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Pulsed field magnetometry

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PULSED FIELD MAGNETOMETRY

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IEC 62331, 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
68/299/DTR	68/303/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.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

In order to measure the full magnetic characterization of magnetically hard (permanent magnet) materials, it is necessary to apply a magnetic field sufficient to saturate the test specimen of magnetic material.

The generation of this magnetic field can become a practical limiting factor and can determine the appropriate measurement techniques.

Super-conducting magnets can generate very high static or slowly changing magnetic fields but their complexity, high capital outlay and running costs, requiring cryogenic gases make them far from ideal. It is necessary to change fields slowly to avoid "quenching" the super-conducting magnet.

Conventionally wound electro-magnets with slowly changing magnetic fields have a significant heat generation problem through I^2R loss. This can be alleviated through the use of a high relative permeability "iron yoke". However, saturation of the iron prevents maximum characterization of the loop of rare earth permanent magnet materials to be determined.

A pulsed field system utilizing conventional conductors minimizes heating effects by limiting field durations and by limiting heat generation to acceptable levels. Fields up to 40 Tesla (T) can be generated in this way.

Careful consideration, however, must be given to the instrumentation and method to take account of dynamic effects due to the short duration of the magnetic field.

While work on pulsed field magnetometry is carried out in many parts of the world, the two main groups are MACCHARETEC [ref. 29][1] in Europe and EMAJ [ref. 30] in Japan. The approach adopted in Japan is one of supporting a standard with fixed specimen sizes, magnetic field strengths and frequencies in a limited number of configurations.

1 References in square brackets refer to the bibliography.

PULSED FIELD MAGNETOMETRY

1 Scope and object

This Technical Report reviews methods for measuring magnetically hard materials using pulsed field magnetometers.

The methods of measurement of the magnetic properties of magnetically hard materials have been specified in IEC 60404-5 for closed magnetic circuits and in IEC 60404-7 for open magnetic circuits. The measurement result of the magnetic properties of magnetically hard materials at elevated temperatures is given in IEC 61807.

Pulsed field magnetometers have been developed to provide rapid measurement facilities to match high speed production rates with 100 % quality control.

The object of this report is to describe the principles and practical implications of pulsed field magnetometry in order to enable the full potential of the technique to be considered, including its application using small and large magnets of varying geometries, to various magnetic field strengths and frequencies.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60404-5:1993, *Magnetic materials – Part 5: Permanent magnet (magnetically hard) materials – Methods of measurement of magnetic properties*

IEC 60404-7:1982, *Magnetic materials – Part 7: Method of measurement of coercivity of magnetic materials in an open magnetic circuit*

IEC 61807:1999, *Magnetic properties of magnetically hard materials at elevated temperatures – Methods of measurement*

IEC 60404-14:2002, *Magnetic materials – Part 14: Methods of measurement of the magnetic moment of ferromagnetic material specimen by the withdrawal or rotation method*

3 Pulsed field magnetometer (PFM)

A pulsed field magnetometer consists of the following parts:

a) The magnetic field strength generator consisting of
   i) the power supply (usually a capacitive discharge system)
   ii) magnetizing solenoid
b) Magnetization and magnetic field strength sensors (pick-up coils)
c) Instrumentation for transient processing and digitizing hardware
   i) integration
   ii) digitization
d) Data processing facilities to enable the processing of

i) zero signal

ii) *M*(*H*) loop positioning

iii) self-demagnetization correction

iv) low band pass filtering

v) calibration factors

vi) eddy current correction.

3.1 General principles

The basic principle of operation of the pulsed field magnetometer depends upon an intense transient magnetic field being generated by the magnetic field strength generator and being applied to the test specimen to be measured. The magnetic field strength and resultant magnetization of the test specimen are recorded and processed.

During a measurement cycle, the test specimen in the *J* coil increases flux. The output voltage of this coil is the time derivative of the flux Φ coupled to that coil. This flux is due largely to the magnetization of the specimen but also to the zero signal (see 7.1.1) and possible eddy currents (see the eddy current correction techniques in 7.1.6) etc. As a consequence the coil is usually referred to as the “*J*coil,” or on occasions the “*M* coil.” It is however, truly a $\mathrm{d}\Phi/\mathrm{d}t$ coil. In this standard it will be referred to as the “*J* coil.”

In the case of the *H* coil, the output voltage is the time derivative of the magnetic flux that is coupled to that coil and is largely the magnetic field strength applied to the specimen. This coil is usually referred to as the “*H* coil,” although it is truly a $\mathrm{d}H/\mathrm{d}t$ coil.

The outputs of these two coils are integrated (see 6.2). In the case of the integrated signal from the *J*coil, the zero signal is removed and the result calibrated to generate an *M*’ signal, that is, the magnetization of the specimen being measured in an open magnetic circuit. By combining this with the *H* signal, an *M’*(*H*) hysteresis loop is obtained (see Clause 7).

If the *M*’(*H*) loop is corrected for the self-demagnetization of the open magnetic circuit measurement, (see 7.1.3), the intrinsic *M*(*H*) or *J*(*H*) loop data can be obtained (or *B*(*H*) if required) by the usual conversion.

The two signal channels, that is, from pick-up coil, through integration, digitization and data collection and processing within the computer, are generally known as the “*J*” and “*H*" channels.

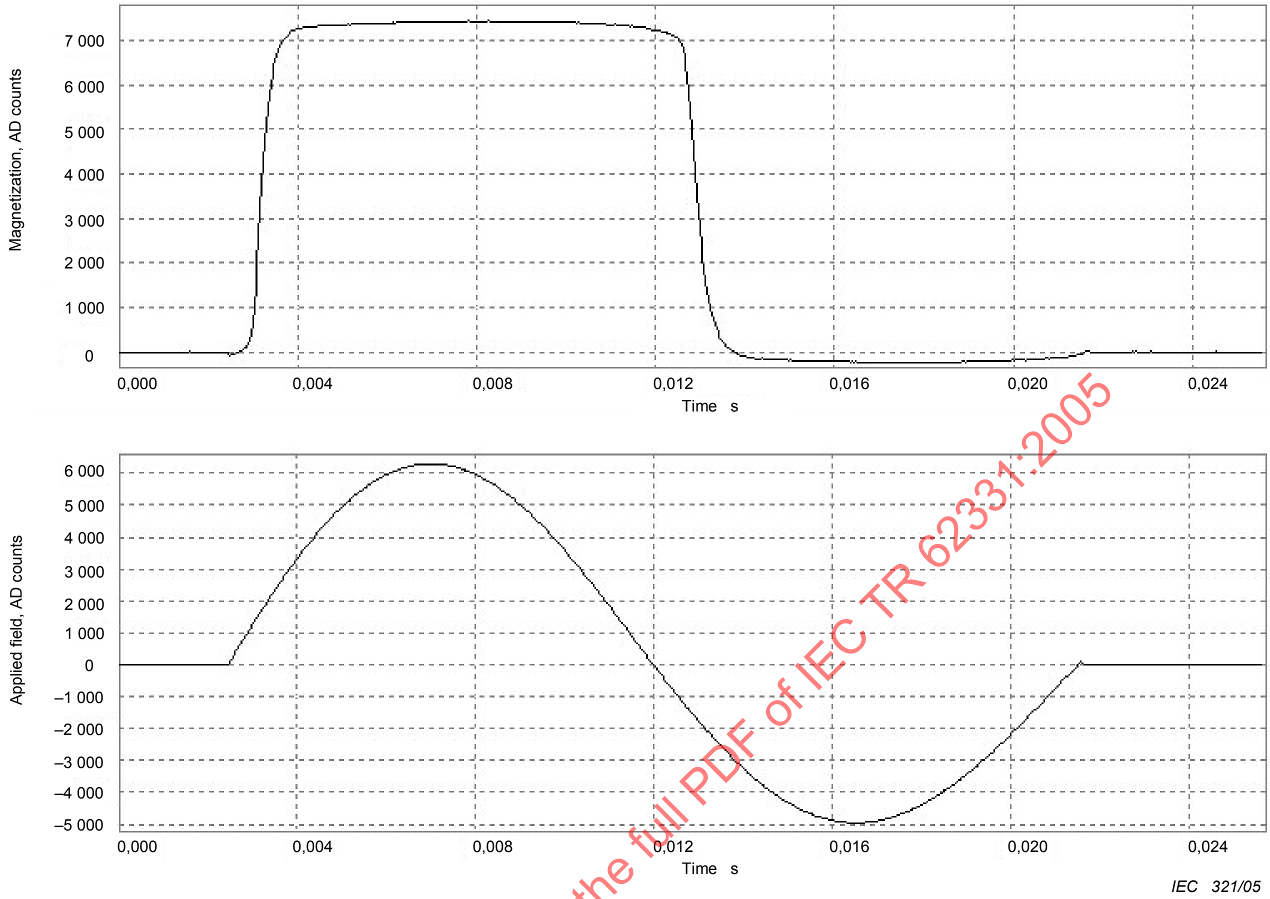


Figure 1 – *M*' and *H* time traces for a permanent magnet

The lower trace (above) is the time trace of the magnetic field strength (*H*) based upon the field generator configuration discussed in 3.2.2.1. The upper trace represents the time trace of the specimen magnetization; a specimen of sintered Neodymium Iron Boron; data obtained after initial integration and digitization of the *J* and *H* coil outputs, in arbitrary units [ref. 32].

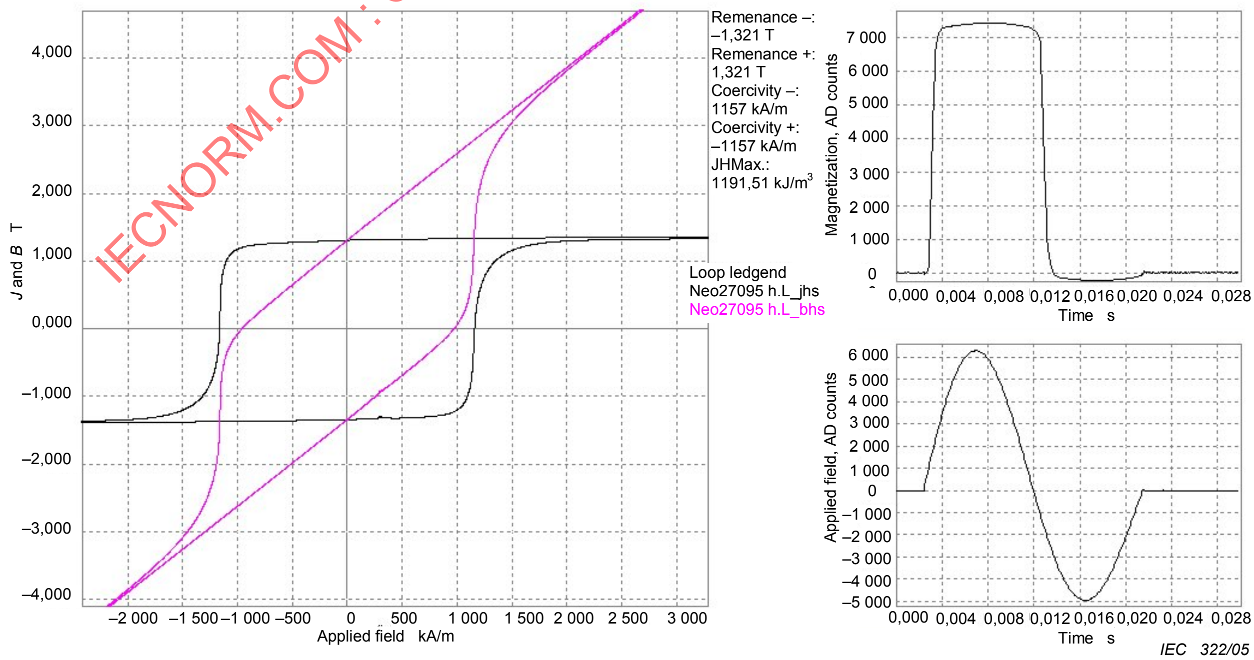


Figure 2 – *J*(*H*) and *B*(*H*) loop for a permanent magnet

The complete hysteresis loop is obtained by plotting the J data against the H data shown in Figure 1, without using the time domain data. The time domain J and H data are again shown to the right. [ref. 32]. The inner loop represents the $B(H)$ loop.

3.2 Size of test specimen

As the test specimens are measured in an open magnetic circuit, there is no immediate limit to the size of specimens that can be tested. Small and large test specimens can be measured providing that eddy current considerations, and the practical considerations of the instrumentation, are taken into account (see 7.1.6).

The results shown in this report are for cylinders of a maximum dimensions of 30 mm diameter and 25 mm length and minimum dimensions of 5 mm diameter and 5 mm length, although this is not a practical limitation for the PFM technique.

Cylindrical test specimens with diameters less than 3 mm and lengths of 3 mm have been measured while cylinders of NdFeB of 40 mm diameter and 30 mm length have also been measured.

The Japanese group EMAJ measure test specimens of a cylindrical shape of 10 mm diameter and 7 mm length and a cube of 7 mm x 7 mm x 7 mm (see Figures 14–16).

4 Field generator

4.1 General

The field generator consists of a system that enables the magnetic field to be applied to the test specimen.

This will consist of a power supply and a magnetizing solenoid. The power supply provides the magnetizing current to the magnetizing solenoid in order to generate the applied magnetic field.

4.2 Power supply

4.2.1 General

Power supplies normally have the capacity to apply an electrical potential (over the range of 400–10 000 V but more typically 1 000–3 000 V) at currents (with a current range of 1 000–40 000 A but more typically 5 000–20 000 A), in both positive and negative polarities.

This can be accomplished by one of two methods:

a) capacitive discharge;

b) direct mains supply.

4.2.2 Capacitive discharge

The capacitive discharge arrangement enables electrical energy to be accumulated in capacitors over an extended period of time, before being discharged in a short time period to provide high currents from the low impedance source.

The energy storage:

$$E = \tfrac{1}{2} C U_0^2 \qquad (1)$$

where

E is the energy, in joules;

C is the capacitance, in farads;

U_0 is the capacitor voltage, in volts.

For commercial PFM measurement systems, it is necessary to minimize costs and it is therefore, normally necessary to achieve the required magnetic performance with the minimum of capacitor energy. The capacitance and energy of the capacitive discharge system is matched with the magnetizing solenoid to provide the required magnetizing conditions of peak field strength, field volume, field homogeneity and period. The maximum magnetic field strength achieved is proportional to the current density; the proportionality factor being dependent on the geometry of the magnetising solenoid.

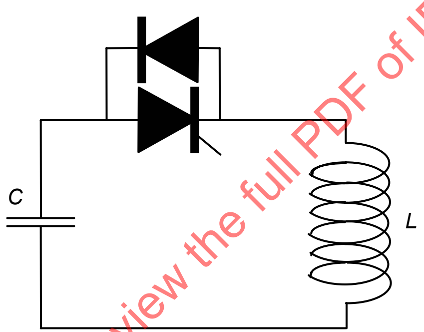
The discharge can be applied in the following forms:

a) sine wave (decaying);

b) unidirectional pulses (1/2 sine wave);

c) two unidirectional pulses (with decay).

4.2.2.1 Sine wave (decaying)



IEC 323/05

Figure 3 – Sine wave (decaying) electrical configuration

The current *I(t)*, and therefore the magnetic field strength is determined by:

$$I(t) = \frac{U_0}{\omega L}.e^{-\beta t} \sin \omega t \qquad (2)$$

where ω is given by

$$\omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \qquad (3)$$

and is given by

$$\beta = R/2L \qquad (4)$$

Due to the resistive losses in the magnetizing solenoid, the peak field strength created in the magnetizing solenoid in the reverse direction is reduced, depending on the damping factor β. It is therefore necessary to apply a higher initial field, in order to achieve the necessary reverse field.

The sine wave technique has the advantage of a continuous process to apply positive and negative polarities and to avoid discontinuities. This is important in the testing of conductive materials where eddy current effects are taken into consideration (see 7.1.6).

4.2.2.2 Unidirectional pulses (1/2 sine wave)

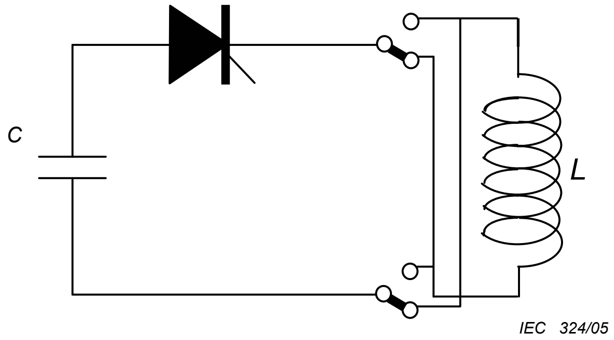


Figure 4 – Unidirectional pulses (1/2 sine wave) electrical configuration

The current is determined by:

$$I(t) = \frac{U_0}{\omega L}.e^{-\beta t} \sin \omega t \qquad (5)$$

where

$$\omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \qquad (6)$$

and

$$\beta = R/2L \qquad (7)$$

However, after the first half sine wave of the current, the reverse charge that is generated across the capacitors is not permitted to discharge due to the diode characteristic of the thyristor.

The resultant current waveform is a half sine wave (0–180°).

By applying an identical pulse with a reverse polarity, a maximum positive and negative field can be applied with identical peak fields of positive and negative polarities.

The overall measurement is accomplished by two separate discharges. This approach does have the advantage of achieving the same peak fields on positive and negative pulses. However, two discrete pulses are applied with their inherent discontinuities of current.

4.2.2.3 Unidirectional pulses (decaying)

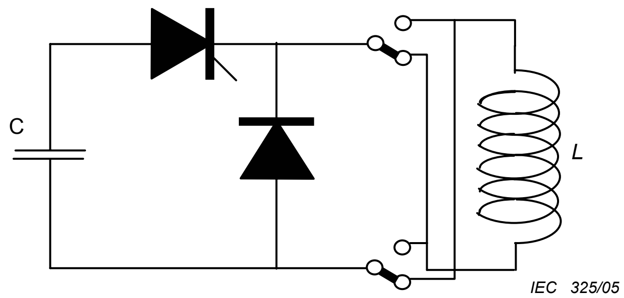


Figure 5 – Unidirectional pulses (decaying) electrical configuration

The current discharge is determined by:

$$I(t) = \frac{U_0}{\omega L}.e^{-\beta(t - t_0)} \sin \omega t \qquad (8)$$

where t_0 is the time at the start of the discharge.

When the capacitor is completely discharged, the diode becomes conducting and prevents the capacitor from becoming charged reversely. From this point in time the current is determined by:

$$I(t) = I_0 . e^{\frac{-R.(t_1+t)}{L}} \quad (9)$$

where

t_1 occurs when $U_0 = 0$

I_0 is the current at the instant in time when the clamping diode becomes forward biased.

As with method 4.2.2.2 a complete positive and negative magnetic field strength period can be achieved by applying two pulses, one of reverse polarity.

While this technique suffers from the necessity of applying two pulses, it also has two very different dynamic responses on the rising and falling current waveforms, thereby offering a lower dH/dt during the period after peak field.

Table 1 – Comparison of methods of generating the magnetic field strength

	Fixed frequency	**Continuous**	**Single wave function**	**Identical positive and negative fields**
Sine wave (decaying) 4.2.2.1	YES	YES	YES	NO
Unidirectional ½ wave 4.2.2.2	YES	NO	YES	YES
Unidirectional pulse (decaying) 4.2.2.3	NO	NO	NO	YES

The preferred approach is the sine wave (decaying) as described in 4.2.2.1, particularly in consideration of possible eddy currents in conductive specimens as the resulting applied magnetic field strength is of a continuous waveform in the case of 4.2.2.1 as opposed to the discontinuities created by the discrete positive and negative periods required by 4.2.2.2 and 4.2.2.3.

It should be noted that the preferred approach of EMAJ [ref. 30] is 4.2.2.2, unidirectional pulse (1/2) sine wave.

4.2.2.4 The repeatability of the applied voltage

The repeatability of the voltage applied to the capacitor of the capacitor bank is relatively unimportant provided that the energy is sufficient to saturate the magnet material of the test specimen. The repeatability is, however, very important for correcting the zero signal. A repeatability of ±1 % can be easily achieved and is adequate. A repeatability of ±0,1 % is more typically available.

The magnetic field strength is dependent upon the resistance of the magnetizing solenoid. The temperature variation of the magnetizing solenoid can have a small influence on the result and must be considered.

4.2.3 Direct mains supply

Some high field facilities around the world utilize power supplies that are directly coupled to mains supplies. These systems are able to create high fields (20–40 T) for periods of around 1 s.

Although these facilities offer a valuable resource, they will not be considered in this report.

It is also possible to construct power supplies of this type on a much smaller scale. The difficulty with this type of equipment is that it is directly coupled to a mains supply and cannot comply with mains supply power demand regulations, and therefore is not likely to be of great significance.

4.3 Magnetizing solenoid

The magnetizing solenoid can be considered as a conventional solenoid.

The design of the solenoid must take into account the following factors:

4.3.1 Peak magnetic field strength

The peak value of magnetic field strength must be sufficiently large to saturate the test specimen in both positive and negative directions. This should include a margin of +10 % overshoot.

The required magnetic field strength depends upon the material, the orientation and the demagnetization factor of the test specimen.

4.3.2 Volume to be magnetized

The volume of the magnetizing solenoid must be sufficiently large to enclose the test specimen and the pick-up coil system.

4.3.3 Field homogeneity across the volume of the specimen under test

The field homogeneity throughout the entire test specimen volume should be within ±1 %.

4.3.4 Field frequency

Rate of change of field with time, dH/dt, should be kept as low as possible either to avoid inducing significant eddy currents in conductive specimens, or to be suitable for eddy current correction.

It should be noted that the preferred approach of EMAS [ref. 31]) is to avoid eddy currents.

5 Polarization and magnetic field strength sensors (pick-up coils)

5.1 General

It is necessary to measure correlated values of polarization J of the test specimen and the magnetic field strength H during that test.

This is usually achieved using pick-up coils. While it is feasible that other forms of detectors could be used, such as Hall sensors, such alternative detectors are not considered in this report.

It may be considered reasonable to utilize a single channel system and measure *J* and *H* transients on successive magnetizing pulses. Apply a field pulse while recording *J* and when the magnetizing solenoid has regained its original temperature, apply a second (and hopefully identical) pulse and measure *H*. This, however, seems an unnecessary complication and can be a source of procedural error. Two channels and simultaneous recording of both channels are required.

Pick-up coils can be configured in a variety of geometries, however all have common features.

Thus, what is needed is, in principle:

a) the polarization sensor (*J* coil);

b) the magnetic field strength sensor (*H* coil).

5.2 The polarization sensor (*J* coil)

The polarization sensor or *J* coil assembly consists of two (or more) coils connected in series opposition. The coils have equal area turns products but different coupling to the test specimen and so measure only the magnetization of the test specimen and not the applied magnetic field.

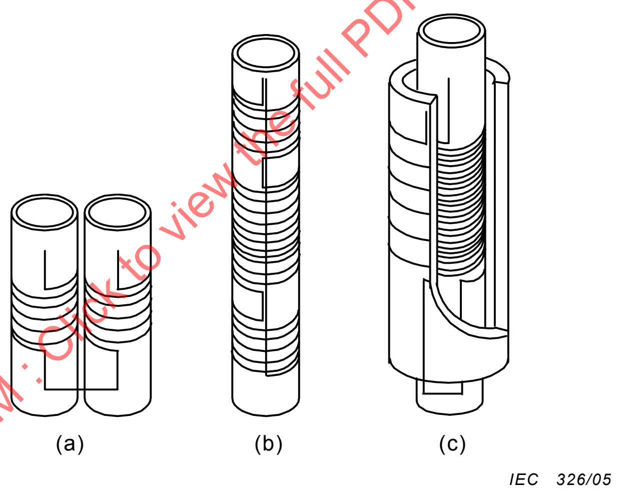


Figure 6 –Three arrangements of *J* coil assembly configurations
(drawing with permission of EMAJ [ref. 30])

As discussed earlier, during a measurement cycle, flux is increased by the presence of the specimen in the *J* coil assembly. The output voltage of this coil is the time derivative of the flux Φ coupled to that coil. This flux signal is due largely to the magnetization of the specimen but also to the zero signal (see 7.1.1) and possible eddy currents (see 7.1.6) etc.

Considering the *J* coil assembly in Case 6(a), often known as an “n+n coil,” the two constituent coils have identical cross-sectional area and numbers of turns (equal area turns product). The coils are connected in opposition so no coil output results from applying a pulsed homogeneous field (*H*) to both coils.

When a test specimen is located in one of the two coils, it will be coupled strongly to that coil (the test specimen coil) and coupled weakly to the neighbouring coil (the compensation coil). When a pulsed homogeneous field is applied to the coil assembly, the output will be proportional to the time derivatives of the magnetization of the test specimen (see NOTE below).

In the case of *J* coil assembly, Case 6(b) often known as a "½ n+n+½ n coil," the compensation coil is divided into two smaller coils at each end of the *J* coil assembly. These two coils each have half the area turns product of the specimen coil that is positioned between them. The compensation coils are connected in opposition to the specimen coil.

The test specimen is located in the specimen coil and is strongly coupled to it, while only weakly coupled to the compensation coils. Again, the output will be proportional to the time derivatives of the magnetization of the test specimen.

In the case of *J* coil assembly, Case 6(c) often known as a "coaxial coil," the compensation coil has a much larger cross-sectional area, but correspondingly fewer turns in order to equal the area turns product of the specimen coil which is positioned coaxially, inside the compensation coil. The compensation coil is connected in opposition to the specimen coil. The test specimen is positioned within the specimen coil and is strongly coupled to it. Due to the weaker coupling of the test specimen to the compensation coil, once again, the output will be proportional to the time derivatives of the magnetization of the test specimen. Variations of these pick-up coil geometries and other geometries are possible.

Ideally, the *J* coil assembly signal should be uniform over the maximum expected test volume, i.e. with a homogeneous test specimen material, the response signal should be strictly proportional to the volume of the test specimen.

Such arrangements permit the measurement of magnetization so that the response, in the ideal case, is not dependent upon test specimen shape or position. However, systems that do not have such a pick-up homogeneity must be calibrated with a sample of an identical geometry to that of the test specimen to be measured.

A value of homogeneity of the pick-up coil of ±1 % or better is typical.

NOTE As the area turns of the two coils are never exactly equal, a suitable correction must be provided. This may prove to be a mechanical adjustment or additional electronic components. In either case, careful consideration must be made to avoid compromising the integrity of the coil output during a measurement cycle.

5.3 The magnetic field strength sensor (*H* coil)

The magnetic field strength sensor may consist of one or more, coils which are coupled to the magnetic field strength in the region of the test specimen, but not significantly coupled to the test specimen. These coils are often positioned on the same structure as the *J* coil.

Also as discussed earlier, the *H* coil output is the time derivative of the magnetic flux that is coupled to that coil and is largely due to the magnetic field strength. This coil is usually referred to as the "*H* coil," although it is truly a d*H*/d*t* coil.

6 Transient instrumentation and digitizing hardware

6.1 General

The outputs of the pick-up coils are proportional to the time derivatives of magnetic flux.

The magnetic field strength pick-up coil (*H*) the coil output voltage is:

$$U_H \propto \frac{dH}{dt} \qquad (10)$$

The polarization, *J* pick-up coil output voltage is:

$$U_J \propto \frac{dJ}{dt} \qquad (11)$$

It is necessary to obtain the integrals of these signals in order to obtain *J* and *H* signals.

Two approaches may be used for integration:

a) analogue integration and digitization;

b) digitization and numerical integration.

6.2 Analogue integration and digitization

The signals from the pick-up coils are fed to the input of an analogue integrator and are incorporated. The output of the integrator is then fed to an analogue-to-digital converter (ADC) and digitized.

The advantage of this approach is that the analogue integrators have a very wide input dynamic range and can inherently cope with magnetization time derivatives, from a given test specimen across a wide range of magnetic field strengths.

6.3 Digitization and numerical integration

The signals from the pick-up coils are fed to the input of an analogue-to-digital converter and are digitized. A numerical approach is then used to integrate the data.

The disadvantage of this approach is that the ADC must have a very wide input range and higher resolution than in 6.2 when dealing with the $d\Phi/dt$ signals.

This approach does not require an analogue integrator although analogue amplifiers or attenuators may be required.

6.4 Digitization rate

The digitization process must occur on a rate that is high enough to obtain sufficient points over the minimum data density region, i.e. close to the coercivity of the test specimen.

This will occur when $d\Phi/dt$ is at maximum and the rate will be determined by the applied dH/dt and the characteristic of the test specimen.

A minimum sample rate of 2×10^5 samples/s for a magnetic field strength with sine wave period of 50 ms is recommended.

The resolution of measurements should be a minimum of 12 bits.

7 Data processing

The *H* coil output is proportional to dH/dt. In order to process this data to obtain valid *H* data (applied magnetic field strength), it is necessary to integrate the signal and apply an *H* channel calibration factor. The *H* channel calibration factor is specific to the *H* coil and *H* channel integrator arrangement of the individual PFM system.

The *J* channel signal processing involves more steps:

The *J* pick-up coil output is proportional to dΦ/dt plus the derivative of the zero signal. (Where Φ is the flux produced by the magnetization of the test specimen.)

This signal is first integrated and the zero signal (see 7.1.1) removed to obtain an *M'* signal, that is, a signal proportional to Φ. The *M'* signal is then multiplied by the *J* channel calibration factor and divided by the test specimen volume consideration, in order to obtain *M**, that is, the intrinsic open magnetic circuit magnetization of the test specimen material. By applying a self demagnetization factor to the *M** signal the intrinsic *J* signal can be obtained (see 7.1.3).

The *J* calibration factor is specific to the *J* coil and *J* channel integrator arrangement of the individual PFM system. (see 7.1.5).

As the initial magnetization of the test specimen is unknown, it may be necessary to position the *M** signal in the *M** domain (see 7.1.2).

The synchronized *J* and *H* signals can now be combined to obtain a *J*(*H*) hysteresis loop. It is not uncommon to carry out many or all of the *J* channel processing steps in the *J* (*H*) domain (i.e. the *M*'(*H*), *M**(*H*) or *J*(*H*) domains).

The *B*(*H*) loop can be obtained by the usual conversion.

In the event that eddy currents have occurred in the test specimen during the measurement process, eddy current correction may need to be considered (see 7.1.6).

7.1 Data processing elements

The following must be taken into consideration when carrying out data processing:

– zero signal;
– loop positioning;
– self-demagnetization;
– filtering;
– calibration factors/scaling;
– eddy currents.

In order to convert the raw data (“*J*” and “*H*”) from the measurement, into a *J*(*H*) and/or *B*(*H*) data set, it is necessary to process the data with respect to the following elements:

7.1.1 Zero signal

When a measurement is made on a PFM system, without a test specimen, a signal is observed. For a well designed and constructed system, this signal will be small compared to the size of the measured test specimen signal, and very repeatable. This signal is generally known as the “zero signal.”

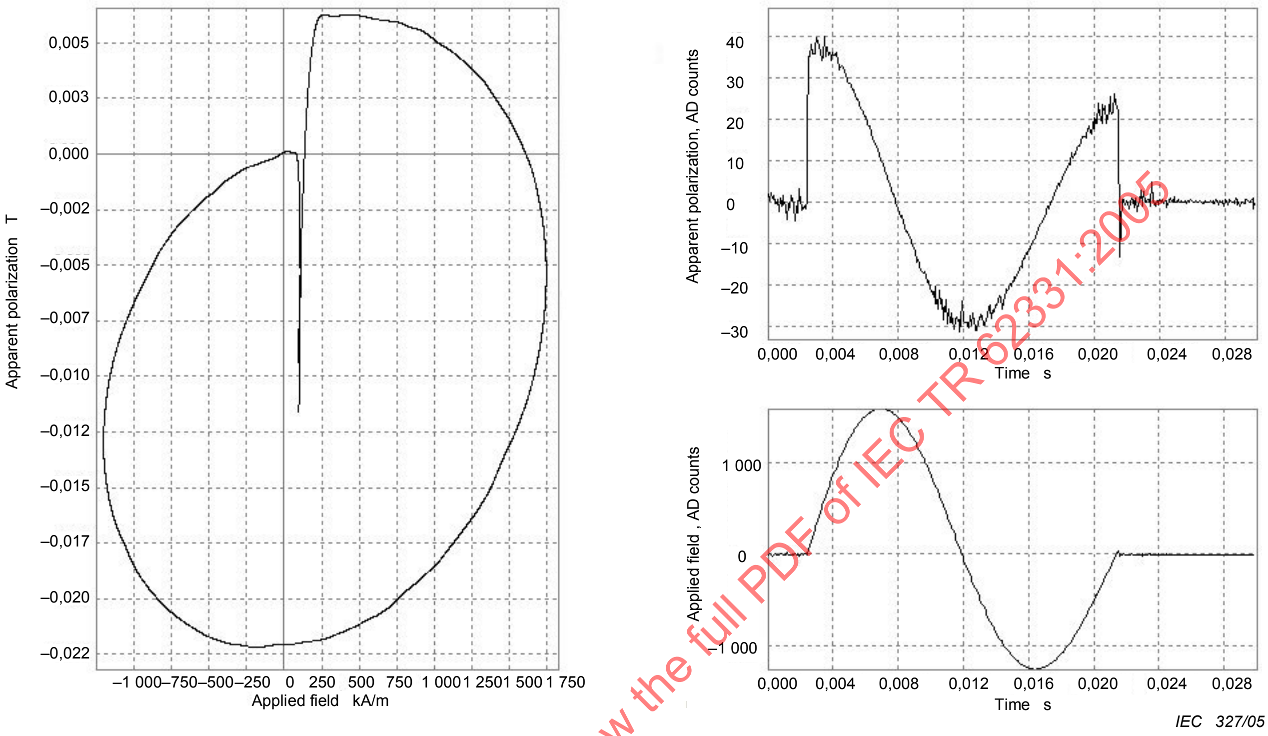
The zero signal is caused by eddy currents in conductive materials and other effects in the region of the applied magnetizing field.

This signal can be expected to change in magnitude, and possible shape, for different magnetic field strengths.

It is necessary to numerically subtract the zero signal obtained from a prior measurement without a test specimen, from the real measurement data. The amplitude of the zero signal can limit the minimum size of the test specimen to be measured.

While a zero signal of say 5 % (compared to the overall measurement signal) might be acceptable, a variation (from measurement to measurement) in the zero signal of, say 10 %, will offer a single source of error of 0,5 % in the *M* measurement process.

A resulting error of 0,1 % should be considered acceptable.



NOTE See Figure 10 for an explanation of "apparent polarization".

Figure 7 – *M* and *H* time traces and *Φ*(*H*) plot of a "zero signal"

The measurement result is obtained after the integration and digitization of the *J* and *H* coil signals in arbitrary units (counts). The zero signal recorded above (top right) represents a peak value of ± 30 counts in a system with a ± 8 192 count range. The time trace, bottom right, represents the magnetic field strength. The loop (left) represents the zero signal in the *Φ*(*H*) domain [ref. 32] .

7.1.2 Loop positioning

As the pick-up coil sensors are AC coupled systems, the DC portion of the measured signals is unknown. It is necessary to position the *M*(*H*) loop within the *M*(*H*) domain.

While the magnetic field strength can be expected to start and end at zero, the magnetization signal can be related to a magnetic specimen of unknown magnetization.

To obtain the centre position for the *M*(*H*) loop in the *M*(*H*) domain, two approaches can be used:

7.1.2.1 Specimen injection

The test specimen is placed into position by means of a mechanical actuator at a rate such that the dynamic signal induced in the *J* pick-up coil system is comparable to that induced during a measurement.

By nulling the –J integrator before the specimen injection and continuing to integrate during the insertion, the results can be considered as starting from the $M(H)$ origin. The J integrator will integrate during the injection process arriving at the residual magnetization (if any) of the test specimen ensuring that the zero point is determined and the starting condition of the test specimen is known.

As this process does not involve the application of a magnetic field strength to the test specimen, it is not necessary to apply this procedure to the H channel.

7.1.2.2 Data centring

If the test specimen has been satisfactorily saturated with both positive and negative fields and the measurement result data is considered to be symmetrical, then the mid point between the remanence values can be considered to occur at $M = 0$.

This approach operates satisfactorily and has the advantage of enabling captured data to be centred by post processing of data.

7.1.3 Self-demagnetization

The PFM is an open magnetic circuit. In order to obtain the intrinsic magnetic characteristics of the test specimen, it is necessary to apply a self-demagnetization factor correction. The self-demagnetization factor depends on the geometry of the test specimen and of the differential permeability of the material. This is also the case for all forms of open magnetic circuit measurement.

By applying an appropriate self-demagnetization factor to an $M'(H)$ loop determined directly from the J channel signal, an intrinsic of $M(H)$ or $J(H)$ loop is obtained.

As this technical report is concerned with pulsed field magnetometry and not with the more general matter of self-demagnetization factors, a detailed discussion is not considered here. It is, however, appropriate to point out that tables of correction values for simple geometries such as cylinders are available (ref [19]) while more recent work offers self-demagnetization factors for any complexity of a three-dimensional shape that is an extrusion of a two-dimensional shape (refs. [21] to [26].

The EMAJ have adopted an approach where a limited number of configurations are employed in order to reduce the errors caused by self-demagnetization correction, eddy currents, heating effects on specimens and also to achieve consistent data with good reproducibility. By restricting the specimen to a single shape, a single self-demagnetization value can be adopted for all measurements.

The MACCHARECTECH approach is to permit a wide range of geometries and sizes and to process the resultant data to take account of self-demagnetization correction, eddy currents, heating effects on specimens and to use these techniques to obtain the consistent results with good reproducibility.

All measurement results produced utilizing the PFM technique should clearly state if a self-demagnetization correction has been employed and state the self-demagnetization factor used in the self-demagnetization correction process.

7.1.4 Filtering

It may be deemed necessary to filter signals to reduce the effects of system noise, particularly when small test specimens are measured.

The filter can be an analogue, real time (electronic) filter or a numerical (software) low pass band filter. It is very important that the design of filter used does not introduce phase shift and can allow an appropriate cut-off frequency.

Filtering must not have too low a cut-off frequency as this will dramatically distort the measurements.

All measurement systems that offer a low pass band filter should permit operation without such a filter. The filter should also have cut-off frequencies that can be altered. Appropriate filter frequencies are dependent upon the dΦ/dt of the J signal, which in turn is dependent upon the magnet material characteristic, and the dH/dt of the magnetic field strength.

Appropriate filtering must be applied with care.

7.1.5 Calibration factors/scaling

In order to obtain calibrated measurements it is necessary to scale M and H signals and to take into account the mass and density or volume of the test specimen and calibration of the magnetic field strength (see 7.4).

7.1.6 Eddy currents

7.1.6.1 General

When an electrically conductive material, such as some permanent magnet materials, is subjected to a time varying magnetic field, such as in the case of a pulsed magnetic field, it will experience eddy currents.

These eddy currents will, in turn, produce magnetic fields.

For a given conductive test specimen and magnetic field strengths of a given profile and magnitude, the resultant eddy currents will increase with increasing frequency of the magnetic field strength. The following situations can be considered:

Table 2 – Classification of the influences of eddy currents

EC 0	Eddy currents are small and their resultant magnetic field is not significant compared to the magnetization of the specimen under measurement
EC 1	Eddy currents are large enough to create a resultant magnetic field that is significant compared to the magnetization of the specimen under measurement. The eddy currents are not large enough to distort the distribution of magnetic field strength within the body of the test specimen under measurement to a degree that will significantly affect the magnetization of the test specimen
EC 2	Eddy currents are large enough to create resultant magnetic fields that are significant compared to the magnetization of the specimen under measurement. The eddy currents are also large enough to significantly distort the distribution of magnetic field strength within the body of the test specimen under measurement but not large enough to stop field penetration completely
EC 3	Eddy currents are large enough to create resultant magnetic fields that are significant compared to the magnetization of the specimen under measurement. The eddy currents are also large enough to significantly distort the distribution of magnetic field strength within the body of the test specimen and large enough to stop field penetration completely in some parts of the body of the specimen under measurement

The scope of this technical report with respect to eddy currents is limited to EC 0 and EC 1.

In consideration of the possible eddy current effects of a pulsed field measurement, three approaches are used to address this effect:

– low frequency fields (EC 0);
– eddy current correction by “best fit” approach (EC 1);
– eddy current correction by measurement (EC 1).

7.1.6.2 Low frequency fields (EC 0)

Eddy currents in a conductive body are described by the following equation:

$$\nabla \times j_{\text{eddy}} = -\sigma \frac{\mathrm{d}B}{\mathrm{d}t} \tag{10}$$

where j_{eddy} is the induced eddy current density (vector) and σ is the conductivity of the specimen.

For a given class of magnetic materials (and expected range of resistivities), limited test specimen diameters and frequency of magnetic field strength can be determined to reduce eddy current effects to levels which have insignificant effects on the result of the measurement.

It should be noted that this is the preferred approach of EMAS which employs a fixed size of test specimen.

The disadvantage of this low frequency approach is that for test specimens larger than a quite modest size, it becomes increasingly uneconomical to use the pulsed field magnetometer system as the overall energy requirements increase dramatically.

If a test specimen and the applied magnetic field strength is such that it is known that no eddy currents are generated, it is not necessary to consider applying any form of eddy current correction. Care should be taken, however, as eddy currents can occur at low levels so as to effect coercivity measurements by few per cent and not be obvious.

7.1.6.3 Eddy current correction by "best fit" approach (EC 1)

If certain assumptions are made about the magnet material of the test specimen, a "correction" can be applied to the measurement results to compensate for the assumed eddy current effects.

By making the assumptions that the specimen conductivity, geometry and the eddy current paths are known, it is possible to make an analytical approximation of the effects of eddy currents. An approximate solution of the governing equations can be generated for a particular test specimen geometry and can be used to approximate the effects of eddy currents. This effect can then be subtracted from the measured signal. The approximation only solves first order effects, whilst higher order effects are assumed to be negligible. Any imperfections or non-homogeneity of test specimen will also be neglected. If a single pulse measurement is then made it is possible to approximate and subtract the eddy current effect from the measured result. This cannot, however, be considered a valid measured result as any imperfections or non-homogeneities are not taken into account and these possible effects can greatly effect the eddy currents that may flow in the specimen. Hence the effects caused by the eddy currents will deviate from the theoretical values and an erroneous correction will be made.

7.1.6.4 Eddy current correction by measurement (EC 1)

Eddy currents are proportional to the rate of change of magnetic field strength. They are also proportional to the conductivity and surface area of the test specimen, perpendicular to the magnetic field strength. If two pulses of differing frequency are applied to the same test specimen, then the eddy currents and the measured effects of those eddy currents will be proportional to the frequencies of the two applied pulses. The lower frequency pulse is named H_{L} and the higher frequency pulse H_{H}. Each pulse will have an eddy current effect proportional to the frequency of the pulse combined with the signal due to the magnetization of the test specimen. If the signals from the two pulses are subtracted, then the signals due to the magnetization of the test specimen cancel out, as do part of the eddy current effect (on the measurement result) leaving only the extra error component that is present in H_{H} but is not present in H_{L}.

$$\Delta\, Error \quad = H_H - H_L$$

Since the frequencies of the two pulses are known, this change in error can be scaled and used to subtract the eddy current error to find the static (no eddy current effects) curve. As the same specimen is used for both pulses, all imperfections and non-homogeneities of the material will be accounted for. Neodymium Iron Boron is measured at two frequencies represented by the two outer loops. This enables the eddy current to be deduced and removed to obtain the resultant inner loop, eddy current free, characteristic (ref. [33].

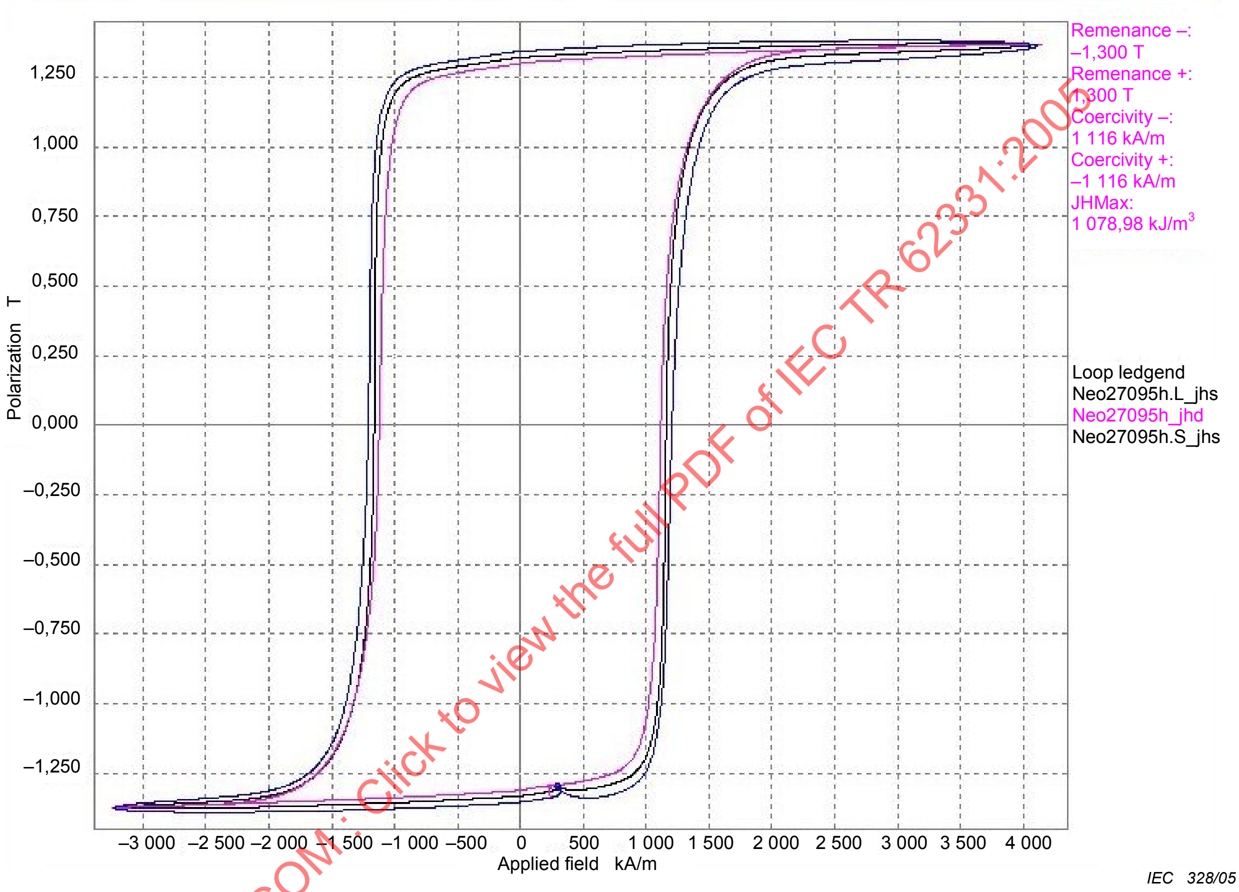


Figure 8 – *J*(*H*) loops of a sintered NdFeB permanent magnet

7.2 Temperature

As magnetic materials exhibit a temperature dependency, it is necessary to consider thermal effects and temperatures of test specimens in PFM systems. The temperature of the test specimen may be the ambient temperature or may be increased due to heating effects.

7.2.1 Errors due to heating effect

Test specimens can be heated from sources that can introduce errors by changing the temperature of the specimen. These sources can fall into two categories:

7.2.1.1 Eddy current heating of specimens

Eddy currents in the test specimen will create a I^2R heating effect which will change the specimen temperature. In systems where the test specimen is exposed to a small number of magnetic impulses, the temperature rise can be expected to be small, even with significant eddy currents. Temperature rises of less than 1 °C are expected from theoretical calculations. These assumptions are supported by experiment.

7.2.1.2 Heat transfer

The main source of heat in the region of the test specimen, is that of the magnetizing solenoid. Depending upon the design of the specific solenoid, a maximum field, or maximum heat transfer may have been a primary consideration. Either way, the temperature of the solenoid can be expected to either operate at above ambient temperature (in the case of high speed systems) or experience temperature rises above ambient temperature (in the case of research applications).

High-speed systems can avoid significant heat transfer to the test specimen by a short stay of the test specimen in the solenoid (typically of a few seconds) during which the temperature rise can be expected to be minimal.

In the case of research systems, where temperature control is not employed, forced cooling may be achieved by pumping air at ambient temperatures through the solenoid.

7.2.2 Temperature measurement

The temperature of the test specimen can be determined by a number of methods:

7.2.2.1 Thermocouple contact

A thermocouple can be mounted in contact with the specimen under test. This approach can have the disadvantages of introducing magnetic, eddy current or instrumentation errors.

7.2.2.2 Laser temperature measurement

An optical window can allow a temperature measurement to be offered by a laser passing through the free bore of the bottom of the magnetizing solenoid.

7.2.2.3 Indirect measurement

The temperature of the gases within the specimen area can be measured by means of a thermocouple at a small distance from the specimen under test. Provided that this temperature is stable for a sufficient period of time, the specimen can be considered to be at the gas temperature.

In order to determine this temperature stabilization period, a test specimen can be mounted with a thermocouple inside it. By monitoring the gas temperature, and monitoring the response time of the test specimen, a safe stabilization period can be determined for test specimens of equal mass, geometry, specific heat capacity and thermal conductivity.

7.2.2.4 Industrial temperature measurement

In the case of measurements on industrial test specimens, temperature measurements fall into two categories:

- individual test specimens measured at a number of temperatures where concepts similar to research applications are more appropriate;
- industrial application test specimen masses, often much larger, requiring longer temperature stabilization periods.

Normally, in the case of individual test specimens in industrial measurements being measured at specific temperatures, the time consuming temperature control approach is prohibitive. An alternative approach is to pre-heat specimens to the required temperature as a batch and measure the individual test specimens quickly. This approach is applicable where the mass of the specimen is large and the heat losses from the test specimen lead to small temperature variations.

7.3 Magnetic viscosity

The measured coercivity of a magnetic test specimen can be dependent upon the rate of change of the magnetic field strength. This effect is particularly notable on recording media such as gamma ferric oxide. The effect is referred to as "magnetic viscosity." In higher coercivity materials, such as permanent magnet materials, there exists a theoretical effect, which has been observed at cryogenic temperatures. At room temperatures, a theoretical effect can be expected for Sm_2C0_{17}, but experimental work has, so far, identified very small effects. In the case of barium ferrite, observations indicate effects, i.e. a relative change of magnetic characterization of less than 0,025 %.

Some experimental, non-commercial materials are reported to show much larger effects.

7.4 Calibration

Calibration of a PFM system (with homogeneous pick-up over the maximum volume of the specimen) involves the correct determination of calibration factors for the *H* and *J* channels.

Errors due to eddy current effects can occur in conductive materials, while measurement techniques that utilize a static field for calibration offer possible errors when applying dynamic fields.

7.4.1 *H* channel calibration

The *H* channel calibration involves determining the exact field strength to be applied to the test specimen (see 5.2).

7.4.1.1 Direct methods

7.4.1.1.1 Hall sensor

A Hall sensor that has been calibrated in a static field can be placed in the magnetizing solenoid and the magnetic field strength measured. The main source of errors can be the dynamic field applied inducing additional voltages in the Hall probe other than those caused by the Hall effect. This can introduce errors when compared to the static field within which the Hall probe is calibrated.

7.4.1.1.2 Integrating fluxmeter

The *H* pick-up coil can be placed in a uniform, static, calibrated field and rapidly removed to determine the performance of the pick-up coil and integrator.

7.4.1.1.3 Current measurement

By applying a known low DC current to the solenoid and measuring the associated DC field strength using a calibrated magnetometer, the field strength/current characteristics of the magnetizing solenoid can be determined. A peak current measurement can be used to deduce the field strength when a high current pulse is applied. Unfortunately this usually involves differences between DC and pulsed currents of orders of magnitude and is not usually an effective technique.

7.4.1.2 Single reference specimen

7.4.1.2.1 Polymer bonded reference specimens

A polymer bonded reference specimen of known coercivity and known influence of magnetic viscosity can be used to calibrate the magnetic field strength. The influence of magnetic viscosity and the temperature dependence of the coercivity will be small.

7.4.1.2.2 Anisotropy measurement of hard ferrite (SPD)

A good quality differentiator can process the *M* response of a magnetic material with a known anisotropy field using the “singular point detection” technique. Unfortunately, uncertainties due to the effect of demagnetizing field and the temperature dependence of the anisotropic field strength H_A can limit the effectiveness of this technique (see [ref. 20]).

7.4.2 *J* Channel calibration

The *J* channel calibration involves accurately determining the sensitivity of the *J* channel to the magnetization of the test specimen.

7.4.2.1 Reference specimen

The measurement of *J* at DC can be established using a calibrated magnetic moment such as a reference test specimen of NdFeB of suitable dimensions. The magnetic moment can be measured with a low uncertainty. By extracting this from the *J* coil system the scaling can be determined. Various geometries can be used to check the uniformity of the coupling coefficient (see IEC 60404-14).

A soft ferrite specimen of a known magnetic moment in its saturated state can be used to calibrate a PFM by measuring its magnetic moment by applying a magnetic field strength sufficient to saturate the material.

Unfortunately, soft ferrites usually have a low Curie temperature and therefore offer a magnetic moment that can be rather temperature dependent.

7.4.2.2 Multiple reference test specimen combination

A nickel test specimen with simple copper eddy current correction can be used in the regions where the test specimen is saturated.

A nickel test specimen can be measured in a static magnetometer to determine its moment. The nickel test specimen is then measured in a PFM. The resultant eddy currents are not dependent upon the relative magnetic permeability in the regions where the nickel is saturated.

By measuring the eddy currents in a similar shaped copper test specimen, having the same magnetic field strength applied, an iterative process is used where by varying proportions of the copper eddy current data can be numerically subtracted from the nickel measurement results until the eddy current content is removed in the saturated nickel regions. The value of the statically determined magnetic moment for the nickel can then be used.

As complex as this technique appears to be, it can give excellent results.

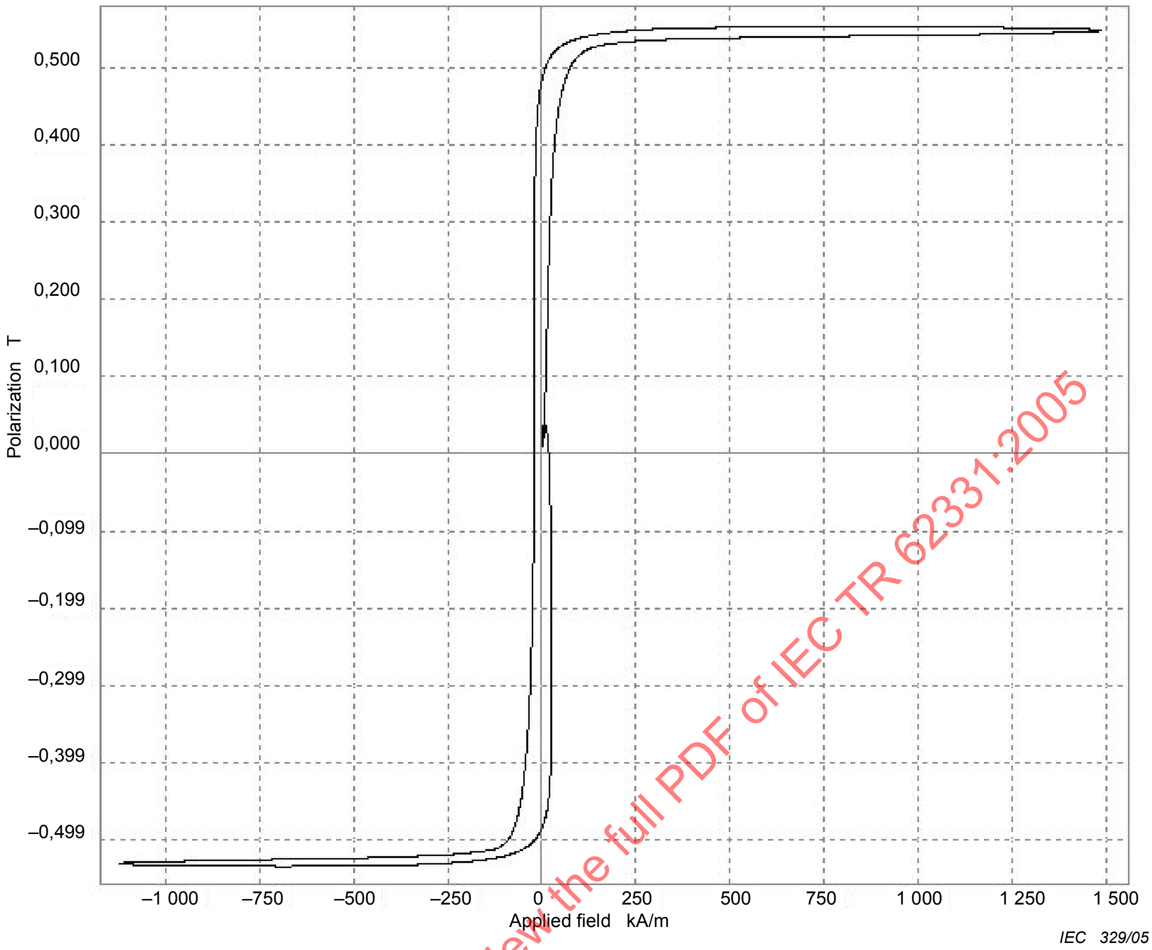


Figure 9 – *J*(*H*) loop including eddy currents of a conductive bulk nickel specimen measurement result from a PFM system

The result contains errors due to eddy currents, evident in the saturated regions [ref. 32].

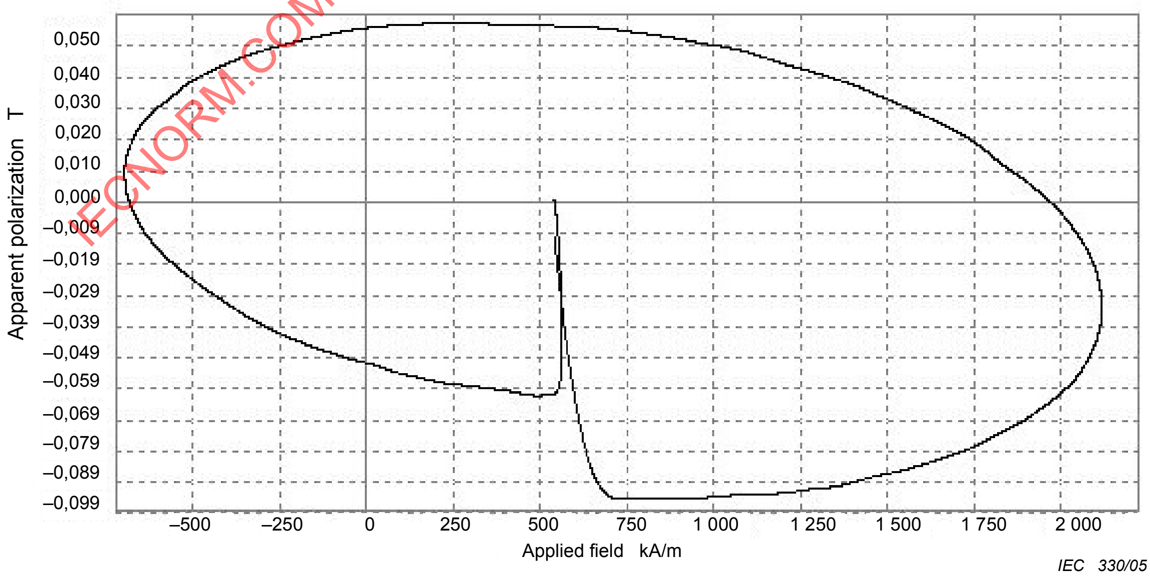


Figure 10 – Copper specimen eddy current measurement result

The graph represents eddy currents in a copper specimen with the same dimensions as the nickel specimen of Figure 9 (see [ref. 33]). Note the "apparent polarization" is due to the eddy current effects and is not due to ferromagnetic moments.

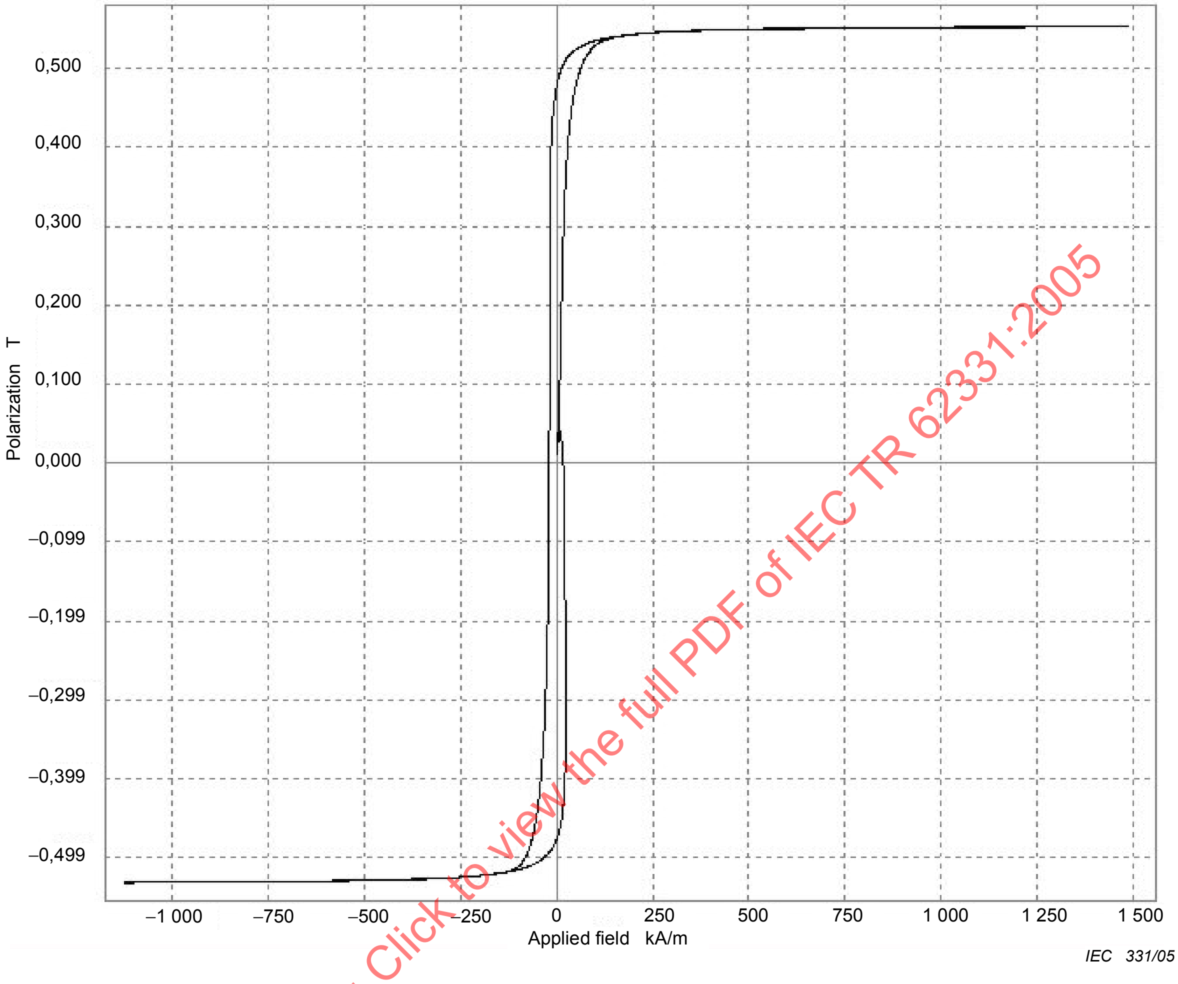


Figure 11 – *J*(*H*) loop for eddy current "corrected" nickel specimen

The graph represents the magnetic characteristics of nickel specimen (Figure 9) after a proportion of the copper sample eddy current dynamic (Figure 10) has been subtracted from the nickel specimen results to remove the eddy current effects in the saturated region of the nickel characteristic see [ref. 33]).

7.4.3 Calibration practicality

For practical purposes, calibration processes based upon non-conductive specimens of simple geometries (cylinder, sphere, ellipsoid) of known coercivity (for *H* calibration) and known remanence (*J* calibration) offer a practical solution.

Unfortunately, non-conductive materials that might be used for remanence values have a high temperature dependence.

As nickel is already a calibration standard, the technique based upon 7.4.2.2 may offer a practical solution.

8 Comparison of measurements

8.1 Permeameter, "large magnet" comparison

The following shows measurement results from a pulsed field magnetometer compared with more established techniques.

NOTE Bonded NdFeB, ring magnet OD 21 mm, ID 16 mm, length 23 mm ([27]).

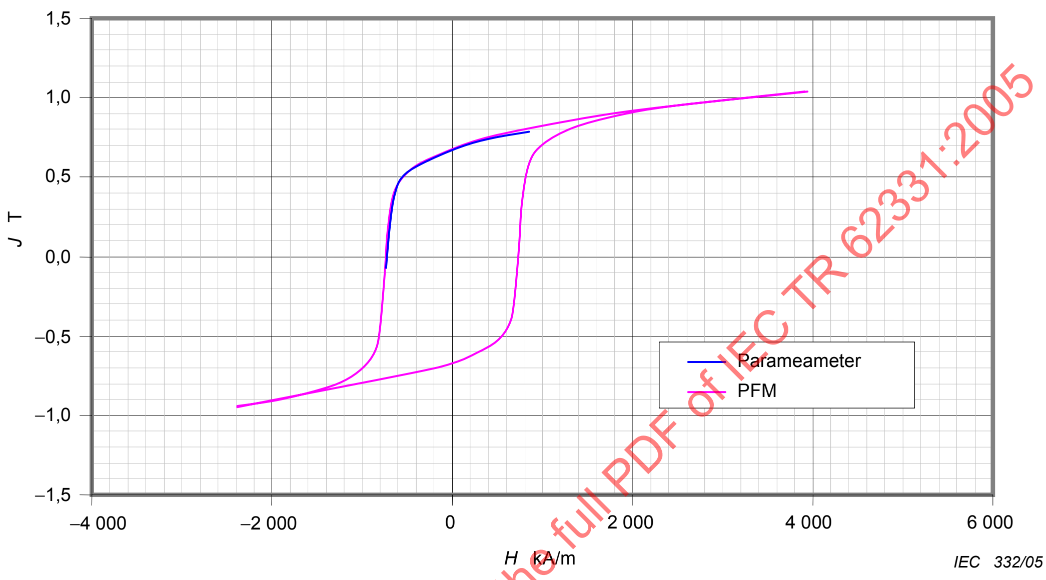


Figure 12 – Results of a permeameter and a PFM measurement of a "large" specimen

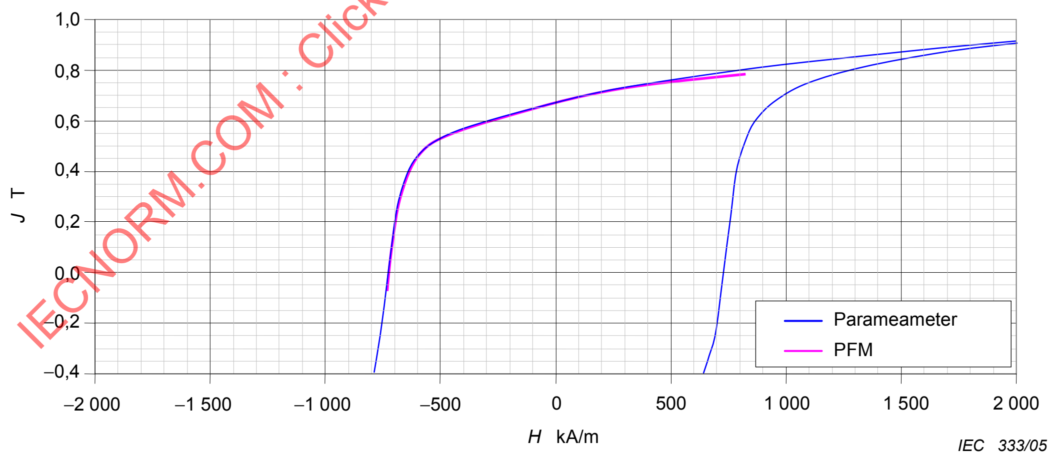
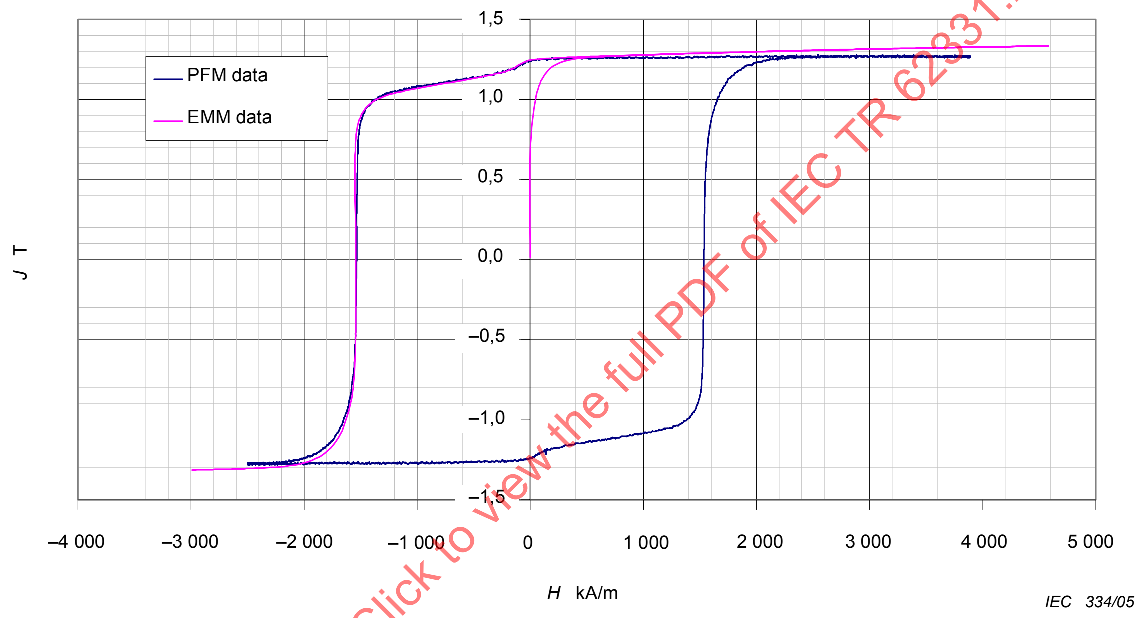


Figure 13 – Detail of the 1st and 2nd quadrants of the measurement results shown in Figure 12 "large magnet"

Table 3 – A comparison of values taken from the measurement results presented in Figure 11 and Figure 12

	Remanence Br	**Coercivity related to polarization (intrinsic coercivity)** H_{CJ}
Permeameter measurement	0,672 T (tesla)	–723,4 kA/m
Pulsed field magnetometer measurement	0,673 T (tesla)	–727,1 kA/m
Relative difference between measurements	0,15 %	0,51 %

8.2 Extraction method, "small" test specimen comparison



The following results represent measurements of a "small magnet" measured on a PFM system and a super-conducting solenoid extraction method magnetometer.

NOTE Sintered NdFeB cylinder magnet diameter 5 mm, length 10 mm ([28]).

Figure 14 – Comparison of a "small magnet" measured in a super-conducting, extraction method magnetometer (EMM) compared with a PFM measurement result of the same magnet [28]

Table 4 – Comparison of values measured in Figure 14 above (see NOTE)

	Remanence Br	**Coercivity related to polarization (intrinsic coercivity)** H_{CJ}
Extraction method measurement	1.240 T (tesla)	–1 545 kA/m
Pulsed Field Magnetometer measurement	1.254 T (tesla)	–1 536 kA/m
Difference between measurements	1,1 %	–0,6 %
NOTE Comparison of a "small magnet" measured in a super-conducting, extraction method magnetometer compared with a PFM measurement result of the same magnet. Sintered NdFeB cylinder magnet diameter 5 mm, length 10 mm. Manufactured by Magnetfabrik Schramberg (see ref. [33]).		

Below are three measurements made on the Toei Industry Co. machine TPM-2-10. These measurements conform to the Japanese specification on pulsed field magnetometry.