Application of Parameterized Macro-Models in Power Electronic Converter Design

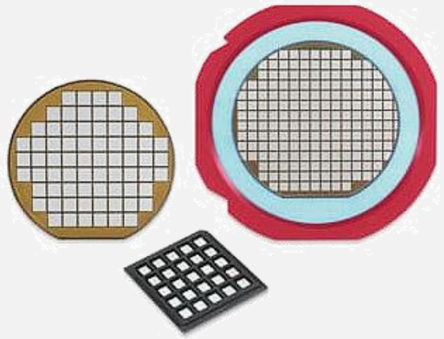
Arne Schröder (Hitachi Energy Research) & Tommaso Bradde (POLITO)

EMC Forum 2026, Sønderborg, Denmark, June 28th, 2026

Motivation

Power Electronics at Hitachi Energy

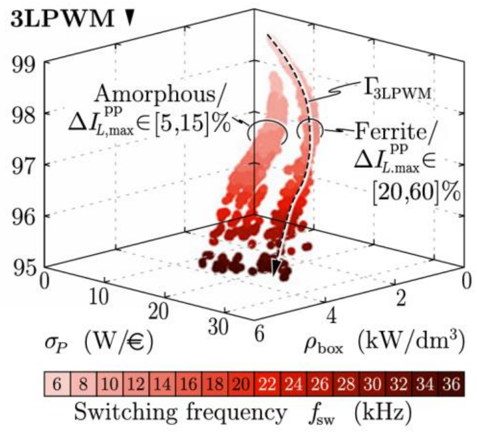
Power Semiconductors & Modules

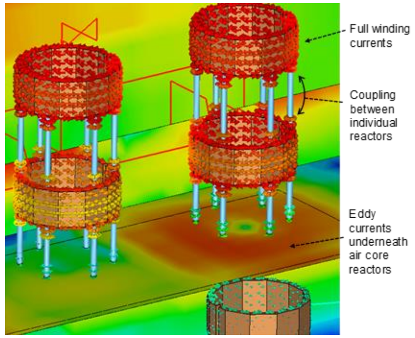


Low Voltage and Medium Voltage Converters

High Voltage Converters

Power Electronics at Hitachi Energy





Concepts → **Virtual Prototyping** → **Physical Prototyping**

- Efficient (multi-domain) models
- 3D Simulations
- Measurements
- Circuit Simulations

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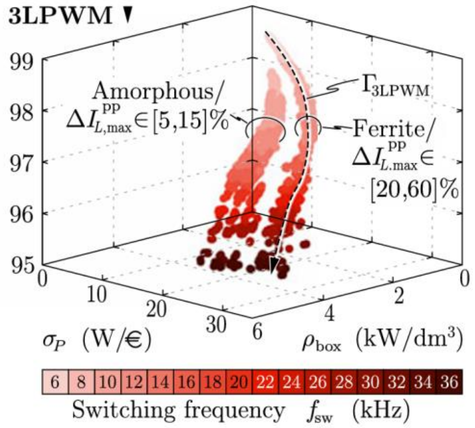

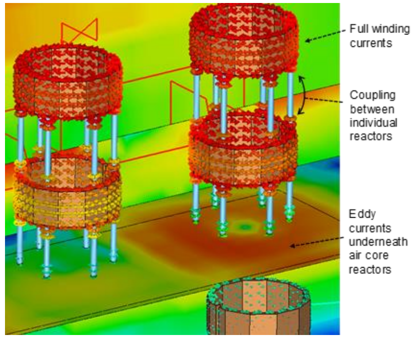

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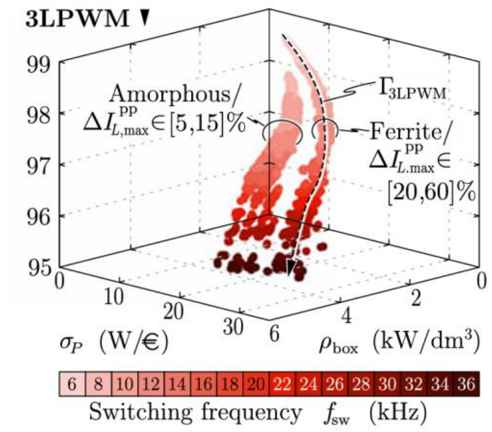
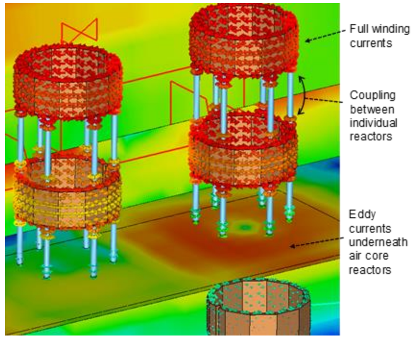
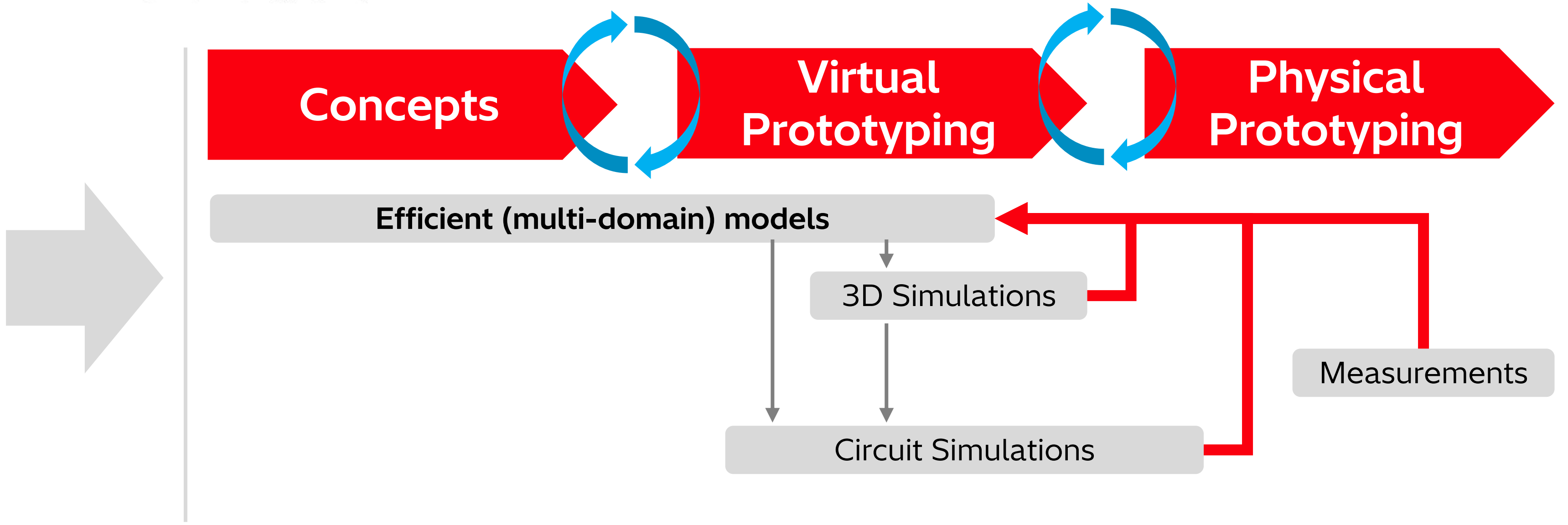
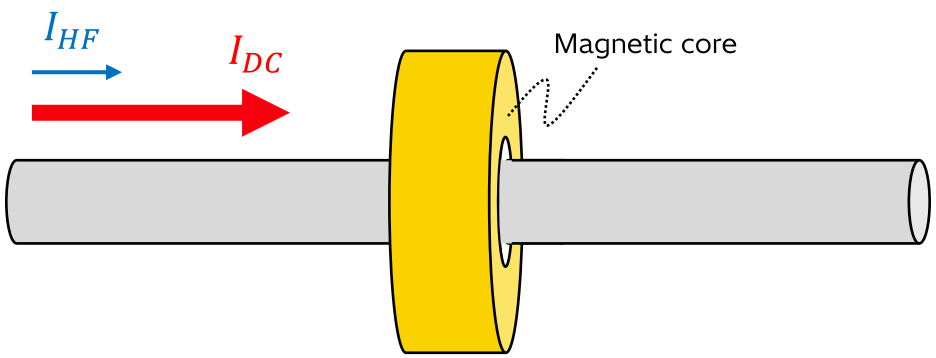






Magnetic Material Models

Attenuation of HF Noise in Applications with High DC Currents



Goal: Constraint-based multi-objective optimization of inductors

- Cost, volume, losses, …

Challenges

- Saturation of magnetic materials
- Low permeability materials required: powder cores
- No HF properties under DC bias available

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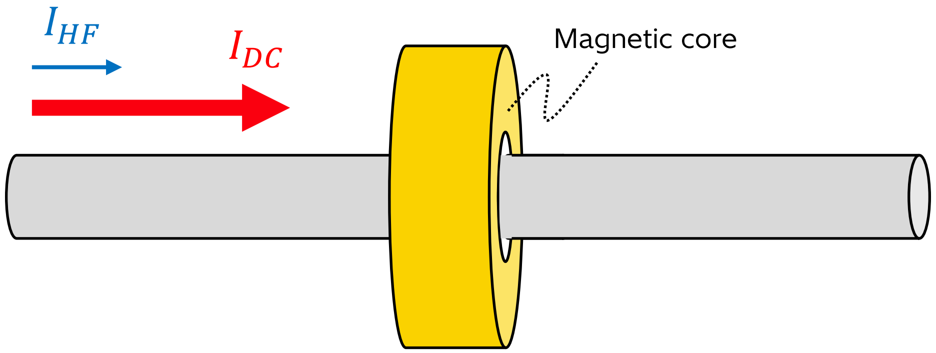

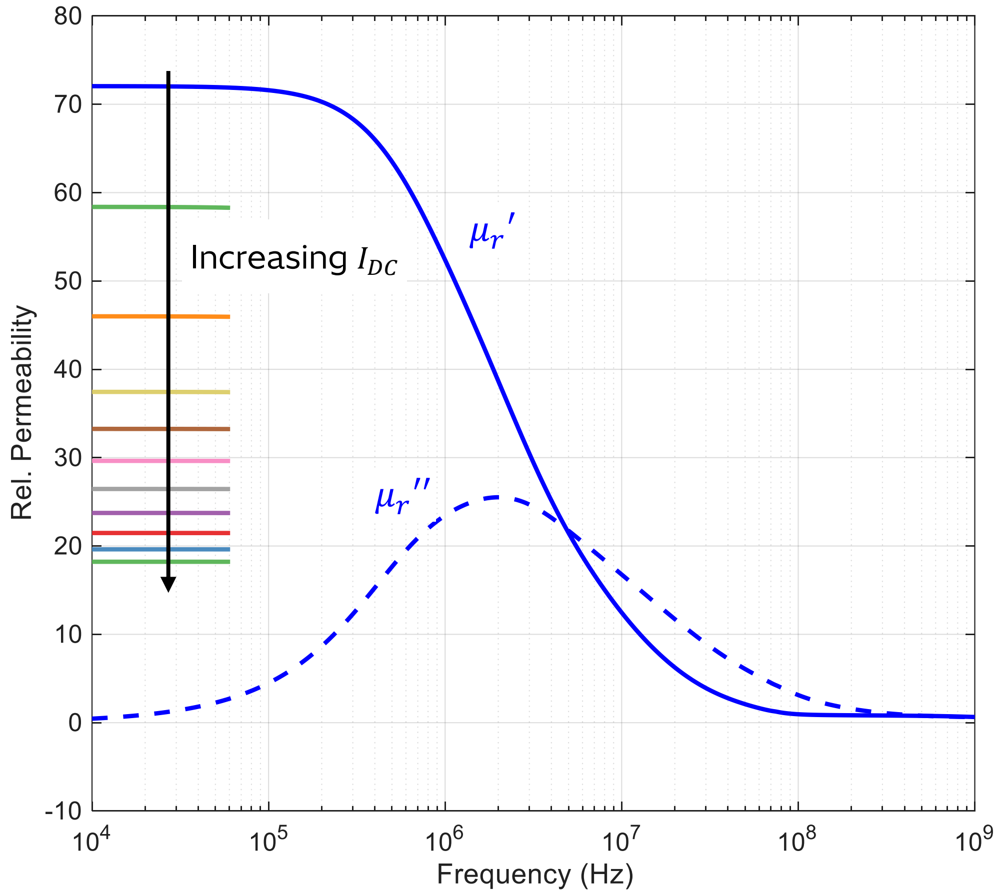

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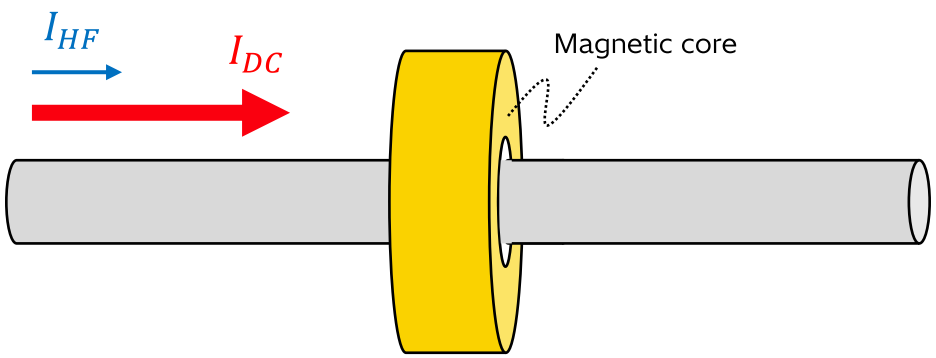

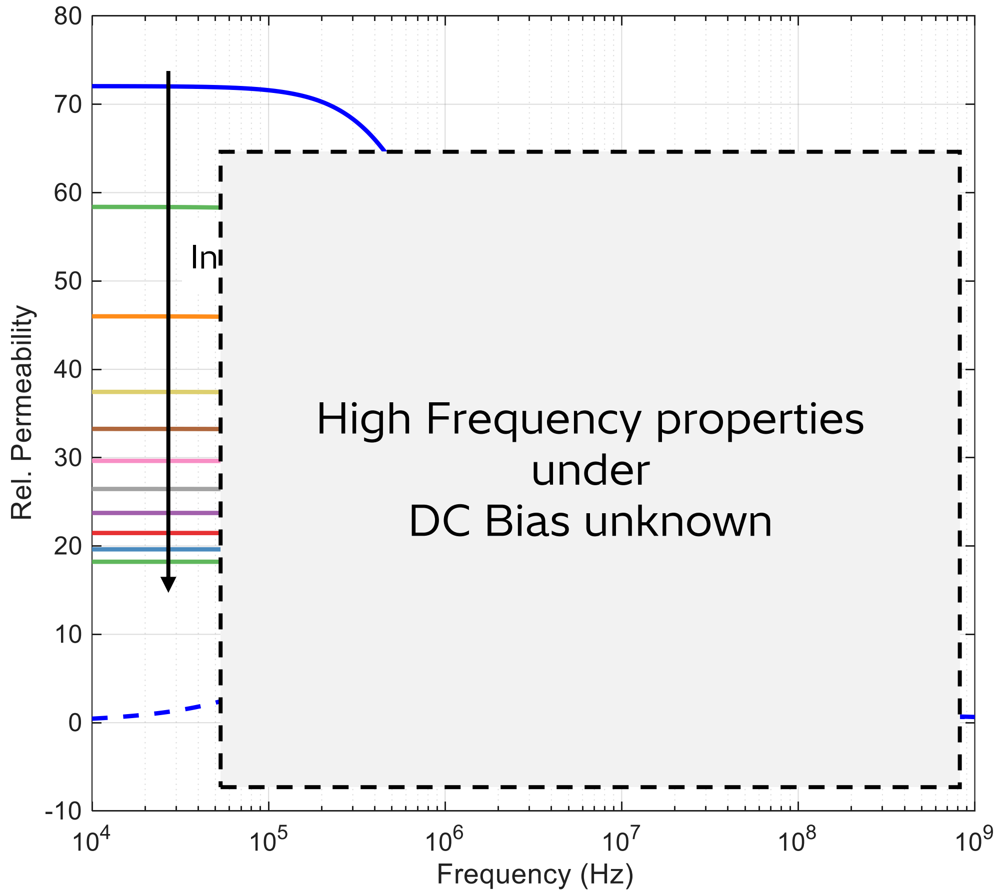

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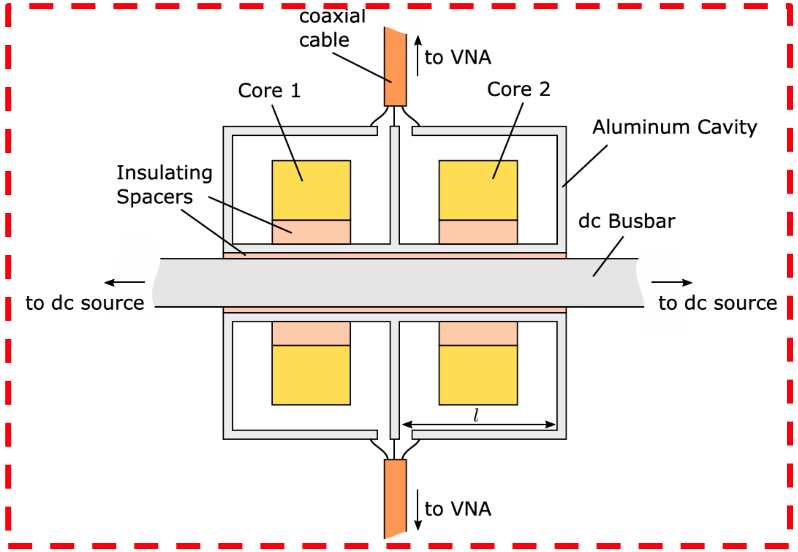
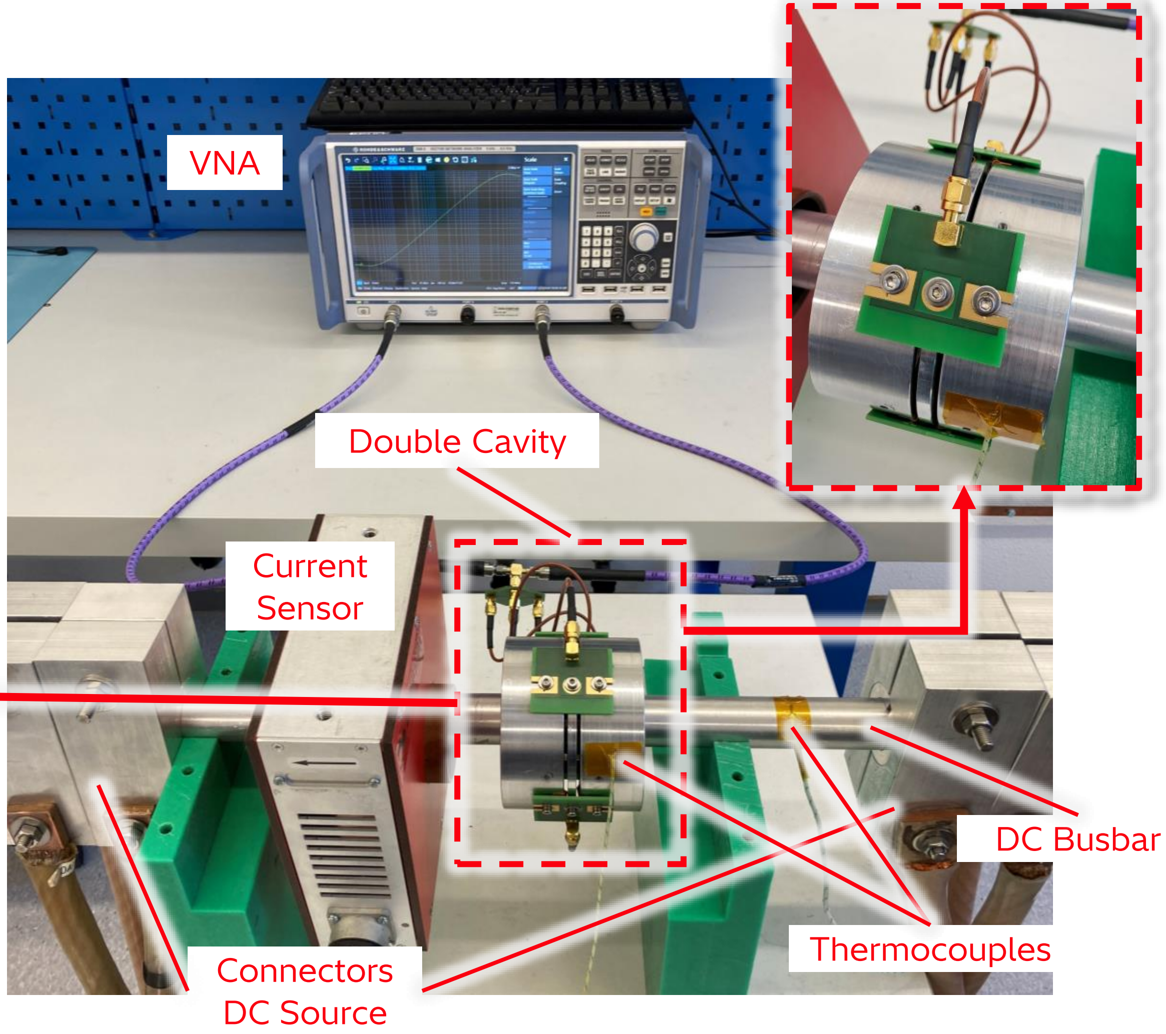
Data Acquisition – Measurements under DC Bias

Double Cavity Measurement Setup [1]

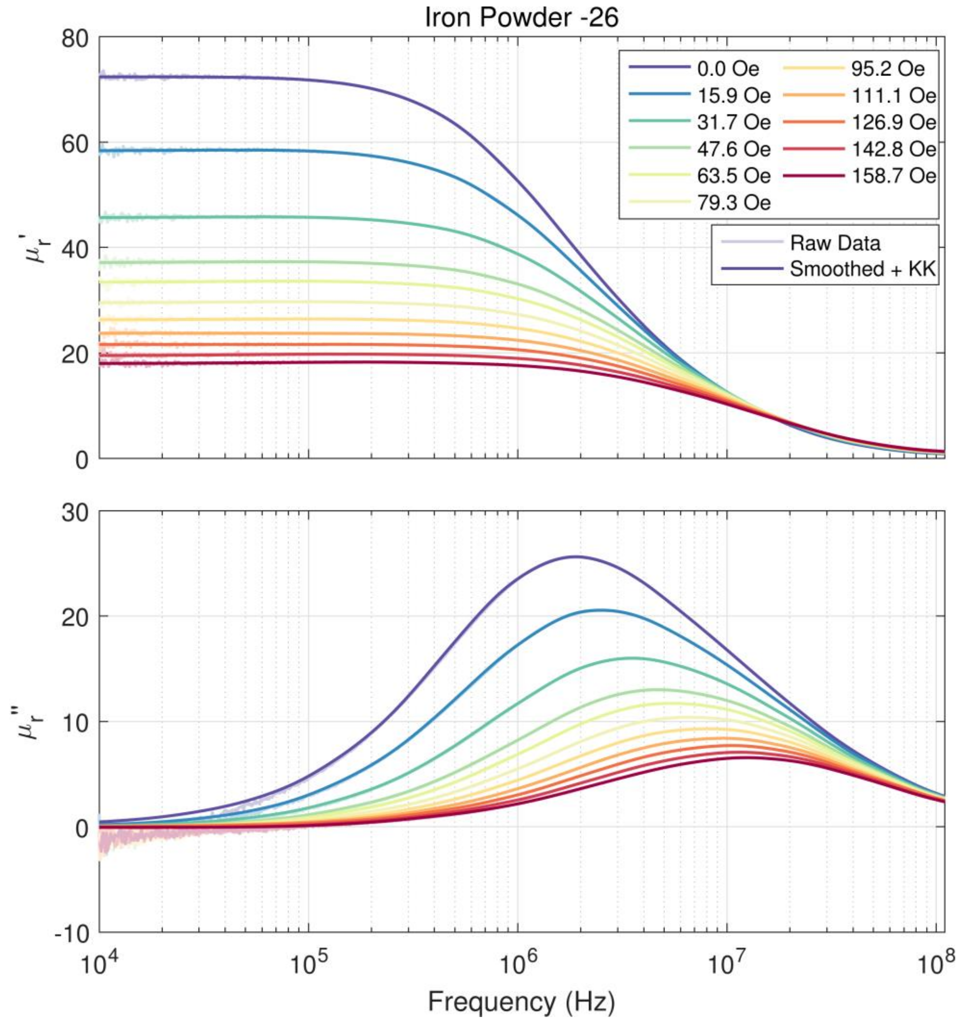
- Frequency range: 9kHz – 100MHz
- DC bias currents 0A – 3.5kA
- Customized measurement setup





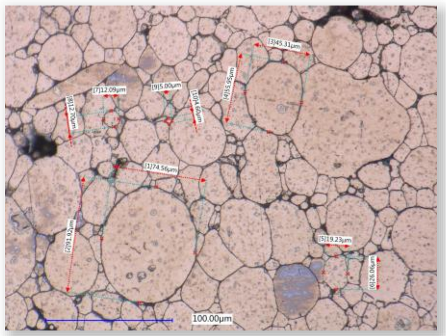
[1] A. Schröder, A. Savca and D. Bormann, "High Frequency Permeability Measurements and Modeling of Magnetic Powder Cores Under DC Bias," in IEEE Transactions on Power Electronics, vol. 39, no. 12, pp. 16361-16370, Dec. 2024

Example Results

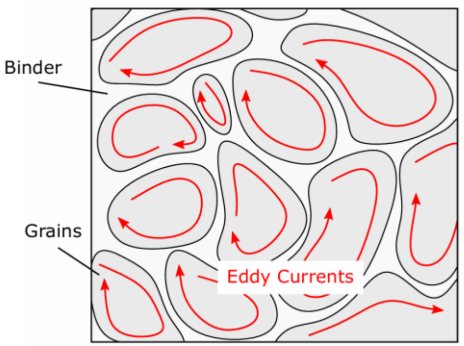


- Permeability spectrum follows a Debye-type relaxation behavior
- Dissipation peak shifted towards higher frequencies under DC bias
- Physics-inspired modelling possible [1]; however non-readily available data required, limited to Debye-type relaxation [2]

$$\mu_\mathrm{r}(\omega, I_\mathrm{dc}) = \mu_\mathrm{r}(0, I_\mathrm{dc}) \sum_{i=1}^{n} \frac{\alpha_i}{1 + \mathrm{j}\omega\,\tau_i(I_\mathrm{dc})},$$



Microscope picture of grains in powder cores



[2] A. Schröder, A. Savca and T. Christen, "Dimensional Resonances in Magnetic Powder Cores," 2024 International Symposium on Electromagnetic Compatibility – EMC Europe, Brugge, Belgium, 2024, pp. 517-52

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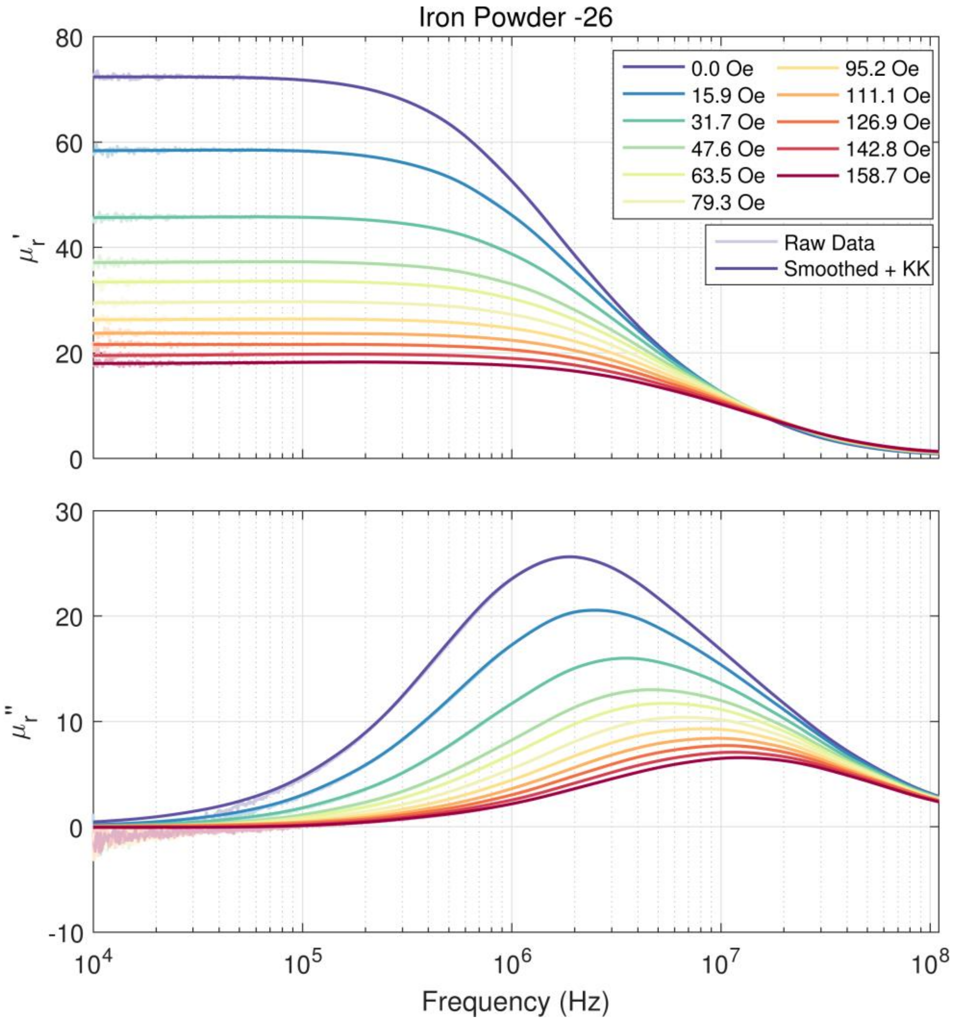

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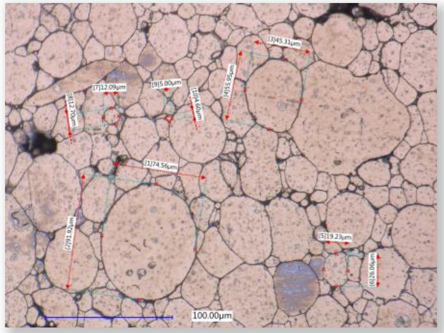
Goals of this work:

- **A purely data-driven, macro-model to be created**
- **Circuit representation (passive + stable) for system-level EMC analysis**



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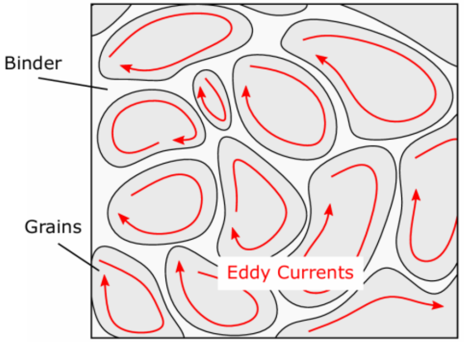

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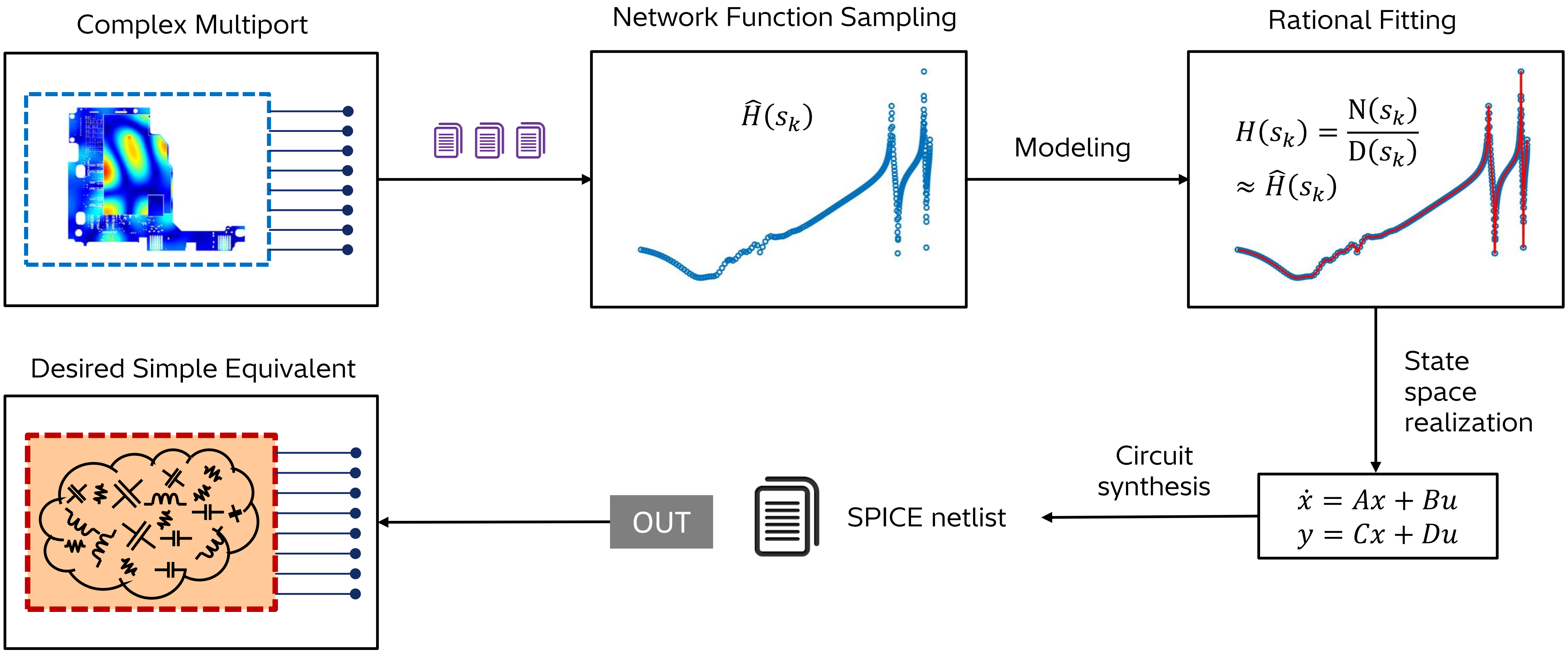
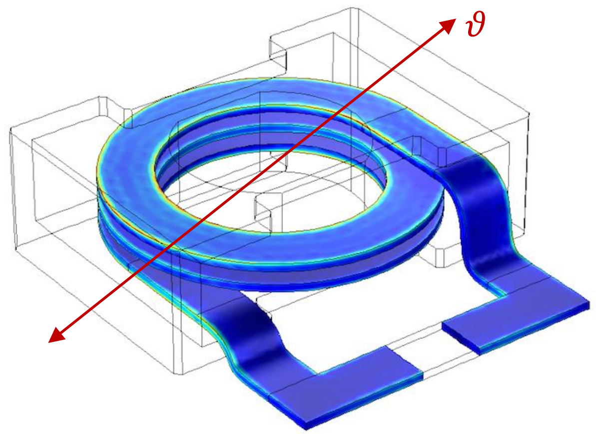
Macro-Modeling



Public

Parameterized Macro-Modeling

$\vartheta = [\theta_1 \quad \cdots \quad \theta_Z]^T$



Parameter sweep

Simulation or Measurement

IN

Multiple S-parameters

$$\hat{H}_{k;m} = \hat{H}(j\omega_k, \vartheta_m)$$
$$k = 1, \dots, K; \; m = 1, \dots, M$$

Multivariate Rational Fitting

Stability & Passivity

$$\mathrm{H}(s, \vartheta) = \frac{\mathrm{N}(s, \vartheta)}{\mathrm{d}(s, \vartheta)}$$

Parameterized model

State-space realization

Circuit synthesis

$$\dot{x} = A(\vartheta)x + B(\vartheta)u$$
$$y = C(\vartheta)x + D(\vartheta)u$$

OUT

SPICE netlist

The Output for the User

OUT SPICE netlist

$$\dot{x} = A(\vartheta)x + B(\vartheta)u$$
$$y = C(\vartheta)x + D(\vartheta)u$$

```
* Test Netlist for AC sweep
*****************************

*Arbitrarily complex external system
xExternal 1 0 ExternalNet

*****************************
* The macromodel instance
xMODcir 1 0 MyParModel par1 = {theta}
*****************************
*The macromodel definition
* BEGIN: parameterized macromodel
.subckt MyParModel n1 n2 params:par1=1

[Synthesis…]

.ends
* END: parameterized macromodel
*****************************
* Analysis Setup
* Run a parameter sweep
.step param theta -1 1 0.1
.ac list […]
.end
```

Fast
AC, OP, or transient analyses

Public

Machinery: PSK Algorithm

$$Z(s, I_{DC}) = \frac{\mathrm{N}(s, I_{DC})}{\mathrm{d}(s, I_{DC})} = \frac{\sum_n \sum_\ell \mathrm{R}_{n,\ell}\, b_{\bar{\ell},\ell}(I_{DC})\varphi_n(s)}{\sum_n \sum_\ell r_{n,\ell}\, b_{\bar{\ell},\ell}(I_{DC})\varphi_n(s)} \longrightarrow \begin{cases} \varphi_0(s) = 1 \\ \varphi_{n>0}(s) = (s - q_n)^{-1} \\ b_{\bar{\ell},\ell}(I_{DC}) \text{: Bernstein Pol.} \\ \mathrm{R}_{n,\ell}, r_{n,\ell} \text{: Free coeffs.} \end{cases}$$

$Z(j\omega, I_{DC}) \approx \hat{Z}(j\omega, I_{DC})$
at sampling points

for $\nu = 1,2, \ldots$ $\qquad$ $\mathrm{d}_0 = 1;$

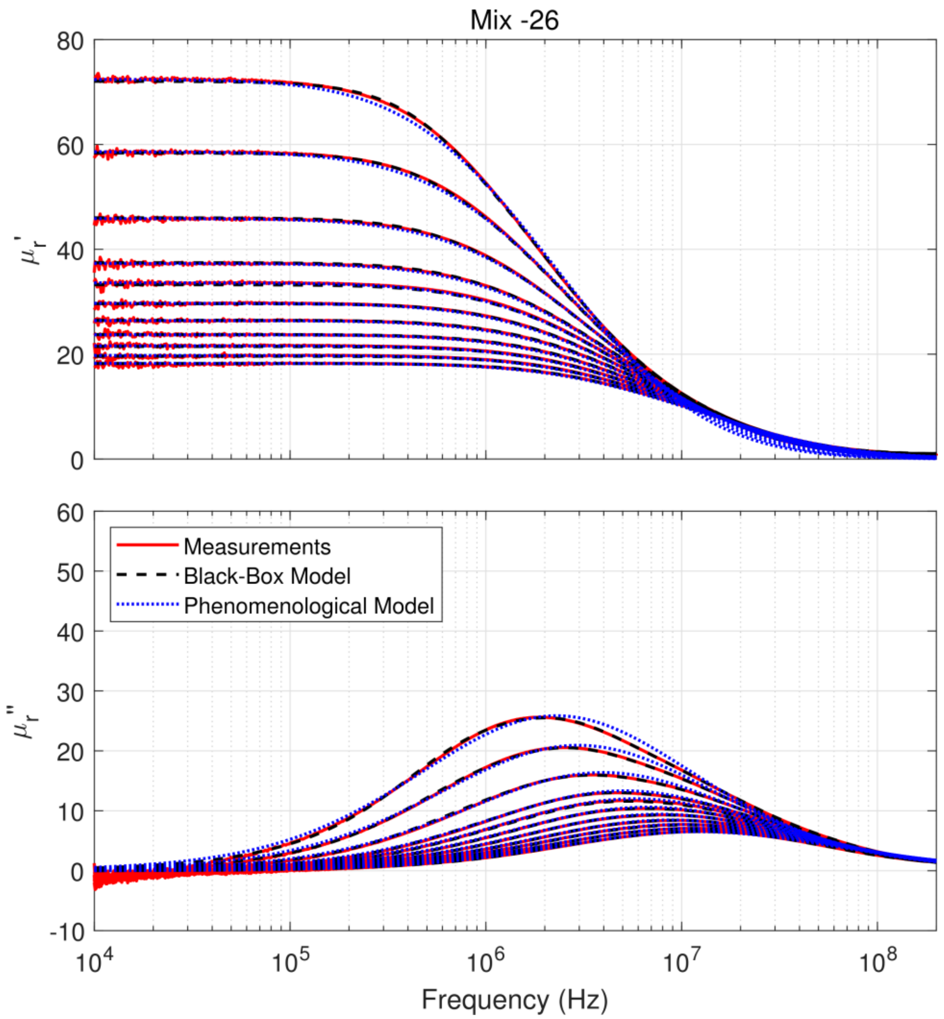
$$\min \left\| \frac{\mathrm{N}_\nu(s_k, I_{DC}^m) - \mathrm{d}_\nu(s_k, I_{DC}^m)\hat{Z}(s_k, I_{DC}^m)}{\mathrm{d}_{\nu-1}(s_k, I_{DC}^m)} \right\|$$

Known!

Model **generation** is

1. Based on **deterministic** and robust algorithms
2. **Constrained** to guarantee stability and **passivity** of the resulting equivalent circuit
3. May include **additional** design **parameters** (Temperature, coil dimension, …)

Fitting Results [3]



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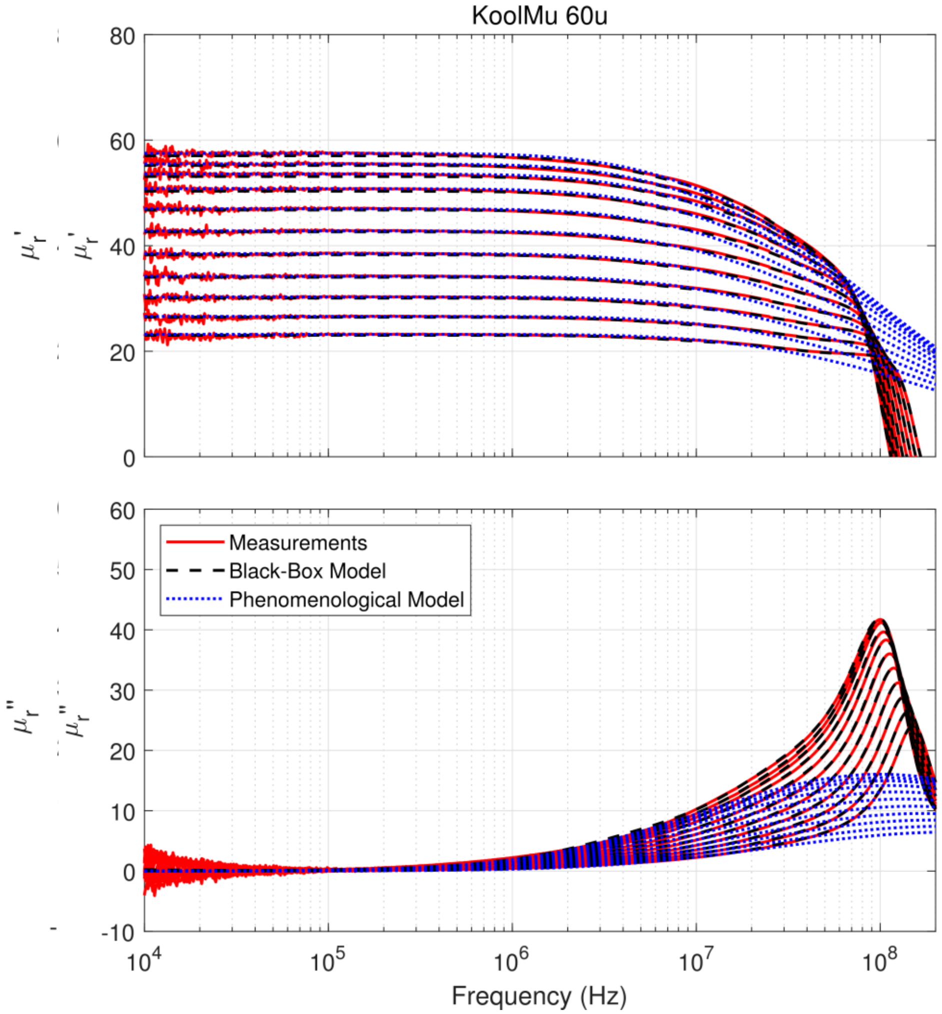

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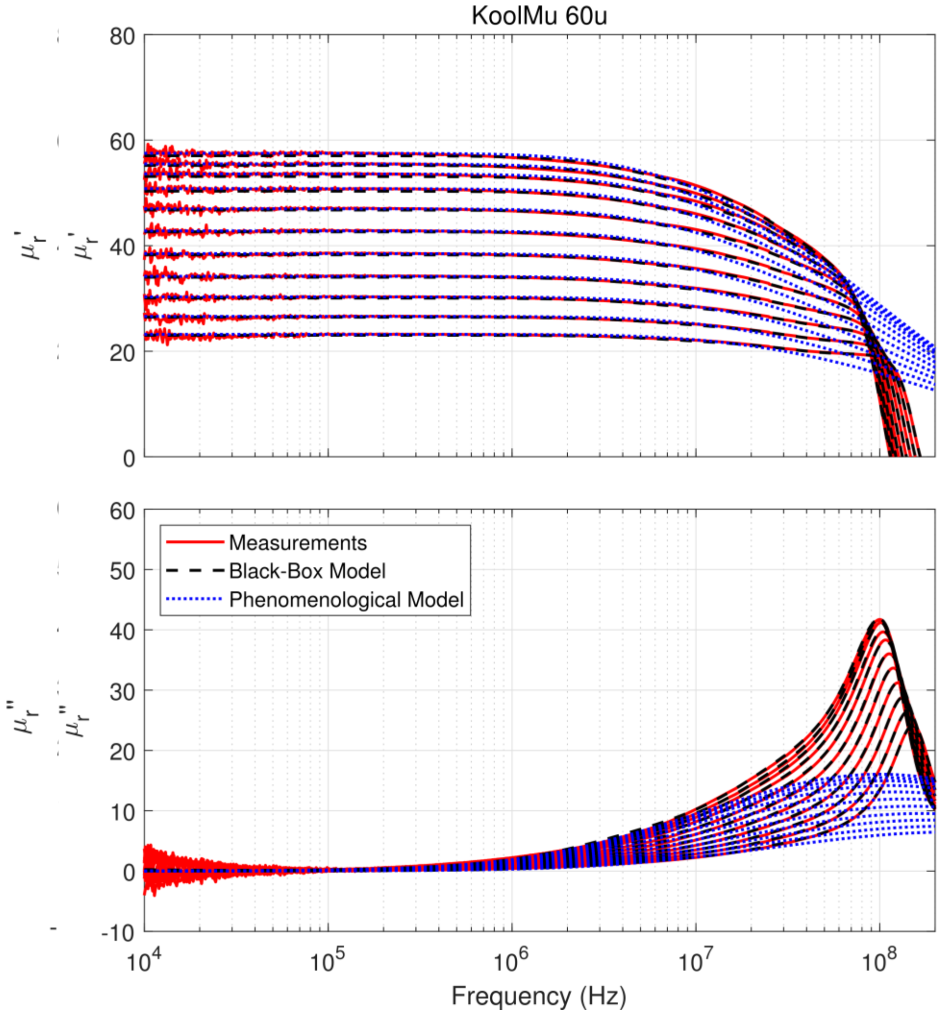

	Black-Box Model		Phenomenological Model	
	RMS Error	# Circuit Elements	RMS Error	# Circuit Elements
Mix -26	1.38 %	77	4.90 %	10
Mega Flux	1.05 %	45	10.50 %	10
Kool MμMAX	1.29 %	69	12.33 %	10
MPP	1.08 %	69	20.5 %	10

- **Higher accuracy** over the full bandwidth
- **Behavioral** circuit synthesis with more circuit elements
- **Physical consistency** guaranteed
- **Phenomenological model** not able to capture all physical effects

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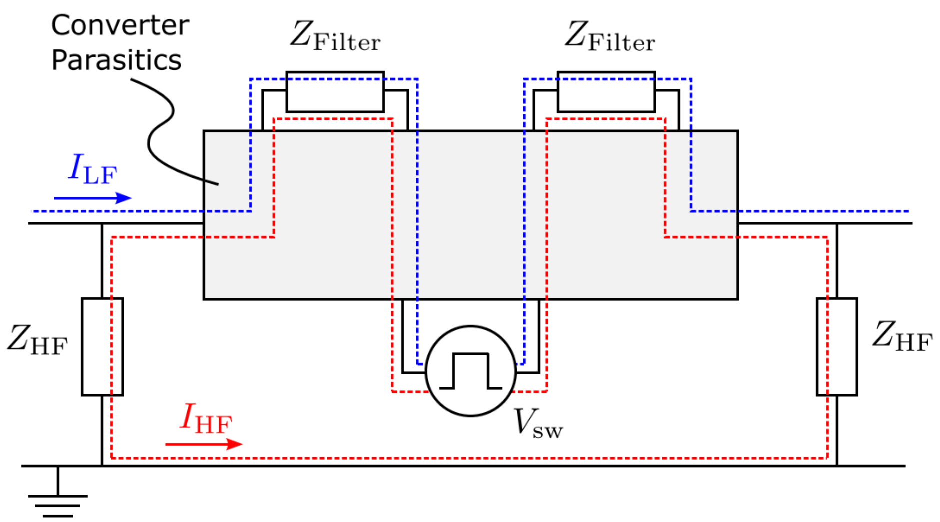
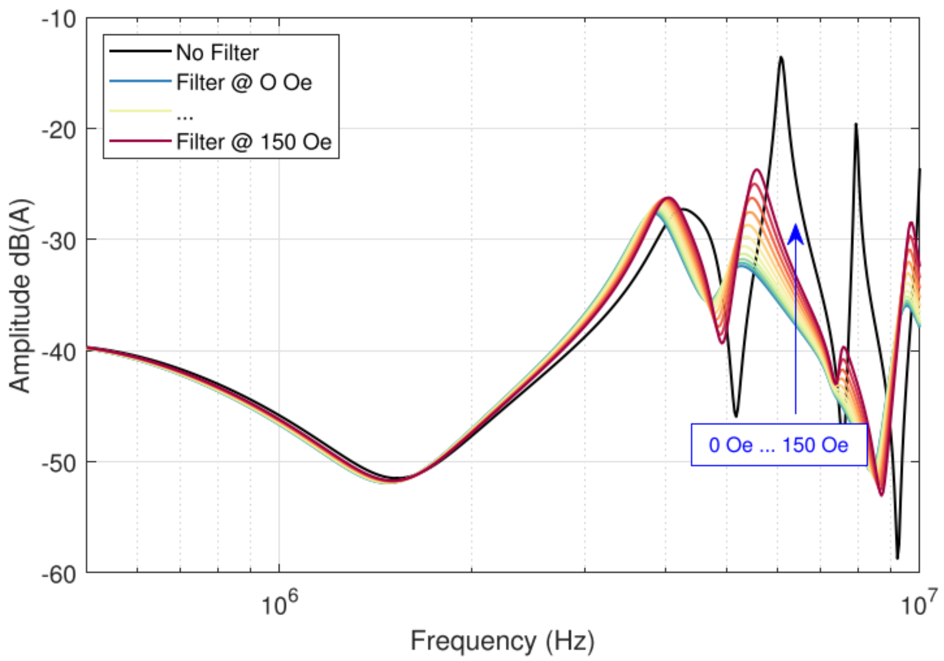
Circuit-Level Examples [3]

Noise propagation from generic converter

- Attenuation of HF currents by filtering
- Efficiency of filtering under DC bias?





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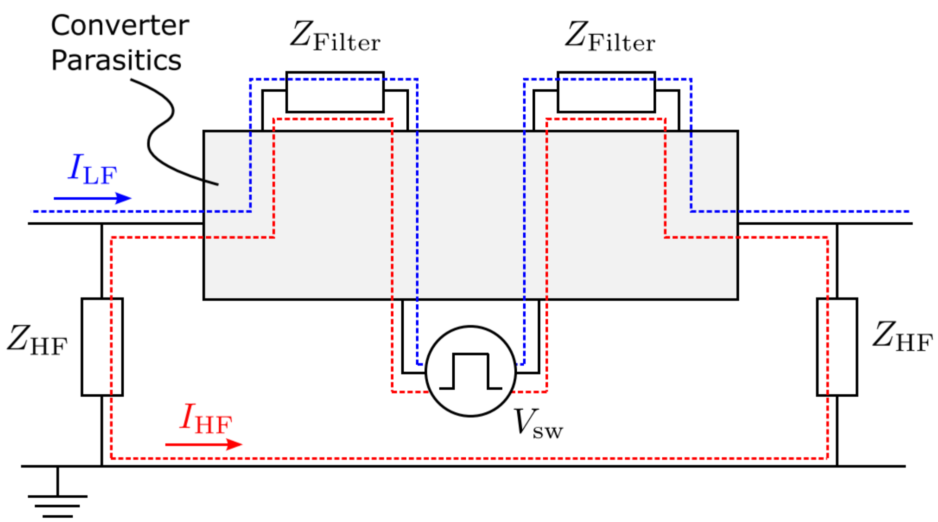

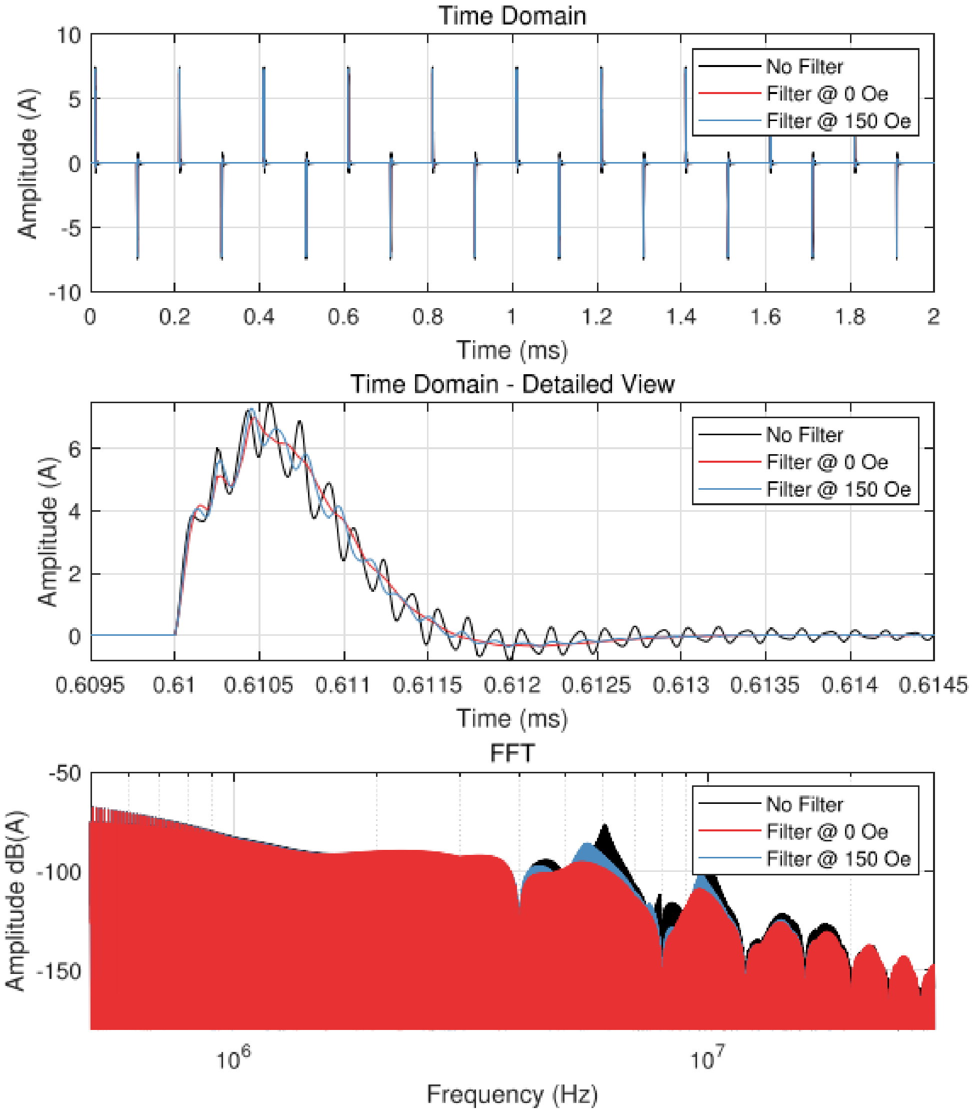

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Conclusions

- **Parameterized macro-models important** for
  - **Multi-objective optimization** of components and systems
  - Circuit-based **noise propagation analysis**
- Magnetic powder cores: **behavioral model** has **advantages over physics-inspired models** while retaining physical consistency

Future Topics in this Domain

- Optimized sampling of data → reduce effort for data generation
- Simulate time-dependency of the bias current
- Include additional design parameters in the macromodel (e.g. temperature)

Thanks for your attention! Questions?

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