Validating quality and verification of core loss measurements for databases

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MagNet database

V-I method for core loss measurement

Sources of error:

- Delay between voltage and current measurements
- Probes and oscilloscope error
- Parasitic elements in the circuit
- Non-ideal excitations
- Variation of temperature during testing

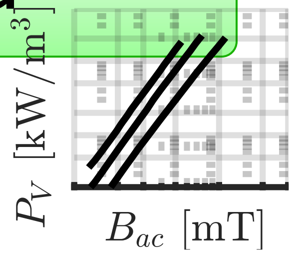
Assessing reproducibility

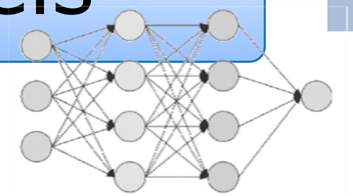
Variation of core parameters

The challenge of core losses

Low quality data → Inaccurate models → Design iterations

Data → Models → Designs

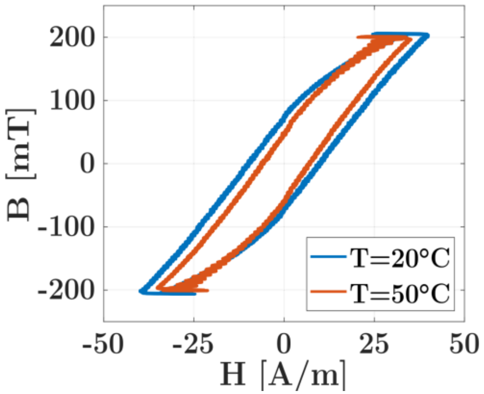




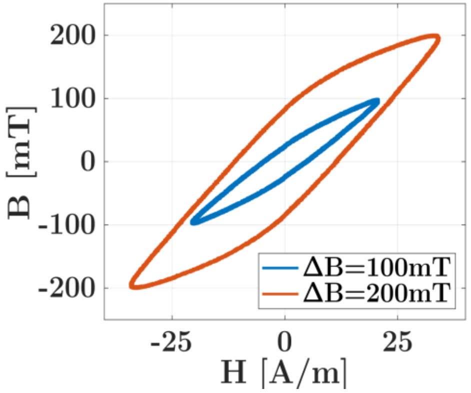
$P_V = k \cdot f^{\alpha} \cdot B_{ac}^{\beta}$

Datasheets | Software | Publications | ...

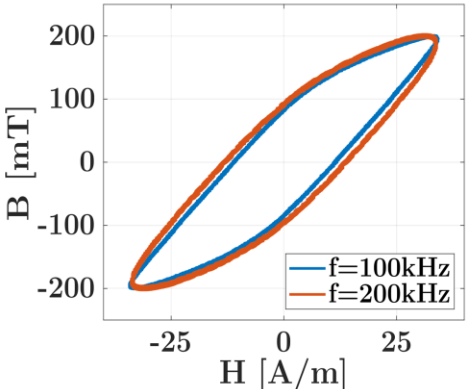
Temperature



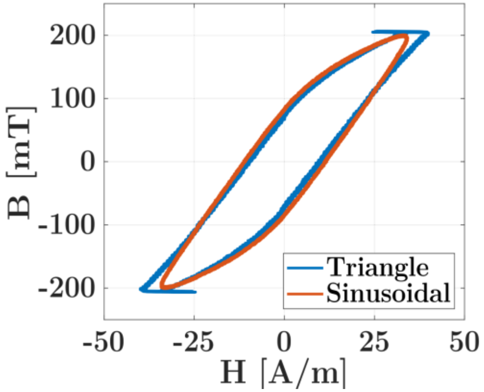
Flux density



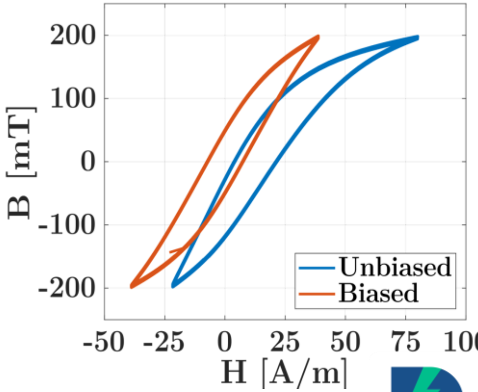
Frequency



Waveform shape



DC bias



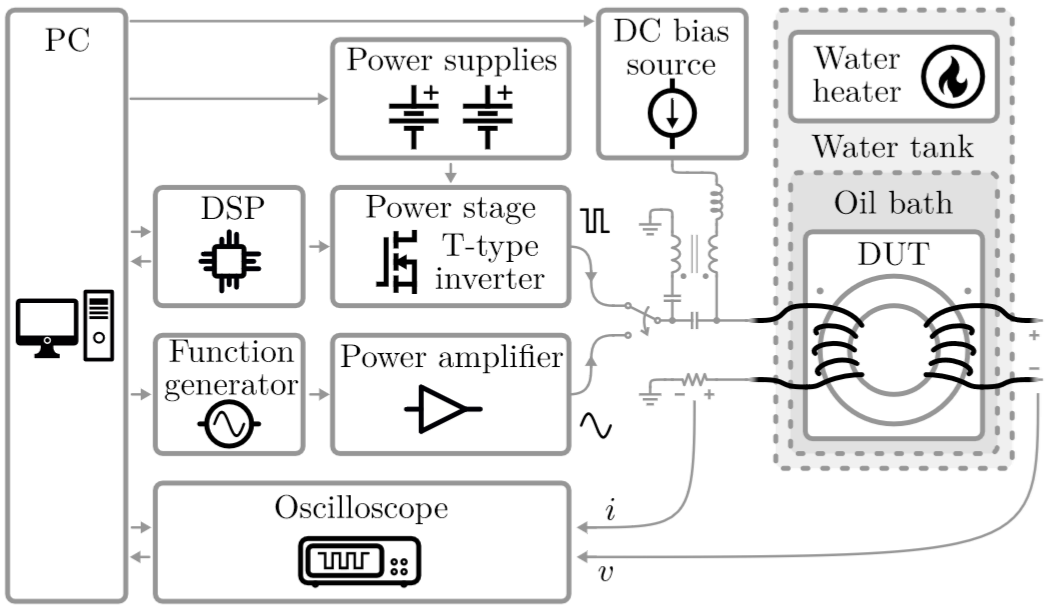
Area of B-H loop ∝ loss

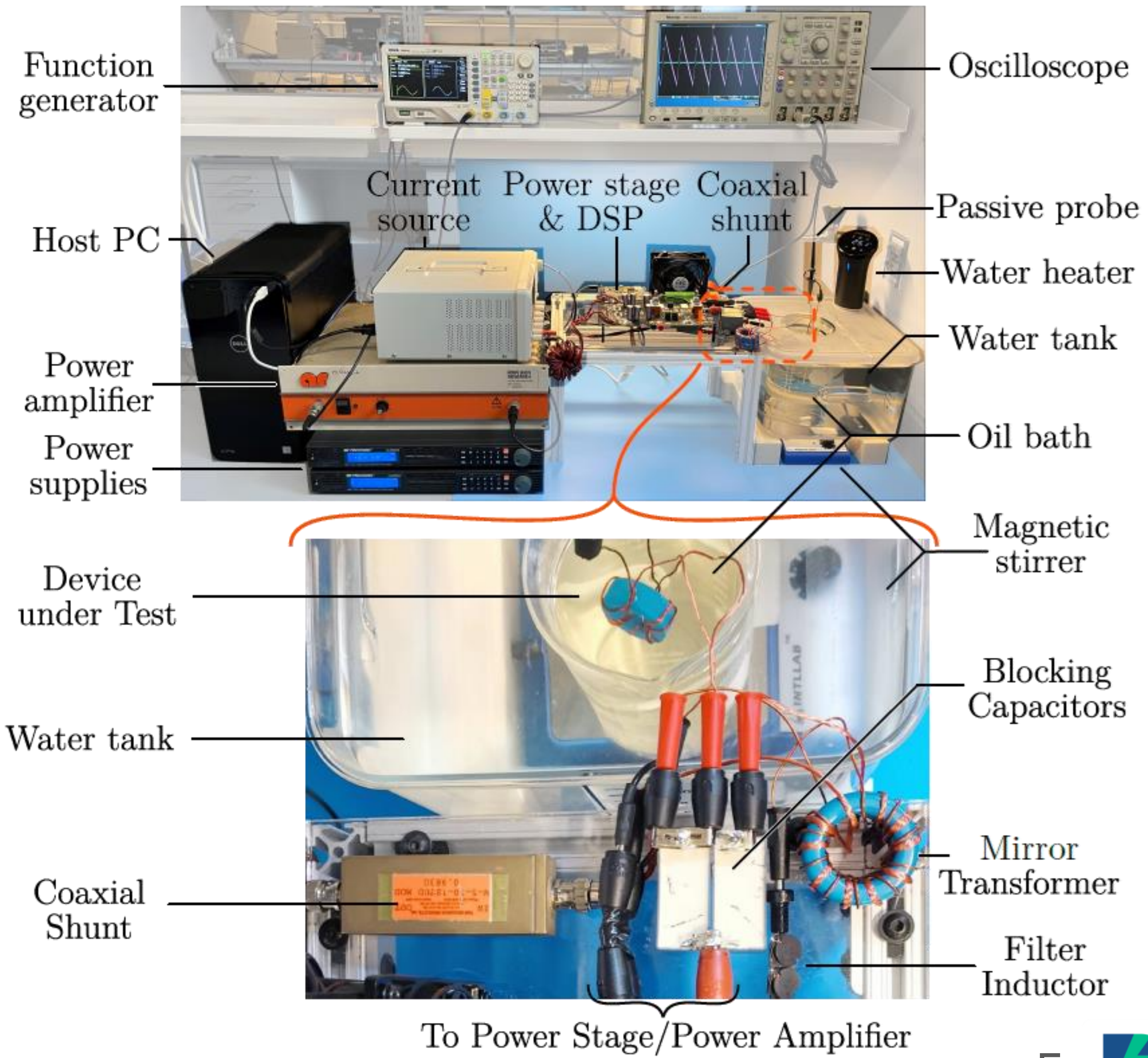
MagNet database: Set-up

Automated V-I method, steady state

Wide range of operating conditions:

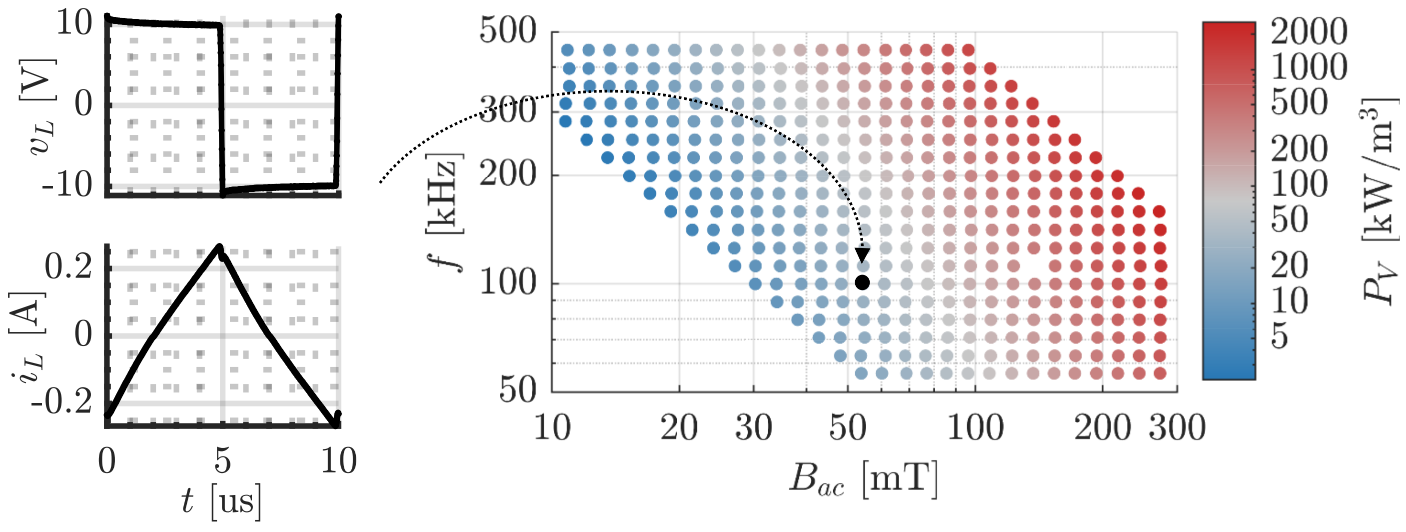
- Flux density → 10 mT to 300 mT
- Frequency → 50 kHz to 500 kHz
- Wave shape → Sinusoidal & PWMs
- Temperature → 25 °C to 90 °C
- DC bias → 0 A/m to ~B_{sat}/μ





MagNet database

N87, R34.0X20.5X12.5, triangular 50% duty cycle, $T = 25°\text{C}$, unbiased

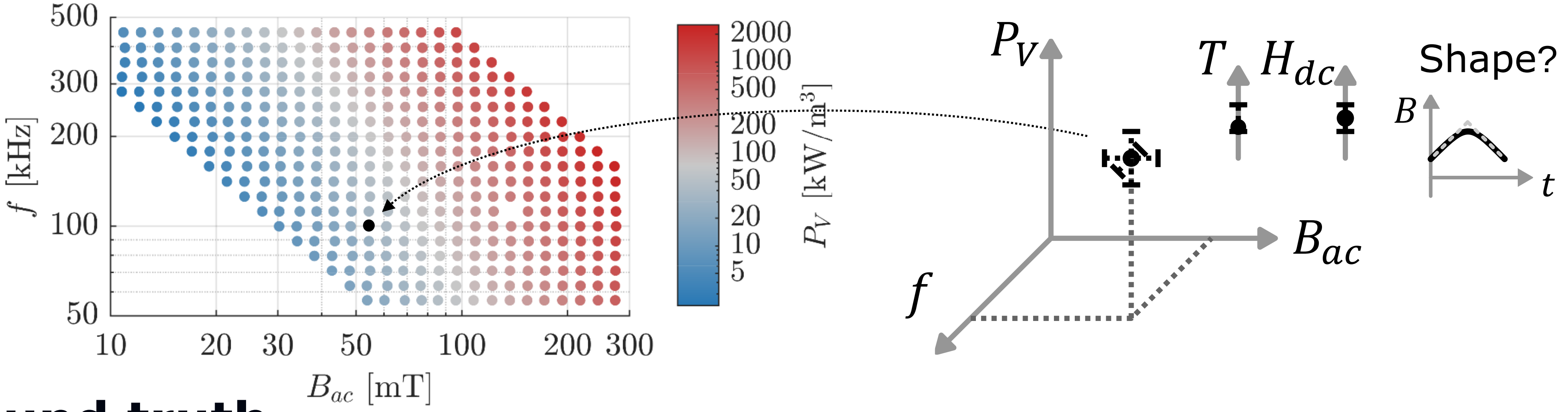


	Field	Value
Test metadata	Date_info	'2022-07-14'
	Place_info	'Princeton Power Electro
	Trap_info	'Power stage: Prototype
	Sine_info	'Signal generator: RIGOL
	Bias_info	'Configuration: DC curre
	Temp_info	'Oil Bath: Mineral Oil; Wa
	Meas_info	'Voltage Measurement: P
	Acquisition_info	'Oscilloscope: Tektronix
	Discarding_info	'Data discarded: Voltage
	Freq_info	'Frequency estimation ba
	Cycle_info	'Saving a single cycle by
	Processing_info	'Flux estimated based on
	Date_processing	'2022-10-04'
Core metadata	Material	'N87'
	Shape	'R34.0X20.5X12.5'
	Effective_Area	8.2600e-05
	Effective_Volume	6.7780e-06
	Effective_Length	0.0821
	CoreN	1
	Primary_Turns	5
	Secondary_Turns	5
	Dataset	5
Measured data	Voltage	*142871x1024 double*
	Current	*142871x1024 double*
	Sampling_Time	*142871x1 double*
	Temperature	*142871x1 double*
Processed data	Hdc	*142871x1 double*
	DutyP	*142871x1 double*
	DutyN	*142871x1 double*
	Frequency	*142871x1 double*
	Flux	*142871x1 double*
	Volumetric_Loss	*142871x1 double*
	B_Field	*142871x1024 double*
	H_Field	*142871x1024 double*

Measurements formatted as database

- Formats: MAT, JSON, HDF5, CSV
- 10 magnetic materials
- 575.009 measurements
- Data available at https://mag-net.princeton.edu/

Datapoints have uncertainty ranges, in all the variables considered



No ground truth

- Measurements can be compared to datasheets or other research data, but their accuracy is not always reported…

Sources of error:

Delay | Acquisition | Parasitics | Temperature | Part-to-part Δ …

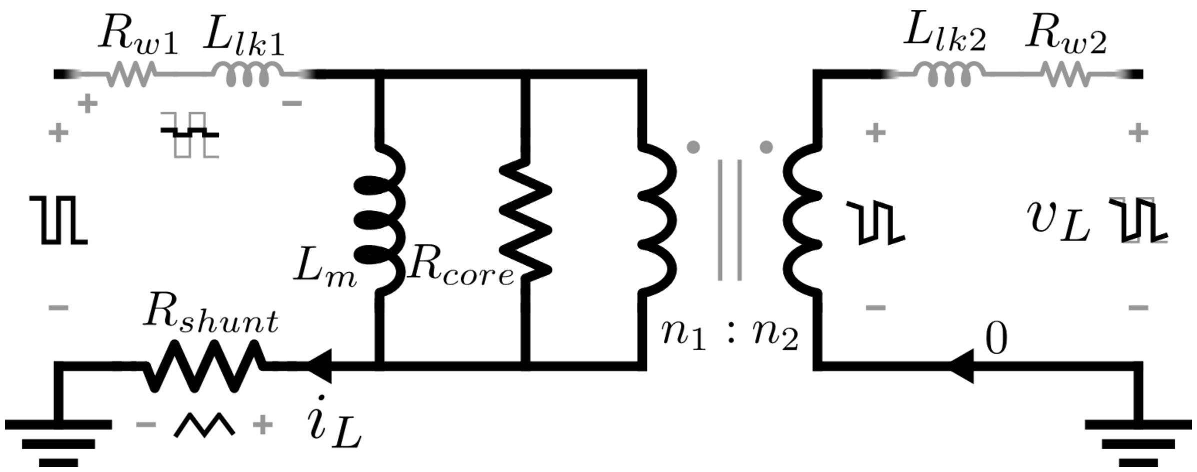
Review: V-I or two-winding method

Valid for any type of waveform

- Excitation applied to primary
- Current measured in primary
- Voltage measured in secondary

Not affected by L_{lk}, R_w, R_{shunt}

Only core variables measured



$$P_V = \frac{1}{V_e}\frac{1}{T}\int_0^T v_L(t)\, i_L(t)\mathrm{d}t$$

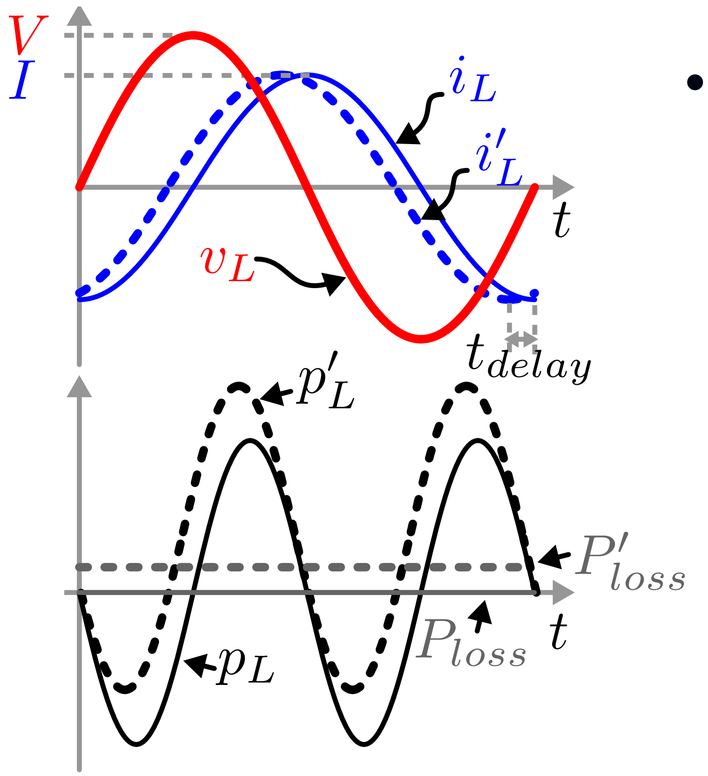
$$H(t) = \frac{n_1}{l_e} i_L(t)$$

I_{DC} as bias

$$B(t) = \frac{1}{n_2 \cdot \mathrm{A}_e}\int v_L(t)\mathrm{d}t$$

B_0 unknown

Effect of phase delay in the measurements



- Small delay between the voltage and current leads to large errors in the measurement:
  - This delay cannot be distinguished from losses
  - Sinusoidal: $\Delta P_{loss} \approx V \cdot I \cdot |t_{delay}| \cdot \pi \cdot f$
  - Triangular: $\Delta P_{loss} \approx V_{in} \cdot I_{pk} \cdot |t_{delay}| \cdot 4 \cdot f$

Neglecting losses; small angle approximation

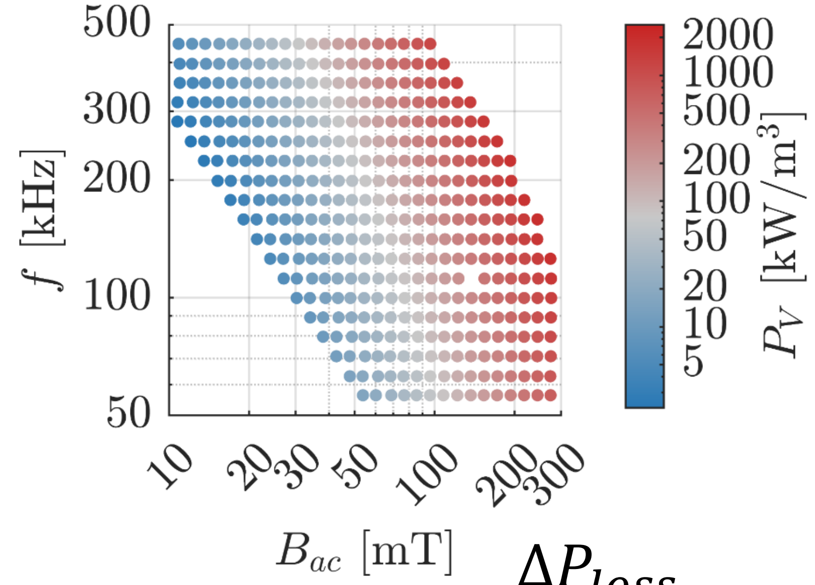
Well studied issue and known limitation of this method:

- High frequencies
- Low loss materials

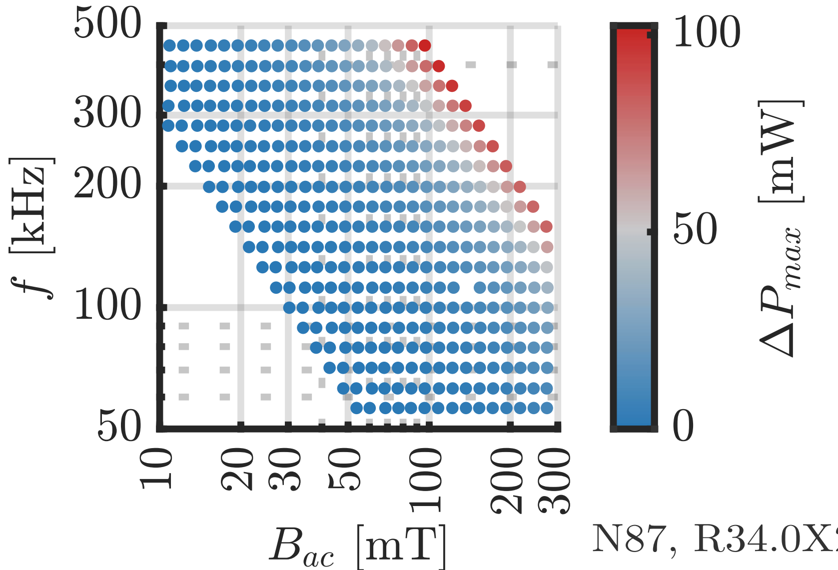
Main reason to use other methods instead

Effect of phase delay

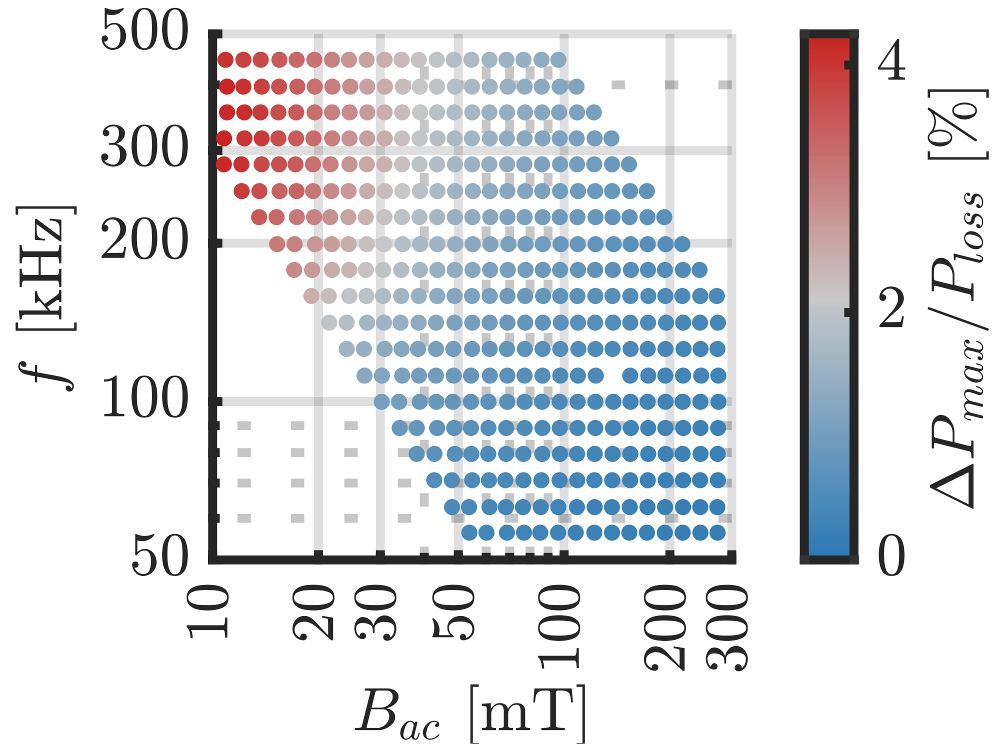
P_{loss}



ΔP_{loss}



Relative error: $\Delta P_{loss}/P_{loss}$

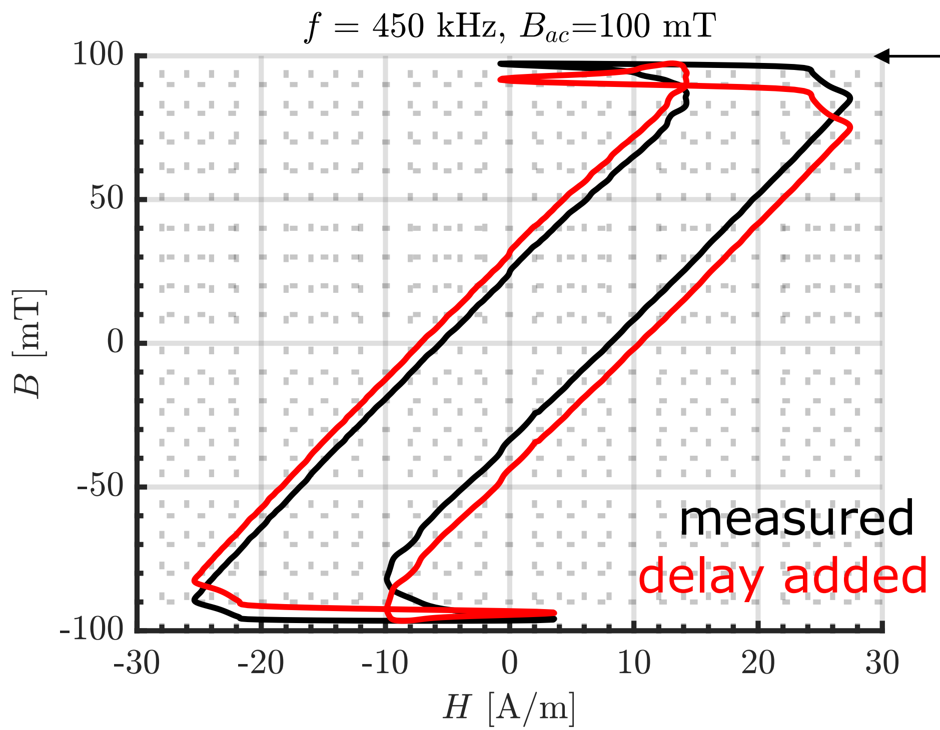


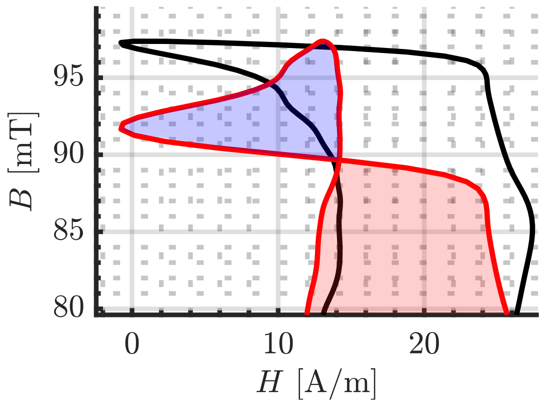
$P_{loss}\downarrow$ and $\Delta P_{loss}\uparrow \rightarrow \Delta P_{loss}/P_{loss}\uparrow$

N87, R34.0X20.5X12.5, triangular 50% duty cycle, $T = 25°C$, unbiased

1.6 ns delay

B-H loop enlarged (or shrank depending on the sign of the delay)
Shape severely affected when switching noise is present





The B-H loop may have crossing points due to the delay

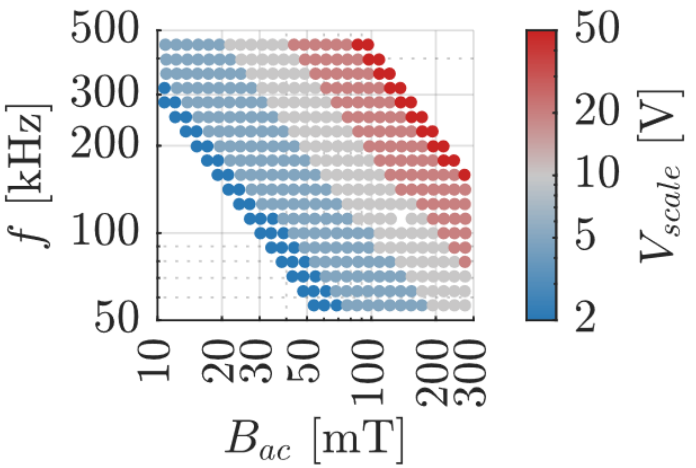
N87, R34.0X20.5X12.5, triangular 50% duty cycle, $T = 25°C$, unbiased

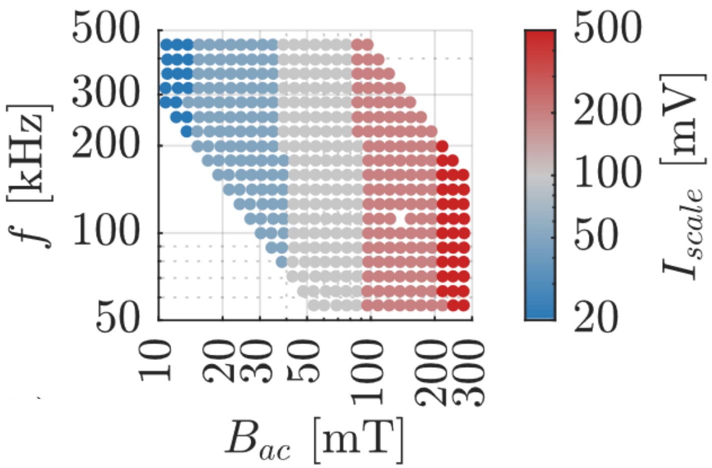
Effect the oscilloscope: gain error

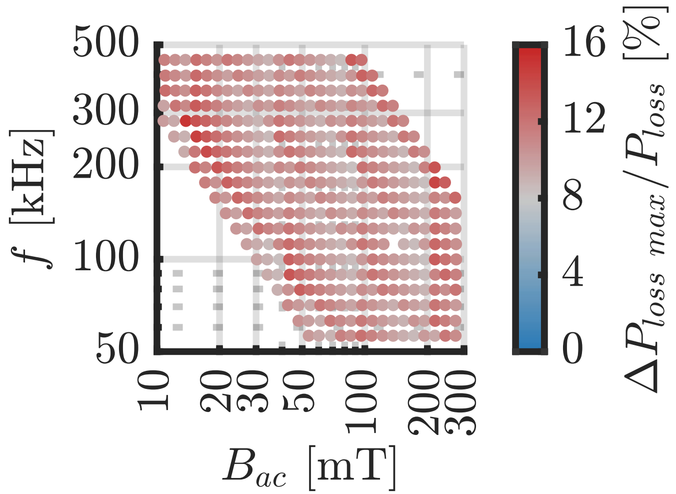
Tektronix DPO4054

Gain error depends on the vertical scale:

- Scale selected to maximize the range for each point
- Error affecting B_{ac} readings and P_V
  - $\text{Error} = 1.5\% \cdot |\text{read}| + 0.15\ \text{div} + 1.2\ \text{mV}$





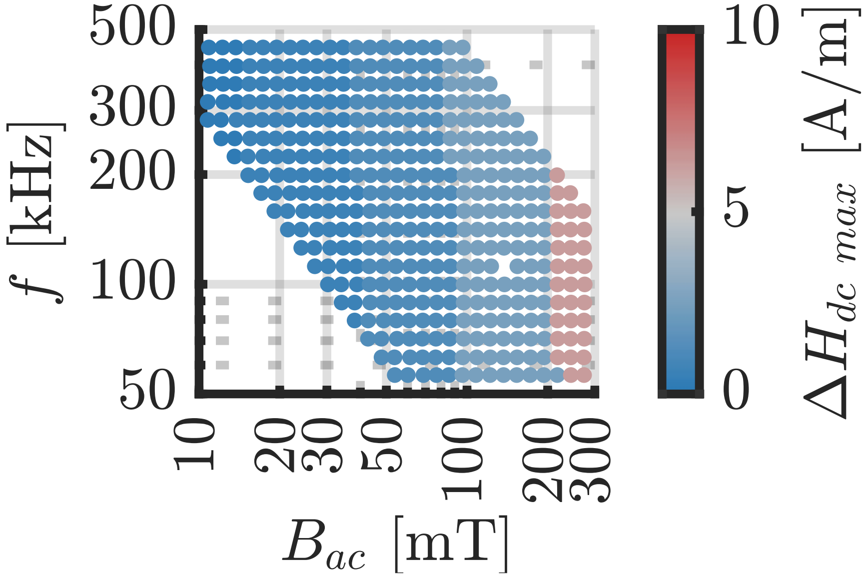


- For a 10 $V_{pk\text{-}pk}$ signal, measured at 5 V/div → 7.5% error!
- Error concentrated in the regions where the scale changes

N87, R34.0X20.5X12.5, triangular 50% duty cycle, $T = 25°\text{C}$, unbiased https://download.tek.com/manual/077024701Rev_A_web.pdf

Offset error depending on the vertical scale too

Offset error affecting H_{dc}



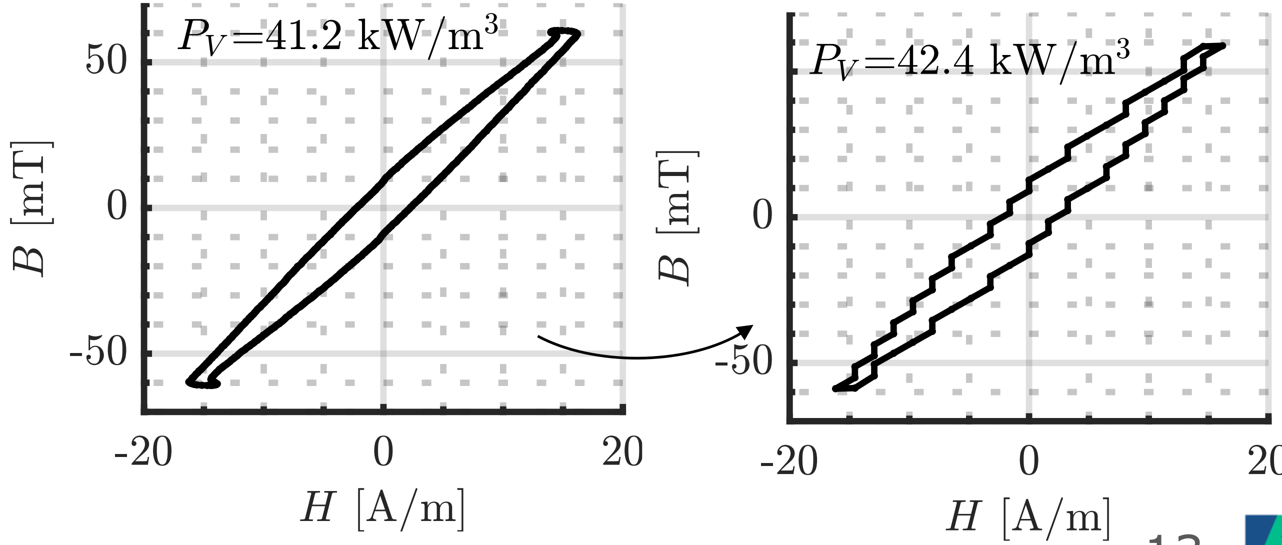
A better scope might help

Vertical and horizontal sampling is enough in most cases (8 bits, 8 ns)

Example of heavy downsampling

- 1 sample every 16 in the original
- v_L and i_L rounded to 1/10th of pk-pk

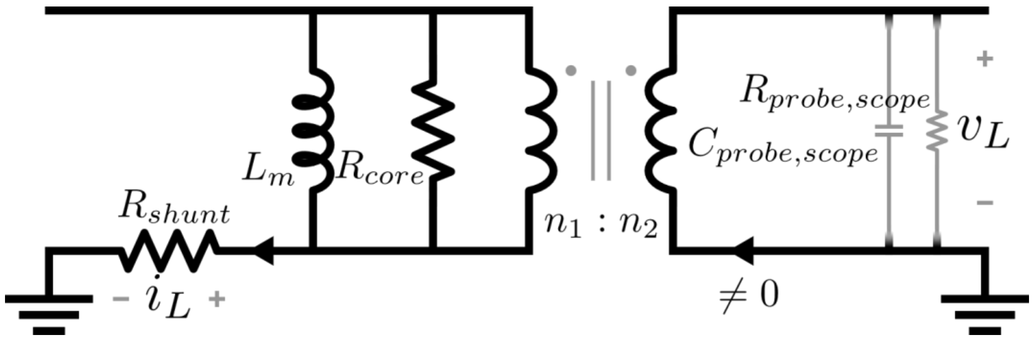
Core losses barely affected

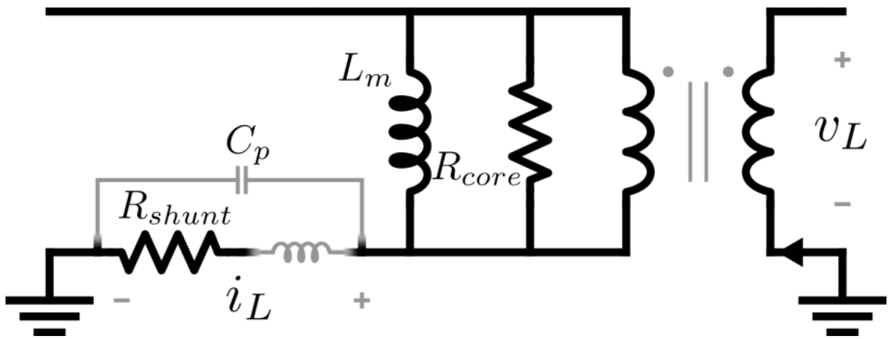


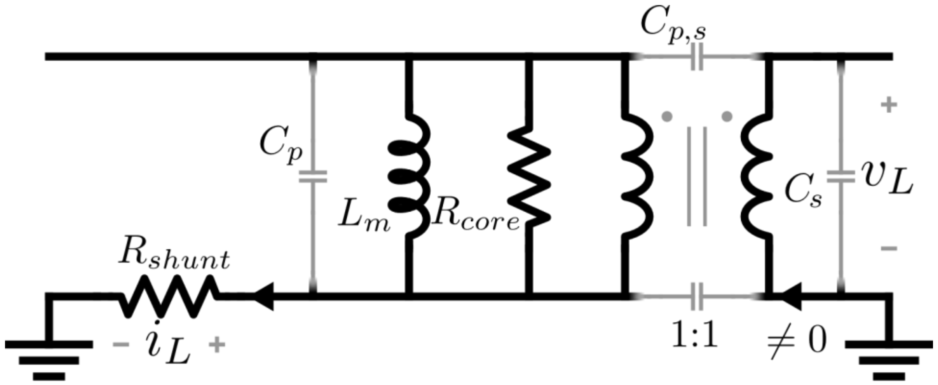
N87, R34.0X20.5X12.5, triangular 50% duty cycle, $T = 25°C$, unbiased $f = 100$ kHz, $B_{ac} = 60$ mT

Effect of parasitic elements in the circuit

- On the voltage measurement, change the current measured:
  - Scope and probe resistance ($R_{probe,scope}$ >> "R_{core}"→ ok)
  - Scope and probe capacitance
- On the current measurement:
  - Parasitic inductances and capacitances should be minimized
- On the DUT:
  - Affect the amount of current flowing through the core
  - C_{ps} is not so significant if a 1:1 transformer is used







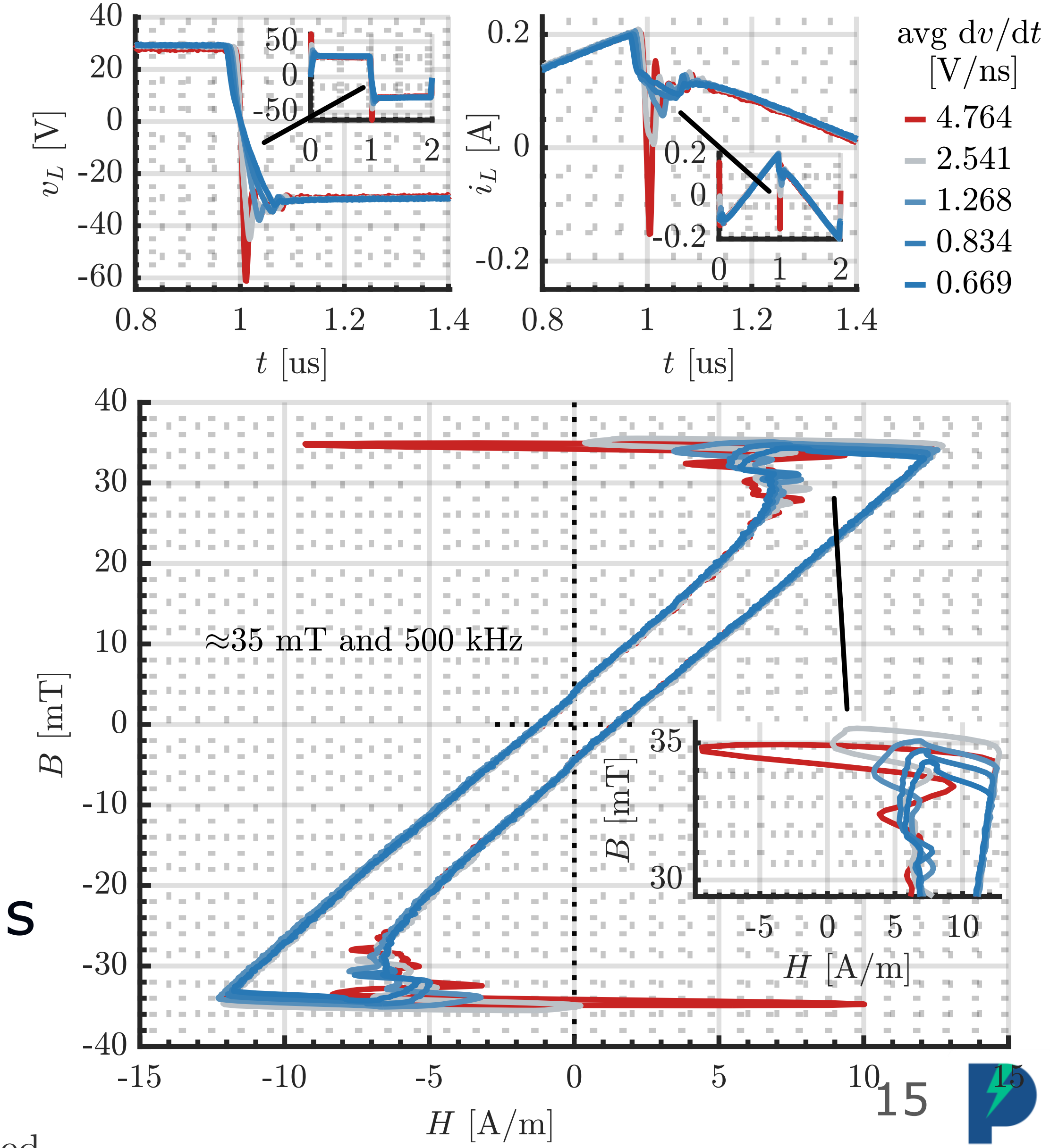
Non-ideal excitations

Capacitive effects:

- B-H loops are affected by switching speed
- Dip in the current waveform

Other non-idealities:

- Current + shunt→ voltage drop
- Power amplifier → distortion
- Fixed clock times → limited PWM resolution
- Dead time (70 ns)→different transitions
  - 500 kHz 10% duty→200 ns rise time



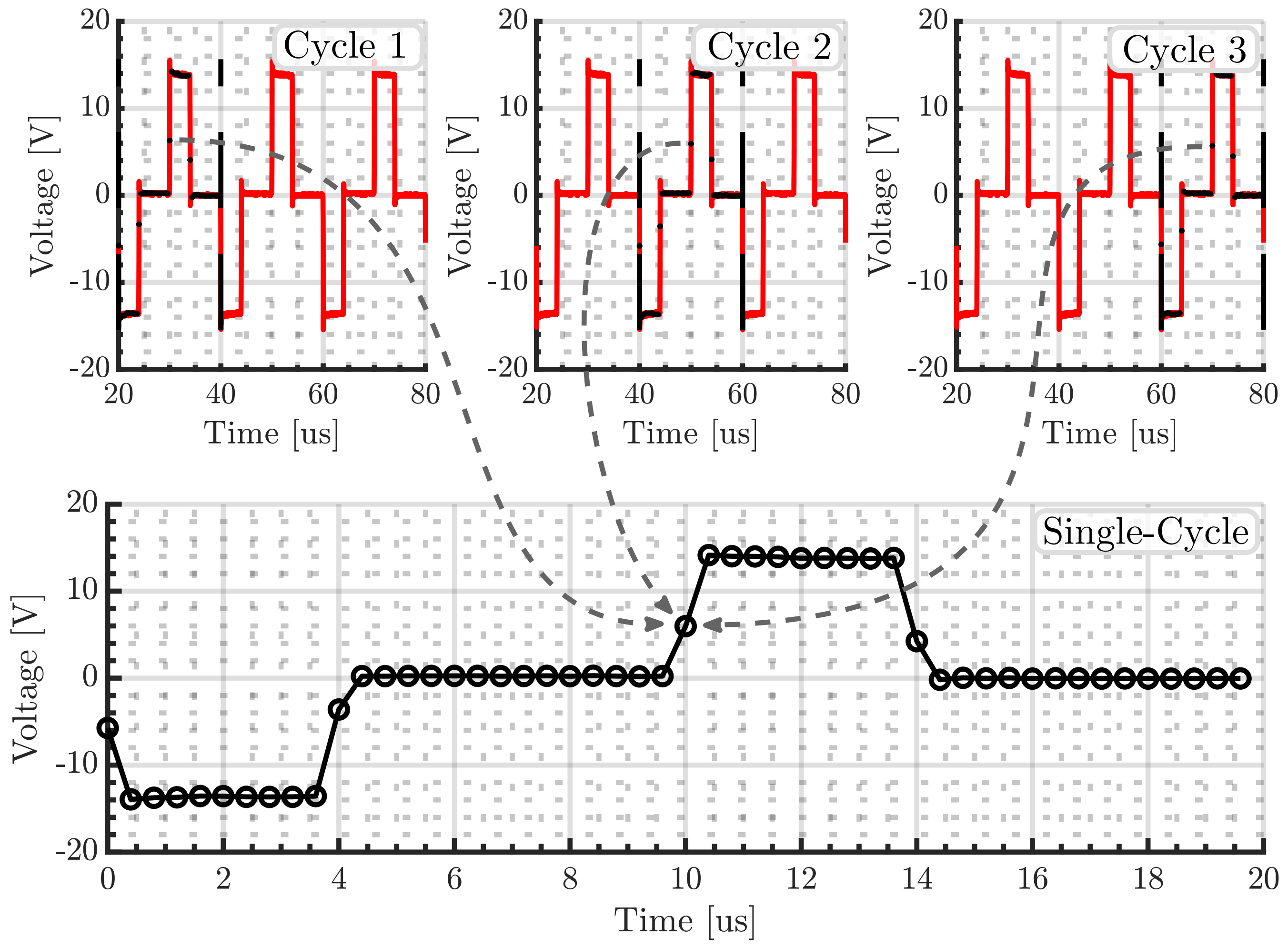
N87, R34.0X20.5X12.5, triangular 50% duty cycle, $T = 25°C$, unbiased

Voltage, current →
fundamental frequency →
P_V, B, H, etc

Single cycle algorithm:

- Horizontal resolution affected
- Vertical resolution ↑
- Possible filtering effect

Measures must be taken to ensure that data quality is not impaired

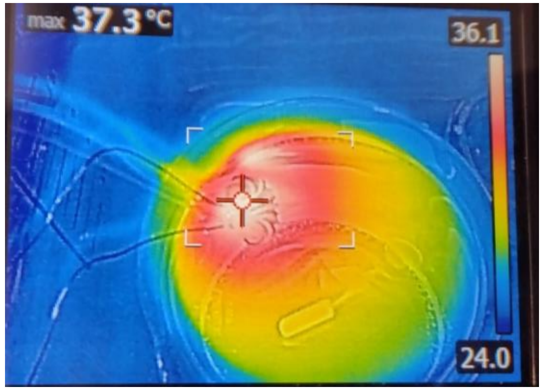


Effect of the variation of temperature

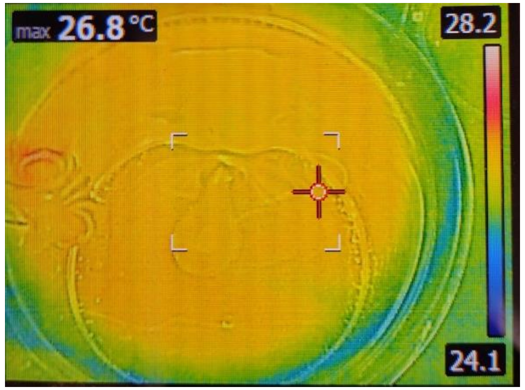
$$P_{loss} \rightarrow T \uparrow\uparrow \quad \longleftrightarrow \quad P_{loss} = f(T)$$

Thermal management is a must

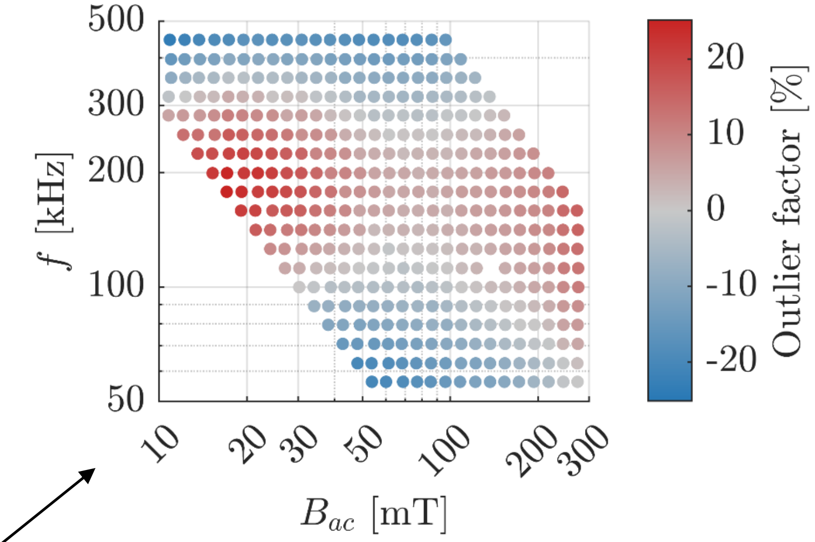
Oil bath + magnetic stirrer → Good solution … but some ΔT still



Without stirrer



With stirrer



ΔT during testing can affect P_V distribution

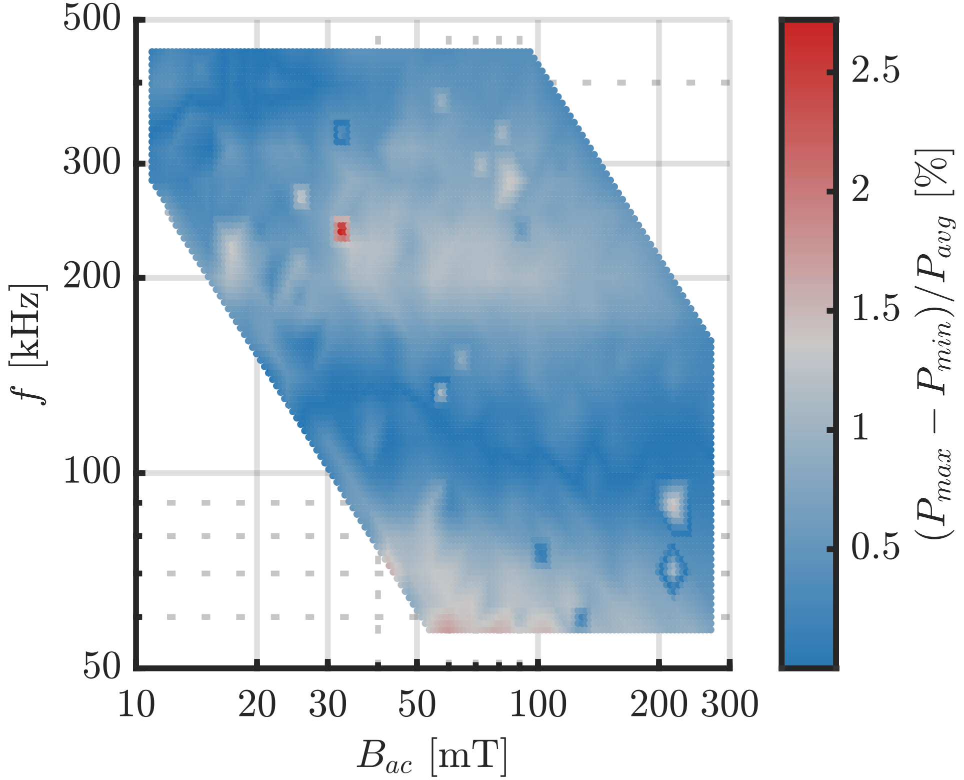
Future work: report temperature for each test measured

N87, R34.0X20.5X12.5, triangular 50% duty cycle, $T = 25°C$, unbiased

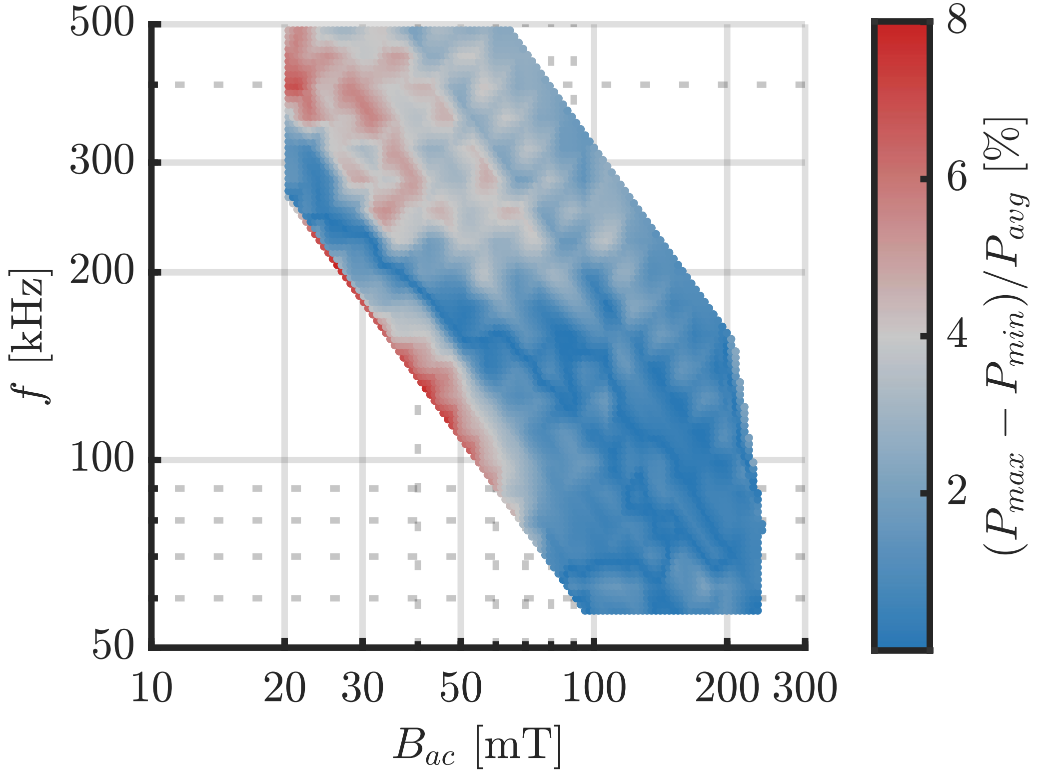
Data is reproducible when the same core is tested again

Slight differences when N_{turns} changes → different voltage and current

N=5, measurement repeated 5 times



N=3 vs N=7, same core



N87, R34.0X20.5X12.5, triangular 50% duty cycle, $T = 25°\text{C}$, unbiased

Core-to-core variation: tolerances

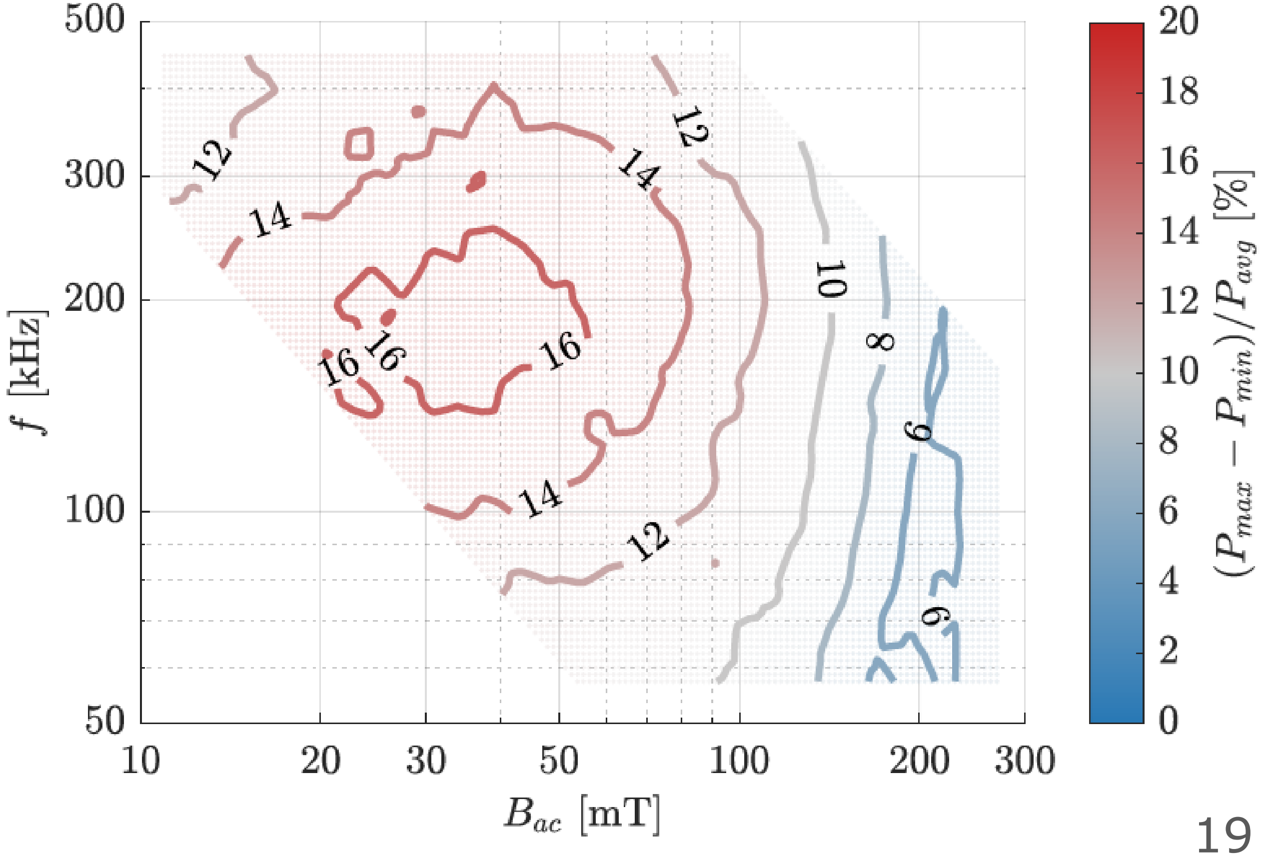
Differences during sintering/firing also add tolerance to properties.
Tolerances in dimensions add to core loss variation.

- $l_e \pm 2.3\%$ $\quad l_e = \dfrac{\pi \ln \frac{d_o}{d_i}}{\frac{1}{d_i} - \frac{1}{d_o}}$
- $A_e \pm 11\%$ $\quad A_e = \dfrac{h}{2} \dfrac{\ln^2 \frac{d_o}{d_i}}{\frac{1}{d_i} - \frac{1}{d_o}}$
- $V_e \pm 10.5\%$ $\quad V_e = \dfrac{h}{2} \dfrac{\pi \ln^3 \frac{d_o}{d_i}}{\left(\frac{1}{d_i} - \frac{1}{d_o}\right)^2}$

d_a (mm)	d_i (mm)	Height (mm)
34.0 ±0.7	20.5 ±0.5	12.5 ±0.3

https://www.tdk-electronics.tdk.com/inf/80/db/fer/r_34_0_20_5_12_5.pdf

Variation between 5 "equal" cores



N87, R34.0X20.5X12.5, triangular 50% duty cycle, $T = 25°$C, unbiased

Summary

- Error analysis is a **must**
- Needed to compare data gather using different methods
- Best if specified for each datapoint and each source
- We need to find a standard way to report losses in measurements

Future work

- Add errors to the webpage
- Provide specific temperature measurements
- Study the impact of $\mathrm{d}v/dt$ on core losses

Further reading

- Quantifying the Complexity of Modeling Power Magnetic Material Characteristics.
- Machine Learning Framework for Modeling Power Magnetic Material Characteristics.

Minjie Chen | Yuxin Chen | Haor an Li | Evan Dogari u | Charles Sullivan | Andrew Nadler | Min Luo | Thomas Guillod | Shukai Wang | Arielle Rivera | Vineet Bansal

PRINCETON UNIVERSITY

Dartmouth

plexim
electrical engineering software

Princeton MagNet

Princeton Power Electronics Research Lab

Thank you for your interest!

Data available at:
https://mag-net.princeton.edu/

IS01 - Core Loss Measurements for Different Materials and Excitations

By Diego Serrano and Minjie Chen; Email: minjie@princeton.edu