

## **Title: Quantum-enabled nanoscale magnetic field metrology for traceable standards**

### **Abstract**

Europe is a global leader in solid-state quantum spintronics and quantum optics, but strengthening the competitiveness in quantum metrology and technology requires establishing quantum standards for nanoscale magnetic field measurements at European National Metrology Institutes (NMIs). Proposals addressing this topic should address this need by developing metrological tools for quantum-enabled spatially resolved nanoscale magnetic field metrology, establishing Nitrogen vacancy centres (NVc) techniques as quantum standards, establishing traceability chains, and carrying out round-robin comparisons to confirm the feasibility of reference materials as transfer standards.

### **Keywords**

Nitrogen vacancy centres (NVc), nanomagnetometry, scanning probe microscopy, metrology chain, quantum standard, nanoscale resolution, vacuum magnetic force microscope, ambient magnetic force microscope, traceable nanomagnetism standard

### **Background to the Metrological Challenges**

Reliable and traceable measurement techniques for nanoscale magnetic fields are urgently needed across various fields and areas, such as magnetic based logic and data storage (e.g. magneto-resistive random access memory, MRAM), magnetic positioning using magneto-resistive (XMR) sensors and scales, on-chip current and stray field sensing, quantum computing, semiconductors, and clean energy technologies (spintronics, spin waves, energy conversion, battery materials and diagnostics, etc.), aligning with EU industrial, quantum and sustainability policies. Nanoscale magnetic measurements also play a crucial role in advancing biomedical applications, supporting EU health policies. For these applications, it is essential to understand material parameters and relate them to device functionality, as well as accurately characterise devices and verify conformity. The required metrology must span magnetic fields from the sub- $\mu\text{T}$  range (e.g., antiferromagnetic spintronics) to several 100 mT (e.g., magnetic scales) while resolving dimensions down to the nanometre scale (e.g. domain walls), and GHz frequencies typical of dynamic phenomena (e.g. spin waves). However, at present, there is lack of traceability in magnetic high-resolution microscopy techniques as highlighted by the International Committee for Weights and Measures (CIPM) Consultative Committee for Electricity and Magnetism (CCEM). At the nanoscale, ensuring traceability in field measurements requires linking to a quantum standard that has yet to be established. Accordingly, the European Metrology Network (EMN) for Quantum Technologies [1] has identified the development of quantum-enabled magnetometers as essential for meeting standardisation needs in testing and measurement, covering infrastructure, measurement protocols, and device performance. However, these capabilities are still missing at European NMIs and, as such, must be established and validated.

The current state-of-the-art for calibration techniques, reference samples, and the publication of the first International Electrotechnical Commission (IEC) draft technical specification for traceable spatially resolved classical magnetic field measurements were achieved through the EMPIR projects 15SIB06 NanoMag and 20SIP04 qMOIF. These efforts represent the first steps toward standardised quantitative nanoscale magnetic field imaging. However, a comprehensive quantum-based traceability chain for spatially resolved magnetic field measurements, comprising calibration services, validated reference materials, and guidelines, remains to be established. Classical room-temperature magnetic field measurements with high spatial resolution face

several limitations: poor field sensitivity (in the mT range), a minimum spatial resolution of ~25 nm, and calibration errors primarily due to reference sample uncertainties and intrinsic measurement noise. Furthermore, magnetic force microscopy is invasive and prone to disturbing the sample under measurement. These challenges can be effectively addressed by transitioning to NVc-based quantum high-resolution measurement techniques.

An NVc is a nitrogen substitutional atom, near a vacancy, in a host material such as diamond, and it is a quantum system with unique properties. Widefield magnetometers utilising arrays, rather than single NVcs, offer exceptional magnetic sensitivity and vector field reconstruction with unparalleled spatio-temporal resolution. European companies have developed the first commercial scanning NVc systems for quantum-enabled nanoscale magnetic field measurements, creating an urgent need for metrological validation and international standardisation. However, traceably calibrated NVc magnetometry is not yet available at European NMIs, and no metrology standards exist for such high-resolution magnetometry. Some aspects of NVc characterisation have been addressed by EMPIR project 20IND05 QADET and Metrology Partnership project 23NRM04 NoQTeS. However, highly spatially resolved measurements using NVc's require precise localisation of the centre within the diamond host material on a nanometre scale, to allow reliable standardised techniques for traceability. Additionally, NVc-based measurements are not always suitable for industrial samples and can only detect fields up to some mT. Also, only few nitrogen vacancy setups are available in Europe. Therefore, these measurements must be complemented with robust classical techniques (e.g. magnetic force microscopy - MFM) that are widely available and can be linked to the quantum standard via reference samples as transfer standards. This will allow to establish traceable nanoscale field measurements with high accessibility and across the range, from below 1  $\mu$ T to above several hundred mT.

## Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The proposal shall focus on the traceable measurement and characterisation of quantum-enabled nanoscale magnetic field systems.

The specific objectives are

1. To design and implement novel methods and algorithms for reliable quantum-enabled nanoscale magnetic field imaging and measurement. Additionally, to combine NVc scanning techniques with i) widefield NVc microscopy and ii) vacuum/ambient MFM techniques, to achieve a sensitivity better than 1  $\mu$ T in a measurement range up to 100 mT, spatial resolution < 10 nm, and functionality across a wide frequency range from DC to GHz.
2. To develop robust calibration methods for NVc magnetometry, ensuring nanometre-scale precision in NVc localisation within the diamond host material, including corrections for temperature-dependent effects. To create quantitative models, supported by micromagnetic simulations, for vector field and magnetisation calculations with comprehensive uncertainty budget analysis. To derive secondary parameters, relevant for stakeholders, traced back to primary quantum standards. These advancements should establish NVc techniques as quantum standards.
3. To establish traceability frameworks linking single NVc-based methods with i) ambient and vacuum MFM systems and ii) widefield NVc based approaches. To develop and validate reference materials (e.g. magnetic multilayers, skyrmion-hosting materials, nanofabricated current-carrying coils, magnetic arrays, and active devices) for cross-platform compatibility as transfer standards and validate their performance through by micromagnetic simulations. Additionally, to provide case studies of MFM systems calibrated using NVc techniques.
4. To validate the methodologies from objectives 1 and 2 by carrying out round-robin comparisons and proof-of-concept case studies. This should include the development of guidelines for traceable measurements with 1  $\mu$ T sensitivity, spatial resolution < 10 nm, and wide frequency applicability, from DC to GHz. To collaborate with stakeholders to demonstrate the application of these methods to novel materials (e.g. 2D materials, multiferroics, synthetic antiferromagnetic structures) and industrial samples (e.g., MRAM, magnetic nanoparticles for drug delivery and XMR sensors based on giant magnetoresistance Wheatstone bridges), ensuring practical relevance and industry adoption.

5. To demonstrate the establishment of an integrated European metrology infrastructure and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (calibration laboratories), standards developing organisations (IEC, CCEM) and end users (manufacturers).

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. To enhance the impact of the research work, the involvement of the larger community of metrology R&D resources both within and outside Europe, plus engagement with existing European research infrastructures and European Partnerships is recommended. A strong industry involvement is expected in order to align the project with their needs and guarantee an efficient knowledge transfer into industry and end users. Where relevant, proposals are encouraged to build on, or seek collaboration with, existing projects and develop synergies with other relevant European, national or regional initiatives and funding programmes. In particular, links are encouraged with (i) the projects funded under earlier relevant topics of the Horizon Europe programme; or (ii) other relevant European Partnerships.

Proposers should establish the current state of the art and explain how their proposed project goes beyond this. In particular, proposers should outline the achievements of the EMPIR projects 15SIB06 NanoMag, 20SIP04 qMOIF and 20IND05 QADET, and Metrology Partnership project 23NRM04 NoQTes and how their proposal will build on those.

Proposers should note that the programme funds the activity of researchers to develop the capability, not the required infrastructure and capital equipment, which must be provided from other sources.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 2.1 M€ and has defined an upper limit of 2.6 M€ for this proposal.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 25 % of the total EU Contribution across all selected projects in this TP.

Any industrial beneficiaries that will receive significant benefit from the results of the proposed project are expected to be beneficiaries without receiving funding or associated partners.

## Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the 'end user' community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the "end user" community (e.g. letters of support) is also encouraged.

You should detail how your proposal's results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Facilitate improved industrial capability, or improved quality of life for European citizens in terms of personal health, protection of the environment and the climate, or energy security,
- Transfer knowledge to the quantum and biomedical technologies sectors.

You should detail other impacts of your proposed JRP as specified in the document "Guide 4: Writing Joint Research Projects (JRPs)"

You should also detail how your approach to realising the objectives will further the aim of the Metrology Partnership to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

## Timescale

The project should be of up to 3 years duration.

## **Additional information**

The link provided in this section is only correct at the time of publication up until the end of the Call year.

The reference below was provided by PRT submitters; proposers should therefore establish the relevance of any references.

- [1] EMN Quantum Technologies Orientation Paper 2025 All Calls  
<https://www.metpart.eu/applicants-2025/integrated-metrology-call-2025-s1.html>