FAST CORRECTOR MAGNETS FOR PETRA IV: SIMULATIONS AND MEASUREMENTS

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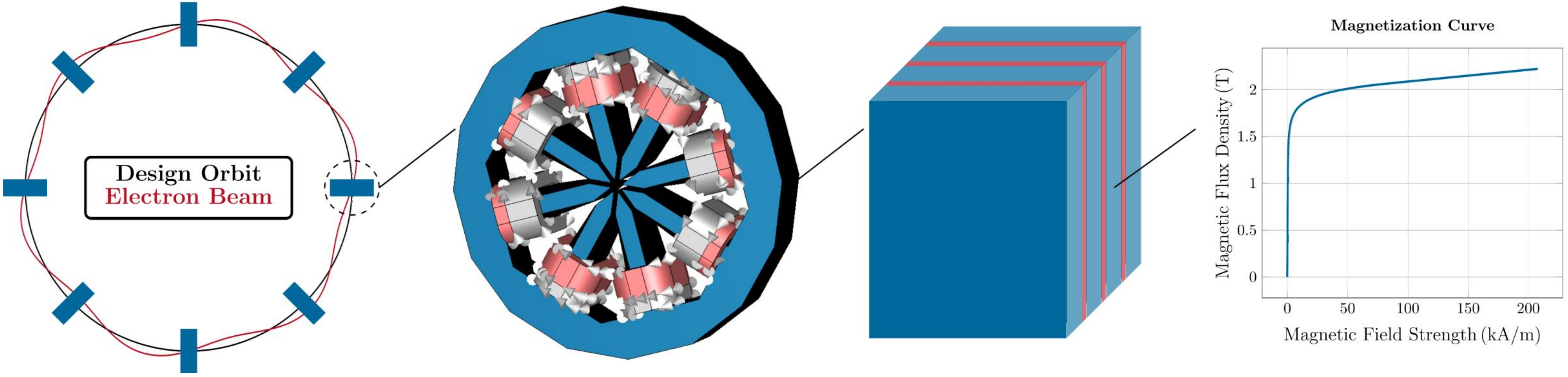

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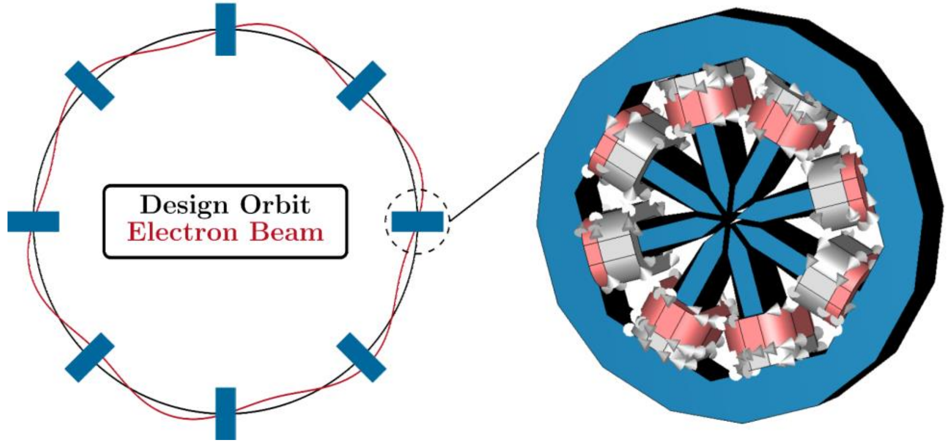
INTRODUCTION

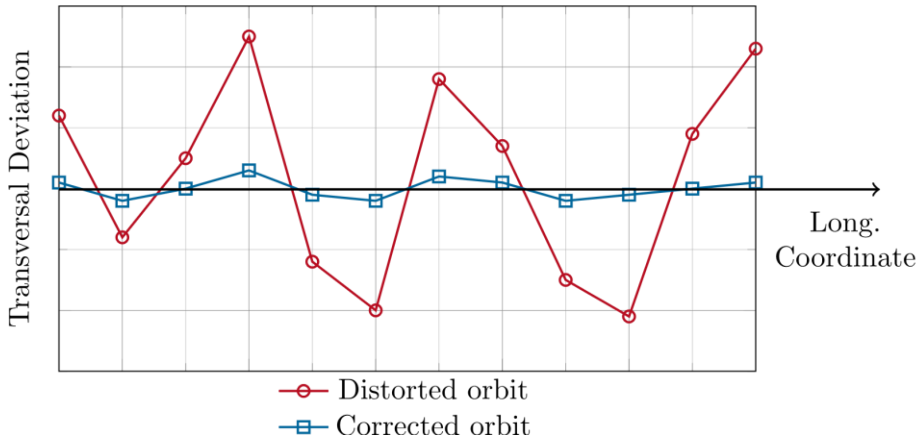
- PETRA III ➔ PETRA IV: hor. emittance must be reduced from 1300 pmrad to 20 pmrad
- **Electron beam must be stabilized within a few hundred nanometers**

➔ Need for fast orbit feedback system with fast corrector magnets powered at frequencies in kHz-range

- **Strong eddy currents ➔** power loss, time delay, and field attenuation
- Simulation challenging due to **small skin depths and laminated yoke**

➔ Need for technique to simplify simulations





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EDITORS' SUGGESTION | OPEN ACCESS

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Homogenized harmonic balance finite element method for nonlinear eddy current simulations of fast corrector magnets

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HOMOGENIZATION

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- Magnetoquasistatic PDE: $\nabla \times (\nu(\vec{r})\nabla \times \underline{\vec{A}}(\vec{r})) + j\omega\sigma(\vec{r})\underline{\vec{A}}(\vec{r}) = \underline{\vec{J}}_s(\vec{r})$
- Replace reluctivity $\nu(\vec{r})$ and conductivity $\sigma(\vec{r})$ in the laminated yoke with spatially constant tensors

➔ No need to resolve laminations and skin depth with FE mesh

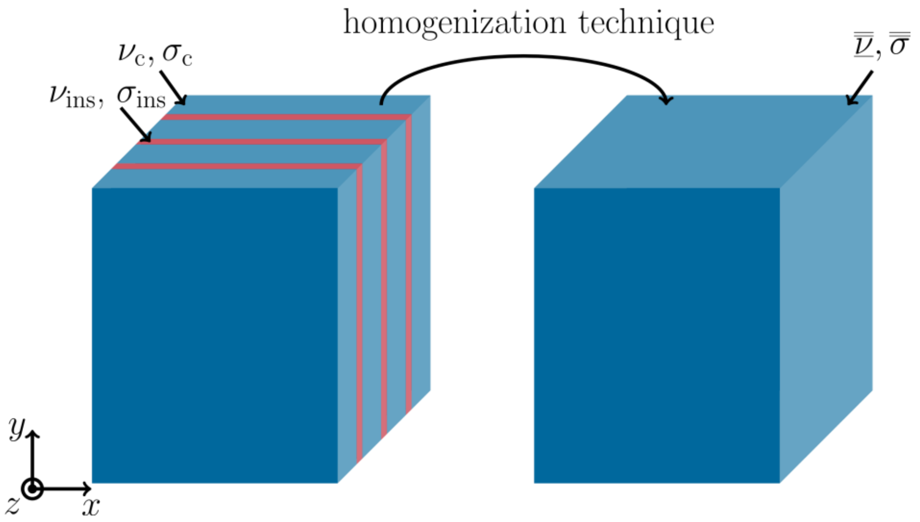
$$\nu(\vec{r}) \rightarrow \bar{\bar{\underline{\nu}}} = \frac{1}{8}\sigma_c d\delta\omega(1+j)\frac{\sinh((1+j)\delta^{-1}d)}{\sinh^2\left((1+j)\delta^{-1}d/2\right)}\begin{bmatrix}1&0&0\\0&1&0\\0&0&0\end{bmatrix} + \nu_c\begin{bmatrix}0&0&0\\0&0&0\\0&0&1\end{bmatrix}$$

$$\sigma(\vec{r}) \rightarrow \bar{\bar{\sigma}} = \gamma\sigma_c\begin{bmatrix}1&0&0\\0&1&0\\0&0&0\end{bmatrix}$$

Skin depth $\delta = \sqrt{2/\omega\sigma_c\mu_c}$

Stacking factor $\gamma = \frac{V_c}{V_{Yoke}}$

P. Dular et al., 2003



HOMHBFEM

- To consider **nonlinear B-H curve**: **combine homogenization technique and harmonic balance FEM (HBFEM)**
- HBFEM is a technique to approximate periodic solutions of nonlinear transient PDEs in frequency domain
- Example: excitation current with 1st and 3rd harmonic, include field quantities up to 3rd harmonic

$$\nabla \times (\nu(t) \nabla \times \vec{A}(t)) + \sigma \frac{\partial \vec{A}(t)}{\partial t} = \vec{J}_s(t)$$

$$\nabla \times \left(\underline{\nu}(\omega) \circledast \nabla \times \underline{\vec{A}}(\omega) \right) + j\omega\sigma \underline{\vec{A}}(\omega) = \underline{\vec{J}}_s(\omega)$$

For n-th harmonic: $\sum_{k=-\infty}^{\infty} K_{\nu_k}(\underline{a})\underline{a}_{n-k} + jn\omega_f M_\sigma \underline{a}_n = \underline{j}_n$

S. Yamada and K. Bessho (1988)
H. De Gersem, H. Vande Sande, K. Hameyer (2001)

$$\begin{bmatrix} K_{\overline{\underline{\nu}}_0(3\omega_\mathrm{f})} + 3j\omega_\mathrm{f} M_{\overline{\overline{\sigma}}} & K_{\underline{\nu}_2} & 0 & 0 \\ K_{\underline{\nu}_{-2}} & K_{\overline{\underline{\nu}}_0(\omega_\mathrm{f})} + j\omega_\mathrm{f} M_{\overline{\overline{\sigma}}} & K_{\underline{\nu}_2} & 0 \\ 0 & K_{\underline{\nu}_{-2}} & K_{\overline{\underline{\nu}}_0(\omega_\mathrm{f})} - j\omega_\mathrm{f} M_{\overline{\overline{\sigma}}} & K_{\underline{\nu}_2} \\ 0 & 0 & K_{\underline{\nu}_{-2}} & K_{\overline{\underline{\nu}}_0(3\omega_\mathrm{f})} - 3j\omega_\mathrm{f} M_{\overline{\overline{\sigma}}} \end{bmatrix} \begin{bmatrix} \underline{a}_3 \\ \underline{a}_1 \\ \underline{a}_{-1} \\ \underline{a}_{-3} \end{bmatrix} = \begin{bmatrix} \underline{j}_3 \\ \underline{j}_1 \\ \underline{j}_{-1} \\ \underline{j}_{-3} \end{bmatrix}$$

J. Christmann et al. (2025)

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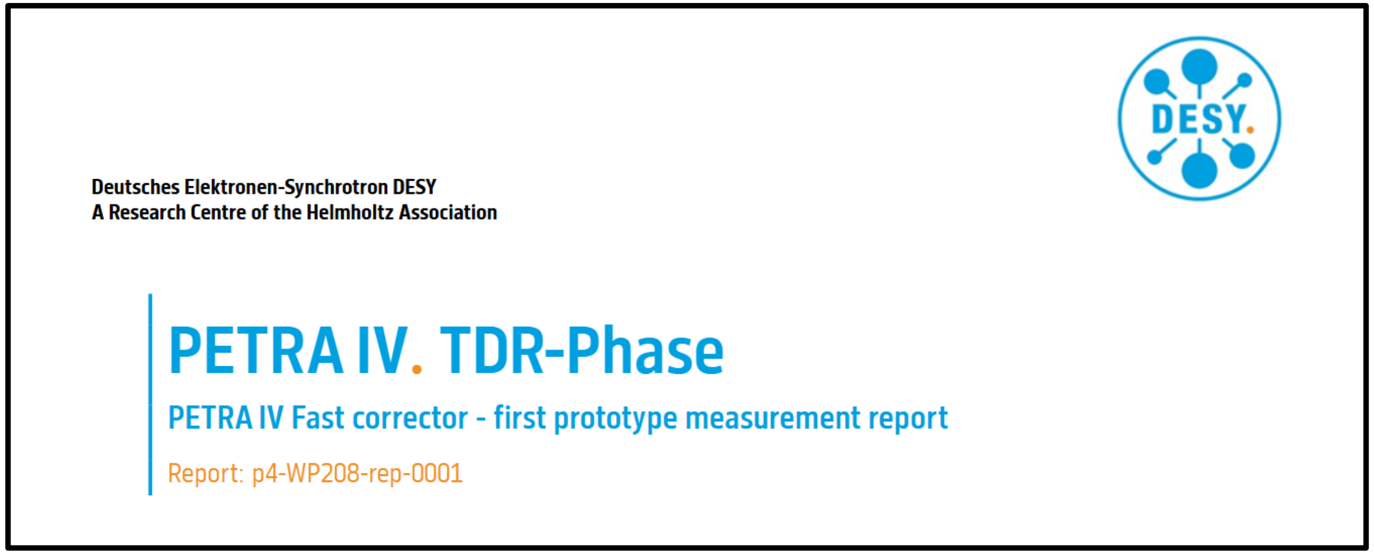
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A Research Centre of the Helmholtz Association

PETRA IV. TDR-Phase

PETRA IV Fast corrector - first prototype measurement report

Report: p4-WP208-rep-0001

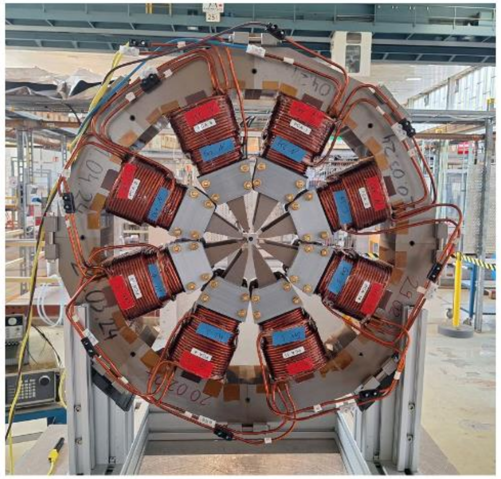
MAGNET DESCRIPTION

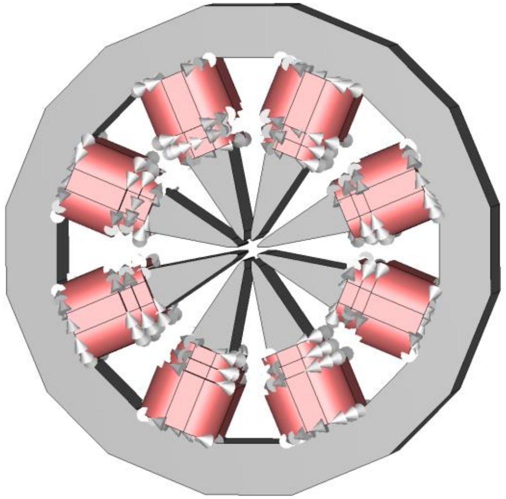
- Dipole magnet with octupole-like design
  ➔ correction in both planes, good field quality

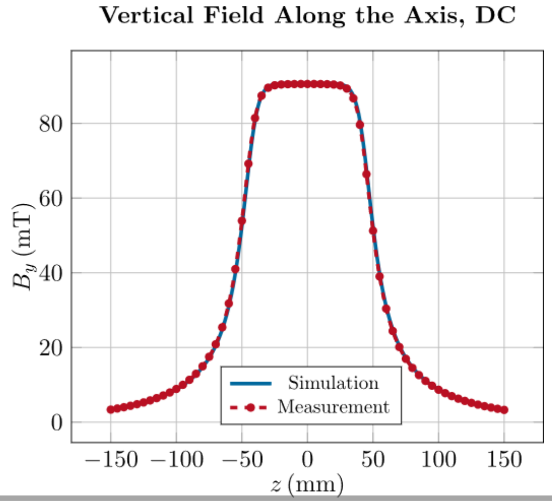
- Yoke material: powercore 1400-100AP (thyssenkrupp)
- DC inductance: 18.5 mH
- DC deflection angle: 560 urad
- Insertion length: 140.5 mm

Yoke Details	
Diameter	560 mm
Length	86 mm
Lamination	1 mm
Stacking fac.	98 – 99 %
El. resistivity	0.172 µΩm

Coil Details	
# Turns (Main)	65
# Turns (Aux.)	27
Max. DC current	15 A

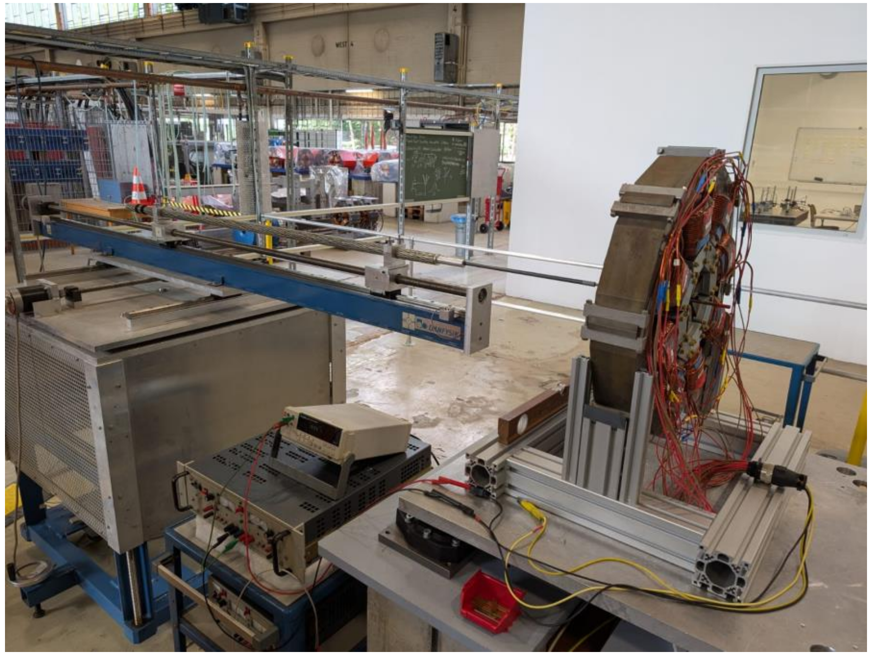


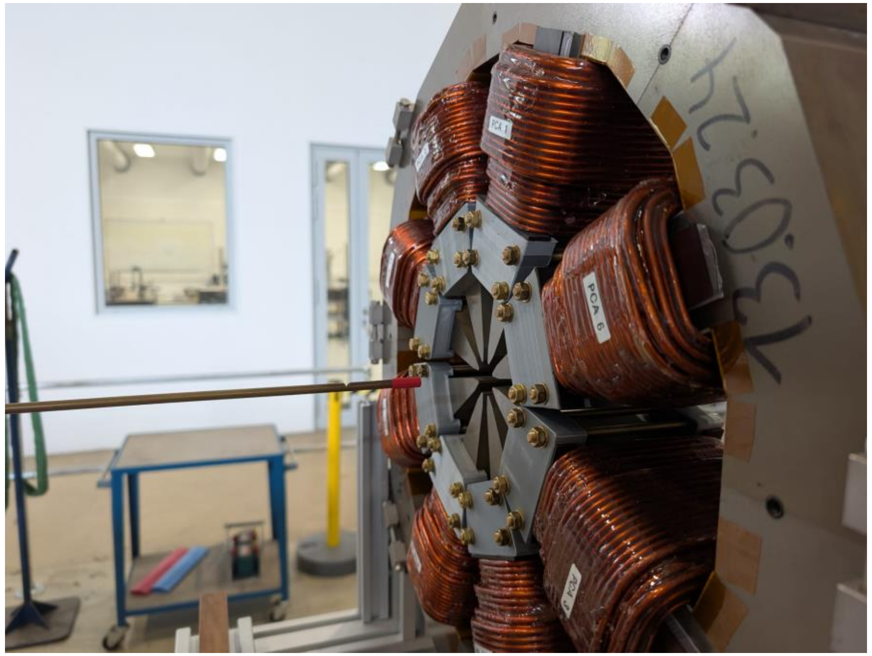




SETUP

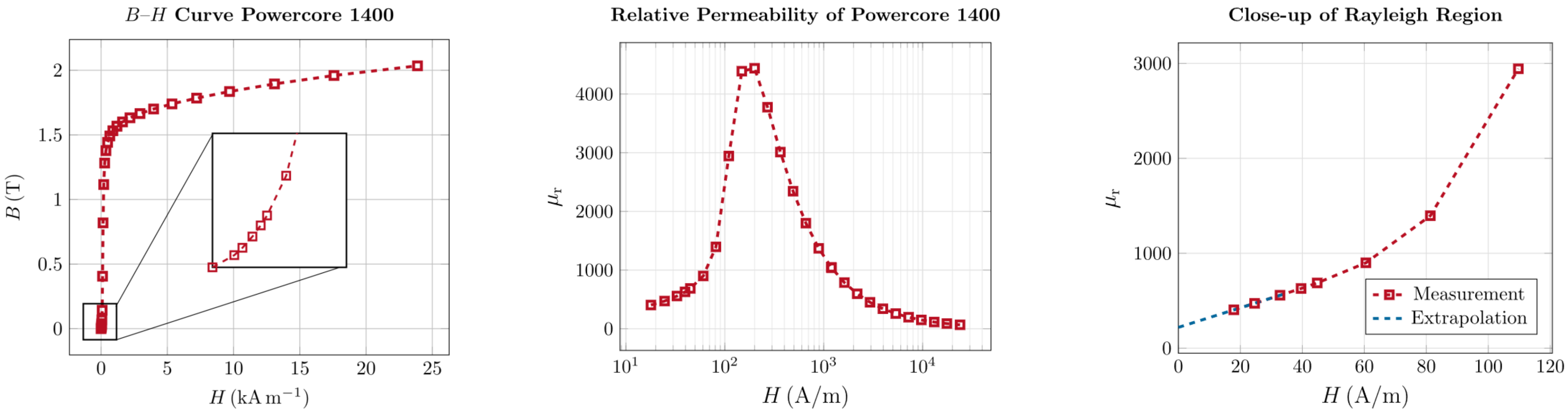
- Measure magnetic flux density (magnitude and phase) along longitudinal axis
- Hall sensor is moved from $z_{\mathrm{min}} = -150\ \mathrm{mm}$ to $z_{\mathrm{max}} = +150\ \mathrm{mm}$ in steps of $\Delta z = 2\ \mathrm{mm}$
- Investigated frequency range: from DC up to $5\ \mathrm{kHz}$





INITIAL PERMEABILITY

- Small AC measurement current ➔ use initial permeability μ_{init} in simulation instead of nonlinear B-H curve
- Rayleigh law on low-field magnetization: $B(H) = \mu_{\mathrm{init}}H + \eta H^2$
- Determine μ_{init} from measured B-H curve by plotting $\mu(H)$ and extrapolating to $H = 0$
- For powercore 1400 we find for the relative initial permeability $\mu_{\mathrm{r,init}} = 220$



FIELD PROFILES

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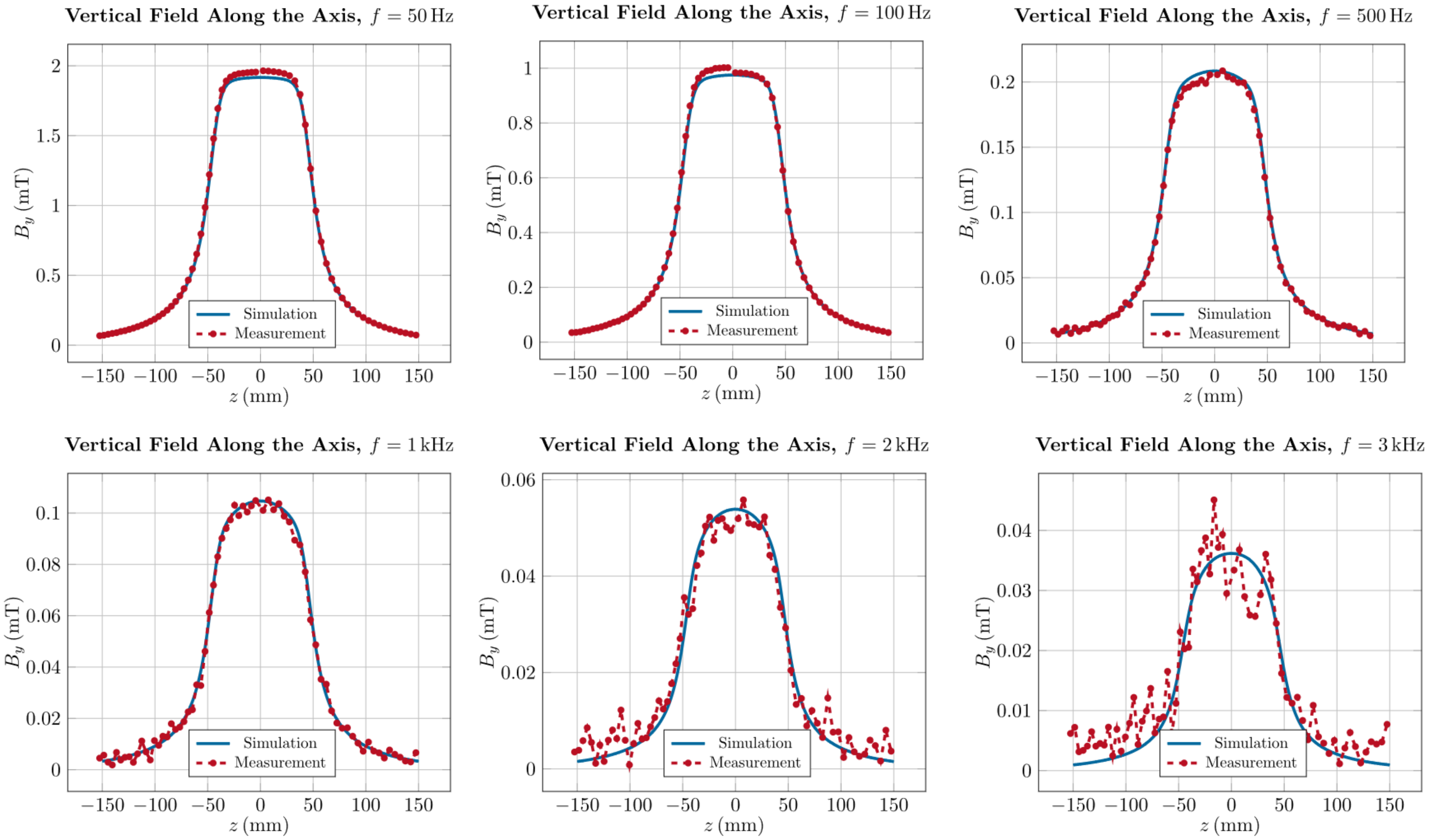
- Good agreement for frequencies $f \leq 3\,\mathrm{kHz}$
- At higher frequencies measurements are too noisy due to low magnitude of fields
- Some issues remain for $f < 50\,\mathrm{Hz}$ ➔ we will come back to this later



INTEGRATED TRANSFER FUNCTION

MAGNITUDE

- Decay of int. field with increasing frequency at const. current
- Coil current decays according to $\underline{I}(f) = \frac{\underline{U}(f)}{R(f)+j2\pi f L(f)}$
- Subtract current decay from the measured damping:

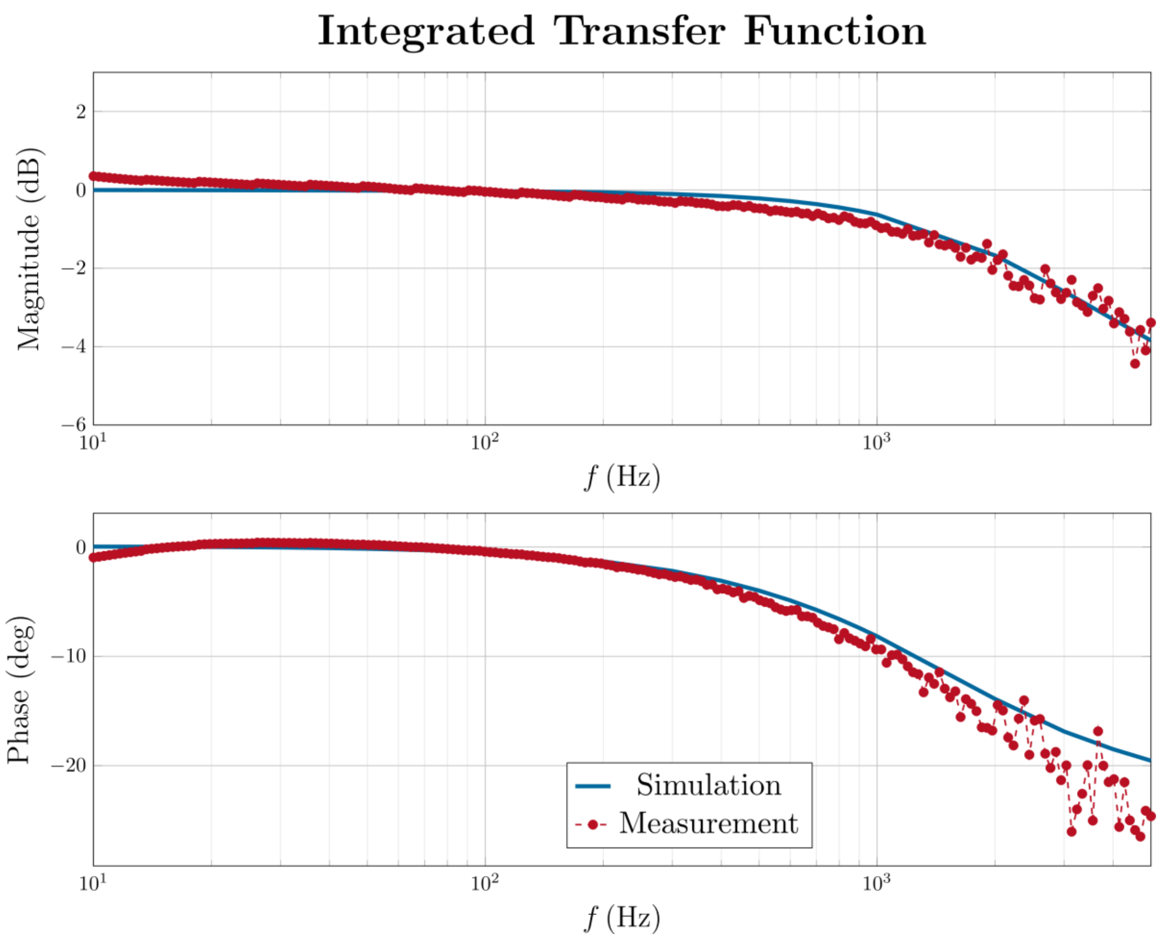
$$|\underline{\mathrm{ITF}}(f)| = 20\log\left(\frac{\int |\underline{B}_y(z,f)|\mathrm{d}z}{\int B_{\mathrm{dc}}(z)\ \mathrm{d}z}\right) - 20\log\left(\frac{\underline{I}(f)}{I_{\mathrm{dc}}}\right)$$

$$= K_0\, 20\log\left(\frac{\int |\underline{B}_y(z,f)|\mathrm{d}z}{|\underline{I}(f)|}\right)$$

PHASE

- Phase difference between coil current and field in aperture

$$\measuredangle\underline{\mathrm{ITF}} = \varphi_B - \varphi_I$$

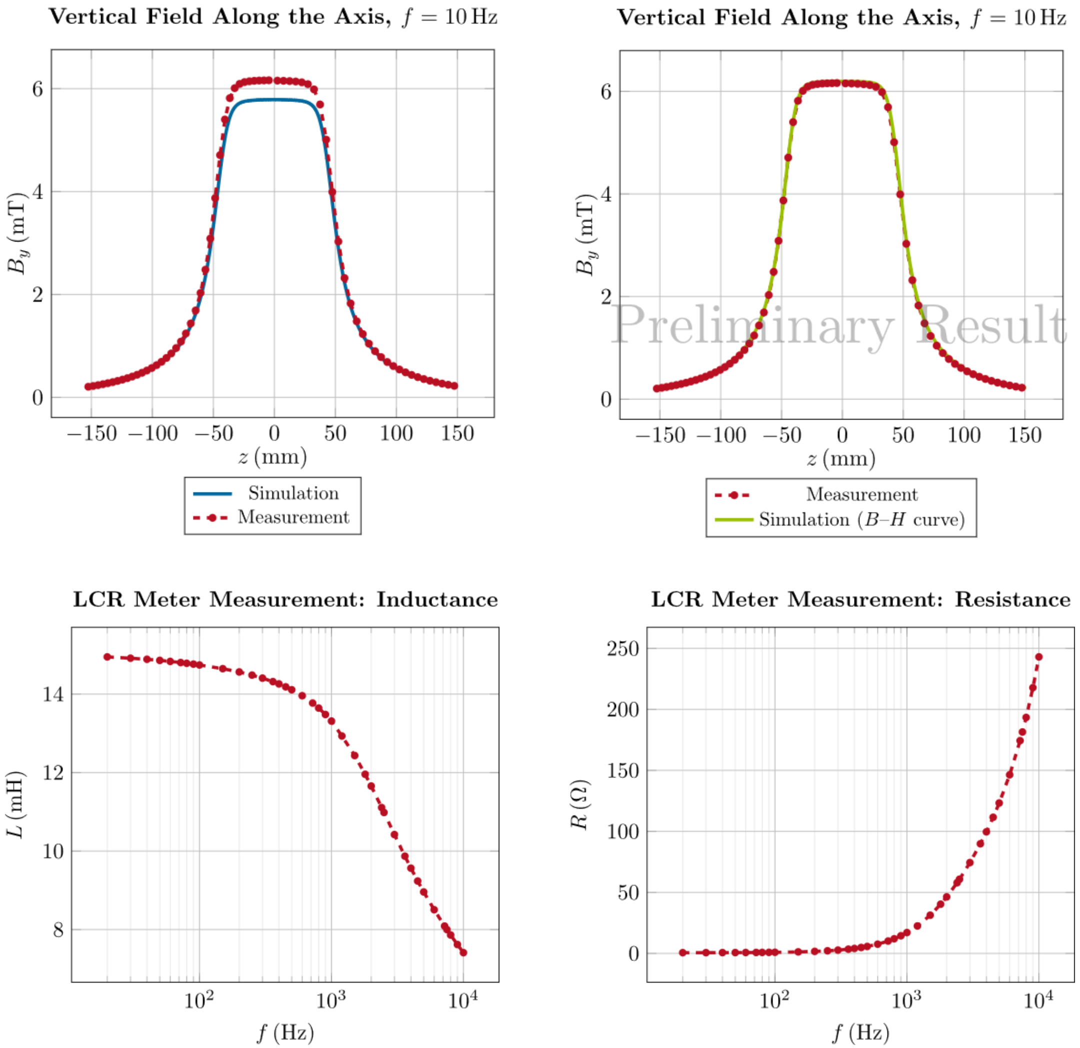


REMAINING ISSUES

- Discrepancies in field profiles at $f < 50\ \mathrm{Hz}$
- At these lower frequencies coil current is not low enough to simulate with μ_{init}

➔ Here we need to simulate with nonlinear B-H curve

- Problem: we did not have clean current measurement at the lower frequencies
- Instead we had to rely on an estimate according to $\underline{I}(f) = \frac{\underline{U}(f)}{R(f)+j2\pi f L(f)}$ (with $R(f)$ and $L(f)$ from LCR meter)
- This should be fixed in the future



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MAGNET DESCRIPTION

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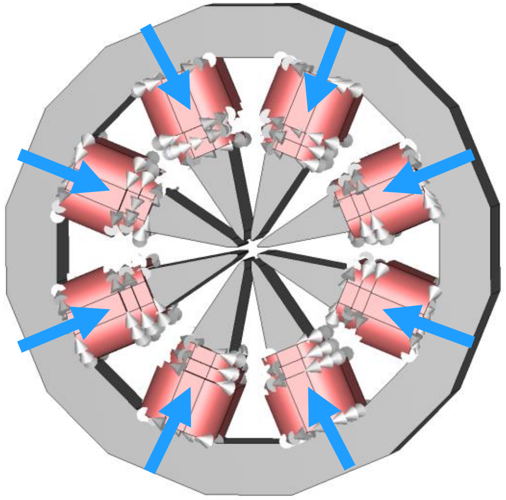
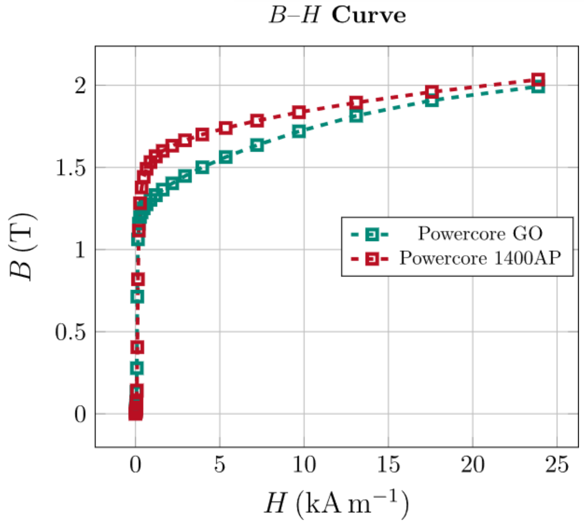
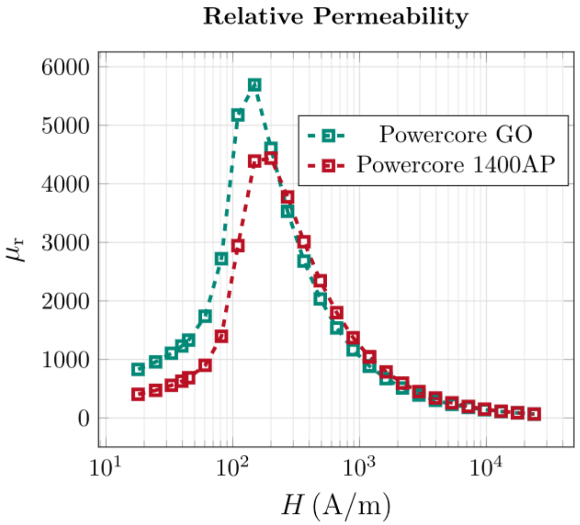
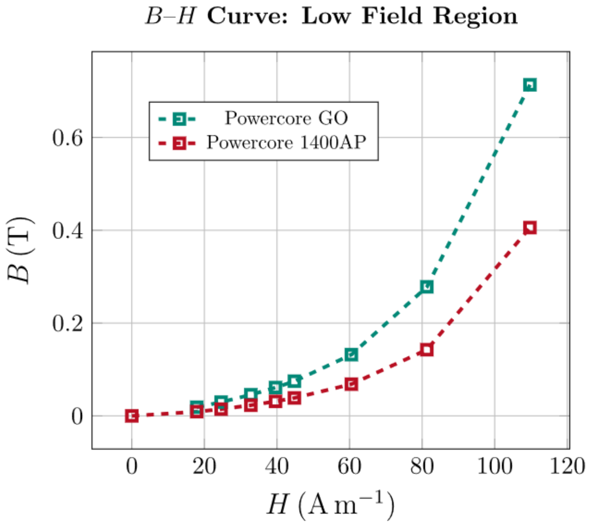
- **Grain-oriented steel**, rolling direction in each octant in pole direction
- 0.35 mm lamination thickness
- Available B-H curve is averaged over different angles w.r.t. rolling direction
- Conductivity at the moment unknown to us

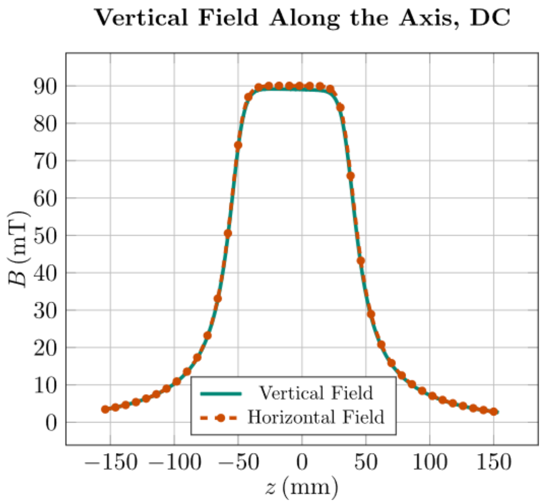


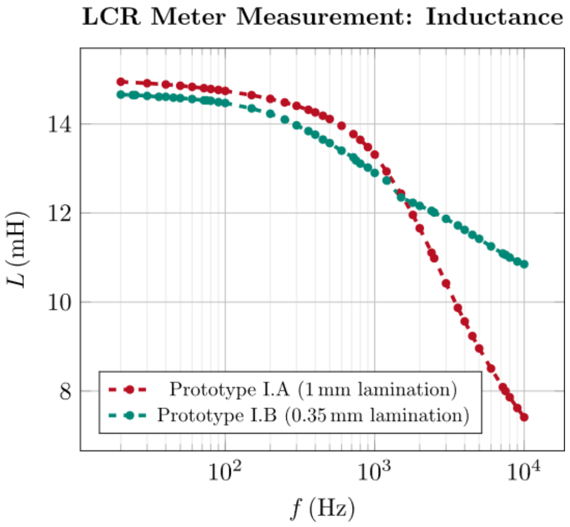


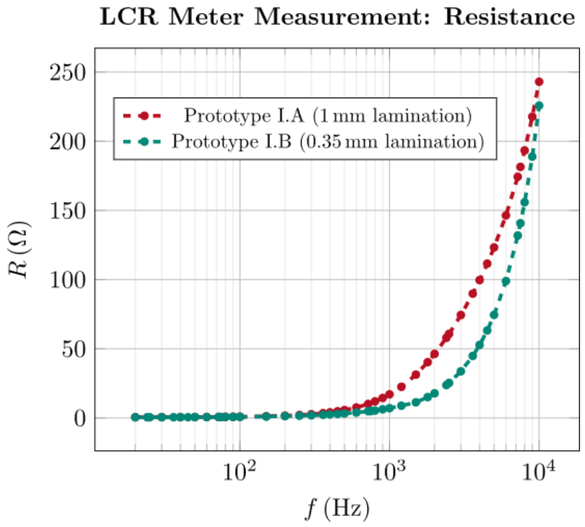




FIRST RESULTS







- DC field at 15 A very similar to prototype I.A ($B_y \approx 90\ \mathrm{mT}$)
- Inductance decreases less rapidly with increasing frequency ➔ this is expected due to smaller lamination thickness
- Inductance at low frequencies is a bit smaller than before, this is unexpected
- First field profile & ITF measurements have been done, work in progress…

CONTENTS

CONCLUSION & OUTLOOK

SIMULATION METHOD

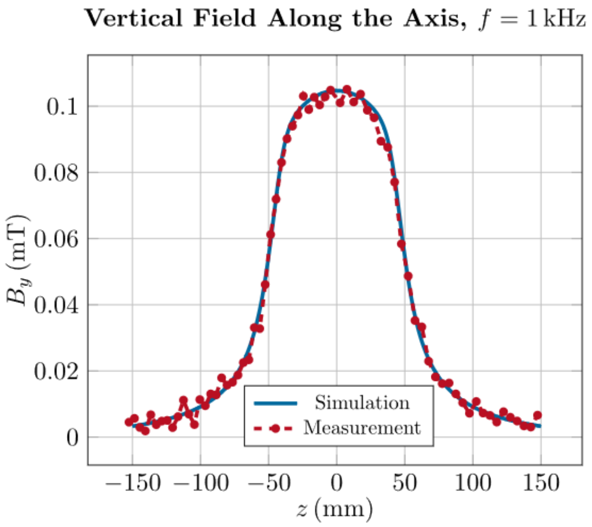
- Dedicated method to enable nonlinear simulation of fast laminated magnets
  ➔ Combines homogenization technique with HBFEM

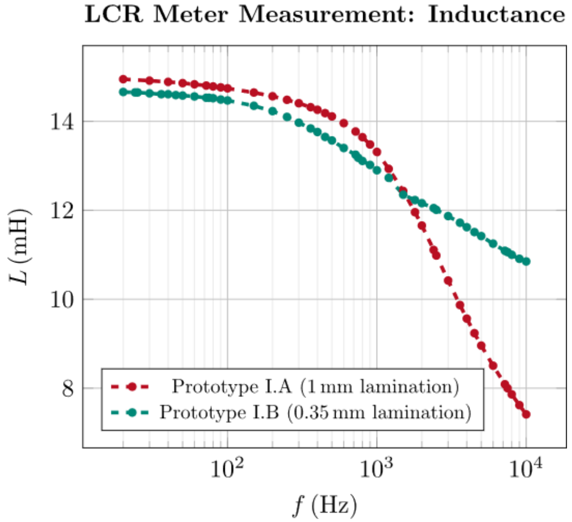
MEASUREMENTS PROTOTYPE I.A

- Field profiles
  - $50\ \text{Hz} \le f \le 3\ \text{kHz}$ ➔ good agreement
  - $f > 3\ \text{kHz}$ ➔ measurements noisy, better power amplifier needed
  - $f < 50\ \text{Hz}$ ➔ consider B-H curve, need new current measurement
- Integrated transfer function
  - Magnitude matches up to $f = 5\ \text{kHz}$, phase discrepancy in kHz-range

MEASUREMENTS PROTOTYPE I.B

- First measurements recorded, work in progress





THANK YOU!
QUESTIONS?

… special thanks also to Jörg Ludwig for the support during the measurements!

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