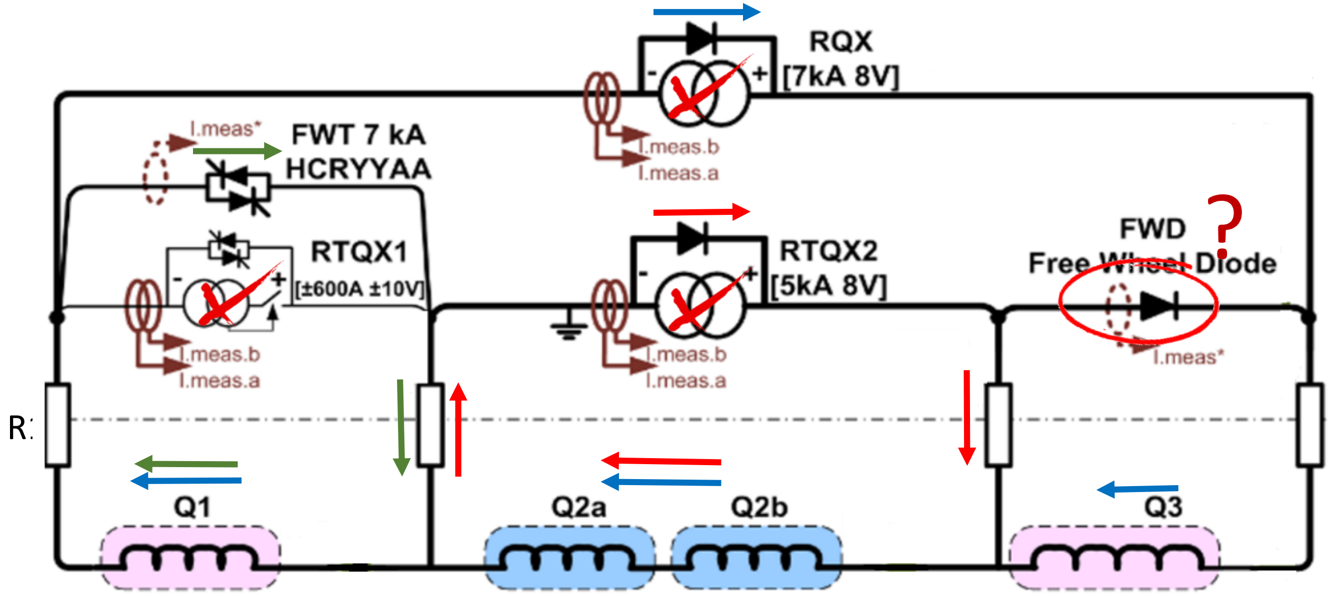
PCs OFF
QHs not triggered



Validation of the RQX circuit model:

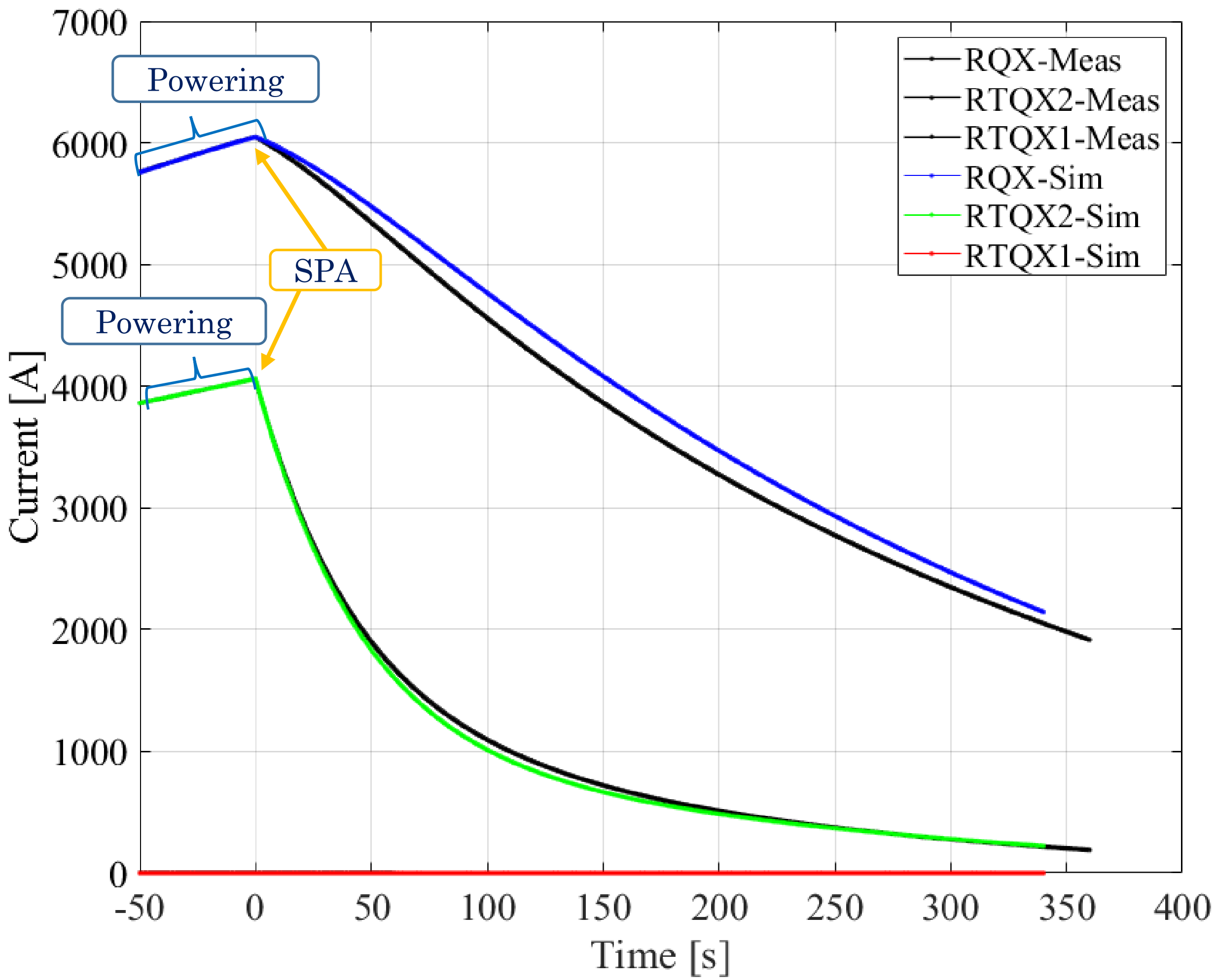
RQX electrical circuits have been tested using Slow Power Abort (SPA) tests performed during the LHC Hardware Commissioning.

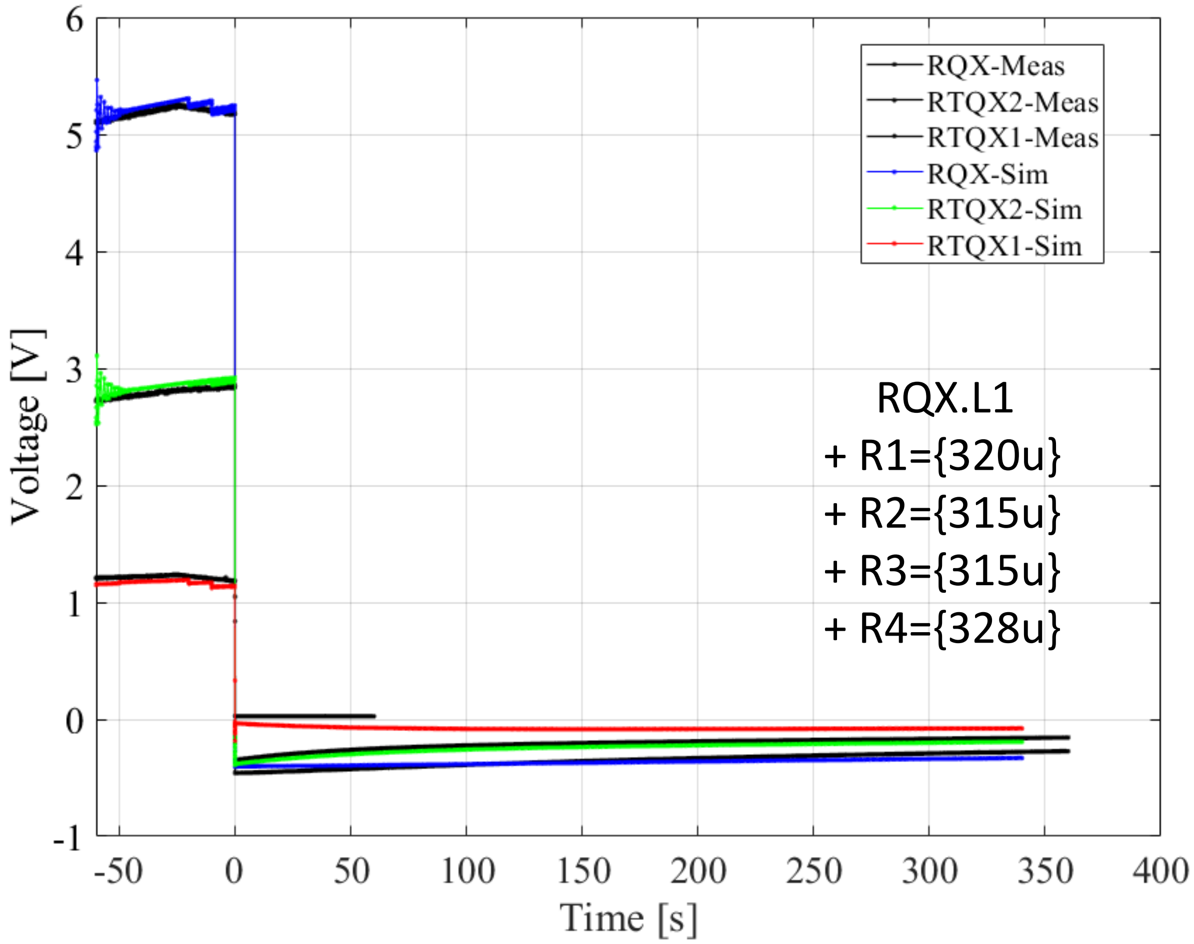
During the SPA the power converters are switched-off.
The current decays in a few hundred seconds.



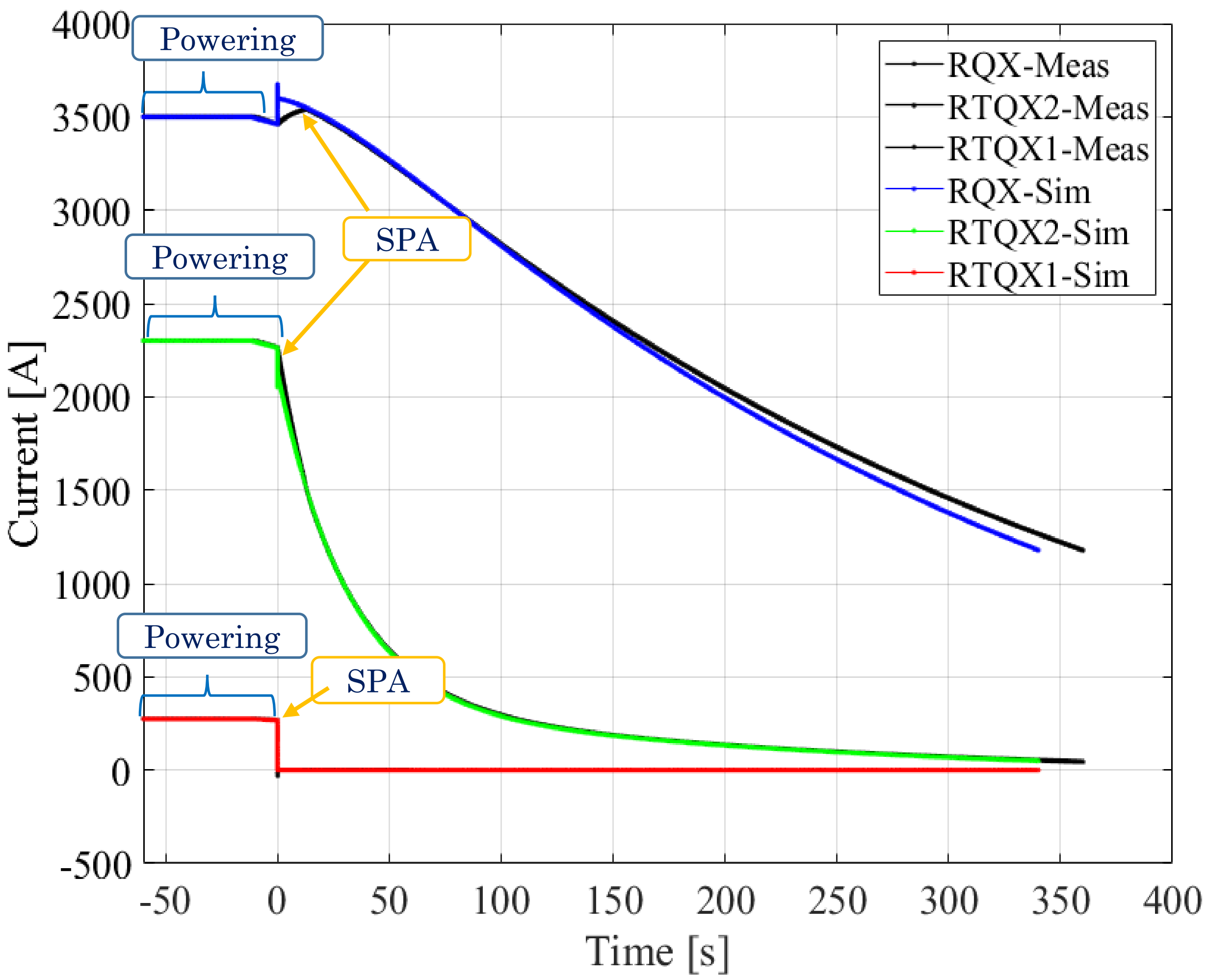
Generating PSPICE model
Using STEAM-SING[2]

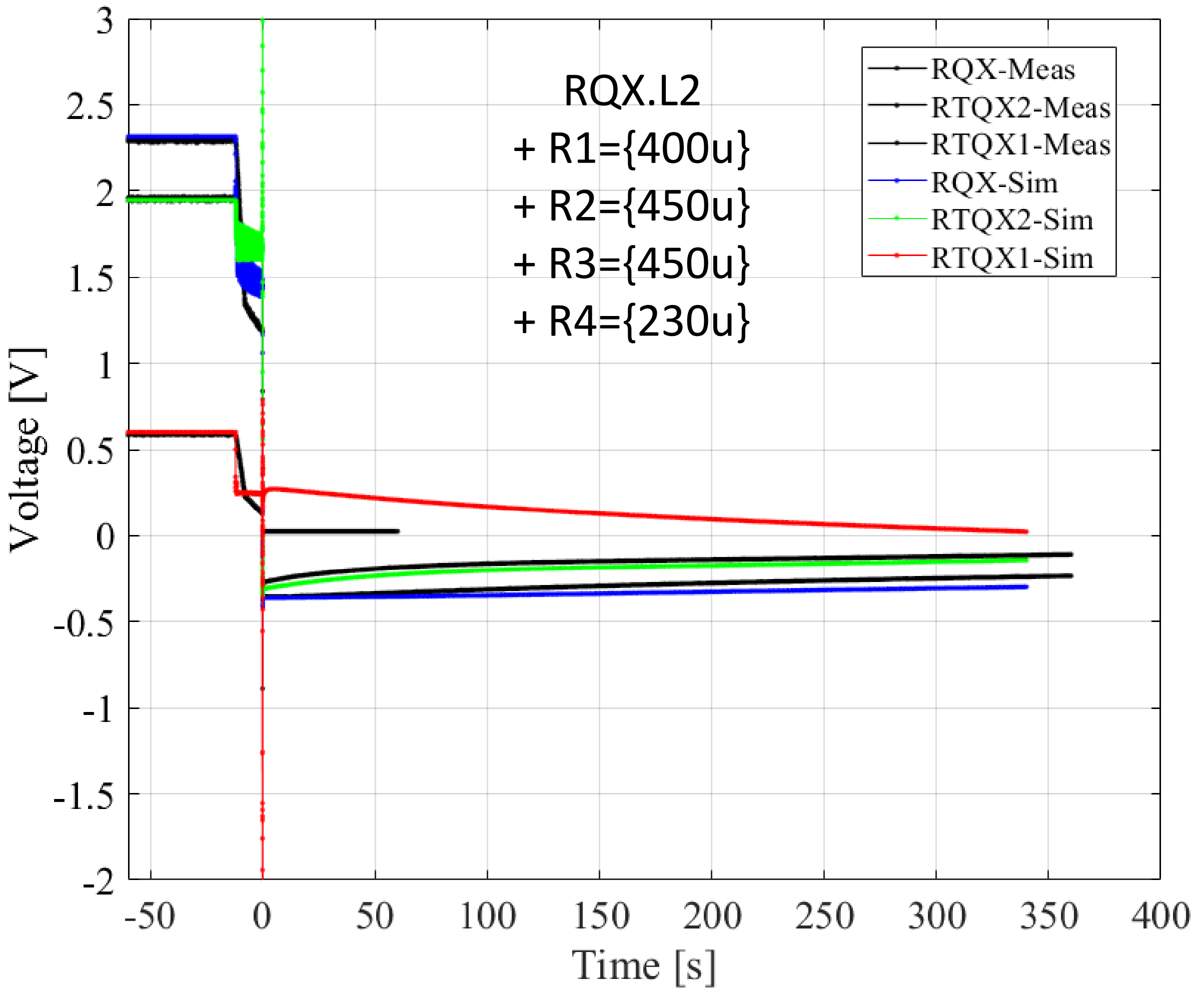
Validation of the RQX.L1 circuit model:



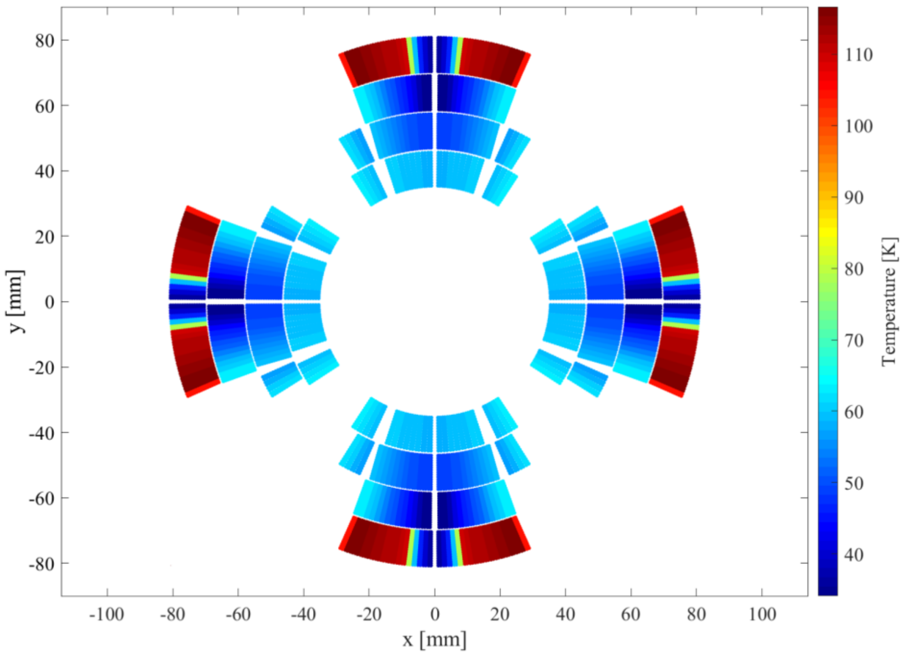


Validation of the RQX.L2 circuit model:



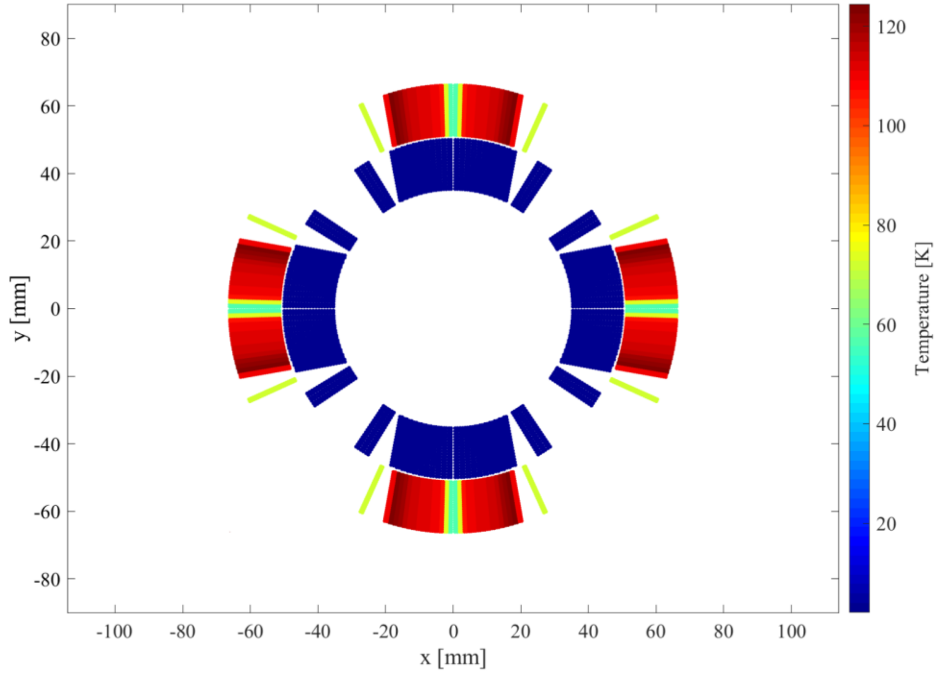


Validation of the MQXA and MQXB magnet model:



MQXA

MQXB



Generating LEDET[3] model

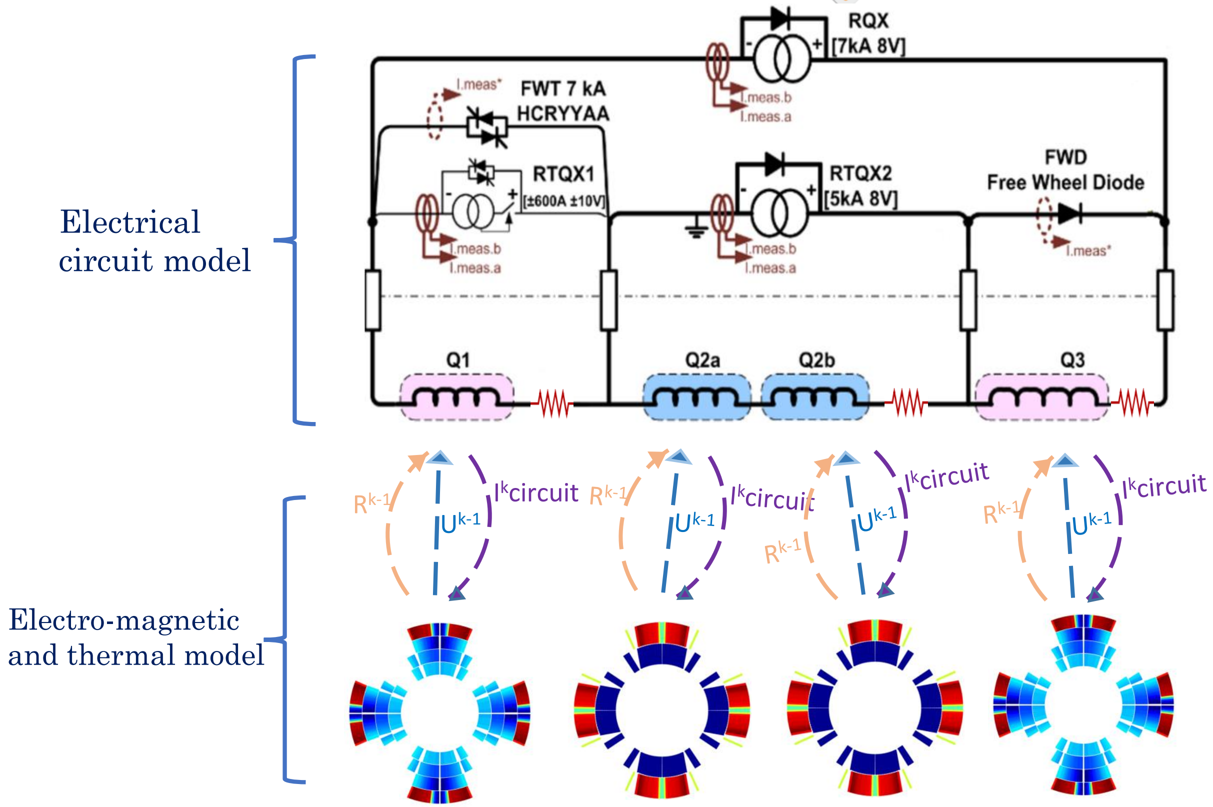
LEDET application comes as a stand-alone executable based on Matlab.

Co-simulation:

Now it's necessary to co-simulate the electrical circuit and the electro-thermal models.

During the FPA, the power converters are switched-off and the quench protection system is triggered. The current discharges due to the coil resistance in less than a second.

STEAM-COSIM[4] → Framework based on cooperative simulation



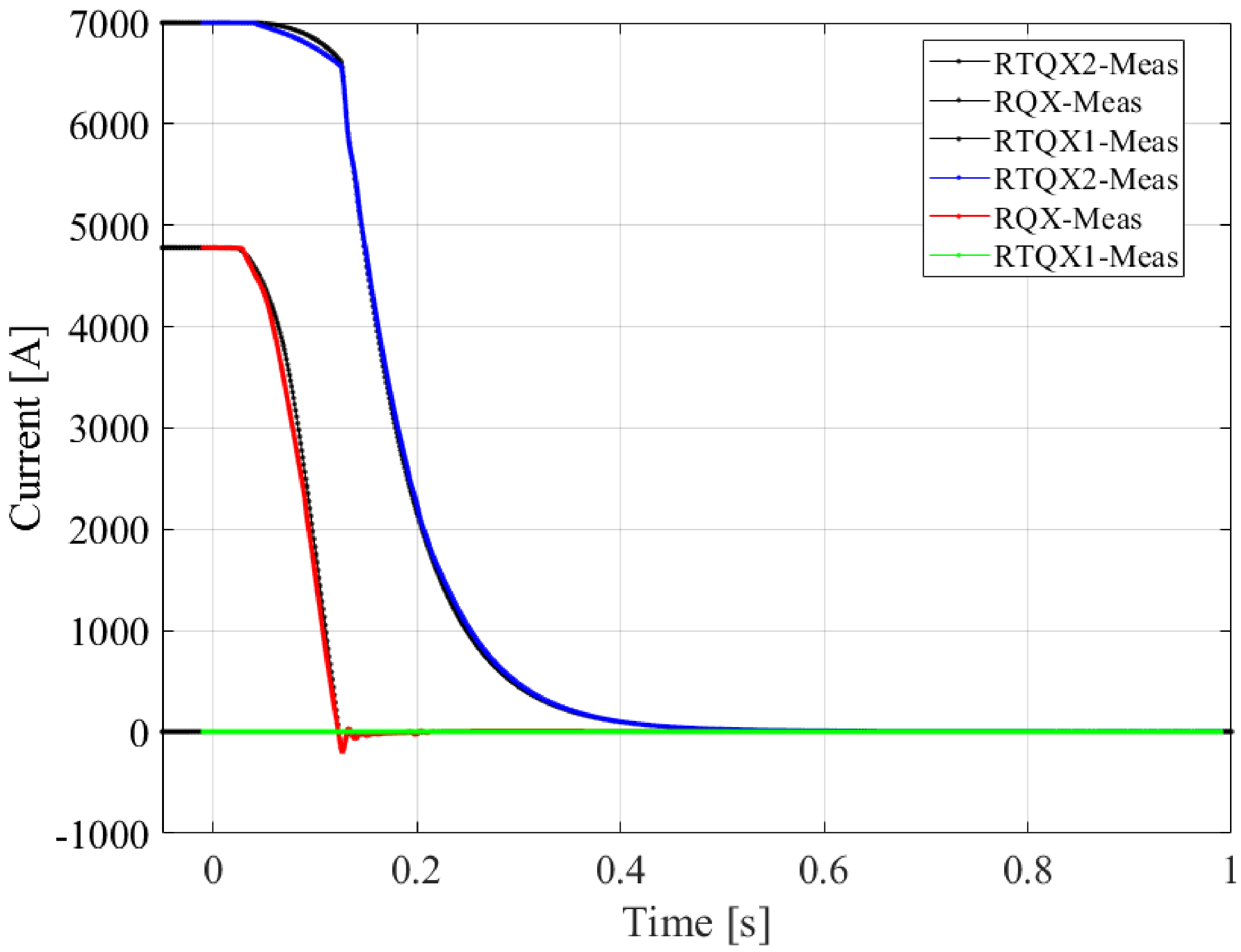
The signals exchange is the core of the co-simulation.

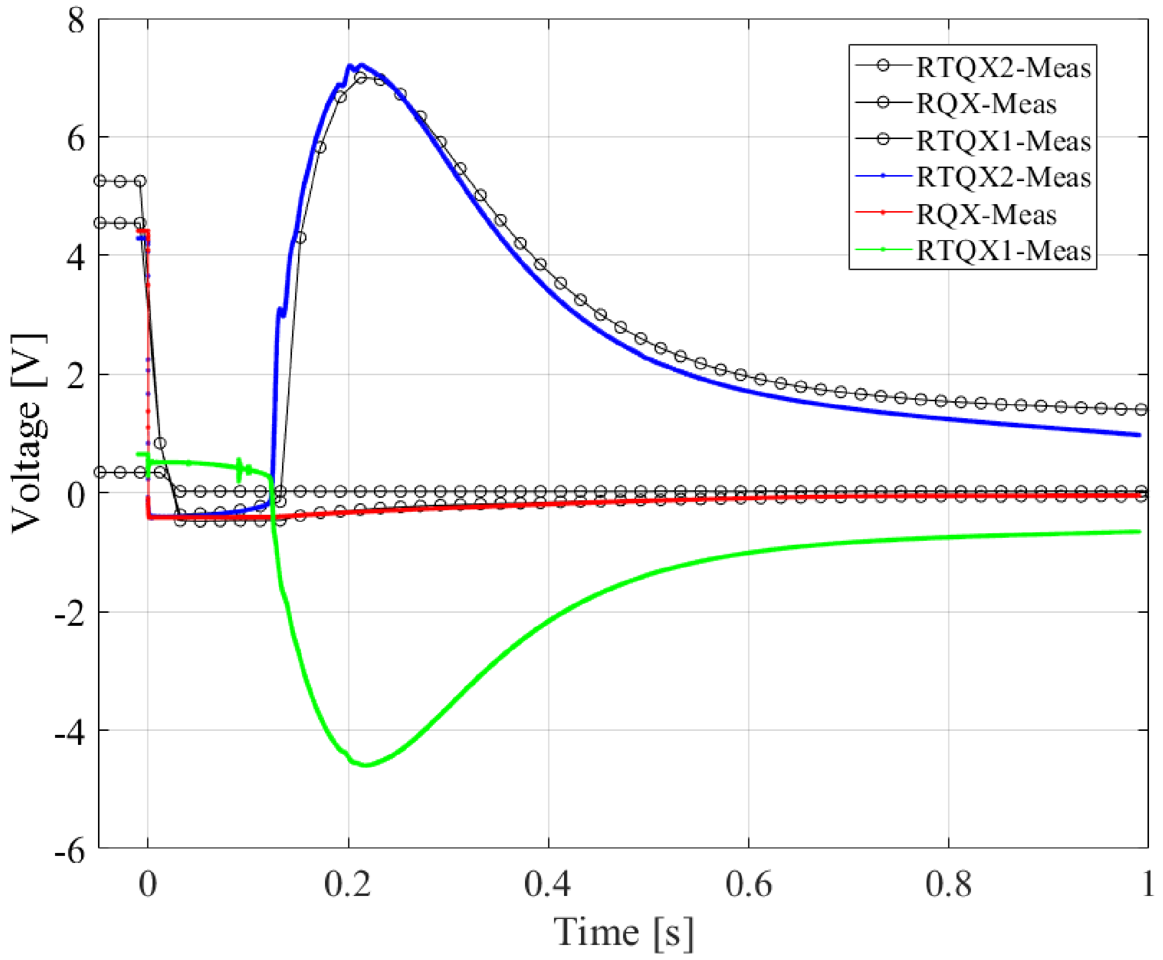
The data exchange is based on the concept of the ports.

- Resistance of the aperture
- Inductive voltage of the aperture
- Current through the aperture

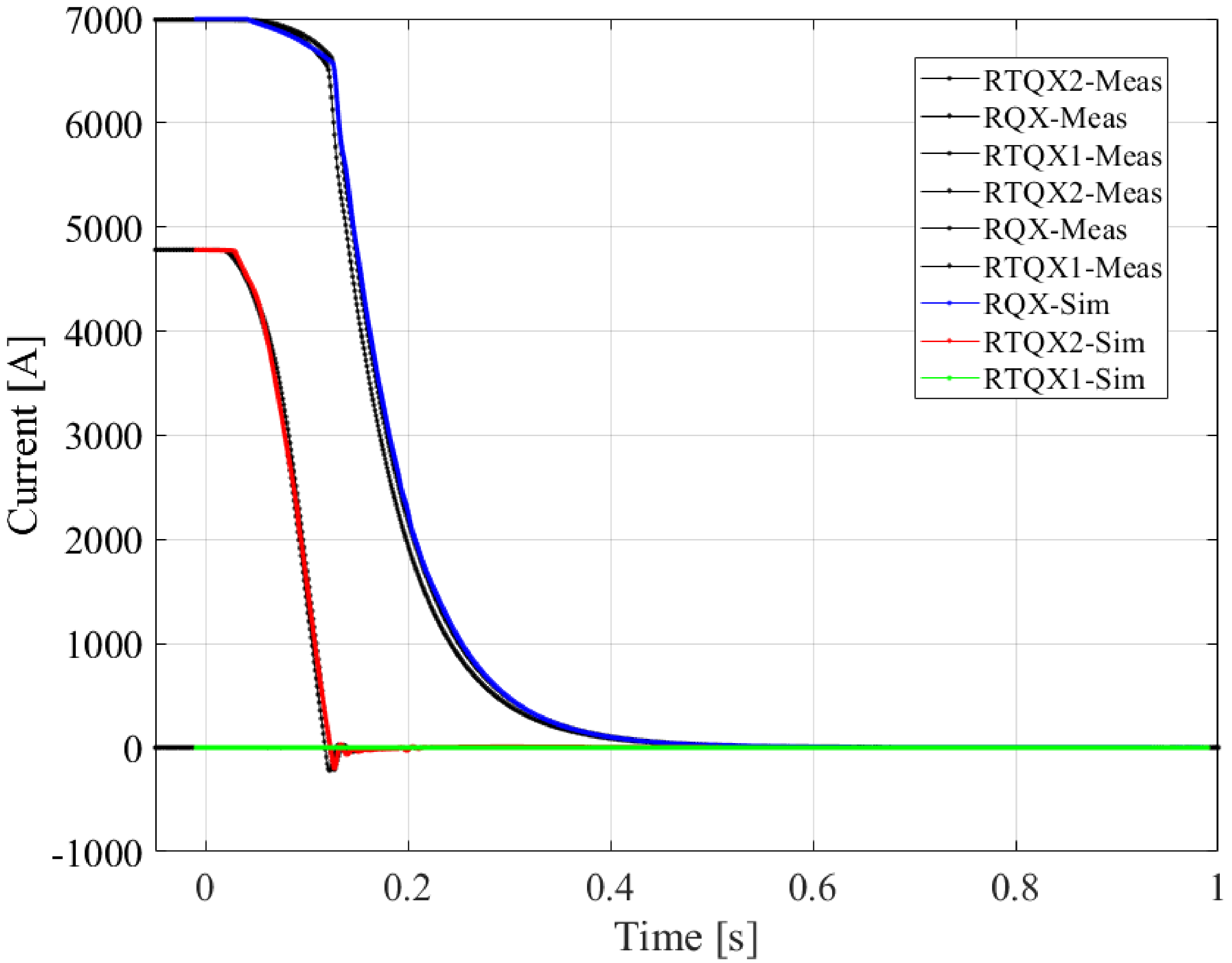
Iteration will be repeated until the convergence level, in terms of relative and absolute error is achieved.

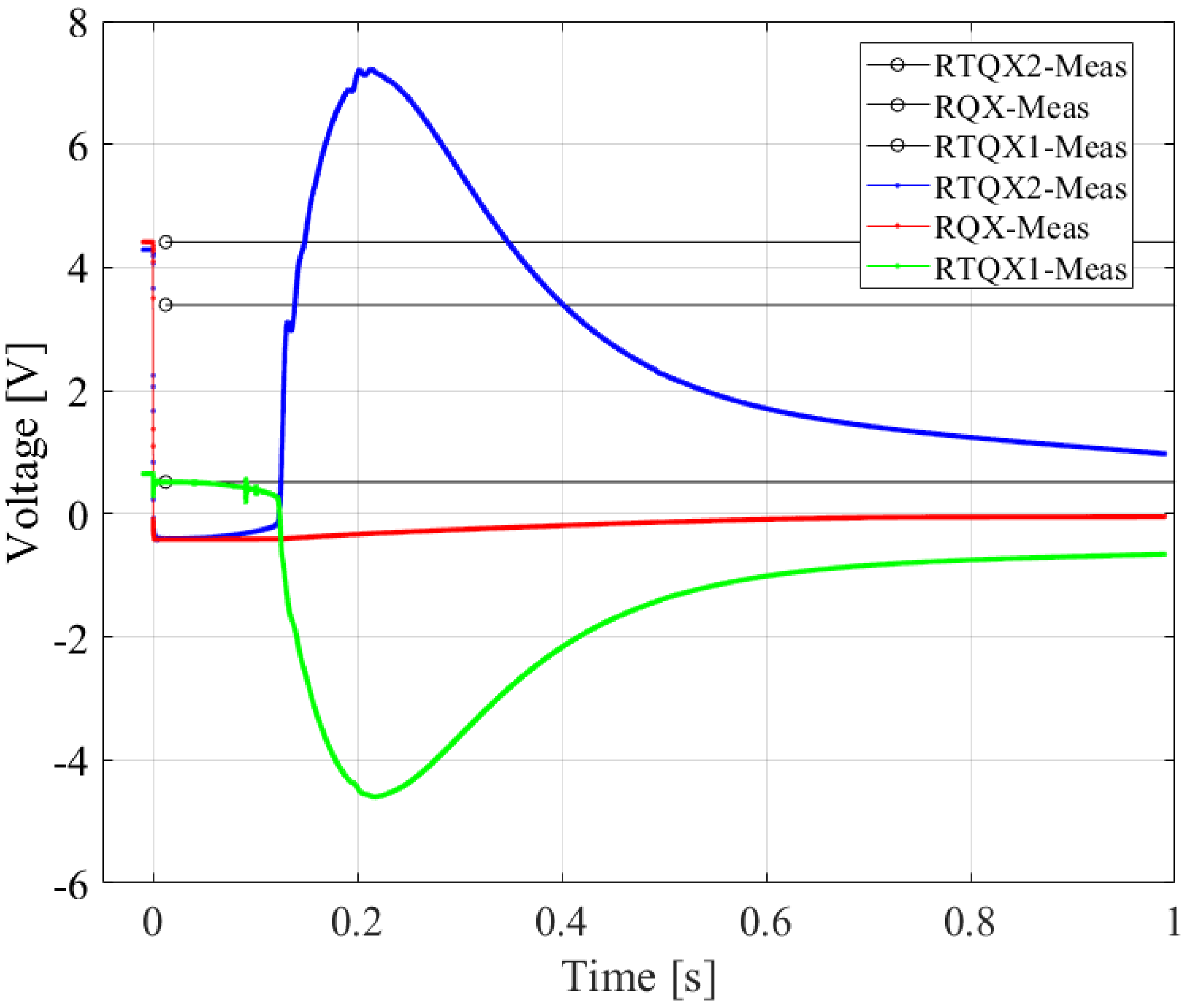
Validation of the co-simulation: RQX.R8





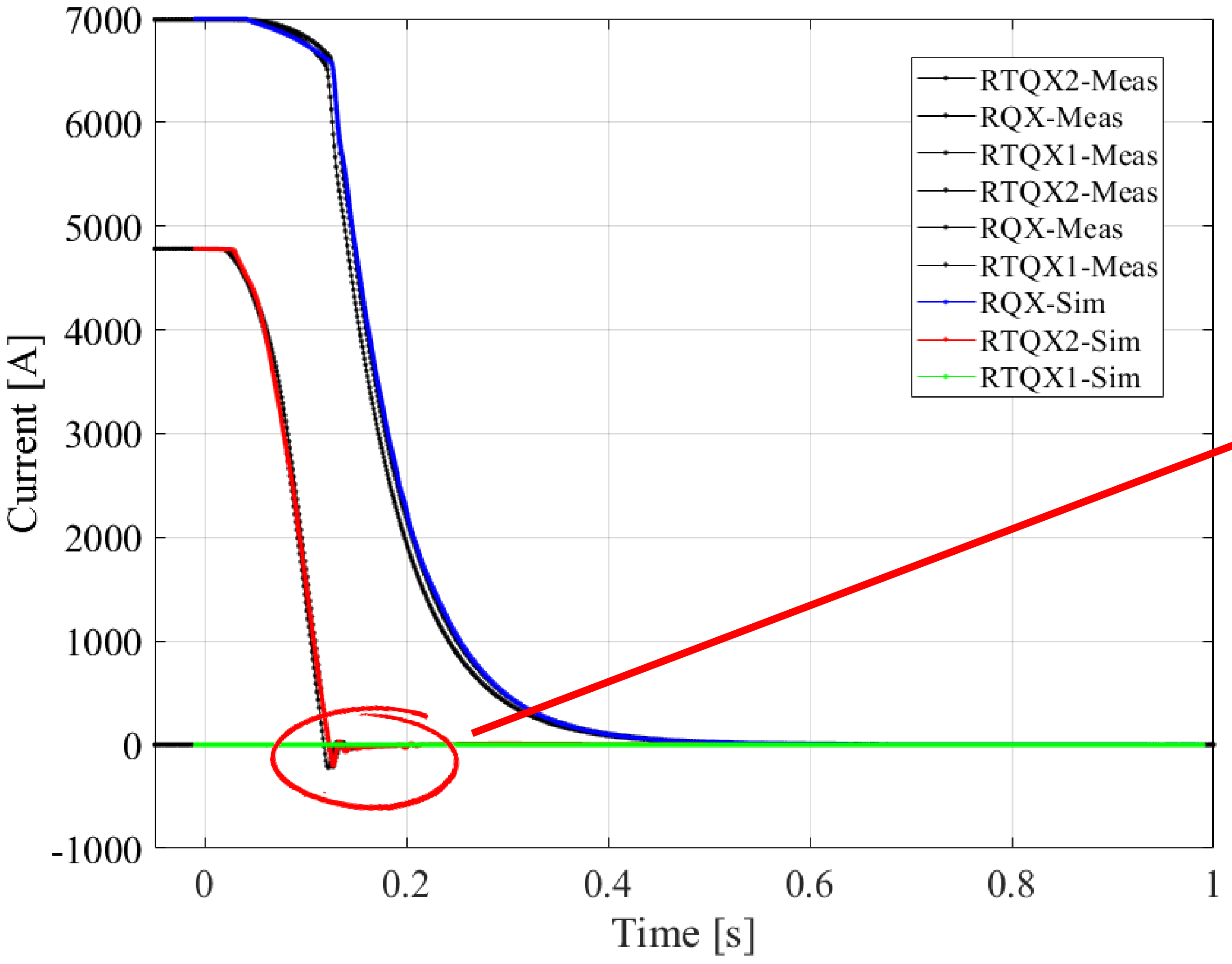
Validation of the co-simulation: RQX.L2

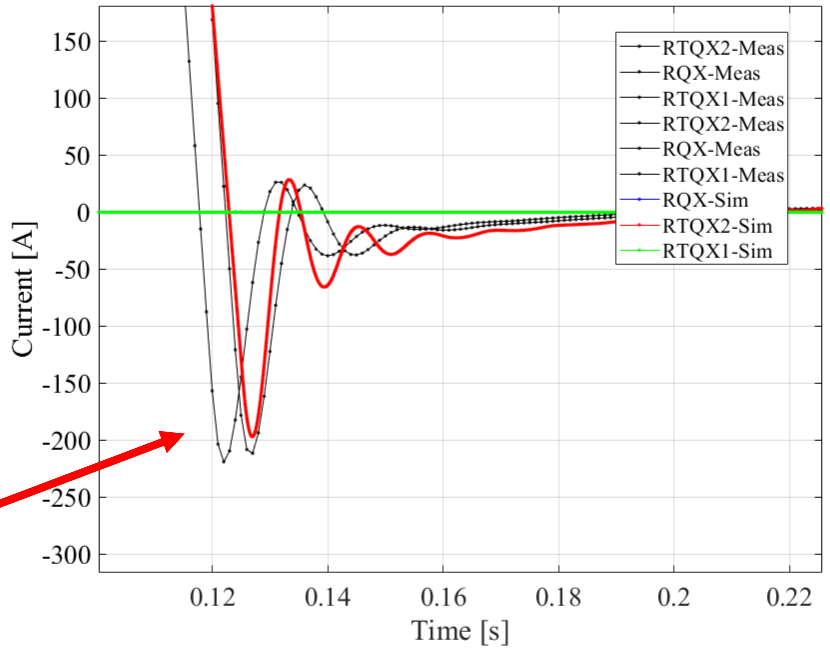




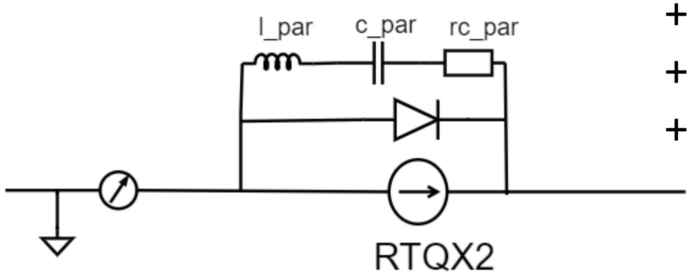
*Probably the voltages are not measured after 0s

Validation of the co-simulation: RQX.L2



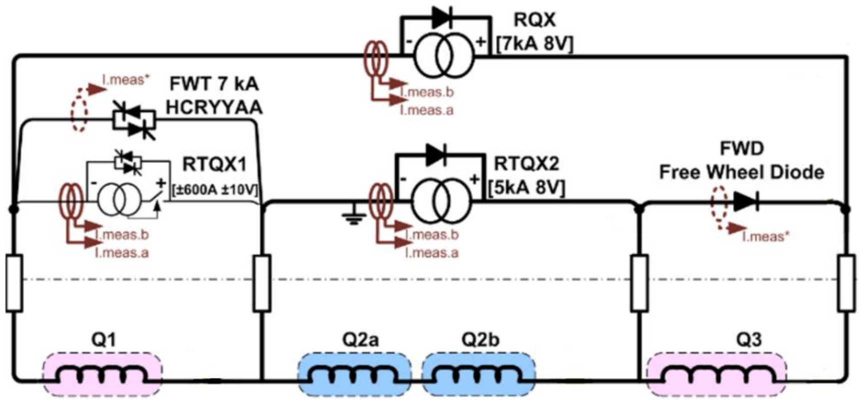


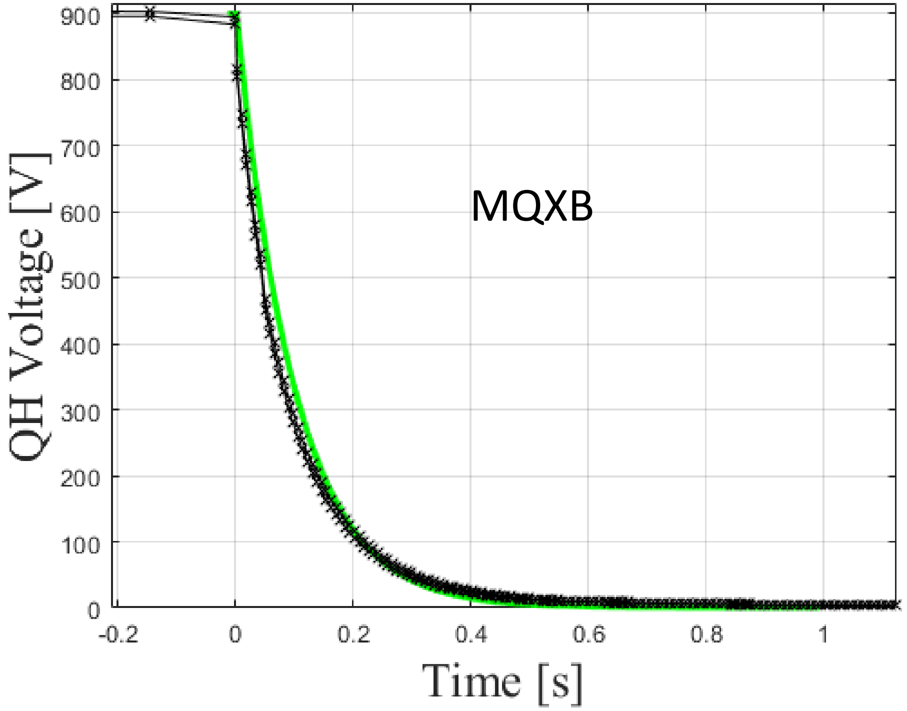
A RLC branch was added in order to reproduce the oscillation of the circuit

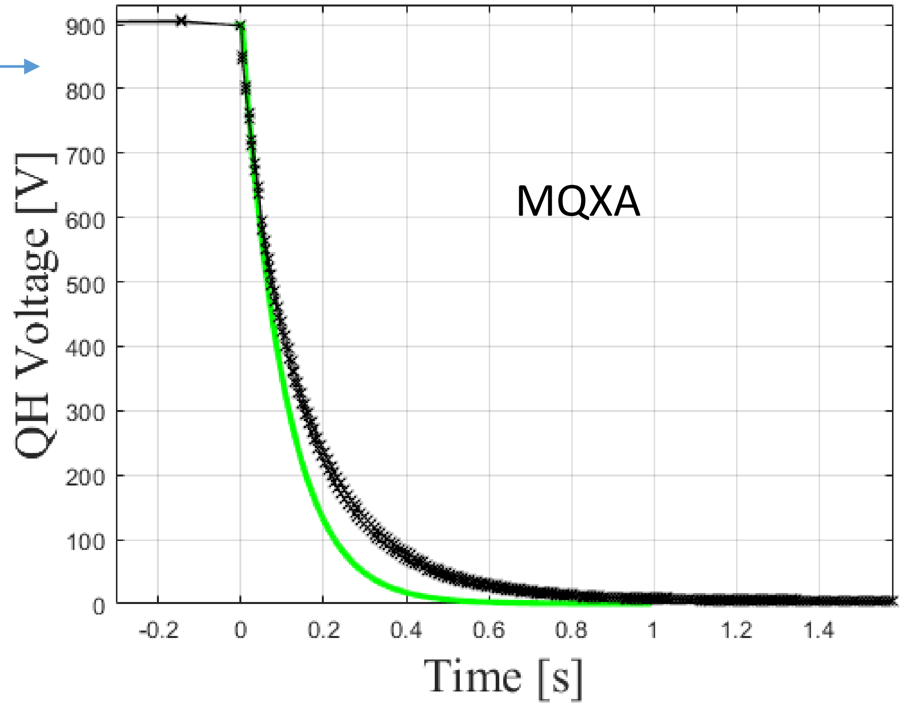


- + rc_par= 1m ΩF
- + l_par= 2u H
- + c_par=300m F

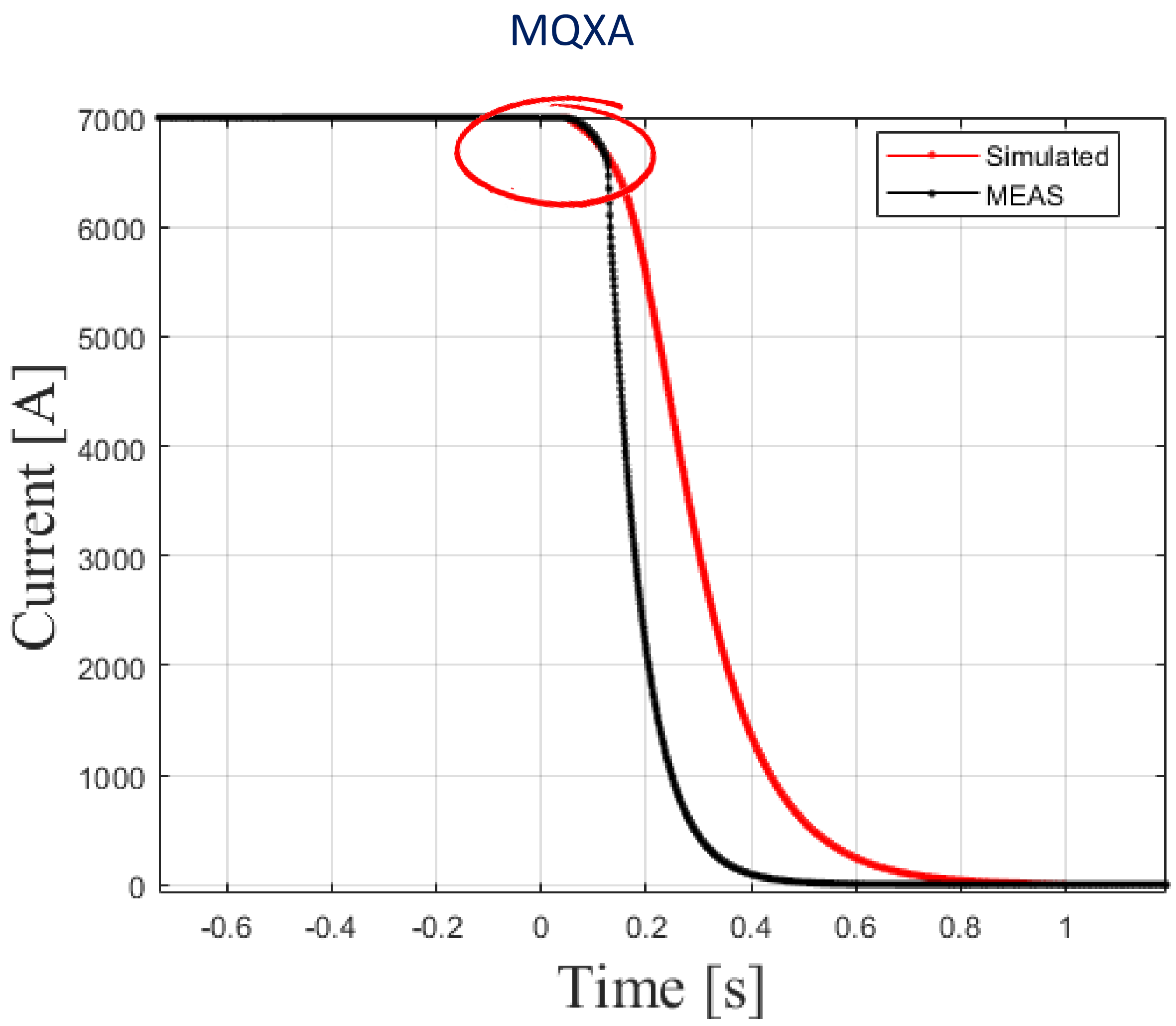
Validation of the co-simulation: RQX.L2

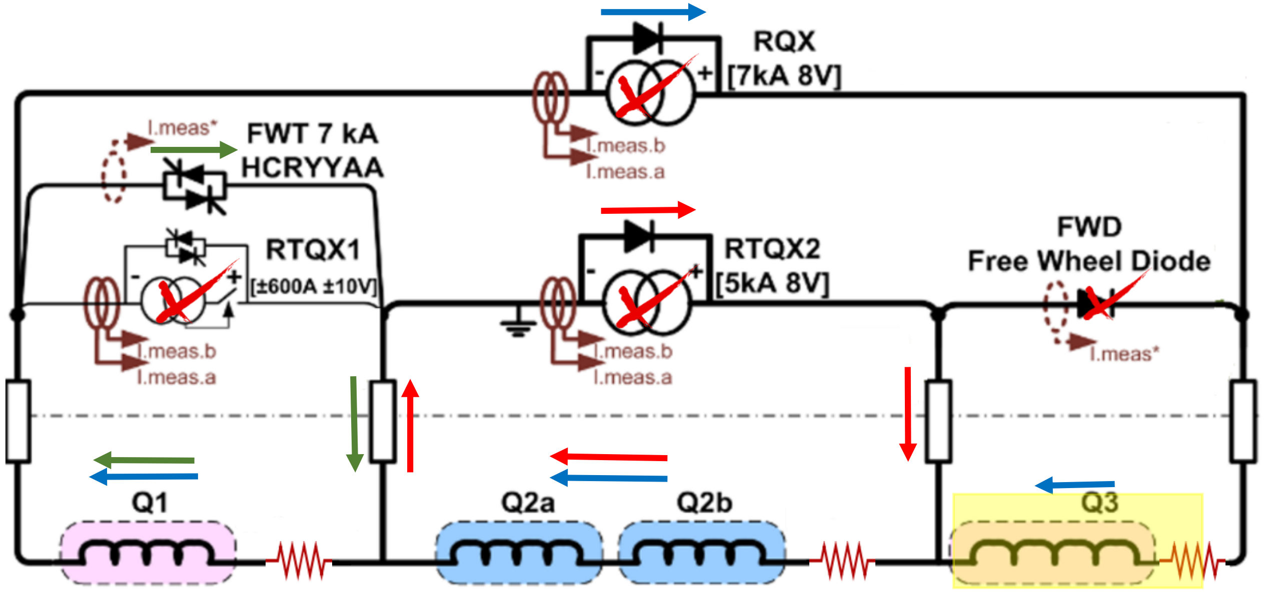






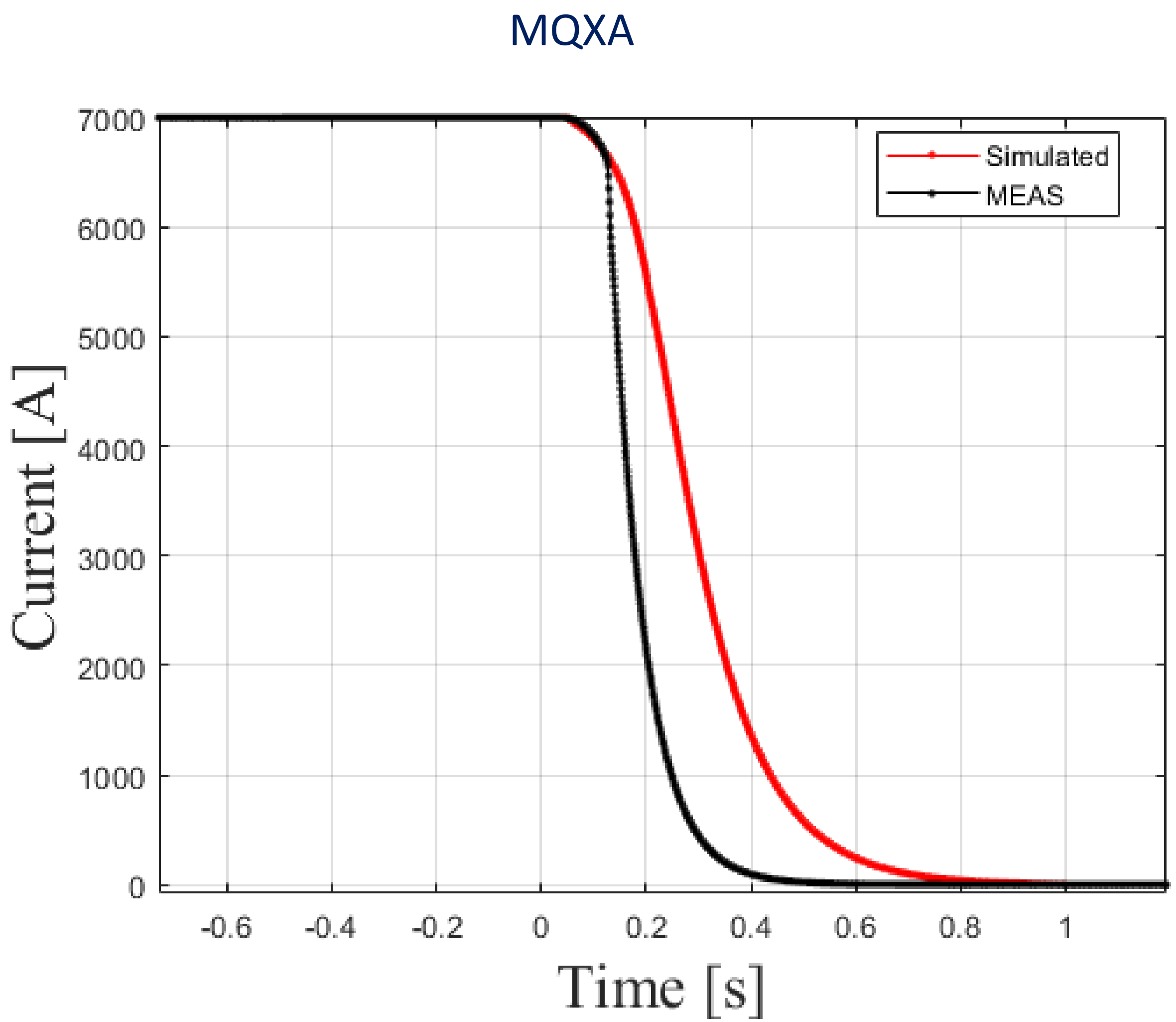
Validation of the co-simulation: RQX.L2

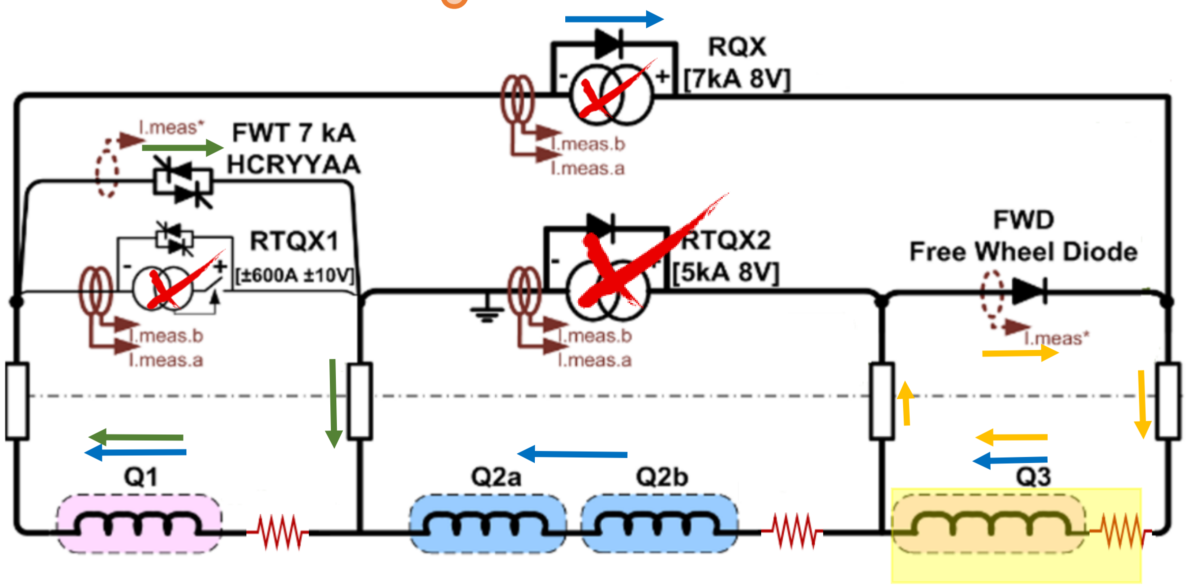




t<130ms $I_{Q3}=I_{RQX}$

Validation of the co-simulation: RQX.L2

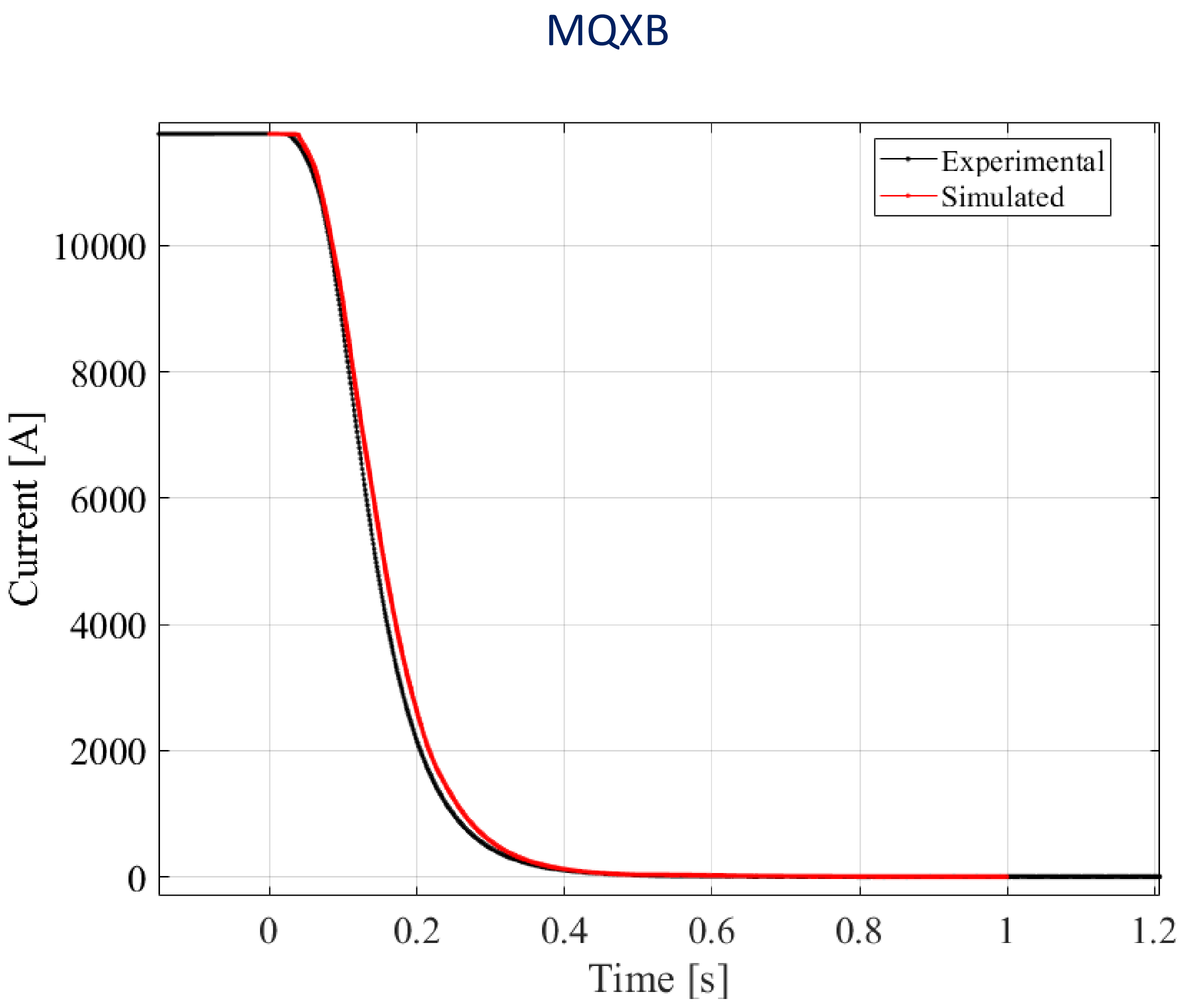


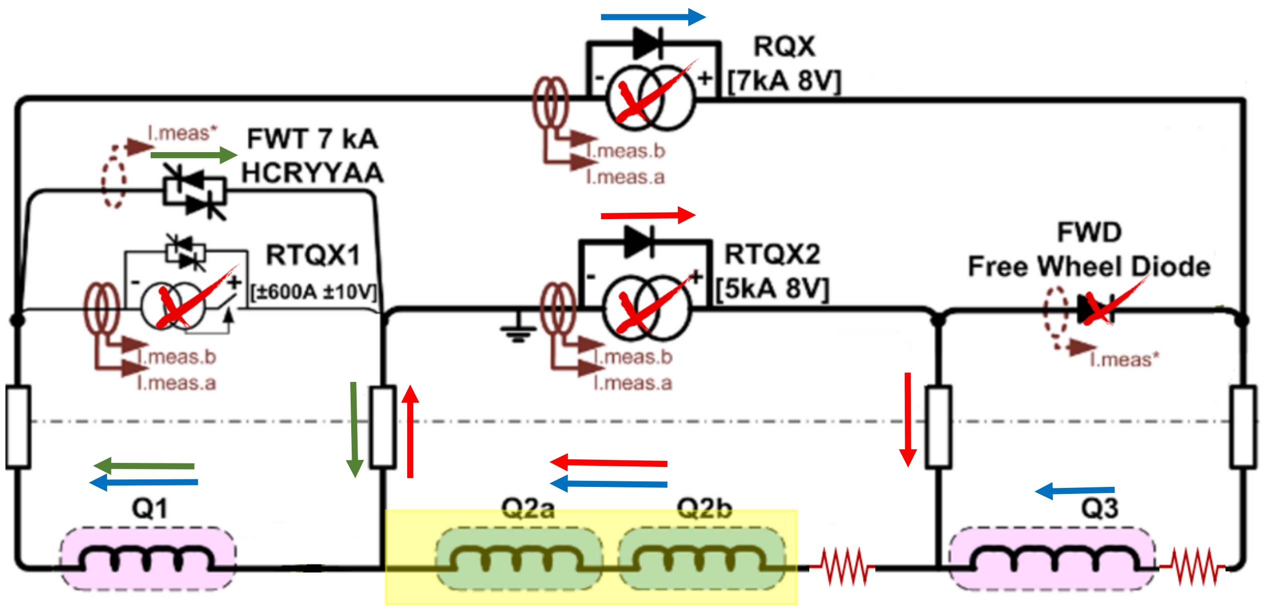


t>130ms $I_{Q3} \neq I_{RQX}$

$I_{Q3} = I_{FWD} + I_{RQX}$

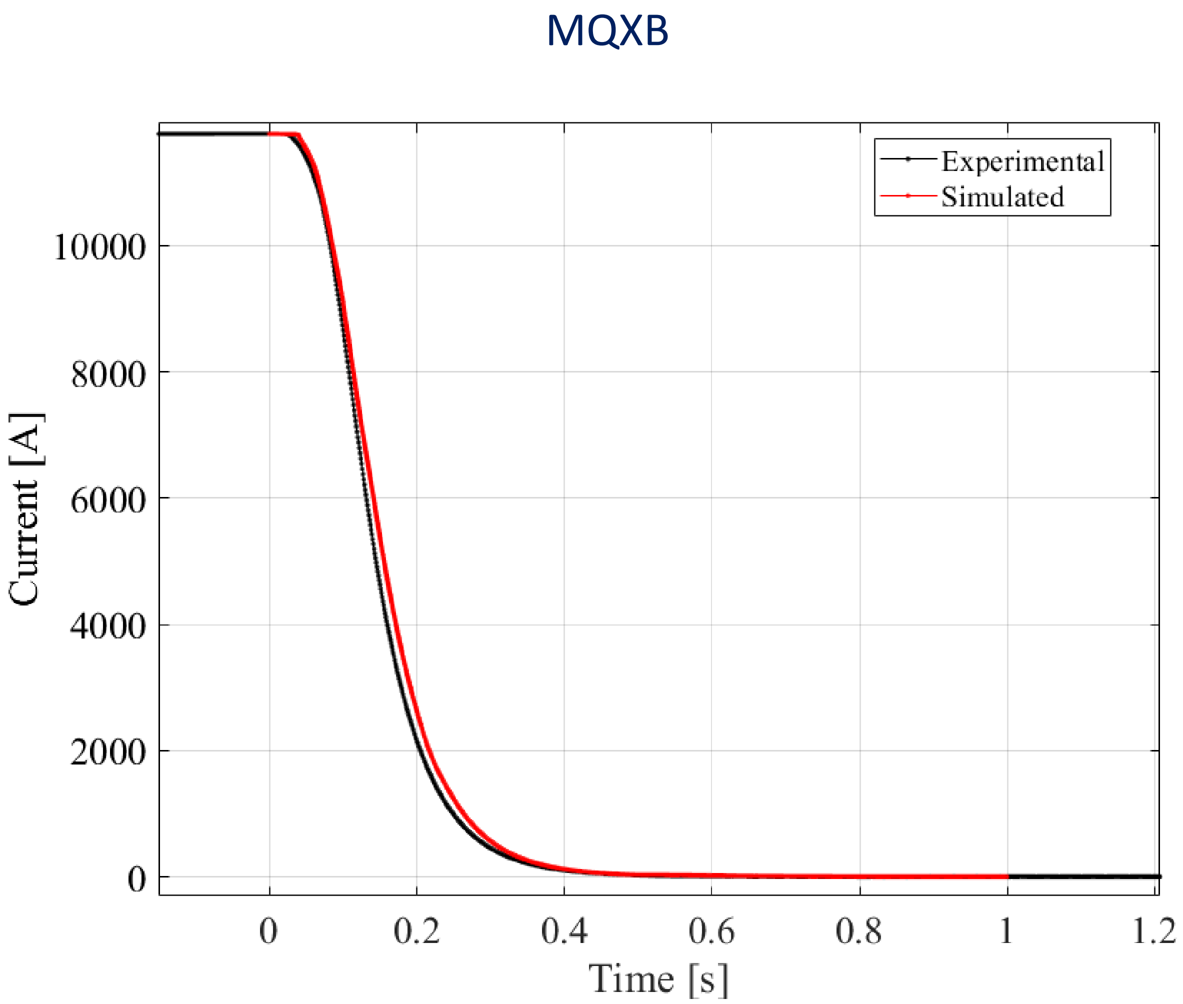
Validation of the co-simulation: RQX.L2

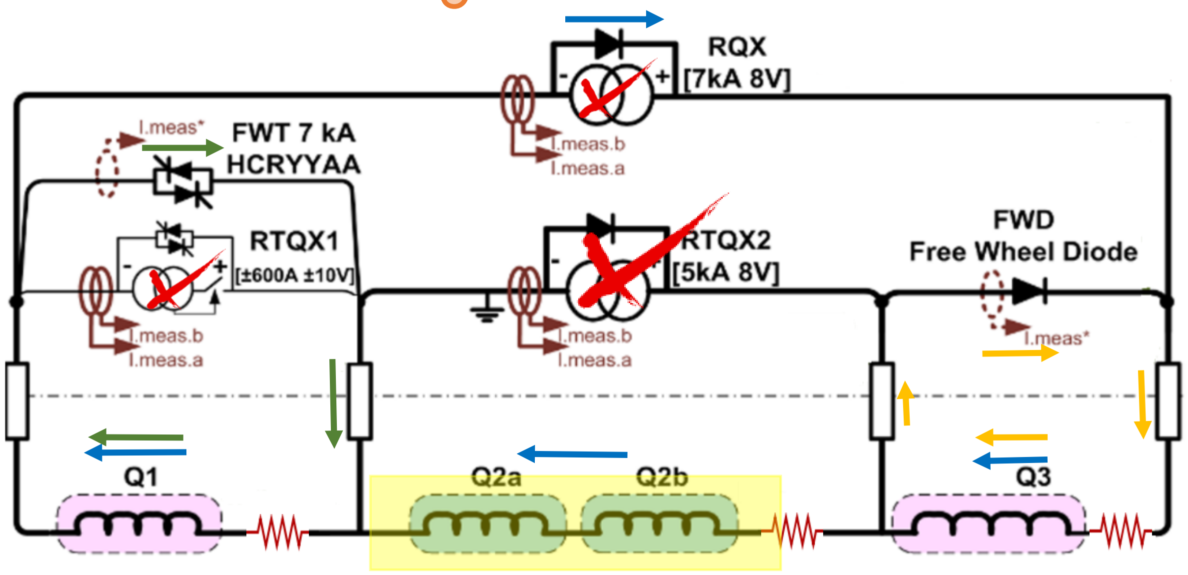




t<130ms $I_{Q2}=I_{RQX}+I_{RTQX2}$

Validation of the co-simulation: RQX.L2





t>130ms $I_{Q2}=I_{RQX}$

Conclusion and future work

- Due to the complexity of the circuit, more accurate analysis of the electrical circuit will be performed.
- For a more complete and reliable validation of the superconducting circuit RQX it is necessary to find the magnet data in order to be able to validate the **electro-thermal model** in a stand-alone configuration using STEAM-LEDET.
- Once the electro-thermal model will be validated, will be possible to update the model from 2D to 2D+1D using the specific LEDET feature. This will allow to have a better approximation of the circuit.
- Two of the eight RQX circuits models were **validated using SlowPowerAbort** data from the LHC Hardware Commissioning. The validation gave good agreement with the experimental results. It is necessary to continue with the validation of the other RQX circuits.
- RQX circuit model and MQXA and MQXB magnet models were **combined in a co-simulation model using the tool STEAM-COSIM**. The co-simulations were **validated using FastPowerAbort** data from the LHC Hardware Commissioning. The validation gave a good agreement with the experimental results.
- The two circuits validated in PSpice and in COSIM (Pspice+LEDET) are ready to use for the upcoming LHC hardware commissioning and operation.

Thanks for the attention!

Any questions?

References:

[1] Bortot, Lorenzo, et al. "STEAM: A hierarchical cosimulation framework for superconducting accelerator magnet circuits." *IEEE Transactions on applied superconductivity* 28.3 (2017): 1-6.

[2] https://gitlab.cern.ch/steam/steam-sing

[3] Ravaioli, E., et al. "Lumped-element dynamic electro-thermal model of a superconducting magnet." *Cryogenics* 80 (2016): 346-356.

[4] M. Maciejewski. "Co-Simulation of Transient Effects in Superconducting Accelerator Magnets". PhD thesis. Geneva, 2019.

[5]CERN video https://videos.cern.ch/record/1709736

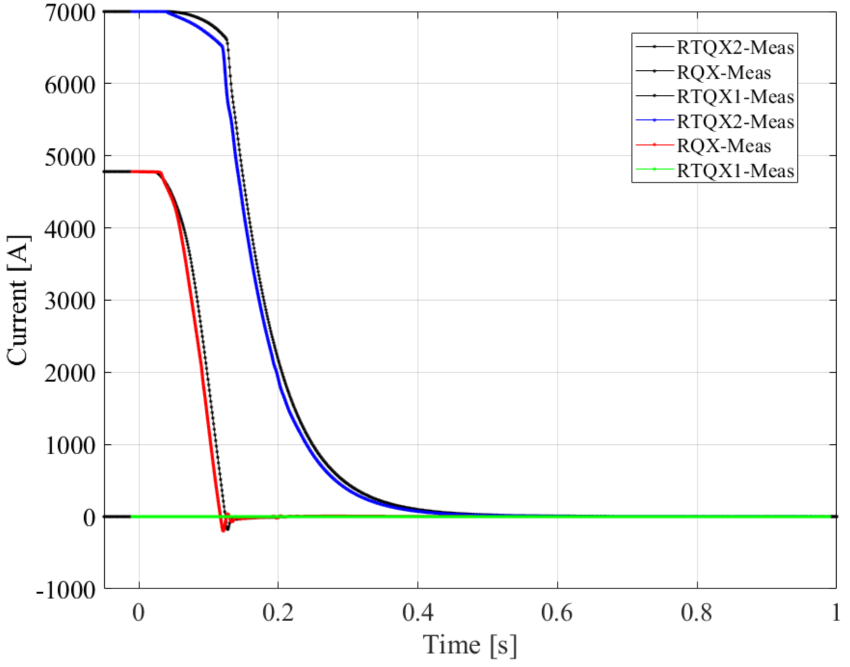
[6] E. Ravaioli and L.Brouwer "SMIC Documentation"

[7] S. Russenschuck"Roxie: the routine for the optimization of magnet x-sections, inverse field computation and coil end design". CERN,1993

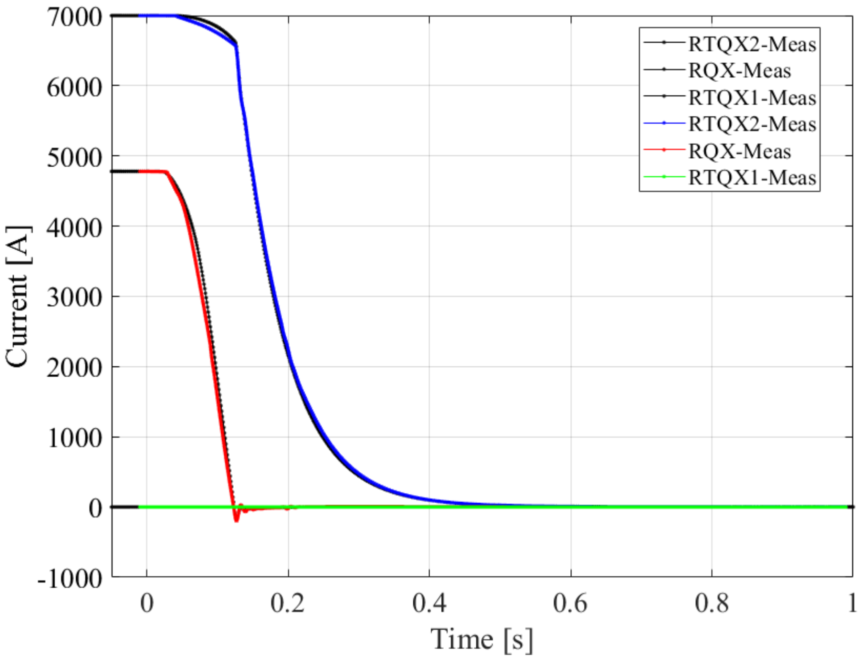
Annex

Validation of the co-simulation: RRR effect

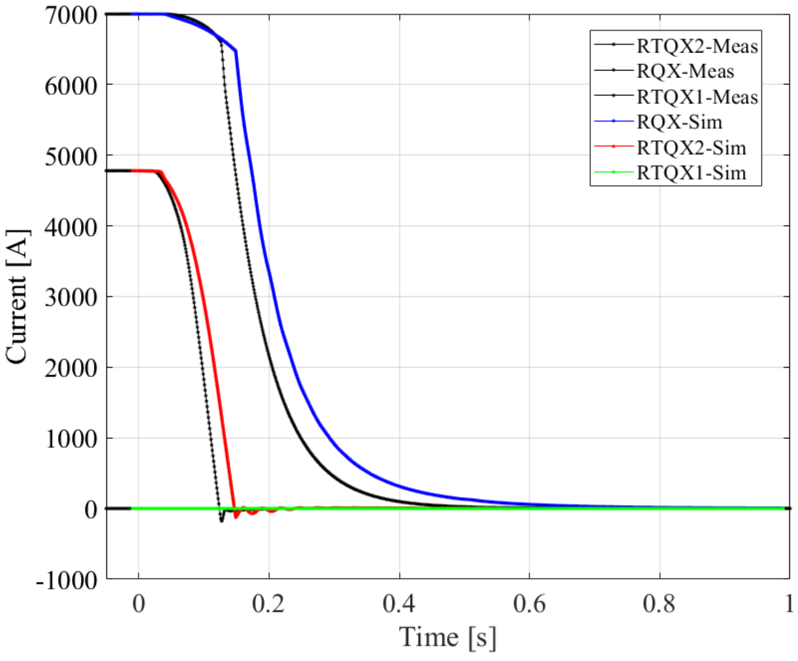
RRR=70



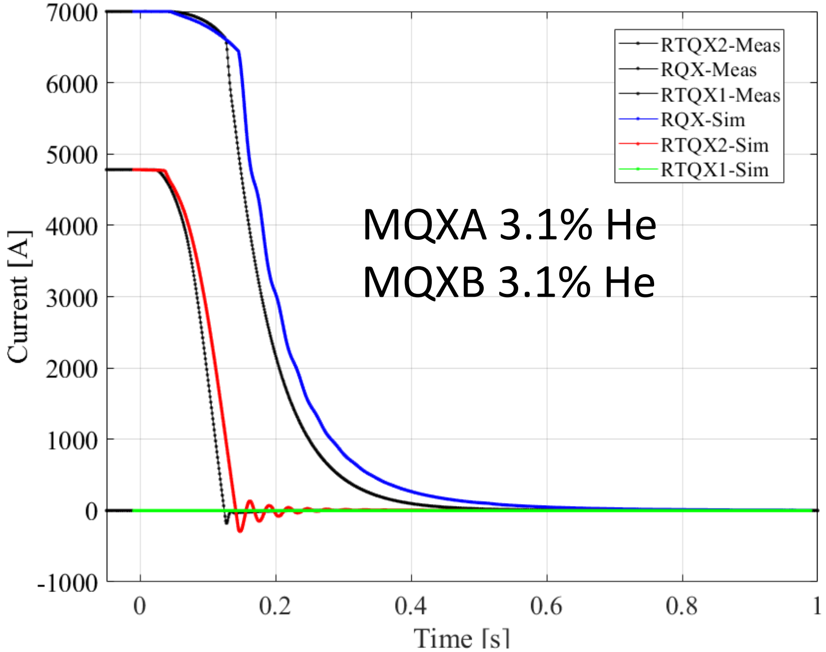
RRR=100

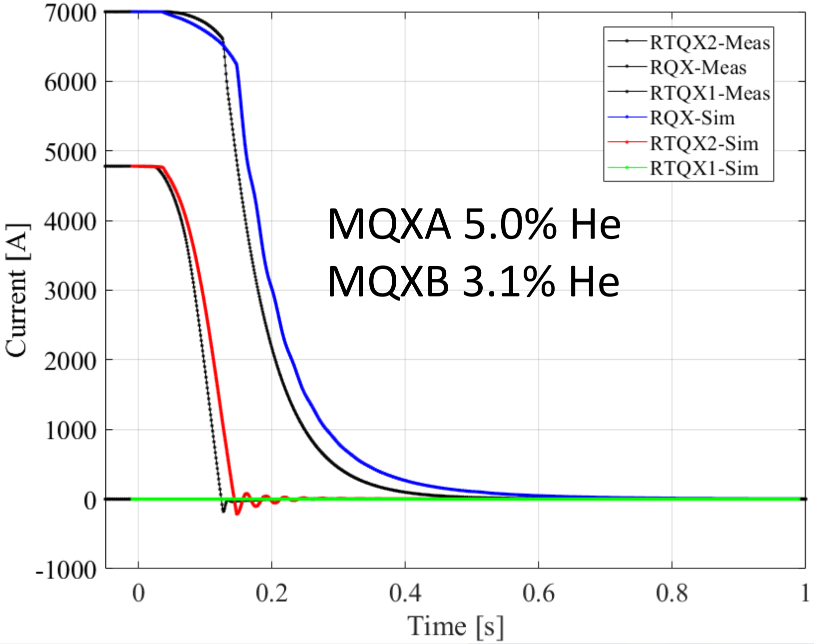


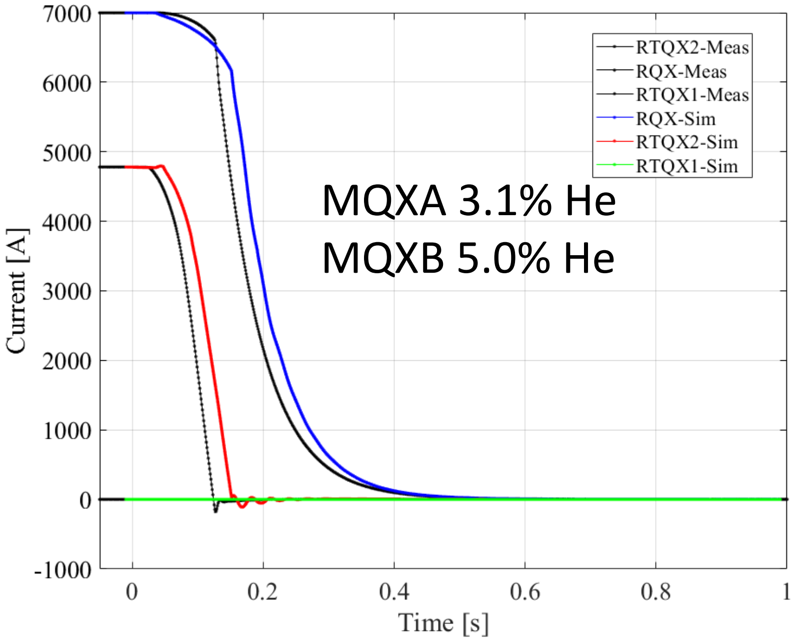
RRR=150

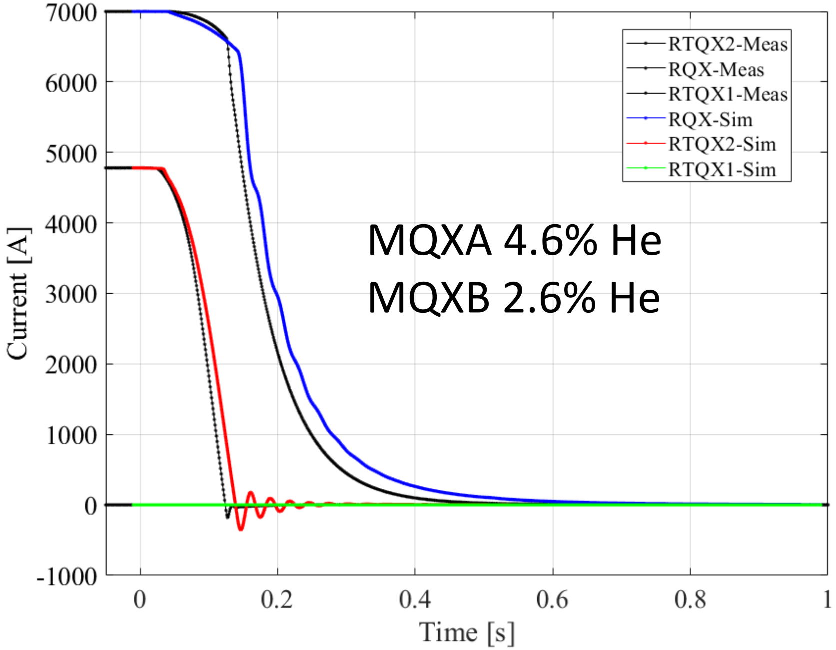


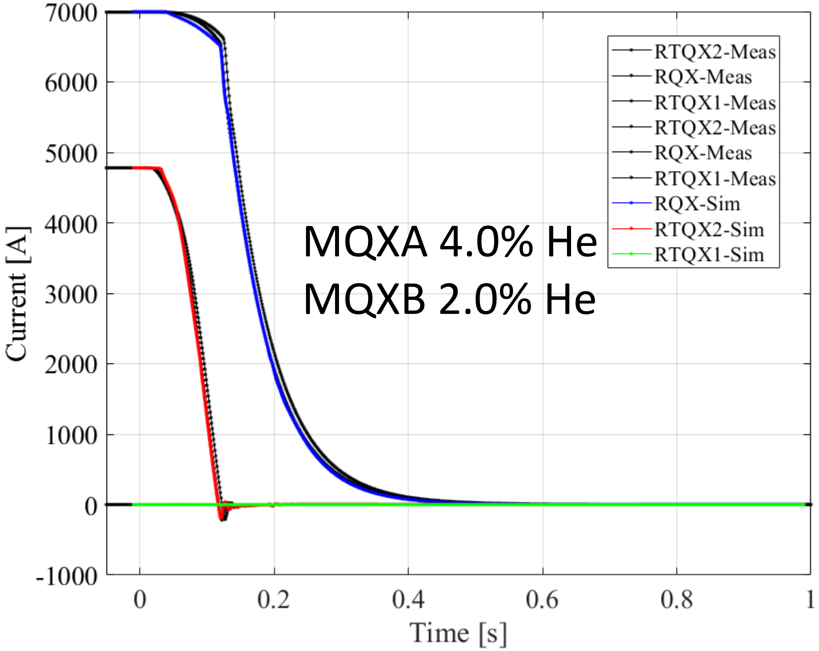
Validation of the co-simulation: He inside the cable cross-section effect

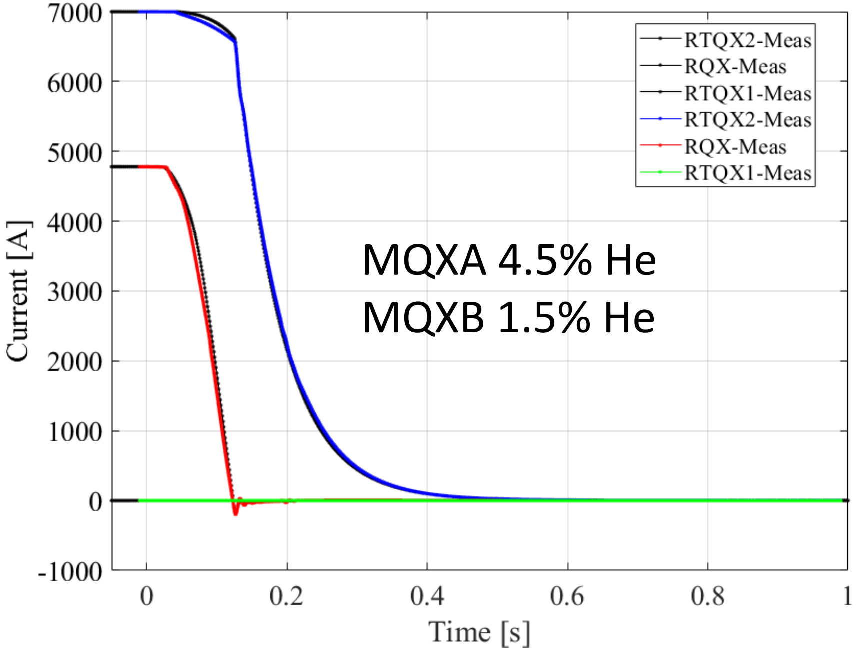




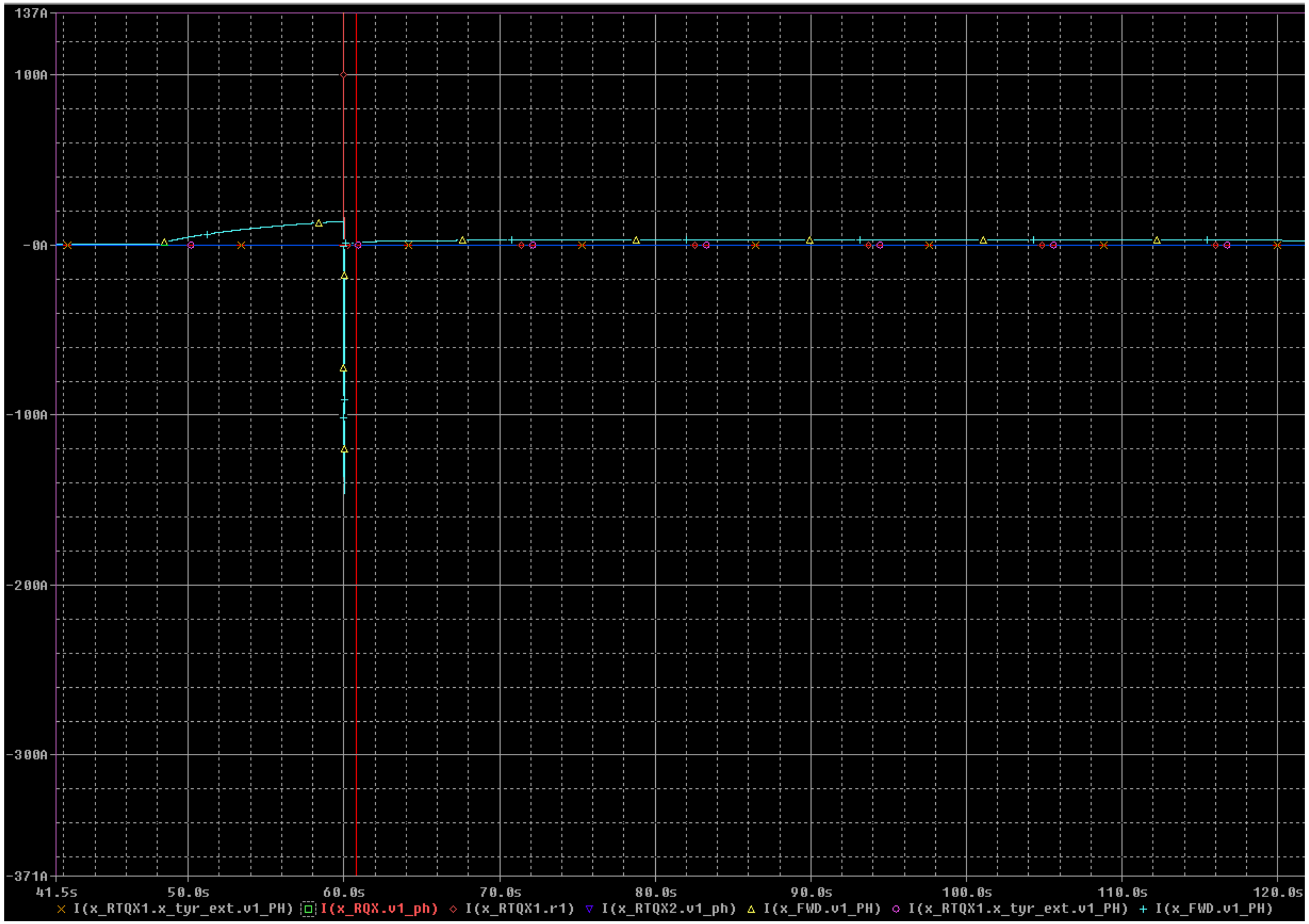




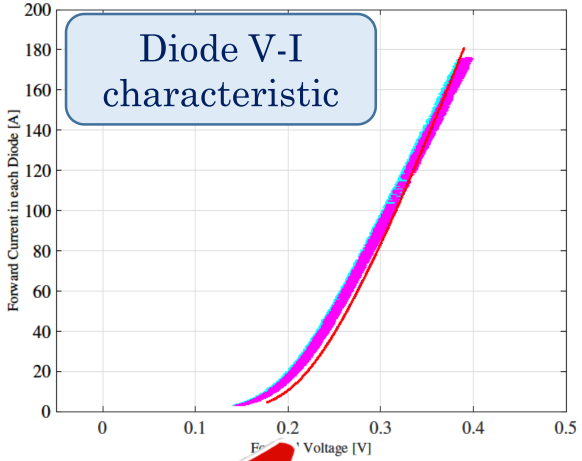




FWD SPA RQX.L2

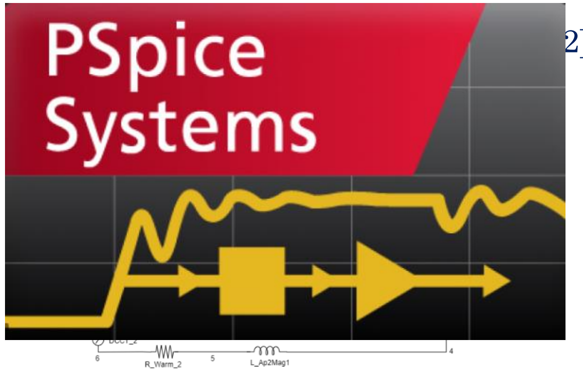


Generation of the RQX circuit model:



SMIC [6]

Generating PSPICE model



2]

Import Java gateway and STEAM API (SING, UTILS)
Import ligthweight STEAM API in python
Input paths
Create netlist template
Set global parameters
Power supply and DCCT
Busbar
Diodes and Parasite elements
Chain of magnets in series
Earthing circuit
Simulation options
Print the library subcircuit netlist
Write netlist to a file

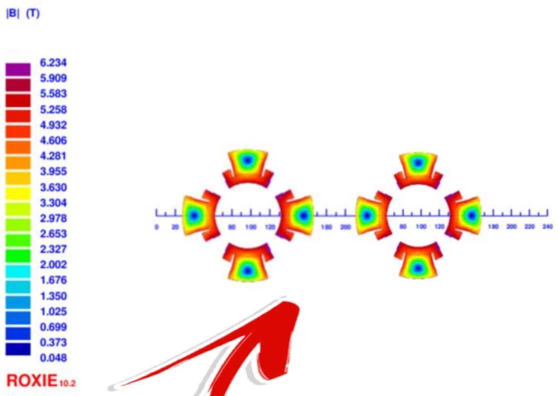
Validation of components

Calculation of self and mutual inductance

Semi-automatic model generation

Simula are r in PS

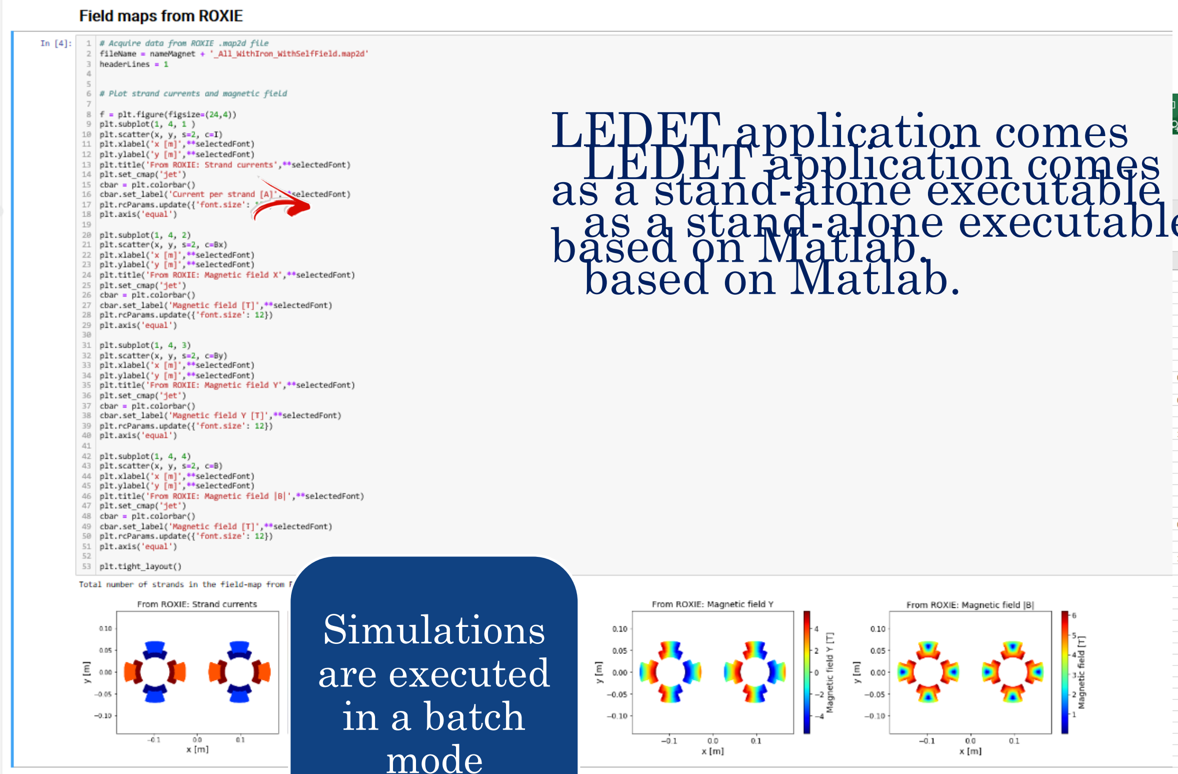
Generation of the RQX magnet model:

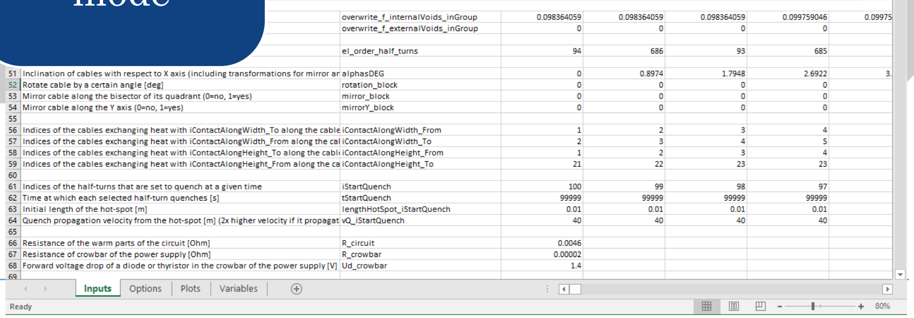


Field maps (ROXIE[7])

Semi-automatic model generation

Input f… an exce…



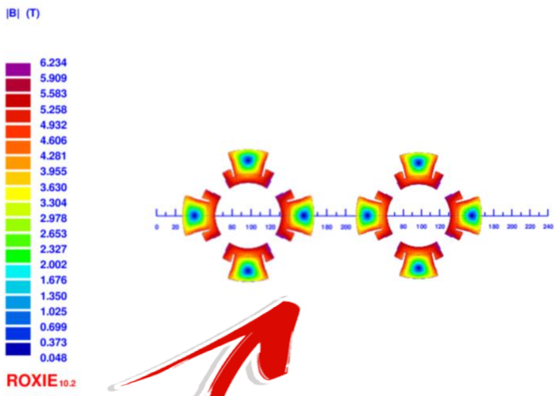


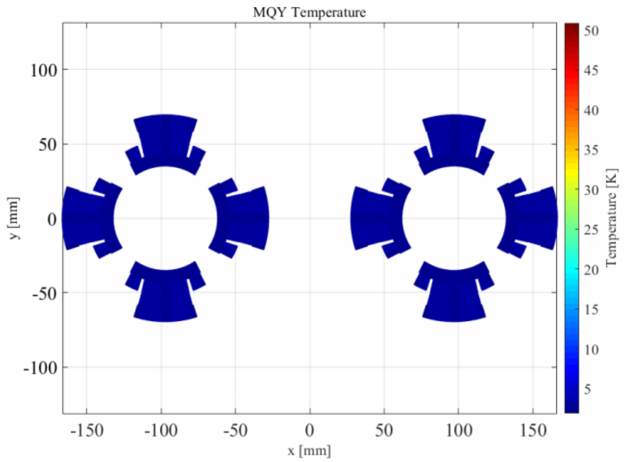
Simulations are executed in a batch mode

LEDET application comes as a stand-alone executable based on Matlab.

LEDET application comes as a stand-alone executable based on Matlab.

Generation of the RQX magnet model:





Magnetic model (ROXIE[7])

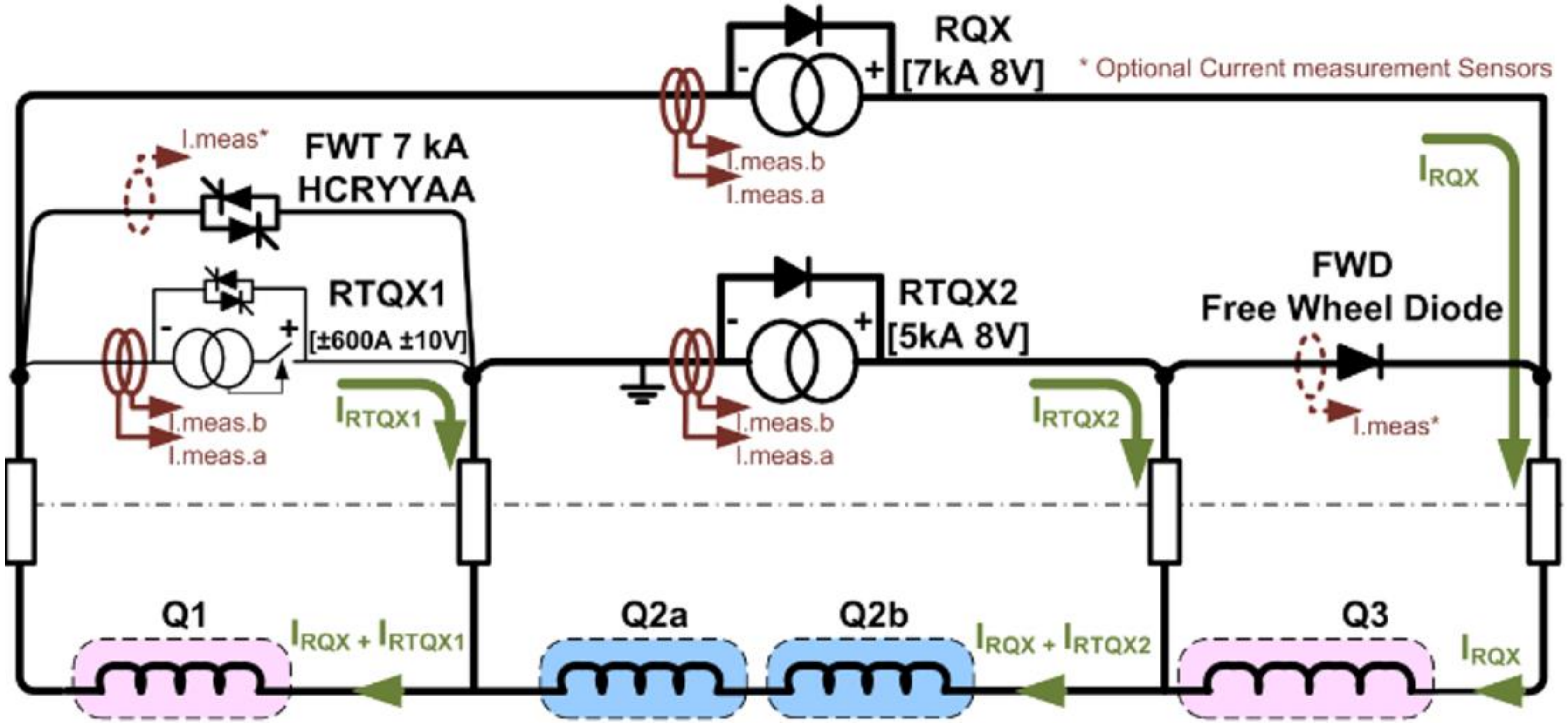
Semi-automatic model generation

Input file is an excel file

Simulations are executed in a batch mode

Output as txt files, figures, animated GIFs, pdf report,…

```
"t_0":   [0.000, 0.020, 0.10, 0.2, 0.5 ],
"t_end": [0.020, 0.100, 0.2, 0.50, 1.0 ],
"t_step_max": [[1.0e-5, 1.0e-5, 1.0e-5, 1e-4, 1e-4],
                                [2.5e-5, 2.5e-5, 2.5e-5, 5e-4, 1e-3],
                                [2.5e-5, 2.5e-5, 2.5e-5, 5e-4, 1e-3],
                                [2.5e-5, 2.5e-5, 2.5e-5, 5e-4, 1e-3],
                                [2.5e-5, 2.5e-5, 2.5e-5, 5e-4, 1e-3]],
"relTolerance": [8e-4,
                                  null,
                                  null,
                                  null,
                                  null],
"absTolerance": [5,
                                  null,
                                  null,
                                  null,
                                  null],
"executionOrder": [1,
                                        2,
                                        2,
                                        2,
                                        2],
"executeCleanRun": [true,
                                         true,
                                         true,
                                         true,
                                         true]
```


RQX
[7kA 8V]
* Optional Current measurement Sensors
I.meas.b
I.meas.a
I.meas*
FWT 7 kA
HCRYYAA
RTQX1
[±600A ±10V]
I.meas.b
I.meas.a
RTQX2
[5kA 8V]
I.meas.b
I.meas.a
FWD
Free Wheel Diode
I.meas*
I_{RQX}
I_{RTQX1}
I_{RTQX2}
Q1
Q2a
Q2b
Q3
$I_{RQX} + I_{RTQX1}$
$I_{RQX} + I_{RTQX2}$
I_{RQX}