Voltage transient simulations of the LHC main dipoles

Marvin Janitschke, TE-MPE-PE, DOCT

Acknowledgements:
*Special thanks to: E. Ravaioli, C. Wiesner, M. Wozniak, M. Bednarek,
R.G. Saederup and all colleagues involved in the LHC FPA snapshot tests*

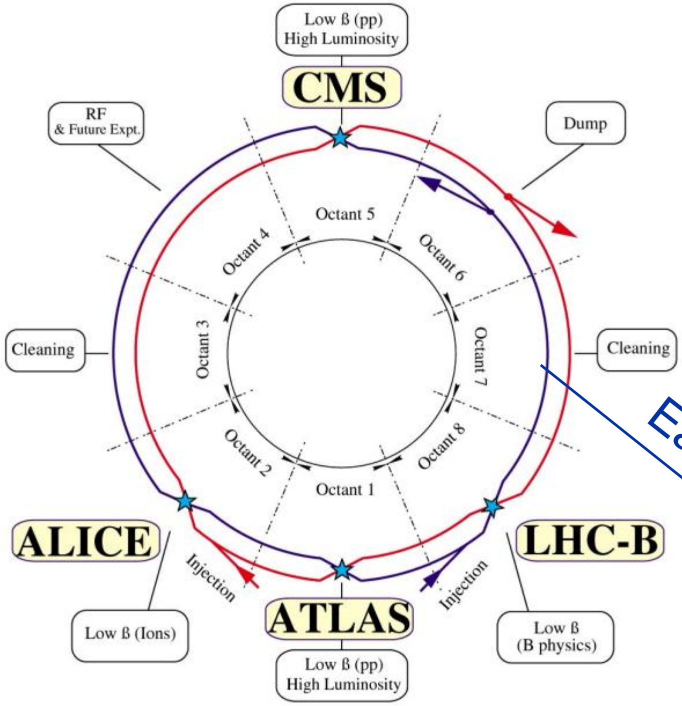
Universität Rostock

Traditio et Innovatio

Bundesministerium
für Bildung
und Forschung

Gentner scholarship

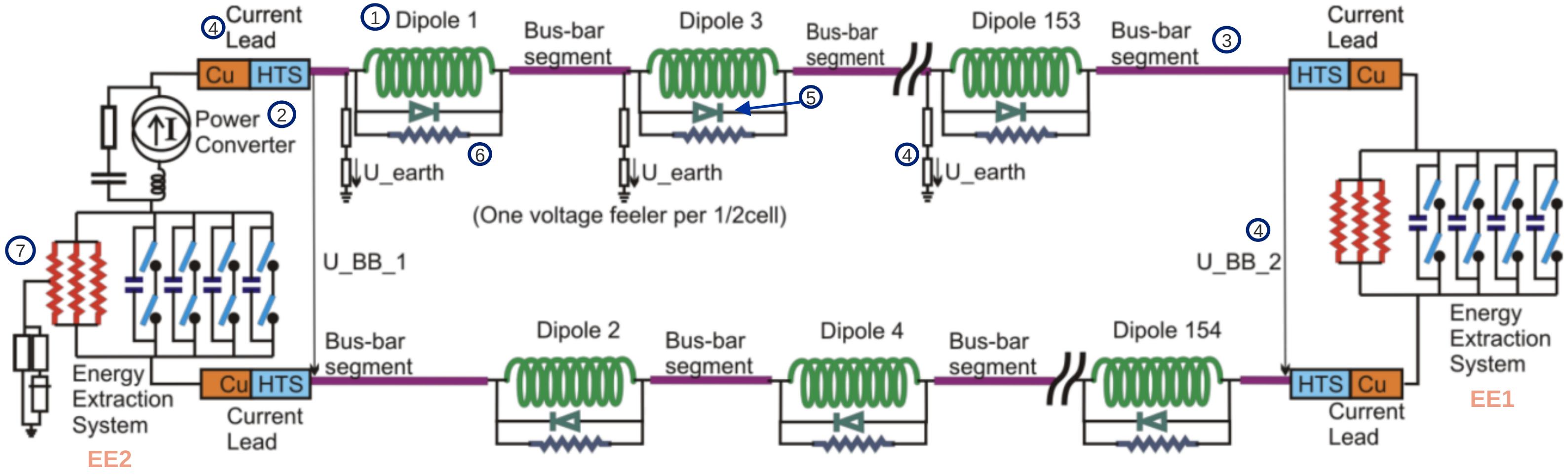
Main dipole LHC circuit



Each octant

<u>Each circuit consists of:</u>

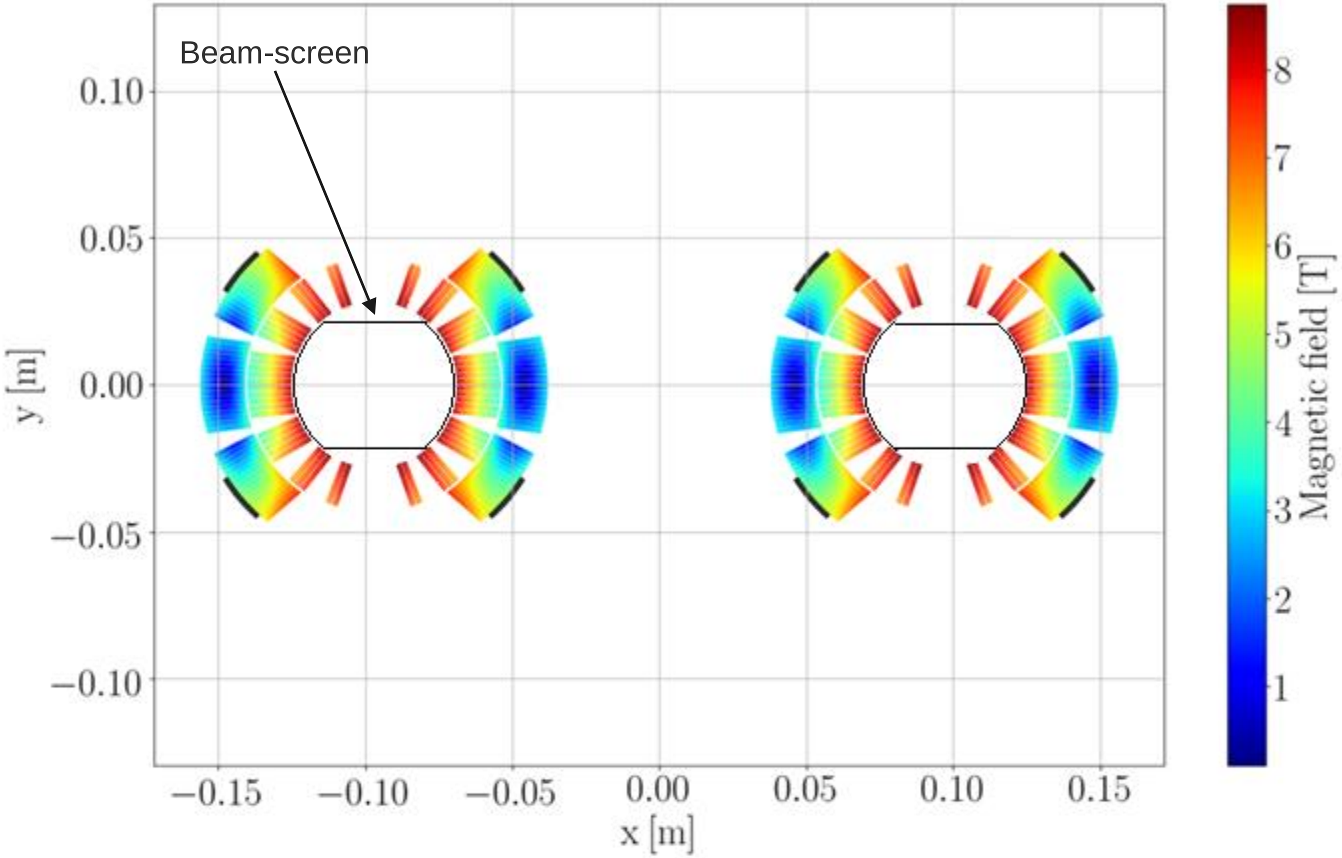
- 154 MB dipoles ①
- 13 kA power converter (PC) ②
- Bus-bars between magnets ③
- Current leads, sensing devices and earth fault systems ④



<u>Protection</u>

- Protection by-pass diodes ⑤
- Protective parallel resistors ⑥
- 4x Quench heater per magnet aperture
- 2x Energy extraction systems for protection (EE) ⑦

LHC main dipole magnet



Beam-screen and quench heaters not to scale

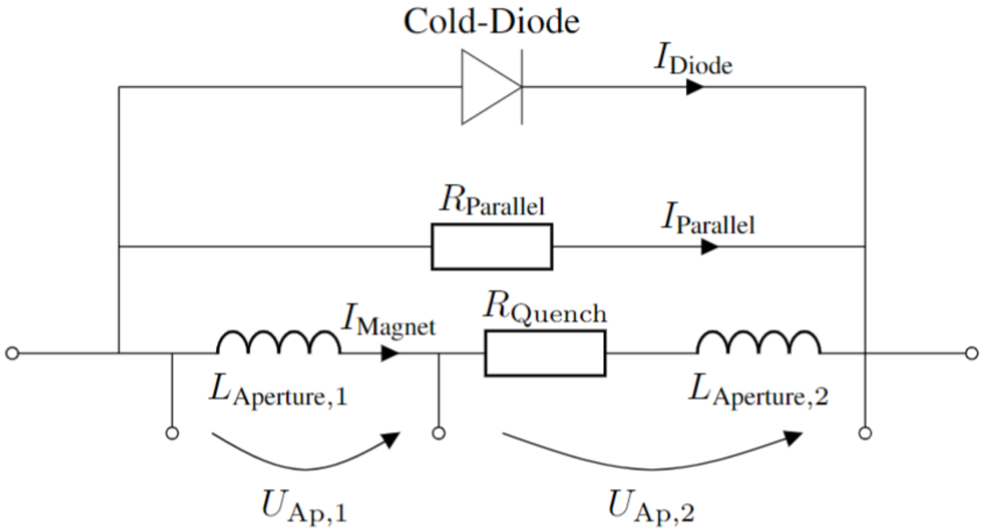
Parameter	Value	Unit
Length	14.3	m
Operating temperature	1.9	K
Nominal field	8.33	T
Current at nominal field	11850	A
Inductance at nominal field	98.7	mH
Stored energy at nominal field	1.3	GJ
Inner coil diameter	56	mm

Quench detection systems

- Quenches in the main dipoles are detected in 2 ways:

① Via voltage taps at extremes and middle point:

iQPS



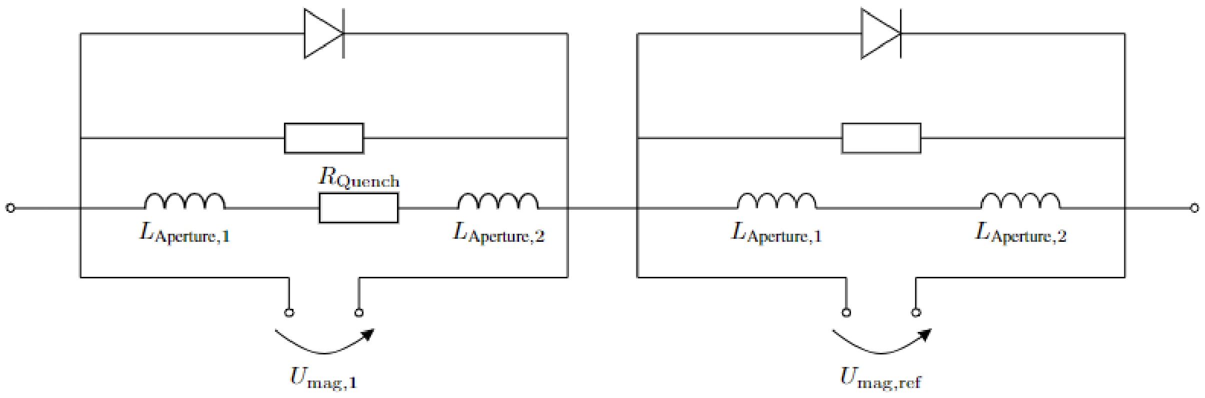
$$U_{QS,0} = U_{Ap,1} - U_{Ap,2}$$

If $U_{QS,0} > 100$ mV: Quench detected!

Problem: Symmetric quench!

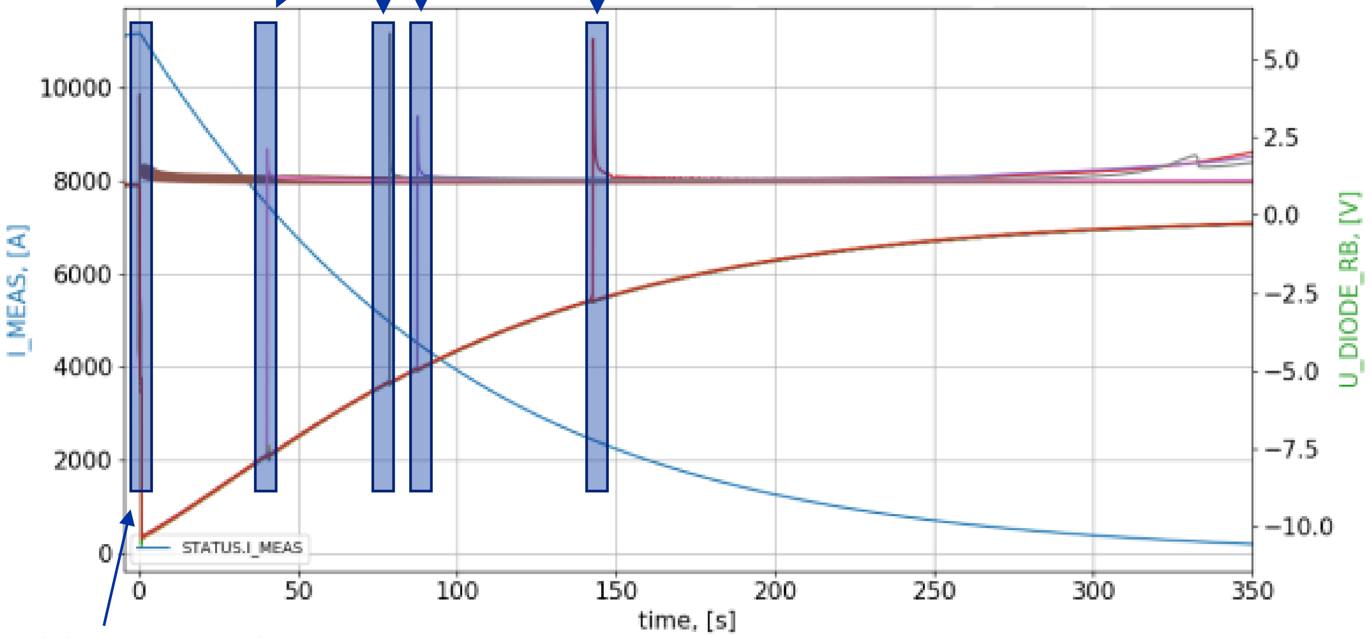
② Comparing voltages across 4 adjacent magnets:

nQPS



If voltage across a full magnet differs from its reference:
→ Quench detected

Usual transient in main dipole circuit



Subsequent quenches

Initial quench

Event	Name	Time
1.	Quench detection	~ -10 ms
2.	Fast Power Abort	~ 0 s
3.	Opening of the first energy extraction (middle of chain)	~ 100 ms
4.	Opening of the second energy extraction (end of chain)	~ 600 ms
5.	End of discharge	~ 350-400 s

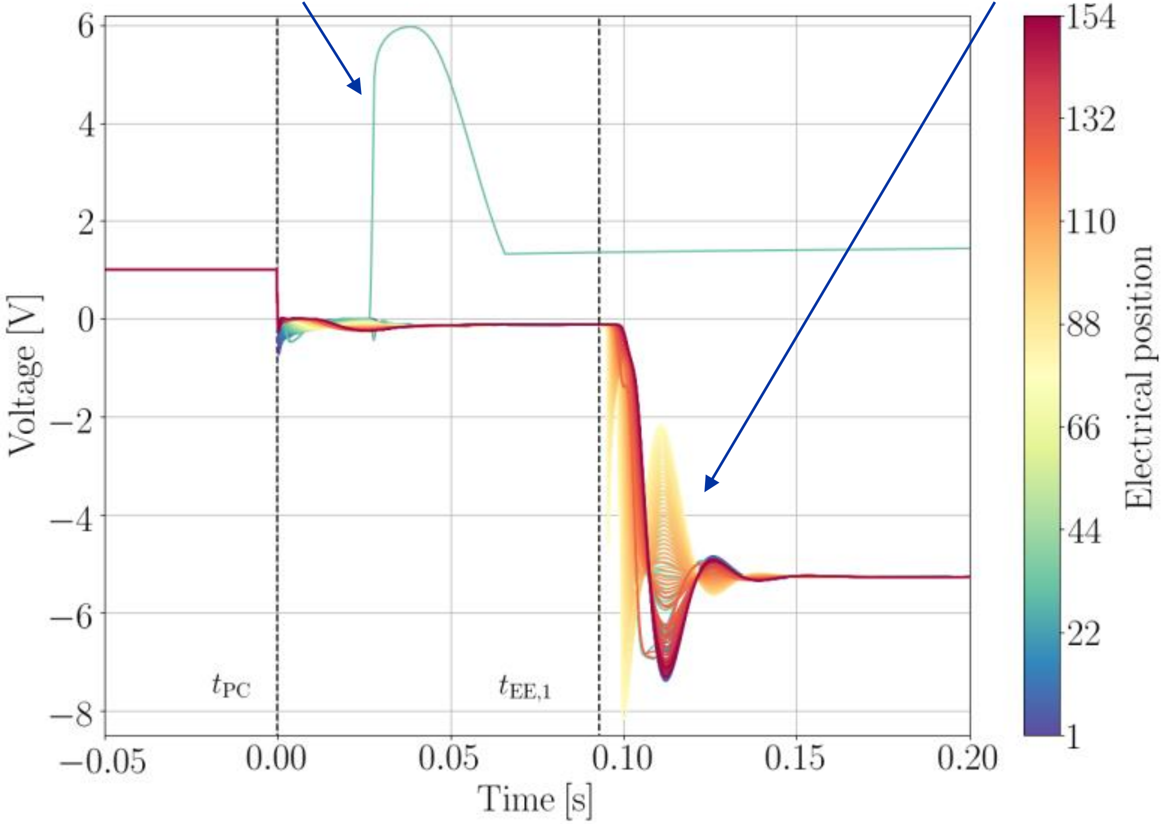
Subsequent quenches due to:

- Gaseous helium propagation
- **Spurious triggering of quench protection**
- …

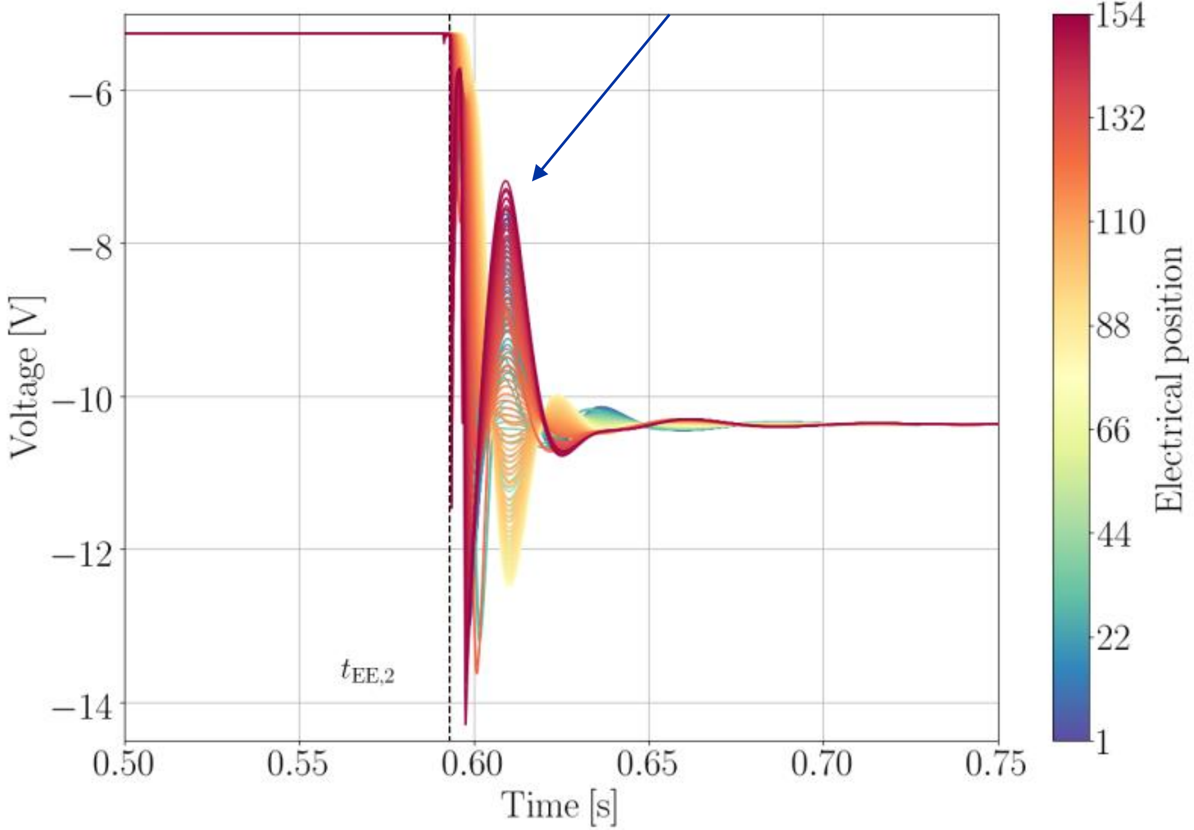
Usual transient in Main dipole circuit

Developed resistance in magnet leads to diode opening

Wave progagates from the middle towards the ends



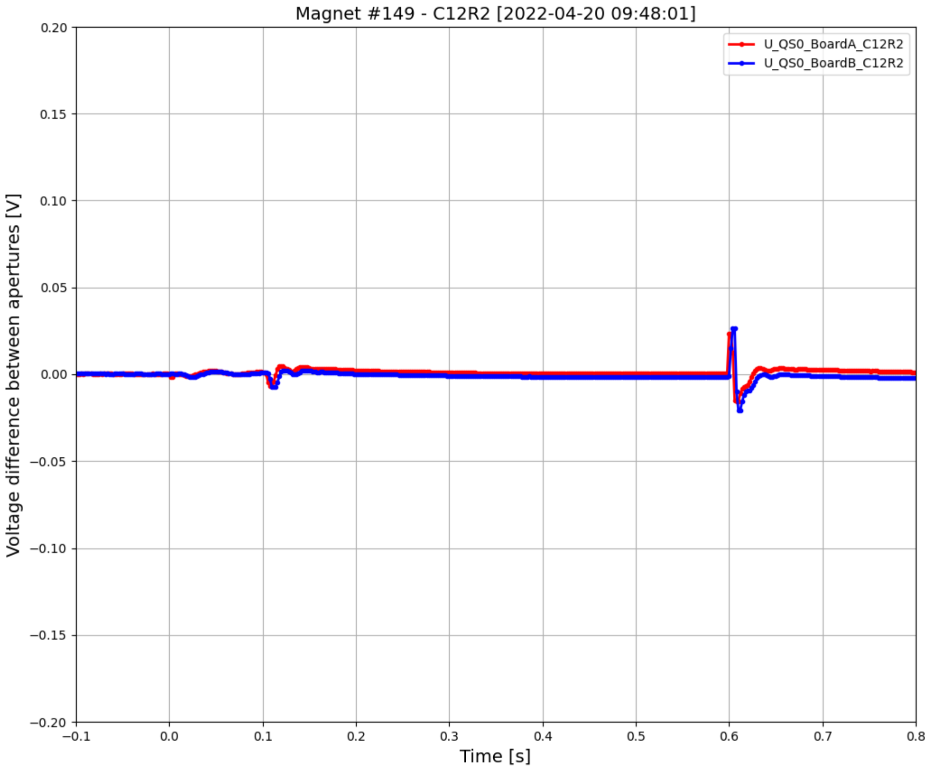
From the beginning towards the center



After each switch opening (PC, EE1, EE2) we observe voltage waves travelling through the magnet
→ Exponentially decaying wave seeing a different phase shift at each magnet
+ Further phenomena like superposition/ reflection etc.

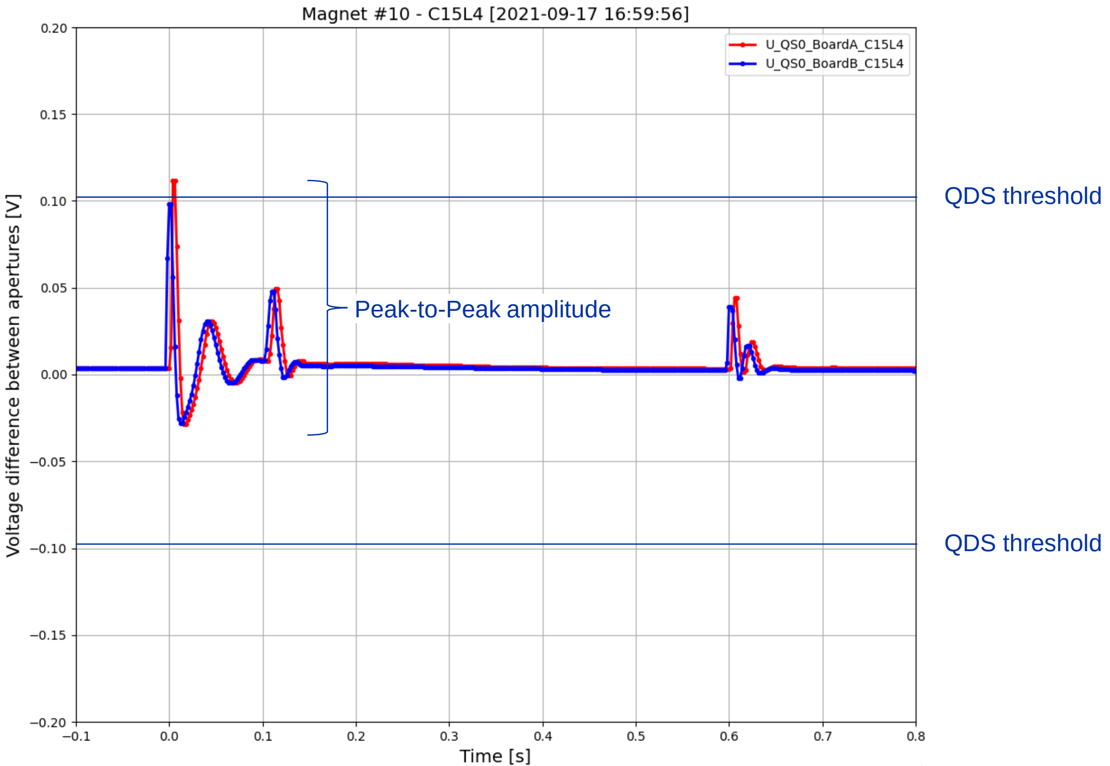
Typical examples of the $U_{QS,0}$ signal

Normal $U_{QS,0}$ signal in a transient



Flat signal with only very little bumps
Expected, as magnet apertures are supposingly identical

Other recorded $U_{QS,0}$ signals



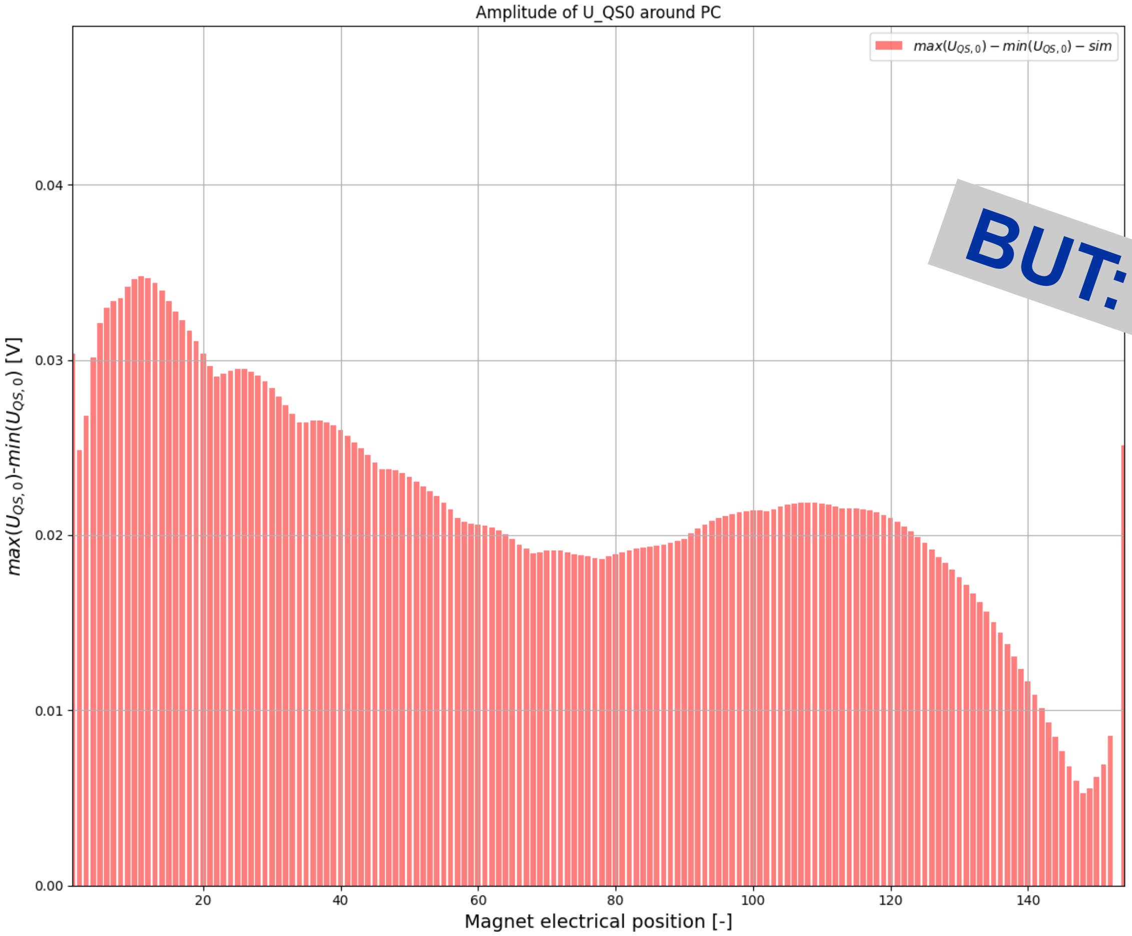
Significant bumps, which can occur at PC, EE1 or EE2
Bumps sometimes even shortly cross QDS thresholds
→ potential spurious triggering
Indicate impedance differences between the apertures

Unbalanced dipole impedance

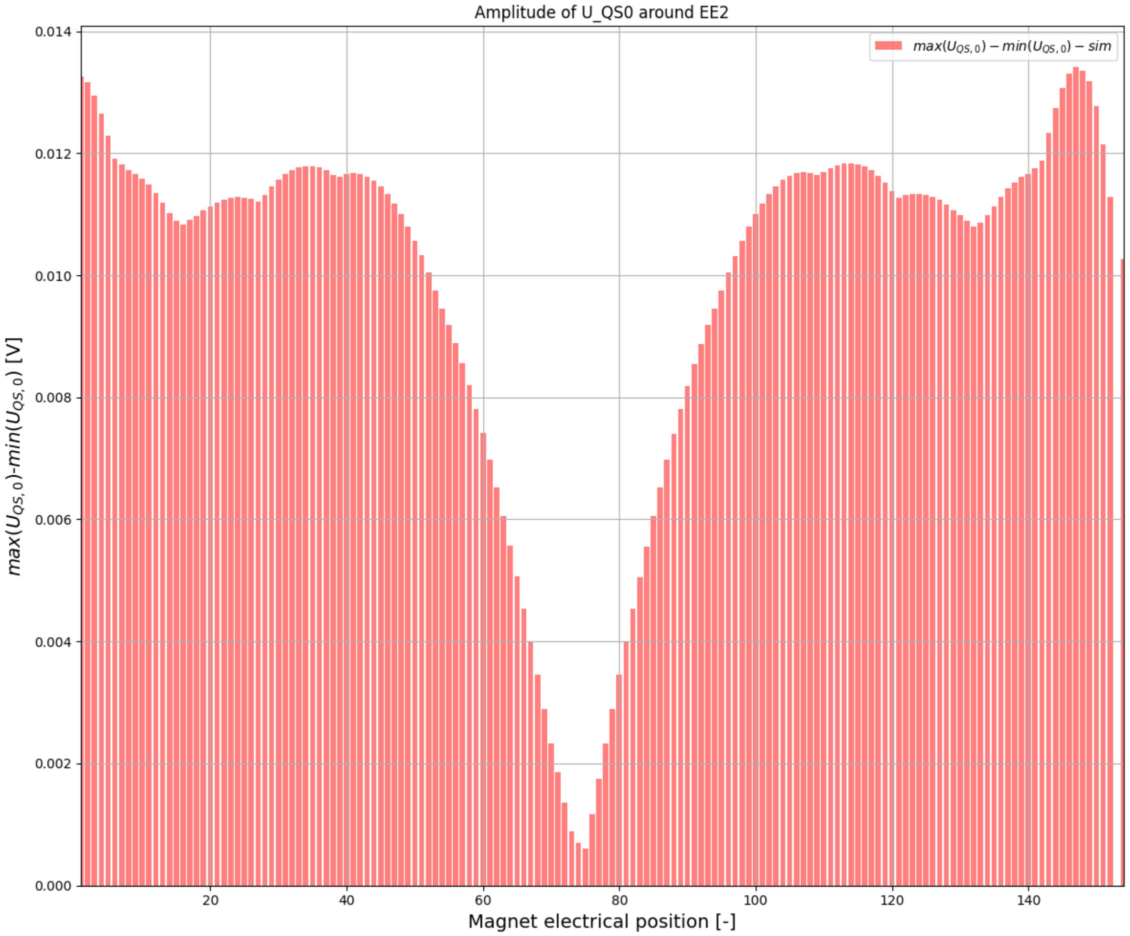
More examples can be found: MP3 day 2022, 01.12.2022,
E. Ravaioli & M. Janitschke: FPA tests: Results and plans for the future

Unexplained behavior:
Unbalanced dipole impedance

Expected $U_{QS,0}$ voltage signals from simulations

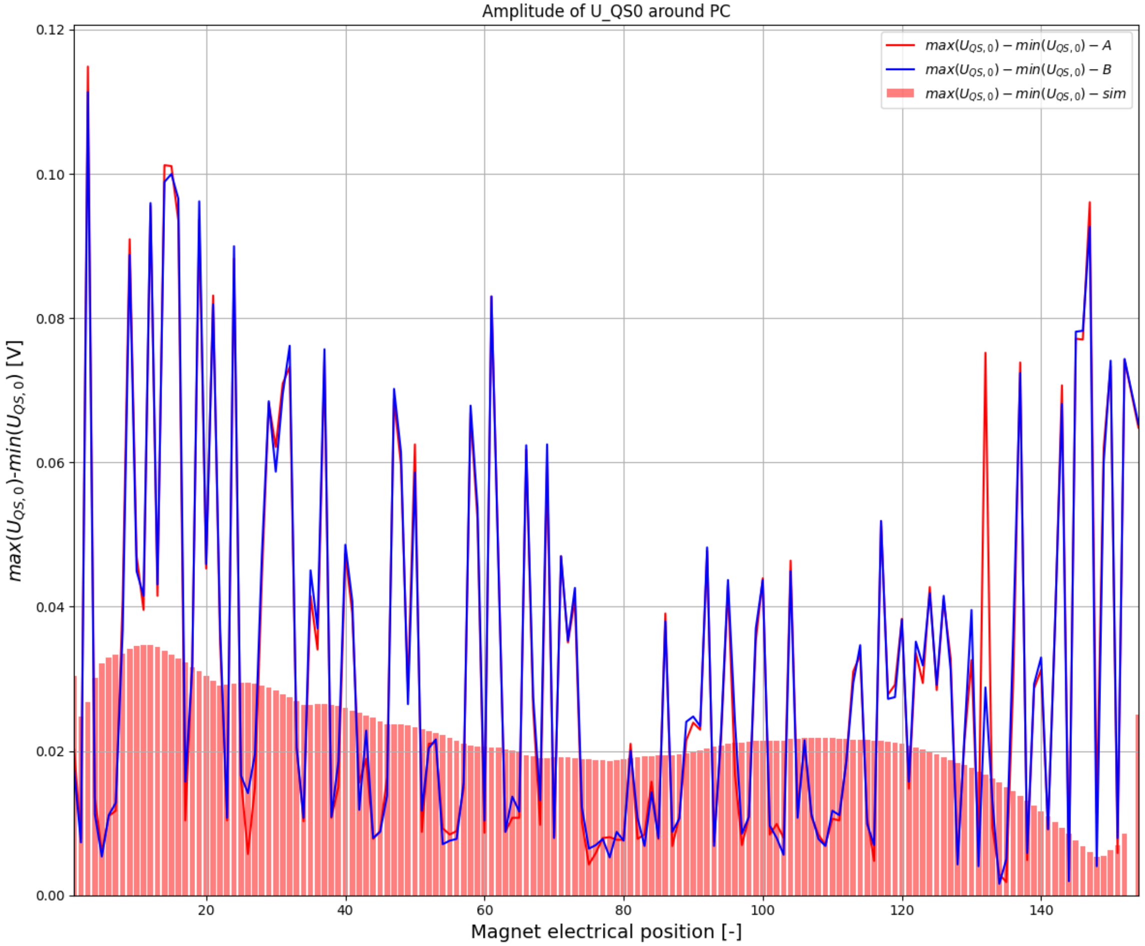


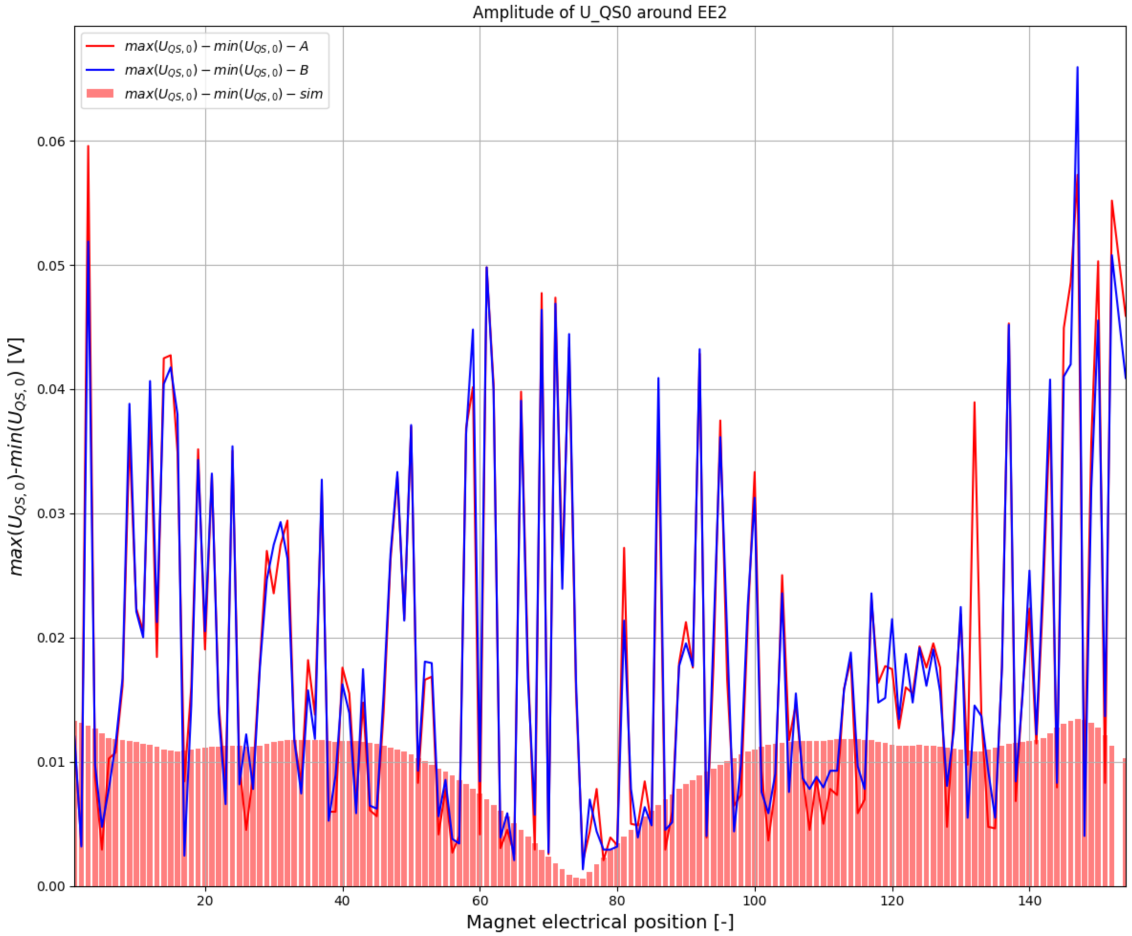
BUT:



Unexplained behavior:
Unbalanced dipole impedance

Measured $\boldsymbol{U_{QS,0}}$ voltage signals



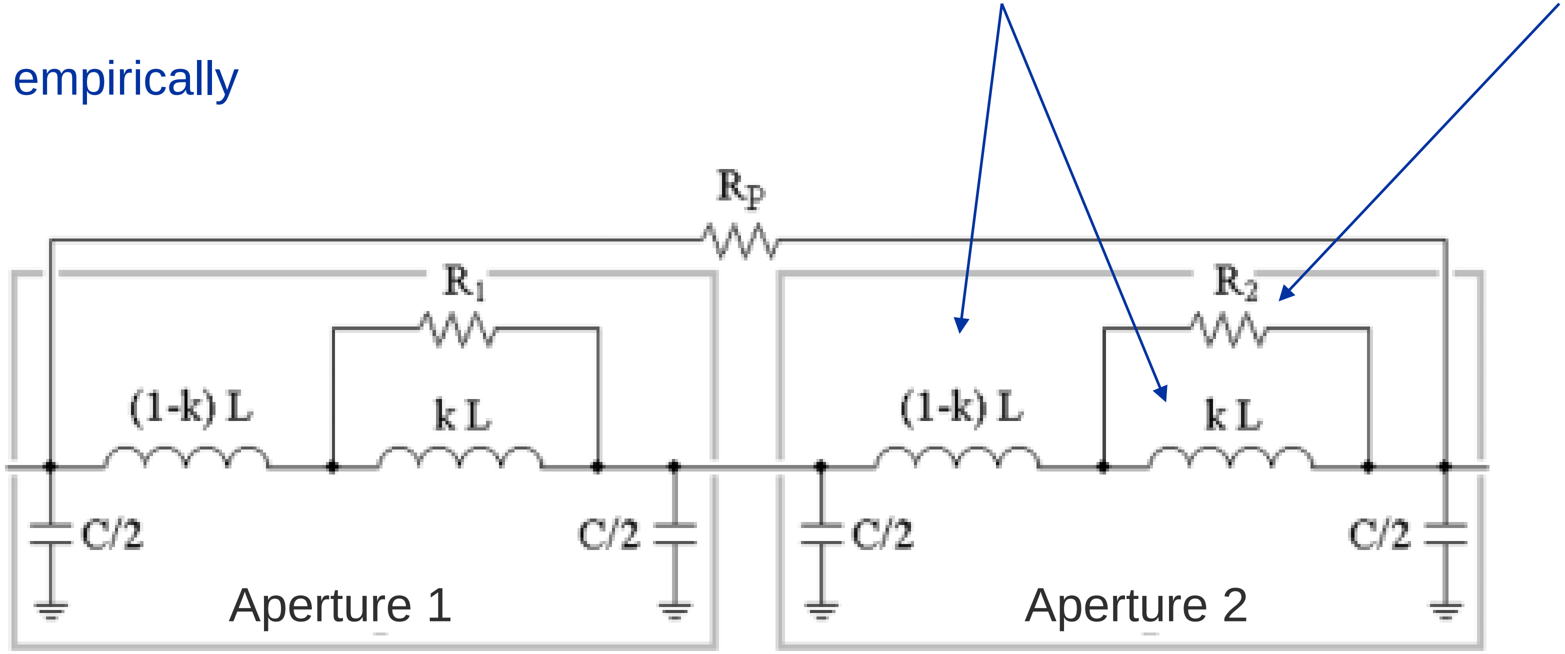


Modelling of the magnets – so far

- In case of no quench, the circuit behavior can be captured relatively precisely by a pure electrical model, utilizing ideal inductors → Simulation in SPICE

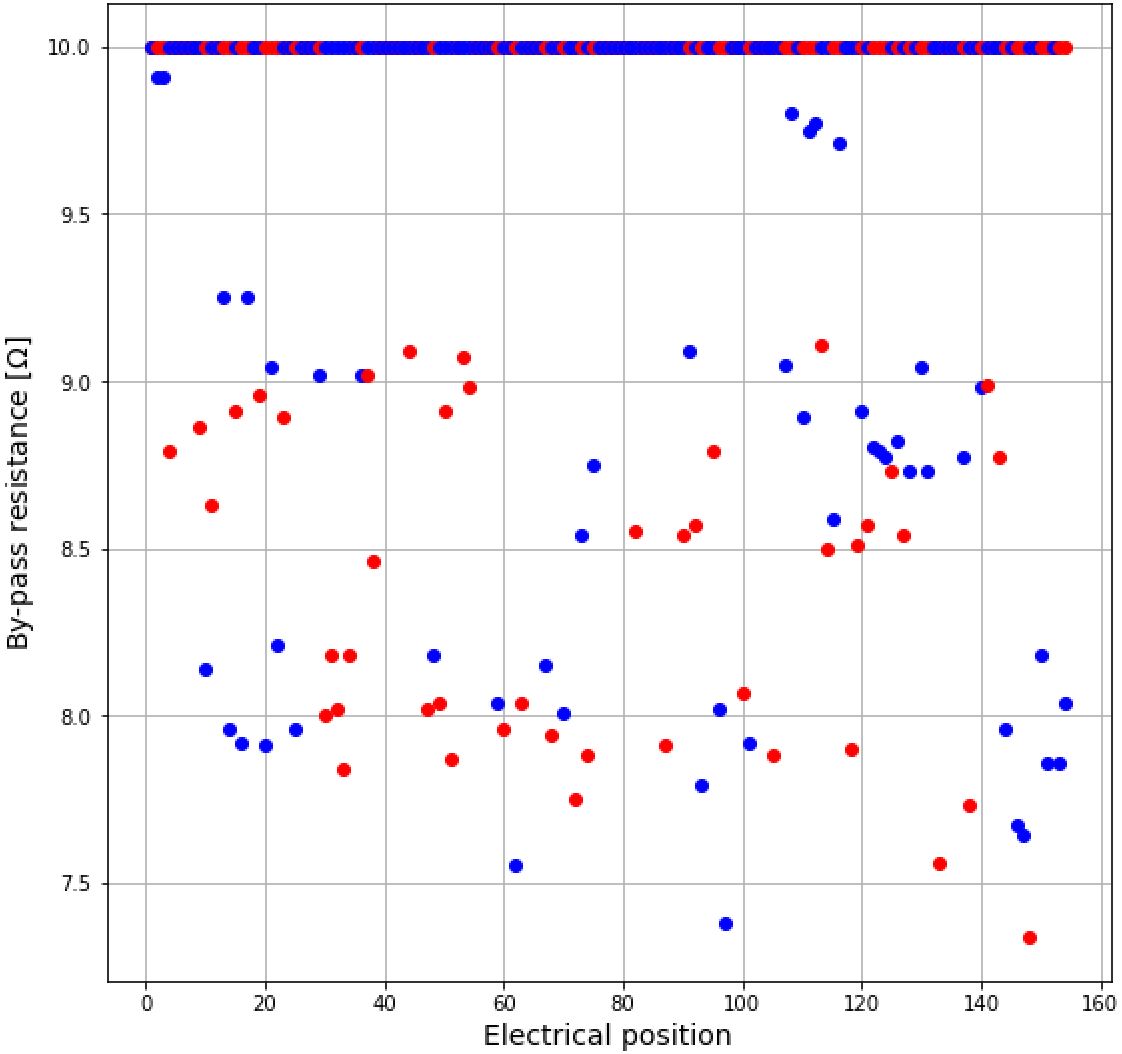
- In order to account for the unbalanced impedance, the magnet model got replaced
→ Instead of pure inductors, each aperture is split up into two inductors, one bridged by a resistor

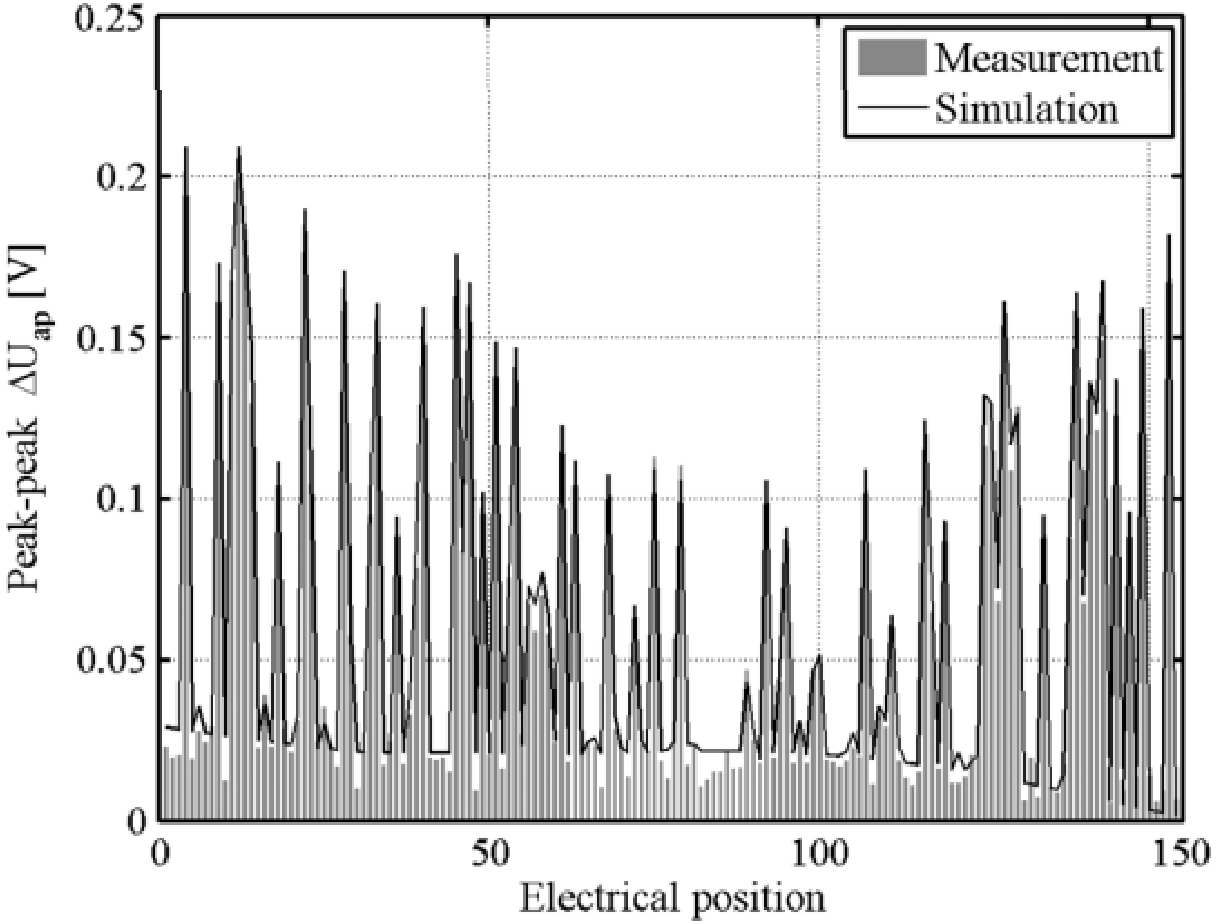
- Values were found empirically



E. Ravaioli, K. Dahlerup-Petersen, F. Formenti, J. Steckert, H. Thiesen, **A. Verweij**, "Modeling of the Voltage Waves in the LHC Main Dipole Circuits", IEEE Trans. Appl. SC, Vol 22, June 2012 , DOI: 10.1109/TASC.2011.2176306.

Modelling of the magnets – so far

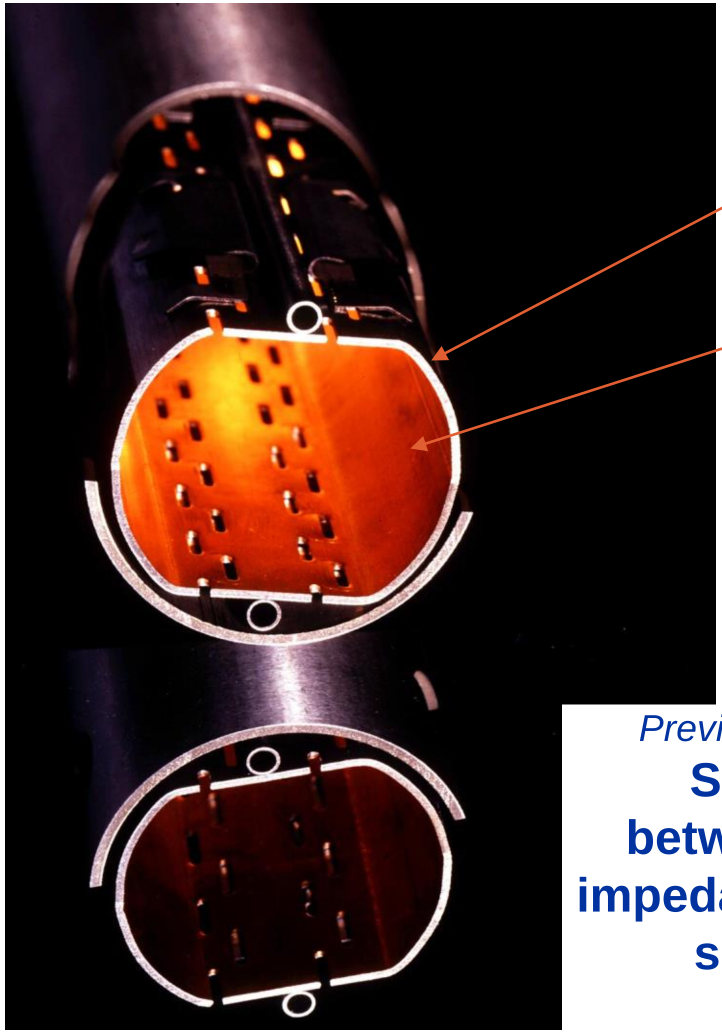




Fitting works pretty good at low current
→ At high currents this breaks down

E. Ravaioli, K. Dahlerup-Petersen, F. Formenti, J. Steckert, H. Thiesen, **A. Verweij**, "Modeling of the Voltage Waves in the LHC Main Dipole Circuits", IEEE Trans. Appl. SC, Vol 22, June 2012 , DOI: 10.1109/TASC.2011.2176306.

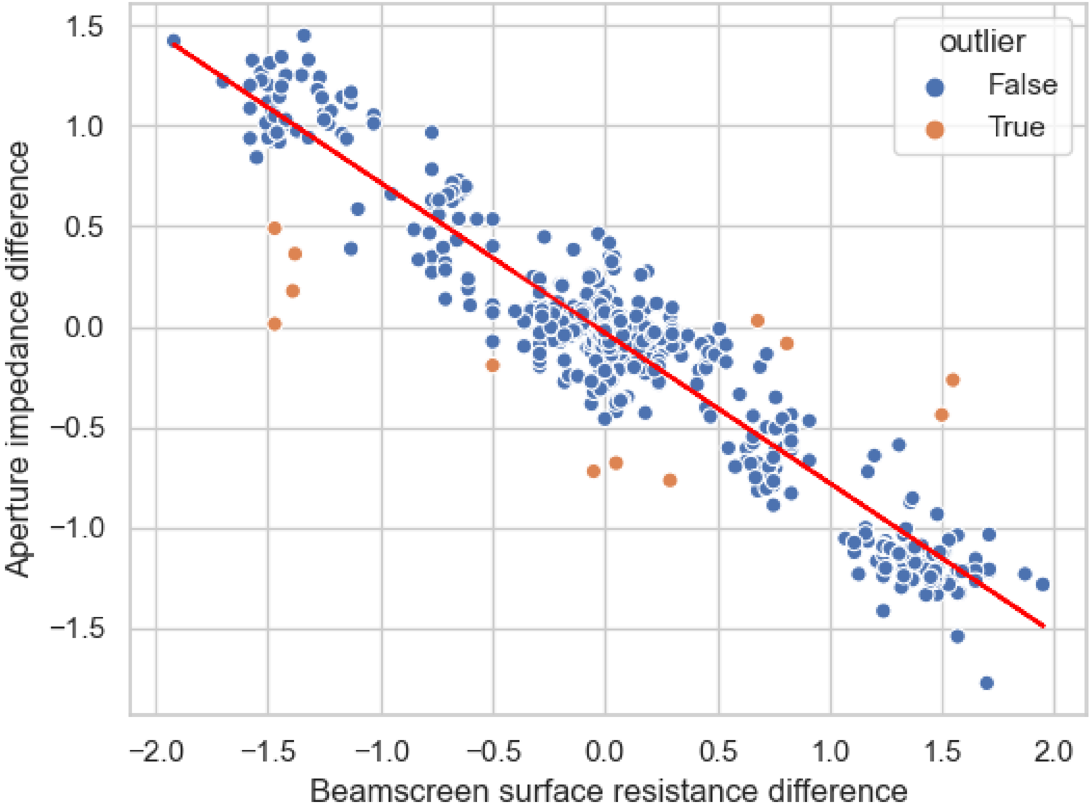
The beam-screen and its effects



- Included in the magnet to protect the coils from particle and radiation impact
- **1 mm of steel** and **~75 µm** of co-laminated **copper**

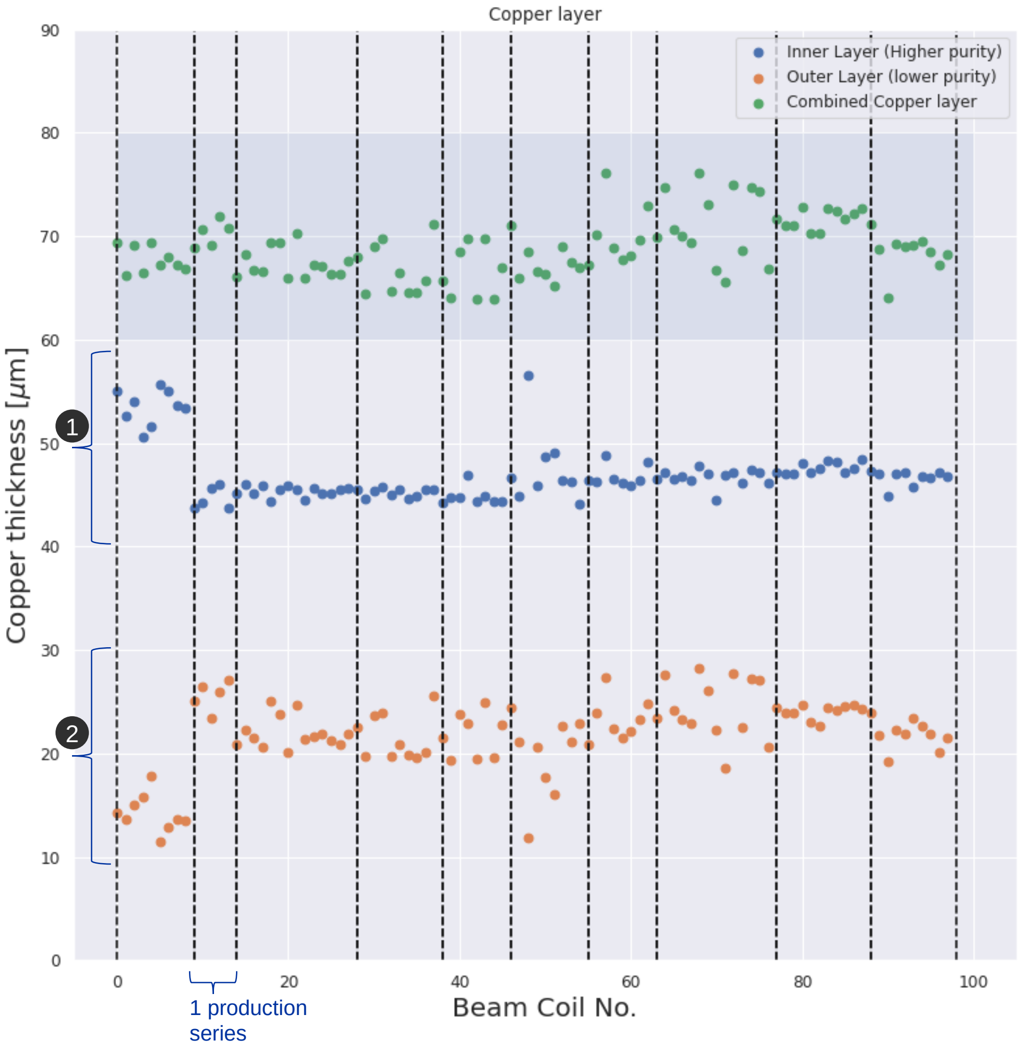
Previous investigations showed:

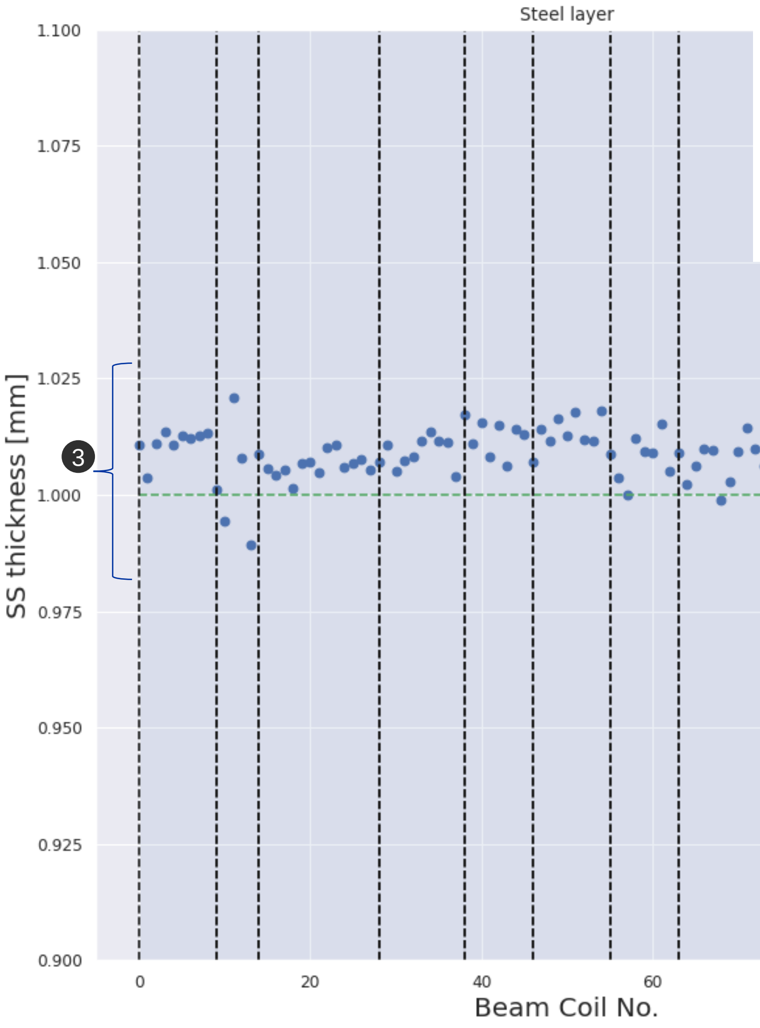
Strong correlation between the unbalanced impedance and beam screen surface resistance



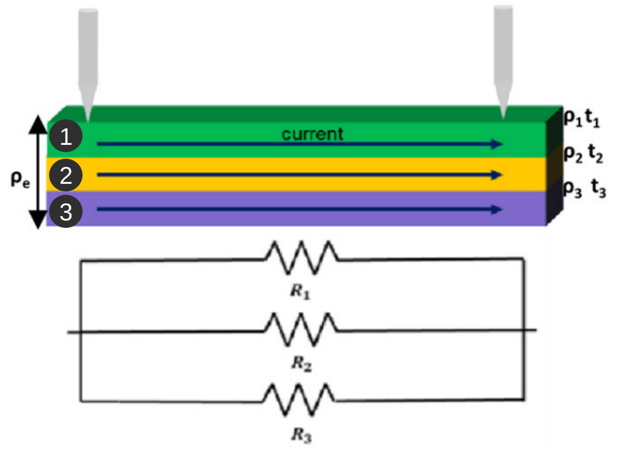
R.G. Saederup, "Local Transfer Function Measurement (TFM) Data Analysis", edms 2675917

The beam-screen and its layers

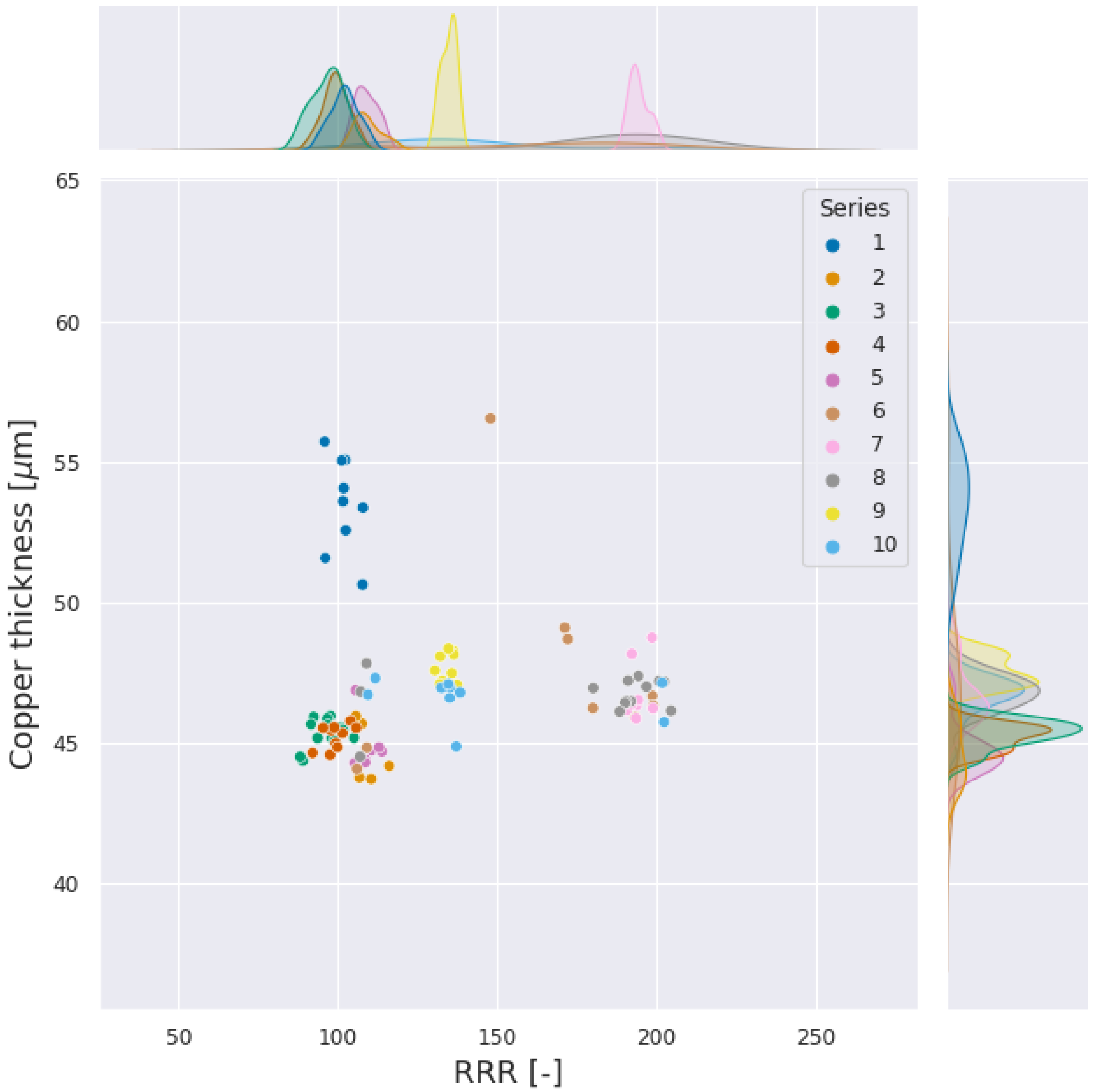




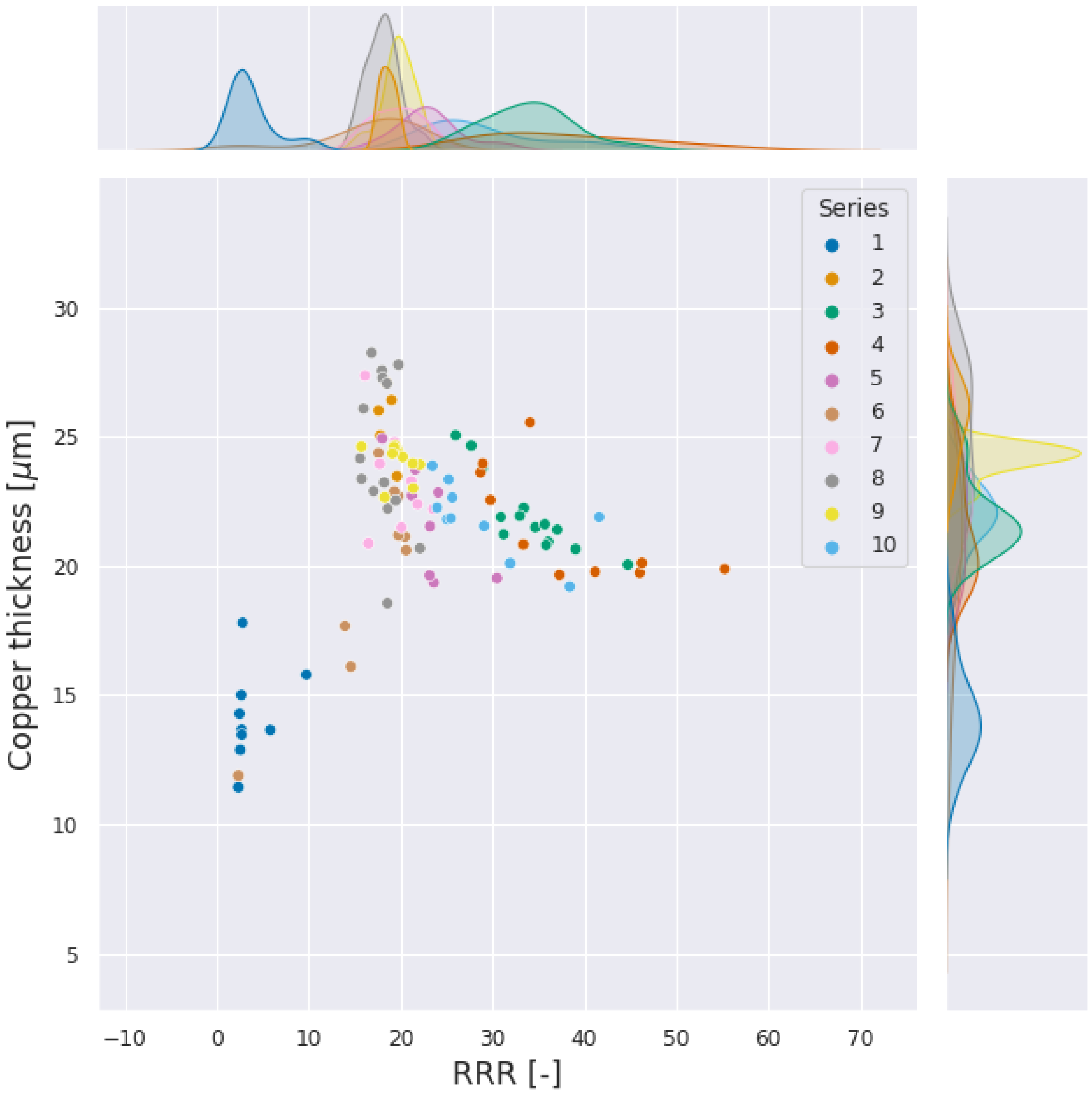
① Pure copper
② Polluted copper
③ Steel layer



Inner layer with higher purity

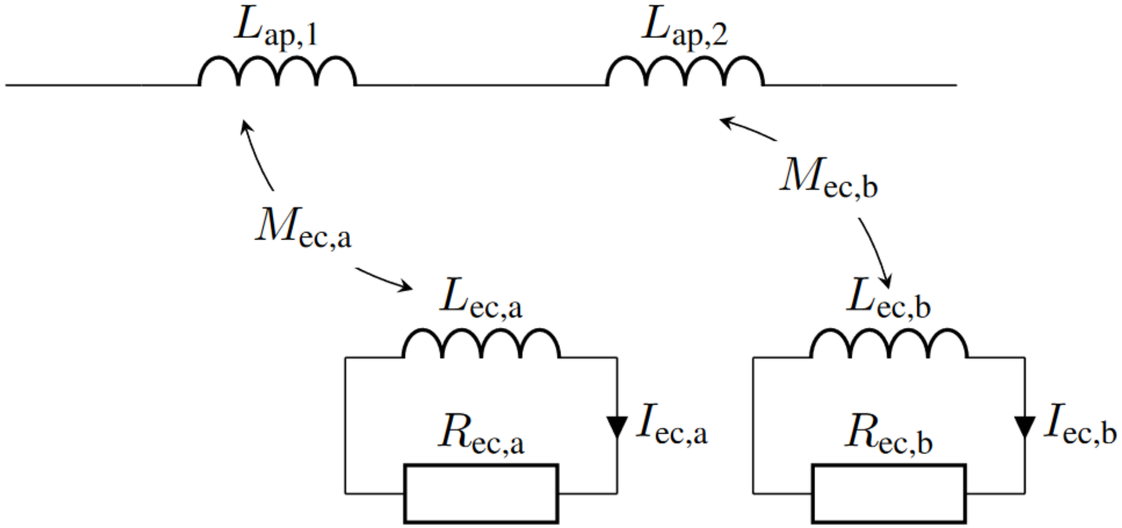


Outer layer with lower purity



Main dipole – the new model

The eddy current effect is taken into account with coupling loops consisting of R_{ec}, L_{ec} and are mutually coupled with M_{ec} to the magnets main inductances



Simplified schematic, only showing 1/3 beam-screen layer

$$\begin{cases} R_{\mathrm{ec}} = \dfrac{\pi t_{\mathrm{b}}(d_{\mathrm{b}} - t_{\mathrm{b}}) l_{\mathrm{m}} \rho_{\mathrm{b}}(T, B)}{2 d_{\mathrm{b}}^2 \delta^2 \left[1 - \exp\left(-\dfrac{t_{\mathrm{b}}}{\delta}\right)\right]^2} & [\Omega] \\ L_{\mathrm{ec}} = \dfrac{\mu_0 \pi t_{\mathrm{b}}(d_{\mathrm{b}} - t_{\mathrm{b}}) l_{\mathrm{m}}}{8 d_{\mathrm{b}} \delta \left[1 - \exp\left(-\dfrac{t_{\mathrm{b}}}{\delta}\right)\right]} & [\mathrm{H}] \\ M_{\mathrm{m,ec}} = \dfrac{\pi t_{\mathrm{b}}(d_{\mathrm{b}} - t_{\mathrm{b}}) l_{\mathrm{m}} f_{\mathrm{m,ec}}}{4\delta \left[1 - \exp\left(-\dfrac{t_{\mathrm{b}}}{\delta}\right)\right]} & [\mathrm{H}] \end{cases} .$$

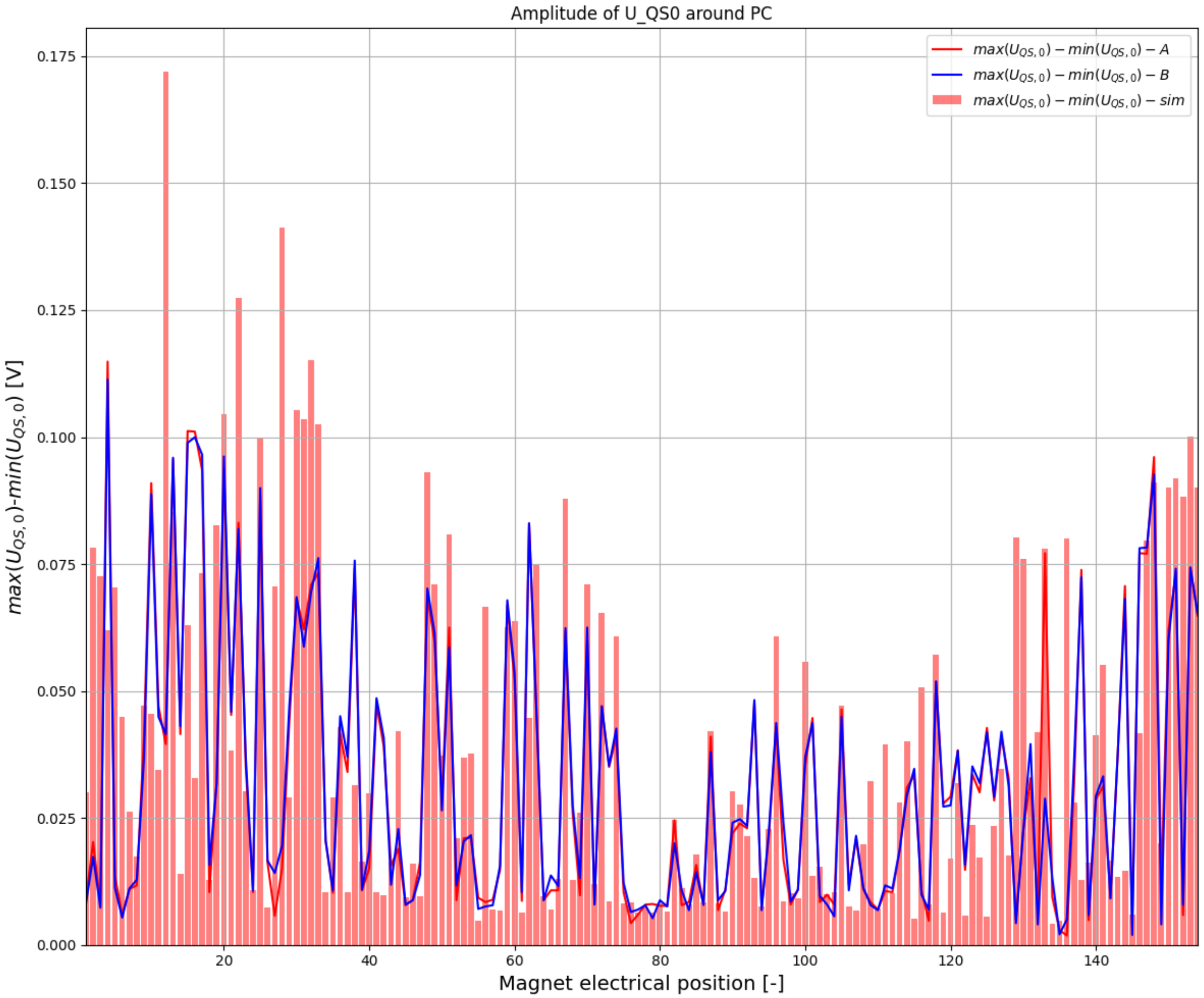
- t_b – copper layer thickness
- d_b – diameter of beam screen
- l_m – length of the magnet
- δ – characteristic skin depth
- $\rho_b(RRR, T, B)$ – resistivity of copper
- $f_{m,ec}$ – magnet transfer function on the beam screen

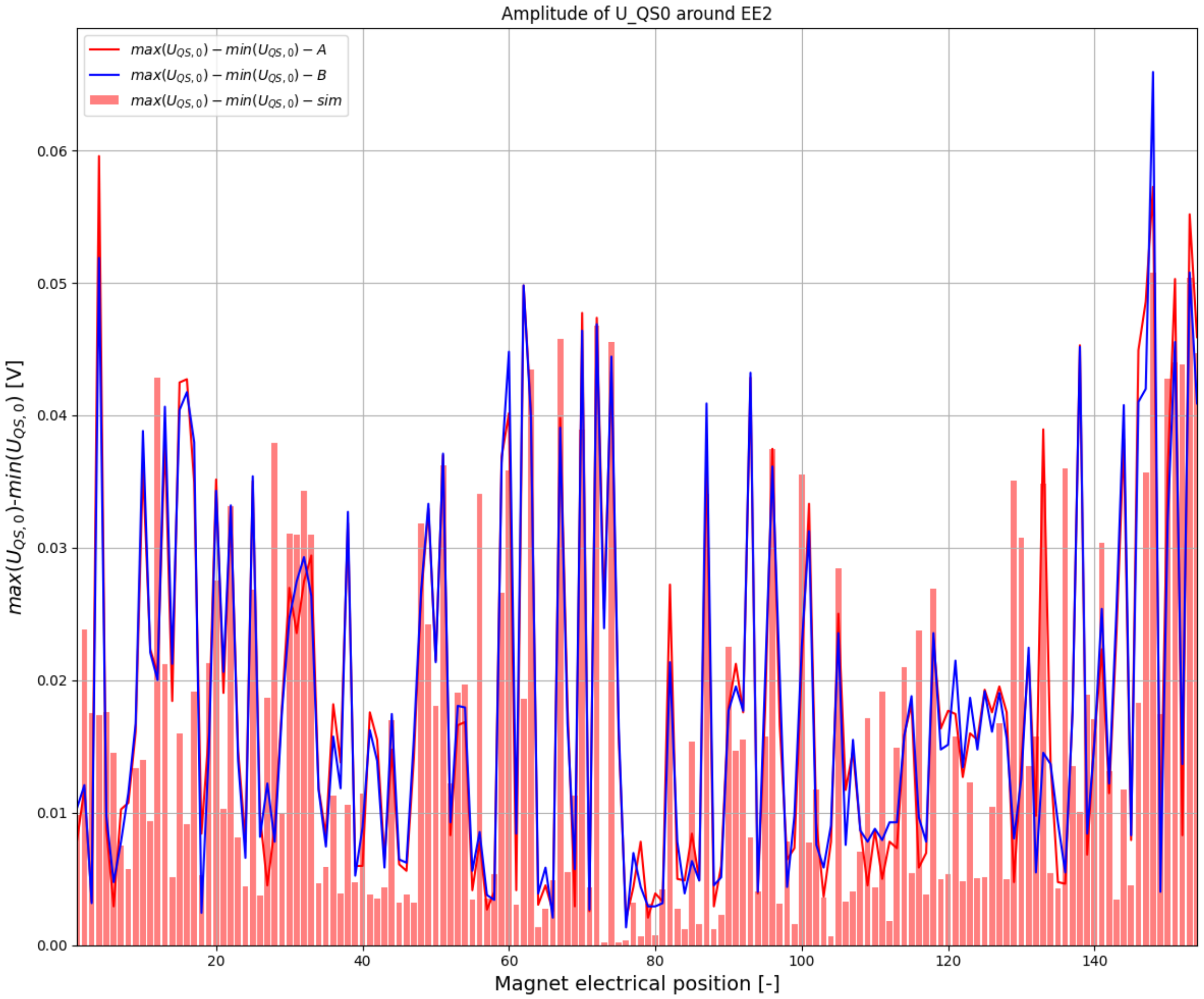
Derivation only requires measured values

Main dipole – the new model: Results

Low current

$\mathbf{U_{QS,0}}$ of an FPA @ **2 kA** w/ 10A/s ramp

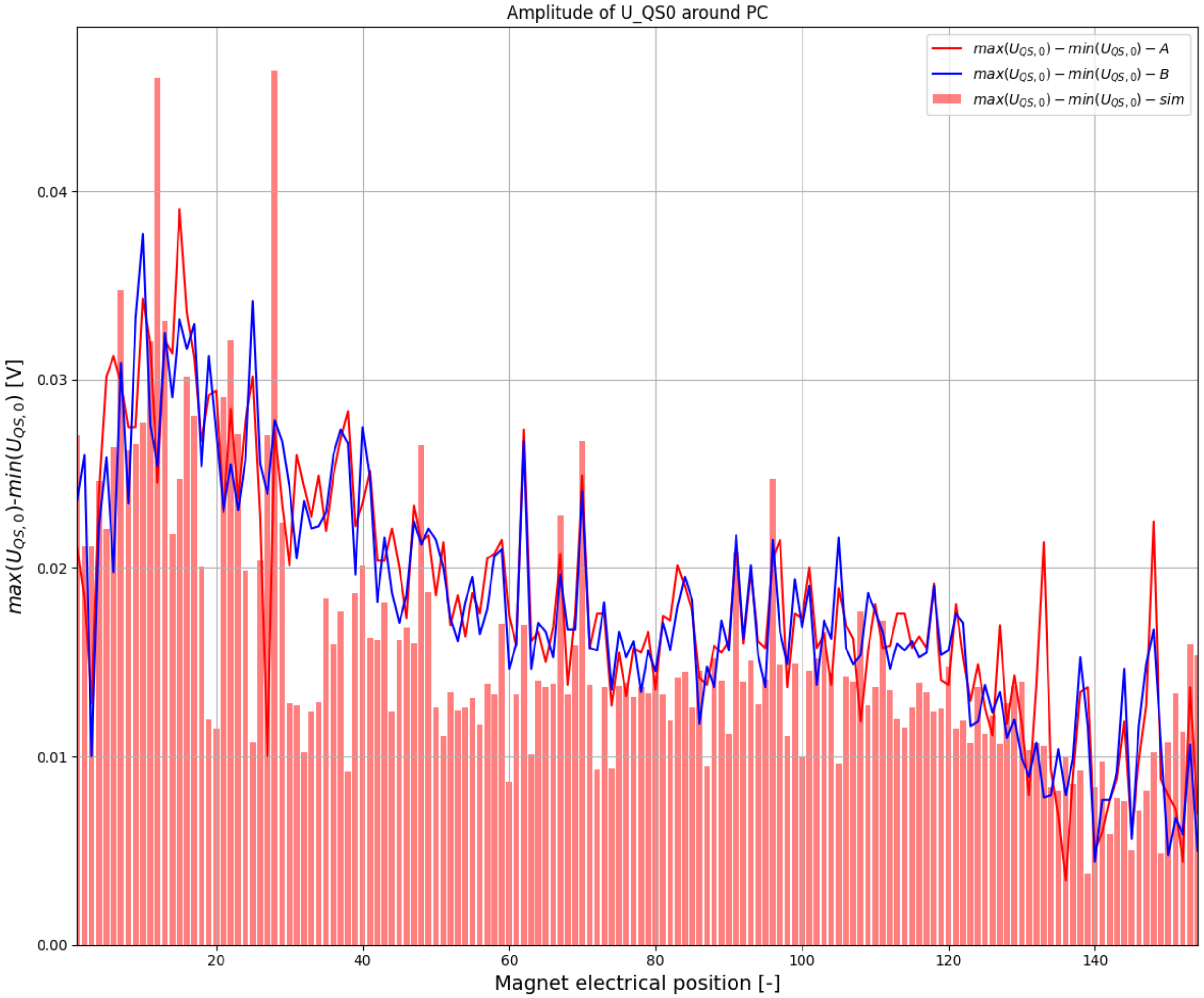


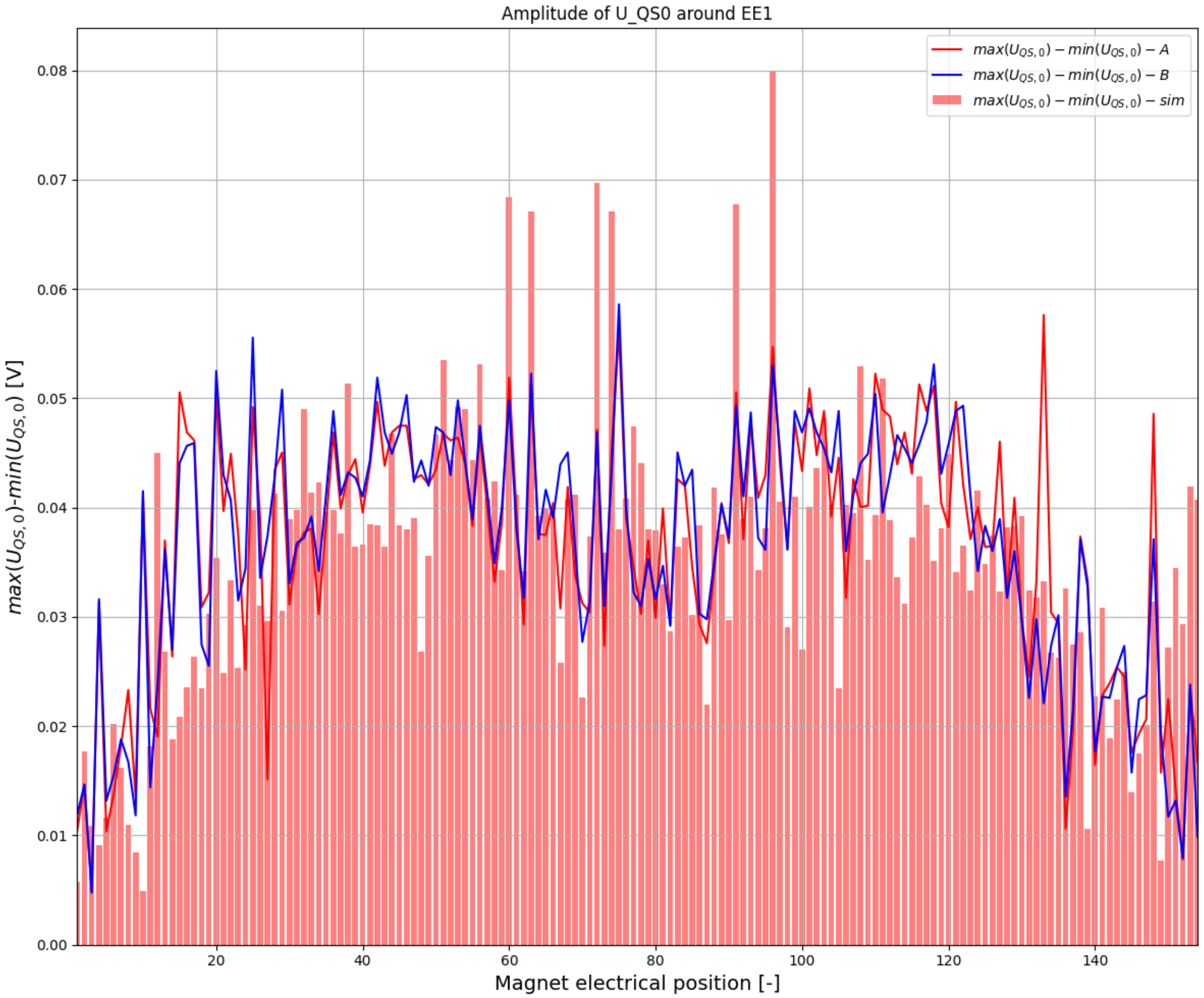


Main dipole – the new model: Results

High current

$\mathbf{U_{QS,0}}$ of an FPA @ **11 kA** w/ 10A/s ramp

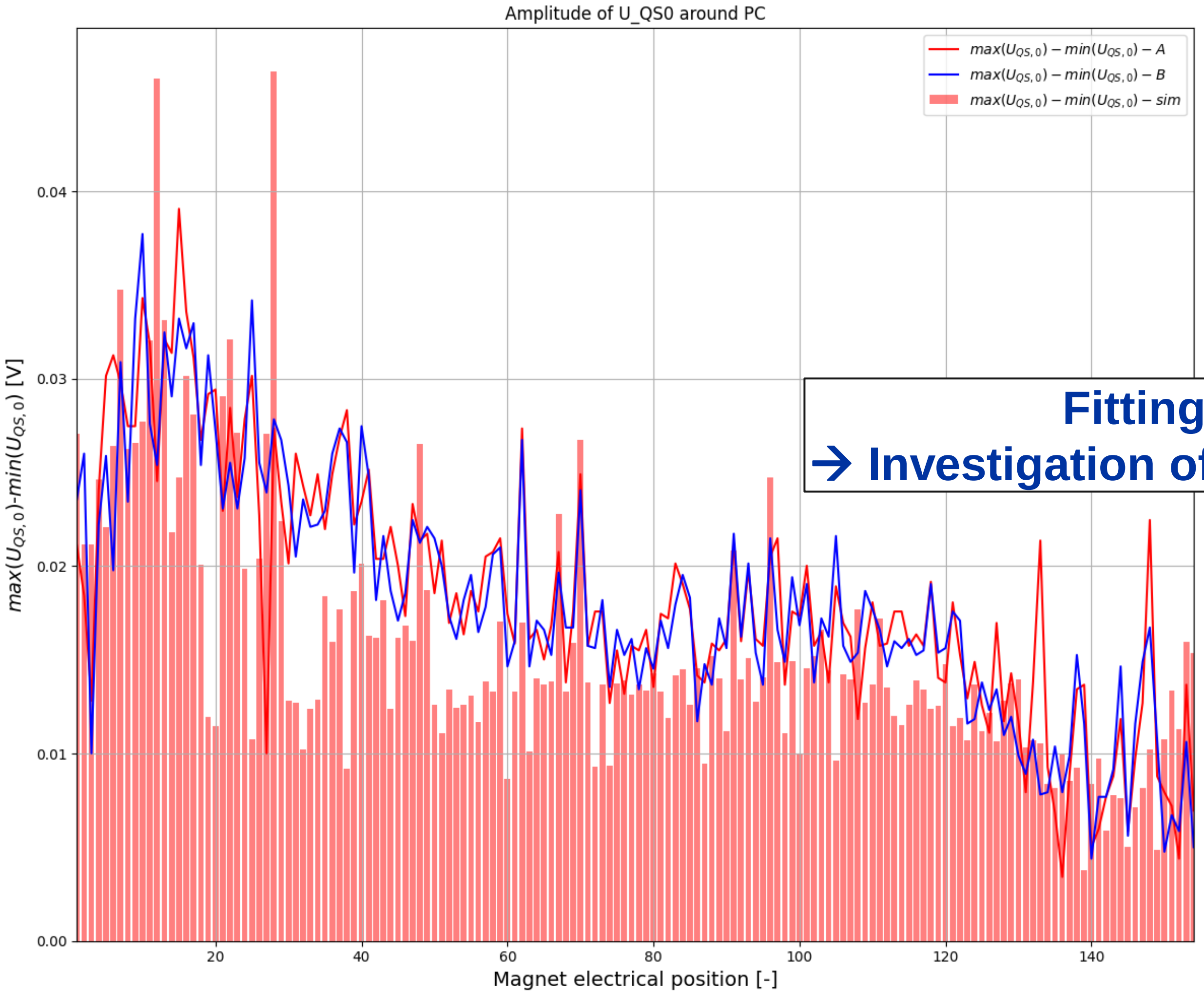

Amplitude of U_QS0 around PC

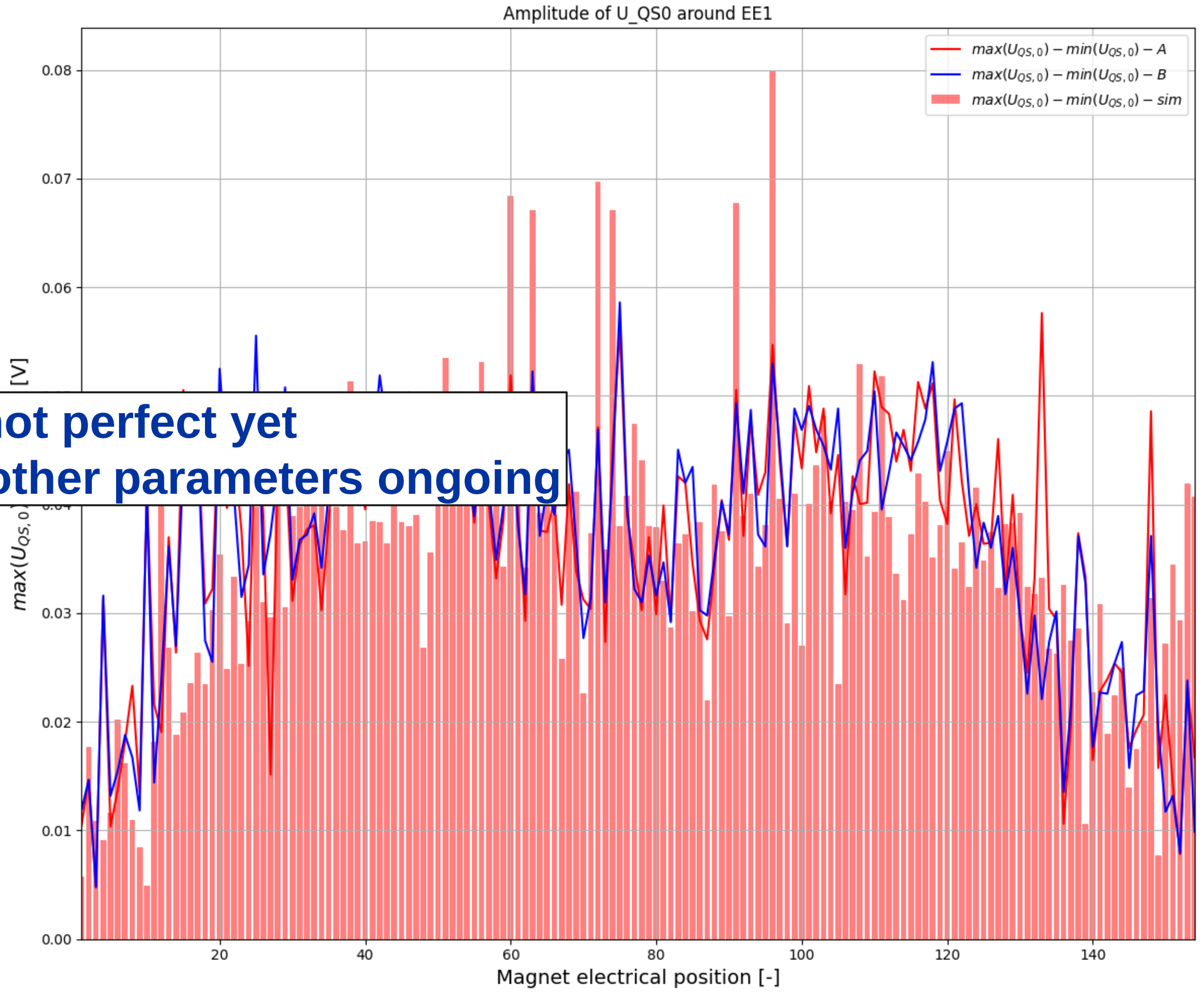

Amplitude of U_QS0 around EE1

Main dipole – the new model: Results

High current

$U_{QS,0}$ of an FPA @ **11 kA** w/ 10A/s ramp

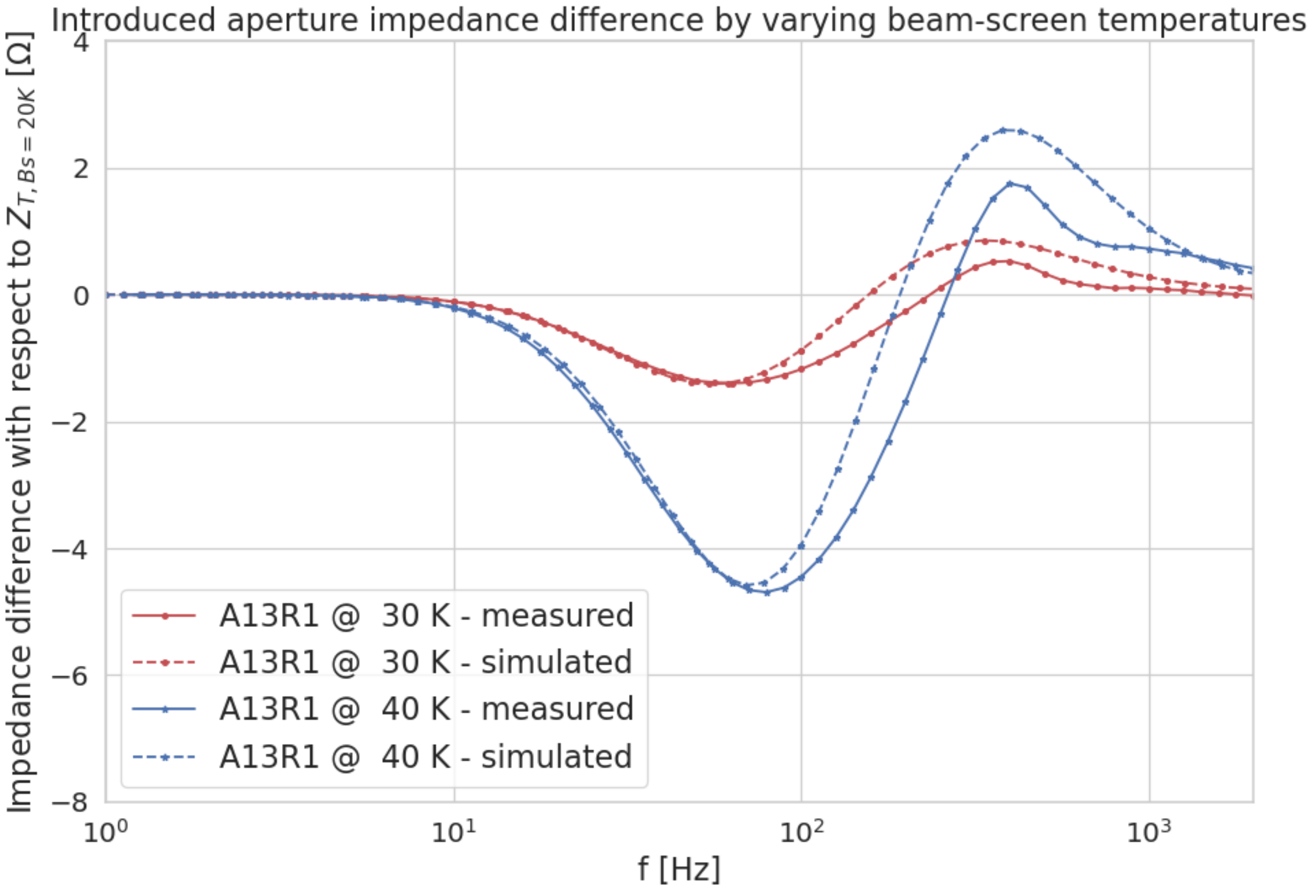




Fitting not perfect yet

→ Investigation of other parameters ongoing

Main dipole – the new model: Results



The beam-screen effect can also be seen and reproduced in the frequency domain

Transfer Function Measurements with the beamscreen at:

1. 20 K
2. 30 K
3. 40 K

The introduced impedance differences can be accurately reproduced

Modelling of the main dipole in the frequency domain is work in progress

Conclusion

Further analysis of the beam-screen surface resistances showed a **significant spread in purity and thickness** of the different copper layers of the beam-screen
→ **Novel electrical network model of the main dipole**

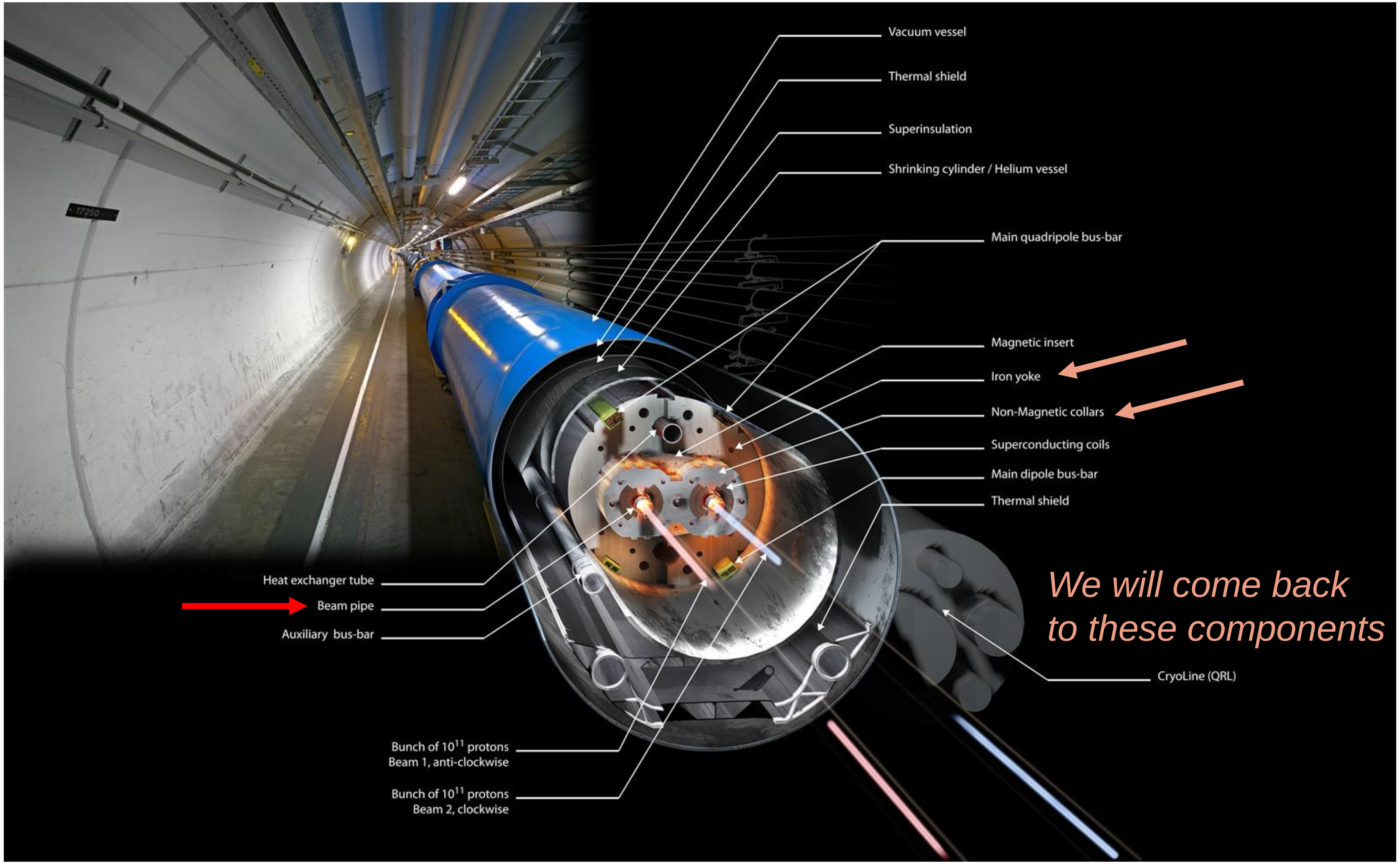
2011 equivalent model	2022 equivalent model
Good accuracy	Good accuracy
Empirical (not physics-driven)	Physics-driven
Predictive only for FPA	Predictive for various events
	Able to predict new magnet's behavior (?)
	Possible to add a short circuit to the model
Not easily scaled	Scaled with current
Not easily expandable	Expandable with other effects
	Expandable to frequency behaviour
Practical	Difficult to develop

Courtesy to E. Ravaioli

Thanks a lot for your attention! ☺

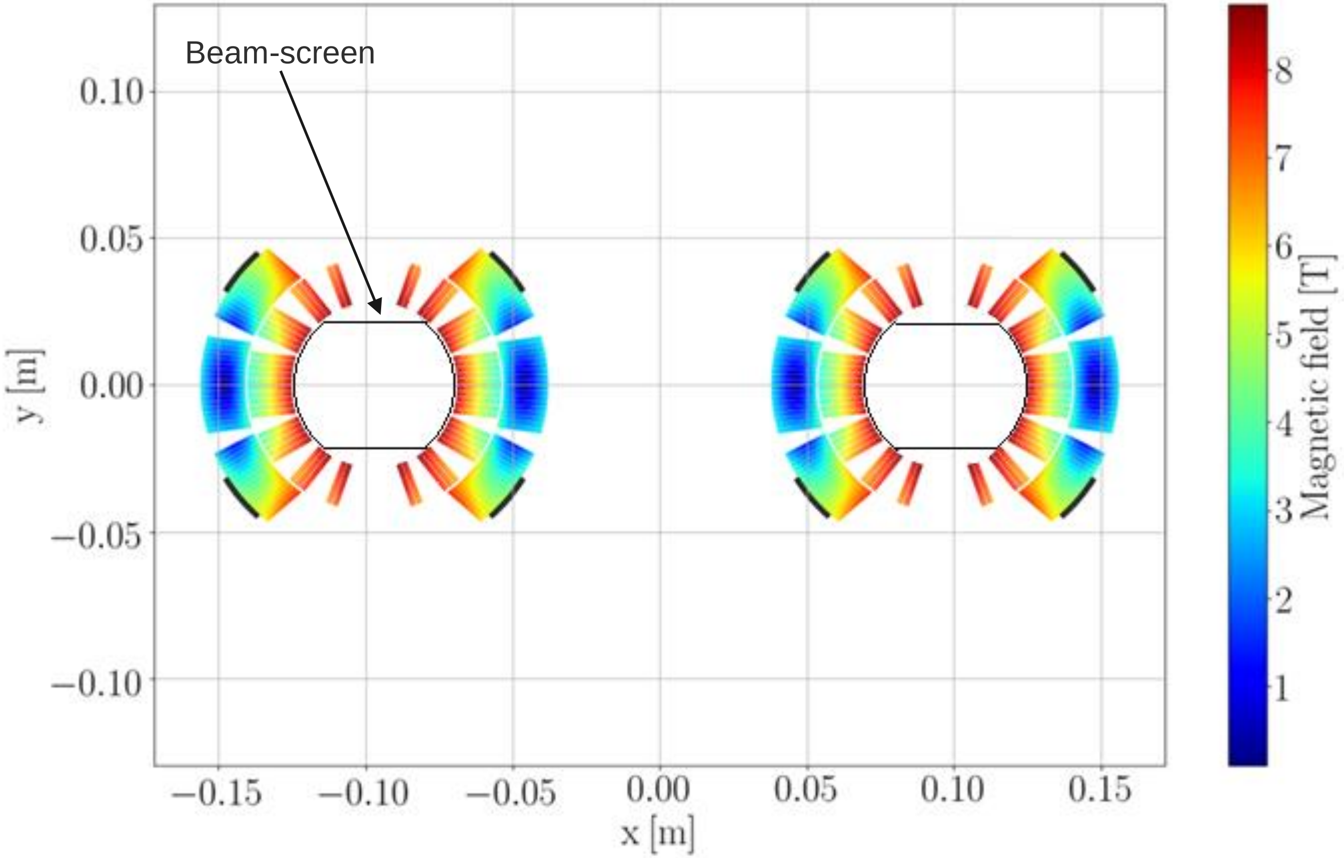
Appendix

LHC main dipole magnet (MB)



We will come back to these components

LHC main dipole magnet



Parameter	Value	Unit
Length	14.3	m
Operating temperature	1.9	K
Nominal field	8.33	T
Current at nominal field	11850	A
Inductance at nominal field	98.7	mH
Stored energy at nominal field	1.3	GJ
Inner coil diameter	56	mm

Parameter	Value	Unit
Number of turns	320	-
Number of strands per turn	28/36	-
Number of filaments per strand	8900/6500	-
Critical current @ 10 T, 1.9 K	13.75	kA

Data from Butting (2003/2004) – Random example

Series	Specimen Tube No.	Charge-No. (Bohler)	Coil No.	RRR Cu	U @293 K [V]	U @77 K [V]	U @4.2 K [V]	Length [m]	Width [m]	Thickness (total)	Thickness I (OFE-Cu)	Thickness (P506)	R_s @ 4.2 K
10	P. 5358	391324/1	96/1	145.820	0.00699600	0.00112400	0.00006300	0.07586000	0.00200000	0.00107800	0.00008360	0.00099440	1.66
10	P. 5399	387025/2	95/1	81.218	0.00695900	0.00116000	0.00011200	0.07586000	0.00200000	0.00107500	0.00008280	0.00099220	2.95

$$R_s = \Delta U \frac{w}{l * I}$$, I = 1 A

CERN acceptance criteria $R_s < 3.5\ \mu\Omega$

RRR and t_{Cu} were not included (?)

Material	ρ(T= 293 K) $[\Omega m]$	ρ(T= 77 K) $[\Omega m]$	ρ(T= 4.2 K) $[\Omega m]$
Copper (RRR = 146)	1.7e-8	2.0e-9	1.06e-10
Copper (RRR = 81)	1.7e-8	2.1e-9	1.92e-10
Steel	6.8e-7	5.3e-7	5.0e-7

Now inserting all values from above (Butting) yields:

$$\Delta U = R_s \frac{l}{w} I = \frac{\rho * l}{t * w} I \qquad R_s = \frac{\rho}{t}$$

Calculated voltages based on provided $\rho(RRR, T)$, $w,\ l,\ t_{Cu}$

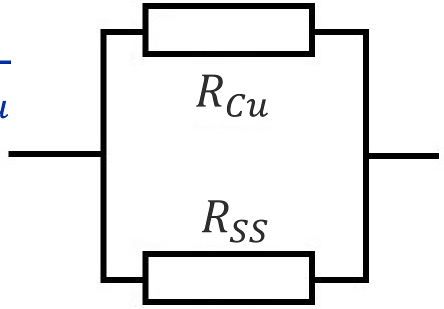
Specimen	U @293 K [V]	U @77 K [V]	U @4.2 K [V]
P. 5358	0.0059 15%	0.00086 23%	0.0000482 23%
P. 5399	0.0060 13%	0.00092 20%	0.0000872 22%

Error to Butting voltages

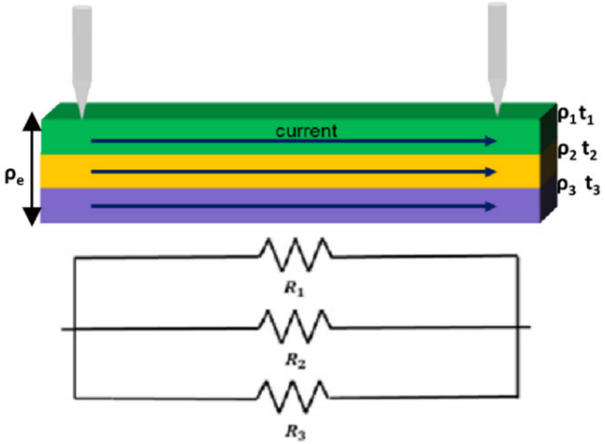
Correction for Stainless-Steel at 293 K:

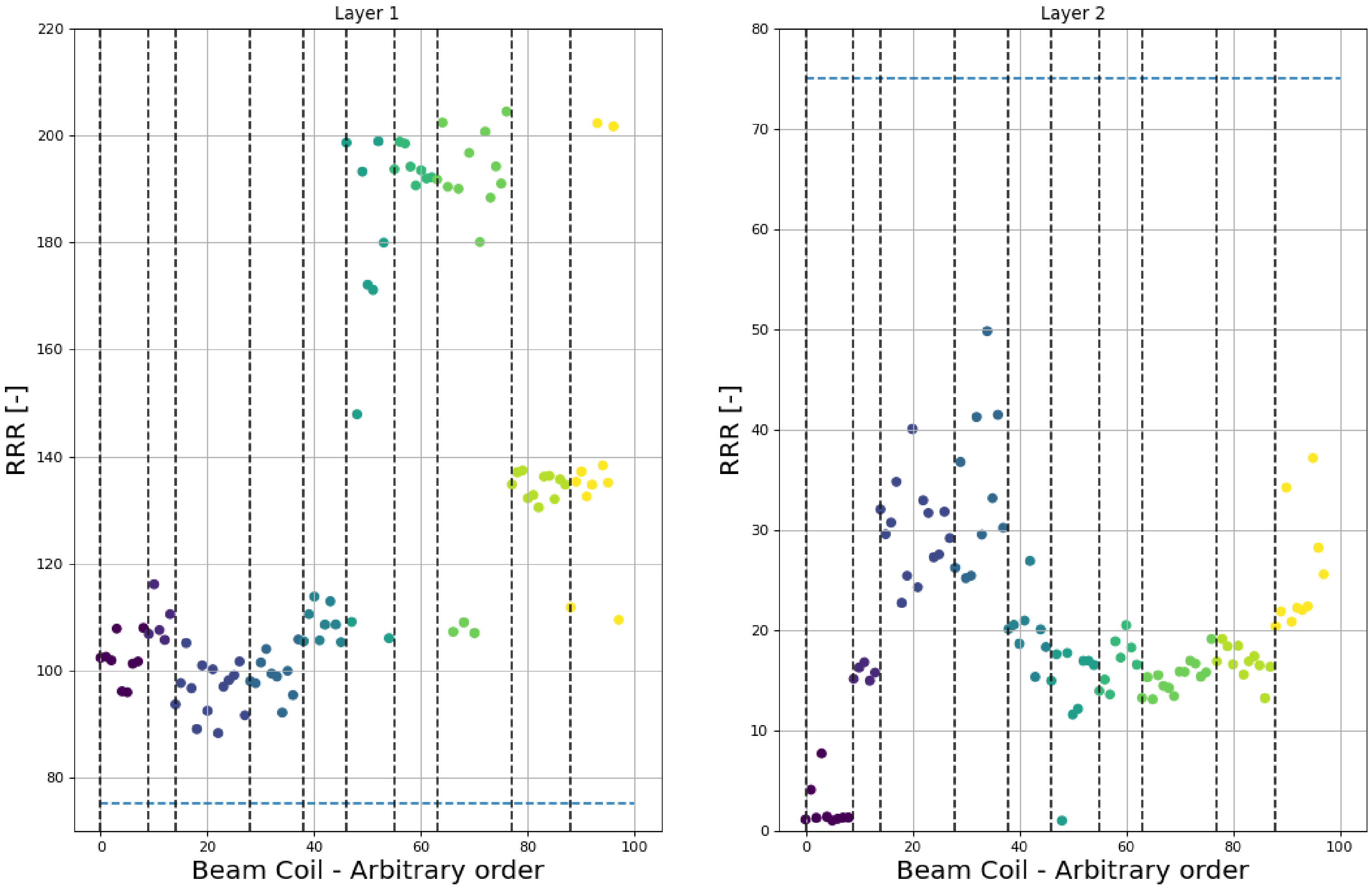
$$I_{Cu} = \frac{R_{Cu} R_{SS}}{R_{Cu} + R_{SS}} * \frac{1}{R_{Cu}}$$

$$I = I_{Cu}$$

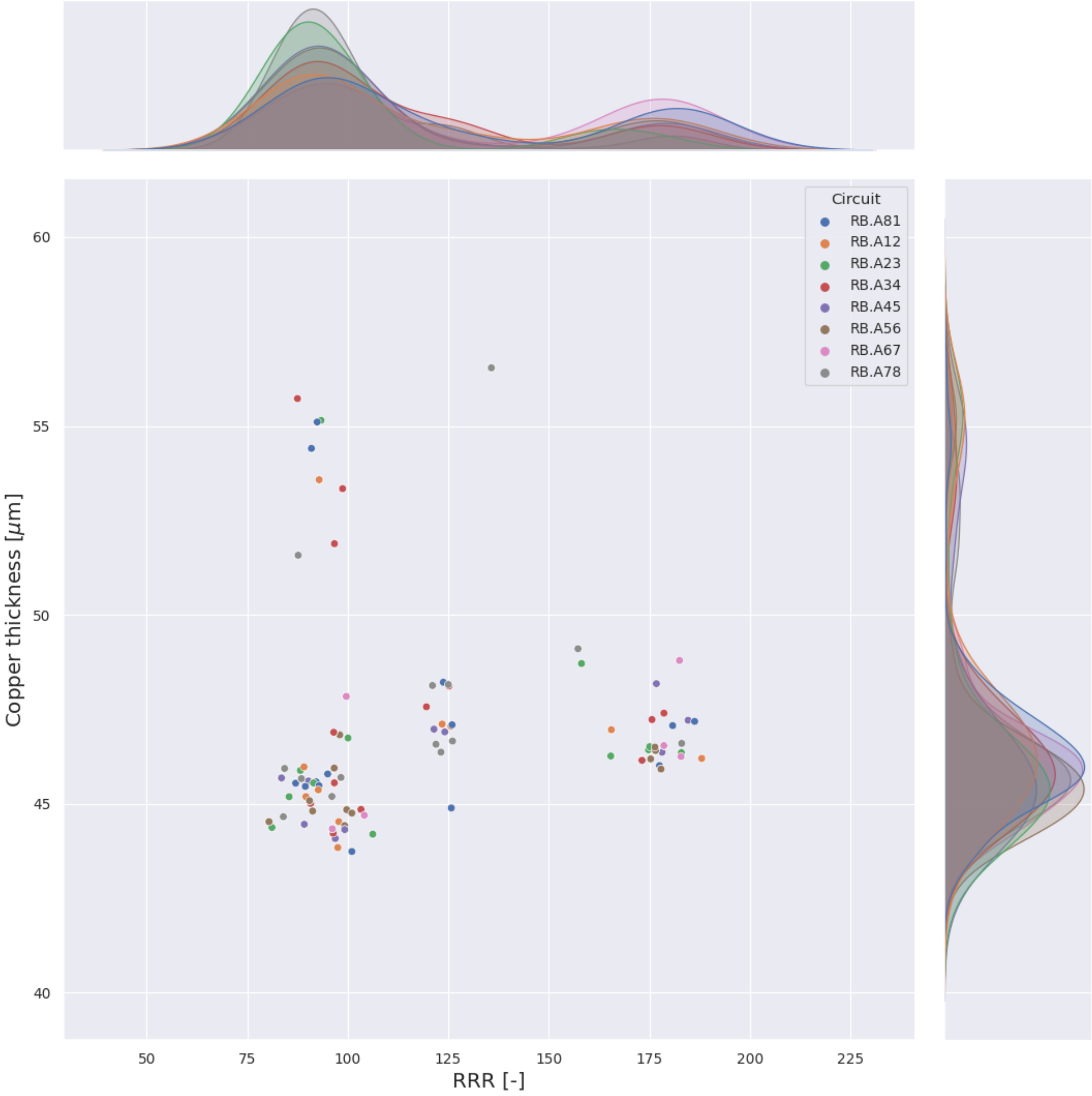


New approach – multi-layered copper

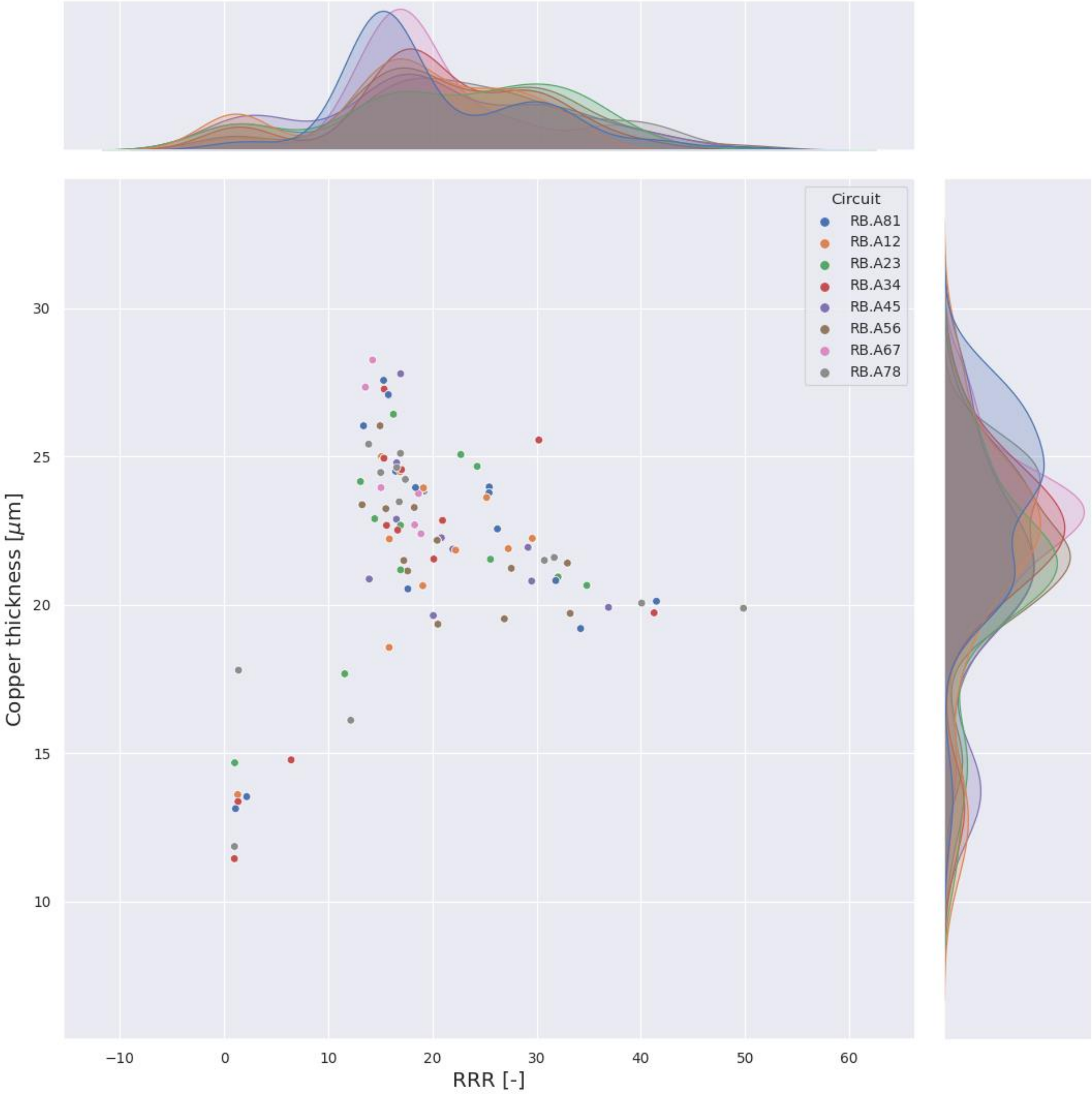




Inner layer with higher purity



Outer layer with lower purity

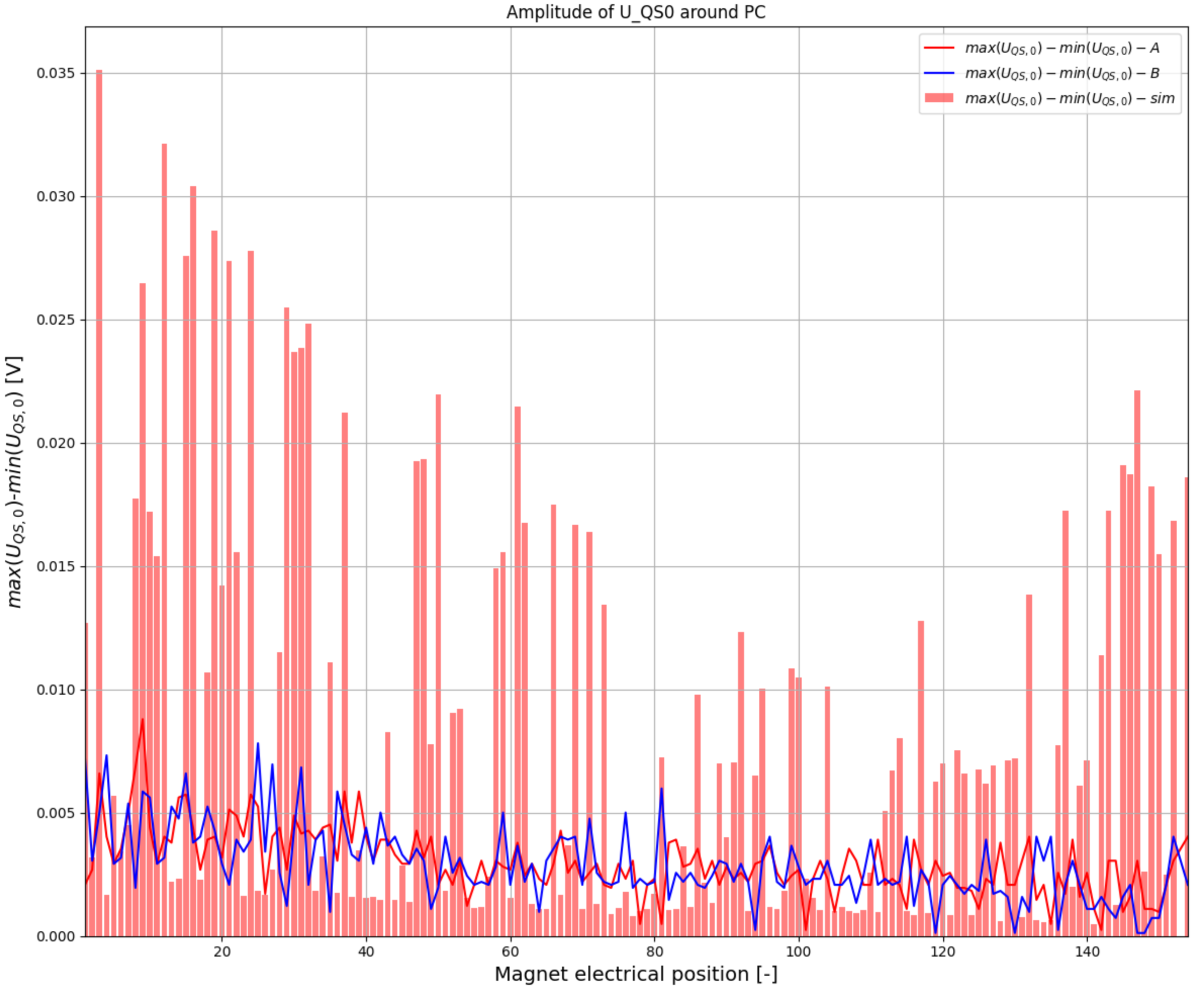


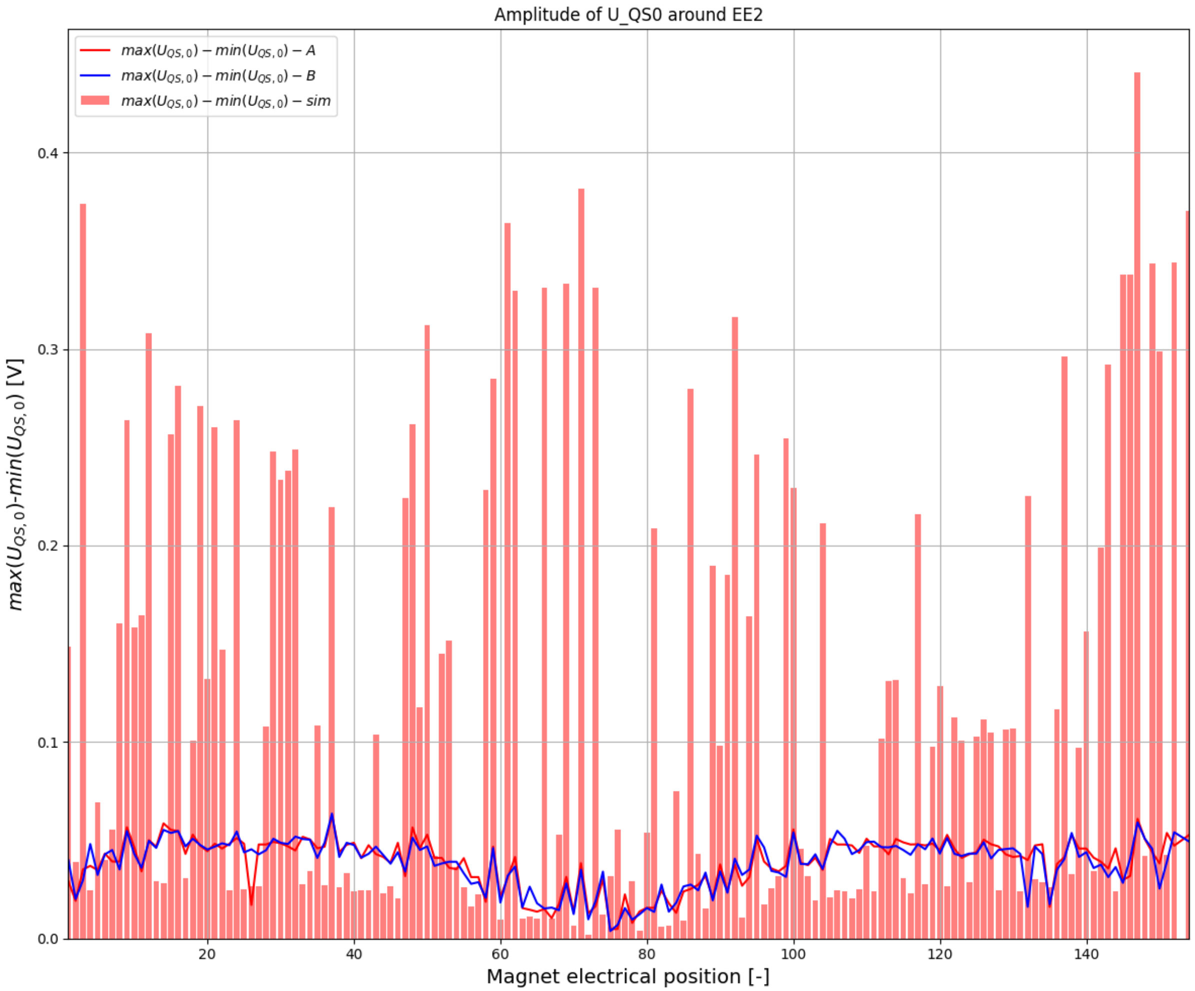
Main dipole – the new model: Results

High current

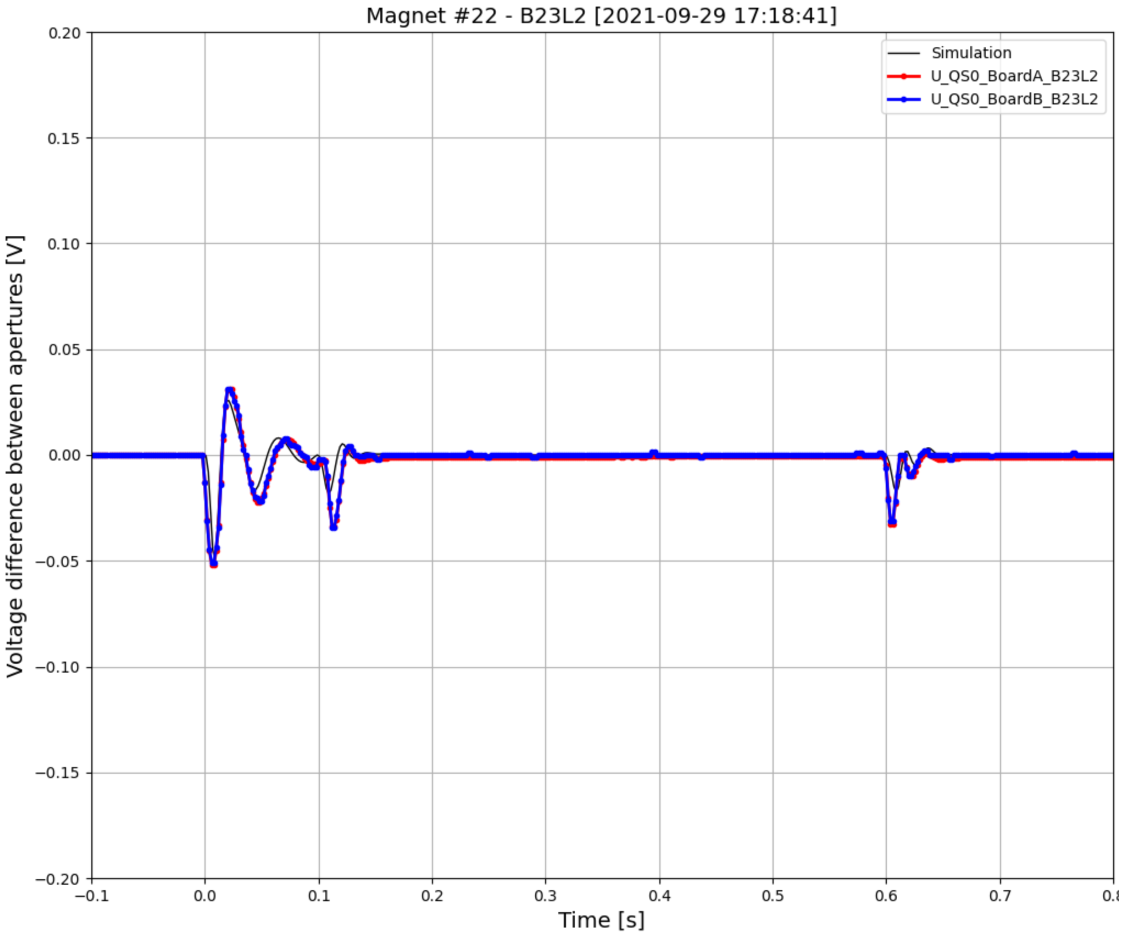
$U_{QS,0}$ of an FPA @ **11 kA** w/ 10A/s ramp

Modelling results from 2011

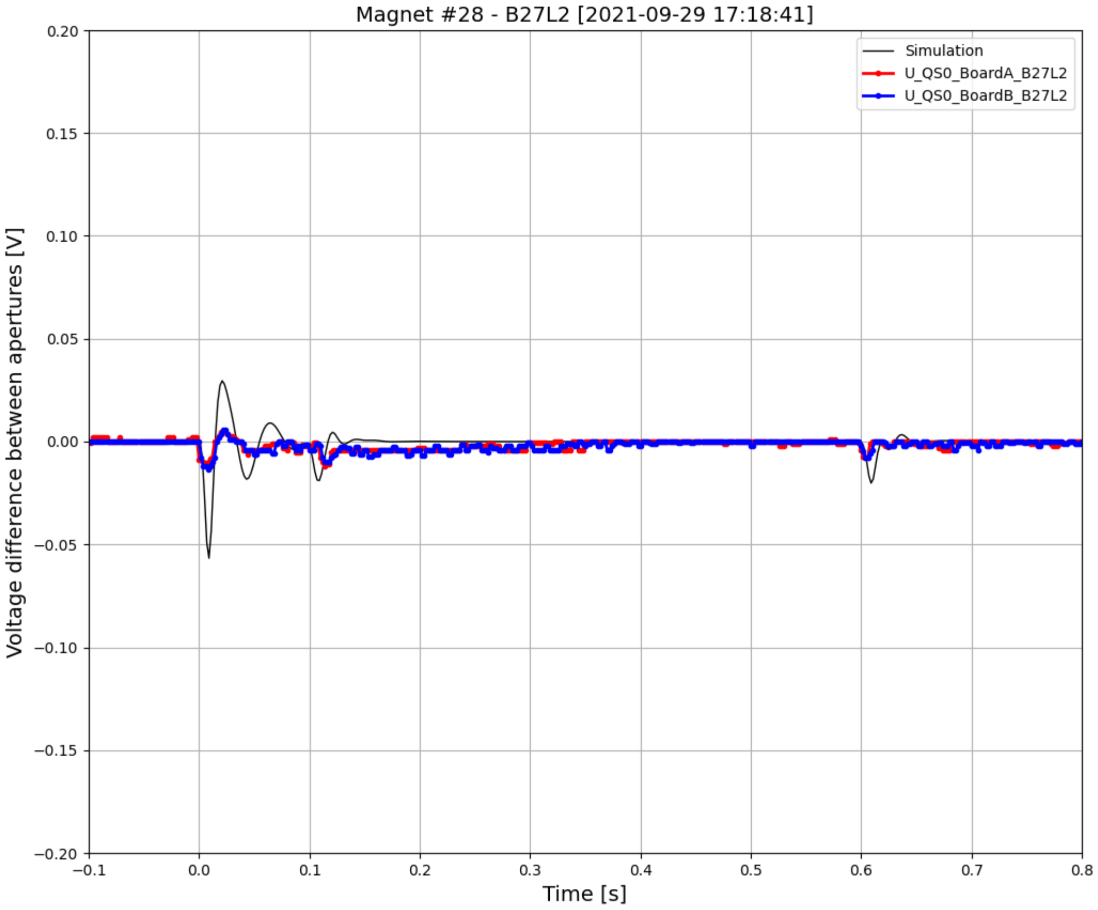




Modelling result - Examples

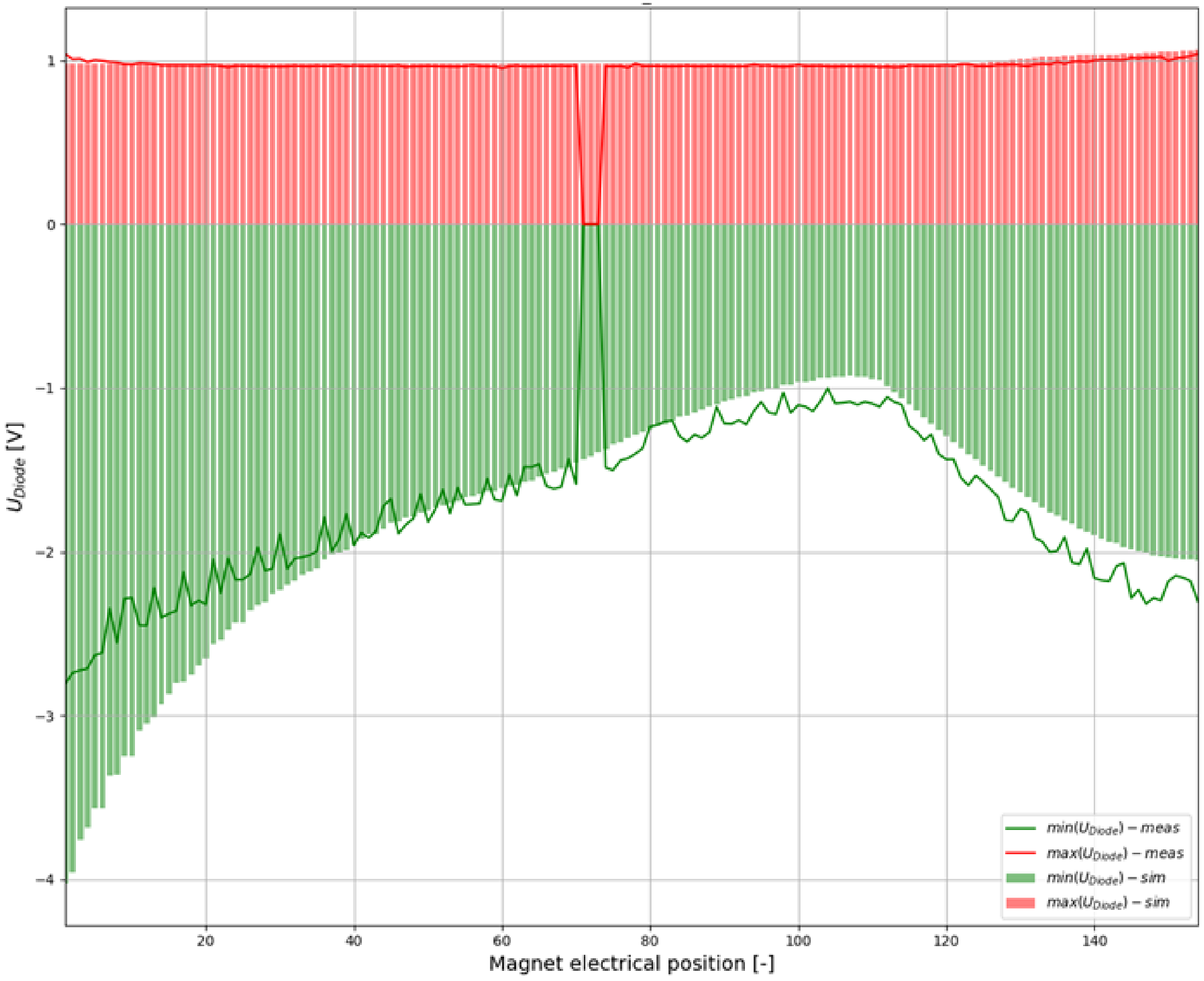


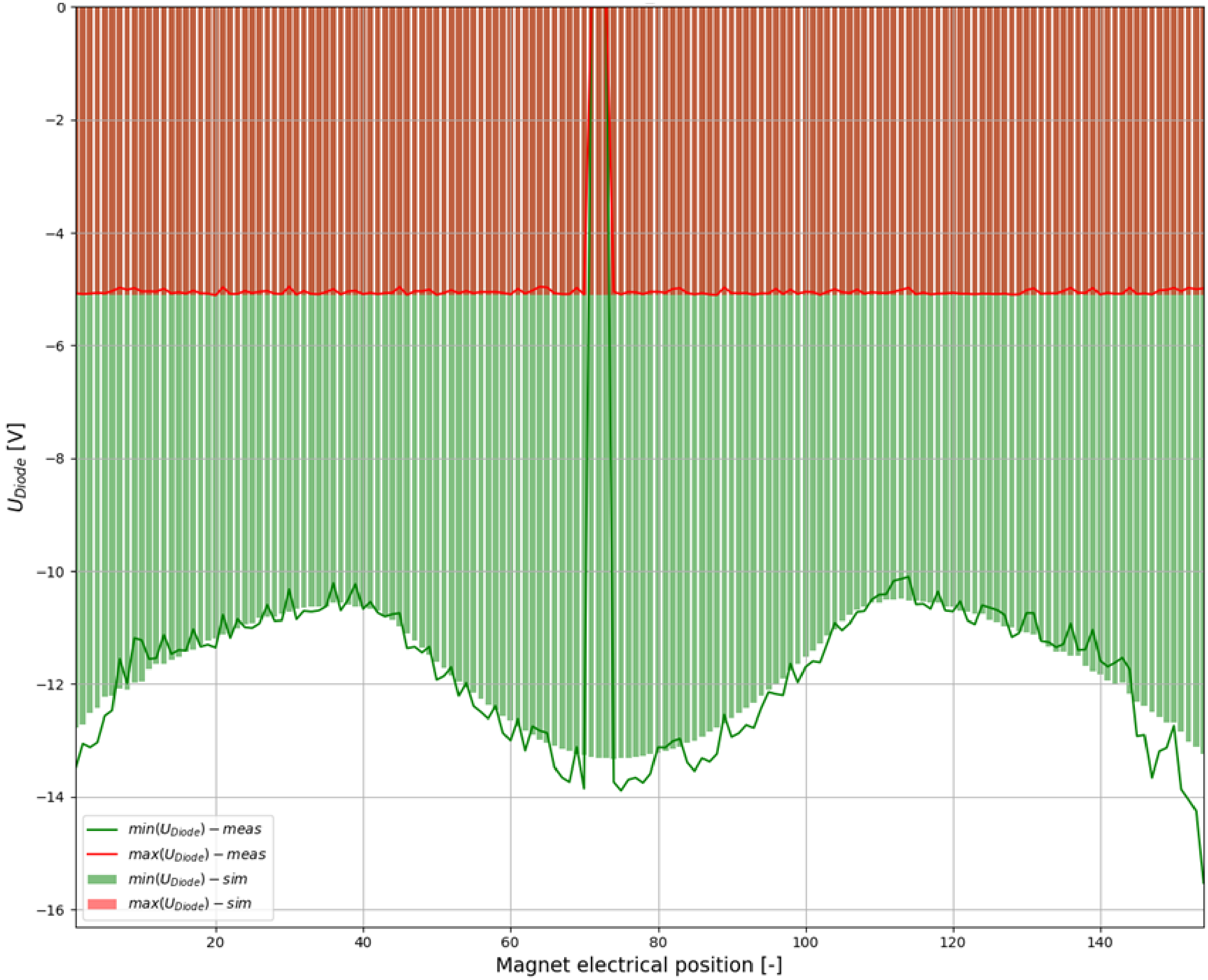
Magnet #22 - B23L2 [2021-09-29 17:18:41]



Magnet #28 - B27L2 [2021-09-29 17:18:41]

Voltages across the magnet





Conclusion

- Previous modelling approaches of the main dipole were **not** able to reproduce the unbalanced dipole behavior at **all** current level

- Past investigations showed a strong correlation of beam-screen surface resistances and unbalancedness

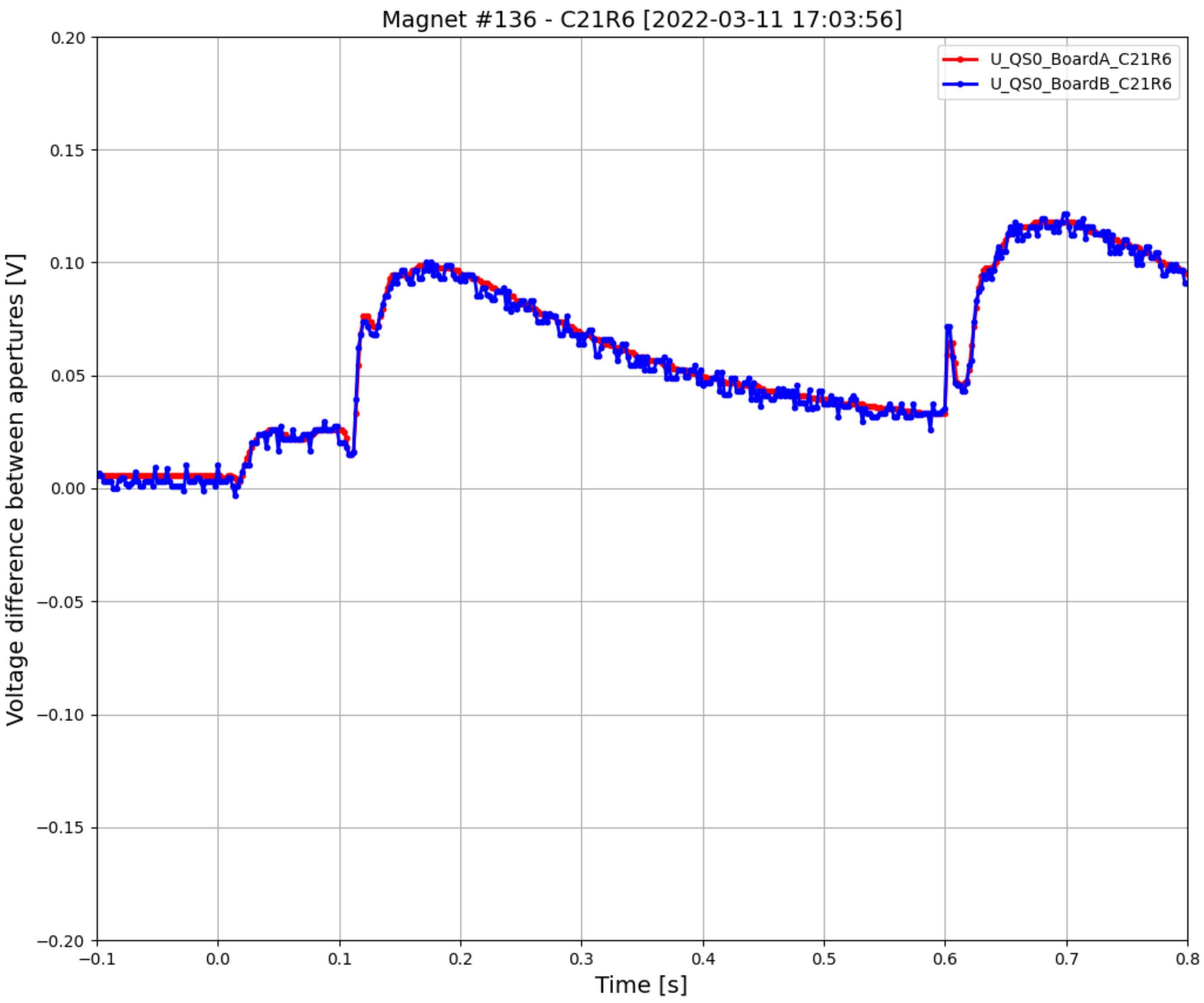
→ Further analysis of the surface resistances shows a **significant spread in purity and thickness** of the different copper layers of the beam-screen

- These measured parameters were utilized in a novel model, which couples the magnet‘s main inductance to the induced eddy currents loops in the beam-screen
- The results indicate to **agree** with measurements on **low- as well as on high current levels**

→ Still work in progress to continue analyzing other parameters in the process in order to improve the fit

- The results and the model can also be used in the frequency domain, to reproduce Transfer Functions measured of the magnet → to be shown soon

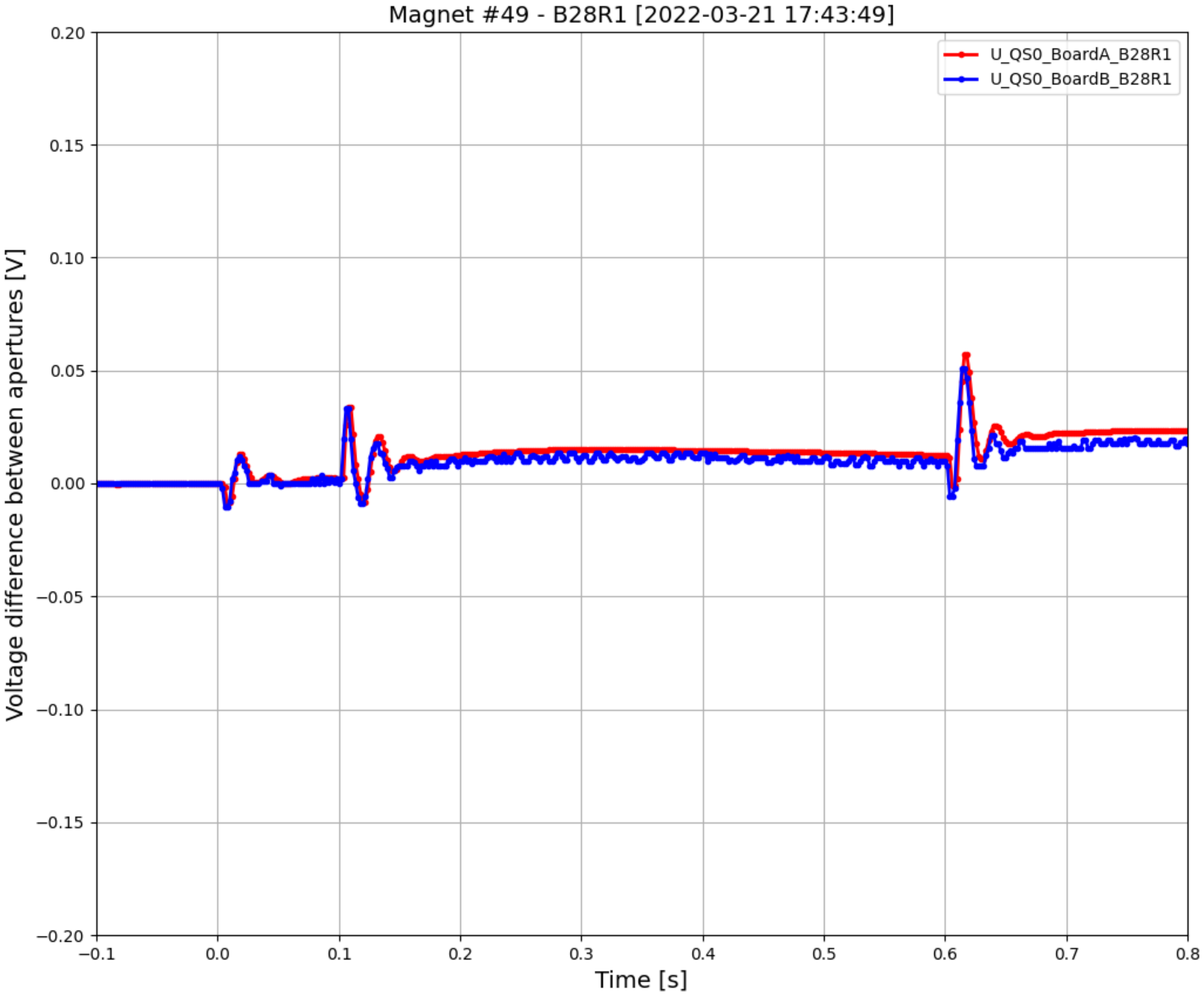
The outliers



What is going on here?

Can we model this? And if so, what could it be?

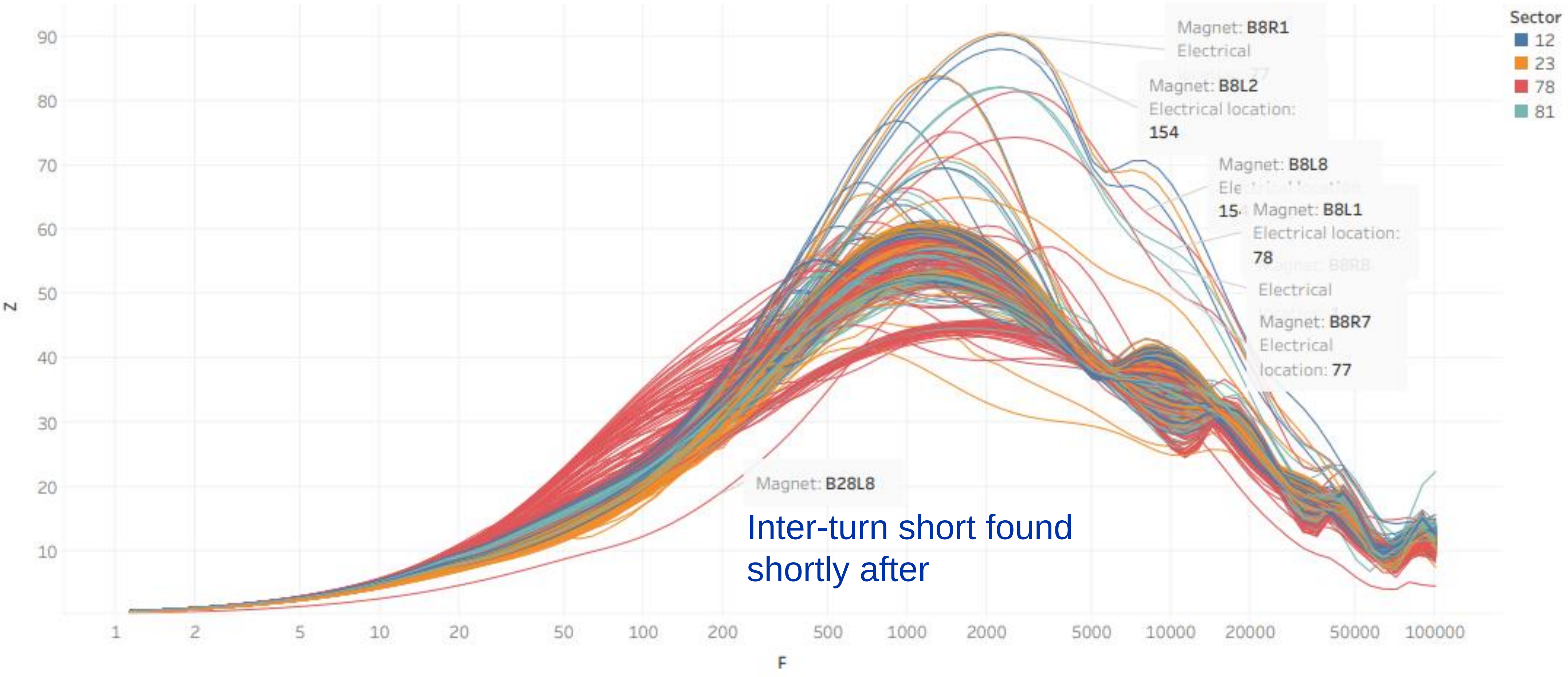
The outliers



What is going on here?

Can we model this? And if so, what could it be?

The outliers



Inter-turn short found
shortly after

R.G. Saederup, "Local Transfer Function Measurement (TFM) Data Analysis", edms 2675917