

## Title: Advancing European quantum-based pascal infrastructure: Innovation and integration in pressure metrology

### Abstract

The development and consolidation of quantum-based pressure measurement systems will support Europe in its leadership in quantum measurement science, driving progress in quantum-based instrumentation and innovation across a wide range of industries. While significant progress has been made to establish a metrological infrastructure for a traceable quantum-based pascal, its integration in quantum-based instruments with existing pressure standards requires novel methods and the simplification of systems for wider adoption. Proposals addressing this topic should improve the measurement performance, paving the way for Calibration and Measurement Capabilities (CMCs) for absolute and differential pressure, extend capabilities to gauge-mode measurements, develop cost-effective systems, and validate performance through comparisons and calibrations.

### Keywords

Pascal, pressure, density, quantum, refractivity, infrastructure, sensors, differential pressure, Fabry-Pérot refractometry

### Background to the Metrological Challenges

Currently, several different methods are required to realise the pascal in the 1 Pa to 1 MPa range, which have different relative uncertainties in the range from  $10^{-4}$  to  $10^{-6}$ . To realise the pascal, either a liquid of known density (typically mercury) in a manometer or, alternatively, weights of known mass on a piston in a pressure balance are utilised. With the planned decommissioning of mercury, following World Health Organization recommendations, the only remaining conventional means of realising the pascal with high accuracy will be pressure balances. These devices are however affected by various degrees of bulkiness, fragility, and complexity of operation, and, critically, they are also restricted in their use below 10 kPa. As such, for pressures below 10 kPa, National Metrology Institutes (NMIs) typically rely on Force-balance Piston Gauges (FPGs), which are no longer being produced or supported. The International Committee for Weights and Measures (CIPM) Consultative Committee for Mass and Related Quantities (CCM) and the EURAMET Technical Committee for Mass and Related Quantities (EURAMET TC-M) have repeatedly identified a need to address this.

Significant progress has been made in Europe in recent years through several EURAMET initiatives. Following exploratory investigations within the EMPIR project 14IND06, which demonstrated that optical, quantum-based techniques have the potential to measure and realise pressure, the EMPIR project 18SIB04 QuantumPascal showed that quantum-based methods, such as Fabry-Pérot based refractometry, Rayleigh scattering and polarising gas thermometry methods have great potential to replace the best conventional methods for pressure assessment. This is especially true in the low-pressure range where there is a strong metrological need at NMI level for improved standards. This was followed by the ongoing Metrology Partnership project 22IEM04 MQB-Pascal, which involves all leading actors in this field in Europe, where the overall objective is to establish a metrological infrastructure for a traceable quantum-based pascal.

The development of quantum-based means to assess and realise pressure has so far mainly been applied to absolute measurements. The highest accuracy of any pressure realisation by a quantum-based method was

achieved by 22IEM04 MQB-Pascal in 2024, where a Fabry-Pérot based refractometer demonstrated an expanded uncertainty better than the accuracy demonstrated by NIST in 2016. This motivates and justifies continued efforts to further develop the established infrastructure to allow for future CMC-entries. It also shows that these quantum-based systems are among the few quantum sensors that have the technological readiness to be used for real-world end-user applications.

Just as with absolute pressure assessments, there is a strong need for improvement and innovation in differential and gauge pressure measurements. These are widely used in industry, leading to nearly twice as many BIPM CMC entries for gauge and differential pressures compared to absolute pressures. In the 22IEM04 MQB-Pascal project it was found that quantum-based technology is promising for differential pressure measurements, including gauge mode measurements, but more work is needed to develop the quantum-based technique for such assessments. In addition, there is a clear stakeholder interest in exploring the systems' temporal resolution, ability to operate in extended temperature ranges, and its applications in leak measurement and calibration.

Although these technologies have shown great promise and preliminary results, they are still often complex and expensive to be deployed for applications outside the most advanced pressure laboratories. Therefore, for stakeholders, including NMIs, accredited calibration laboratories, and industry to take full advantage of the technologies, there is also a strong need to develop simplified and less complex systems, and provide access to open-source drawings, source code for various methodologies and other relevant resources.

## 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-based pressure measurement systems.

The specific objectives are

1. To improve the measurement performance of the European infrastructure of quantum-based pascal prototypes in the 1 Pa to 300 kPa range for absolute pressure, and  $\pm 15$  kPa for differential pressure, both with an uncertainty of 2 mPa + 10 ppm ( $k=2$ ). This should include the development of novel methods for reducing the calibration time, seamless operation across an extended working range, robust and automated functionality, and integration with existing conventional pressure standards.
2. To develop novel systems for gauge mode measurements in the -95 kPa to 1 MPa range with a target uncertainty of 10 mPa + 30 ppm ( $k=2$ ). Additionally, to verify the temporal resolution of quantum-based systems, their ability to operate in various temperature ranges, and use in leak measurement and calibration.
3. To develop simplified, small and cost-effective quantum-based systems for operating in the 1 Pa to 300 kPa range. This should include the development and testing of compact optical packages, integrated sensors, self-calibrating solutions and miniaturised components. The novel systems should be suitable to operate as traceable secondary standards for NMIs, calibration laboratories and industry.
4. To validate and verify the performance of quantum-based systems as a viable alternative to FPGs in the 1 Pa to 10 kPa range. This should include proof-of-concept calibrations, with reference metrics on accuracy, resolution and calibration time, for various commercial sensors, both in absolute and differential modes, within the ranges specified in objectives 1 and 2.
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 (ISO), technical committees (CCM, EURAMET TC-M) and end users (instrument 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 14IND06 Pres2Vac and 18SIB04 QuantumPascal, and Metrology Partnership project 22IEM04 MQB-Pascal 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 pressure technologies sector.

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.