HEFMAG European Metrology Labs Correlation Project

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hefmag.inrim.it

APEC 2025 Industry Sessions Thu March 20 - IS24.2

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

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Presenter’s Bio

Massimo Pasquale (Senior Member, IEEE) received the degree in particle physics from the University of Torino, in 1988. He has been a Researcher with the Istituto Elettrotecnico Nazionale Galileo Ferraris, since 1991, now Istituto Nazionale di Ricerca Metrologica (INRIM), Turin. He has authored more than 130 papers on applied magnetism, phase transitions and magnetocalorics, magnetostriction, sensors, and magnetic measurements up to the microwave regime. He has coordinated Euramet-EU projects on magnetics, including the HEFMAG (2020-2023) and NANOSPIN (2008-2010) as well as several research projects with NATO SfP, South Korea, Japan and many national research contracts. He has served in the IEEE Magnetics Society AdCom also as Conference Chair of Intermag 2009, Publications Chair (2010–2011), and Conference Executive Committee Chair (2012–2015), and Conference Publications Chair (since 2018).

INRiM
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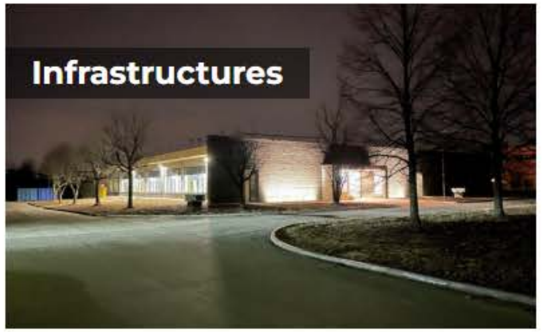
DI RICERCA METROLOGICA

Affiliation 1/2 INRIM www.inrim.it - Ministry of University and Research (MUR) www.mur.gov.it

INRiM's metrological activities from fundamental scientific research to technological innovation

The services that the Institute provides to the national system



The infrastructures for the enhancement of experimental research activities

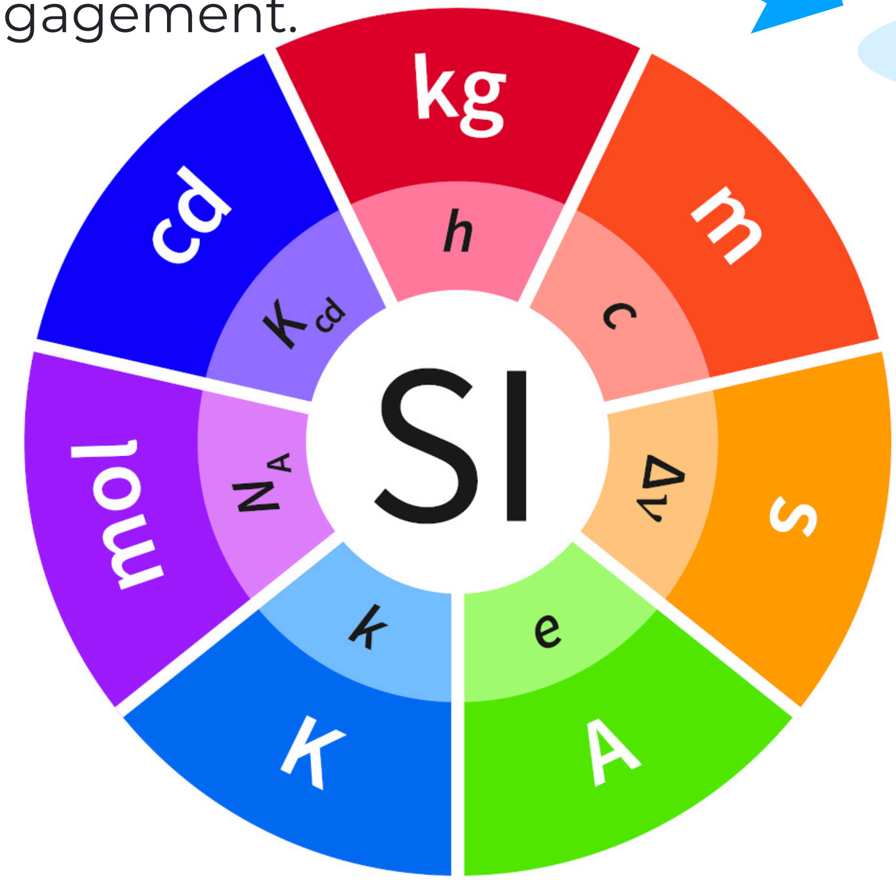
132	138	305
Laboratories	Projects	People

Affiliation 2/2 www.inrim.it

INRIM's three missions
- Research and development;
- INRiM's role as National Metrology Institute (NMI);
- Knowledge transfer and public engagement.

As NMI INRIM provides

- 400 Capacity of Calibration and Measurement (CMCs) registered at BIPM **https://www.bipm.org/kcdb/**
- 300 calibration services of standards used in
- **mechanics**,
- **thermodynamics**,
- **time and frequency, electricity**,
- **photometry**,
- **acoustics**
- **chemistry**.



Scientific Sectors

- Acoustics and ultrasounds
- Electromagnetic fields and systems
- Physical chemistry and nanotechnology
- Quantum electronics
- Magnetism, Materials and Spintronics
- Length metrology
- Metrology of Mass and Related Quantities
- Electrical and electronic measurements
- Quantum optics and Photometry
- Nanoscale science and technology
- Biomedical sciences and technologies
- Time and frequency
- Applied thermodynamics
- Physical thermodynamics

Need:

Assess and validate power loss measurement results and uncertainties in magnetic materials (increase frequency!)

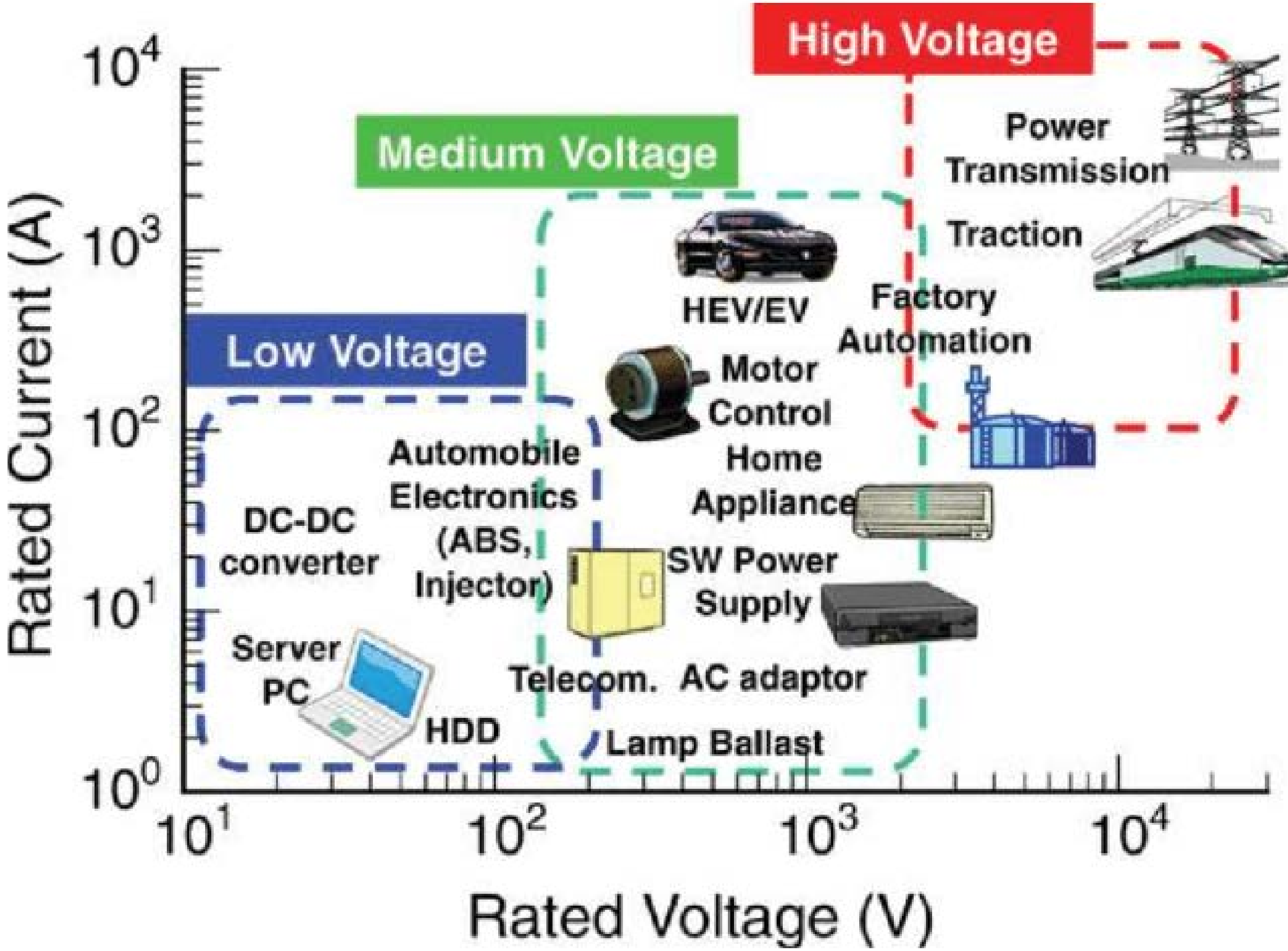
Ensure accurate characterization, optimize energy efficiency performance, and enhance the reliability in real-world applications.

Background market data:

Power electronics 45 G€/y

Electrical steel laminations 20 G€/y

Generic steel 180 G€/y



THESIS Letellier, Juliette 2019/12/18

Need:Assess and validate loss measurement capabilities with increasing frequencies with uncertainties

Solution → Round Robin (EU magnetic metrology) among NMIs-National Metrology Institutes

DC ← f → 400Hz (1-2 kHz)

IEC 60404-2 - ASTM A932/A932M ASTM A343/A343M-14

IEC 60404-3 Single sheet tester DC- 400 Hz ASTM A1036-04(2020)

400 Hz ← f → 10 kHz

IEC 60404-10 ASTM A927 ASTM A348/A348M

10 kHz ← f → 200kHz (1 MHz) → 10 MHz

IEC 60404-6 IEC 62044-3:2023 IEC 63300:2023 ASTM A1013-00(2020)

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1 MHz ← f → 1-3 GHz

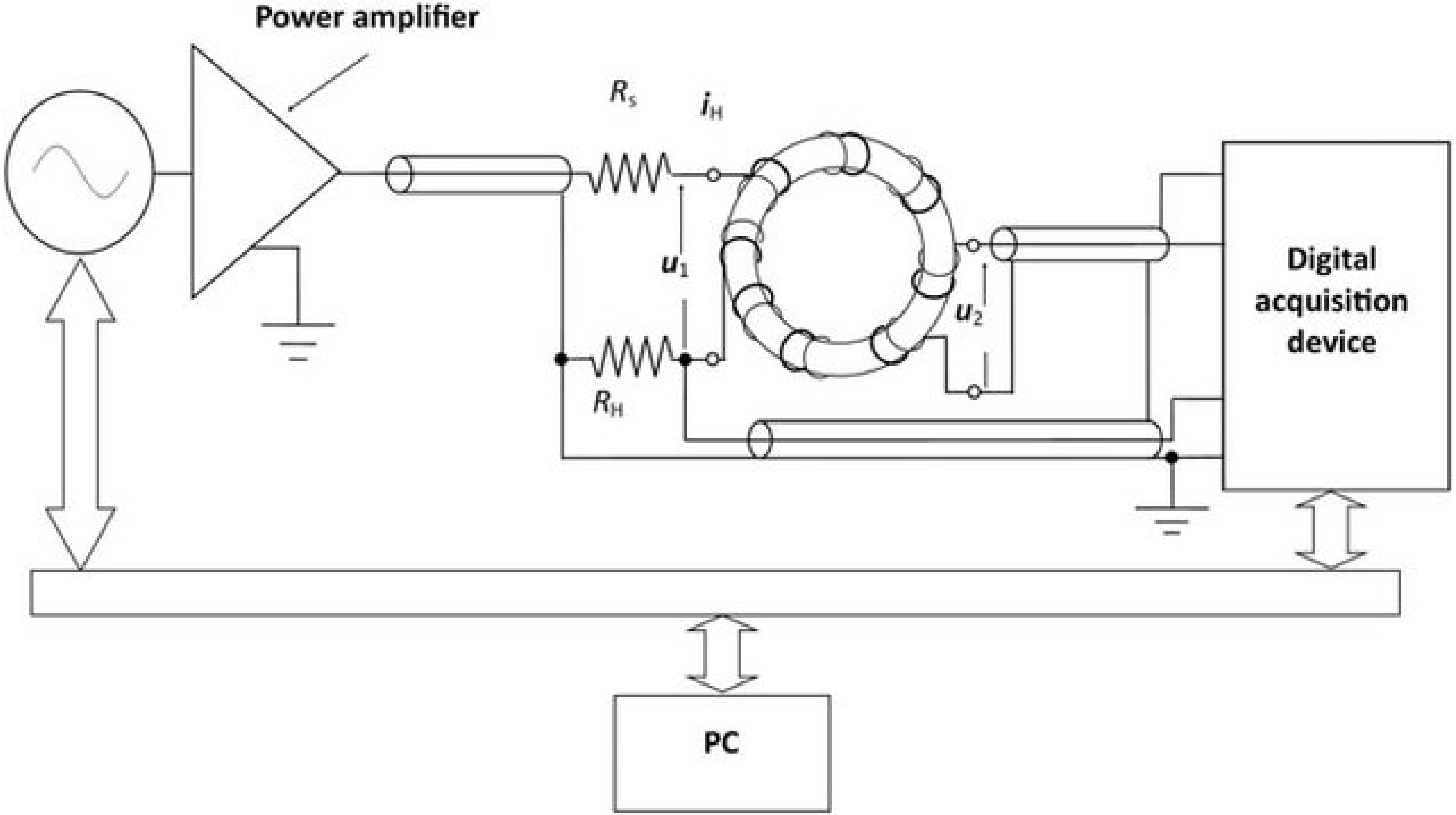
IEC 60556 (ferrites) –IEC 60392 ASTM D5568-22 (100 MHz)

Waveguide ASTM A1033 (300 MHz-40 GHz)

INRIM Magnetic Standard Measurements Laboratory- Wattmeter hysteresisgraph DC -10 MHz

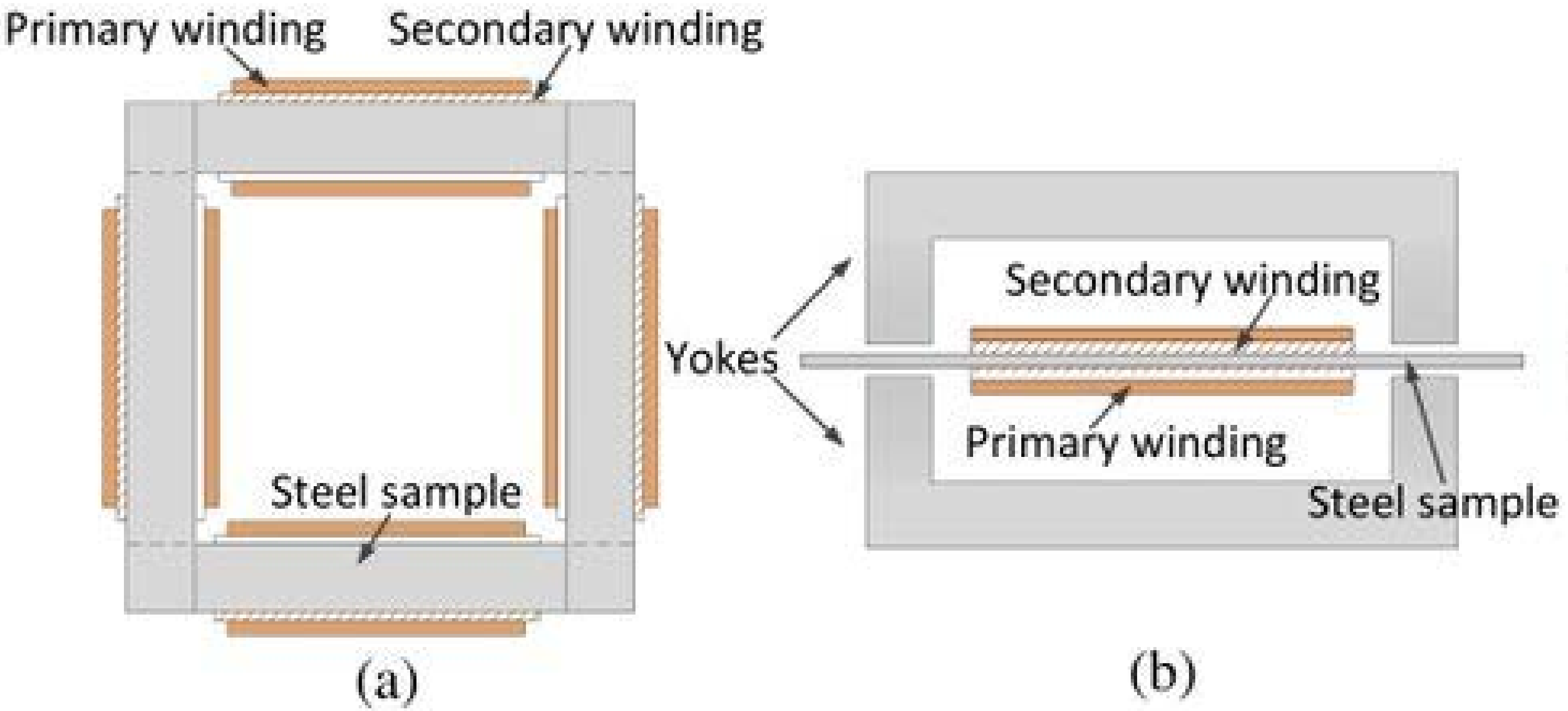
Round Robin Comparisons (Standard Conditions)

Fluxmetric measurements (sinusoidal flux) ~DC – 10 MHz



Round Robin Comparisons (Standard Conditions)

Fluxmetric measurements samples ~DC – 1 kHz DC-10 MHz



Single Sheet Tester

Epstein yoke Ring

INRIM declared calibration and measurement capabilities

Calibration or Measurement Service bipm.org KCDB		Measurand Level or Range			Measurement Conditions/Independent Variable		Expanded uncertainty 2σ
Quantity	Method	Min	Max	Units	Parameter	Specifications	Value
Soft magnetic sheet materials: specific power loss and apparent power	Hysteresisgraph-wattmeter (IEC 60404-2, IEC 60404-3, IEC60404-6, IEC 60404-10)	5.00E-03	200	W/kg	Frequency Polarisation Sample mass Primary current	1 Hz to 10 kHz 0.2 T to 1.8 T > 0.1 kg < 15 A	10E-03 to 50E-03
Soft magnetic sheet materials: specific apparent power	Hysteresisgraph-wattmeter (IEC 60404-2, IEC 60404-3, IEC60404-6, IEC 60404-10)	5.00E-03	200	VA/kg	Frequency Polarisation Sample mass Primary current	1 Hz to 10 kHz 0.2 T to 1.8 T > 0.1 kg < 15 A	20E-03 to 80E-03
Soft magnetic sheet materials: value of AC magnetic polarisation	Mean value voltmeter (IEC60404-6, IEC 60404-10)	0.05	2	T	Frequency Primary current	1 Hz to 10 kHz < 15 A	4E-03 to 1.5E-02
Soft magnetic sheet materials: value of magnetic field strength	Hysteresisgraph-wattmeter/ballistic setup (IEC 60404-2, IEC 60404-3, IEC 60404-4, IEC60404-6, IEC 60404-10)	0.5	10000	A/m	Frequency Primary current	DC to 10 kHz < 15 A	4E-03 to 1.6E-02
Soft magnetic sheet materials: peak permeability	Hysteresisgraph-wattmeter/ballistic setup (IEC 60404-2, IEC 60404-3, IEC 60404-4, IEC60404-6, IEC 60404-10)	1.00E-04	0.1	H/m	Frequency	DC to 10 kHz	5E-03 to 5E-02

Details of the Round Robins (50 Hz - 10 kHz)

Hysteresis loops and power loss Round Robin Comparisons performed by:

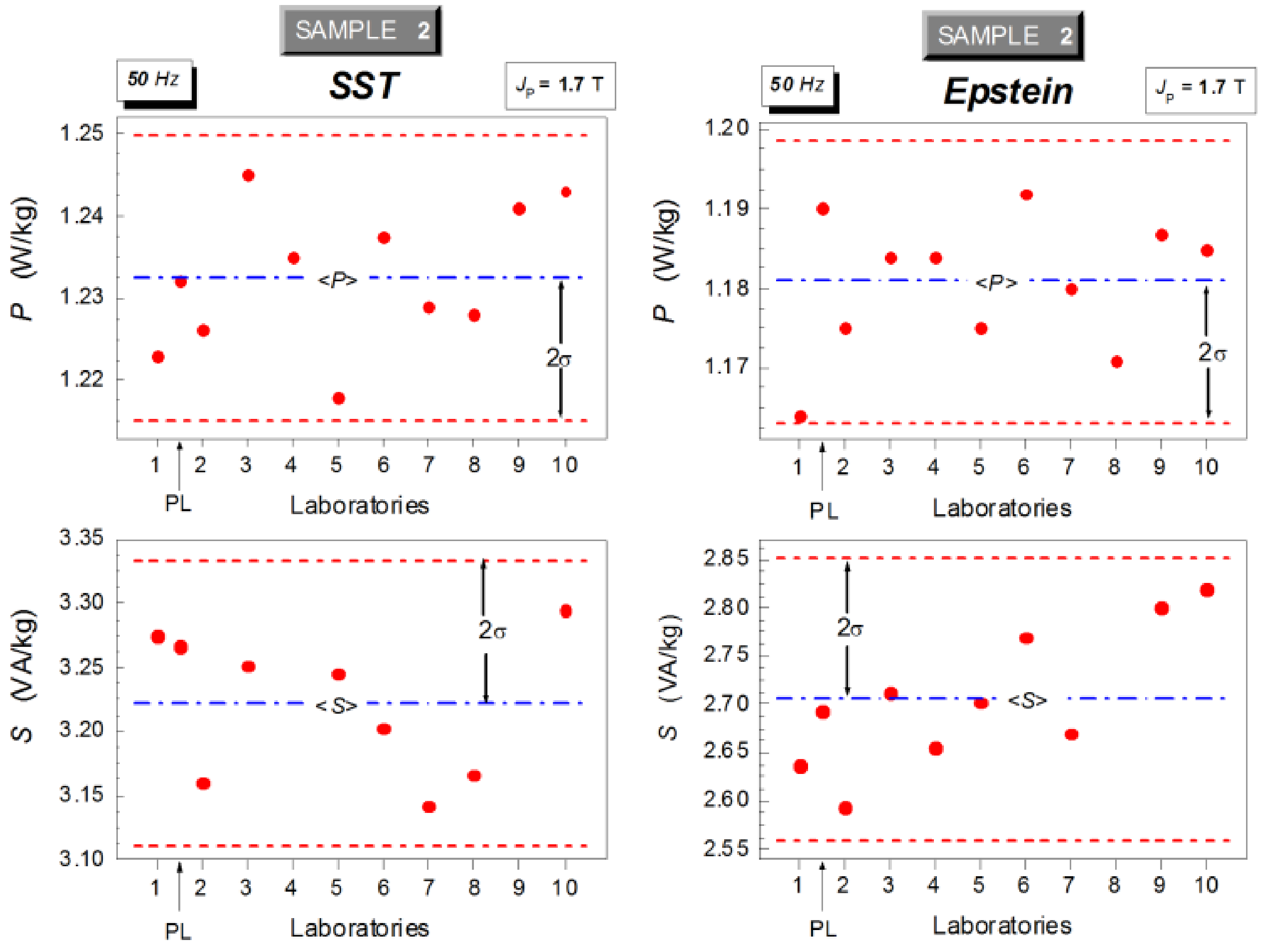
5 EU National Metrology Institutes: INRIM-IT, PTB-DE, NPL-UK, CMI-CZ, UME-TK, NIM-CN + POLITO-IT, UNOTT-UK

3 Steel producers: ThyssenKrupp-DE , Baosteel-CN, ArcelorMittal-BE)

Laminations from ThyssenKrupp-DE , Baosteel-CN, ArcelorMittal-BE NipponSteel-JP

Nanocrystalline Rings from VacuumSchmeltze-DE

N30 ferrite from Epcos



Sample Results from a previous International Comparison Metrologia 2018 doi:10.1088/0026-1394/55/1A/01006

Round Robin Comparisons - **Samples**

Standard characterization – Magnetic Loss on FeSi and FeCo laminations and FeCo, ferrite or nanocrystalline rings

Low frequency Laminations (0.5-0.3-0.2 mm thick)

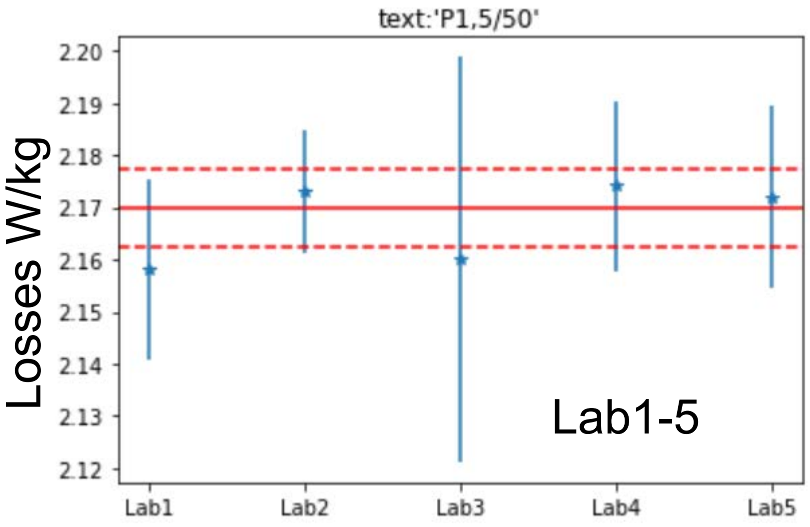
- IEC 60404-2 **Epstein frame** DC-400 Hz(ASTM A343/A343M-14)
- IEC 60404-3 **Single sheet tester** DC- 400 Hz ASTM A1036 04(2020)

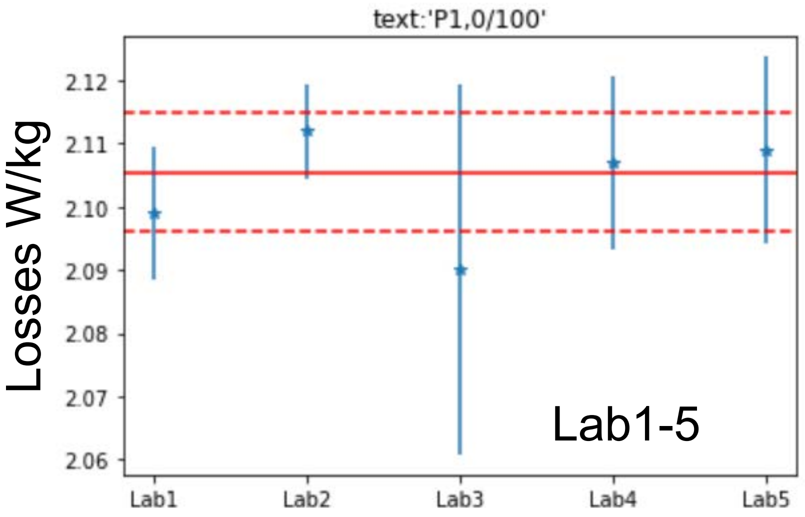
Medium frequency (0.2 mm thick)

- IEC 60404-10 **Epstein frame** 400 Hz-10 kHz

High frequency (20 um thick-powder)

- IEC 60404-6 **Rings** 20 Hz-1 MHz





Standard loss measurements results in extended exp. conditions

D1a Results of the Epstein Round Robin https://doi.org/10.5281/zenodo.8288792 ;

D1b Results of the SST Round Robin https://doi.org/10.5281/zenodo.8288797 ;

D1d Round Robin including NIM China and Stakeholder Epstein results https://doi.org/10.5281/zenodo.10032755 ;

D1e Round Robin including NIM China and Stakeholder SST results https://zenodo.org/doi/10.5281/zenodo.10014600 ;

D2 Loss measurements Good Practice Guide https://doi.org/10.5281/zenodo.8304171 ;

D2a Report on loss measurements in distorted flux conditions https://doi.org/10.5281/zenodo.8296466

State of the art Round-Robin results Epstein (5 partners) and SST (3 partners)

Loss measurements performed on NO and GO FeSi laminations achieved a relative standard deviation σ of 1 %.

- Epstein NO and GO FeSi laminations (with dimensions of 300 mm x 30 mm x 0.18-0.2-0.3 mm)
  σ <1% was achieved in 79/87 measurements (91%) f 50 Hz-10 kHz
- FeCo Epstein laminations (with dimensions of 300 mm x 30 mm x 0.2 mm),
  σ<1.5% was achieved in 18/27 cases (66%) f 50 Hz-10 kHz

  due to the extreme magnetic softness and magnetostriction issues.
- FeSi SST samples (with dimensions of 500 mm x 500 mm x 0.18-0.2-0.3 mm),
  σ< 1% was achieved in 34/41 measurements (92%) f 50 Hz-100 Hz.

Publications links: hefmag.inrim.it

Round Robin Comparison **Ring Results (Standard Conditions)**

State of the art Round-Robin results HF rings (2 partners + 1) :

Power losses on N30 (m ~ 25k) ferrite ring < 10 mm and in two nanocrystalline Co rings (μ ~ 30k-100k) from 10 kHz up to 1 MHz between INRIM and NPL results (+ Tunkia)

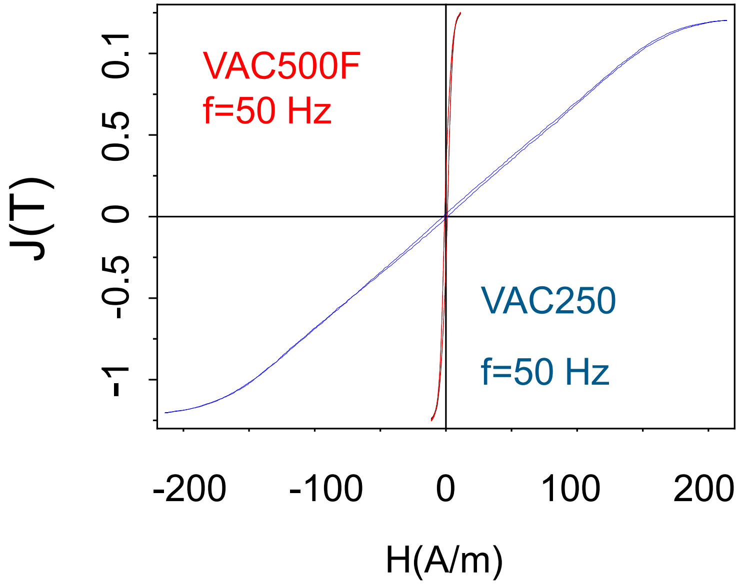
- Loss N30 (μ ~ 25k) ferrite ring < 10 mm

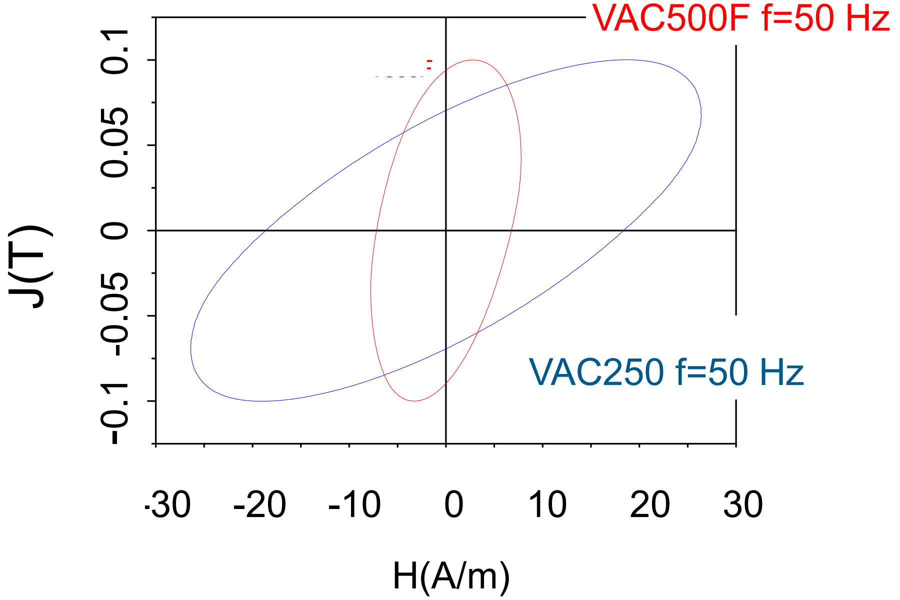
σ <1.5% f< 200 kHz and σ <2.6% f< 1 MHz

- Loss nanocrystalline Co based Vitroperm 500F-250F

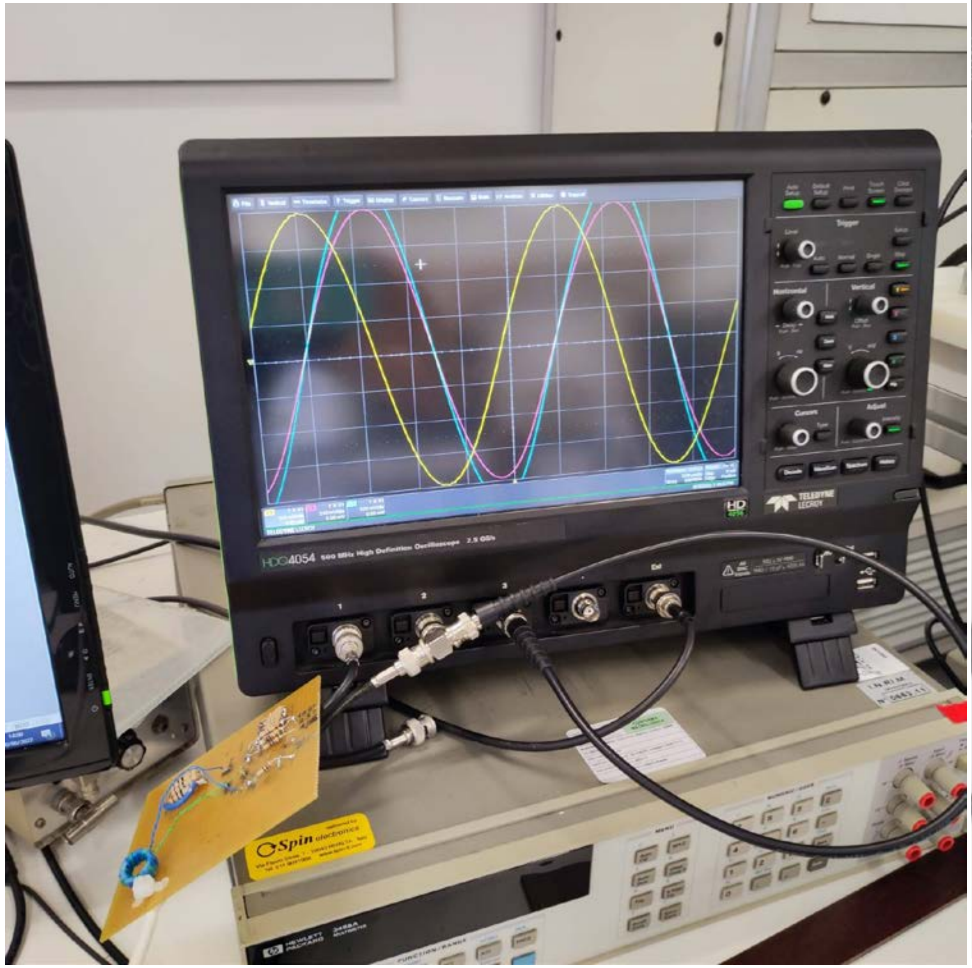
σ <2.5-4% f > 100 kHz

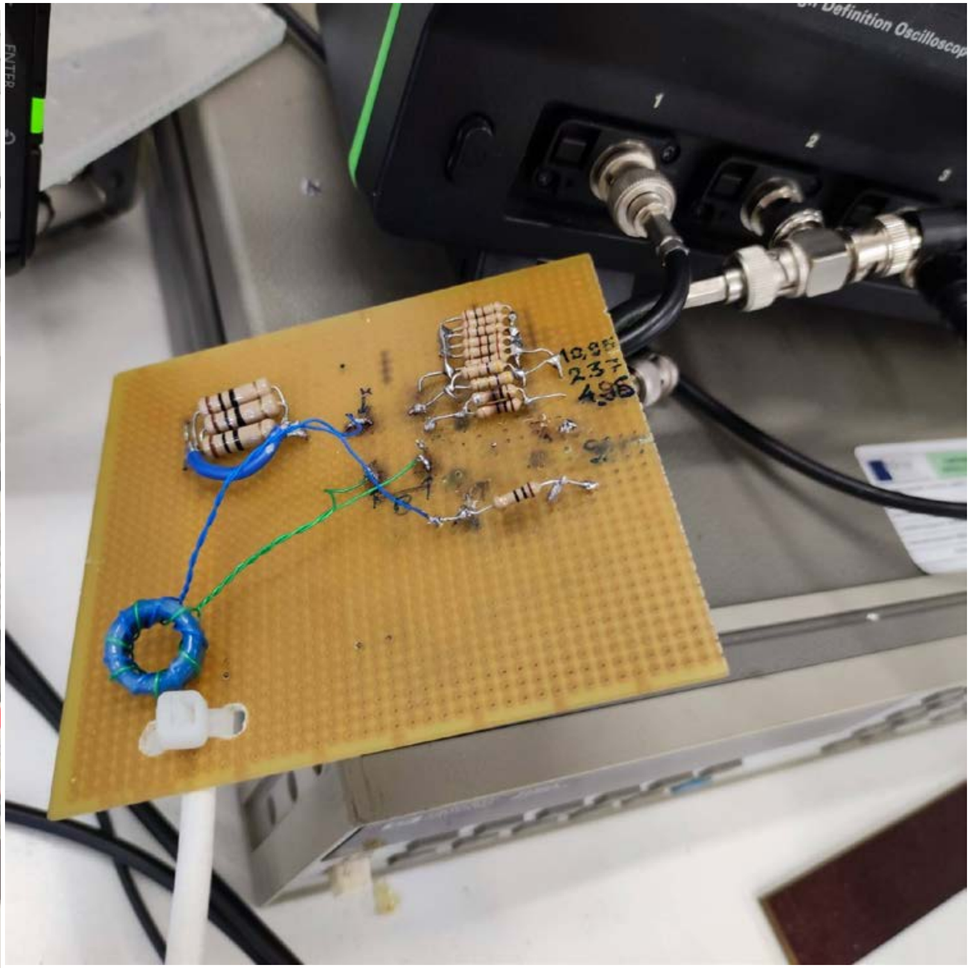
Magnetic Losses in Soft Ferrites Magnetochemistry 2022, 8, 60. https://doi.org/10.3390/magnetochemistry8060060;





Fluxmetric measurements (sinusoidal flux) ~DC – 10 MHz NOTICE SHORT CABLES!!

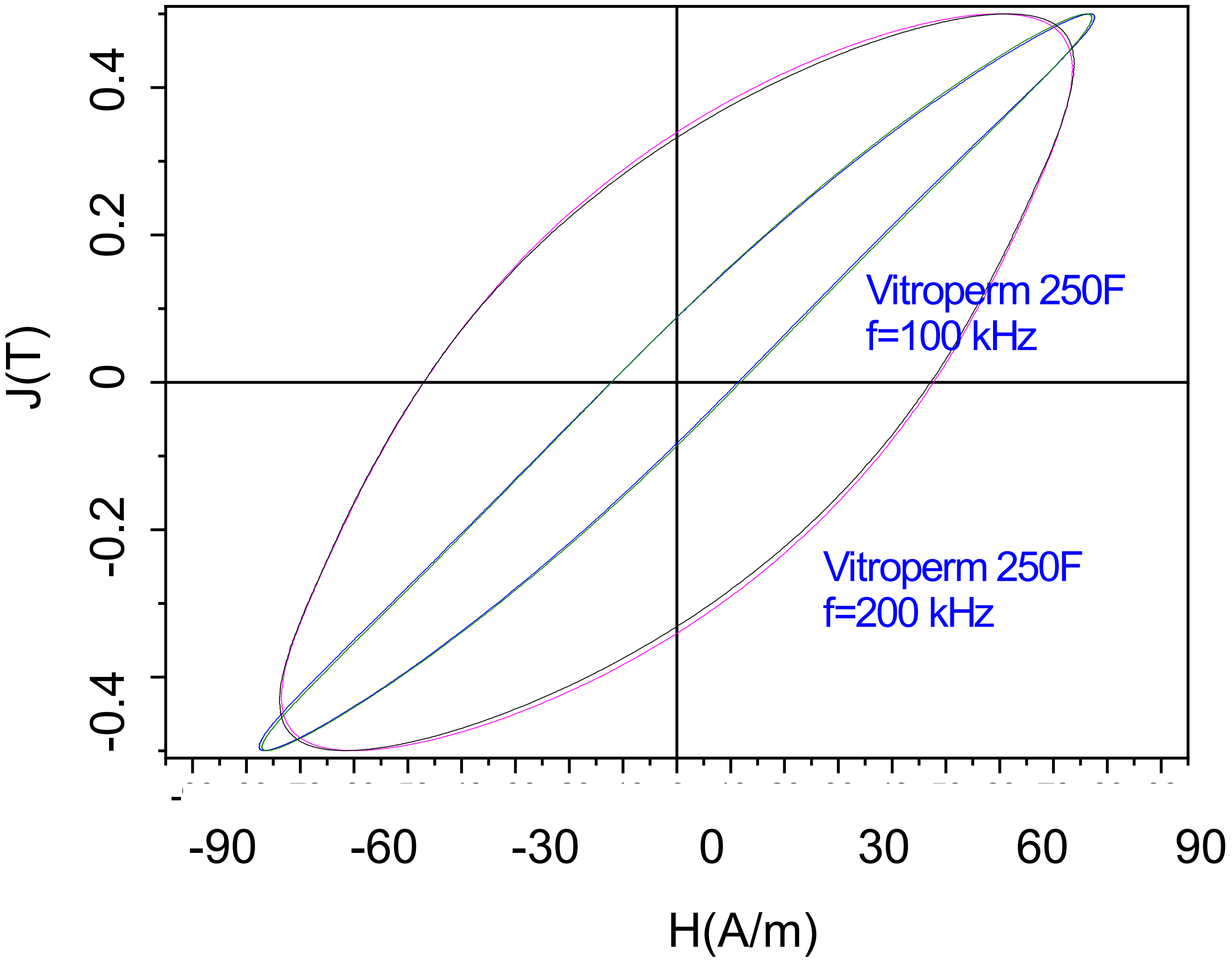


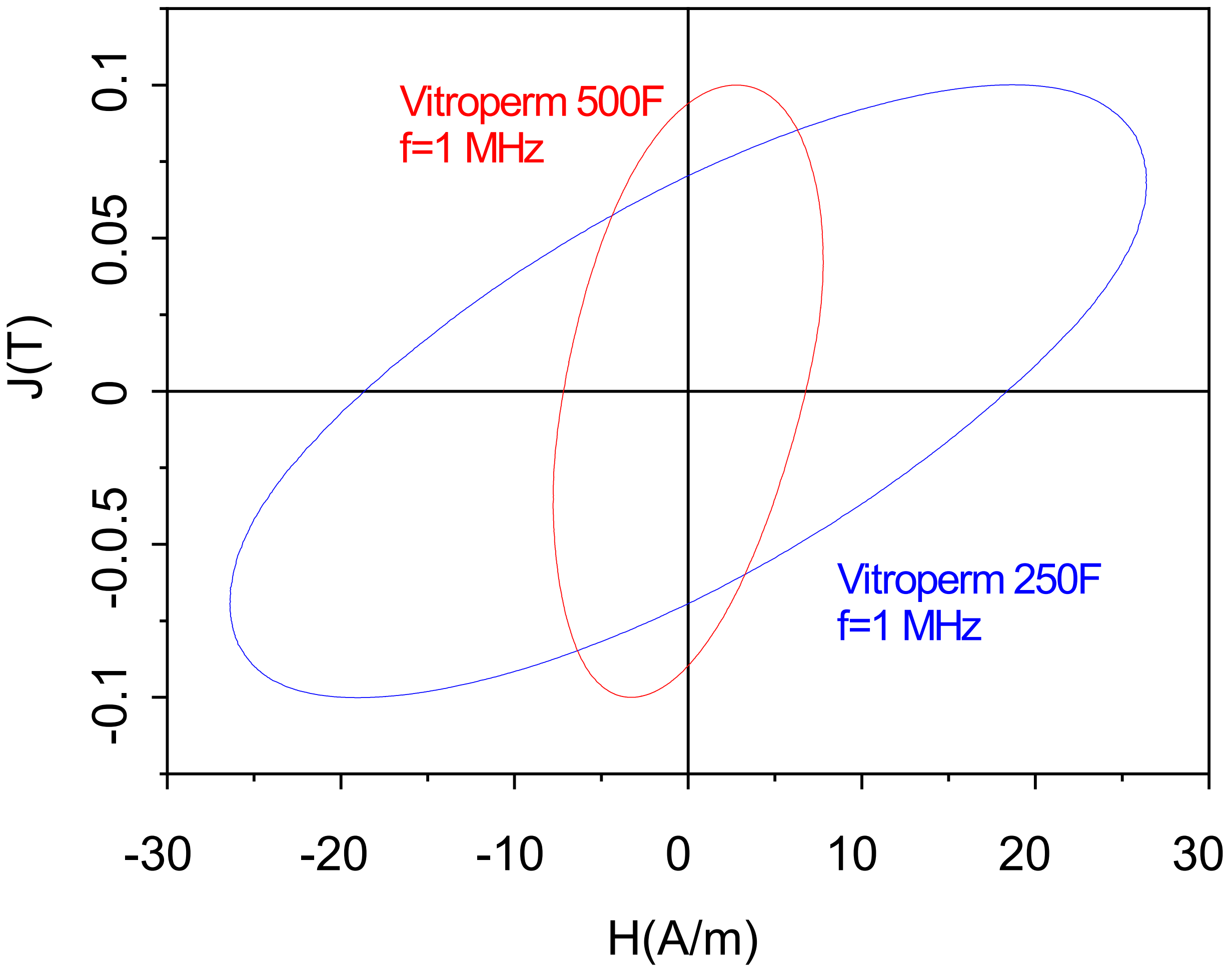


Loss measurements Good Practice Guide https://doi.org/10.5281/zenodo.8304171

Round Robin Comparisons (Standard Conditions)

INRIM Vitroperm FeCo 20-25 um thick

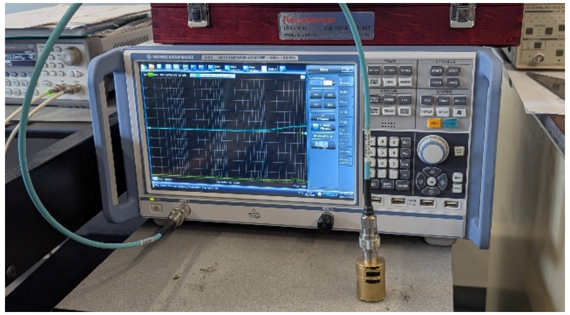




Wideband measurements kHz-GHz VNA S11-RLC meter

Vector Network Analyzer or Impedance analyzer (Keysight E4991B-16454A)

Coaxial short S11 measurements with VNA (kHz-GHz) or RLC meters (Hz-MHz-GHz)



RohdeSchwarz ZNB8 9 kHz-8,5 GHz

Keysight E4991B-16454A

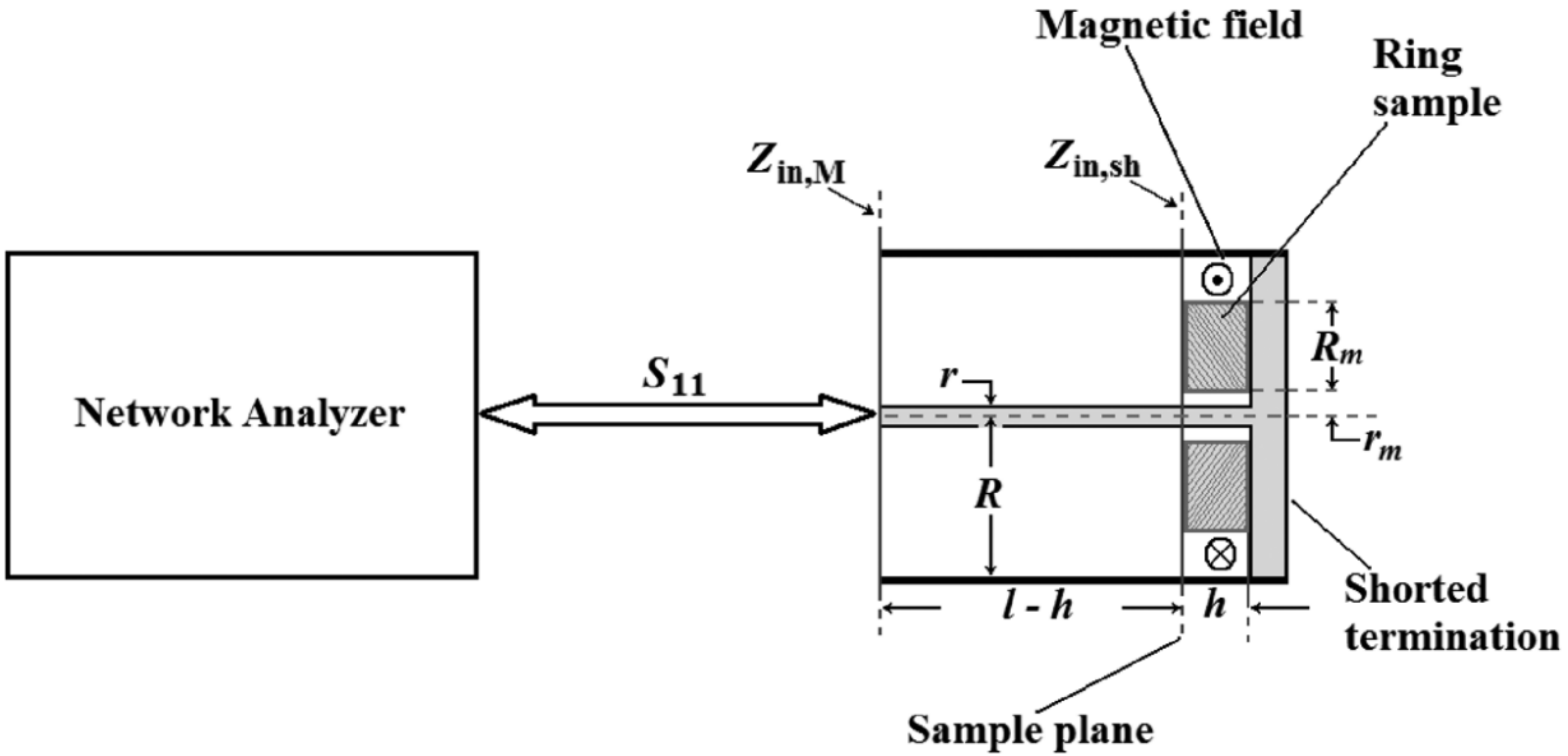
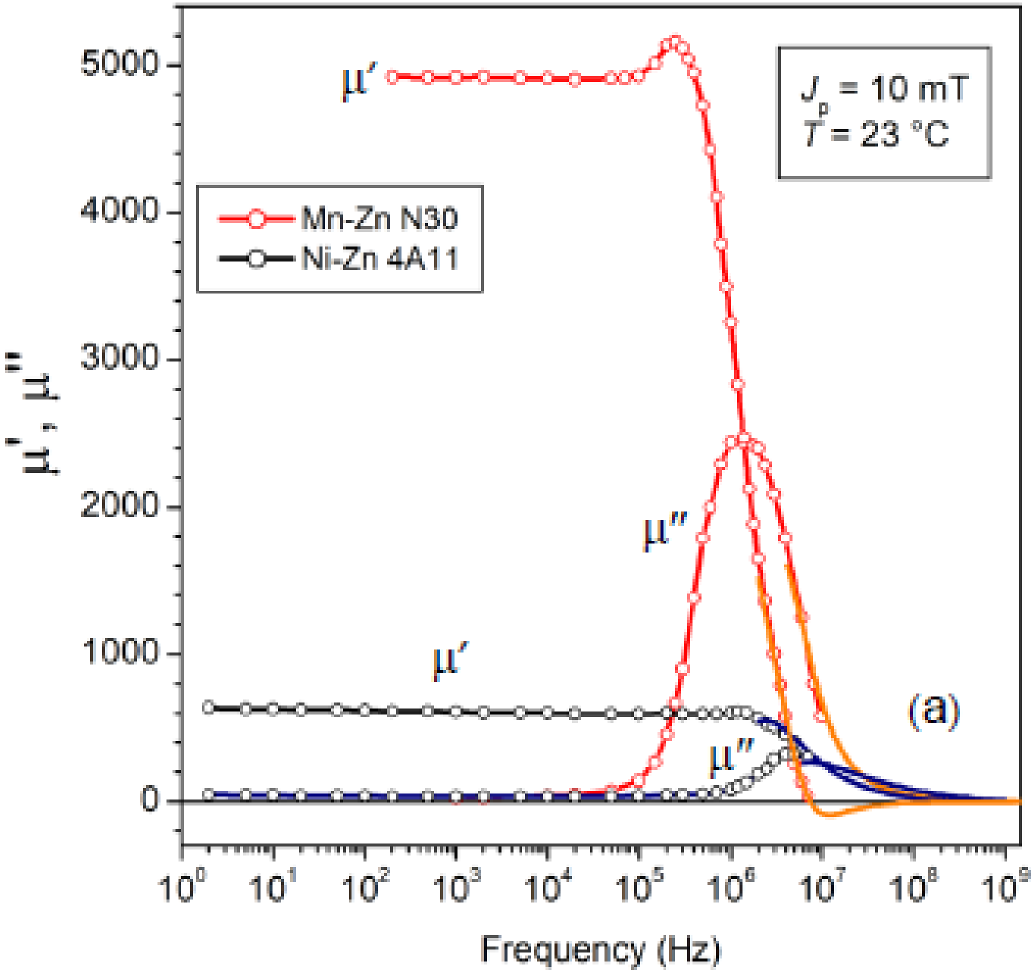


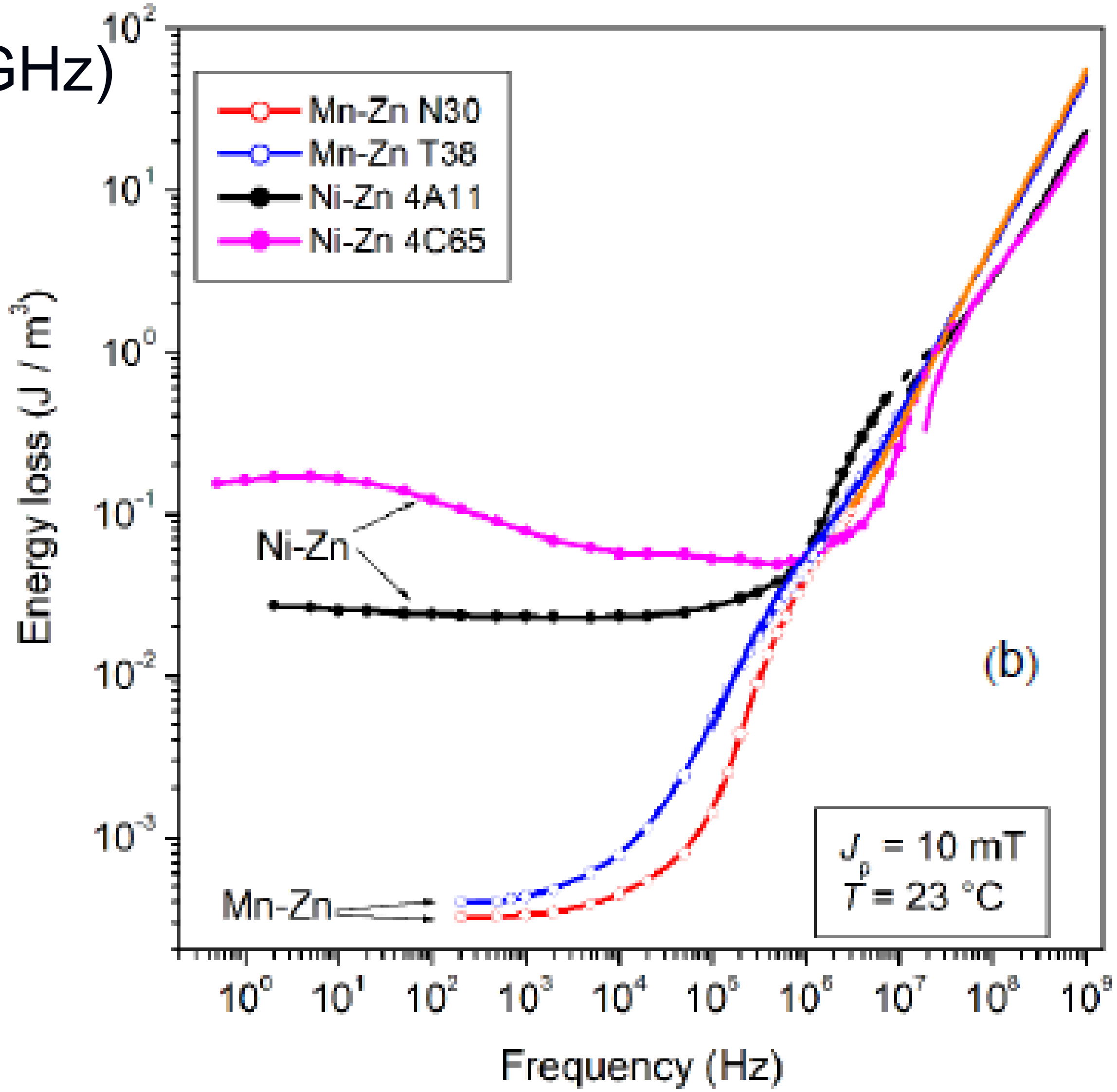
Fig. 1. VNA setup with a shorted termination.

Wideband measurements kHz-MHz Fluxmetric + kHz-GHz VNA S11

Vector Network Analyzer

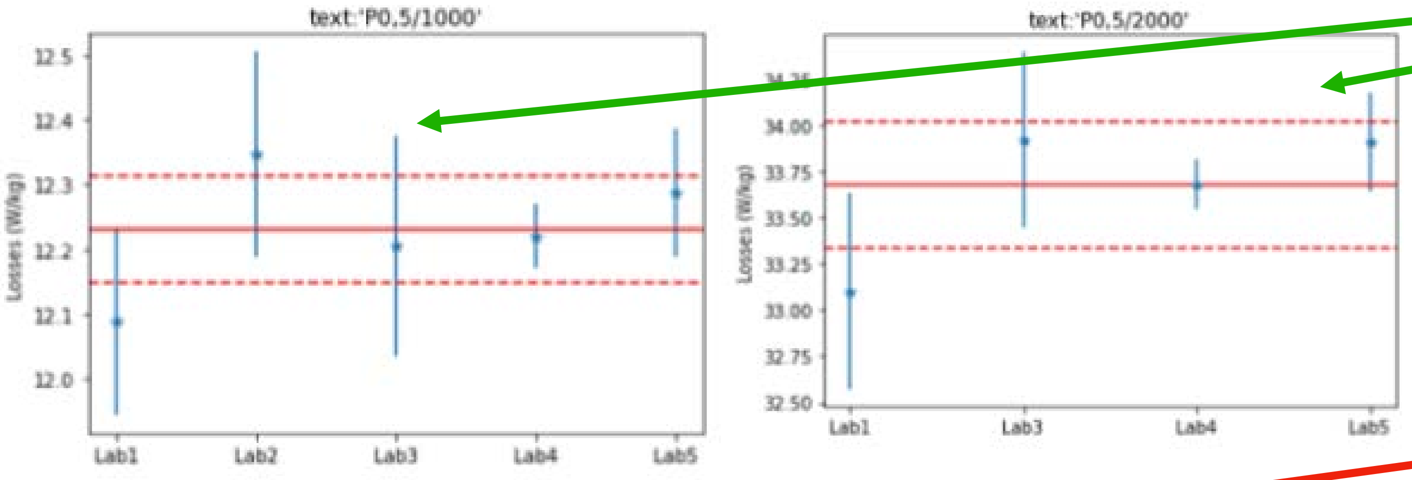
Coaxial short S11 measurements (kHz-GHz)



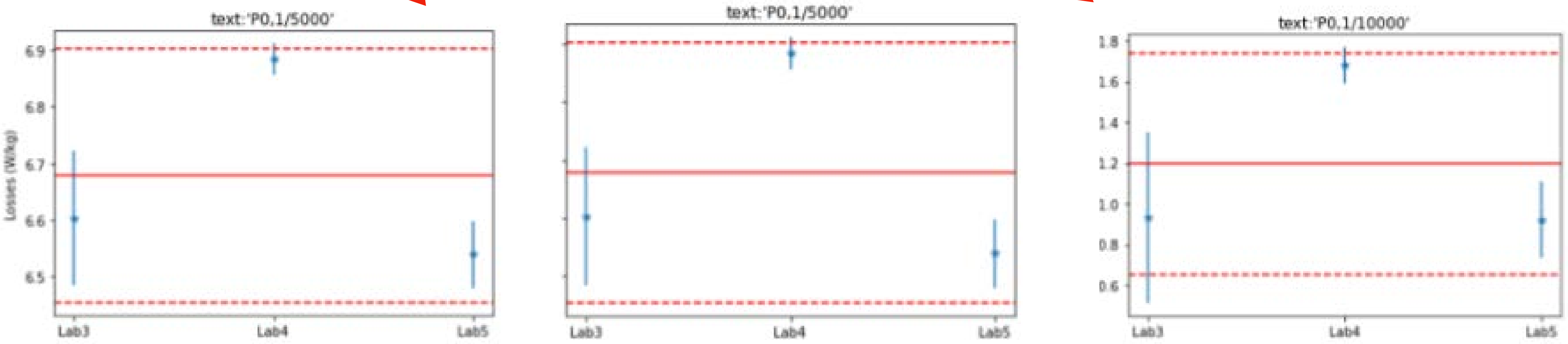


Details of the Round Robins- Mean and uncertainty determination – Examples NO 0.2 mm

Compatible datapoints



Notice scattering of datapoints and incompatibility of declared uncertainties



S Pommé and J Keightley 2015 *Metrologia* **52** S200**DOI** 10.1088/0026-1394/52/3/S200 (Appendix B)

What to do if $\chi^2 > 1$ (incompatible data and uncertainties)

Possible Actions:

- **Investigate Outliers**: Identify if any laboratory significantly deviates from the others.
- **Reassess Uncertainties**: Check whether some laboratories are underestimating their uncertainties.
- **Examine Systematic Errors**: Consider whether systematic biases are present.
- **Use a Robust Method**: If large discrepancies exist, consider using robust statistics that are less sensitive to outliers or reweighting the data.

$$\chi^2 = \sum_{i=1}^{N} \frac{(x_i - \mu)^2}{\sigma_i^2}$$

S Pommé and J Keightley 2015 *Metrologia* **52** S200**DOI** 10.1088/0026-1394/52/3/S200 (Appendix B)

Mandel–Paule mean

The M–P mean helps to deal with discrepant da sets, with a chi-squared value $\chi^2 > 1$.

The declared laboratory variances u_i are incremented by a further variance s^2 .

The value of the unexplained variance s^2 is chosen to obtain $\chi^2 = 1$.

$$\tilde{\chi}^2_{\mathrm{obs}} = \frac{1}{N-1} \sum_{i=1}^{N} \frac{\left(x_i - x_{\mathrm{ref}}\right)^2}{u_i^2 + s^2},$$

The M–P mean and its uncertainty are computed as the the weighted mean, replacing the stated variances with increased values

$$x_{\mathrm{ref}} = u^2\left(x_{\mathrm{ref}}\right) \sum_{i=1}^{N} \frac{x_i}{u_i^2 + s^2}, \frac{1}{u^2\left(x_{\mathrm{ref}}\right)} = \sum_{i=1}^{N} \frac{1}{u_i^2 + s^2}.$$

As the M–P mean x_{ref} occurs in the equation for χ, an iterative procedure is applied to find the appropriate value of the variance s^2.

S Pommé and J Keightley 2015 *Metrologia* **52** S200**DOI** 10.1088/0026-1394/52/3/S200 (Appendix B)

1. Fix as many parameters as possible (sample weight,sample cross section, primary/secondary windings, external cabling)
2. Measurement method should be the same for all
3. Consistent Lab Temperature (23°C ±5) may be too wide a range
4. Local uncertainty estimates may be too small → increase uncertainty to satisfy $\tilde{\chi}^2_{obs} = 1$ where

$$\tilde{\chi}^2_{obs} = \frac{1}{N-1}\sum_{i=1}^{N}\frac{(x_i - x_{ref})^2}{u_i^2 + s^2},$$

otherwise results may be incorrectly shifted

S Pommé and J Keightley 2015 *Metrologia* **52** S200**DOI** 10.1088/0026-1394/52/3/S200 (Appendix B)

Thank you for your interest.

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Loss modeling

Study of Domain Wall power losses under sinusoidal or distorted flux conditions

Loss separation based on structural and magnetic analysis

1) Sinusoidal induction

$$W_{\mathrm{class}}(J_{\mathrm{p}}, f) = \frac{\pi^2}{6\delta} \cdot \sigma J_{\mathrm{p}}^2 d^2 f \,, \qquad \text{[J/kg]}$$

$$W_{\mathrm{exc}}(J_{\mathrm{p}}, f) = \left(\frac{8.76}{\delta}\right)\sqrt{\sigma G S V_0 f}\, J_{\mathrm{p}}^{3/2}, \qquad \text{[J/kg]}$$

d = 0.18 mm, $\sigma = 2.083 \cdot 10^6$, δ = 7650 kg/m^3, G = 0.1356, $S = 0.18 \cdot 10^{-3} \cdot 30 \cdot 10^{-3}$ m^2

V_0 = 0.102 A/m. Fitting of W_{exc} under sinusoidal regime.

2) Distorted induction:

$$W_{\mathrm{class}}(J_{\mathrm{p}}, f) = \frac{\sigma d^2}{12\delta} \cdot \int_0^T \left(\frac{\mathrm{d}J}{\mathrm{d}t}\right)^2 \mathrm{d}t \,, \qquad \text{[J/kg]}$$

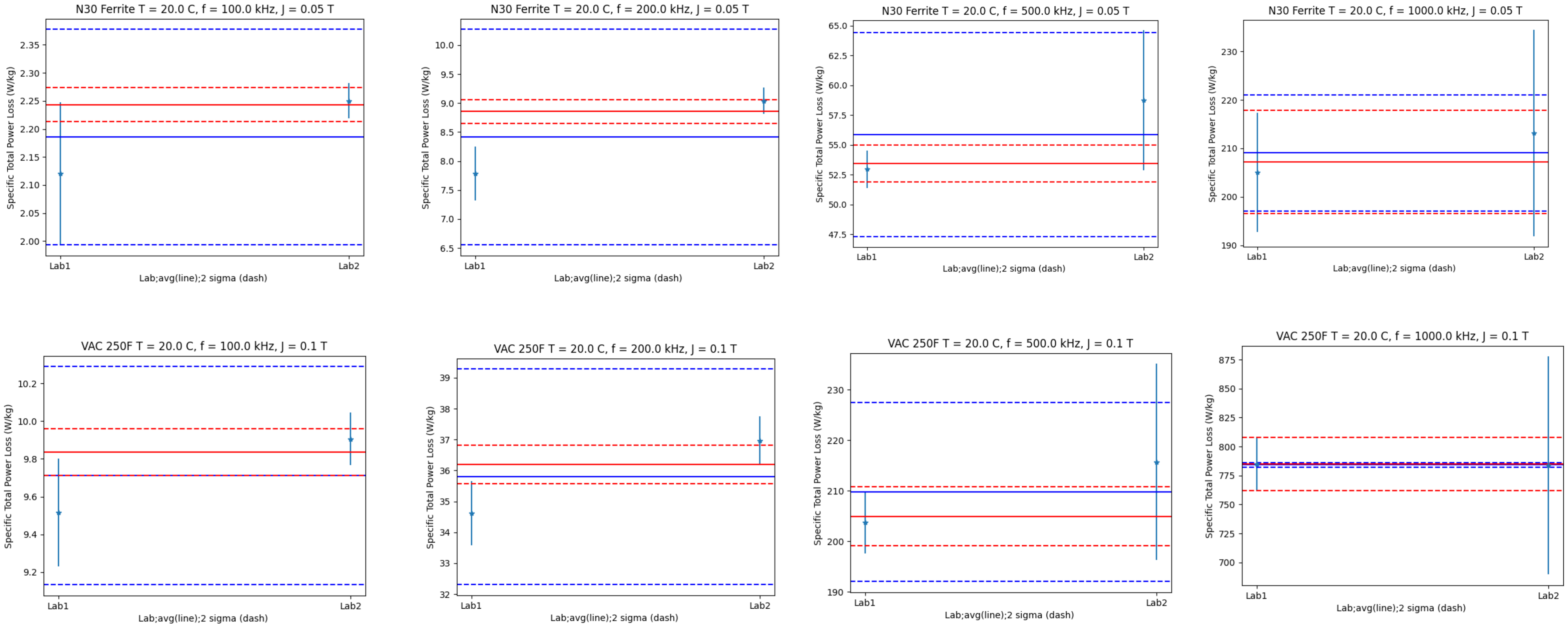
$$W_{\mathrm{exc}}(J_{\mathrm{p}}, f) = \left(\frac{1}{\delta}\right)\sqrt{\sigma G S V_0} \int_0^T \left|\frac{\mathrm{d}J}{\mathrm{d}t}\right|^{3/2} \mathrm{d}t \qquad \text{[J/kg]}$$

$$W(J_{\mathrm{p}}, f) = W_{\mathrm{hyst}}(J_{\mathrm{p}}, f) + W_{\mathrm{class}}(J_{\mathrm{p}}, f) + W_{\mathrm{exc}}(J_{\mathrm{p}}, f)$$

TPEL paper A. Banu 2025

Submitted

Mean and uncertainty determination – Examples HF rings



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