Simulations of electromagnetic responses in superconducting magnet circuits in the time and frequency domains

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Acknowledgements:
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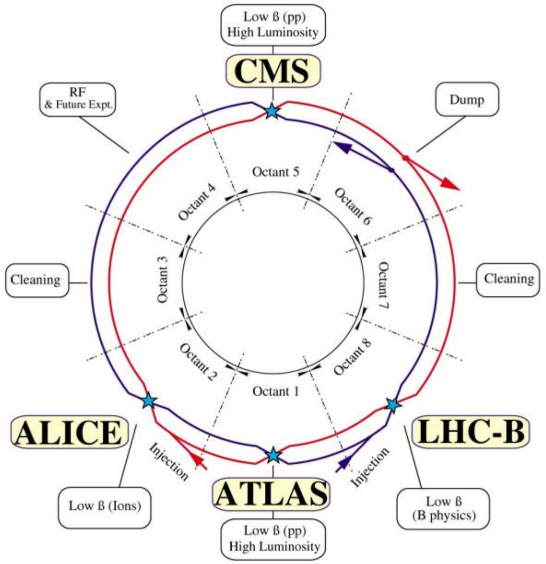
Gentner scholarship

The Motivation – LHC main dipole

All simulations in this presentation concentrate on the LHC main dipole circuits



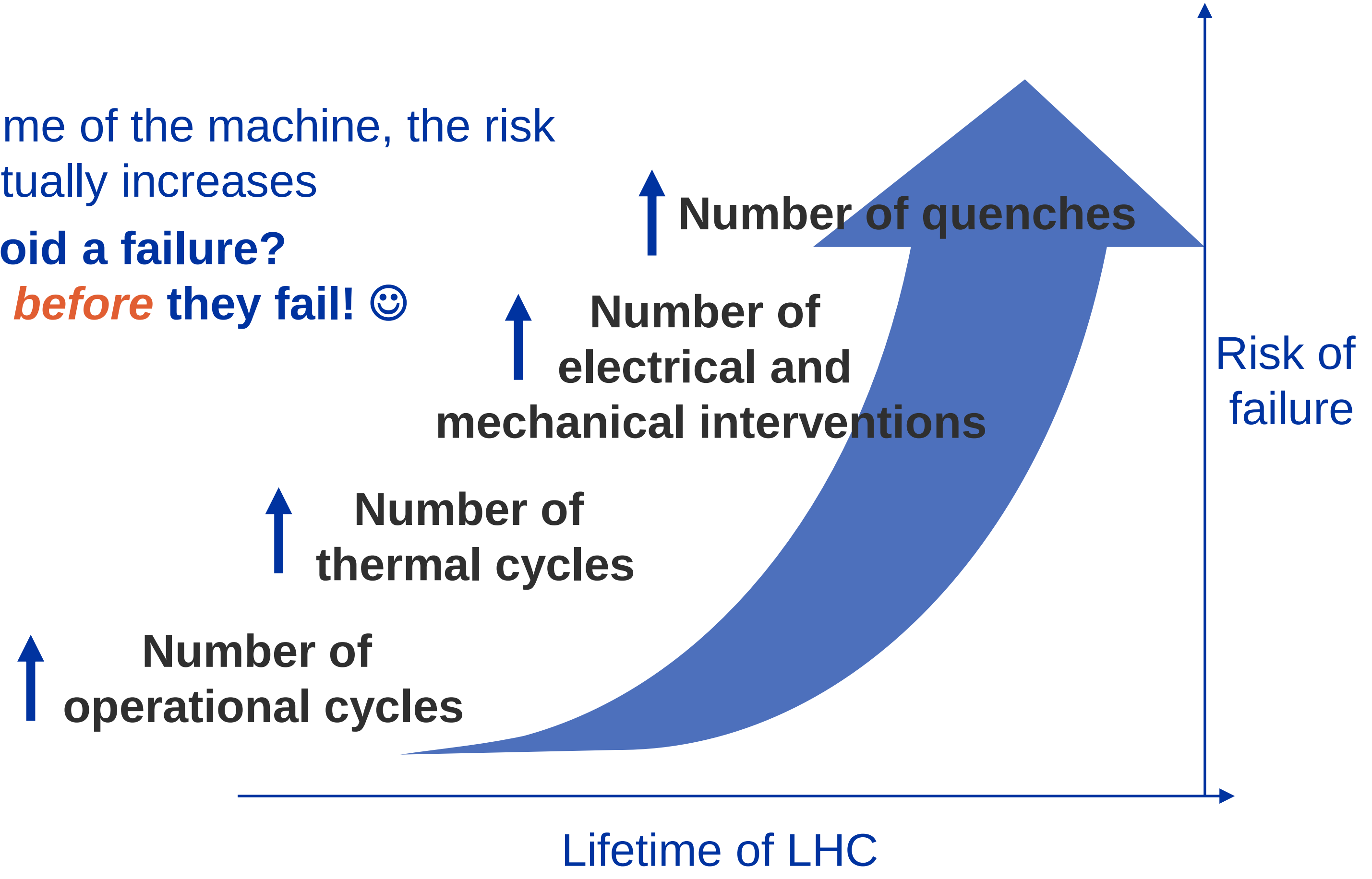
Per octant

Chain of 154 superconducting dipoles in series

Superconducting magnets are constantly subject to high forces, heat, strain, stress radiation etc.

→ Over the lifetime of the machine, the risk of a failure eventually increases

How can we avoid a failure?
Let‘s find them *before* they fail! ☺



↑ Number of quenches

↑ Number of electrical and mechanical interventions

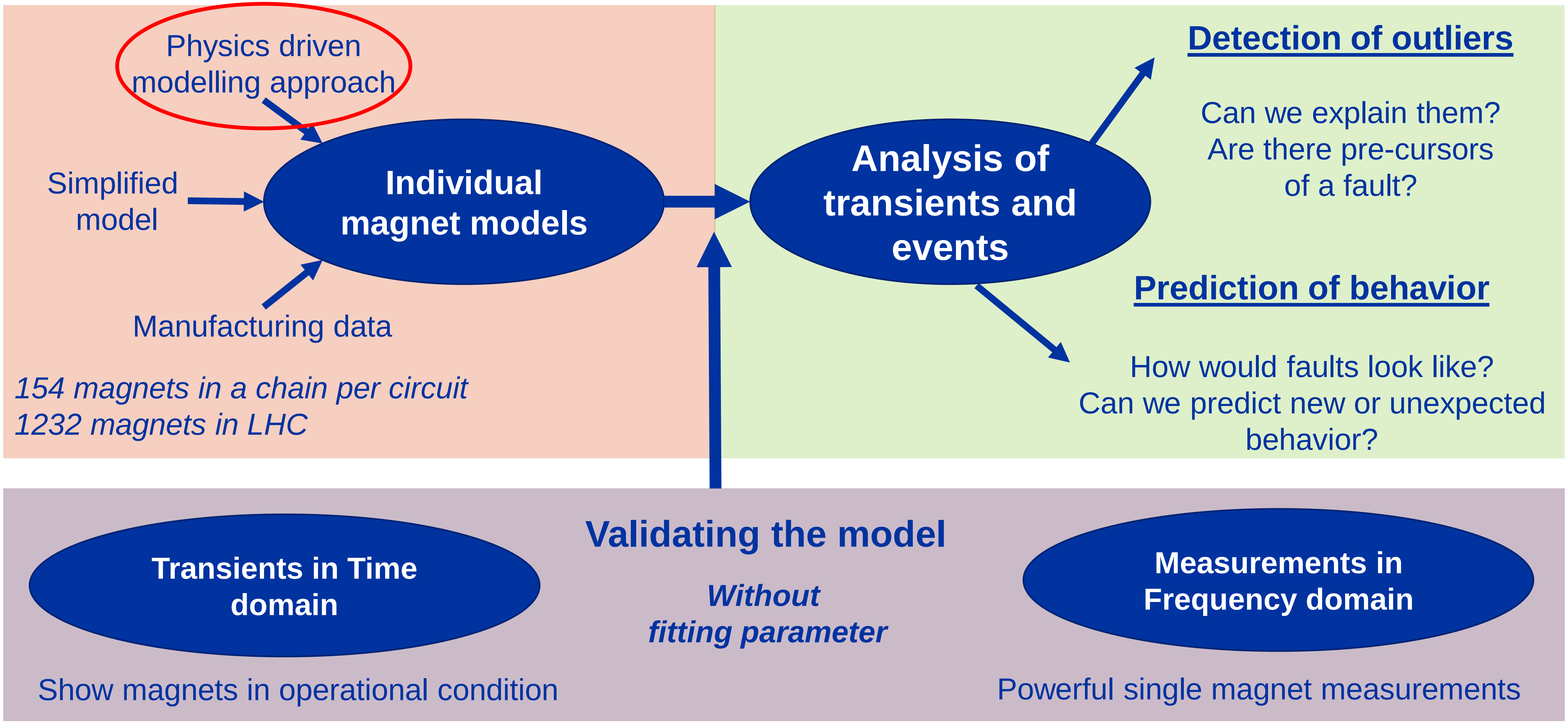
↑ Number of thermal cycles

↑ Number of operational cycles

Risk of failure

Lifetime of LHC

The Motivation



Physics driven modelling approach

Simplified model

Manufacturing data

Individual magnet models

154 magnets in a chain per circuit
1232 magnets in LHC

Analysis of transients and events

Detection of outliers

Can we explain them?
Are there pre-cursors of a fault?

Prediction of behavior

How would faults look like?
Can we predict new or unexpected behavior?

Validating the model

Without fitting parameter

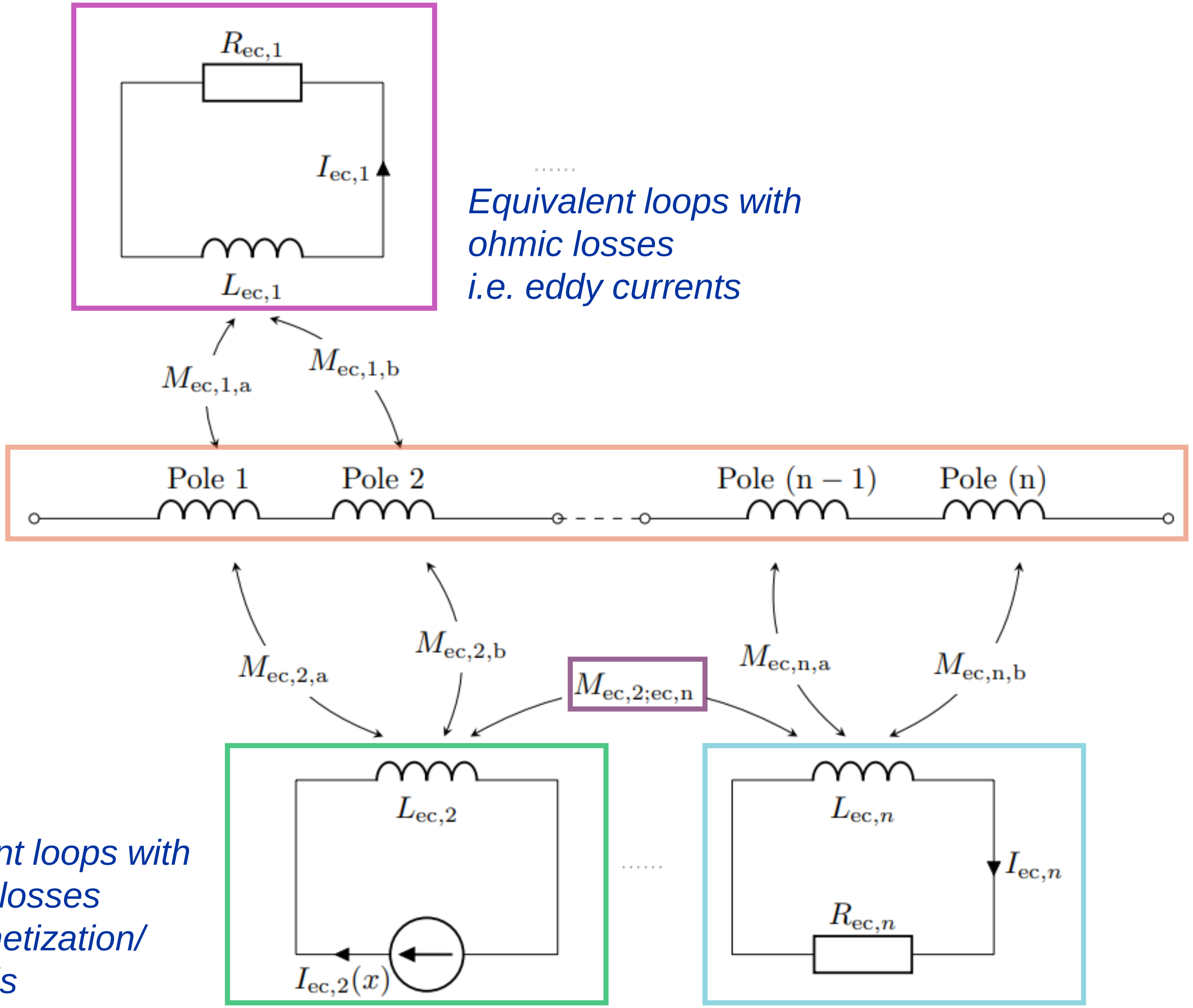
Transients in Time domain

Show magnets in operational condition

Measurements in Frequency domain

Powerful single magnet measurements

The modelling approach



Equivalent loops with
ohmic losses
i.e. eddy currents

Equivalent loops with
dynamic losses
i.e. magnetization/
hysteresis

- Electrical network model incorporating all components of the circuit as lumped elements
- Magnets main inductances are coupled to equivalent loops

- Equivalent loops represent a specific physical phenomena
  → Can be coupled to the whole coil, apertures, poles, turns …
- Loops can be also coupled to other loops

- Equivalent loop parameter $\boldsymbol{L_{ec,n}}$, $\boldsymbol{R_{ec,n}}$ and $\boldsymbol{M_{ec,n}}$ are derived based on for example:
  1. Physical phenomena
  2. Geometrical and
  3. Material properties

The derivation of the equivalent parameter

A generic, electro-magnetic loss mechanism can be described as:

$$
\begin{aligned}
P_{\text{ec}} &= \beta_{\text{ec}} V_{\text{ec}} \left(\frac{\partial B_t}{\partial t} \right)^2 \\
I_{\text{ec}} &= -\gamma_{\text{ec}} \frac{\partial B_t}{\partial t} \\
\frac{\partial B_t}{\partial t} &= -\,\tau_{ec} B_{ec}
\end{aligned}
$$

Description of the loss depends on the physical phenomena and requires a certain level of assumptions/ simplifications

+

Electrical coupling between an electrical element *e* and the equivalent circuit-loop

$$
-R_{\text{ec}} I_{\text{ec}} = \sum_{e=1}^{N_E} M_{\text{ec},e} \frac{\partial I_e}{\partial t} + L_{\text{ec}} \frac{\partial I_{\text{ec}}}{\partial t}
$$

Derivation of the equivalent circuit parameter

$$
\begin{aligned}
R_{\text{ec}} &= \frac{P_{\text{ec}}}{I_{\text{ec}}^2} = \frac{\beta_{\text{ec}} V_{\text{ec}}}{\gamma_{\text{ec}}^2} \\
L_{\text{ec}} &= \tau_{\text{ec}} R_{\text{ec}} = \tau_{\text{ec}} \frac{\beta_{\text{ec}} V_{\text{ec}}}{\gamma_{\text{ec}}^2} \\
M_{\text{ec}} &= \frac{\beta_{\text{ec}} V_{\text{ec}}}{\gamma_{\text{ec}}} f_{\text{ec}}
\end{aligned}
$$

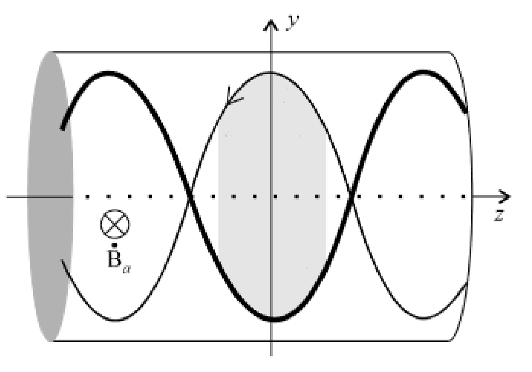
E. Ravaioli et al. , 2016, Cryogenics, „Lumped-Element Dynamic Electro-Thermal model of a superconducting magnet”, https://doi.org/10.1016/j.cryogenics.2016.04.004

E. Ravaioli, 2015, PhD Thesis, „CLIQ. A new quench protection technology for superconducting magnets”, https://doi.org/10.3990/1.9789036539081

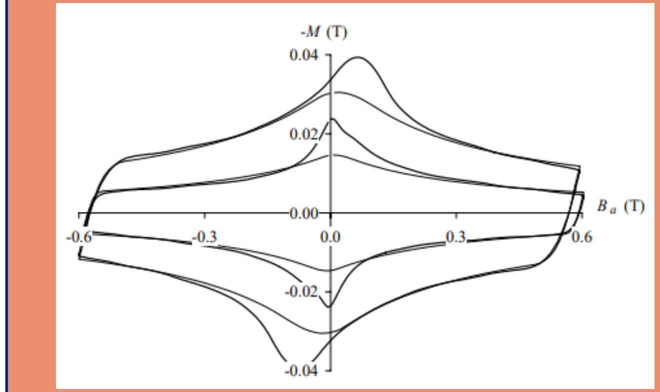
Equivalent circuit-loops

3 examples

Inter-filament and Inter-strand coupling currents



Persistent currents and magnetization



Eddy currents in Magnet components

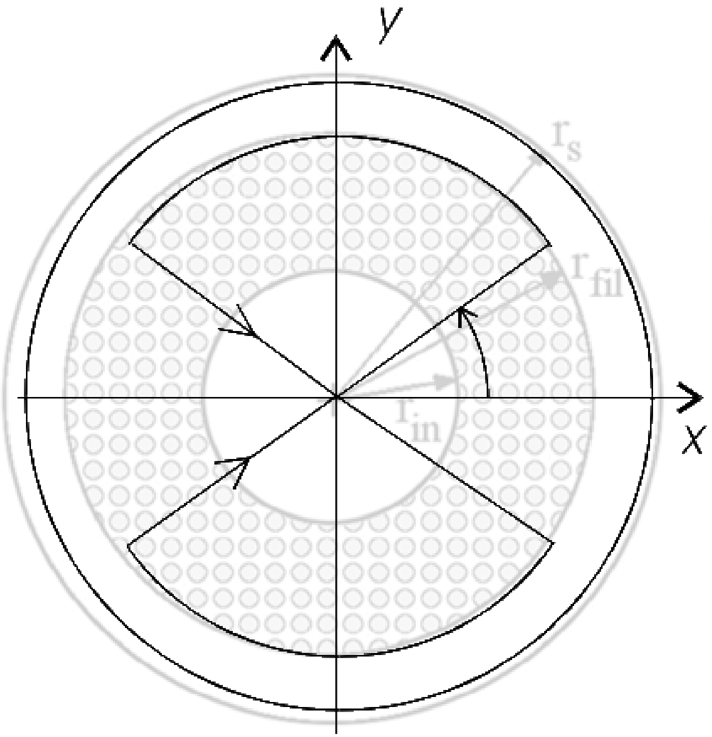
Beam-screen

Equivalent circuit-loops:

1. Inter-filament- and Inter-strand-coupling loops

Well studied and modelled phenomena in the literature

Inter-filament Coupling Currents
(IFCL) closing through the conductive matrix

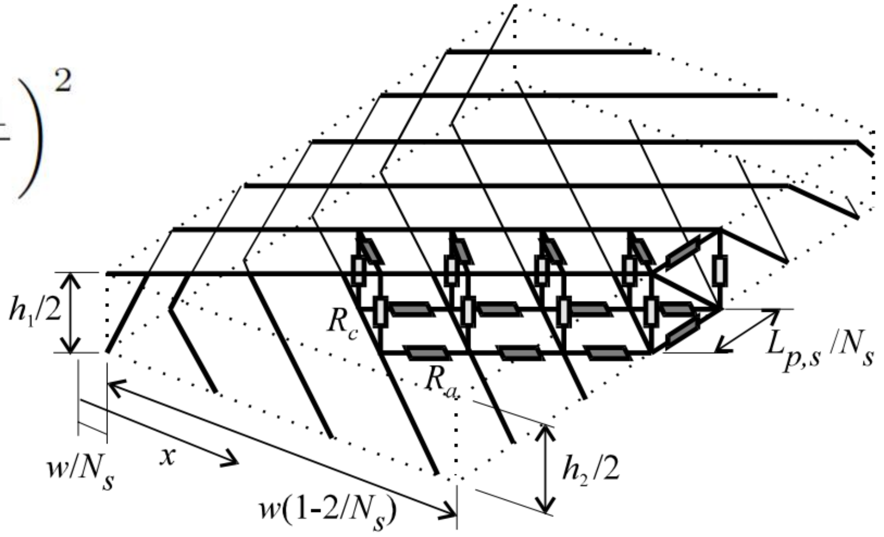


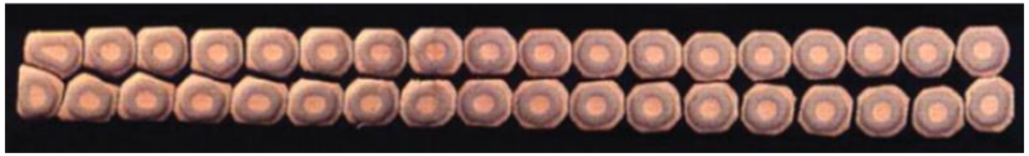
$$P_{\text{IFCL}} = \left(\frac{l_f}{2\pi}\right)^2 \frac{1}{\rho_{eff}} V_s \left(\frac{\partial B_t}{\partial t}\right)^2$$

$$P_{\text{ISCL}} = \underbrace{\frac{1}{120}\frac{l_s}{R_c} N_s (N_s - 1)\frac{w}{h}}_{\beta_{ec}} V_C \left(\frac{\partial B_{t,\perp}}{\partial t}\right)^2$$

Loss mechanisms depend
on geometrical and strand-/filament
parameters

Inter-strand Coupling currents
(ISCL) closing through the strand contact resistances



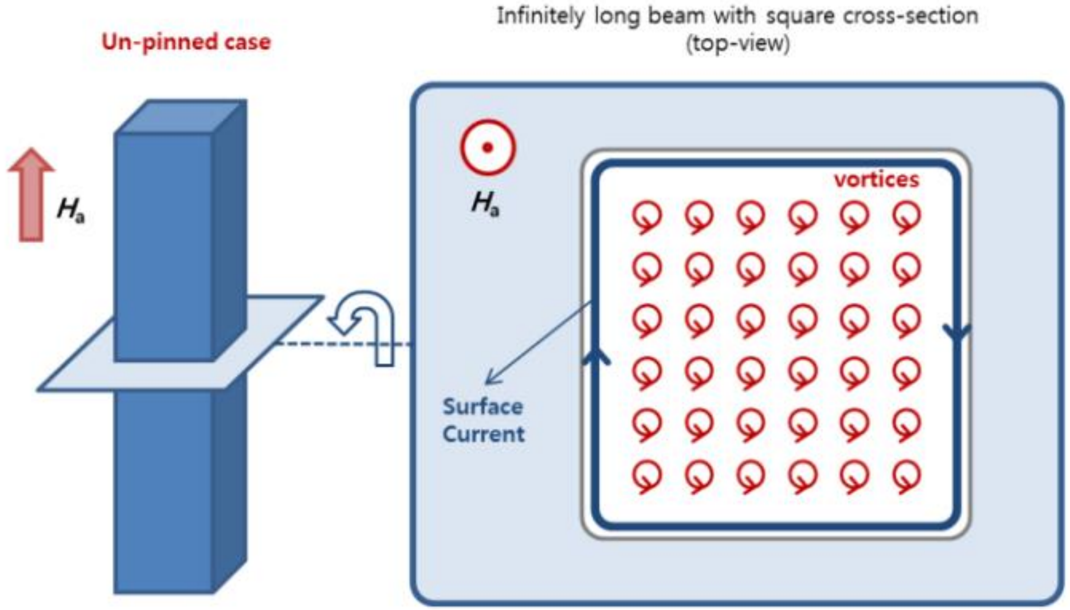


Theory and figures from:
E. Ravaioli, 2015, PhD Thesis, „CLIQ. A new quench protection technology for superconducting magnets", https://doi.org/10.3990/1.9789036539081
A. P. Verweij, 1995, PhD Thesis, "Electrodynamics of Superconducting Cables in Accelerator Magnets" , http://cds.cern.ch/record/292595

Equivalent circuit-loops:

2. Persistent currents and magnetization

The magnetization phenomena includes:



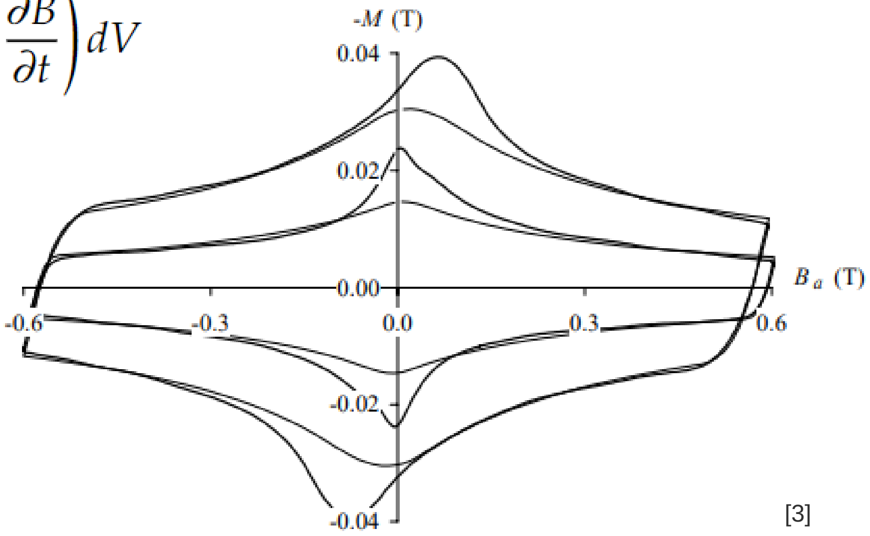
[2]

1. Power loss due to magnetization heat [1]

$$P_{\text{Lost}} = \iiint_{V,M\neq 0} \left(M \cdot \frac{\partial B}{\partial t} \right) dV$$

2. Stored power in persistent current loops [1]

$$P_{\text{Stored}} = \iiint_{V} \left(H \cdot \frac{\partial B}{\partial t} \right) dV$$



[3]

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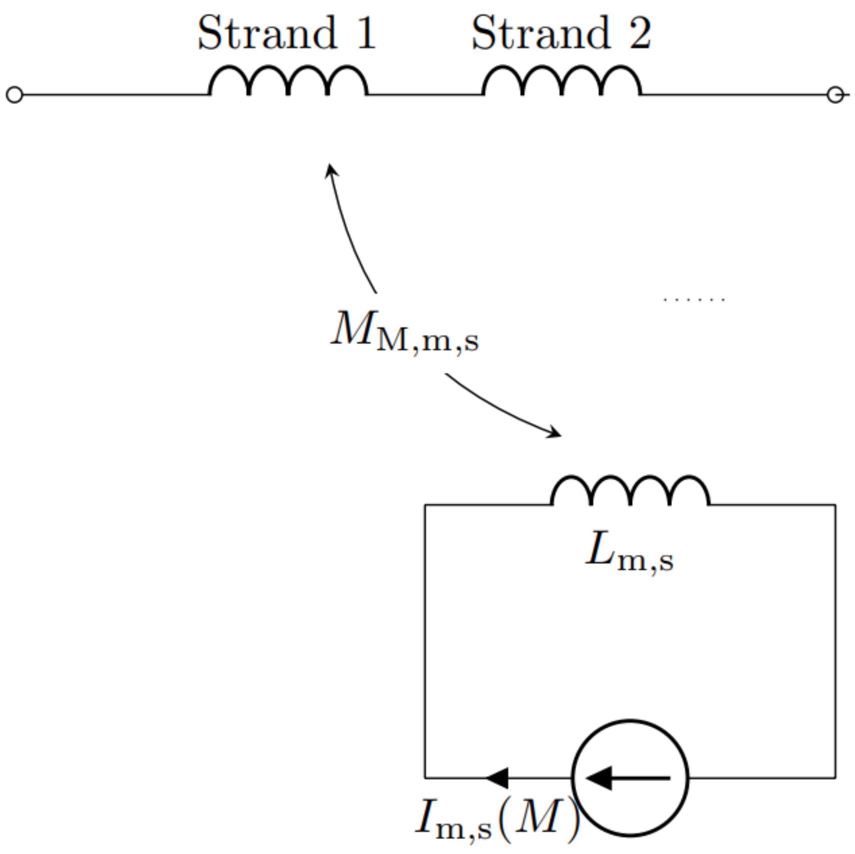
[1] M. Sorbi, V. Marrinozzi, IEEE Transaction on Applied Superconductivity, 2016,, Magnetization Heat in Superconductors and in Eddy Current Problems: A Classical Thermodynamic Approach“, https://doi.org/10.1109/TASC.2016.2544823
[2] S. Oh et al., arXiv, “Beyond Bean’s critical state model: On the origin of paramagnetic Meissner effect”, https://doi.org/10.48550/arXiv.1612.04893
[3] A. P. Verweij, 1995, PhD Thesis, “Electrodynamics of Superconducting Cables in Accelerator Magnets” , http://cds.cern.ch/record/292595

Equivalent circuit-loops:

2. Persistent currents and magnetization



Deriving the formulas before and comparing them to the circuit voltage laws we find that:

$$
\begin{aligned}
I_{\mathrm{m,s}} &= M_{\mathrm{m,s}} d_{\mathrm{w,s}} \\
L_{\mathrm{m,s}} &= \mu_0 \frac{\pi}{4} l_{\mathrm{magnet,s}} \\
M_{\mathrm{M,m,s}} &= \mu_0 \frac{\pi}{4} d_{\mathrm{w,s}} l_{\mathrm{magnet,s}} f_{\mathrm{H,s}} \text{ [1]}
\end{aligned}
$$

$M_{\mathrm{m,s}}$ – Strand magnetization
$d_{\mathrm{w,s}}$ – Strand diameter
$f_{\mathrm{H,s}}$ – Magnetic transfer function
$l_{\mathrm{magnet,s}}$ – Magnet length

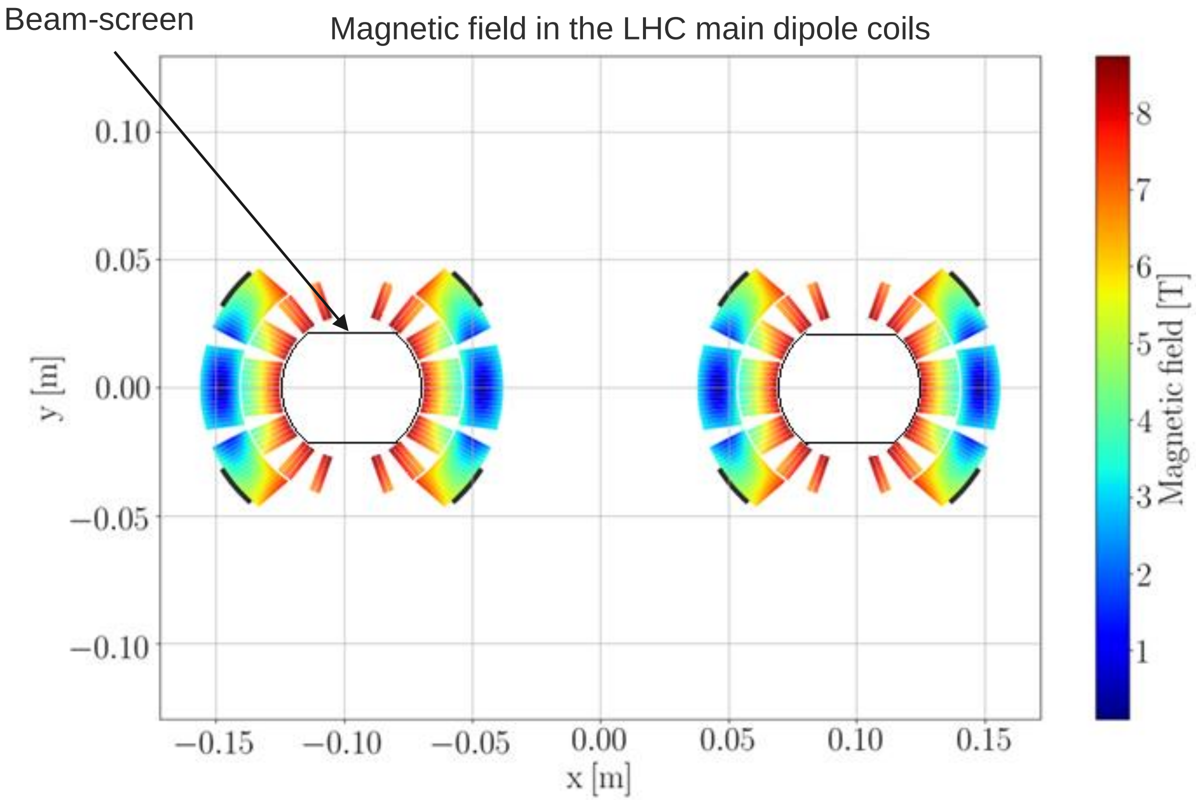
The current in the equivalent loop depends on the magnetization of the strand (i.e. its history)
→ Setting the current $I_{ec,2}(x) = I_{m,s}(M)$ can be used to model dynamic losses in the lumped elements

[1] E. Ravaioli, 2020, Internal Document, "Persistent-currents magnetization in STEAM-LEDET", EMDS 2418186

Equivalent circuit-loops:

3. *Beam-screen eddy currents*

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



Beam-screen and quench heaters not to scale, Field simulated using ROXIE https://roxie.docs.cern.ch/

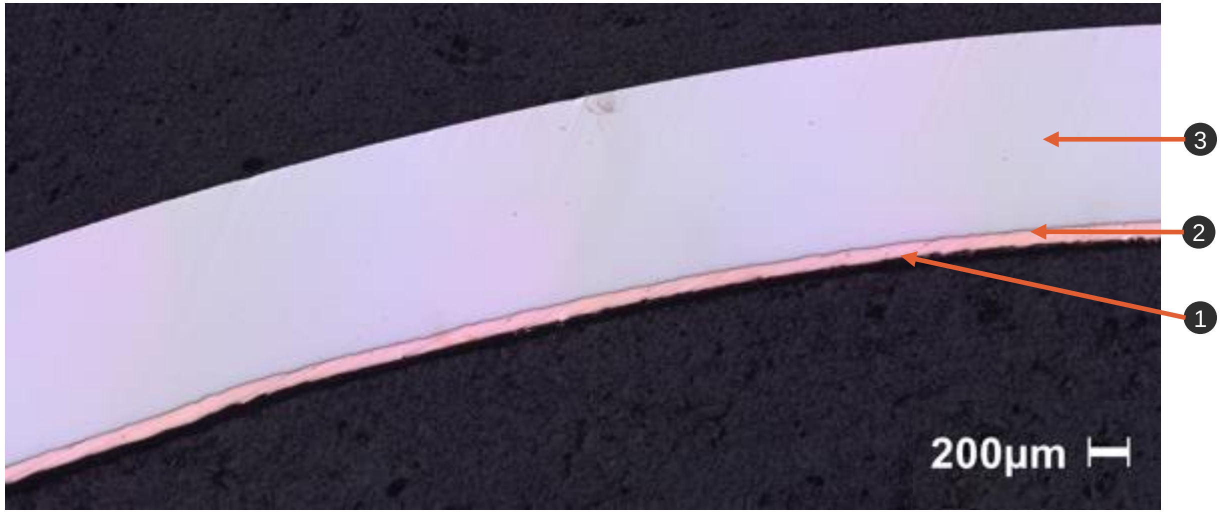
Photograph: P. Loïez, http://cds.cern.ch/record/39110

Equivalent circuit-loops:

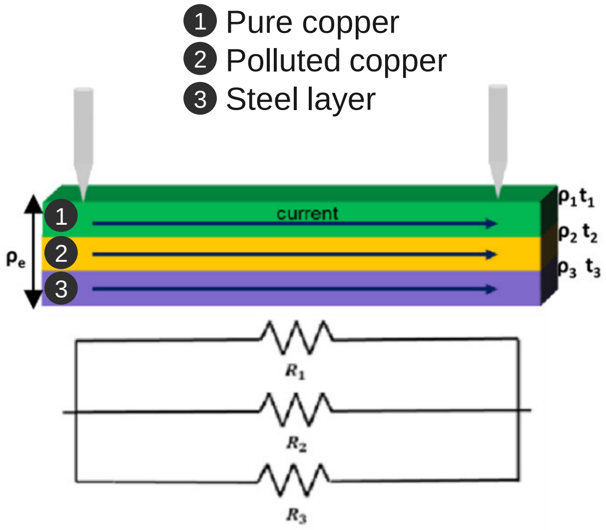
3. *Beam-screen eddy currents*

- Due to co-lamination, some steel particles diffused into the copper layer and impacted the purity

- The manufacturing process of the beam-screens as well as different copper charges introduced some differences in copper purity and thickness (see next slide)

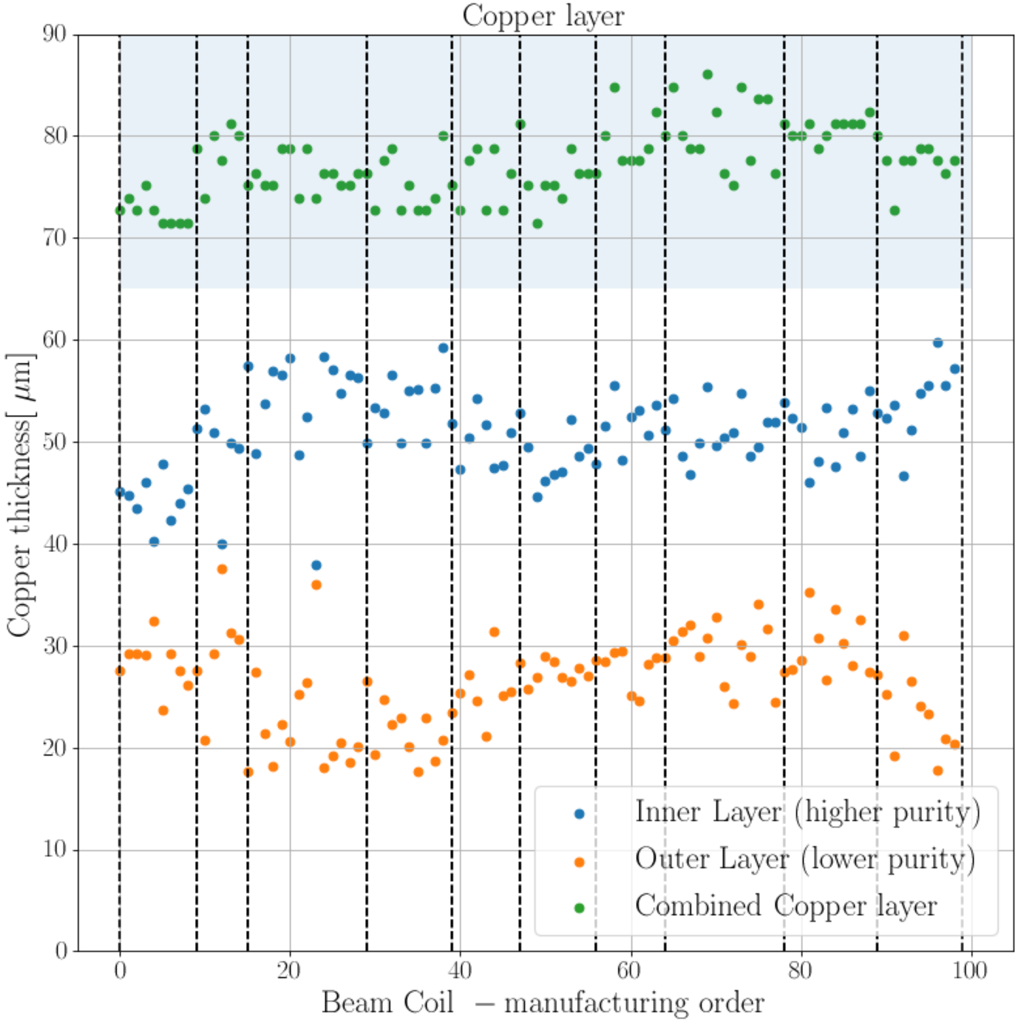


Microscopic picture by: K. Buchanan, CERN, 2023



Equivalent circuit-loops:

3. Beam-screen eddy currents



$t_{\mathrm{Cu}} \in [40, 60]\ \mu m$

RRR $\in [75, 180]$

Usually the two beam-screens installed in the two apertures of an LHC main dipole **are from different production series**

→ **Significant difference** in build-up eddy currents between the electrically connected apertures (We'll see that later)

Derivation of equivalent circuit parameters (similar as before)

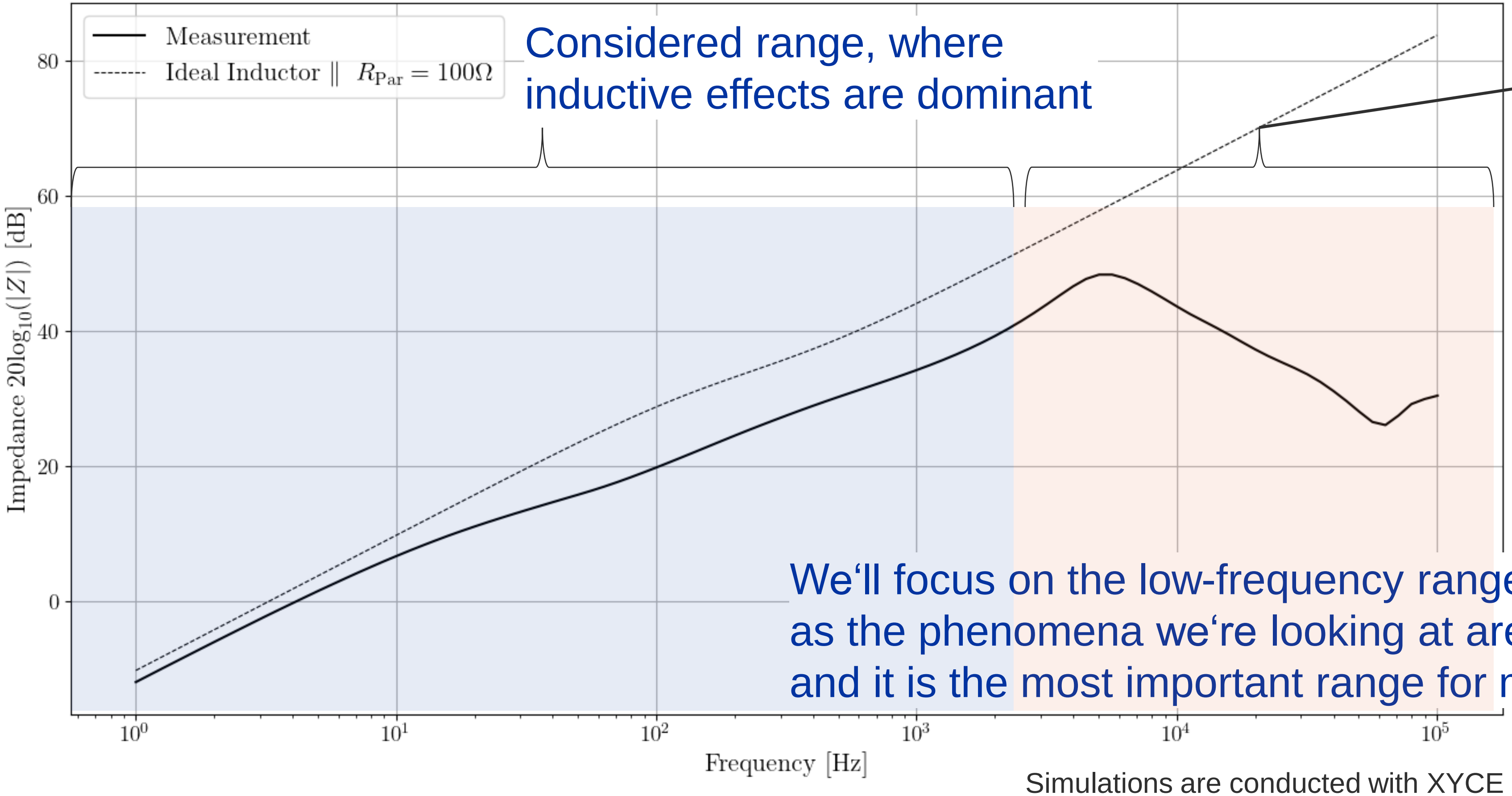
$$\begin{cases} R_{\mathrm{ec}} = \dfrac{\pi t_{\mathrm{b}}(d_{\mathrm{b}} - t_{\mathrm{b}}) l_{\mathrm{m}} \rho_{\mathrm{b}}(T, B)}{2 d_{\mathrm{b}}^2 \delta^2 \left[1 - \exp\left(-\dfrac{t_{\mathrm{b}}}{\delta}\right)\right]^2} & [\Omega] \\ L_{\mathrm{ec}} = \dfrac{\mu_0 \pi t_{\mathrm{b}}(d_{\mathrm{b}}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

- 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

Validation of the model

1. Transfer Function Measurements

Measurement of the complex impedance of the magnets in the RB chain from 1 Hz to 100 kHz



Considered range, where inductive effects are dominant

Capacitive effects are becoming very significant

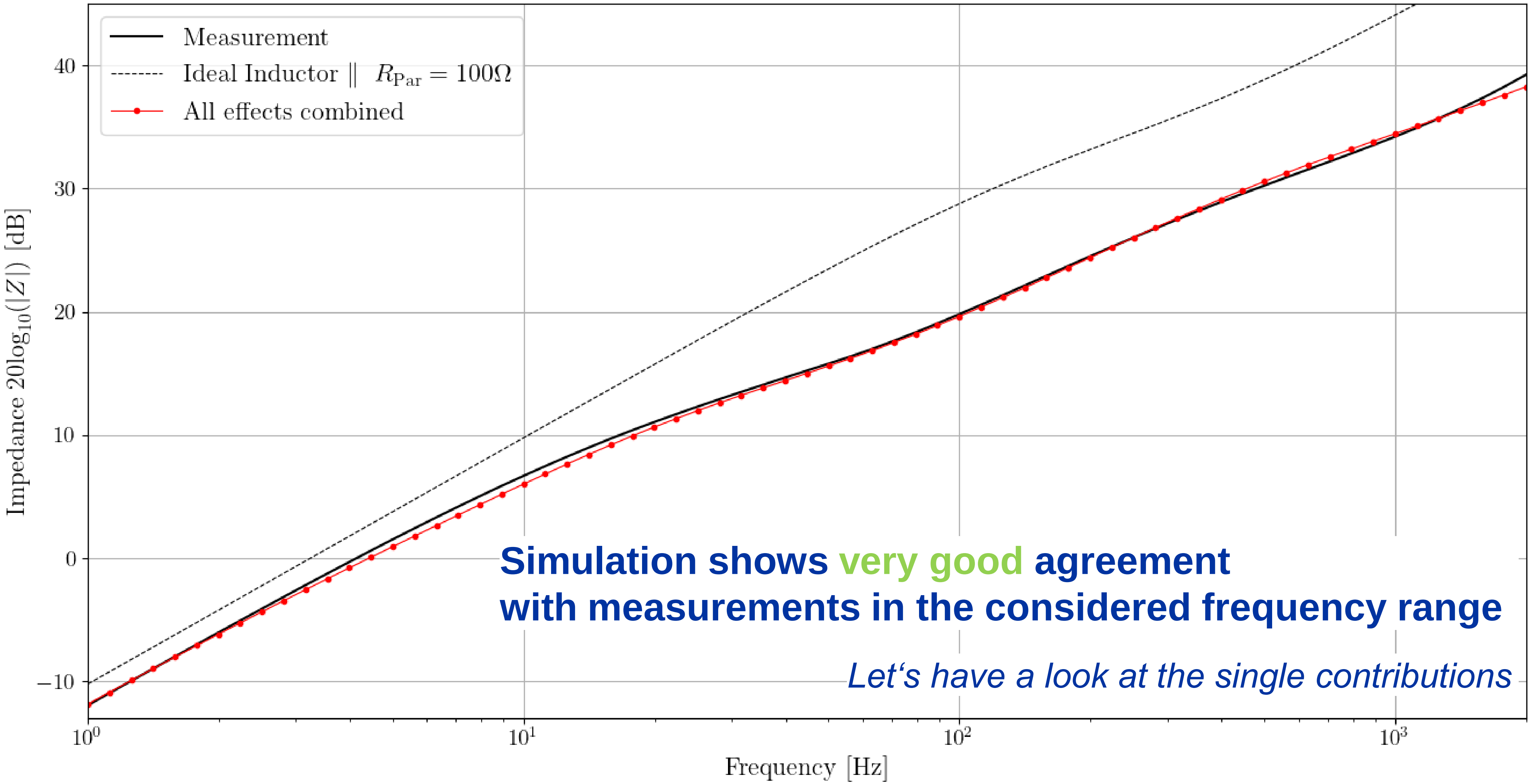
We‘ll focus on the low-frequency range up to ~2 kHz as the phenomena we‘re looking at are mostly visible there and it is the most important range for magnet operation

Simulations are conducted with XYCE (SPICE based solver) https://xyce.sandia.gov

Measurements were taken during YETS22/23 by CERN ELQA in Sector 78

Validation of the model

1. Transfer Function Measurements

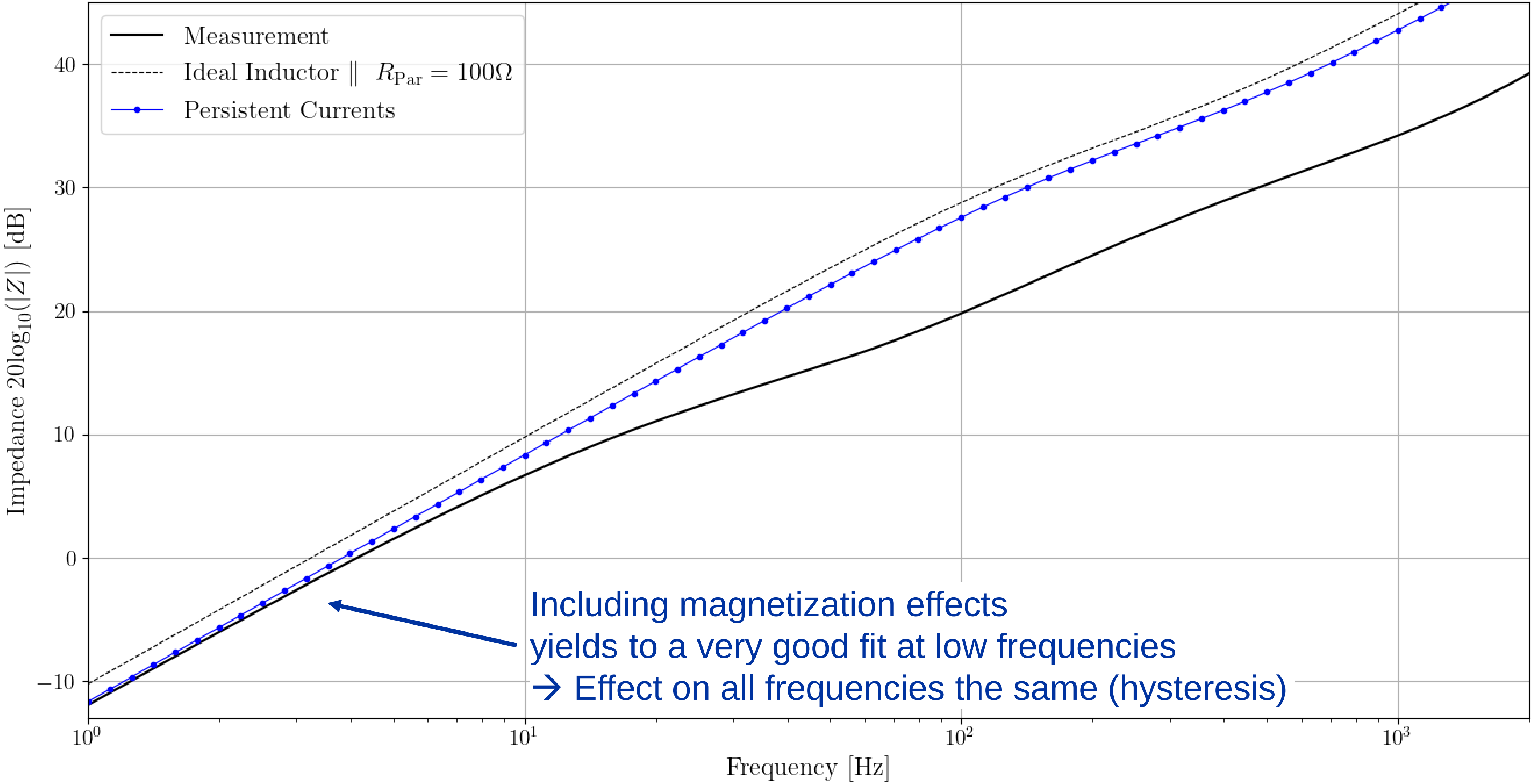


Simulation shows very good agreement with measurements in the considered frequency range

Let‘s have a look at the single contributions

Validation of the model

1. Transfer Function Measurements



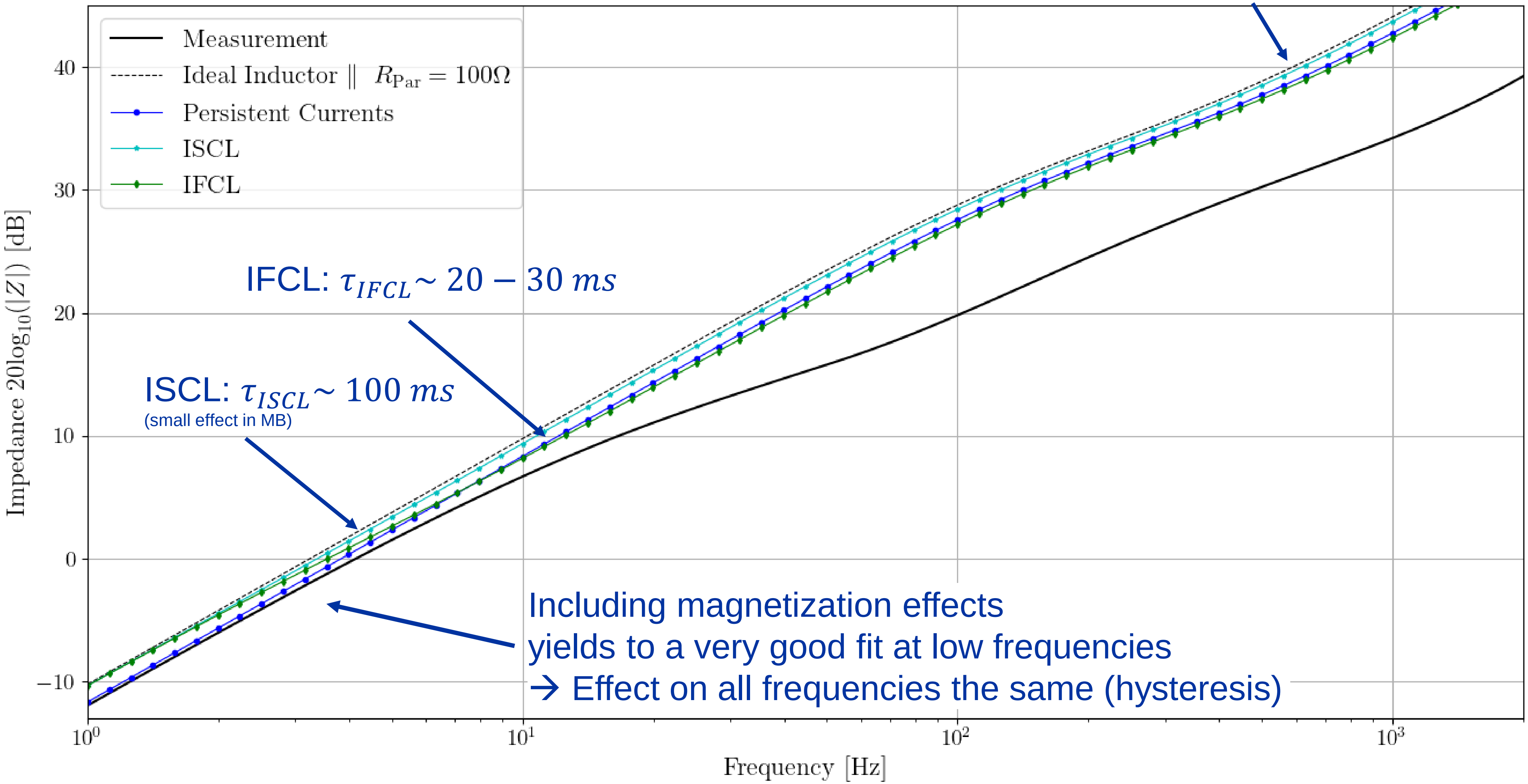
Including magnetization effects
yields to a very good fit at low frequencies
→ Effect on all frequencies the same (hysteresis)

Validation of the model

1. Transfer Function Measurements

IFCL and persistent currents give same effect, as both assume currents on the outer strand surface

→ Loops need to be coupled together, to account for shielding



IFCL: $\tau_{IFCL} \sim 20 - 30\ ms$

ISCL: $\tau_{ISCL} \sim 100\ ms$

(small effect in MB)

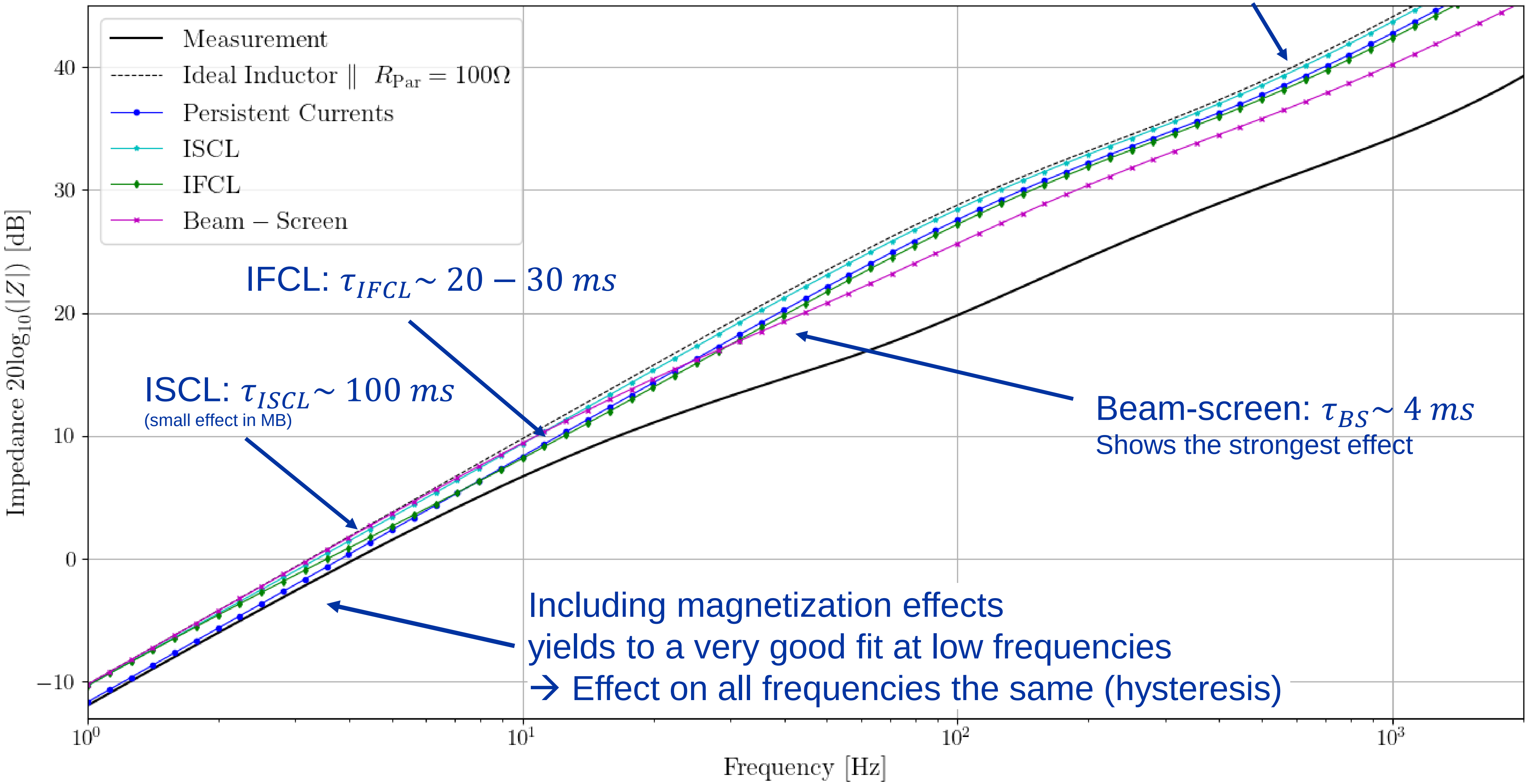
Including magnetization effects yields to a very good fit at low frequencies

→ Effect on all frequencies the same (hysteresis)

Validation of the model

1. Transfer Function Measurements

IFCL and persistent currents give same effect, as both assume currents on the outer strand surface
→ Loops need to be coupled together, to account for shielding



IFCL: $\tau_{IFCL} \sim 20 - 30\ ms$

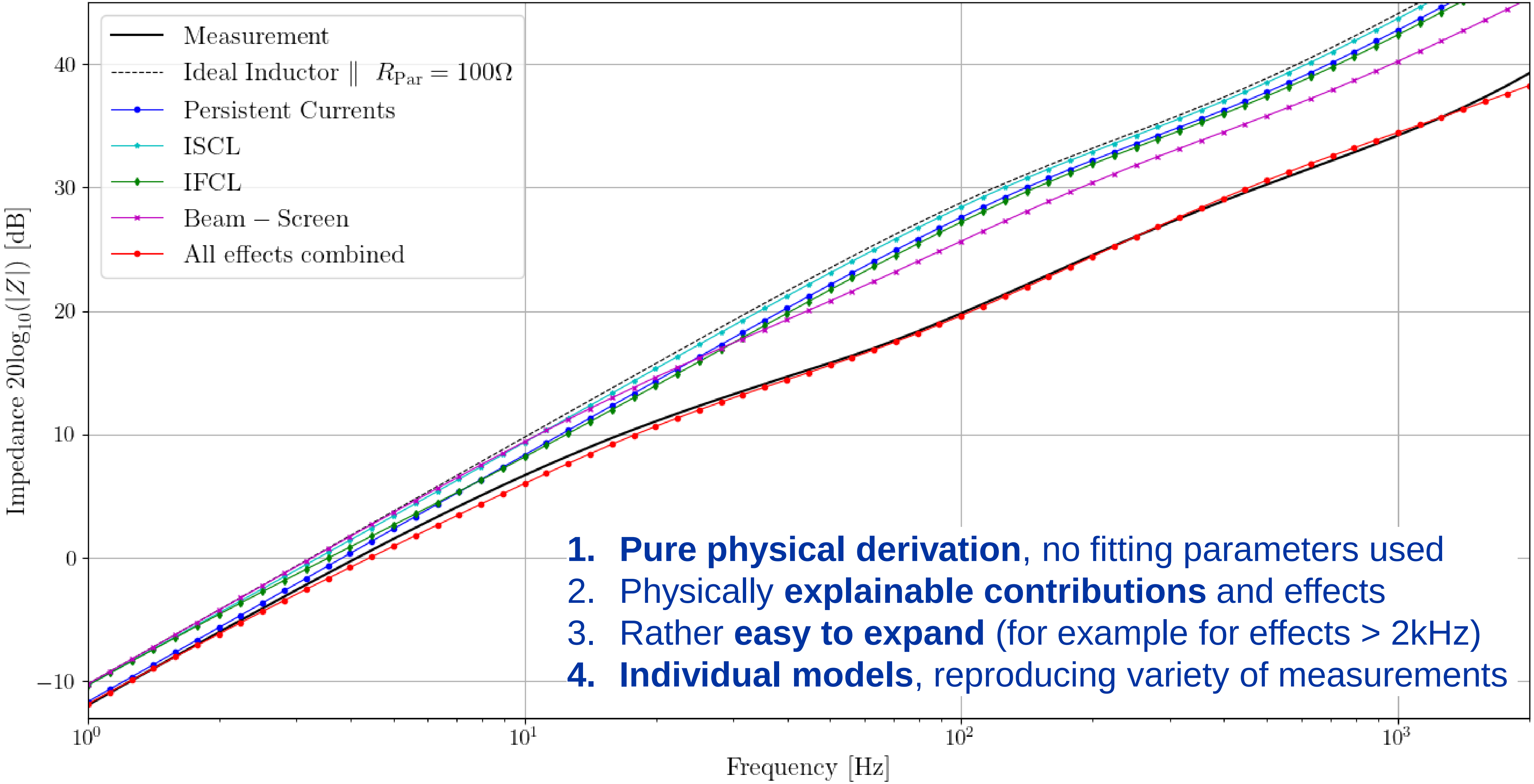
ISCL: $\tau_{ISCL} \sim 100\ ms$
(small effect in MB)

Beam-screen: $\tau_{BS} \sim 4\ ms$
Shows the strongest effect

Including magnetization effects
yields to a very good fit at low frequencies
→ Effect on all frequencies the same (hysteresis)

Validation of the model

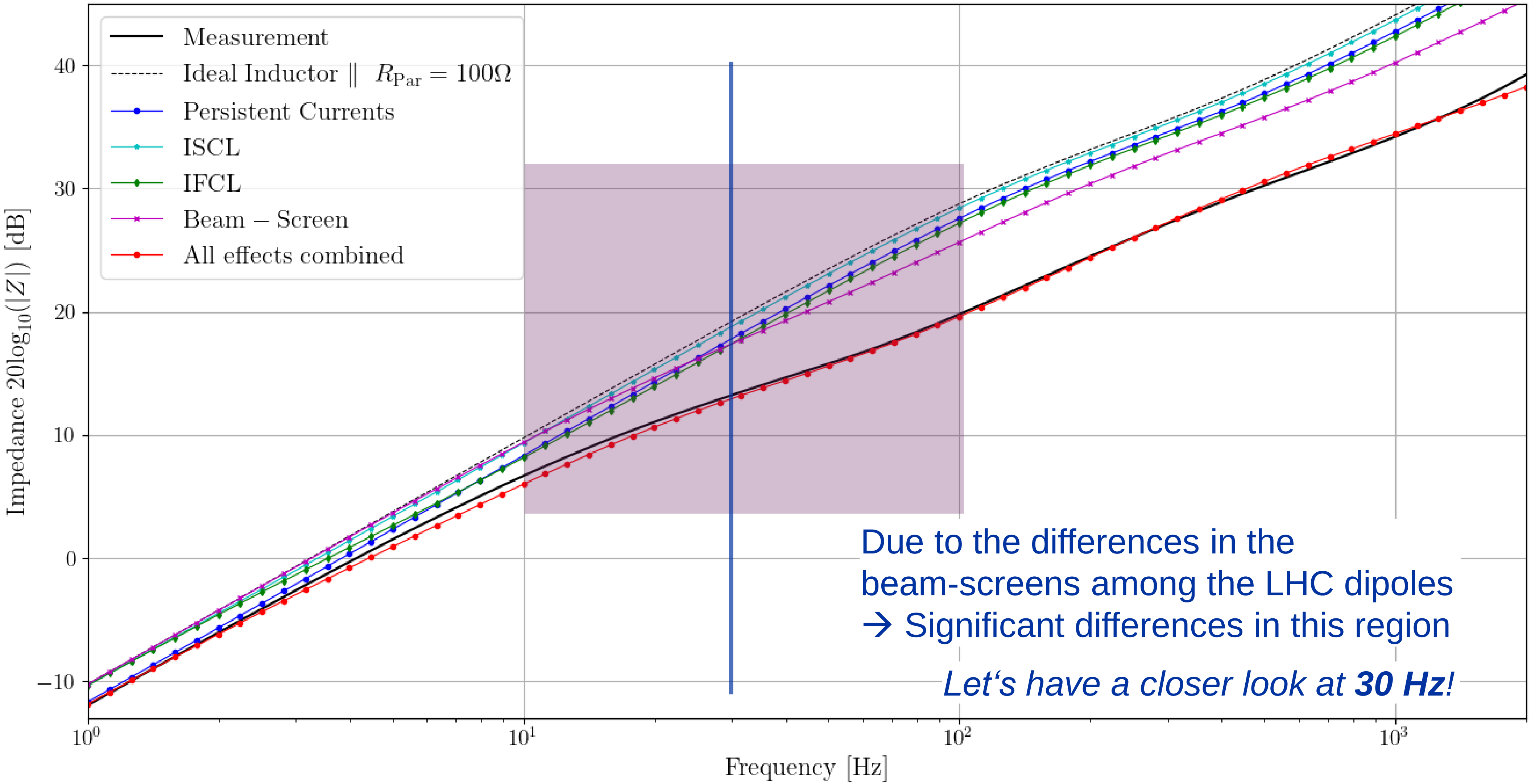
1. Transfer Function Measurements



1. **Pure physical derivation**, no fitting parameters used
2. Physically **explainable contributions** and effects
3. Rather **easy to expand** (for example for effects > 2kHz)
4. **Individual models**, reproducing variety of measurements

Validation of the model

1. Transfer Function Measurements



Due to the differences in the beam-screens among the LHC dipoles
→ Significant differences in this region

*Let's have a closer look at **30 Hz**!*

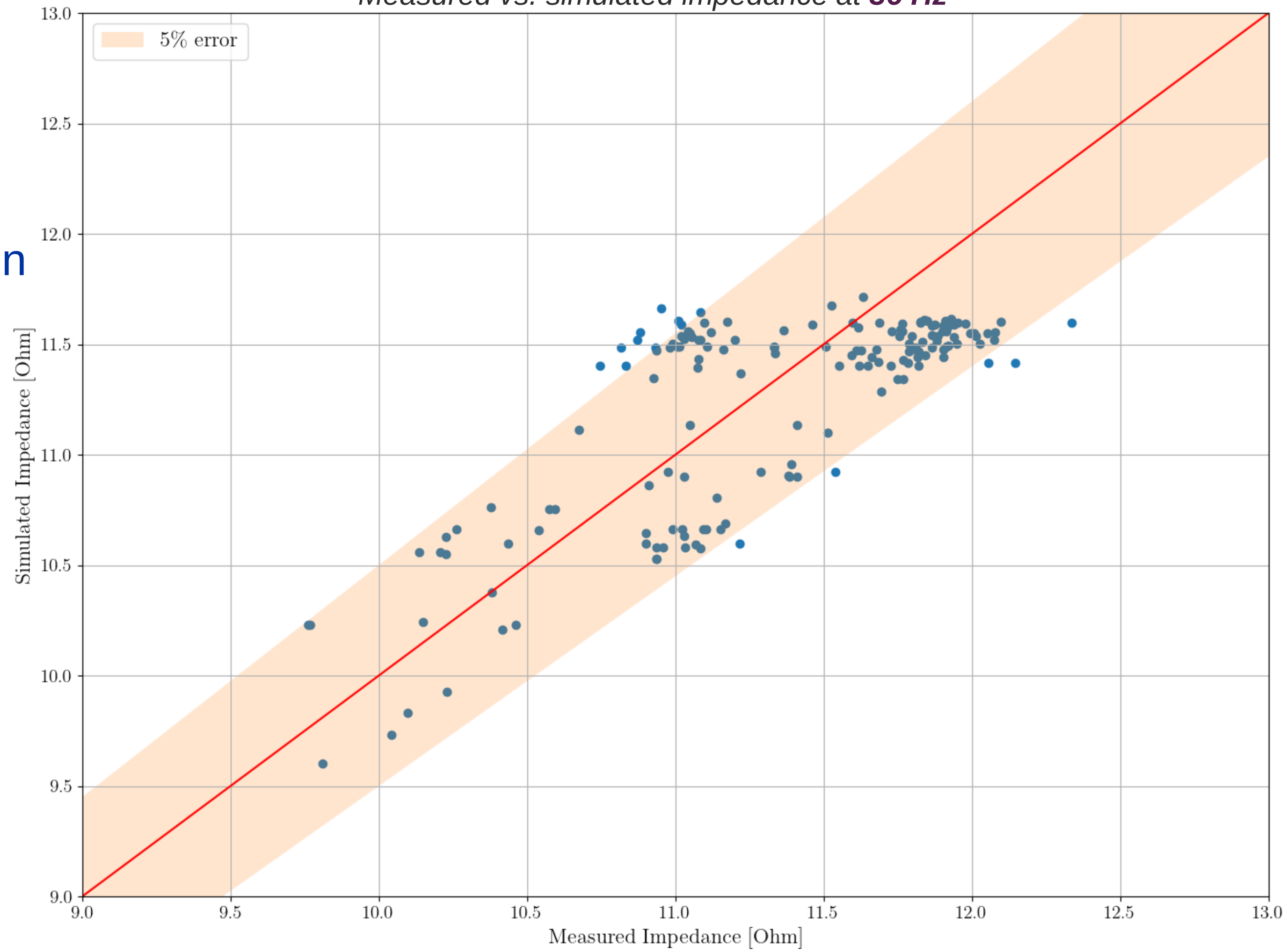
Validation of the model

1. Transfer Function Measurements

Manufacturing tolerances of the beam-screen led to a **spread** of impedance **around 30 Hz**

→ Utilizing the **beam-screen parameters for each aperture** leads to a good fit along the complete chain of 154 magnets

Measured vs. simulated impedance at ***36 Hz***



Spread of +/-30 % in measurements

Validation of the model

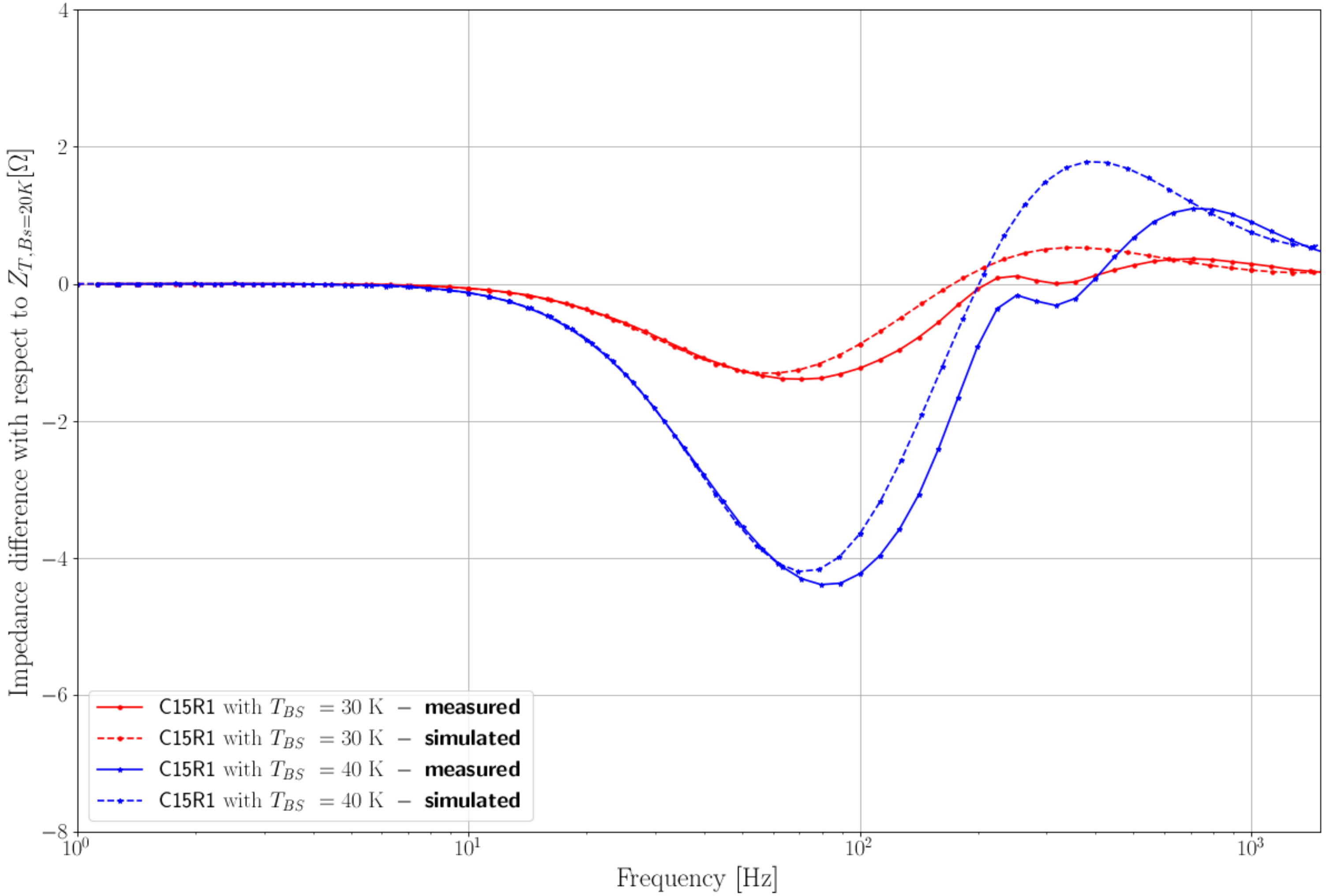
2. Temperature changes in the beam-screen

Dedicated Transfer Function Measurements

- **Magnet** was kept at **nominal conditions**
- Temperature of the **beam-screen** was changed from $T_{nom} = \mathbf{20\ K}$ **to** $\mathbf{30\ K}$ **and** $\mathbf{40\ K}$

As $\rho_{Cu}(T, RRR, B)$
→ different eddy-current effect on the magnet

Induced impedance difference, with respect to nominal condition can be quite well reproduced



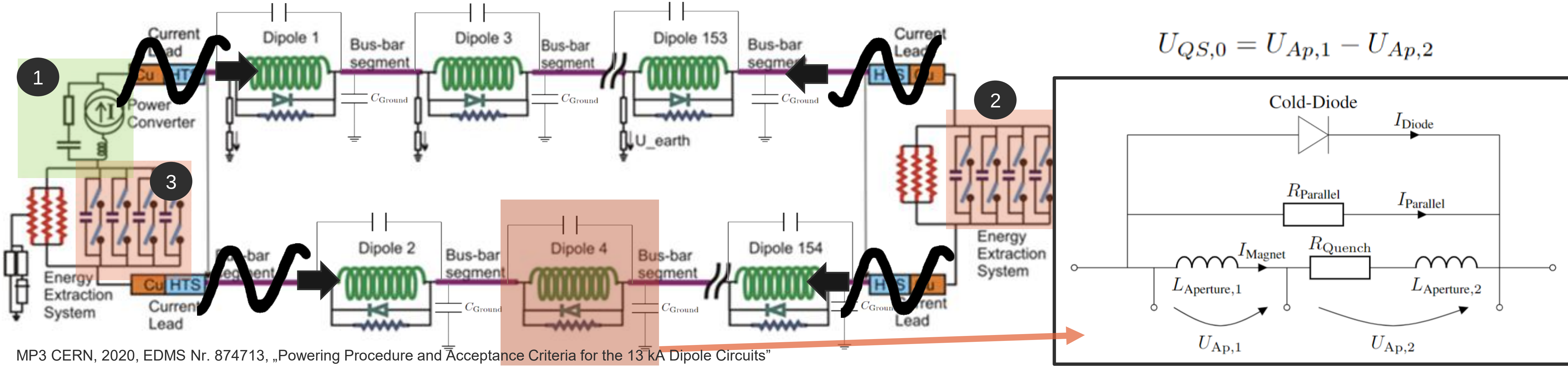
Validation of the model

3. Fast Power Aborts in the LHC circuits

In case of failure, quench, machine stop etc. the energy in the LHC main dipole circuits is discharged in resistors → Fast Power Abort (FPA)

1. Power Converter are disconnected from the chain of magnets ($t \approx 0s$)
2. 1st Energy extraction switches are opened and force current through resistors ($t \approx 100\ ms$)
3. 2nd Energy extraction switches are opened ($t \approx 600\ ms$)

Distributed capacitances & inductances → Transmission line → Travelling voltage wave



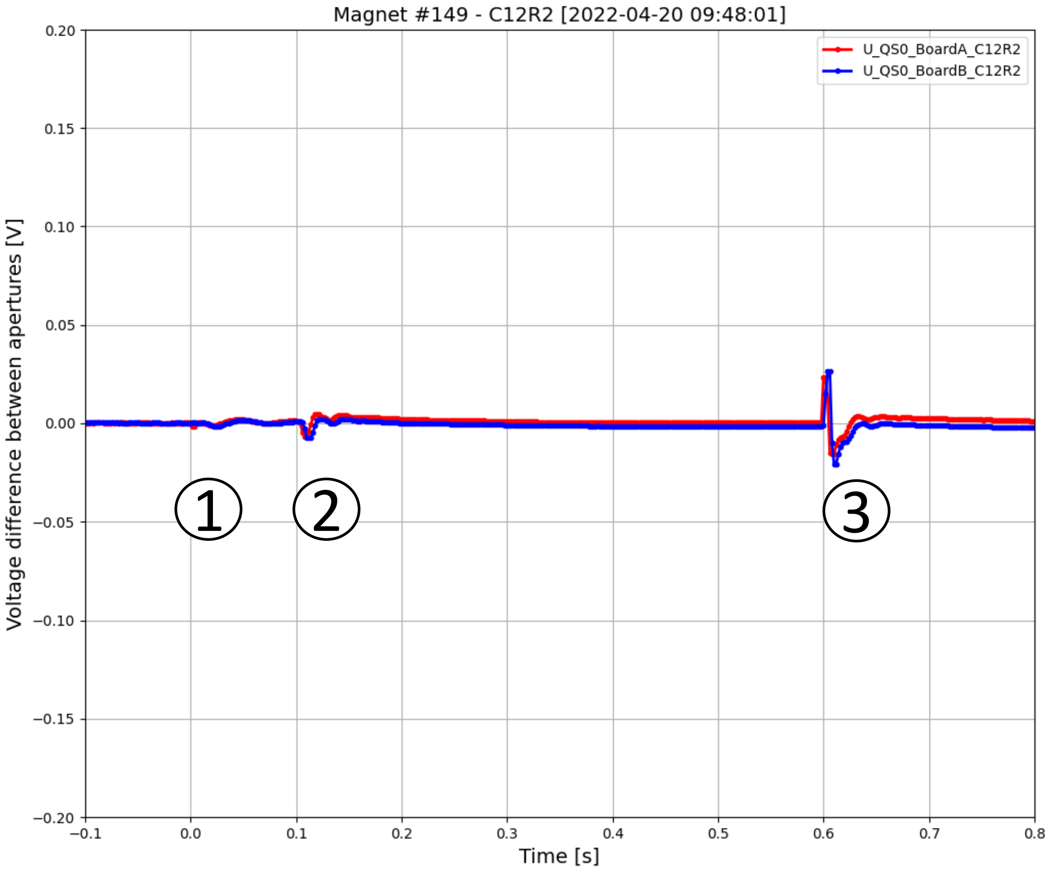
$$U_{QS,0} = U_{Ap,1} - U_{Ap,2}$$

MP3 CERN, 2020, EDMS Nr. 874713, „Powering Procedure and Acceptance Criteria for the 13 kA Dipole Circuits"

Validation of the model

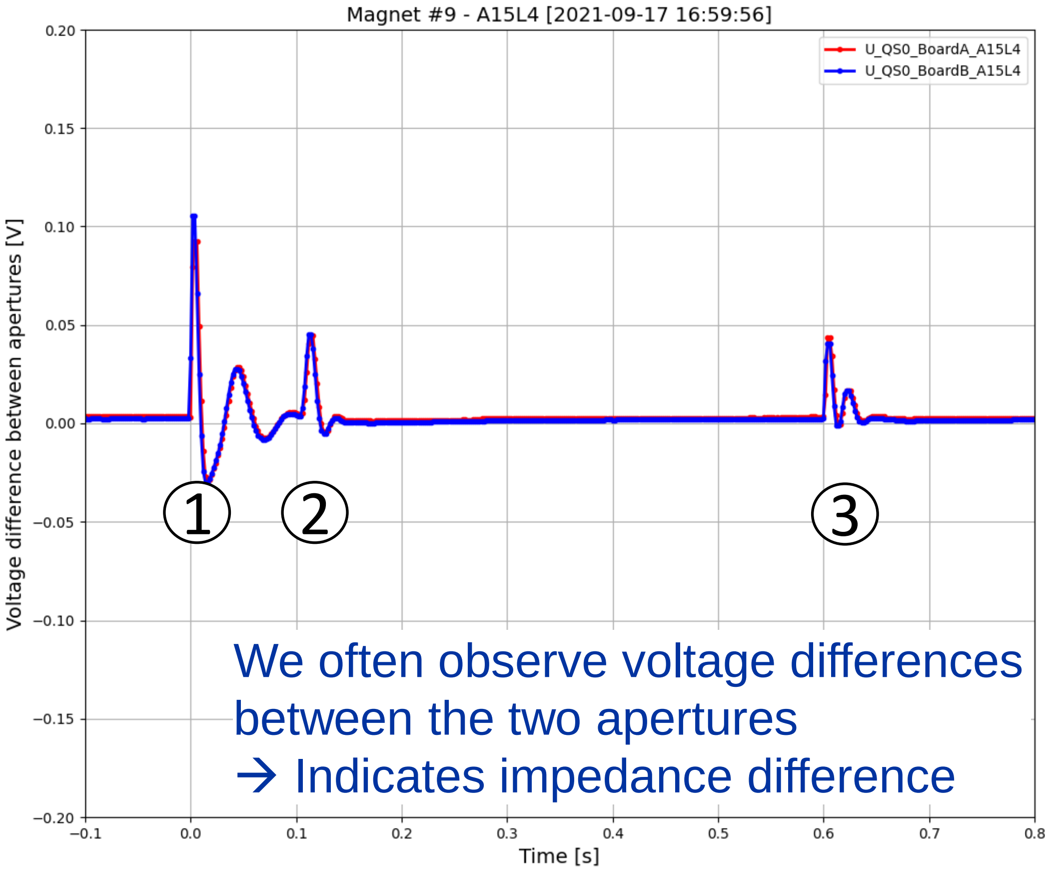
3. Fast Power Aborts in the LHC circuits

„Normal“ $U_{QS,0}$ signal



Frequency of these waves ~ 35 Hz

„Unbalanced“ $U_{QS,0}$ signal



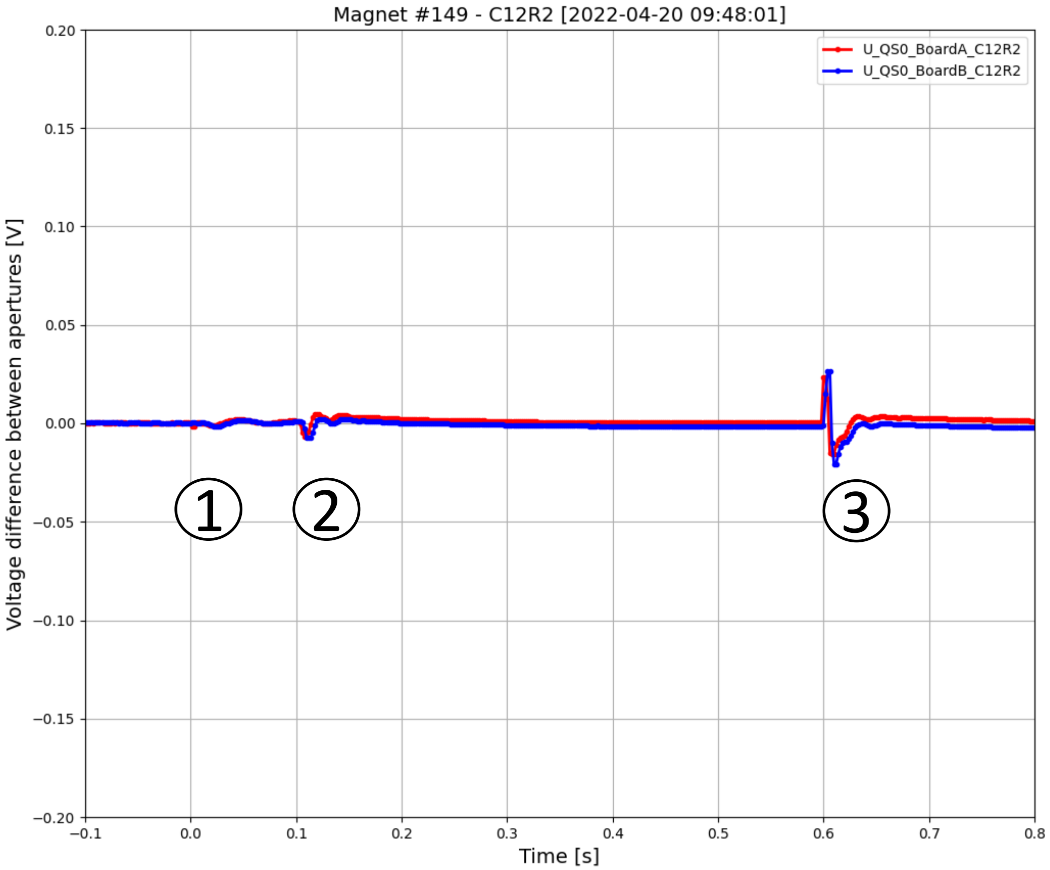
We often observe voltage differences between the two apertures

→ Indicates impedance difference

Validation of the model

3. Fast Power Aborts in the LHC circuits

„Normal“ $U_{QS,0}$ signal



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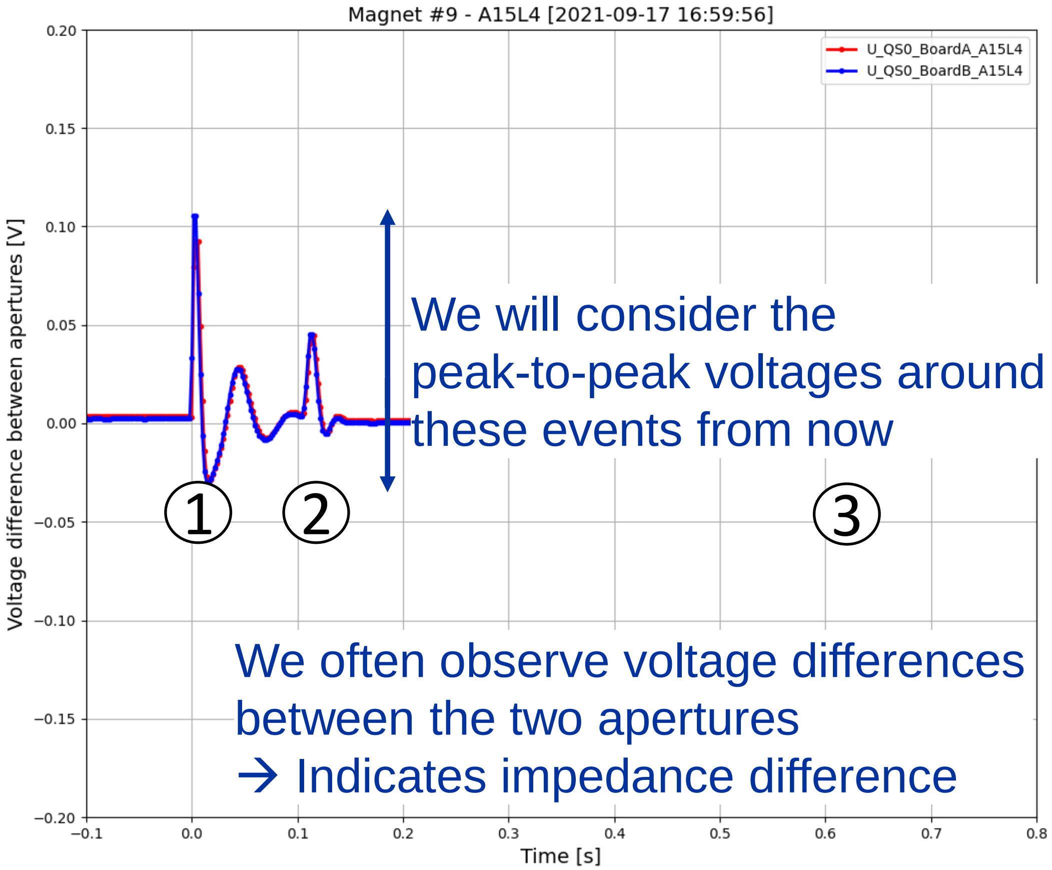


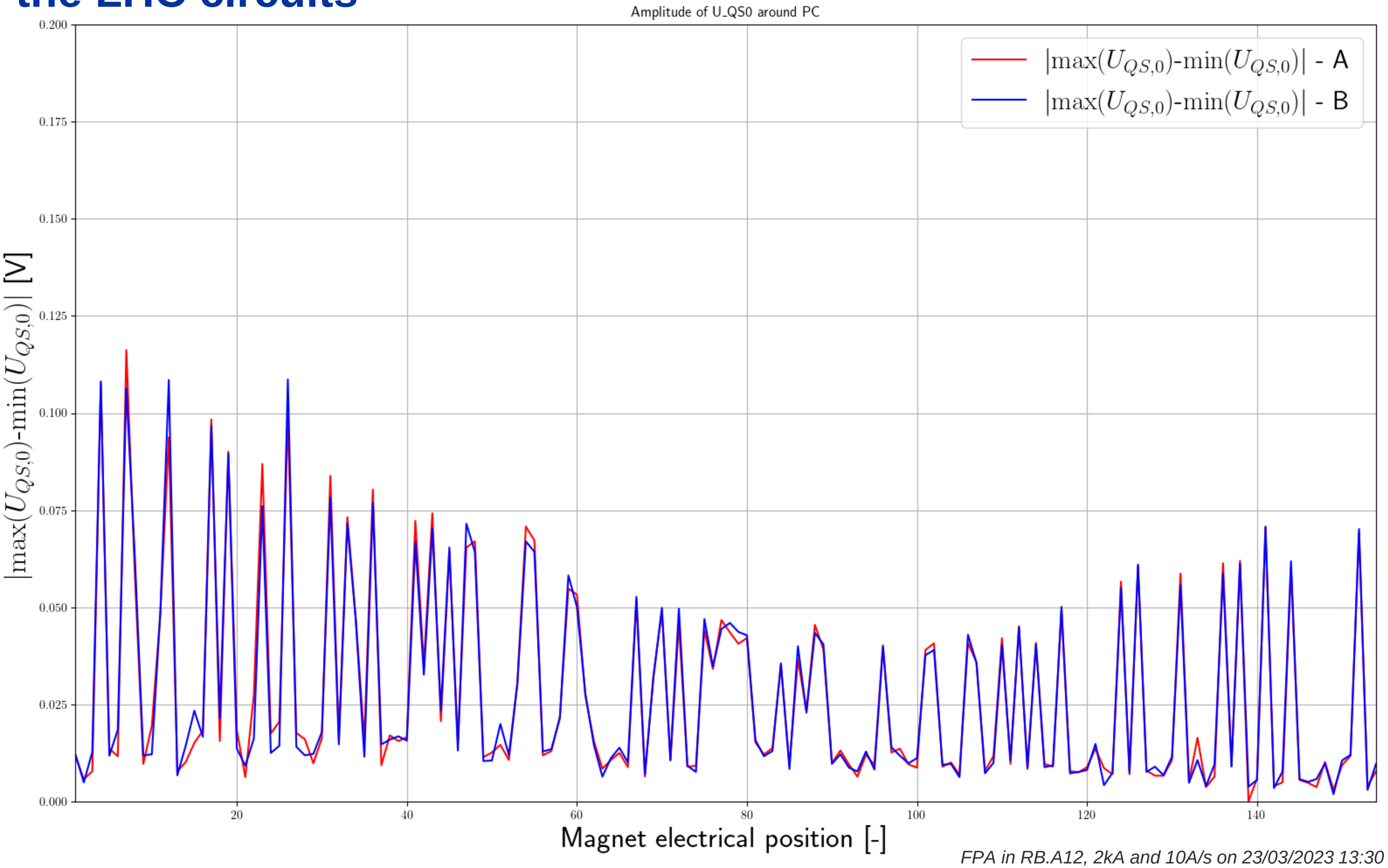
We will consider the peak-to-peak voltages around these events from now

We often observe voltage differences between the two apertures
→ Indicates impedance difference

Validation of the model

3. Fast Power Aborts in the LHC circuits

Actual measurements show an apparent **random** distribution of voltage spikes along the chain



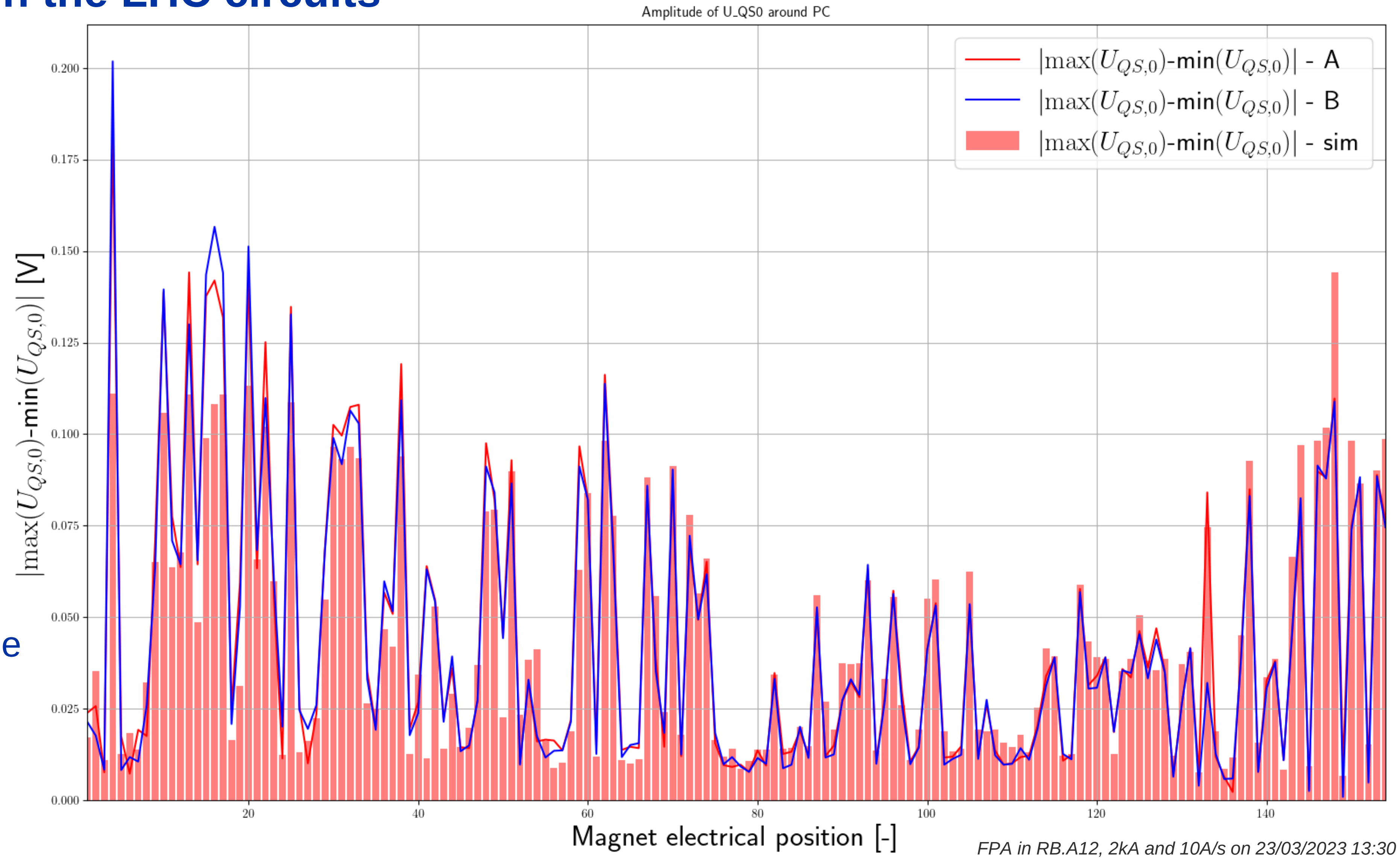
FPA in RB.A12, 2kA and 10A/s on 23/03/2023 13:30

Validation of the model

3. Fast Power Aborts in the LHC circuits

Eddy currents in the different **beam-screens** of a magnet induce voltage differences

→ Model can reproduce these with good accuracy

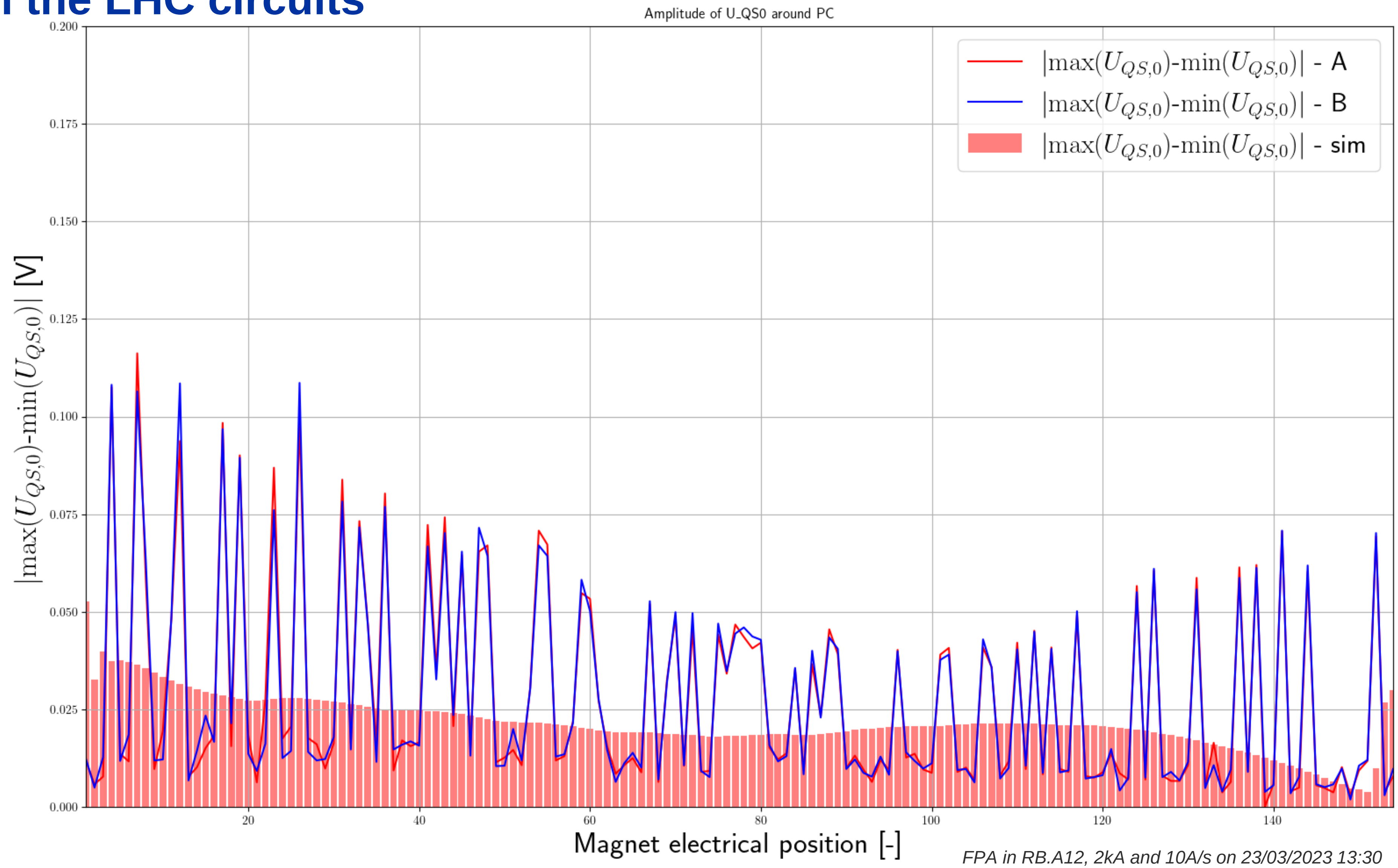


FPA in RB.A12, 2kA and 10A/s on 23/03/2023 13:30

Validation of the model

3. Fast Power Aborts in the LHC circuits

However, not taking any effects into account, the peak-to-peak distribution would compare like this



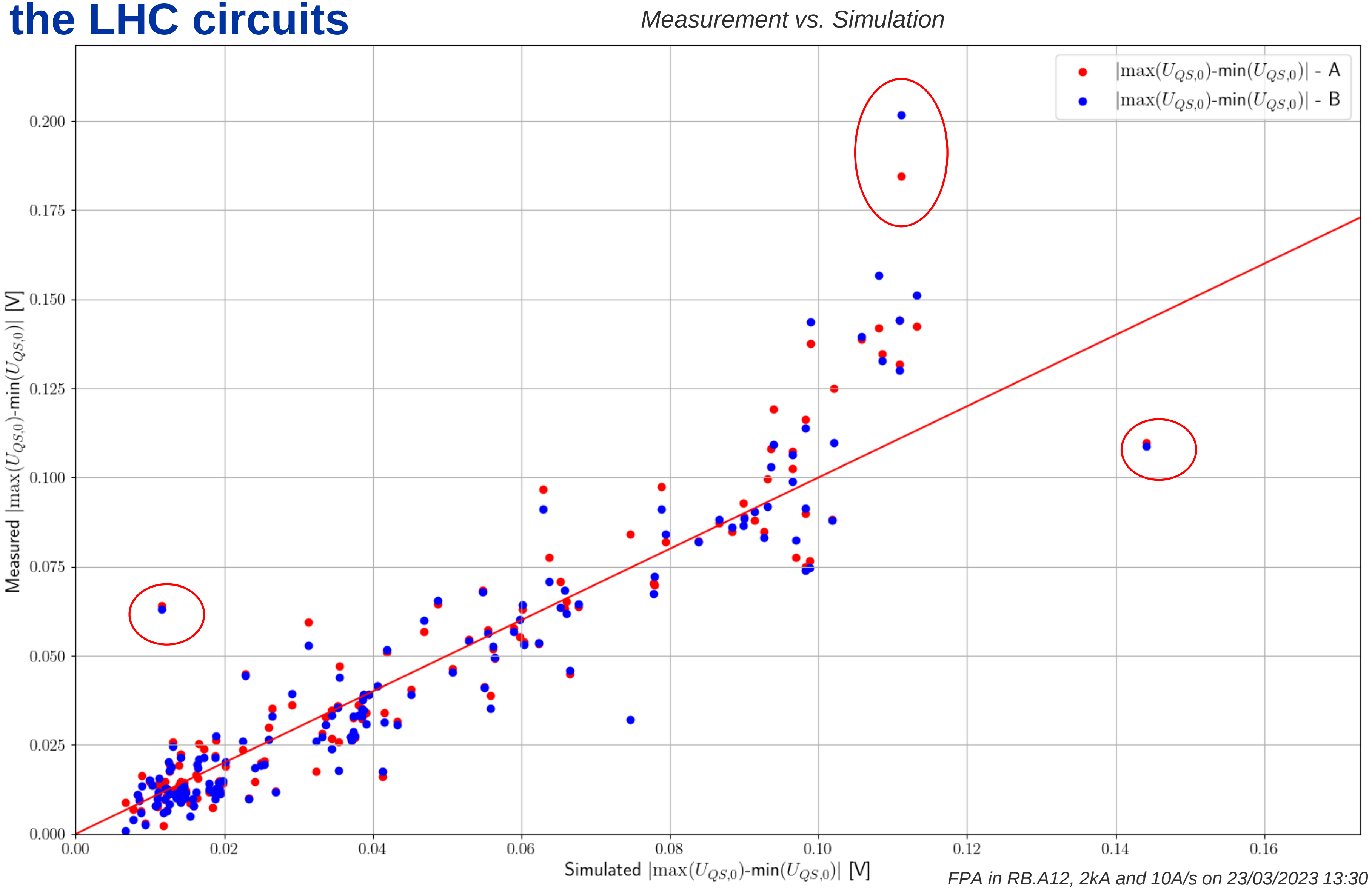
FPA in RB.A12, 2kA and 10A/s on 23/03/2023 13:30

Validation of the model

3. Fast Power Aborts in the LHC circuits

→ Model can reproduce these with good accuracy

However, we see some fair outliers which still need to be explained



FPA in RB.A12, 2kA and 10A/s on 23/03/2023 13:30

Conclusion

In order to **detect outliers** in the large number of LHC magnets and to **find potential pre-cursors** we need:

1. A **simple** and **coherent model** across domains, to accurately simulate complex interactions and systems
2. **Individual magnet models**, taking specific features for every magnet into account
3. **Physics driven**, **explainable models** that could point to faults/pre-cursors

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In order to **detect outliers** in the large number of LHC magnets and to **find potential pre-cursors** we need:

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This work applies a **general coupling mechanism** for losses, occuring in superconducting magnets

→ **Analytical** derivation of the loss mechanism and its equivalent parameter

→ **Coupling** of these **equivalent loops** to the magnets main inductance

Conclusion

In order to **detect outliers** in the large number of LHC magnets and to **find potential pre-cursors** we need:

1. A **simple** and **coherent model** across domains, to accurately simulate complex interactions and systems
2. **Individual magnet models**, taking specific features for every magnet into account
3. **Physics driven**, **explainable models** that could point to faults/pre-cursors

This work applies a **general coupling mechanism** for losses, occuring in superconducting magnets

→ **Analytical** derivation of the loss mechanism and its equivalent parameter

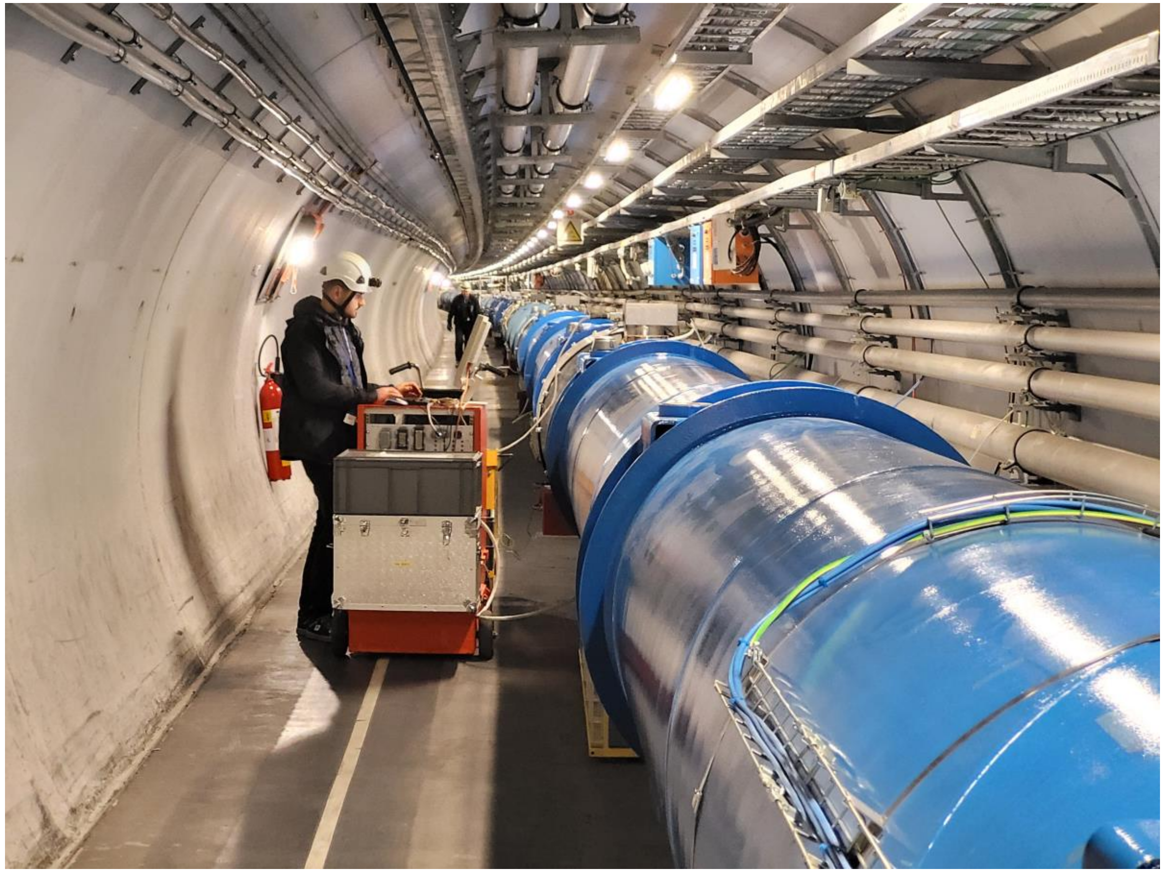
→ **Coupling** of these **equivalent loops** to the magnets main inductance

Can accurately reproduce **Frequency Impedance measurements** and observed **voltage-wave phenomena**

→ **We start to build a foundation for upcoming modelling & diagnostics**

Thanks a lot for your attention! ☺

Any questions?

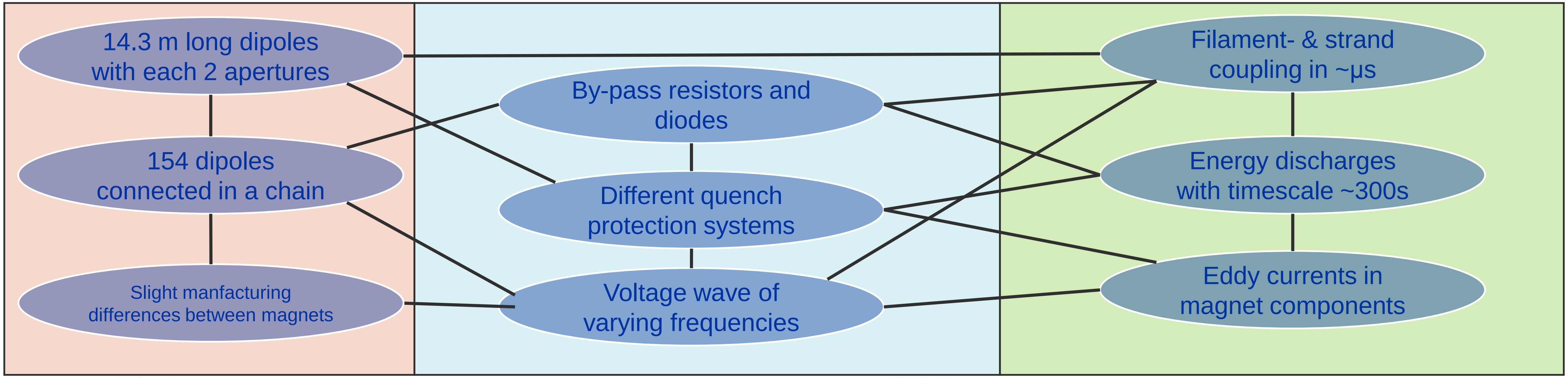


Me, in the tunnel, performing some measurements :)

Appendix:

The LHC main dipole and its circuit

All simulations in this presentation concentrate on the LHC main dipole circuits



14.3 m long dipoles with each 2 apertures

154 dipoles connected in a chain

Slight manfacturing differences between magnets

By-pass resistors and diodes

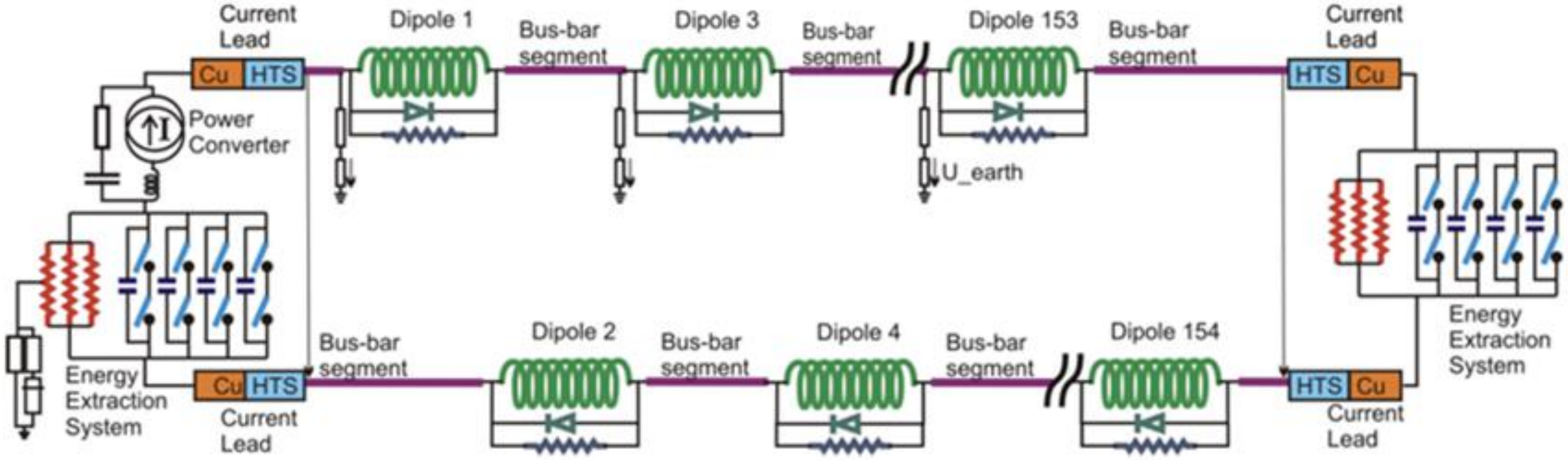
Different quench protection systems

Voltage wave of varying frequencies

Filament- & strand coupling in ~µs

Energy discharges with timescale ~300s

Eddy currents in magnet components



MP3 CERN, 2020, EDMS Nr. 874713, „Powering Procedure and Acceptance Criteria for the 13 kA Dipole Circuits"

… and many more

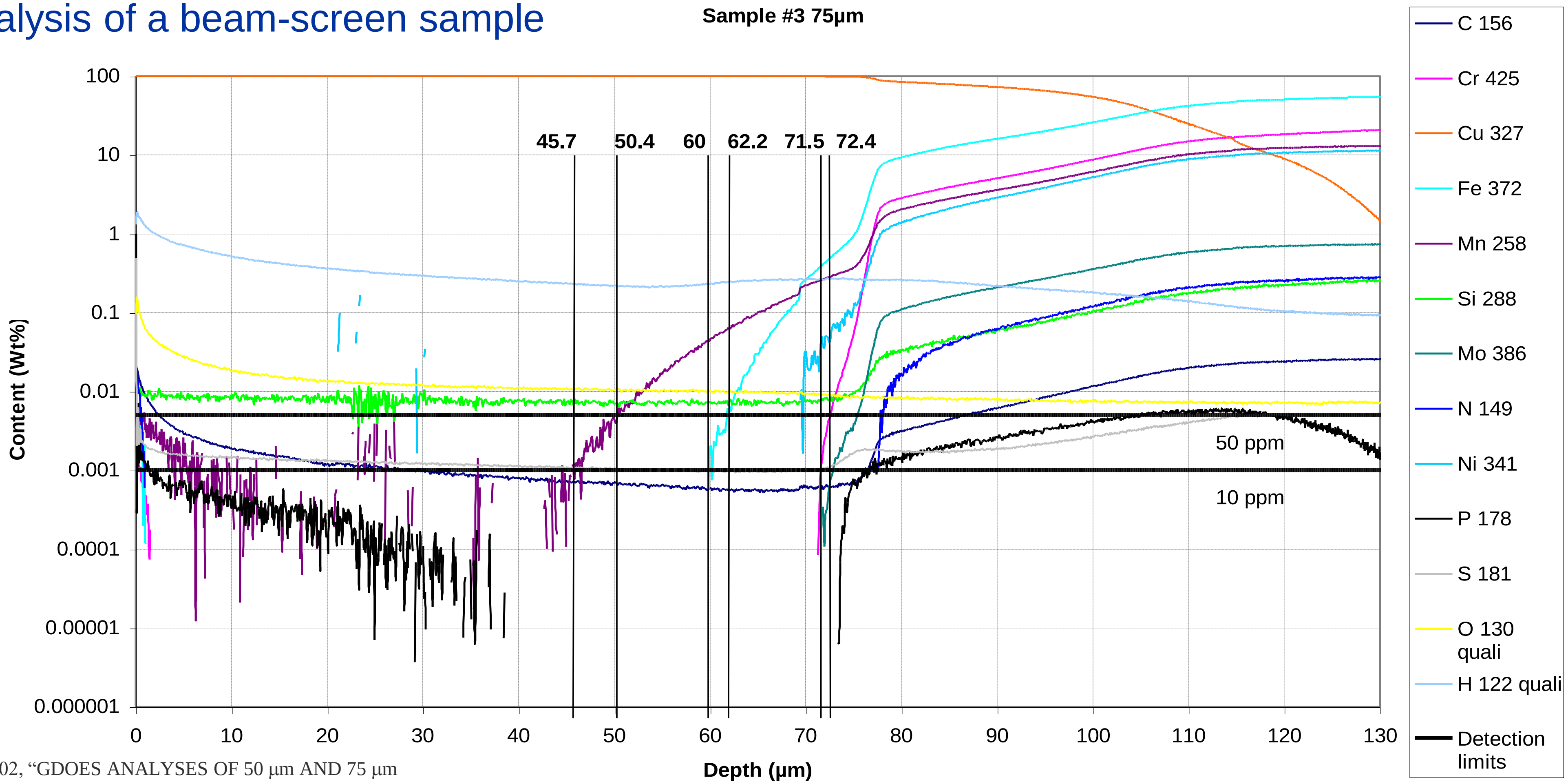
Complex, mutual interactions which are difficult to analyze

.. But how can we see if a magnet is about to fail?

Equivalent circuit-loops:

3. *Beam-screen eddy currents*

GDOES analysis of a beam-screen sample



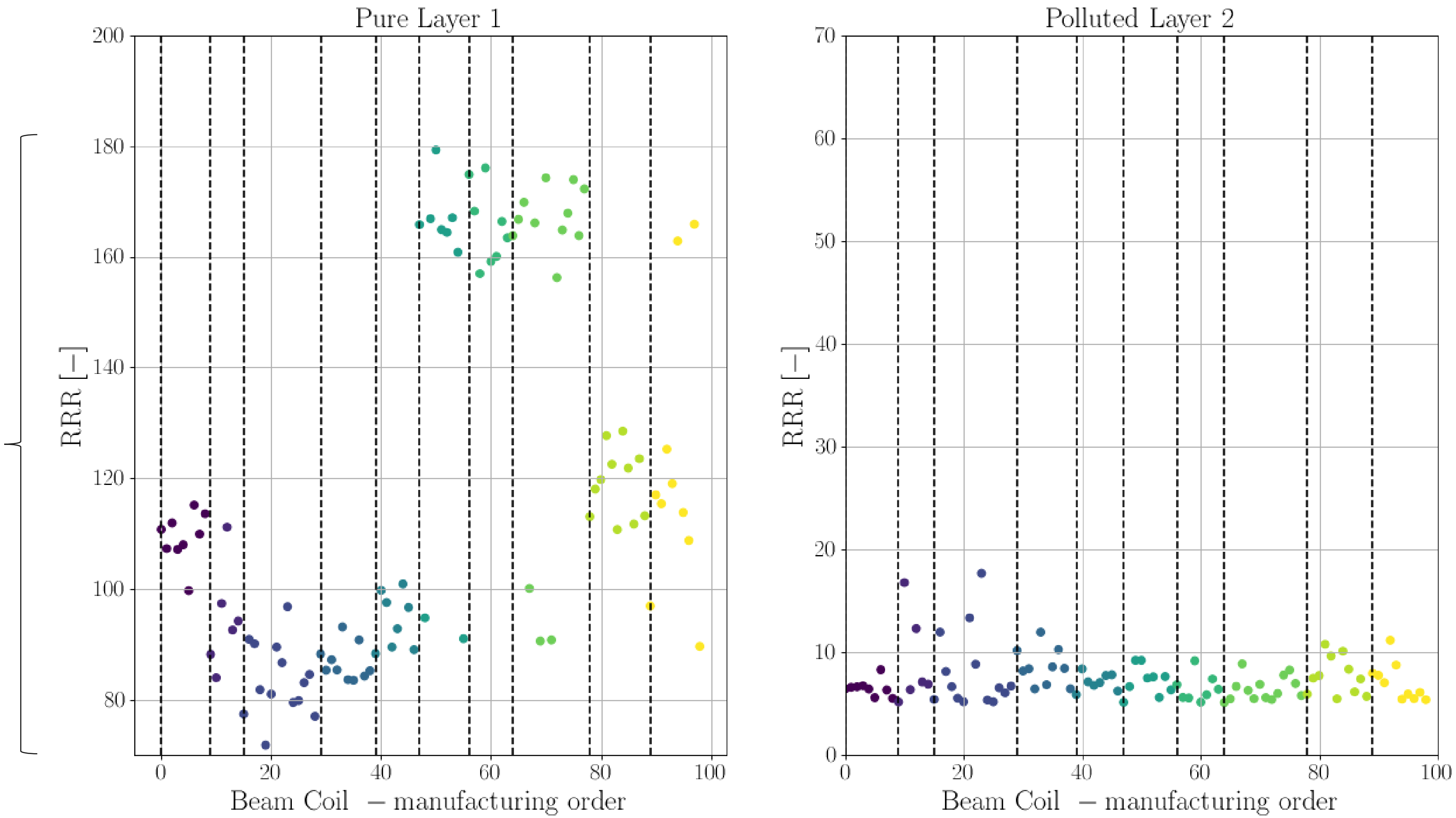
N. Kos et al. EDMS Nr. 340852, 2002, “GDOES ANALYSES OF 50 µm AND 75 µm COPPER LAYER BEAM SCREEN SAMPLES, PRODUCED BY HEREAUS”

Equivalent circuit-loops:

3. Beam-screen eddy currents

Wide spread in the purity of the inner layer

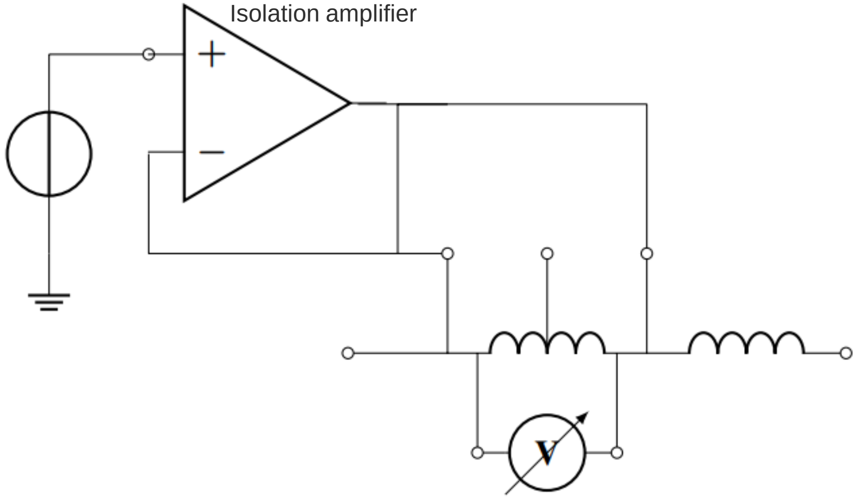
$\mathrm{RRR} \in [75, 180]$

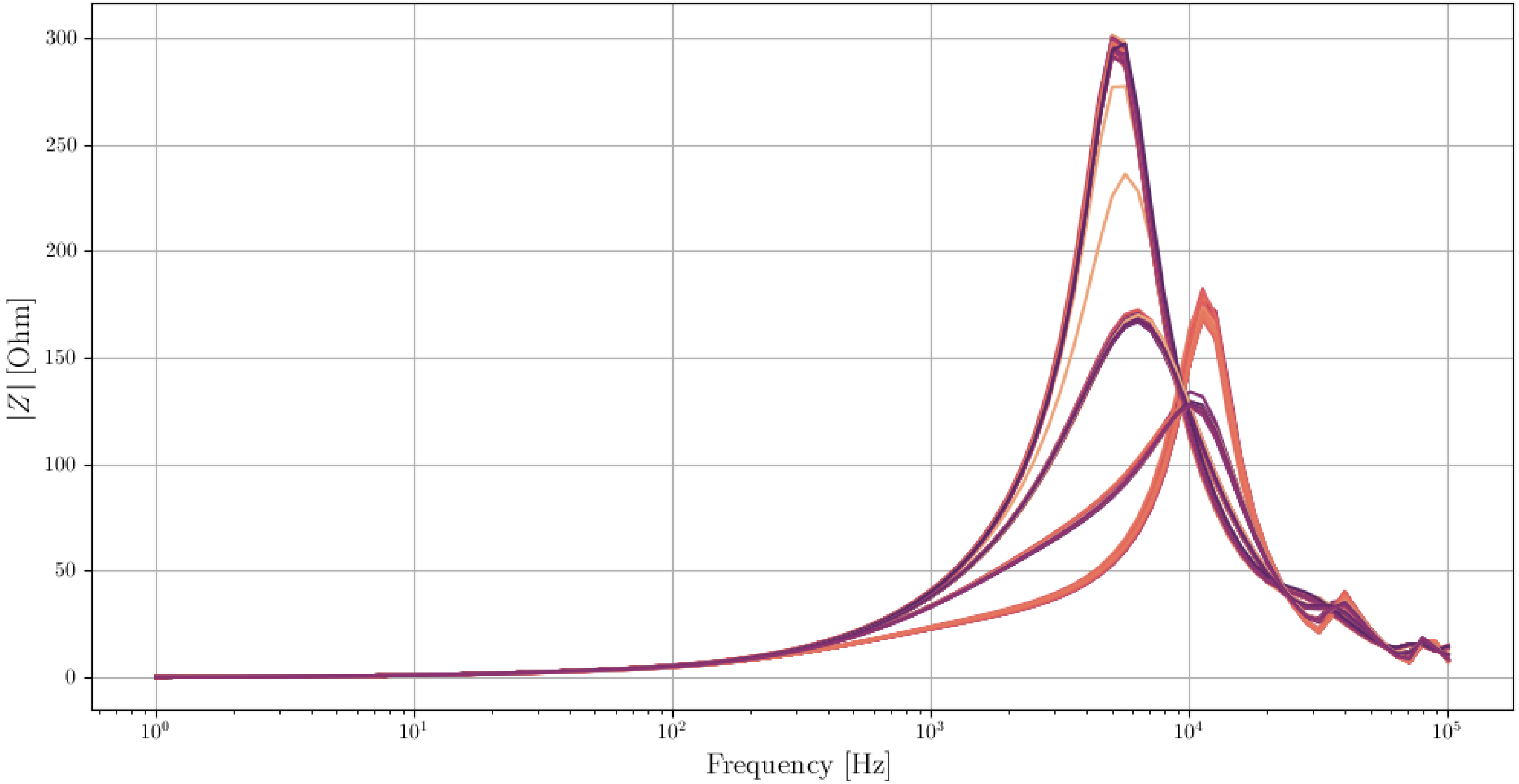


Validation of the model

1. Transfer Function Measurements

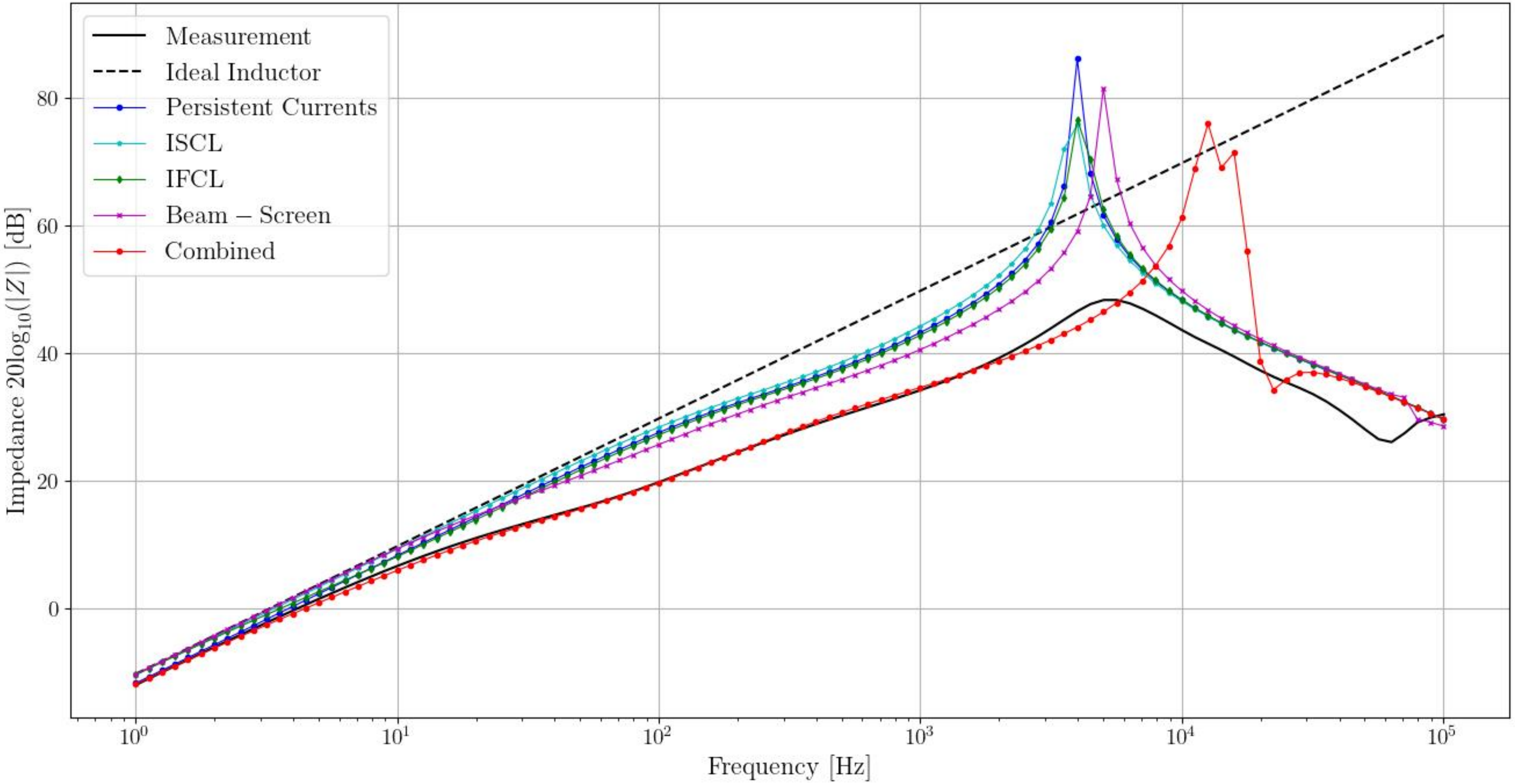
Measurement of the complex impedance of the magnets in the RB chain from 1 Hz to 100 kHz during YETS 22/23





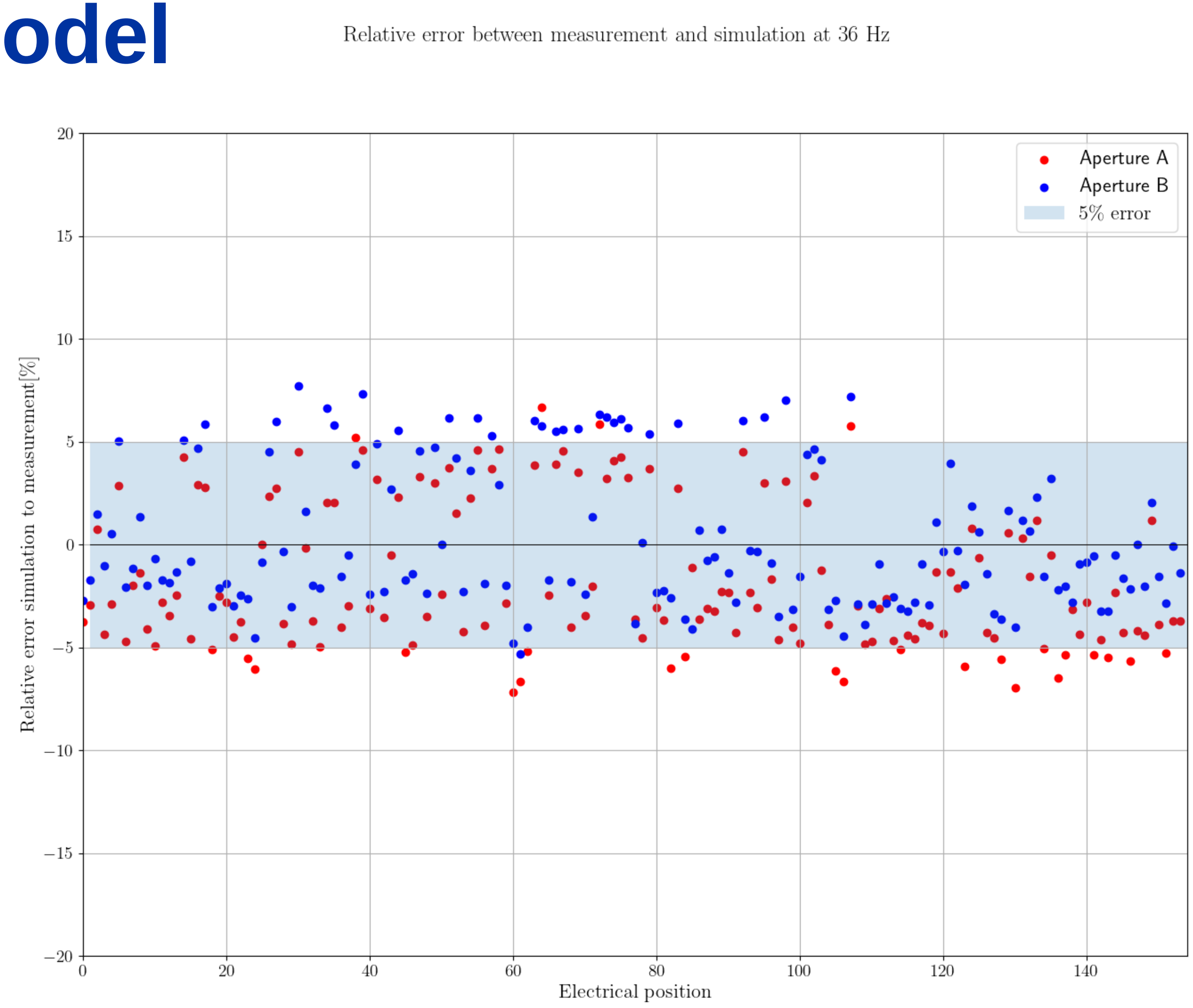
Validation of the model

1. Transfer Function Measurements



Validation of the model

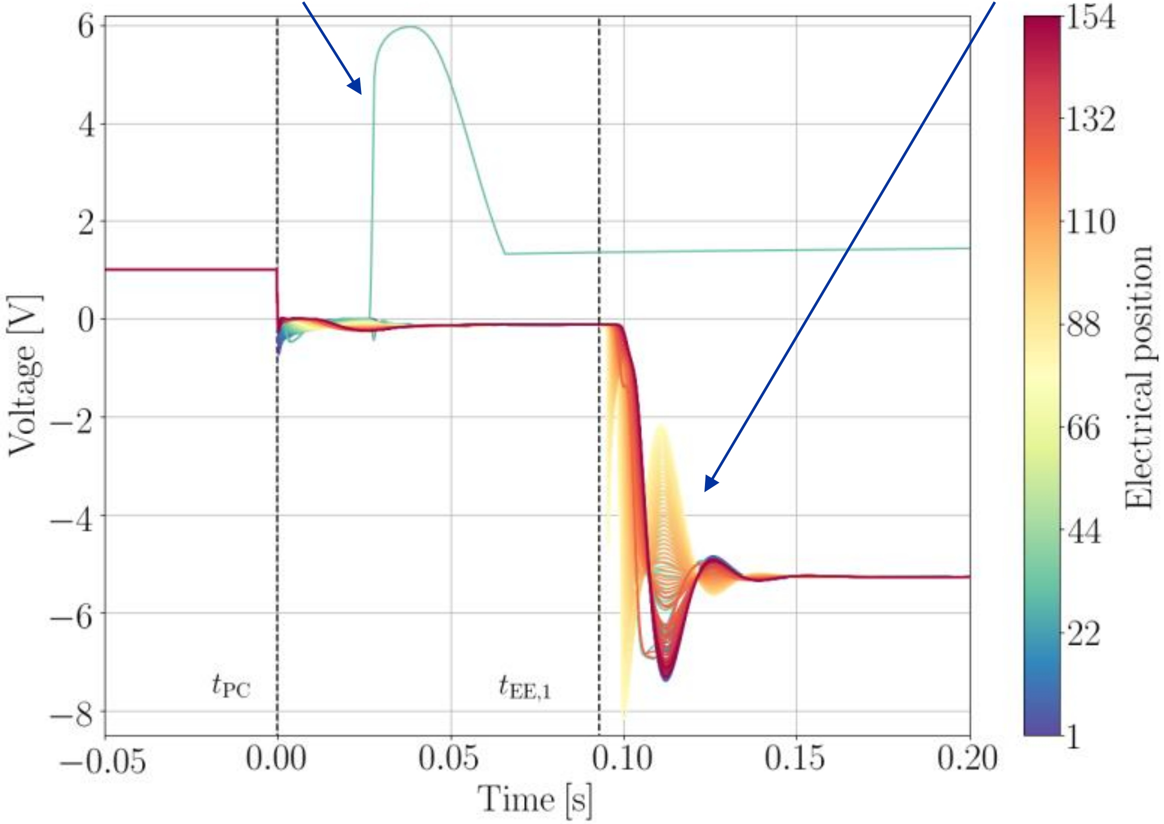
1. Transfer Function Measurements



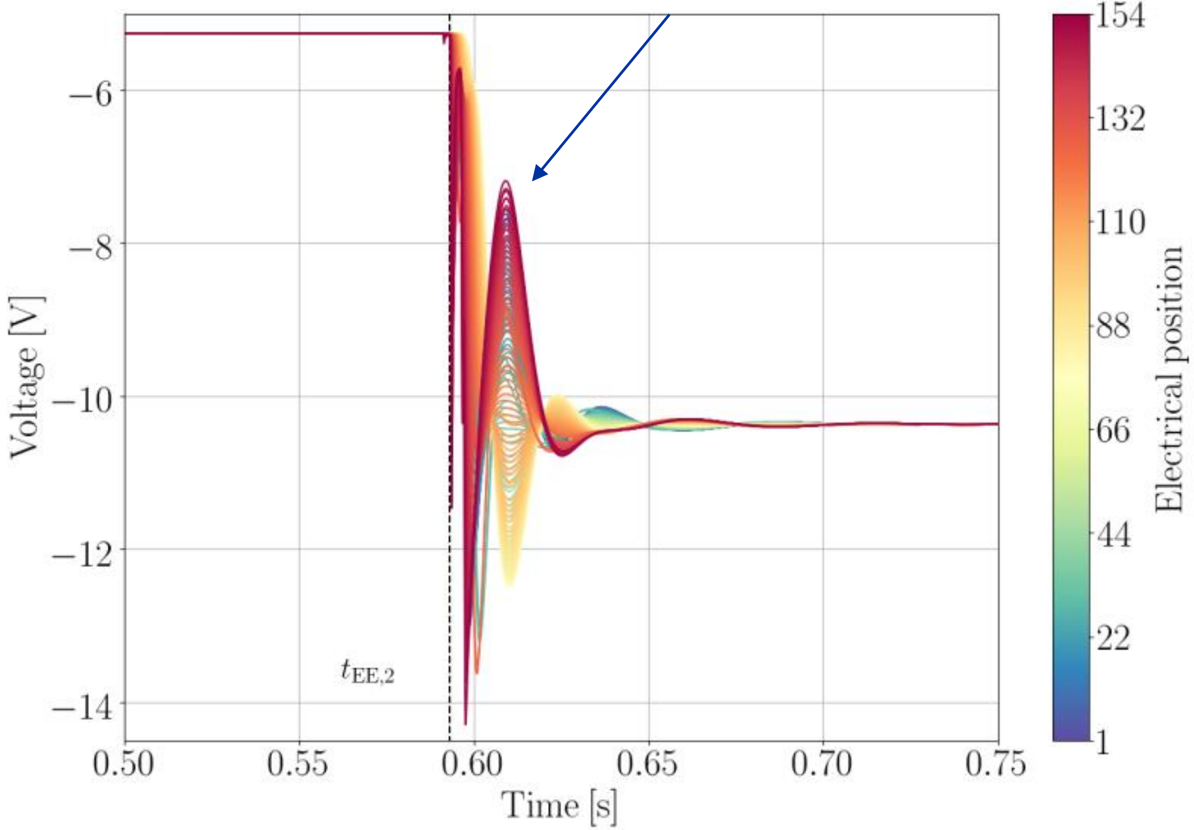
Usual transient in Main dipole circuit

Developed resistance in magnet leads to diode opening

Wave progagates from the middle towards the ends

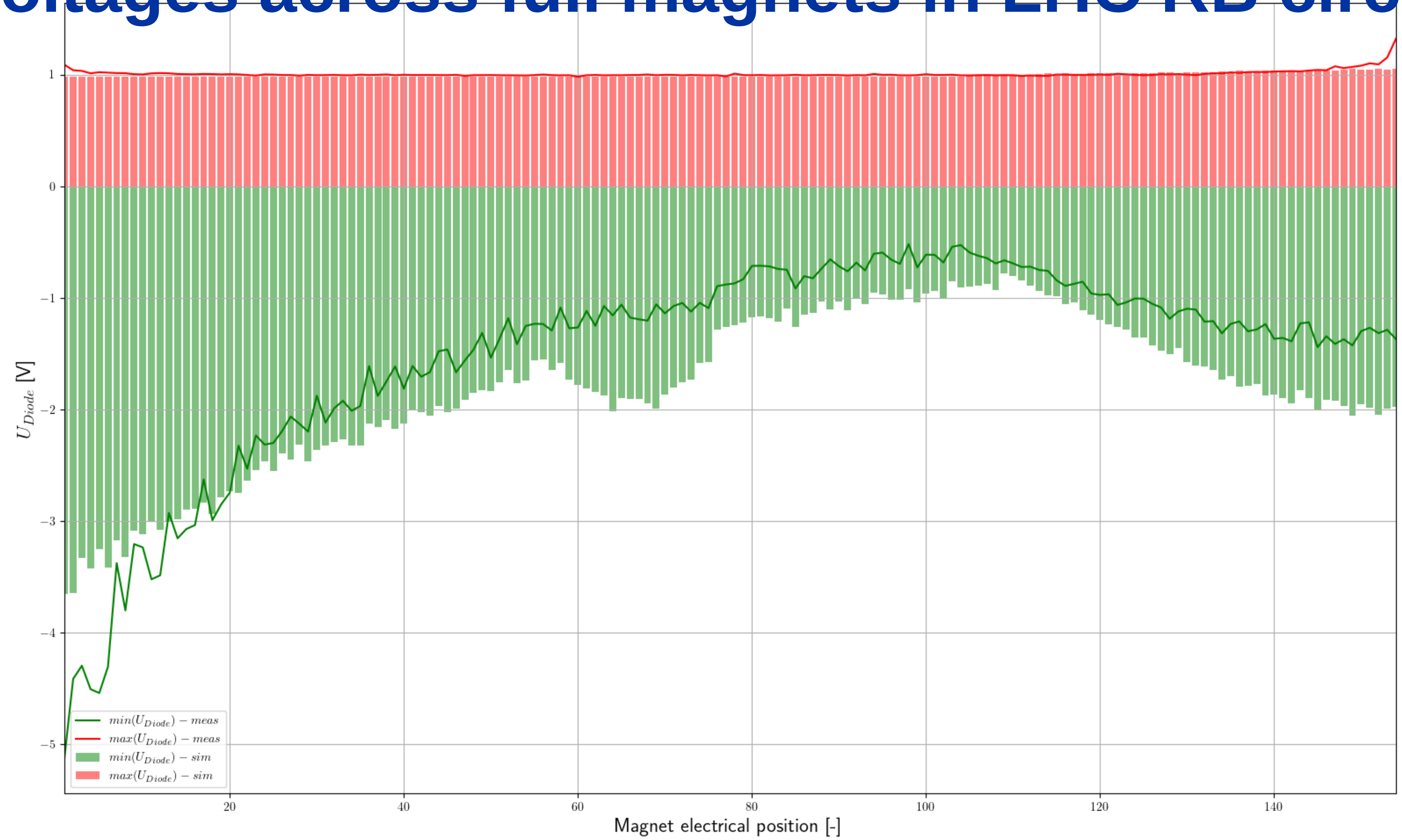


From the beginning towards the center



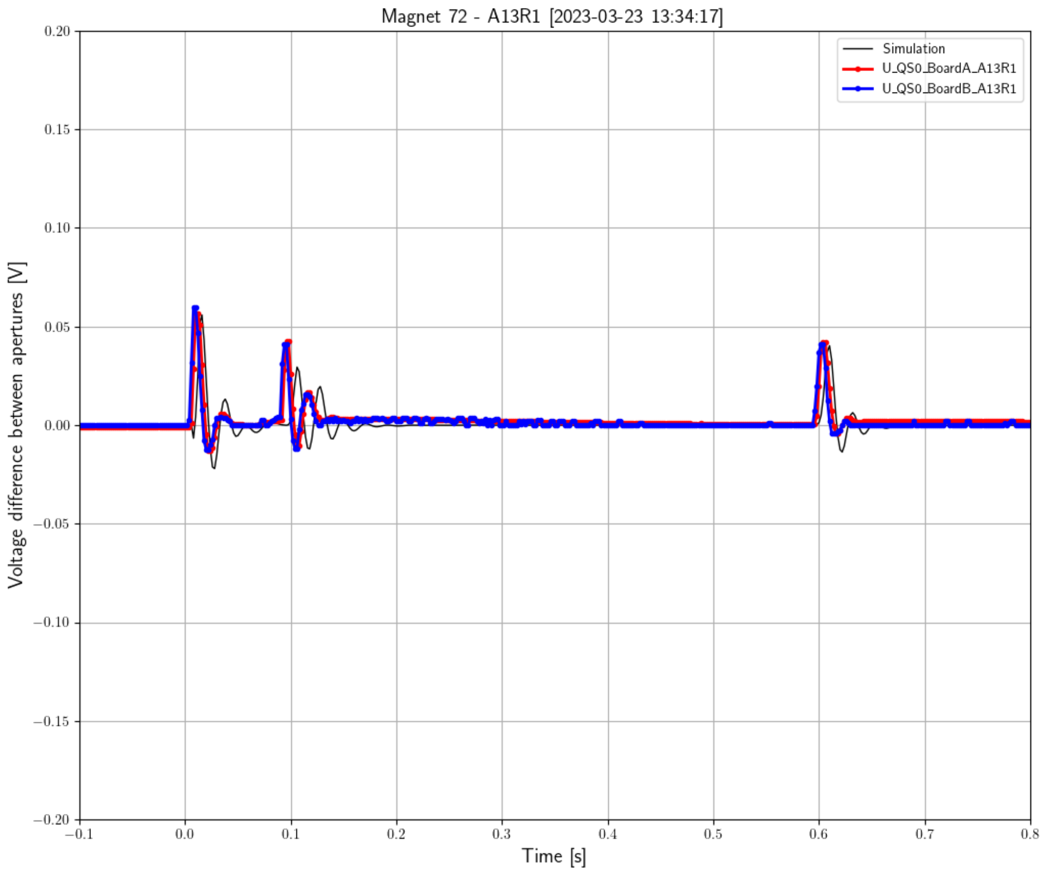
After each switch opening (PC, EE1, EE2) we observe voltage waves travelling through the magnet
→ Exponentially decaying wave seeing a different phase shift at each magnet
+ Further phenomena like superposition/ reflection etc.

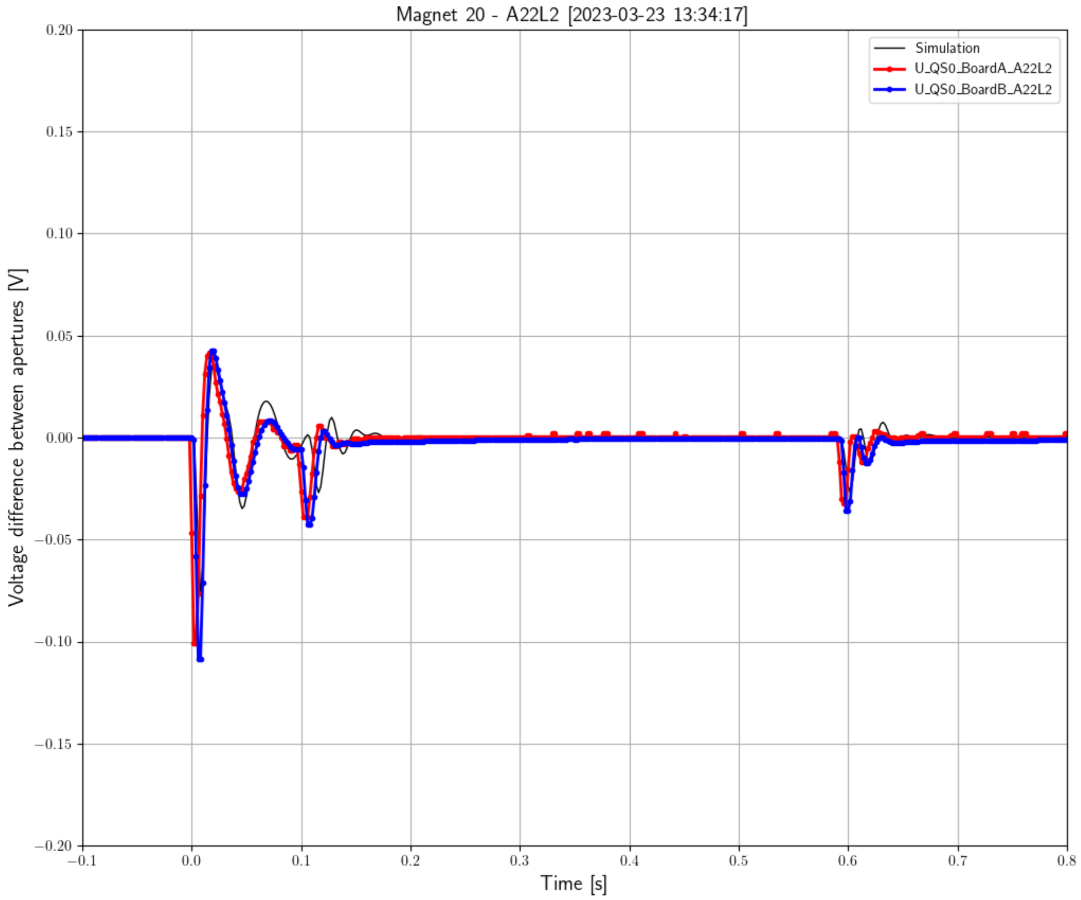
Voltages across full magnets in LHC RB circuit



Validation of the model – 2 Examples

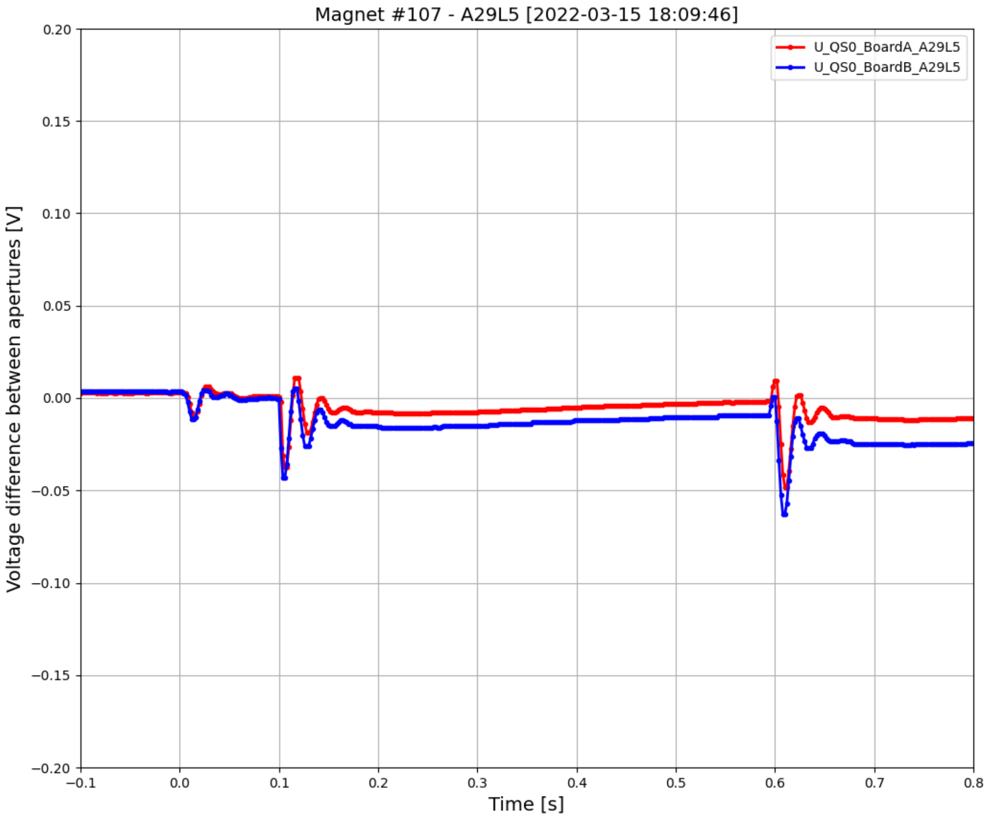
3. Fast Power Aborts in the LHC circuits

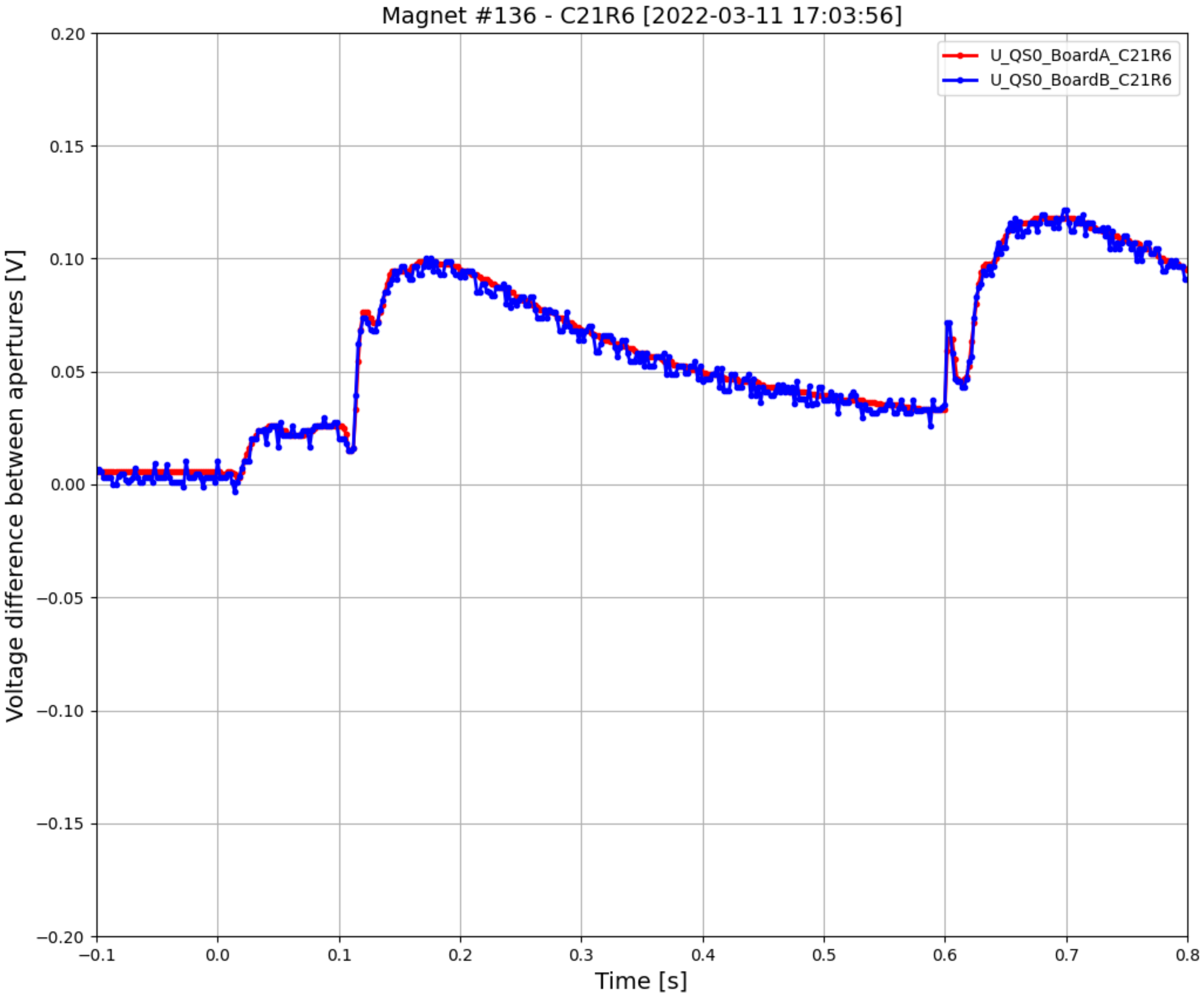




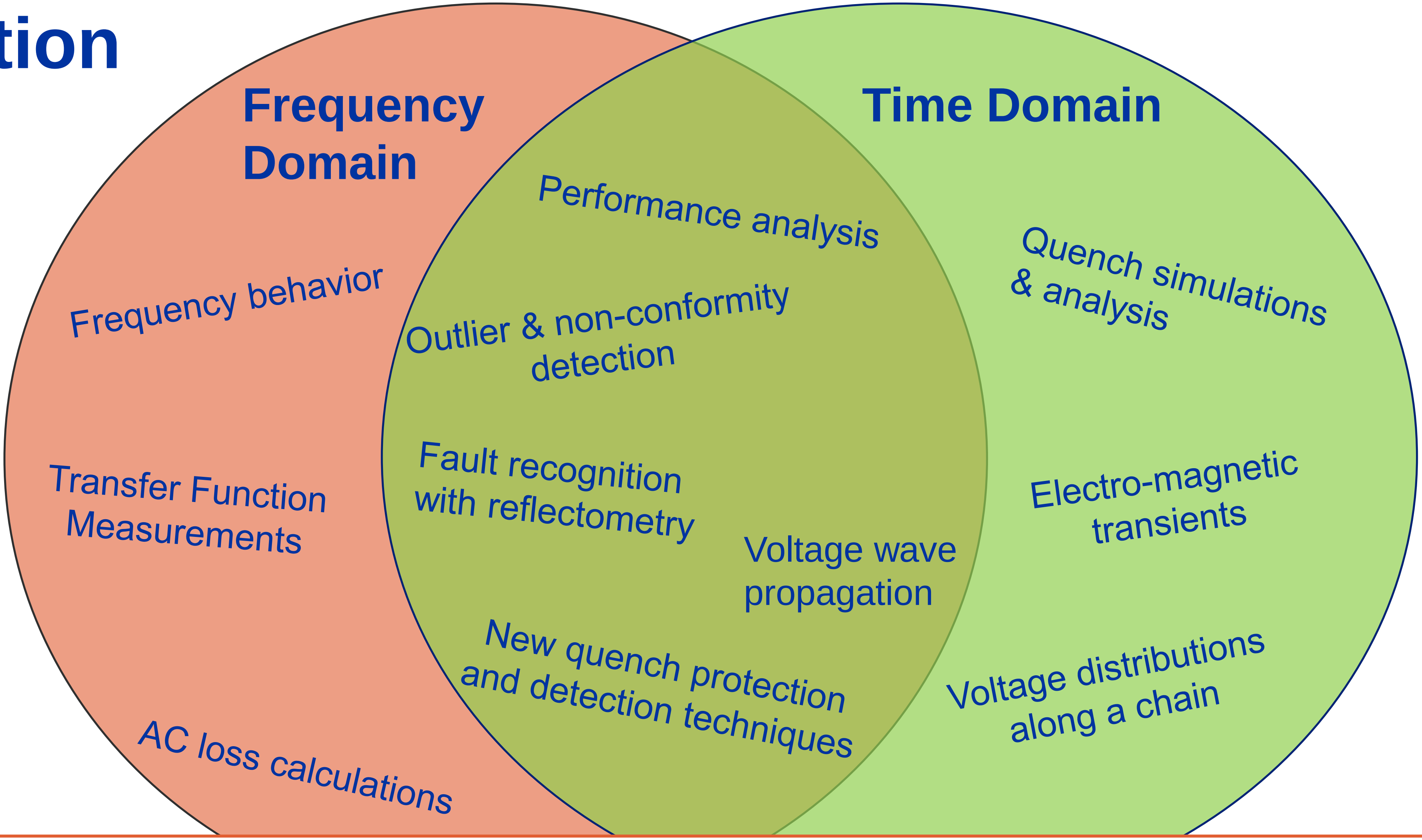
Validation of the model - Outlier

3. Fast Power Aborts in the LHC circuits





Motivation



Frequency Domain

Frequency behavior

Transfer Function Measurements

AC loss calculations

Performance analysis

Outlier & non-conformity detection

Fault recognition with reflectometry

Voltage wave propagation

New quench protection and detection techniques

Time Domain

Quench simulations & analysis

Electro-magnetic transients

Voltage distributions along a chain

Frequency and **Time** domain are always **tightly coupled**, often it can be **not enough** to only look at **one.**
A model, **coherently** able to accurately **reproduce both** domains, can give valuable insights!