CONVERSION MODEL TO MINIMIZE EDDY CURRENT EFFECTS ON THE SHAPE OF THE B-H HYSTERESIS LOOPS MEASURED AT DIFFERENT FREQUENCIES

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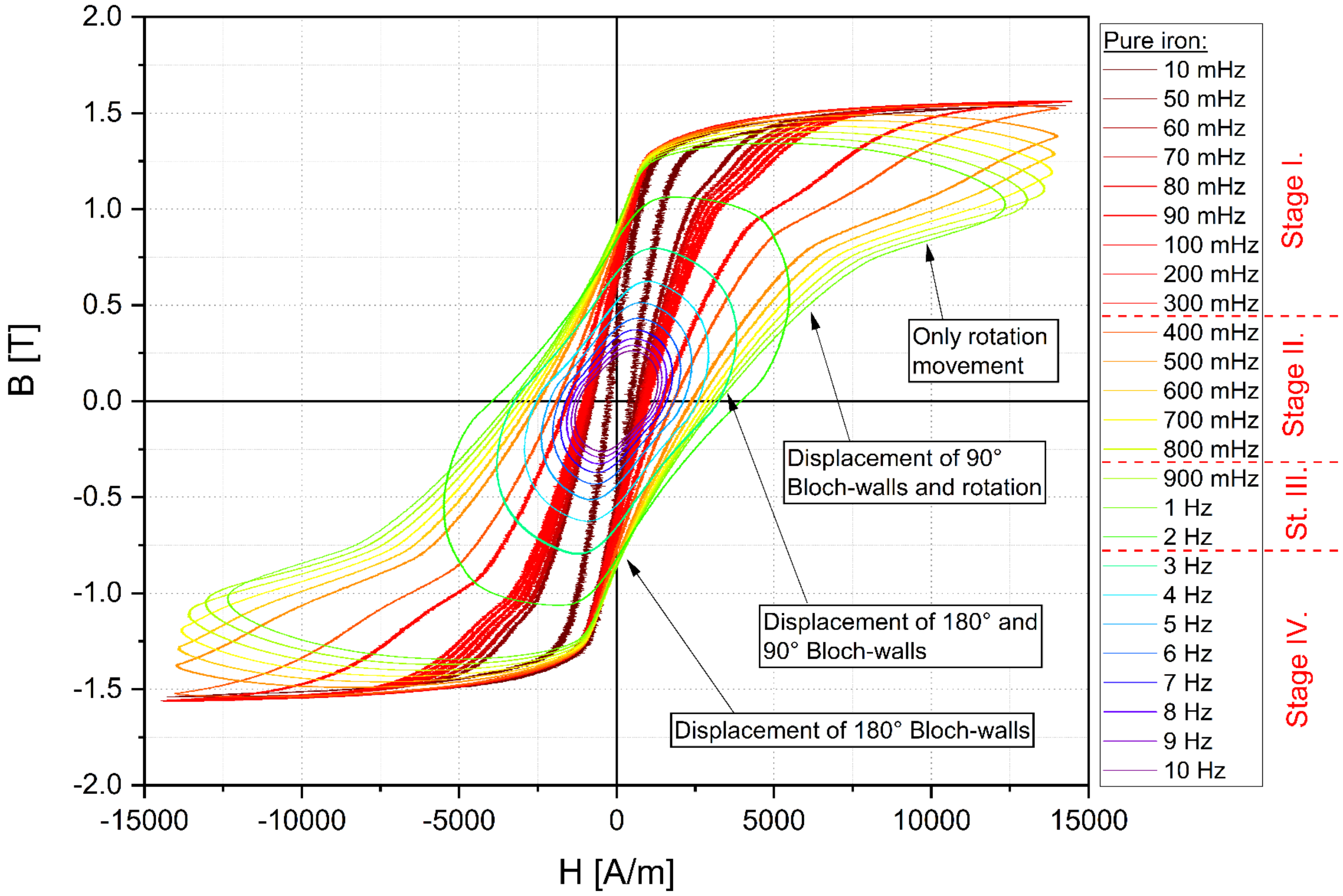
Determination of <u>non-linear</u> and <u>temperature dependent</u> <u>magnetic</u> material properties without technological influences



[1] V. Jászfi, P. Raninger, J.M. Riedler, P. Prevedel, D.G. Mevec, Y. Godai, R. Ebner, Introduction of a novel yoke-based electromagnetic measurement method with high temperature application possibilities, Journal of Magnetism and Magnetic Materials, Volume 537, 2021, 168159, ISSN 0304-8853, https://doi.org/10.1016/j.jmmm.2021.168159.

Electromagnetic measurements at room temperature

Introduction

a. Max. Power: 30 kW, Frequency: 15 kHz / 50 kHz (middle frequency)

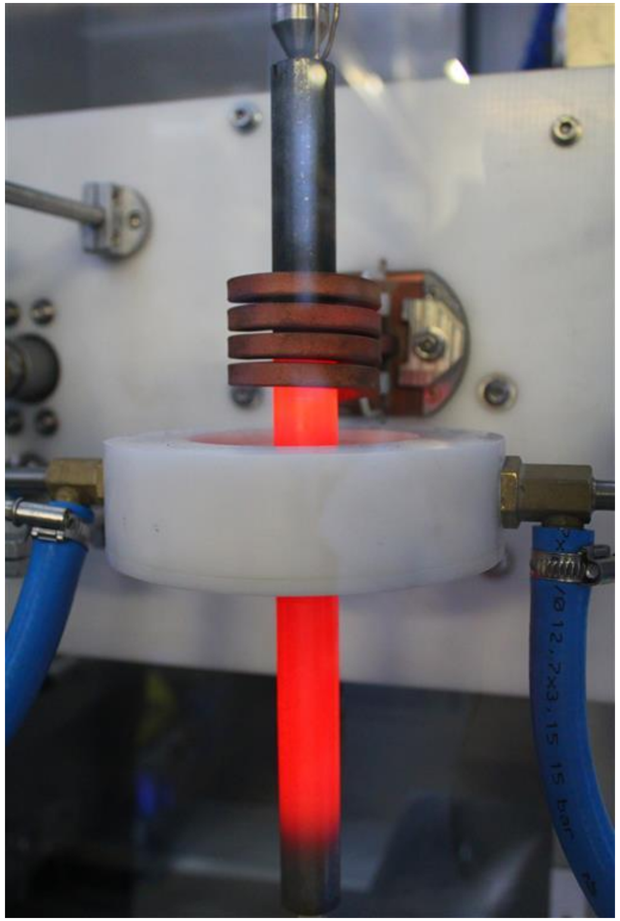
b. Rapid inductive heating of rods (Ø 10-30 mm, l=100-300 mm, inductor movement velocity 1-100 mm/s)

c. Static and dynamic heating (diverse quenching options (H_2O, air, N_2))

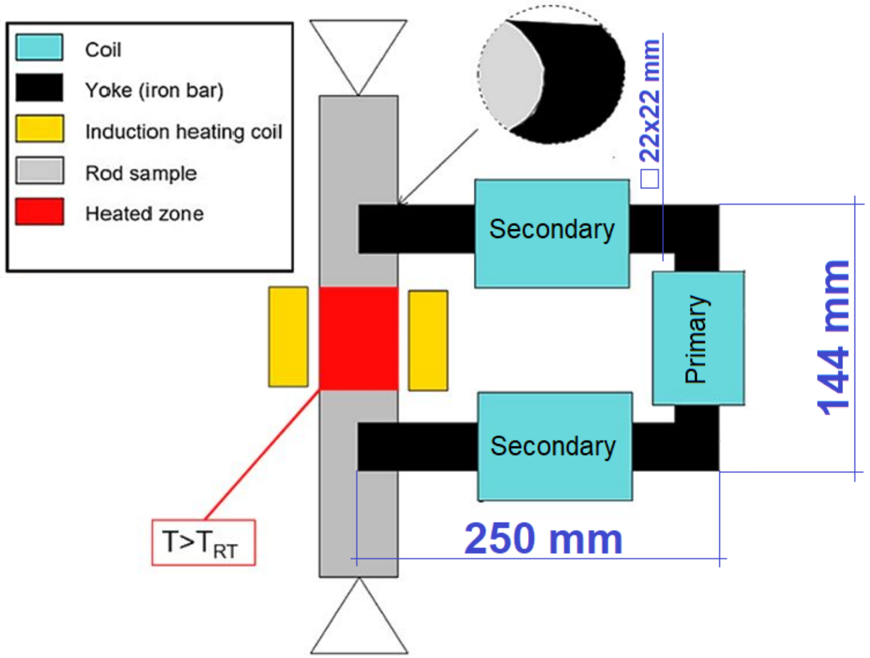
d. Power and temperature control with thermo- couples

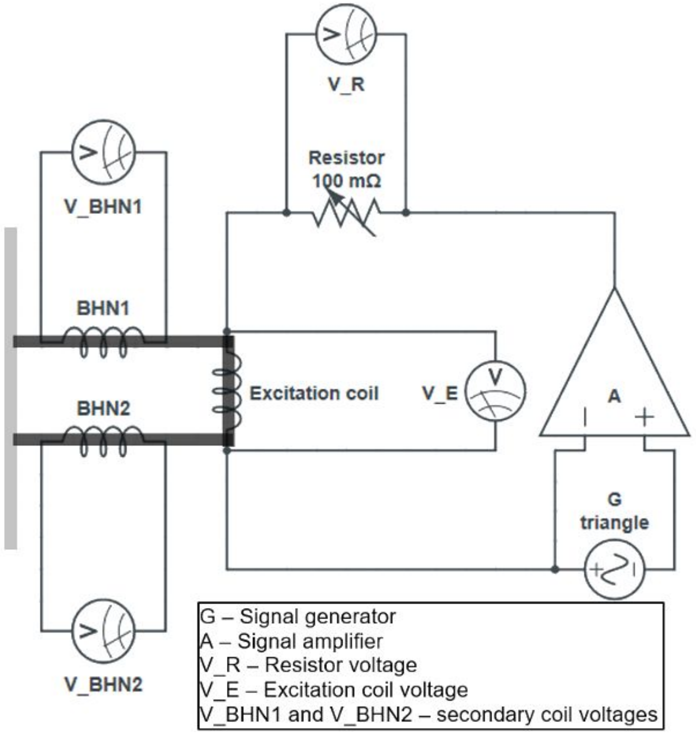
e. Vertical and horizontal operation

f. Coupling of experiment with simulation (inverse determination of heat treatment parameters)



Schematic presentation and electrical circuit plan of the measurement setup



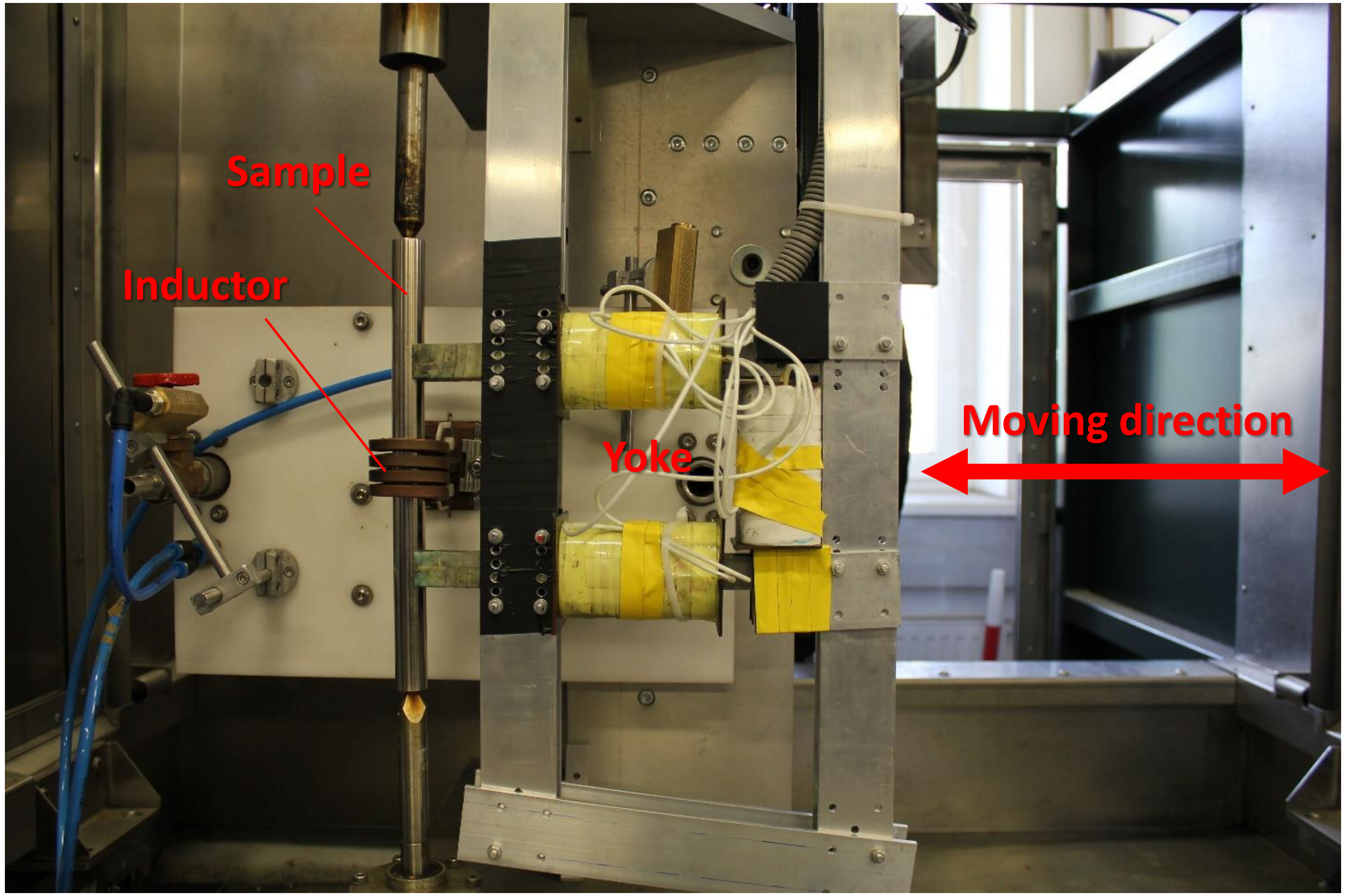


- Custom made signal amplifier for electromagnetic excitation based on multiple operational amplifier chips.
- Mobile excitation yoke, adjustable to the experimental requirements.
- Most important parameters for the calculations at room temperature: resistor voltage (V_R) and secondary coil voltages (V_BHN1 and V_BHN2).
- Capability of the setup to measure temperature dependent properties using the induction coil of the facility for heating.

[1] V. Jászfi, P. Raninger, J.M. Riedler, P. Prevedel, D.G. Mevec, Y. Godai, R. Ebner, Introduction of a novel yoke-based electromagnetic measurement method with high temperature application possibilities, Journal of Magnetism and Magnetic Materials, Volume 537, 2021, 168159, ISSN 0304-8853, https://doi.org/10.1016/j.jmmm.2021.168159.

Electromagnetic measurements at room temperature

Realisation of the B-H measurement setup in the induction heat treatment facility



- Indirect yoke measurement setup and method to determine the magnetic properties of induction hardened products.
- The setup is supported with an aluminium frame and it can be moved back and forth to the sample using a pneumatic horizontal drive at the bottom of the frame.

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H and B-field calculation of the magnetic system

The magnetic **field stregth** is calculated using a **non−solenoid formula** taken from[2]:

$$H(t) = \frac{N_p I(t)}{\sqrt{4r^2 + l^2}},$$

where „N_p“ is the number of turns of the excitation coil (1000), “I(t)” is the excitation coil current in [A], “r” is the equivalent circle-radius of the electromagnetic circuit (length weighted average of the whole cross section of the electromagnetic circuit) in [m] and “l” is the length of the electromagnetic circuit in [m] (average magnetic field path).

Corrections:

$$H_{sample}(t) = H(t) - H_{symmetry}(t)$$

The magnetic **flux density** is calculated as follows[2]:

$$B(t) = \frac{1}{N_s A_{yoke}} \int V_{secondary}(t)\, dt,$$

where „$V_{secondary}(t)$“ is the secondary coil voltage in [V], „N_s“ is the number of turns of the secondary coil (5000) and “A” is the cross-sectional area of the yoke in [m^2].

Corrections:

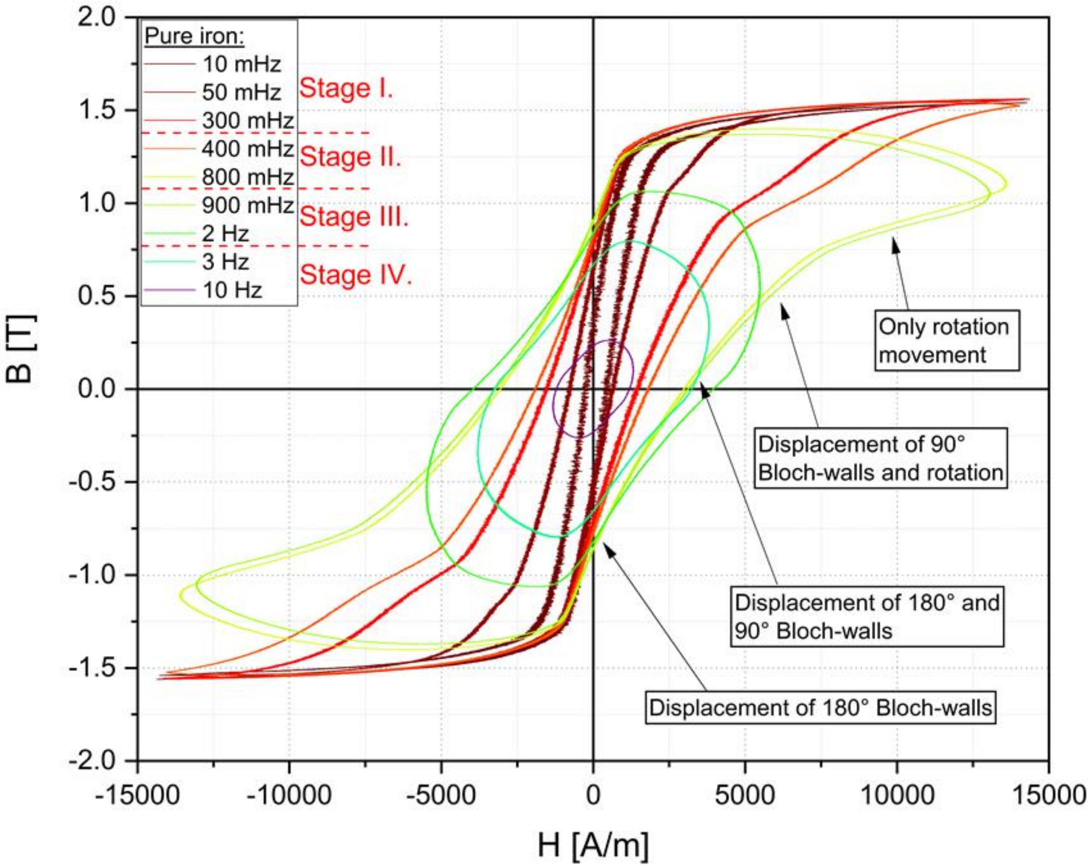
$$B_{combined}(t) = \frac{B_1(t) - B_2(t)}{2}$$

$$B_{sample}(t) = B(t) - B_{shift}(f, t) - B_{symmetry}$$

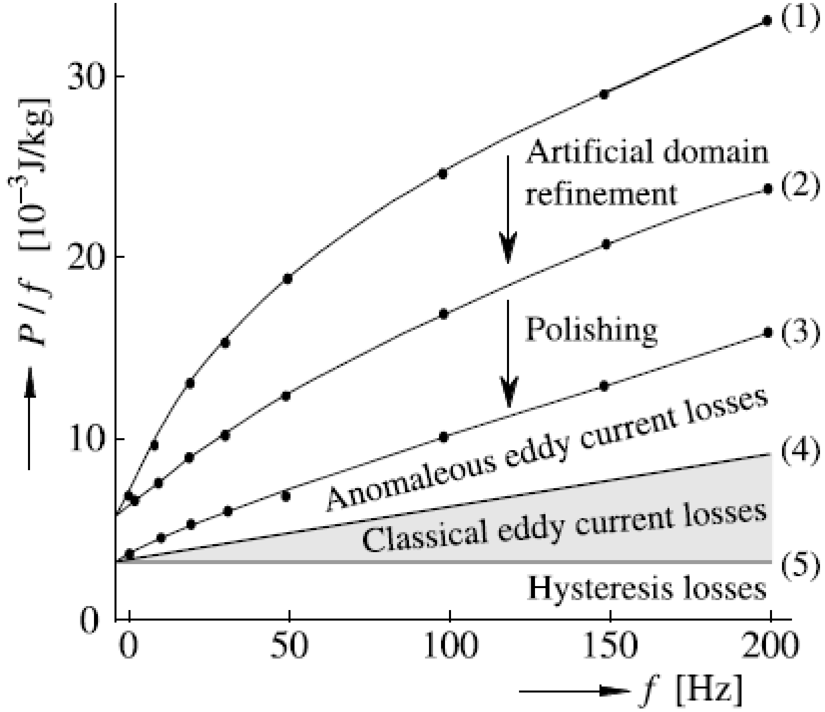
[2] F. Fiorillo, C. Appino, and M. Pasquale, Hysteresis in magnetic materials. Academic Press Amsterdam, Netherlands Vol. III (2005)

Electromagnetic measurements at room temperature

B-H measurement using different frequencies[1]



Different influencing factors on the area of a B-H hysteresis[3]



- Assumed stages of the influence of frequency on hysteresis shape due to different domain movements.
- Eddy current effects more pronounced with yoke made of full core material → good for demonstration of conversion model
- The effect of the eddy currents and other additional effects on the shape of the B-H hysteresis can be calculated and subtracted, but it is a very complex task → first simplified approach presented in the following

[1] V. Jászfi, P. Raninger, J.M. Riedler, P. Prevedel, D.G. Mevec, Y. Godai, R. Ebner, Introduction of a novel yoke-based electromagnetic measurement method with high temperature application possibilities, Journal of Magnetism and Magnetic Materials, Volume 537, 2021, 168159, ISSN 0304-8853, https://doi.org/10.1016/j.jmmm.2021.168159.
[3] A. Huber and R. Schäfer, Magnetic Domains. Springer, ISBN 978-3-540-64108-7 (2008)

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II. Maxwell-equation, the induction law[4]:

$$rot\ E = -\frac{\partial B}{\partial t}$$

and the material equation:

$$J = \sigma E$$

For scalar σ at room temperature

results:

$$\frac{1}{\sigma} rot\ J = -\frac{\partial B}{\partial t}$$

$$rot\ J = -\sigma \frac{\partial B}{\partial t} \propto -c(\sigma)\frac{\partial B}{\partial t}$$

So the time derivative of the B-field times the electrical conductivity of the material is influenced by the eddy currents. The correction for the B-field is as follows:

$$B_{new} = B - c_1(\sigma)\frac{\partial B}{\partial t},$$

because σ is linearly dependent of H-field and E-field, the term can be separated as follows (material equation and field diffusion in 1D for electric conducting material)[5]:

$$rot\ J = \sigma\ rot\ E = \sigma\mu\sigma E \propto -c(\mu, \sigma^2)H$$

rot E $\widehat{=}$ $\mu\sigma E$ for 1D[5]

$$\boldsymbol{B_{new}} = B - c_1(\mu, \sigma)\frac{\partial B}{\partial t} - c_2(\mu, \sigma^2, a)H$$

Where a is an acceleration term (probably caused by the acceleration voltage in the shunt resistor).

[4] J. Donnevert, Maxwell´s Equations: From Current Density Distribution to the Radiation Field of the Hertzian Dipole. Springer Vieweg Verlag, ISBN13 978-3658293758 ()2020)
[5] M. Leone, Theoretische Elektrotechnik, Eletromagnetische Feltheorie für Ingineure. Springer Vieweg Verlag, ISBN 978-3-658-18316-5, DOI: 10.1007/978-3-658-18317-2 (2018)

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Frequency dependence of the H-field

Inhomogeneous field wave equation (similar to the „Telegrafengleichung“)[5]:

$$\Delta H - \mu\varepsilon \frac{\partial^2 H}{\partial t^2} = -\,rot\ J$$

where „H“ is the measured H-field "$\mu\varepsilon$” is 1/c, which is the dependency of the phase velocity of the field in a medium. This equation describes the influence of the rotational eddy-currents to the H-field development. ΔH can be written as $\mu\sigma \frac{\partial H}{\partial t}$ (field diffusion equation in 1D. Therefore, the dependency of the H-field of the frequency is presented as follows:

$$\boldsymbol{H_{new}} = H - c_3\,(\mu, \sigma, g)\frac{\partial H}{\partial t} + c_4(\mu, \varepsilon, g)\frac{\partial^2 H}{\partial t^2} - c_5(N_d)H$$

where c_3 and c_4 are the frequency dependent factors, and c_5 (N_d) is the demagnetisation term and g is the cross-sectional area, through which the H-field is conducted.

There are controvert thoughts regarding the effect of the second time derivative of the H-field that it can not play a significant role at the presented frequency range. Other effects of the measurement setup as the signal amplifier, the heating up of the primary coil and other unknown effects can still include the second derivative of the H-field as an influencing factor, which was needed for the conversion especially at lower frequencies.

From these equations, one can try to determine the frequency dependency of the eddy current effects on the B-H hysteresis.

[5] M. Leone, Theoretische Elektrotechnik, Eletromagnetische Feltheorie für Ingineure. Springer Vieweg Verlag, ISBN 978-3-658-18316-5, DOI: 10.1007/978-3-658-18317-2 (2018)

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Steps for the frequency conversion

1. Step

Calculation of H-field and B-field from the measured signal.

2. Step

Corrections of H and B for drift and symmetry effects.

3. Step

Calculation of first and second time-derivative of the H- and the B-fields using the formula i.e. $\frac{dB}{dt} = \frac{B(t+dt)-B(t)}{\mathrm{dt}}$ and Savitzky-Golay filter[6].

4. Step

Determination of the parameters c_1-c_5 in the conversion model separately for each B-H hysteresis measured at different frequencies. Determination of c_1-c_5 in the conversion model separately for each B-H hysteresis for the conversions.

5. Step

Analysis of the frequency dependence of the parameters c_1-c_5.

6. Step

Reconstruction of the B-H hysteresis at a different frequency.

[6] A. Savitzky, M. J. E. Golay, Smoothing and Differentiation of Data by Simplified Least Squares Procedures. Analytical Chemistry, Band 36, Nr. 8, S. 1627–1639, doi:10.1021/ac60214a047 (1964)

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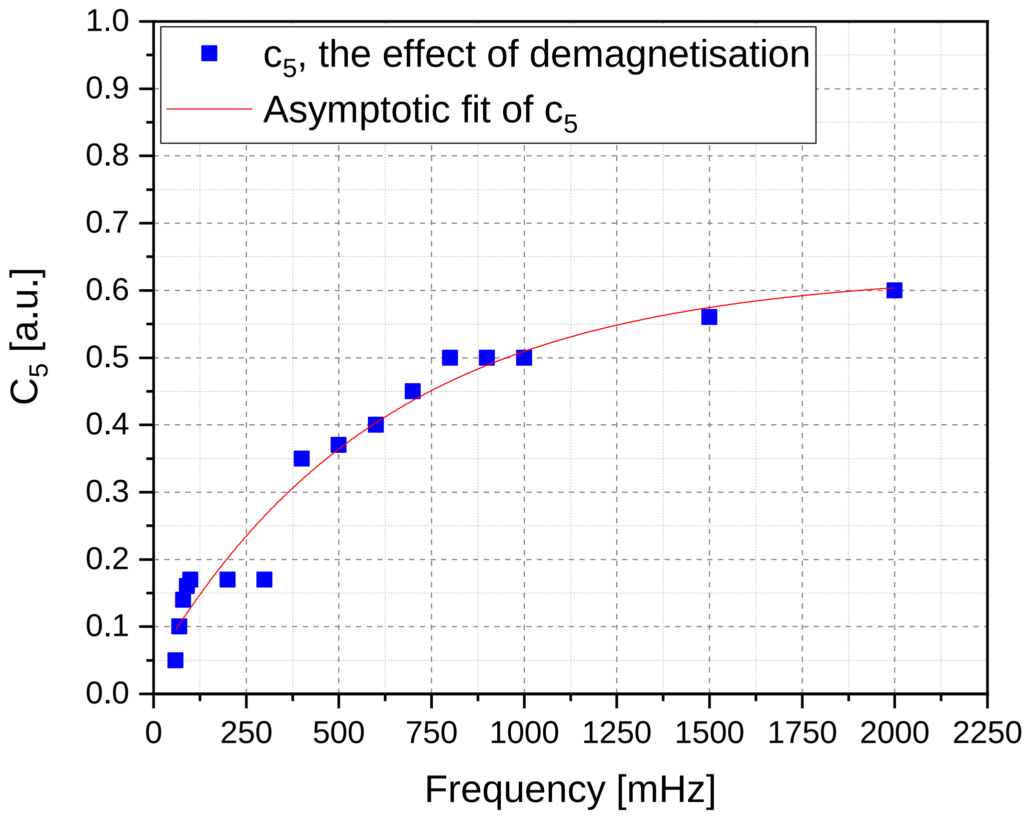
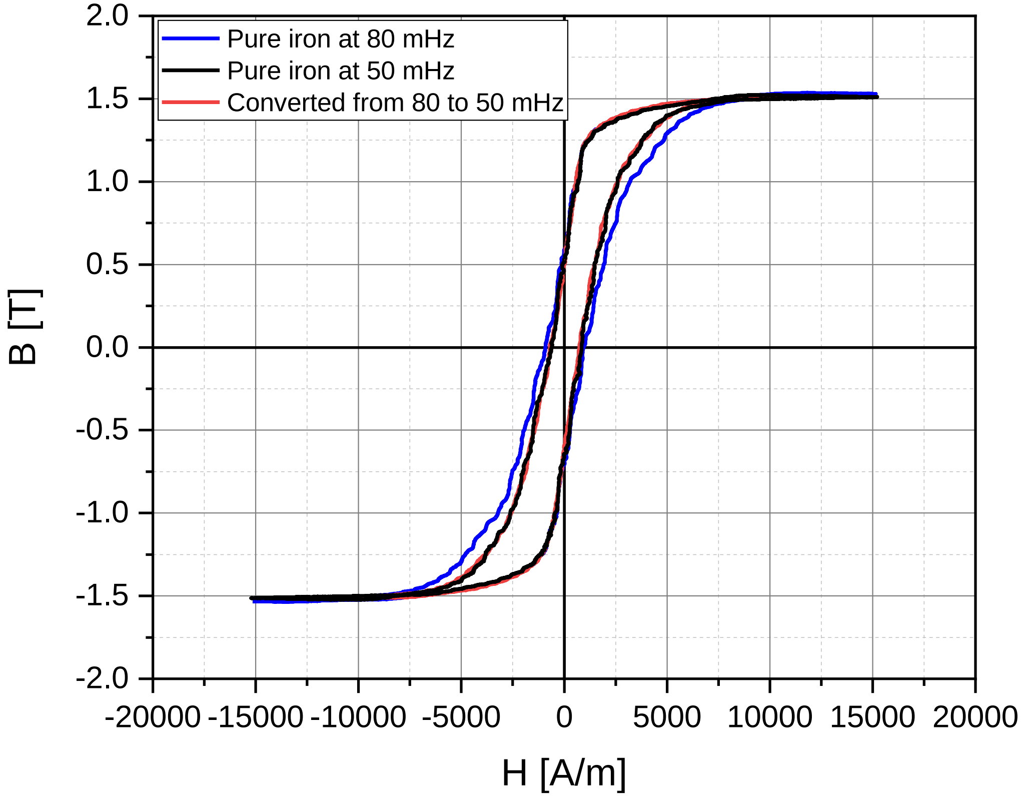
Results – example of the parameters, c_5 in the case of converting the hystereses to 50 mHz

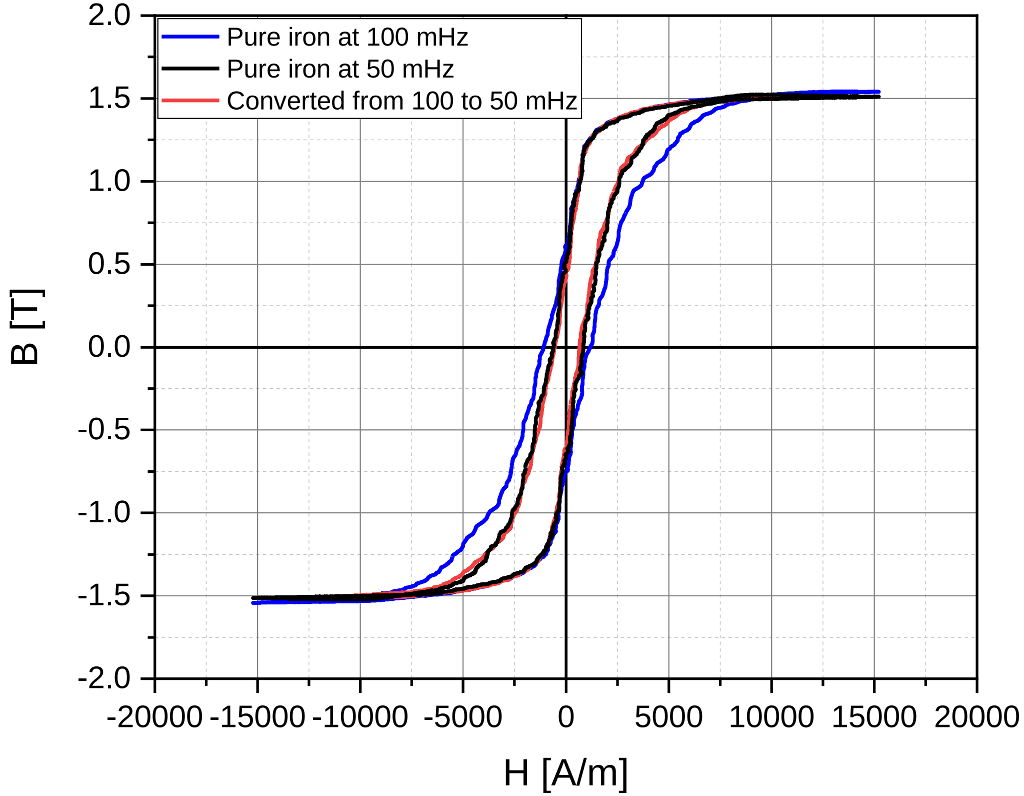


- The parameters c_1-c_4 show a not yet fully physically described tendency. The investigation is ongoing on this matter.
- c_5 shows a systematic behaviour, which correspond to a frequency dependent demagnetisation effect of the measurement system. The impedance of the measurement system is increasing with increasing frequency.
- As a first approximation, an asymptotic fit was used to determine, how good the tendency is: the R^2 value is 0.957.
- The filtering of the derived data is a great influencing factor for getting a describable tendency of the fitting parameters.

conversion model for achieving lower eddy current effect on the B-H hysteresis

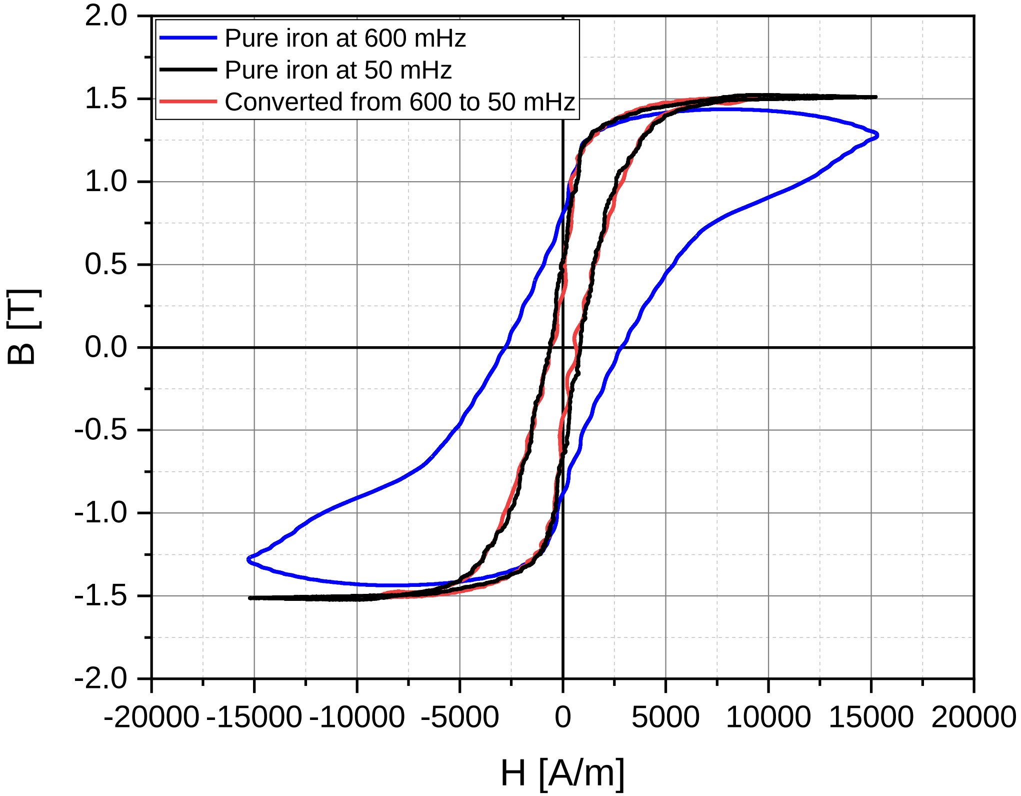
Results – conversion of the B-H hysteresis from f in Stage I. to reference 50 mHz

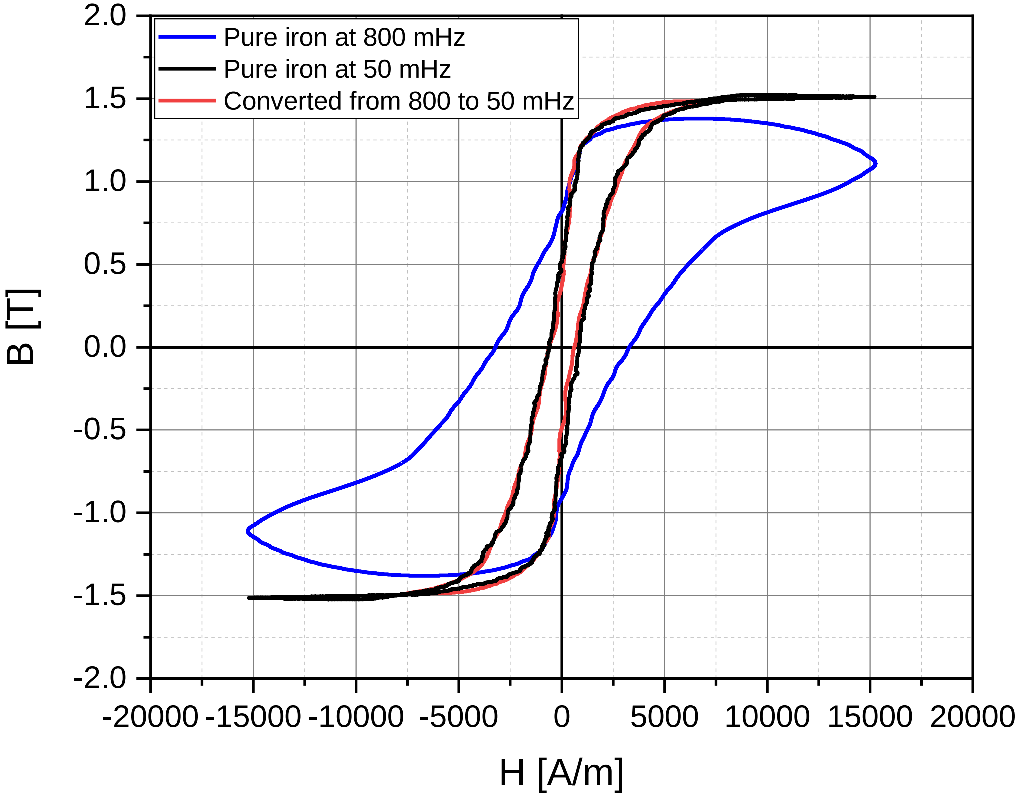




- Two choice of different frequencies were selected in each stages to present the results.
- These hystereses of higher frequencies than 50 mHz were each converted to the form of the 50 mHz hysteresis.
- Considering also the demagnetisation, the maximum achievable H-field decreases.
- The conversion in stage I. is clearly successful.

Results – conversion of the B-H hysteresis from f in Stage II. to a reference 50 mHz

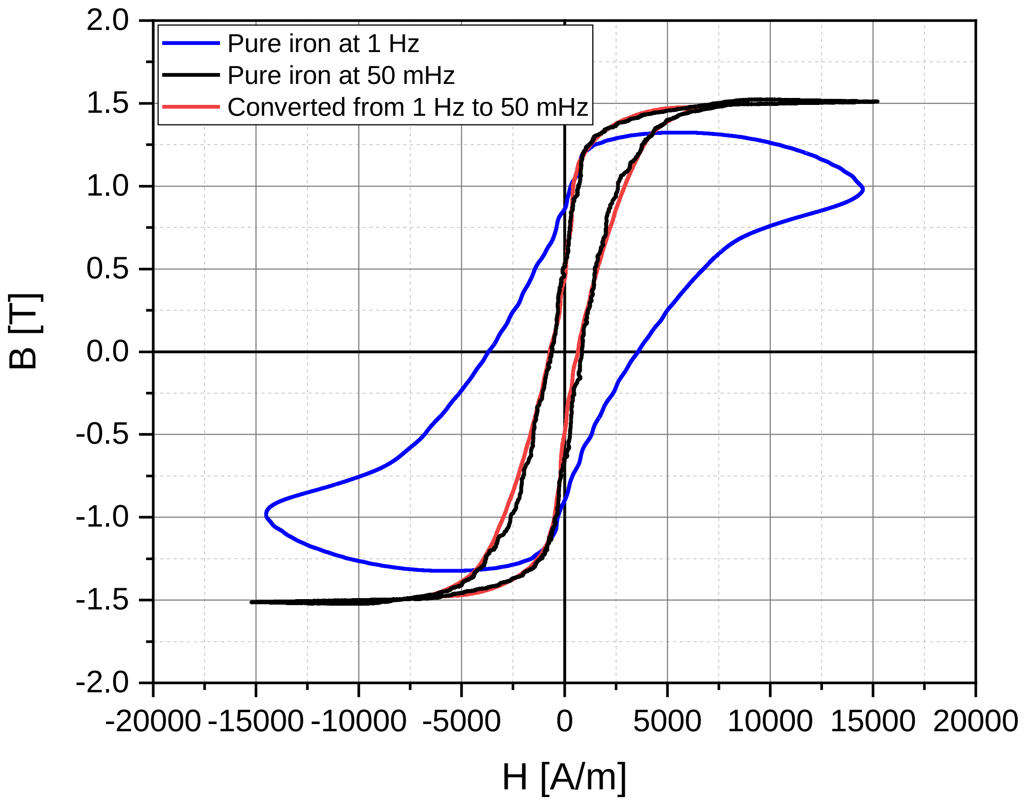


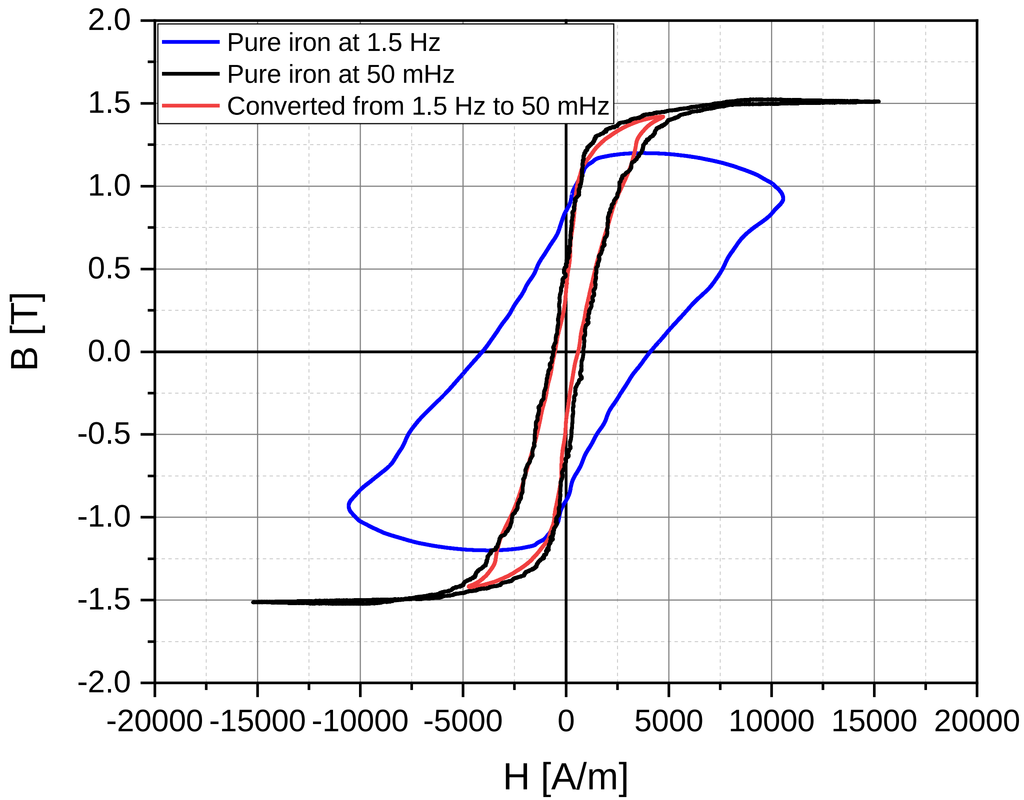


- Stage II. shows a greater distortion of the B-H hysteresis compared to the reference B-H hysteresis (50 mHz).
- Inspect of the increased shape distortion, the conversion works very well also in this stage.

conversion model for achieving lower eddy current effect on the B-H hysteresis

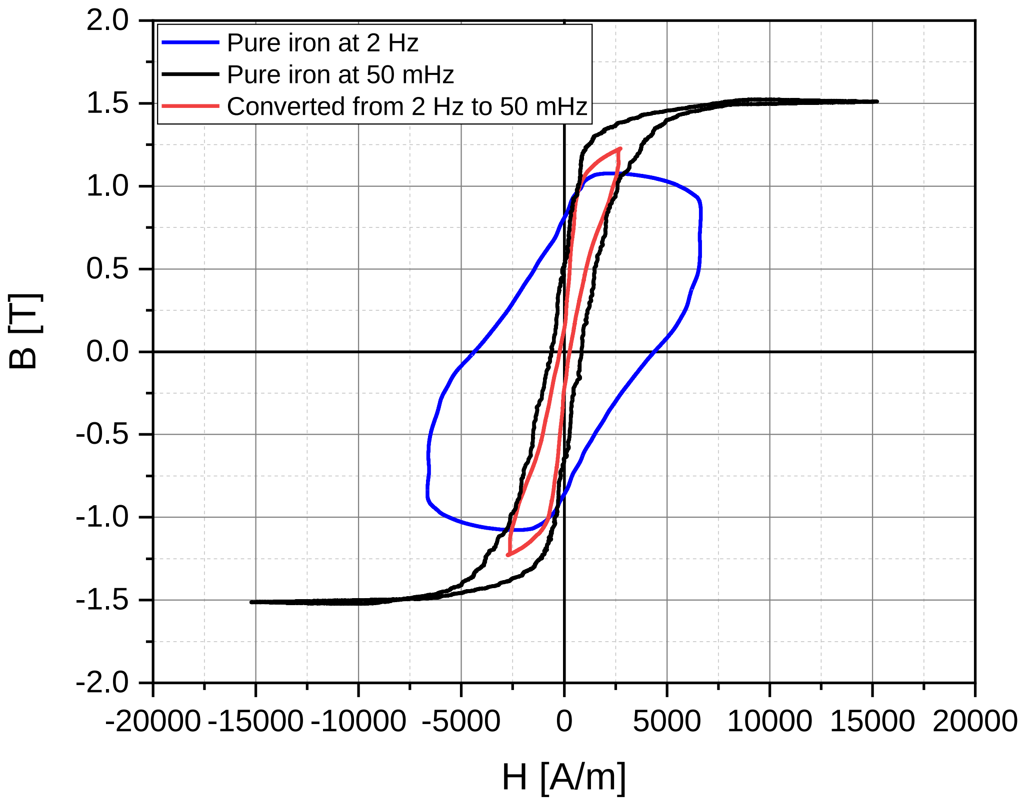
Results – conversion of the B-H hysteresis from f in Stage III. to a reference 50 mHz





- Stage III. shows even a greater distortion of the B-H hysteresis compared to the reference B-H hysteresis (50 mHz).
- The conversion from 1 Hz to 50 mHz works still, but this seems to be the limit of the model for this measurement series at a maximum field strength of 10 – 15 kA/m.
- The impedance of the measurement setup reaches a value, at which the maximum H-field decreases.

Results – conversion of the B-H hysteresis from f in Stage IV. to a reference 50 mHz



- Stage IV. can not be converted in this measurement series, because the minimal H-field for the B-field saturation can not be reached.
- A solution for this problem can be a stronger signal amplifier and / or using a sheet-like core material for the excitation yoke instead of the bulk pure iron material. The separation of the material properties has to be considered for this case with the different core material of the excitation yoke.

Content

Summary, Outlook

- **A frequency conversion model of B-H hysteresis is presented based on the induction law, the one-directional wave propagation and field diffusion equations in matter.**
- **This model contains an uncertainty based on the filtering process and the empirical determination of the fitting parameters, but it delivers promising results.**

- **The exact physical description of the fitting parameters c_1-c_5 and using a multi- and / or non-linear fit will be the next steps to minimize the uncertainties of the model.**
- **After the physical description of the fitting parameters c_1-c_5, a conversion of a technological B-H hysteresis in a purely magnetic loss-dependent B-H hysteresis will be possible.**

We innovate Materials

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Thank you for your kind attention!

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