MagNet Challenge Webinar #4
Data Quality and Error Analysis

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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

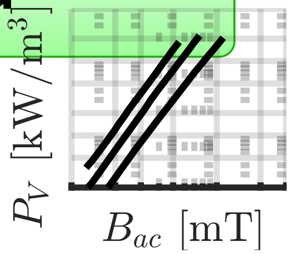
Assessing reproducibility

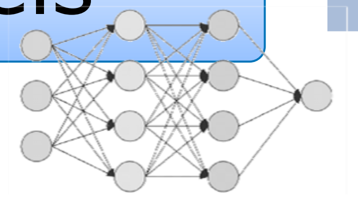
Variation of the core parameters

Introduction: the challenge of core losses

Data Error | **Model Error** | **Design Approximations**

Data → Models → Designs

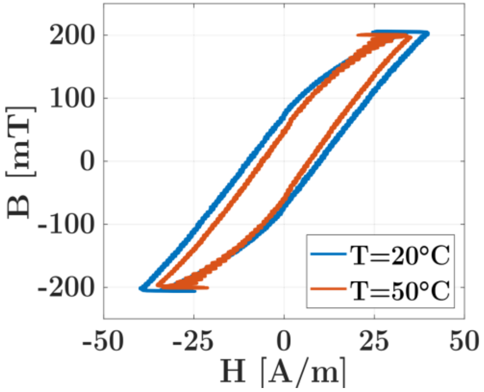




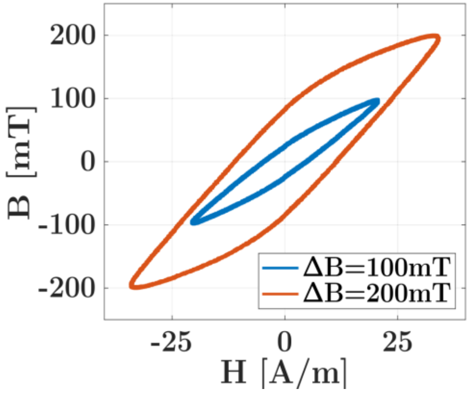
$$P_V = k \cdot f^{\alpha} \cdot B_{ac}^{\beta}$$

Datasheets | Software | Publications | …

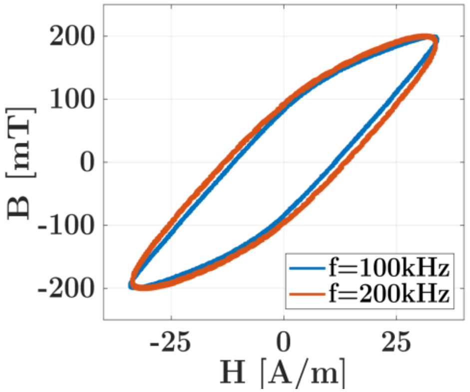
Temperature



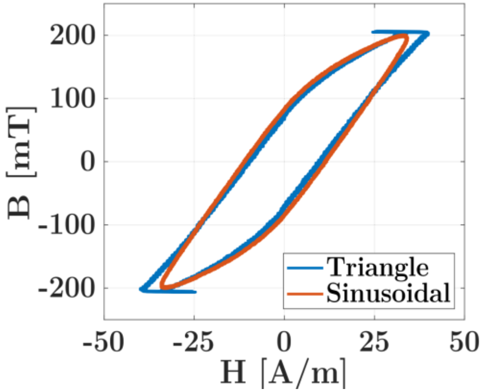
Flux density



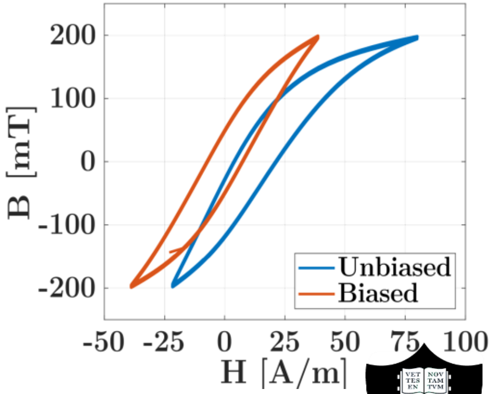
Frequency



Waveform shape



DC bias



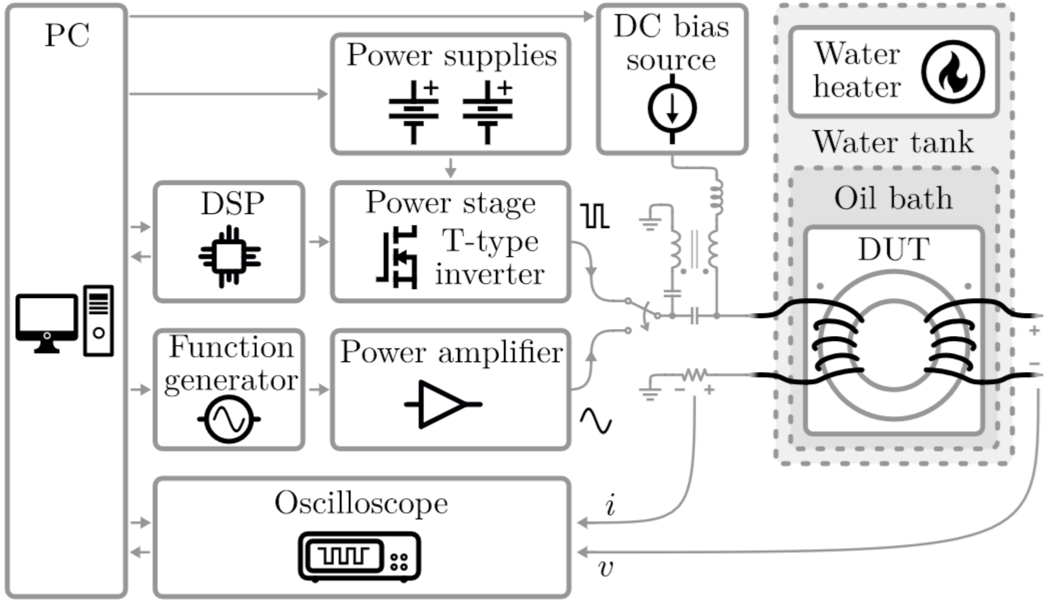
Area of B-H loop ∝ loss

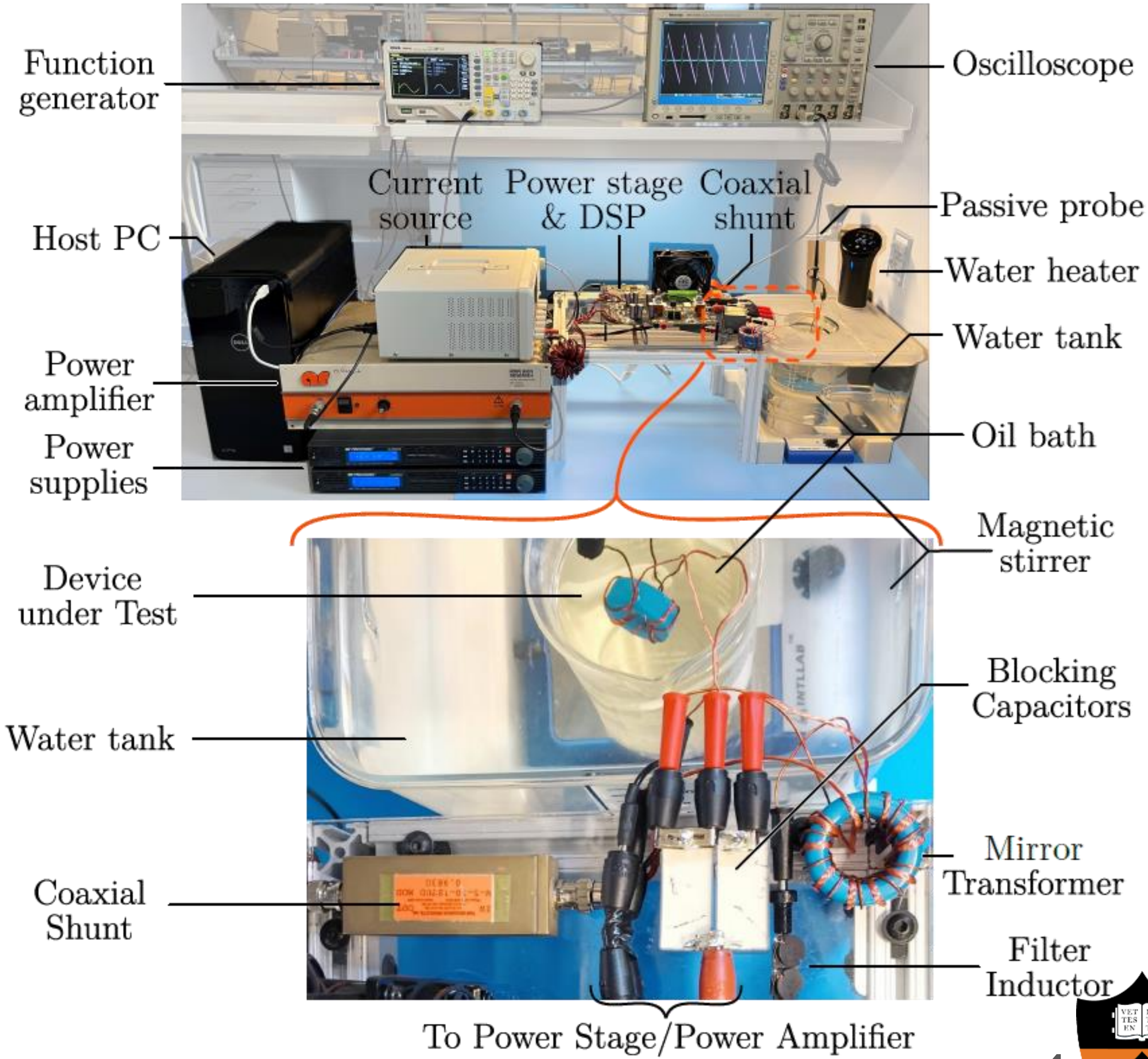
MagNet database: Set-up

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





Speed: 1.2 seconds per data

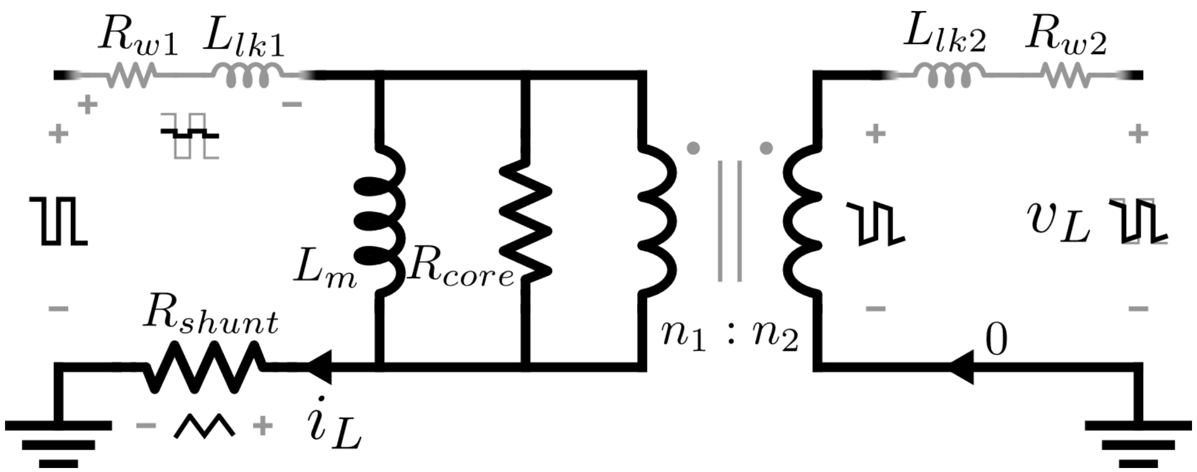
Review: V-I or two-winding method

Valid for any type of waveform

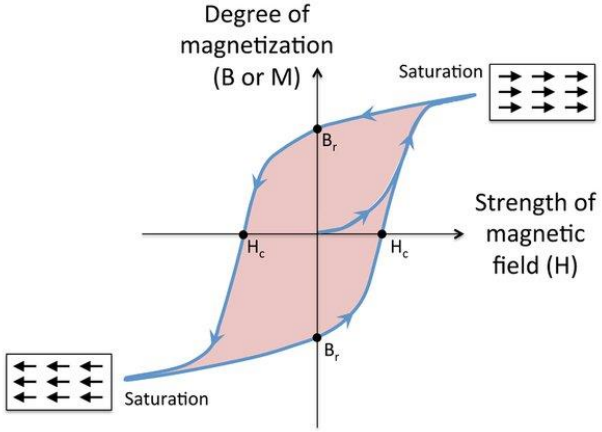
- Excitation applied to primary
- Current measured in primary
- Voltage measured in secondary

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

Only core variables measured



Core loss – B-H Loop Area



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

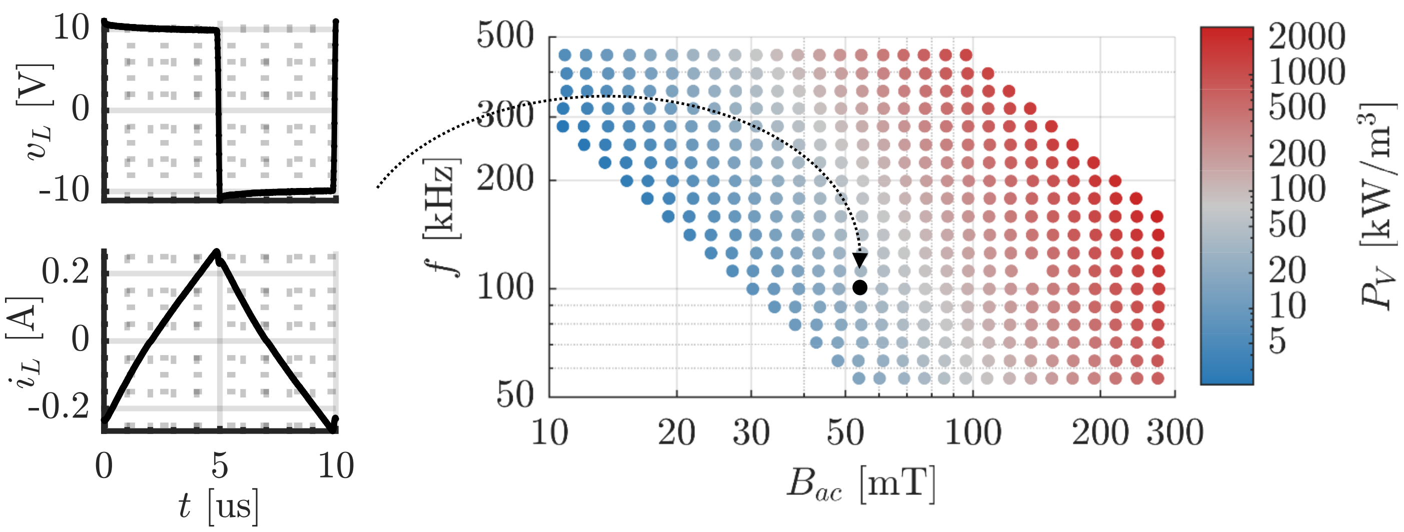
(I_{DC} as bias)

$$B(t) = \frac{1}{n_2 \cdot A_e} \int v_L(t) dt$$

(B_{dc} unknown)

MagNet database

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



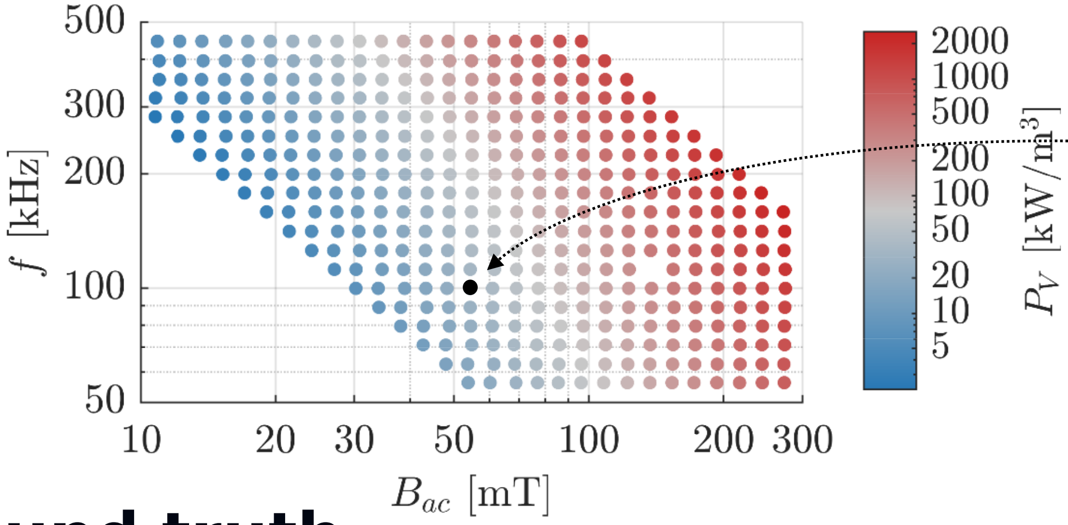
	Field	Value
Test metadata	Date_info	'2022-07-14'
	Place_info	'Princeton Power Electro
	Trap_info	'Power stage: Prototype
	Sine_info	'Signal generator: RIGOL
	Bias_info	'Configuration: DC curre
	Temp_info	'Oil Bath: Mineral Oil; Wa
	Meas_info	'Voltage Measurement: P
	Acquisition_info	'Oscilloscope: Tektronix
	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*

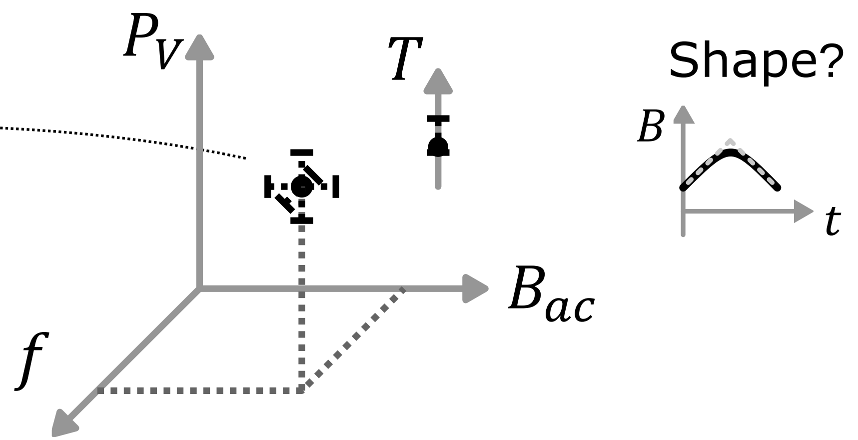
Measurements formatted as database

- Formats: MAT, JSON, HDF5, CSV
- 10 magnetic materials
- 575,009 measurements
- Data available at https://mag-net.princeton.edu/

Understanding error

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:

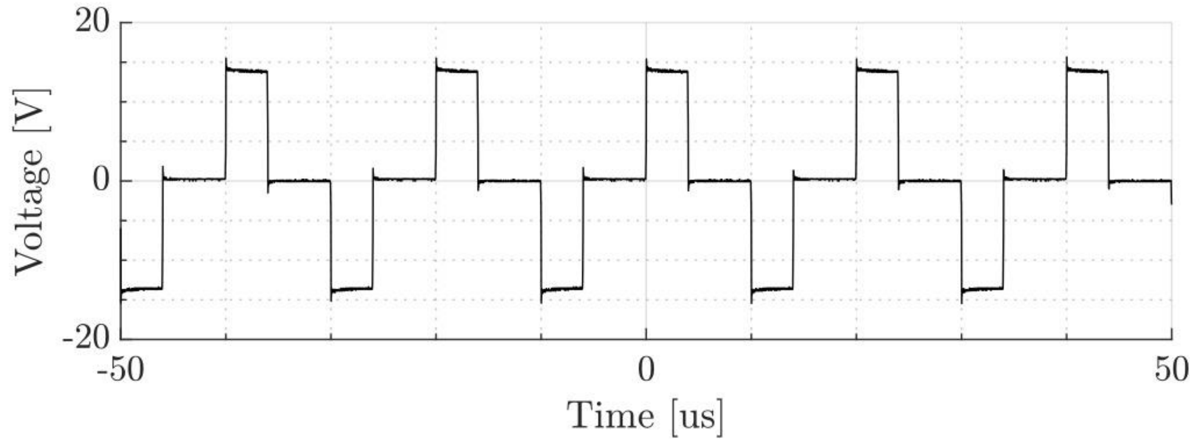
Delay | Acquisition | Parasitics | Temperature | Part-to-part Δ …

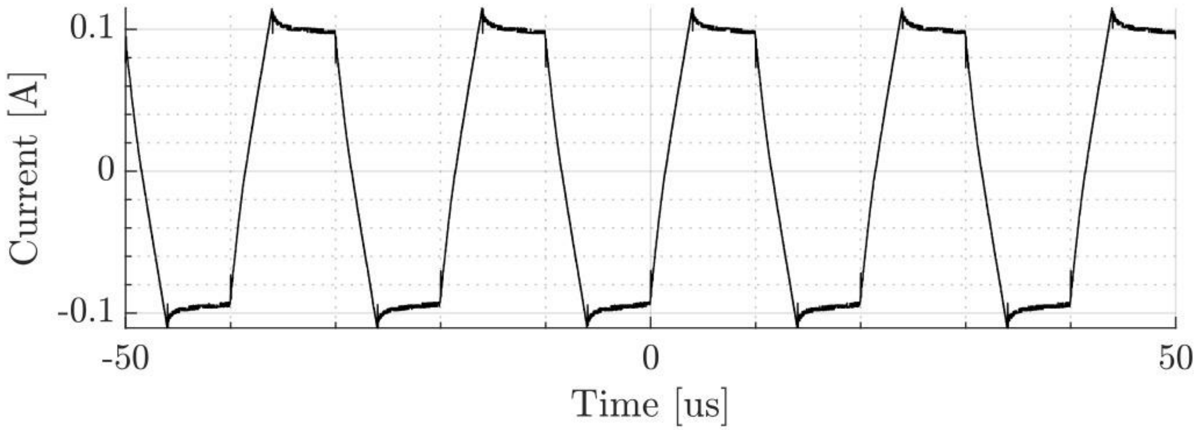
Postprocessing

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

Single cycle algorithm:

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





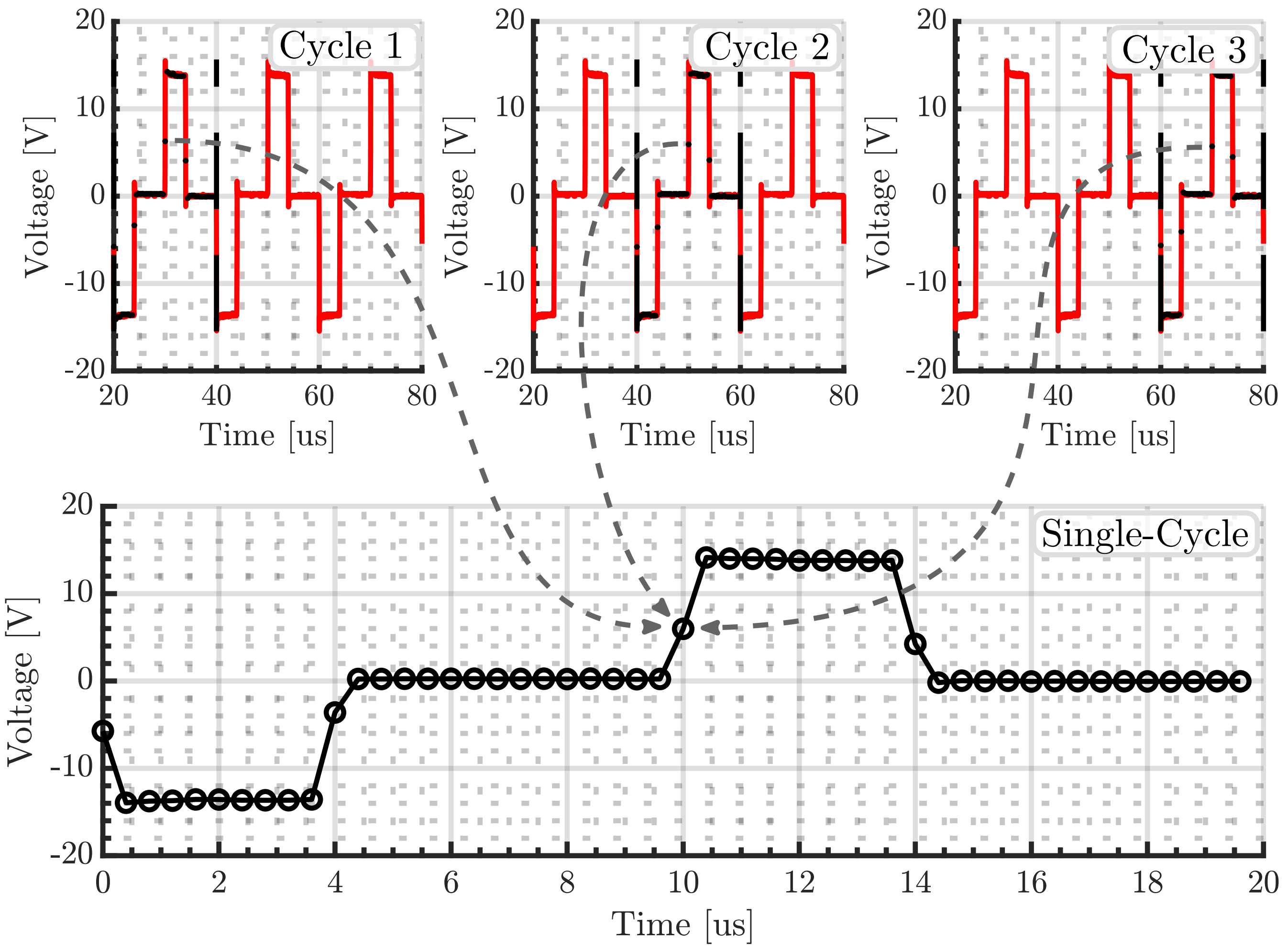
Postprocessing

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



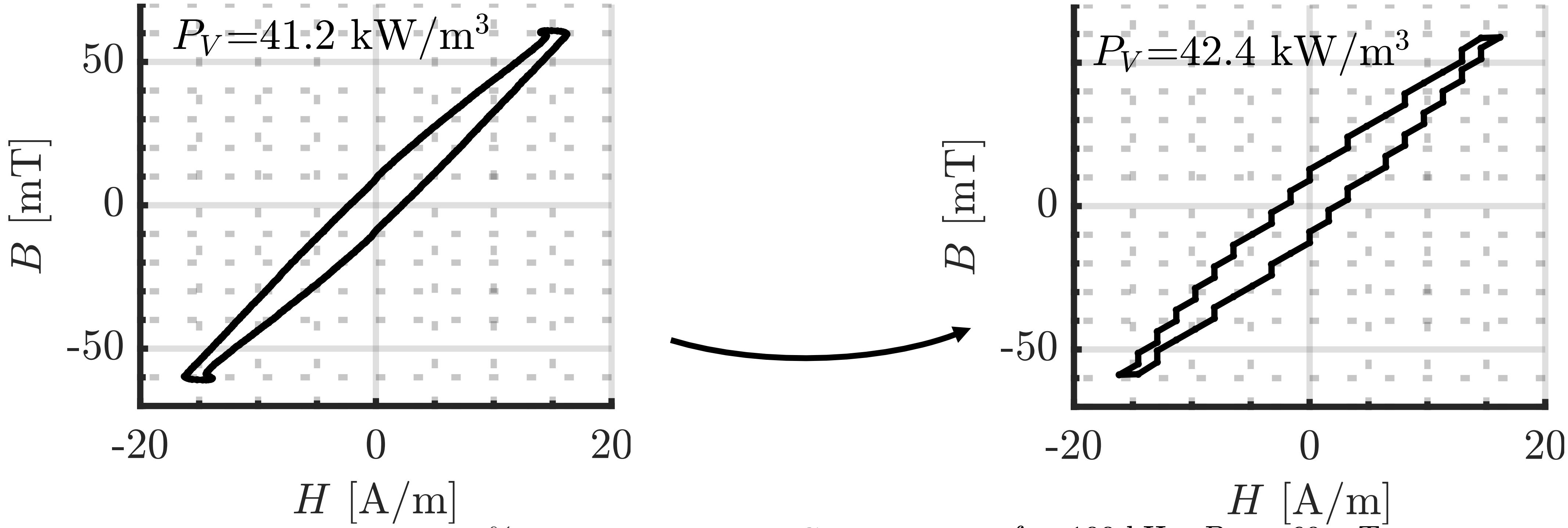
Sampling Error:

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

Example of heavy down sampling

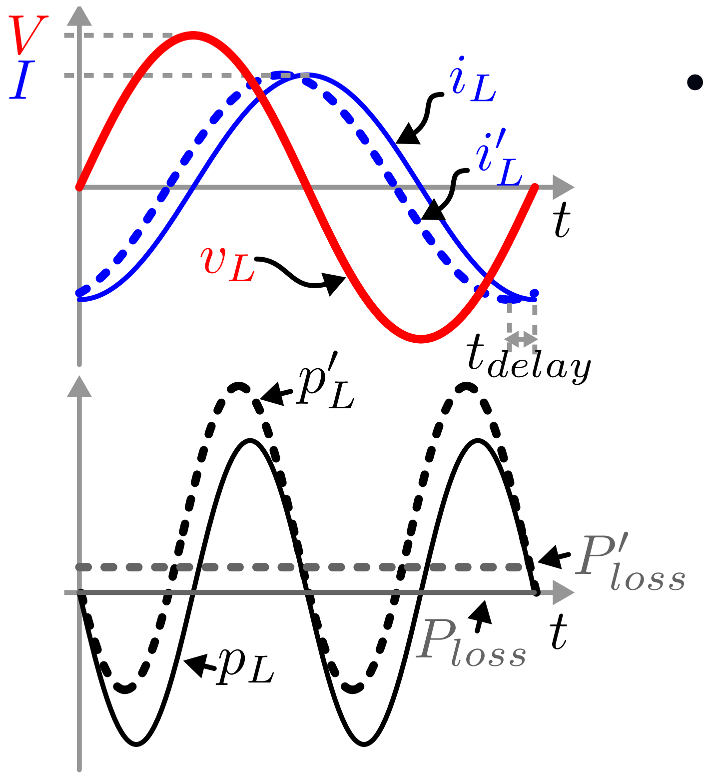
- Down sample from 1024/cycle to 64/cycle

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 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

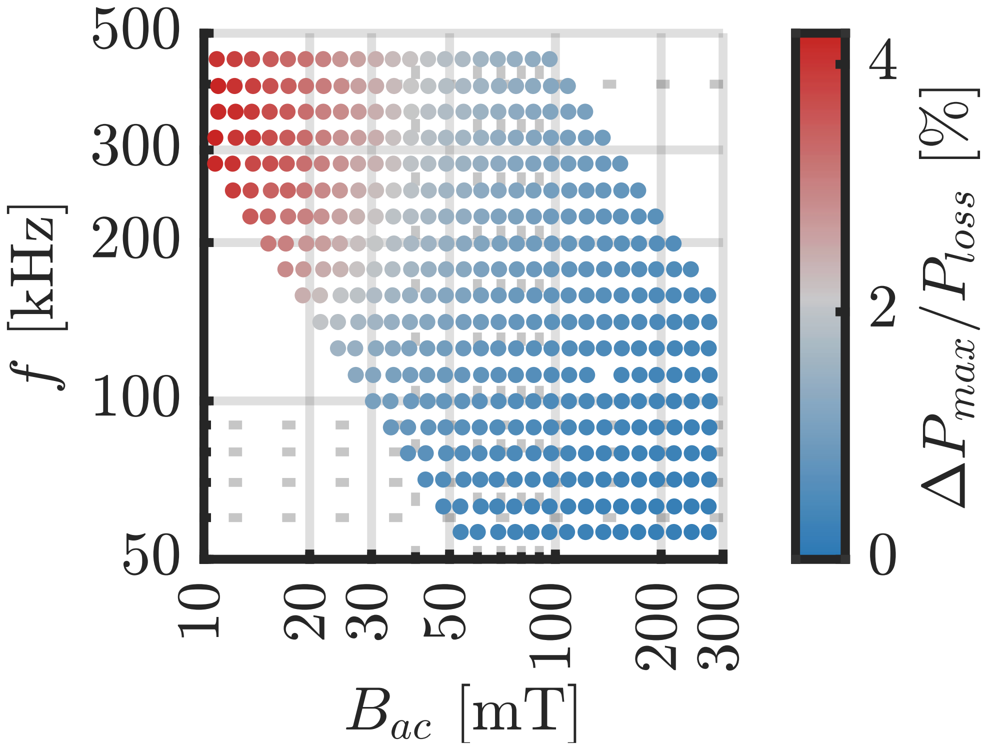
Effect of phase delay

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

Well studied issue and known limitation of this method:

- High frequencies
- Low loss materials

Main reason to use other methods instead



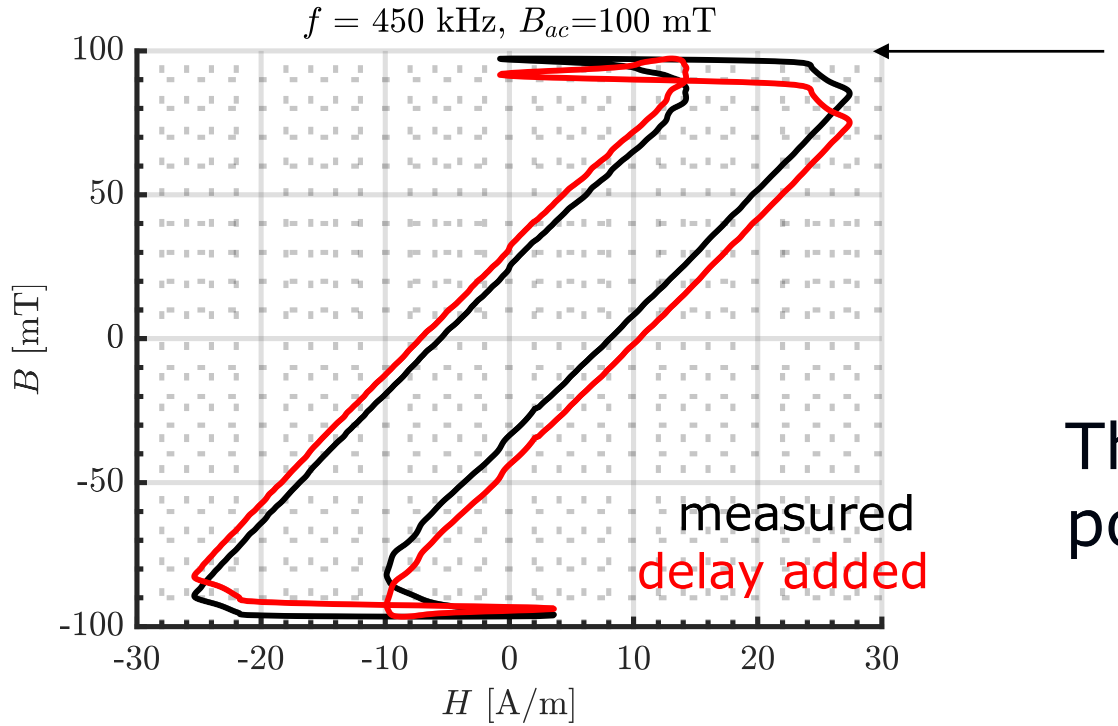
$P_{loss} \downarrow$ and $\Delta P_{loss} \uparrow \rightarrow \Delta P_{loss}/P_{loss} \uparrow$

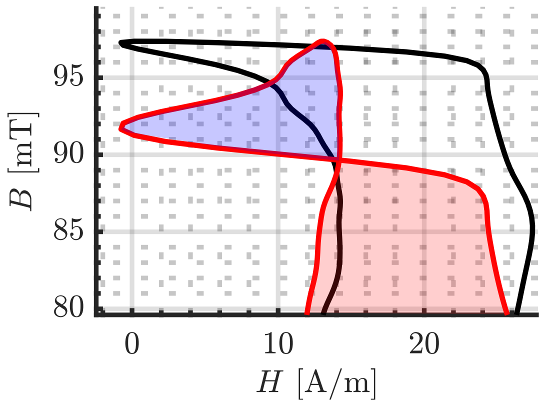
N87, R34.0X20.5X12.5, triangular 50% duty cycle, $T = 25°C$, unbiased

1.6 ns delay

Effect of phase 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

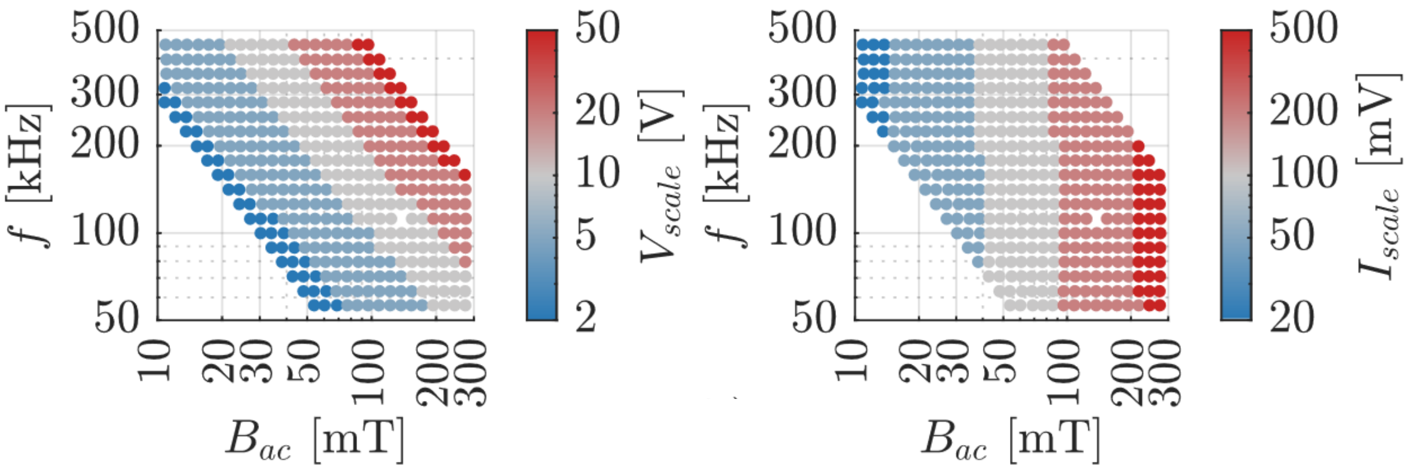
N87, R34.0X20.5X12.5, triangular 50% duty cycle, $T = 25°C$, unbiased

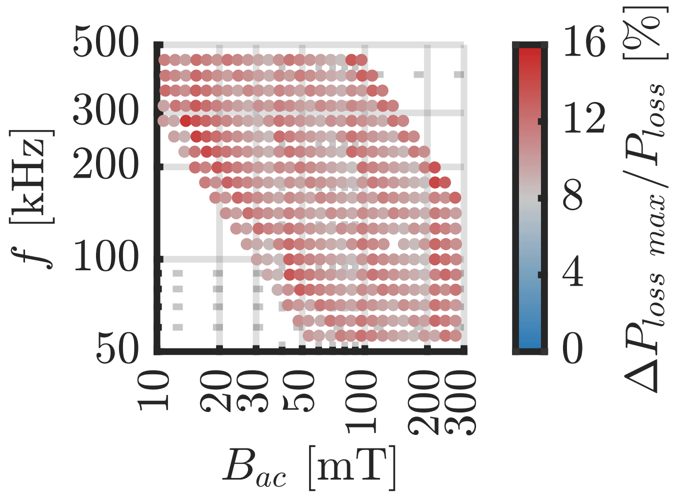
Effect the oscilloscope: gain error

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
  - $\text{Error} = 1.5\% \cdot |\text{read}| + 15\% \cdot \text{div} + 1.2\text{ mV}$



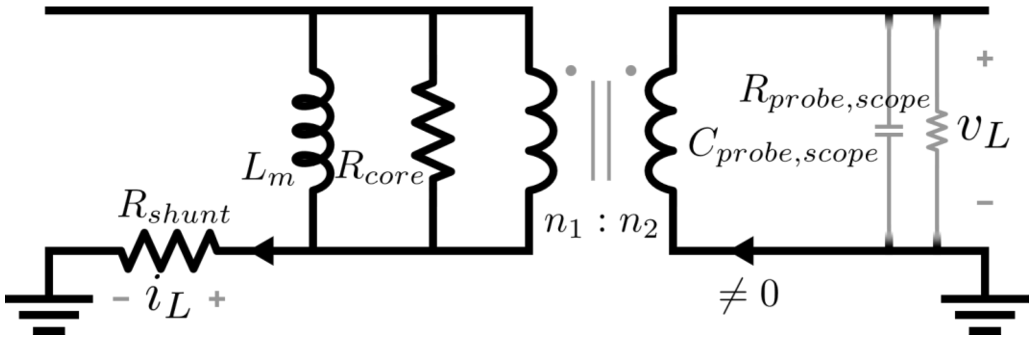


- Error concentrated in the regions where the scale changes

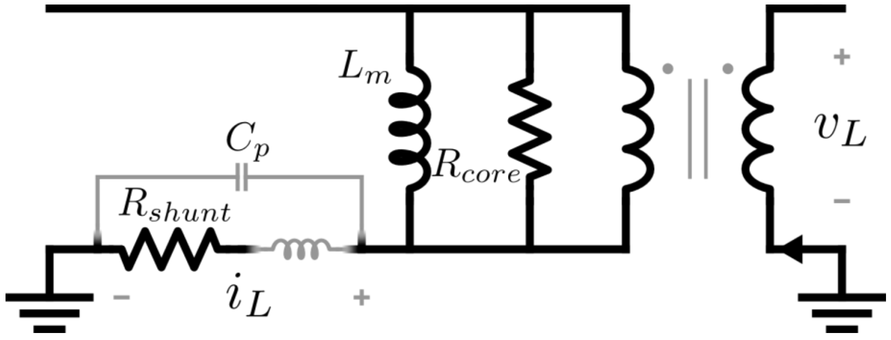
N87, R34.0X20.5X12.5, triangular 50% duty cycle, $T = 25°\text{C}$, unbiased https://download.tek.com/manual/077024701Rev_A_web.pdf

Effect of parasitic elements in the circuit

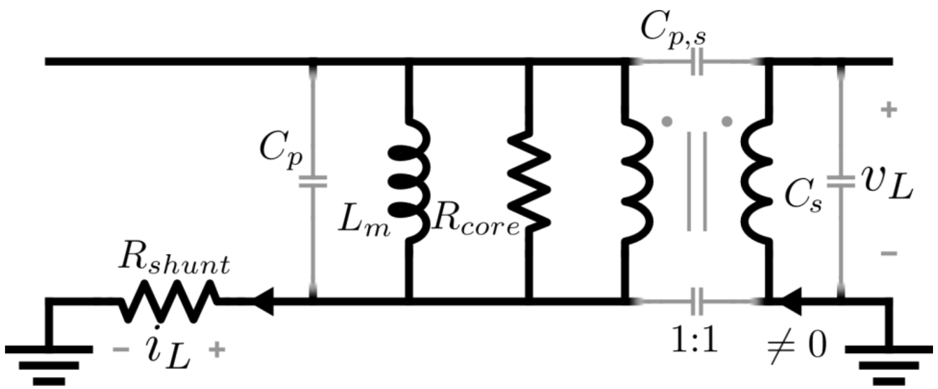
- On the voltage measurement, change the current measured:
  - Scope and probe resistance



  - 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



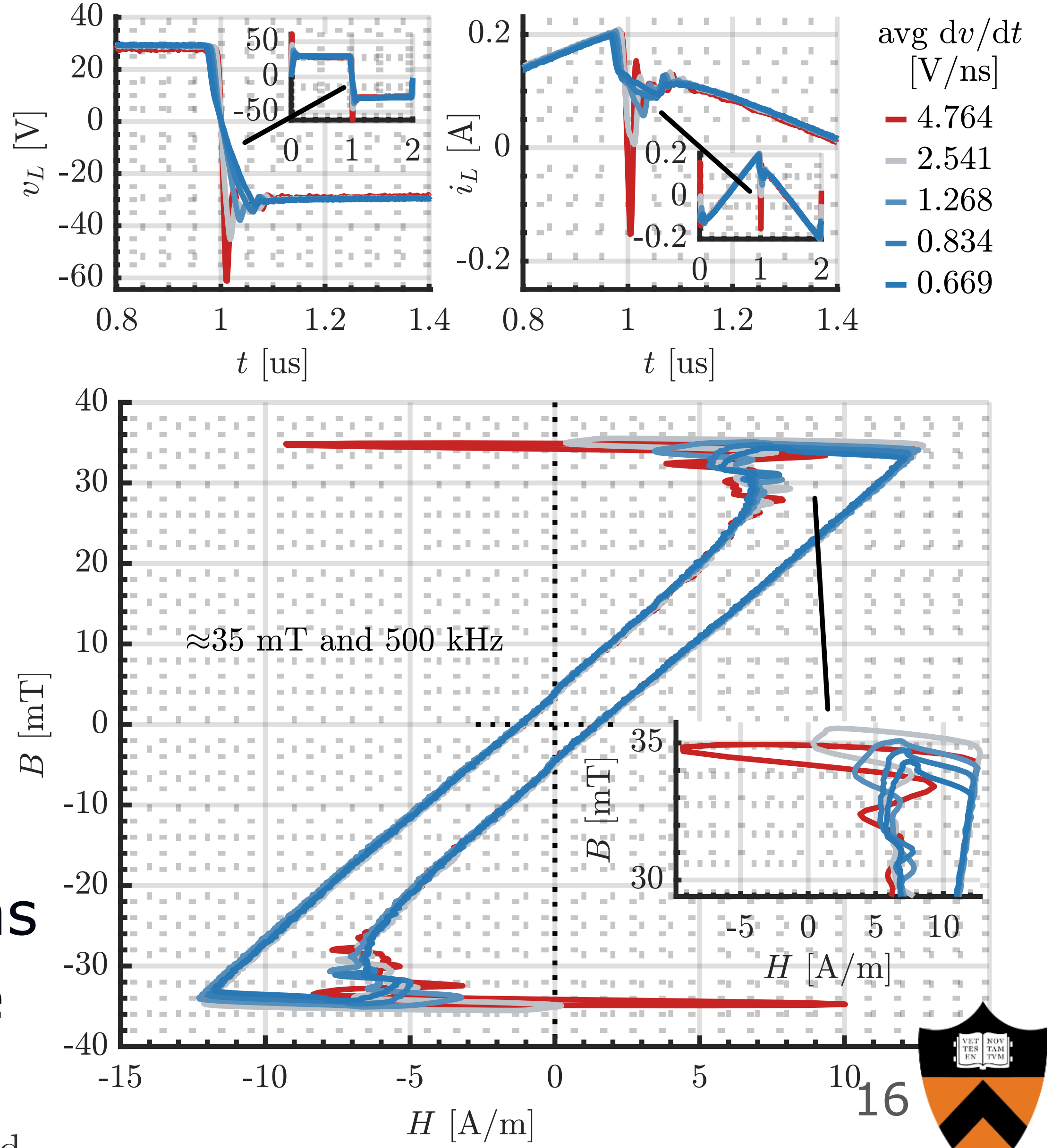
Non-ideal excitations

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



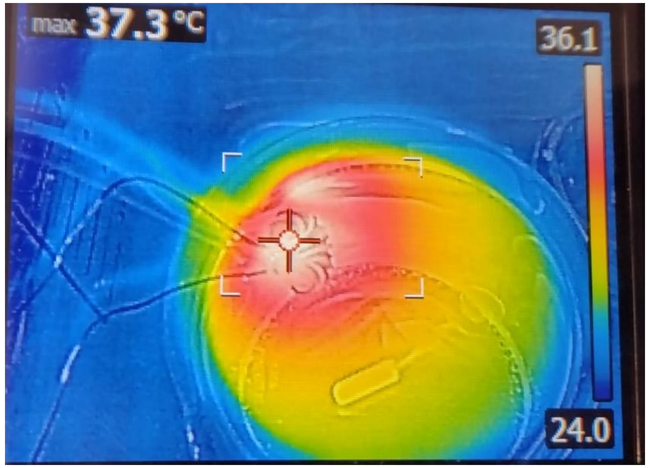
N87, R34.0X20.5X12.5, triangular 50% duty cycle, $T = 25°C$, unbiased

Effect of the variation of temperature

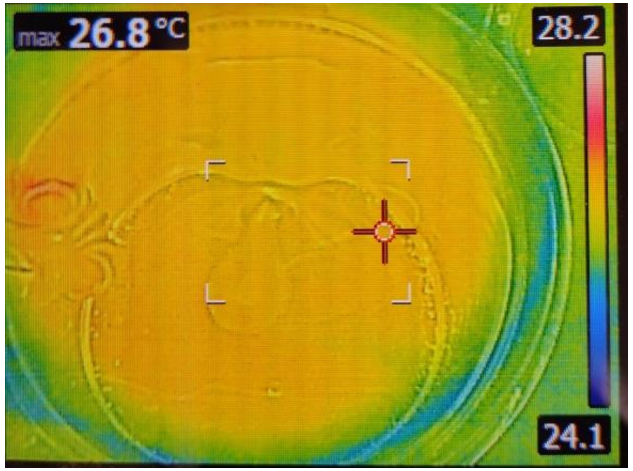
$P_{loss} \rightarrow T \uparrow\uparrow \longleftrightarrow P_{loss} = f(T)$

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

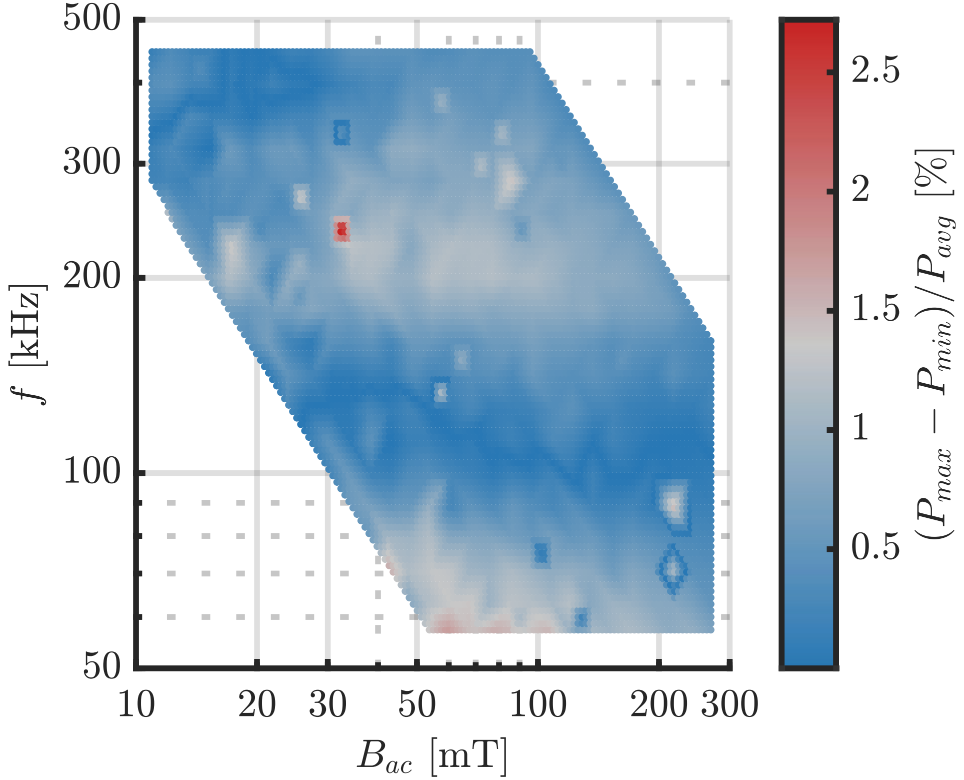
N87, R34.0X20.5X12.5, triangular 50% duty cycle, $T = 25°C$, unbiased

Assessing reproducibility

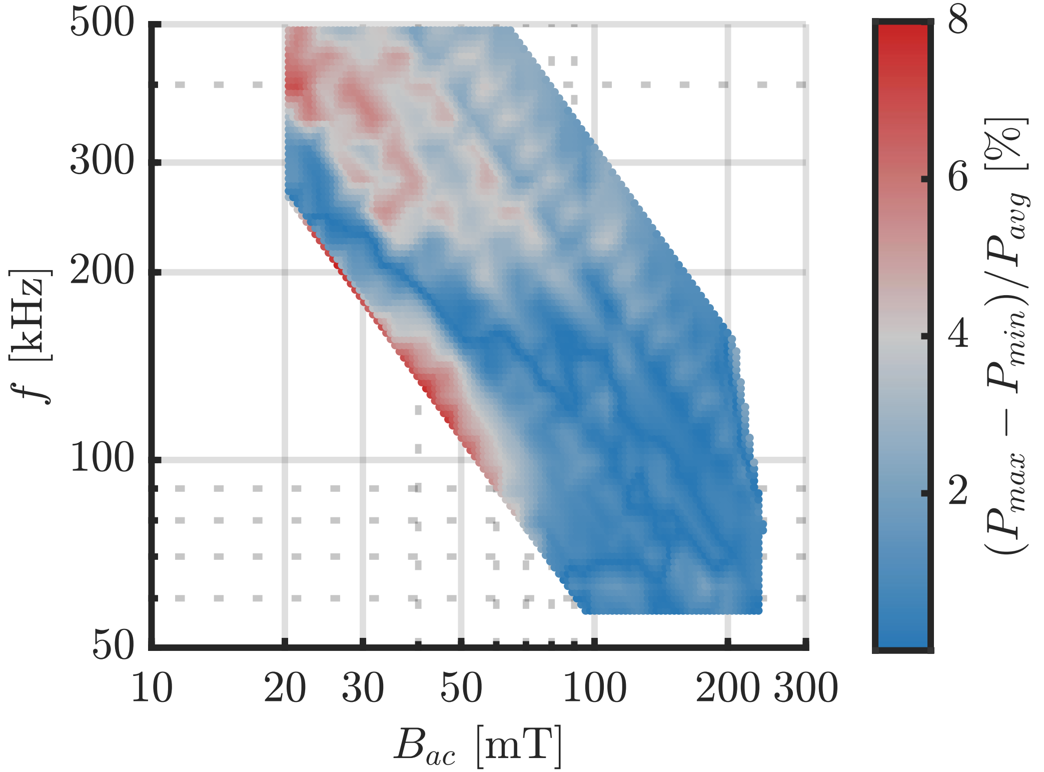
Data is reproducible when the same core is tested again

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, $T = 25°C$, unbiased

Core-to-core variation: tolerances

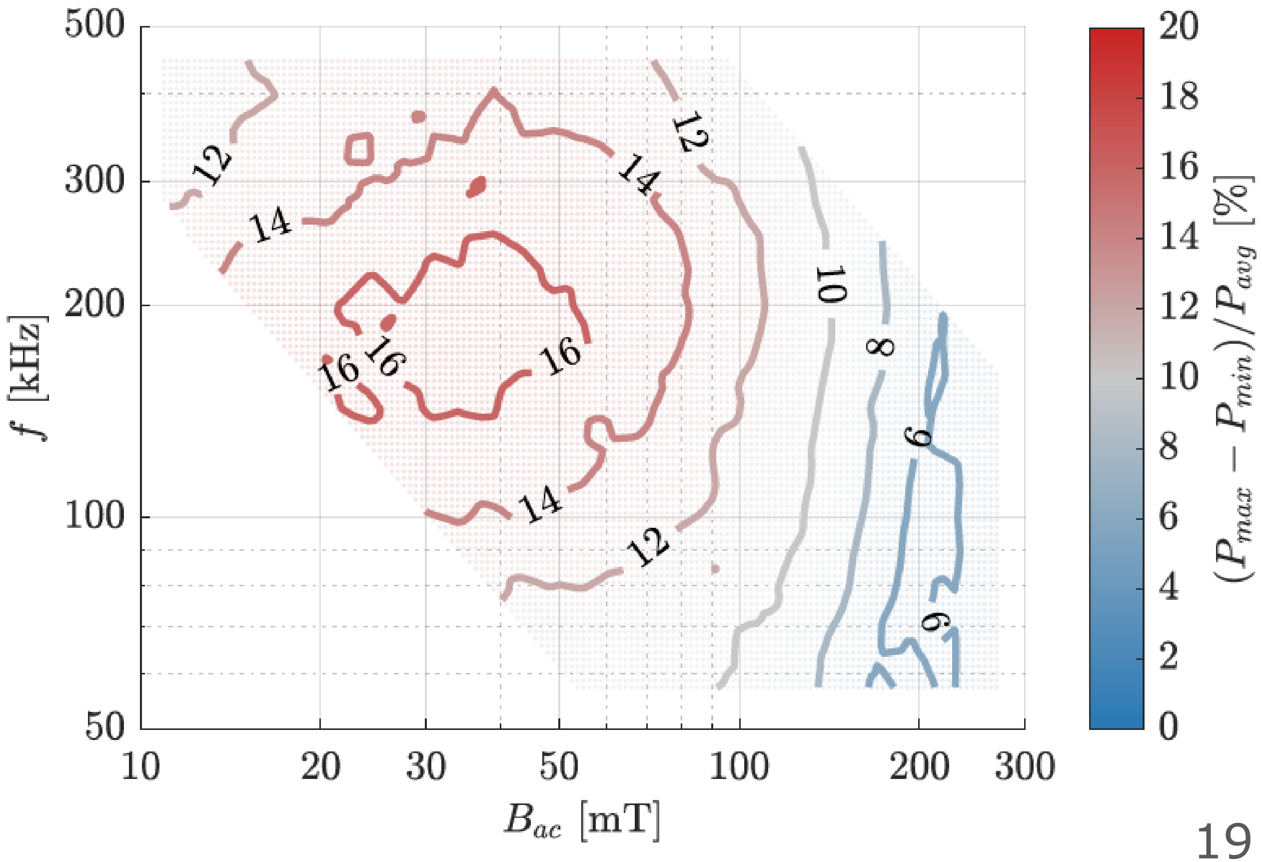
Differences during sintering/firing also add tolerance to properties. Tolerances in dimensions add to core loss variation.

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

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

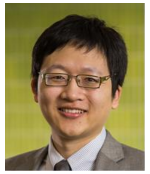
- Error analysis is a **must**
- Needed to compare data gather using different methods
- Best if specified for each datapoint and each source
- We need to find a standard way to report losses in measurements

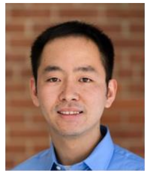
Future work

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

Further reading

- [Why MagNet: Quantifying the Complexity of Modeling Power Magnetic Material Characteristics].
- [How MagNet: Machine Learning Framework for Modeling Power Magnetic Material Characteristics].


Minjie Chen

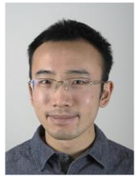

Yuxin Chen


Haoran Li

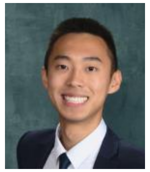

Evan Dogariu


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