New additions to the STEAM LHC circuit model library

Marvin Janitschke, TE-MPE-PE

Acknowledgements

Special thanks to: E. Ravaioli, F. Murgia, CERN SIGMON Team, and in particular M. Maciejewski, CERN ELQA Team, and in particular J. Ludwin and M. Bednarek, F. Rodriguez-Mateos (TE-MPE-EE) and J.Muratore (BNL)

Introduction

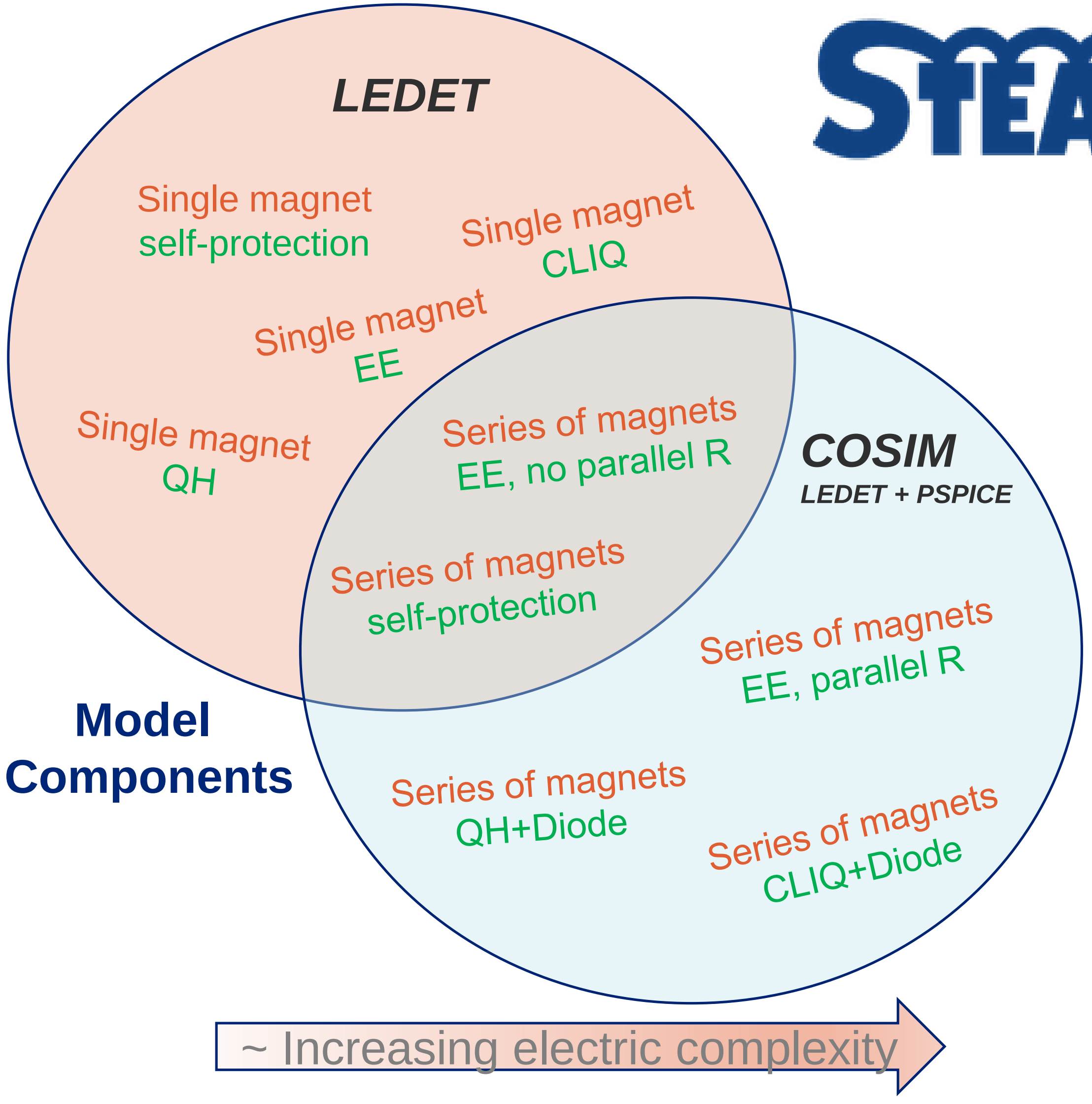
- **Simulation of superconducting magnets is a complex challenge**
- **Need to include many effects, especially when simulating fast transients**
- **STEAM LHC circuit library shall provide models for all LHC circuits, including all necessary effects/ domains to:**
  - Accurately simulate slow discharges/ fast transients
  - Investigate failure cases in the circuits/ magnets
  - Investigate quenches or quench scenarios
- **The library therefore includes models for the different domains**

Simulation tools

- Selection of necessary tools for transient simulation always depends on circuit/magnet

1. Simulation of electrical circuits
   PSPICE
   - simulates precisely electrical transients and discharge
   - can include chain of magnets, crowbar, power supplies, parasitic capacitances and inductances
2. Simulation of magneto-thermal model
   STEAM LEDET
   - simulates thermal diffusion, quenches, state transitions and coupling losses in magnet (IFCC, ISCL)
   - can also simulate simple electrical circuits/ single magnets
3. Simulation of magneto-thermal-electric model
   STEAM COSIM
   - Co-simulation of LEDET and PSPICE to include all effects

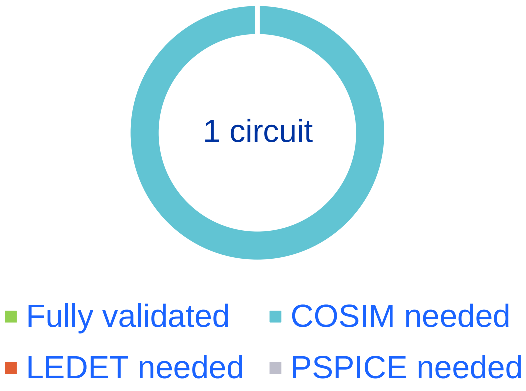
- When possible, experimental data is acquired using the LHC-SM api/notebooks



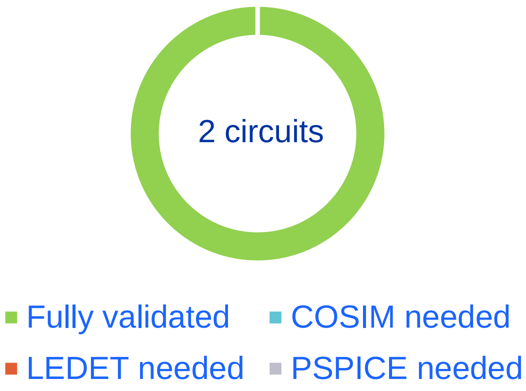
+ additional FEM models in SIGMA/COMSOL

Current status of the STEAM LHC circuit library

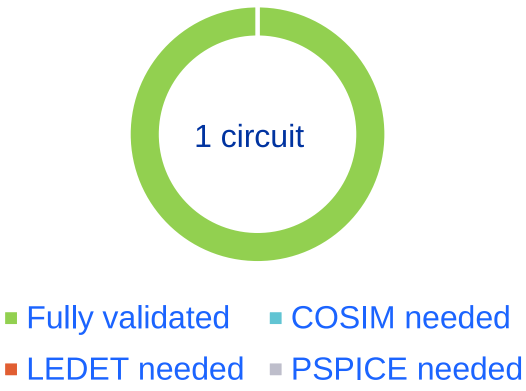
Main dipoles (RB)



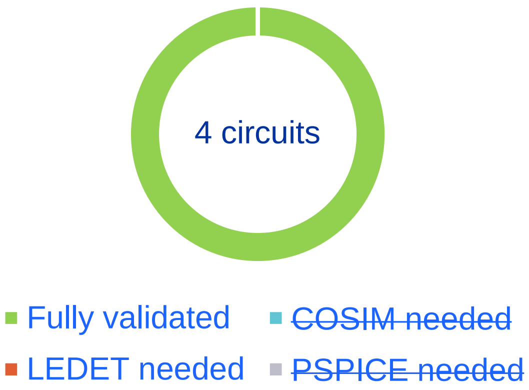
Main quadrupoles (RQ)



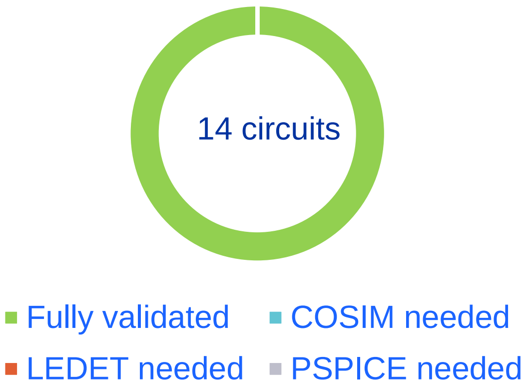
Inner triplet (RQX)



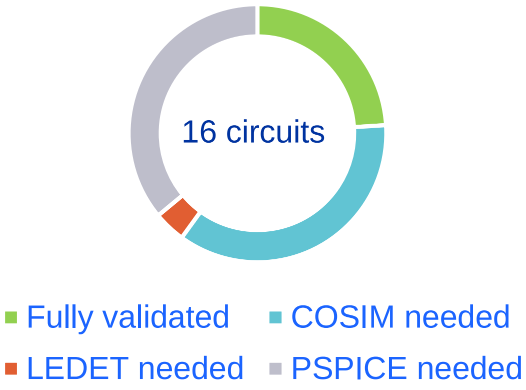
Separation dipoles (IPD)



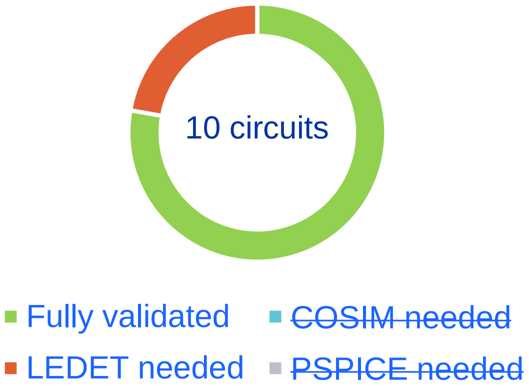
Matching Section (IPQ)



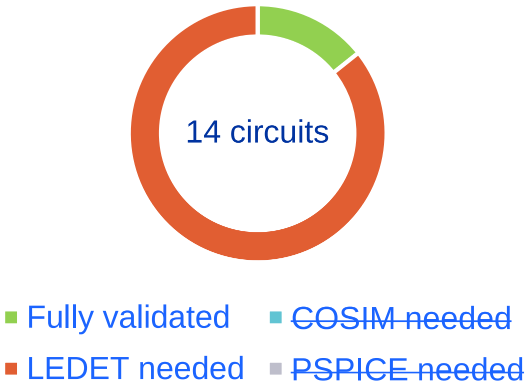
600A with EE



600A no EE

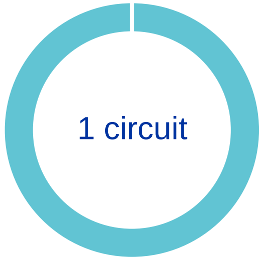


60-120A



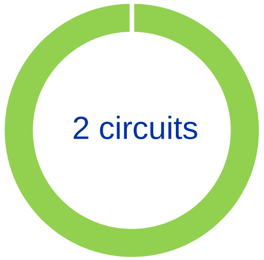
Current status of the STEAM LHC circuit library

Main dipoles (RB)



- Fully validated
- COSIM needed
- LEDET needed
- PSPICE needed

Main quadrupoles (RQ)

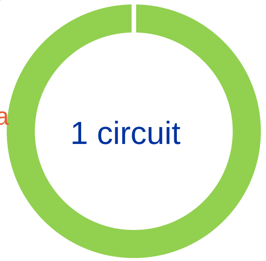


- Fully validated
- COSIM needed
- LEDET needed
- PSPICE needed

Inner triplet (RQX)

~~New additions~~

Presented by Federica

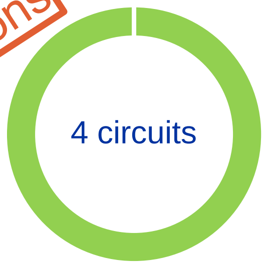


- Fully validated
- COSIM needed
- LEDET needed
- PSPICE needed

Separation dipoles (IPD)

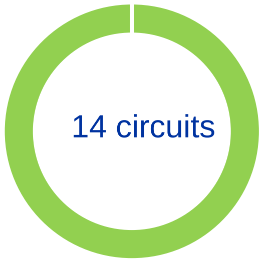
New additions

RD1
RD2
RD3
RD4



- Fully validated
- ~~COSIM needed~~
- LEDET needed
- ~~PSPICE needed~~

Matching Section (IPQ)

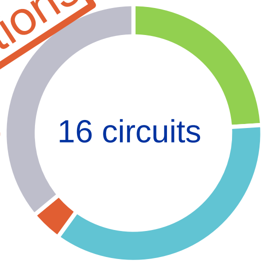


- Fully validated
- COSIM needed
- LEDET needed
- PSPICE needed

600A with EE

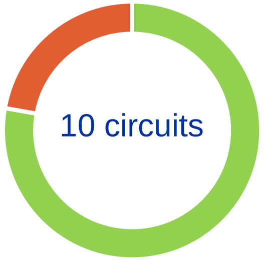
New additions

ROD
ROF
RCD



- Fully validated
- COSIM needed
- LEDET needed
- PSPICE needed

600A no EE

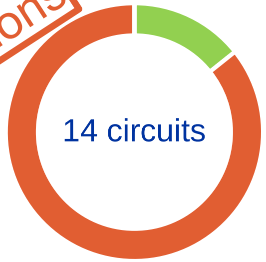


- Fully validated
- ~~COSIM needed~~
- LEDET needed
- ~~PSPICE needed~~

60-120A

New additions

RCO
RCBY



- Fully validated
- ~~COSIM needed~~
- LEDET needed
- ~~PSPICE needed~~

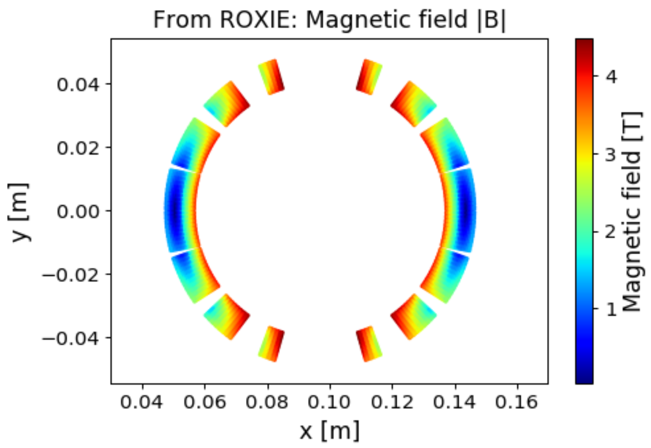
Separation dipoles (IPD)

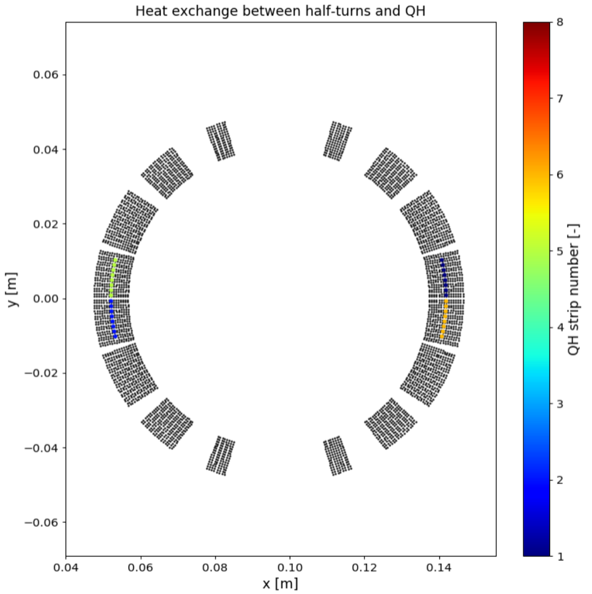
- Separation and Recombination Dipoles
- 4 different magnets and circuits in total (RD1-4 **-** MBX, MBRC/S/B) [difference: Nominal current + No. Of Apertures and distance]
- Peak field of **~4.5T** at nominal currents
- Magnets are protected by **QH**
- Circuits only contain **single magnets**

→ **Given the circuits include only one magnet, the transient following a quench can be simply simulated with STEAM-LEDET**

	IPD magnets
Inner diameter	80 mm
Magnetic length	9.45 m
Operating Temp.	4.5 K/ 1.9 K(MBX)
Aperture separation distance	188 mm (MBRC) 194 mm (MBRB) 414 mm (MBRS)
Nominal current	5750 A (MBX, MBRS) 6050 A (MBRB/C)
Inductance [I_nom] per aperture	26 mH

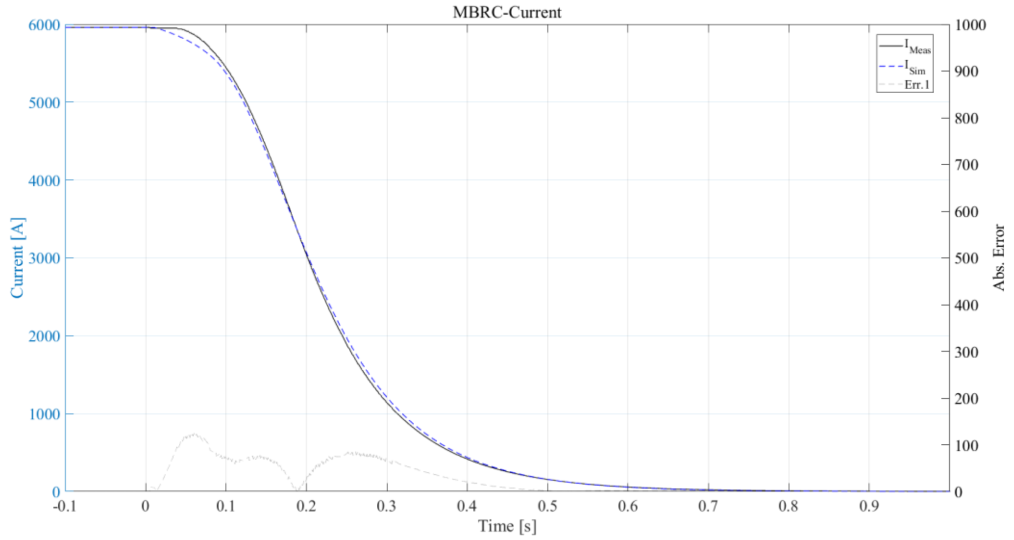
	QH design
No. of QH circuits per aperture	4
No. of strips in series	2
Power Supply	900 V, 7.05 mF
Strip width	14.5 mm
Pattern (SS/Cu)	.127 m/.75 m

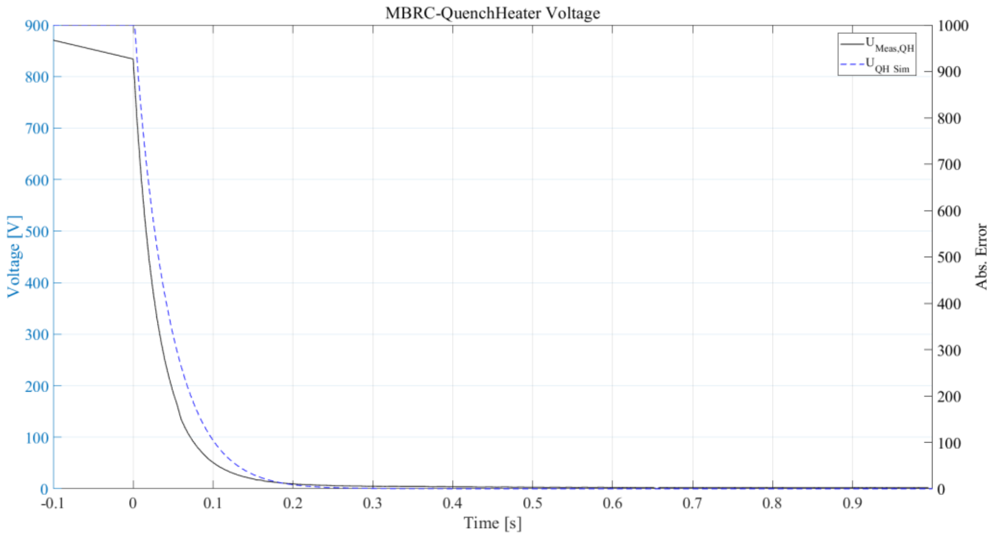


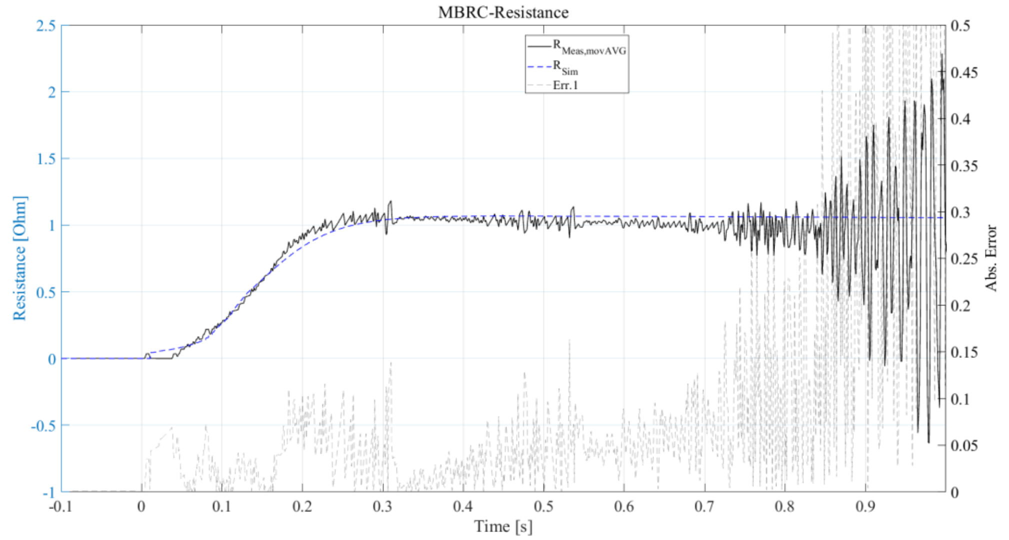


Separation dipoles (IPD) – Validation Results

LEDET Fast Power Abort Simulation





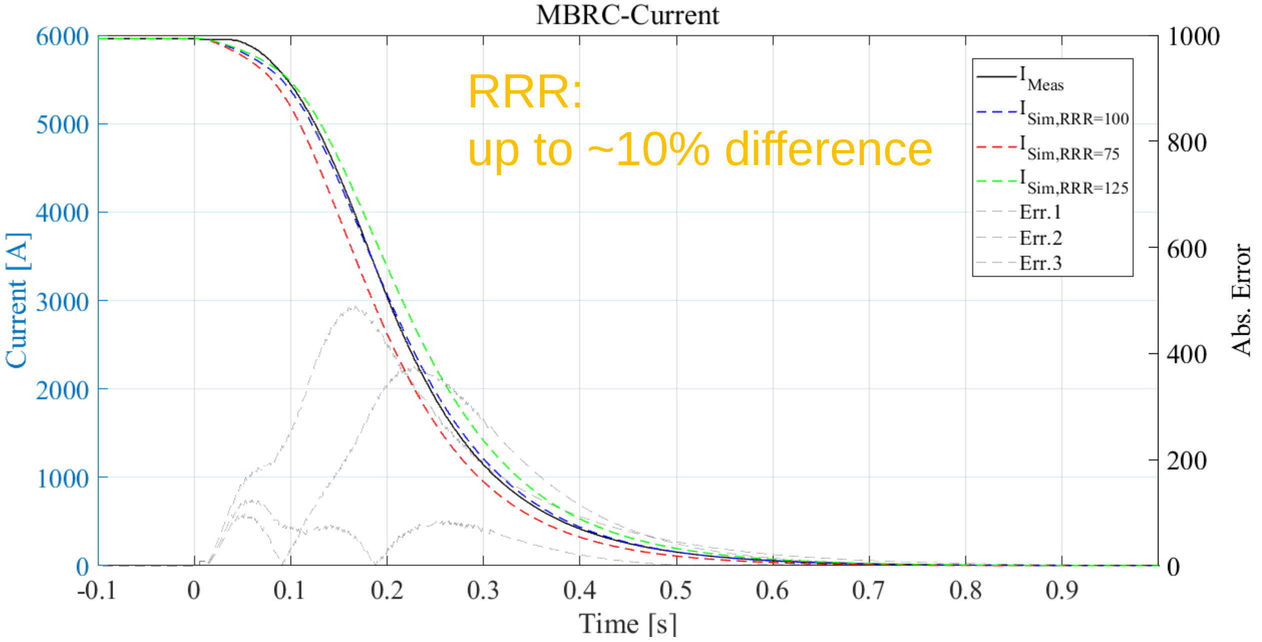


	Absolute Largest Deviation	Largest relative deviation	Mean Square Error	Root mean Square Error
MBRB (RD4.L4)	187.62 A	3.2 %	21.11 A^2	4.59 A
MBRC (RD2.L8)	124.3 A	2.1 %	22.47 A^2	4.74 A
MBRS (RD3.R4)	112.6 A	1.93 %	18.04 A^2	4.25 A

Very good agreement of measurement and simulation!

MBRC magnet - Measurement: RD2.L8 - 2018.12.03 13:13:07 PM Browser

Separation dipoles (IPD) – Parametric Study



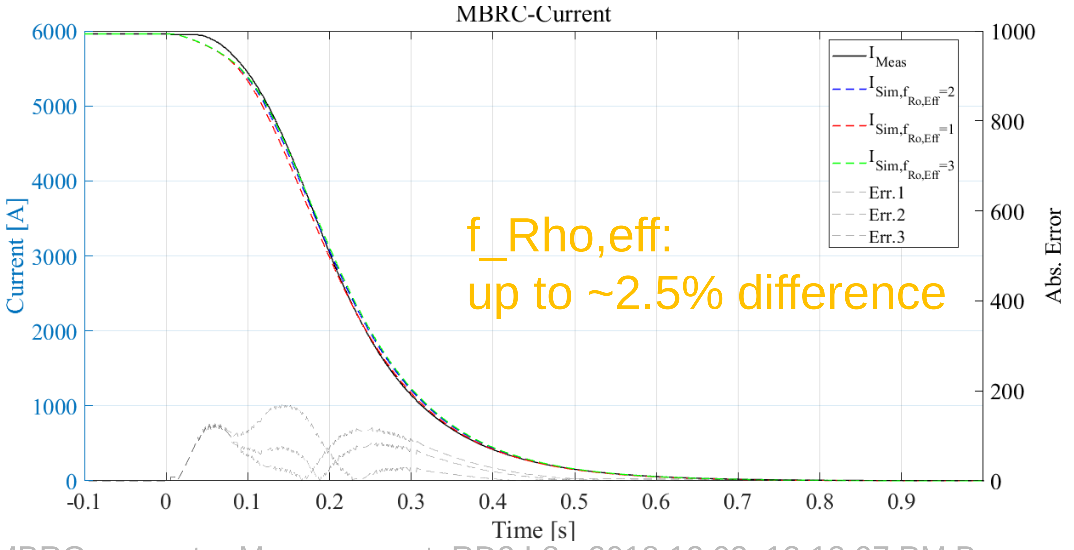
Sweep of the unknown parameters was conducted with the new framework
[STEAM Meeting 08.06.2020, https://indico.cern.ch/event/913508/]

Sweeped parameters:

1. RRR
2. f_rho_eff
3. Cross contact resistance [negligible effect]
4. Helium fraction [negligible effect, T_op = 4.5K!]

- Simulation showed, that **RRR = 100, f_rho,eff = 1** represent the measurements the best
- **Changing RRR has significant impact**
  - Increasing → Slowing down discharge
  - Decreasing → Speeding up
- **Changing f_rho,eff had little effect**

Similar behavior and parameters were obtained for all magnets of that group



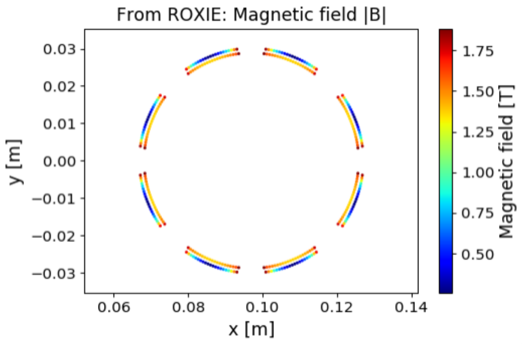
MBRC magnet - Measurement: RD2.L8 - 2018.12.03 13:13:07 PM Browser

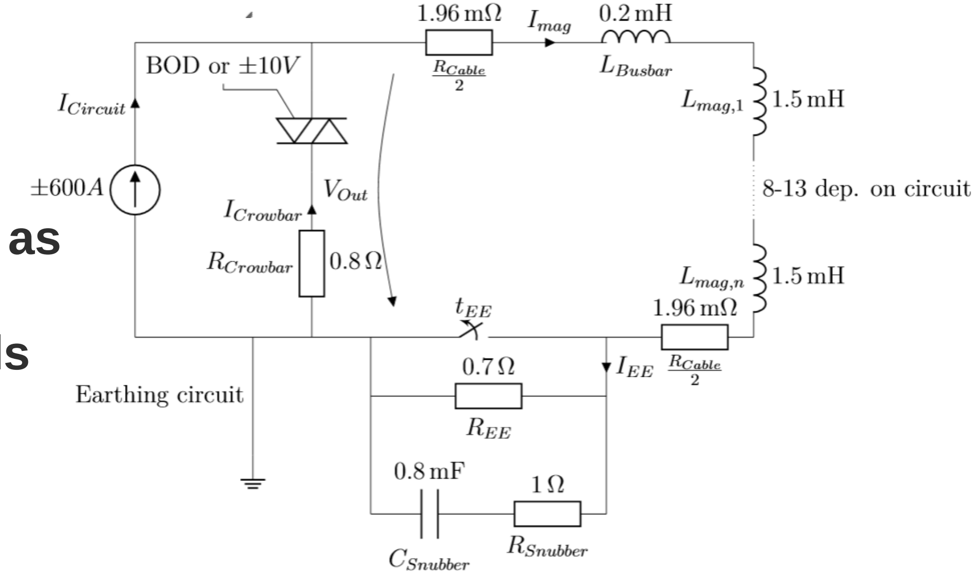
600A EE – ROD/ROF

- lattice-correcting octupole magnet, with 2 independent apertures
- Peak field of **~1.9T** at nominal current
- Magnets are protected by **EE**
- Circuits contain either **8 or 13 magnets in series**
- 600A circuits have very long busbars [~4km]
  → including them as an **additional inductance**
- each aperture is modeled separately
  [presence of iron + independently powered]

	MO magnet
Inner diameter	56 mm
Magnetic length	0.32 m
Operating Temp.	1.9 K
Nominal current	550 A
Inductance [I_nom]	1.6 mH

	Conductor properties
Wire section	0.689 mm^2
Cu/SC ratio	1.6-1.9
RRR	>100
Filament Twist Pitch	0.015



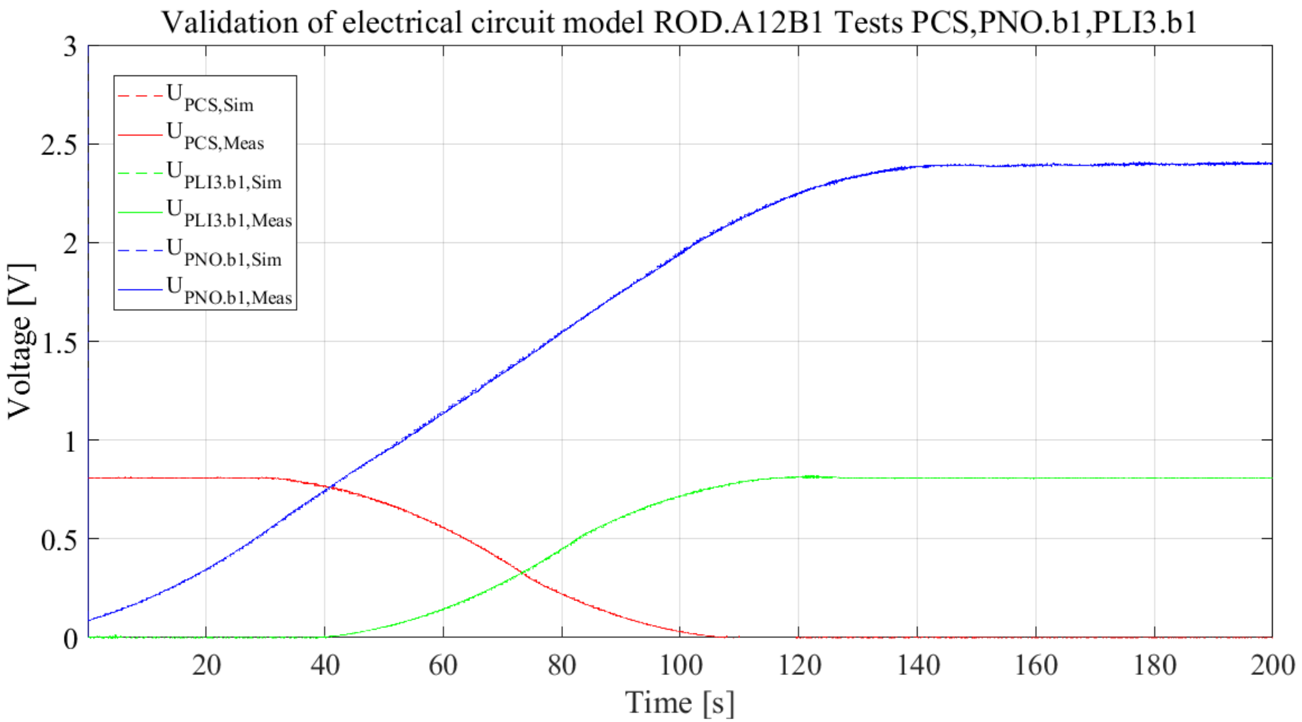


→ **The 600A EE ROD/ROF circuits include a chain of magnets as well as a more complex electrical circuit**
→ **Validation requires LEDET, PSPICE and COSIM models**

600A EE – ROD/ROF – Validation Results
PSPICE model Validation

- Cable resistance was automatically calculated for all circuits of that family
  [STEAM meeting 02.04.2020 https://indico.cern.ch/event/904043/]
- Different ramp up/down tests were applied as Stimuli to PSPICE model

→ **Agreement of Simulations and Measurements very good** [negligible error]

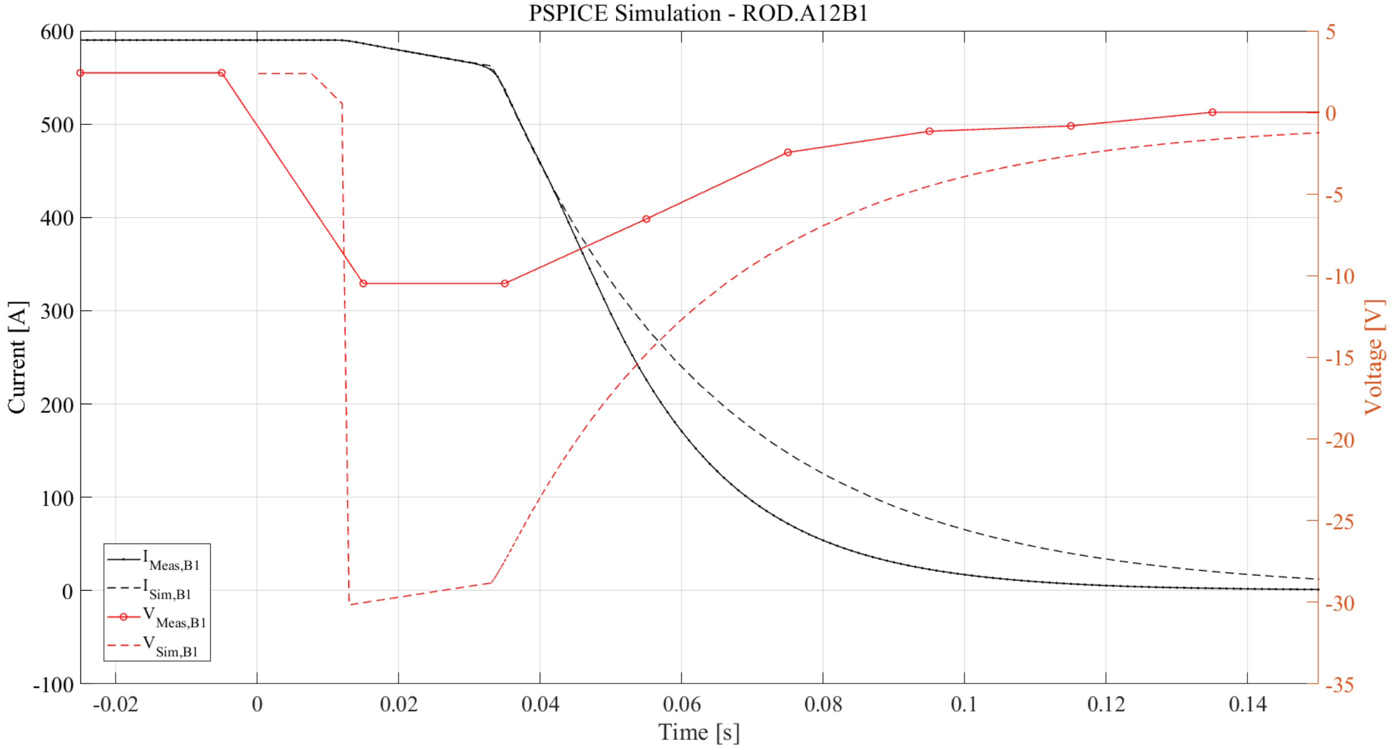


ROD.A12B1 circuit, various tests obtained with the LHC-SM notebooks, HWC campaign 2017

600A EE – ROD/ROF – Validation Results
PSPICE model Validation

- Simulation of the whole transient, with PSPICE stand-alone model shows the discussed weakness of the purely electrical model
- Validation of the discharge far too slow, because no coupling losses, state transistions and quenches are considered

→ Shows the necessity of model expansion/ additional model [see Slide 12,13]



ROD.A12B1 circuit; Measurement: HWC_2017, PNO.d3, 2017-04-22 02:00:12, LHC-SM notebook

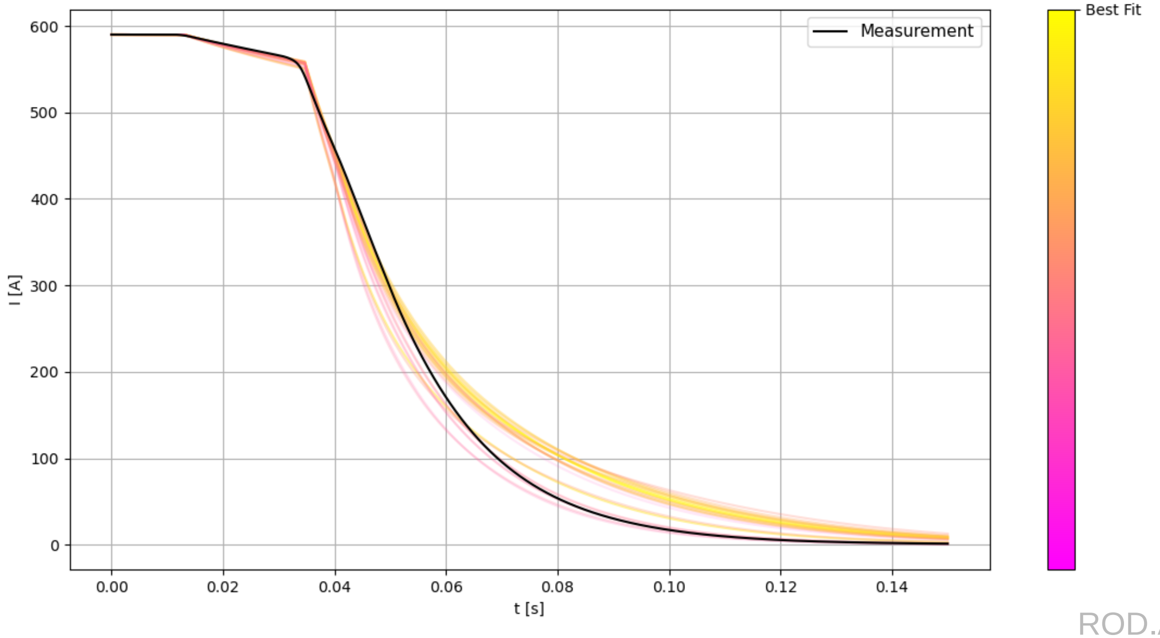
600A EE – ROD/ROF – Validation Results
Parametric Study

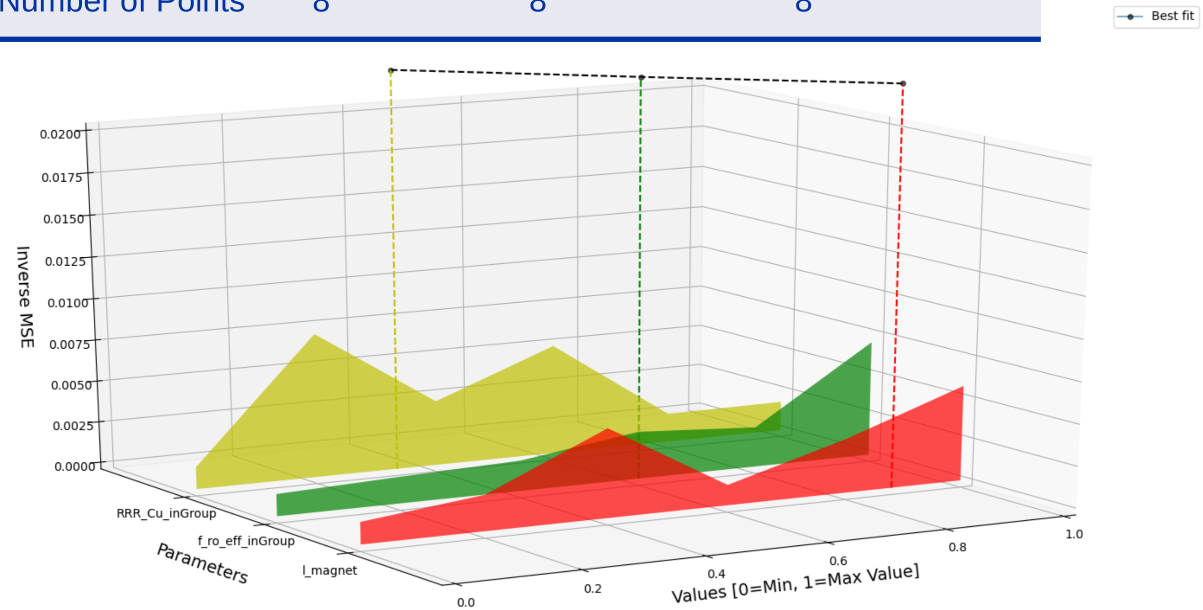
- **Parametric Sweep included:**

1. RRR
2. f_Rho,eff
3. Busbar inductance per unit length

- All parameters show to have a huge impact on the discharge and can change various sections of the transients

	L_BB per Meter [μH/m]	RRR	f_Rho,Eff
Minimum	0	100	1
Maximum	1.4	300	3
Number of Points	8	8	8





ROD.A12B1 circuit; Measurement: HWC_2017, PNO.d3, 2017-04-22 02:00:12, LHC-SM notebook

600A EE – ROD/ROF – Validation Results
LEDET model Validation

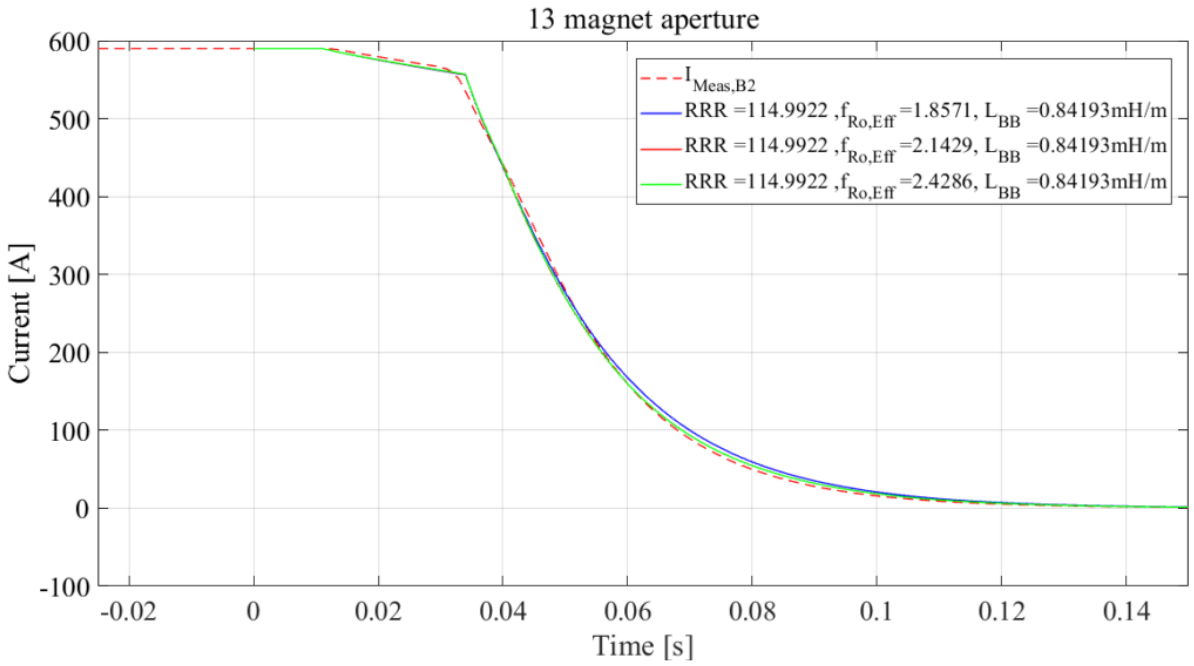
- Simulation with LEDET includes the chain of magnet as a single magnet [l_magnet * Number of magnets]
- Necessary busbar inductance was added as a small addition to magnetic length, s.t. resulting self-inductance equals the busbar inductance

→ **Simulation already show very good result with the LEDET stand-alone model compared to measurement**

- Also for this circuit family the Parameter Sweep framework was used to investigate the model behavior, shown are the best parameter combinations

	L_BB	RRR	f_Rho,eff
ROD.A12B1 (13mag)	0.8 µH/m	100	2.7
ROD.A12B2 (8mag)	0.8 µH/m	115	2.4

	Absolute Largest Deviation	Largest relative deviation	Mean Square Error	Root mean Square Error
ROD.A12B1 (13mag)	18.5 A	3.1 %	42 A^2	6.49 A
ROD.A12B2 (8mag)	15.97 A	2.7 %	17.8 A^2	4.22 A



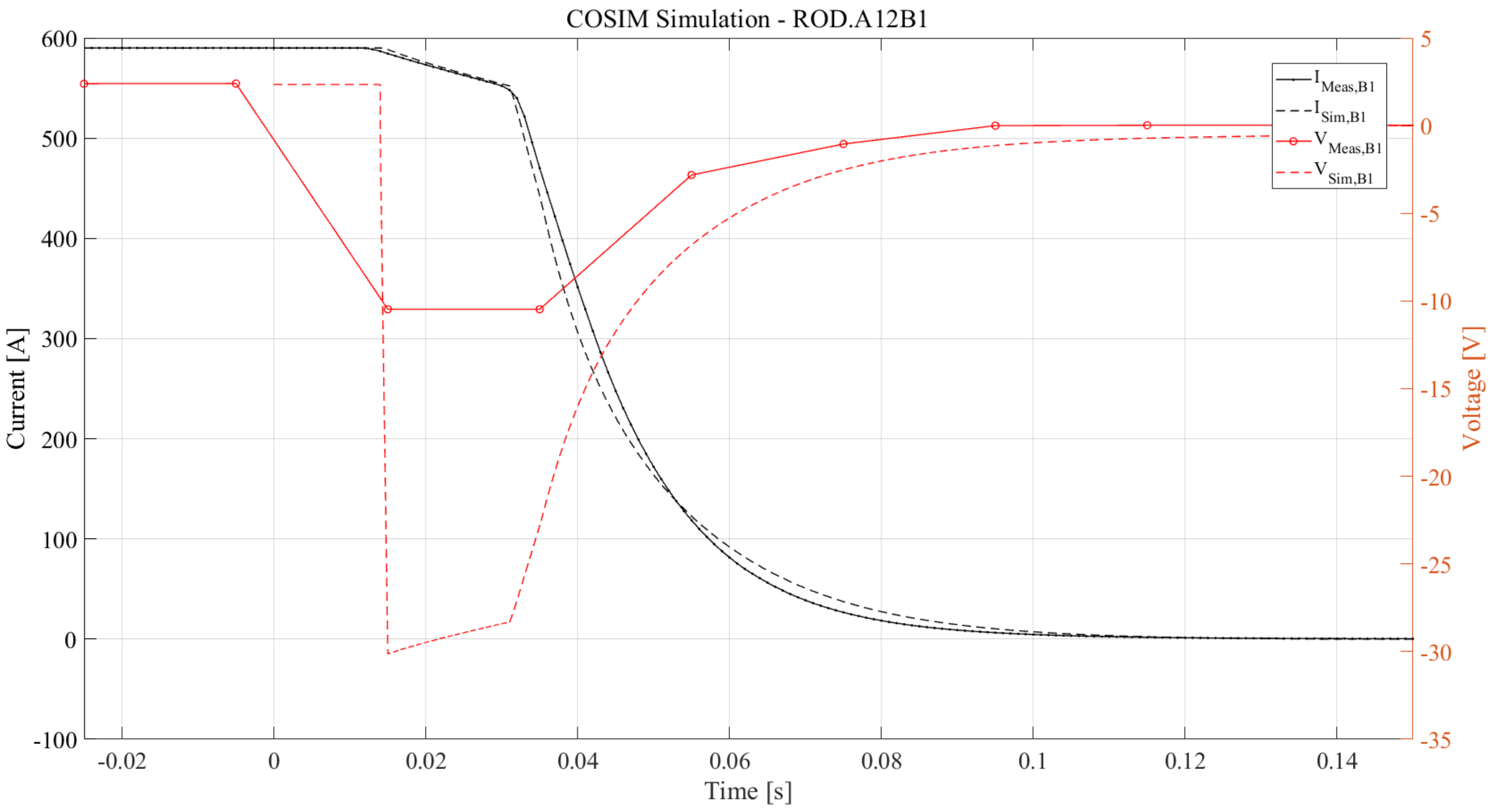
ROD.A12B1 circuit; Measurement: HWC_2017, PNO.d3, 2017-04-22 02:00:12,

600A EE – ROD/ROF – Validation Results

COSIM Validation

- Though there were already very good results obtained with the LEDET stand-alone simulations, including the electrical model in PSPICE :
  - Increases complexity, reliability and improves physical interpretation
  - Likely to be more resilient, when studying failure cases etc.

→ COSIM also shows good results!



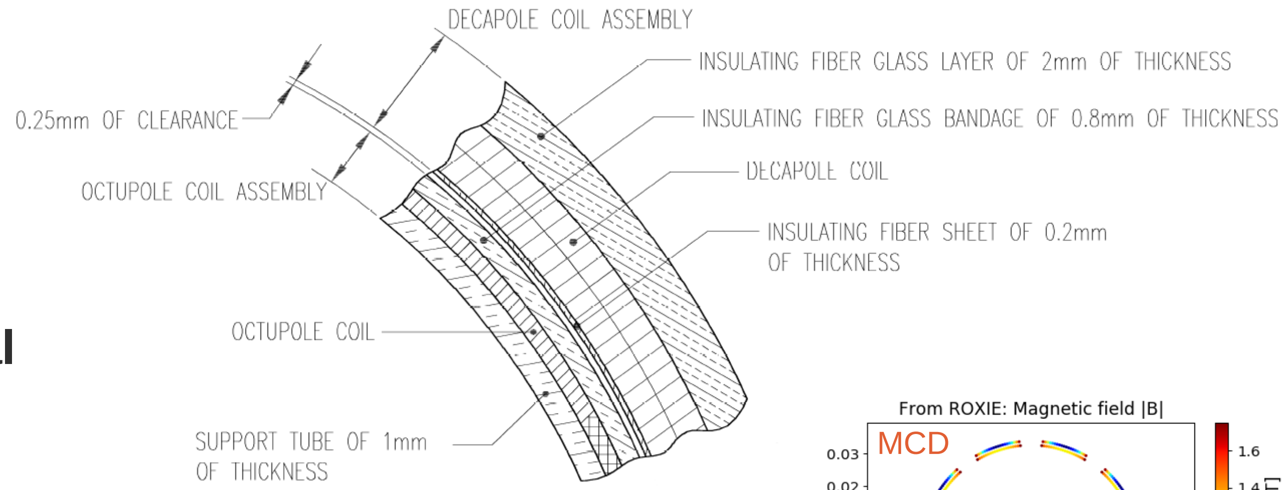
	Absolute Largest Deviation	Largest relative deviation	Mean Square Error	Root mean Square Error
ROD.A12B1 (13mag)	45 A	7.6 %	26.21 A^2	5.12 A

ROD.A12B1 circuit; Measurement: HWC_2017, PNO.d3, 2017-04-22 02:00:12, LHC-SM notebook

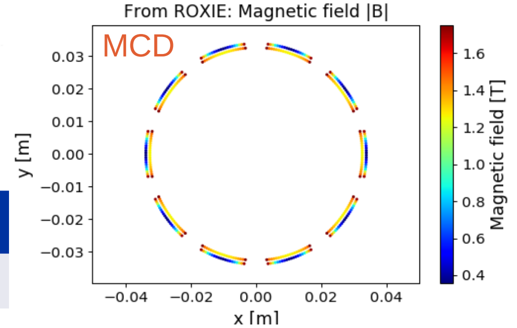
600A EE and 80-120A nested magnet (MCDO)

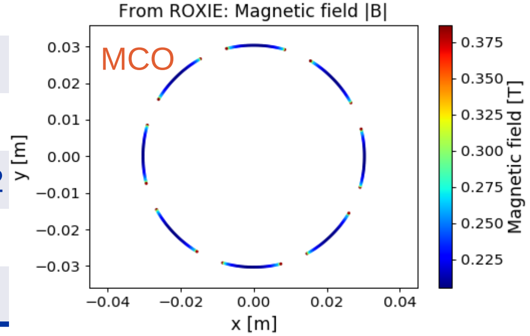
- **Two independently powered magnets**, nested in each other [outer: MCD(RCD), inner: MCO(RCO)]
- Spool Piece Corrector Magnets of the Main Dipoles
- Though they are nested in each other, the **mutual coupling is small**/ negligible [-2.63E-10 H/m]
- Both circuits contain **77 magnets in series**
- MCD magnet is protected by **EE**
  MCO magnet is **self-protected**
- Circuits have **additional busbar** induct. [~5.5km]

→ **Because of the negligible mutual coupling, both circuits are validated in independent LEDET models**



	MCD	MCO
Type	Decapole	Octupole
Nominal field [I_nom]	~1.75 T	~0.4 T
Nominal current	550 A	100 A
Operating Temp.	1.9 K	1.9 K
Conductor Type	LHC Type 3	LHC Type 2
Inductance [I_nom]	0.4 mH	0.4 mH
Magnetic length	0.066 mm	0.066 mm



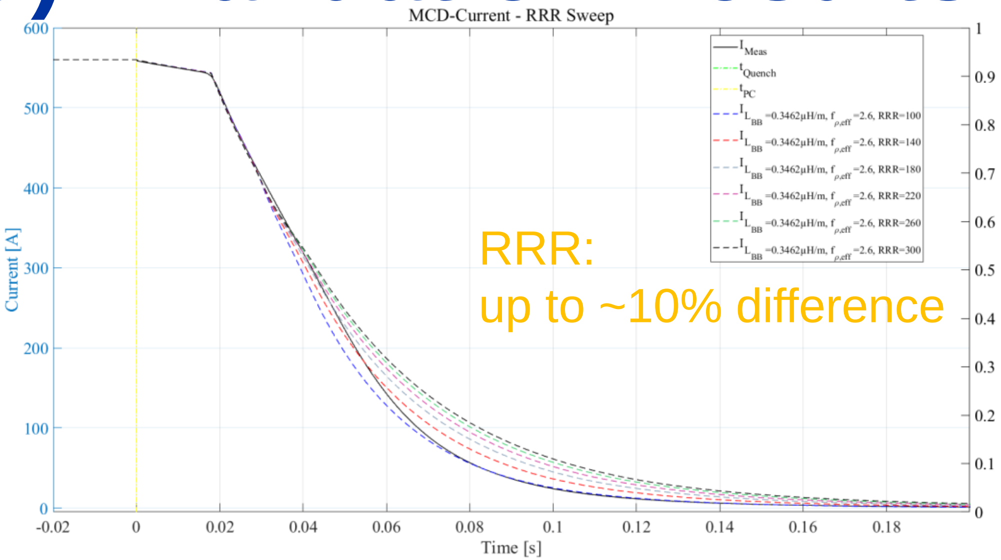


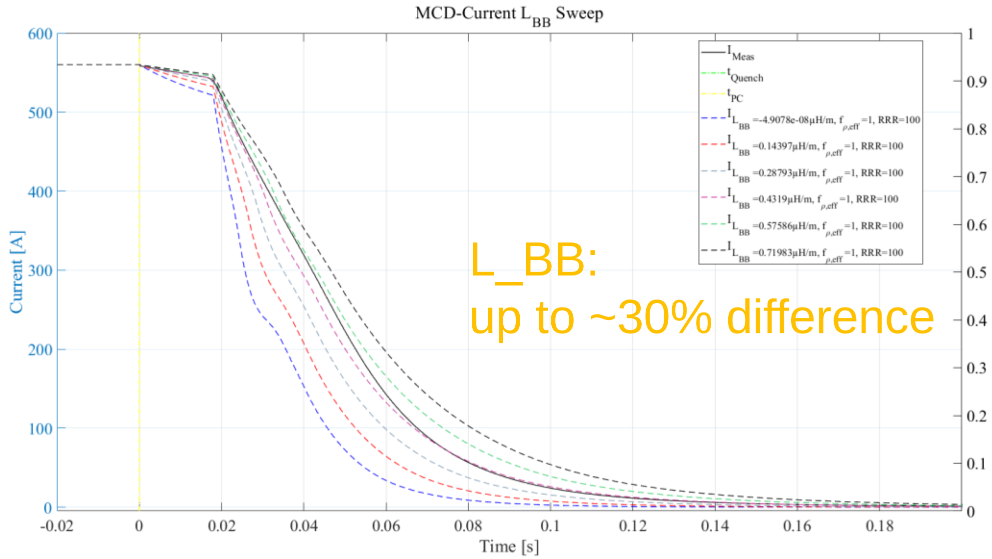
600A EE and 80-120A (MCDO) - Validation Results

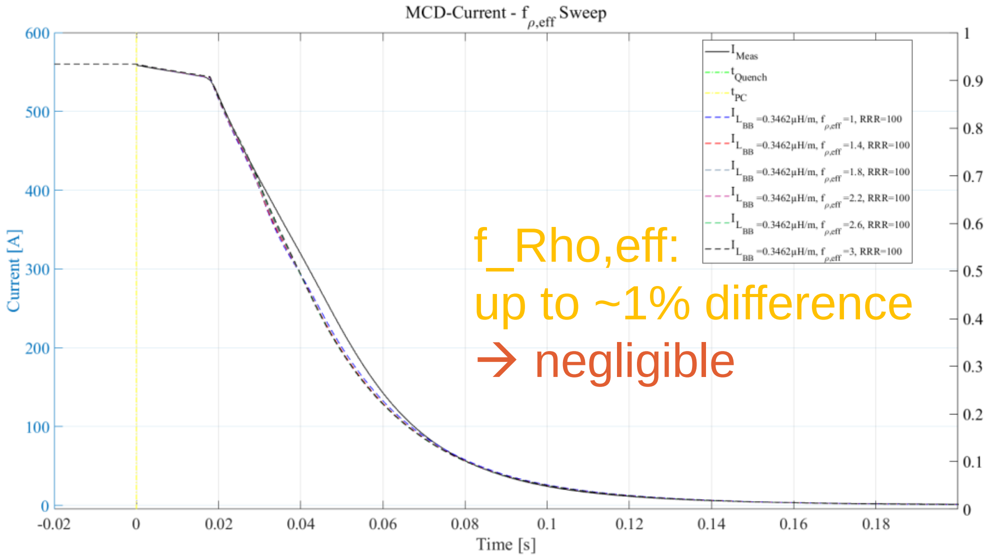
Parametric Study – MCD magnet

- Parametric Sweep included again RRR, f_rho,eff and the additional Busbar inductance

	L_BB per Meter [µH/m]	RRR	f_Rho,Eff
Minimum	0	100	1
Maximum	0.63	300	3
Number of Points	6	6	6







RCD.A56B1 circuit; Measurement: 2018-03-16 22:04:17 , PNO.x2

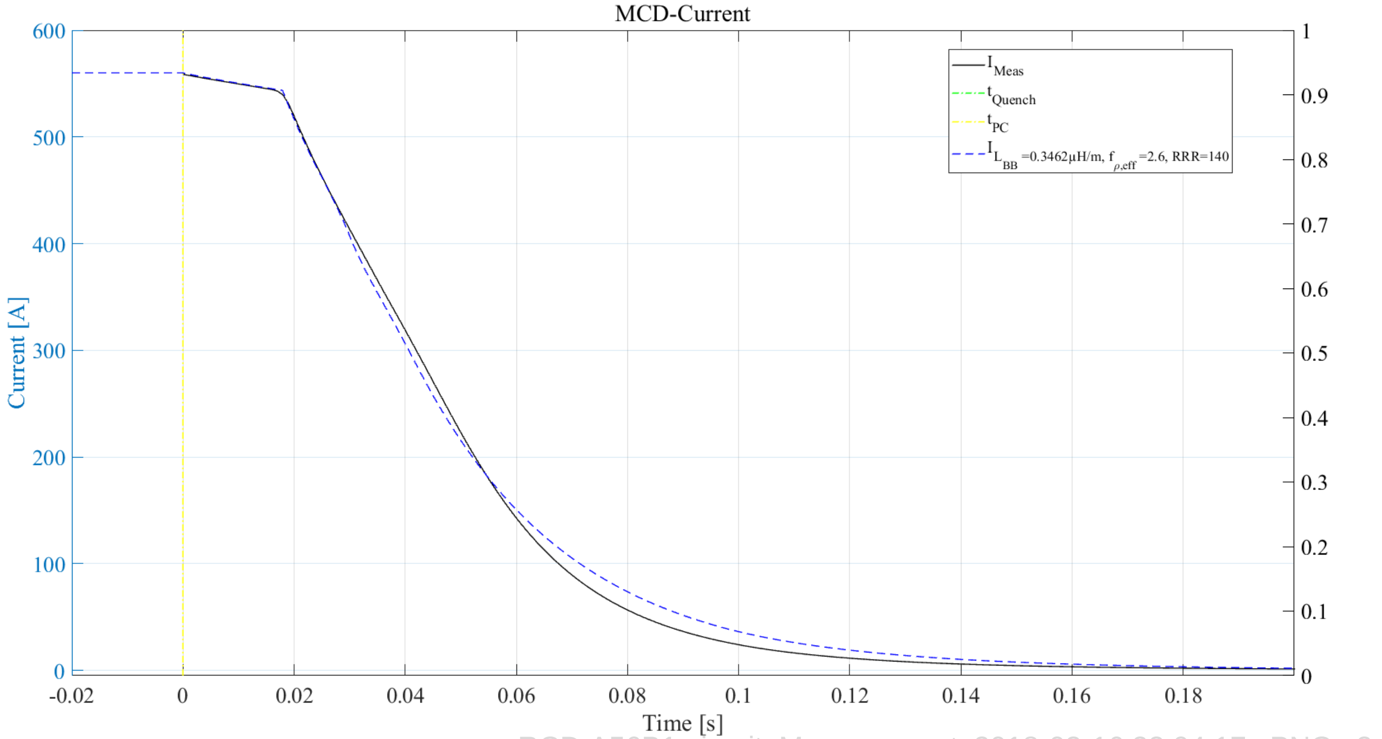
600A EE and 80-120A (MCDO) - Validation Results

LEDET Validation – MCD magnet

- LEDET stand-alone simulation of the FPA of the **outer decapole** magnet shows **excellent results**
- Found parameter values are in physical reasonable ranges
  [ELQA measurements showed for these circuits a busbar inductance of ~0.5µH/m]

	L_BB	RRR	f_Rho,eff
RCD.A56B1	0.35 µH/m	140	2.6

	Absolute Largest Deviation	Largest relative deviation	Mean Square Error	Root mean Square Error
RCD.A56B1	17.24 A	3.07 %	1.57 A^2	1.25 A



RCD.A56B1 circuit; Measurement: 2018-03-16 22:04:17 , PNO.x2

600A EE and 80-120A (MCDO) - Validation Results

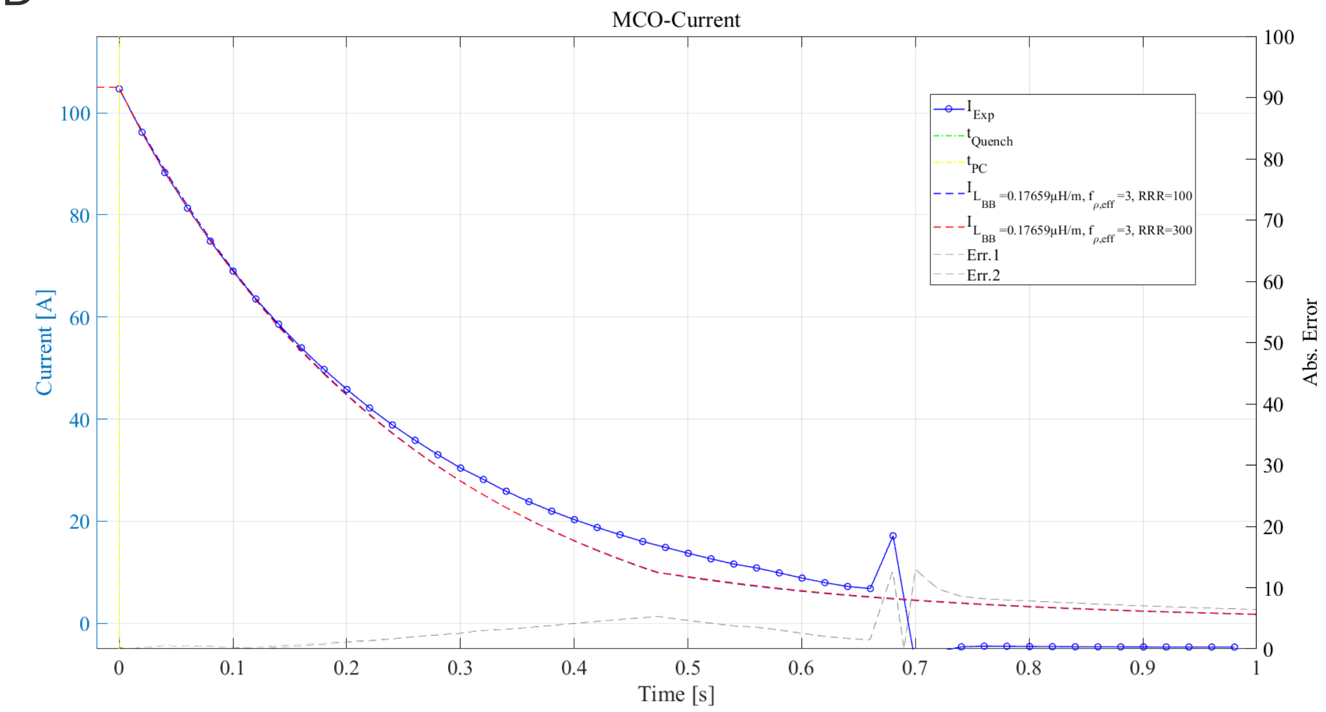
LEDET Validation – MCO magnet

- LEDET stand-alone simulation of the FPA of the **inner octupole** magnet shows also **very good results**
- As a 80-120A magnet, the RCO circuits do not include DCCT during a FPA → Circuit current has to be calculated based on Crowbar-Voltage/Resistance and measured Output-Voltage
- Parameter values show similar results to MCD

	L_BB	RRR	f_Rho,eff
RCO.A56B1	0.18 µH/m	100	3

	Absolute Largest Deviation	Largest relative deviation	Mean Square Error	Root mean Square Error
RCO.A56B1	5.27 A	5.02 %	1.48 A^2	1.22 A

Performance calculation only in t=[0,0.65]s



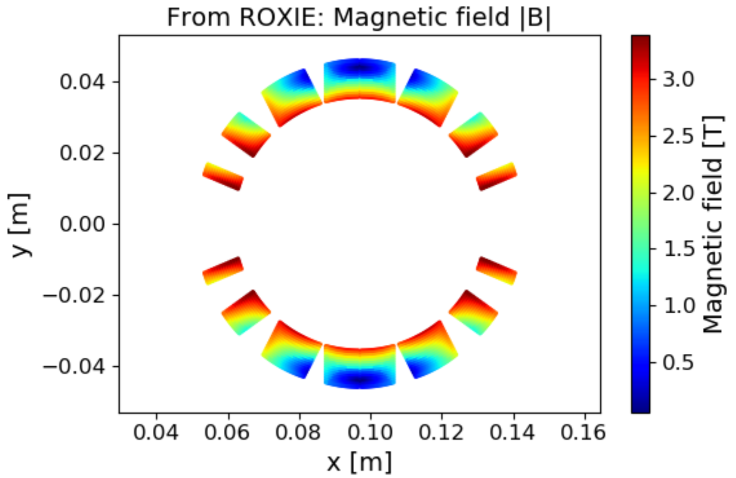
RCO.A56B1 circuit; Measurement: 2018-03-16 22:04:17 , PNO.x2

80-120A self-protected (MCBY)

- Orbit correcting dipole magnet with 2 apertures,
  but both are magnetically decoupled because of the presence of iron
- Comes in two ‘identical’ versions: Vertical and Horizontal orientation
- **Self-protected magnet**
  - magnets of this type significantly depend on heat-propagation within themselves
  - **Copper Wedges** connecting the Coil blocks were additionally modelled and implemented in LEDET [will be presented in next STEAM meeting Sept.]

  → Heat diffusion from the initial Quench hot-spot throughout the whole coil
- Electrical circuit only contains **single magnet**

→ Given the circuit includes only one magnet, the transient following a quench can be simply simulated with STEAM-LEDET



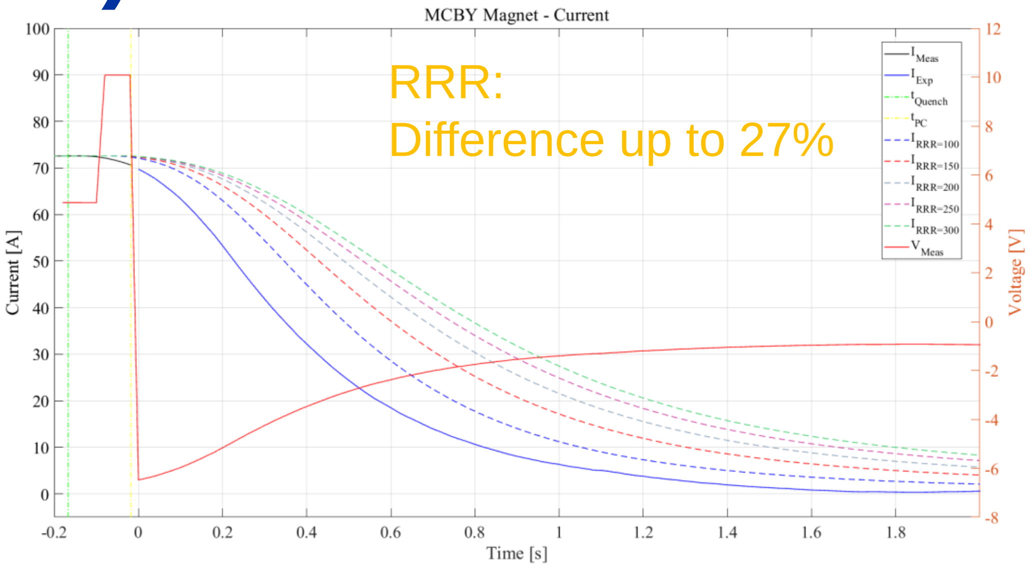
	MCBY magnet
Inner diameter	70 mm
Magnetic length	0.9 m
Operating Temp.	1.9 K
Nominal current	88 A
Inductance [I_nom]	5.27 H
Nominal field [I_nom]	3.4 T

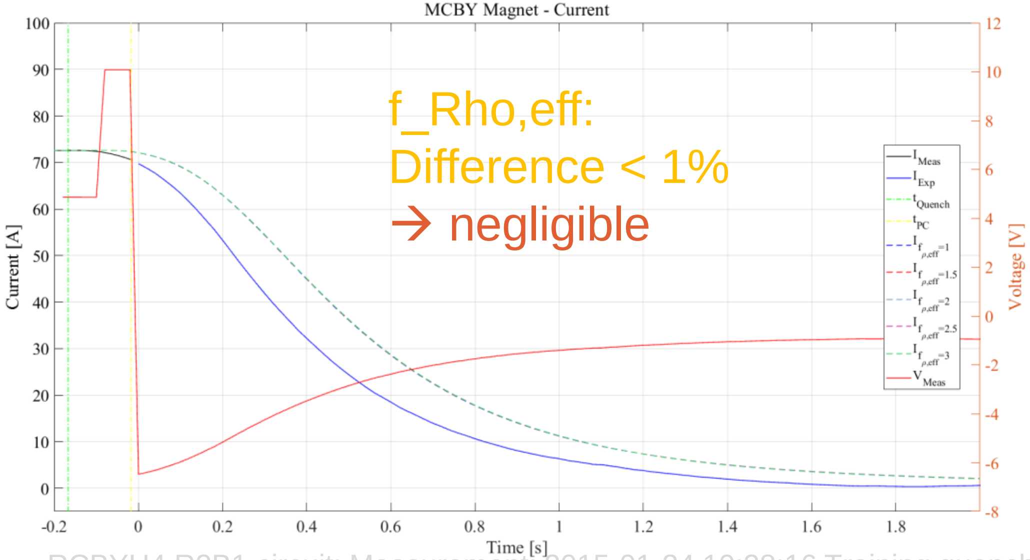
	Conductor properties
Wire section	0.214 mm^2
Cu/SC ratio	4.0 – 4.8
RRR	>100
Filament Twist Pitch	0.015

80-120A self-protected (MCBY) – Validation Results

Parametric Study - LEDET

- MCBY magnet has ~5300 turns
  → computational expensive Simulations
- Only a few parametric simulations
- **Clearly changing RRR has a significant impact**
  - Increasing RRR → slowing down discharge
  - Decreasing RRR → speeding up discharge
  - RRR=100 showed best agreement with measurements
- **Changing f_Rho,eff had negligible effect**





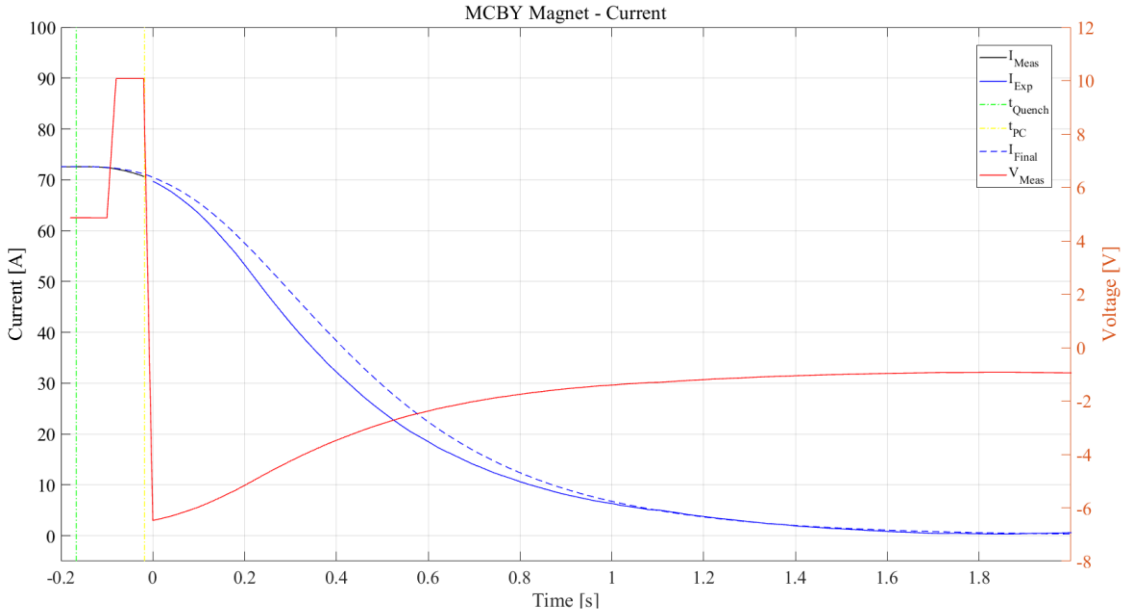
RCBYH4.R2B1 circuit; Measurement: 2015-01-24 10:28:16 Training quench

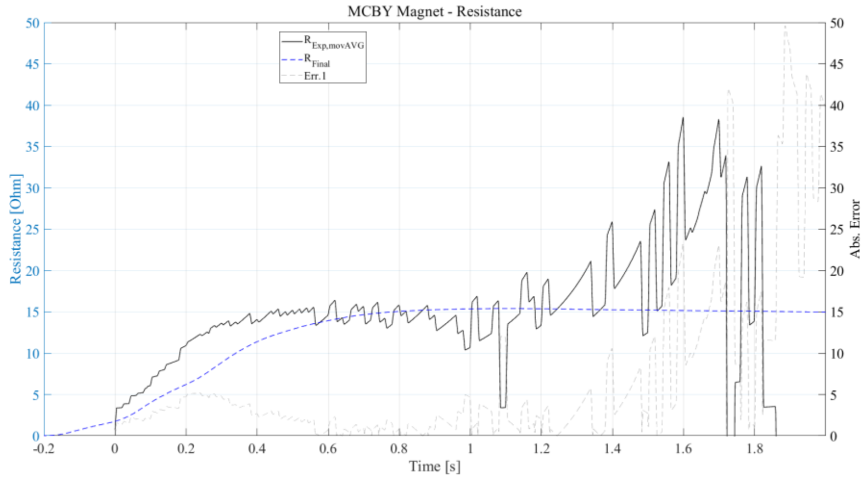
80-120A self-protected (MCBY) – Validation Results

LEDET Validation – Final Results

- Final results include a quench in Midplane Block + additional artificial quench of the electric return line
- RRR = 100, f_Rho,Eff = 1
- Copper Wedges included to allow heat diffusion

→ **Agreement with the measurement is good**





	Absolute Largest Deviation	Largest relative deviation	Mean Square Error	Root mean Square Error
RCBYH4.R2B1	4.55 A	6.27 %	0.76 A^2	0.87 A

RCBYH4.R2B1 circuit; Measurement: 2015-01-24 10:28:16 Training quench

Conclusion and Outlook

- STEAM LHC circuit library got extended by **9 new circuit families**, with complete models including the most important effects [state transitions, heat diffusion, coupling losses, precise behavior of electric components…]
- New additions are a **variety of LHC magnets** and circuits
  - Different Quench protections [EE, QH, self-protection, mixed]
  - Magnet configurations [single magnets, chain of magnets, nested magnets]
  - Different current level and electrical circuits [80A – 6kA, Busbars, Crowbar…]
- All validations showed **very good agreements** with the measurements [in general error between 2-8%]
- Additional parametric studies were conducted to better understand the behavior and effects of the unknown parameters in the LEDET models
  - New framework for parametric sweep + automatic calculation of R_cable speeded up validation significantly
  - Fast experimental data acquisition with the LHC-SM api/notebooks
- Ongoing work to add more circuit families to the library
  - E.g. MCBXH/V magnets [nested, self-protection]

Thanks for your attention!
Any Questions?

Acknowledgements

I would like to thank my colleagues for their work/ ideas and discussions, which helped me a lot during conducting the work for this presentation! Namely I want to express special gratitude to:

- *My supervisor Emmanuele Ravaioli*
- *STEAM Team, and in particular F. Murgia*
- *CERN SIGMON Team, and in particular M. Maciejewski*
- *CERN ELQA Team, and in particular J. Ludwin and M. Bednarek*
- *F. Rodriguez-Mateos (TE-MPE-EE) and* J.Muratore (BNL)

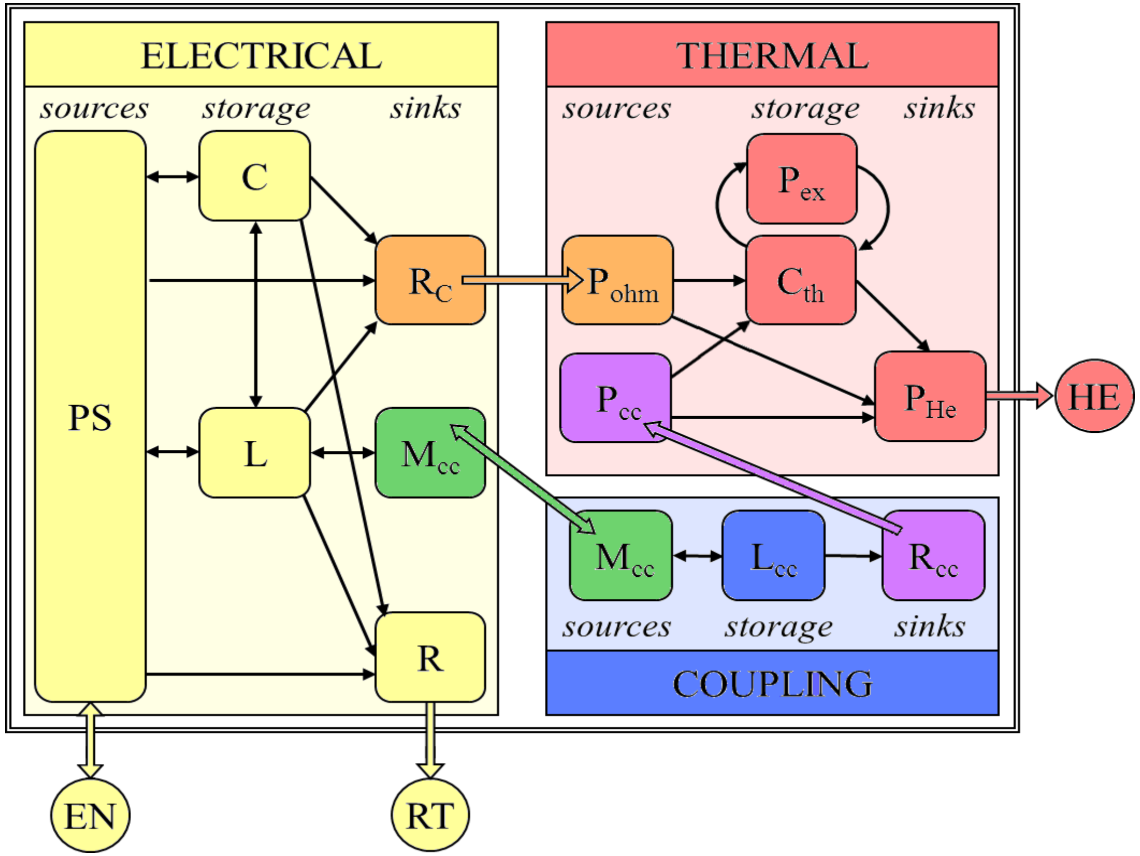
Annex: Superconductor Types

Table 7.18: Main parameters of the corrector magnet superconducting strands

	Type 1	Type 2	Type 3	Type 4
Overall dimensions (mm) (insulated)	∅ 0.435	0.38×0.73	0.73×1.25	0.97×1.65
Metal dimensions (mm)	∅ 0.375	0.32×0.67	0.61×1.13	0.85×1.53
Nominal Insulation Thickness (mm)	0.03	0.03	0.06	0.06
Critical current at 4.222 K and 5 T (A)				
Perpendicular to wire axis	>55			
Perpendicular to broad face		>100	>630	>1190
Parallel to broad face		>110	>700	>1320
Copper Matrix RRR	> 100			
Cu/Sc volume ratio	≥ 4.0-4.8	≥ 4.0-4.8	≥1.6-1.9	≥1.6-1.9
Superconductor	Nb-Ti with Ti = 47.0 % by weight			
High voltage insulation (V)	1000			
Insulation material	PVA enamel			

O. Bruening, P. Collier et. al. ”LHC Design Report - Volume I The LHC Main Ring”.In:
Geneva, 4 June 2004, ISBN 92–9083-224 0
Chapter 7: MAIN MAGNETS IN THE ARCS

LEDET energy exchanges

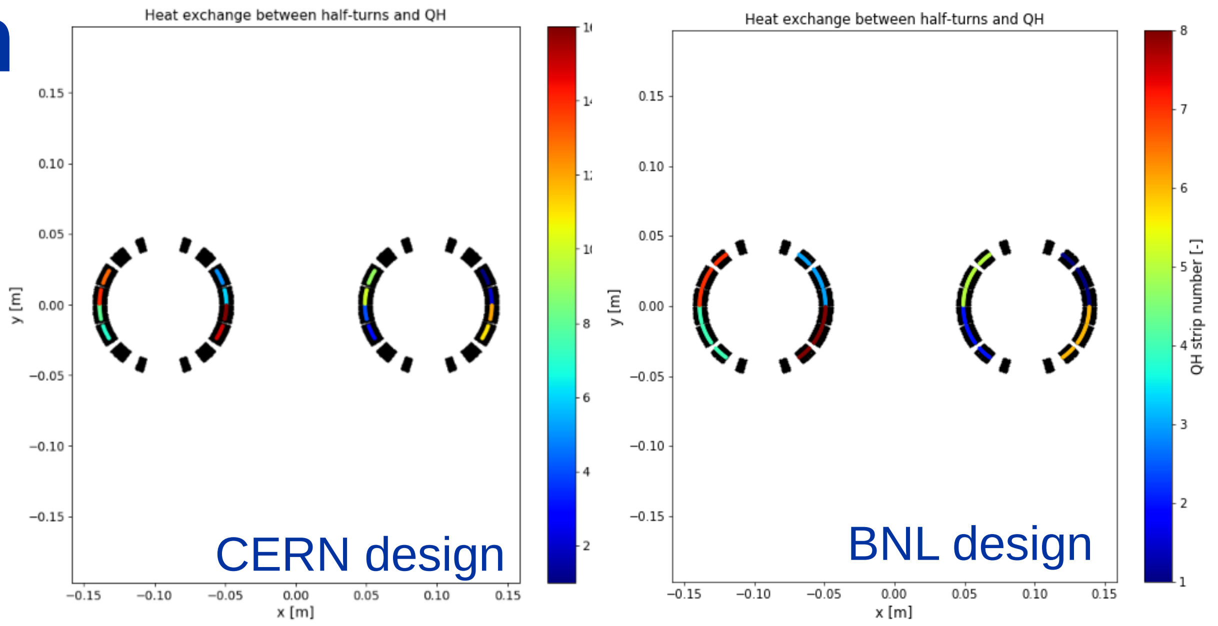


Courtesy
E. Ravaioli

IPD Quench Heater Design

- Magnets are actively protected by Quench Heaters
  → Due to the fact they were produced at BNL it is unfortunately not 100% clear, which QH were used

- Both Version were tried and compared to measurements



	CERN QH design	BNL QH design
No. of QH circuits per aperture	2	2
No. of strips in series	4/8	2
Power Supply	CERN QH supply (900V, 7.05mF)	-
Strip width	15mm	44.45mm
Pattern (SS/Cu)	(0.1m/0.4m)	(0.127m/0.75m)
Length (magnet length = 9.45m)	9.646m	10.16m

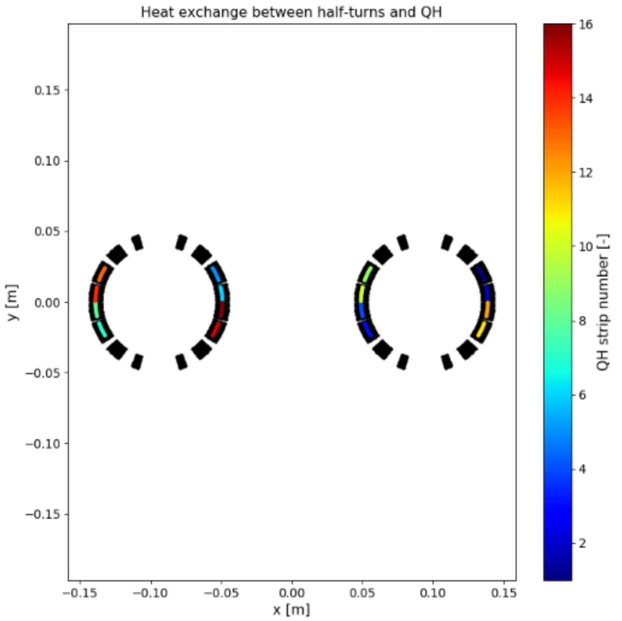
	CERN QH	BNL QH
Peak current	63.5 A	416.7A
Time constant	~99ms	~15.7ms

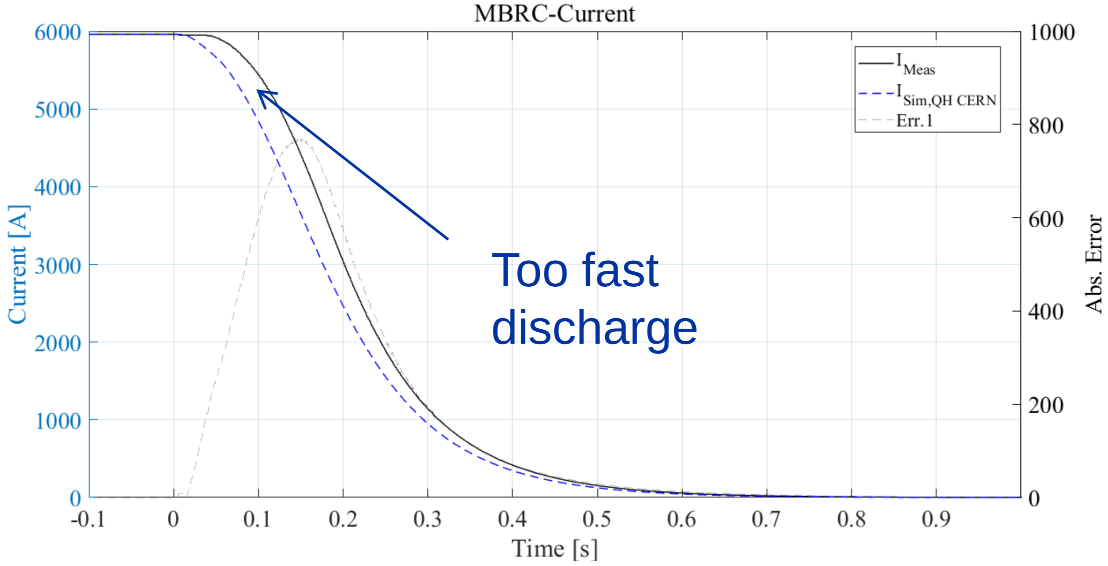
→ Huge difference !

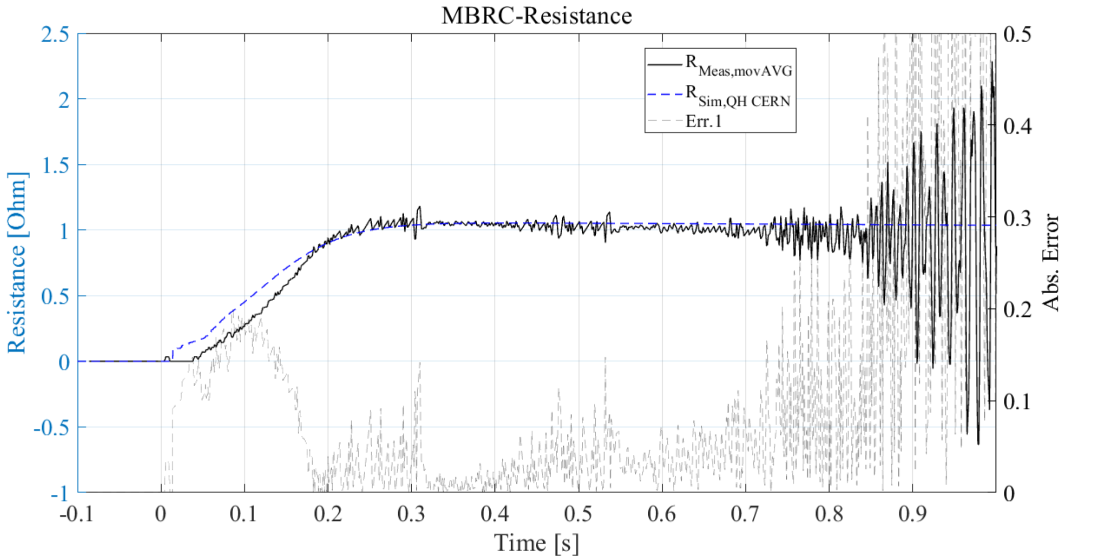
Simulation Results and Validation – QH Version 1

- First Validation approach, the CERN QH design parameters were used

Parameter	Value
Total No. of strips	16
No. of strips in Series	4
No. Of Power supplies	4
Strip Width	15mm
Pattern (SS/Cu)	.1m / .4m





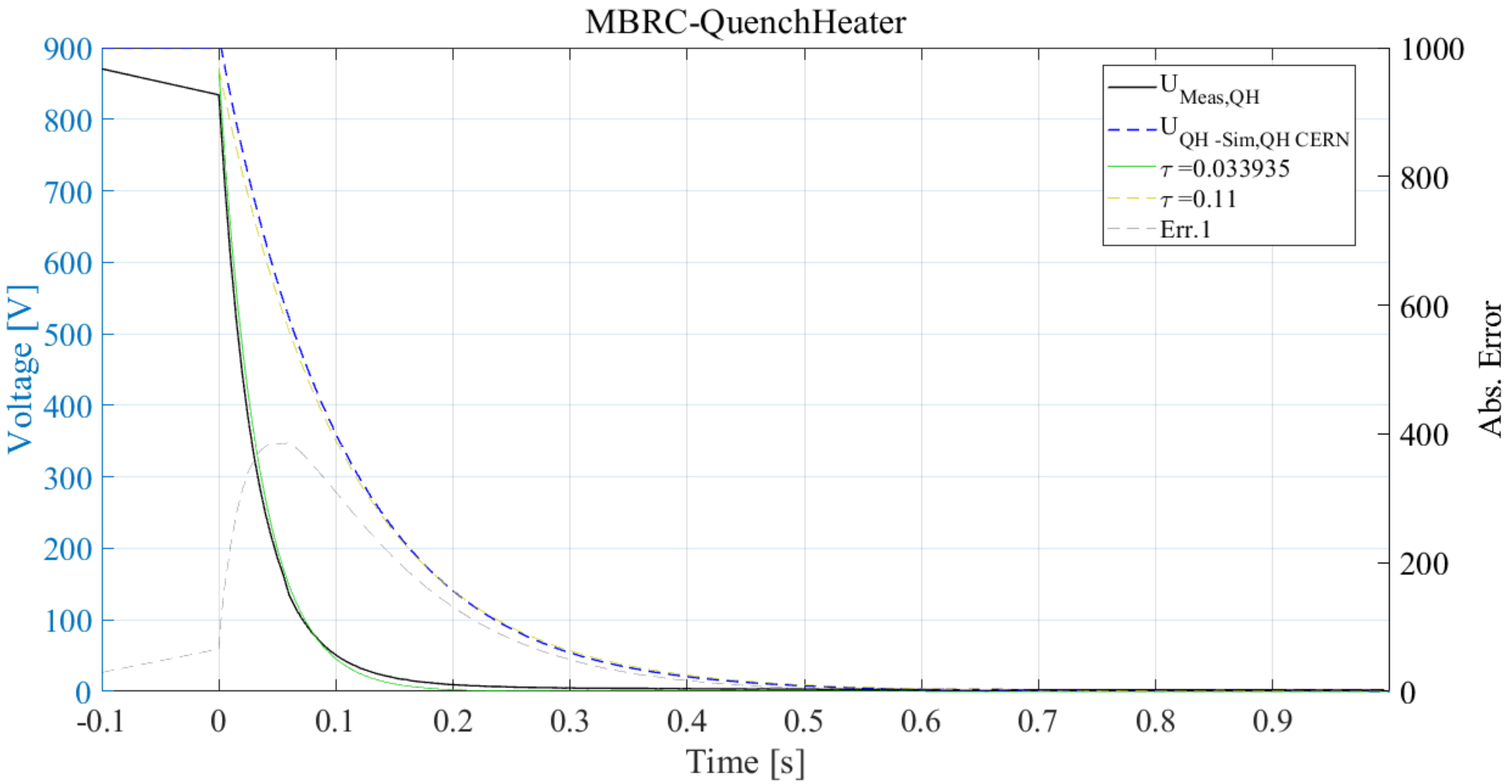


→ Agreement with measurement is not very good

Measurement: RD2.L8 - 2018.12.03 13:13:07 PM Browser

Simulation Results and Validation – QH Version 1

- **Additionally Quench Heater Voltages showed clearly no agreement**
→ Discharge of the QH Voltages by a factor ~3 faster

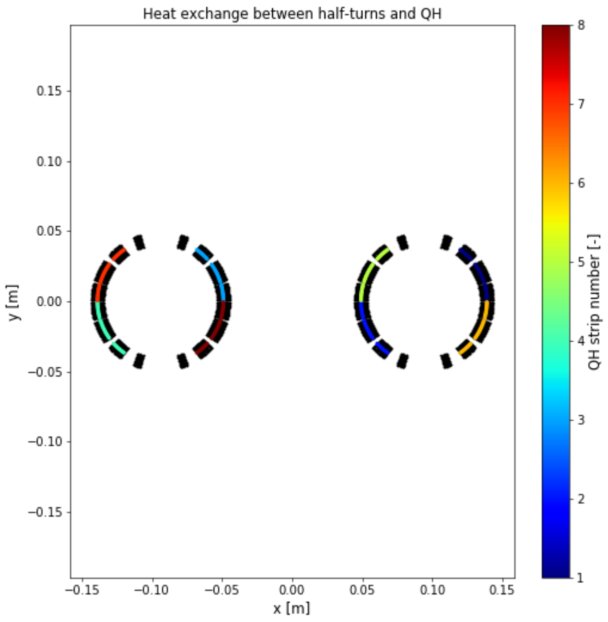


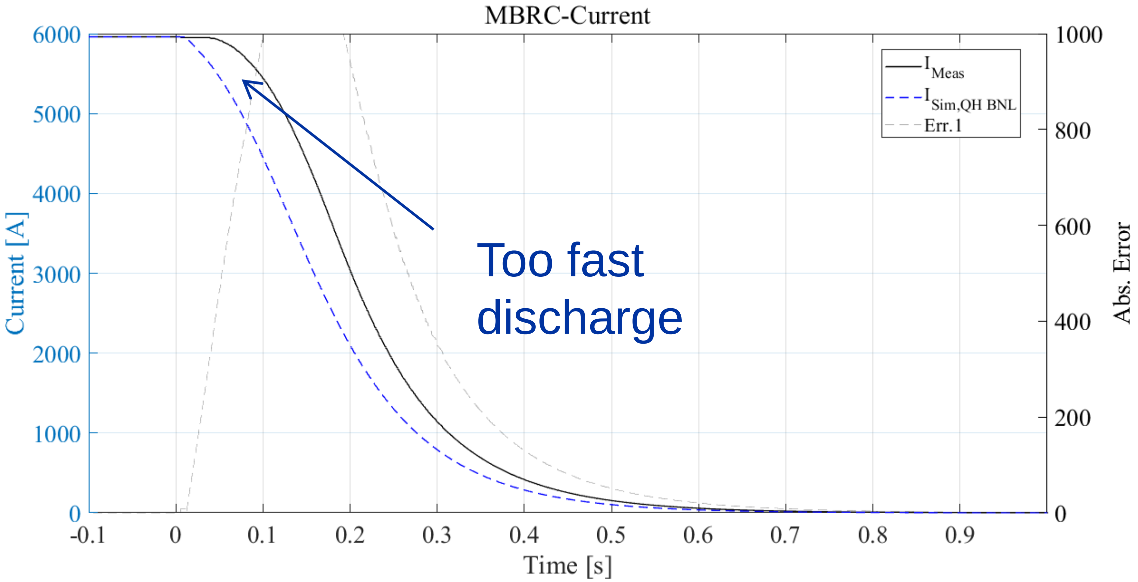
Measurement: RD2.L8 - 2018.12.03 13:13:07 PM Browser

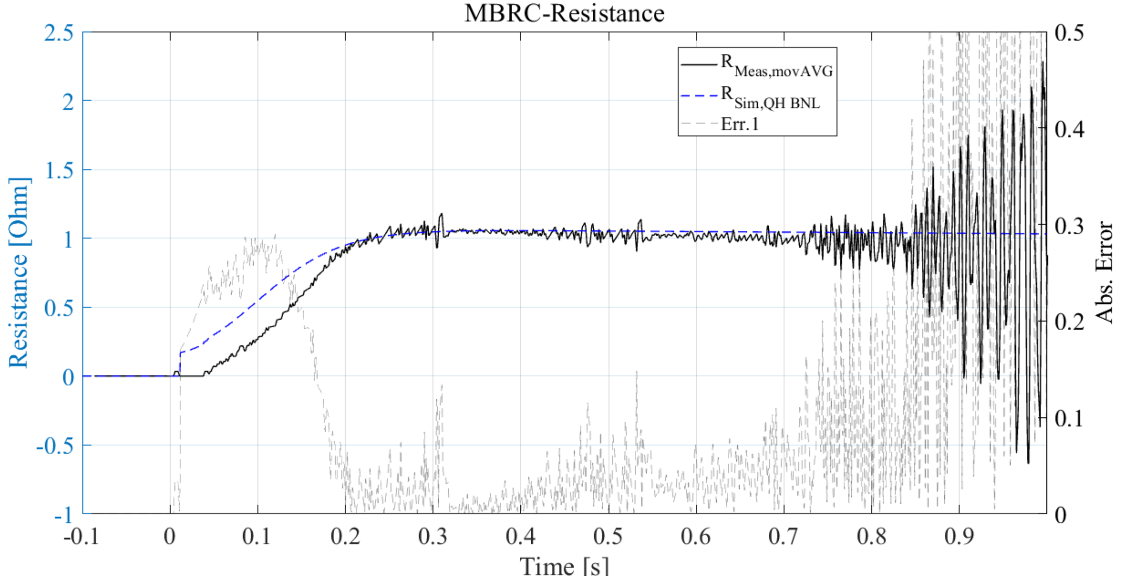
Simulation Results and Validation – QH Version 2

- 2nd approach: The parameters from BNL were tried

Parameter	Value
Total No. of strips	8
No. of strips in Series	2
No. Of Power supplies	4
Strip Width	44.45mm
Pattern (SS/Cu)	.127m / .75m







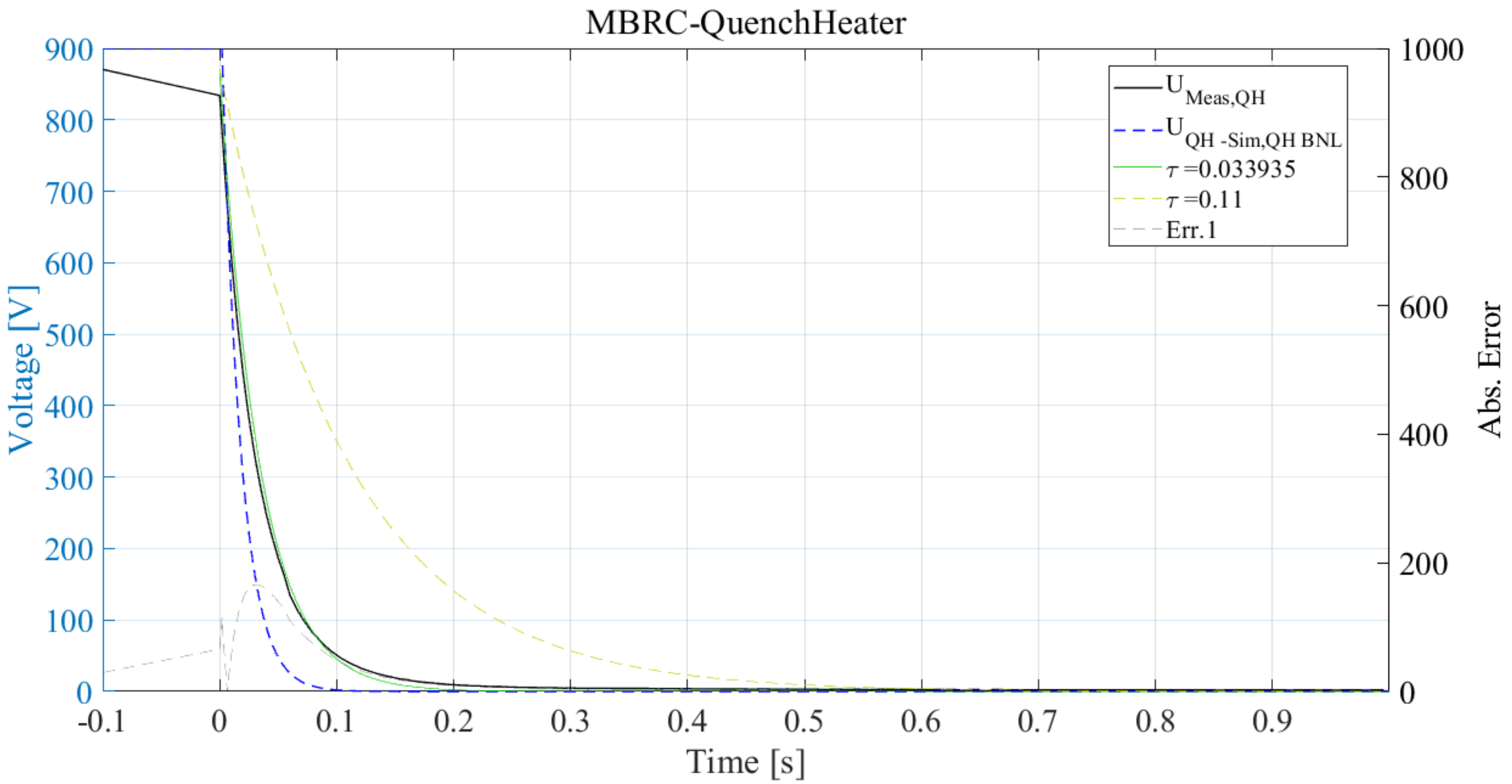
→Agreement with measurement again not very good

+Very large QH strips, which cover almost the whole magnet

Measurement: RD2.L8 - 2018.12.03 13:13:07 PM Browser

Simulation Results and Validation – QH Version 2

- **But Quench Heater Voltages are fitting with these Values relatively good to the measurements**

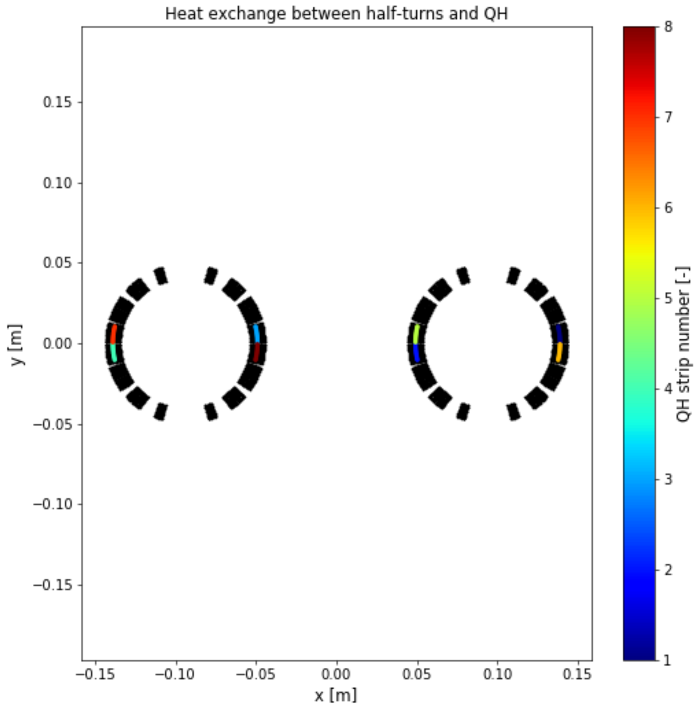


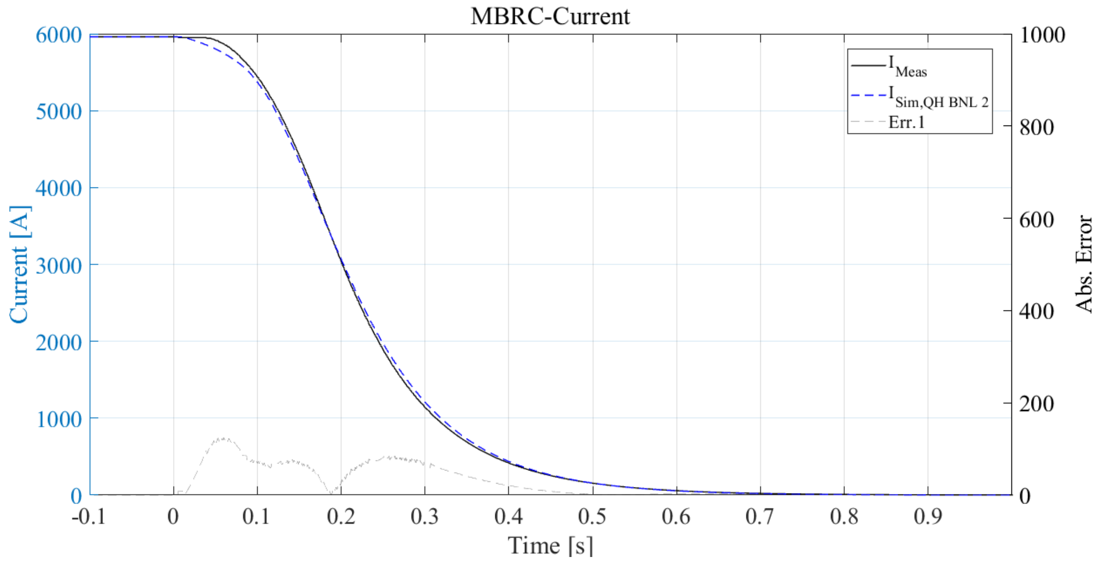
Measurement: RD2.L8 - 2018.12.03 13:13:07 PM Browser

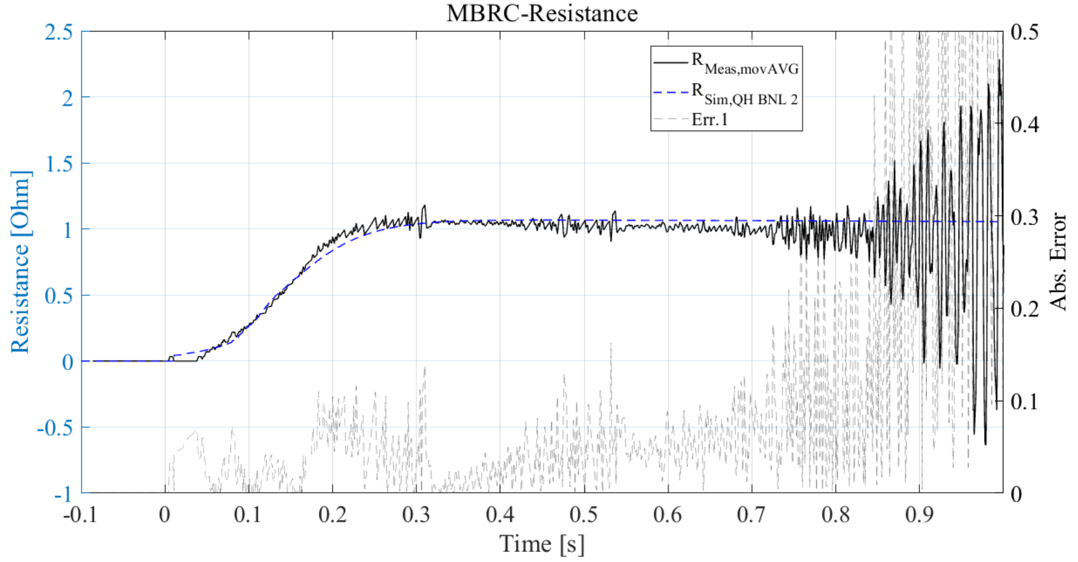
Simulation Results and Validation – QH Version 3

- 3rd approach: BNL parameter, but smaller strip width

Parameter	Value
Total No. of strips	8
No. of strips in Series	2
No. Of Power supplies	4
Strip Width	**14.5mm**
Pattern (SS/Cu)	.127m / .75m







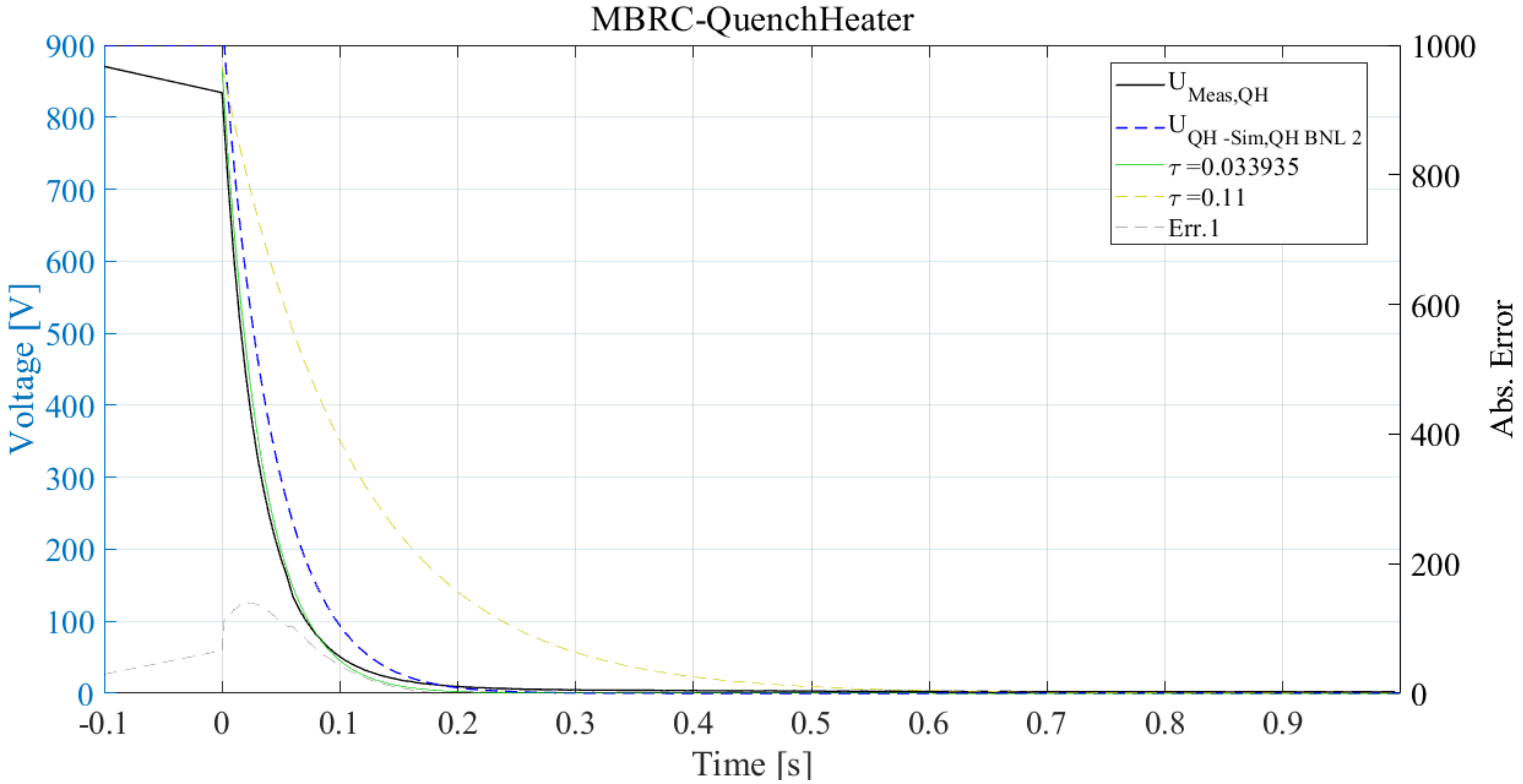
→Agreement with measurement very good!!

Error during FPA <3%, Max. abs. Error: 160A

Measurement: RD2.L8 - 2018.12.03 13:13:07 PM Browser

Simulation Results and Validation – QH Version 3

- **Agreement of Quench Heater Voltages also very good!**

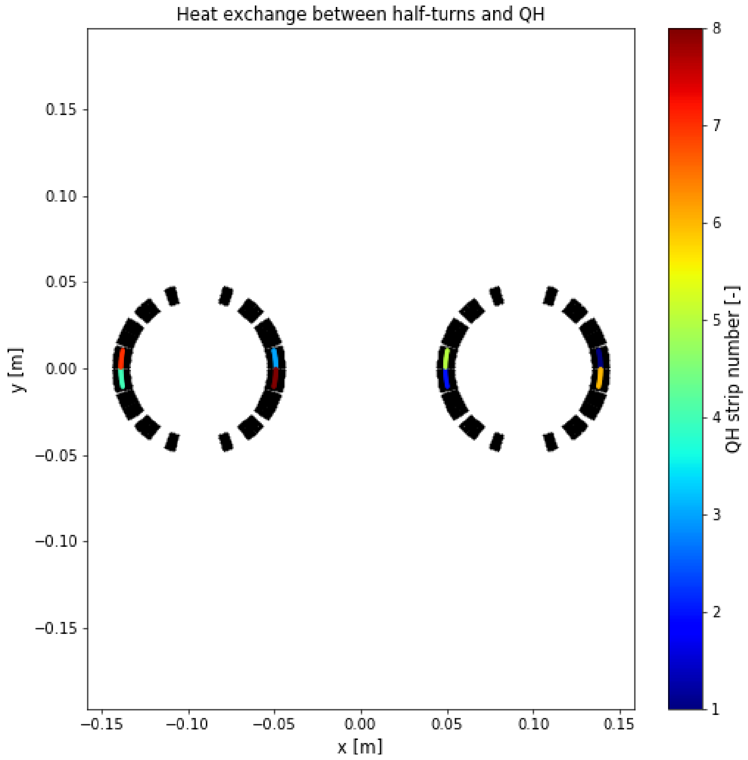


Measurement: RD2.L8 - 2018.12.03 13:13:07 PM Browser

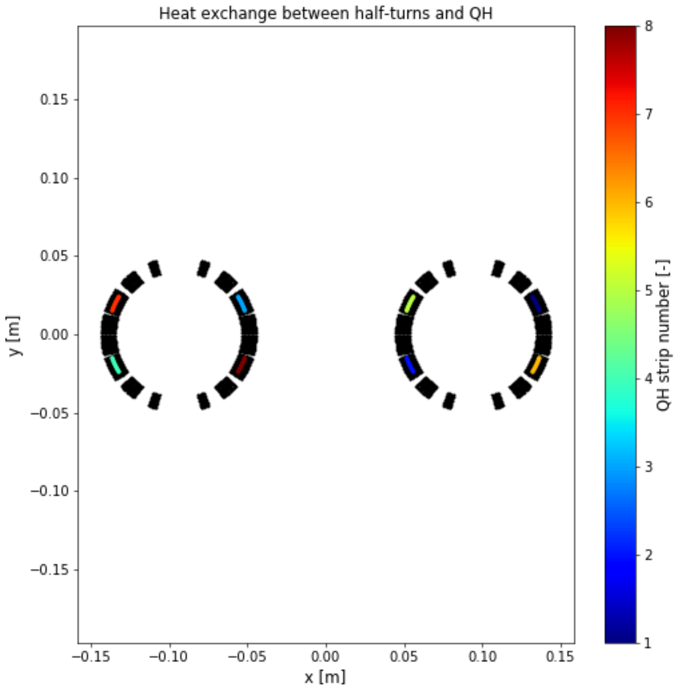
Simulation Results and Validation – QH Version 3
Trying different QH positions

- Based on the previous parameters, I tried different QH positions

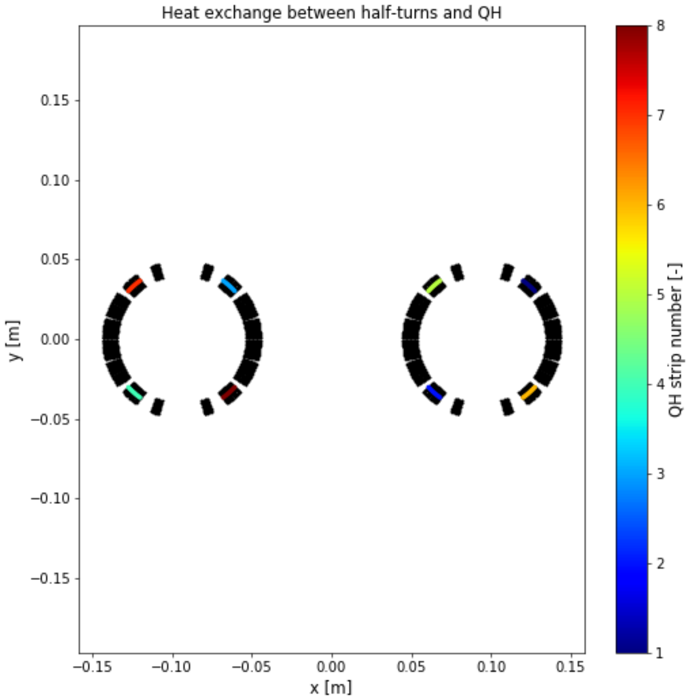
Center Block



Middle Block

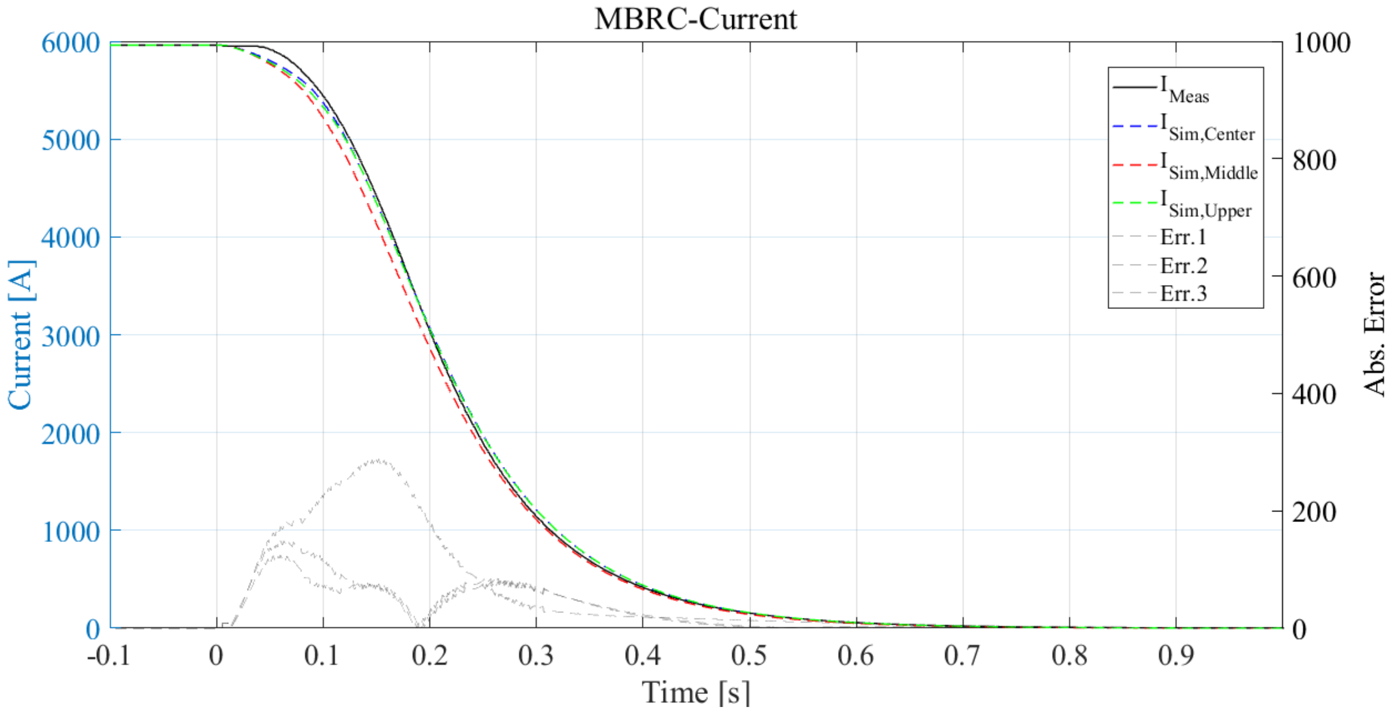


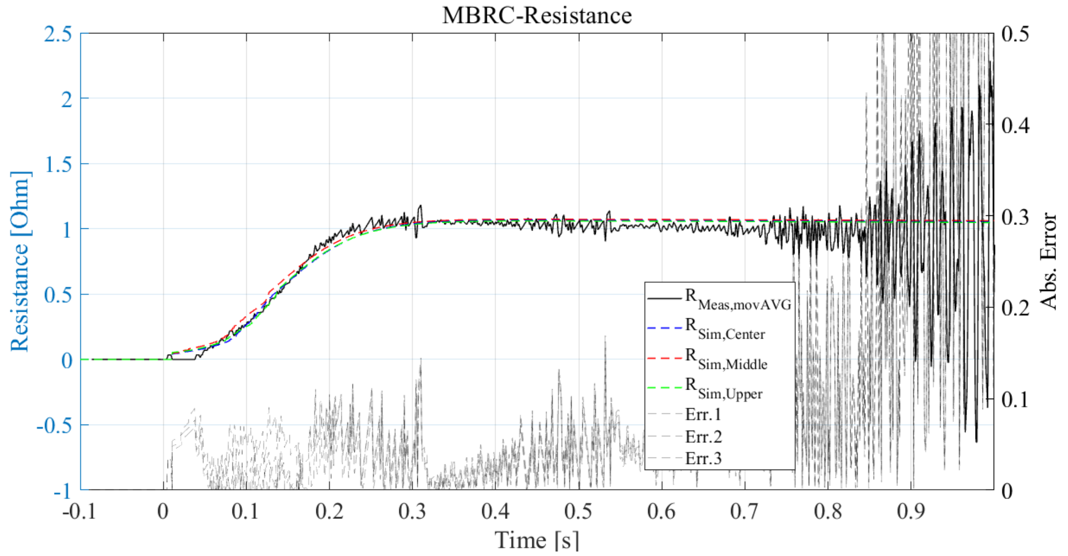
Upper Block



Simulation Results and Validation – QH Version 3

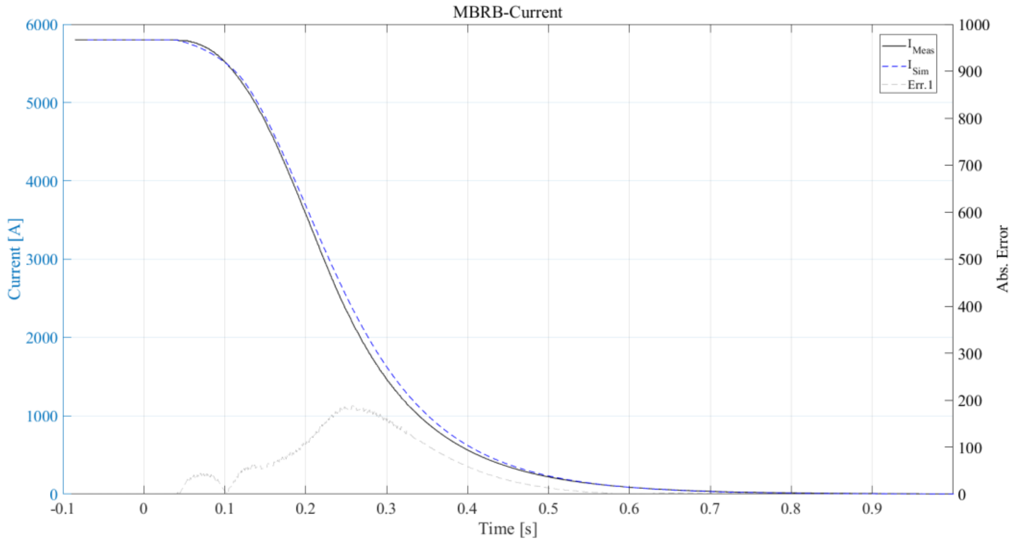
- Varying QH position shows no huge differences (Number of turns touched in all versions the same)
→ Slightly better agreement of the QH Positions on the center Block

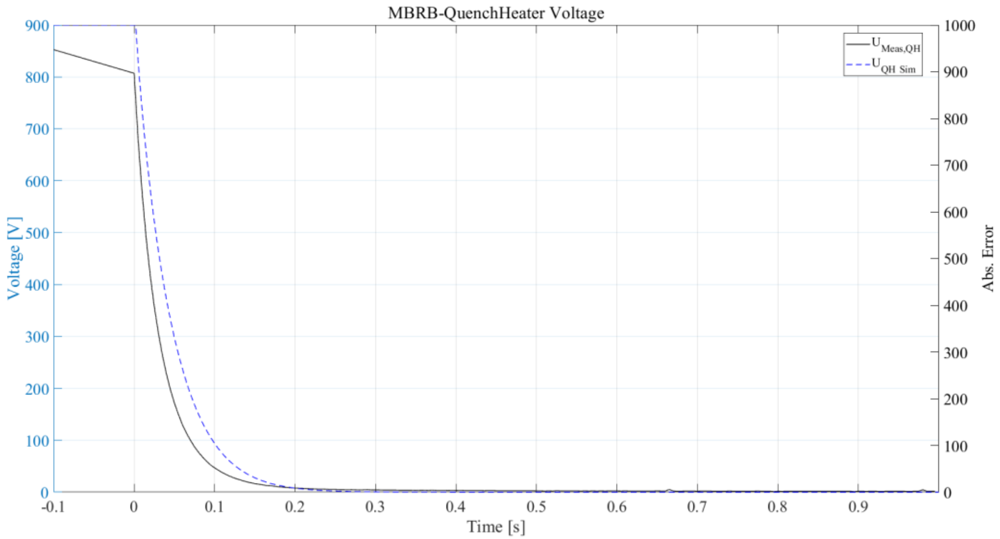


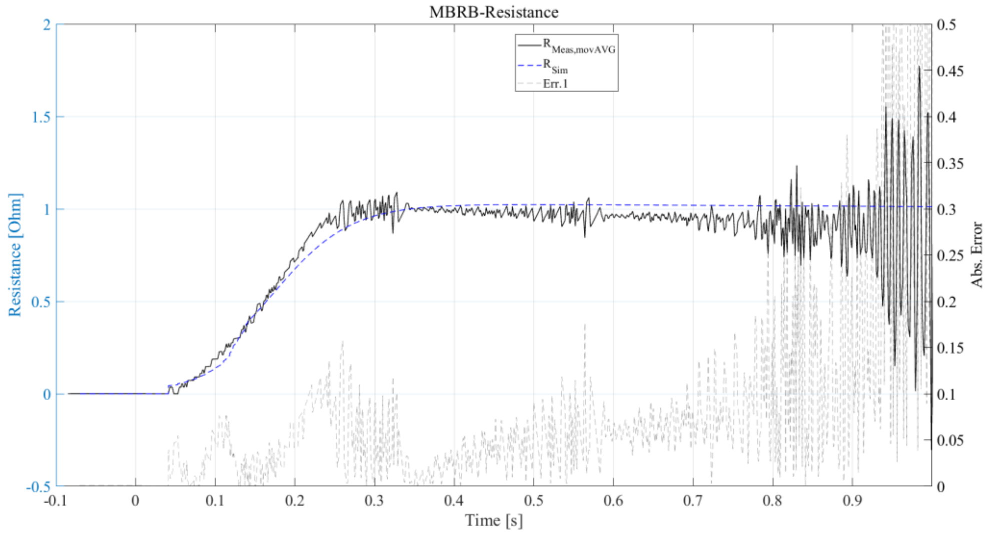


Measurement: RD2.L8 - 2018.12.03 13:13:07 PM Browser

Separation dipoles (IPD) Validation Results [MBRB]



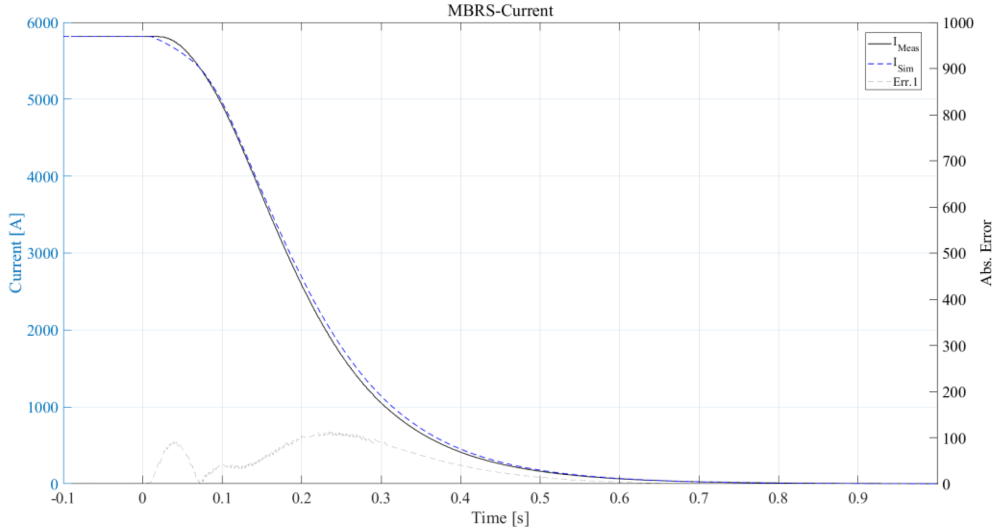


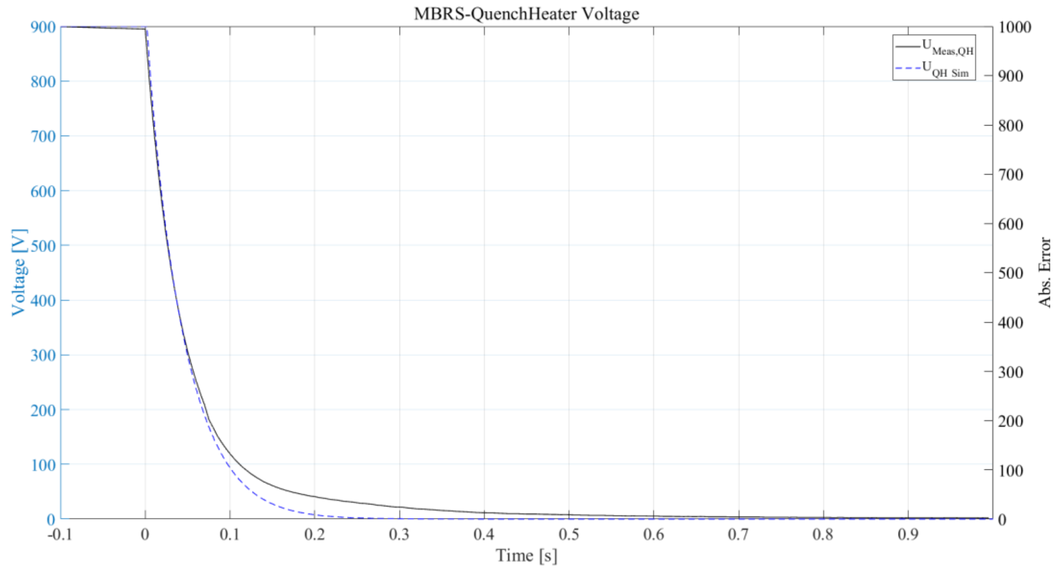


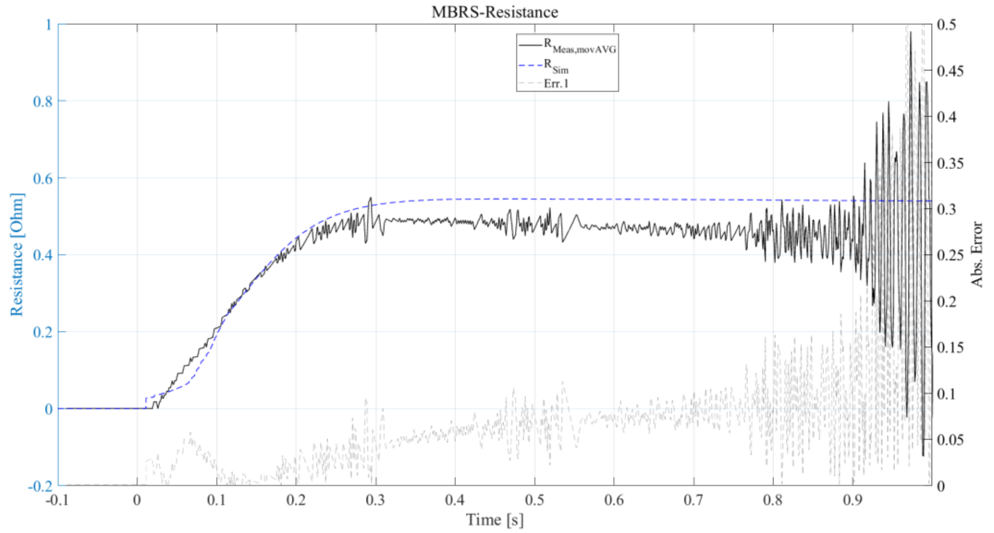
	Absolute Largest Deviation	Relative largest deviation	Mean Square Error	Root mean Square Error
MBRB (RD4.L4)	187.62 A	3.2 %	21.11 A^2	4.59 A
MBRC (RD2.L8)	124.3 A	2.1 %	22.47 A^2	4.74 A
MBRS (RD3.R4)	112.6 A	1.93 %	18.04 A^2	4.25 A

Measurement: RD4.L4 - 2015.28.02 14:22:45 PM Browser

Separation dipoles (IPD) Validation Results [MBRS]







	Absolute Largest Deviation	Relative largest deviation	Mean Square Error	Root mean Square Error
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MBRC (RD2.L8)	124.3 A	2.1 %	22.47 A^2	4.74 A
MBRS (RD3.R4)	112.6 A	1.93 %	18.04 A^2	4.25 A

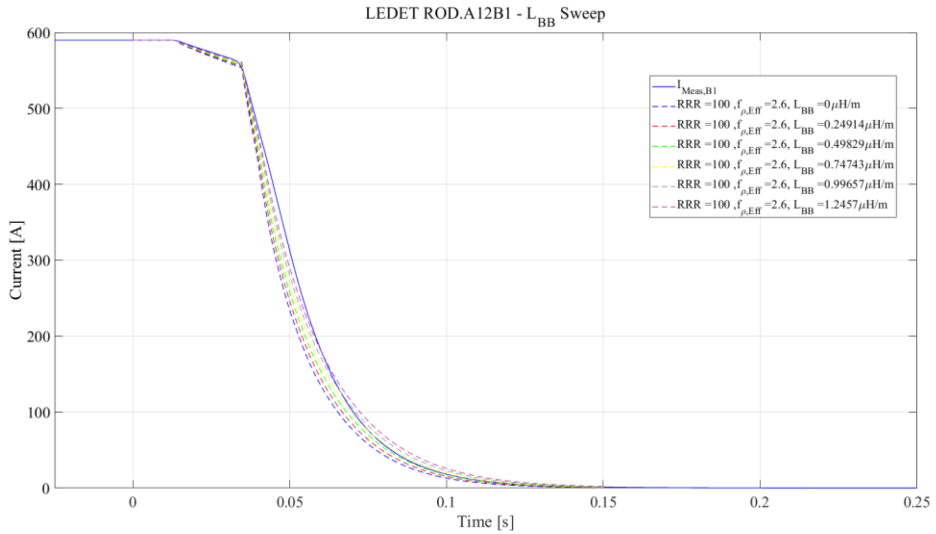
Measurement: RD3.R4 - 2018.03.12 13:59:59 PM Browser

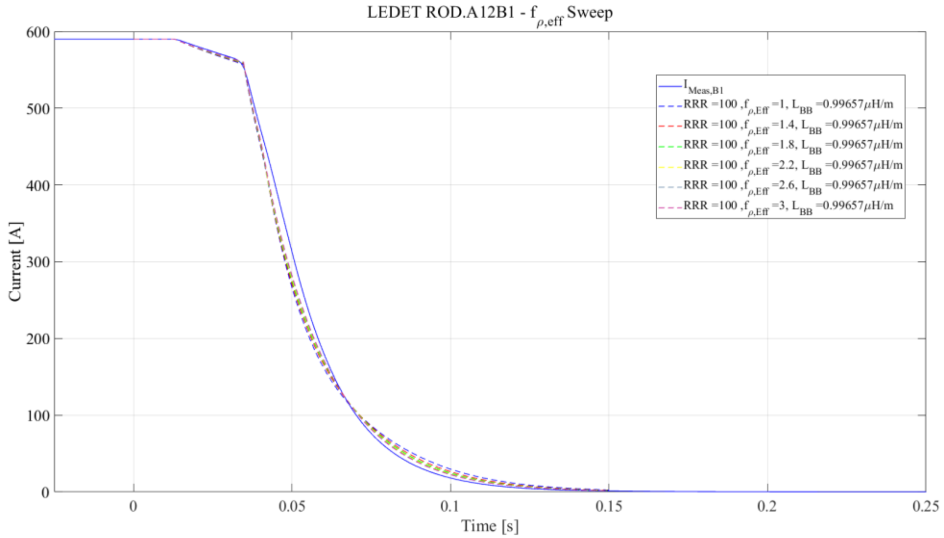
600A EE – ROD/ROF – Validation Results

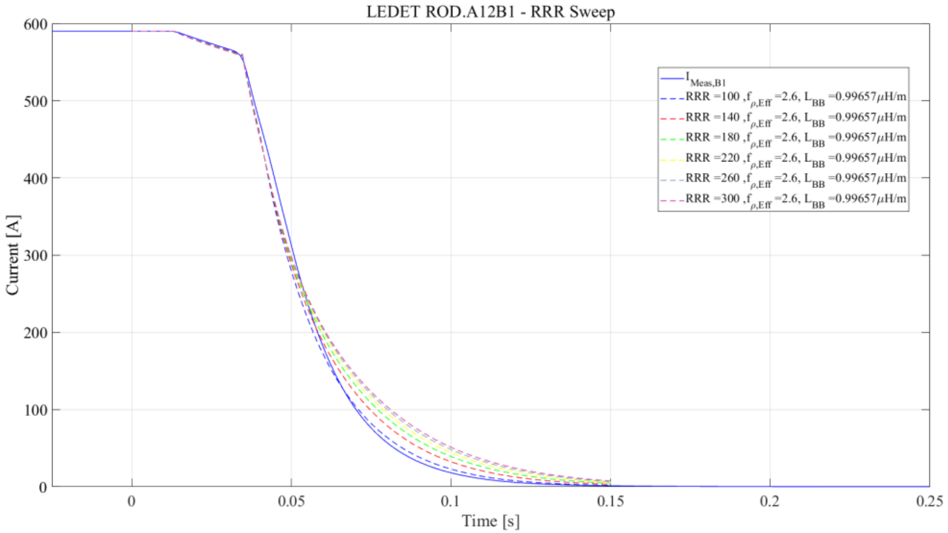
Parametric Study

Best parameter combinations for the two different groups in the ROD/ROF family:

	L_BB	RRR	f_Rho,eff
ROD.A12B1 (13mag)	0.8 µH/m	100	2.7
ROD.A12B2 (8mag)	0.8 µH/m	115	2.4



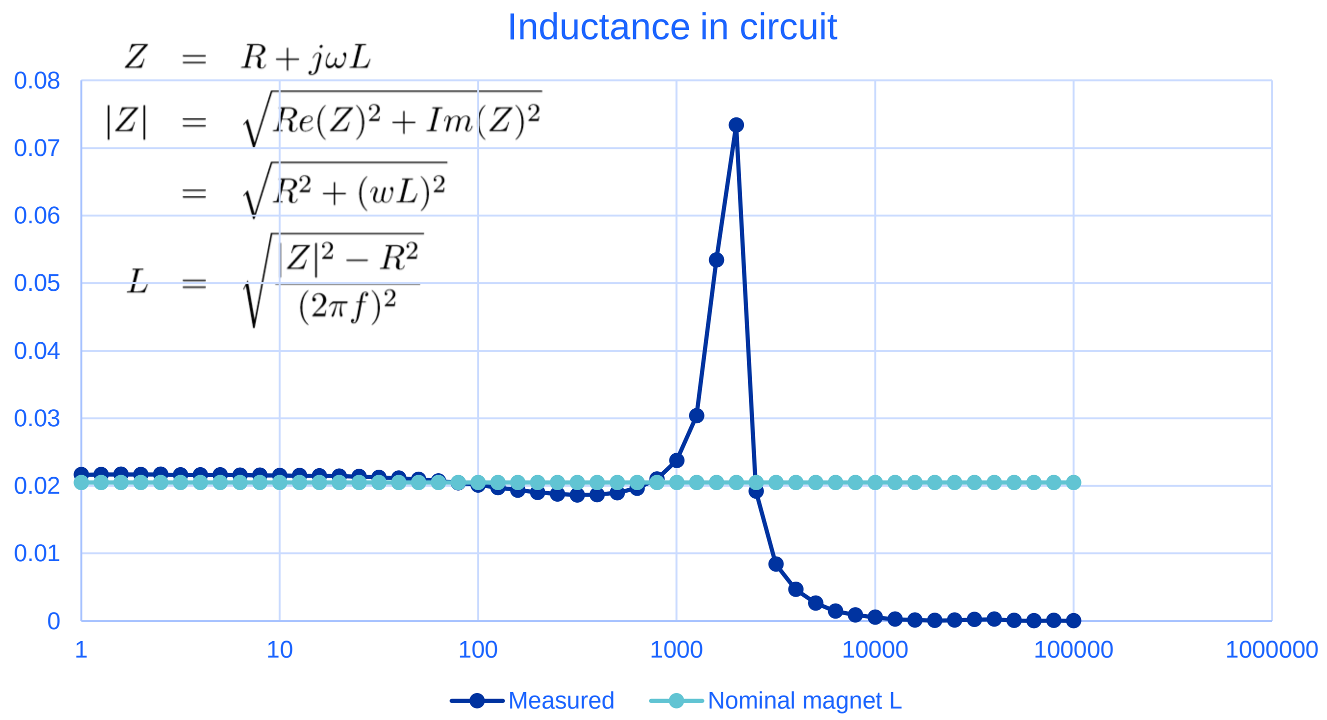


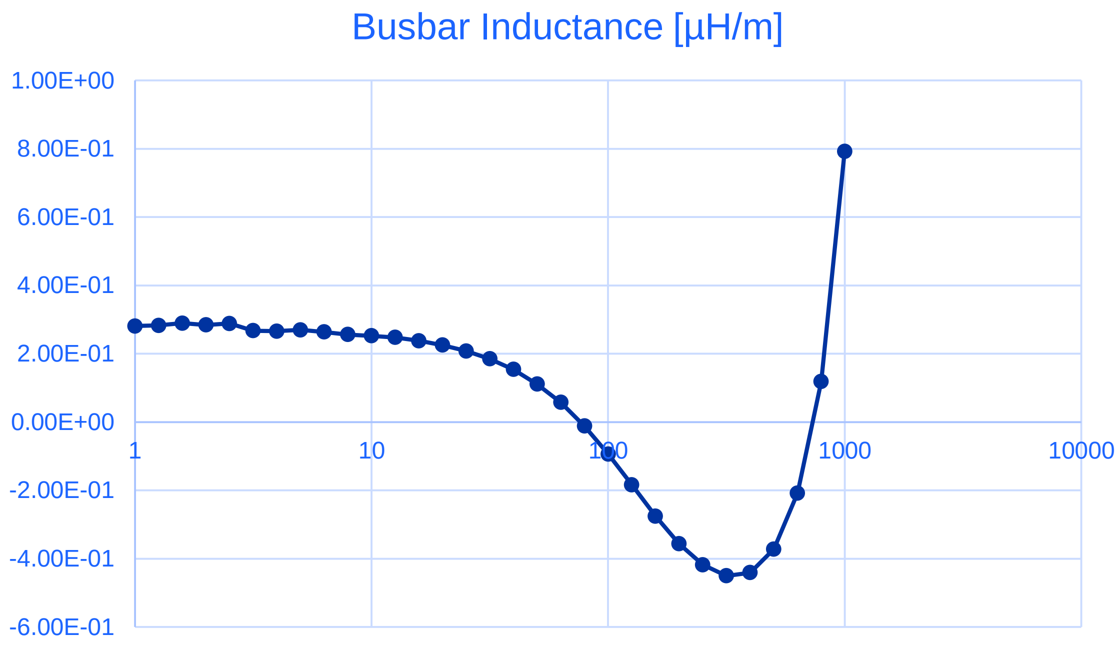


ROD.A12B1 circuit; Measurement: HWC_2017, PNO.d3, 2017-04-22 02:00:12, LHC-SM notebook

Busbar Inductance in real Measurements ROD/ROF

TFM-Measurements, LS2 Tests at cold in sector 1-2





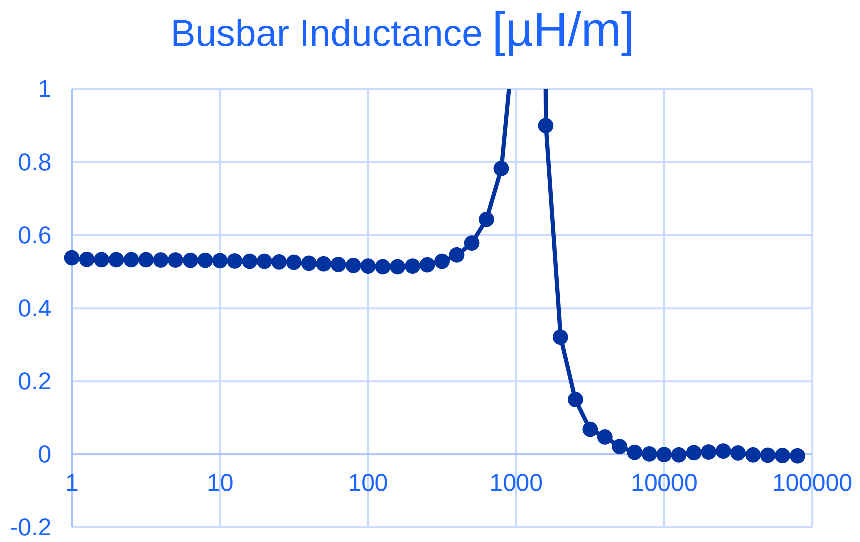
ELQA Measurements CERNLS2 Tests at warm in sector 1-2 before DISMAC
Test-ID: 15192, Operator: Maciej Turzanski, Test-Type: TFM vs GND

- TFM Measurements show Busbar inductance in the circuit
  BUT: Value per m is lower than simulations require

Initial guess	Real measurements	Simulations
0.5 µH/m	0.3 µH/m	0.8 µH/m

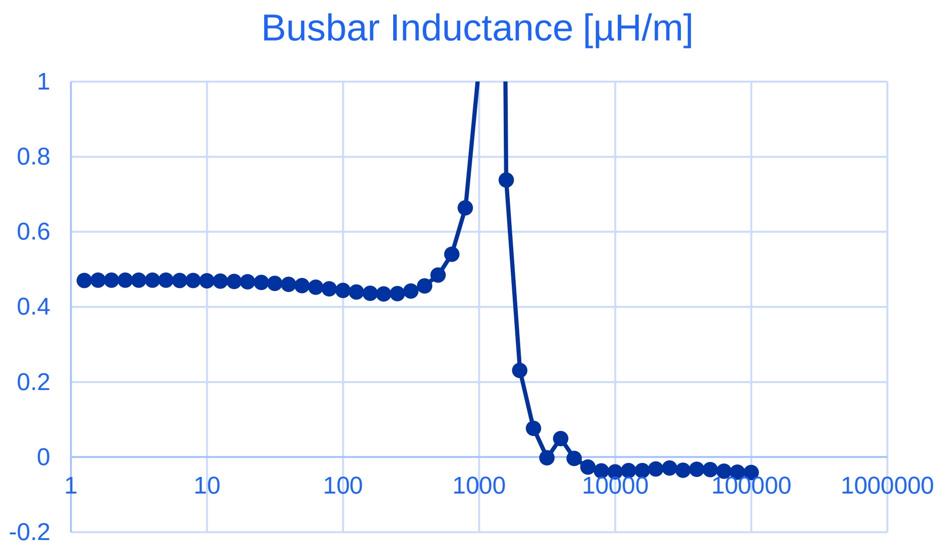
Busbar Inductance in real Measurements MCDO

ELQA measurements of the circuit impedance at different frequencies
Cable resistance and nominal inductance used to calculate Busbar inductance [see Sl. ROD/ROF Busbars]



RCD.A56B1

LS2 Tests at warm in sector 5-6 before DISMAC
Test ID: 16881, Operator: Mikolaj Bednarski
26-04-2019 08:28, TFM vs GND



RCO.A56B1

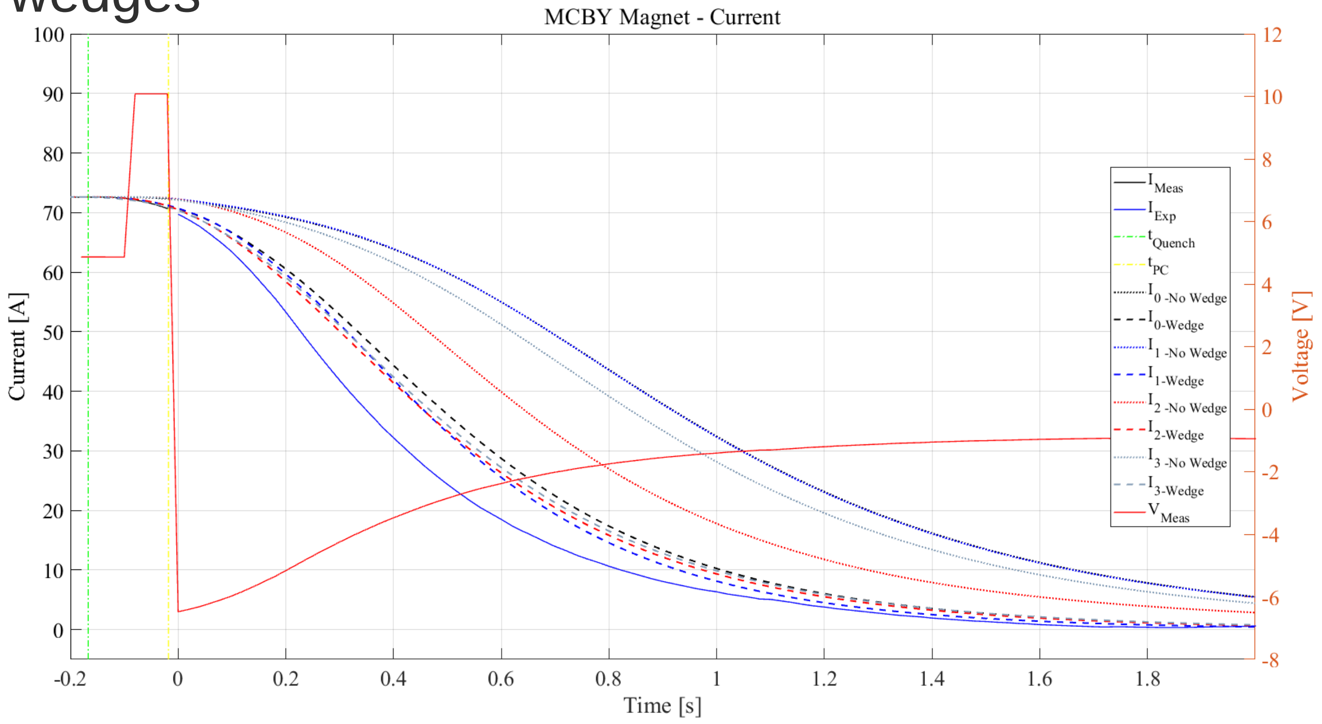
LS2 Tests at warm in sector 5-6 before DISMAC
Test ID: 16889, Operator: Mikolaj Bednarski
26-04-2019 08:28, TFM vs GND

80-120A self-protected (MCBY) – Validation Results

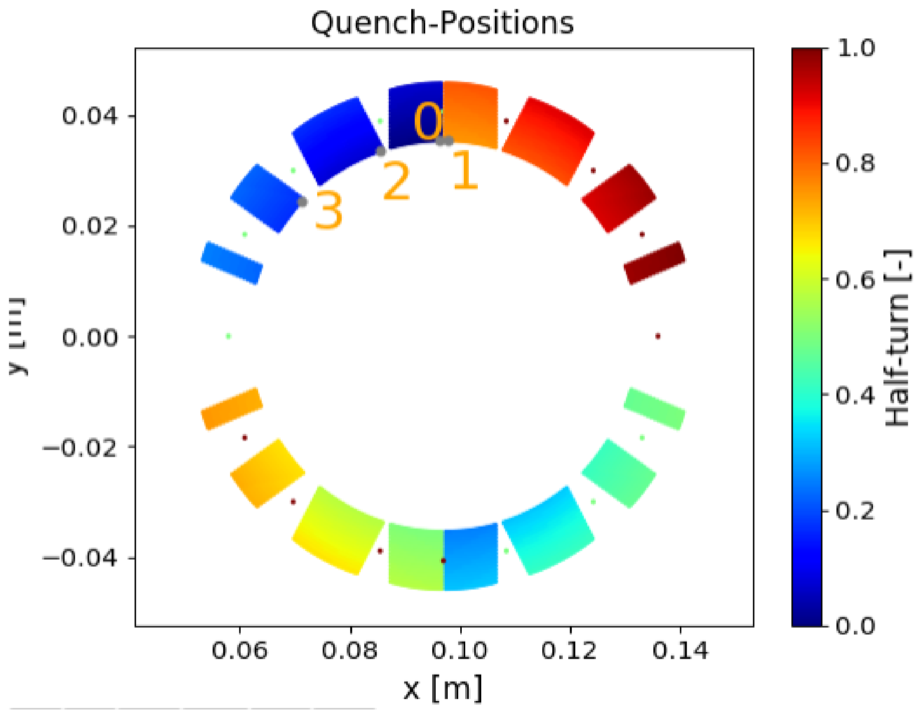
LEDET Validation – Comparing Model with/without Copper Wedges

- Including the Copper Wedges into the LEDET model improved the model and its agreement with the measurement a lot [by ~25-40%]

- Different quench positions compared to show the effect of the heat diffusion through the wedges



RCBYH4.R2B1 circuit; Measurement: 2015-01-24 10:28:16 Training quench



Additionally the electric return line is always artificially quenched as well with calc. delay