

TECHNICAL REPORT



International comparison of measurements of the magnetic moment using vibrating sample magnetometers (VSM) and superconducting quantum interference device (SQUID) magnetometers

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE



ICS 29.030

ISBN 978-2-8322-1018-5

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

INTERNATIONAL COMPARISON OF MEASUREMENTS OF THE MAGNETIC MOMENT USING VIBRATING SAMPLE MAGNETOMETERS (VSM) AND SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE (SQUID) MAGNETOMETERS

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IEC 62797, which is a technical report, has been prepared by IEC technical committee 68: Magnetic alloys and steels.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
68/448/DTR	68/454/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

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INTRODUCTION

Following a proposal made at the meeting of IEC TC 68 Working Group 2 (Magnetic alloys and steels – Measuring methods) in Braunschweig (PTB, 13-14 November 2006), an intercomparison exercise was started regarding the measurement of the magnetic moment by means of the vibrating sample magnetometer (VSM) method. The VSM finds widespread use in industrial and research laboratories, because of its sensitivity, ruggedness, and relative simplicity of use [1]¹. It is not an absolute method and requires calibration by means of a reference sample. This is typically represented by a very pure Ni sphere, calibrated by means of an independent method [2]. The VSM is generally applied for the characterization of hard magnetic materials, but, depending on the specific sensitivity of the apparatus, can also be used to test paramagnetic and diamagnetic materials. Its application to magnetically soft materials is generally restricted to the determination of the saturation magnetization. In fact, being an open circuit method, the VSM is not suited to the measurement of the magnetization curve of soft magnetic materials.

The basic aim of this comparison is to verify the degree of reproducibility of the method, a prerequisite for the prospective development of a related IEC measuring standard. The existing ASTM Standard A894/894M-00 [3] is devoted to the determination of the saturation magnetization of nonmetallic magnetic materials. Ten different research laboratories, listed in Annex B, agreed to participate in the comparison exercise. Each laboratory was assumed to have appropriate traceability of measurements and was required to determine the measurement uncertainty according to the ISO/IEC Guide to the expression of uncertainty in measurement [4]. Two laboratories used superconducting quantum interference device (SQUID) magnetometers.

The comparison was coordinated by INRIM (Istituto Nazionale di Ricerca Metrologica, Torino, Italy) and the Hannam University (Taejon, Korea). A summarizing paper on these experiments was presented at the International Workshop on One- and Two-Dimensional Measurement and Testing (Vienna, September 2012) and is to be published on the Int. J. Appl. Electromagnetics and Mechanics [8].

¹ Numbers in square brackets refer to the Bibliography.

INTERNATIONAL COMPARISON OF MEASUREMENTS OF THE MAGNETIC MOMENT USING VIBRATING SAMPLE MAGNETOMETERS (VSM) AND SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE (SQUID) MAGNETOMETERS

1 Scope

This Technical Report provides the results of an international comparison of measurements of the magnetic moment, using vibrating sample magnetometers (VSM) and superconducting quantum interference device (SQUID) magnetometers.

The basic object of this comparison is to verify the degree of reproducibility of the method employed as a prerequisite for the prospective development of a related IEC measuring standard.

2 Overview

In this report an intercomparison exercise on the measurement of the magnetic moment by means of the vibrating sample magnetometer (VSM) and superconducting quantum interference device (SQUID) magnetometer is presented. The VSM finds widespread use in industrial and research laboratories, because of its sensitivity, ruggedness, and relative simplicity of use. The basic aim of this comparison was to verify the degree of reproducibility of the VSM method, as a prerequisite for the prospective development of a related IEC measuring standard. At present time, the VSM method is invoked in the ASTM Standard A984, which is devoted, however, exclusively to the determination of the saturation magnetization of nonmetallic magnetic materials. An exercise was carried out by ten different laboratories regarding the measurement of the hysteresis loop parameters in hard ferrites and the magnetic moment in tape samples by means of the VSM (SI units). Each laboratory was assumed to have appropriate traceability of measurements and was required to determine the measurement uncertainty according to the ISO/IEC Guide to the expression of uncertainty in measurement. The comparison was coordinated by INRIM. The results were analyzed according to standard rules (e.g. ISO and EURAMET guidelines).

The following relative standard deviations of the laboratories best estimates around the unweighted mean were found:

- a) Anisotropic hard ferrites: coercive field $H_{cJ} \sim 1,0 \%$; coercive field $H_{cB} \sim 0,9 \%$; polarization at applied field $H_a \sim 800 \text{ kA/m}$ $J_{800k} \sim 0,80 \%$; remanent polarization $J_r \sim 1,8 \%$; maximum energy product $(BH)_{\max} \sim 1,2 \%$.
- b) Isotropic hard ferrites: coercive field $H_{cJ} \sim 1,0 \%$; coercive field $H_{cB} \sim 3,5 \%$; polarization at applied field $H_a = 800 \text{ kA/m}$ $J_{800k} \sim 1,2 \%$; remanent polarization $J_r \sim 3,2 \%$; maximum energy product $(BH)_{\max} \sim 6,2 \%$.
- c) Magnetic tape samples: magnetic moment at $H_a = 400 \text{ kA/m}$ $m_{400k} \sim 1,8 \% - 2,8 \%$; remanent magnetic moment $m_r \sim 1,3 \% - 1,6 \%$; squareness $S \sim 2,0 \%$; coercive field $H_{cJ} \sim 1,1 \% - 2,2 \%$.

3 Samples

3.1 Hard ferrites

Two different types of hard ferrite spherical samples (isotropic and anisotropic) were prepared at INRIM by grinding commercial sintered ferrite specimens. Two samples for each type were circulated.

- Isotropic hard ferrite spherical sample. Label: HF_iso1. Mass $m = 74,50$ mg. Density $\delta = 4\,950$ kg/m³. Volume $V = 15,05$ mm³.
- Isotropic hard ferrite spherical sample. Label: HF_iso2. Mass $m = 77,15$ mg. Density $\delta = 4\,950$ kg/m³. Volume $V = 15,59$ mm³.
- Anisotropic hard ferrite spherical sample. Label: HF_anis1. Mass $m = 73,33$ mg. Density $\delta = 4\,870$ kg/m³. Volume $V = 15,06$ mm³.
- Anisotropic hard ferrite spherical sample. Label: HF_anis2. Mass $m = 73,31$ mg. Density $\delta = 4\,870$ kg/m³. Volume $V = 15,06$ mm³.

The circulation of the samples started with measurements made at INRIM. After completion of the measurements by all the other laboratories, INRIM measured the sample mass again and repeated the magnetic measurements. A slight decrease of the mass, which ranged from 0,2 % to 0,3% in all samples, was eventually found. No attempt was made, however, to correct for this loss of mass, which presumably took place gradually along the exercise. Its effect has been assumed to be incorporated in the overall measuring uncertainty.

3.2 Magnetic tapes

Disk samples were cut from two different types of magnetic tape at Hannam University and dispatched to INRIM before starting the circulation. Two samples for each type were tested.

- Tape 1A. Mass $m = 1,258$ mg. Diameter $d = 3$ mm.
- Tape 1B. Mass $m = 1,248$ mg. Diameter $d = 3$ mm.
- Tape 2A. Mass $m = 1,246$ mg. Diameter $d = 3$ mm.
- Tape 2B. Mass $m = 1,205$ mg. Diameter $d = 3$ mm.

Again, INRIM tested the samples at the beginning and at the end of the exercise. It was found that Tape 1B and Tape 2B samples were damaged. The measurements concerning Tape 1A and Tape 2A only were therefore retained for analysis.

4 Measuring quantities and measuring conditions

4.1 General

A demagnetization procedure before starting the measurements was recommended. The suggested maximum peak value of the magnetic field strength to be progressively and cyclically decreased, was $H_{a,peak,max} \geq 800$ kA/m.

4.2 Hard ferrite spheres

Before starting the measurement, the demagnetized spherical samples were oriented with their macroscopic easy axis aligned with the applied field direction. A simple way to achieve alignment is to let the sample free to orient itself in a weak field. Fine adjustments may possibly be done on site by looking for maximum VSM response. Notice that the nominally isotropic sample is endowed with slight macroscopic anisotropy. Previous experiments showed that a $\pm 5^\circ$ misalignment in anisotropic samples can lead to a decrease of the measured remanence around 1 %. A similar decrease occurs in the typical isotropic ferrites for a misalignment as high as $30^\circ - 40^\circ$. The measurement in this material is therefore negligibly affected by imperfect orientation of the easy axis along the applied field direction.

The applied field was then increased up to $H_{a,peak} = 800$ kA/m and the return magnetization curve was recorded, after correction for the demagnetizing effect. The effective field was

obtained as $H = H_a - \frac{N_d}{\mu_0} J$, with H_a the applied field, J the magnetic polarization, $\mu_0 = 4\pi \cdot 10^{-7}$ Vs/Am, and the demagnetizing coefficient, under the assumption of a perfectly spherical sample, $N_d = 1/3$. The following quantities were measured:

- Magnetic polarization J_{800k} at $H_a = H_{a,peak} = 800$ kA/m;
- Remanent polarization J_r for $H = 0$;
- Coercive fields H_{cB} and H_{cJ} ;
- Maximum energy product $(BH)_{max}$.

4.3 Magnetic tape samples

Before starting the measurement, the demagnetized disk-shaped samples were oriented with their macroscopic easy axis aligned with the applied field direction. A faint mark on the disk surface indicated the easy axis. The applied field was increased up to $H_{a,peak} = 400$ kA/m and subsequently decreased down to the symmetric value $-H_{a,peak} = -400$ kA/m. No correction for the demagnetizing field was made.

The following quantities were determined:

- Magnetic moment m_{400k} for $H_a = H_{a,peak} = 400$ kA/m;
- Remanent moment m_r for $H_a = 0$;
- Squareness $S = m_r / m_{400k}$;
- Coercive field H_{cJ} .

While the intercomparison was specifically directed at evaluating the reproducibility of the VSM method, two of the laboratories (PTB and NPL) performed their measurements by means of a SQUID magnetometer. SI units were used all along the experiments.

4.4 Role of the measuring temperature

The prescribed measuring temperature was $23 \text{ }^\circ\text{C} \pm 1 \text{ }^\circ\text{C}$. This temperature refers to the region occupied by the sample and the sensing coils, which, due to possible heating of the electromagnet, may be slightly different from the room temperature.

INRIM performed specific measurements by changing the sample temperature between $19 \text{ }^\circ\text{C}$ and $26 \text{ }^\circ\text{C}$, in order to determine the temperature coefficient of the measured quantities. Laboratories making the measurements at temperatures different from $23 \text{ }^\circ\text{C}$ could correct their results according to value and sign of these coefficients.

1) Isotropic and anisotropic hard-ferrites (HF_iso1, HF_iso2, HF_anis1, HF_anis2).

- | | |
|---|--|
| a) Coercive field H_{cJ} | $\alpha_{hcJ} = \frac{1}{H_{cJ}} \cdot \frac{dH_{cJ}}{dT} = +0,2 \text{ } \%/^\circ\text{C}$ |
| b) Coercive field H_{cB} | $\alpha_{hcB} = \frac{1}{H_{cB}} \cdot \frac{dH_{cB}}{dT} = +5 \cdot 10^{-2} \text{ } \%/^\circ\text{C}$ |
| c) Remanence and peak polarization values J | $\alpha_J = \frac{1}{J} \cdot \frac{dJ}{dT} = -0,12 \text{ } \%/^\circ\text{C}$ |

2) Magnetic tapes (1A, 1B, 2A, 2B)

- | | |
|-------------------------|---|
| a) Coercive field H_c | $\alpha_{hc} = \frac{1}{H_c} \cdot \frac{dH_c}{dT} = -8 \cdot 10^{-2} \text{ } \%/^\circ\text{C}$ |
|-------------------------|---|

b) Magnetic moment m

$$\alpha_m = \frac{1}{m} \cdot \frac{dm}{dT} = -0,2 \% / C^\circ$$

5 Analysis of the measured quantities

The figures provided by the participating laboratories were collected and analyzed according to standard rules [4]. For each measured quantity y_i and each sample, two types of reference values were determined. The first is the unweighted mean value $\langle y \rangle = \sum_{i=1}^N y_i / N$ of the N laboratories best estimates. The second is the weighted mean value $\bar{\bar{y}}$, which is generally preferred when dealing with a range of individual measuring uncertainties, as is usually the case with intercomparisons. It is defined as

$$\bar{\bar{y}} = \frac{\sum_{i=1}^N \frac{y_i}{u_c^2(y_i)}}{\sum_{i=1}^N \frac{1}{u_c^2(y_i)}} \quad (1)$$

where $u_c^2(y_i)$ is the combined (1σ) variance of the i -th best estimate. The weighted variance is in turn given by the equation

$$\frac{1}{u_c^2(\bar{\bar{y}})} = \sum_{i=1}^N \frac{1}{u_c^2(y_i)} \quad (2)$$

One important point in analyzing and comparing the results from different sources regards the identification of outliers, which could lead to invalid conclusions regarding the reference values and the related uncertainty. An objective rule can be devised for their identification, which consists in calculating the normalized error

$$E_{ni} = \frac{|y_i - y_{ref}|}{\sqrt{U_i^2 + U_{ref}^2}} \quad (3)$$

where $y_{ref} \equiv \bar{\bar{y}}$, $U_i = k u_{ci}$ is the expanded uncertainty of the individual best estimate (with k the coverage factor), and U_{ref} is the expanded weighted uncertainty. When the dispersion of the individual estimates is in a correct relationship with the correspondingly provided uncertainties, it is expected that $E_{ni} < 1$ [5]. We have loosely applied this rule to the present collection of data, by discarding those individual estimates for which $E_{ni} > 2$.

The detailed analysis of the above-mentioned quantities measured in the isotropic and anisotropic hard ferrites and in the magnetic tape samples is provided in Annex A. For each quantity, the following data are given:

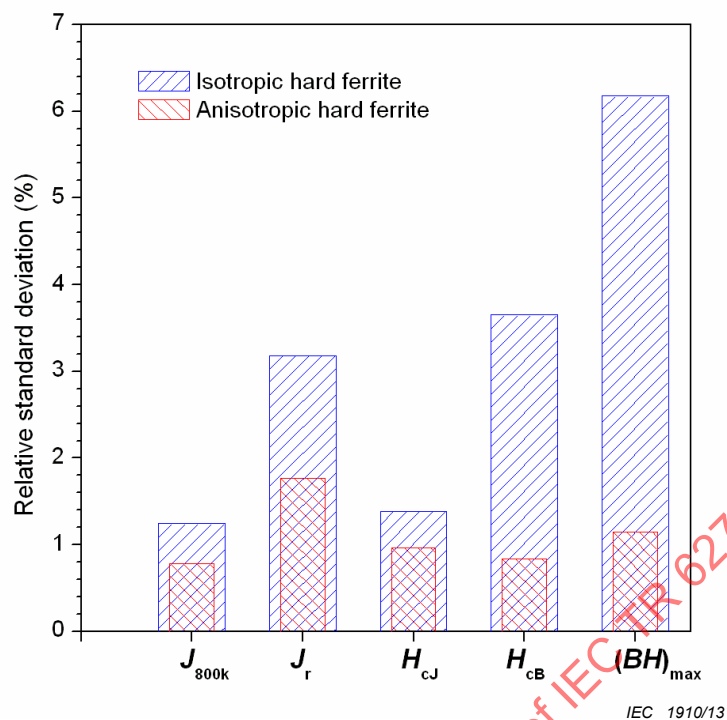
- The individual laboratories best estimates y_i and the related combined uncertainties u_{ci} ;
- The unweighted mean $\langle y \rangle$ and the standard deviation of the individual values around it $s(y_i)$;
- The weighted mean y_{ref} and the expanded weighted uncertainty (confidence interval) $U(y_{ref})$.

Figures 1 and 2 summarize the dispersion of the laboratories best estimates around $\langle y \rangle$ in the different materials. It is noted that the measurements on anisotropic ferrites show the best

reproducibility. The standard deviation of coercive field H_{cJ} and polarization J_{800} is slightly larger than 1 % in both isotropic and anisotropic ferrites. The dispersion of the measured energy product values $(BH)_{max}$ is substantial (around 6 %) in isotropic ferrites, much larger than in the anisotropic counterpart. The quantities measured in the magnetic tapes show a standard deviation oscillating around 2 %. Comparing the behaviour of the return curves in anisotropic and isotropic materials, it is understood that the smoother shape of the latter is conducive to greater uncertainty in the determination of H_{cB} , J_r , and $(BH)_{max}$. Figures 3 and 4 provide the expanded weighted uncertainty $U(y_{ref})$ for the reference value y_{ref} of the different measured quantities. It is recalled here that the true value of the measured quantity is expected to lie in the interval $y = y_{ref} \pm U(y_{ref})$ with a confidence level $p \sim 95$ %.

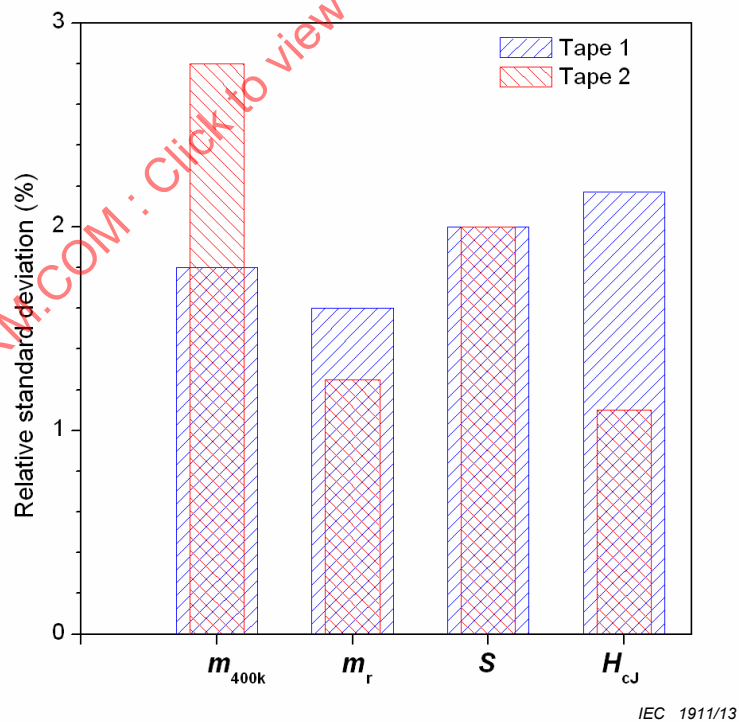
It is interesting to recall the conclusions of a similar exercise carried out in the nineties [7], where the comparison, involving 12 laboratories, regarded both the closed magnetic circuit method (IEC 60404-5 [9]) and the VSM method. Anisotropic Nd-Fe-B magnet specimens were tested. The standard deviation around the unweighted mean was found to be 4,7 % for H_{cJ} and 3,6 % for $(BH)_{max}$ using the closed circuit method. With the VSM open circuit method these quantities became 3,6 % and 2,3 %, respectively. As sketched in Figure 5, the dispersion of the present experiments on the ferrite anisotropic samples favourably compares with these results. It is fair to say that reproducibility of results could be affected to some extent by the very high coercivity of the extra-hard rare-earth magnets.

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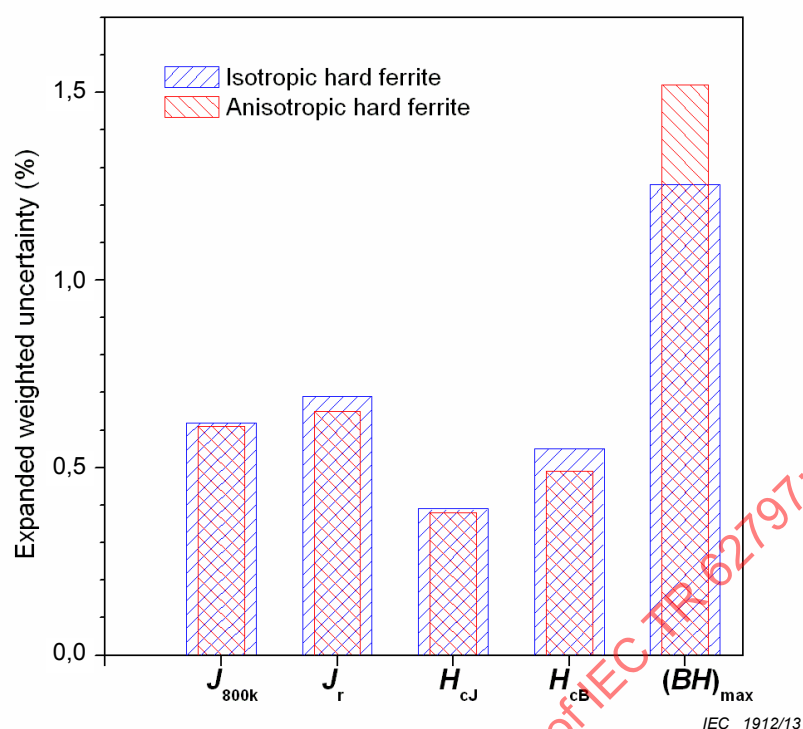
Relative standard deviation of the laboratories best estimates of the magnetic polarization J_{800k} at 800 kA/m, remanent polarization J_r , coercive fields H_{cJ} and H_{cB} , and maximum energy product $(BH)_{max}$ around their unweighted mean.

Figure 1 – Isotropic and anisotropic ferrites: standard deviations



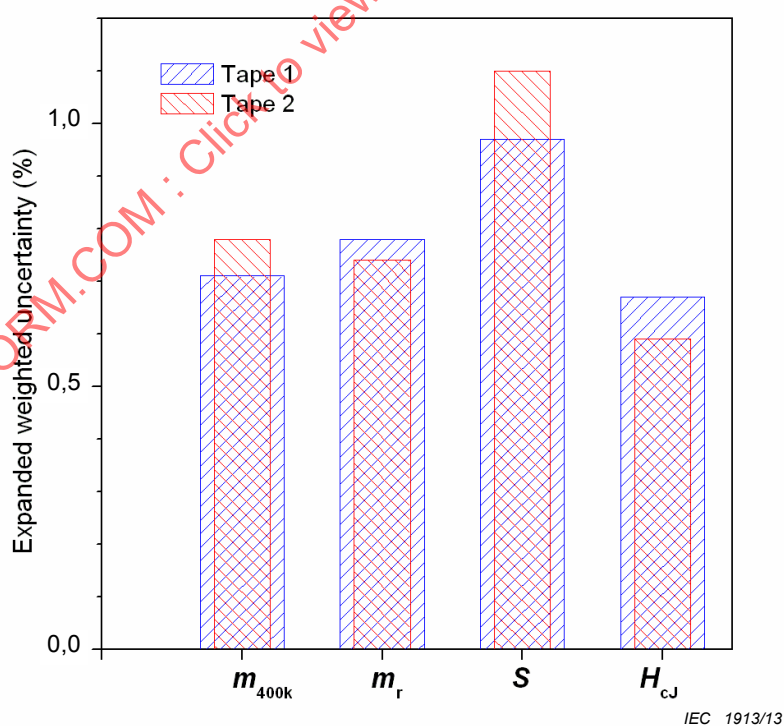
Relative standard deviation of the laboratories best estimates of the sample magnetic moment at 400 kA/m m_{400k} , remanent moment m_r , squareness ratio $S = m_r/m_{400k}$, and coercive field H_{cJ} around their unweighted mean.

Figure 2 – Magnetic tape samples: standard deviations



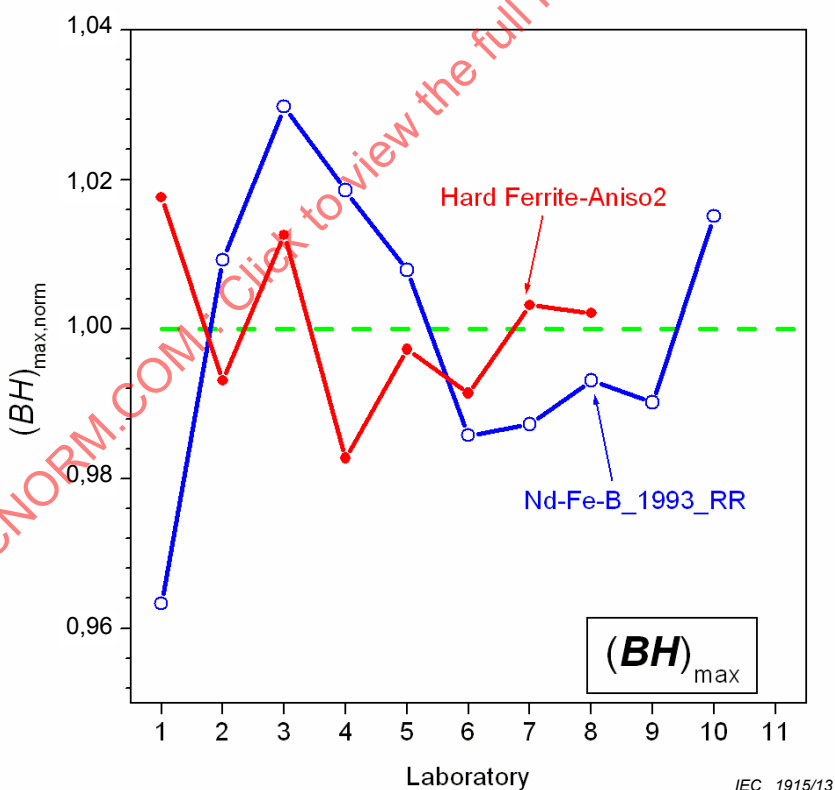
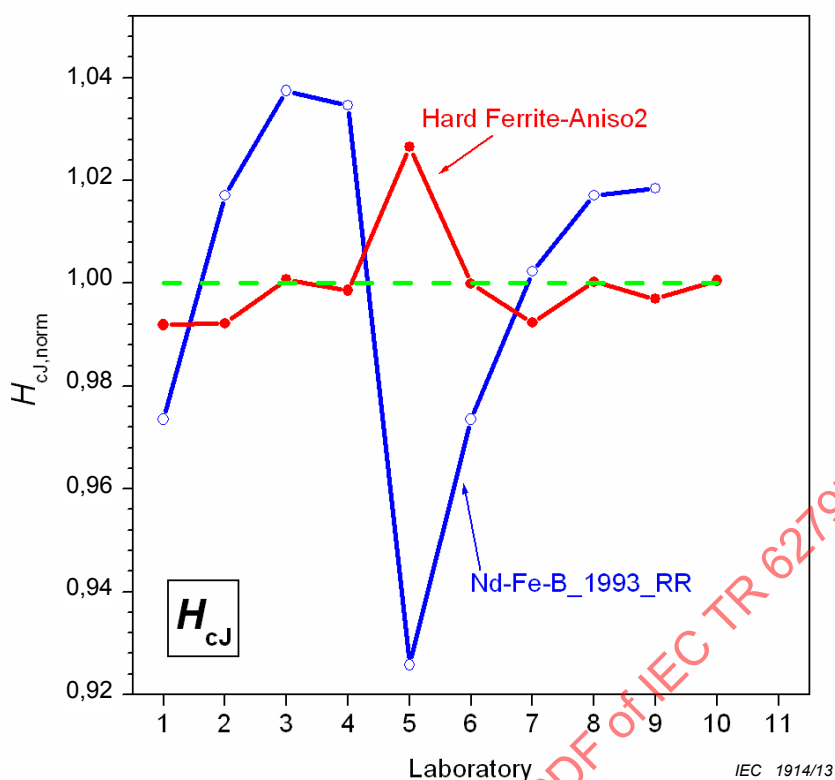
Relative expanded weighted uncertainty $U(y_{ref})$ for the polarization J_{800k} , remanent polarization J_r , coercive field strengths H_{cJ} and H_{cB} , and maximum energy product $(BH)_{max}$. The true value of the measured quantity is expected to lie in the interval $y = y_{ref} \pm U(y_{ref})$ with a confidence level $p \sim 95\%$.

Figure 3 – Isotropic and anisotropic ferrites: weighted uncertainties



Relative expanded weighted uncertainty $U(y_{ref})$ for the sample magnetic moment m_{400k} , remanent moment m_r , squareness ratio $S = m_r/m_{400k}$, and coercive field strength H_{cJ} . The true value of the measured quantity is expected to lie in the interval $y = y_{ref} \pm U(y_{ref})$ with a confidence level $p \sim 95\%$.

Figure 4 – Magnetic tape samples: weighted uncertainties



Normalized best values $y_i / \langle y \rangle$ of the coercive field strength H_{cJ} and maximum energy product $(BH)_{max}$ obtained by the participating laboratories in the present exercise (anisotropic hard ferrite sample) and in a previous VSM comparison [6] regarding anisotropic Nd-Fe-B samples.

Figure 5 – Normalized best values $y_i / \langle y \rangle$ of the coercive field strength H_{cJ} and maximum energy product $(BH)_{max}$

Annex A (informative)

International comparison of measurements of the magnetic moment using vibrating sample magnetometers and SQUID magnetometers

A.1 General

Material 1: Isotropic hard ferrite, anisotropic hard ferrite.

Measured quantities: J_{800k} , J_r , H_{cJ} , H_{cB} , $(BH)_{max}$

Material 2: Magnetic tape (two types).

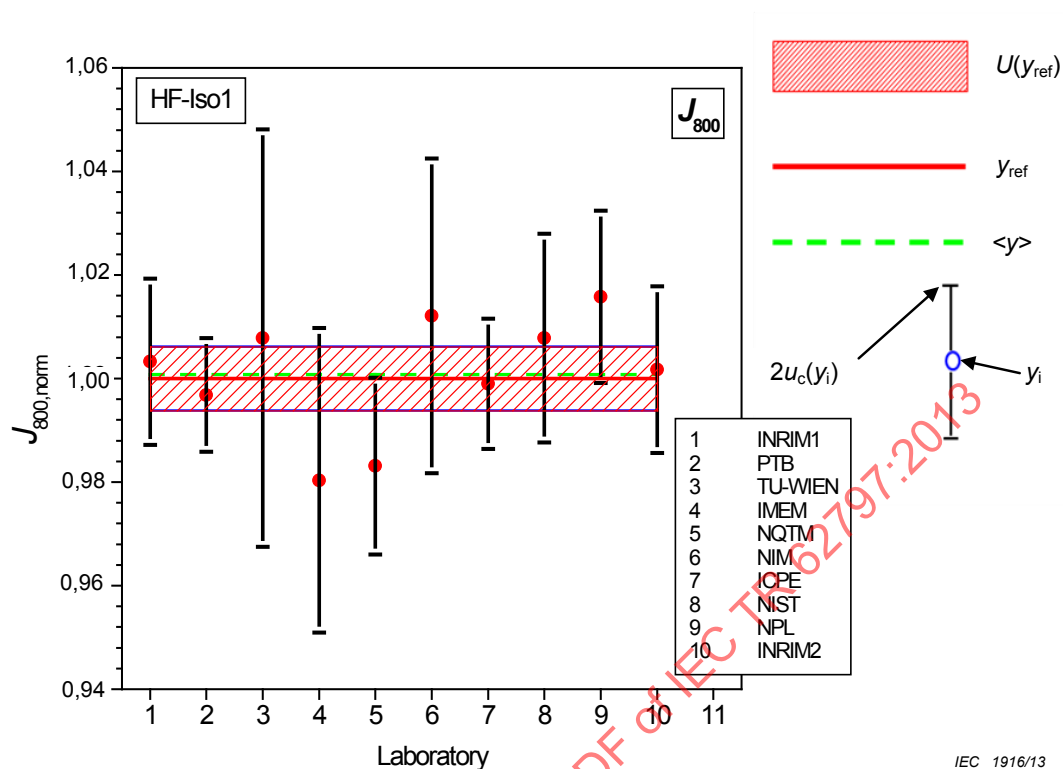
Measured quantities: m_{400k} , m_r , S , H_{cJ}

This annex provides in detail a few significant results regarding the measurements carried out by the participating laboratories in the isotropic and anisotropic hard ferrites and the magnetic tapes. It is an abridged version of a full length annex, reporting the complete statistical analysis of the measurements. Such a document was made available as a WG2 Document N210B at the TC 68 Working Group 2 Meeting, Ghent, 27/09/2011.

A.2 Isotropic hard ferrite

Table A.1 – Magnetic polarization value J_{800k} at $H_a = H_{peak} = 800$ kA/m measured by the participating laboratories on the isotropic hard ferrite HF-Iso1

Isotropic hard ferrite Iso-1		
	J_{800k} (T)	combined uncertainty u_{ci} (%)
INRIM1	0,3285	0,8
PTB	0,3264	0,55
TU-WIEN	0,330	2,0
IMEM	0,321	1,5
NQTM	0,3219	0,87
NIM	0,3314	1,5
ICPE-CA	0,3271	0,63
NIST	0,33	1,0
NPL	0,3326	0,82
INRIM2	0,328	0,8
Unweighted average $\langle J_{800k} \rangle = 0,3277$ T		
Standard deviation $s(J_{800k}) = 1,16$ %		
Weighted average $J_{800k,ref} = 0,3274$ T		
Expanded weighted uncertainty $U(J_{800k,ref}) = 0,62$ %		



Key

y_i best estimate of the i-th laboratory

$u_c(y_i)$ combined uncertainty of the i-th laboratory

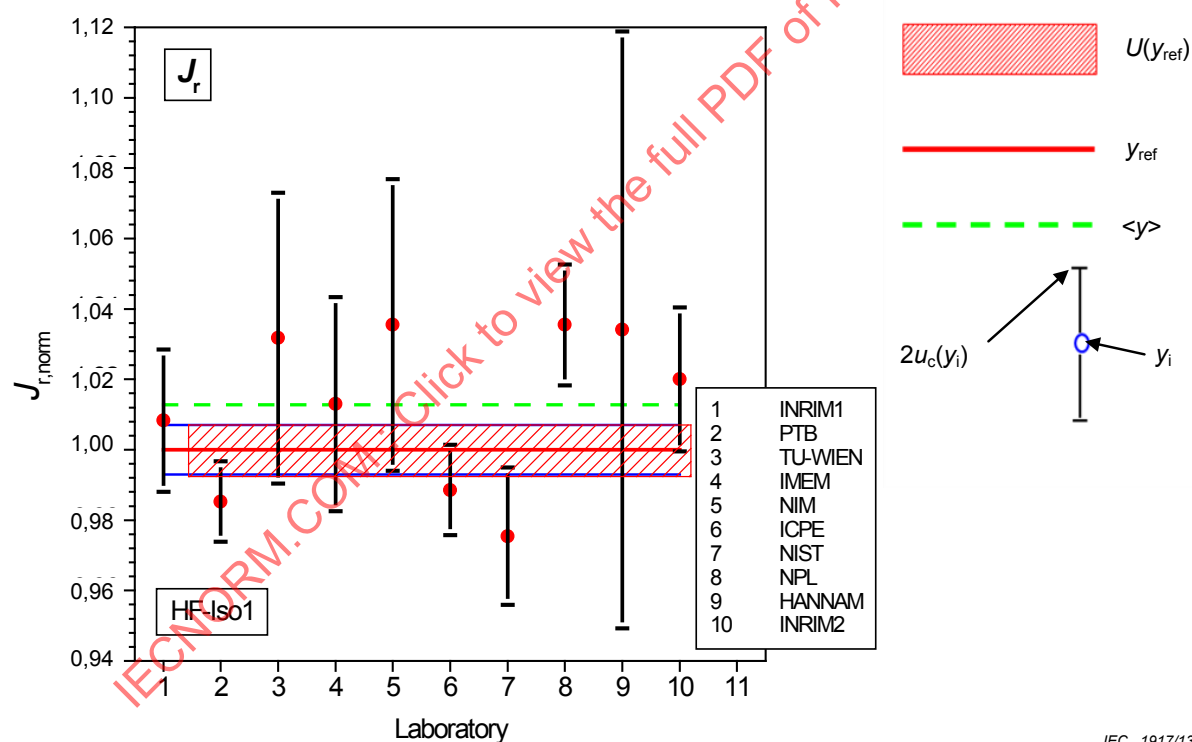
$\langle y \rangle$ unweighted average

These J_{800k} values are normalized with respect to the reference value (weighted average) y_{ref} .

Figure A.1 – Dispersion of the J_{800k} values measured by the participating laboratories on the isotropic ferrite sample HF-Iso1

Table A.2 – Remanent magnetic polarization J_r measured by the participating laboratories on the isotropic hard ferrite HF-Iso1

Isotropic hard ferrite Iso-1		
	J_r (T)	combined uncertainty u_{ci} (%)
INRIM1	0,215	1,0
PTB	0,2101	0,58
TU-WIEN	0,22	2,0
IMEM	0,216	1,5
NIM	0,2208	2,0
ICPE-CA	0,2108	0,65
NIST	0,208	1,0
NPL	0,2208	0,83
HANNAM	0,2205	4,1
INRIM2	0,2175	1,0
Unweighted average $\langle J_r \rangle = 0,216$ T		
Standard deviation $s(J_r) = 2,24$ %		
Weighted average $J_{r,ref} = 0,2132$ T		
Expanded weighted uncertainty $U(J_{r,ref}) = 0,69\%$		



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Key

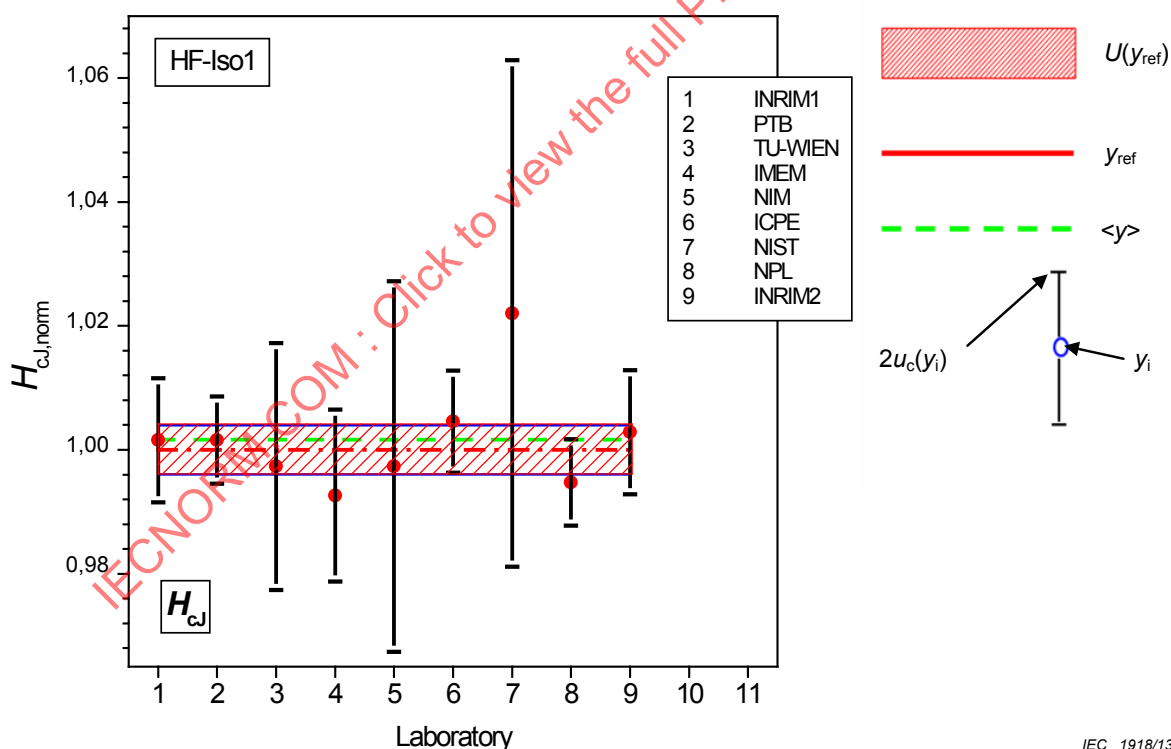
- y_i best estimate of the i-th laboratory
 $u_c(y_i)$ combined uncertainty of the i-th laboratory
 $\langle y \rangle$ unweighted average

These J_r values are normalized with respect to the reference value (weighted average) y_{ref} .

Figure A.2 – Dispersion of the J_r values measured by the participating laboratories on the isotropic ferrite sample HF-Iso1

Table A.3 – Coercive field H_{cJ} measured by the participating laboratories on the isotropic hard ferrite HF-Iso1

Isotropic hard ferrite Iso-1		
	H_{cJ} (kA/m)	combined uncertainty u_{ci} (%)
INRIM1	235,2	0,5
PTB	235,2	0,35
TU-WIEN	234,2	1,0
IMEM	233,1	0,7
NIM	234,2	1,5
ICPE-CA	235,9	0,41
NIST	240,0	2,0
NPL	233,6	0,35
INRIM2	235,5	0,5
Unweighted average $\langle H_{cJ} \rangle = 235,2$ kA/m		
Standard deviation $s(H_{cJ}) = 0,86$ %		
Weighted average $H_{cJ,ref} = 234,8$ kA/m		
Expanded weighted uncertainty $U(H_{cJ,ref}) = 0,39$ %		



Key

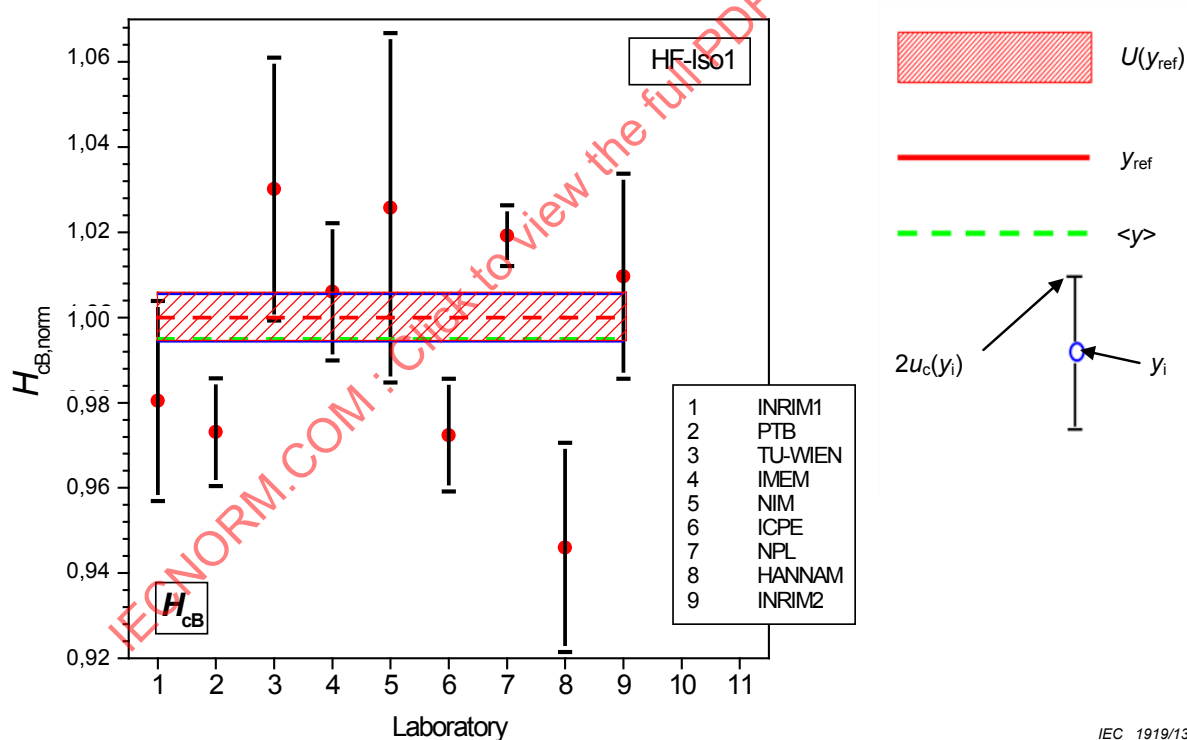
- y_i best estimate of the i-th laboratory
- $u_c(y_i)$ combined uncertainty of the i-th laboratory
- $\langle y \rangle$ unweighted average

These H_{cJ} values are normalized with respect to the reference value (weighted average) y_{ref} .

Figure A.3 – Dispersion of the H_{cJ} values measured by the participating laboratories on the isotropic ferrite sample HF-Iso1

Table A.4 – Coercive field H_{cB} measured by the participating laboratories on the isotropic hard ferrite HF-Iso1

Isotropic hard ferrite Iso-1		
	H_{cB} (kA/m)	combined uncertainty u_{ci} (%)
INRIM1	134,0	1,2
PTB	133,0	0,65
TU-WIEN	140,8	1,5
IMEM	137,5	0,8
NIM	140,2	2,0
ICPE-CA	132,9	0,68
NPL	139,3	0,35
HANNAM	129,3	1,3
INRIM2	137,0	1,2
Unweighted average $\langle H_{cB} \rangle = 136,0$ kA/m		
Standard deviation $s(H_{cB}) = 2,9$ %		
Weighted average $H_{cB,ref} = 136,7$ kA/m		
Expanded weighted uncertainty $U(H_{cB,ref}) = 0,55$ %		

**Key**

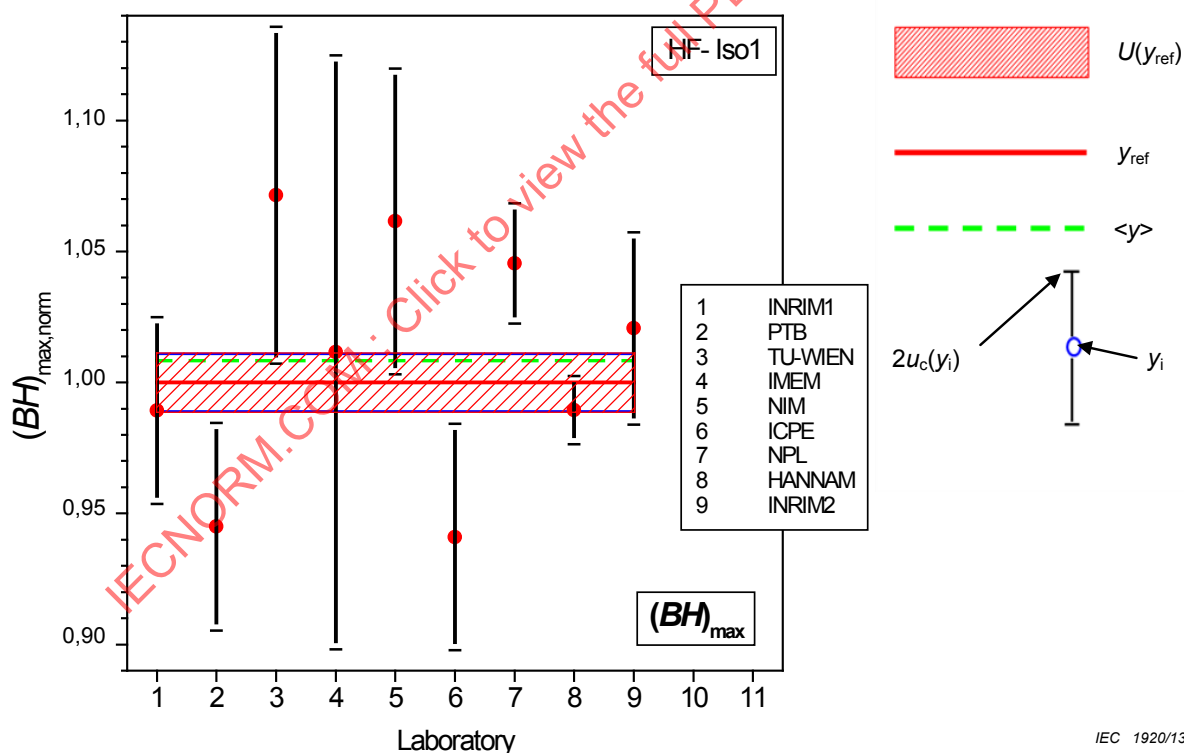
- y_i best estimate of the i -th laboratory
 $u_c(y_i)$ combined uncertainty of the i -th laboratory
 $\langle y \rangle$ unweighted average

These H_{cB} values are normalized with respect to the reference value (weighted average) y_{ref} .

Figure A.4 – Dispersion of the H_{cB} values measured by the participating laboratories on the isotropic ferrite sample HF-Iso1

Table A.5 – Maximum energy product $(BH)_{\max}$ measured by the participating laboratories on the isotropic hard ferrite HF- Iso1

Isotropic hard ferrite Iso-1		
	$(BH)_{\max}$ (J/m ³)	combined uncertainty u_{ci} (%)
INRIM1	7580	1,9
PTB	7240	2,1
TU-WIEN	8210	3,0
IMEM	7750	5,6
NIM	8133	2,75
ICPE-CA	7210	2,3
NPL	8010	1,1
HANNAM	7581	0,66
INRIM2	7820	1,9
Unweighted average $\langle (BH)_{\max} \rangle = 7726$ J/m ³		
Standard deviation $s((BH)_{\max}) = 4,65$ %		
Weighted average $(BH)_{\max,ref} = 7662$ J/m ³		
Expanded weighted uncertainty $U((BH)_{\max,ref}) = 1,1$ %		



Key

y_i best estimate of the i-th laboratory

$u_c(y_i)$ combined uncertainty of the i-th laboratory

$\langle y \rangle$ unweighted average

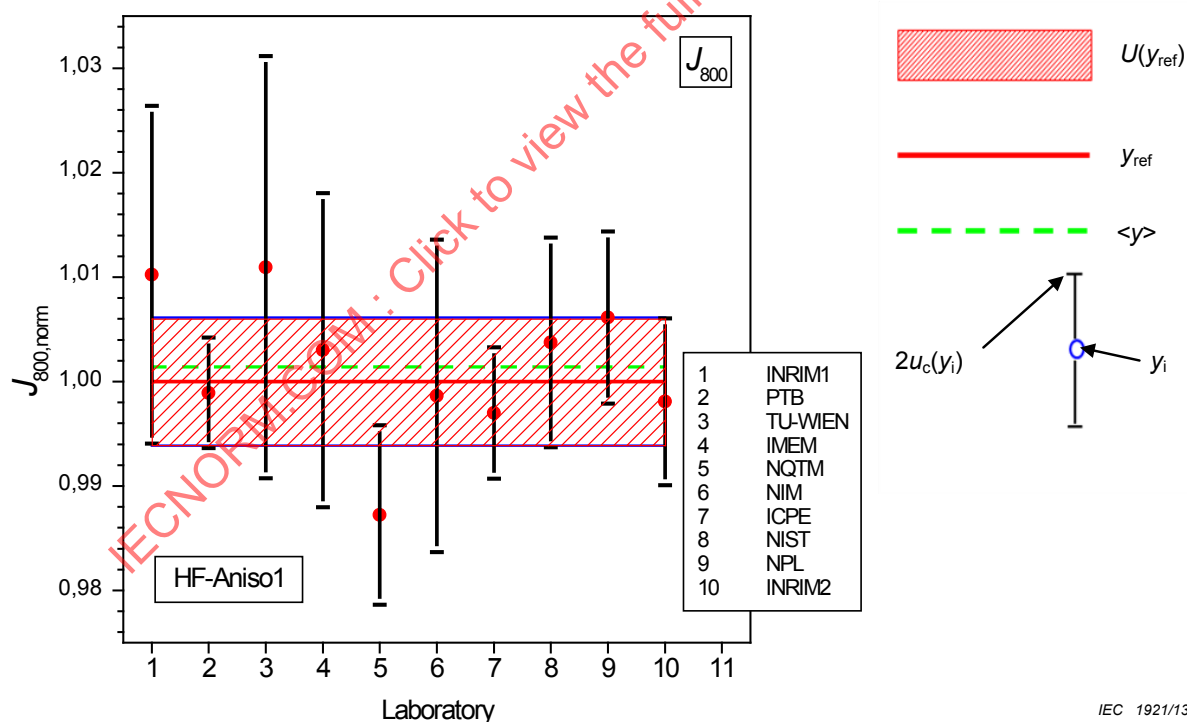
These $(BH)_{\max}$ values are normalized with respect to the reference value (weighted average) y_{ref} .

Figure A.5 – Dispersion of the $(BH)_{\max}$ values measured by the participating laboratories on the isotropic ferrite sample HF-Iso1

A.3 Anisotropic hard ferrite

Table A.6 – Magnetic polarization value J_{800k} at $H_a = H_{peak} = 800$ kA/m measured by the participating laboratories on the anisotropic hard ferrite HF-Aniso1

Anisotropic hard ferrite Aniso-1		
	J_{800k} (T)	combined uncertainty u_{ci} (%)
INRIM1	0,4197	0,80
PTB	0,415	0,53
TU-WIEN	0,42	2,0
IMEM	0,4167	1,5
NQTM	0,41015	0,87
NIM	0,41488	1,5
ICPE-CA	0,4142	0,63
NIST	0,417	1,0
NPL	0,418	0,82
INRIM2	0,41465	0,80
Unweighted average $\langle J_{800} \rangle = 0,416$ T		
Standard deviation $s(J_{800}) = 0,70$ %		
Weighted average $J_{800,ref} = 0,415$ T		
Expanded weighted uncertainty $U(J_{800,ref}) = 0,61$ %		



Key

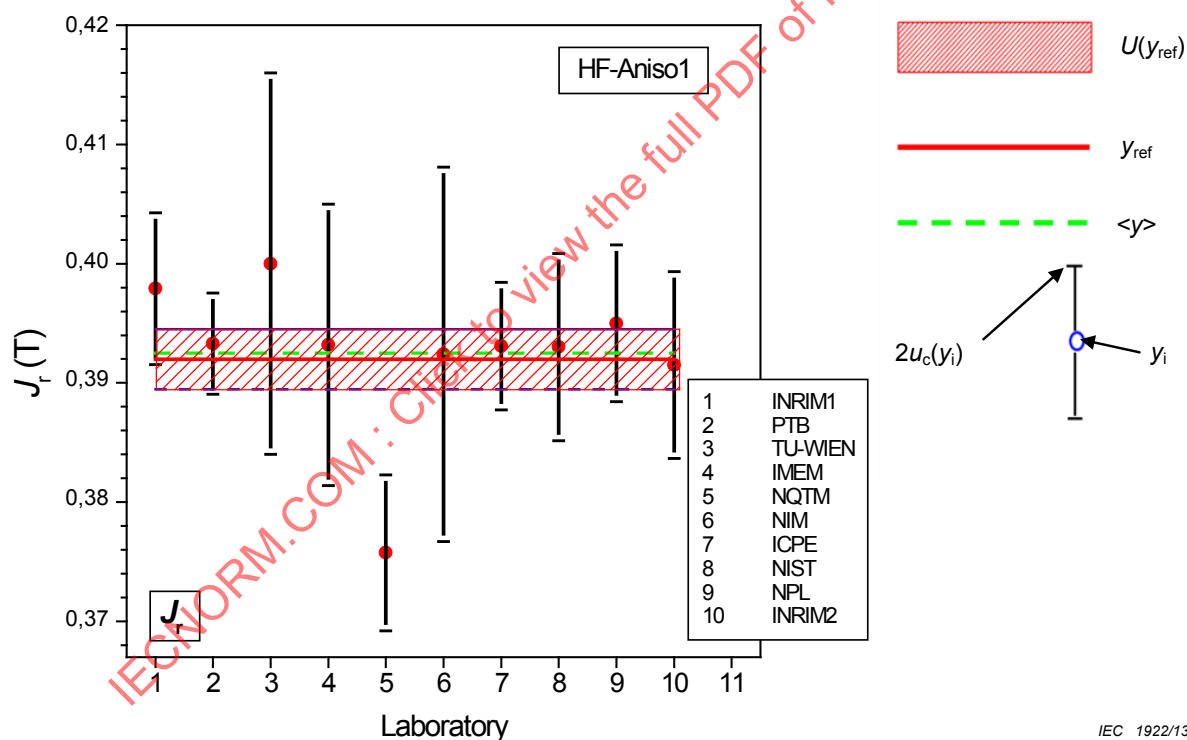
- y_i best estimate of the i-th laboratory
 $u_c(y_i)$ combined uncertainty of the i-th laboratory
 $\langle y \rangle$ unweighted average

These J_{800k} values are normalized with respect to the reference value (weighted average) y_{ref} .

Figure A.6 – Dispersion of the J_{800k} values measured by the participating laboratories on the anisotropic ferrite sample HF-Aniso1

Table A.7 – Remanent magnetic polarization J_r measured by the participating laboratories on the anisotropic hard ferrite HF-Aniso1

Anisotropic hard ferrite Aniso-1		
	J_r (T)	combined uncertainty u_{ci} (%)
INRIM1	0,3979	0,80
PTB	0,3933	0,54
TU-WIEN	0,4	2,0
IMEM	0,3932	1,5
NQTM	0,37576	0,87
NIM	0,3924	2,0
ICPE-CA	0,3931	0,68
NIST	0,393	1,0
NPL	0,395	0,83
INRIM2	0,3915	1,0
Unweighted average $\langle J_r \rangle = 0,3925$ T		
Standard deviation $s(J_r) = 1,65$ %		
Weighted average $J_{r,ref} = 0,3920$ T		
Expanded weighted uncertainty $U(J_{r,ref}) = 0,64$ %		



Key

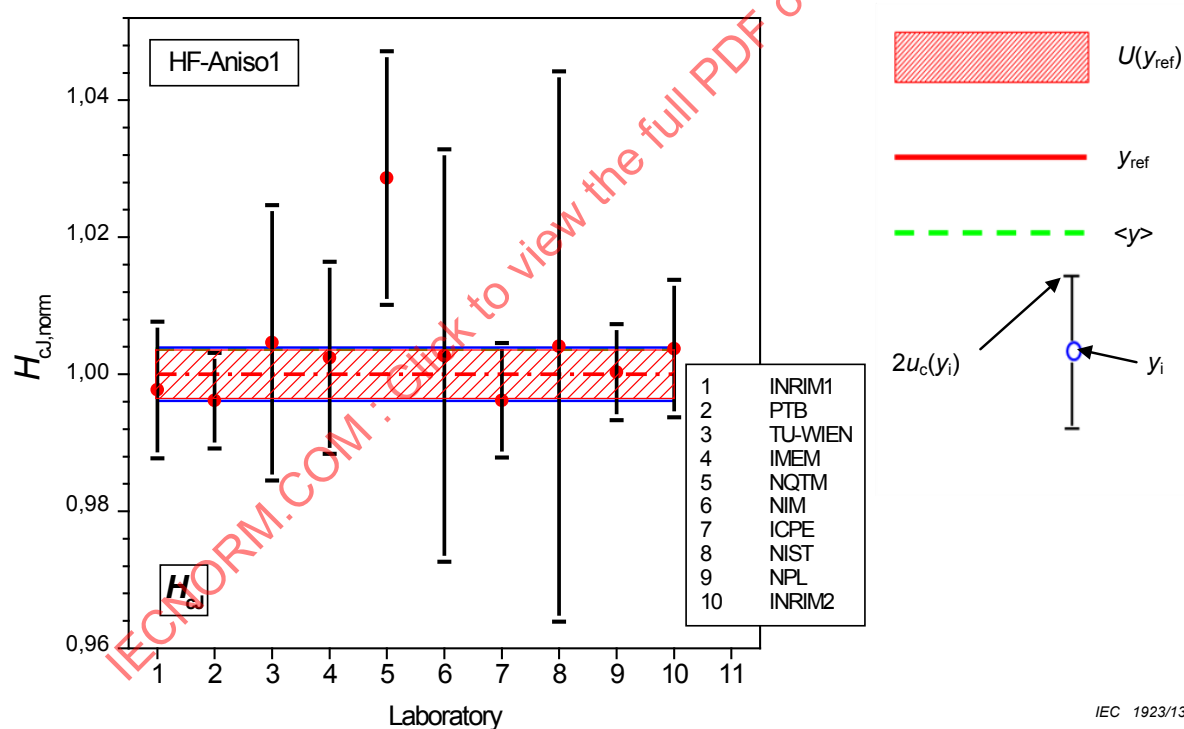
- y_i best estimate of the i-th laboratory
 $u_c(y_i)$ combined uncertainty of the i-th laboratory
 $\langle y \rangle$ unweighted average

These J_r values are normalized with respect to the reference value (weighted average) y_{ref} .

Figure A.7 – Dispersion of the J_r values measured by the participating laboratories on the anisotropic ferrite sample HF-Aniso1

Table A.8 – Coercive field H_{cJ} measured by the participating laboratories on the anisotropic hard ferrite HF-Aniso1

Anisotropic hard ferrite Aniso-1		
	H_{cJ} (kA/m)	combined uncertainty u_{ci} (%)
INRIM1	238,48	0,50
PTB	238,11	0,35
TU-WIEN	240,13	1,0
IMEM	239,60	0,70
NQTM	245,87	0,90
NIM	239,67	1,5
ICPE-CA	238,12	0,42
NIST	240,00	2,0
NPL	239,10	0,35
INRIM2	239,92	0,50
Unweighted average $\langle H_{cJ} \rangle = 239,9$ kA/m		
Standard deviation $s(H_{cJ}) = 0,93$ %		
Weighted average $H_{cJ,ref} = 239,0$ kA/m		
Expanded weighted uncertainty $U(H_{cJ,ref}) = 0,37$ %		



Key

y_i best estimate of the i-th laboratory

$u_c(y_i)$ combined uncertainty of the i-th laboratory

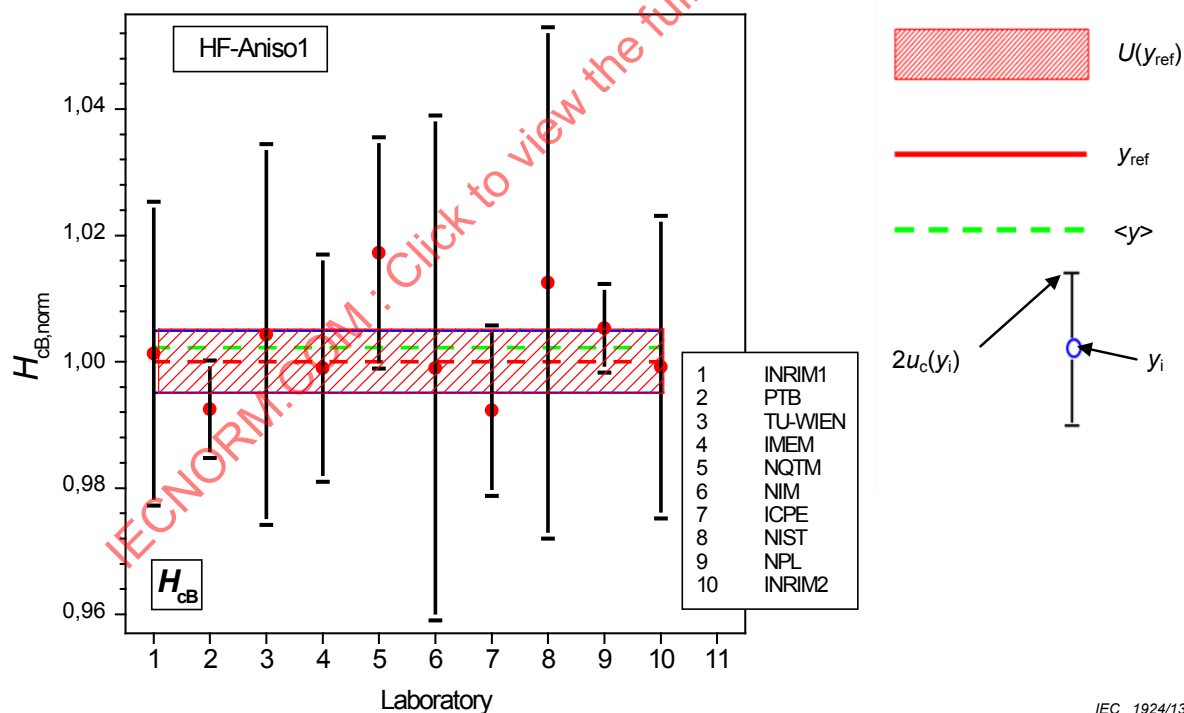
$\langle y \rangle$ unweighted average

These H_{cJ} values are normalized with respect to the reference value (weighted average) y_{ref} .

Figure A.8 – Dispersion of the H_{cJ} values measured by the participating laboratories on the anisotropic ferrite sample HF-Aniso1

Table A.9 – Coercive field H_{cB} measured by the participating laboratories on the anisotropic hard ferrite HF-Aniso1

Anisotropic hard ferrite Aniso-1		
	H_{cB} (kA/m)	combined uncertainty u_{ci} (%)
INRIM1	237,35	1,2
PTB	235,26	0,39
TU-WIEN	238,06	1,5
IMEM	236,80	0,90
NQTM	241,12	0,90
NIM	236,81	2,0
ICPE-CA	235,21	0,68
NIST	240,00	2,0
NPL	238,30	0,35
INRIM2	236,84	1,2
Unweighted average $\langle H_{cB} \rangle = 237,6$ kA/m		
Standard deviation $s(H_{cB}) = 0,80$ %		
Weighted average $H_{cB,ref} = 237,0$ kA/m		
Expanded weighted uncertainty $U(H_{cB,ref}) = 0,49$ %		



Key

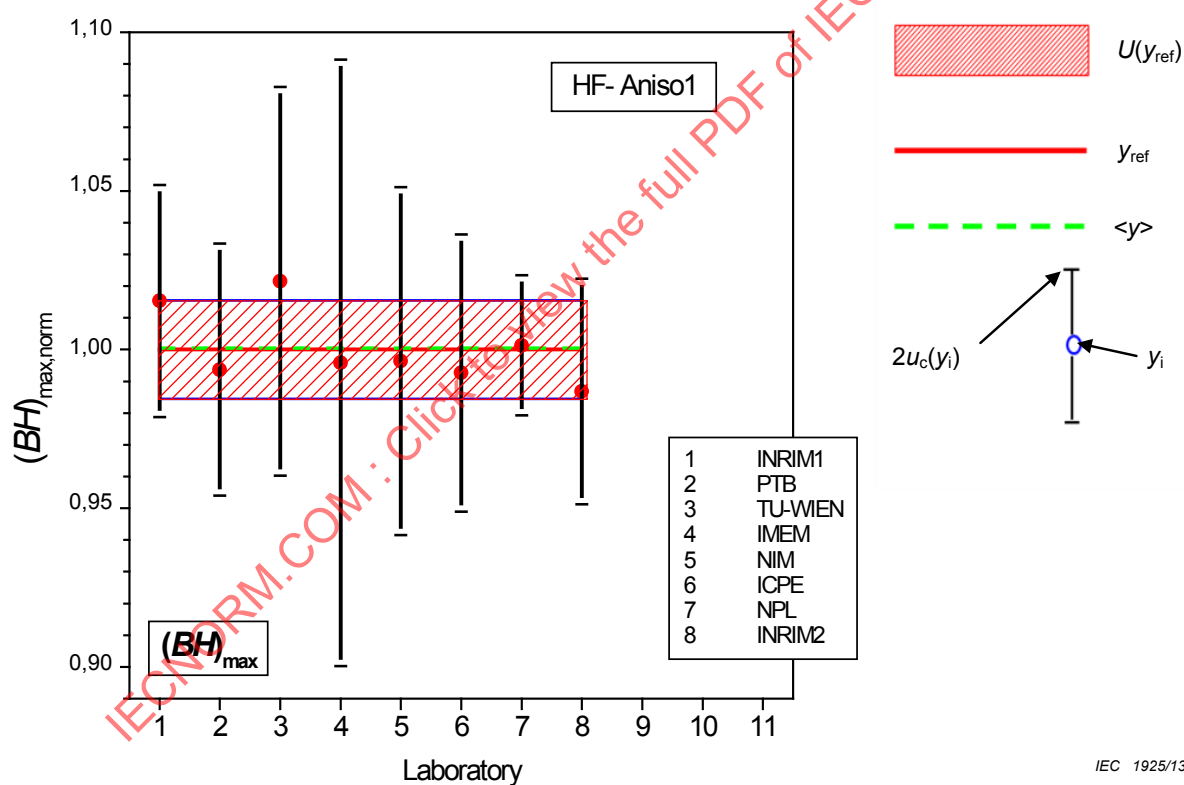
- y_i best estimate of the i-th laboratory
- $u_c(y_i)$ combined uncertainty of the i-th laboratory
- $\langle y \rangle$ unweighted average

These H_{cB} values are normalized with respect to the reference value (weighted average) y_{ref} .

Figure A.9 – Dispersion of the H_{cB} values measured by the participating laboratories on the anisotropic ferrite sample HF-Aniso1

Table A.10 – Maximum energy product $(BH)_{\max}$ measured by the participating laboratories on the anisotropic hard ferrite HF- Aniso1

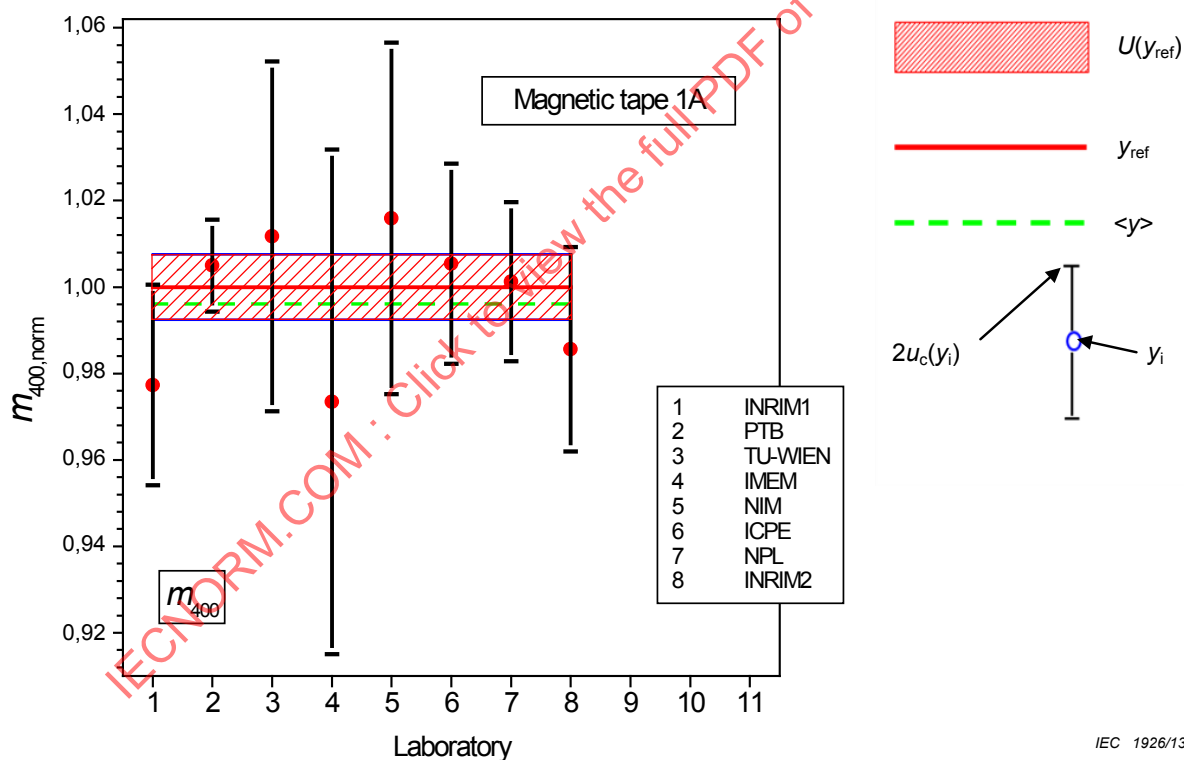
Anisotropic hard ferrite Aniso-1		
	$(BH)_{\max}$ (J/m ³)	combined uncertainty u_{ci} (%)
INRIM1	29162	1,8
PTB	28540	2,0
TU-WIEN	29340	3,0
IMEM	28600	4,8
NIM	28616	2,75
ICPE-CA	28510	2,2
NPL	28760	1,1
INRIM2	28341	1,8
Unweighted average $\langle (BH)_{\max} \rangle = 28734$ J/ m ³		
Standard deviation $s((BH)_{\max}) = 1,2$ %		
Weighted average $(BH)_{\max, ref} = 28721$ J/m ³		
Expanded weighted uncertainty $U((BH)_{\max, ref}) = 1,54$ %		

**Key** y_i best estimate of the i -th laboratory $u_c(y_i)$ combined uncertainty of the i -th laboratory $\langle y \rangle$ unweighted averageThese $(BH)_{\max}$ values are normalized with respect to the reference value (weighted average) y_{ref} .**Figure A.10 – Dispersion of the $(BH)_{\max}$ values measured by the participating laboratories on the anisotropic ferrite sample HF-Aniso1**

A.4 Magnetic tape sample

Table A.11 – Magnetic moment m_{400k} measured at $H_a = H_{peak} = 400$ kA/m by the participating laboratories on the magnetic tape sample 1A

Magnetic tape sample 1A		
	m_{400k} (Am ²)	combined uncertainty u_{ci} (%)
INRIM1	$4,442 \cdot 10^{-6}$	0,90
PTB	$4,619 \cdot 10^{-6}$	0,53
TU-WIEN	$4,65 \cdot 10^{-6}$	2,0
IMEM	$4,474 \cdot 10^{-6}$	3,0
NIM	$4,6692 \cdot 10^{-6}$	2,0
ICPE-CA	$4,621 \cdot 10^{-6}$	0,65
NPL	$4,602 \cdot 10^{-6}$	0,92
INRIM2	$4,53 \cdot 10^{-6}$	0,90
Unweighted average $\langle m_{400k} \rangle = 4,58 \cdot 10^{-6}$ Am ²		
Standard deviation $s(m_{400k}) = 1,8$ %		
Weighted average $m_{400k,ref} = 4,60 \cdot 10^{-6}$ Am ²		
Expanded weighted uncertainty $U(m_{400k,ref}) = 0,71$ %		



Key

y_i best estimate of the i-th laboratory

$u_c(y_i)$ combined uncertainty of the i-th laboratory

$\langle y \rangle$ unweighted average

These m_{400k} values are normalized with respect to the reference value (weighted average) y_{ref} .

Figure A.11 – Dispersion of the m_{400k} values measured by the participating laboratories on the magnetic tape sample A1