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Round robin comparison of power losses performed by epstein frame and sst above 50 hz at room temperature[☆]

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ABSTRACT

Epstein frame and single sheet tester are two methods used for measurement of power losses of the electrical steel sheets or strips. Both methods and the setups are described in the IEC standards. Each national metrology institute or other metrological laboratory has different setups for power losses measurement and the validation of its accuracy and parameters can only be done by comparisons. So far, every performed comparison was carried out only at 50 Hz or 60 Hz. Within the EMPIR project "HEFMAG", improved metrological infrastructure for the determination of power losses using Epstein frame at induction values close to saturation and at frequency ranges between 2 kHz and to 10 kHz was built. To validate the improved setups, a round robin comparison of power loss measurements was conducted by five laboratories. The results of the round robin comparison are discussed including measurement uncertainties.

1. Introduction

The push toward electrification and greener technologies will see an unprecedented uptake in use of electrical machines and in turn their associated magnetic materials. Electrical steels in particular have a central role to play in these developments and to build machines with greater efficiencies it is imperative that accurate, traceable measurements of the magnetic properties of these materials are available to industry. The total power loss is incredibly important in this regard accounting for a significant portion of the overall machine losses. The EMPIR (The European Metrology Programme for Innovation and Research) project "HEFMAG" aims to develop the metrology covering all aspects related to the measurement of magnetic losses in electrical steels.

The two most common experimental setups for the measurement of power losses in grain-oriented (GO) and non-oriented (NO) electrical steel are the Epstein frame and the single sheet tester (SST). Measurement of power losses at room temperature using Epstein frame up to 400 Hz is described in IEC 60404–2 [1] and up to 10 kHz in IEC 60404–10 [2]. Measurement of power losses at room temperature using SST is described in IEC 60404–3 [3] with no frequency range stated. Round robin (RR) comparisons are motivated by a permanent need to monitor and validate existing calibration and measurement capabilities (CMCs) at national metrology institutes (NMIs). Comparisons ensure reproducibility, reliability, and quantitative correct measurement values and uncertainties (MUs). In addition, metrological infrastructure at NMIs is constantly updated and modernized due to better electronics, software, and overall improved procedures. Small changes in the protocol might have an incremental effect on calibration results and MUs, however, those changes need to be monitored carefully to keep reliability in the data. RR comparisons on a regular basis are crucial to keep up with the high standards and performances at NMIs.

To date, several international comparisons, promoted by EURAMET (European Association of National Metrology Institutes), COOMET (The Euro-Asian Cooperation of National Metrological Institutions) and the IEC working group TC 68, have confirmed good reproducibility for both

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the Epstein and SST methods, with an uncertainty around 1% in power loss measurements. These comparisons, however, have only focused on measurements at 50 Hz or 60 Hz and they have been carried out at room temperature [4–8].

Within the HEFMAG project, a new reference round robin comparison was performed using Epstein frame and SST at extended frequencies (Epstein up to 400 Hz, SST at 50 Hz and 100 Hz) using non-oriented and grain-oriented samples. A new Epstein round robin comparison up to higher frequencies of 10 kHz using non-oriented electrical steel samples was also performed using improved setups. Here, we give a detailed description of the applied measurement procedures, use of reference samples, samples under test (SUT), and measurement setups, and discuss the results of round robin power losses in two steps. First, we compare the data taken between five partners in the HEFMAG project and secondly extending to NIM China and three interested stakeholders.

2. Epstein and SST setups description

Four national metrology institutes (NMIs) – PTB Germany, INRIM Italy, CMI Czech Republic and NPL United Kingdom - improved their Epstein and SST measurement setup compared to the last RR comparisons [4–8]. All NMIs have experimental setups following standard regulation, but each is realized slightly differently. The form factor of the sine wave signal on the secondary of the Epstein frame must be maintained at 1.11 ± 1% according to the standards [1–3]. This is achieved by using a feedback control. All NMIs apply different approaches to the feedback control and this also means that all NMIs achieve different levels of measurement uncertainties (MUs). The types of feedback control and typical MUs are found in Table 1.

Setups improvements were in uncertainty analysis, that leads to smaller uncertainty values, in expanding the frequency range above 400 Hz or in better feedback control. Detailed information about the PTB setup can be found in [9,10], about CMI setup in [11], details about INRIM and NPL setup can be found in [12]. The fifth laboratory involved in the round robin comparison was the University of Nottingham (UNOTT), United Kingdom. UNOTT is using a custom built setup from Brockhaus Messtechnik. It is a variant of MPG-200 type but has a flexible open box option with enhanced frequency, flux density and excitation routines.

The demagnetisation parameters also varied among NMIs. For example some always demagnetised the test specimens at 50 Hz and up to saturation magnetic polarization, while other NMIs always demagnetised at the same frequency of measurements to a polarization level, starting at levels of 1.8 T. The effect of this is discussed later.

Table 1
Feedback control and measurement uncertainty range at different NMIs.

NMI	Feedback control	Expanded uncertainty ($k = 2$) of Epstein measurement (%)	Expanded uncertainty ($k = 2$) of SST measurement (%)
INRIM	Iterative method based on loop shape	1–2 [a)]	1–2 [a)]
PTB	FFT analysis with analog and digital suppression of higher harmonics	0.2 to 2[a)]	0.3 to 0.7[a)]
CMI	based on the iterative method with proportional controller	0.5 to 1.6 [a)]	×
NPL	based on the iterative method with PID (proportional integral derivative) controller	0.40 to 1.0[a)]	0.40 to 1.0[a)]

a) depending on material properties and measurement parameters, e.g. J, f, m.

3. NO and GO electrical steel samples

3.1. Reference sample for Epstein frame

Six Epstein samples were prepared for the comparison. Each sample consisted of strips of at least 300 mm length and 30 mm width with each set consisting of a multiple of 4 strips. The transfer standards are:

- Two samples of NO electrical steel with approximate thicknesses of 0.2 mm and 0.3 mm
- Three samples of GO electrical steel with approximate thicknesses of 0.18 mm, 0.2 mm and 0.3 mm
- One sample of $Fe_{50}Co_{50}$ steel with an approximate thickness of 0.2 mm

For measurements below 400 Hz, the weight of each sample was at least 240 g and for measurements above 400 Hz a minimum of 12 strips were used. For the GO samples, all the strips were cut in the rolling directions, while for the NO samples half the strips were cut in the rolling direction (RD) and half in the transverse direction (TD).

Detailed parameters of the Epstein samples are given in Table 2. The first RR participant determined the cross section of whole sample by measuring length and mass of the sample and using the nominal density of the strips. These cross section values were used by all other participants.

3.2. Reference sample for SST

Five SST samples were prepared for the comparison. Each sample was a sheet with width of 500 mm and length of 500 mm. The transfer standards are:

- Two samples of NO electrical steel with approximate thicknesses of 0.2 mm and 0.3 mm
- Three samples of GO electrical steel with approximate thicknesses of 0.18 mm, 0.2 mm and 0.3 mm

The same grades of NO and GO steel were used for both the Epstein and SST comparisons. For the GO samples, measurements were carried out along the rolling direction, while for the NO samples measurements were carried out along the RD (length) and the TD (width).

Detailed parameters of the SST samples are given in Table 3. Again, the cross sections were determined by the first RR participant by measuring length and mass of the sample and using the nominal density of the sheets. Consecutively, the cross section values were used by all other participants.

Table 2
Parameters of the reference Epstein samples.

Sample	Density (kg/m^3)	Cross section (10^{-5} m^2)	Weight (kg)	Number of strips (−)	Nominal length (m)
Laser scribed GO 0.18	7650	3.3105 2.2073 1.6545	0.30924 0.20618 0.15455	24 16 12	0.305
GO 0.18	7650	2.61590 2.09280	0.25640 0.20504	20 16	0.320
NO 0.3	7600	2.64974	0.24140	12	0.300
GO 0.3	7650	4.2840	0.39331	20	0.300
NO 0.2	7650	2.89547 1.73397	0.26576 0.15917	20 12	0.300
FeCo 0.2	8120	3.5662 1.7834	0.34755 0.1736	24 12	0.300

Table 3
Parameters of the reference SST samples.

Sample	Density (kg/m^3)	Cross section (mm^2)	Weight (kg)	Length L (m)	Width W (m)
Laser scribed GO 0.18	7650	93.571	0.35793	0.50003	×
GO 0.18	7650	87.823	0.33587	0.49992	×
NO 0.3	7600	147.28 (L)/ 147.17 (W)	0.5592	0.49959	0.49995
GO 0.3	7650	144.11	0.55161	0.50036	×
NO 0.2	7650	97.397 (L)/ 97.413 (W)	0.37244	0.49986	0.49978

4. Round Robin comparison

4.1. Description of the measurements

To validate the improved Epstein and SST setups described above, a round robin power loss measurements were conducted by the five laboratories mentioned above. All participated in Epstein measurements and only three (PTB, INRIM, NPL) in SST measurements. Each participant performed the measurements using their standard equipment and measurement procedure according to their official CMC entries.

The specific total losses were measured for a series of peak polarization values, J_m, stepwise from the lowest to the highest value. Epstein samples were measured up to 1 kHz or 2 kHz for GO samples and up to 10 kHz for NO and $Fe_{50}Co_{50}$ with a target polarization of $J_m = 1.5$ T (NO) and to the $J_m = 1.8$ T (GO). SST samples were measured at 50 Hz and 100 Hz up to $J_m = 1.5$ T (NO) and to $J_m = 1.8$ T (GO).

The measurements were carried out at a temperature of either 23 °C ± 1 °C or 20 °C ± 1 °C.

4.2. Evaluation of comparison results

For all measurements, the evaluation of this comparison was performed following procedure B in [13]. Based on the power losses data and their uncertainties from all participants the following characteristics were calculated using M-P (Mandel-Paul) mean [14], and the modified reduced observed chi-squared value is:

$$\mathrm{X_{ref}} = \frac{\sum_{i=1}^{N} \frac{\mathrm{X_i}}{\mathrm{u^2(X_i)}}}{\sum_{i=1}^{N} \frac{1}{\mathrm{u^2(X_i)}}}, \text{где } \widetilde{\chi}_{obs} = \sqrt{\frac{1}{N-1}\sum\nolimits_{i=1}^{N} \frac{\left(x_i - x_{ref}\right)^2}{u_i^2 + s^2}}, \tag{1}$$

where N is the number of participants, x_i is the total loss results of the i-th participant of the comparisons and u_i is the declared standard uncertainty of the i-th participant for coverage factor $k = 1$ (coverage probability of approximately 68%). The value of the unexplained variance s^2 is chosen such that chi-squared value <1.

The reference value of total losses x_{ref} is estimated by

$$x_{ref} = u^2\left(x_{ref}\right)\sum\nolimits_{i=1}^{N} \frac{x_i}{u_i^2 + s^2}\, \mathrm{u}\left(\mathrm{X_{ref}}\right) = \sqrt{\frac{1}{\sum_{i=1}^{N} \frac{1}{\mathrm{u^2(X_i)}}}}, \tag{2}$$

and the standard uncertainty of the reference total loss value $u(x_{ref})$ is

$$u\left(x_{ref}\right) = \left[\sum\nolimits_{i=1}^{N} \frac{1}{u_i^2 + s^2}\right]^{-1/2}. \tag{3}$$

The degree of equivalence of the measurement standard d_i with a corresponding uncertainty $\mathrm{u}(d_i)$ is estimated according to equation.

$$d_i = x_i - x_{Ref}, \text{ and} \tag{4}$$

$$u(d_i) = \sqrt{u^2(x_i) - u^2\left(x_{ref}\right)} \tag{5}$$

Finally, the E_n factor was calculated according to

$$E_n = \frac{|d_i|}{2u(d_i)}. \tag{6}$$

The consistency between NMIs is confirmed, if inequality $|E_n| < 1$ is satisfied. Example of the calculated values of E_n are presented in Table 4.

4.3. Comparison results

Due to the large volume of measured data for the comparison, only the results for maximal J_m value at each frequency of one GO (0.3 mm) thickness and one NO (0.2 mm thickness) sample are shown. All results can be found in [15,16].

The Epstein comparison results for the GO sample, up to a frequency of 1 kHz are shown in Fig. 1, while the results for the NO sample up to a frequency of 10 kHz are given in Fig. 2. The SST comparison results for the GO and NO samples are shown in Fig. 3 and Fig. 4 respectively. All results are shown for $k = 2$.

5. Conclusion and discussion

The RR results are shown in Figs. 1 to 4 with the reference value x_{ref} marked as red solid line and the uncertainty $u(x_{ref})$ for coverage value $k = 2$ as dashed red line. The data overall shows very good agreement between all participants and corresponding E_n-values are smaller than 1. The RR comparison confirms calibration results at NMIs and validates their respective CMC entries.

Power loss measurements performed by the relevant partners on NO and GO FeSi laminations achieved a relative standard deviation σ of 1% or better. More specifically on conventional Epstein NO and GO FeSi laminations σ < 1% was achieved in 79/87 measurements (91%), while on special $Fe_{50}Co_{50}$ Epstein laminations, σ <1.5% was achieved in 18/27 cases (66%), due to the extreme magnetic softness and magnetostriction issues, which are discussed further below. On conventional FeSi SST samples, σ < 1% was achieved in 34/41 measurements (92%).

During the round robin comparison, several measurement challenges were identified, which are discussed below.

Differences were found between the measurements carried out using the 700 turn and 100 turn Epstein frames above 100 Hz [17]. Depending on the setup used there can be a significant difference when using the 700 turns frame above 100 Hz. From the comparison it seems that using 100 turns Epstein frame is better choice for frequencies above 100 Hz. This issue could also be connected to the high voltages observed in the secondary windings of the Epstein frame, which may induce a small but not negligible current flow in the secondary circuit. As such future comparisons may benefit from the inclusion of an Epstein frame to be exchanged together with reference sample to further minimize unwanted effects of the magnetic circuit on the data.

Specific care should be taken in the calibration and evaluation of phase shifts due to amplifiers, attenuators or shunts. In general, the presence of multiple components for the measurement of loss in different ranges may lead to additional uncertainty sources, which should be estimated beforehand and properly compensated.

The technical protocol was changed during the RR comparison, because setups of partners are optimized for different power ranges and the initially specified samples mass (number of stripes of the Epstein samples) did not work for every setup. As a consequence, the sample mass was reduced, which had a measurable effect on the loss values. We ascribe this observation to a non-negligible inhomogeneity of electrical steel sheets.

Issues can occur, when the environment temperature is outside the range stated in the IEC standard. The standard states the measurements should be made 23 °C ± 5 °C. It was verified that outside of this range an

Table 4
Example of the calculated values of E_n for Epstein samples.

Sample	f (Hz)/J_m (T)	x_{ref} (W/kg)	U(x_{ref}) (W/kg)	E_n				
				Lab1	Lab2	Lab3	Lab4	Lab5
GO 0.3	50/1.8	1.230	0.0030	0.033	0.260	0.033	0.258	×
	100/1.8	3.441	0.0090	0.460	0.799	0.034	0.259	×
	200/1.8	10.402	0.026	0.625	0.712	0.041	0.022	×
	400/1.8	34.48	0.10	0.534	0.708	0.081	0.198	×
	1000/1.0	45.40	0.12	0.469	0.186	0.000	0.359	0.984
NO 0.2	50/1.5	2.261	0.011	0.946	0.265	0.207	0.492	0.854
	100/1.5	4.931	0.037	0.990	0.595	0.177	0.268	0.569
	200/1.5	11.32	0.10	0.968	0.801	0.252	0.342	0.498
	400/1.25	17.85	0.15	0.975	0.225	0.162	0.219	0.437
	1000/1.25	65.67	0.38	×	0.331	0.139	0.821	0.573
	2000/0.5	33.68	0.17	0.920	×	0.401	0.010	0.508
	5000/0.35	72.06	0.28	×	×	0.010	0.494	0.610
	10,000/0.15	45.93	0.22	×	×	0.540	0.549	0.185

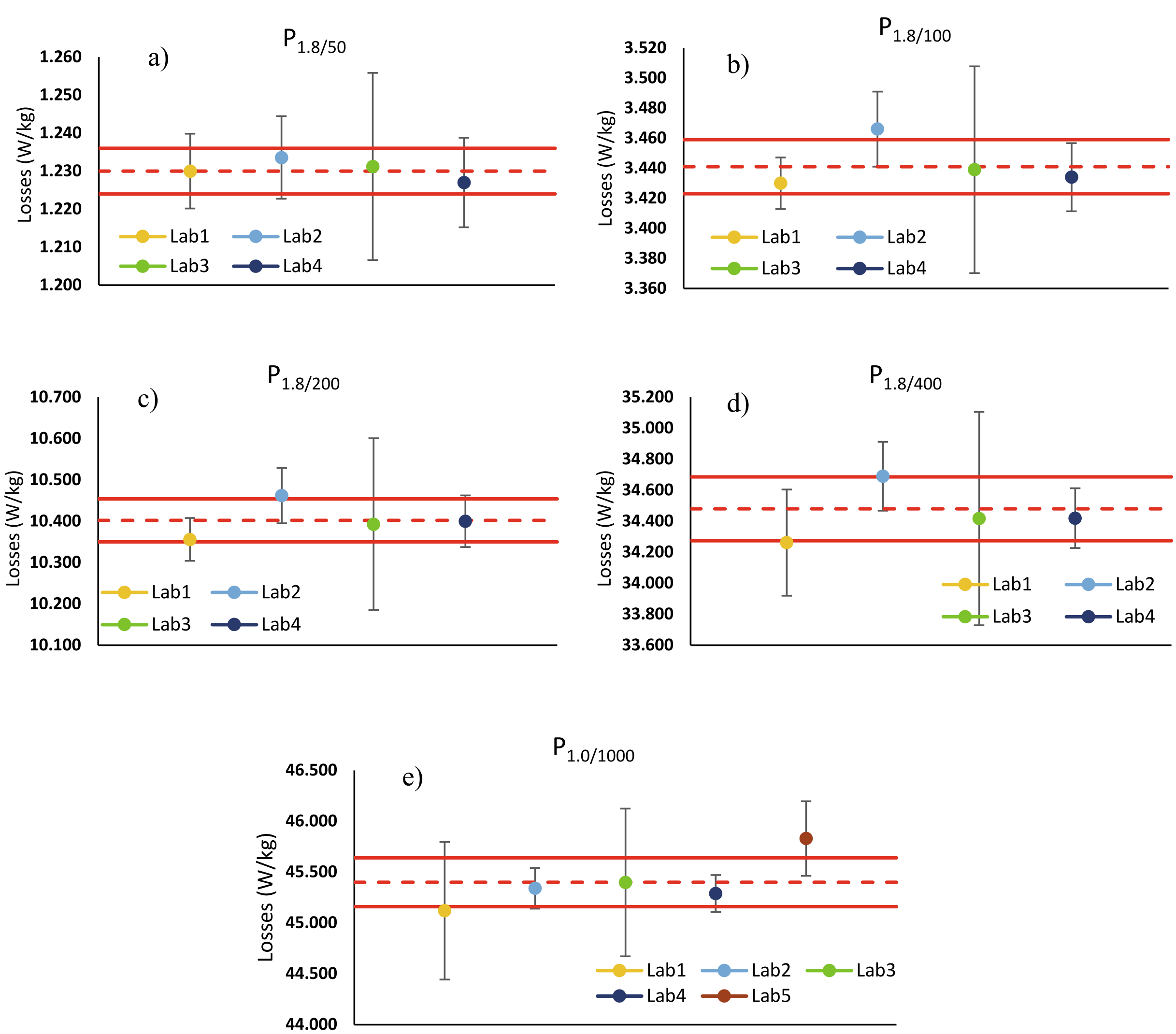

Fig. 1. Comparison results of Epstein sample GO 0.3 at: a) $J_m = 1.8$ T at 50 Hz, b) $J_m = 1.8$ T at 100 Hz, c) $J_m = 1.8$ T at 200 Hz, d) $J_m = 1.8$ T at 400 Hz and e) $J_m = 1.0$ T at 1000 Hz.

additional systematic measurement uncertainty should be included. Since temperature studies from the literature are limited to a coarse grit, e.g. data points at 20 °C, 50 °C and higher [18], it is currently impossible to extrapolate to small temperature changes. We also expect that climate conditions in the laboratory space, like air movement or fans need to be considered when regarding temperature effects and further investigations are highly recommended.

Power loss measurements (and the associated hysteresis loops) need to be performed ensuring a "single shot" acquisition of the H and dB/dt waveforms over a single period, without any averaging. Averaging the

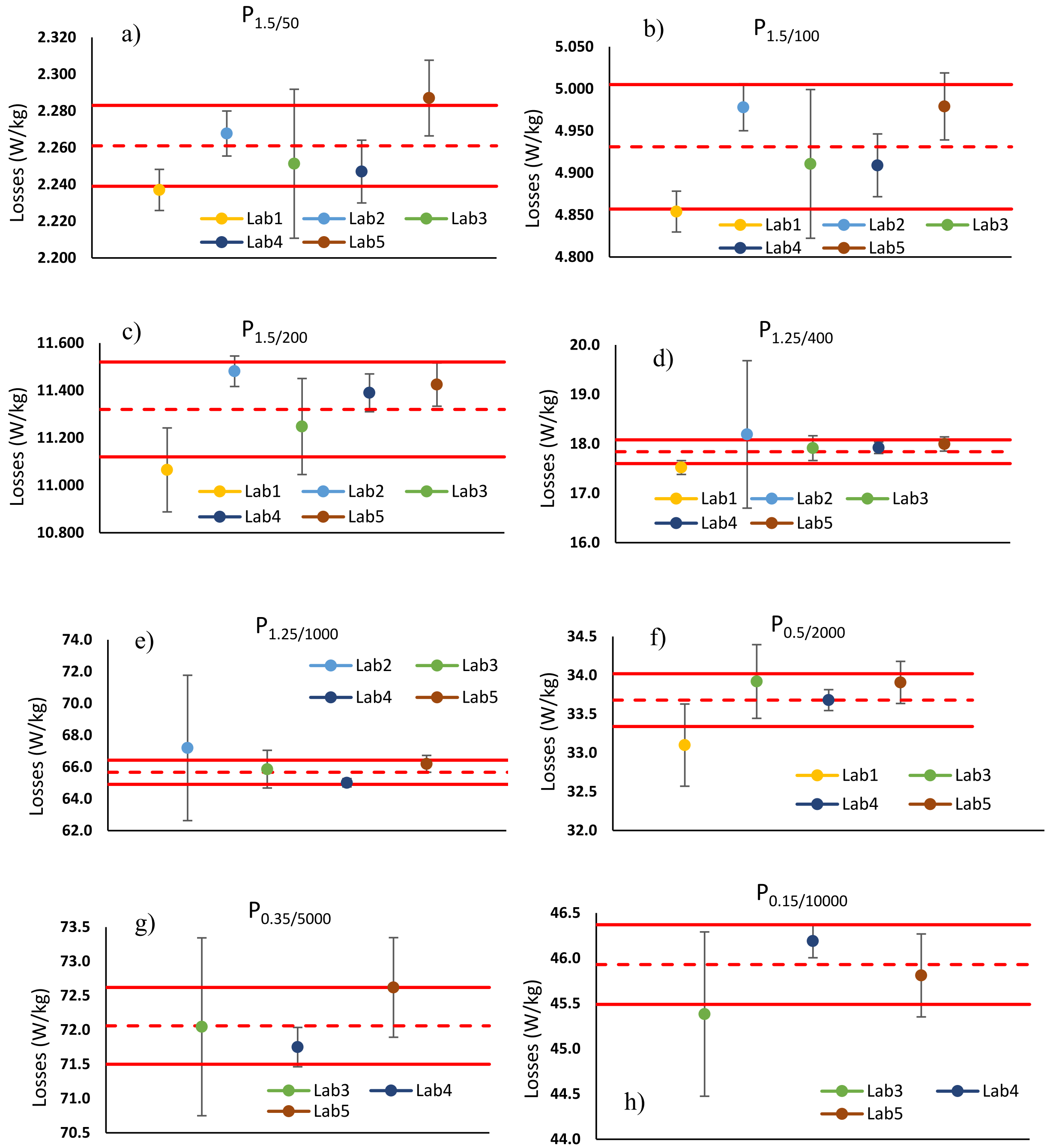

Fig. 2. Comparison results of Epstein sample NO 0.2 at: a) $J_m = 1.5$ T at 50 Hz, b) $J_m = 1.5$ T at 100 Hz, c) $J_m = 1.5$ T at 200 Hz, d) $J_m = 1.25$ T at 400 Hz, e) $J_m = 1.25$ T at 1000 Hz, f) $J_m = 0.5$ T at 2000 Hz, g) $J_m = 0.35$ T at 5000 Hz and h) $J_m = 0.15$ T at 10000 Hz.

waveforms over several measurement periods will mask the stochastic nature of the hysteresis phenomenon and may lead, depending on the type of material, to significant additional uncertainties. A loss average can only be obtained by averaging the results of several single shot one period measurements. Additionally peak polarization measurement at specific magnetic field strengths (e.g. determining J_m at 800 A/m) also need to be performed as single shot experiments. The vertices of the loops obtained should then for a cloud of points from which and uncertainty in H and J can be derived.

Measurements of magnetostrictive Epstein strips, such as $Fe_{50}Co_{50}$ and Fe—Si at high frequency, should be performed taking particular care in the positioning of the Epstein strips in the circuit, allowing the cyclical deformation of the strips, while avoiding large strip motions due to the vibrations.

The loop must be as symmetric as possible. Single shot acquisitions may help to determine which loops can be used to determine the average loss and which should be discarded, being asymmetric. In the case of FeCo minor loops ($B < 1.5$ T) it was frequently observed a large intrinsic asymmetry of the loop shapes, possibly connected to the extreme magnetic softness and the large saturation value. The asymmetric behaviour consisted in a natural tendency of the hysteresis loop to reach saturation preferentially upon positive (or negative) values of the applied field, regardless of small corrections of the primary dc bias, and upon exceeding a dc bias threshold correction it would simply switch the asymmetry toward the opposite saturation. To alleviate this problem, it was necessary to repeat the measurements several times, after a careful sample demagnetization. Regardless of these mitigation procedures, a higher uncertainty of the FeCo results was found, even though loops

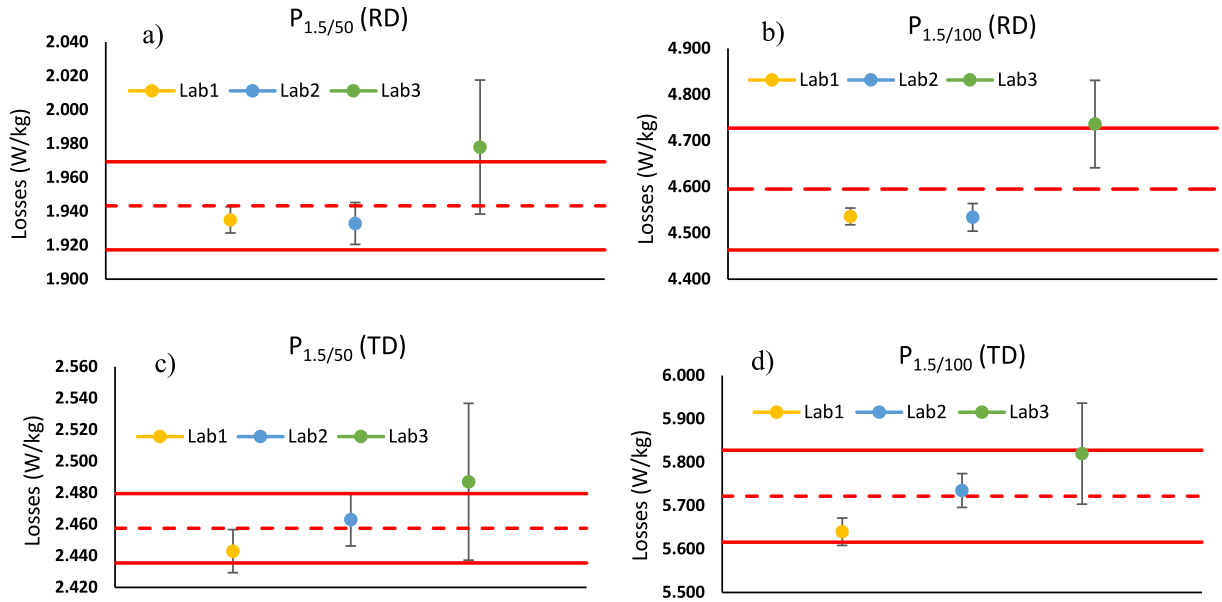

Fig. 3. Comparison results of SST sample NO 0.3 at: a) $J_m = 1.5$ T at 50 Hz in the direction RD, b) $J_m = 1.5$ T at 50 Hz in the direction RD, c) $J_m = 1.5$ T at 100 Hz in the direction TD and d) $J_m = 1.5$ T at 100 Hz in the direction TD.

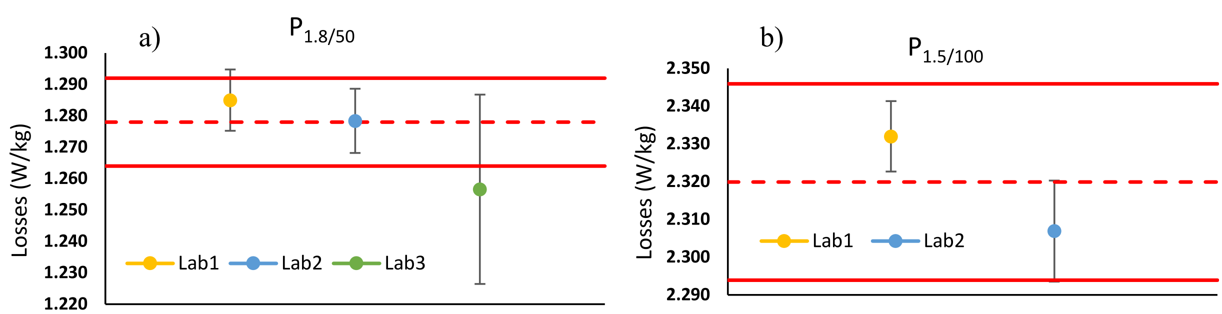

Fig. 4. Comparison results of SST sample GO 0.3 at: a) $J_m = 1.8$ T at 50 Hz and b) $J_m = 1.5$ T at 100 Hz.

were captured under the same requirements of form factor and saturation accuracy as all the other measurements.

Due to a failure in one of the participants Epstein frame‘s mutual inductor, the magnetic flux density B was measured instead of the polarization J. It was found the air flux correction described in the IEC 60404–6 (power loss on rings) [19] was sufficient to correct the data. In cases where the mutual inductor cannot be use it is important to have an accurate determination of the cross section of the secondary windings of the Epstein frame. This can be done either by determination of the average dimensions of four Epstein limbs or through use of a mutual inductance bridge. To perform this correction it is also advised to take several points around either side of the target polarization to determine the power loss curve in this region. Fitting this curve and using the calculated change in field, a correction can then be applied to the measured power loss value.

It was found that varying the demagnetization procedure changes the sample properties. The power loss standards are nonspecific when defining the demagnetization parameters, i.e. it states in [19]:

Prior to measurement, the test specimen shall be carefully demagnetized from a value of field strength of not less than ten times the coercivity by slowly reducing the corresponding magnitude of the magnetizing current to zero. Demagnetization shall be carried out at the same or lower frequency as will be used for the measurements.

From domain observation experiments at the surface of GO magnetic sheets, it is known that domain refinement occurs, meaning the domain size decreases, if the sample is demagnetized with higher frequencies [20]. As a result of domain refinement, the magnetic loss decreases for certain polarization ranges. The maximum polarization value, at which the demagnetization process is started, also changes the loss results, as observed during the experiments. This effect is more pronounced for loss values at intermediate polarizations in the order of 1 T, and not obvious for data taken at maximum J of about 1.8 T. Therefore, it was only recognized lately, when loss calibrations at intermediate Js have been requested by stakeholders more frequently. Systematic follow up studies are necessary to quantify the influence of demagnetization parameters on the loss data of different kinds of materials. As such for future comparison, the demagnetization should be agreed and used by all participants.

CRediT authorship contribution statement

Michal Ulvr: Writing – original draft, Validation, Supervision, Investigation, Formal analysis. **Franziska Weickert:** Writing – original draft, Validation, Investigation. **Korbinian Pfnuer:** Validation, Investigation. **Joachim Lüdke:** Validation, Investigation. **Katja Hoffmann:** Validation, Investigation. **Stuart Harmon:** Writing – review & editing, Investigation. **Daniel Brunt:** Writing – original draft, Investigation. **Adam Wilson:** Validation, Investigation. **Massimo Pasquale:** Writing – review & editing, Supervision, Investigation, Formal analysis. **Carlo Appino:** Writing – review & editing, Validation, Investigation. **Chris Gerada:** Validation, Investigation. **Ram Ramanathan Mathavan jeyabalan:** Validation, Investigation. **Gaurang Vakil:** Validation, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michal Ulvr reports financial support was provided by EURAMET European Metrology Programme for Innovation and Research and partly financial support was provided by Institutional Subsidy for Long-Term Conceptual Development of a Research Organization granted to the Czech Metrology Institute by the Ministry of Industry and Trade. Franziska Weickert reports financial support was provided by EURAMET European Metrology Programme for Innovation and Research. Korbinian Pfnuer reports financial support was provided by EURAMET European Metrology Programme for Innovation and Research. Joachim Ludke reports financial support was provided by EURAMET European Metrology Programme for Innovation and Research. Katja Hoffmann reports financial support was provided by EURAMET European Metrology Programme for Innovation and Research. Stuart Harmon reports financial support was provided by EURAMET European Metrology Programme for Innovation and Research. Daniel Brunt reports financial support was provided by EURAMET European Metrology Programme for Innovation and Research. Adam Wilson reports financial support was provided by EURAMET European Metrology Programme for Innovation and Research. Massimo Pasquale reports financial support was provided by EURAMET European Metrology Programme for Innovation and Research. Carlo Appino reports financial support was provided by EURAMET European Metrology Programme for Innovation and Research. Chris Gerada reports financial support was provided by EURAMET European Metrology Programme for Innovation and Research. Ram Ramanathan Mathavan jeyabalan reports financial support was provided by EURAMET European Metrology Programme for Innovation and Research. Gaurang Vakil reports financial support was provided by EURAMET European Metrology Programme for Innovation and Research. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Raw data from different laboratories had to be reformatted for comparison purposes. The reformatted data is available upon request.

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