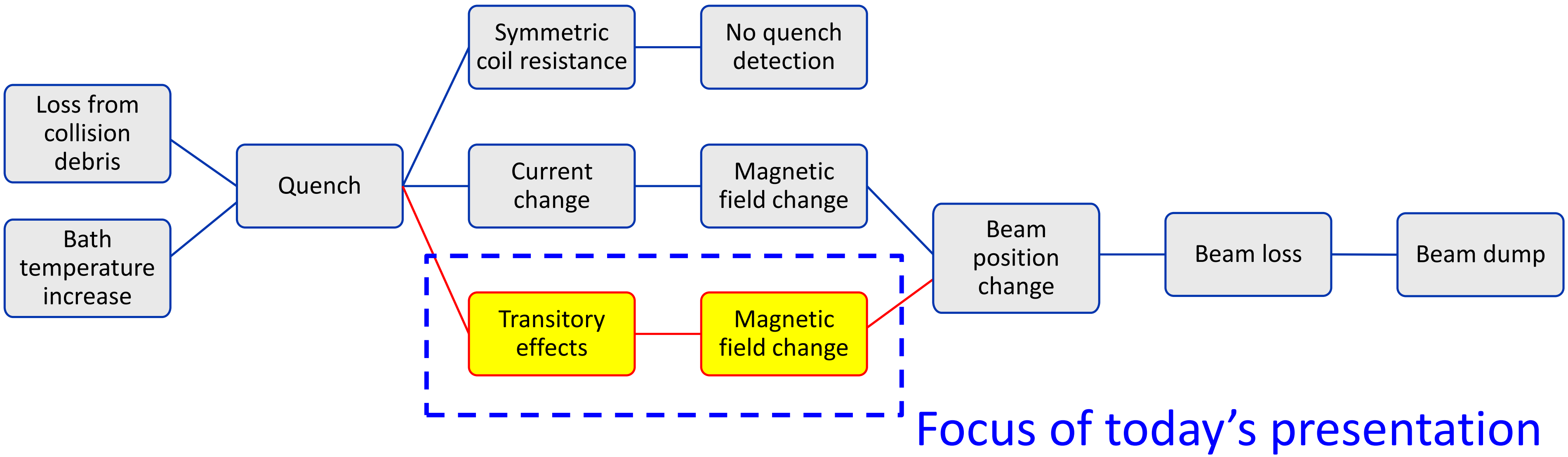
RQX simulations using STEAM
Event in RQX.R1 on 3 June 2018
→Update #3 (Last?)

E. Ravaioli (TE-MPE) on behalf of the STEAM team

Thanks to D. Nisbet (TE-EPC), L. Bortot, Z. Charifoulline, Björn Lindström, M. Prioli, S. Rowan, R. Schmidt, A. Verweij, D. Wollmann (TE-MPE)

14 September 2018

Event in RQX.R1 on June 3 2018 – Summary



- Event description: https://issues.cern.ch/browse/TEMPECOMS-685
- Arjan's LMC presentation of 2018/6/20: https://indico.cern.ch/event/738302/
- Emmanuele's and Björn's MPP presentations 2018/9/14: https://indico.cern.ch/event/752454/
- Thanks to D. Nisbed (TE-EPC) for the useful summary!

Dipole kicks acting on the two beams

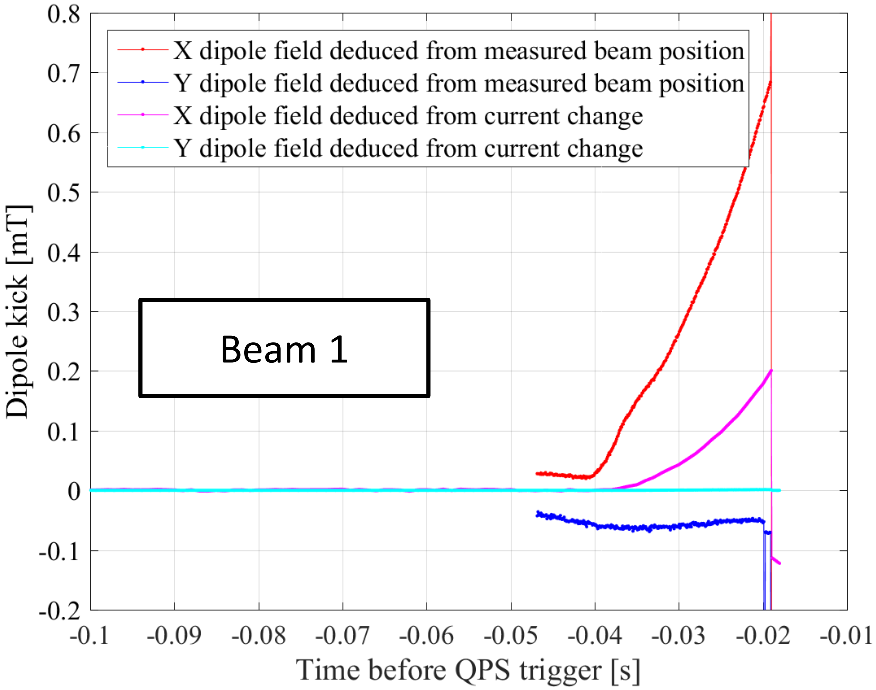
Thanks to
B. Lindström

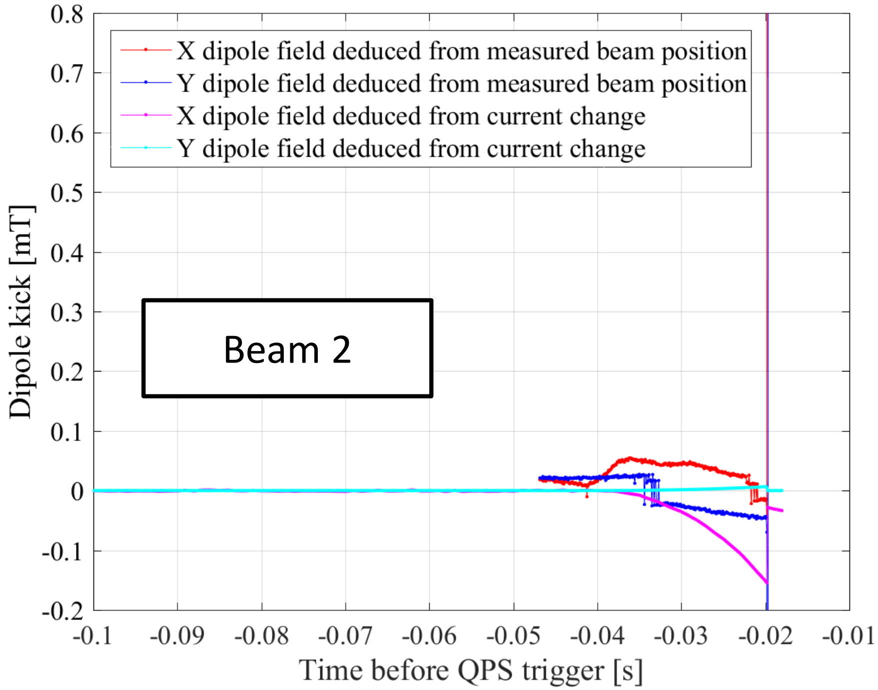
in [mT]	From BPM	From ΔI
B1, ΔB_X	+0.7	+0.233
B1, ΔB_Y	<0.1	+0.000
B2, ΔB_X	<0.1	–0.197
B2, ΔB_Y	<0.1	+0.000

!

!

ΔB_X~0.7 mT dipole field acting on B1 deduced from measured Y offset of ~250 μm at BPMS.2R1.B1 (0.2 μrad), corresponding to ~180 μm at the center of MQXA.1R1 (Q1)



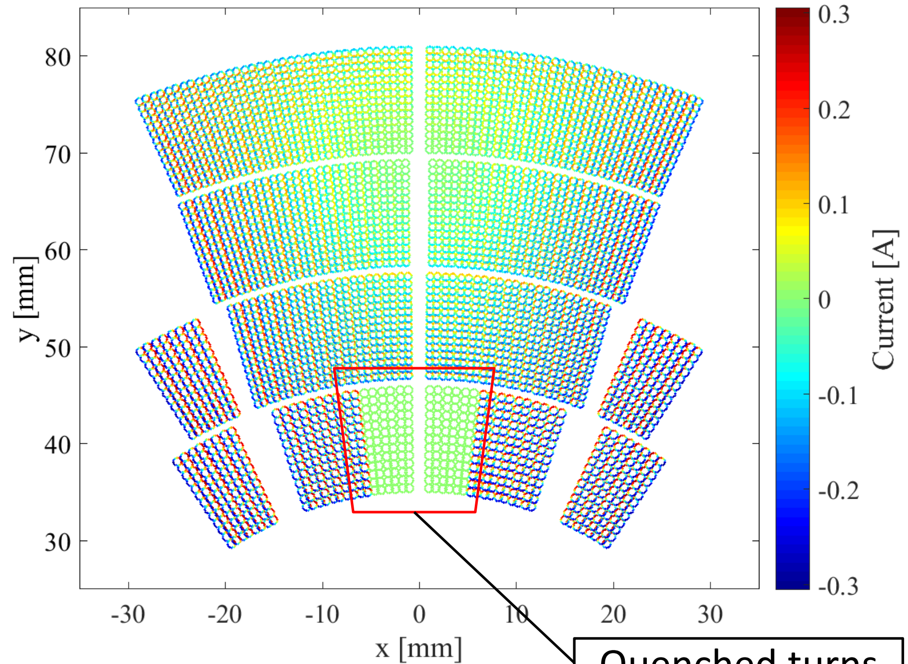


Three transitory effects in the superconductor

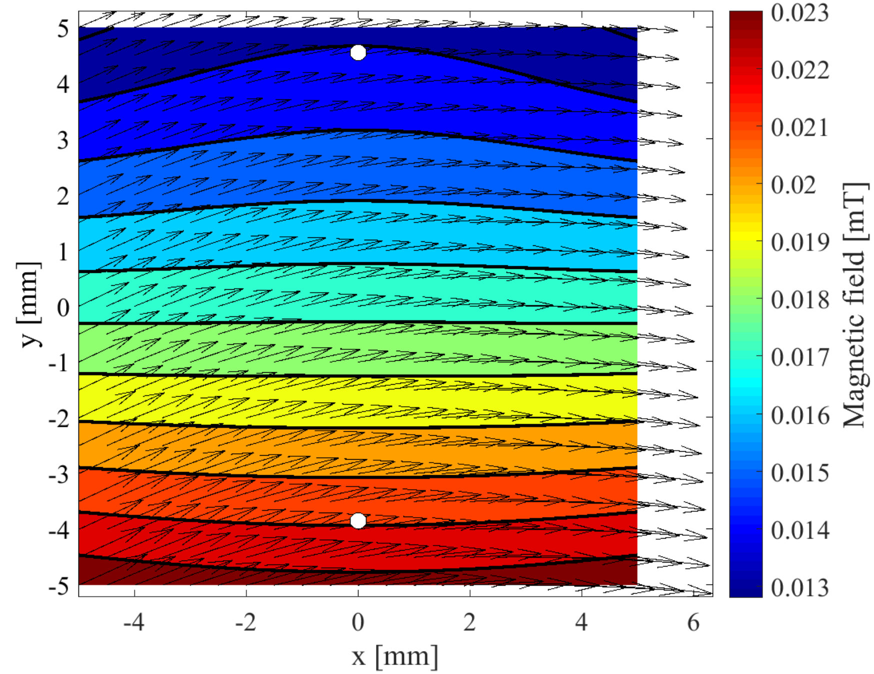
1. Inter-Filament Coupling Currents (IFCC) [already presented on 2018/08/31]
2. Inter-Strand Coupling Currents (ISCC)
3. Current Redistribution in the Cable (CRC)

Inter-Filament Coupling Currents (IFCC)

Currents (only 1/4 magnet cross-section shown)



Magnetic field induced in the magnet aperture

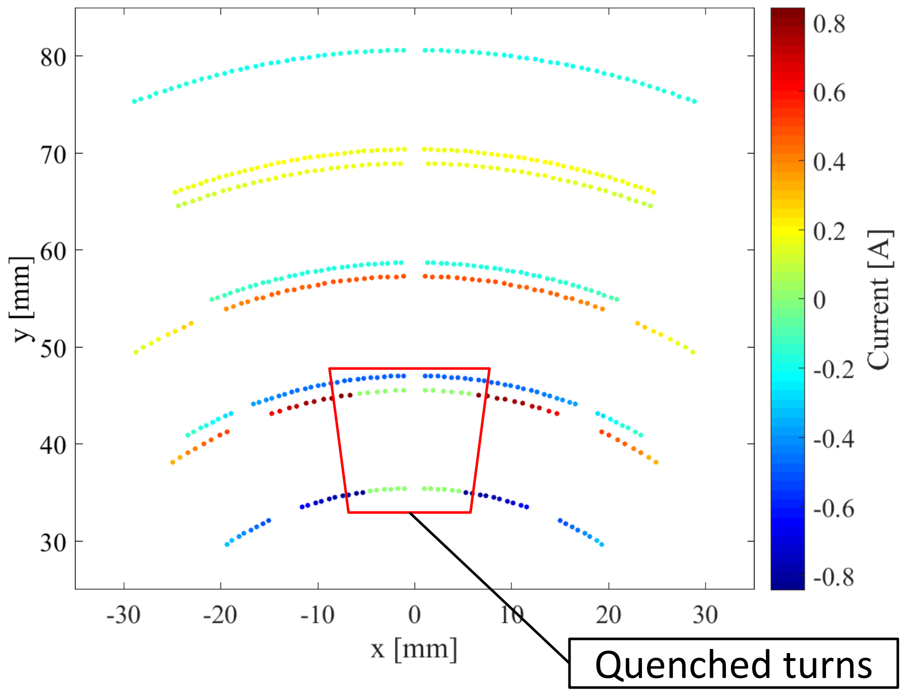


in [mT]	From BPM	From ΔI	IFCC	ISCC	CRC	All
B1, ΔB_X	+0.7	+0.233	+0.014			
B1, ΔB_Y	<0.1	+0.000	+0.002			
B2, ΔB_X	<0.1	–0.197	+0.022			
B2, ΔB_Y	<0.1	+0.000	+0.003			

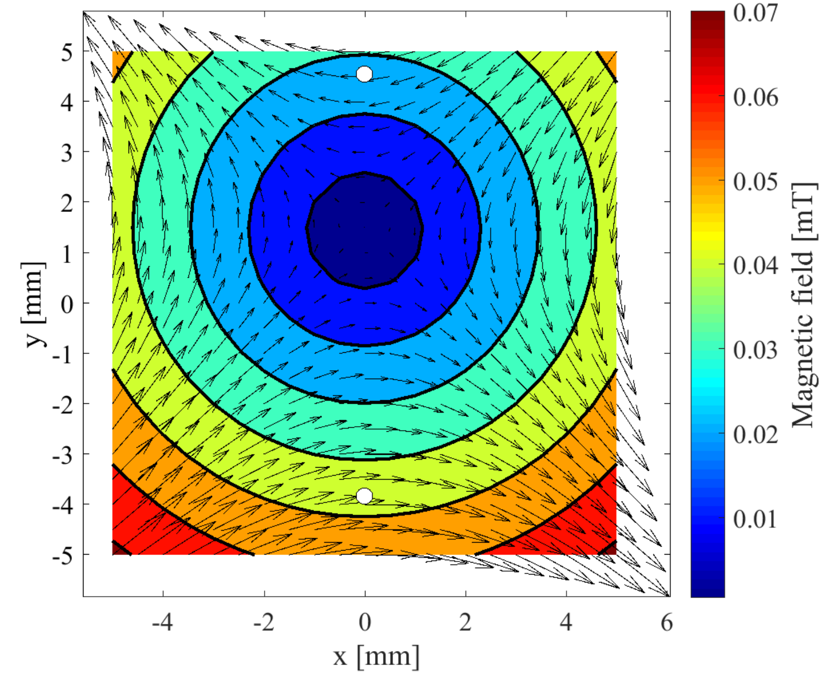
Inter-Strand Coupling Currents (ISCC)

STEAM

Currents (only 1/4 magnet cross-section shown)



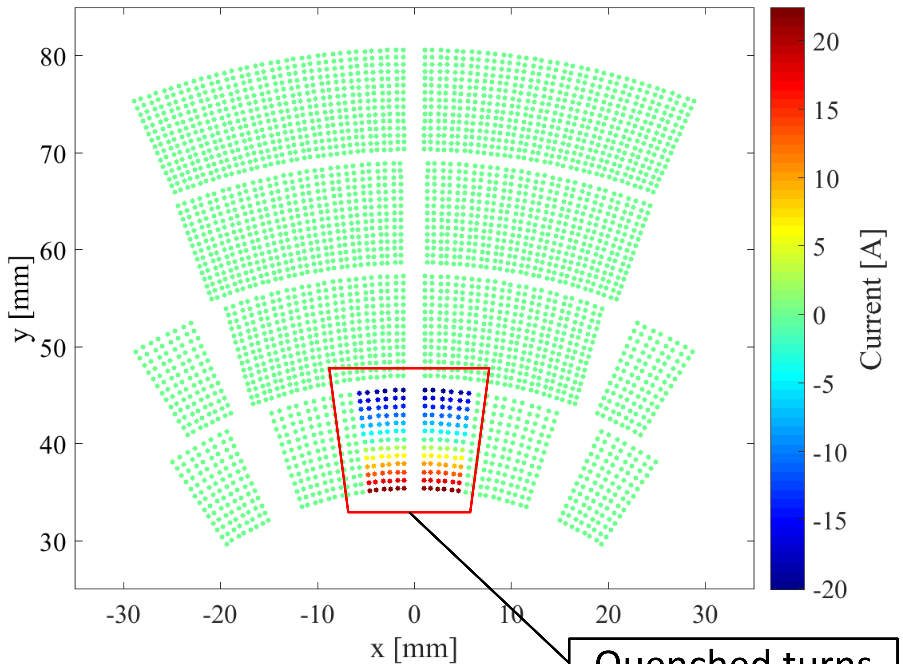
Magnetic field induced in the magnet aperture



in [mT]	From BPM	From ΔI	IFCC	ISCC	CRC	All
B1, ΔB_X	+0.7	+0.233	+0.014	–0.026		
B1, ΔB_Y	<0.1	+0.000	+0.002	+0.000		
B2, ΔB_X	<0.1	–0.197	+0.022	+0.048		
B2, ΔB_Y	<0.1	+0.000	+0.003	+0.000		

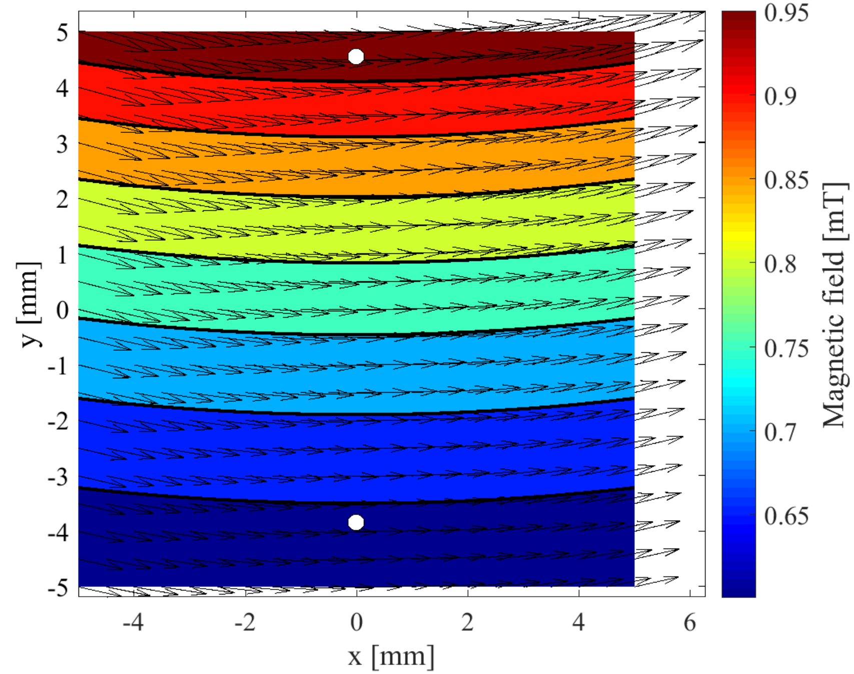
Current Redistribution in the Cable (CRC)

Currents (only 1/4 magnet cross-section shown)



Quenched turns

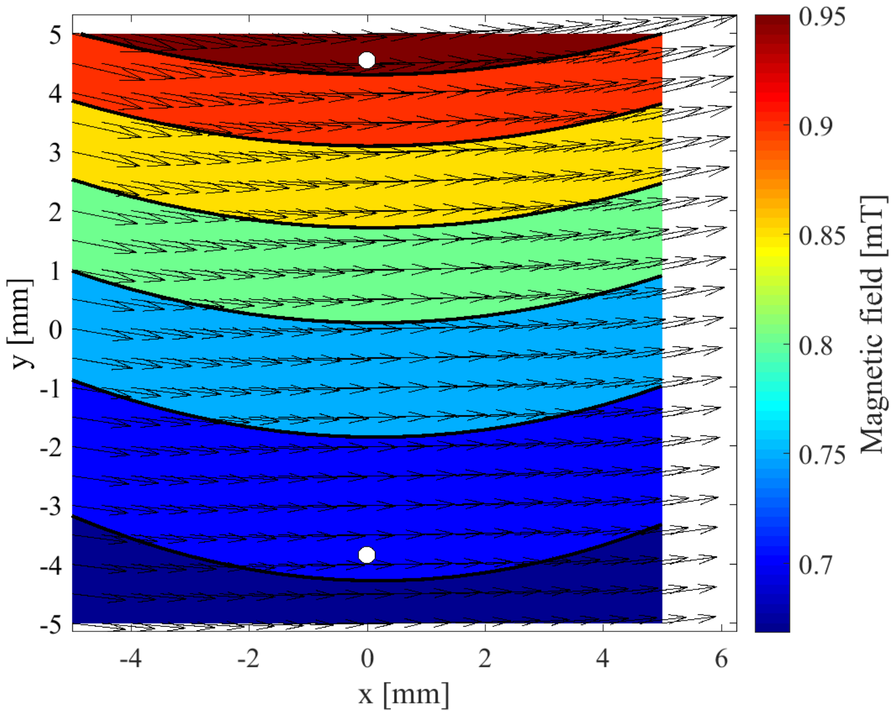
Magnetic field induced in the magnet aperture



in [mT]	From BPM	From ΔI	IFCC	ISCC	CRC	All
B1, ΔB_X	+0.7	+0.233	+0.014	–0.026	+0 / +0.967	
B1, ΔB_Y	<0.1	+0.000	+0.002	+0.000	+0.000	
B2, ΔB_X	<0.1	–0.197	+0.022	+0.048	+0 / +0.636	
B2, ΔB_Y	<0.1	+0.000	+0.003	+0.000	+0.000	

Dipole kicks acting on the two beams

in [mT]	From BPM	From ΔI	IFCC	ISCC	CRC	All
B1, ΔB_X	+0.7	+0.233	+0.014	–0.026	+0 / +0.967	+0.221 / +1.188
B1, ΔB_Y	<0.1	+0.000	+0.002	+0.000	+0.000	+0.002
B2, ΔB_X	<0.1	–0.197	+0.022	+0.048	+0 / +0.636	–0.127 / +0.509
B2, ΔB_Y	<0.1	+0.000	+0.003	+0.000	+0.000	+0.003



- The real cable redistribution currents are between two extreme cases
  - Infinite contact resistance between strands: Effect is zero
  - Zero contact resistance between strands: Effect is maximum (full redistribution)
- Dipole kicks deduced from the BPM reading lie in the range that can be explained by CRC
- The simulation includes many unknowns, including the number of quenched turns, the initial length of the quenched region, the normal-zone propagation velocity, the turn-to-turn quench propagation time, and the conductor properties, …

Three unusual features – Conclusions

1. <u>Magnet current was discharged very quickly</u>

→ Simulations reproduce power supply voltages/currents before the power abort
→ Simulations confirm that current in Q1 equals measured RQX+RTQX1 currents
→ In order to match the fast current discharge, very high normal zone propagation velocity is assumed (Hot-spot starts in eight turns, 20 cm, 50 m/s NZPV, 1 ms turn-to-turn propagation)

2. <u>Quench detection system was not triggered until 20 ms after beam dump</u>

→ Hypothesis: Quench propagating very quickly AND symmetrically
→ Bath temperature at the moment of the event was >2.15 K

3. <u>B1 and B2 change their positions more/less quickly than expected, respectively</u>

→ Analysis includes three transitory effects in the superconductor: inter-filament coupling currents, inter-strand coupling currents, current redistribution in the cables. They all affect the magnetic field in the bore.
→ Field induced by cable current redistribution is one order of magnitude higher than other contributions. It is high enough to explain the observed beam position changes.

→ **<u>Report on the event is ready</u>**: B. Lindström and E. Ravaioli, "Analysis of the sequence of events in the RQX.R1 circuit on 3 June 2018", EDMS 2025613, 2018.

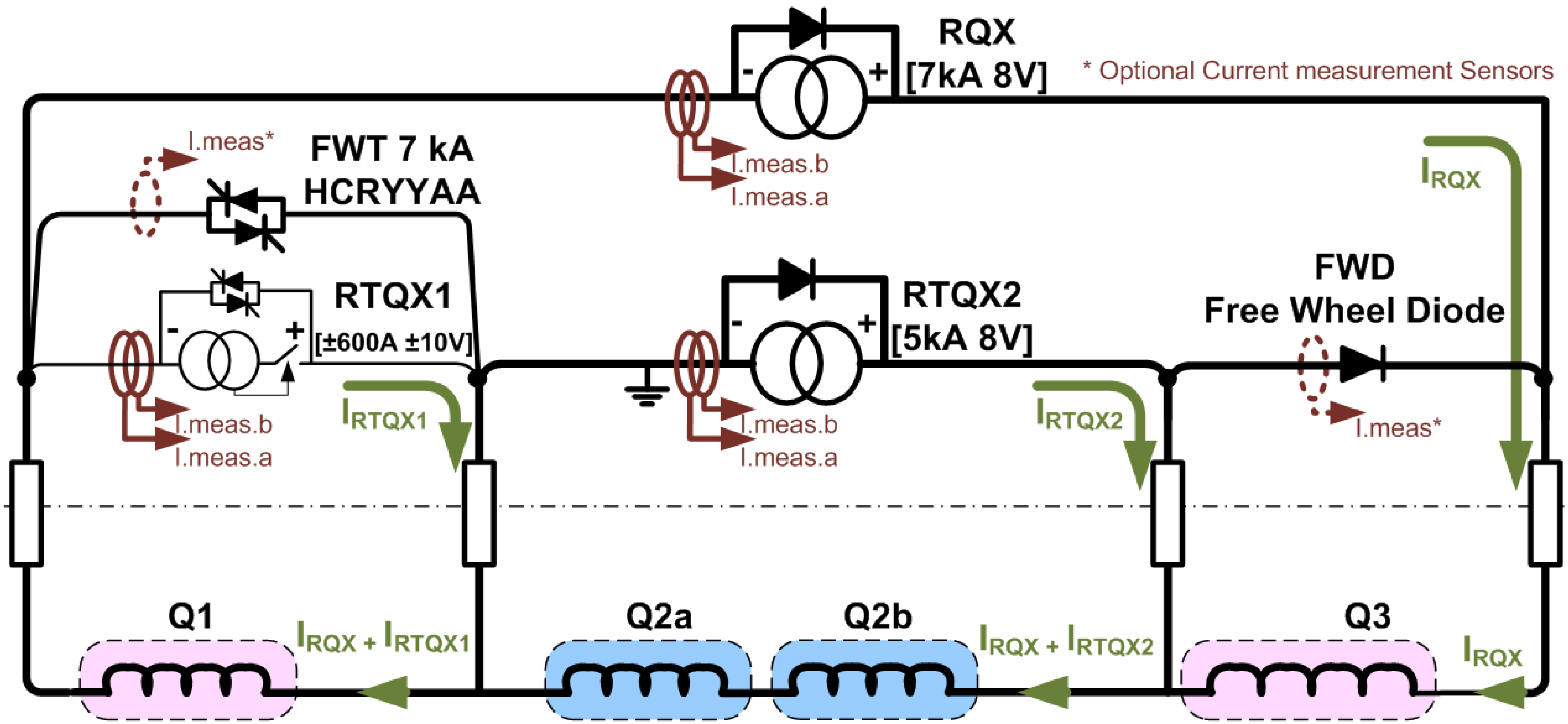
Annex

Event in RQX.R1 on June 3 2018 – Summary

- Event description: https://issues.cern.ch/browse/TEMPECOMS-685
- Arjan's LMC presentation of 2018/6/20: https://indico.cern.ch/event/738302/
- Emmanuele's and Björn's MPP presentations 2018/9/14: https://indico.cern.ch/event/752454/
- Thanks to D. Nisbed (TE-EPC) for the useful summary!

	BEAM POSITION CHANGES	**RTQX1 CURRENT CHANGES**	**BEAM DUMP**	**FAST ABORT**	**QUENCH DETECTION**
Absolute time [s]	19:28:13.81648	19:28:13.818	19:28:13.838	19:28:13.8562	19:28:13.857
Relative time [s]	-0.04052	-0.039	-0.019	-0.0008	0
Δ Beam position	**starts changing** (242*88.924µs before beam dump)	→	Max Δ= ~-0.25 mm @BPM (~-0.7 mT kick)		
ΔI_PC_RTQX1	~0	**starts changing**	Δ= -1.7 A	→	Max Δ= -6.8 A
ΔI_PC_RTQX2	~0	~0	~0	~0	
ΔI_PC_RQX	~0	~0	~0	~0	
ΔU_PC_RTQX1	~0	~0	~0	~0	
ΔU_PC_RTQX2	~0	~0	~0	~0	
ΔU_PC_RQX	~0	~0	~0	~0	
ΔU_RES_Q1	~0	~0	**Spike?**	**pos/neg swing**	**Trigger after 2nd point below -100 mV**
ΔU_RES_Q2	~0	~0	~0	~0	
ΔU_RES_Q3	~0	~0	~0	~0	

RQX.R1 circuit

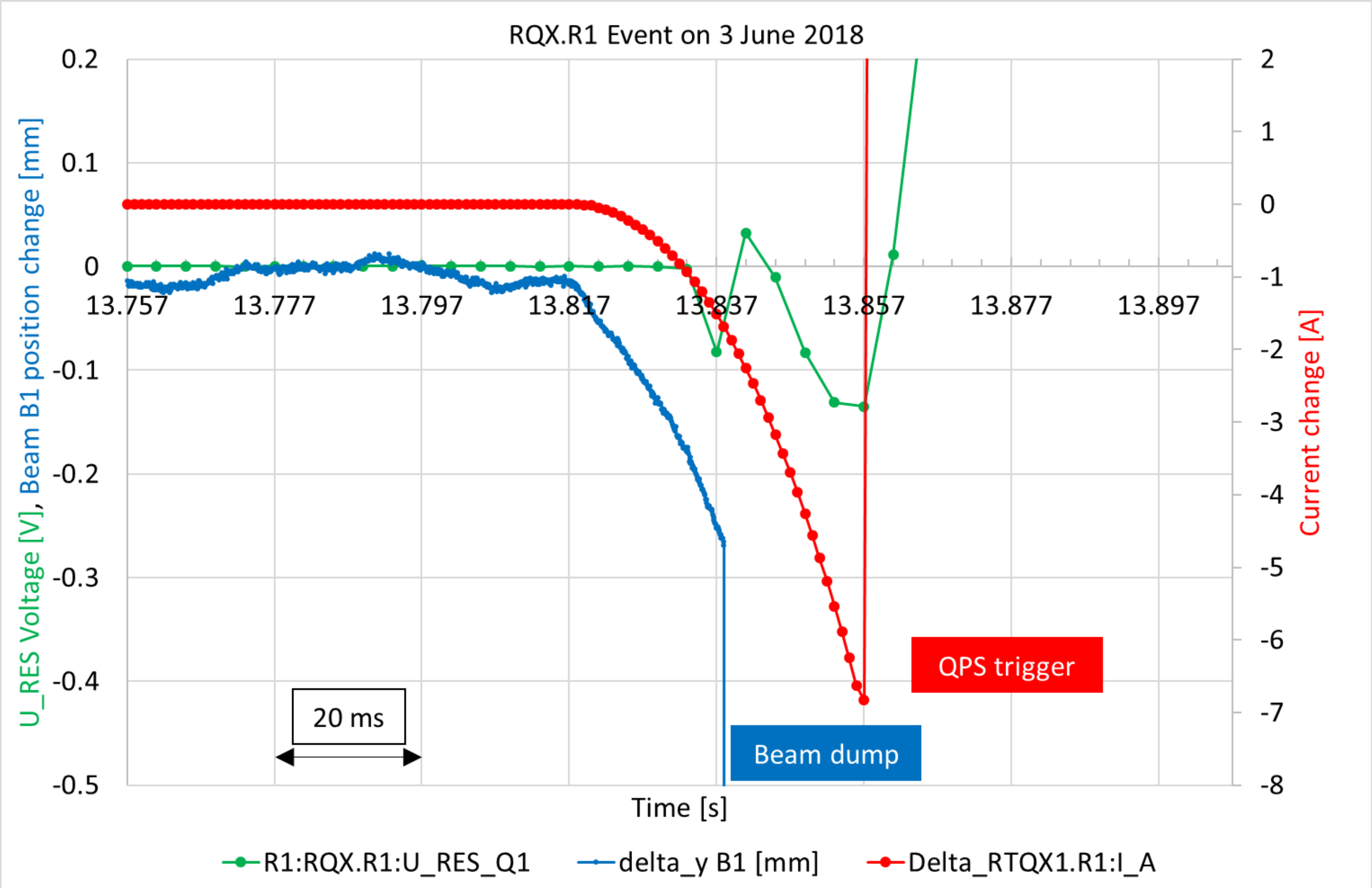


KEK / **MQXA**
Ultimate current : **6800 A**
Inductance : **90.7 mH**
Ej @ I.nom : **2100 kJ**

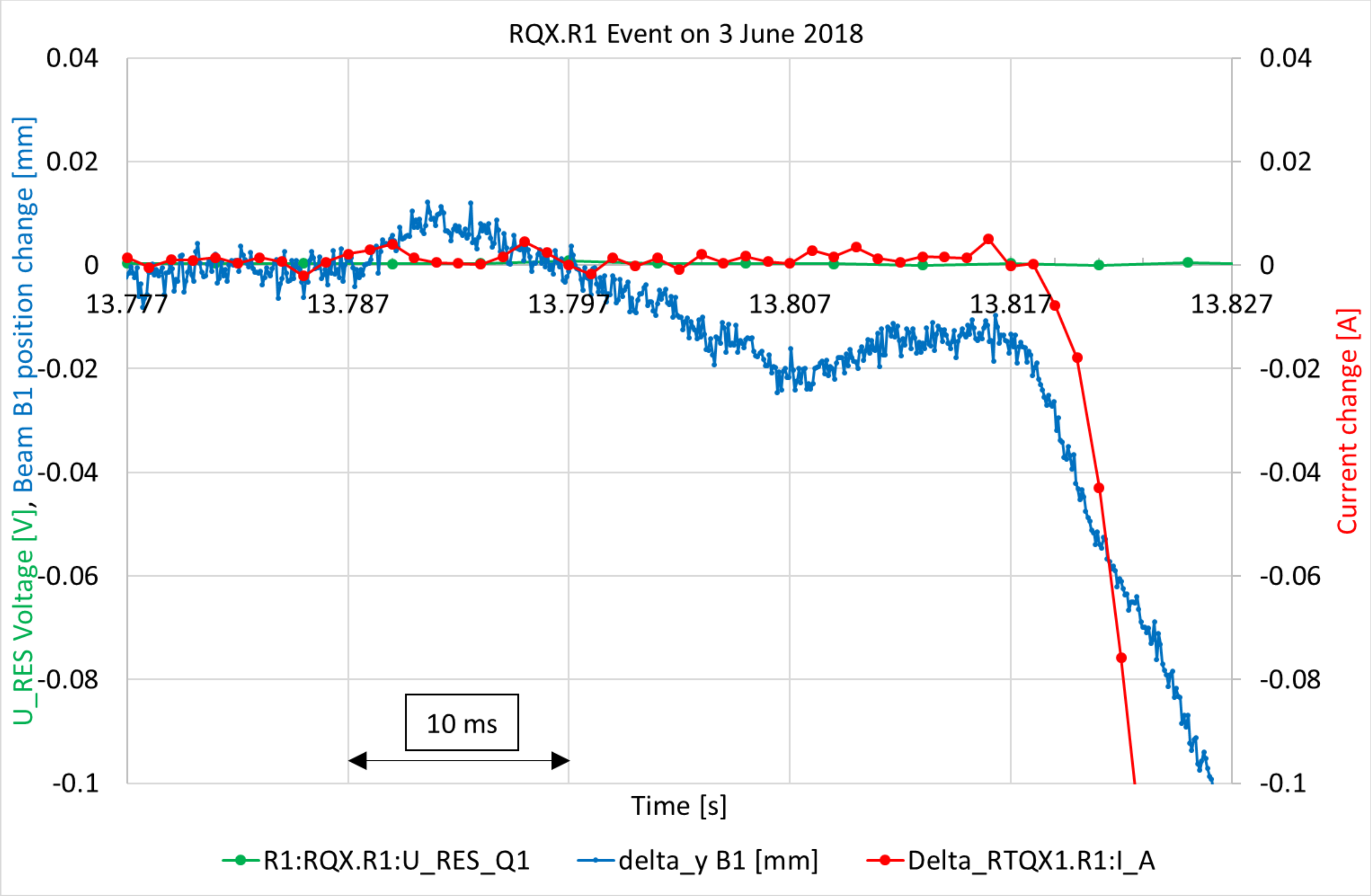
FERMILAB / **MQXB**
Ultimate current : **11580 A**
Inductance : **18.5 mH**
Ej @ I.nom: **1200 kJ**

KEK / **MQXA**
Ultimate current : **6800 A**
Inductance : **90.7 mH**
Ej @ I.nom : **2100 kJ**

Event in RQX.R1 on June 3 2018

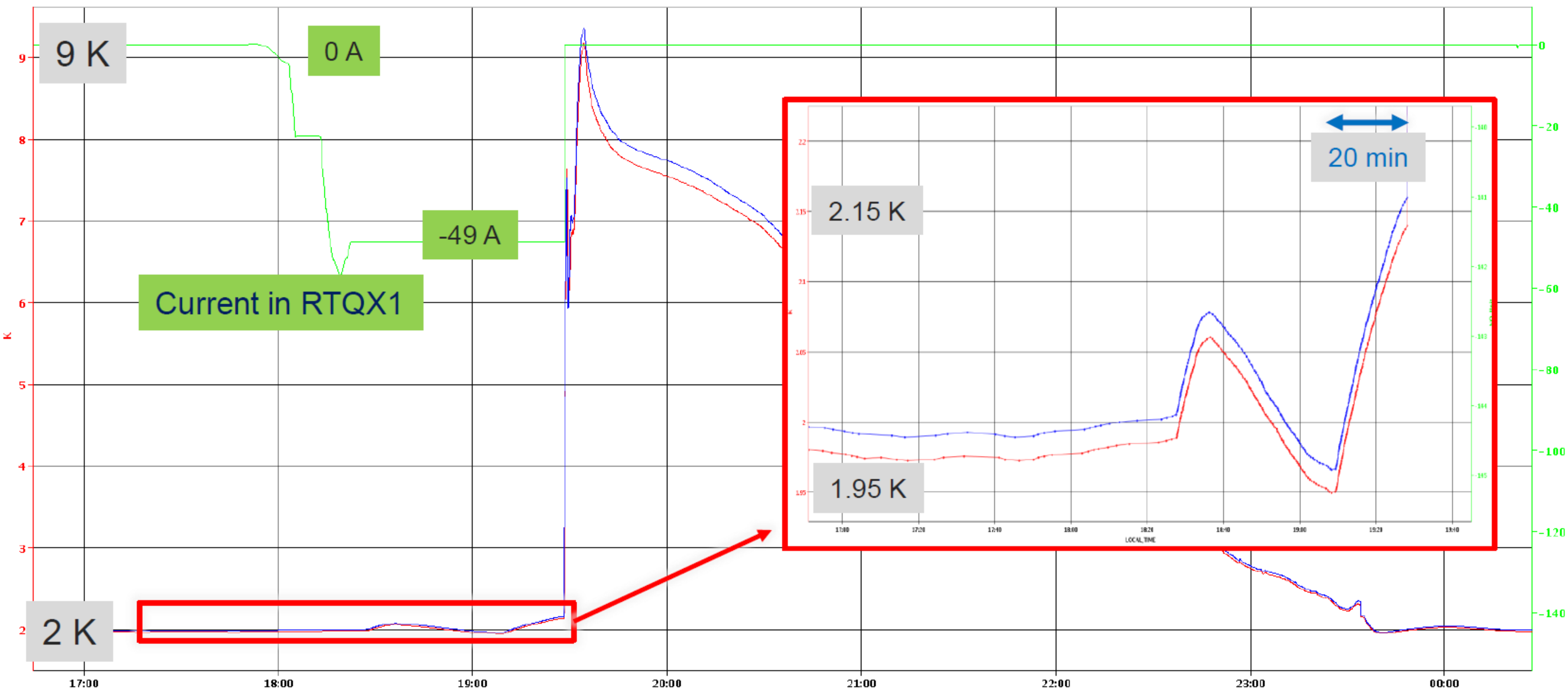


Event in RQX.R1 on June 3 2018 – Zoom



Hypothesis: Fast & symmetric quench

A symmetric quench would not trigger the magnet quench detection based on voltage monitoring. Very fast propagating AND symmetric quench seem rather improbable events, especially occurring simultaneously. However, the measured bath temperature at the moment of the event was >2.15 K, which makes the event less unlikely.



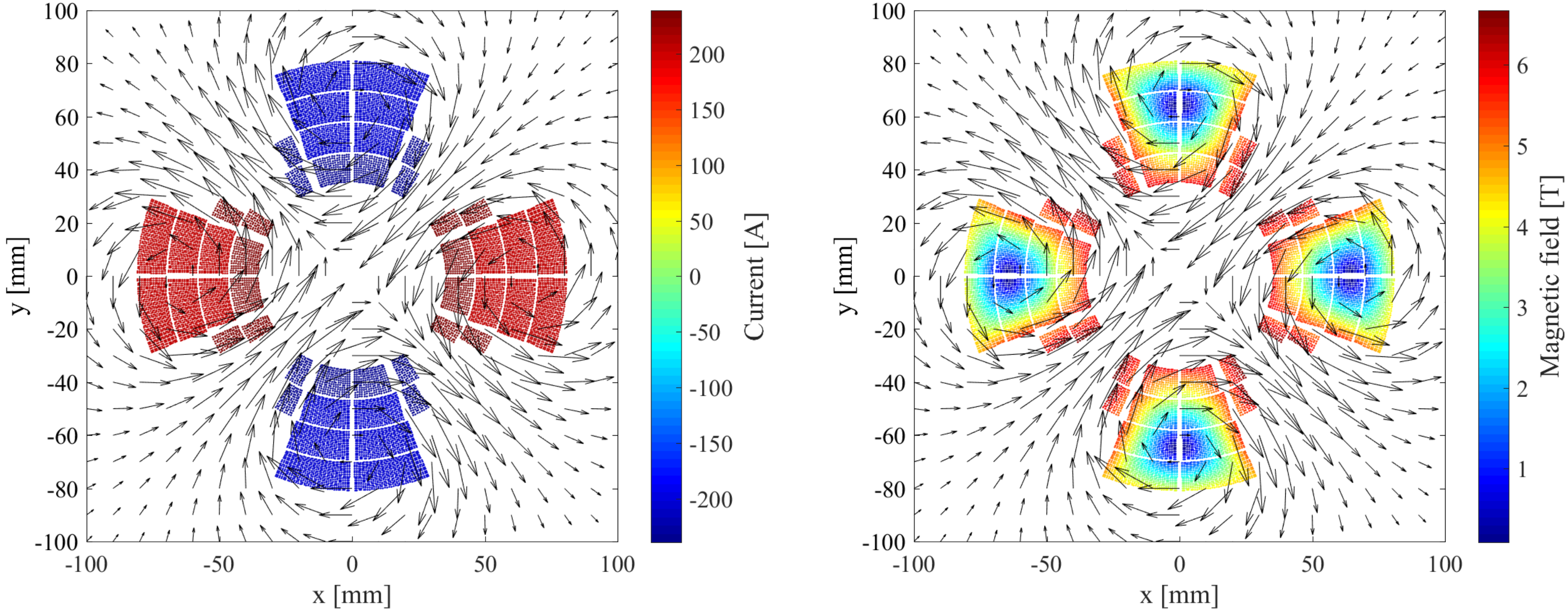
From Arjan's LMC presentation of 20 June: https://indico.cern.ch/event/738302/

Effect of coupling currents during transients

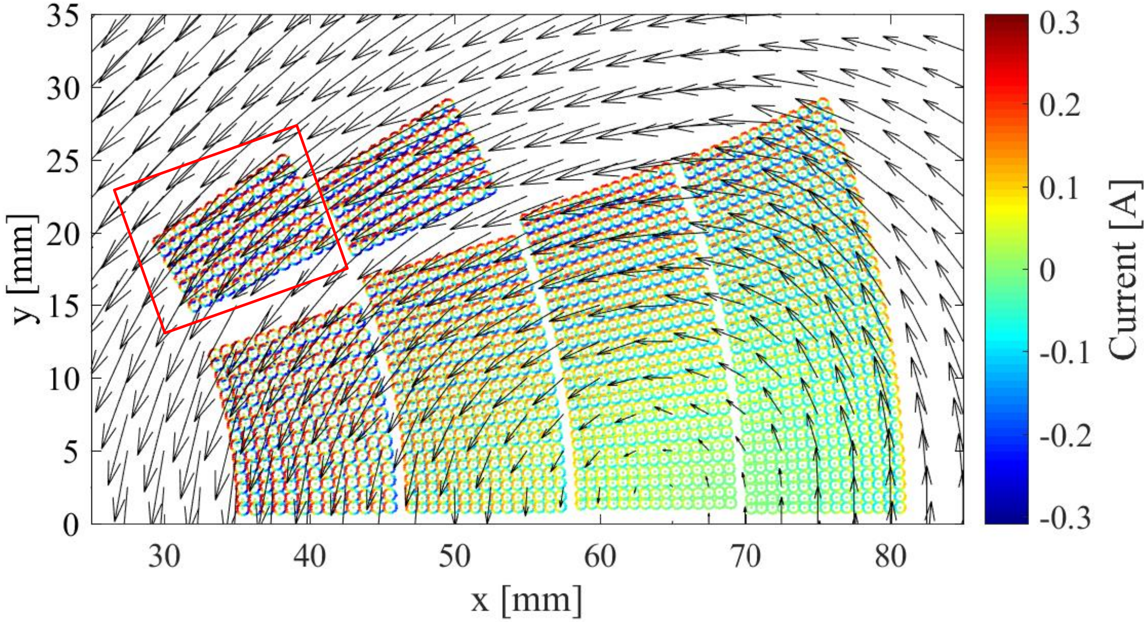
→ How significant is the influence of coupling currents on the magnetic field in the bore?
Equivalent model developed to investigate this phenomenon (with LEDET and a Matlab script)

Transport current and Magnetic field lines

Magnetic field strength and magnetic field lines



Inter-filament coupling currents (IFCC)

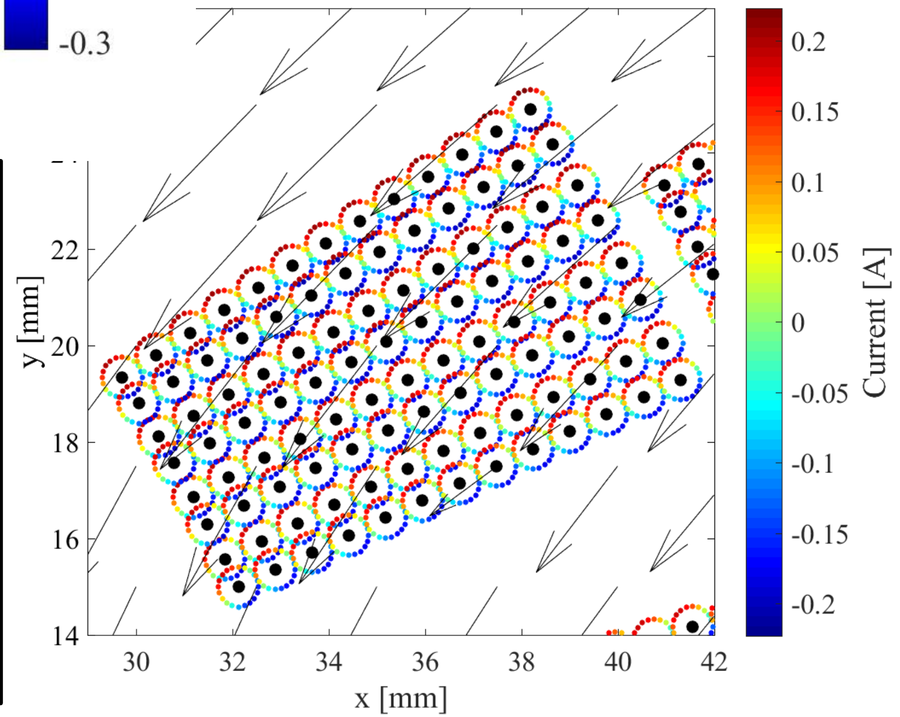


Magnetic field lines and currents distributed around the circumferences of the strands

Coupling currents generate local magnetic fields that oppose to the main applied field change

In first approximation, IFCCs are proportional to the amplitude of the magnetic-field change

The proposed model applies the Biot-Savart law to calculate the magnetic field generated by the coupling currents in the magnet bore



Model description

- Starting point: STEAM model presented on 13 June 2018
  - Electrical circuit validated
  - Electro-thermal magnet models partially validated
- In the electrical circuit, ideal current sources are now replaced by constant voltage sources (since in reality the power supplies don not correct their voltage during the relatively short transient)
- Investigate the effect of a quench in different points of the magnet, and/or starting in more than one turn at the same time

	BEAM POSITION CHANGES	RTQX1 CURRENT CHANGES	BEAM DUMP	FAST ABORT	QUENCH DETECTION
Absolute time [s]	19:28:13.81648	19:28:13.818	19:28:13.838	19:28:13.8562	19:28:13.857
Relative time [s]	-0.04052	-0.039	-0.019	-0.0008	0

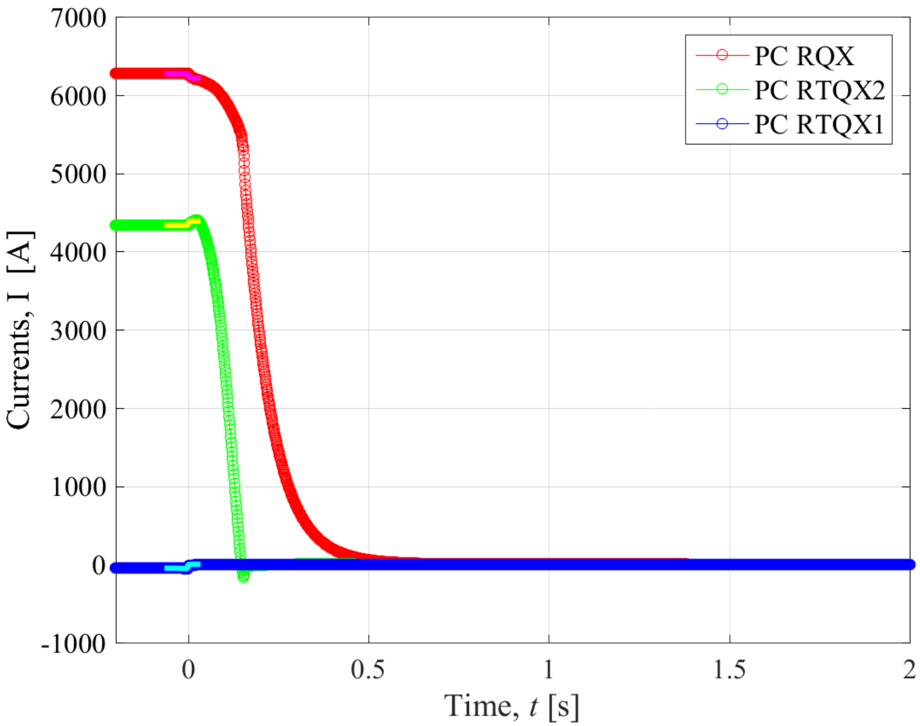
Following the current hypothesis, in the simulation the quench is started at this time

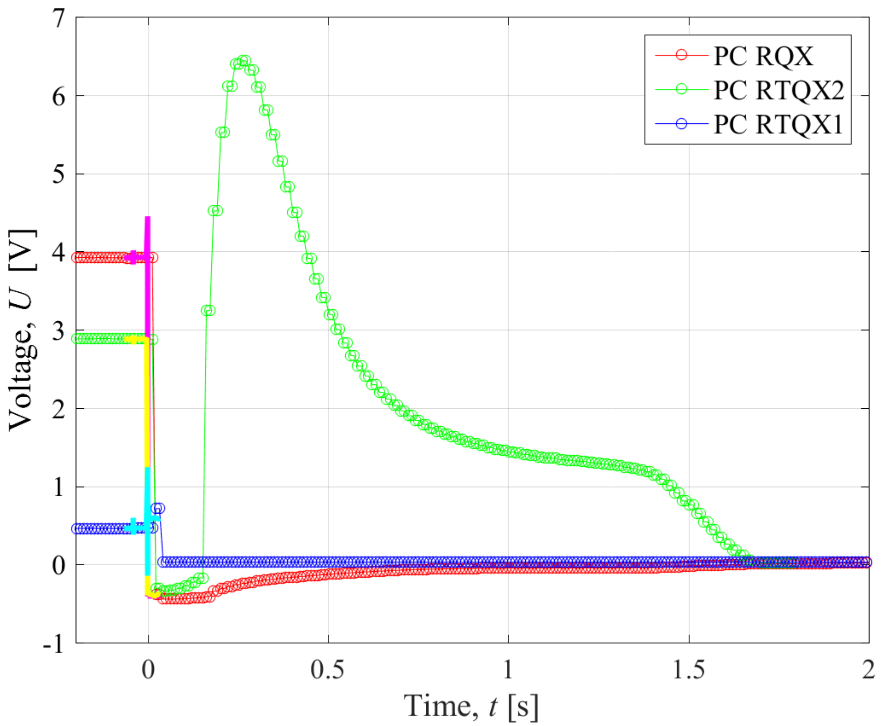
Simulation of the event

Next slides present the results of the simulation with quench developing as follows

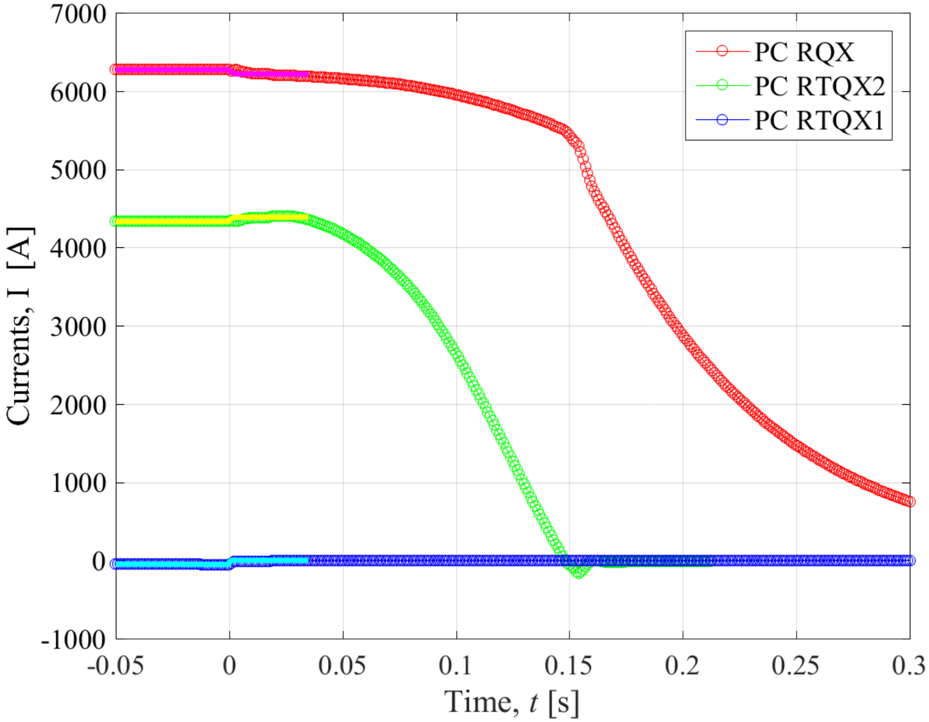
- *Starts in 2 turns (from 0 quenched length)*
- *Quench propagation velocity = 150 m/s*
- *Turn-to-turn propagation: 5 ms*
- *RRR=193-226*
- *Magneto-resistivity included*
- *NIST properties*
- *No temperature increase in the hot-spot in the first 40 ms*

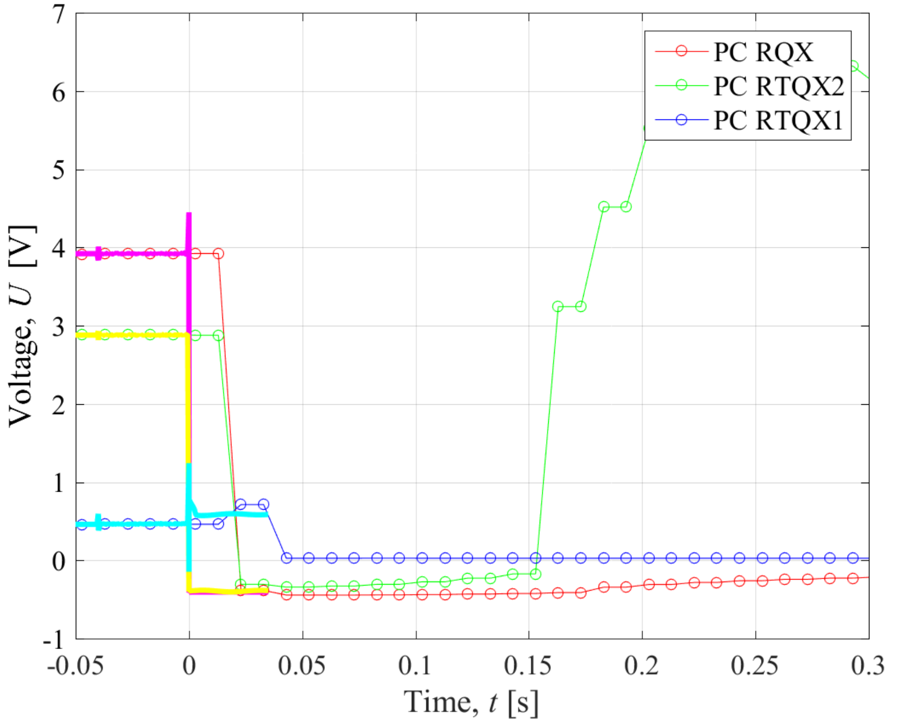
Simulation of the event



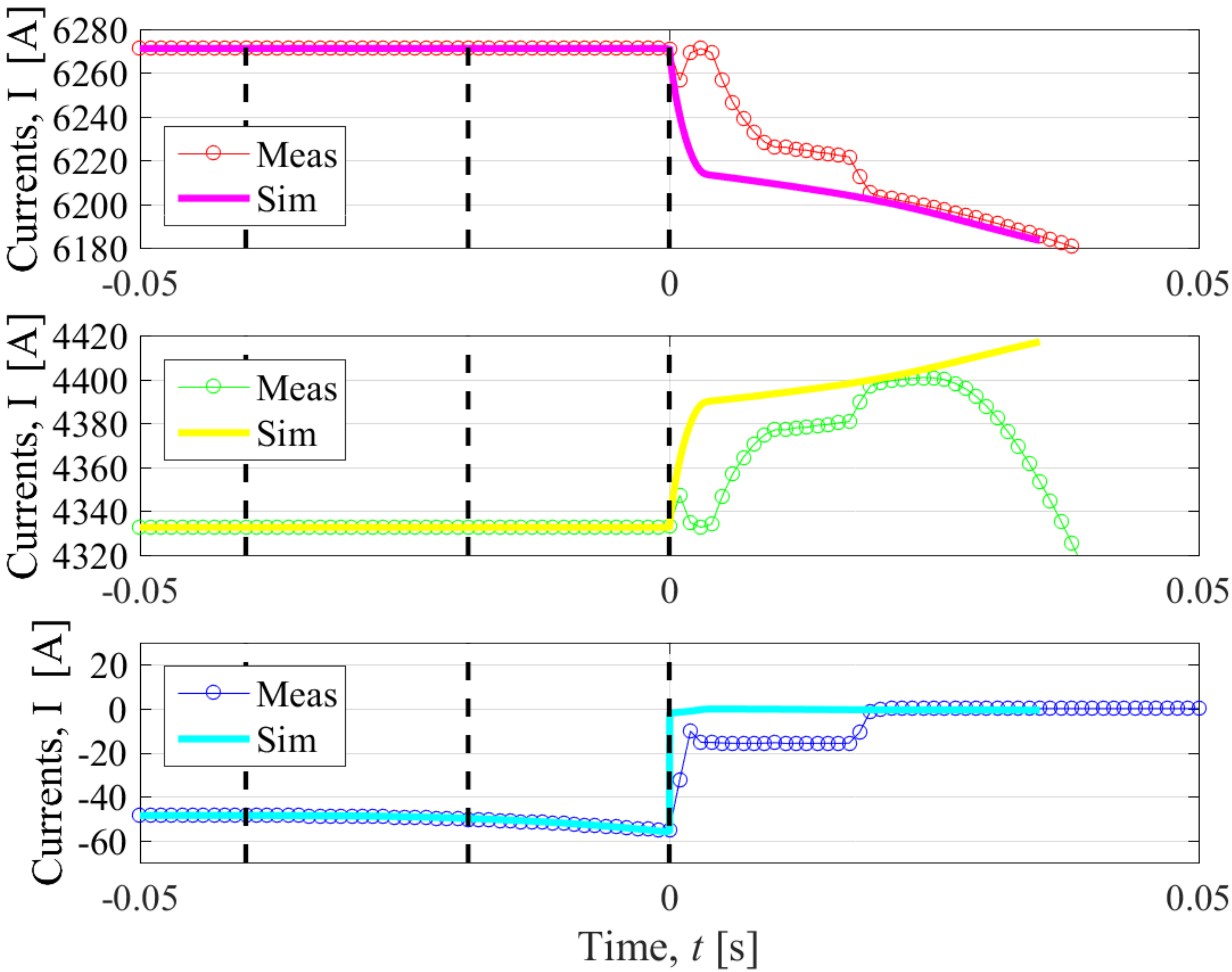


Simulation of the event – Zoom



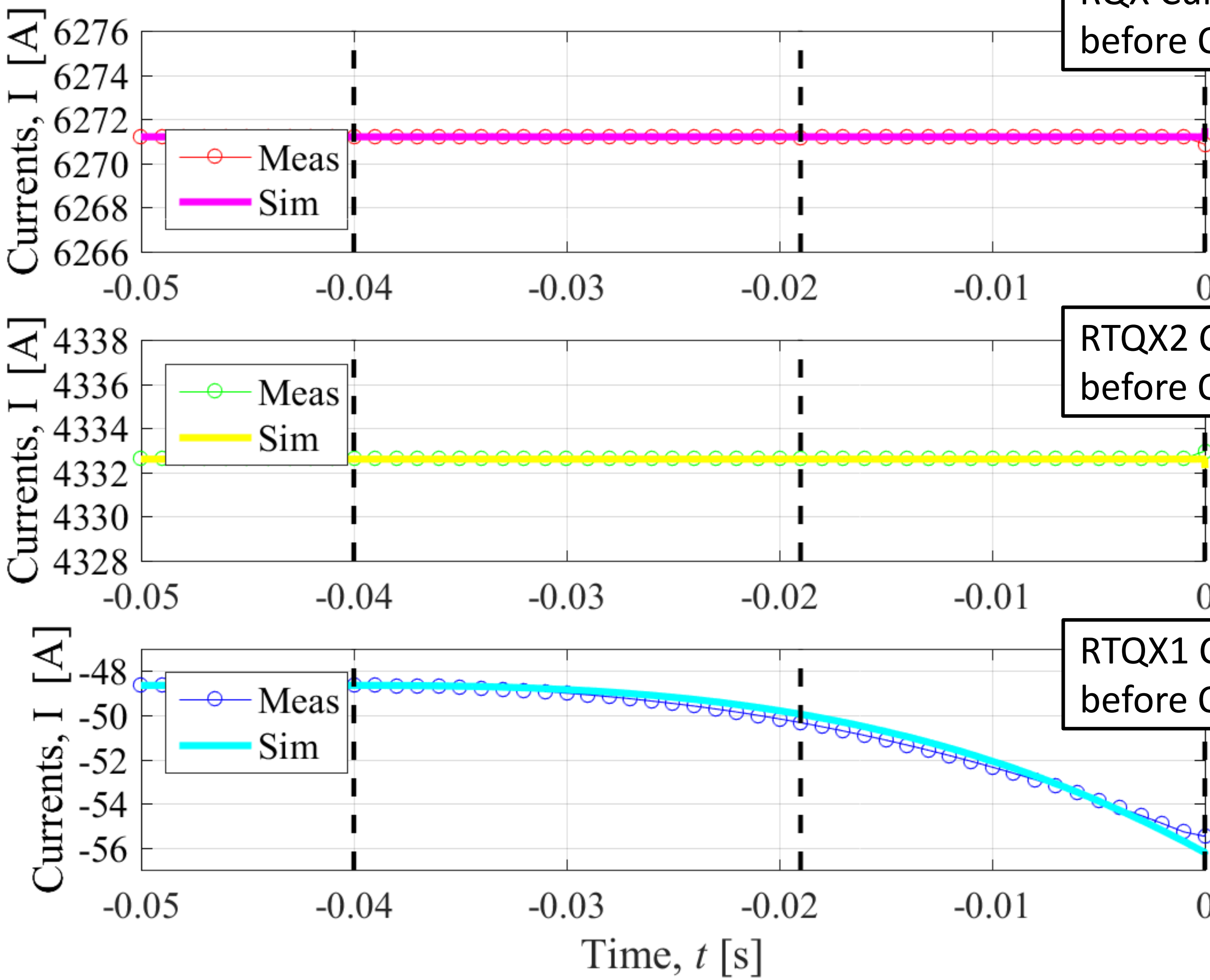


Power supply currents



Sim tools:
- PSPICE
- LEDET
- COSIM

Power supply currents - Zoom



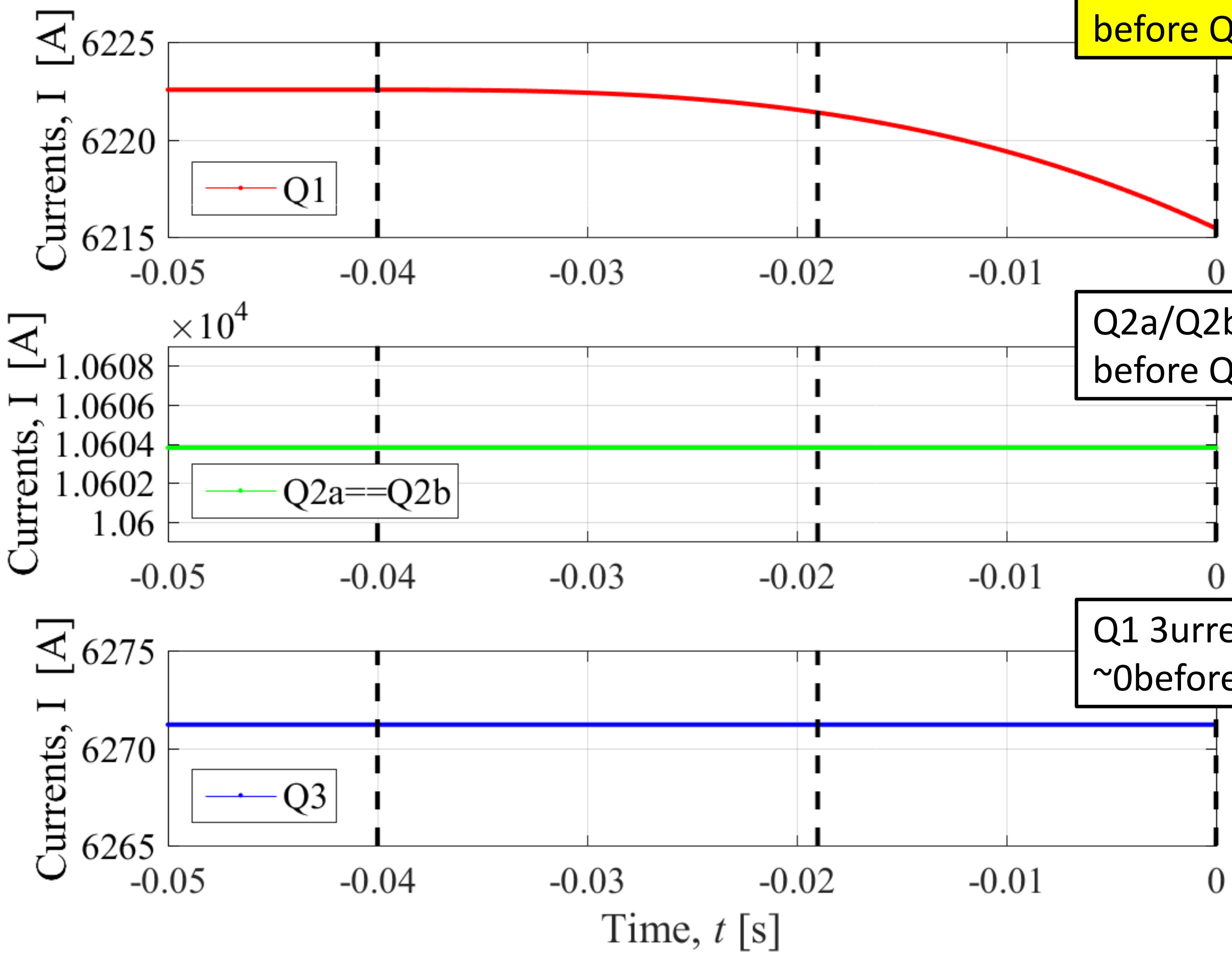
RQX Current change ~0 before QPS triggering

RTQX2 Current change ~0 before QPS triggering

RTQX1 Current change ~7 A before QPS triggering

Sim tools:
- PSPICE
- LEDET
- COSIM

Simulated magnet currents



Q1 current change ~7 A before QPS triggering

Q2a/Q2b current change ~0 before QPS triggering

Q1 3urrent change ~0before QPS triggering

Sim tools:
- PSPICE
- LEDET
- COSIM

Model description

STEAM

LEDET

Electro-magnetic and thermal model of the four MQXA and MQXB magnets (quench heaters, coupling losses, heat propagation, differential inductance, etc)

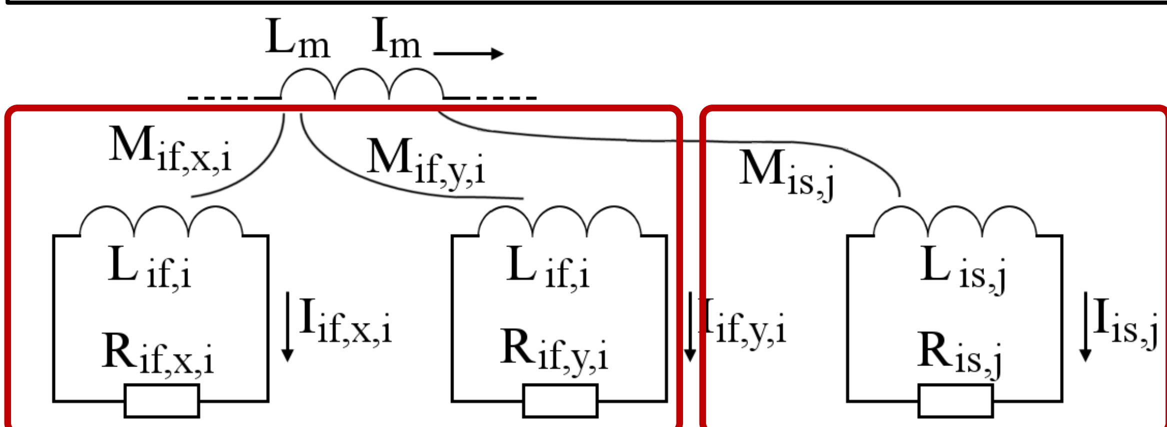
SPICE

Electrical network of the circuit including the internal short (power supplies, Diodes, thyristors, leads, etc)

Runs in 3 minutes!

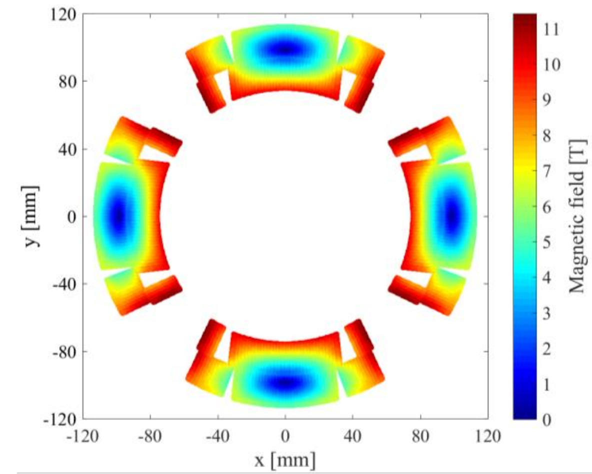
The **interaction** between the superconducting magnet and the local coupling currents is modeled with an array of **RL dissipative loops mutually coupled** with the magnet self-inductance

All simulations presented today are performed with the **LEDET** 2D model (Lumped-Element Dynamic Electro-Thermal)



Inter-filament coupling currents

Inter-strand coupling currents

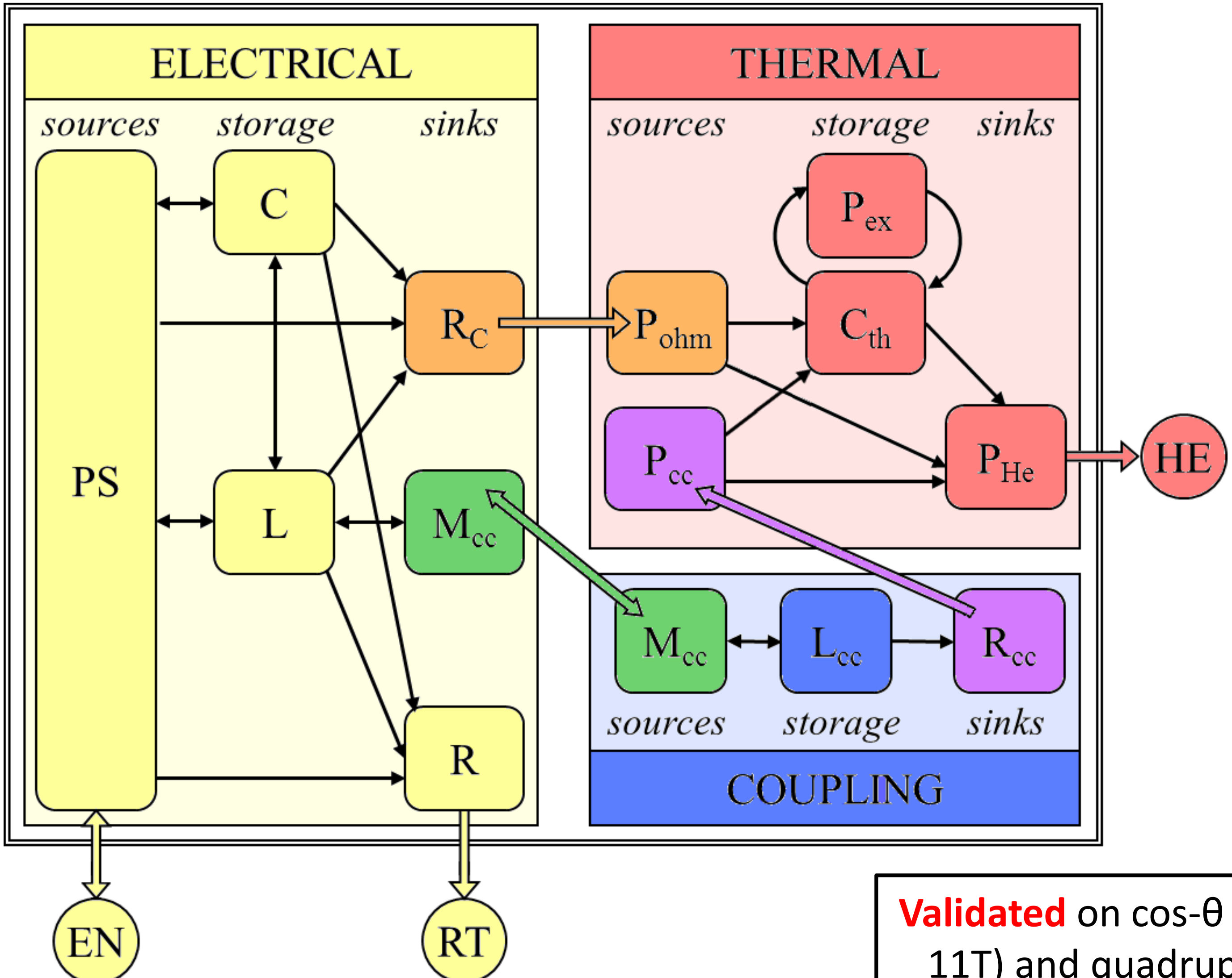


Example: HL-LHC 12 T Nb_3Sn quadrupole magnet (MQXF)

- 2x 16000 IFCL loops
- 400 ISCL loops

[1] E. Ravaioli, "CLIQ", PhD thesis, 2015
[2] E. Ravaioli et al., Cryogenics 2016

LEDET (Lumped-Element Dynamic Electro-Thermal)



Validated on cos-θ dipole (MB, 11T) and quadrupole (MQY, MQXC, HQ, MQXF) magnets