

**Comparison of Permanent Magnet Measurements
Report on values measured using methods compliant with IEC
60404 part 5 and Pulse Field Magnetometers**

**Dr. Michael Hall, Dr. Harshad Virji Patel
National Physical Laboratory, UK
&
Dr. Anli Lin, Jian He
National Institute of Metrology (NIM), China**

JANUARY 2012

IEC TC 68 WG2 Round Robin:

Comparison of Permanent Magnet Measurements

Report on values measured using methods compliant with

IEC 60404 part 5 and Pulse Field Magnetometers

Dr. Michael Hall

Dr. Harshad Virji Patel

National Physical Laboratory, UK

&

Dr. Anli Lin

Jian He

National Institute of Metrology (NIM), China

January 2012

© Queen's Printer and Controller of HMSO, 2012

ISSN 1754-2979

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Extracts from this report may be reproduced provided the source is
acknowledged and the extract is not taken out of context.

Approved on behalf of NPLML by Alan Brewin, Head of Materials Division.

Acknowledgements

Dr Michael Hall and Dr Harshad Patel would like to thank all participants for their involvement in this comparison. Special thanks go to Dr Anli Lin and Jian He from NIM for their role as a Pilot Laboratory. They provided additional support with writing the protocol, sourcing the magnets, providing boxes for the careful shipping on the magnets, managing the shipment of the magnets from laboratory to laboratory on a strict schedule, performing a second set of control measurements for essential stability checks and commenting on drafts of this report.

TABLE OF CONTENTS

1. Introduction.....	1
2. Co-ordinators	2
3. Participants.....	2
4. Measurements	3
Diameter.....	3
Length	3
5. Measurement conditions and methods.....	3
6. Traceability	4
7. Sample Uncertainty Budget	4
8. Transfer standard behaviour	5
9. Comparison reference value	5
10. Results.....	7
10.1 Intrinsic coercivity, H_{cJ}	7
10.2 Remanence (B_r), magnetic flux density coercivity (H_{cB}) and energy product (BH_{max}).....	11
11. Discussion.....	18
11.1 Intrinsic coercivity, H_{cJ}	18
11.2 Remanence (B_r), magnetic flux density coercivity (H_{cB}) and energy product (BH_{max}).....	20
12. Conclusions.....	21
References.....	21
APPENDIX 1: H_{cJ} Results.....	23
APPENDIX 2: Each measurement method viewed separately.....	26
APPENDIX 3: B_r , H_{cB} and $(BH)_{max}$ Results.....	32
APPENDIX 4: Sample Uncertainty Budget	38
APPENDIX 5: Reversal rates	40
APPENDIX 6: Explanation of negative slope for some reversals using an electromagnet.	45
APPENDIX 7: Field versus current/time plots.....	49

1. INTRODUCTION

IEC TC 68 WG 2 recently worked on the Technical Report PD IEC/TR 62331:2005 "Pulse Field Magnetometry". To consider this for a standard it is necessary to determine the agreement between this method and the electromagnet based method of IEC 60404 part 5. The comparison reported here involved the measurement of a number of permanent magnets by laboratories using their established methods. For the purpose of a comparison, each laboratory was required to present details of their measurement traceability and to provide an uncertainty budget that has been determined in accordance with the ISO Guide to the Expression of Uncertainties in Measurement.

Initially two reports were prepared so that the intrinsic coercivity results could be considered on their own. This was due to the large and significant differences found for the intrinsic coercivity between the two methods. After the IEC TC 68 meeting at BSi in London on 26th to 28th October 2009, it was decided that this final report would be produced with this significant difference in the intrinsic coercivity discussed in connection with the influence of the measurement speed. It is acceptable that as long as the influence of the measurement speed is formally considered and acknowledged, both the electromagnet method of IEC 60404 part 5 and the pulse field magnetometer method of the Technical Report PD IEC/TR 62331:2005 can be used to measure the properties of permanent magnets.

At the IEC TC 68 WG5 and WG2 meetings held in Ghent, Belgium, on 26th and 27th September 2011 respectively, it was agreed to define "Polarization Reversal Time" and use this to replace Reversal Time.

Polarization Reversal Time is defined as the time taken for the polarization to reduce from 90% of the value at B_r to zero (Time to sweep the magnetic field from H_k to H_{cJ}).

All participants were asked to update their values in Table 2 based on this definition. Responses were received from NPL, Hirst, NIM, INRiM and Hitachi. If available, the field versus current/time plots for the measurements should also be provided for information. These were received from NPL and Hirst and are included in Appendix 7.

NOTE: the parties involved in the measurements (test house, instrument supplier, PM user etc.) need to agree what the influence of the measurement speed will be on the results and for all parties to accept the implications.

It is technically important to remember that to determine the DC properties of permanent magnets, the increase in the magnetic field necessary for reversal of the polarisation should be performed **quasi statically**. Since this is not possible in most cases, the changes in the measured intrinsic coercivity that can occur for certain magnet types when the magnetic field is increased at the speed required for measurements by industry need to be understood and where necessary evaluated.

National Measurement Institutes with the appropriate capability can provide the measurements needed for this assessment.

2. CO-ORDINATORS

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW, UK
and
Magnetic Material Measurement Laboratory, National Institute of Metrology (NIM),
No.18, Bei San Huan Dong Lu, Beijing 100013, P.R.China

3. PARTICIPANTS

Pilot Laboratory 1:
Dr. Michael Hall, Dr. Harshad Virji Patel,
National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW,
UK

Pilot Laboratory 2:
Dr. Anli Lin, Dr. Jian He
Magnetic Material Measurement Laboratory, National Institute of Metrology (NIM),
No.18, Bei San Huan Dong Lu, Beijing 100013, P.R.China

Mr. John Dudding, Mr. Paul A Knell
Hirst Magnetic Instruments LTD, Tesla House, Tregoniggiem Falmouth, Cornwall,
TR11 4SN UK

Dr. Wilhelm Fernengel
Vacuumschmelze GmbH & CO. KG, Permanent Magnets, Materials and Fundamental
Research, Germany

Dr. Luc Van Bockstal
Metis Instruments & Equipment, Kapeldreef 60, B-3001 Leuven, Belgium

Mr. Toyonori Ariizumi
Toei Industry Co. Ltd, 8-13, 1-chome Tadao, Machida, Tokyo 194-0035

Mr. Hitoshi Yamamoto
NEOMAX Company, Hitachi Metals, Ltd., Seavans North 2-1, Shibaura 1-chome
Minato-ku, Tokyo 105-8614, Japan

Dr. Fausto Fiorillo
INRim, Strada delle Cacce 91, 10135 Torino, Italy

4. MEASUREMENTS

A number of permanent magnets were provided for this comparison and their details are given in the following table.

Table 1. Summary of magnets circulated

Magnet reference	DIAMETER (mm)	LENGTH (mm)	Approximate B_r (T)	Approximate H_{cJ} (kA/m)	Approximate H_{cB} (kA/m)	Approximate $(BH)_{max}$ (kJ/m ³)
JH1	10	10	1.33	1280		342
CN1	10	10	1.27	1040	880	303
CM1	10	10	1.27	1240	930	303
CH1	10	10	1.27	1480	930	280
JE1	10	10	1.21	1990		280
CE1	10	10	1.18	2590	870	263

* For information only. Measured at 20 °C.

Participants determined the remanence, B_r , intrinsic coercivity, H_{cJ} , magnetic flux density coercivity, H_{cB} , and energy product, $(BH)_{max}$, using their established method(s).

The magnet dimensions in Table 1 were used to determine these quantities.

5. MEASUREMENT CONDITIONS AND METHODS

Following discussions at WG5 and WG2 meetings held at Ghent, Belgium, on 26th and 27th September 2011 respectively each participant where asked to determine the "Polarization Reversal Time" based on the following definition.

Polarization Reversal Time is defined as the time taken for the polarization to reduce from 90% of the value at B_r to zero (Time to sweep the magnetic field from H_k to H_{cJ}).

The values in Table 2 are based on this definition.

For each participant the method of measurement and measuring conditions are summarised in the following table.

Table 2. Measurement conditions

Laboratory	Date Measured	Measurement method	Polarization Reversal time	Temperature °C
NIM	12/07	Permeameter PFM	(0.2 - 0.9) s (38 – 150) μ s	20 $\pm$ 1
Hitachi Metals Ltd	01/08	Permeameter PFM	(92 – 432) ms (56 – 108) μ s	23 $\pm$ 1 23 $\pm$ 1
Toei Industry Co. Ltd	01/08	Permeameter PFM	(26 – 123) ms (56 – 108) μ s	20 $\pm$ 1 20 $\pm$ 1

Hirst	02/08	PFM	(39 – 43) μ s	20 $\pm$ 1
NPL	04/08	Permeameter	(130 – 297) s	20 $\pm$ 1
Metis*	04/08	PFM	5 s	20 $\pm$ 0.5
Vacuumschmelze*	05/08	Permeameter	0.25 s	20 $\pm$ 1
INRi<	02/09	PFM	(0.13-0.15)ms	20 - 22

* No new values submitted after the IEC TC 68 meetings in September 2011.

For measurements not performed at 20 °C a correction has been made using temperature coefficients measured by the laboratory that supplied the magnets.

6. TRACEABILITY

Each participant supplied a statement of traceability to the SI. The following table shows if traceability is to their own National Standards or if their traceability is to another National Measurement Institute (NMI).

Table 3. Traceability

Laboratory	Traceability to own National Standards	Traceable to other National Standards
NIM	√	
Hitachi Metals Ltd		AIST, NMIJ, JEMIC
Toei Industry Co.Ltd		AIST, NMIJ, JEMIC
Hirst		NIM
NPL	√	
Metis	*	*
Vacuumschmelze		PTB
INRim	√	

* Information not supplied in the participants report.

7. SAMPLE UNCERTAINTY BUDGET

Appendix 4 shows an example uncertainty budget used by NPL in the calculation of its uncertainty values for their IEC 60404 part 5 compliant method. The uncertainty budgets shows the contributions associated with the measurement of remanence, B_r , intrinsic coercivity, H_{cJ} , magnetic flux density coercivity, H_{cB} , and energy product, $(BH)_{max}$, of permanent magnets at an ambient temperature of 20 °C. The uncertainty budgets supplied by each participant should consider all these contributions with

individual values evaluated at the time of the measurements. Uncertainty budgets for PFM measurements will contain different contributions.

Dimensions of the magnets have not been included in the uncertainty budget as the dimensions in table 1 were used to calculate values.

See [1] for more information on evaluating uncertainty budgets.

For the calculation of the Reference Value in section 9 one sigma uncertainties are used.

8. TRANSFER STANDARD BEHAVIOUR

NIM measured all the permanent magnets at the start and end of the circulation to determine the stability of the magnets.

Table 4 shows the changes in the measured values from NIM from November 2007 to November 2008. All changes are less than the combined measurement uncertainty.

Table 4. Stability of permanent magnets

	B_r	H_{cJ}	H_{cB}	(BH)_{max}
CN1	-0.08%	-0.28%	-0.59%	-0.70%
CM1	0.08%	-0.17%	-0.42%	-0.22%
CH1	0.00%	-0.12%	-0.42%	-0.52%
JH1	0.08%	-0.15%	-0.03%	0.00%
JE1	0.00%	0.04%	-0.34%	-0.46%
CE1	-0.08%	-0.04%	-0.18%	-0.07%

9. COMPARISON REFERENCE VALUE

The comparison reference values have been calculated using the weighted mean of each set of measurement results. This approach was used because it is less influenced by the presence of extreme values.

The comparison reference value ε_{ref} , calculated as the weighted mean of each set of measurements is given by:

$$\frac{\varepsilon_{ref}}{u_{ref}^2} = \sum_{j=1}^N \frac{\varepsilon_j}{u_j^2} \quad (1)$$

where ε_j is each participant's individual results
 u_j is each participant's estimated one sigma uncertainty for ε_j .

The standard deviation (standard uncertainty) is given by:

$$\frac{1}{u_{ref}^2} = \sum_{j=1}^N \frac{1}{u_j^2} \quad (2)$$

A 95% confidence level is given by:

$$\varepsilon_{ref} \pm k \cdot u_{ref} \quad (3)$$

where k is the coverage factor determined from the t95-distribution table in [1].

10. RESULTS

10.1 Intrinsic coercivity, H_{cJ}

All the results shown in the following graphs have been normalised to the reference value (see section 9).

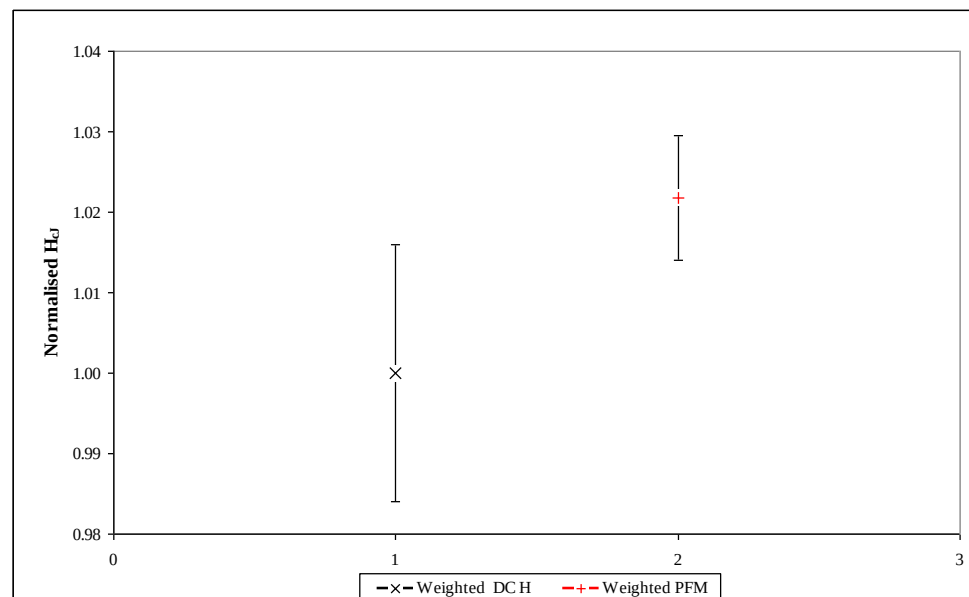
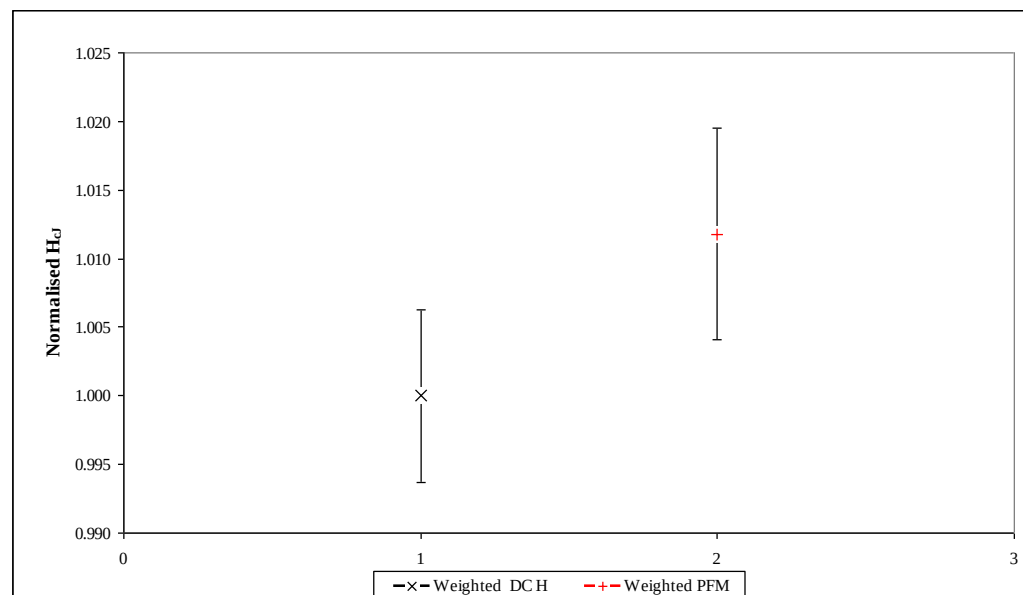
The intrinsic coercivity, H_{cJ} , results obtained from the comparison, are presented below in three ways.

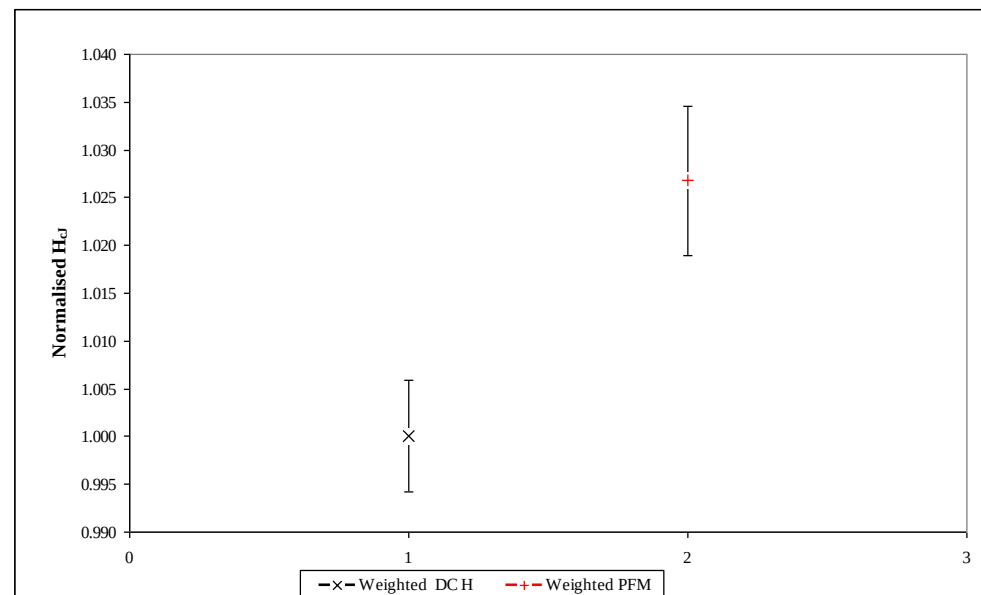
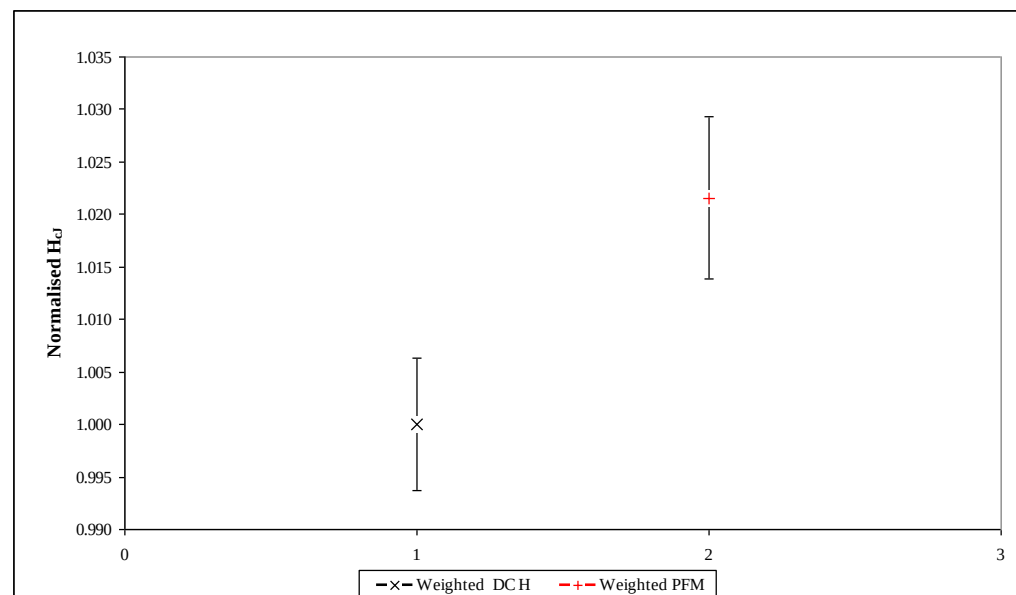
The first is a set of graphs showing the comparison of the Pulse Field Magnetometry method and the DC electromagnet based method of IEC 60404 part 5. The weighted mean was calculated for each measurement method using equation (1) along with the uncertainty of this reference value using equation (2). Values have been normalized for each magnet to the DC electromagnet based method of IEC 60404 part 5.

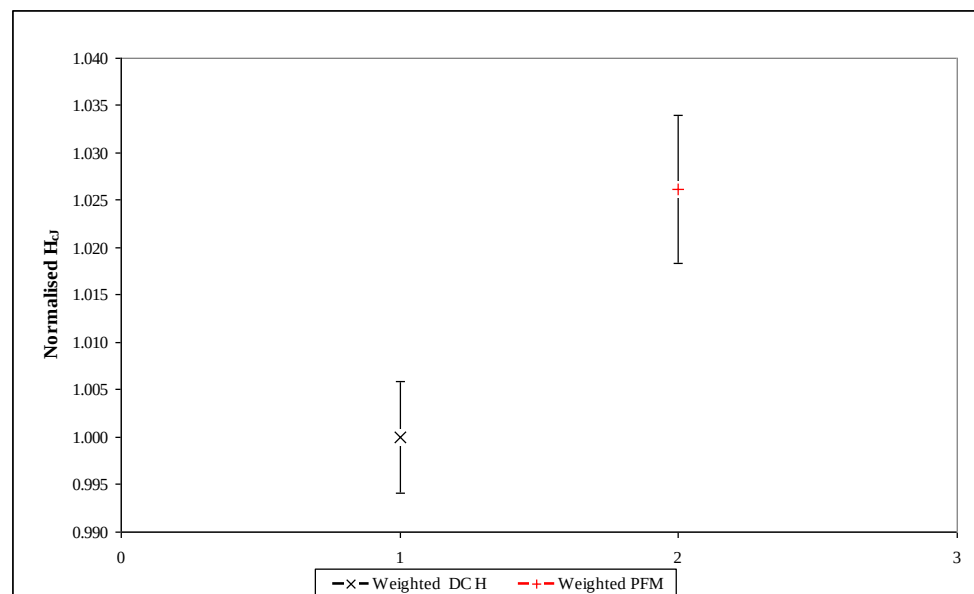
The second set of graphs (shown in Appendix 1) shows the H_{cJ} result for each participant and the corresponding 95% uncertainty along with the comparison reference value calculated using equation (1) and the 95% uncertainty of this reference value calculated using equation (2) and (3). For magnet CE1 (N33EH) the intrinsic coercivity could not be measured using a permeameter as the magnetic field required was too high. Only NPL measured the intrinsic coercivity for magnet JE1 (35EH).

The third set of graphs (shown in Appendix 2) shows the H_{cJ} results for each measurement method for each participant that submitted values for that method and the corresponding 95% uncertainty along with the comparison reference value calculated using equation (1) and the 95% uncertainty of this reference value calculated using equation (2) and (3).

These results are discussed in section 11.1.

Magnet JE1, H_{cJ} **Magnet CH1, H_{cJ}** 

Magnet CN1, H_{cJ} **Magnet JH1, H_{cJ}** 

Magnet CM1, H_{CJ} 

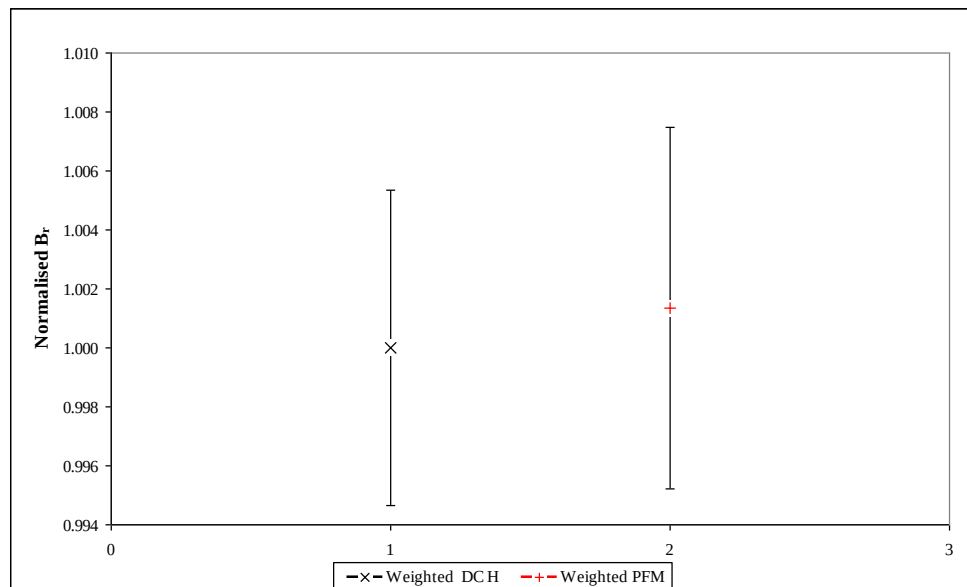
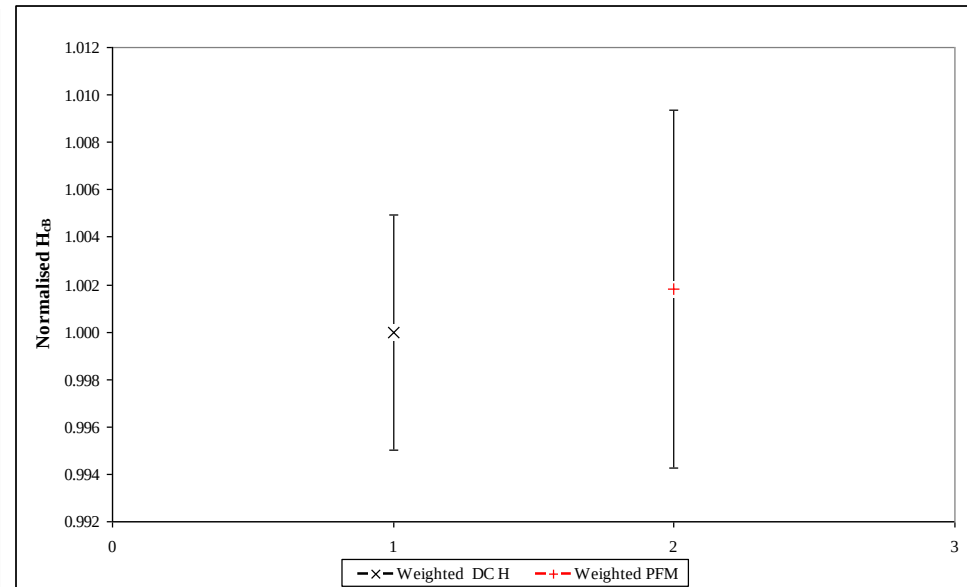
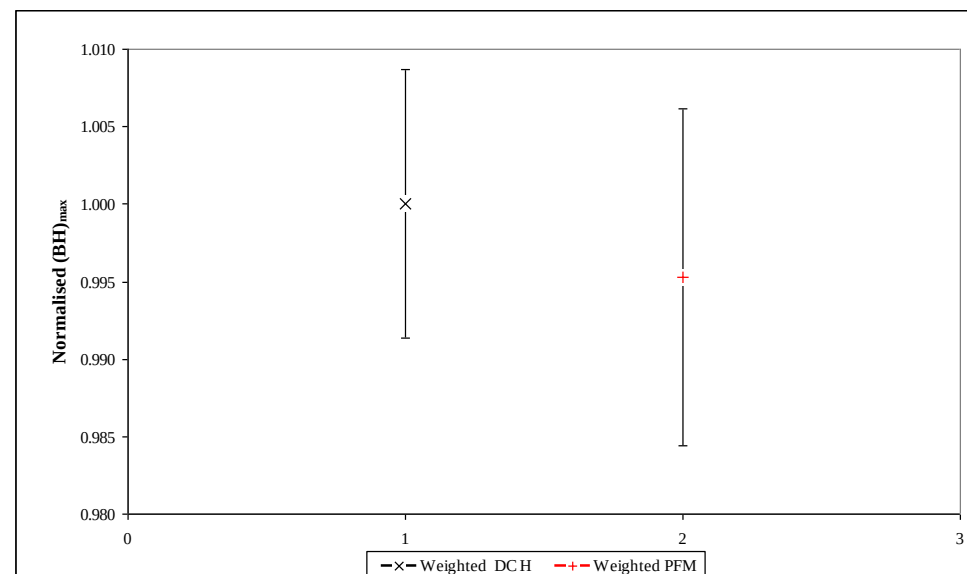
10.2 Remanence (B_r), magnetic flux density coercivity (H_{cB}) and energy product (BH_{max})

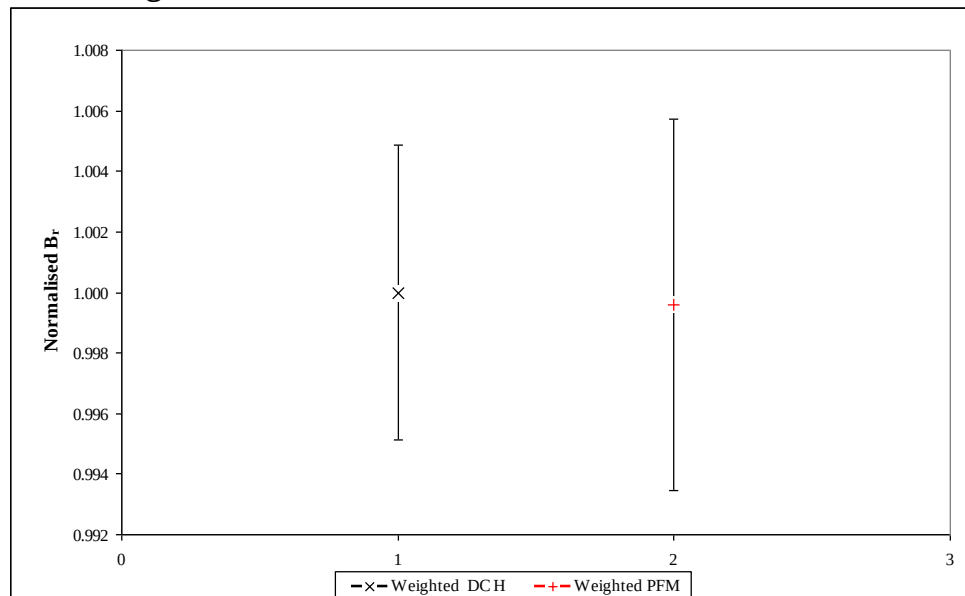
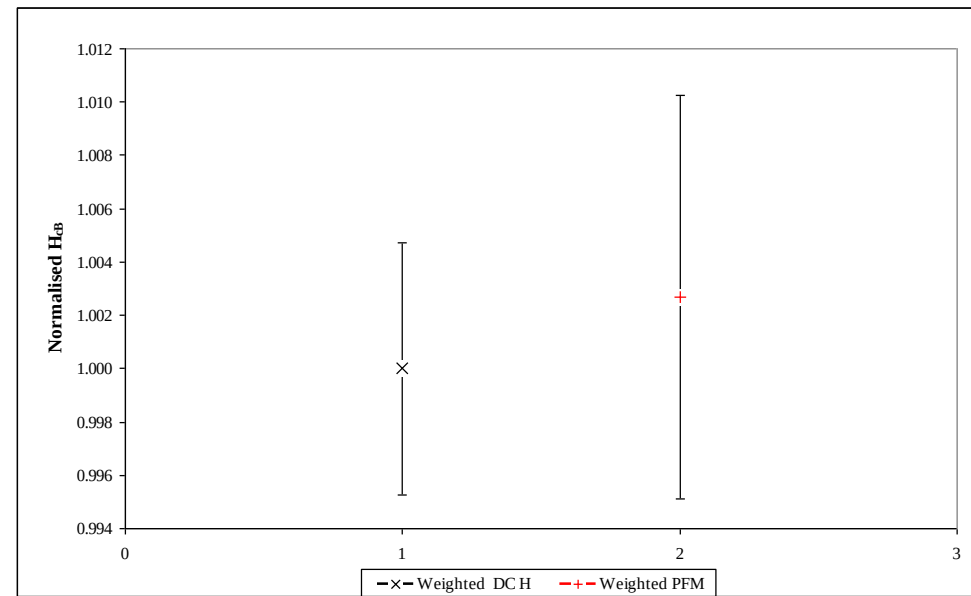
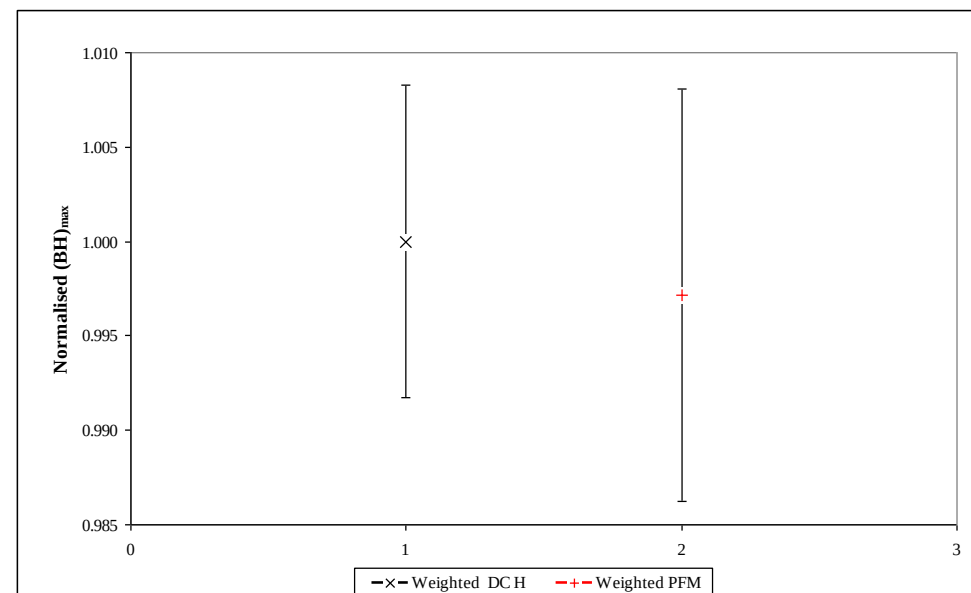
All the results shown in the following graphs have been normalised to the reference value.

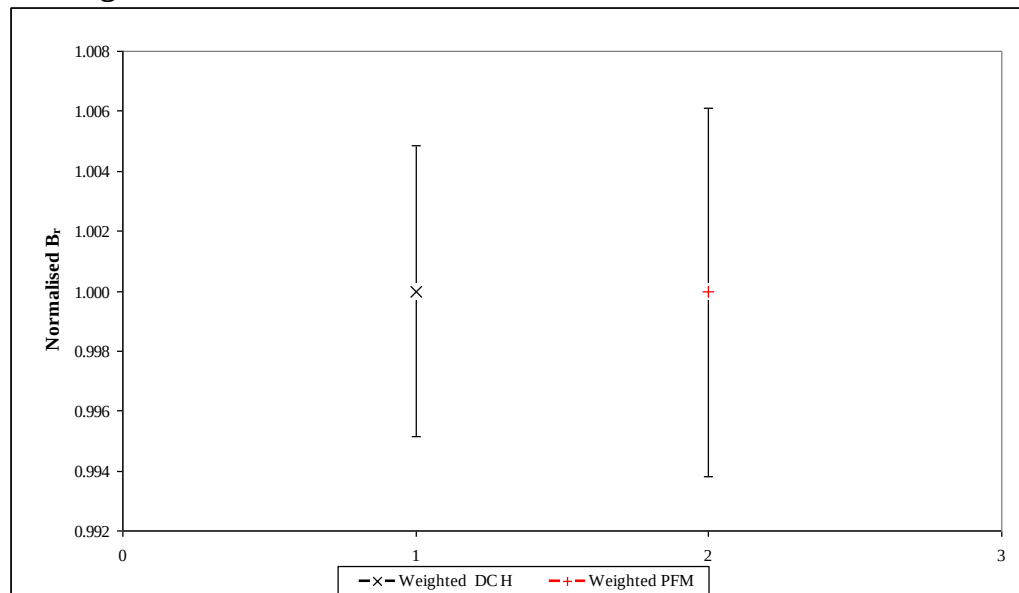
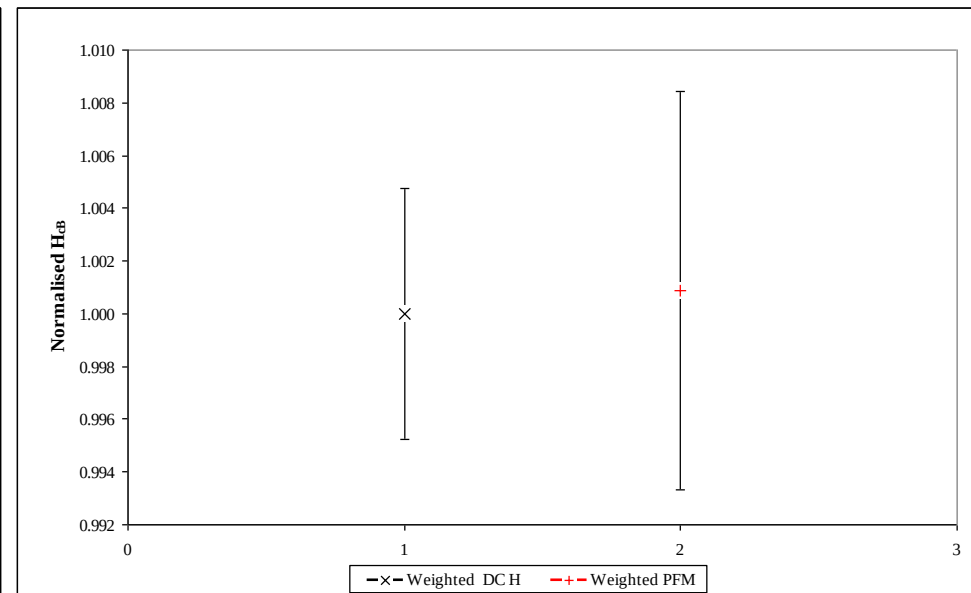
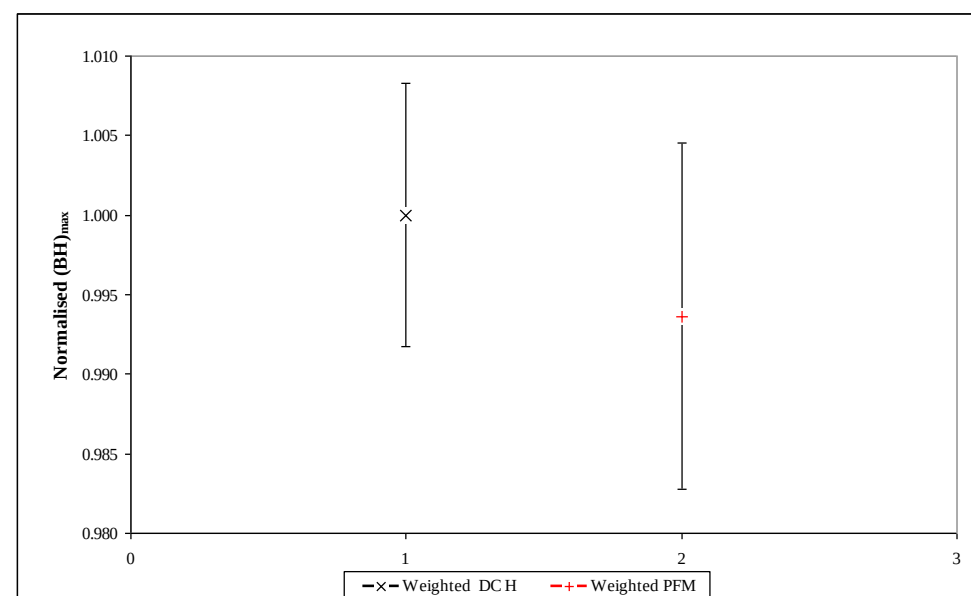
The results obtained from the comparison are displayed in two ways. The first is a set of graphs showing the comparison of the IEC 60404 part 5 method and the Pulse Field Magnetometry method. The weighted mean was calculated for each measurement method using equation (1) along with the 95% uncertainty of this reference value using equation (2). Each parameter (excluding H_{cJ}) measured for each magnet is given in the figures below.

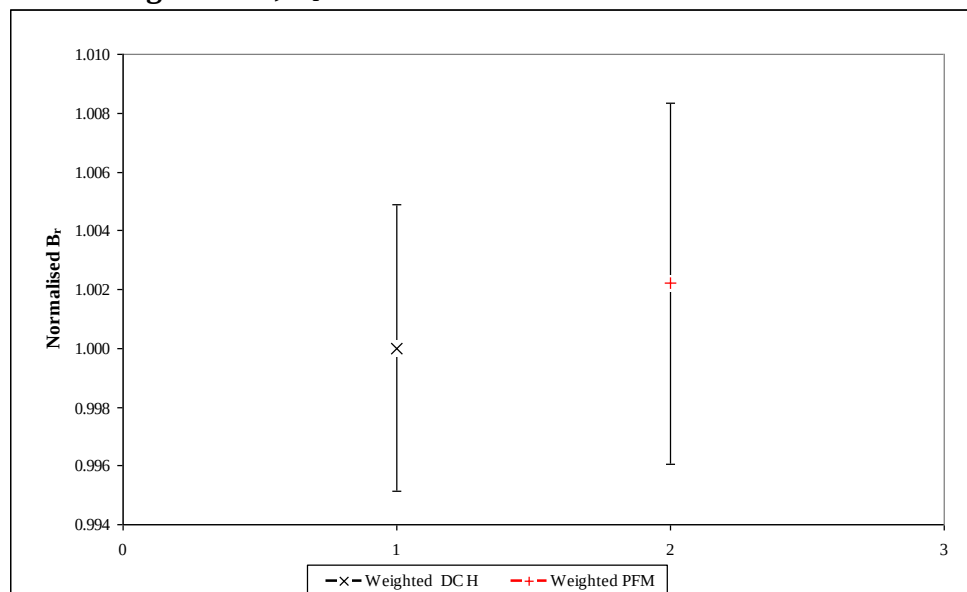
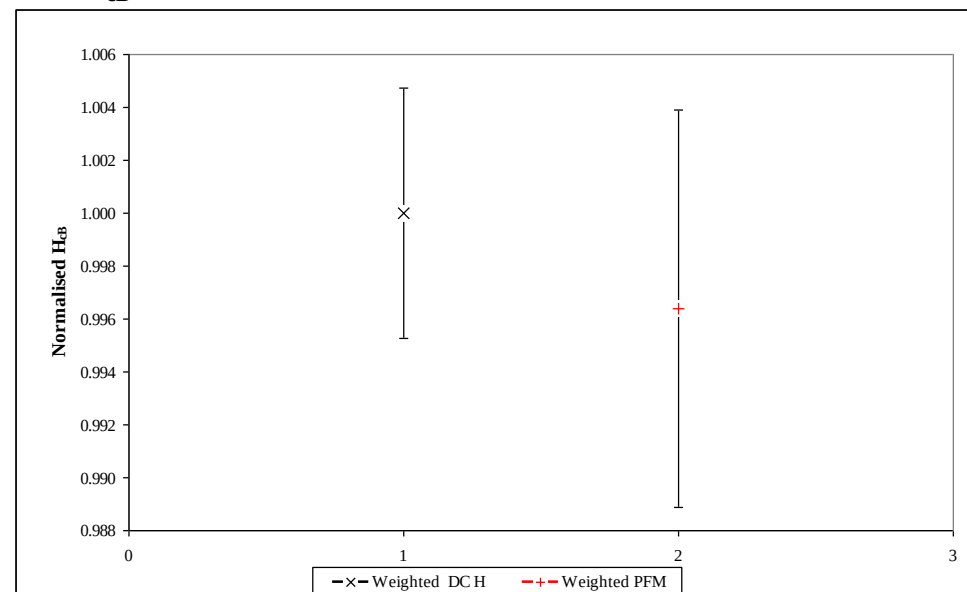
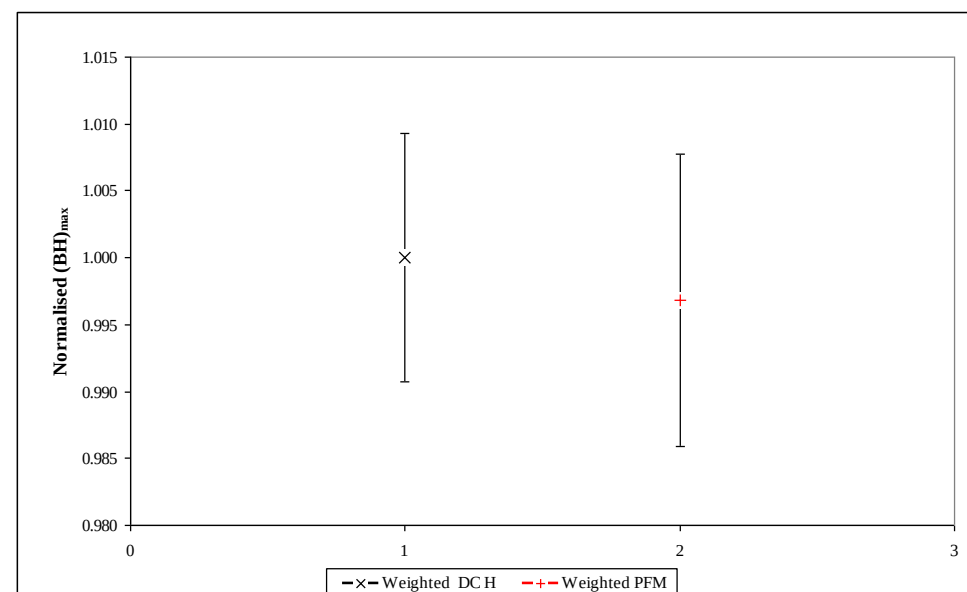
The graphs in Appendix 1 show the results for each participant and the corresponding 95% uncertainty, the weighted mean reference value calculated using equation (1) and the 95% uncertainty of this reference value calculated using equations (2) and (3).

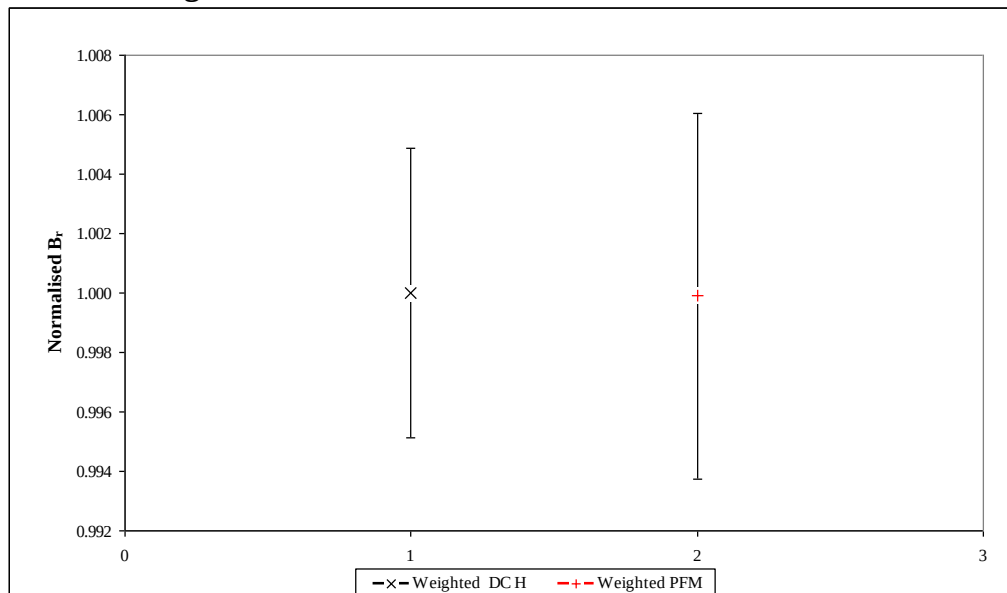
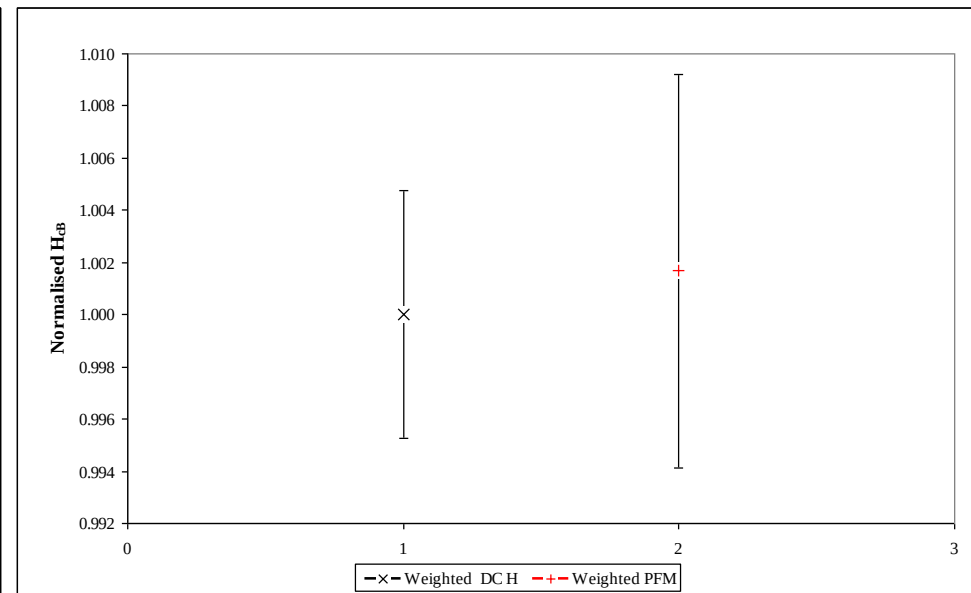
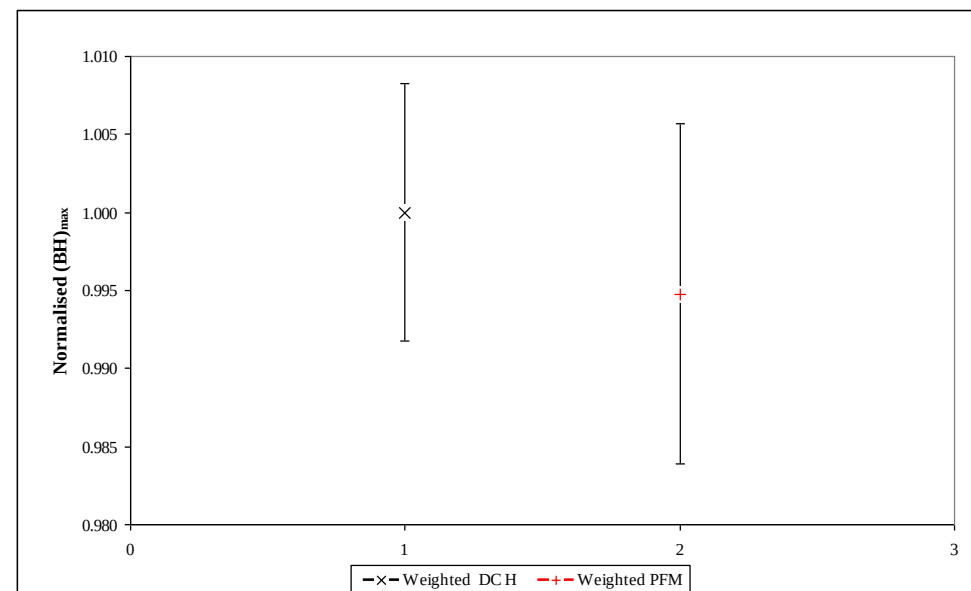
These results are discussed in section 11.2.

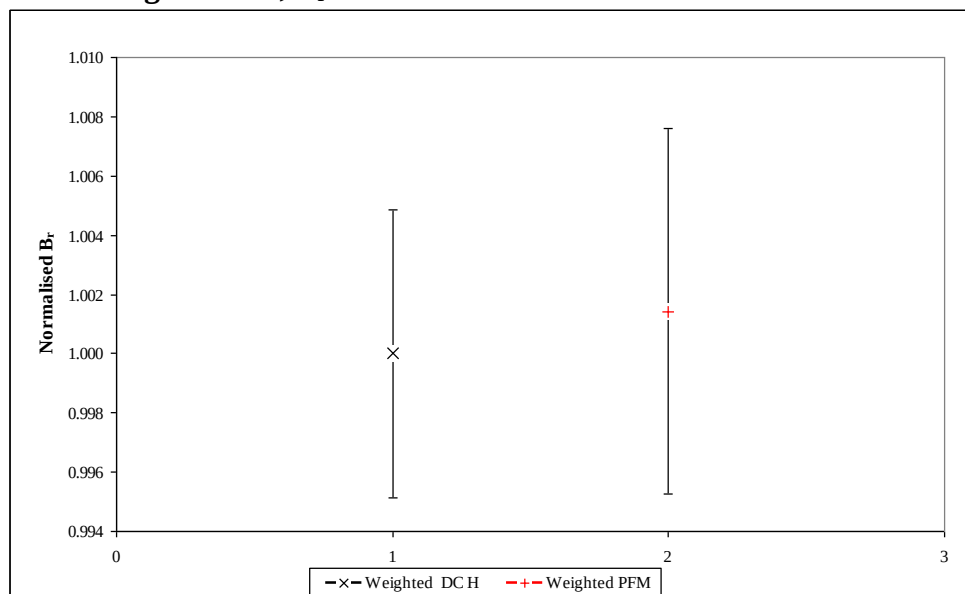
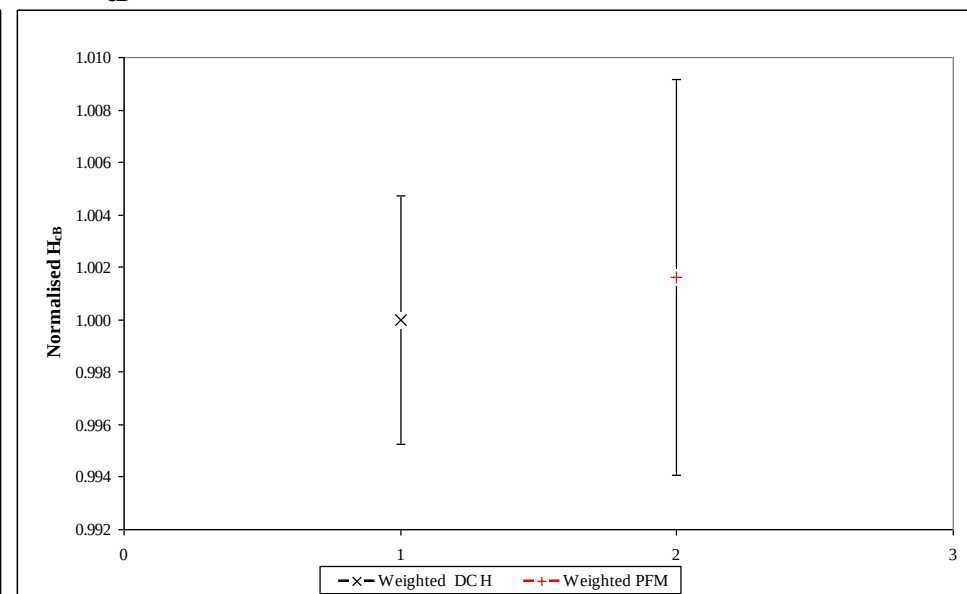
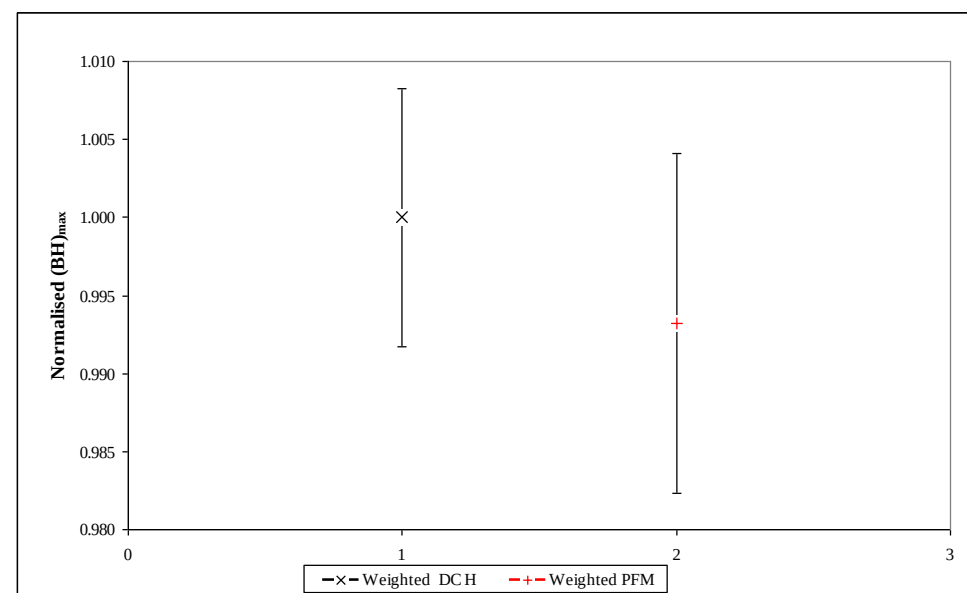
Magnet CE1, B_r  **H_{cB}**  **$(BH)_{\max}$** 

Magnet JE1, B_r  **H_{cB}**  **$(BH)_{\max}$** 

Magnet CH1, B_r  **H_{cB}**  **$(BH)_{\max}$** 

Magnet CN1, B_r  **H_{cB}**  **$(BH)_{\max}$** 

Magnet JH1, B_r  **H_{cB}**  **$(BH)_{\max}$** 

Magnet CM1, B_r  **H_{cB}**  **$(BH)_{max}$** 

11. DISCUSSION

11.1 Intrinsic coercivity, H_{cJ}

From the graphs in section 10.1 showing the comparison of the measured intrinsic coercivities for the Pulse Field Magnetometry method and the traditional DC electromagnet based method it can be seen that for magnets CN1, JH1 and CM1 there is a significant difference. For these magnets and magnets JE1 and CH1 the intrinsic coercivity measured using the DC Permeameter method of IEC 60404 part 5 is always lower than that measured using the Pulse Field Magnetometry method. This is the result of “magnetic viscosity” that is known to introduce a dependence of the measured intrinsic coercivity on the speed at which the reverse magnetic field is increased.

An additional study was conducted at NPL to investigate any magnetic viscosity effects for the NdFeB permanent magnets measured in this comparison. The results are shown in Appendix 5. It can be seen that changing the speed of the reversal can effect the measured intrinsic coercivity by up to 1.89% for the different reversal speeds used. It is expected that using larger reversal speeds would increase this discrepancy. At the IEC TC 68 WG 2 meeting in Paris in September 2010 it was suggested that measurements could be made too slow. The negative slope of the reversal line for magnet CN1 was thought to indicate that these measurements were in error. In Appendix 6 the origin of this behaviour is explained and it is shown that the intrinsic coercivity determined from such a reversal is not subject to any error.

Shown in Table 5 are the intrinsic coercivity reference values measured for both methods for the magnets that could have their polarization reversed by more than one participant using an electromagnet. The difference in the reference values for the methods has been calculated and the result divided by the combined 95% measurement uncertainty. These values are given in the column “D/CU”. When the result of this division is larger than 1 there is a significant difference between the values used in the calculation. This means that for one of the methods a contribution to the measurement uncertainty has not been included. (NOTE it is possible that uncertainty contributions have been missed for both methods and checks may need to be performed if there is evidence that this is the case).

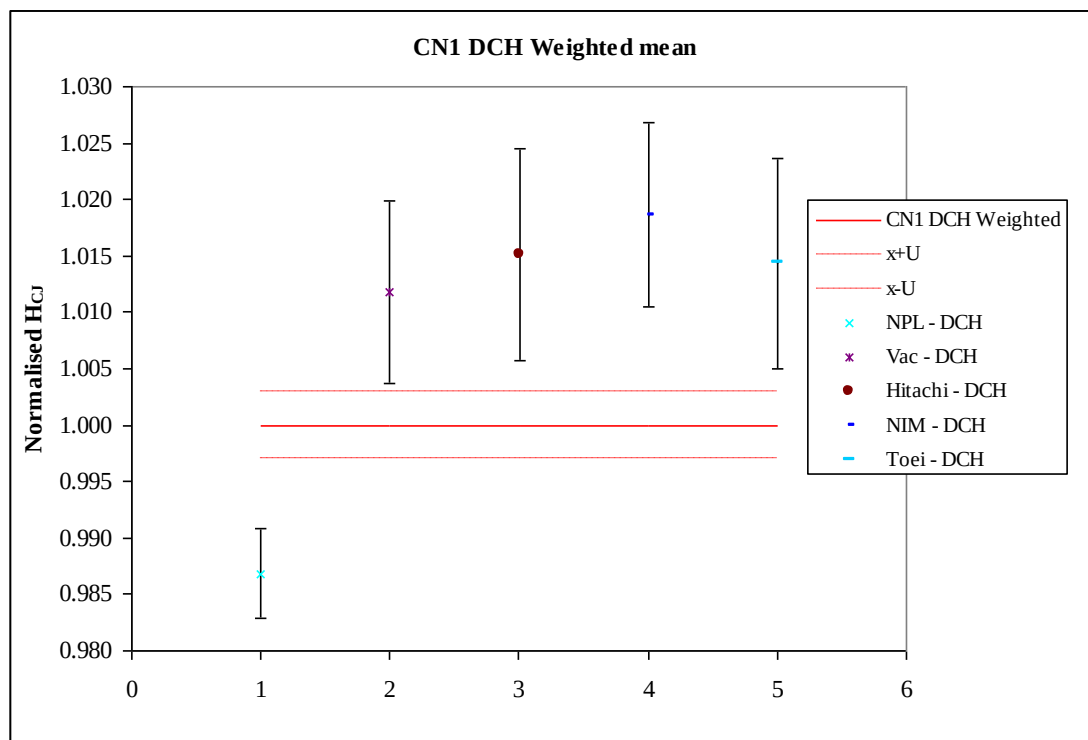
Table 5. Intrinsic coercivity reference values for the two methods

Magnet	EM	PFM	CU (%)	D/CU
CN1	1062.5	1091.0	0.96	2.79
CM1	1206.2	1237.7	0.96	2.73
CH1	1522.0	1540.0	0.99	1.20
JH1	1358.7	1388.0	0.99	2.19

In the table EM = Electromagnet method, PFM = Pulse field method, CU = combined uncertainty and D = difference.

Referring to Appendix 5, it is shown that the speed at which the magnetic field is increased during the reversal of the magnetic polarization alters the measured intrinsic

coercivity, with a quicker increase in the magnetic field (higher reversal speed) resulting in a larger intrinsic coercivity. This phenomenon occurs for all intrinsic coercivity measurements to some degree. This can be seen in the following graph where there is significant scatter in the electromagnet results. Since the speed of the reversal is not defined in IEC 60404 part 5 it may not be typical for the laboratory performing the measurements to consider the speed as a significant measurement parameter. Since NPL systematically varied the speed of the reversal and reported the intrinsic coercivity value measured for the slowest possible reversal speed, their measured value is lower than those of the other laboratories. This is true for all the electromagnet measurements reported and is consistent with NPL using the slowest reversal speeds. Since IEC 60404 part 5 considers DC measurements, then the measurements should be made using as slow a reversal speed as can be obtained.



Since the reversal speed for the Pulse Field Magnetometer method is orders of magnitude quicker than for the electromagnet measurements (see Table 2) there will, for certain types of magnets, be a difference between the DC intrinsic coercivity and the value measured.

It was considered interesting by permanent magnet industry experts of IEC TC 68 WG2 and WG5 to consider the agreement between intrinsic coercivity measurements for these two methods when the values measured for, as close as practically possible, quasi static conditions were not used in the analyses. Shown in Table 6 are the results of the analyses with the NPL values excluded.

Table 6. Intrinsic coercivity reference values for the two methods with the NPL results excluded

Magnet	EM	PFM	CU (%)	D/CU
CN1	1078.4	1091.0	1.14	1.01
CM1	1220.9	1237.7	1.14	1.21
CH1	1538.8	1540.0	1.26	0.06
JH1	1375.3	1388.0	1.26	0.73

In the table EM = Electromagnet method, PFM = Pulse field method, CU = combined uncertainty and D = difference.

It can be seen from the “D/CU” column of Table 6, when compared to Table 5, that the agreement is much better since the values are closer to or less than one. From the previous discussions this is to be expected. While the agreement is better there still exists a speed related measurement uncertainty that, because faster speeds are used, is sufficiently small (relative to the PFM measurements) to remove any discrepancy. The results presented in Table 6 require a correction to be applied to obtain the DC intrinsic coercivity. It is therefore not sufficient to use an electromagnet measurement that has not measured the DC intrinsic coercivity to “calibrate” the pulse field magnetometer method.

11.2 Remanence (B_r), magnetic flux density coercivity (H_{cB}) and energy product (BH_{max})

From the results in section 10.2 it can be seen that for the quantities B_r , H_{cB} and BH_{max} the reference values for the method of IEC 60404 part 5 and the Pulse Field Magnetometer method agree within the uncertainties provided.

Points to note:

- For the results corrected to 20 °C, (see Table 2 in section 4), no additional contribution to the uncertainty was included.
- The quoted uncertainties given by each participant were quite varied over all the measured quantities. An extreme example is for BH_{max} where the quoted uncertainty ranges from 0.25% to 1.80%.

The results presented in Appendix 1 generally show good agreement for B_r , H_{cB} and BH_{max} .

Issues related to the measurement of the intrinsic coercivity, H_{cJ} , are being considered separately. The exploitation of the increased magnetic field strength, as well as other aspects, possible using PFM methods requires agreement between the methods for this quantity.

12. CONCLUSIONS

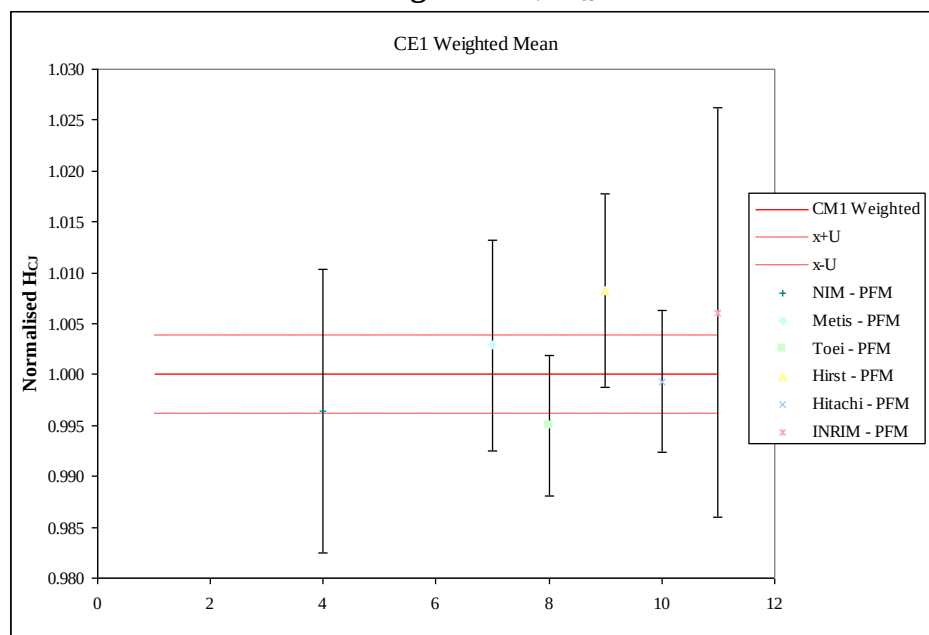
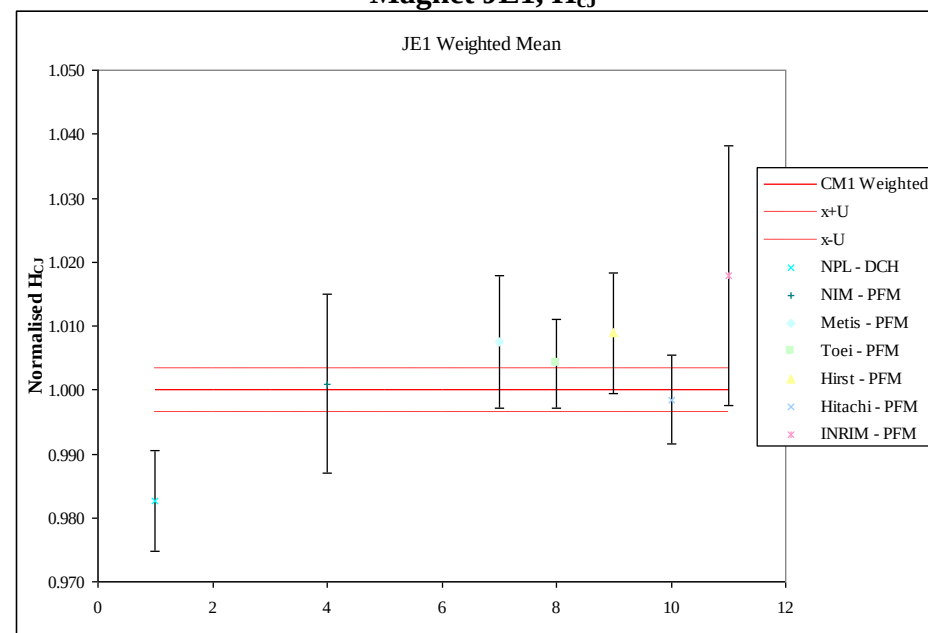
For the measurement of permanent magnets the electromagnet based method of IEC 60404 part 5 and the Pulse Field Magnetometer method of the Technical Report PD IEC/TR 62331:2005 agree within the combined uncertainties for the quantities B_r , H_{CB} and BH_{max} .

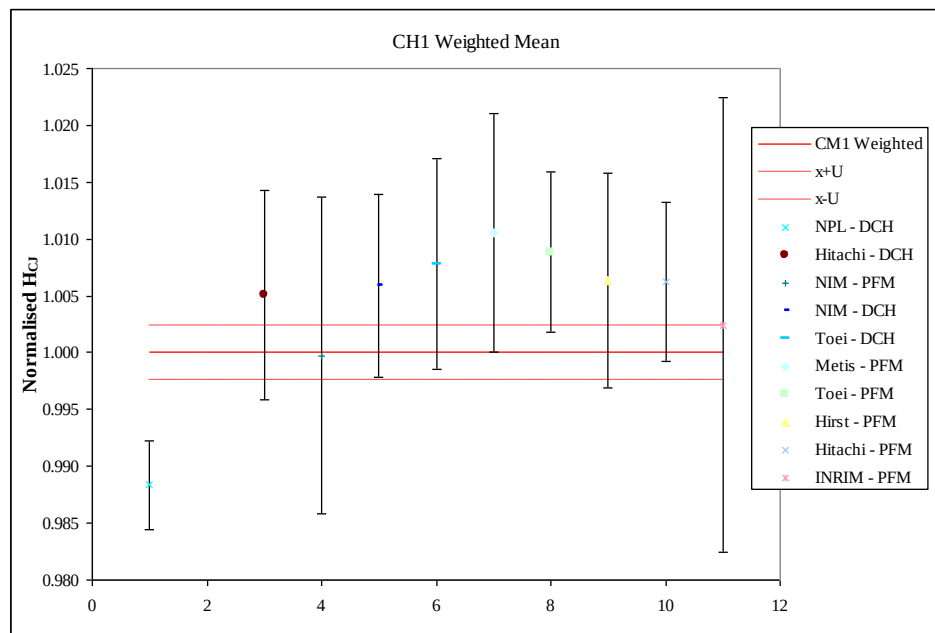
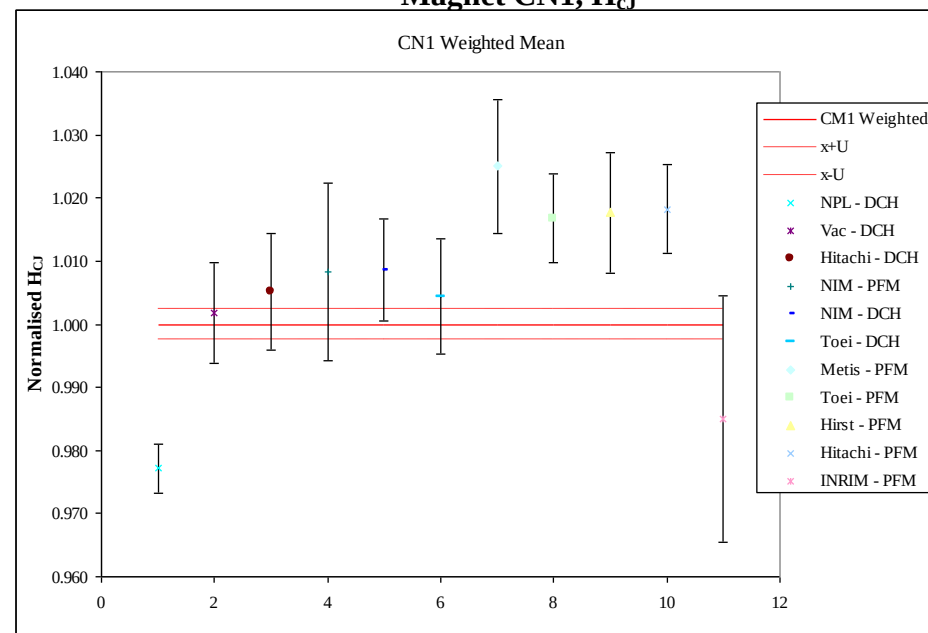
For H_{CJ} the dependence of the measurement of this quantity on the speed at which the magnetic field is reversed is significant with the largest changes in value occurring as a DC measurement condition is approached.

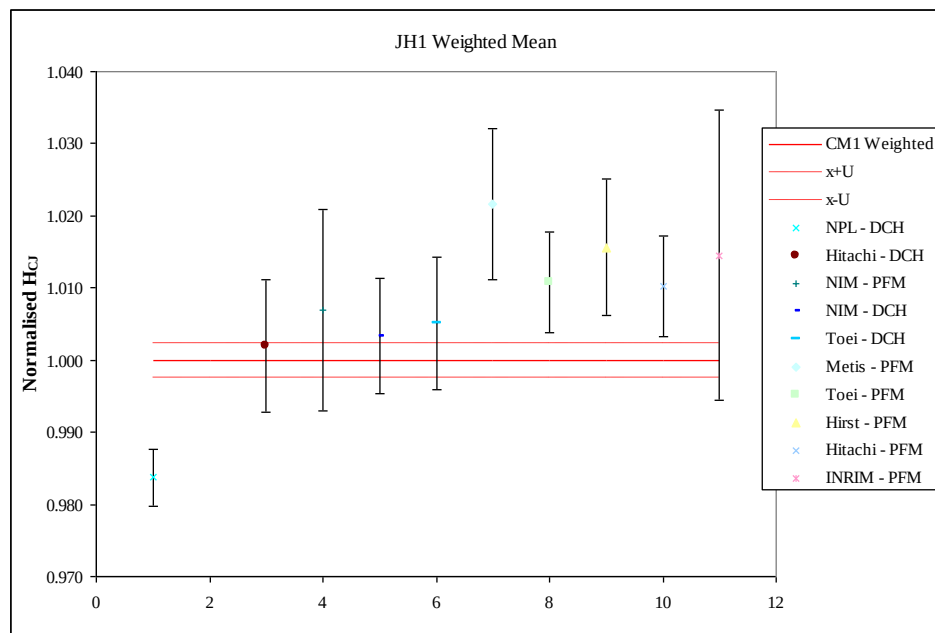
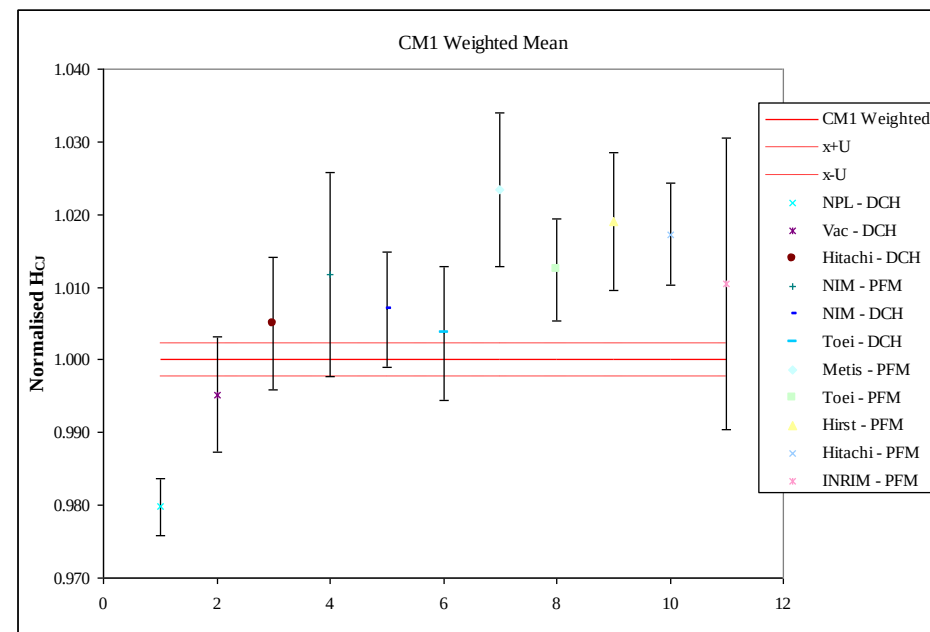
The current issue of IEC 60404 part 5 discusses the measurement speed in clause 9.2 and states “The speed of variation of the magnetic flux density shall be sufficiently slow to avoid the production of a phase difference between H and B or of eddy currents in the test specimen. With some materials there is a significant delay between the change in the magnetic flux density and the change in the magnetic field strength.” This work has shown that it may be beneficial to include information on the dependence of the intrinsic coercivity on the reversal speed for NdFeB magnets.

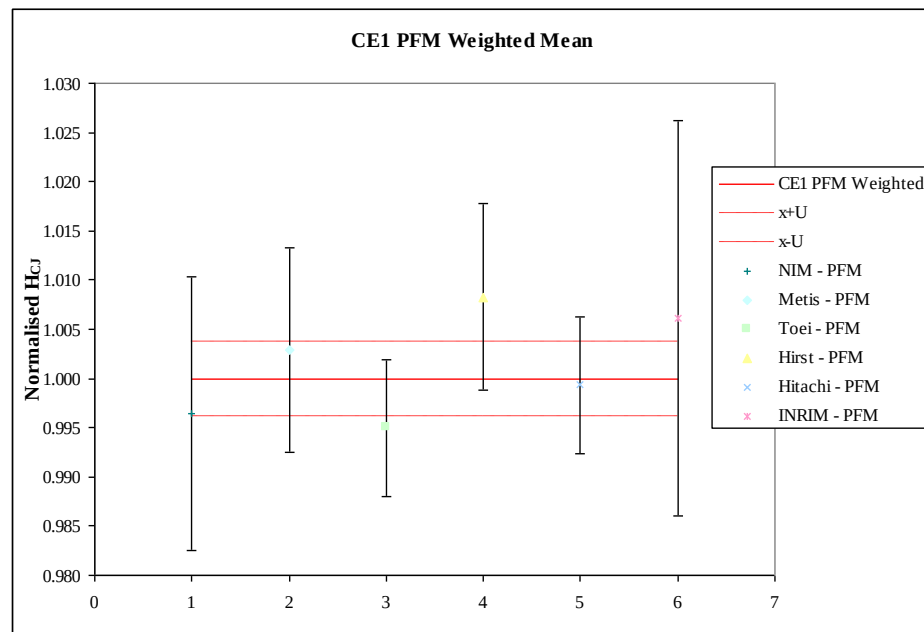
REFERENCES

- [1] BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, Guide to the expressions of uncertainty in measurement, International organisation of standardisation, Geneva, First edition 1993.

APPENDIX 1: H_{CJ} RESULTSMagnet CE1, H_{CJ} Magnet JE1, H_{CJ} 

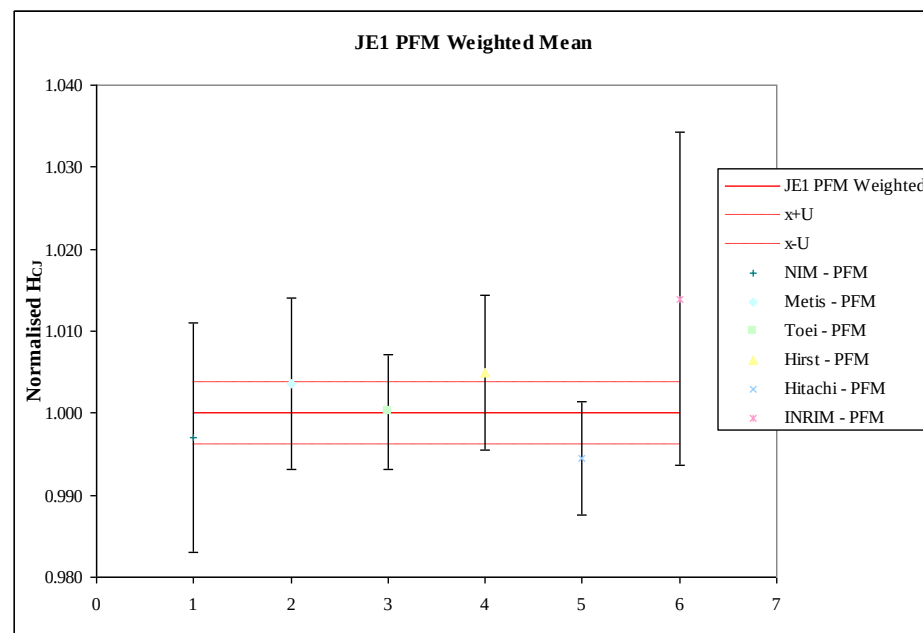
Magnet CH1, H_{cJ} **Magnet CN1, H_{cJ}** 

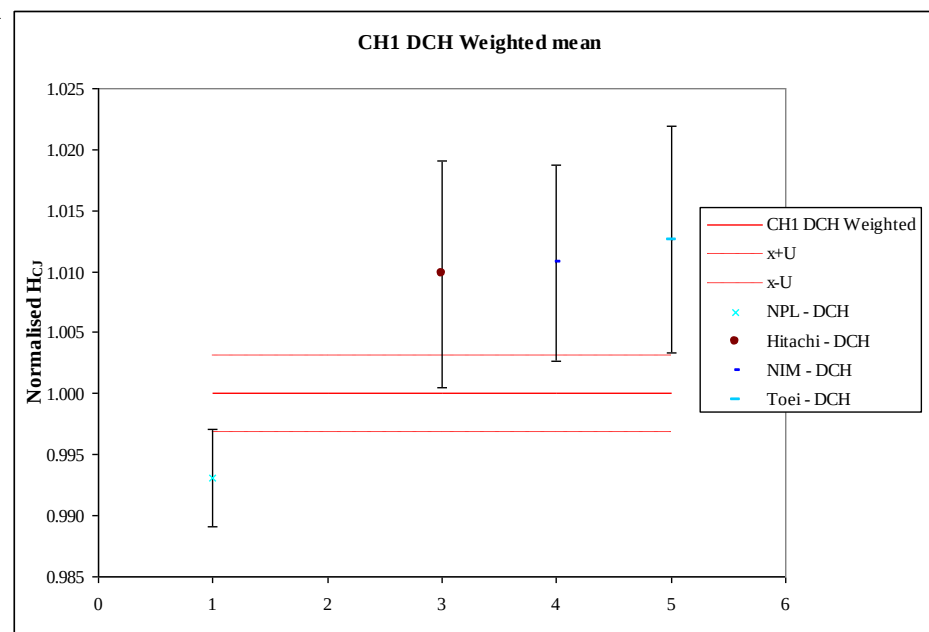
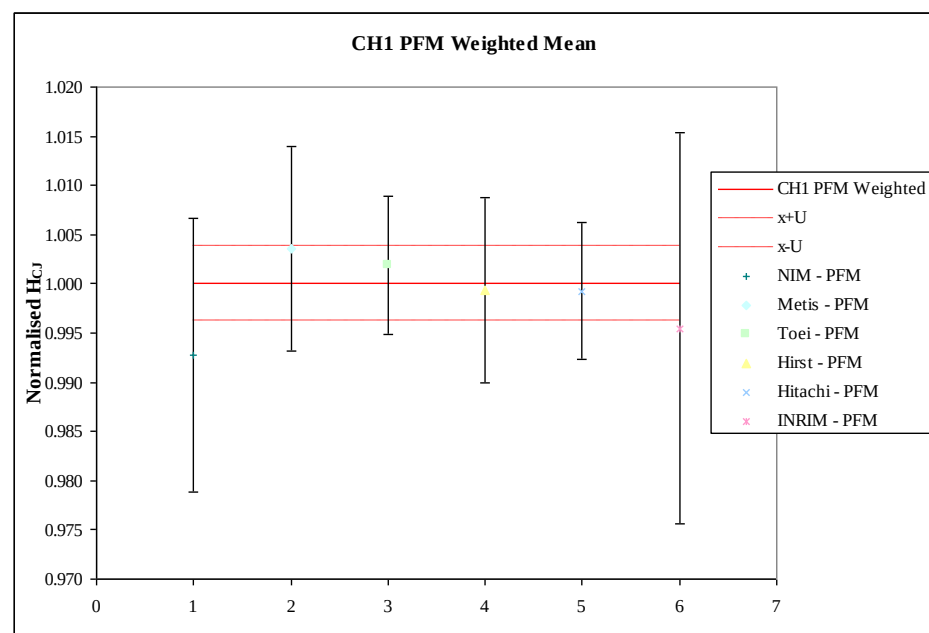
Magnet JH1, H_{cJ} **Magnet CM1, H_{cJ}** 

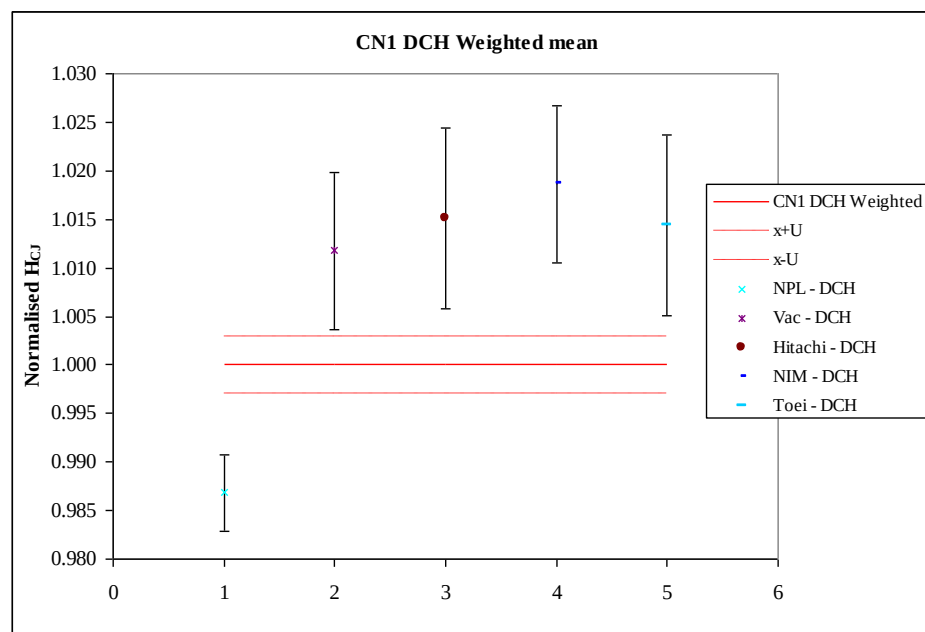
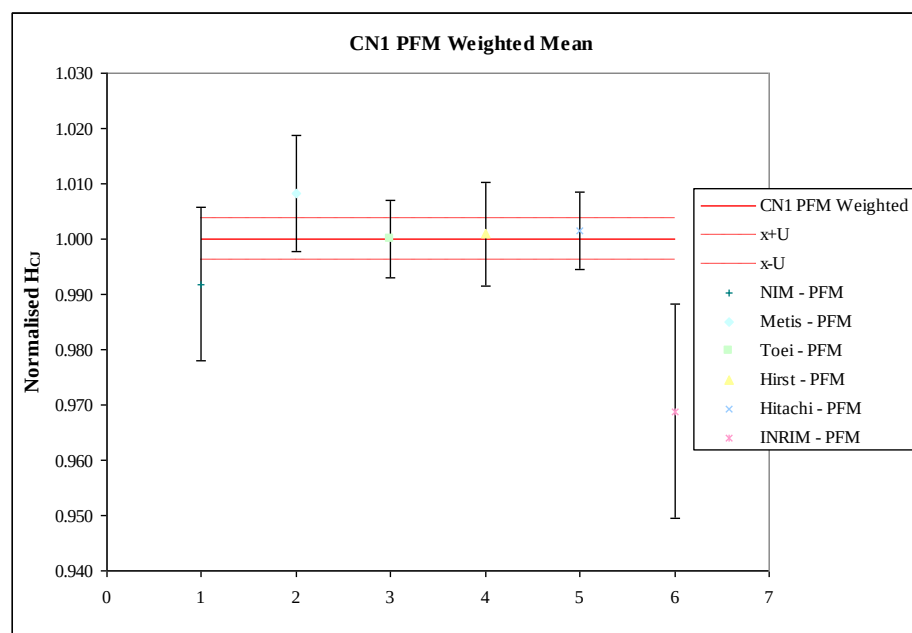
APPENDIX 2: EACH MEASUREMENT METHOD VIEWED SEPARATELY**Magnet CE1, Method: DCH, H_{cJ} – could not be reversed in DCH****Magnet CE1, Method: PFM, H_{cJ}** 

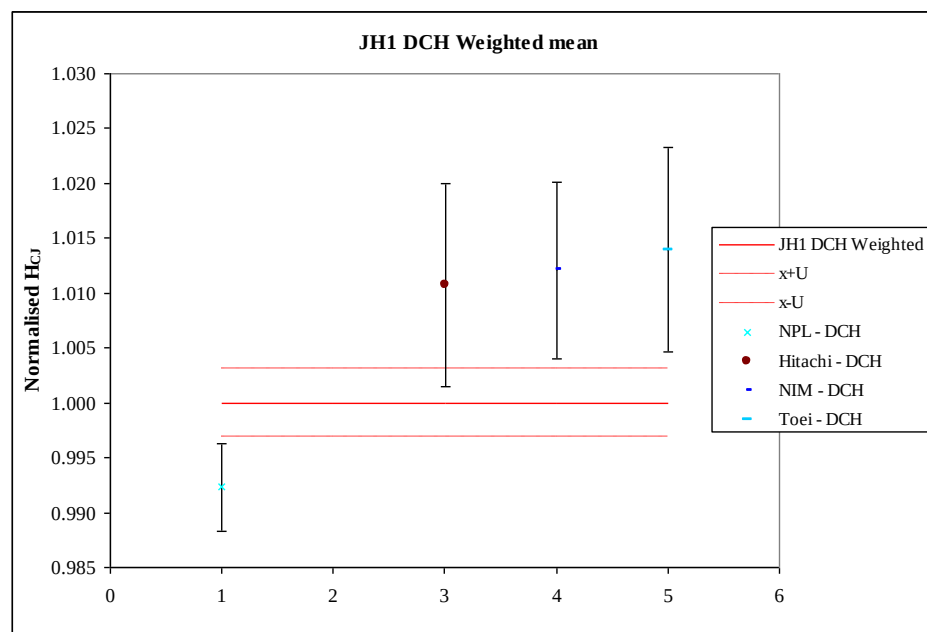
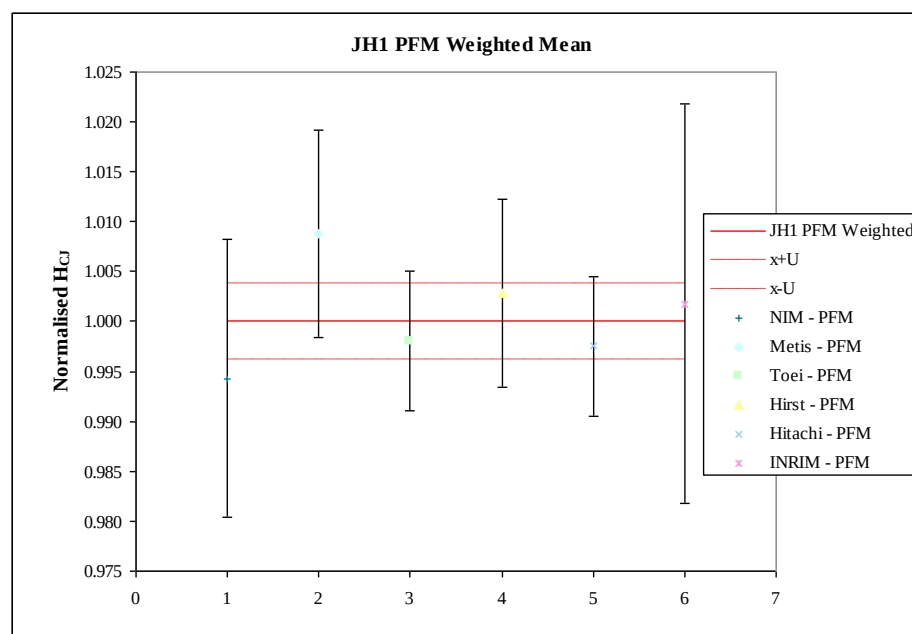
Magnet JE1, Method: DCH, H_{cJ} – Only NPL could reverse.

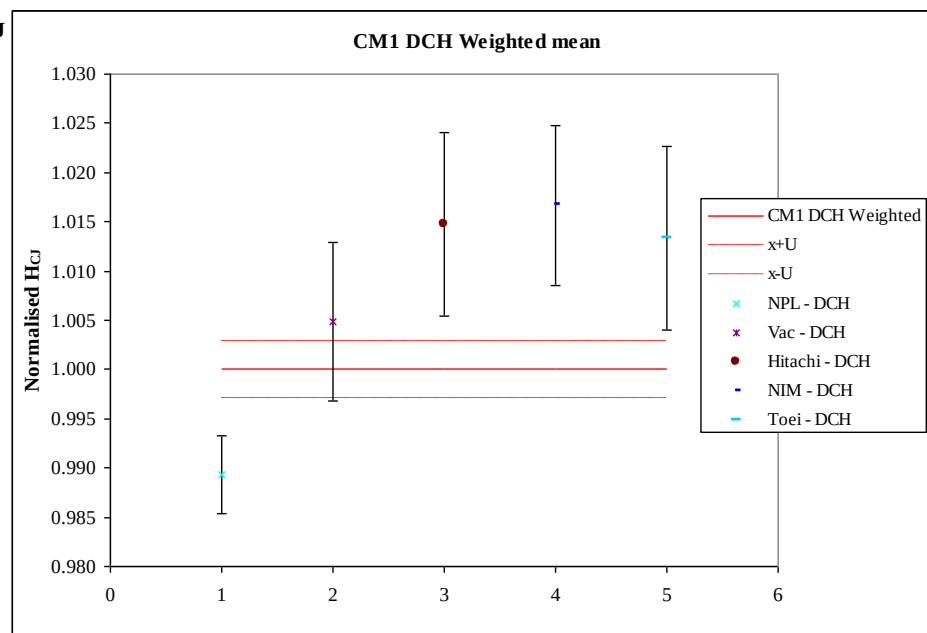
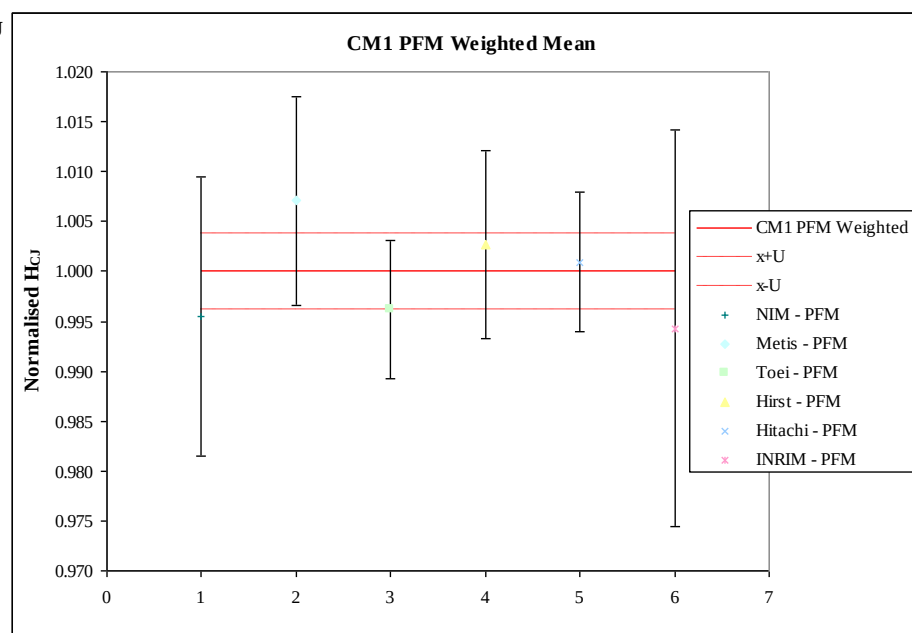
Magnet JE1, Method: PFM, H_{cJ}



Magnet CH1, Method: DCH, H_{cJ} **Magnet CH1, Method: PFM, H_{cJ}** 

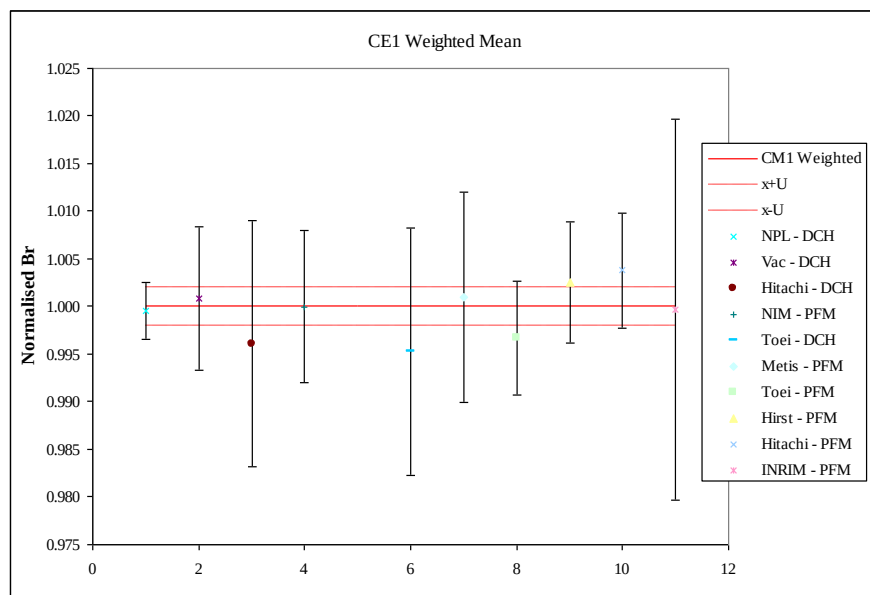
Magnet CN1, Method: DCH, H_{cJ} **Magnet CN1, Method: PFM, H_{cJ}** 

Magnet JH1, Method: DCH, H_{cJ} **Magnet JH1, Method: PFM, H_{cJ}** 

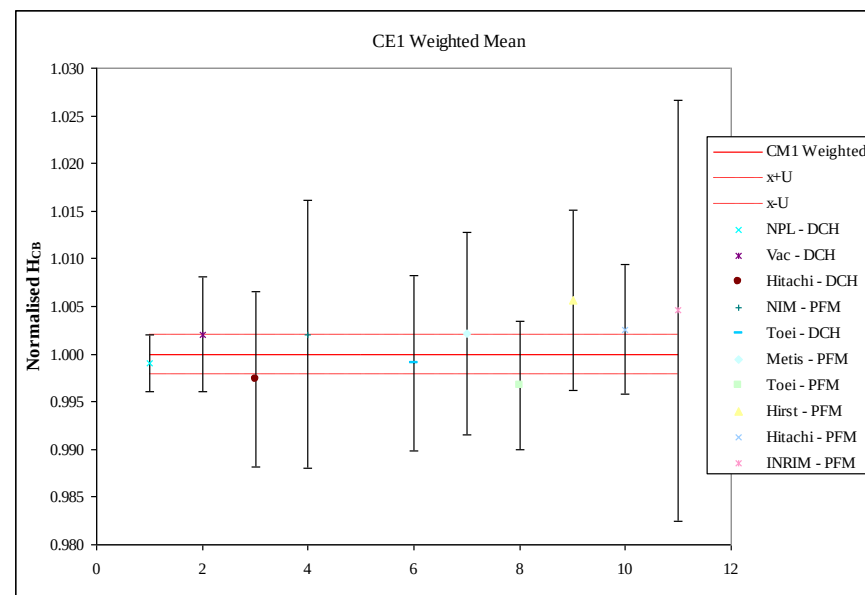
Magnet CM1, Method: DCH, H_{cJ} **Magnet CM1, Method: PFM, H_{cJ}** 

APPENDIX 3: B_R , H_{CB} AND $(BH)_{MAX}$ RESULTS

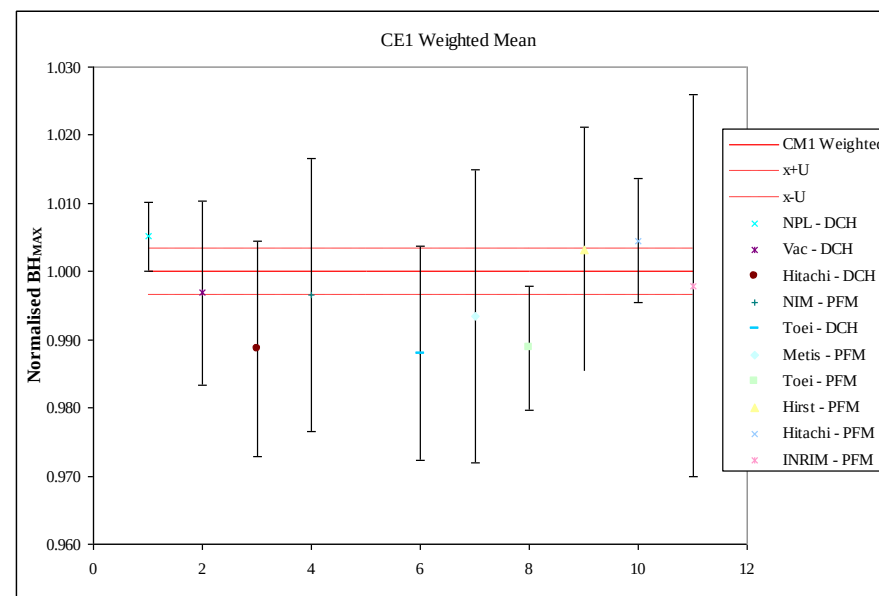
Magnet CE1, B_r



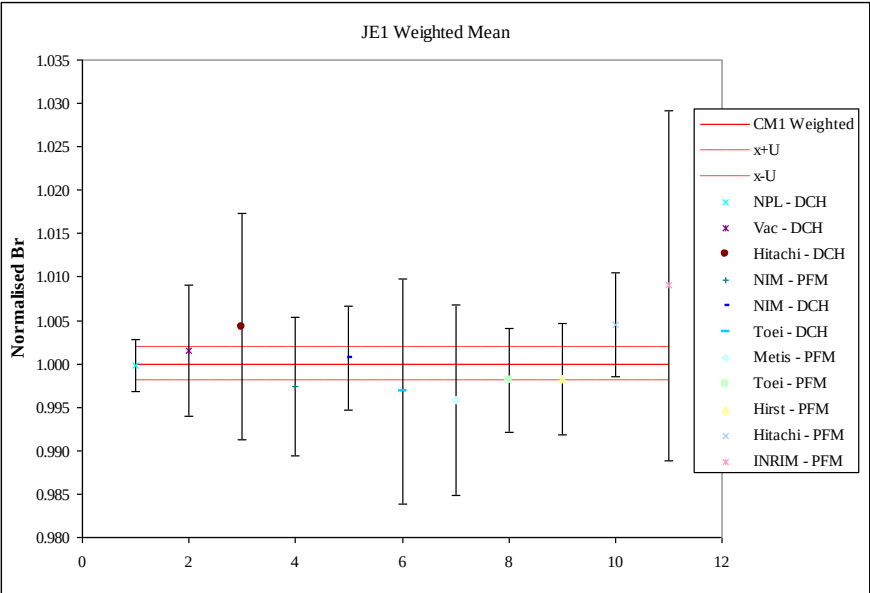
H_{CB}



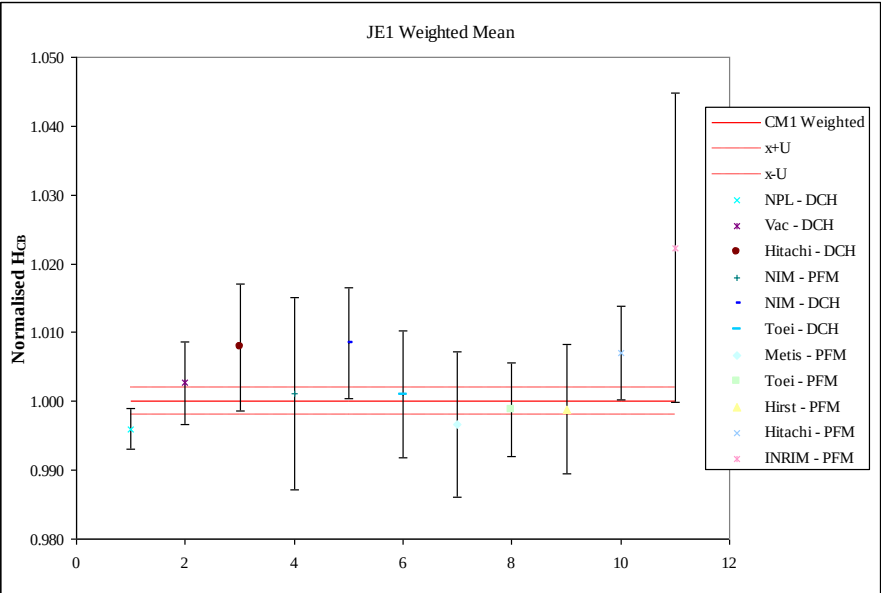
$(BH)_{max}$



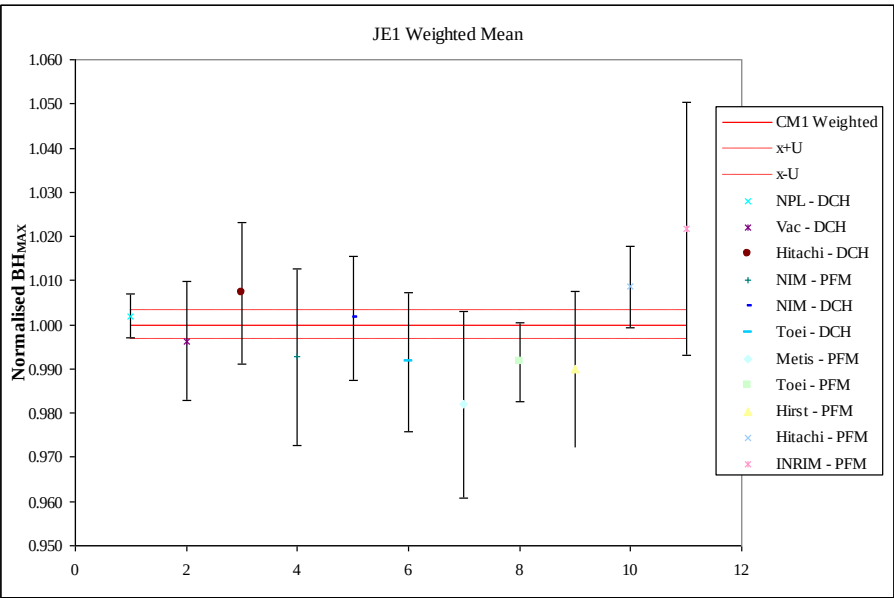
Magnet JE1, B_r



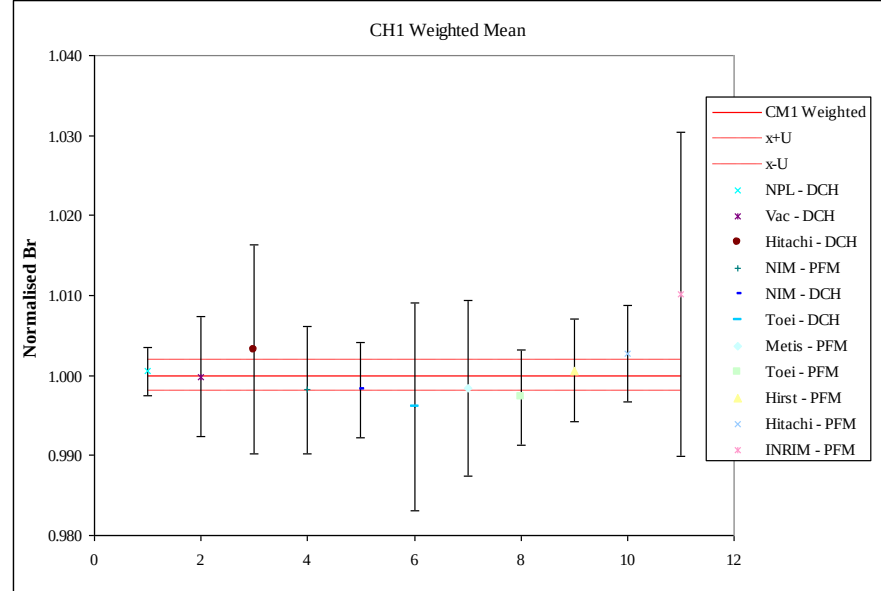
H_{cB}



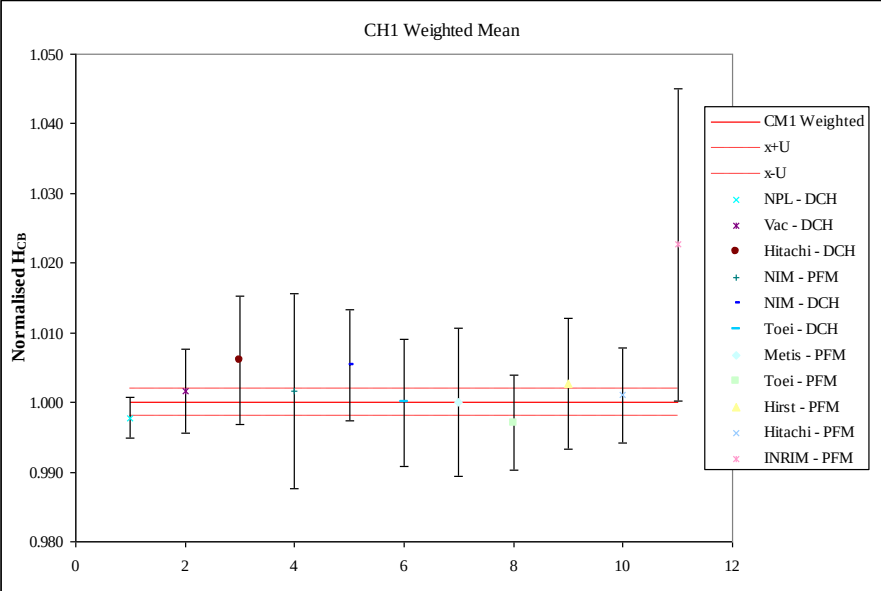
$(BH)_{max}$



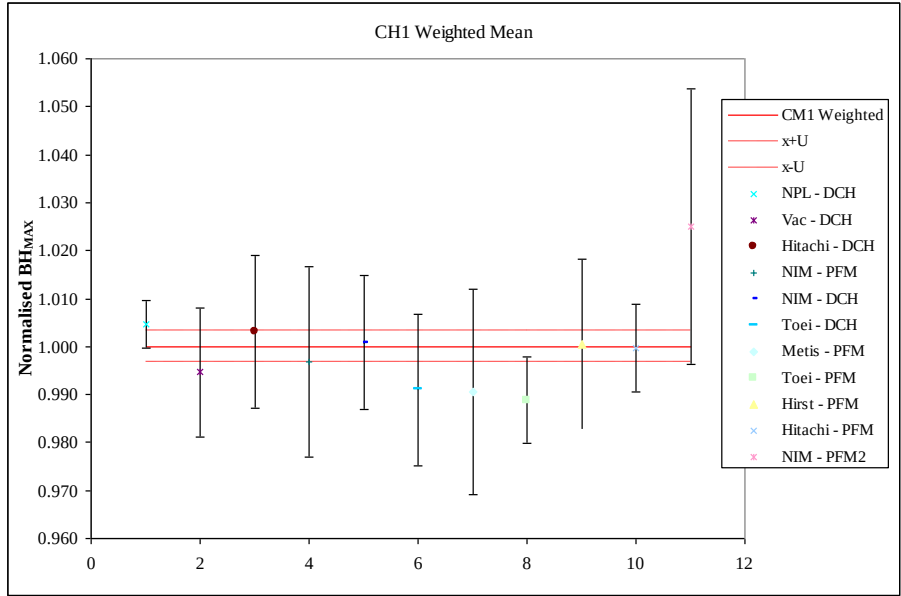
Magnet CH1, B_r

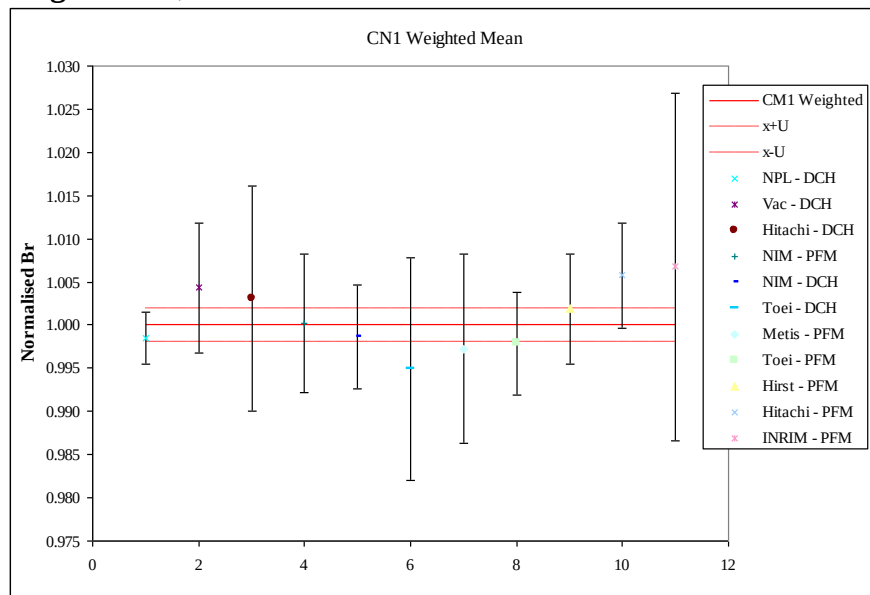
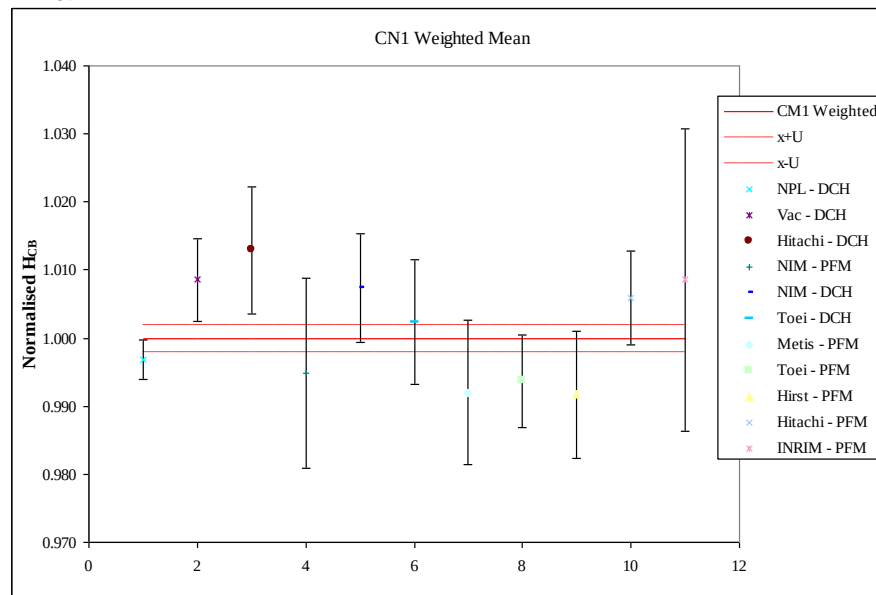
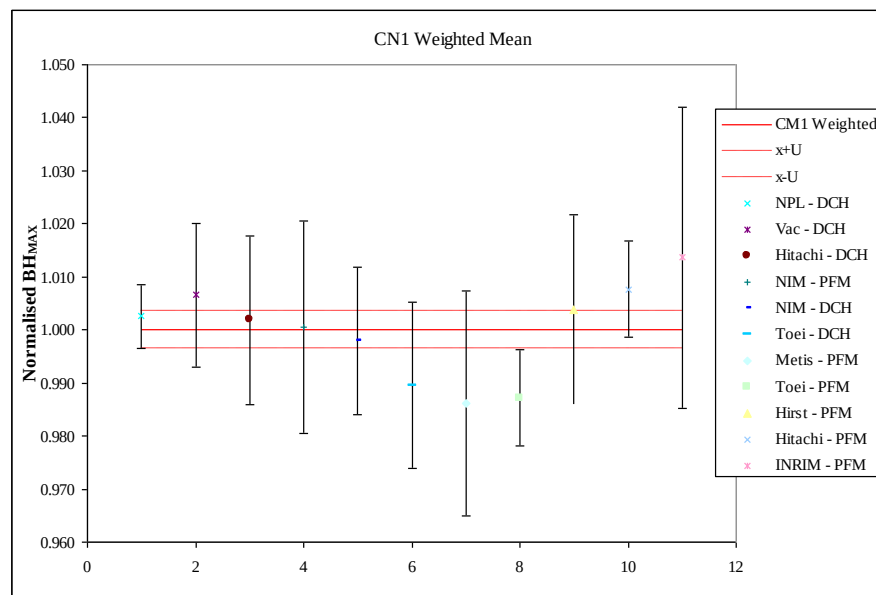


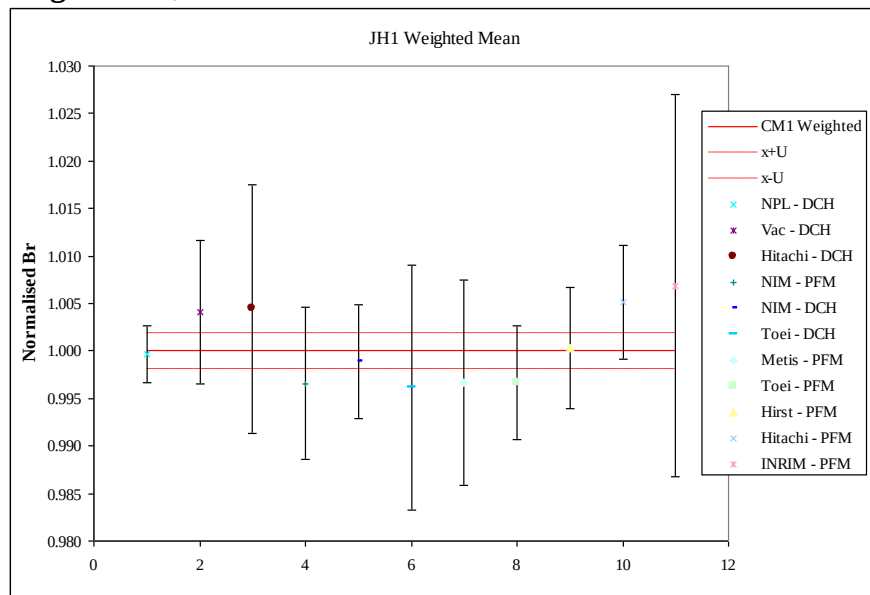
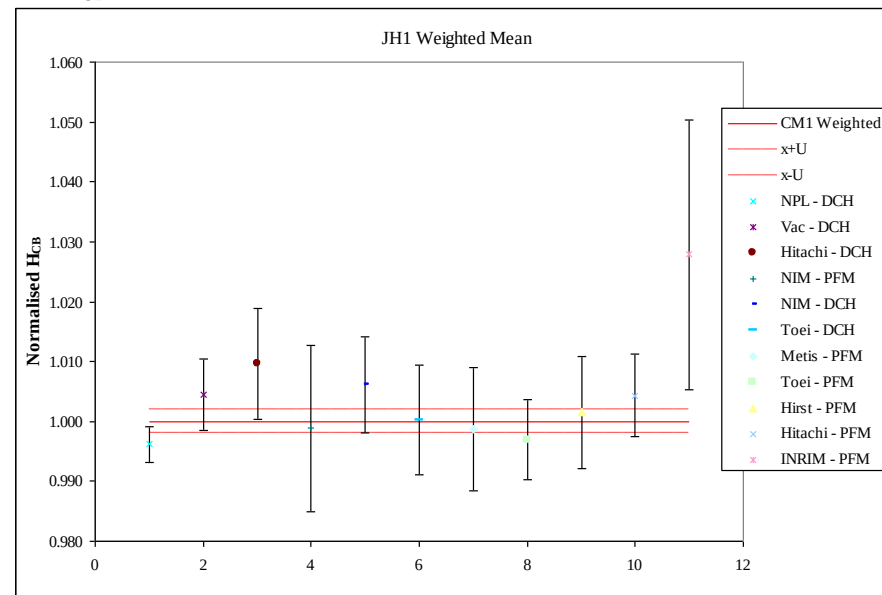
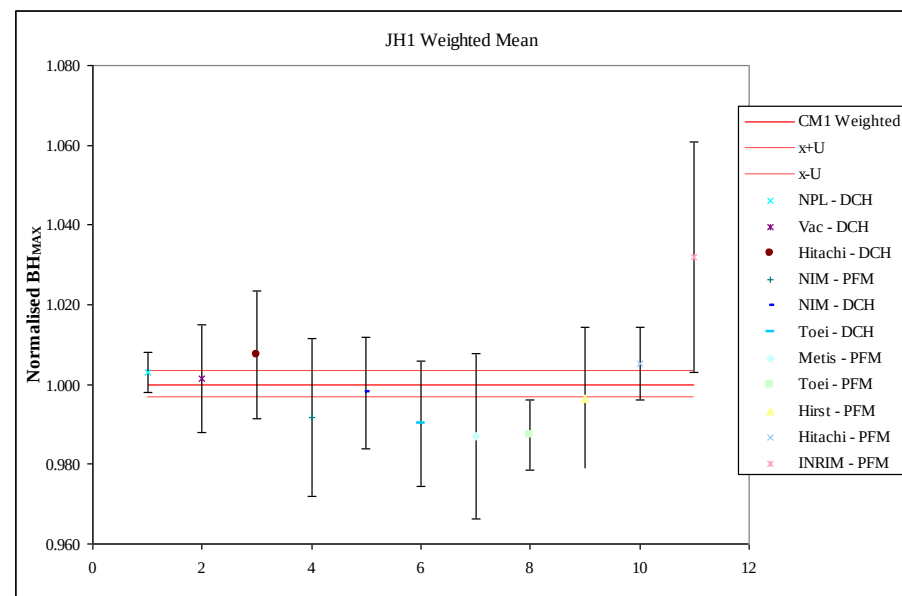
H_{CB}



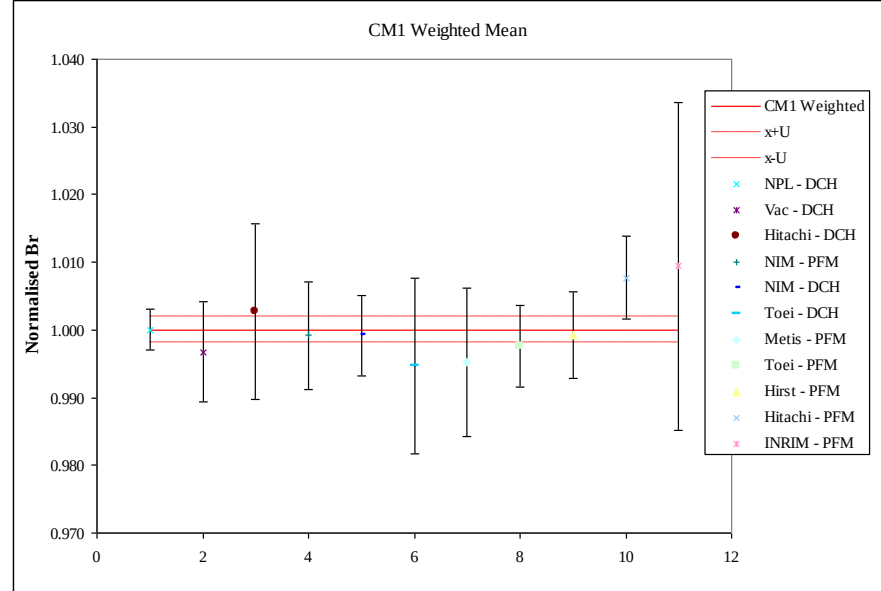
$(BH)_{max}$



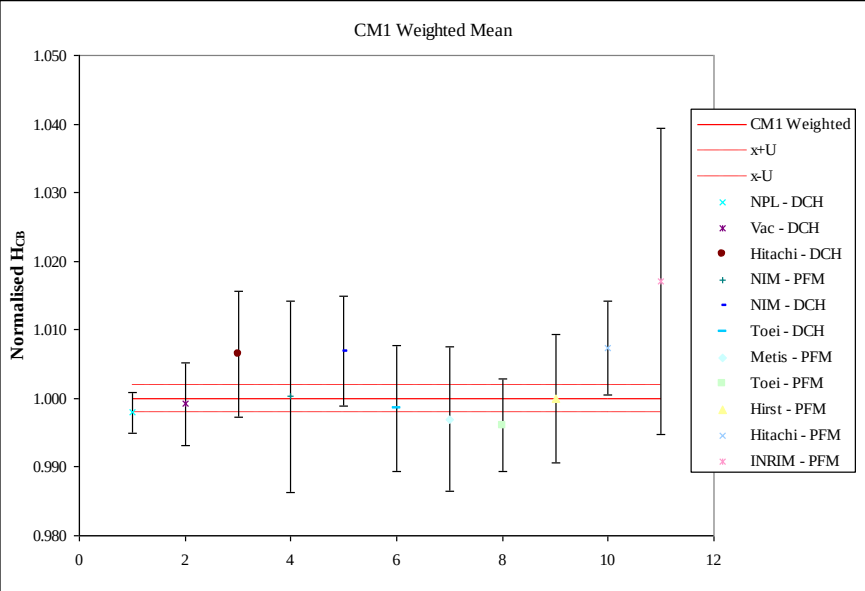
Magnet CN1, B_r  **H_{CB}**  **$(BH)_{max}$** 

Magnet JH1, B_r  **H_{cB}**  **$(BH)_{max}$** 

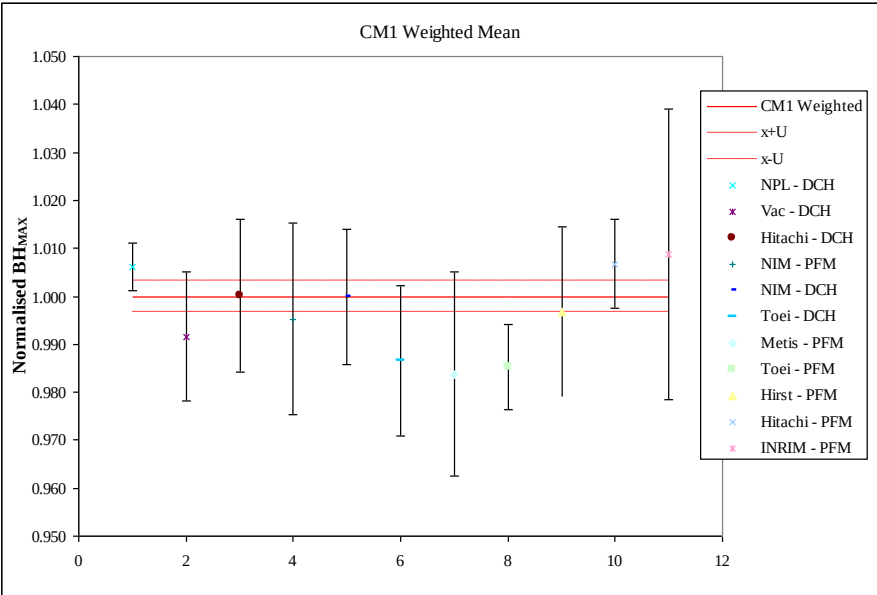
Magnet CM1, B_r



H_{cB}



$(BH)_{max}$



APPENDIX 4: SAMPLE UNCERTAINTY BUDGET

UNCERTAINTY IN THE MEASUREMENT OF MAGNETIC FLUX DENSITY REMANENCE, B_r							
Source of Uncertainty	Reference	Value $\pm$ %	Probability distribution	Divisor	c_i	u_i % $\pm$	V_i or V_{eff}
Integrator Calibration							
DMM for search coil calibration			normal	2	1	0.0000	inf
DMM for search coil calibration resolution (1 in 1800)			rectangular	1.7321	1	0.0000	inf
Mutual inductor for search coil calibration			normal	2	1	0.0000	inf
1 Ohm Tinsley resistor for search coil calibration			normal	2	1	0.0000	inf
Repeatability of integrator calibration			normal	1	1	0.0000	9
Measurement							
Magnetic Moment Repeat			normal	1	1	0.0000	inf
DMM resolution (1 in 1800)			rectangular	1.7321	1	0.0000	inf
Magnetic circuit contribution			rectangular	1.7321	1	0.0000	inf
Temperature effects			rectangular	1.7321	1	0.0000	inf
Repeatability of measurement			normal	1	1	0.0000	4
Combined uncertainty			normal			0.00000	#DIV/0!
Expanded uncertainty			normal	k= 1		0.0000	
Uncertainty given was +/- X %							

UNCERTAINTY IN THE MEASUREMENT OF INTRINSIC COERCIVITY, H_{ci}							
Source of Uncertainty	Reference	Value $\pm$ %	Probability distribution	Divisor	c_i	u_i % $\pm$	V_i or V_{eff}
Hall Probe Calibration							
Calibration of NMR Probe			normal	2	1	0.0000	inf
Calibration of frequency meter			normal	2	1	0.0000	inf
Value of the gyromagnetic ratio of the proton			rectangular	1.7321	1	0.0000	inf
Resolution of instrument for alignment			rectangular	1.7321	1	0.0000	inf
Uniformity of field for instrument position			rectangular	1.7321	1	0.0000	inf
DMM resolution (1 in 4000)			rectangular	1.7321	1	0.0000	inf
DMM calibration			normal	2	1	0.0000	inf
Repeatability of Hall probe calibration			normal	1	1	0.0000	4
						0.00000	#DIV/0!
Measurement							
DMM resolution (1 in 4000)			rectangular	1.7321	1	0.0000	inf
DMM calibration			normal	2	1	0.0000	inf
Resolution of instrument for alignment			rectangular	1.7321	1	0.0000	inf
Temperature effects			rectangular	1.7321	1	0.0000	inf
Magnetic Viscosity			rectangular	1.7321	1	0.0000	inf
Repeatability of measurement			normal	1	1	0.0000	4
Combined uncertainty			normal			0.00000	#DIV/0!
Expanded uncertainty			normal	k= 1		0.0000	
Uncertainty given was +/- X %							

UNCERTAINTY IN THE MEASUREMENT OF MAGNETIC FLUX DENSITY COERCIVITY, H_{cb}							
Source of Uncertainty	Reference	Value $\pm$ %	Probability distribution	Divisor	c_i	u_i % $\pm$	V_i or V_{eff}
Hall Probe Cal Calibration	From above	0.0000	normal	1	1	0.0000	#DIV/0!
DMM resolution (1 in 4000)			rectangular	1.7321	1	0.0000	inf
DMM calibration			normal	2	1	0.0000	inf
Resolution of instrument for alignment			rectangular	1.7321	1	0.0000	inf
Temperature effects			rectangular	1.7321	1	0.0000	inf
Magnetic Viscosity			rectangular	1.7321	1	0.0000	inf
Repeatability of measurement			normal	1	1	0.0000	4
Combined uncertainty			normal			0.00000	#DIV/0!
Expanded uncertainty			normal	k= 1		0.0000	
Uncertainty given was +/- X %							

UNCERTAINTY IN THE MEASUREMENT OF ENERGY PRODUCT, BH_{max}							
Source of Uncertainty	Reference	Value $\pm$ %	Probability distribution	Divisor	c_i	u_i $\pm$ %	V_i or V_{eff}
UNCERTAINTY IN THE MEASUREMENT OF MAGNETIC FLUX DENSITY REMANENCE, B_r		0.0000	normal	2	1	0.0000	#DIV/0!
UNCERTAINTY IN THE MEASUREMENT OF MAGNETIC FLUX DENSITY COERCIVITY, H_{cB}		0.0000	normal	2	1	0.0000	#DIV/0!
Repeatability of measurement			normal	1	1	0.0000	4
Combined uncertainty			normal			0.00000	#DIV/0!
Expanded uncertainty			normal	k= 1		0.0000	
Uncertainty given was +/- X %							

APPENDIX 5: REVERSAL RATES

The slow curves in the following graphs were obtained by carefully controlling the field in the NPL electromagnet. When the reversal speed slowed too much the field was slightly increased and this resulted in the step like behaviour that can be seen in the graphs for magnets JE1 and CM1.

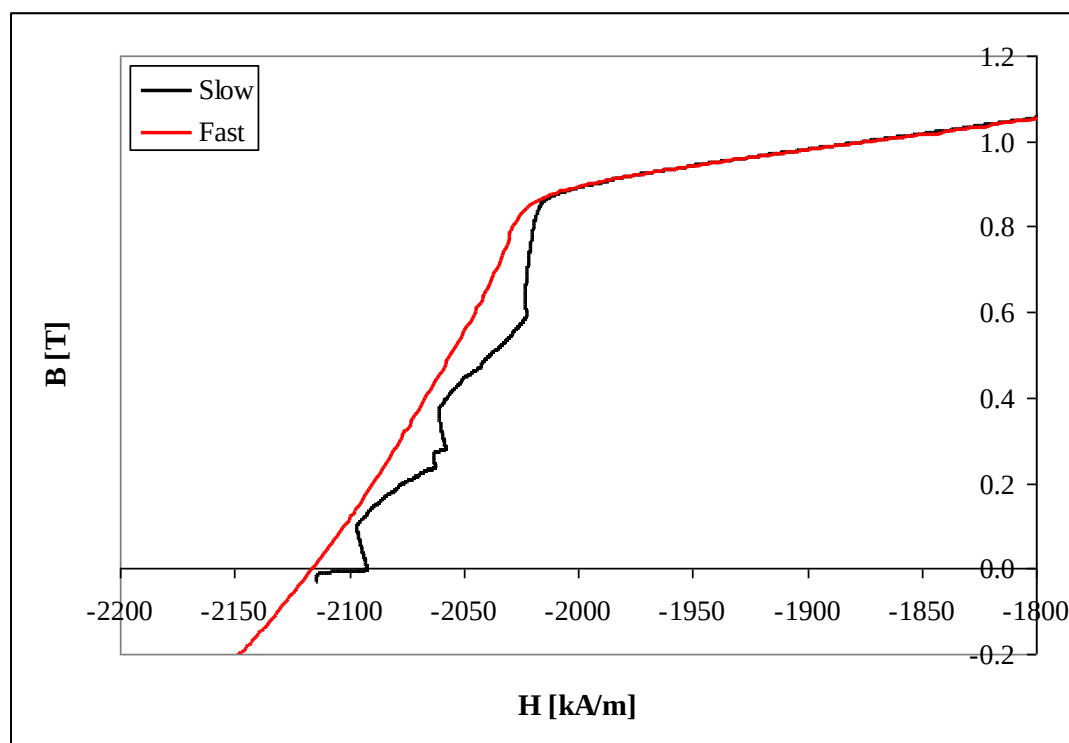
See Appendix 6 for an explanation of the negative slope of the reversal that was observed for magnet CH1.

For the curves labelled “Slow” the time for the polarization to reduce from approximately 90 % of the value at B_r to zero was typically 230 s

For the curves labelled “Fast” the time for the polarization to reduce from approximately 90 % of the value at B_r to zero was typically 1 s.

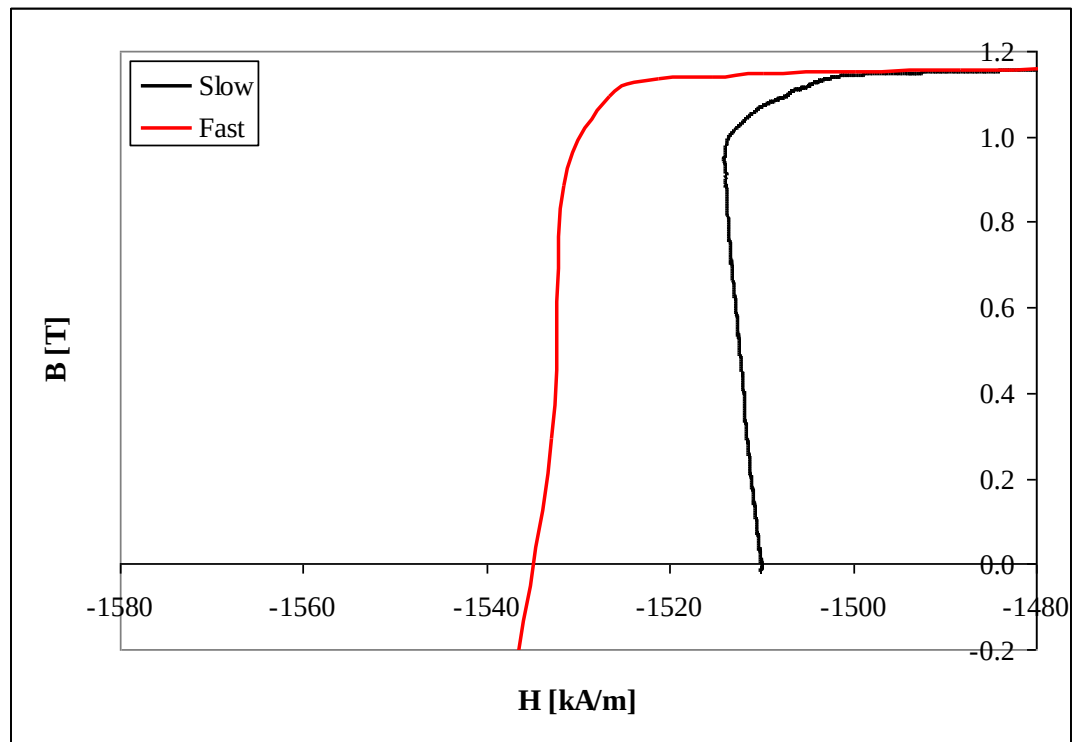
CE1 could not be reversed in the NPL electromagnet.

JE1



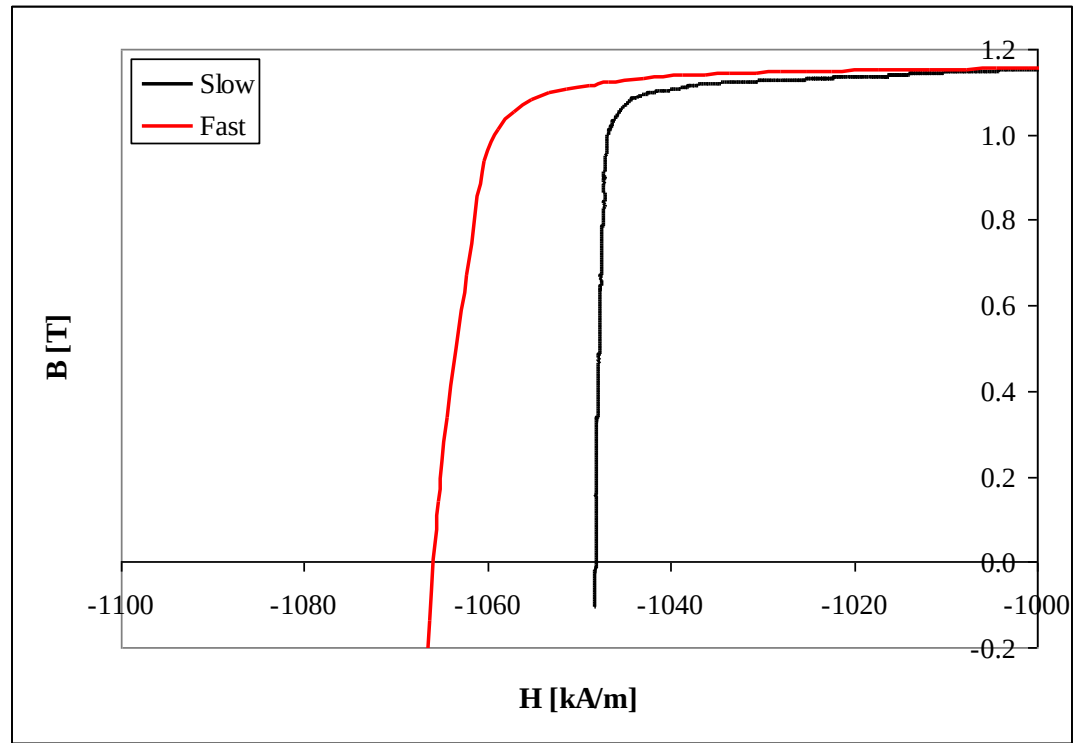
	Percentage difference
H_{CJ}	1.13 %

CH1



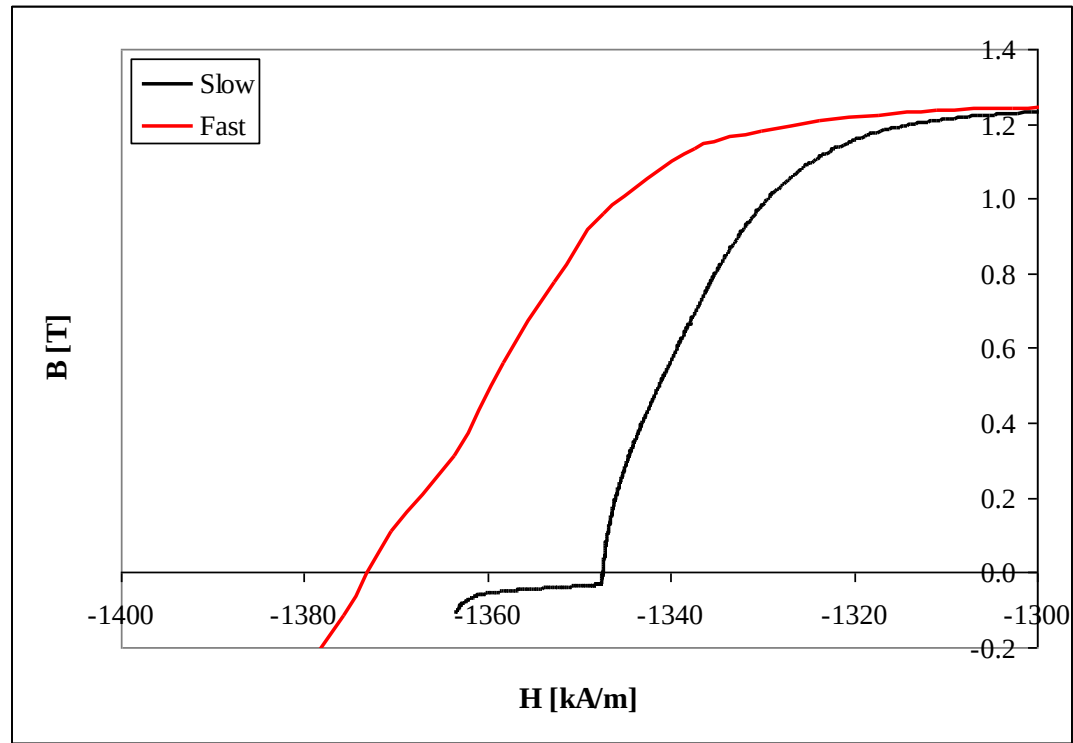
	Percentage difference
H_{CJ}	1.66 %

CN1



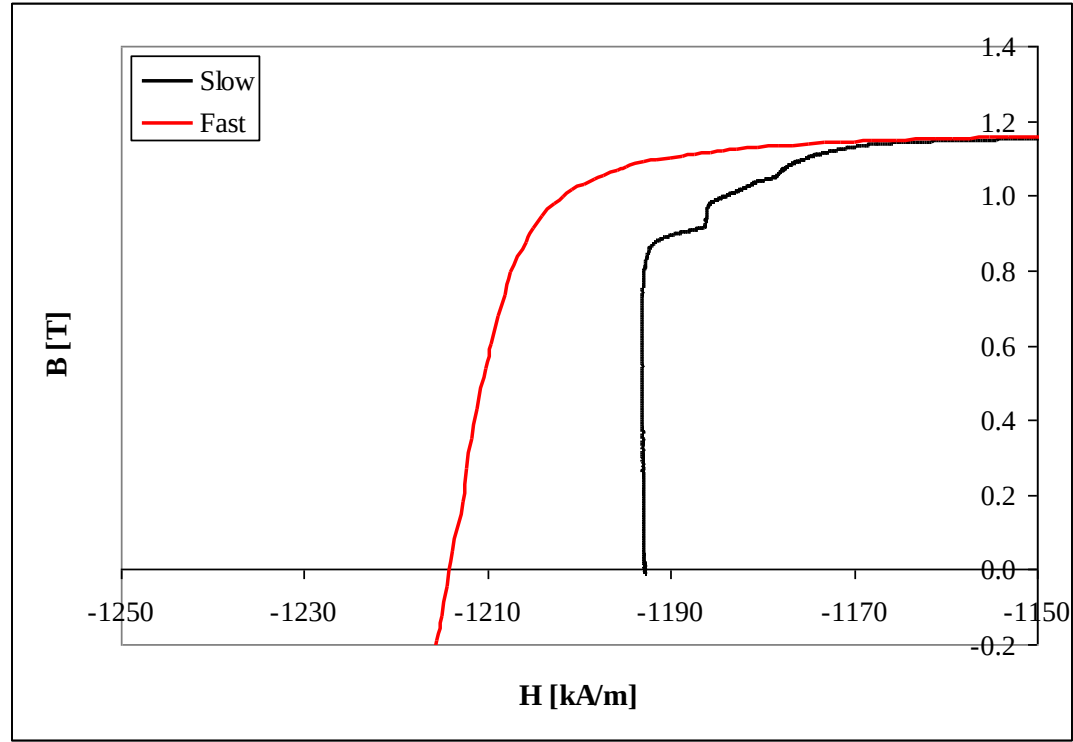
	Percentage difference
H_{CJ}	1.67 %

JH1



	Percentage difference
H_{CJ}	1.89 %

CM1



	Percentage difference
H_{CJ}	1.76 %

APPENDIX 6: EXPLANATION OF NEGATIVE SLOPE FOR SOME REVERSALS USING AN ELECTROMAGNET.

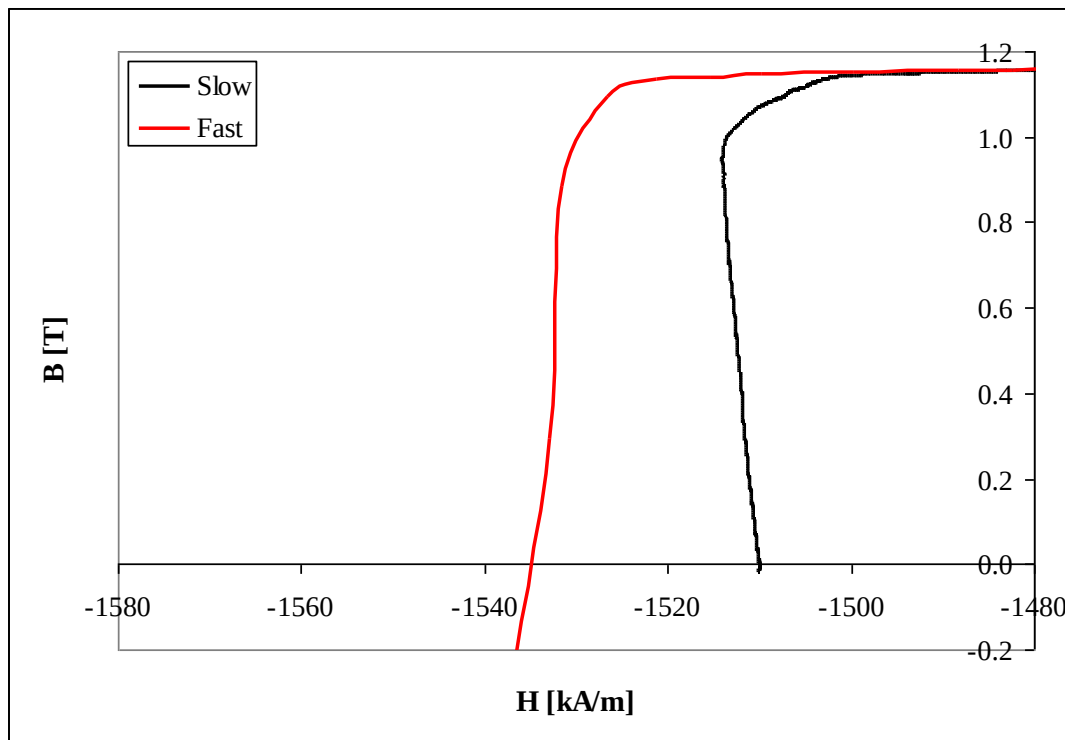


Figure 1. NdFeB magnet CH1. Measurements made using an electromagnet at NPL.

An explanation of the negative slope of the black line in Figure 1 is presented.

As described in IEC 60404 part 5, a Hall probe is used to measure the magnetic field as close to the surface of the magnet as possible. For a **completely closed** magnetic circuit with uniform magnetic field in the air gap of the electromagnet, this near surface field is required to plot the demagnetisation curve. If there is flux leakage from the magnet, the field measured has an additional contribution.

Using measurements made on a Nickel test specimen the negative slope of the black line in Figure 1 is shown to be caused by flux leakage from the magnet. Importantly, there is **no error** in the intrinsic coercivity that is determined by the intercept of this line on the H axis since at this point the polarisation is zero and the leakage is also zero.

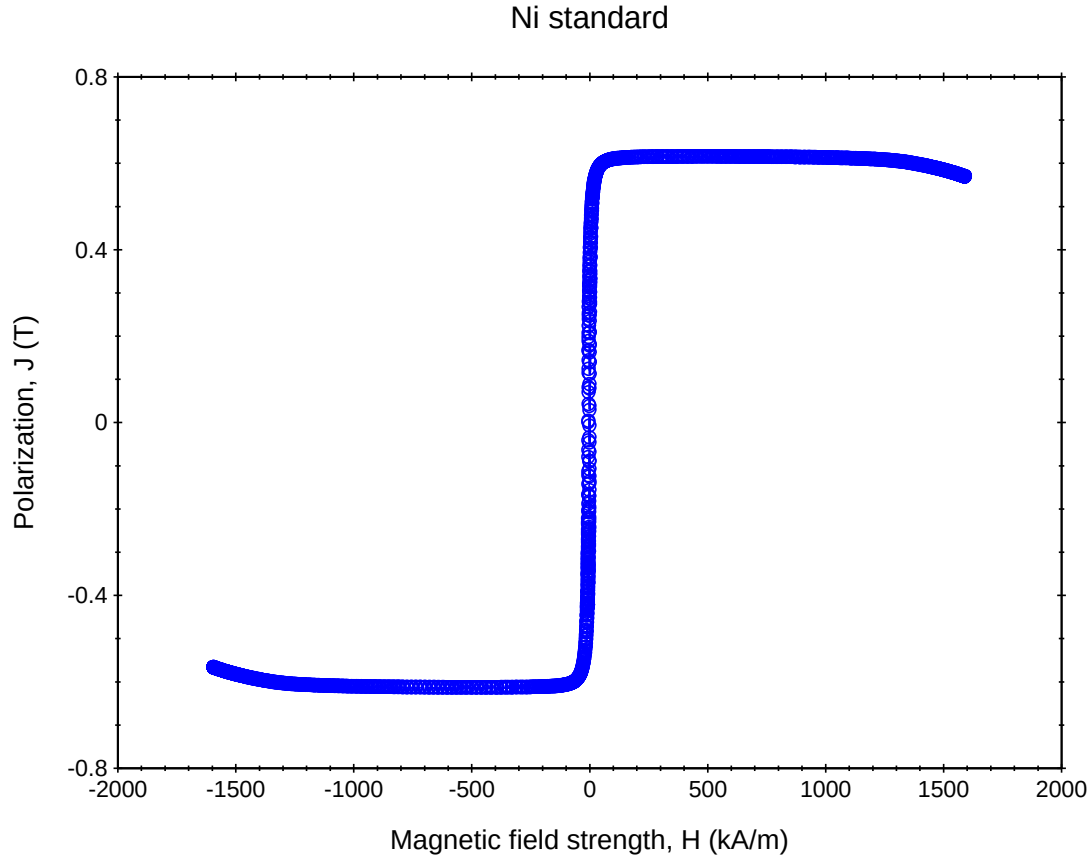


Figure 2. BH curve of a Ni test specimen.

Shown in Figure 2 is the BH curve for a Nickel test specimen with the same dimensions as those of the magnet. A loose fitting air compensated J coil was used to measure the polarisation. It can be seen that for magnetic fields larger than 1200 kA/m the measured polarisation begins to decrease. This is due to the saturation of the electromagnet yokes. As the yoke saturates the magnetic flux from the magnet leaks into the air gap and a slight demagnetising field is setup. This field couples with the measuring area of the J coil in the opposite direction to the polarisation and therefore reduces the polarisation value measured. As the electromagnet yoke is taken further into saturation, the conductance of the yoke reduces further, this demagnetising effect increases and the reduction in the measured polarisation increases. This is the behaviour seen in Figure 2.

When measuring the demagnetisation curve of a permanent magnet, this onset of flux leakage as the electromagnet yoke saturates can have an effect on the magnetic field measured by the Hall probe.

The Hall probe measures the field at the surface, H_s , where,

$$H_s = H_a + H_d \quad (4)$$

In equation (4), H_a is the applied magnetic field and H_d is the demagnetising field that results from any flux leakage. H_d will be zero at values of H in Figure 2 where there is no significant reduction in the measured polarisation.

For the curves shown in Figure 1, H_a and H_d are in the same direction and so numerically add.

In the usual way, H_d is given by

$$H_d = NJ \quad (5),$$

Where, N is an **effective** demagnetisation factor used to illustrate that slight demagnetisation is occurring and J the polarisation.

For slow reversals of J the applied magnetic field, H_a , is constant. As J reduces to zero, H_d also reduces. From (4), the measured H_s also reduces.

As a consequence of the leakage of the polarisation of the magnet, illustrated in Figure 2, the measured H reduces as the polarisation reduces to zero. This is seen in Figure 1 as a negative slope during reversal.

There is no error in the measured intrinsic coercivity since at this point the polarisation is zero. From equation (5), H_d is also zero and therefore $H_s = H_a$. This means that the magnetic field strength measured at $J = 0$ is the required intrinsic coercivity.

For a magnet that has an intrinsic coercivity at a magnetic field strength for which there is no leakage of the flux this effect will not happen. Shown in Figure 3 is the demagnetisation curve for a magnet with an intrinsic coercivity of 1048 kA/m.

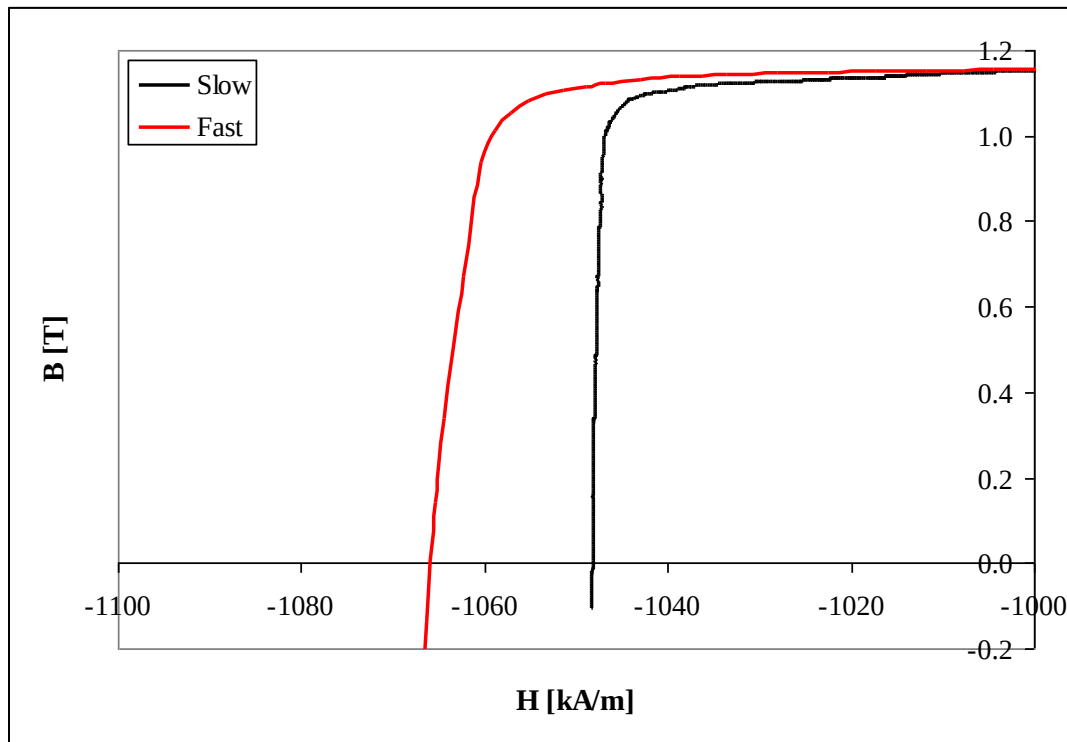


Figure 3. NdFeB magnet CN1.

It can be seen from Figure 2 that there is no significant leakage of flux at this point since the measured polarisation of the Nickel is still constant.

The onset of the negative slope seen in Figure 1 will depend on the details of the electromagnet used. Performing the measurements shown in Figure 2 will indicate when this happens.

Summary

When the reversal of the polarisation of a permanent magnet, measured using an electromagnet, occurs at magnetic field strengths at which the yoke is beginning to saturate, flux leakage from the magnet will occur. This will add to the magnetic field measured by the Hall probe. As the polarisation reduces during reversal this additional field reduces with the result that the slope of the reversal is negative.

APPENDIX 7: FIELD VERSUS CURRENT/TIME PLOTS.

Shown in Figure 4 is the field versus current curve for the electromagnet measurement method used at NPL.

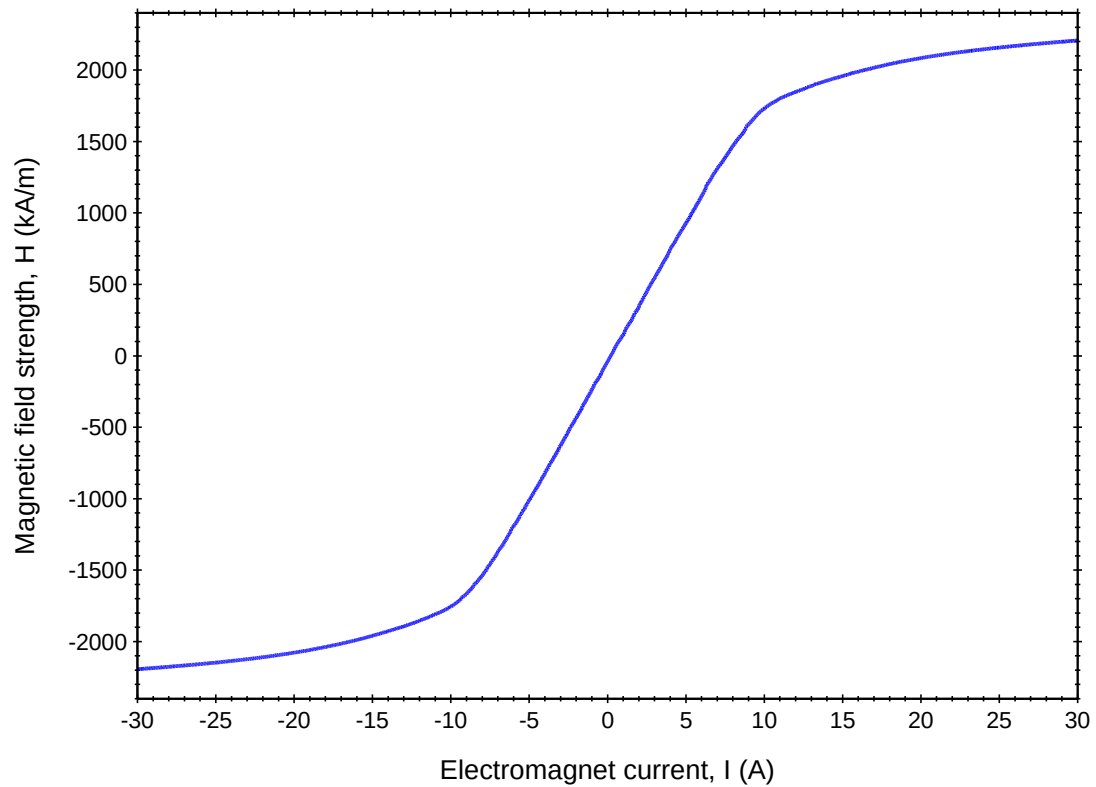


Figure 4. Magnetic field strength in the air gap against current for a 10 mm gap for the NPL electromagnet measurements.

Shown in Figure 5 is the field versus time curve for the pulse field magnetometer method used at Hirst.

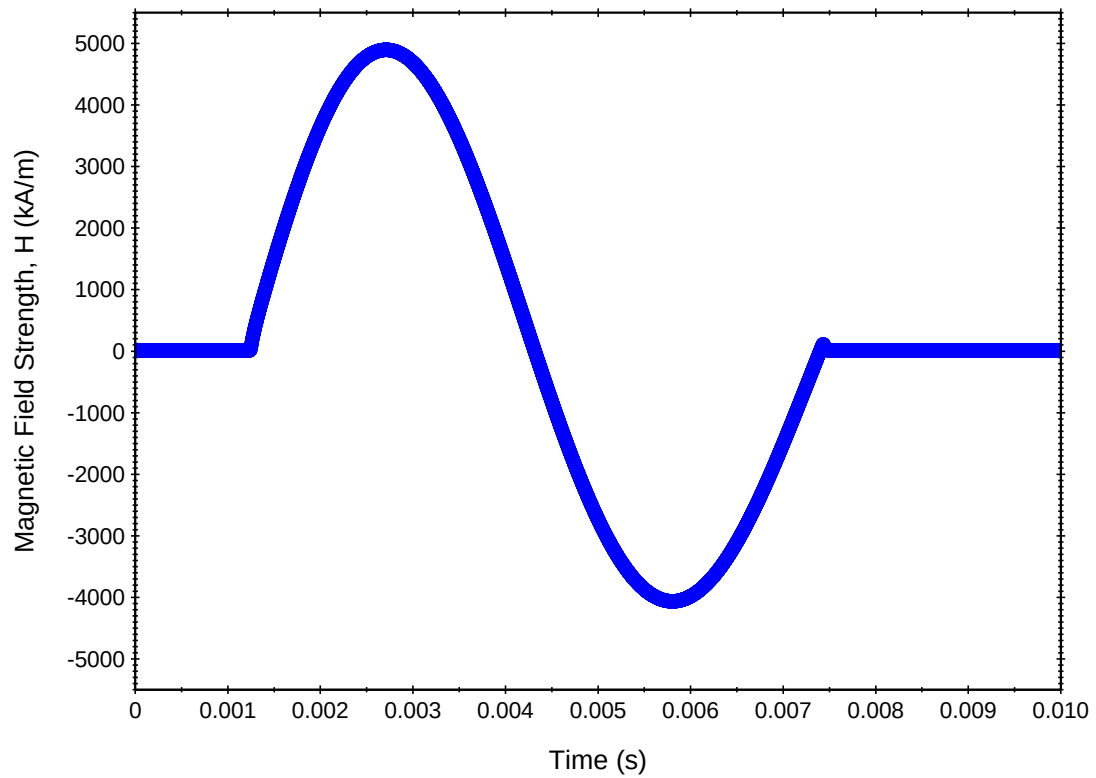


Figure 5. Magnetic field strength versus time curve for the pulse field magnetometer method used at Hirst.