

This is a preview of "PD IEC TS 62607-9-1:...". [Click here to purchase the full version from the ANSI store.](#)



**BSI Standards Publication**

## **Nanomanufacturing — Key control characteristics**

---

Part 9-1: Traceable spatially resolved nano-scale stray magnetic field measurements — Magnetic force microscopy

This is a preview of "PD IEC TS 62607-9-1:...". [Click here to purchase the full version from the ANSI store.](#)

## National foreword

This Published Document is the UK implementation of IEC TS 62607-9-1:2021.

The UK participation in its preparation was entrusted to Technical Committee NTI/1, Nanotechnologies.

A list of organizations represented on this committee can be obtained on request to its committee manager.

### Contractual and legal considerations

This publication has been prepared in good faith, however no representation, warranty, assurance or undertaking (express or implied) is or will be made, and no responsibility or liability is or will be accepted by BSI in relation to the adequacy, accuracy, completeness or reasonableness of this publication. All and any such responsibility and liability is expressly disclaimed to the full extent permitted by the law.

This publication is provided as is, and is to be used at the recipient's own risk.

The recipient is advised to consider seeking professional guidance with respect to its use of this publication.

This publication is not intended to constitute a contract. Users are responsible for its correct application.

This publication is not to be regarded as a British Standard.

© The British Standards Institution 2022  
Published by BSI Standards Limited 2022

ISBN 978 0 539 14152 8

ICS 07.030; 07.120

### Compliance with a Published Document cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 30 November 2022.

### Amendments/corrigenda issued since publication

Date	Text affected
------	---------------

---

This is a preview of "PD IEC TS 62607-9-1:...". [Click here to purchase the full version from the ANSI store.](#)



Edition 1.0 2021-10

# TECHNICAL SPECIFICATION



---

**Nanomanufacturing – Key control characteristics –  
Part 9-1: Traceable spatially resolved nano-scale stray magnetic field  
measurements – Magnetic force microscopy**

INTERNATIONAL  
ELECTROTECHNICAL  
COMMISSION

---

ICS 07.120

ISBN 978-2-8322-1032-9

**Warning! Make sure that you obtained this publication from an authorized distributor.**

This is a preview of "PD IEC TS 62607-9-1:...". [Click here to purchase the full version from the ANSI store.](#)

## CONTENTS

FOREWORD.....	5
INTRODUCTION.....	7
1 Scope.....	9
2 Normative references .....	9
3 Terms and definitions .....	9
3.1 General terms .....	9
3.2 General terms related to magnetic stray field characterization .....	10
3.3 Terms related to the measurement method described in this document.....	11
3.4 Key control characteristics measured according to this document .....	16
3.5 Symbols and abbreviated terms .....	17
4 General .....	18
4.1 Measurement principle, general .....	18
4.2 Application to scanning systems, discretization.....	20
4.3 Preparation of the measurement setup.....	20
4.4 Measurement principle, MFM .....	20
4.4.1 General .....	20
4.4.2 Field detection process.....	21
4.4.3 Lever correction function $F^{LCF}$ .....	21
4.4.4 Effective magnetic charge density of the tip.....	23
4.4.5 Characteristics of the MFM $F^{ICF}$ .....	23
4.4.6 Concept of calibration by deconvolution.....	24
4.4.7 Regularized deconvolution approach .....	25
4.5 MFM setup key control characteristics .....	26
4.5.1 General .....	26
4.5.2 Cantilever spring constant $C$ .....	27
4.5.3 Cantilever resonance quality factor $Q$ .....	28
4.5.4 Sensitivity of the detection and analysis electronics.....	28
4.5.5 Measurement height .....	29
4.5.6 Scan size, pixel resolution .....	29
4.5.7 Canting angle of the cantilever in the setup .....	29
4.5.8 Magnetization orientation of the tip .....	29
4.5.9 Regularized deconvolution.....	30
4.6 Ambient conditions during measurement.....	30
4.7 Reference samples .....	30
4.7.1 General .....	30
4.7.2 "Well-known" and calculable reference sample .....	30
4.7.3 Band domain patterns as self-referencing calibration samples .....	30
4.7.4 Detailed stray field calculation procedure for perpendicularly magnetized band domain reference samples .....	31
5 Measurement procedure for calibrated magnetic field measurements .....	34
5.1 Calibrated stray field measurement of a sample under test .....	34
5.2 Detailed description of the measurement and calibration procedure .....	35
5.3 Measurement protocol .....	35
5.4 Measurement reliability .....	37
5.4.1 Artefacts in MFM measurements.....	37
5.4.2 Artefacts resulting from strong stray field samples .....	37

This is a preview of "PD IEC TS 62607-9-1:....". [Click here to purchase the full version from the ANSI store.](#)

5.4.3	Artefacts when measuring samples with low coercivity.....	38
5.4.4	Distortion of the domain structure .....	38
5.4.5	Contingency strategy .....	39
5.4.6	Strategies to improve the quality of the measurements .....	39
5.5	Uncertainty evaluation .....	39
5.5.1	General .....	39
5.5.2	Reference sample.....	39
5.5.3	ICF determination .....	40
5.5.4	Calibrated field measurement .....	40
6	Data analysis / interpretation of results.....	41
6.1	Software for data analysis.....	41
7	Results to be reported .....	43
7.1	General.....	43
7.2	Product / sample identification .....	43
7.3	Test conditions .....	43
7.4	Measurement set-up specific information .....	43
7.5	Test results.....	44
8	Validity assessment.....	44
8.1	General aspects.....	44
8.2	Requirements .....	45
8.3	Example.....	45
8.3.1	Determination of the Instrument Calibration Function $F^{ICF}$ .....	45
8.3.2	Calibrated measurement.....	47
Annex A (informative)	Algorithm.....	49
A.1	Mathematical basics .....	49
A.1.1	Continuous Fourier transform versus discrete Fourier Transform .....	49
A.1.2	Partial (two-dimensional) Fourier space .....	49
A.1.3	Cross correlation theorem.....	49
A.2	Magnetic fields in partial Fourier space .....	50
A.2.1	Differentiation in partial Fourier space .....	50
A.2.2	Magnetic fields in partial Fourier space.....	50
A.3	Signal generation in magnetic force microscopy.....	50
A.3.1	General .....	50
A.3.2	MFM phase shift signal .....	51
A.3.3	L-curve criterion for pseudo-Wiener filter-based deconvolution process .....	52
Annex B (informative)	Uncertainty evaluation.....	54
B.1	Definition for instrument calibration.....	54
B.2	Definition for calibrated field measurement .....	54
B.3	A type uncertainty evaluation .....	55
B.4	B type uncertainty evaluation .....	55
B.4.1	General .....	55
B.4.2	Propagation of uncertainty from the real to the Fourier domain .....	55
B.4.3	Propagation of uncertainty from the Fourier to the real space domain .....	56
B.4.4	Uncertainty propagation based on the Wiener filter .....	57
B.4.5	Uncertainty evaluation for the tip calibration .....	59
B.4.6	Uncertainty evaluation for the stray field evaluation .....	60
B.5	Monte Carlo technique .....	61
Bibliography	.....	62

This is a preview of "PD IEC TS 62607-9-1:2021". [Click here to purchase the full version from the ANSI store.](#)

Figure 1 – Spatial resolution of magnetic stray field characterization techniques and their possible maximum scan area .....	8
Figure 2 – Field measurement with finite-size sensors .....	19
Figure 3 – Schematic MFM setup .....	20
Figure 4 – Lever correction function ( $F^{LCF}$ ) in Fourier space .....	22
Figure 5 – Lever correction function ( $F^{LCF}$ ) and distance losses .....	23
Figure 6 – Instrument calibration function ( $F^{ICF}$ ) in real and Fourier space. Line plots of the partial Fourier space (absolute value, left) and real space (right). .....	24
Figure 7 – Typical resonance curve of a cantilever.....	28
Figure 8 – Typical amplitude–distance plot of a cantilever with the linear transition region indicated .....	29
Figure 9 – Band domain reference sample .....	31
Figure 10 – Artefacts that occur if the tip magnetization is switched by the stray field of the sample .....	38
Figure 11 – Artefacts if the sample domain orientation is switched by a strong tip stray field .....	38
Figure 12 – Typical distortion of an MFM image: different domain widths .....	39
Figure 13 – Normalized Fourier amplitudes of the measured reference sample signal $\Delta\varphi^{ref}$ and the reference sample magnetic field .....	46
Figure 14 – Typical transfer functions in Fourier and real space for different values of the regularization parameter $\alpha$ .....	47
Figure 15 – Comparison of the reference sample signal $\Delta\varphi^{ref}$ and the SUT signal $\Delta\varphi^{SUT}$ .....	47
Figure A.1 – Plot of the 2-norm of the residual as a function of the regularization parameter .....	53
Figure A.2 – Example of an L-curve .....	53
Figure A.3 – Illustration of the curvature of the L-curve as a function of the regularization parameter .....	53
Table 1 – MFM setup key control characteristics .....	27
Table 2 – Ambient conditions key control characteristics .....	30
Table 3 – Stray field estimation key control characteristics .....	32
Table 4 – Stray field estimation protocol .....	33
Table 5 – Measurement protocol .....	36
Table 6 – Uncertainty evaluation key control characteristics .....	41
Table 7 – Software implementation of stray field calculation of band domain samples.....	42
Table 8 – Software-based realization of calibrated measurement.....	42

This is a preview of "PD IEC TS 62607-9-1:...". Click here to purchase the full version from the ANSI store.

## INTERNATIONAL ELECTROTECHNICAL COMMISSION

### NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

#### Part 9-1: Traceable spatially resolved nano-scale stray magnetic field measurements – Magnetic force microscopy

#### FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

IEC TS 62607-9-1 has been prepared by IEC technical committee 113: Nanotechnology for electrotechnical products and systems. It is a Technical Specification.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
113/584/DTS	113/606/RVDTS

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

The language used for the development of this Technical Specification is English.

This is a preview of "PD IEC TS 62607-9-1:...". [Click here to purchase the full version from the ANSI store.](#)

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at [www.iec.ch/members\\_experts/refdocs](http://www.iec.ch/members_experts/refdocs). The main document types developed by IEC are described in greater detail at [www.iec.ch/standardsdev/publications](http://www.iec.ch/standardsdev/publications).

A list of all parts of the IEC TS 62607 series, published under the general title *Nanomanufacturing – Key control characteristics*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under [webstore.iec.ch](http://webstore.iec.ch) in the data related to the specific document. At this date, the document will be

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

**IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.**



This is a preview of "PD IEC TS 62607-9-1:...". [Click here to purchase the full version from the ANSI store.](#)

## INTRODUCTION

Measurements of magnetic fields that are homogeneous over macroscopic volumes can be made traceable to the SI standards, and traceable calibration chains from the national metrology institutes to the end users are well-established.

However, many important industrial applications such as magneto-resistive position, angle, or motion control rely on precision sensing of spatially varying magnetic fields. Such spatially varying magnetic fields can, for example, be generated by a magnetic bit pattern of a magnetic encoder scale. Today, magnetic encoder bit patterns have typically a lateral periodicity above 100  $\mu\text{m}$ . Based on stray field interpolation, such encoders are applied, for example, for precision positioning systems with sub-micrometre resolution. However, such precision positioning requires reliable local field measurements which are not yet underpinned by any suitable standards.

Today, local magnetic stray field measurements with resolutions from above 50  $\mu\text{m}$  down to below 500 nm can be realized by scanning magnetic field detection (SMF) methods with different field sensors such as Hall sensors, magneto-resistive (MR) sensors and magnetically coated tips on an oscillating cantilever (magnetic force microscopy (MFM)), or with imaging techniques like Kerr and magneto-optical indicator film (MOIF) microscopy. Achievable spatial resolution and typical scanning area are compared in Figure 1.

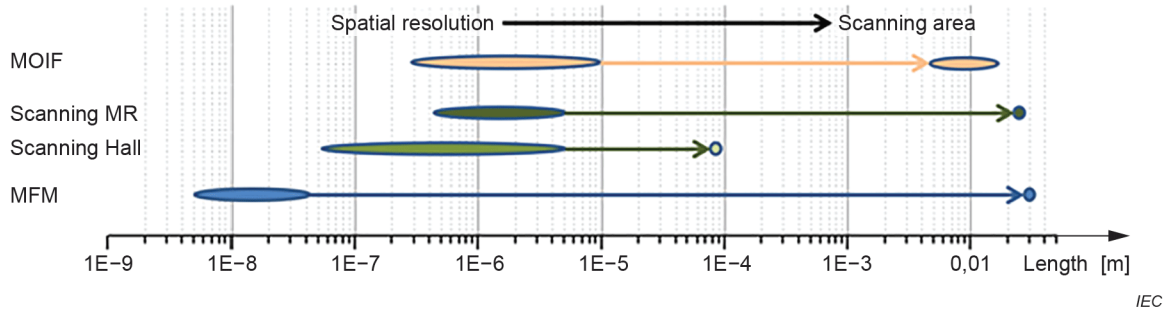
MFM provides a significantly higher resolution than other SMF techniques and MOIF (see Figure 1) and can therefore be considered as the standard tool for nano-scale investigations of the local magnetic properties of magnetic nanostructures, thin films and devices [1]<sup>1</sup>. However, despite its wide use, MFM measurements per se only deliver purely qualitative stray field images that cannot be applied for quantitative data analysis. This results from the fact that the measured signal strongly depends on the properties of the magnetic tip, the mechanical properties of the cantilever and the sensitivity of the detection device. Hence a calibration that includes the characterization of the magnetic tip and the microscope is needed if the MFM method is to be used to provide values of key control characteristics (KCCs) which are ultimately traceable to national calibration standards.

This document aims to provide industry end users, instrument manufactures and calibration laboratories with a description of traceable calibration procedures based on reference materials with well-defined local stray field distributions. This document includes the description of suitable reference samples, the evaluation of MFM key parameters required for the method, and the determination of the instrument calibration function (ICF). Due to the finite dimension of the tip, a spatial broadening of the MFM signal is unavoidable. Mathematically this broadening can be described by the convolution of the ICF and the real magnetic field structure of the sample to be measured. Vice versa, a quantitative analysis of the measured data is achieved by a deconvolution of the MFM measurement data using the ICF. The description of this process is the key part of this document.

---

<sup>1</sup> Numbers in square brackets refer to the Bibliography.

This is a preview of "PD IEC TS 62607-9-1:...". Click here to purchase the full version from the ANSI store.



**Figure 1 – Spatial resolution of magnetic stray field characterization techniques and their possible maximum scan area**

The MFM technique as described in this document has a resolution down to about 10 nm to 20 nm (depending on the signal-to-noise ratio of the instrument), which is at least one order of magnitude superior to other common characterization techniques for spatially varying magnetic fields. MFM systems operated at ambient conditions typically can achieve a resolution of around 50 nm [1]. With optimized tips, a resolution down to below 20 nm is possible [2]. The highest resolution in MFM is achieved in vacuum. With very precise tip-sample distance control [3] and high-resolution tips [4], a resolution down to 10 nm could be demonstrated.

While the MFM technique has the best precision and accuracy of the test methods (see Figure 1), as a scanning technique it is comparatively slow, requires specific ambient conditions such as stable temperatures and can only be used for samples which are flat and smooth on a micrometre scale (depending on the scanning unit). For routine statistical process control (SPC) of the manufacturing process, it may not be suitable in many use cases. Therefore, it is anticipated that the MFM technique needs to be complemented, for example, by:

- the magneto-optical indicator film technique (MOIF), which, as an imaging process, allows high throughput;
- scanning Hall or MR test methods, which can easily be calibrated in homogeneous external fields. In CMOS technique, arrays of parallel Hall sensors can be prepared and thus a high throughput can be achieved in a scanning process.

Wherever possible, existing relevant scanning probe microscopy (SPM) standards are referred to, especially those developed by ISO/TC 201 like ISO 18115-2 [5] and ISO 11952 [6].

In summary, this document provides a traceable method for nanometre-resolution measurements of magnetic field patterns, which is the basis for precise control of fabrication processes and final product qualification. The key control characteristics for those products are very product specific (see, for example, IEC TS 62622:2012 [7]).

This is a preview of "PD IEC TS 62607-9-1:...". Click here to purchase the full version from the ANSI store.

## **NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –**

### **Part 9-1: Traceable spatially resolved nano-scale stray magnetic field measurements – Magnetic force microscopy**

#### **1 Scope**

This part of IEC 62607 establishes a standardized method to characterize spatially varying magnetic fields with a spatial resolution down to 10 nm for flat magnetic specimens by magnetic force microscopy (MFM). MFM primarily detects the stray field component perpendicular to the sample surface. The resolution is achieved by the calibration of the MFM tip using magnetically nanostructured reference materials.

The objective of this document is to define and describe:

- reference materials for traceable high resolution magnetic stray field measurements;
- the calibration procedures to determine the instrument calibration function (ICF) and, if required, MFM key parameters entering the deconvolution process;
- the deconvolution process which allows to calculate quantitative stray field data from the measured MFM data using the ICF;
- the evaluation of the measurement uncertainty, including the prevention of potential artefacts which can occur during the measurement leading to a misinterpretation of the results.

#### **2 Normative references**

There are no normative references in this document.

#### **3 Terms and definitions**

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

##### **3.1 General terms**

###### **3.1.1**

###### **key control characteristic**

###### **KCC**

key performance indicator

measurement process characteristic which can affect compliance with regulations and quality, reliability or subsequent application of the measurement result

Note 1 to entry: The measurement of a key control characteristic is described in a standardized measurement procedure with known accuracy and precision.

Note 2 to entry: It is possible to define more than one measurement method for a key control characteristic, if the correlation of the results is well-defined and known.