A Quench Protection Database-Tool and Analysis of Quench Heater tests in HL-LHC Nb_3Sn Magnets

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Susana Izquierdo-Bermudez (CERN)

with support from the CERN SM-18 test facility team, in particular Hugo Bajas and Gerard Willering

MT-26, Vancouver, 26th September 2019

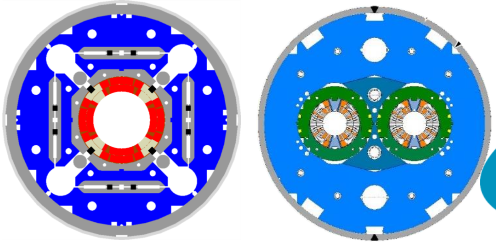
*T. Tarhasaari was with TAU, now with Jalonne OY

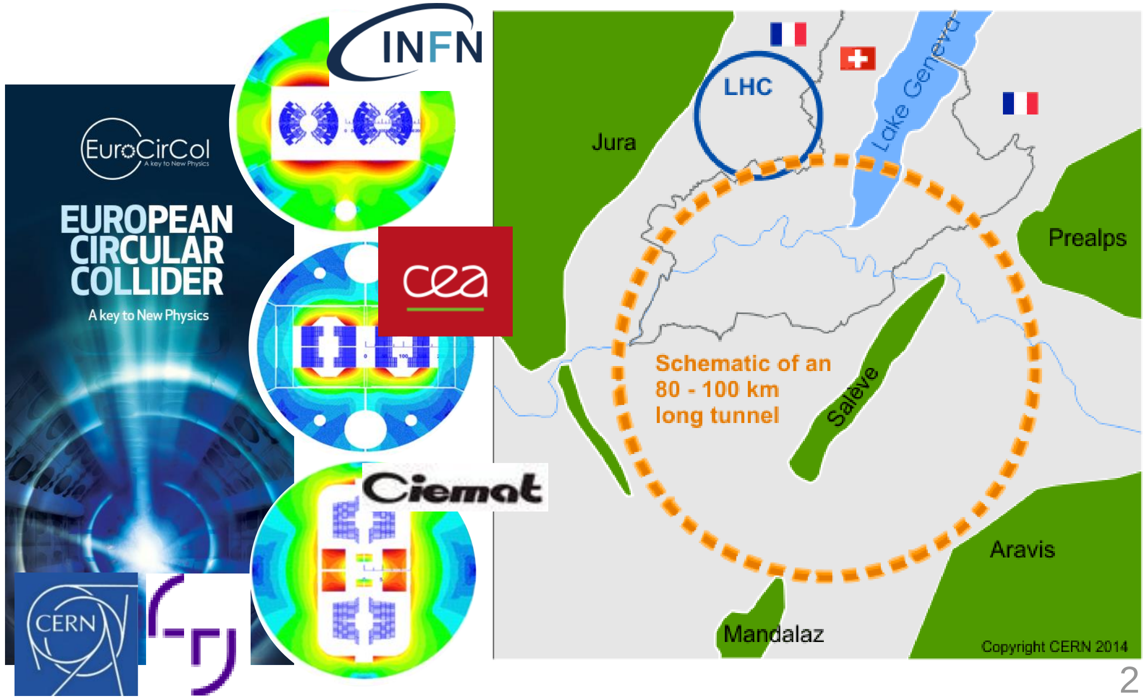
Context

FCC addendum for a CERN-TAU Project (2016-2018)

Project goals:

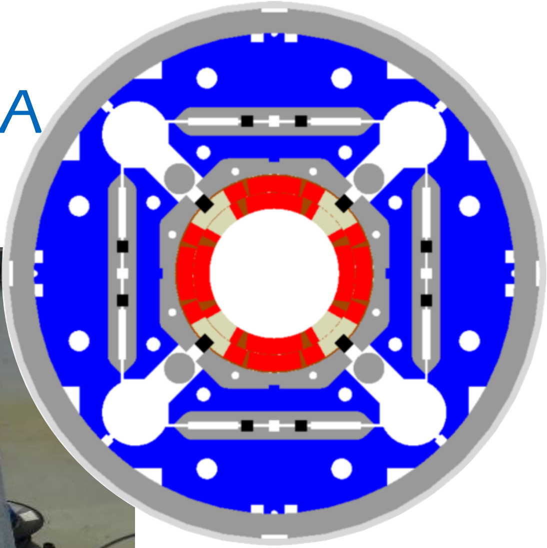
- Systematic analysis of quench heater tests in HL-LHC magnets
- Systematic data storage in an Excel-based database tool
- Validation of the simulation models used for the heater design for the FCC 16 T Nb_3Sn dipoles

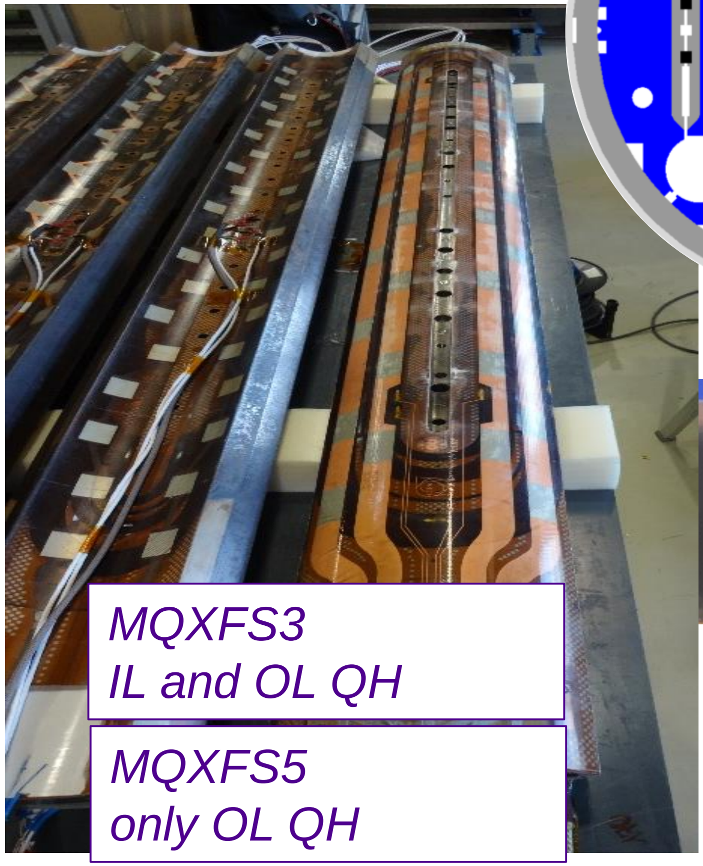




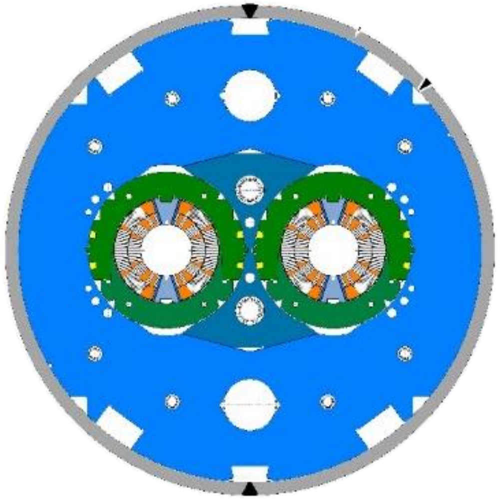
HL-LHC magnet models

MQXFS3, 5
1.2 m, 12 T, 16.5 kA
1.2 MJ/m





11 T:
SP101,3,5,6;
DP101
1.7 m, 11 T, 12 kA,
0.5 MJ/m/ ap.



Details of magnet designs can be found in [1-6],
the main paramters summarized also in the appendix

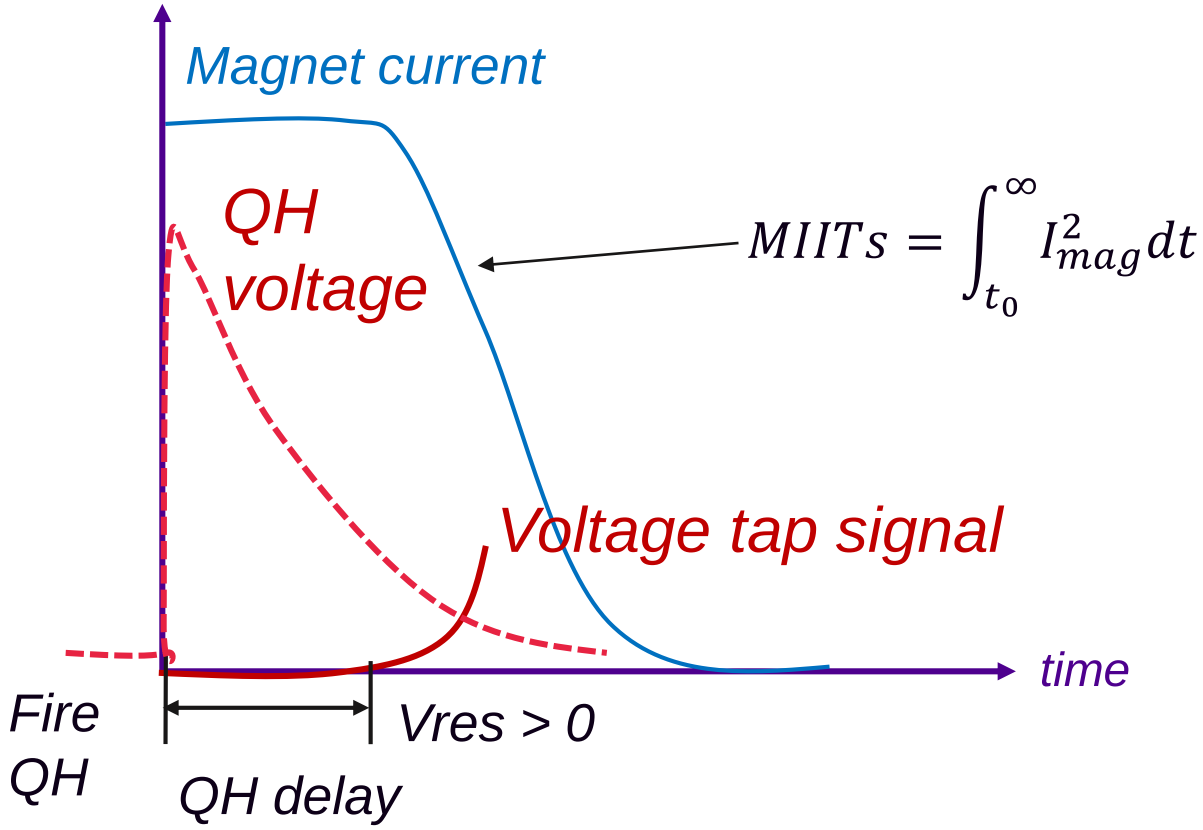
Quench heater (QH) tests

Measurement of heater delays

Time delay between firing a heater and a quench onset in coil

and quench integrals (MIITs)

How fast the current decays after activating heater-based protection?



Heater test results previously analyzed, see for example [4-10].
We re-analyzed the raw data to ensure all stored data is consistently interpretated.

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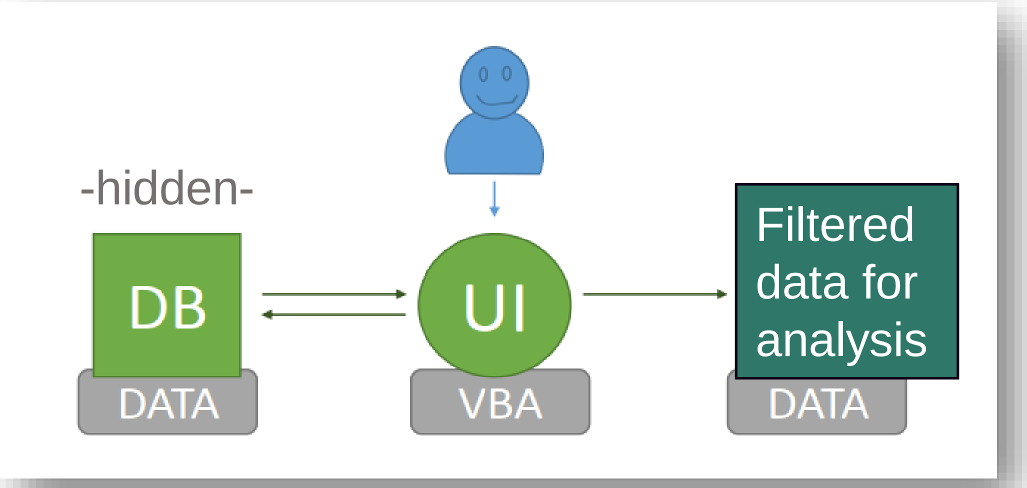
Quench Protection Database tool (QPDB)

- Consists of 2 Excel files:
  - **Datafile (DB)**
  - **User Interface (UI)**

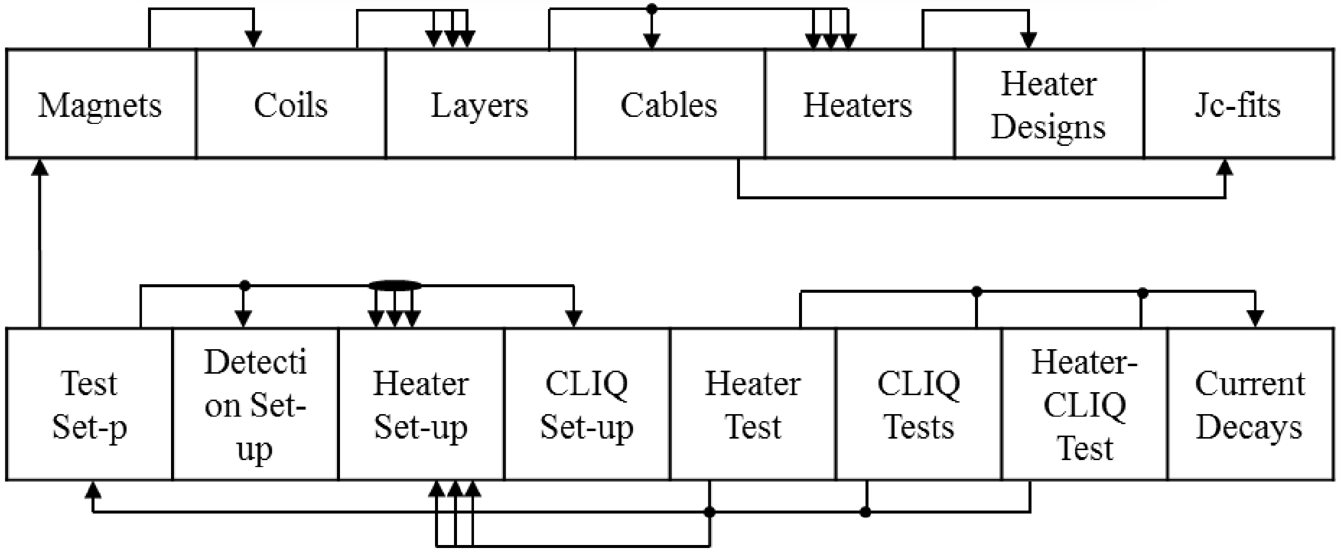
  - Relational
    - Items (coils, cables,..) are tables in their own tabs



- Aimed for logical structure, accounting all parameters relevant for heater tests

- Flexible for future modifications
  - E.g. adding other tests or simulations

- Reference for magnet design evolution



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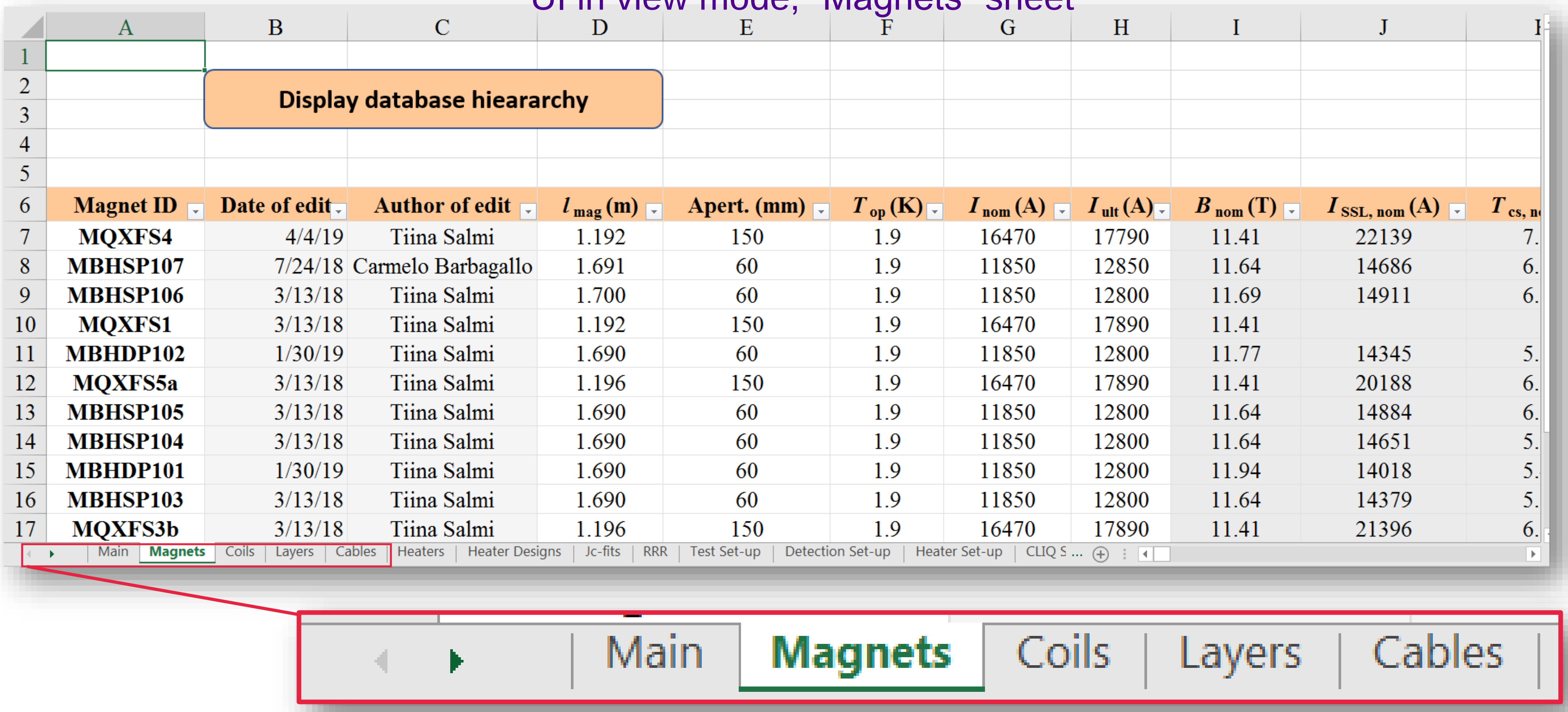
QPDB: Features

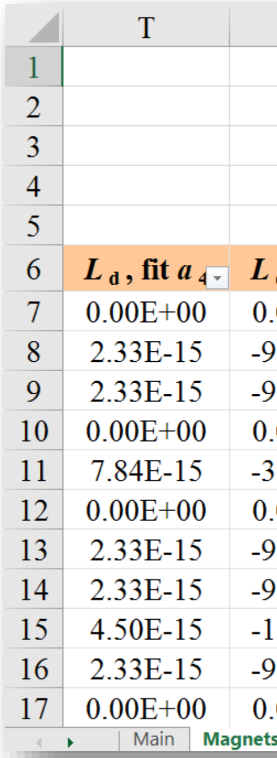
- Example of use and internally computed quantities

UI in view mode, ”Magnets” sheet



Magnet ID	Date of edit	Author of edit	l_{mag} (m)	Apert. (mm)	T_{op} (K)	I_{nom} (A)	I_{ult} (A)	B_{nom} (T)	$I_{SSL, nom}$ (A)	$T_{cs, n...}$
MQXFS4	4/4/19	Tiina Salmi	1.192	150	1.9	16470	17790	11.41	22139	7.
MBHSP107	7/24/18	Carmelo Barbagallo	1.691	60	1.9	11850	12850	11.64	14686	6.
MBHSP106	3/13/18	Tiina Salmi	1.700	60	1.9	11850	12800	11.69	14911	6.
MQXFS1	3/13/18	Tiina Salmi	1.192	150	1.9	16470	17890	11.41		
MBHDP102	1/30/19	Tiina Salmi	1.690	60	1.9	11850	12800	11.77	14345	5.
MQXFS5a	3/13/18	Tiina Salmi	1.196	150	1.9	16470	17890	11.41	20188	6.
MBHSP105	3/13/18	Tiina Salmi	1.690	60	1.9	11850	12800	11.64	14884	6.
MBHSP104	3/13/18	Tiina Salmi	1.690	60	1.9	11850	12800	11.64	14651	5.
MBHDP101	1/30/19	Tiina Salmi	1.690	60	1.9	11850	12800	11.94	14018	5.
MBHSP103	3/13/18	Tiina Salmi	1.690	60	1.9	11850	12800	11.64	14379	5.
MQXFS3b	3/13/18	Tiina Salmi	1.196	150	1.9	16470	17890	11.41	21396	6.

...



L_d, fit a_4	L
0.00E+00	0.
2.33E-15	-9
2.33E-15	-9
0.00E+00	0.
7.84E-15	-3
0.00E+00	0.
2.33E-15	-9
2.33E-15	-9
4.50E-15	-1
2.33E-15	-9
0.00E+00	0.

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QPDB: Features

- Example of use and internally computed quantities

UI in view mode, ”Magnets” sheet

Display database hieararchy

Magnet ID	Date of edit	Author of edit	l_{mag} (m)	Apert. (mm)	T_{op} (K)	I_{nom} (A)	I_{ult} (A)	B_{nom} (T)	$I_{SSL, nom}$ (A)	$T_{cs, n}$
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MBHDP102	1/30/19	Tiina Salmi	1.690	60	1.9	11850	12800	11.77	14345	5.
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Main | Magnets | Coils | Layers | Cables | Heaters | Heater Designs | Jc-fits | RRR | Test Set-up | Detection Set-up | Heater Set-up | CLIQ S ...

Quantities directly input — Internally computed

…

L_d, fit a_4	L
0.00E+00	0.
2.33E-15	-9
2.33E-15	-9
0.00E+00	0.
7.84E-15	-3
0.00E+00	0.
2.33E-15	-9
2.33E-15	-9
4.50E-15	-1
2.33E-15	-9
0.00E+00	0.

Main | Magnets

Internally computed e.g., cross-sections, resistances, I_{SSL}, T_{cs}, MIITs….

QPDB: Features

- Example of use and internally computed quantities

UI in view mode, ”Magnets” sheet

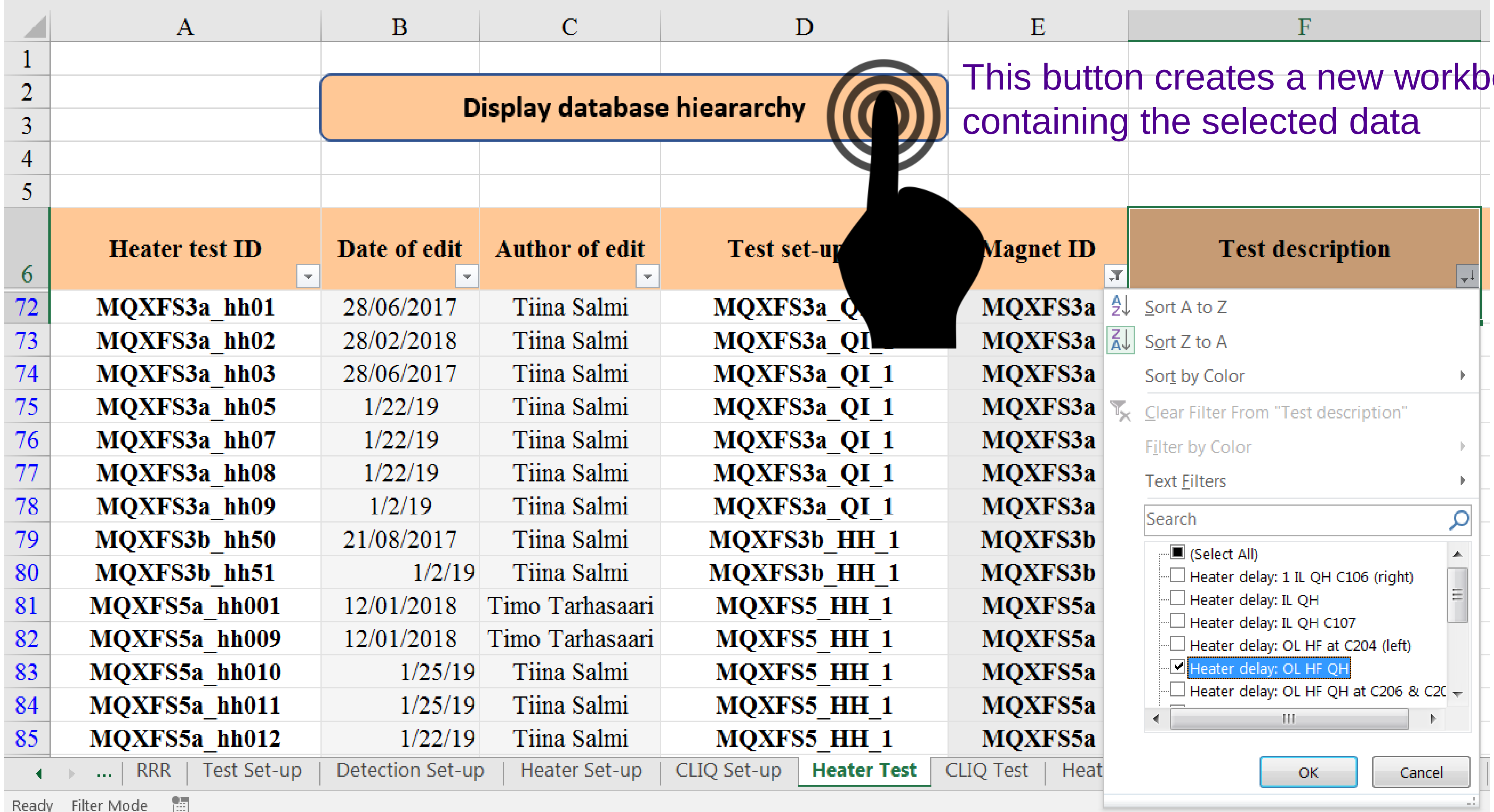
The keys linking magnet to its coils

	Magnet ID	L_d, fit a_4	L_d, fit a_5	L_d, fit a_6	Comments	References	Coil IDs	Column1	Column2	Column3
7	MQXFS4	0.00E+00	0.00E+00	0.00E+00			MQXF - C108	MQXF - C109	MQXF - C110	MQXF - C111
8	MBHSP107	2.33E-15	-9.42E-20	1.41E-24	Loadline wo s	[1] A. V. Zlobi	11T - C120	11T - C121		
9	MBHSP106	2.33E-15	-9.42E-20	1.41E-24			11T - C116	11T - C117		
10	MQXFS1	0.00E+00	0.00E+00	0.00E+00			MQXF - C103	MQXF - C104	MQXF - LP03	MQXF - LP05
11	MBHDP102	7.84E-15	-3.63E-19	6.22E-24	Loadline for 3D Bp with sf		11T - C109	11T - C112	11T - C114	11T - C115
12	MQXFS5a	0.00E+00	0.00E+00	0.00E+00			MQXF - C203	MQXF - C204	MQXF - C205	MQXF - C206
13	MBHSP105	2.33E-15	-9.42E-20	1.41E-24	Loadline wo s	[1] A.V. Zlobi	11T - C114	11T - C115		
14	MBHSP104	2.33E-15	-9.42E-20	1.41E-24	Loadline wo s	[1] A.V. Zlobi	11T - C112	11T - C113		
15	MBHDP101	4.50E-15	-1.50E-19	1.30E-24	Loadline for 3	[1] A.V. Zlobi	11T - C109	11T - C111	11T - C106	11T - C108
16	MBHSP103	2.33E-15	-9.42E-20	1.41E-24	Loadline wo s	[1] A.V. Zlobi	11T - C109	11T - C111		
17	MQXFS3b	0.00E+00	0.00E+00	0.00E+00	The same as MQXFS03a		MQXF - LP07	MQXF - C105	MQXF - C106	MQXF - C107

Main | Magnets | Coils | Layers | Cables | Heaters | Heater Designs | Jc-fits | RRR | Test Set-up | Detection Set-up | Heater Set-up | CLIQ S ...

→ VBA macros follow the links

Data selection & extraction



This button creates a new workbook containing the selected data

Data can be selected in the pivot tables

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Extracted workbook

- Stand-alone workbook with all measurement and manget parameters linked to the selection

Heater Test

Heater test ID	Date of edit	Author of edit	Test set-up ID
MQXFS3a_hh30	04/05/2018	Tiina Salmi	MQXFS3a_QI_1
MQXFS3a_hh31	04/05/2018	Tiina Salmi	MQXFS3a_QI_1
MQXFS3a_hh32	04/05/2018	Tiina Salmi	MQXFS3a_QI_1
MQXFS3a_hh33	04/05/2018	Tiina Salmi	MQXFS3a_QI_1
MQXFS3a_hh34	04/05/2018	Tiina Salmi	MQXFS3a_QI_1
MQXFS5a_hh049	12/01/2018	Timo Tarhasaari	MQXFS5_HH_1
MQXFS5a_hh050	12/01/2018	Timo Tarhasaari	MQXFS5_HH_1
MQXFS5a_hh051	12/01/2018	Timo Tarhasaari	MQXFS5_HH_1
MQXFS5a_hh054	1/22/19	Tiina Salmi	MQXFS5_HH_1
MQXFS5a_hh055	12/01/2018	Timo Tarhasaari	MQXFS5_HH_1
MQXFS5a_hh066	12/5/18	Tiina Salmi	MQXFS5a_HHC204
MQXFS5a_hh063	12/5/18	Tiina Salmi	MQXFS5a_HHC204
MQXFS5a_hh064	12/5/18	Tiina Salmi	MQXFS5a_HHC204
MQXFS5a_hh065	12/5/18	Tiina Salmi	MQXFS5a_HHC204

Test Set-up

Test set-up ID	Date of edit	Author of edit	Magnet ID
MQXFS3a_QI_1	26/04/2017	Tiina Salmi	MQXFS3a
MQXFS5_HH_1	10/11/2017	Tiina Salmi	MQXFS5a
MQXFS5a_HHC204	08/12/2017	Tiina Salmi	MQXFS5a

Magnet | Quench

&

Magnets

Magnet ID	Date of edit	Author of edit	l_{mag} (m)	Apert. (mm)	T_{op} (K)
MQXFS3a	3/13/18	Tiina Salmi	1.196	150	1.9
MQXFS5a	3/13/18	Tiina Salmi	1.196	150	1.9

Coils

Coil ID	Date of edit	Author of edit	N_{layers}	$R_{meas.}$ (Ohm)	$R_{comp.}$ (Ohm)
MQXF - LP07	06/04/2017	Timo Tarhasaari	2		0.200
MQXF - C105	06/04/2017	Timo Tarhasaari	2		0.199
MQXF - C106	06/04/2017	Timo Tarhasaari	2		0.200
MQXF - C107	06/04/2017	Timo Tarhasaari	2		0.199
MQXF - C203	27/10/2017	Tiina Salmi	2	0.184	0.200
MQXF - C204	27/10/2017	Tiina Salmi	2	0.182	0.198
MQXF - C205	27/10/2017	Tiina Salmi	2	0.182	0.198
MQXF - C206	27/10/2017	Tiina Salmi	2	0.182	0.198

Layers

Layer ID	Date of edit	Author of edit	N_{turns}	Cable ID	l_{cable} (m)
MQXF - LP07_L1	09/06/2017	Tiina Salmi	22	P43OL1062A	66
MQXF - LP07_L2	09/06/2017	Tiina Salmi	28	P43OL1062A	84
MQXF - C105_L1	09/06/2017	Tiina Salmi	22	H16OC0199A	66

Magnet | Quench

Simulation models for FCC

Heater delays with CoHDA

2D heat diffusion from heater to coil

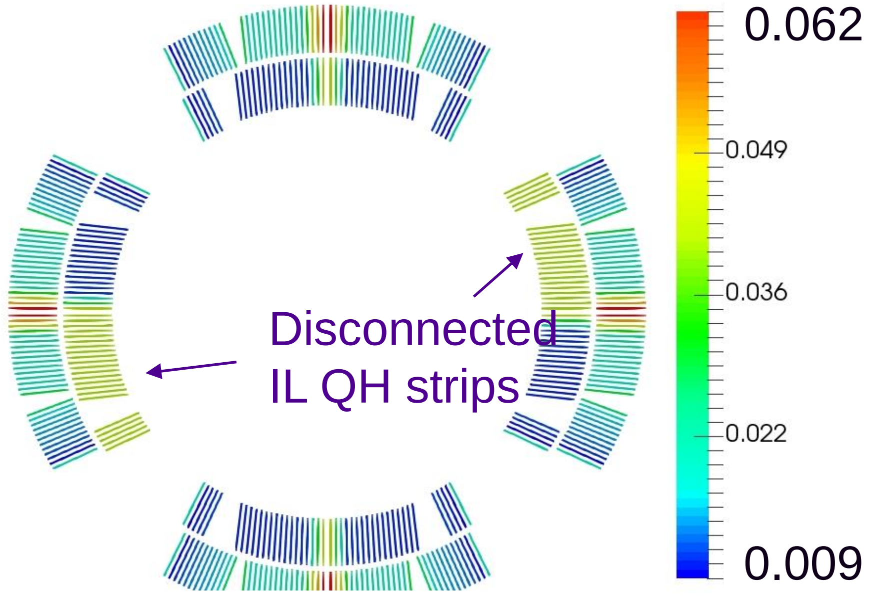
→Quench when cable Tcs reached

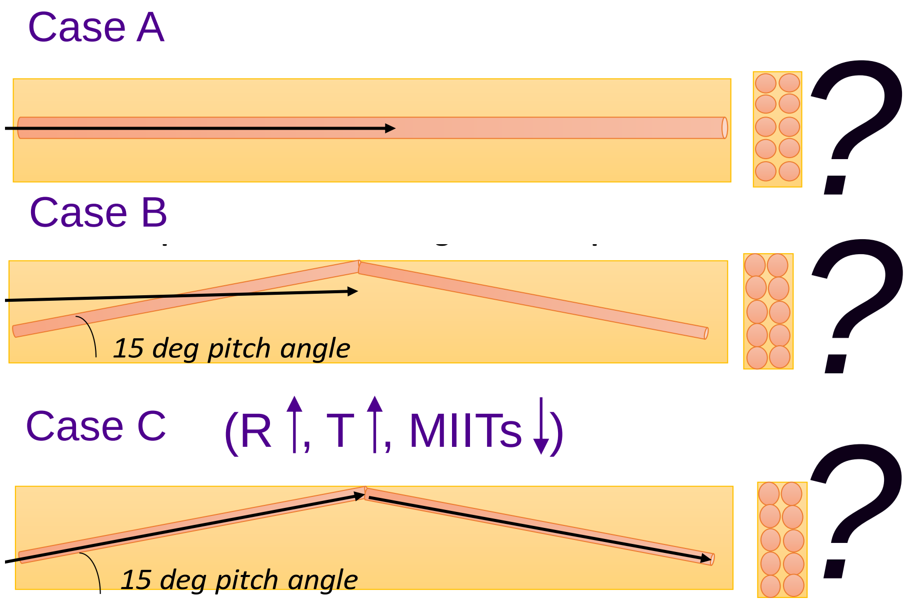
Current decays with Coodi

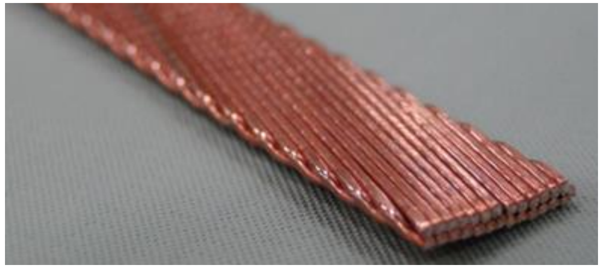
Coodi: Adiabatic model where QH delays & quench propagation input in each turn

Used the data to define how to simulate current flow in the cable

Simulated quench delay in MQXS3 (s)



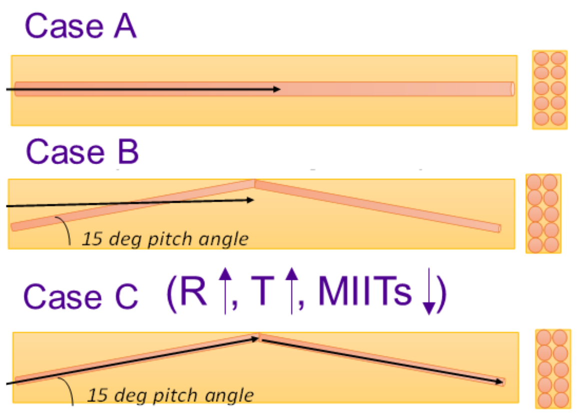




Cable photo from FNAL

Simulated vs. measured magnet resistance: MQXFS3b, QI with OL + IL QH

Options for current flow in cable:



MIITs starting from the heater activation

	$R_{mag,max}$ (Ω)	MIITs ($10^6 A^2 s$)	Δ MIITs (%)
Measurement	0.180	25.8	
Case A	0.175	27	5
Case B	0.163	28.5	11
Case C	0.179	26.3	2

Case C closest, MIITs within 2%

Also the coil RT resistance pointed towards Case C

Measured resistance from current decay

$$R(t) = -\frac{\ln\left(\frac{i(t+\Delta t)}{i(t)}\right) \mathrm{L(i)}}{\Delta \mathrm{t}}$$

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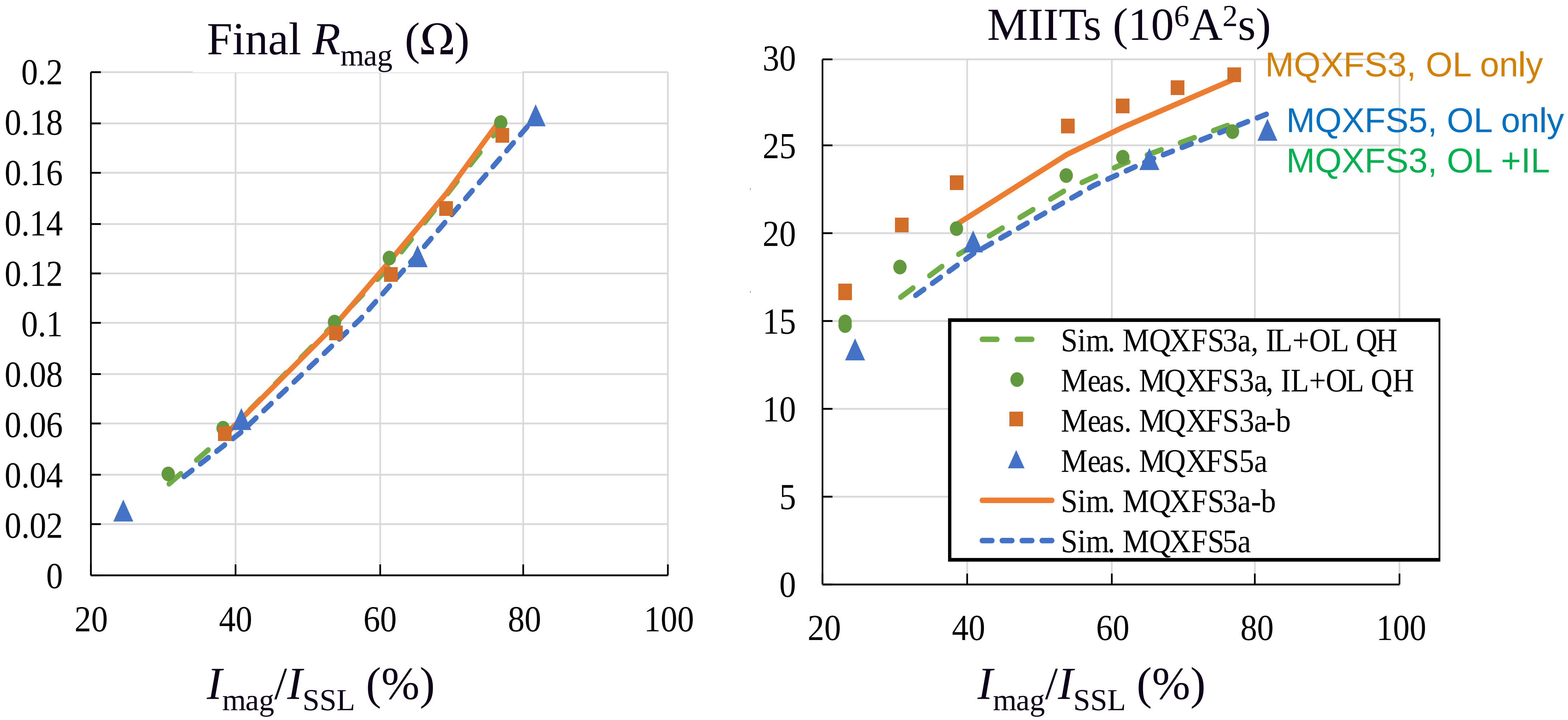
Simulation vs. measurement: MQXF



With Case C excellent agreeement in MQXFS5, tends to underestimate MIITs in MQXFS3 low current

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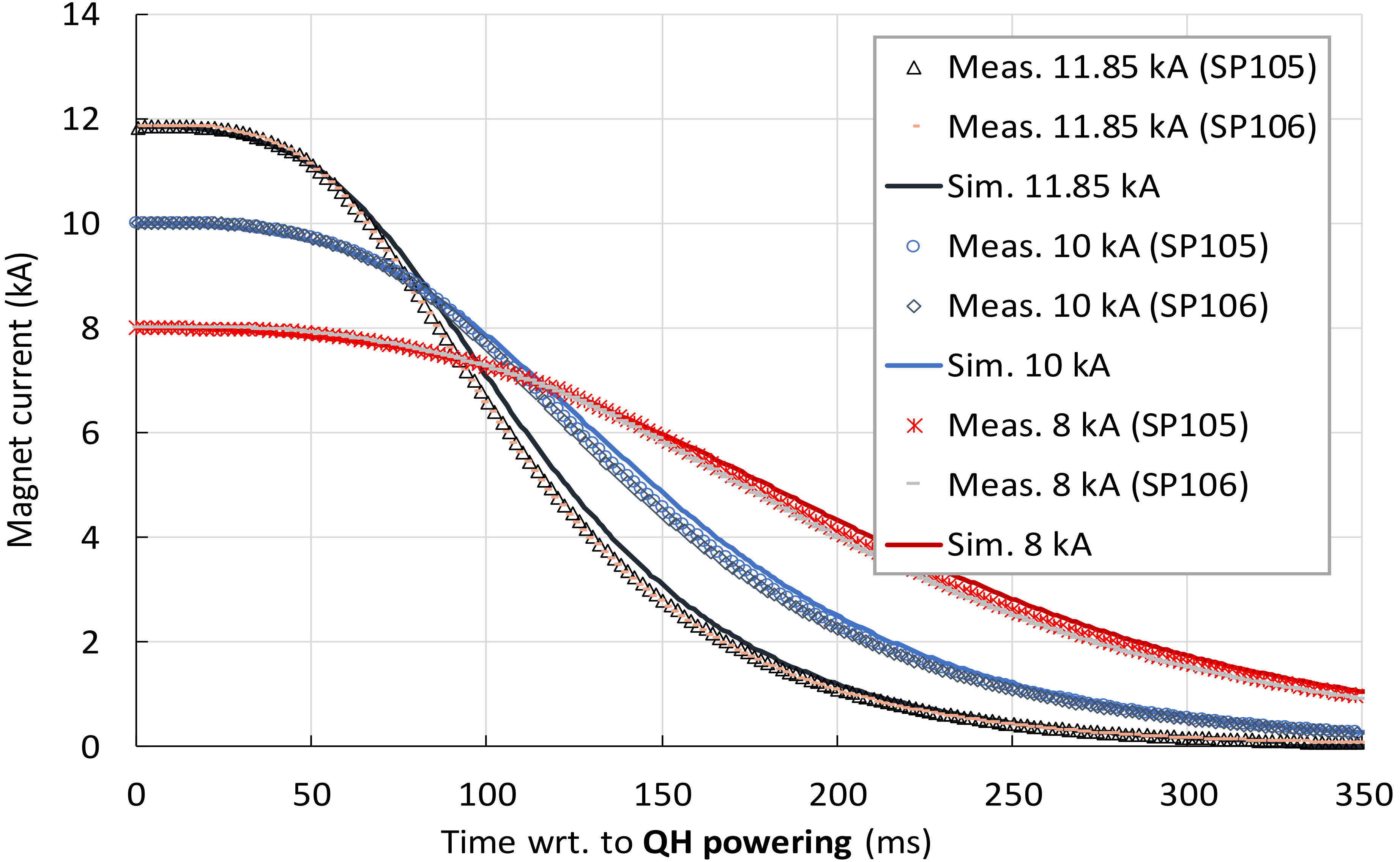
Simulated vs. measured current decay: 11 T

SP105 & SP106,
QI-study, OL QH



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Simulated vs. measured current decay: 11 T 11 T SP105

I_{mag} (kA)	R_{mag} (Ω)		$T_{avg.}$ (K)		MIIts (MA^2s)		Δ MIITs (%)
	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	
11.85	0.23	0.23	106	112	12.34	12.64	3
10.00	0.176	0.176	91	96	11.63	11.78	2
8.00	0.125	0.123	79	81	10.41	10.7	3
6.00	0.80±0.20	0.73	66±8	65	8.85	9.3	6

Simulated and measured MIITs for current decay after heater activation within 3%, above 8 kA

Conclusions

- Proposed a DB for storing magnet parameters and test data
  - Useful in all phases of magnet development

- Stored data from heater tests in HL-LHC prototypes tested at CERN

- Used data for validation of simulation assumptions in the FCC 16 T dipole magnet design
  - Helped to define cable simulation method

- Future of the tool uncertain due to required maintenance and competing systems

- This may be a useful too for personal use thanks to its relative simplicity and accessibility.
  - Contact if interested: tiina.m.salmi@tuni.fi

Thank you!

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References

[1]	P. Ferracin *et al*., "Development of MQXF: The Nb3Sn Low-βQuadrupole for the HiLumi LHC," *IEEE TAS*, 26(4), 2016
[2]	F. Savary et al., "Design and Construction of the Full-Length Prototype of the 11-T Dipole Magnet for the High Luminosity LHC Project at CERN," *IEEE TAS* 28(3), 2018
[3]	E. Ravaioli et al., “Quench Protection System Optimization for the High Luminosity LHC Nb3Sn Quadrupoles”, *IEEE TAS* 27(4), 2017
[4]	S. Izquierdo-Bermudez, et al.,“ Quench Protection of the 11 T Nb_3Sn Dipole for the High Luminosity LHC”, *IEEE TAS* 28(3), 2018
[5]	H. Bajas et al., "Test Result of the Short Models MQXFS3 and MQXFS5 for the HL-LHC Upgrade," *IEEE TAS* 28(3), 2018
[6]	G. Willering et al., "Comparison of Cold Powering Performance of 2-m-Long Nb3Sn 11 T Model Magnets," *IEEE TAS* 28(3), 2018
[7]	S. Izquierdo Bermudez et al., "Overview of the Quench Heater Performance for MQXF, the Nb3Sn Low-βQuadrupole for the High Luminosity LHC," *IEEE TAS* 28(4), 2018
[8]	S. Izquierdo Bermudez et al., "Quench Protection of the 11 T Nb3Sn Dipole for the High Luminosity LHC," *IEEE TAS* 28(3), 2018
[9]	S. Izquierdo Bermudez et al., "Quench Protection Studies of the 11-T Nb3Sn Dipole for the LHC Upgrade," *IEEE TAS* 26(4), 2016.
[10]	S. I. Bermudez et al., "Quench Protection Study of a 11 T Nb3Sn Model Dipole for the High Luminosity LHC," *IEEE TAS* 29(5), 2019

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Simulation tools and assumptions

Heater delays with CoHDA

- 2-D heat diffusion model for heater delays (accounts for the heater station length)
- Quench when cable maximum temperature reaches Tcs, computed based on maximum field in cable
- Thermal properties for based on cable average magnetic field
- T. Salmi et al., "A Novel Computer Code for Modeling Quench Protection Heaters in High-Field Nb_3Sn Accelerator Magnets", *IEEE TAS,* 24(4), 2014.
- T. Salmi et al., “Analysis of uncertainties in protection heater delay time measurements and simulations in Nb_3Sn high-field accelerator magnets” *IEEE TAS,* 25(4), 2015.

Current decay with Coodi

- Heater delay and quench propagation velocity are input for each turn
  - Quench propagation: 18 m/s btw heating stations, 11 ms btw turns, 22 ms btw layers at nominal current
- Adiabatic temperature calculation
- Coil cross-section discretized at turn level
- T. Salmi et al., “Quench protection analysis integrated in the design of dipoles for the Future Circular Collider”, Phys. Rev. Accel. Beams 20, 032401
- T. Salmi et al., ”The Impact of Protection Heater Delays Distribution on the Hotspot Temperature in a High-Field Accelerator Magnet”, *IEEE TAS,* 26(4), 2016.

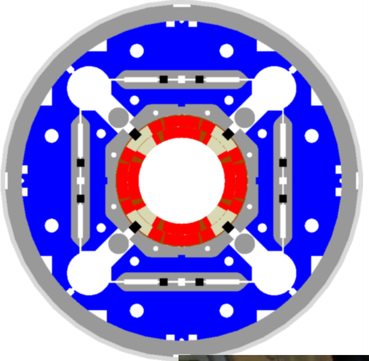
Material properties

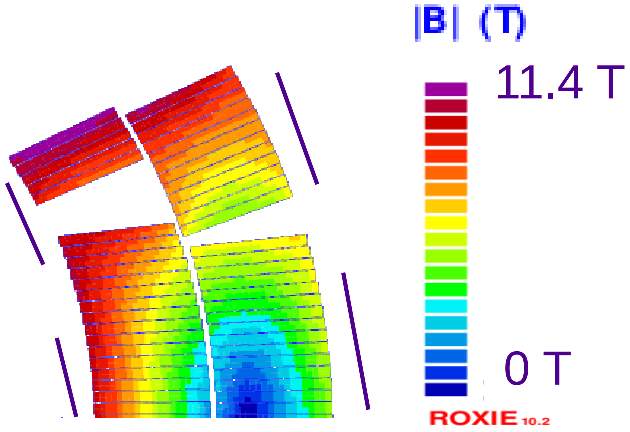
- Nb_3Sn specific heat capacity is based on G. S. Knapp, et al., “Phonon properties of A-15 superconductors obtained from heat-capacity measurements”, Phys. Rev. B 13, 3783–3789, 1976 above 20 K, and on L. Dresner, “Stability of superconductors”, Plenum, 1995 below 20 K
- Other material properties are based on NIST data NIST - E.D. Marquardt et al., "Cryogenic material properties database", in Proc. 11th Int. Cryocooler Conf., Keystone, 2000, http://cryogenics.nist.gov/MPropsMAY/material%20properties.htm

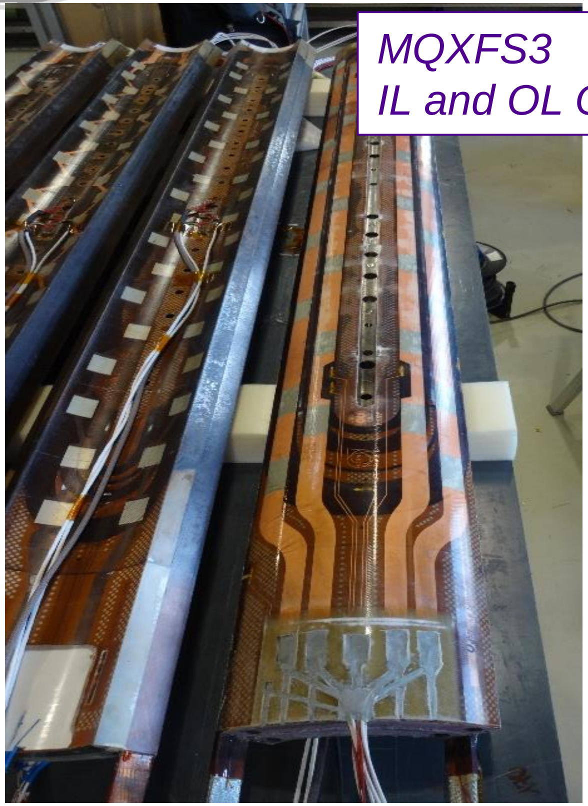
Appendix & extra material

HL-LHC magnets

MQXFS03a-b, 1.2 m

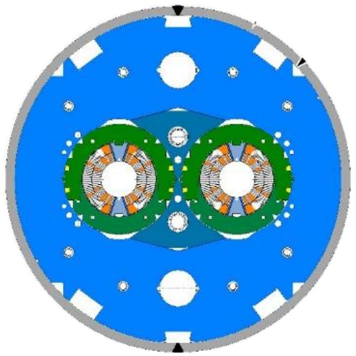


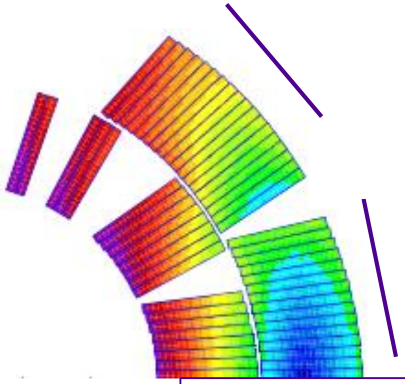




MQXFS3
IL and OL QH

11 T, 1.7 m





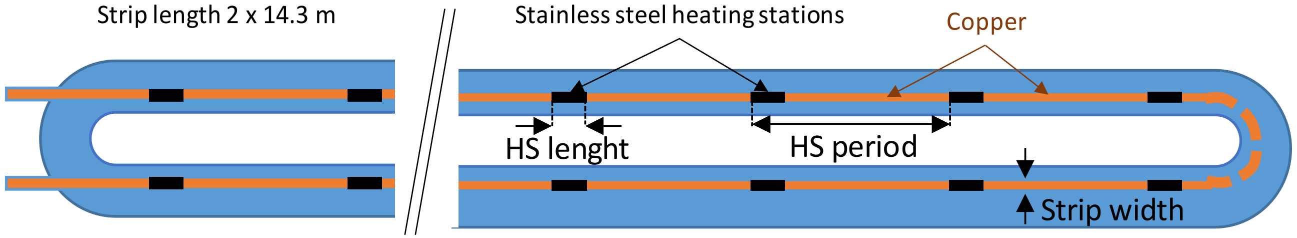
11 T OL QH

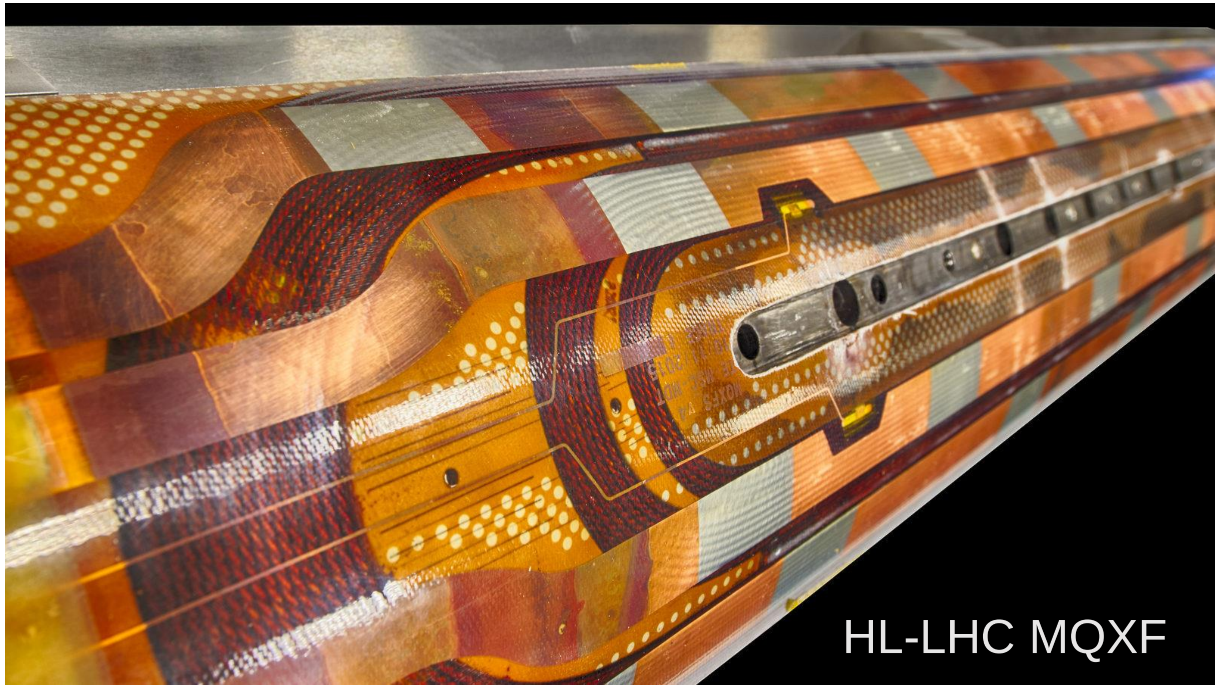
	MQXFS quads	11 T dipole SP104/SP105	ECC Cosθ HF / LF
I_{nom} (A)	16470	11850	11240
B_{peak} (T)	11.4	11.6	16.4
L_d (mH/m)	8.2	5.8	18.4 (1-ap.)
J_{eng} (A/mm^2)	469	523	370 / 515
J_{Cu} (A/mm^2) (one strand)	1330	1374 / 1563	~ 1170/1165
E_{stored} (J/mm^3)	129	130	~ 122
T_{max},40 ms delay (K)	260	280 / 310	310 (@I_{nom})
T_{max}, 20 ms delay (K)	190	200 / 210	240 (@I_{nom})

QH – Quench heaters

- :
  - Cu-plated stainless steel strips:
    - SS thickn. 25 µm, Cu thickn. 10 µm
  - **Insulation to coil: 50 µm polyimide**

- Powering with capacitor bank discharge:
  - (LHC: 900 V and 7 mF)

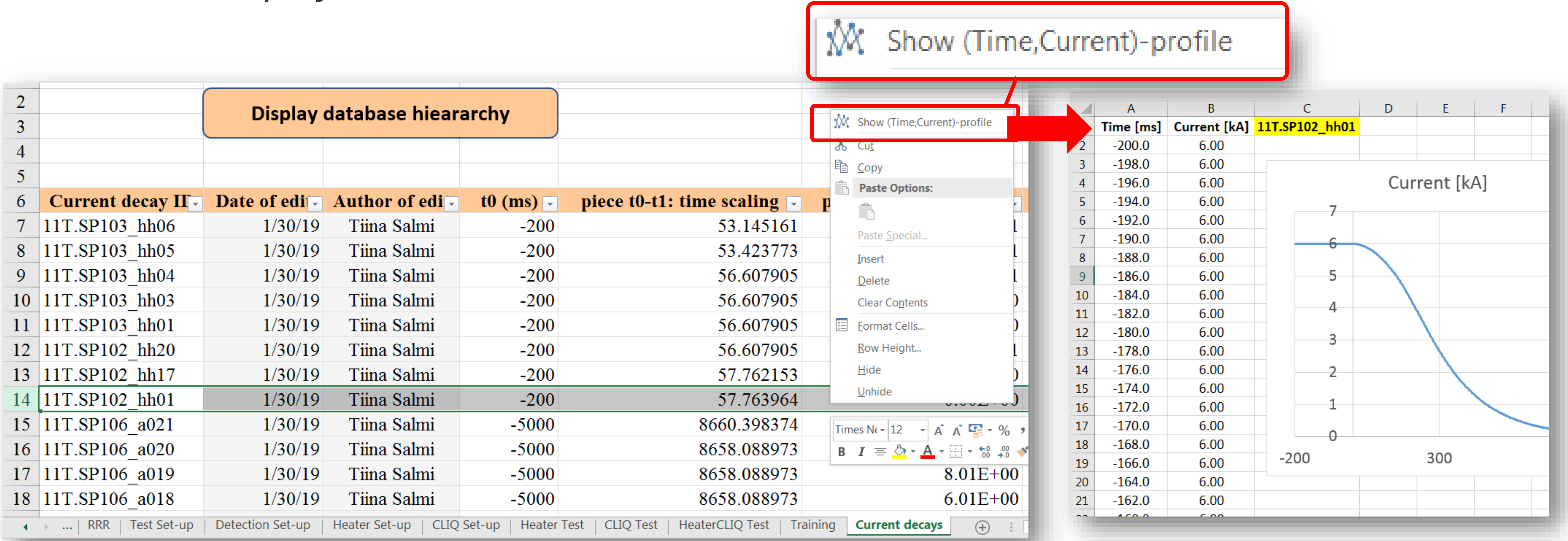




F. Rodriquez-Mateos and F. Sonneman, ”Quench heater studies for the LHC magnets”, Proc. of PAC, 2001.
H. Felice et al., ”Instrumentation and Quench Protection for LARP Nb3Sn Magnets”, *IEEE TAS,* 19(3), 2009.[3]P. Ferracin et al, ”Development of MQXF, the Nb3Sn Low-β Quadrupole for the HiLumi LHC ”, *IEEE TAS,* 26(4), 2016.

Storing of the current decay

- Piecewise polynomial fit

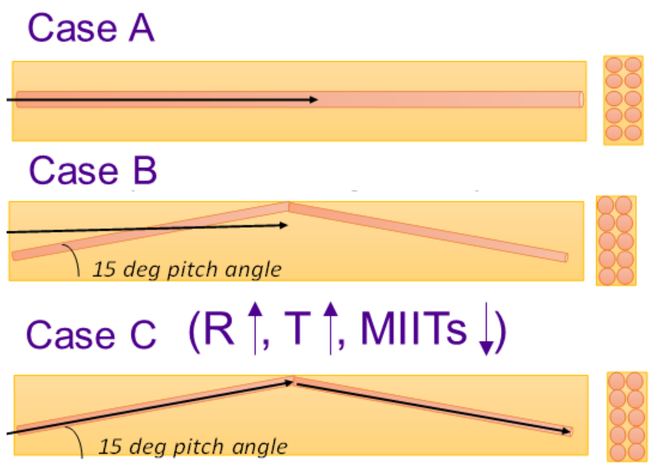


	Current decay ID	Date of edit	Author of edit	t0 (ms)	piece t0-t1: time scaling	p
7	11T.SP103_hh06	1/30/19	Tiina Salmi	-200	53.145161	
8	11T.SP103_hh05	1/30/19	Tiina Salmi	-200	53.423773	
9	11T.SP103_hh04	1/30/19	Tiina Salmi	-200	56.607905	
10	11T.SP103_hh03	1/30/19	Tiina Salmi	-200	56.607905	
11	11T.SP103_hh01	1/30/19	Tiina Salmi	-200	56.607905	
12	11T.SP102_hh20	1/30/19	Tiina Salmi	-200	56.607905	
13	11T.SP102_hh17	1/30/19	Tiina Salmi	-200	57.762153	
14	11T.SP102_hh01	1/30/19	Tiina Salmi	-200	57.763964	
15	11T.SP106_a021	1/30/19	Tiina Salmi	-5000	8660.398374	
16	11T.SP106_a020	1/30/19	Tiina Salmi	-5000	8658.088973	
17	11T.SP106_a019	1/30/19	Tiina Salmi	-5000	8658.088973	8.01E+00
18	11T.SP106_a018	1/30/19	Tiina Salmi	-5000	8658.088973	6.01E+00

	A	B	C
1	Time [ms]	Current [kA]	11T.SP102_hh01
2	-200.0	6.00	
3	-198.0	6.00	
4	-196.0	6.00	
5	-194.0	6.00	
6	-192.0	6.00	
7	-190.0	6.00	
8	-188.0	6.00	
9	-186.0	6.00	
10	-184.0	6.00	
11	-182.0	6.00	
12	-180.0	6.00	
13	-178.0	6.00	
14	-176.0	6.00	
15	-174.0	6.00	
16	-172.0	6.00	
17	-170.0	6.00	
18	-168.0	6.00	
19	-166.0	6.00	
20	-164.0	6.00	
21	-162.0	6.00	

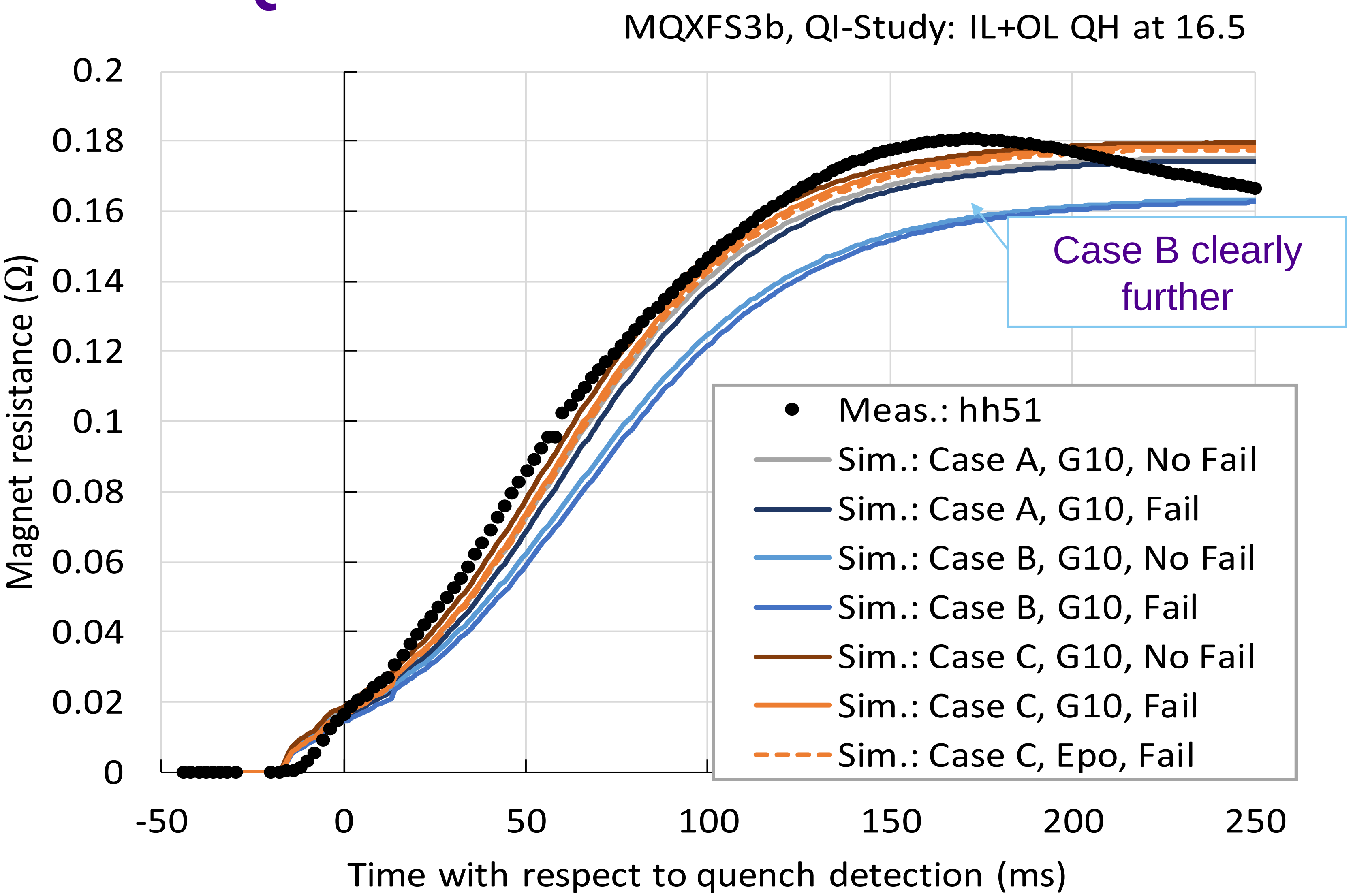
Simulated vs. measured magnet resistance: MQXFS3b, QI with OL + IL QH

Options for current flow in cable:



Measured resistance from current decay

$$R(t) = -\frac{\ln\left(\frac{i(t+\Delta t)}{i(t)}\right) \mathrm{L(i)}}{\Delta \mathrm{t}}$$

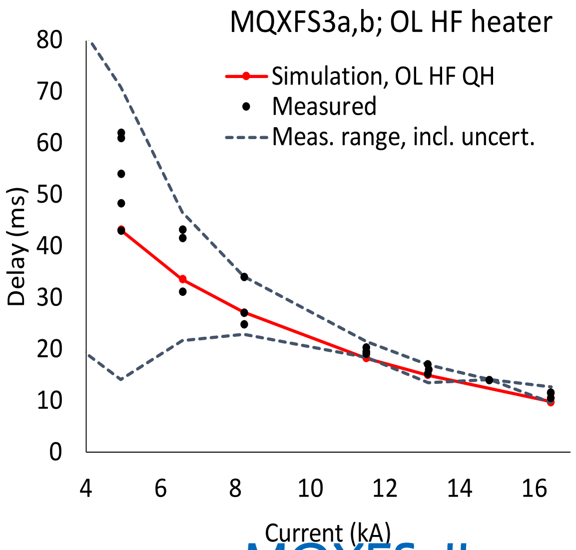


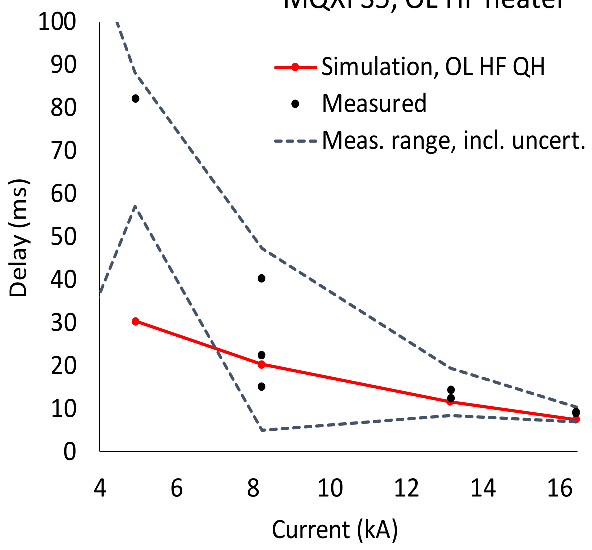
Analysis of quench heater delays

- Defining quench onset is not alwas clear
- We stored best estimate and error bars estimating the range of possible quench onset
- Typically uncertainty is larger at lower currents

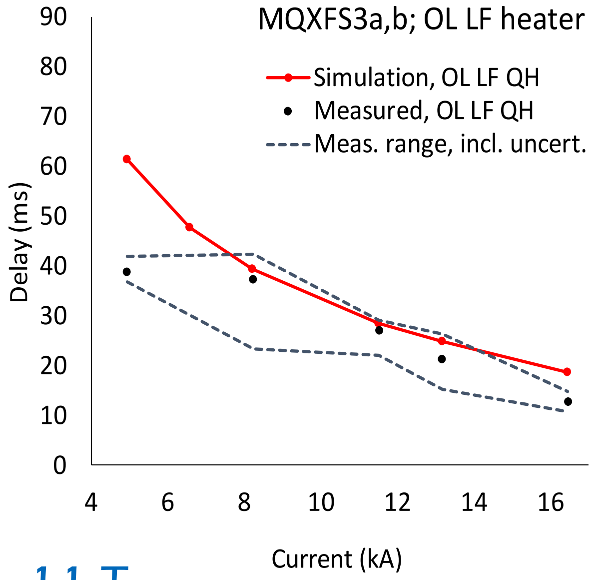
Summary of QH delays: MQXF

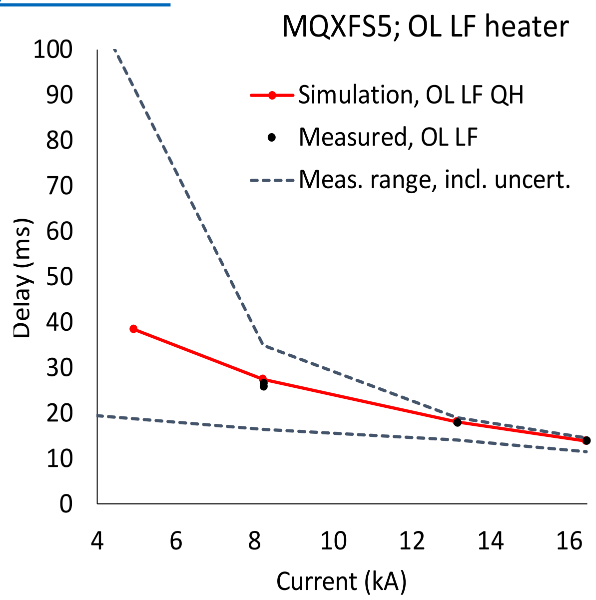
MQXFS, OL HF



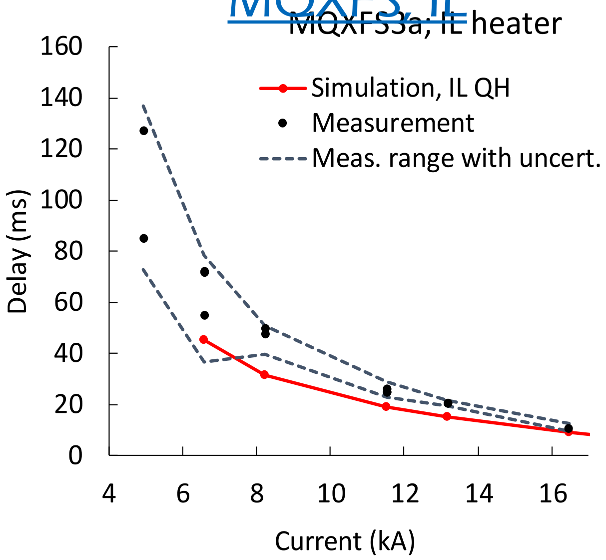


MQXFS, OL LF

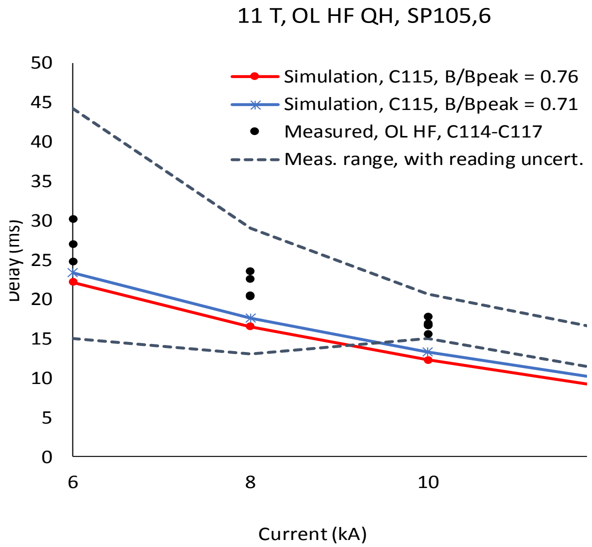


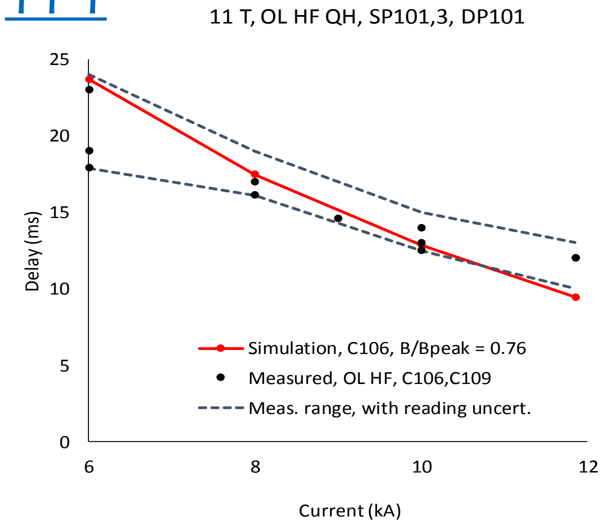


MQXFS, IL



11 T



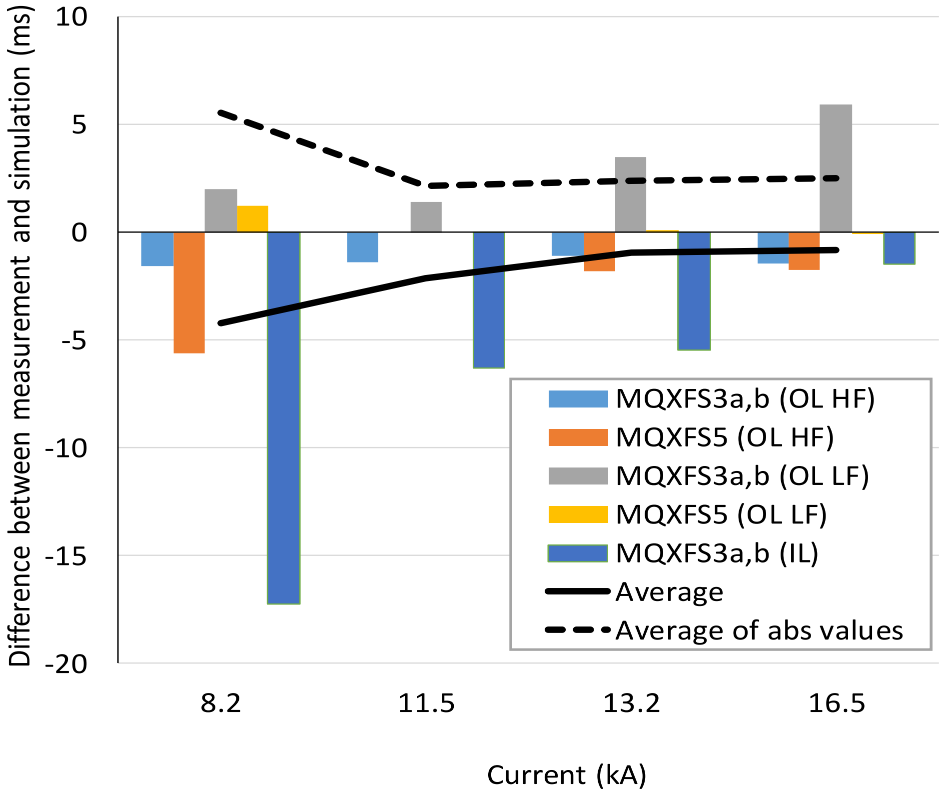


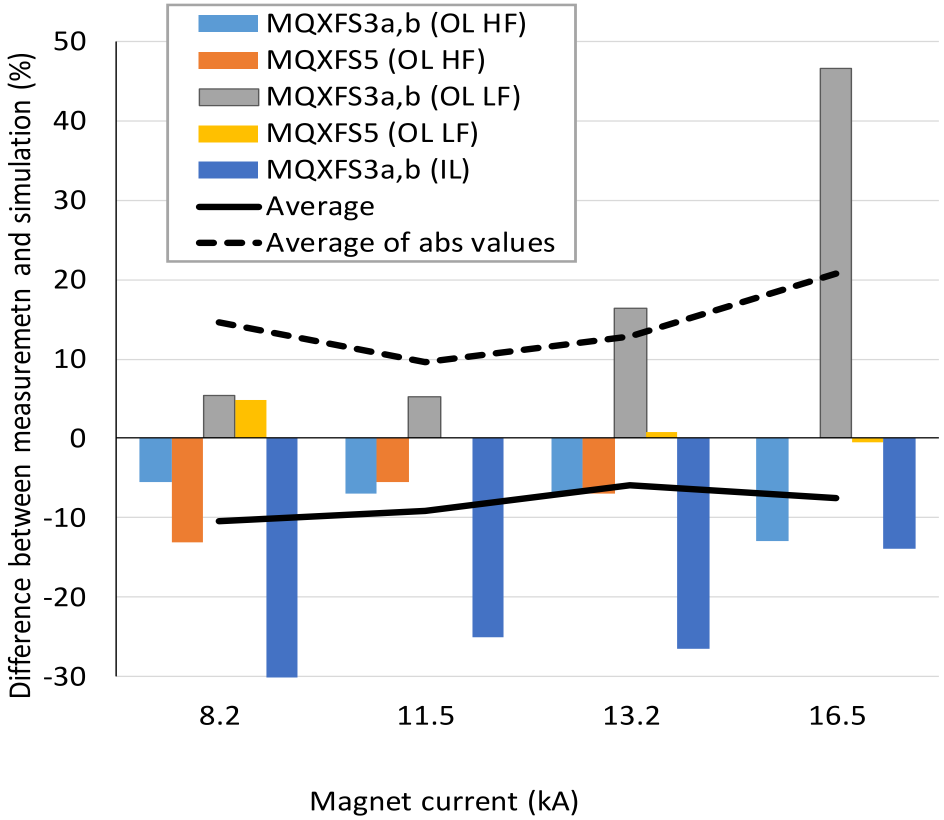
Difference of simulation and average measured is mostly within 20%

The exceptions are MQXFS3 OL LF at I_{nom}, and IL below I_{nom}

Difference between simulation and measurement (MQXF)

- Comparison to average of simulated values at each current, for each heater test type
- The difference is signicant (>20%) for MQXFS3 LF heater at nominal current, and IL heaters at lower than nominal
  - IL expected, LF to be studied better after more measurements





Average uncertainty

- An attempt to include the signal reading uncertainty, and the measurement reproducibility

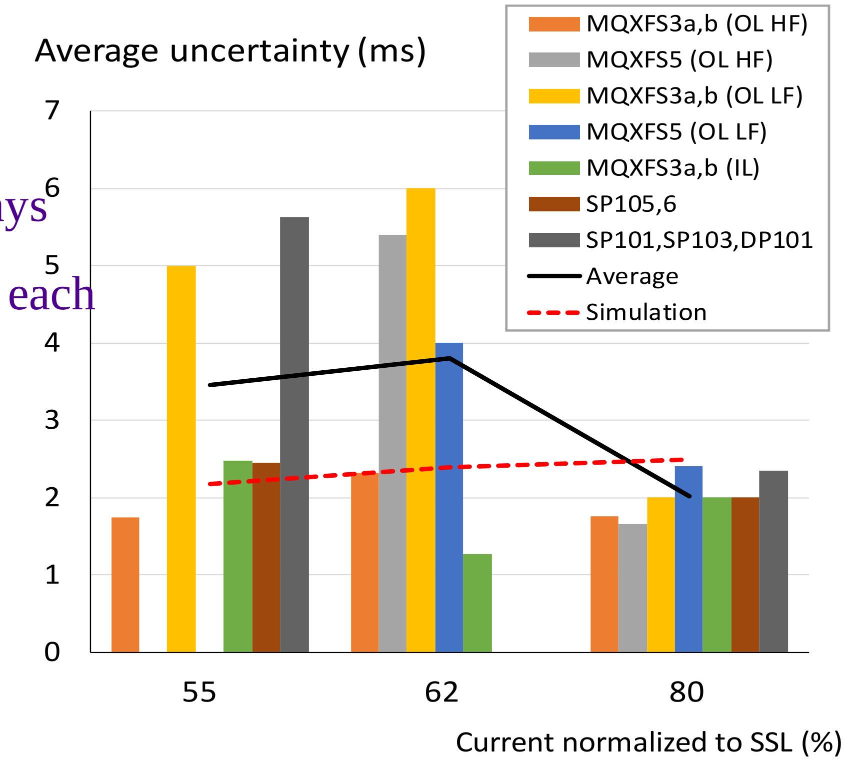
$$\varepsilon_{avg} = \frac{1}{n}\sum_{i=1}^{n}(t_{d,i} - t_{d,avg}) + \frac{1}{n}\sum_{i=1}^{n}(\Delta t_{d,max,i})$$

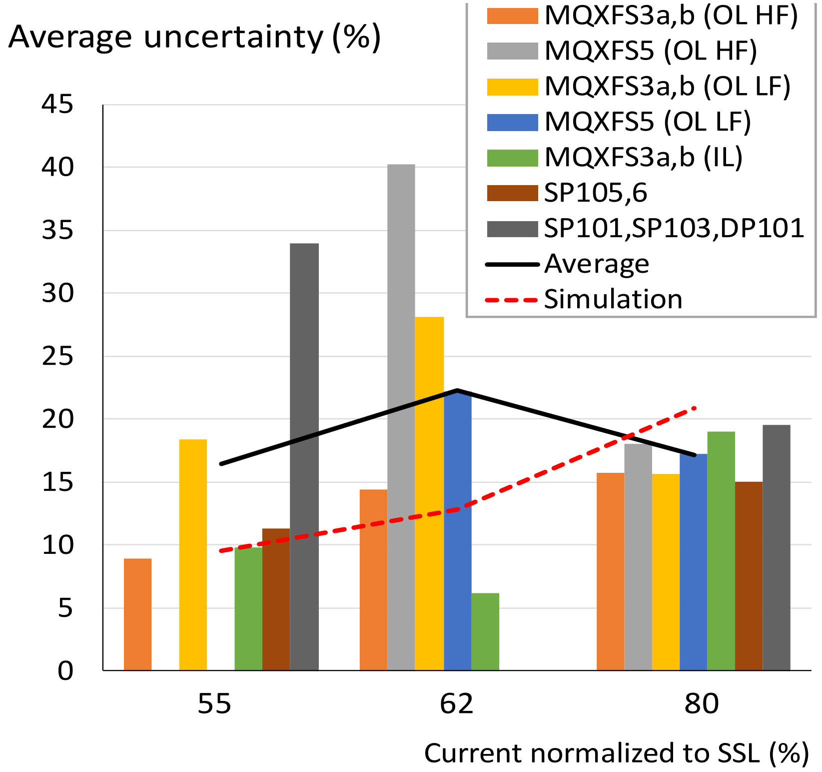
n: Number of measurements

$t_{d,i}$: Measured delay

$t_{d,avg}$: Average of measured delays

$\Delta t_{d,max,i}$: Larger error bar in each delay measurement





Needs more data to be useful parameter

Magnet resistance relation to final average temperature

MQXFS3b, IL + OL QH at nominal current