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Hirst's Pulsed Field Magnetometers – closing the loop on material characterisation

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Pulsed Field Magnetometers – closing the loop on material characterisation

Dr James Mckenzie, CEO & Dr Robin Cornelius, CTO, Hirst Magnetic Instruments Ltd

Introduction

The Pulsed-Field Magnetometer (PFM) is internationally recognised for the complete characterisation of modern magnetic materials. It is a method for generating a hysteresis graph similar to that of a permeameter.

Historically demagnetisation curves were measured using a permeameter. A permeameter uses an iron-core, closed-magnetic-circuit to deliver a uniform magnetic field to the sample. However, modern hard magnetic materials often cannot be accurately characterised using a permeameter because the high coercive fields required will saturate the iron-based cores thus corrupting the measurement and in extreme cases the measurement cannot be obtained.

PFMs have gained in popularity over the years as a measurement technique (compared to the permeameter) as they are easily scalable in sample size (from 1 mm to several tens of mm), with a significantly faster measurement time. Plus crucially can accurately characterise the high coercivity magnet samples used in today's high performance motor applications such as electric vehicles (EV). Larger sample sizes meet the requirements of magnets used in EV rotors, allowing accurate quality control for batch testing of production magnets for the key performance metrics including high temperature coercivity. If a batch does not have the correct composition for whatever reason, its high temperature performance can be compromised causing in extreme cases loss of motor power and possible warranty claims.

PFM measurements are non-destructive, which is particularly important for larger, more expensive high-performance magnets. PFMs have historically found application in production testing and quality control in magnet factories across the world for rapid standard sample block tests, as well as materials research and development requiring magnet samples tested down to -50 ^{o}C and to over 230 ^{o}C requiring the highest level of repeatably and accuracy.

Small size testing down to 1x1x1 mm and thin slices have been used over the years in grain boundary diffusion (GBD) magnets, and more recently developing selective diffusion of heavy rare earths (to toughen up edges and corners of magnets to improve performance cost effectively) in magnet research, development and production testing.

The International Electrotechnical Commission (IEC) has issued IEC TR62331, a draft to define the standard methodology for the characterisation of permanent magnetic materials using the PFM technique.

Hirst Magnetic Instruments Ltd originally manufactured permeameters (hysteresisgraphs) and vibrating sample magnetometers. Research work at Hirst into PFMs began in the 1990s, and Hirst introduced its first commercial PFM in 1998, winning an Institute of Physics award in 2020 for the technology, and launching its latest 8th generation PFMs in early 2023.

In this article we will review magnetic measurements, focussing on the PFM technique to compare it to other standard approaches, and look at Hirst's PFM08 range with its associated software.

Measurement basics

Permanent magnetic materials are characterised and graded by their response to an externally applied magnetic field, which is plotted as a hysteresis loop.

In the second quadrant of the hysteresis loop, the applied magnetic field is in opposition to the sample magnetisation, and this quadrant is referred to as the demagnetisation curve. It is of special interest because this is where most magnetic machines operate.

Above is a typical 2nd quadrant hysteresis curve of a magnet at room temperature showing remanence B_r, intrinsic coercivity H_{cJ}, normal coercivity H_{cB} and maximum energy product BH_{max}

Remanence B_r is the residual flux density or field that remains after the magnet is fully saturated (fully magnetised). Remanence is also the intersection point of the hysteresis curve and vertical axis (B-, or J-axis). The unit of remanence is Tesla (T) or Gauss (G).

Intrinsic coercivity H_{cJ} represents the ability of a magnetic material to resist demagnetisation. The unit of intrinsic coercivity is A/m or Oersted (Oe).

Normal coercivity H_{cB} or coercive field strength is the magnetic field value opposing the magnetisation direction which is strong enough to reduce the flux density through the magnet to zero. Coercivity is the intersection point of B-curve and the horizontal H-axis. The unit of coercivity is A/m or Oersted (Oe).

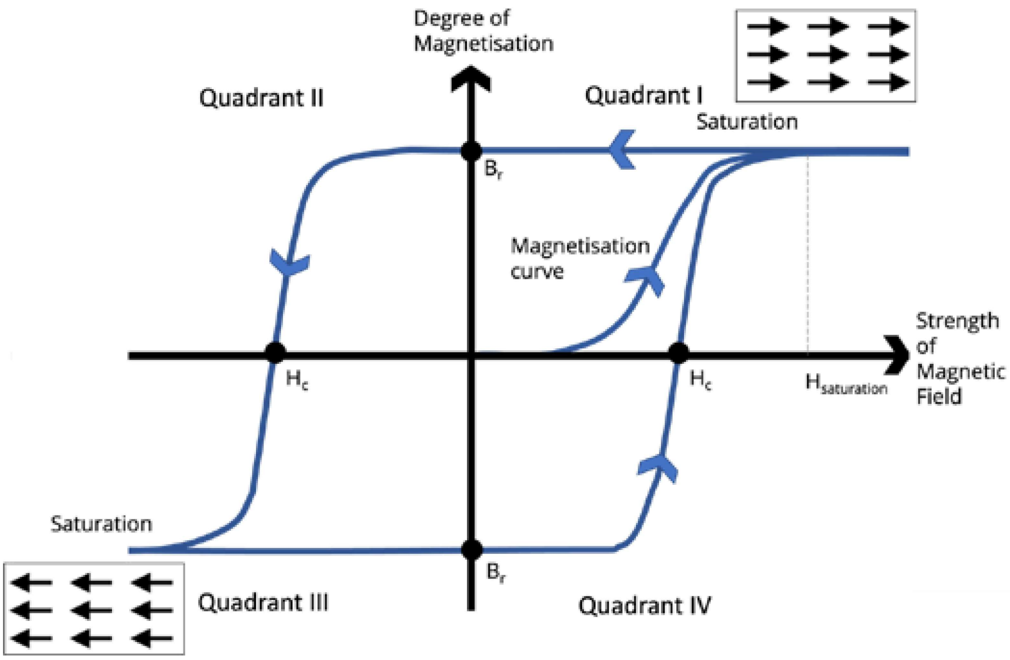
BH_{max} is the maximum energy that a magnetic material can supply to an external magnetic circuit or electrical machine. In a BH diagram the point of BH_{max} is represented by the maximum rectangular area that can be drawn under the BH curve. The units of BH_{max} are kJ/m^3 or MGOe.

A perfect theoretical hysteresis curve showing magnetic polarisation J as a function of opposing magnetic field H would have a sharp angle in its upper left corner. No magnetic material is perfect and thus the curve is always round in its upper left corner. This corner shape is called "roundness" or "squareness" of the curve and it can be described with the parameters H_k and H_{D5}. If the magnet is used in this round area, it will suffer irreversible losses in magnetic polarisation and performance.

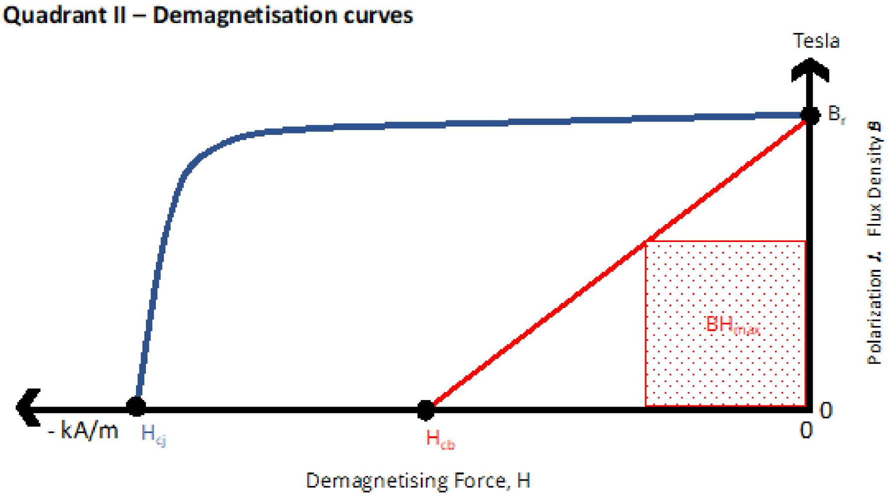
When the field approaches H_{cJ}, the curves start to decline rapidly. This drop indicates the onset of severe irreversible losses, and both H_k and H_{D5} give a good indication for the field value where a significant drop occurs.

H_k is defined as the field where the polarisation J has dropped to 90% of B_r. In magnets with very high coercivity it may be that 90% of B_r is reached while the curves are still perfectly straight and H_{D5} may be more useful. H_{D5} considers the slope of the demagnetisation curve and thus avoids the problem of H_k in magnets with very high H_{cJ}. A line parallel to the demagnetisation curve is drawn from a point at 95% of B_r towards the curve, the intersection with the curve is H_{D5}.

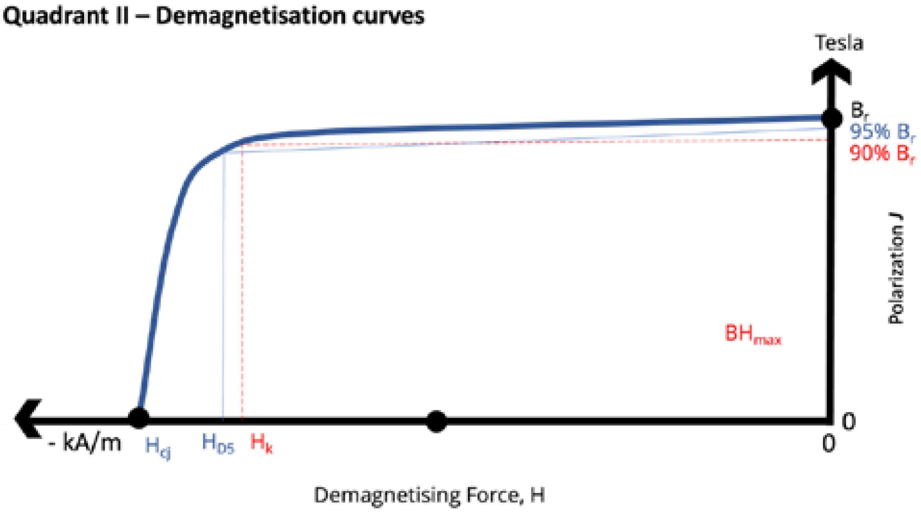
All magnetic properties are temperature dependent. In the Rare Earth (RE) magnets both remanence and intrinsic coercivity drop with increasing temperature. The drop is reversible until a certain point, above which the magnet starts to demagnetise.



Quadrant II – Demagnetisation curves



Quadrant II – Demagnetisation curves



For NdFeB magnets the temperature coefficient of H_{cj} (how H_{cj} varies with temperature) is approximately -0.6%/°C (from ambient +20 °C and +120 °C) and the temperature coefficient of B_r (how B_r varies with temperature) is around -0.12%/°C, from ambient, although these vary significantly with magnet grade.

Linear temperature coefficients are provided in magnet data sheets. However temperature dependence is not linear over the whole temperature range (particularly at higher temperatures), so measurements of magnetic materials need precise temperature set points and precision temperature control of samples during measurement to accurately determine and calculate magnet performance for data sheets.

Traditional approach to characterisation of magnets – the permeameter

Permeameters (or hysteresisgraphs) are a set of devices consisting of a controllable electromagnet forming a closed magnetic circuit, two fluxmeters and the measurement coil set. A magnet sample is placed in a homogenous field between the poles of the electromagnet. During the measurement the field between the poles is increased and the magnetic field strength and the flux through the magnet are measured in hundreds of data points. The output of the measurement is a set of points, where the magnetic flux density B in the magnet and the magnetic polarisation J of the magnet are given as a function of the external field H.

Permeameter measurement is well liked, giving the result in a form of a curve which is easy to understand. It delivers a closed-circuit measurement which helps magnet users understand how magnets perform in their electric motors and generators. Permeameter measurement is practically limited by sample shape and size: the sample must have two flat parallel surfaces within some reasonable distance apart, and parallel sides of arbitrary shape perpendicular to the flat surfaces. A typical sample is a cylinder with thickness of 2.5 mm to say 10 mm with a diameter of 5 mm to 20 mm. Measurement times are relatively slow as the field needs to stabilise at each measurement point resulting in measurement times of tens of minutes per sample.

The technique's accuracy is crucially limited by the material used to make the pole pieces. Normally the pole pieces are made of iron, which saturates around 2 T (although cobalt iron pole pieces can push this limit to 3 T or so). After the pole pieces are saturated, the field between the poles is no longer homogenous and therefore it will underread the closed-circuit performance of the magnet. With today's modern magnets this is an all-too-common occurrence, as the majority of high-performance magnets such as NdFeB and SmCo have such high intrinsic coercivities that they cannot be reliably measured at room temperature up to the field strength corresponding to their intrinsic coercivity (H_{cJ}). An alternative is to measure the samples at high temperatures and some permeameters have heated pole shoes or a heated sample holder making it possible to make measurements at elevated temperatures around 200 °C or higher.

The measurement of magnets using this method are captured in international standards IEC 60404-5:2015.

Can open circuit measurements be used to overcome these challenges?

Measurements in an open circuit do not rely on the sample being sandwiched between pole pieces. This means samples do not need parallel surfaces and may, in principle, have an arbitrary shape. Since there is no need for pole pieces which could saturate, the applied fields can be quite large, and fields of 9 T or more are not uncommon. Complete demagnetisation loops can therefore be measured even in materials with very high coercive fields. In the open circuit measurement, the magnetic field in the samples is different from the externally applied field. The inner field is determined by correcting the applied field for the self-demagnetising fields of the sample, which depend on the sample's shape.

There are 2 mainstream commercial types of open loop instrument: the Vibrating Sample Magnetometer (VSM) and the Pulsed Field Magnetometer (PFM).

VSM - Vibrating Sample Magnetometer

Vibrating Sample Magnetometry (VSM) measures the magnetic moment of a sample by moving it between pick-up coils and measuring the AC voltage induced by the oscillating motion. An external field is provided by large electromagnets, or by superconducting coils surrounding the pickup coils. The setup may also include a small chamber where temperatures can be varied over a large range in a protective atmosphere.

VSMs can measure samples over a wide range of temperatures from 4 K (-269 °C) to 1,000 K (726 °C) . Superconducting coils can apply large fields up to 16 T, more than the 6-10 T needed to characterise modern high-performance magnets. Sample sizes are

Feature	Permeameter / hysteresisgraph	Pulsed Field Magnetometer (PFM)	Hirst 8th Gen PFM with SDFF	Vibrating Sample Magnetometers (VSM)	Vibrating Sample Magnetometers (VSM - superconducting)
Applied field range	0 - 3.2T	0-7T	0-10.5T	0-3.5T	0-16T
Ferrite, SmCo, AlNiCo, NdFeB	Yes	Yes	Yes	Yes	Yes
Grades of NdFeB & SmCo	limited to lower grades N, H, SH	All grades inc UH, EH and AH	All grades inc UH, EH and AH	limited to lower grades N, H, SH	All grades inc UH, EH and AH
Sample hieght	0.5 to 50mm 2.5mm @ 3.2T	1-20mm	1-30mm	Small samples only from mgs to cir10g	Small samples only from mgs to cir10g
Sample width	3-80mm 40mm@3.2T	1-70mm (no upper limit)	1-70mm (no upper limit)	Small samples only from mgs to cir10g	Small samples only from mgs to cir10g
Sample limitations	parallel faces only, hieght limitation at high fields	Few	Few	Small samples only from mgs to cir10g	Small samples only from mgs to cir10g
Speed of measurement	30s	<1s	<1s	minutes	tens of minutes
Temperature stabilisation & meaasurement	tens of minutes	minutes	minutes	tens of minutes	tens of minutes
Closed magnetic circuit measurement	**Yes**	No	**No but delivers closed loop data via SDFF**	No	No
Br repeatibity	+/-1%	+/-1%	+/-0.2%	+/-1%	no data
Hcj repeatablity	+/-1.5%	+/-1%	+/-0.2%	+/-1%	no data
Cost estimates	$$	$$$	$$$	$$	$$$$$
Running cost	low	low	low	low	high- liquid N/He
Temperature range	Ambient to 220degC	From-40 to 220DegC	From-40 to 220DegC	From -196DegC to 900DegC	From -296 DegC to 726DegC
Temperature control during measurement	limited due to pole piece contact	No stabilisation	+/-0.1degC	Not clear	Not clear
Applications	R&D, production & QC	R&D, production & QC	R&D, production & QC	R&D, production & QC	R&D, thin film testing

A high level comparison of measurement techniques limited to only a few millimetres as they need to be vibrated to perform the test. VSM can prove very expensive to purchase and operate in superconducting form as these currently require a cryogenic system.

PFM - Pulsed Field Magnetometer

Pulsed Field Magnetometry (PFM) is a method of completely characterising magnets using a pulsed applied field. The PFM technique not only offers an alternative to existing techniques but also offers major advantages over all established methods as it is extendable from small samples to large samples, offers the range of measurement temperatures needed in industry, and has extremely fast measurement times.

A PFM is a stand-alone magnet characterisation instrument. It consists of a capacitor bank, a magnetisation coil, a pick-up coil, sample coolers, a sample chiller for measurements down to –50 °C, and sample heaters for measurements over 200 °C. The PFM is controlled by a PC which also stores all measurements in an integrated database.

To operate a PFM, a sample is placed onto a sample holder which is inserted into the PFM. Heating and cooling of the sample are integrated into the measurement process.

Hirst and PFM

Historically Hirst Magnetic Instruments Ltd manufactured permeameters, its first instrument being the R.P.1 recording permeameter in 1961. In the early 2000s Hirst stopped its development and sale of these.

Hirst began research on PFMs in the 1990s[1,2] and introduced its first commercial PFM in 1998. Initially there were some limitations associated with eddy currents generated from such fast measurements, but these were quickly overcome[3,4] and development continued to improve performance[5,6,7,8]. Robin Cornelius joined the company following a sponsored PhD on Pulsed Field Magnetometry in 2005[10].

The company began collaboration with the National Institute of Metrology (NIM) in Beijing who were keen to develop measurement techniques for high performance magnets[11,12,13]. Hirst has been shipping PFMs to China for over 20 years with each machine being improved to serve the needs of magnet makers in terms of speed and accuracy.

Hirst's 8th generation range of PFM

In 2023 Hirst launched the PFM08 range – its 8th generation of PFM. These uniquely feature the eddy current correction F-2F algorithm (patented), Self-Demagnetisation Field (SDF) correction function (to allow accurate measurement of a wide range of samples from cylinders, cuboids and arbitrary sample shapes), and Hirst proprietary Self De-magnetisation Field Function SDFF™ (patented) which accurately generates an open to closed circuit mapping (O2C™).

A contract for the first PFM08 placed by NIM led to the integration of HirstLab v2 software and SDFF™ technology in the PFM08 machines.

The applied field

A PFM08's applied field is a single period sine-wave pulse with a maximum amplitude in excess of 10 T. As such the PFM captures the full hysteresis loop. It is in the nature of pulsed-field measurements that rate dependent features are present in the hysteresis loop, due to eddy current effects. These rate dependent effects can be calculated out of the final result by the PFM applying two pulses at different frequencies for each measurement.

Eddy-Current Correction (F-2F)

The PFM08s use Hirst's F-2F algorithm to calculate the hysteresis loop that would be obtained from a zero-frequency measurement. F-2F has been verified to produce the same results as a static measurement obtained from a vibrating sample magnetometer. These results have been presented in peer reviewed publications.[3,4]

Measured Magnetic Moment

The pick-up coil measures the magnetic moment of the sample, whilst remaining insensitive to uniform fields. In this way the pick-up coil rejects the applied magnetic field. The pick-up coil is maintained at a constant temperature in order to ensure the precision of the measurement.

Self-Demagnetisation Field Correction (SDFF and O2C)

A standard self-demagnetisation factor (SDF) feature to correct for sample geometry and aspect ratios has been on many previous generations of machine, and is included on the latest PFM08 range.

HirstLab v2 also contains a powerful SDF calculator for any magnet shape as well as a look up system for standard shape magnet samples. It should be noted that this SDF-corrected demagnetisation curve is not yet equivalent to a permeameter curve.

However, the latest machine generation is now integrated with the Self Demagnetisation Field Function (SDFF™) – a new Hirst algorithm that accurately maps the open-circuit measurement onto a closed-circuit, permeameter equivalent measurement. The unique Self Demagnetisation Field Function (SDFF™) in HirstLab v2 accurately generates an open-to-closed circuit mapping (O2C™) for the magnet sample, giving accurate closed loop magnet parameters to within 1%. This means PFM08s give permeameter-like measurements for the highest grades of magnets.

The model that drives the SDFFTM is a proprietary Extended Ising Model (EIM) that includes long range fields, extended dipole modelling, rotation and crystalline structure as well as magnetic domain formation, domain walls and pinning structures.

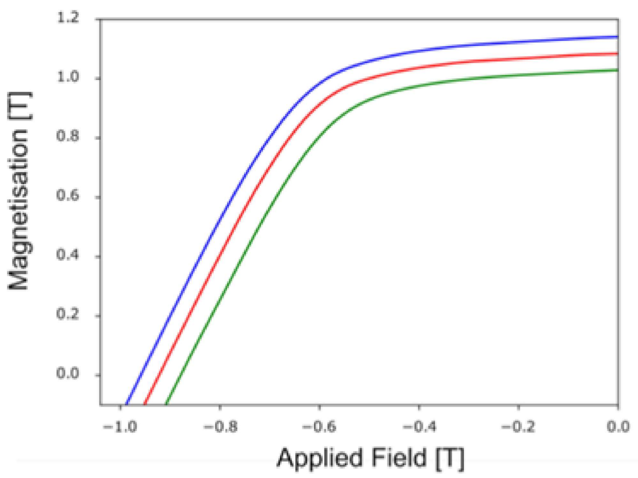
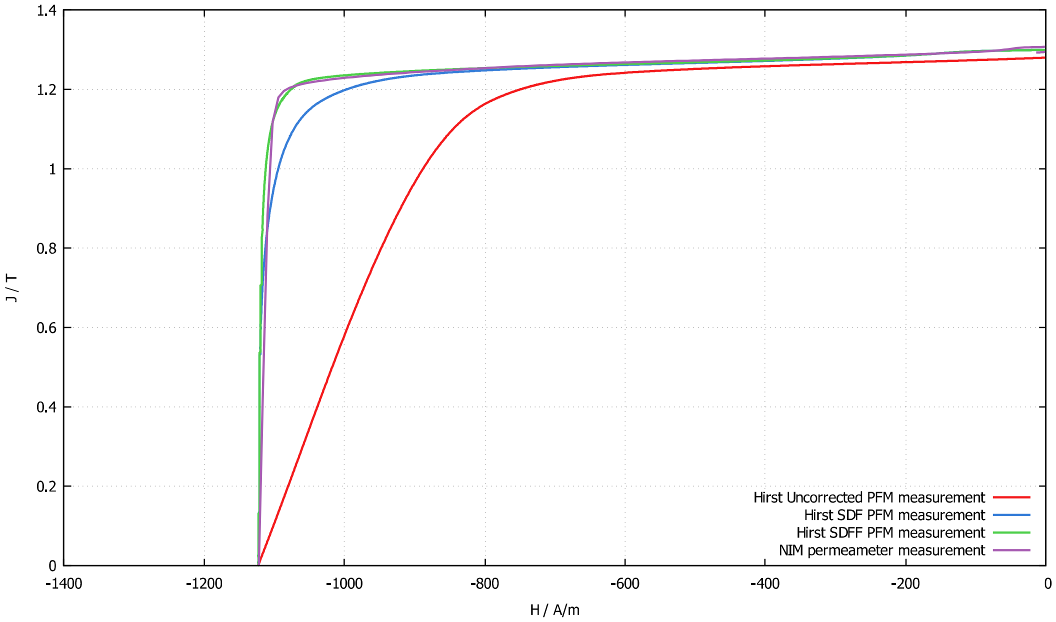
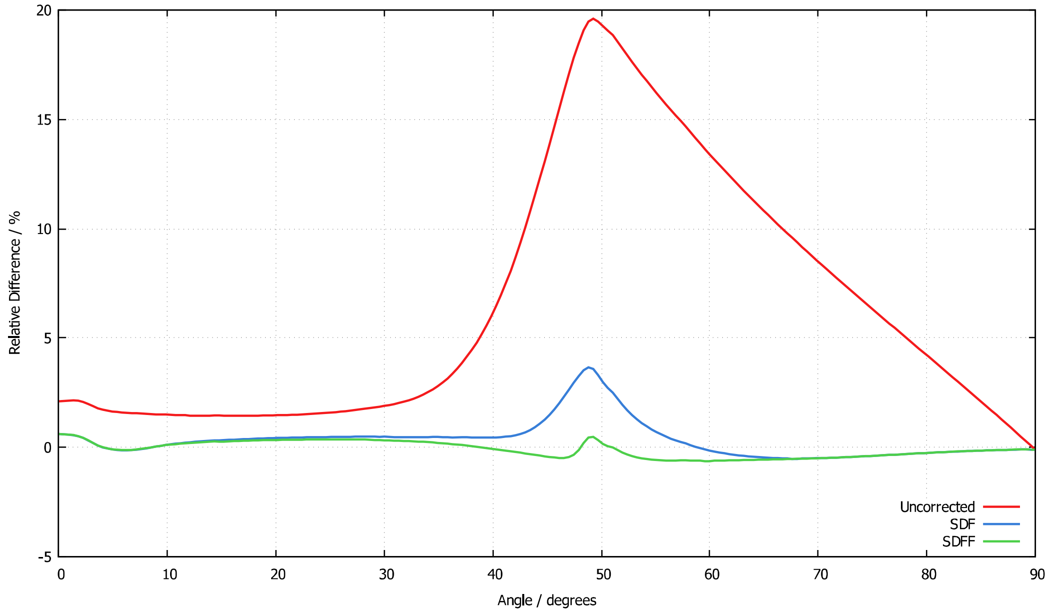


Illustration of the results from the F-2F algorithm.
Blue line: Demagnetisation curve obtained from a short pulse at double frequency.
Red line: Demagnetisation curve obtained from a long pulse at single frequency.
Green line: Calculated zero-frequency demagnetisation curve.





Above we show the difference function between data from a permeameter measurement and: Uncorrected PFM measurement (red), SDF corrected PFM measurement (blue) and an SDFF corrected PFM measurement (green). This shows the maximum deviation between a PFM running SDFF and the permeameter is less than 1%.

To validate this algorithm, Hirst have worked in collaboration with the UK National Physics Laboratory (NPL), the University of Exeter, and the National Institute of Metrology (NIM) in China.

The calculated demagnetisation curve matches with a real permeameter measurements on countless reference samples with a difference better than 1%. This has been verified for all high grades of Neodymium and Samarium Cobalt, many sample geometries, and over a large temperature range.

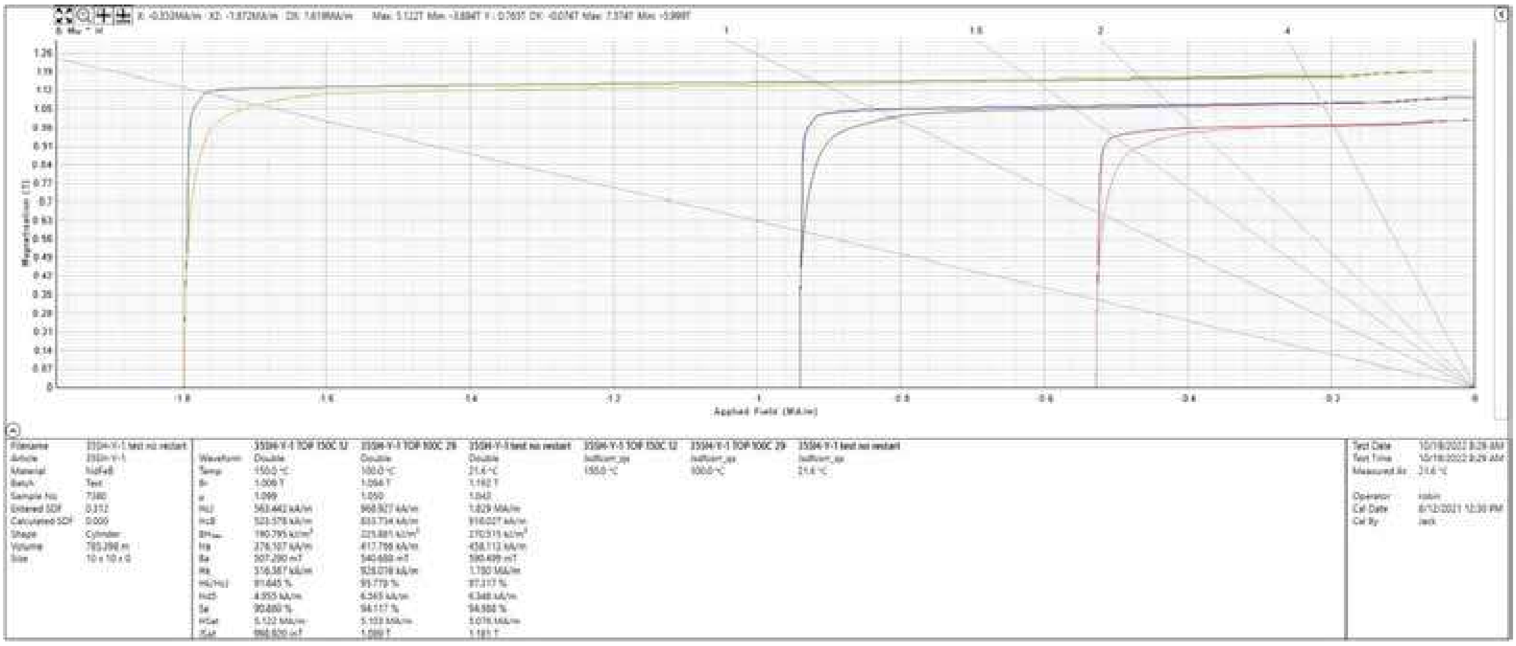
Hirst PFM vs Permeameter	Peak Error
Uncorrected Curve	20%
SDF Corrected	4%
SDFF Corrected	<1%

Thus, this unique, patented Self De-magnetisation Field Function SDFF™ accurately generates an open to closed circuit mapping (O2C™) for the magnet sample, finally delivering the accurate closed loop magnet parameters magnet users need.

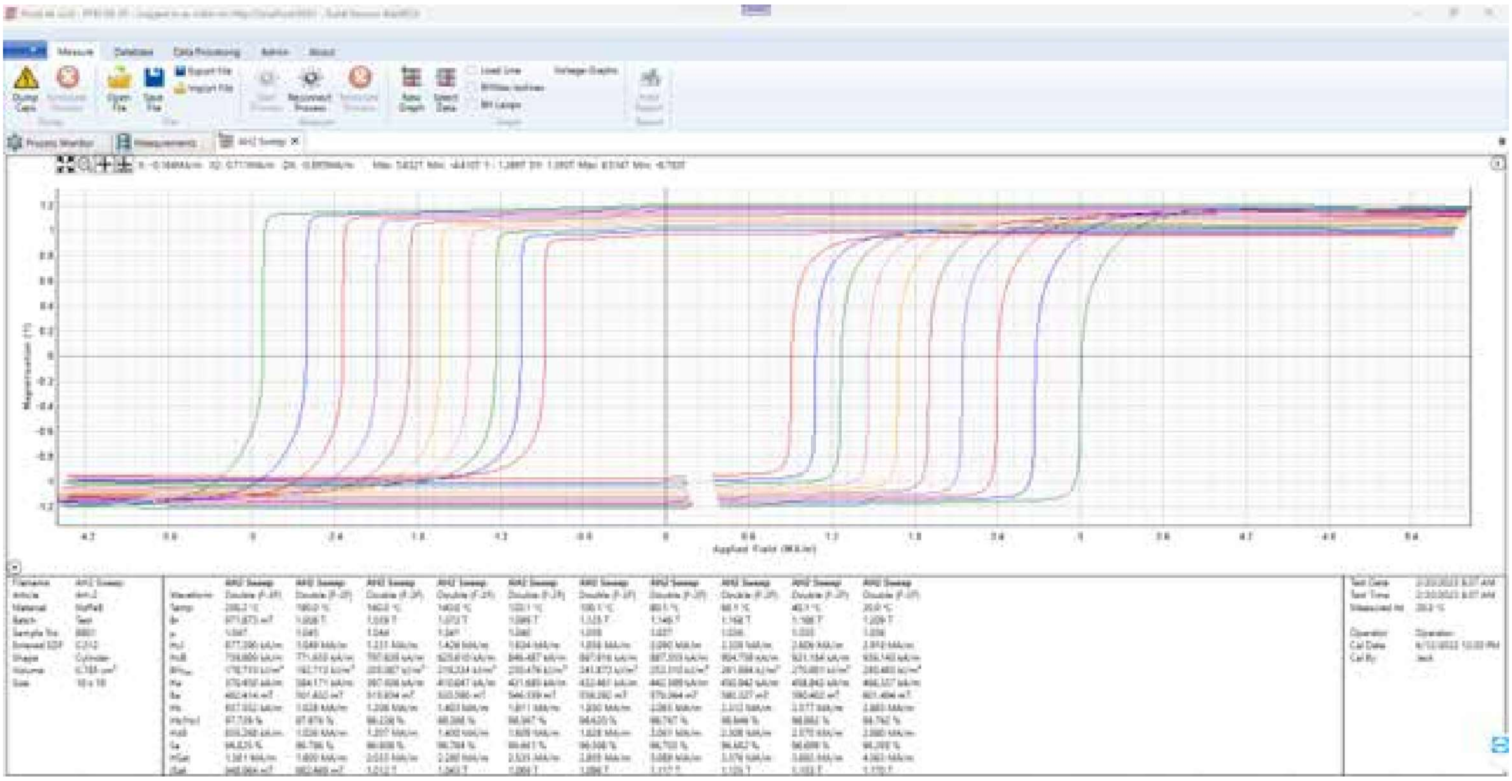
HirstLab software

The latest HirstLab v2 software integrated in the PFM08 range combines all of Hirst's 25-year expertise in PFM technology into a single, easy-to-use package. The software manages the operation of the machine and maintains a comprehensive database with the history of all measurements and reference samples. PFM08s can measure manually loaded virgin or pre-magnetised permanent magnets and measure their full 4 quadrant hysteresis loop in a fraction of the time of any other technique. In addition PFM08s running HirstLab v2 have an end of test sample demagnetisation option for easier sample handling.

A flexible plotting tool provides multiple views of the measured data. By default the SDF-corrected demagnetisation curves are plotted alongside the SDFFTM (permeameter equivalent curve).



Above the SDFF curves alongside the SDF curves to the showing the sharp permeameter like results the PFM08 range delivers. Only the SDF correction was available with HirstLab v1 on 7th generation machines (then PFM12 and PFM14).



HirstLab v2 can produce a detailed report describing the characteristics of the measured sample.

HirstLab v2 extracts all key magnetic parameters automatically and is controlled via a comprehensive windows-based application with extensive database facilities storing full data on every single measurement. HirstLab v2 accurately extracts critical parameters: Remanence B_r, Coercivity H_{cJ}, H_{cB}, Maximum energy product BH_{Max}, Saturation values H_{sat}, J_{sat}, Squareness Coefficients H_k, H_k/H_{cJ}, S_a, and more from every measurement and displays them separately alongside JH and BH loops.

Data can also be exported in a variety of formats. The system offers repeatability of measurements at speeds that are simply unattainable with other methods of measurement.

Hirst PFM08 Range

The **PFM08-10 AT** (Ambient Temperature) is the entry level PFM, which can rapidly test samples in the range of 5-10 mm diameter and 1-20 mm height and can accurately measure cylinders, cuboids and arbitrary shaped samples. Fast sample test time (less than 2 minutes) makes this PFM ideal for routine production testing and quality control in the magnet production supply chain.

The **PFM08-10 HT** (High Temperature) features precision sample temperature control around the temperature set point of ±0.2 °C to ensure exceptional repeatability and supports sample measurement from ambient to 220 °C for development and quality control applications. The latest version of HirstLab v2 also supports a Thin Sample Mode (TSM) for 8 mm and 10 mm discs a min of 1 mm thick used in GBD development and testing.

Both PFM08-10s can fit an optional small sample measurement kit that allows accurate sample measurement down to 1x1x1 mm.

The modular and upgradable **PFM08-40** can work with much larger magnet sample sizes, 5-40 mm diameter and 1-30 mm in height. As the sample volume is larger this model has a much more powerful 45 kJ internal magnetiser / demagnetiser capable of generating 10.5 T peak fields.

PFM08-10 AT & HT

PFM08-40 and PFM08-70

The high temperature version **PFM08-40 HT** supports precision sample measurement from ambient to 220 °C for development and quality control in both the magnet supply chain and for the magnet user. The larger sample size meets the requirements of magnets used in most IPM EV rotors, allowing accurate quality control for batch testing of production magnets. PFM measurements are non-destructive which is particularly important for larger, more expensive high-performance magnets.

The **PFM08-40 MT** is aimed at magnet materials research and development and is capable of testing magnet samples down to -50 °C to over 220 °C with the highest level of repeatably and accuracy in the PFM08 range. The 08-40 is a modular PFM with automatic sample management, TSM and has an optional small sample measurement kit that allows accurate sample measurement down to 1x1x1 mm from ambient to 180 °C.

Hirst recently announced the **PFM08-70 HT** (although a large 70 mm sample machine was originally developed in 1999[2] demand has historically been for smaller sample instruments) a machine optimised for large samples up to 70 mm diagonal typically used in larger IPM motors and high-performance axial flux motors with precise control of temperature from ambient to 230 °C as standard.

Hirst also offers a range of reference magnets to allow uniform results to be achieved across the supply chain.

Thus, with PFM08 many customers will no longer need a permeameter, a magnetiser and demagnetiser – a single PFM is all that is needed as the PFM08 range with SDFFTM gives permeameter-like measurements for even the highest grades of magnets.

Hirst will be presenting a joint paper with NIM on the SDFF technology at the UK Magnetics Society event MMA 23 https:// ukmagsoc.org/events/ mma23/

Technical

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