Co-simulation of quench transients in the HiLumi recombination dipole magnet combining STEAM-LEDET and STEAM-PyBBQ

Lennard Bender (CERN / Hochschule Karlsruhe)

16 September 2022

Acknowledgements
Special thanks to:
B.Caiffi, P.Fabbricatore and MBRD team (INFN-Genoa),
A. Foussat, T.Mulder, E.Ravaioli, G.Willering, M.Wozniak and SM18 team (CERN)

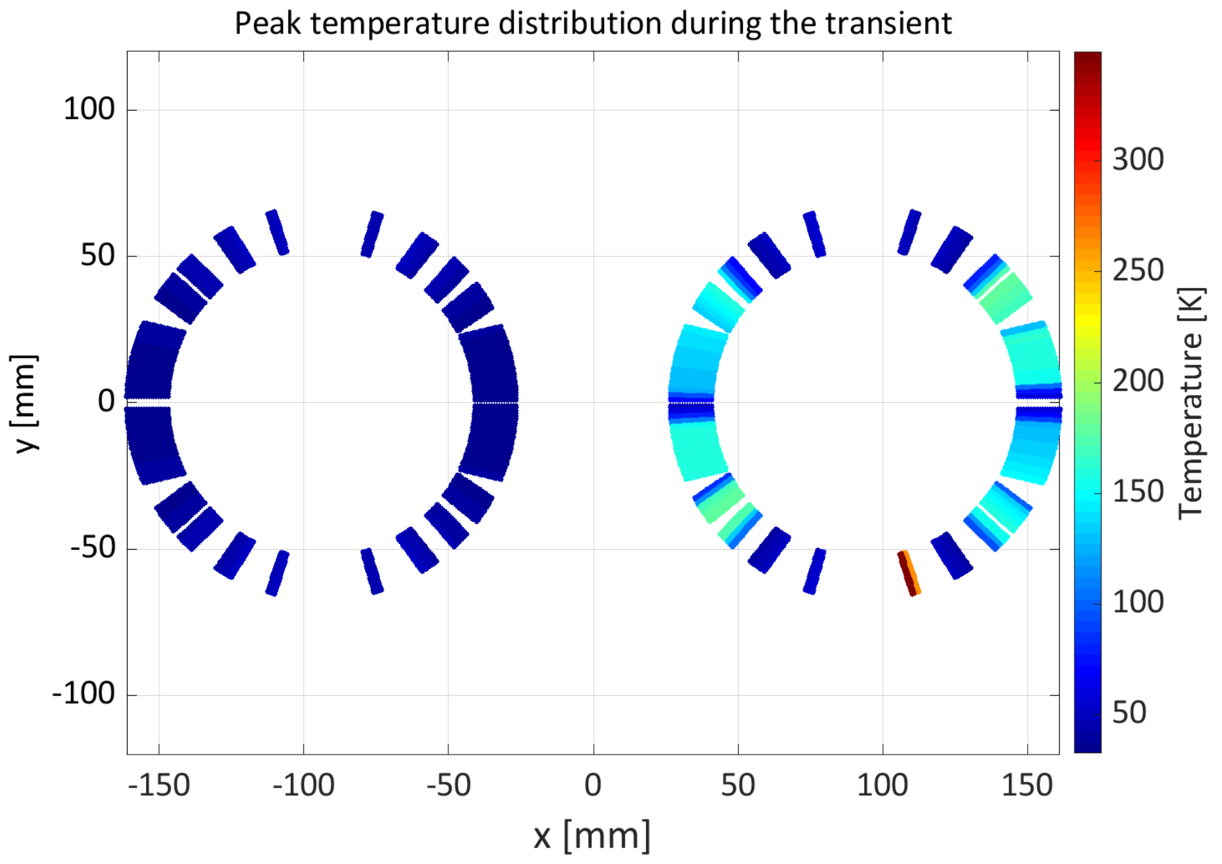
Presentation outline

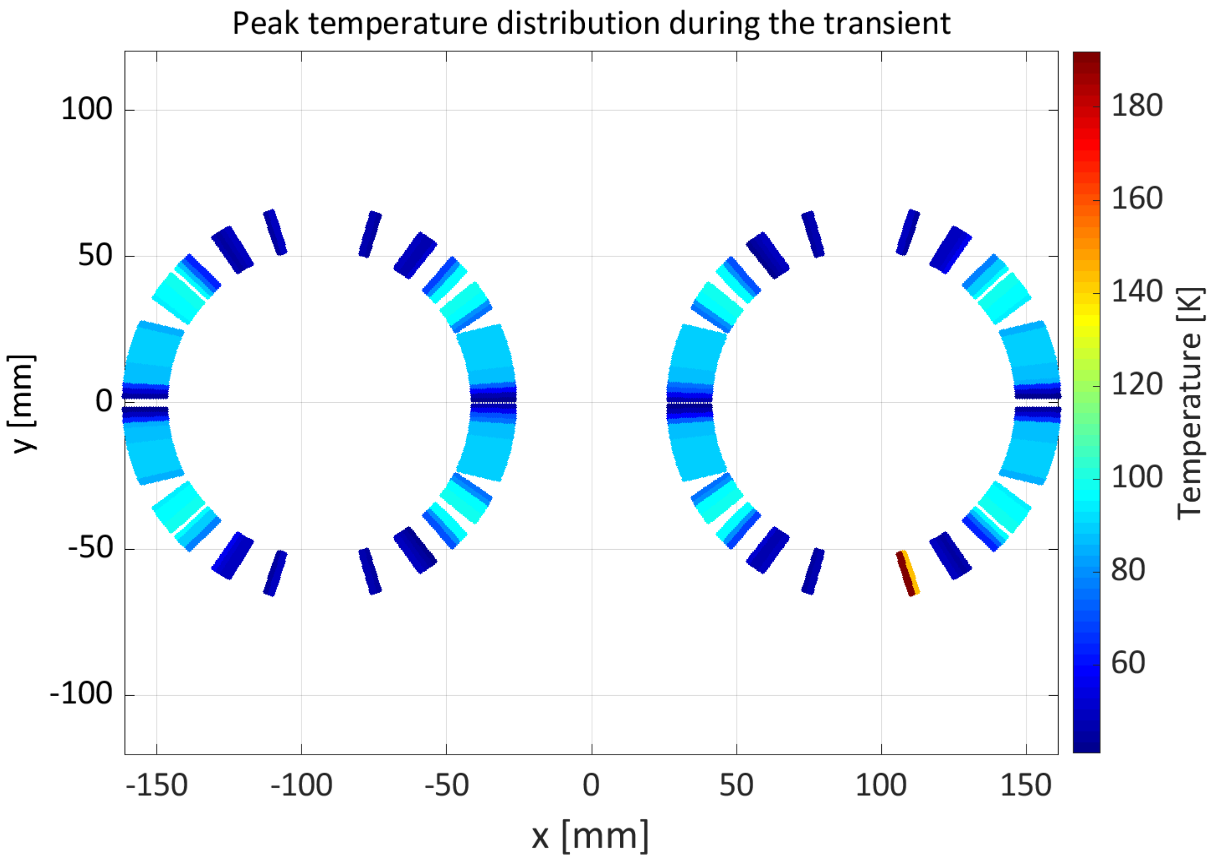
Including longitudinal quench propagation for QH protected magnets

Validation process of co-simulation

Alternative protection of MBRD magnet to decrease hot-spot temperature and voltage to ground

What is the goal of quench protection?





STEAM tools - 2022

- BBQ(Comsol) → PyBBQ BBQ(GetDP)
- FiQuS
- SIGMA
- LEDET
- PROTECCT
- SING → PySING
- COSIM

Conductor

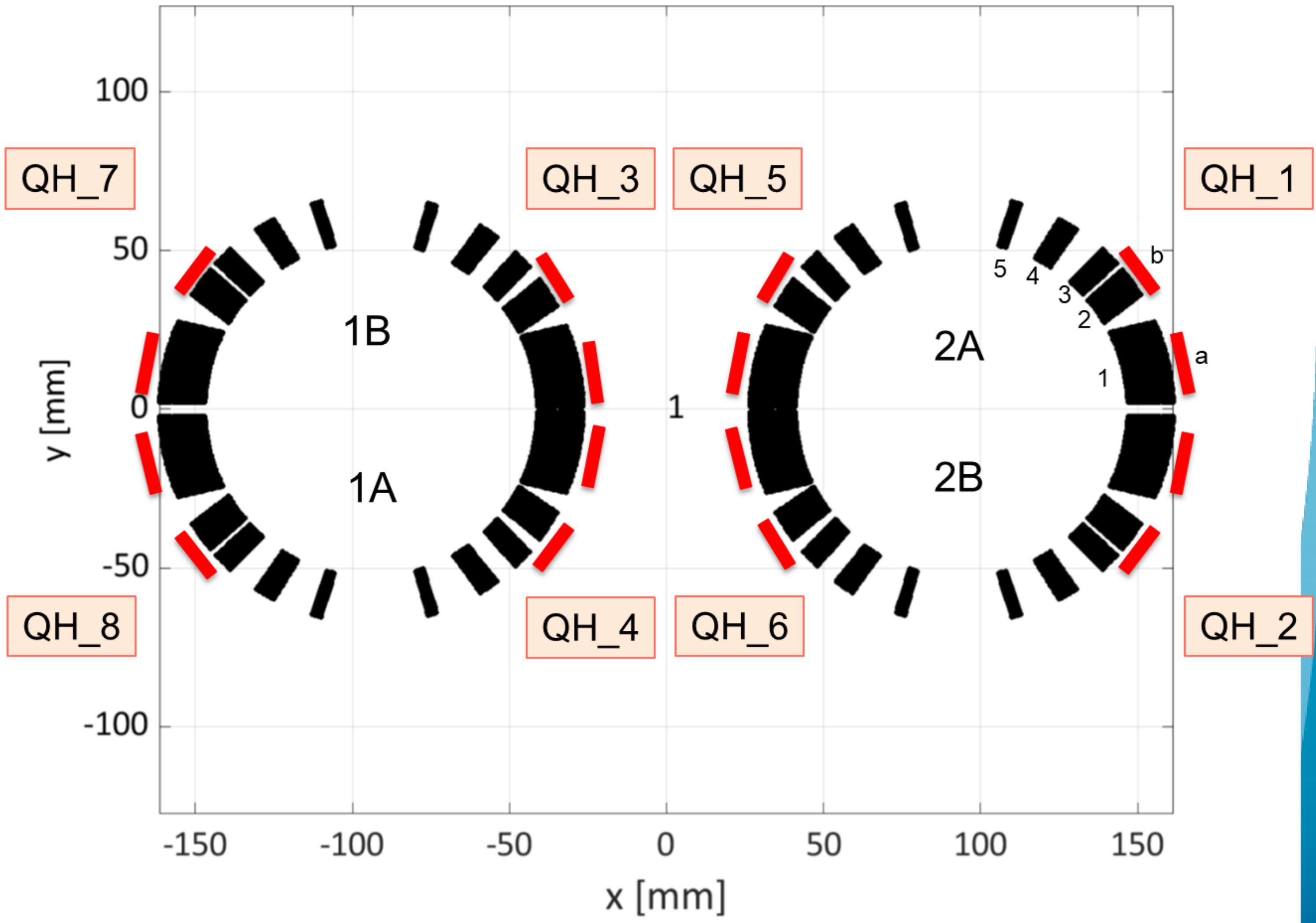
Magnet

Circuit

E. **Ravalioli and M. Wozniak**, "STEAM framework – MPE-PE section meeting," CERN, 07.19.2022, Available: https://indico.cern.ch/event/1183524/

Recombination dipole magnet MBRD

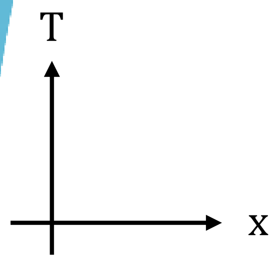
Parameter	Value
Bore magnetic field	4.5 T
Peak magnetic field	5.28 T
Nominal current	12340 A
Ultimate current	13357 A
Magnetic length	7.78 m / 1.378 m
Number of blocks	5

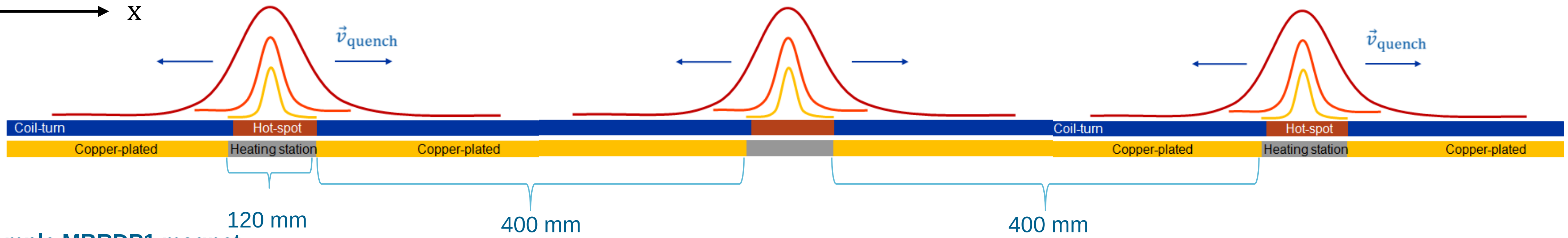


Quench heaters and quench propagation

- After the QH firing, the normal zone is propagating from each heating station into both, longitudinal directions

$$v_q^{QH} = 2 \cdot n_{QH,stations} \cdot v_q$$





Example MBRDP1 magnet:

vQ @ nominal current: ~15 m/s — 13.3 ms | 13.3 ms

All turns, attached to QH would quench in ~13.3 ms at nominal current

vQ @ 2 kA: 0.39 m/s — 510 ms | 510 ms

All turns, attached to QH would quench in ~510 ms at nominal current

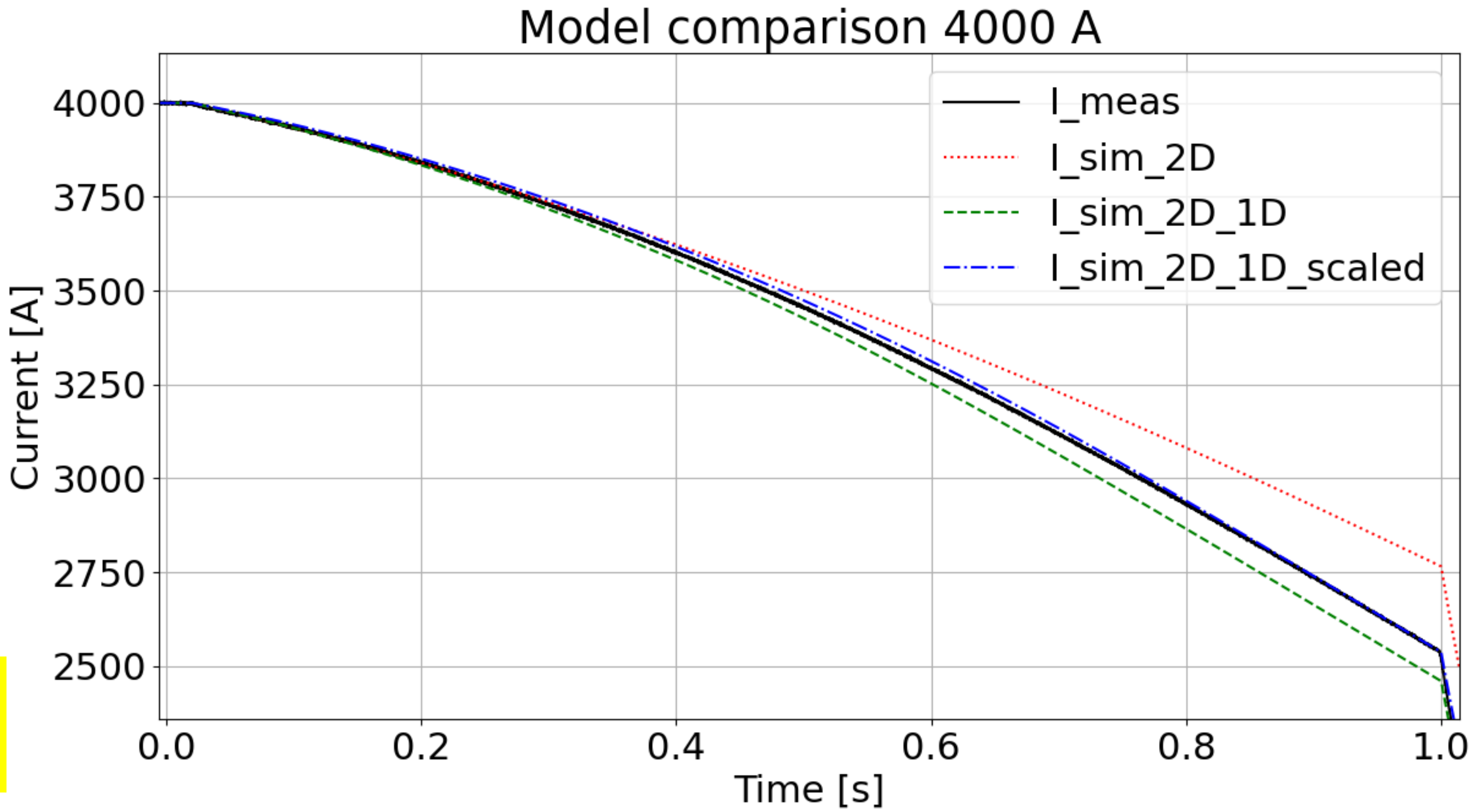
Note: quench propagation velocity calculated with PyBBQ including cooling

Marvin Janitschke: 2nd STEAM Workshop (11-October 15, 2021): Thermal analysis of quench-heater heating stations using STEAM-BBQ · Indico (cern.ch)

Introduction of quench propagation scaling at low currents

- Poor fit for STEAM-LEDET 2D model at low currents [1]
- Improvement by implementing 2D+1D extension [2]
- 2D+1D includes longitudinal quench propagation between heating stations [3]

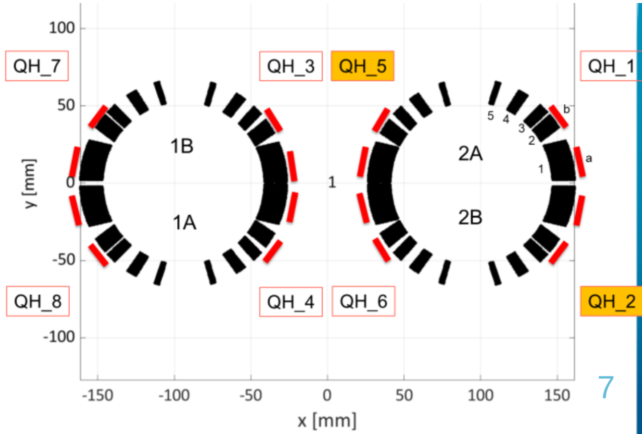
➢ Improved simulation by including scaled quench propagation due to helium cooling



[1] **E. Ravaioli, B. Auchmann, M. Maciejewski, H. ten Kate, and A. Verweij**, “Lumped-element dynamic electro-thermal model of a superconducting magnet,” Cryogenics, 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0011227516300832

[2] **M. Janitschke**, **M. Mentink**, **F. Murgia**, **D. Pracht**, **E. Ravaioli**, **A.P. Verweij**, "A simplified approach to simulate quench development in a superconducting magnet", IEEE Trans. on Appl. SC, 2021

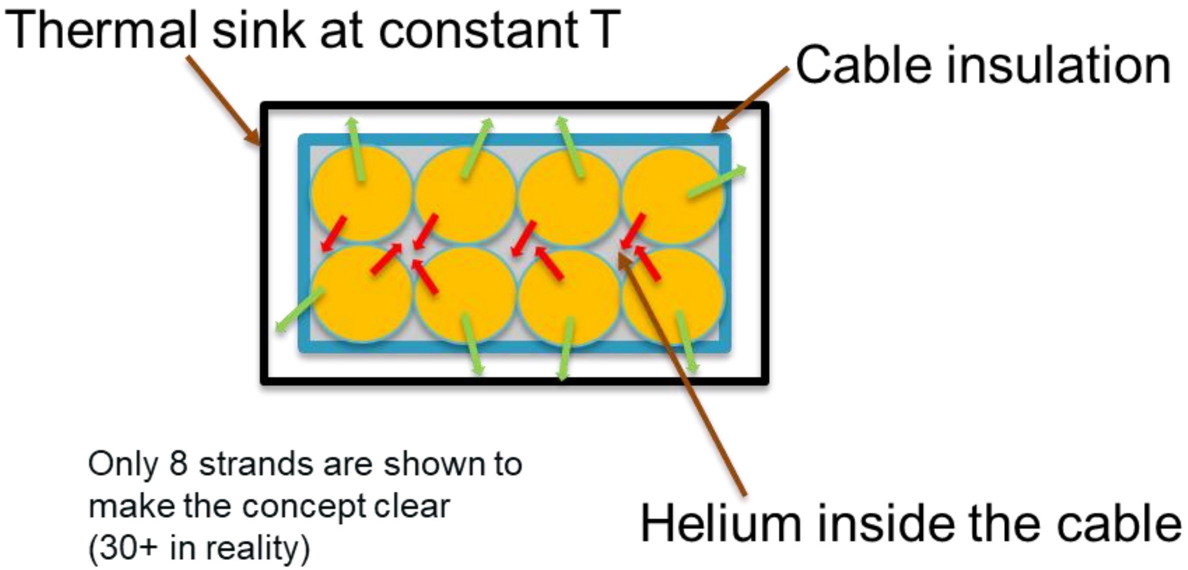
[3] **Marvin Janitschke:** 2nd STEAM Workshop (11-October 15, 2021): Thermal analysis of quench-heater heating stations using STEAM-BBQ · Indico (cern.ch)



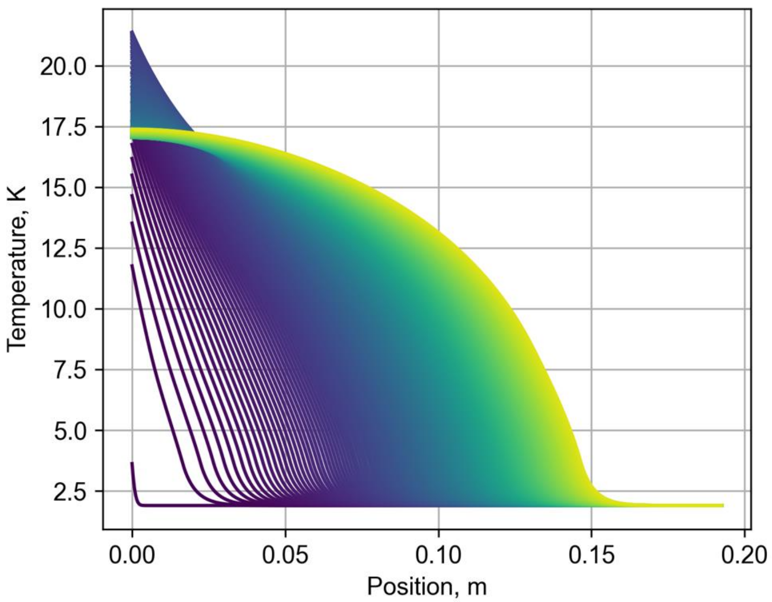
Presentation outline

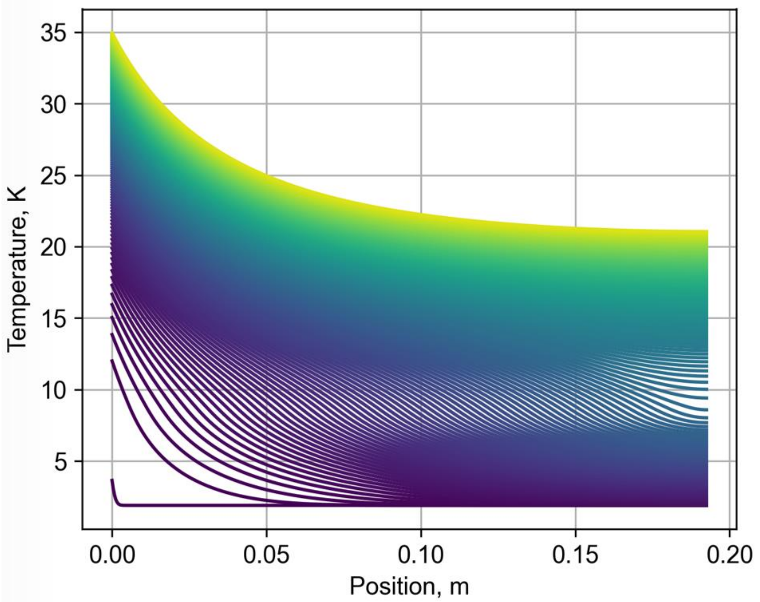
- Including longitudinal quench propagation for QH protected magnets
- **Validation process of co-simulation**
- Alternative protection of MBRD magnet to decrease hot-spot temperature and voltage to ground

STEAM-PyBBQ (**B**us**B**ar **Q**uench in python)



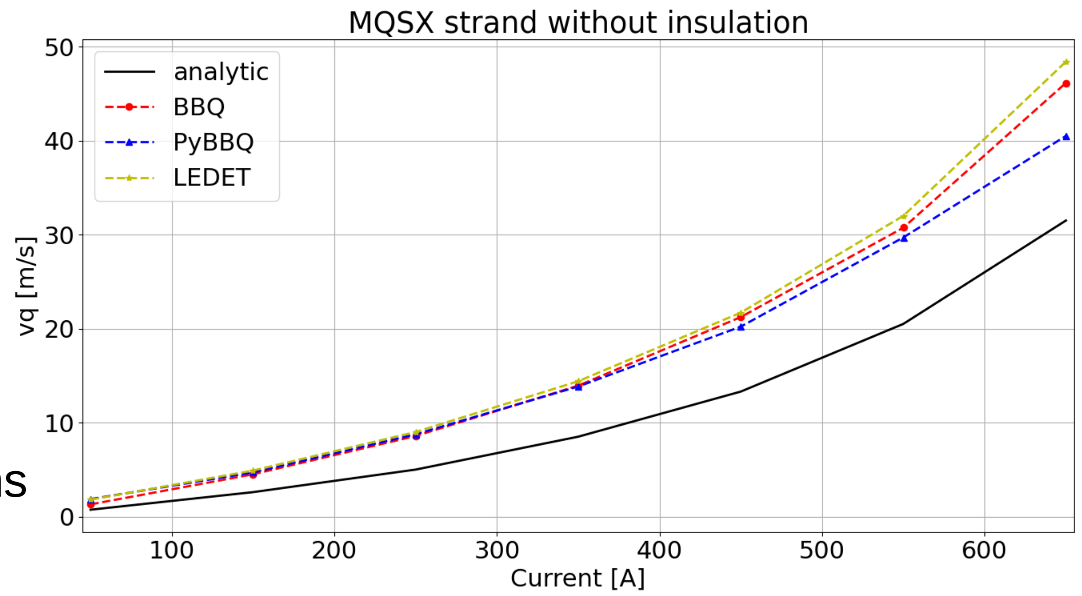
- STEAM-PyBBQ implemented tool in python by T. Mulder [4]
- Able to simulate quench propagation in a cable with and without helium cooling
- Quench initiation through power input at one conductor side
- Crucial to include external and internal cooling of the cable to simulate quench propagation at low currents



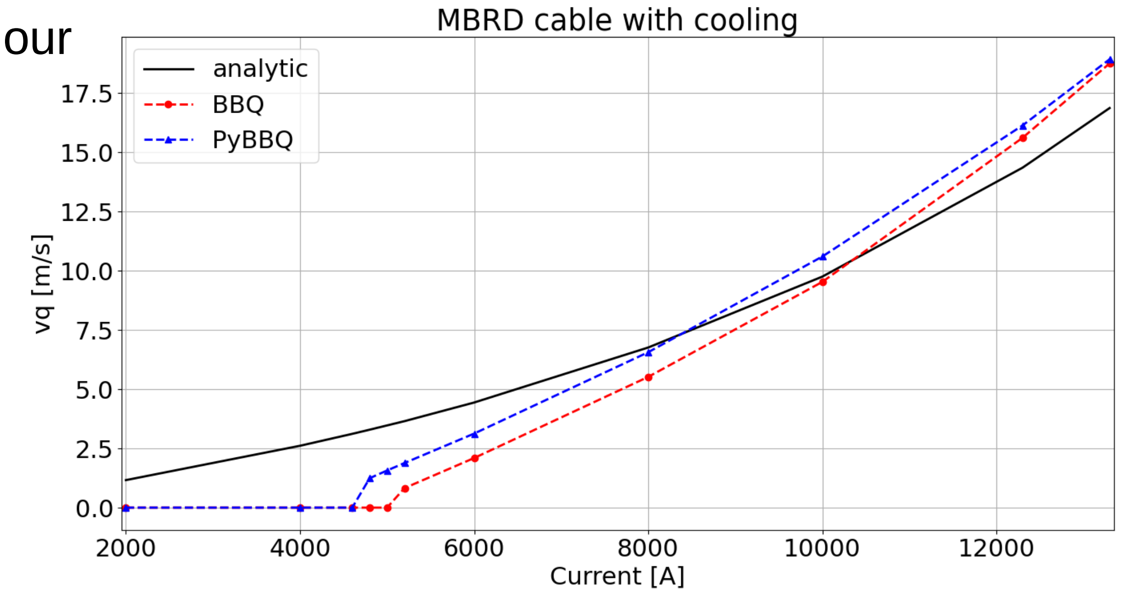


[4] **T. Mulder,** "Documentation", Available: STEAM / steam-pyBBQ · GitLab (cern.ch)

Validation of PyBBQ



- Comparison to STEAM-LEDET 3D and STEAM-BBQ [5], [6]
- Good fit for basic case without insulation and cooling
- Analytical calculation not applicable, further investigations necessary
- STEAM-PyBBQ and STEAM-BBQ show similar behaviour for multi-strand cable and cooling



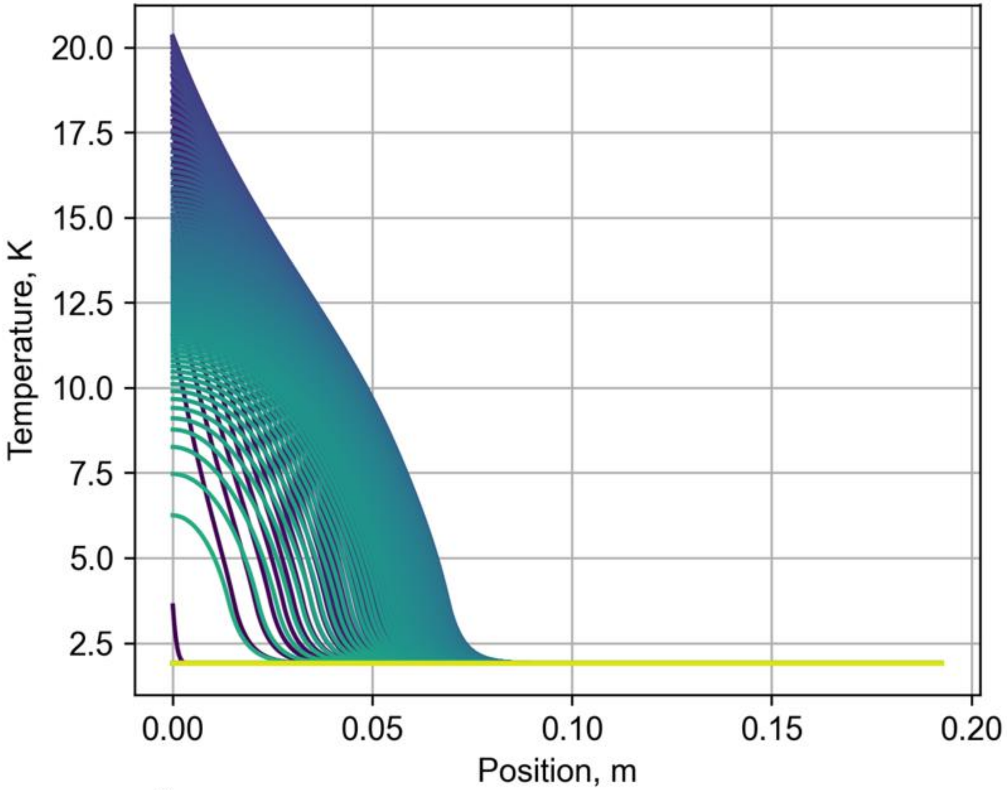
➢ STEAM-PyBBQ can be seen as validated

[5] **E. Ravaioli, O. Tranum Arnegaard, A. Verweij, M. Wozniak,** "Quench Transient Simulation in a Self-Protected Magnet With a 3-D Finite-Difference Scheme", IEEE Trans. on Appl. SC, 2022.

[6] **M. Mentink et al.,** "Quench Behavior of the HL-LHC Twin Aperture Orbit Correctors", IEEE Trans. on Appl. Supercond. 28, p 4004806 (2018)

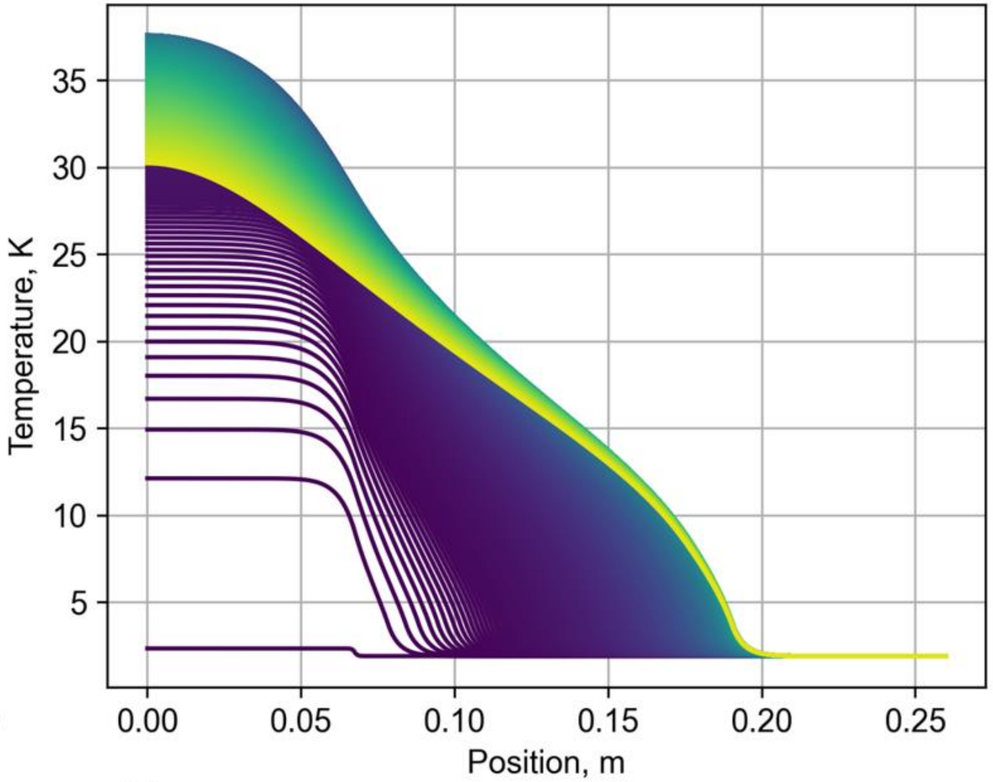
QH heating stations in STEAM-PyBBQ

- No quench propagation simulated by STEAM-PyBBQ for low current



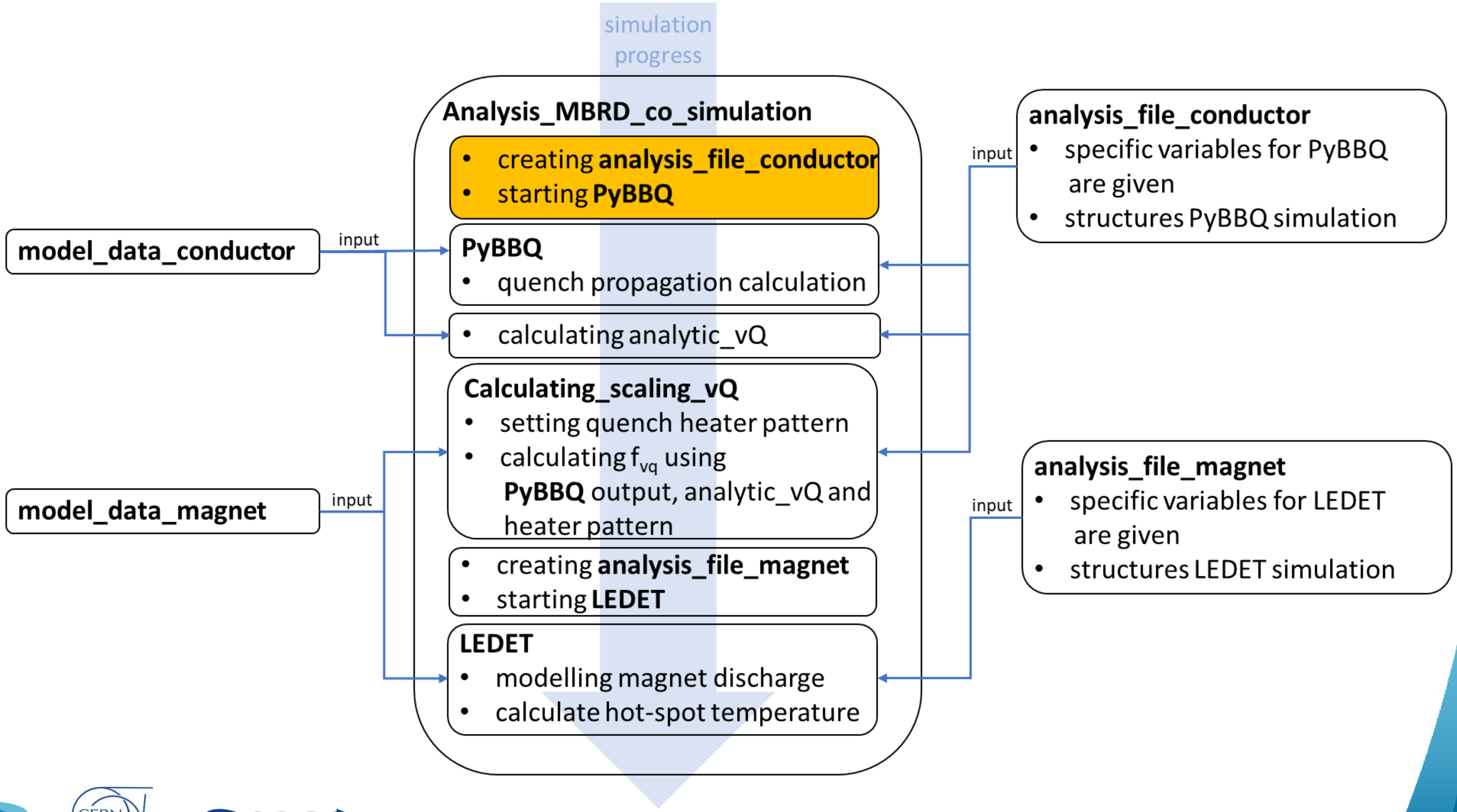
a)

- Implementing a heating station leads to detectable quench propagation in the cable at low current

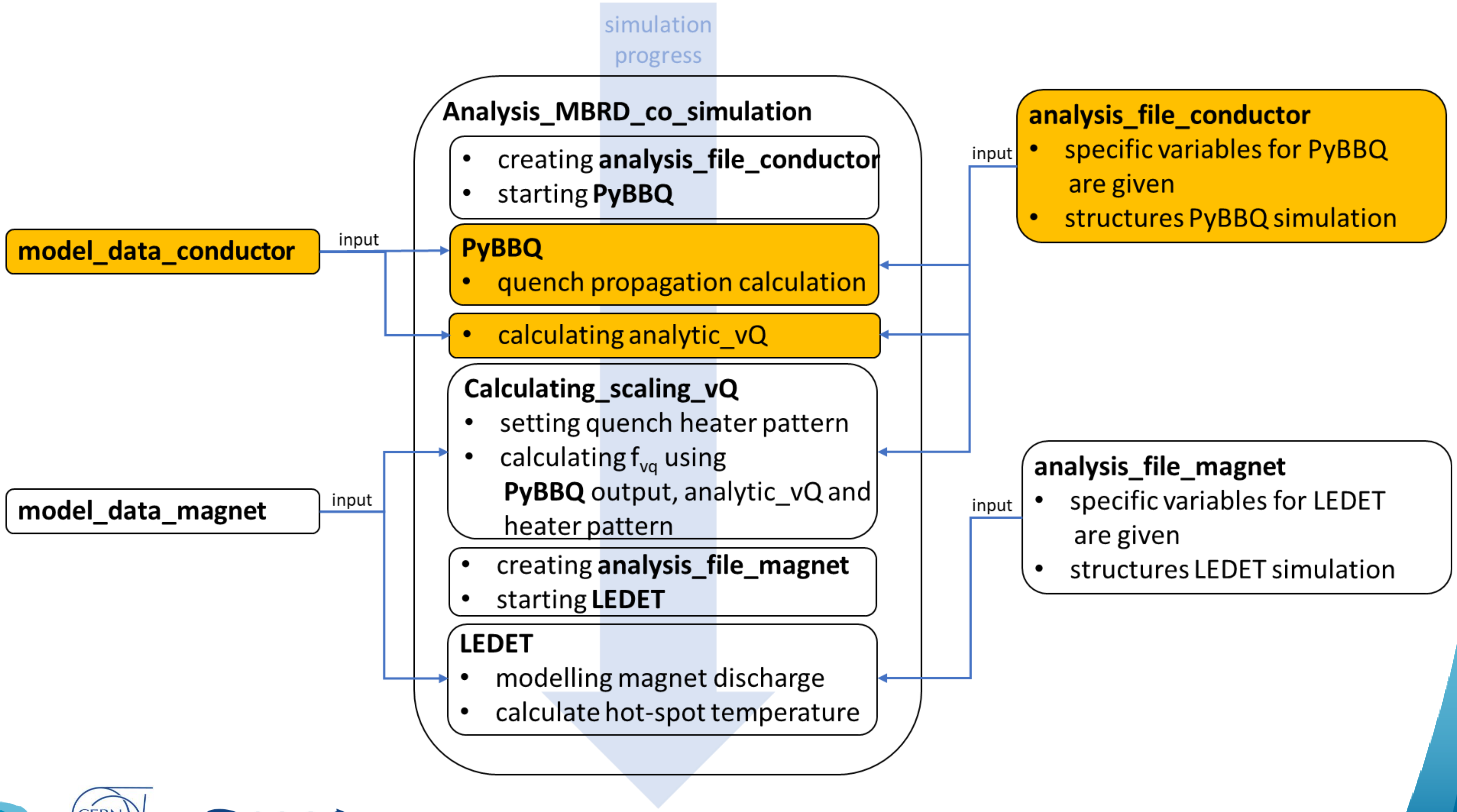


b)

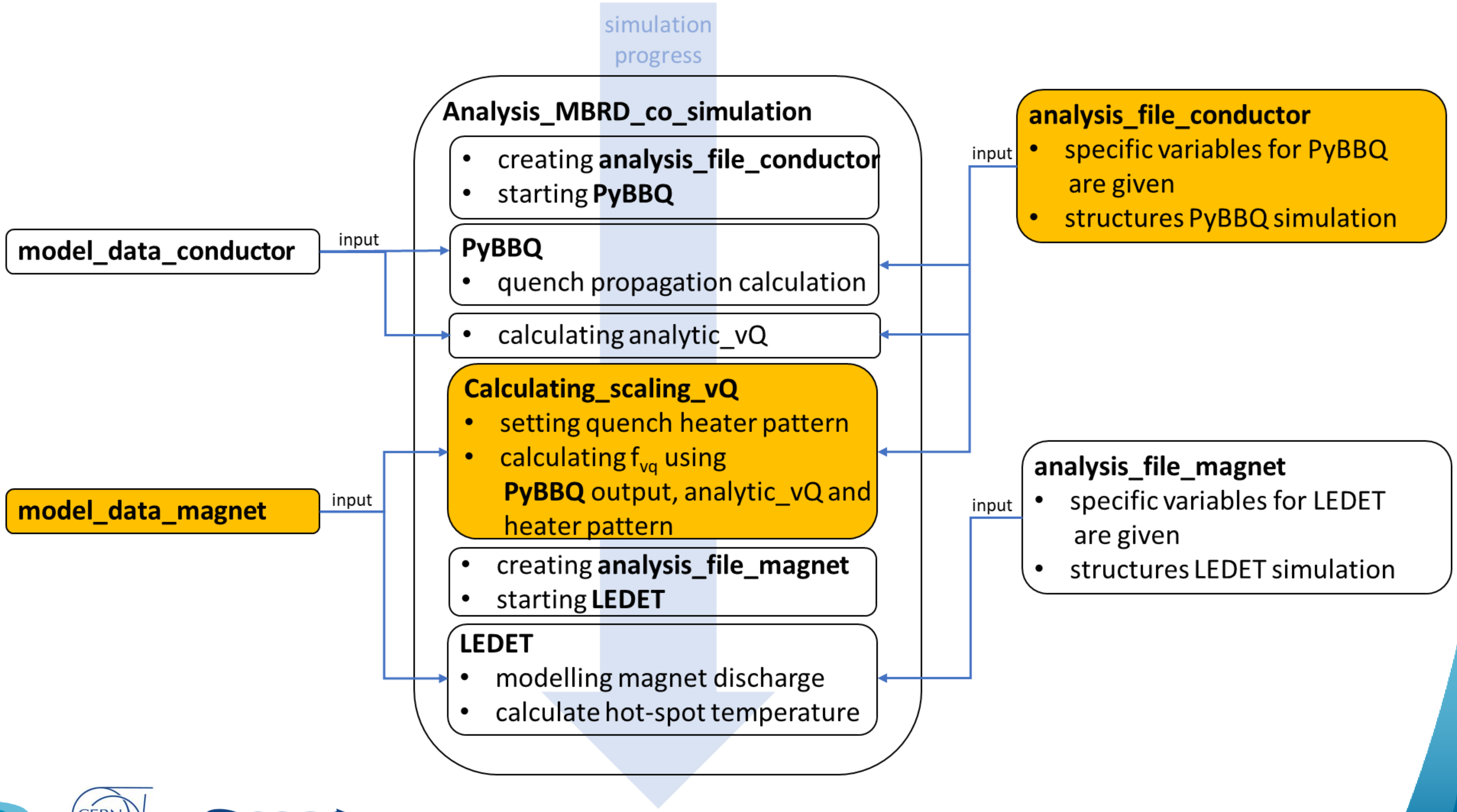
Co-simulation; setting conductor simulation



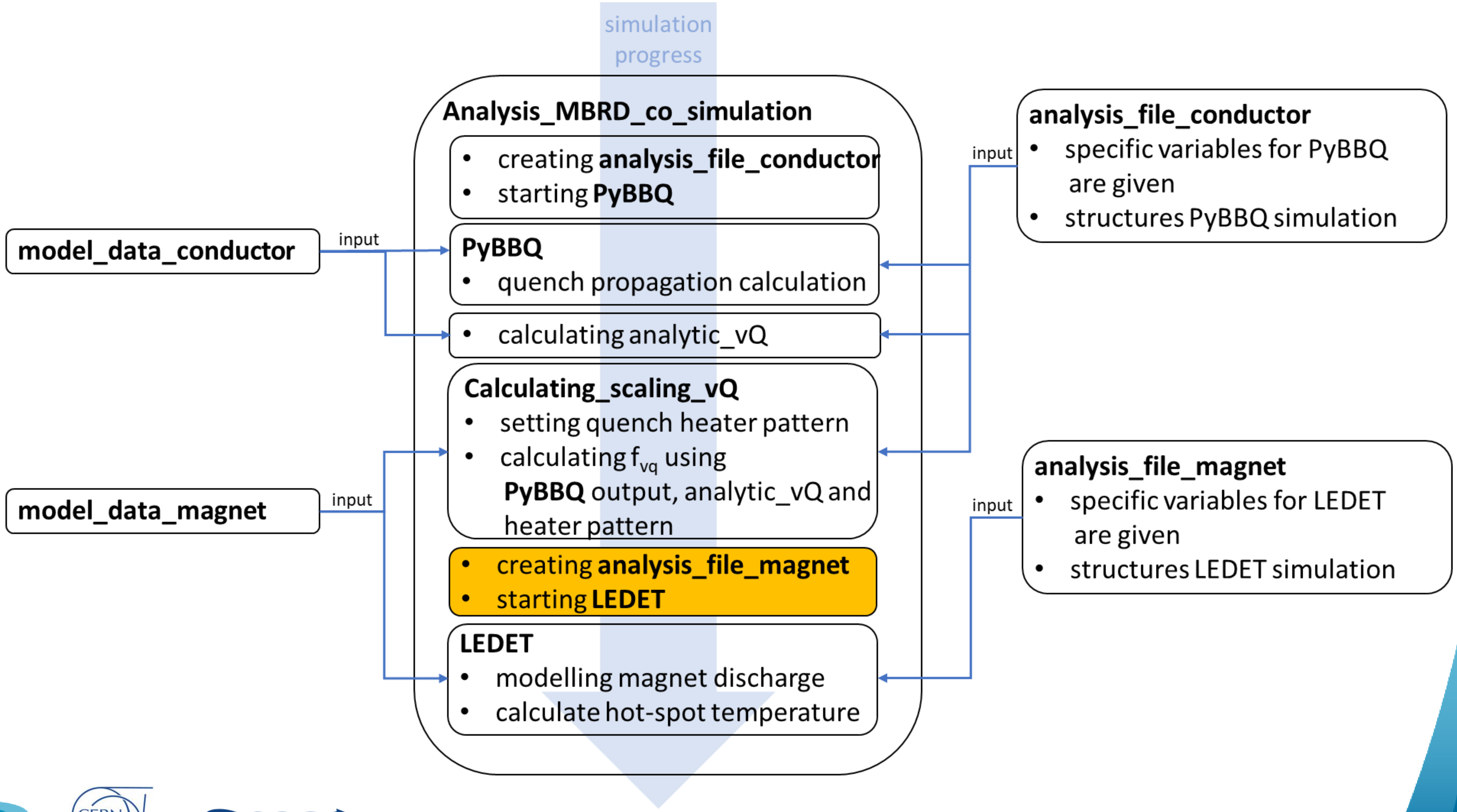
Co-simulation; running conductor simulation



Co-simulation; calculating quench propagation scaling

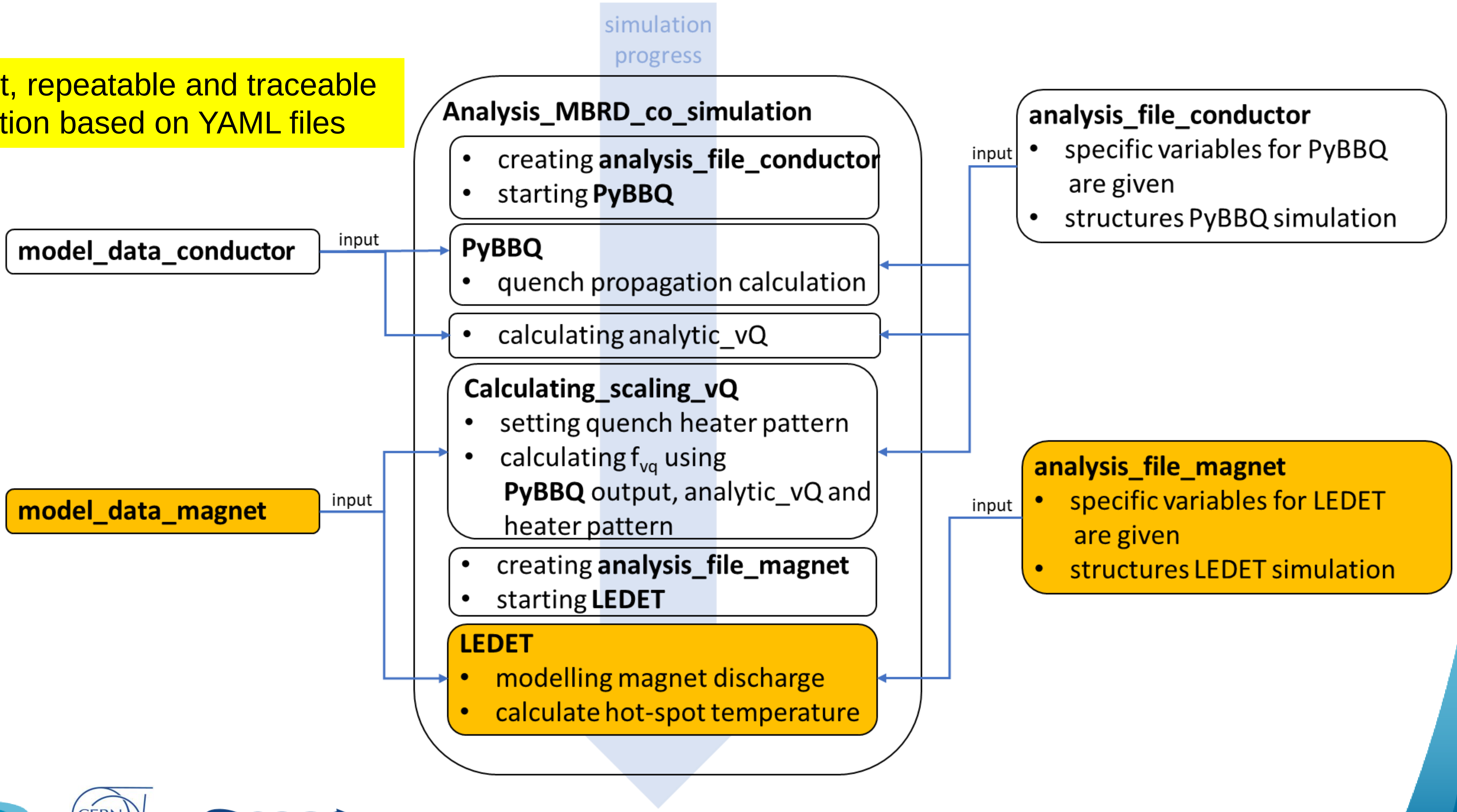


Co-simulation; setting magnet simulation



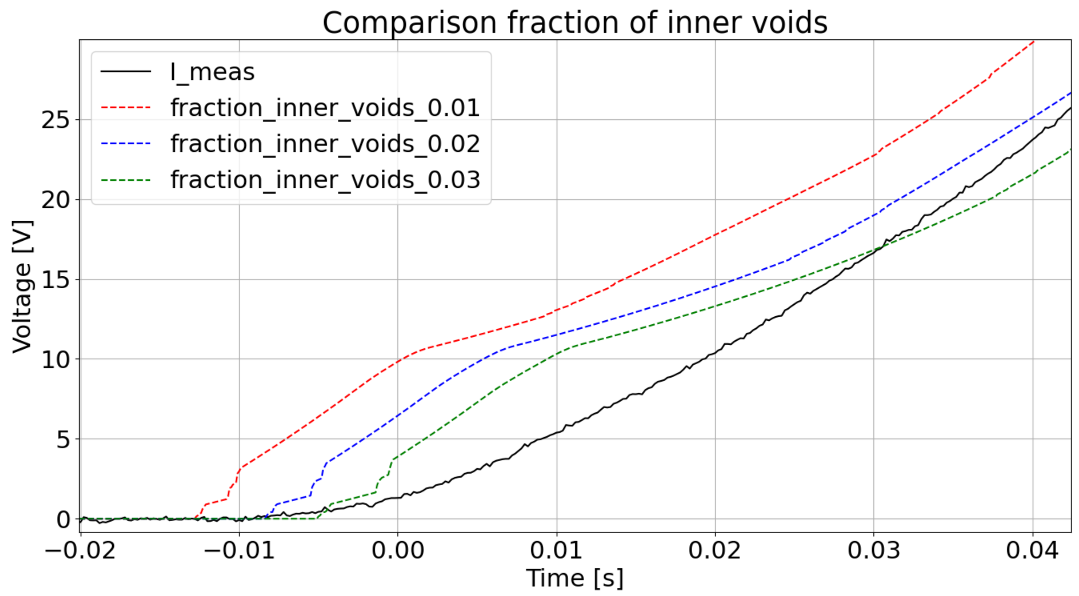
Co-simulation; running magnet simulation

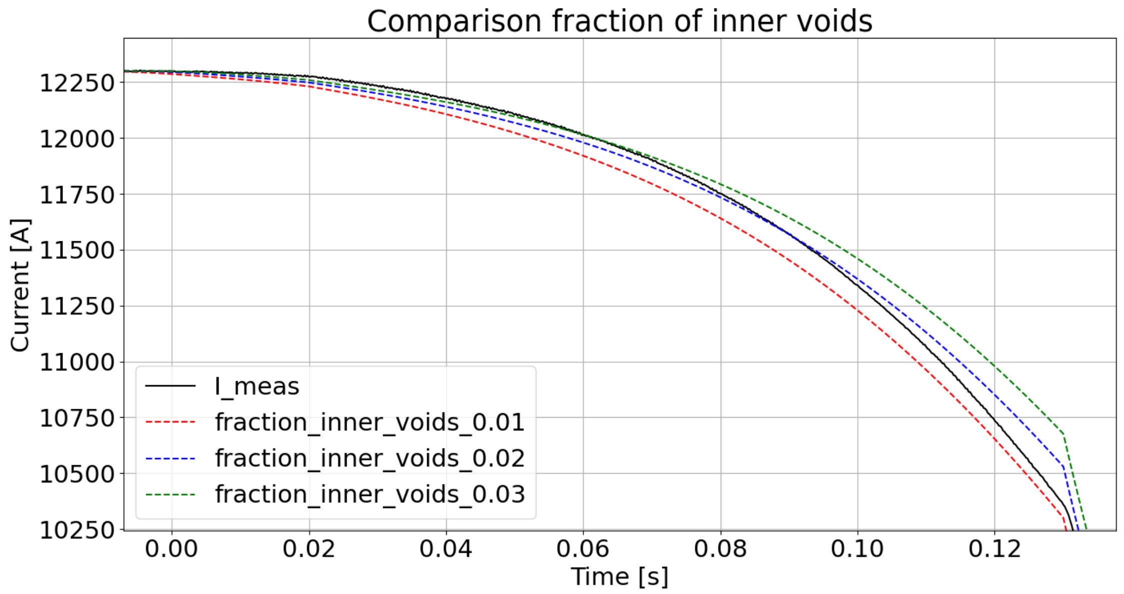
➢ Consistent, repeatable and traceable co-simulation based on YAML files



Quench start at high current

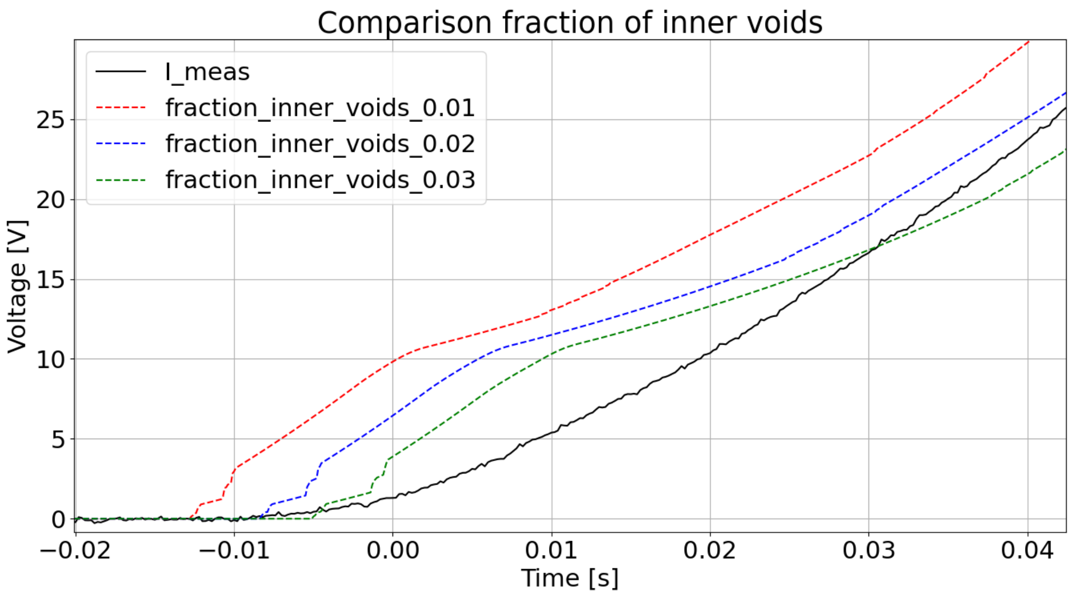
- Variation of the amount of helium inside the cable
- Voltage jumps caused by quench heaters
- Manipulation of heater contact to strands possible

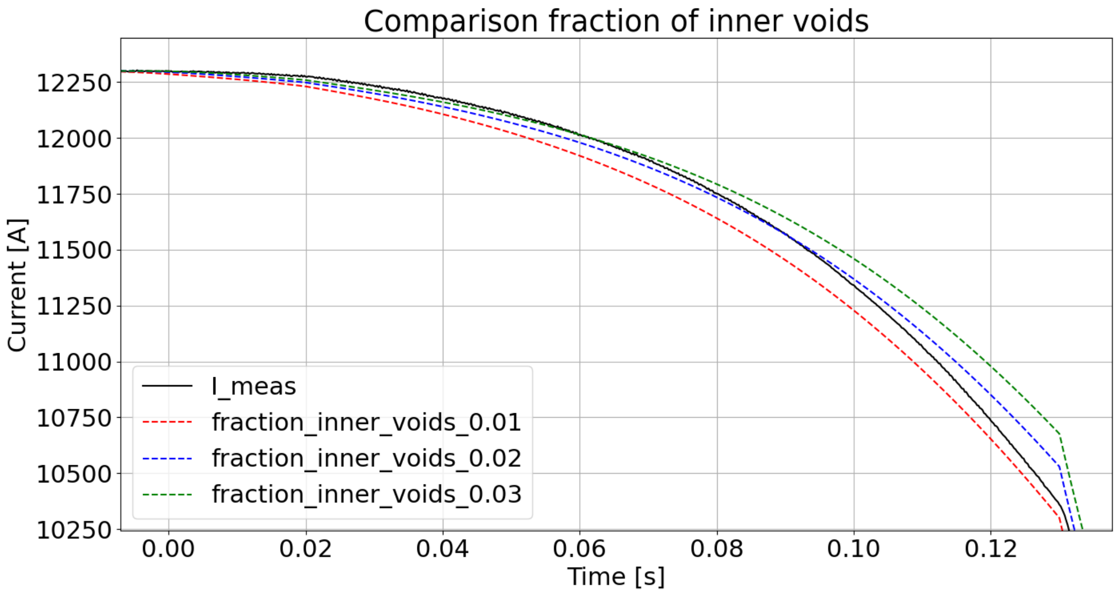




Quench start at high current

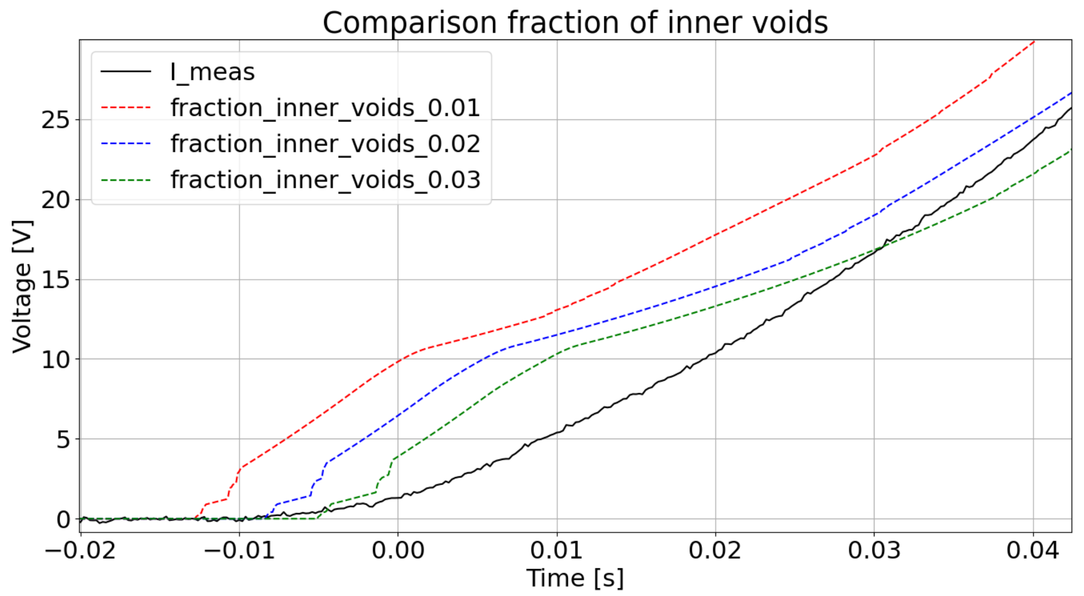
- Variation of the amount of helium inside the cable
- Voltage jumps caused by quench heaters
- Manipulation of heater contact to strands possible
- Matching quench start for fraction_inner_voids at 2 %
- Best fitting discharge at fraction_inner_voids = 2 %
- Faster discharge at quench start, slower discharge before energy extraction triggering

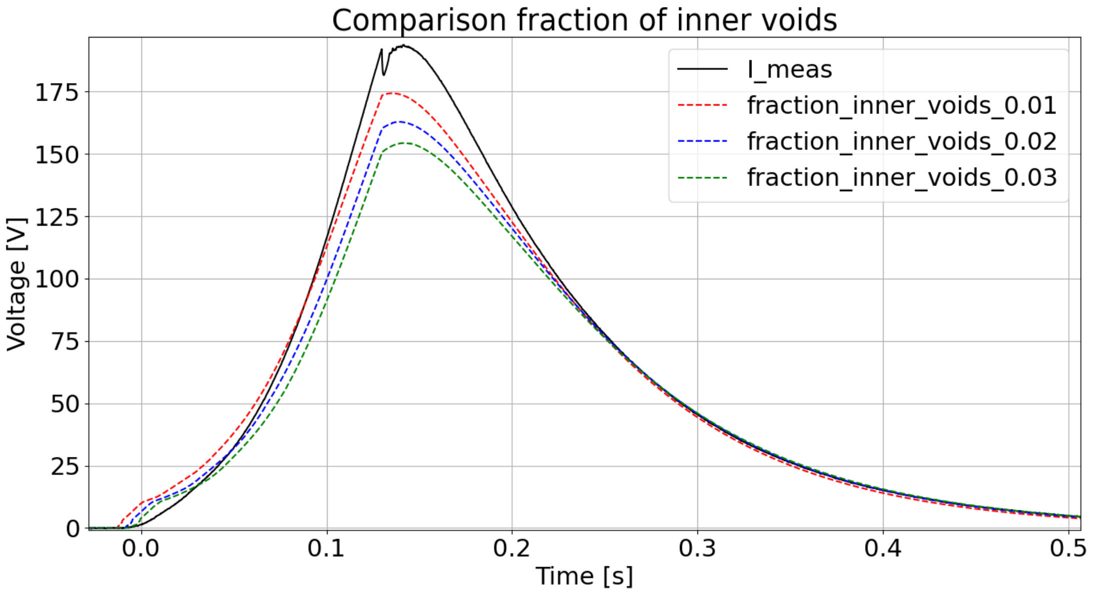




Behaviour of differential voltage

- Variation of the amount of helium inside the cable
- Voltage jumps caused by quench heaters
- Manipulation of heater contact to strands possible
- Matching quench start for fraction_inner_voids at 2 %
- Best fitting discharge at fraction_inner_voids = 2 %
- Faster discharge at quench start, slower discharge before energy extraction triggering
- Similar behaviour visible in global differential voltage



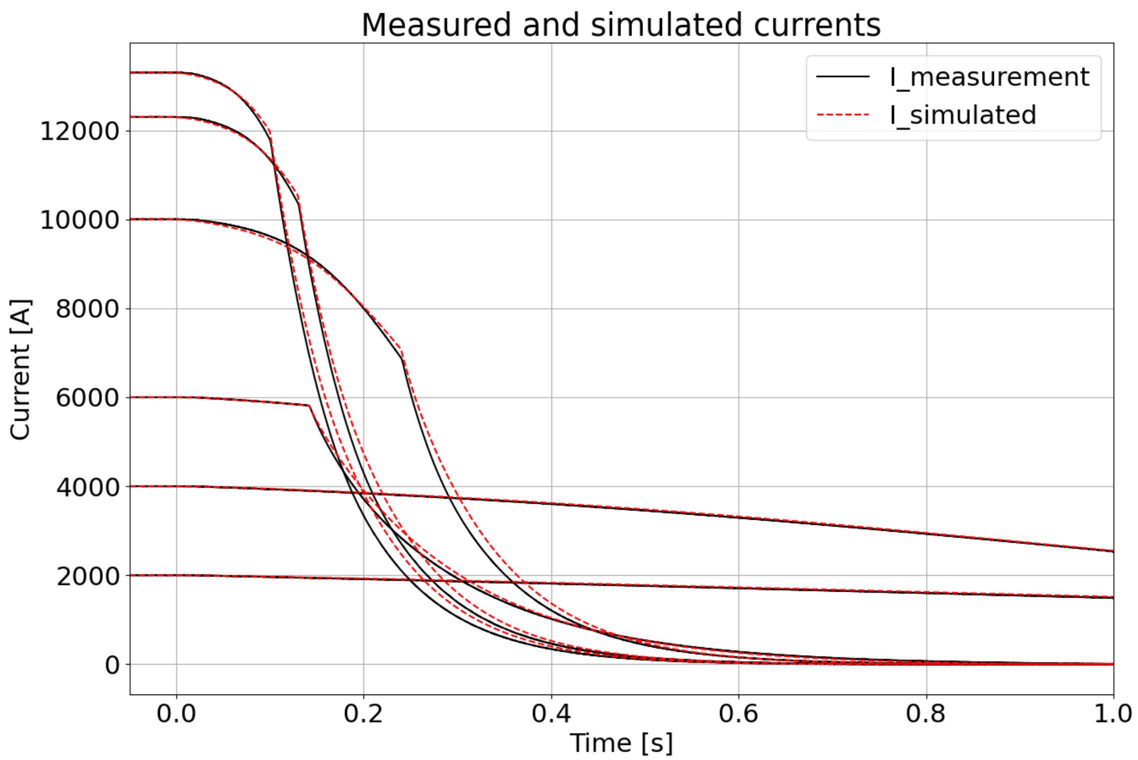


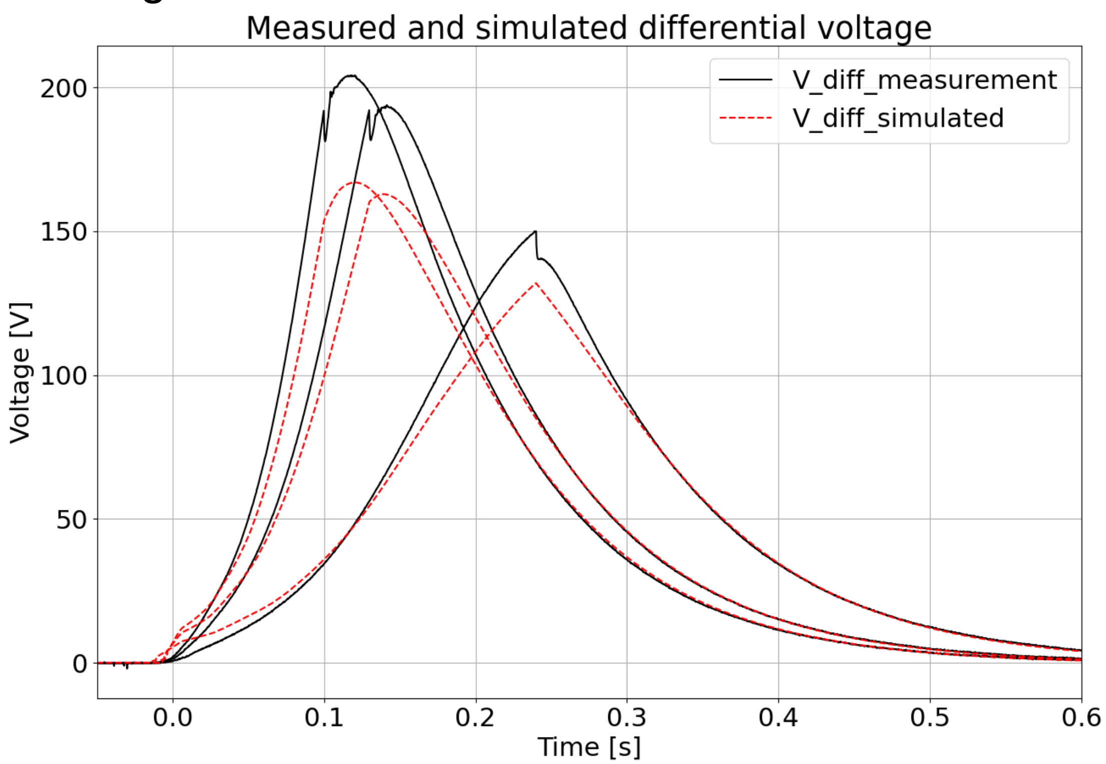
Simulation results of the MBRD

➢ Validated STEAM-LEDET model of the MBRD magnet

- Using the 2D+1D option including quench propagation between heating stations and to turns that are not yet quenched
- Typical RMS error divided by peak value: 1 % for the current and 2-10 % for the voltage

High current:





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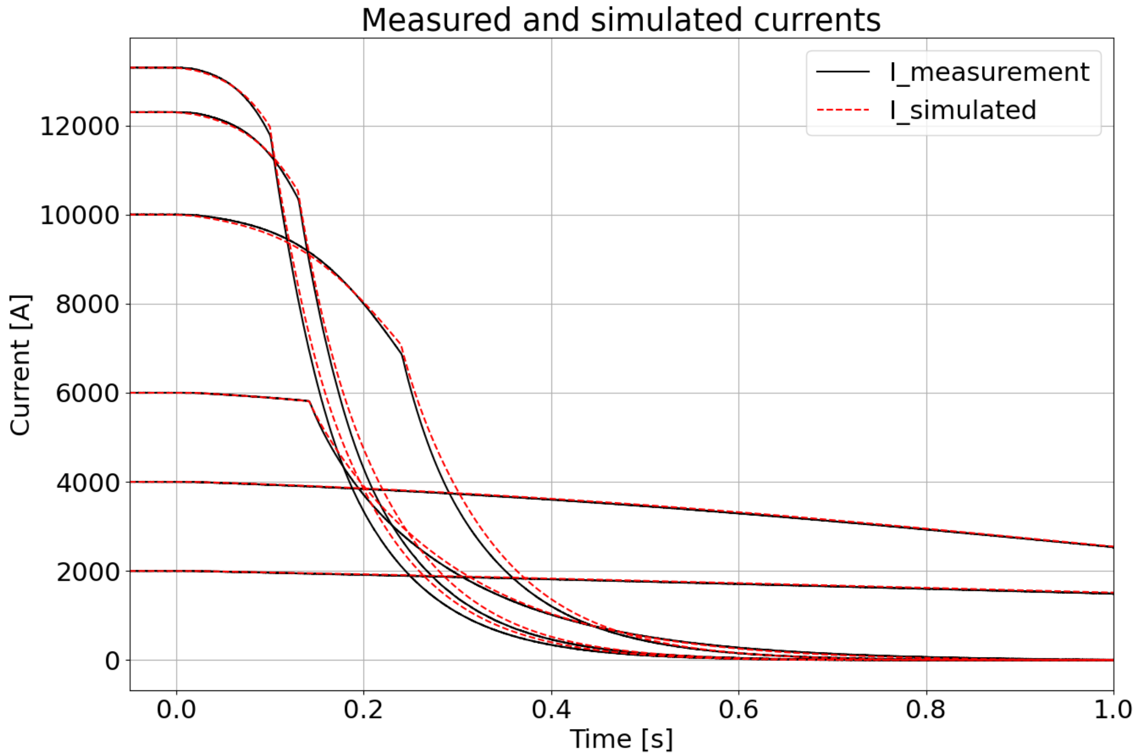
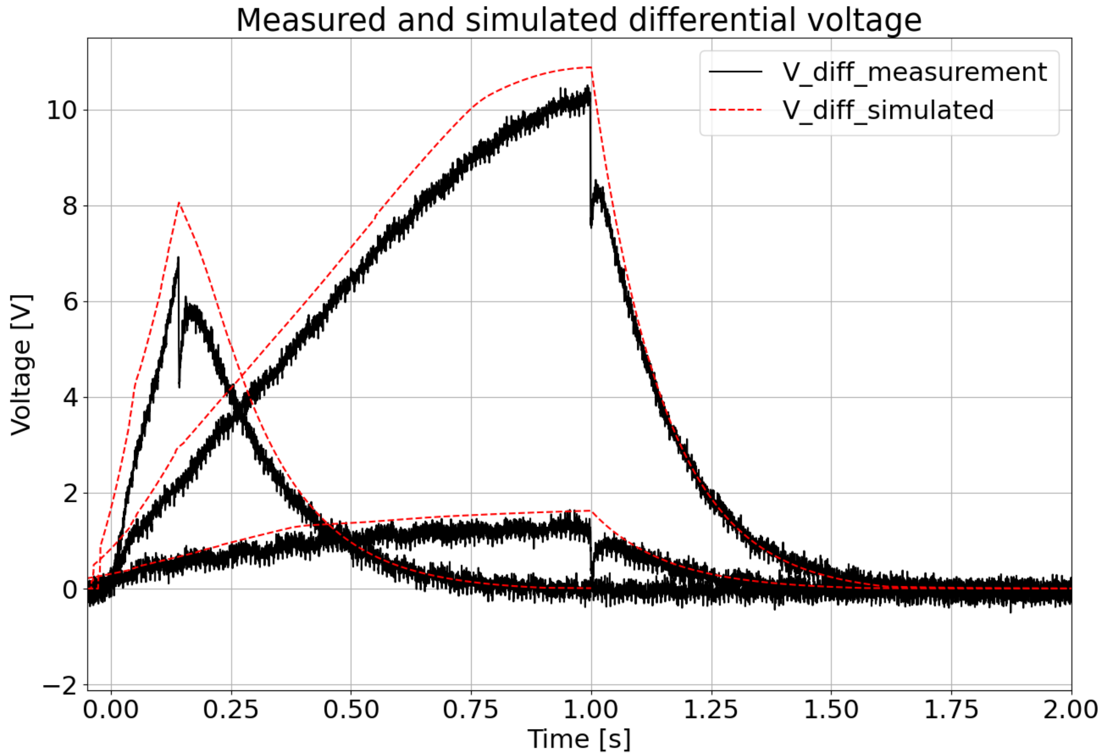


Low current:



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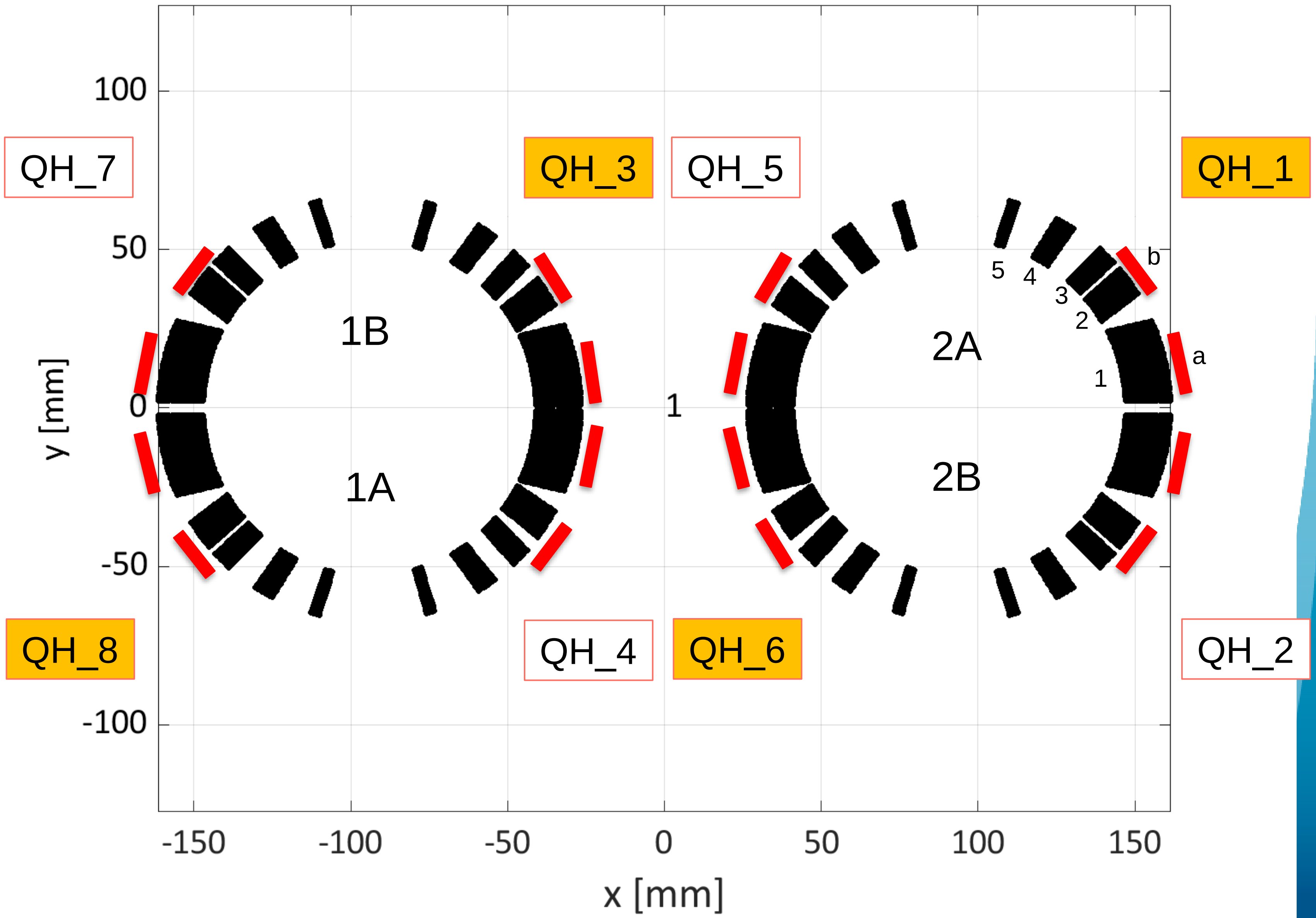
MBRD prototype; Baseline

Baseline:

Case	QH firing
Nominal	QH_1; QH_3; QH_6; QH_8
Ultimate	QH_1; QH_3; QH_6; QH_8
Failure 1	QH_1; QH_3; QH_6
Failure 2	QH_1; QH_3
Failure 3	QH_1; QH_6



MBRD prototype; Failure 1

Baseline:

Case	QH firing
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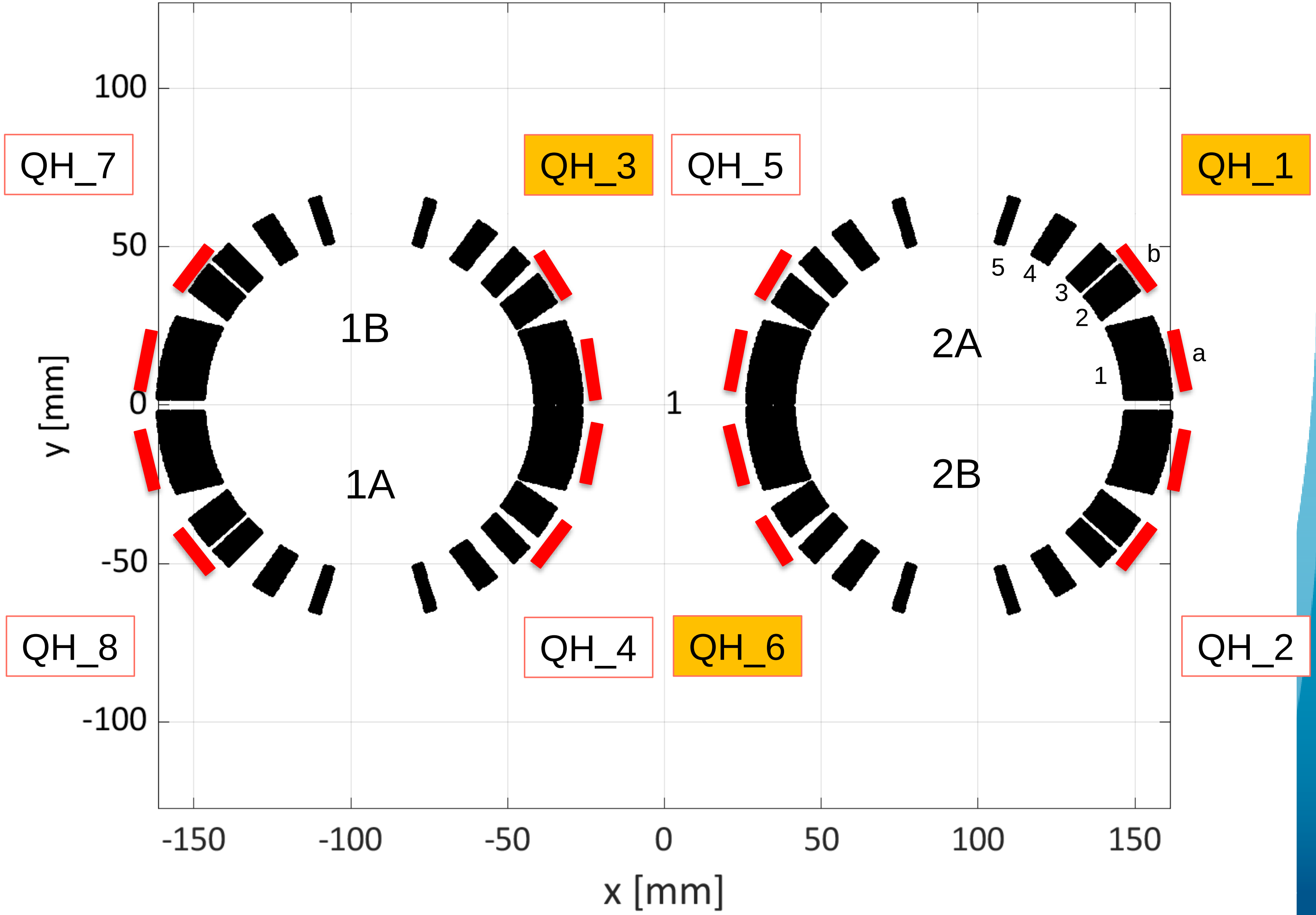
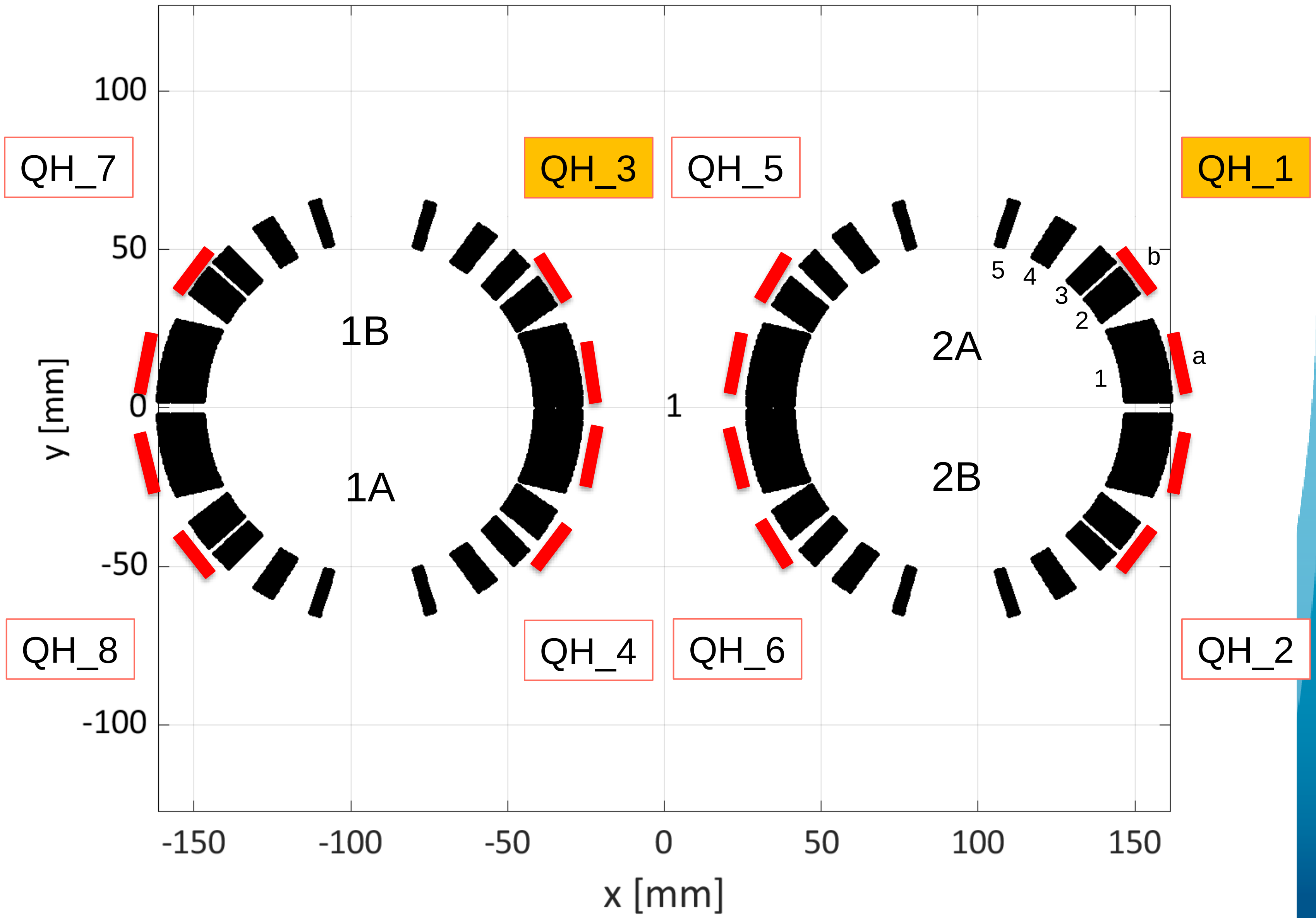
Ultimate	QH_1; QH_3; QH_6; QH_8
Failure 1	QH_1; QH_3; QH_6
Failure 2	QH_1; QH_3
Failure 3	QH_1; QH_6



MBRD prototype; Failure 2

Baseline:

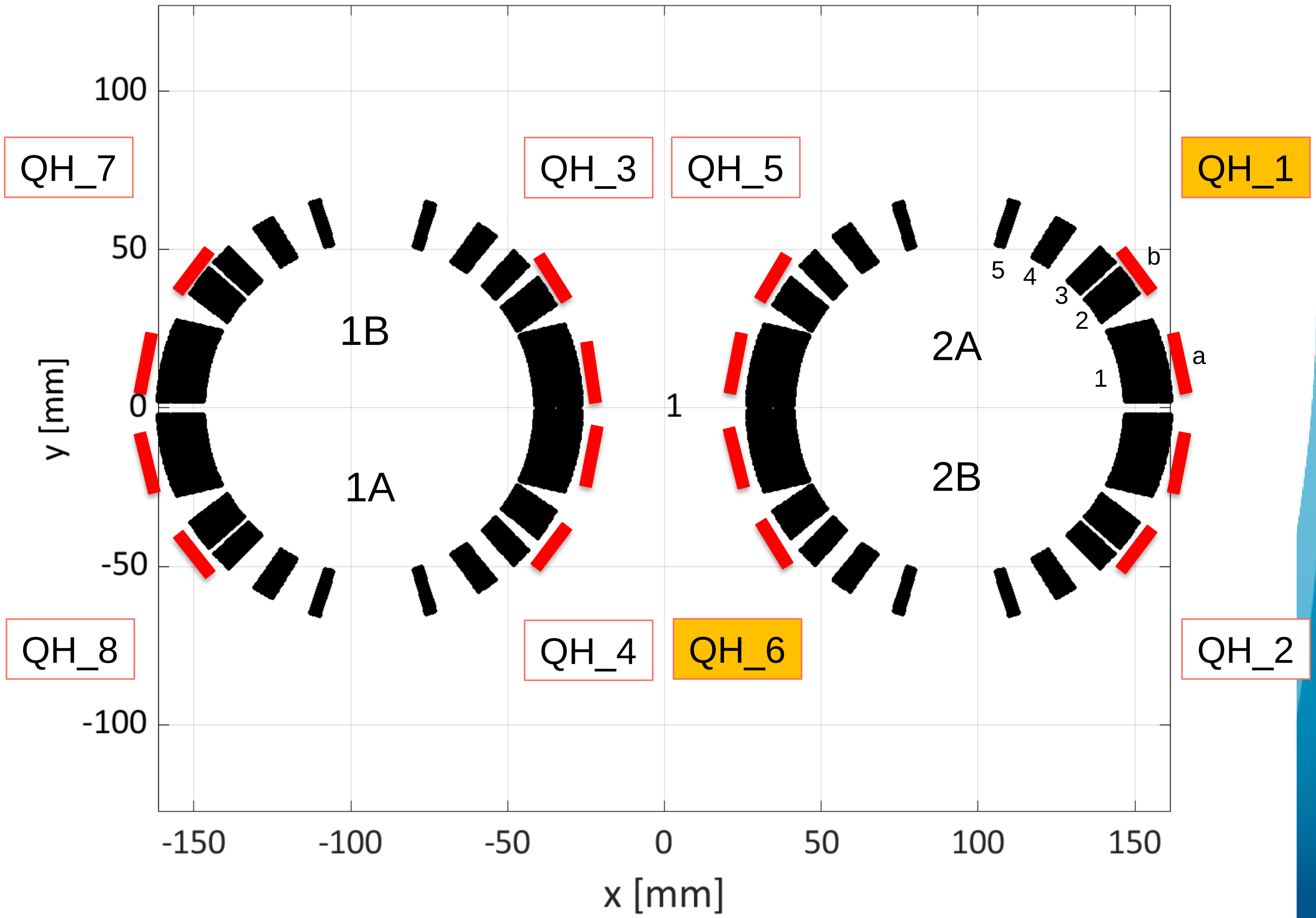
Case	QH firing
Nominal	QH_1; QH_3; QH_6; QH_8
Ultimate	QH_1; QH_3; QH_6; QH_8
Failure 1	QH_1; QH_3; QH_6
Failure 2	QH_1; QH_3
Failure 3	QH_1; QH_6



MBRD prototype; Failure 3

Baseline:

Case	QH firing
Nominal	QH_1; QH_3; QH_6; QH_8
Ultimate	QH_1; QH_3; QH_6; QH_8
Failure 1	QH_1; QH_3; QH_6
Failure 2	QH_1; QH_3
Failure 3	QH_1; QH_6



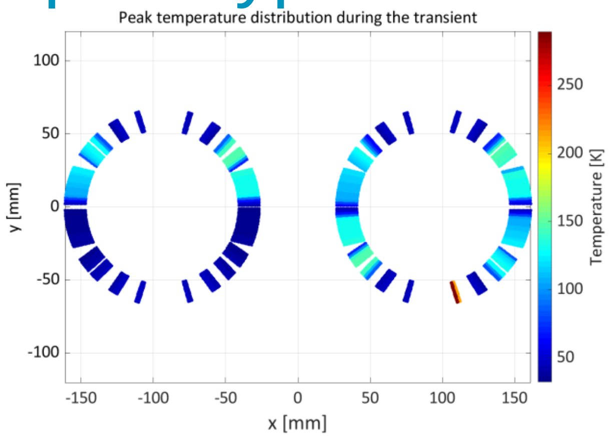
Simulation results of the MBRD prototype

- In the baseline 8 QH strips out of 16 are used
- Failure cases simulated at nominal current

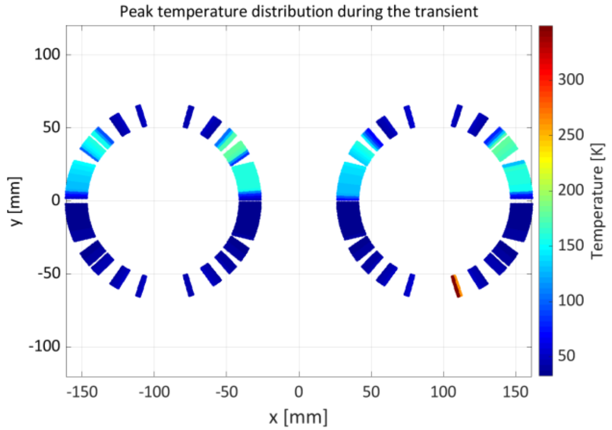
Case	T_adiabatic [K]	Peak voltage to ground [V]	Peak turn to turn voltage [V]
Nominal	292	76	48
Ultimate	348	95	64
Failure 1	336	303	56
Failure 2	410	335	70
Failure 3	410	713	70

→ T_adiabatic is calculated by assuming that a quench occurred 27 ms before the quench detection is triggered

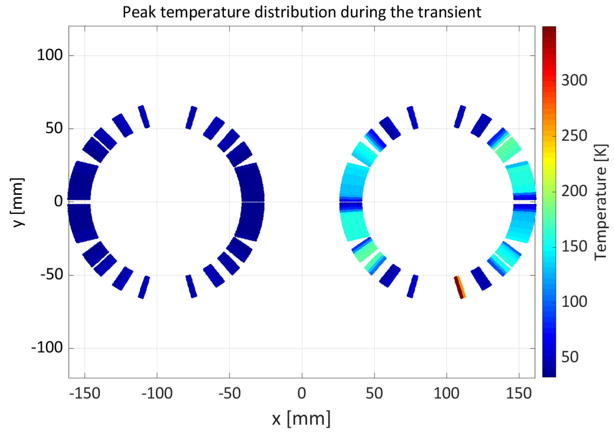
Failure 1



Failure 2



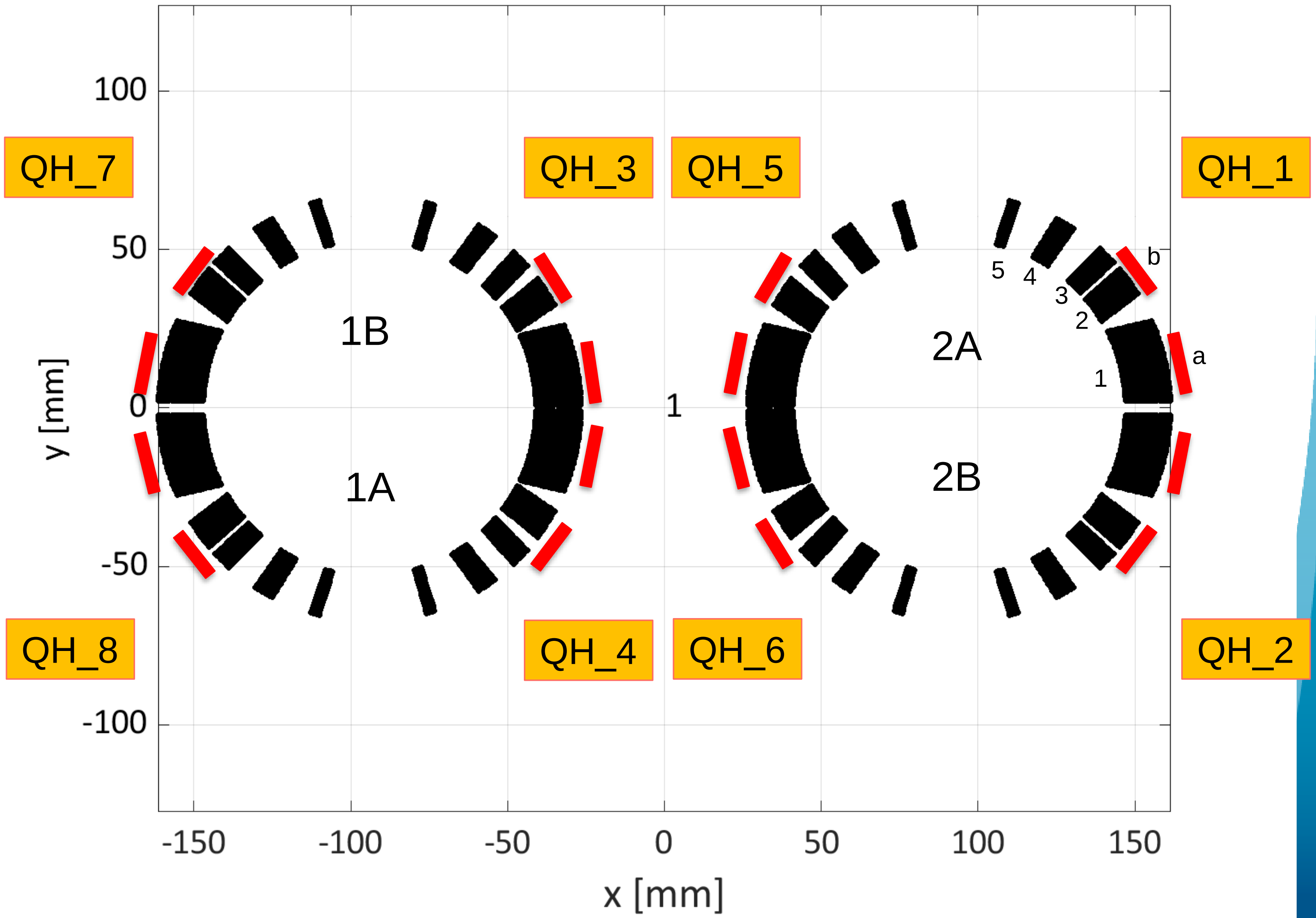
Failure 3



Alternative protection; Baseline

Alternative:

Case	QH firing
Nominal	QH_1-8
Ultimate	QH_1-8
Failure 1	QH_8 fails
Failure 2	QH_2; QH_6 failing
Failure 3	QH_3; QH_7 failing



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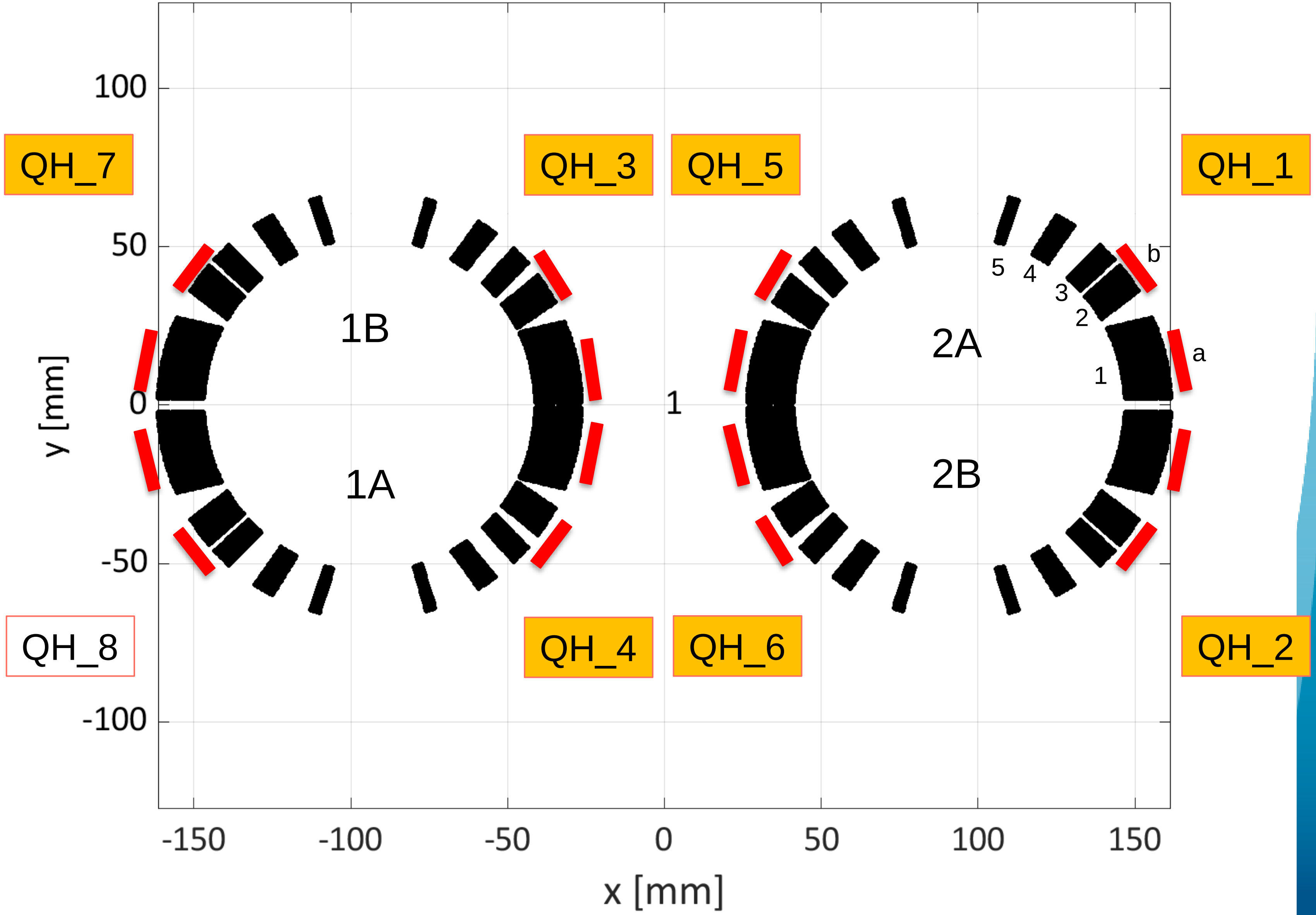

Alternative protection; Failure 2

Alternative:

Case	QH firing
Nominal	QH_1-8
Ultimate	QH_1-8
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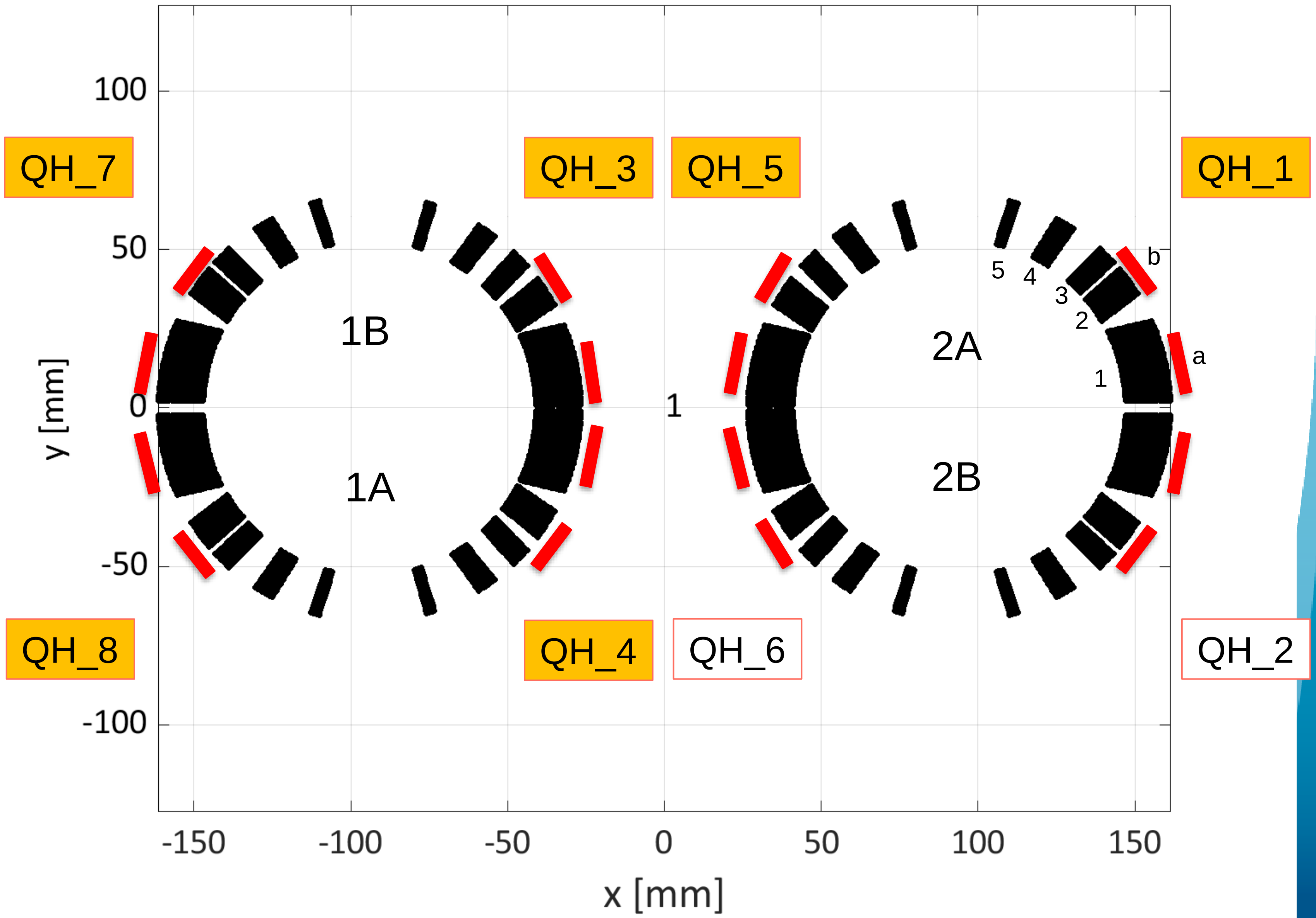

Alternative protection; Failure 3

Alternative:

Case	QH firing
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Ultimate	QH_1-8
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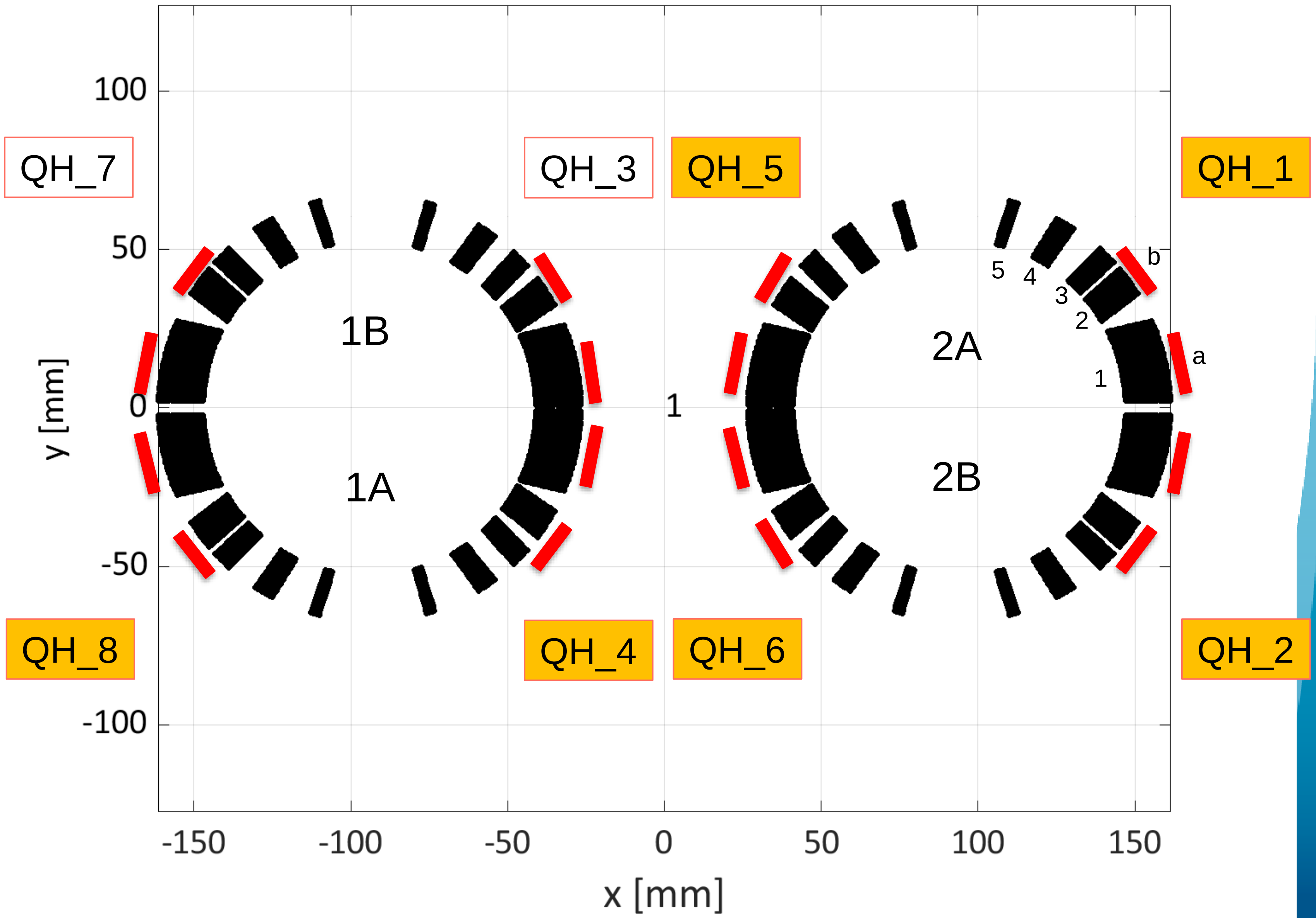
Failure 3	QH_3; QH_7 failing



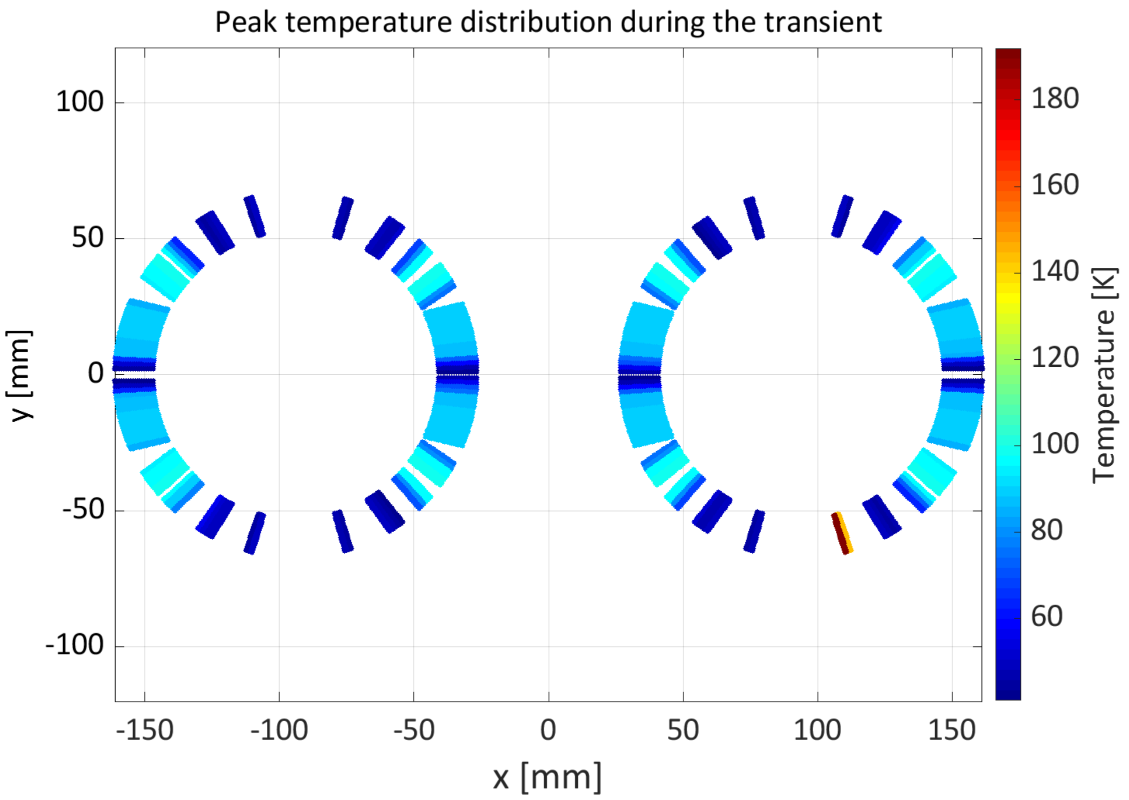
Alternative protection for the MBRD prototype

➢ Significant improvement of hot-spot temperature and voltage to ground

- Alternative: 16 QH strips out of 16 are used
- Failure cases simulated at nominal current

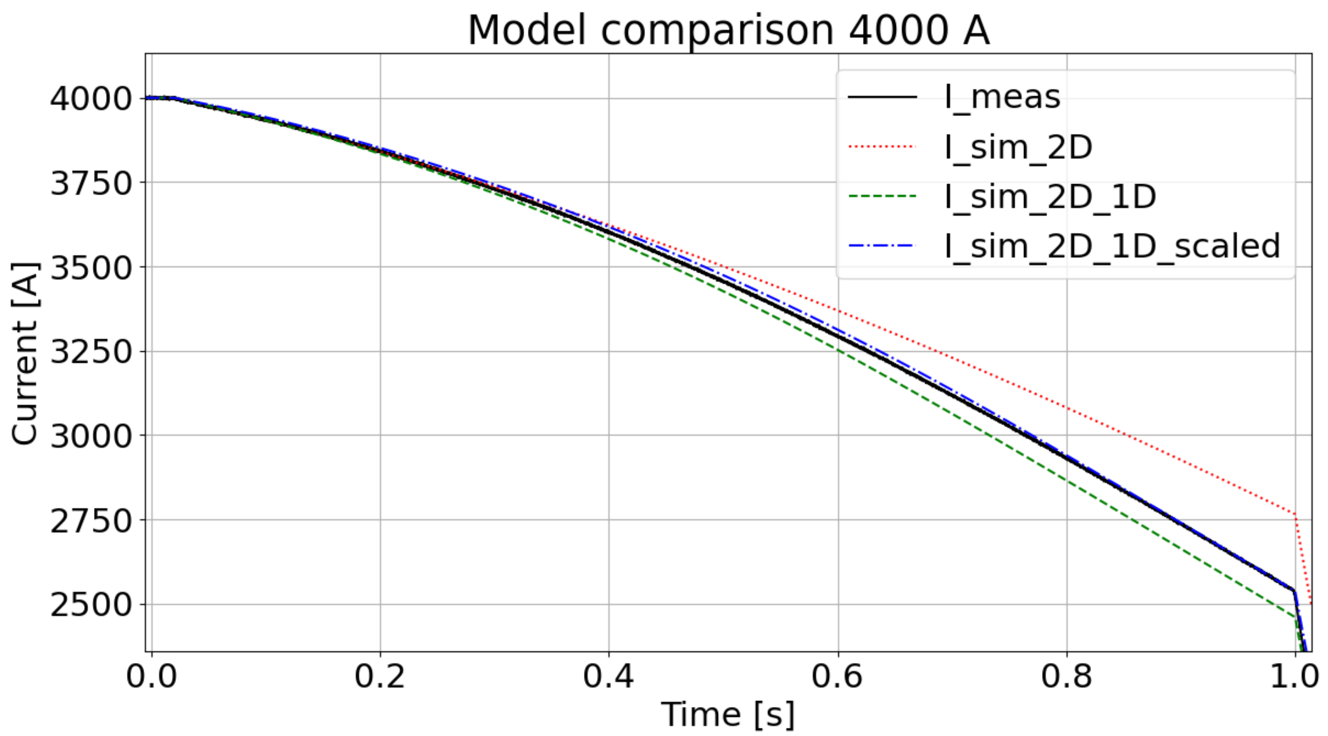
Case	T_adiabatic [K]		Peak voltage to ground [V]		Peak turn to turn voltage [V]	
	8/16	16/16	8/16	16/16	8/16	16/16
Nominal	292	**219**	76	**64**	48	**30**
Ultimate	348	**259**	95	**83**	64	**43**
Failure 1	336	**232**	303	**158**	56	**34**
Failure 2	410	**250**	335	**352**	70	**38**
Failure 3	410	**250**	713	**396**	70	**38**

→ T_adiabatic is calculated by assuming that a quench occurred 27 ms before the quench detection is triggered



Conclusion and lessons learned

- Simulation of QH discharges can be made more accurate, especially at low current, if the quench propagation between heating stations is included in the simulation



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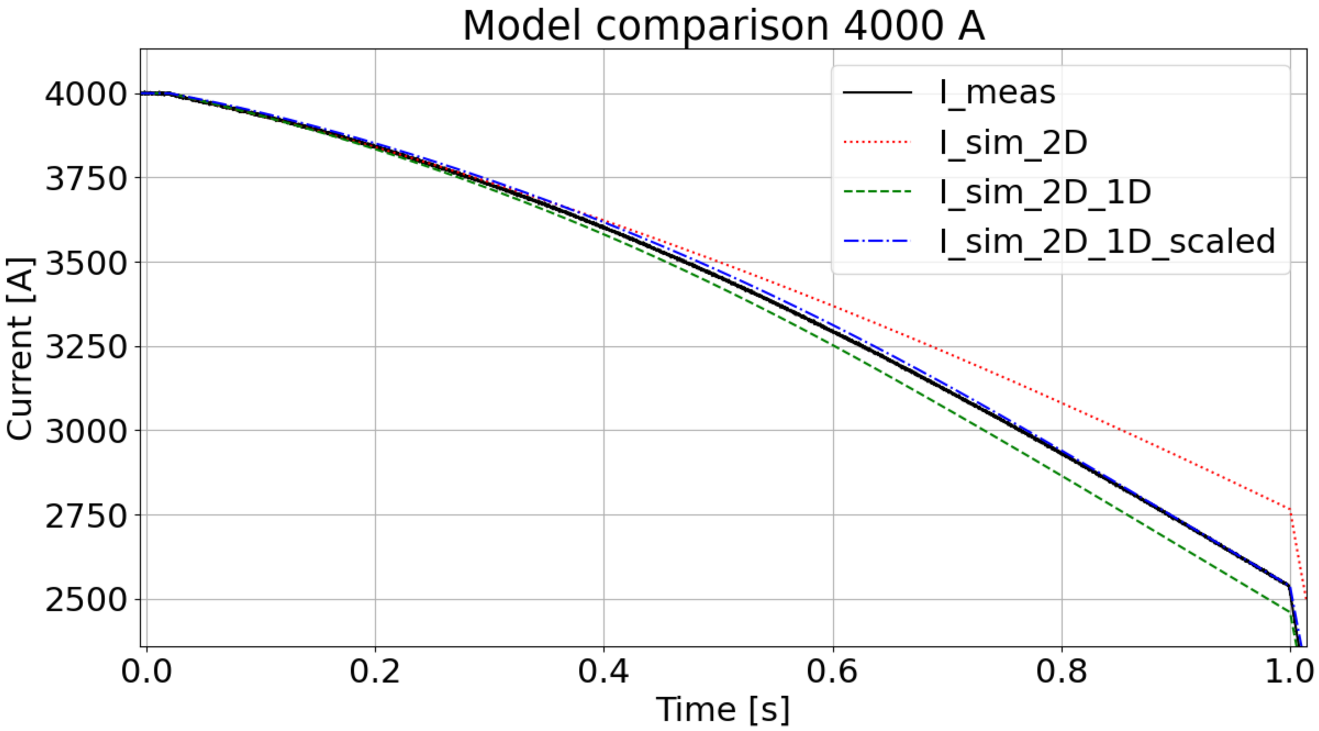

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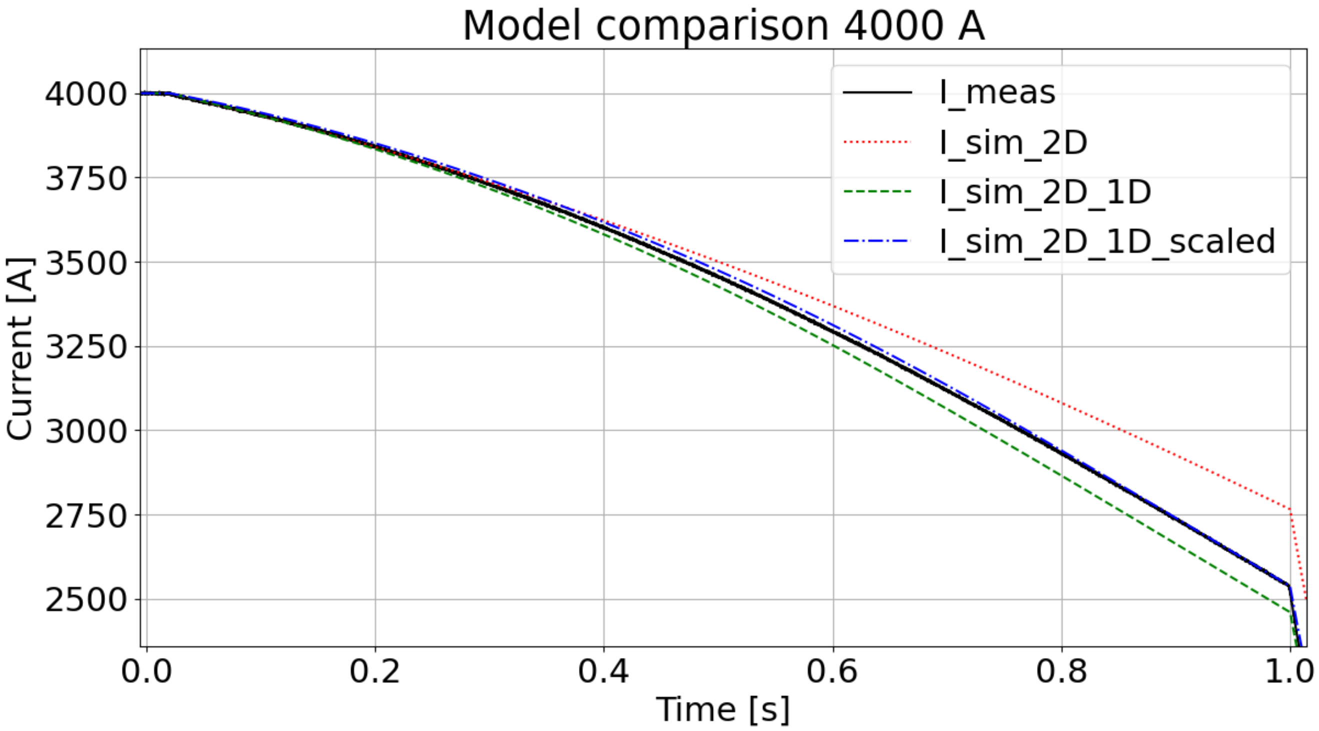

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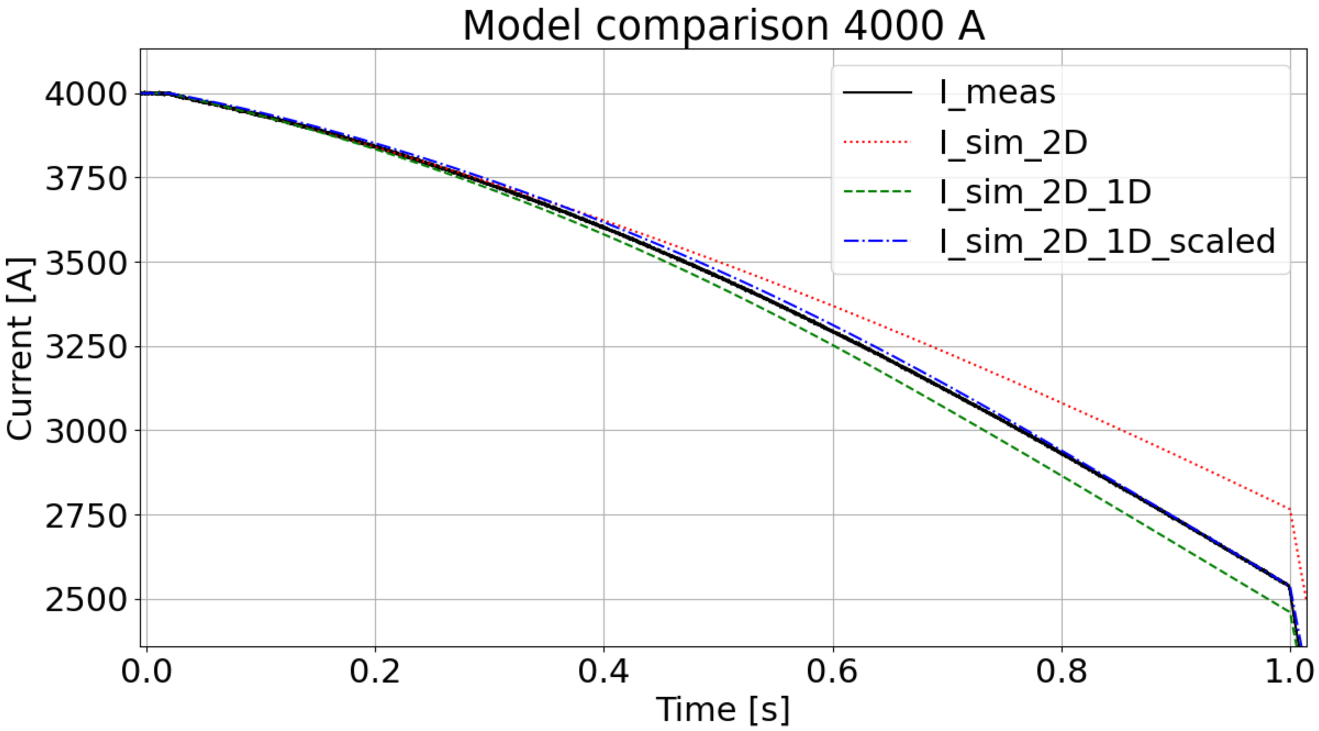
- HL-LHC MBRD STEAM-LEDET model validated against experimental results



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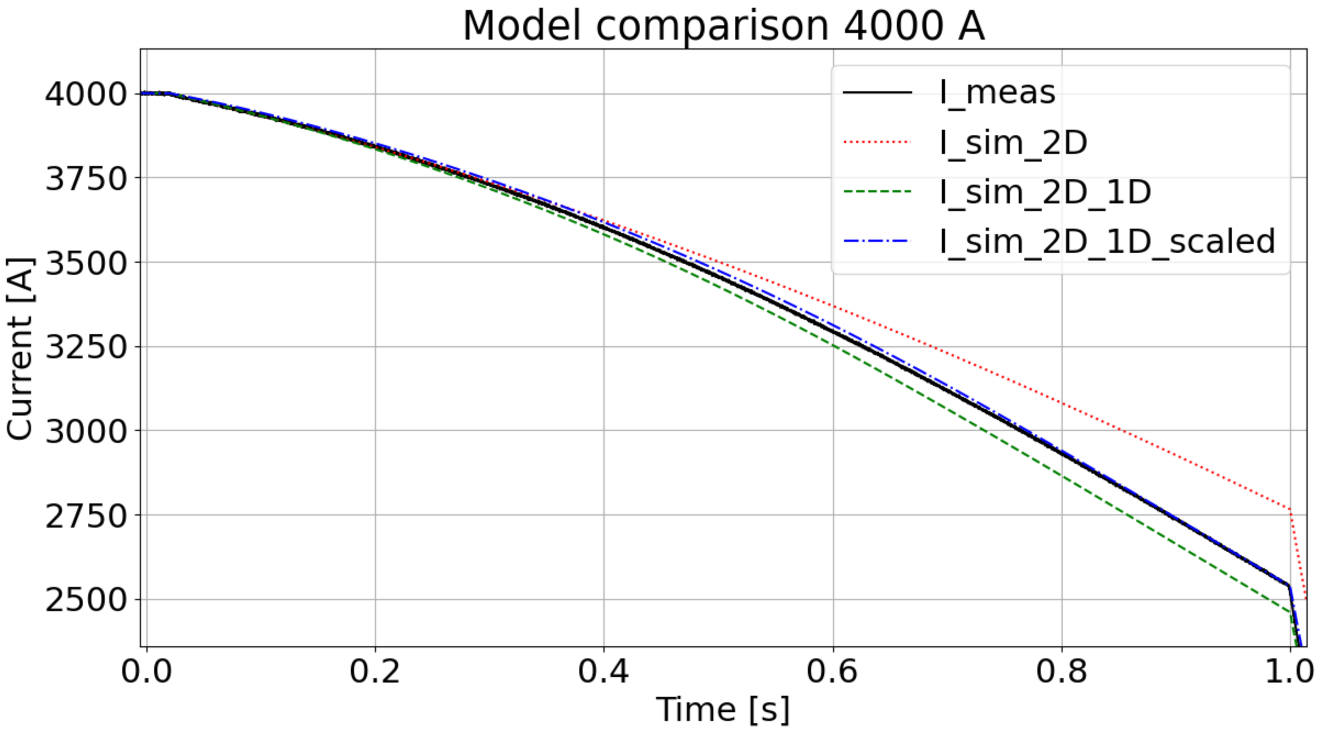
- Co-simulation analysis based on YAML files to be consistent, repeatable, versioned and traceable

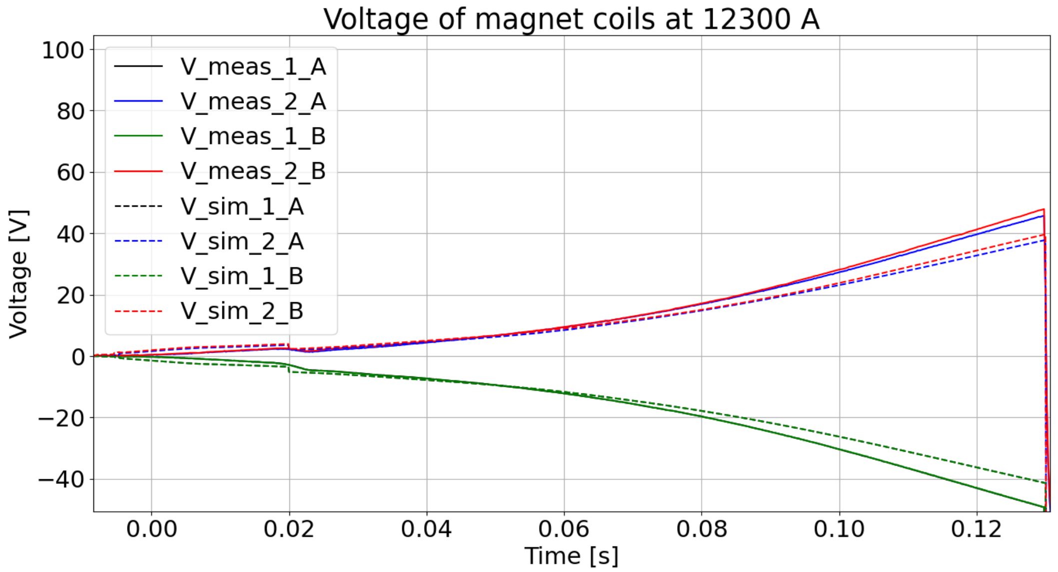
- HL-LHC MBRD STEAM-LEDET model validated against experimental results

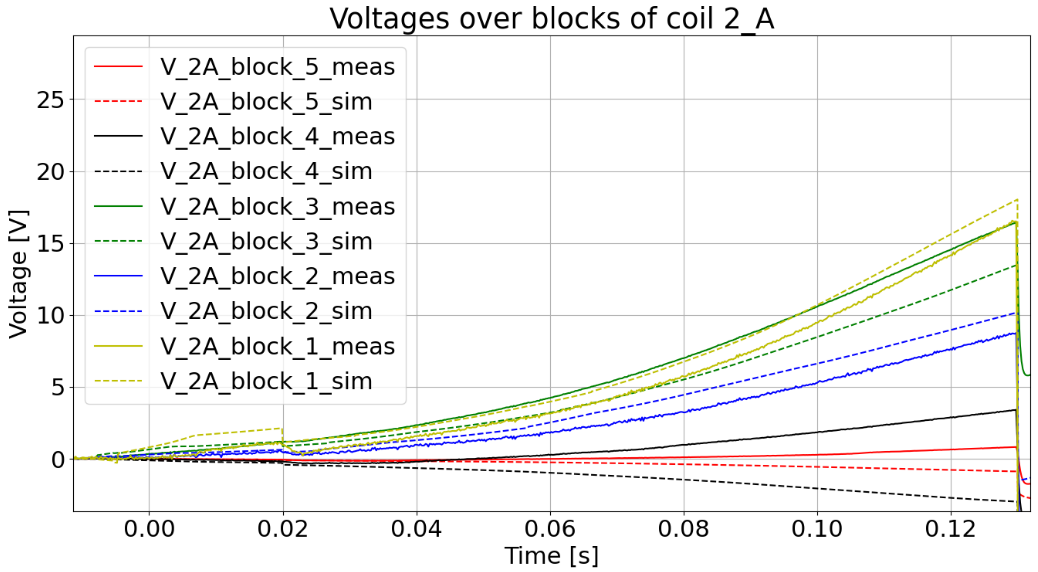


- Studied nominal and failure cases for the HL-LHC baseline case, and an alternative protection with double the QH units, which allows reducing the hot-spot temperature by 160 K and the peak voltage to ground by 44 %

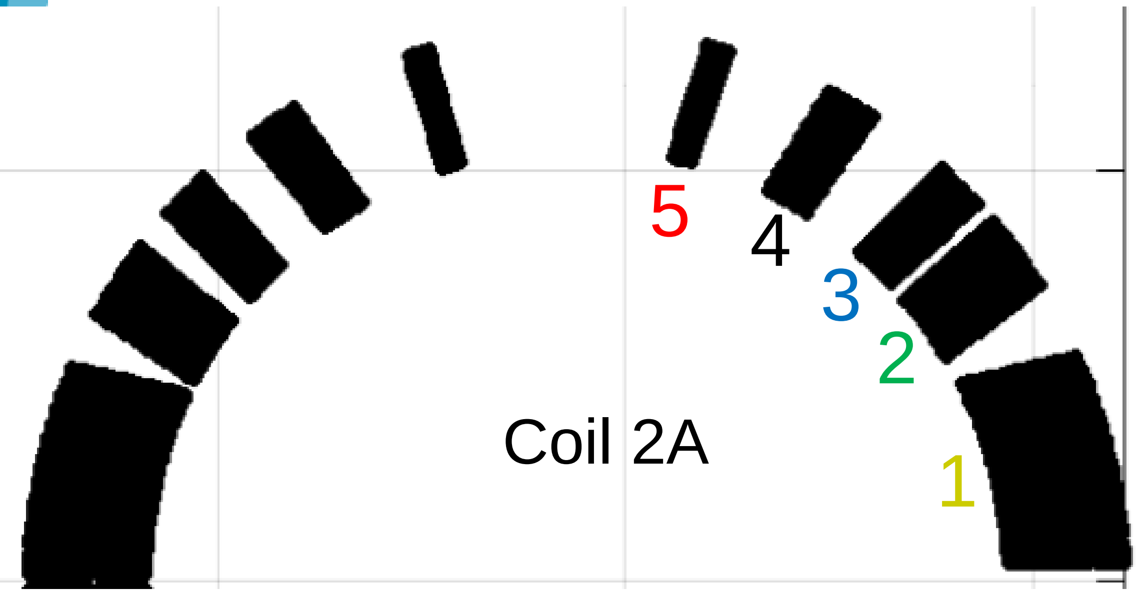
Annex: Coil and block voltages

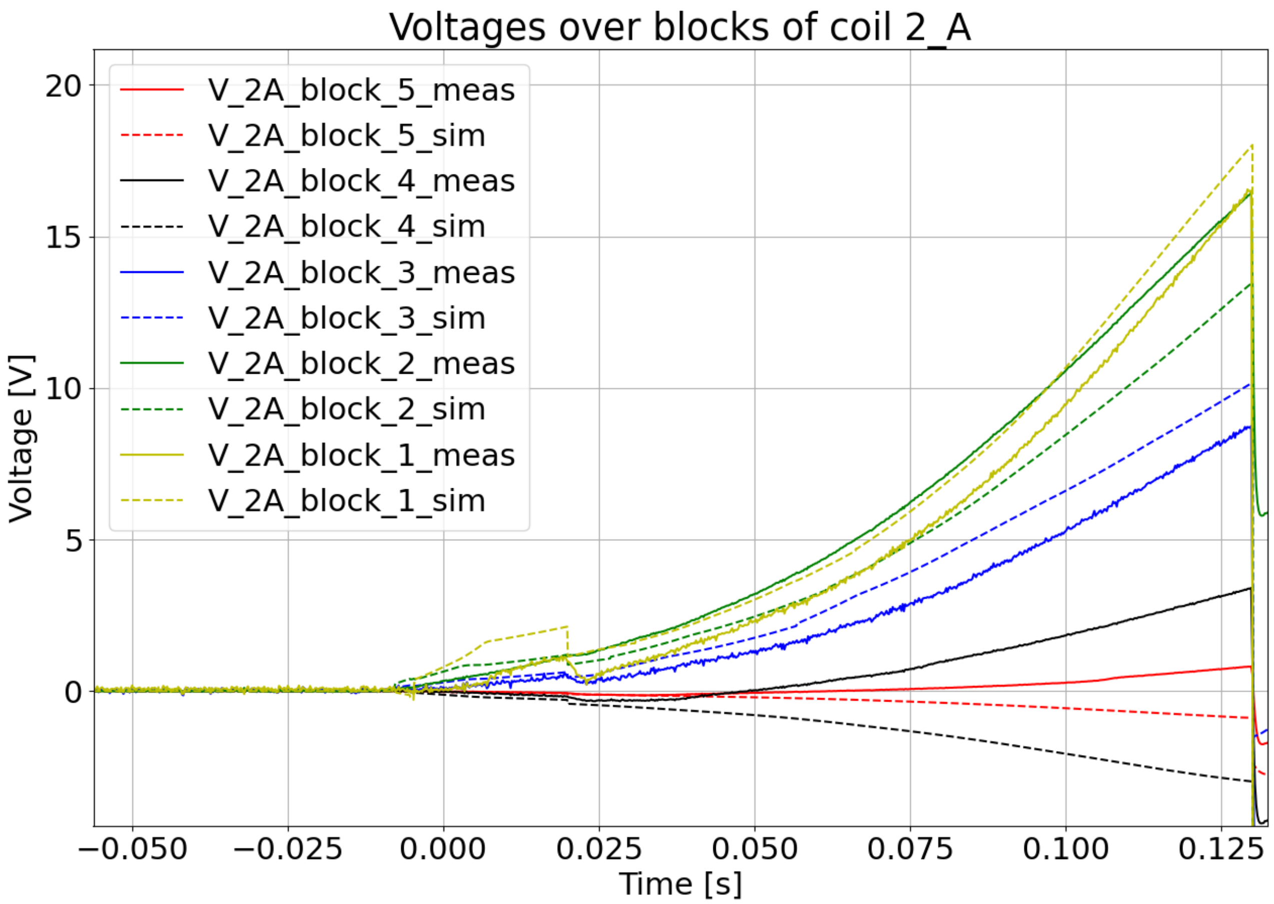
- Coil voltages show similar behaviour as differential voltage
- Underestimation before energy extraction triggering not yet understood
- Block voltages of coil 2A show good overall agreement for blocks in contact to quench heaters
- Outer blocks don't quench but develop inductive voltage



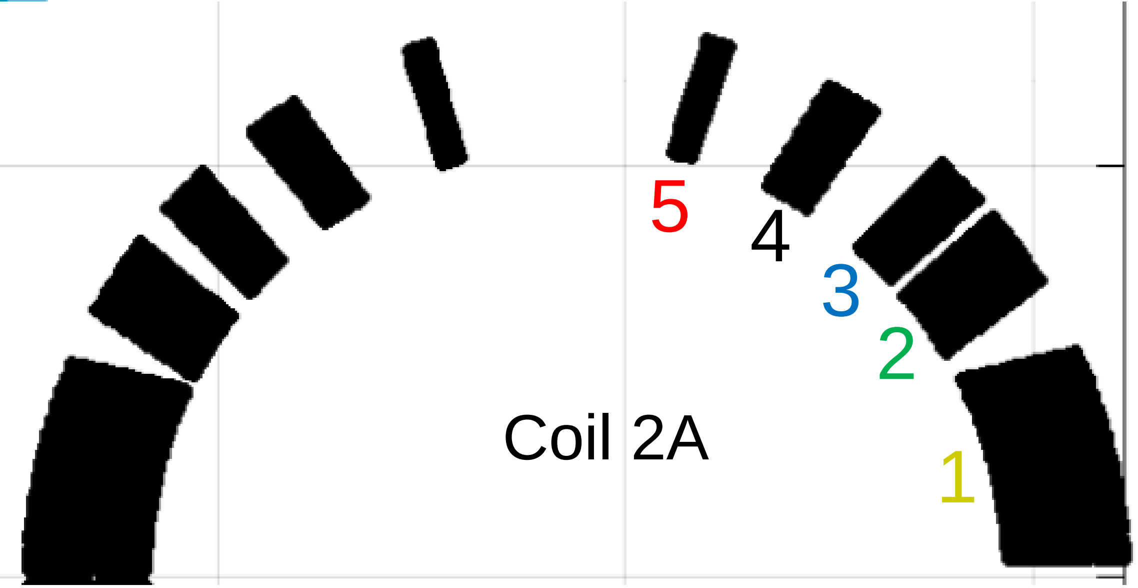


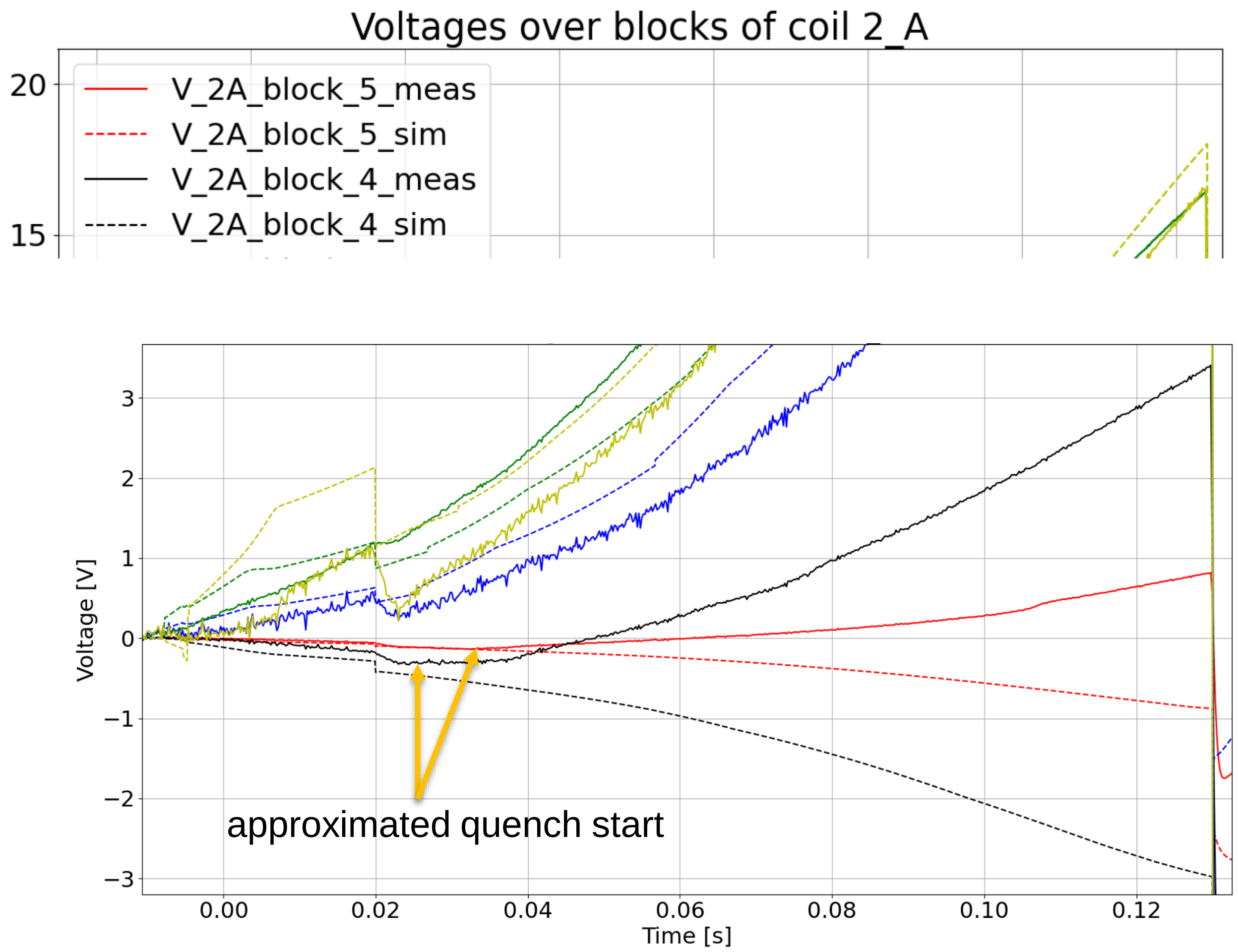
Block voltages





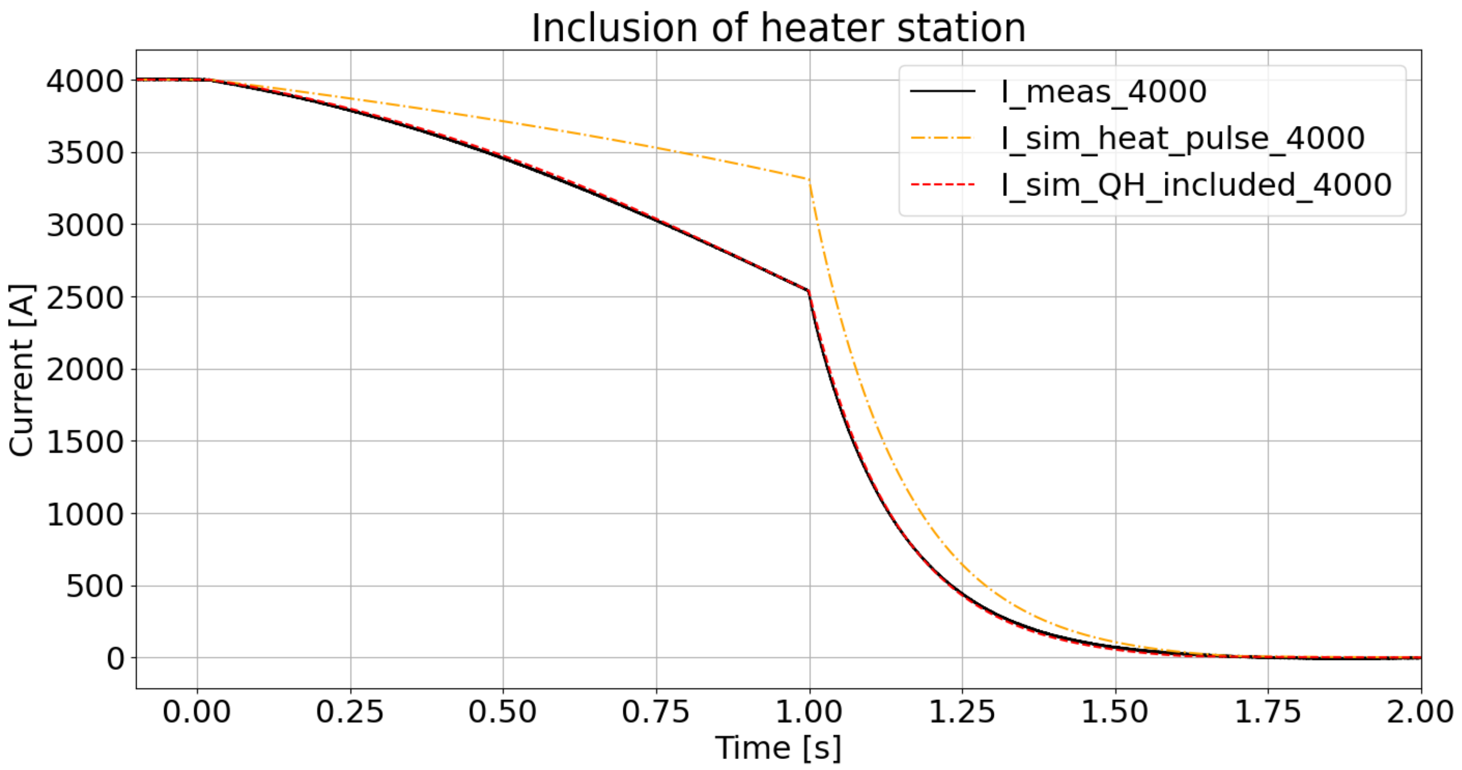
Voltage block 4 and 5





Annex: Improvements at low currents

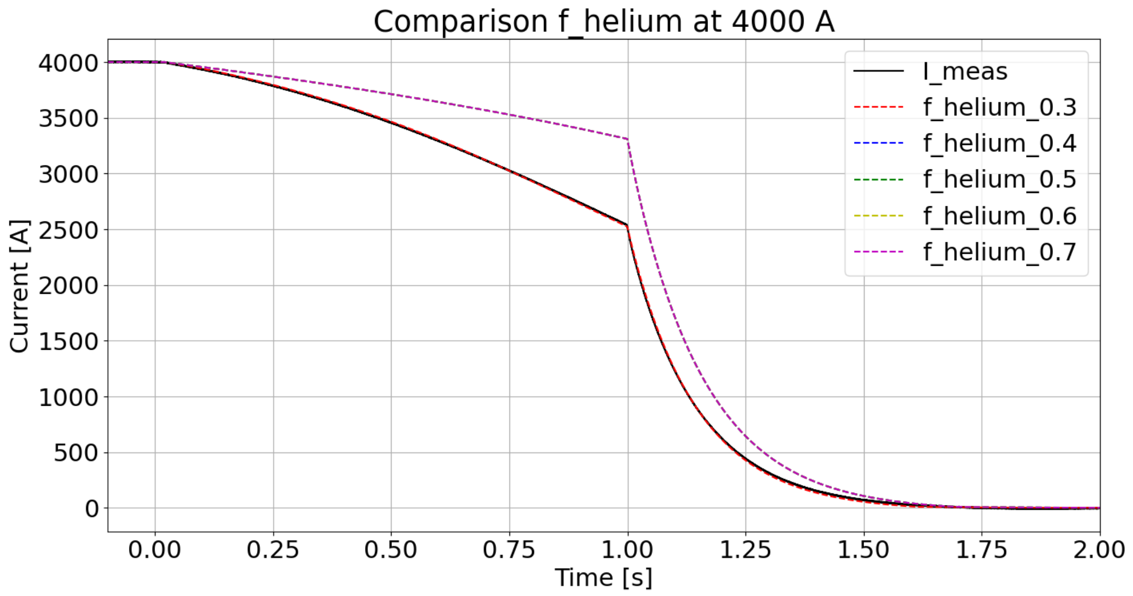
- Major improvement of simulated discharge at low currents by including QH in the PyBBQ simulation
- No changes at high currents due to including QH in PyBBQ

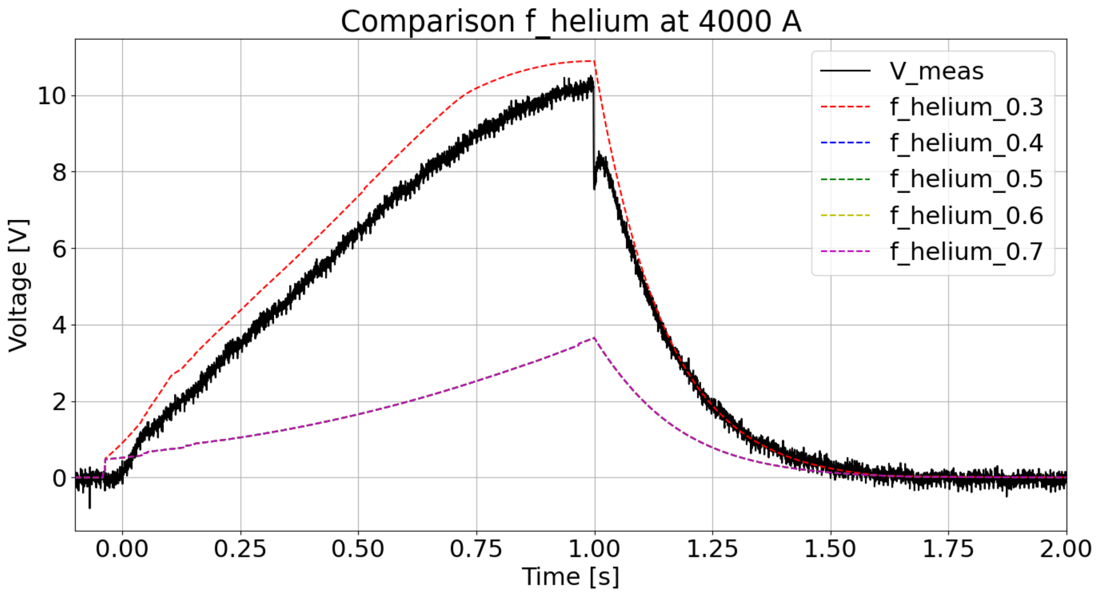


Annex: Variation of f_helium at low currents

- No impact on discharge current and differential voltage at low currents for high f_helium

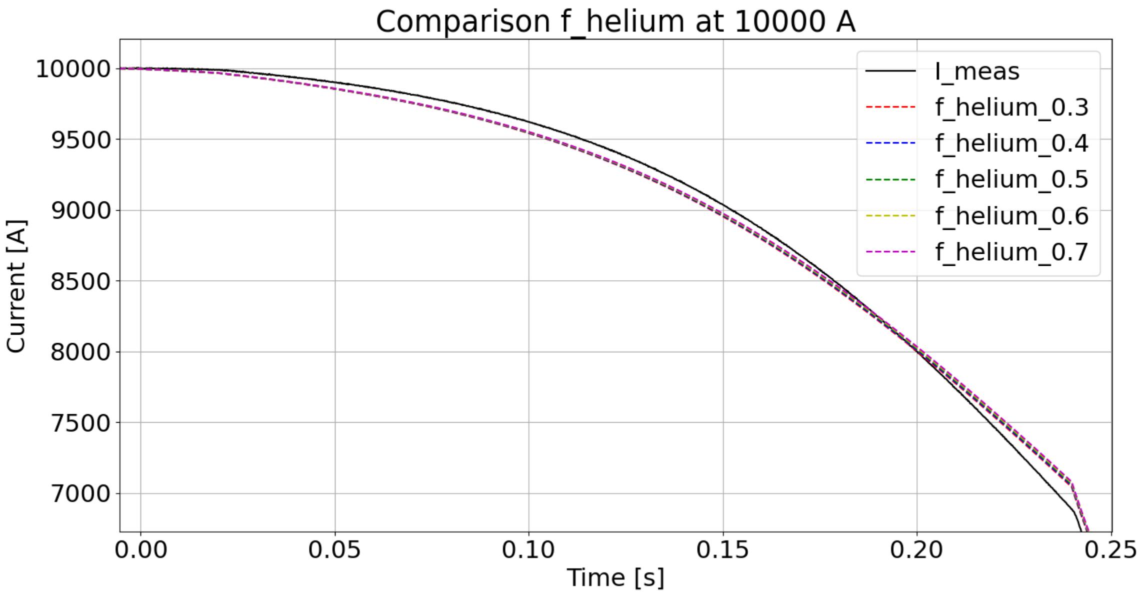
- From certain f_helium quench propagation occurs

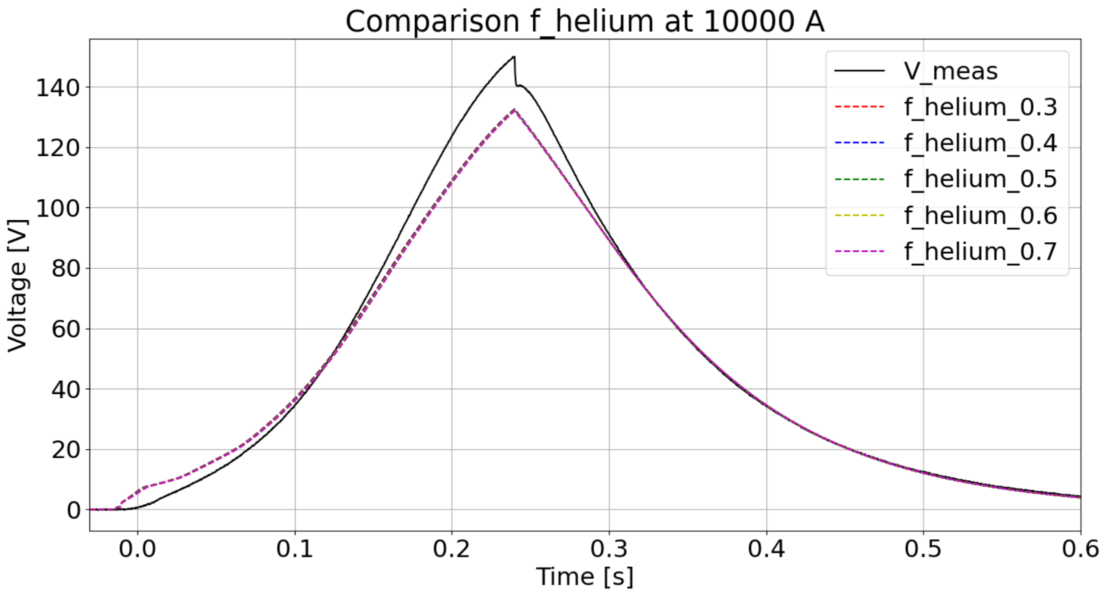




Annex: Variation of f_helium at high currents

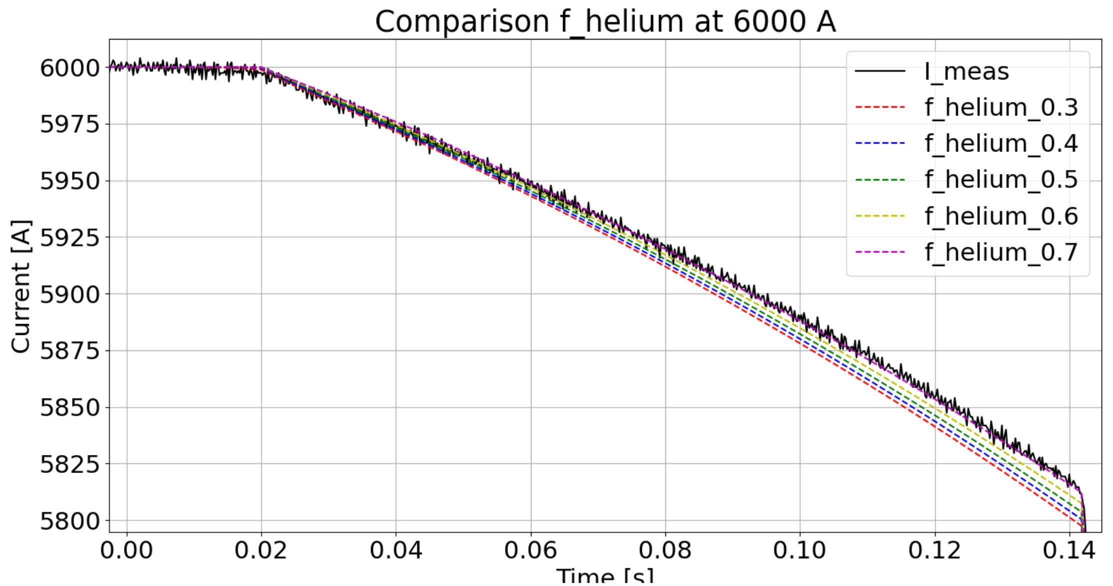
- No impact at low currents for high f_helium
- From certain f_helium quench propagation occurs
- Negligible impact on high currents

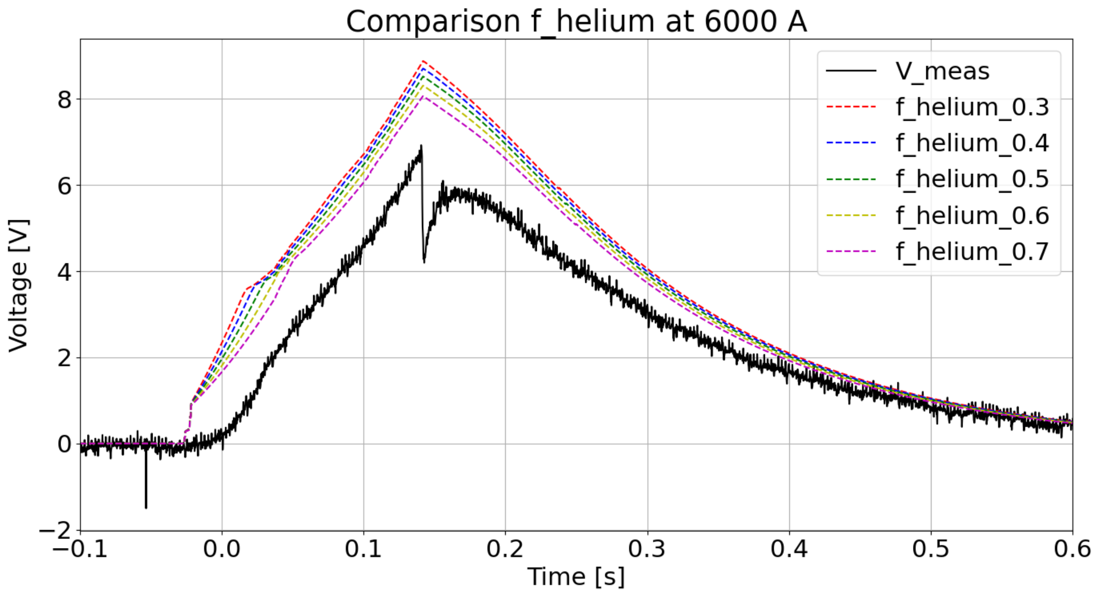




Annex: Identifying value of f_helium

- No impact at low currents for high f_helium
- From certain f_helium quench propagation occurs
- Negligible impact on high currents
- Highest visible impact at 6000 A
- Less helium cooling accelerates discharge
- Best fit for f_helium at 0.7





Annex: Difference of simulated and measured quench start

- Time of quench at high current is simulated well
- At low current, the quench start is simulated too early
- Earlier start maybe due to underestimating the cooling along the longitudinal direction of a half turn