European Metrology Network on Quantum Technologies: Strategic Research Agenda

Content

Success by improved reliability in Quantum Technologies

The 2030 strategy of the European Metrology Network for Quantum Technology

Executive Summary

By 2030 quantum technologies will be ubiquitous, but we are not there yet. Today, quantum technologies are being steadily deployed into mainstream marketplaces, with both large and start-up companies beginning to develop and integrate quantum devices into their product lines. Enhancing confidence in these technologies is essential to their success. This in turn relies on validation and certification, based on internationally agreed standards and metrological traceability, implemented by independent experts. EURAMET´s European Metrology Network for Quantum Technologies supports this technological transformation.

Our Vision

To support competitiveness of the emerging European quantum industry, EMN-Q develops a European Quantum Metrology Infrastructure by coordinating, pooling, and strengthening the National Quantum Metrology Infrastructures.

Our Mission

To support competitiveness and innovation of the emerging European Quantum Industry by metrology science, services, and knowledge transfer.

Our Success

We bring clear direction in our strategy by defining four areas where we want to succeed. These represent for us the biggest opportunities for engagement and differentiation by

- providing the European Quantum Industry access to an enlarged portfolio of coordinated services through the Quantum Metrology Infrastructure,
- representing European interests in standardization and regulation for quantum technologies,
- developing and transferring quantum measurement knowledge to the European Quantum Industry through research and innovation actions, and
- coordinated research to improve measurement capabilities of the European Quantum Metrology Infrastructure to meet the emerging industry need.

Implementation

We implement our strategy through coordination of national and European actions that will enable European industry to succeed through improved reliability and interoperability of Quantum Technologies:

Joint research on Quantum Metrology: realization of units, calibration and measurement capabilities, quantum technology, standardisation, and scientific excellence. Research on Quantum metrology has been supported by the European Metrology Research Programmes and now in the European Partnership on Metrology.

Coordination of national Quantum metrology infrastructures: leveraging resources of European NMIs and DIs, maintaining top-level national standards and fit-for-purpose services. EMN-Q coordinates the development of new measurement capabilities and dedicated services to meet the rapidly growing needs of the European Quantum Industry.

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QUANTUM TECHNOLOGIES

1. Introduction

EURAMET, the Regional Metrology Organisation of Europe, has 37 member countries. It leads the cooperation of **National Metrology Institutes (NMIs)** with nearly 6000 metrologists, in the development of the European metrology infrastructure and services. It represents Europe in the international metrology forum of the CGPM (General Conference of Weights and Measures).

Many of the challenges Europe faces today are the global challenges of health, climate change, environment, energy, and sustainability. Such challenges require global solutions supported by reliable measurement; requirements which often exceed the capacity and capability of individual nations and their NMIs and **Delegated Institutes** (**DIs**). Thus, pooling of metrological resources across national boundaries is essential to tackle key societal challenges.

In addition to this, the pace of development of quantum technologies is accelerating at an unprecedented rate, offering huge opportunities and challenges for generating new industrial products and services. Average product life cycles in many sectors have decreased markedly, and complexities of products and services have increased. Inevitably, the demand for metrology and metrological services is growing in tandem and is entering a new era. Innovation and investment in metrological capability and dissemination are essential to match this trend. With the constraint on national resources in recent years, NMIs in Europe must cooperate to achieve this. EURAMET provides an excellent framework and a vehicle for such cooperation. Through the establishment of dedicated metrology research programmes, such as the current Metrology Partnership [12], and the former EMPIR [13], EURAMET has gained a leading position amongst the Regional Metrology Organisations of the world in cooperative research.

To strengthen European metrology cooperation on quantum, EURAMET decided to establish a new sustainable body called **European Metrology Network for Quantum Technologies** (**EMN-Q**). The EMN-Q will analyse European and global metrology needs and address these in a coordinated manner. EMN-Q members will then formulate common metrology strategies including aspects such as research, infrastructure, knowledge transfer and services.

By providing a single point of contact for information, underpinning regulation and standardisation, promoting best practice and establishing a comprehensive, longer-term infrastructure, the EMNs aim to create and disseminate knowledge, gain international leadership and recognition, and build collaboration across the measurement science community.

1.1 Context and current and future trends in quantum technologies

“Developing Europe’s capabilities in Quantum Technologies will help create a lucrative knowledge-based industry, leading to long-term economic, scientific and societal benefits.” ([1], page 1).

Quantum technologies (QT) are a rapidly growing field and offer huge opportunities in many applications. However, moving them from laboratory or specialist environments to industrial and commercial products and services is a significant challenge. At both national and international levels significant efforts are made to promote and ensure the transition of these technologies from R&D laboratories to the market. One such example is the establishment of the European Union's 1 billion euro "Quantum-Flagship" programme [2], which was triggered by the "Quantum Manifesto" [3] and related European and national programmes and projects, such as the German "QUTEGA" [4] initiative, the UK National Quantum Technologies Programme [5], the Netherlands QUTech programme, The French Quantum Plan, the European H2020 "Quant ERA" [6] and the expected follow-on programmes.

Furthermore, QT and devices have already started to have an impact on industry, and several large companies and SMEs have started to develop quantum devices and/or to integrate them in their products [7-10]. However, there is a huge barrier in persuading end users to implement these technologies. This will involve considerable investment. Demonstrating the advantage of quantum solutions is a prerequisite. Standardisation, as a solid frame of reference, and certification are the key elements for the commercial success of any new technology; especially at the beginning of its development. Globally accepted standards are needed to facilitate the growth and the development of quantum technologies. In order to carry out the pre-standardisation research required for establishing such standards, as well as to certify the compliance of commercial QT devices to such standards, it is necessary to develop the corresponding metrological infrastructure.

1.1.1 Quantum technologies, metrology and grand challenges

The need for coordination by European NMIs and DIs can be found in the Intermediate Report of the Quantum Flagship [1]. It states that: "Key to the initiative's added value is its pan-European dimension. This would allow an optimal integration of the diverse expertise of academic and industry partners across Europe,…, integrate national and European metrological and standardisation institutes in developing quantum based standards, and, …, align existing Member States' strategies and activities ensuring that funding is spent in the most efficient way at all levels, regional, national and international" (page 2); "The Flagship should work closely with existing standardisation institutes (such as the metrology institutes organised in EURAMET) and the European committees for standardisation (e.g. CEN-CENELEC and ETSI) to drive standardisation of quantum technologies." (page 24). Furthermore, the Quantum Technologies Flagship Final Report states that: "The national metrology institutes, organised in EURAMET, already have strong expertise in QT and should be encouraged to put a focus on next generation QT in sensing and metrology" [11].

The active coordination of the research activities of European NMIs and DIs is fundamental to maintain European competitiveness in QT. International leadership for future decades, particularly in the climate where new large players are appearing on the international scene with seemingly limitless economic resources, will be especially important. To maximise the impact of QT metrology research, a strategic plan and significant coordination both at European and global levels is required. NMIs should decide how and where they should focus their limited resources, as no single NMI has the expertise and the resources to tackle even a significant fraction of the most critical priorities without collaboration. Without coordination, there is a strong possibility of unnecessary duplication, with NMIs (nationally and/or regionally) likely to independently choose to focus efforts on the same challenges; consequently neglecting others.

This requires:

- alignment with industrial requirements, those of the EC Quantum Technologies Flagship, national and inter-governmental QT programmes, as well as those of any relevant stakeholder, to guarantee metrological requirements are addressed and ensure the transition of QT research results into QT applications and industries;
- contribution to QT development through NMIs and DIs research and innovation activities. Increase of the expertise on next generation QT, to ensure effective answers to the needs emerging from the QT community;
- input into the standardisation and certification of QT, as the development of globally accepted standards and an anticipatory approach will facilitate the worldwide growth of the QT market and is essential for ensuring the quality of products and European and worldwide acceptance of European products;
- promotion of the benefits of metrology to the stakeholder community in the development of these technologies.

Recognising this need, EURAMET formally established the European Metrology Network for Quantum Technologies (EMN-Q) on 1 July 2019, incorporating the three distinct metrological communities/fields of quantum photonics, quantum electronics, and quantum clocks and atomic sensors, to ensure an effective response is put in place.

Metrology in member states of EURAMET is at different stages of development. The different national requirements also vary widely. This offers real opportunity for synergistic cooperation, but also gives rise to significant challenges. Building metrology capability of individual members has to be balanced between local, national and European requirements. Our overall aim is to raise the level of European metrology to be internationally competitive.

1.2 Purpose of this document

Together with the EMN-Q web platform, EMN-Q events and workshops this Strategic Research Agenda represents, in the intention of the EMN-Q members, one of the main communication channels to QT stakeholders from academia, industry, and standardisation bodies.

The Strategic Research Agenda once developed will be periodically updated by the EMN-Q, with the support of the QT community, to ensure that QT metrology needs, even if evolving, are taken into account and national metrology activities are coordinated, prioritised and focussed. The roadmaps will ensure that NMIs can align their research programmes in anticipation of future needs so that European QTs will be supported far into the future. In turn, QT stakeholders will acquire confidence that their metrological needs will be addressed by a long-term and coherent approach; improving on the present situation where short-term projects are based on ad-hoc needs. NMIs' awareness and involvement early on in device development will provide assurances to the user community and help the QT market to grow.

[1] Quantum Technologies Flagship (Intermediate Report); High-Level Steering Committee (16 FEB 2017), available online at: https://ec.europa.eu/digital-single-market/en/news/intermediate-report-quantum-flagship-high-level-expert-group

[2] https://ec.europa.eu/digital-single-market/en/news/european-commission-will-launch-eu1-billion-quantum-technologies-flagship

[3] https://ec.europa.eu/futurium/en/content/quantum-manifesto-quantum-technologies

[4] http://www.qutega.de/en/home/

[5] https://uknqt.ukri.org (accessed 23.08.2022)

[6] https://www.quantera.eu/

[7] https://en.wikipedia.org/wiki/List_of_companies_involved_in_quantum_computing_or_communication

[8] https://www.persistencemarketresearch.com/market-research/quantum-sensors-market.asp

[9] http://www.iqst.org/newsevents/article/news/detail/News/quantum-incubator-seminar-quantum-technologies-and-their-importance-for-bosch-163.html

[10] https://www.marketresearchfuture.com/reports/quantum-sensors-market-5273

[11] Quantum Technologies Flagship Final Report; High-Level Steering Committee (28 JUN 2017), page 22; available online at: https://ec.europa.eu/digital-single-market/en/news/quantum-flagship-high-level-expert-group-publishes-final-report

[12] European Partnership on Metrology https://www.euramet.org/research-innovation/metrology-partnership/?L=0

[13] European Metrology Programme for Innovation and Research (EMPIR) https://www.euramet.org/research-innovation/research-empir/

2. Recommendations

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3. Quantum electronics

3.1 Strategic Research Agenda

3.1.1 Subfield: Quantum Metrology & Sensing

Preamble

The following text encompasses expected future developments, considering needs from stakeholders in science and technology, industry, economy and society, regarding electrical quantum-based metrology. Stakeholders rely on the development of relevant electrical measurement methods and services for new systems and products emerging in quantum technologies, including for test and validation purposes.

The structure of the text refers to the categories on the colour coded vertical axes of the corresponding roadmap in section 3.2 of this document. This shows the information from top-down in the reverse order of the supply chains. It starts with the Triggers & Needs as the top-level category, followed by Targets, Metrological Application, Experimental Realisation, ending with the foundations given by Enabling Science & Technology. Bullet points in the following text refer to the topical key terms shown in the boxes in the map. Items listed under the bulleted points refer to specific examples.

1. Triggers & Needs

Triggers and needs from various stakeholders in the fields of quantum technology (QT) are the top-level drivers for the strategic efforts in the fields of quantum metrology and sensing within the EMN-Q.

- **1.1 Science & technology** needs quantum-based metrology for measurements and calibration to underpin characterisation or research results quantitatively with utmost accuracy and precision. This requires traceability within the revised SI at the highest accuracy level, based on fundamental metrology using universal standards. This harnesses quantum effects that are independent of time and space and related to constants of nature. In terms of accuracy, quantum metrology standards and methods often surpass 'classical' (non-quantum) ones by orders of magnitude. For example, quantum resistance and voltage metrology reach relative uncertainties of the order of a part in a billion and better. National metrology institutes have been working in these fields for several decades. Also, scientific fundamental metrology, including consistency and universality tests, is needed to verify the understanding of quantum electrical effects as the foundations of quantum electrical metrology and to validate theoretical predictions that are foundational for QT development. Metrological expertise is also required to fully utilise the potential of novel QT methods based on, for example, quantum entanglement and squeezed states.
- **1.2 Society** bears demands in various fields, among them environmental analysis, consumer protection, and health services and care. These require measurement systems and services together with harmonisation for trade and standardisation to provide quality control as well as risk assessment.
  Both advanced information and communication technologies as well as medical diagnosis and treatment will eventually lead to nano-electronic and -magnetic devices,and miniaturised and integrated electronic devices and sensors. These will also be based on structures and materials

with functional units on the single-atom / single-molecule level. Corresponding electromagnetic measurement protocols and traceability are needed.

- **1.3 Industry & economy** demand tools and methods for the development of new products, devices and apparatuses based on quantum technology. This is particularly so in the evolving fields of nanotechnology, quantum sensing, quantum information, computing and communication technologies, as well as for applications in various sectors such as medicine and ICT, through to aeronautics, energy technology and automotive. Innovation relies on reliable and accurate measurements, as well as quantum-based and classical metrology for characterisation, requiring traceable measurements and calibrations at the highest level. As emergent QT must be evaluated to demonstrate their advantage against existing technology before industry and market adoption, measurement standards and written standards are needed to provide harmonised references. Specific demands from industrial metrology, and for instrumentation manufacturers, include fit-for-purpose calibration systems offering facilitated traceability routes, improved stability and operability, and reduced efforts and costs.

2. Targets

Targets in quantum metrology and sensing address the triggers and needs. The primary targets related to industry and economy address the support of new developments and products in the field of electrical QT. Support by metrology is perceived to be fundamental for the take up of the quantum technologies market, specifically in the following fields:

- **2.1 SI unit realisation & dissemination**, mainly pursued by metrology institutes, comprising
  - Quantum-enhanced standards and calibration systems for fundamental metrology
  - Facilitated quantum-enhanced measurement and calibration systems providing fit-for-purpose, multi-functional turn-key solutions tailored to user or customer needs.
- **2.2 Advanced measurement science** exploiting the subtleties of quantum physics is a fundamental topic essential to support QT developments. Measurement of the state of a quantum system, even more so a single quantum object, as well as low-noise measurements below the standard quantum limit, are challenging and require specific and novel approaches.
- **2.3 Technology transfer & commercialisation** of QT products requires metrology tools and methods for QT from metrology core institutes to support the development and creation of relevant products and services in the value chains up to the industrial level, including their verification.
- **2.4 Standardisation** supports technology transfer, commercialisation and industrialisation of QT and related metrology tools. It is indispensable for promoting the uptake of innovations by industry (i.e. manufacturers) and society (i.e. consumers). In future markets, QT components like advanced sensors and detectors need proper quality assurance and standardisation as well as interoperability. Standardisation and related pre-normative activities aim at
  - Definition of metrics like key performance indicators (KPI) and key control characteristics (KCC)
  - Development of reference methods and protocols towards globally accepted reference frames, written standards and measurement standards
  - Evaluation and validation within this reference frames.

  At the application stage, metrology provides expertise, impartiality, and independence to support development, testing, validation, and evaluation in terms of the reference frames. Alongside manufacturing, societal fields like environmental and medical analysis also rely on standardisation as the basis of quality control and risk assessment.

- **2.5 Measurement & calibration services** for QT industry and products need to be routinely provided by metrology institutes together with (industrial) calibration laboratories; as vital parts in the traceability chains of the international metrology infrastructure. Unit dissemination in future will, at least in part, happen through industry by enforcing calibration laboratories with novel ‘intrinsically referenced’ calibration systems, offering direct SI traceability to primary quantum standards as part of the system. This will enable an approach towards the concept of zero-chain traceability which isno longer reliant on traceability provided by or through NMIs.

3. Metrological Application

Metrological applications address innovations aimed at the primary targets in two complementary and distinguished, but highly interrelated categories.

- **3.1 Support & services** refers to measurement and calibration services (including quantum-enhanced and quantum-based ones) offered by metrology institutes like NMIs to support the industrial QT sector (i.e. representing electrical quantum metrology and sensing for QT). They are based on standards, systems and platforms utilising classical and quantum electrical effects, and support developments pursued by external QT stakeholders like instrumentation and sensor manufacturers, calibration laboratories, or quantum computing developers. These services are concerned with quantum technologies as well as associated enabling technologies. Prominent examples are
  - Traceability in voltage metrology provided by quantum standards based on the concept of the Josephson Arbitrary Waveform Synthesizer (JAWS), enabling state-of-the-art dc and ac voltage metrology operating up to the low megahertz frequency range
  - Traceability in resistance metrology provided by standards based on the quantum Hall effect (QHE), enabling state-of-the-art dc resistance and impedance metrology
  - Quantum-enhanced magnetometry using tuned ground state properties of quantum gases, enabling traceability and SI unit realisation in extended magnetic field ranges
  - Waveform metrology, for example to characterise and tailor the electric driving signals of solid-state-based quantum computers
  - Novel quantum-based metrology tools and measurement methods, such as those based on single-electron quantum optics and interferometers, for emerging QT in various fields like quantum information, communication and quantum computing and sensing.
- **3.2 Systems & products** refers to innovative quantum-enhanced and quantum-based measurement tools, instruments and methods for the development and commercialisation of respective products by the QT industry and manufacturers (i.e., representing QT systems and products for electrical quantum metrology and sensing). They emerge from topical developments pursued in metrology institutes like NMIs and enter the QT markets as the result of technology transfer activities into the economic sector, including quantum computation and communication. Examples are
  - Improved, facilitated, versatile, user-friendly and cost-efficient quantum electrical standards and instrumentation and measurement bridges (low Technology Readiness Level, TRL)
  - Primary quantum electrical standards like quantum voltage and resistance standards, operated in user-friendly and economic cryo-systems, pushing towards high TRL
  - Combinations of several primary quantum electrical standards (quantum voltage and resistance standards) operated in a single cryo-(magnet-)system
  - Noise-suppressed electronic amplifiers and signal processing, such as for the readout of qubits in quantum computers

- Innovative sensors and detectors, and systems based upon those - and integrated with - related measurement instrumentation.

4. Experimental Realisation

Experimental realisations, based on innovations from metrological research and development, address concrete methods, systems, devices and instruments as a basis for enabling metrological applications. They comprise advanced applications and services in metrology for supporting QT, as well as the development of QT-related metrology products for commercialisation.

- **4.1 Quantum voltage standards & systems**, based on the concept of the Josephson arbitrary waveform synthesizer (JAWS), refer to improved and facilitated systems for user-friendly and economic applications in voltage metrology. In Europe, access to fabrication capabilities for different kinds of state-of-the-art Josephson voltage standards based on niobium array technology is provided by certain NMIs. Relevant development routes and short-term (1 to 3 years) targets are, for example:
  - Primary quantum voltage standards for dc and ac metrology up to the low MHz frequency regime at the 10-volt level, including applications in electric power metrology
  - Prototypes of JAWS-based digitally enhanced and fully digital measurement bridges for multi-purpose ac metrology
  - Quantum voltage small-signal and noise generators for primary noise measurements and resistance thermometry, and for the calibration of detectors and signal analysers
  - Quantum voltage measurement systems for metrology of non-electrical quantities like temperature (Johnson noise and resistance thermometry) or mass, for example in 'Kibble' balances for fundamental mass metrology, and for commercial instruments aiming at measuring and scaling of 'small' masses significantly below 1 kg.

  Long-term (3 to 10 years) targets are, for example:
  - Multi-purpose, cost-efficient JAWS systems based on Josephson arrays driven with optically generated pulse patterns, enabling improved performance with respect to increased signal amplitude and/or frequency.

- **4.2 Quantum resistance & impedance standards** are improved and facilitated systems based on accurate, user-friendly, portable and economic applications in quantum Hall effect (QHE) resistance and impedance metrology. Relevant developments are based on novel materials with 'Dirac cone' electronic band structures systems, such as those on graphene or on magnetically doped topological insulators, the latter showing the quantum anomalous Hall effect (QAHE). This enables utilisation of the quantum Hall effect for advanced quantum resistance standards which can be operated under relaxed operational conditions compared to 'conventional' semiconducting devices, i.e., at lower or – in case of the QAHE – even at zero magnetic fields, or/and at higher temperatures. In Europe, access to state-of-the-art fabrication capabilities for graphene-based quantum Hall devices is provided by few NMIs. Short-term (1 to 3 years) targets are, for example:
  - Robust and stable graphene-based quantum Hall devices as primary resistance standards for routine calibration applications in the dc and ac regimes
  - Quantum resistance measurement systems for metrology of non-electrical quantities like mass, for example in 'Kibble' balances for fundamental mass metrology.

  Long-term (3 to 10 years) targets are, for example:
  - Prototypes of advanced quantum Hall devices made from materials with 'Dirac cone' electron systems, like van-der-Waals heterostructures or novel organic and metal-organic molecular frameworks

- Prototypes of quantum Hall resistance devices made from magnetically doped topological insulator or other ‘Dirac cone’ materials, exploiting the QAHE at zero magnetic field
- Novel concepts of quantised conductance/resistance devices not being based on the QHE, like memristor devices coupling ionics with electronics in solid-state systems.

● **4.3 Quantum current standards & charge devices** are novel devices and methods based on single-electron effects, enabling innovative applications in various fields of electrical quantum metrology. Emerging routes comprise developments with short-term (1 to 3 years) targets such as:
  - Primary quantum current standards based on combinations of single-electron sources and ultra-sensitive charge detectors in solid-state devices
  - Deterministic single-electron sources and electrically driven single-photons-on-demand sources in solid-state devices, as shot-noise-free quantum current or photon sources.
  - Primary quantum current standards based on the combination of a quantum Hall resistance standard, a Josephson voltage standard and a SQUID-based cryogenic current comparator.

  Long-term (3 to 10 years) targets are, for example:
  - Primary quantum current standards based on the exploitation of the quantum phase slip effect in superconducting nanowires, or Bloch oscillations in superconducting nanostructures
  - Single-electron wave packet interferometers for the ultrasensitive measurement of electromagnetic fields.

● **4.4 Quantum-enhanced measurement bridges** are essential for electrical dc and ac measurement applications requiring highest accuracies. Bridges measure quantity ratios, typically by utilising signal compensation techniques involving null detectors, and so are powerful scaling instruments. Relevant development routes and short-term (1 to 3 years) targets are, for example:
  - Digitally enhanced/assisted, fully digital and electronic bridges for multi-purpose, facilitated and automated applications, such as JAWS-based bridges for impedance metrology at frequencies up to several MHz
  - Resistance and impedance bridges based on integrated quantum Hall resistor circuits
  - Advanced and facilitated resistance and current scaling bridges based on the principle of the cryogenic current comparator (CCC)
  - Advanced transformer bridges based on inductive voltage dividers for, for example,, impedance metrology applications in the audio-frequency ac regime.

  Long-term (3 to 10 years) targets are, for example:
  - Digitally enhanced/assisted or fully digital bridges for high-frequency, high-accuracy impedance metrology up to 100 MHz.

● **4.5 Fundamental metrology experiments** performed to provide fundamental universality or consistency tests, to develop measurement methods or to serve as references in exploratory fields. These are, for example:
  - The realisation of the 'quantum metrological triangle'; involving single-electron transport devices as quantum current sources together with quantum resistance devices and quantum voltmeters to validate the foundations of electrical quantum metrology at highest possible accuracy
  - Single-electron quantum optics experiments
  - Electrical noise measurement setups at high frequency.

● **4.6 Quantum-enhanced sensors & detectors** provide the basis for all measurement systems and are also highly relevant for applications in commercial products, including for future applications in physics, spintronics, chemistry, biology, medicine, materials science, as well as quantum information, computation and communication. Relevant developments are driven by advances in nano-scale circuit fabrication technology as well as in sub-miniature assembling and nano-scale probing techniques. The main targets for sensors and detector developments are high sensitivity, accuracy, stability, and versatility. The physical basis of quantum-enhanced electromagnetic sensors and detectors comprises complex quantum-entangled and many-body systems, enabling devices based on the preparation and control of quantum states. Development routes include potential combinations of advanced sensors and detectors with scanning probe microscopes and systems, for spatially and time resolved measurements on the micro- and nanometre scales. Short-term (1 to 3 years) targets are, for example:

- Colour centres in solid-state systems or matrices, such as nitrogen-vacancy (NV) centres in diamond crystals for magnetometry with sensitivity at the quantum limit
- Artificial single atoms in super- or semiconducting solid-state devices for quantum-enhanced ultra-sensitive sensors based on phase estimation algorithms, approaching the quantum limit
- Spin-polarised quantum gases extending the range of magnetic field measurements
- Rydberg atoms for metrology of electric fields
- Nanometre-sized ultra-sensitive superconducting quantum interference devices (nano-SQUIDs), for various electromagnetic measurement applications such as magnetic characterisations of nano particles at sensitivities enabling the detection of single-spin flips
- Ultra-sensitive electrostatic charge detectors providing single-electron resolution, such as solid-state devices like single-electron transistors and quantum dots which enable the manipulation and control of single-electron wave packets and the implementation of novel (time-resolved) on-chip measurement methods on single-electron quantum states in solid-state structures
- Single-µwave-photon detectors in combination with microwave resonators, such as superconducting cavities with ultra-high quality-factors.

Longer-term (3 to 10 years) targets are,for example:

- NV centres in diamond and other colour centres, for measurements of non-electromagnetic quantities like temperature, force or pressure, and for optical near-field quantities
- Multi-functional hybrid (micro- and nano-scaled) sensors for several quantities, combined with electrical scanning probe microscopy techniques like scanning microwave microscopy, conductive atomic force and/or kelvin probe microscopy, enabling spatially resolved and versatile metrology on small (quantum) systems, also at low temperatures
- Topologically protected spin structures for magnetic field sensing in solid state devices on small local scales
- Sensors and detectors based on control of entangled quantum states and quantum non-demolition (QND) measurement schemes, enabling applications at ultimate sensitivity levels.

* **4.7 Quantum-enhanced measurement schemes** comprise devices, instrumentation and methods that include QND schemes to tackle fundamental quantum limits. For example, to overcome noise limits and to reduce the invasiveness of measurements which will increase sensitivity and accuracy to desired levels. Metrology-driven innovations in this field are particularly relevant for QT in quantum information, computation and communication. Relevant developments with short-term (1 to 3 years) targets are, for example:
  - Superconducting noise-suppressed amplifiers, such as for the readout of qubits and entangled microwave photons implemented by parametric amplifiers.

  Longer-term (3 to 10 years) targets are, for example:
  - Noise-suppressed (superconducting) high-frequency signal processing using, e.g., frequency mixers

- Neuromorphic circuits in hybrid semiconductor-superconductor technology for implementations of neural networks and neuromorphic computing.

- **4.8 Quantum metrology toolbox** ('quantum multimeter') refers to a visionary system integrating different quantum electrical standards together with related measurement instrumentation based on the aforementioned experimental realisations. Ultimately, this comes in a single, compact, user-friendly and affordable device, enabling measurements and calibrations of multiple electrical quantities at the highest accuracy. Such metrology platforms facilitate metrology activities performed in NMIs and, via their commercialisation by the manufacturing industry, also enable and promote user-friendly measurements and calibrations at high accuracy levels outside of NMIs; for example in industrial calibration laboratories. Ideally, the platforms are user-friendly, multi-functional and versatile, enabling cost-efficient metrology in various fields over a wide range of relevant operational parameters such as frequency and temperature. The implementation of cost-efficient turn-key platforms also requires compact, user-friendly and economic cryostats or cryo-magnet systems like cryogen-free cryostat systems ('cryocoolers'), which can be operated without external supply of liquid helium. Relevant developments with short-term (1 to 3 years) targets are based on the integration of a small number of standards to address dc measurements of basic electrical quantities, such as:
  - Integration of quantum Hall resistance and Josephson voltage standards in a single cryo-magnet system, for accurate SI realisations of the ohm and the volt at dc
  - Integration of a quantum Hall resistance standard, a Josephson voltage standard, and a cryogenic current comparator, for accurate SI realisation of the ampere.

  Longer-term (3 to 10 years) targets are:
  - Integration of quantum electrical standards for electrical measurements of multiple electrical quantities in the dc and ac regimes
  - More complex systems integrating (on-chip) various quantum electrical standards and quantum-based sensors or detectors, together with complementary measurement instrumentation including microwave equipment and further QT-based components.

5. Enabling Science & Technology

The foundations for all envisaged developments in quantum metrology and sensing are set by the enabling science and technology at the state-of-the-art level.

- **5.1 Fundamental science** relates to, for example, solid-state quantum physics and quantum state engineering as the foundation for understanding and harnessing relevant physical phenomena and effects for metrology, including quantum electrical effects and novel phases of matter (e.g., with topological properties). Essential requirements for future advances are:
  - Advanced means for the preparation of complex and quantum-entangled many-body systems, and
  - Advanced physical understanding for controlling quantum (de-)coherence.

- **5.2 Materials & fabrication** relates to materials science and engineering, providing the basis for the development and optimisation of materials and devices, as needed for enhanced quantum standards and sensors. Examples are:
  - Novel materials for advanced quantum electrical standards, like graphene, topological insulators or other ‘Dirac cone’ systems such as those for advanced QHE-/QAHE-based resistance standards
  - Novel materials for advanced sensors and detectors

- Advanced chemical and physical characterisation and analysis of matter and materials down to the nanometre scale
- Chemical functionalisation of materials and structures, such as for advanced low-dimensional electronic systems or for devices with surface functionality.

Nano-scale device and circuit fabrication technologies are ubiquitous key technologies, and so are inevitably required in nearly all fields of quantum technology. For applications in quantum metrology and sensing they comprise, for example:

- Advanced micro- and nano-fabrication capabilities for devices and circuits based on epitaxy, thin film technology and high-resolution lithography
- Advanced chip and/or device packaging and integration methods
- Integration of photonic, optic, and electronic components, for example to realise novel opto-mechanical or opto-electronic sensors or probes for electromagnetic quantities
- Atomic scale analysis, assembly, and control for the e ultimate downscaling of devices and structures such as for scanning probe microscopy and manipulation.

● **5.3 Basic engineering** comprises the fields of conventional and classical (i.e., non-quantum) performance electronics and instrumentation hardware, as well as cryogenic and magnet technologies. Performance electronics includes:

- Electronic measurement and control systems (also integrated with optic components)
- High-speed data acquisition and processing technology
- Low-noise circuits and systems, for minimising interference with the environment and the device under test
- Electronic circuits operating at cryogenic temperatures and microwave hardware.

Cryogenic and magnet technologies are key to many QT measurement and calibration platforms, such as for quantum Hall resistance metrology. They are required for the development of turn-key platforms tailored for specific application purposes, with reduced operational efforts and costs for the users. Relevant developments are compact, liquid-He-free (i.e. dry) cryocoolers. Reducing vibration interference from these systems is a current challenge. Applications requiring high magnetic fields rely on performance magnets which are typically based on superconducting solenoids, or (for lower fields) on performance permanent magnets. Multi-coil / multi-axis magnet systems are needed for things like the active compensation of stray fields or of the magnetic field of the earth.

3.1.2 Subfield: Quantum computing

Preamble

Until relatively recently, quantum computers were seen as a futuristic technology and real-world applications were rarely seriously discussed. In the past few years, however, quantum processors of rapidly increasing complexity have been successfully demonstrated and what was once lab-based technology is now being scaled up with the goal of making quantum processors that can solve real-world problems.
We are currently at the beginning of the Noisy Intermedia Scale Quantum (NISQ) processor era. Quantum computers are based on 'qubits' which take the place of the bits in conventional computes, and several state-of-the-art systems with ~10s of qubits have been demonstrated and the current pace of development suggests that NISQ processors with ~100s of qubits will become available in the next few years.

The involvement of companies such as IBM, Google and Honeywell, all pursuing aggressive roadmaps, have also dramatically raised the profile of the field. An emerging eco-system including not only academia and large enterprises but also many start-ups funded by venture capital has also dramatically altered the landscape.

There are several different competing quantum computing technologies which reflect the many ways of making a qubit. As of this writing the main competitors are superconducting qubits, ion-based qubits, neutral atom-based qubits, semiconductor (also known as spin-) based qubits and finally photonic systems. Although the latter is conceptually quite different from the other platforms, photonic quantum computing can still be thought of as being part of the NISQ paradigm.

All these systems have their own advantages and disadvantages; it has been found that systems where it is relatively easy to make a good *single* qubit (e.g. qubits based on ions) are often hard to scale up. Conversely, solid-state systems (superconductors and semiconductor qubits) benefit from decades of experience of microelectronic fabrications but building good, reproducible qubits remains hard.

As the complexity of systems increases, so do the challenges related to controlling and reading out an increasing number of qubits. Qubits are manipulated using RF/MW signals (superconducting and spin qubits) and/or lasers (ion-based qubits). Each qubit typically requires at least one separate control signal and it follows that existing quantum computers (with tens of qubits) are highly complex RF/MW or laser systems which require a significant amount of control electronics; which in turn are controlled by increasingly complex software. Photonic systems face their own set of unique challenges when it comes to control and read-out.

It follows that many of the challenges facing the field are entirely classical in nature, that is, problems related to designing, fabricating and calibrating complex systems. Each step in this process will have associated metrological challenges.

The availability of cloud accessible NISQ processors has also resulted in a significant boost to the development of quantum software. Developers now have real machines that can be used to run and test small-scale quantum algorithms. Whereas the current generation of NISQ processors are too small to run real-world problems, this development has nevertheless stimulated the growth of a burgeoning industry where potential end-users of quantum computers are able to test "toy model" versions of problems. This development is now helping to establish a quantum computing software stack, which in turn will allow stakeholders to test their software on many different types of hardware. For example the same code can be tested on machines from different vendors which might be using completely different technologies. At the time of writing both Microsoft and AWS are operating cloud services that offer end users access to different NISQ processor technologies.

A natural consequence of the fact that stakeholders now can directly compare different hardware is that *performance metrics* and *benchmarking* are becoming increasingly important. As the technology matures and becomes part of the wider high-performance computing (HPC) landscape, stakeholders will need objective metrics that can be used to compare different solutions. This will require the development of agreed upon metrics as well as benchmarking algorithms tailored for different classes of problems. Work on standards in this area is already ongoing within IEEE (P7131 - Standard for Quantum Computing Performance Metrics & Performance Benchmarking).

1. Science

1.1. Development of NISQ Processors

-The development of Noisy Intermediate Scale Quantum (NISQ) processors is currently driven mainly by US-based companies (IBM, Google, Honeywell etc.,), large collaborations such as the Quantum Flagship projects, and through various quantum computing initiatives within countries:

- The current generation of Noisy Intermediate Scale Quantum (NISQ) processors will, over the next decade, be scaled up from ~10s of qubits to 100-1000s of qubits;

-**Integration** is a significant challenge since a scaled-up quantum computer will require a large number of components and sub-systems;

-Short term objectives [1-3 years]: Over the next couple of years we can expect to see the first demonstration of full error correction, keeping a qubit 'alive' and paving the way towards a fault-tolerant quantum computer;

-Long term objectives [3-10 years]: NISQ processors with >100 qubits of sufficient performance to run quantum software that can solve problems of practical interest, possibly even with a quantum advantage.

1.2 Algorithms & metrics development

-Most of the well-known algorithms (e.g. Shor's algorithm for factorization) will require a fully error-corrected system with a large number of logical qubits to run. There is a need to develop more algorithms tailored specifically for near-term NISQ processors.

-Existing metrics such as quantum volume or algorithmic qubits tells the user something about the potential of a system but remains challenging to translate into real-world performance. There is a need to develop more relevant metrics for application.

-Short term objectives [1-3 years]: Development of algorithms and metrics for the NISQ era.

-Long term objectives [3-10 years]: Development of new and more efficient algorithms that give a -speedup for a wider class of problems.

1.3. Error-corrected logical qubits

-Towards the end of the decade [7-10 years] we will see the first examples of error-corrected **logical** qubits (each one comprising many **physical** qubits and auxiliary elements). These logical qubits can then for example be 'tiled' to create a QC system of -in theory- unlimited complexity.

2. Enabling Technologies

2.1 Devices: qubits, couplers, microtraps and amplifiers

-A quantum processor is made up of several different building blocks. These are implemented in a variety of ways depending on the different technologies they are being applied in. A qubit can be made from a microfabricated circuit or comprise an ion or atom in a trap. Additional elements are required to control, read-out and couple the qubits together.

-Short term objectives [1-3 years]: Development of elements with better reproducibility and improved (quantum limited) performance

-Long term objectives [3-10 years]: Miniaturisation and development of technology that allows for integration into large scale systems.

2.2. Systems, subsystems and packaging

-As QC continue to grow there will be an increased focus on the development of scalable **systems. This** includes not only the quantum processor but also control electronics, software, cryogenics, vacuum systems, RF sub-systems and so on. Packaging of quantum processors is also an important area.

-Short term objectives [1-3 years]: Development of custom software, interfaces and instrumentation for control of scalable quantum processors.

-Long term objectives [3-10 years]: Development of large-scale system integration which allows for control and readout of ~1000s of physical qubits. This will also include sub-systems tailor made for this sector.

2.3. Development and optimization of fabrication processes

-The main challenge for scaling up solid state quantum computing (technologies based on superconductors or semiconductors) and systems based on ion trap chips is developing robust, highly reproducible fabrication recipes and processes.

-Short term objectives [1-3 years]: Improved reproducibility and performance of circuits with ~10s of qubits.

-Long term objectives [3-10 years]: Multi-layer fabrication processes and added functionality in the case of ion traps, such as integrated electronics and optics, that allow for scaling to ~10 000s of qubits.

3. Metrological validation

Metrology of key enabling technologies

-Quantum computing systems incorporate many technologies: vacuum systems, cryogenics, EM shielding, electronic instrumentation etc. In order to work well together, all sub-systems need to be tested and evaluated.

-Short term objectives [1-3 years]: Use and, where necessary, adapt existing metrology to support the development of QC in the NISQ era.

-Long term objectives [3-10 years]:   Develop new metrological methods that allow for test and evaluation of components and sub-systems unique to QC.

3.1 Measurement protocols for qubits and processors

-Measurement methods for circuits with a small number of qubits are relatively well established (e.g. tomography and randomized benchmarking). However, there is, as of yet, no standardised methodology for developing measurement protocols, such as statistical power, analysis of parameter fluctuations, number of samples. nor are there any agreed upon ways to present data.

-Short term objectives [1-3 years]: Development of standardised measurement protocols for circuits with few (<5) qubits that can be used to for example optimise fabrication processes.

-Long term objectives [3-10 years]: Development of standardised measurement protocols for complex circuits.

3.2 Metrology of materials and surfaces

-Qubits are sensitive to defects and impurities that would go unnoticed in conventional electronics. This can be mitigated by the use of very pure materials, but defects/impurities at surfaces and interfaces are difficult to detect and eliminate. In solid state qubits these directly lead to noise, and in ion traps to excess heating.

-Short term objectives [1-3 years]: Develop methods for detecting and characterising defect and impurities at surfaces. This might include novel methods and improvements to existing scanning probe microscopy techniques.

-Long term objective [3-10 years]: Develop methods suitable for characterising complex multi-layer samples.

3.4 RF metrology for quantum computing systems

-Most QC technologies utilise microwave pulses to control and read out the qubits. This is done at low powers (often using single microwave photons) and in environments (millikelvin temperatures, ultra-high vacuum) not used in conventional electronics. For ion traps, rf and dc electronics operate at a few kelvins but at higher MW power is required.

-There is a need to develop methods for accurately characterising and calibrating microwave components and subsystems used in QC. This includes S-parameter measurements of passive devices/components cooled to/used at millikelvin or kelvin temperatures as well as accurate noise temperature measurements of cryogenic amplifiers. There is also a need to develop methods to characterise novel microwave devices such as wide-band quantum limited parametric amplifiers and the performance of devices such as digital-to-analog converters.

-Short term objectives [1-3 years]: Establish a capability to calibrate QC devices and components *in-situ.*
-Long term objectives [3-10 years]: Develop a capability and methodology for characterising rf/mw parameters for large scale QC systems and sub-systems. Examples include cryogenic on-wafer characterisation of large-scale microwave circuits, and the characterisation of cryogenic active control electronics (made from CMOS and other technologies).

4. Software

4.1 Software for benchmarking and validation

-A growing ecosystem with competing technologies and stakeholders means that potential end-users need a way to compare and validate products and services.
-Metrics are part of the answer, but there is also a need to develop benchmarking software that can give stakeholders a realistic idea of how well a particular product/service would work for their application. End-users want performance validated by independent entities.
-Short term objectives [1-3 years]: Development of 'toy algorithms' that can be used to benchmark and validate NISQ processors.
-Long term objectives [3-10 years]: Development of a full suite of benchmarking tools that can be used on arbitrary-scale QC systems.

4.2 Applications in chemistry, fintech, machine learning

-The first real-world applications of NISQ processors is expected to be in chemistry, but there are also promising signs that important optimisation problems can be addressed with processors of moderate size, which could be utilised in fields such as finance. Machine learning is likely to be another important application area.

5. Targets, applications and services

5.1 Test and measurement services for QC systems and components

-As the development of the commercialisation of QC continues, we will see an increased need for measurement services. This can include calibration of components used in control systems or characterisation of materials.
-Short term objective [1-3 years]: Use and adapt existing services to the QC sector
-Long term objective [3-10 years]: Services tailored to the QC sector, including testing and evaluation of quantum devices.

5.2 Metrology of software

-Validation/benchmarking of algorithms and software on behalf of stakeholders and end-users
-Short term objective [1-3 years]: Validation of software for NISQ processors/systems.
-Long term objective [3-10 years]: Validation of critical software, initially running NISQ processors and later fully-error corrected QC systems.

5.3 Standardization and benchmarking

-Standardisation in the QC sector will encompass many different aspects. Examples of important areas are terminology/nomenclature, metrics and benchmarking.

-There will also be a need to develop agreed upon specifications for software and hardware interfaces to allow components and sub-systems from different stakeholders in the supply chain to work together.

5.4 Practical QC in the cloud

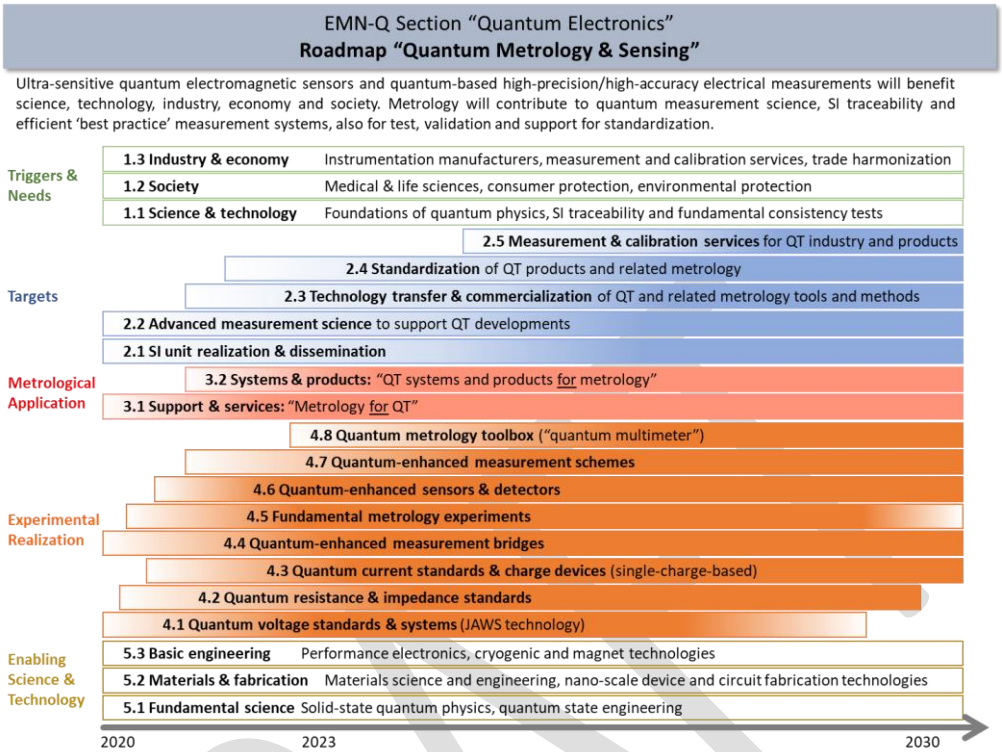
-The goal is to give stakeholder access to a QC system powerful enough to tackle a wide variety of important problems

-We are currently seeing the start of this development, with QC as a service being offered by several companies even though utilizing QC hardware is too limited to be used for practical problems.

-A likely scenario is that QC will be part of a heterogenous environment where the user can utilize different HW platforms depending on the problem at hand.

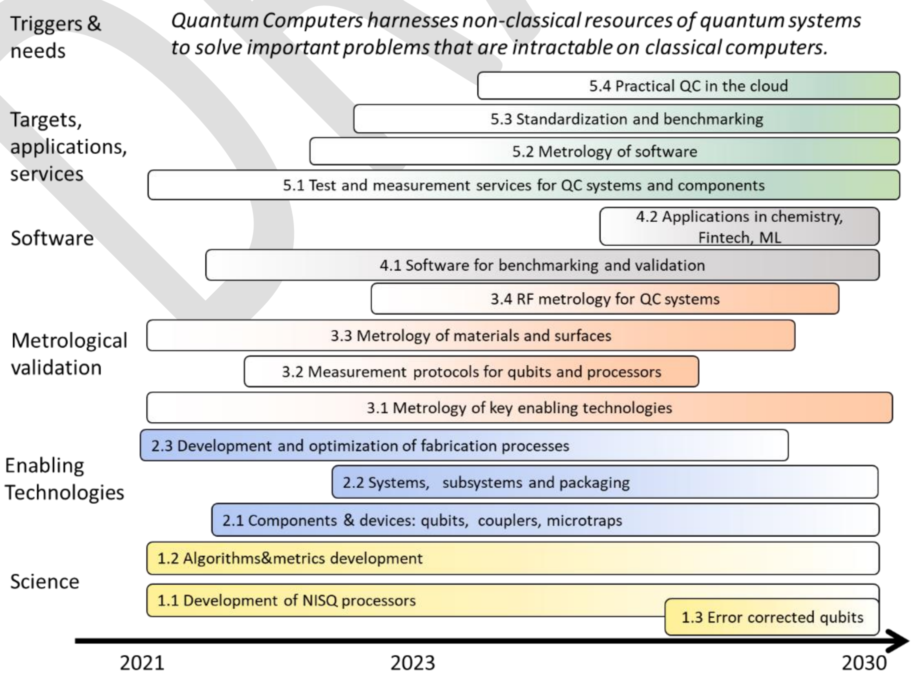
3.2 Quantum Electronics: Quantum metrology & sensing roadmap

The numbers in the boxes below refer to the numbering in section 3.1 of this document.



3.3 Quantum Electronics: Quantum computing roadmap

The numbers in the boxes below refer to the numbering in section 3.1 of this document.



4 Quantum photonics

4.1 Strategic Research Agenda

4.1.1 Subfield: Quantum communications

The EMN-Q Quantum Communications metrology roadmap anticipates the metrology requirements for quantum communication technologies over the next 10 years. The triggers and needs from the stakeholder communities (vendors, supply chains, users, regulators) generate the NMI targets and therefore the metrology required to achieve them. The enabling science and technology serve both the stakeholders and the NMIs.

Quantum communications can be considered to refer to the exploitation of quantum resources for the purpose of:

- securing the communication of information
- transmitting quantum information
- transmitting information at a higher capacity than possible with purely classical systems

Quantum-secured communications is the most commercially advanced area of quantum communications. Quantum key distribution (QKD) can be used to take an initial shared secret between two distant parties and create new secret key material that has no algorithmic dependence on the initial shared secret. This key material can then be used in traditional cryptographic schemes to secure communications between the two parties. A more correct description of QKD would be quantum-secured key expansion. The development of quantum random number generators can be considered to lie within this area.

Transmitting quantum information can be used to create a ‘quantum internet'; distributing single and entangled quantum states to facilitate applications such as distributed quantum computing, quantum sensing, and quantum-enhanced clock synchronisation.

Increasing channel capacity above that achievable with traditional systems can be achieved with quantum resources. This field is still at a very early stage with a few experimental proofs of principle.

The distances over which quantum communications should be considered ranges from short-range communications at the sub-metre range to satellite-to-ground and satellite-to-satellite.

This version of the SRA focusses on quantum-layer hardware, but we note that there are also classical ancillary devices, such as trusted nodes, that will also require testing and evaluation using classical techniques.

1. Triggers & Needs

These are the top-level drivers for the strategic efforts in the fields of quantum communications within the EMN-Q. They are driven by the needs of industry, government and society.

- **1.1 National and international certification frameworks**. The provision of national and international communications and its infrastructure is heavily regulated by governments and international agreements, and quantum technology will need to satisfy these regulations before it can be deployed into active communications networks. Formal structures for testing and certifying the conformance of quantum communications hardware will be required.
- **1.2 Certification of quantum hardware**. The security of QKD systems depends not only on theoretical security proofs, but on their physical implementation. It therefore requires standardized physical test and evaluation procedures created by experts, such as those in standards developing organizations. These procedures will be implemented by specialist test laboratories such as security evaluation laboratories (SELs), which are accredited by the relevant national agencies as having the necessary expertise and facilities to perform the tests.
- **1.3 Assurance of QKD networks.** Many QKD networks are in various stages of development. Within the EURAMET area, the most notable are the UK Quantum Network (UKQN), the OPENQKD testbeds, and the planned EU quantum communications infrastructure (Euro-QCI) initiative. The latter aims to build a secure quantum communications infrastructure that spans the EU and its overseas territories. One purpose of these networks is to use them as testbeds for working out and evidencing how they can be used to secure communications.

These networks will not be limited to terrestrial fibre links, and will eventually incorporate satellite-to-ground, satellite-to-satellite, and short-range terrestrial free-space links, with lengths ranging from the sub-metre to hundreds of kilometres.

Testing will not be limited to the quantum layers and will also require the traditional testing of the classical layers sitting above them, and the operation of such systems in dynamically reconfigurable network topologies. Furthermore, testing will not only be required at the factory, but is likely to include lifetime testing and failure detection while deployed on the ground or in space.

- **1.4 Delivery and assurance of multiple quantum services**. There is the potential to use existing and future networks to disseminate multiple quantum services, for example time signal dissemination and QKD over the same link and, in the longer term, using quantum signals to secure the time signals. This implementation could be driven by NMIs, given their pre-eminence in distributing time signals.
- **1.5 Quantum internet.** As described in the preamble, a quantum internet, distributing single and entangled quantum states to facilitate newer quantum-enhanced applications, is seen as the next stage in quantum communications networks. If these are used for security applications, the same regulatory requirements as described for QKD will apply. Even if this is not the case, effective provision of these new services will

require some degree of test and evaluation. Technology for realising such a quantum internet could be provided by NMIs – for example for timing and synchronisation.

Timescales. Items 1.1 to 1.3 require work now, while work in anticipation of items 1.4 should start by 2023 and for 1.5 around 2025.

2 Targets

The targets address the triggers and needs stated above.

- **2.1 Standardised, traceable, measurement and data analysis procedures**. The security requirements for QKD hardware need to be identified, and the ensuing security-relevant parameters identified. Test methods for characterizing these parameters, and the application of their measured values to assess the security of a QKD system need to be formalized by standards developing organisations to ensure globally-accepted standards. Using current knowledge of the above as a starting point, a gap analysis to identify where test methods are lacking can be used to inform work in this area. Work towards this has already been published by the OPENQKD Consortium [4.1], while current work by the OPENQKD Consortium, the CEN/CENELEC Focus Group on Quantum Technologies (FGQT) and the ITU-T Quantum Information Technology for Networks (FG-QIT4N) will also inform this gap analysis. In the longer term, requirements driven by the needs of the quantum internet will also arise.
- **2.2 Measurement services.** Measurement facilities will need to be delivered to SELs to enable them to evaluate the deployed implementations of QKD systems. Evaluation for other applications, such as those driven by the quantum internet, may not need dedicated SELs; these services could be deployed by Test & Evaluation [2] laboratories. These services should address systems assembled from discrete components, as well as those fabricated on quantum photonic integrated circuits (QPICs) and enable production-line testing.
- **2.3 In-service testing.** Networks, be they for quantum-secured communications or other quantum communications applications, will require some degree of in-service testing to monitor performance and identify impending hardware failures. This can then enable reconfiguration of the networks to maintain service provision. This in turn requires cheap, deployable and robust test hardware that can be deployed at the nodes of networks.

Timescales. 2.1 requires work now, while work for 2.2 should begin in 2022, given the developing maturity of QKD networks. Work towards 2.3 should start by 2024, but this will need to be reviewed in line with network development.

3. Metrological applications

The metrological applications are driven by NMIs and EURAMET to address the targets described above. They can be grouped into two complementary activities – metrology developments and delivery of test capabilities.

Metrology developments

- **3.1 Metrology of key-enabling components (macro, in-fibre, on-chip).** Advanced methods for characterizing components and assemblies of quantum communications hardware are required. These methods need to address macroscopic, free-space, in-fibre, and on-chip implementations. Some of the main components are listed below; measurement of modules comprising these elements is also required.
    - Passive components
        - Filters
        - Couplers
        - Isolators
        - Circulators
        - Beamsplitters
    - Active components
        - Sources: Single-photon, correlated-photon, entangled-photon, etc
        - Detectors: Single-photon, few-photon, photon-number resolving (PNR), non-PNR, homodyne and heterodyne circuits, single-pixel, multi-pixel
        - Encoders (e.g. phase and amplitude modulators)
        - Decoders (e.g. interferometers, Bell-state analysers)
        - Switches
        - State storage media
        - Frequency conversion systems.
- **3.2 Comparisons, equivalence and terminology.** Confidence in the accuracy of the methods developed and their implementation requires comparisons between laboratories. This can be pursued by performing initial comparison studies to understand the peculiarities of performing such comparisons, followed by formal ones to establish the degree of equivalence between laboratories.

Developing a robust terminology for the properties to be measured and the metrics used is essential for providing clarity to the field. This should be performed in close collaboration with the development of more applied terminology/vocabulary documents by SDOs. CCPR WG-SP TG7 (discussion forum on few-photon metrology) is currently creating an open-access publication on terminology in single/few photon metrology; progress on this needs to be accelerated in order to keep up with work in SDOs.

Delivery of test capability

- **3.3 Traceable physical testing of quantum hardware.** The expertise and capability developed for 3.1 and 3.2 shall be deployed to characterize the important security and operational parameters of modules and key components of quantum communication systems. As described in 3.1, these need to address macroscopic, free-space, in-fibre, and on-chip implementations, with an immediate focus on device-dependent protocols, ultimately leading to systems with a greater degree of device-independence. Measurements will need to be performed on hardware that could be operating at GHz clock-rates. Some of these modules are listed below:

- Discrete-variable QKD modules
- Continuous-variable QKD modules
- Quantum random number generators (QRNGs)
- Quantum memory
- Quantum repeaters

3.4 Testing hardware in the field. The requirement in 2.3 for in-service testing necessitating the development of cheap, deployable and robust test hardware for lifetime testing of installed hardware points towards compact solutions either requiring no re-calibration (SI-in-the-field), allowing for long intervals between recalibration, or accommodation re-calibration in-situ. In the short-term, transportable systems can be utilized to provide assurance on current networks.

Timescales. Work towards all of these items is, to various degrees, in progress. Work on 3.1, 3.2 and 3.3 needs to continue at pace, with 3.4 starting in 2023.

4. Experimental realizations

Experimental realizations describe the fundamental and applied metrology that needs to be developed in order to meet the triggers and needs for quantum communications. It therefore describes work that NMIs are best placed to carry out.

- **4.1 Quantum metrics and measurement methods.** Many of the properties that require measurement are new to the field of metrology. Examples of these are the nth-order correlation functions used to characterize the emission from photon sources, metrics used to define and measure Bell inequalities, and the various properties of single-photon detectors. Other properties, such as the spectral extent of photon emission, are similar to properties measured in conventional radiometry.

  Metrics and measurement methods will need to be identified and developed where necessary to enable the characterization of parameters important to quantum communications, for example, to serve security analysis of QKD systems or estimate the available entropy from a QRNG. One ETSI standard [4.2] describes procedures for measuring some of the parameters of components of QKD systems, while other documents in draft by ETSI and ISO/IEC look at modules. The requirements for current commercial QKD protocols will be informed by work described in 2.1, while new requirements will arise as the field develops. Engagement with industry and SDOs is essential for understanding these evolving needs.

- **4.2 Advanced sources and detectors.** All quantum photonic metrology is ultimately based on SI-traceable reference sources and detectors, as well as robust techniques for properties which can be described by relative measurements. Below some key requirements and potential routes to enable this provision are identified. The current focus is on current requirements for quantum communications, but in the longer term, entangled-photon sources and entanglement-metric analysers will be required.

- SI-scale artefacts
  - Reference sources – ideal (Fock-state) photon sources, sources with uncertainty-bounded number distributions (e.g. attenuated Poissonian sources, heralded single-photon sources). Many systems are currently being intensively researched to achieve Fock-state sources, the most advanced of which are based on quantum dots operating at cryogenic temperatures
  - Reference detectors – detectors with traceably or absolutely measured detection efficiency, and characterized for imperfections such as dark counts, non-linearity, and non-photon number resolution The most advanced detector systems currently operate at cryogenic temperatures and are based on bolometric or superconducting methods.
- Absolute SI in the field – no traceability chain
  - Various approaches can be developed – a miniaturized cryogenic radiometer, a predictable quantum efficient detector, a heralded single-photon source, or an absolute radiometer.
- Miniaturized artefact compatible with commercial hardware
  - Low-cost operation without expensive cryogenic cooling is required for this application. Appropriate, absolute or traceable calibrated devices can be employed, with the calibrated artefact replaced at predetermined intervals.

- **4.3 Bespoke instrumentation and test procedures.** Bespoke instrumentation will be required to interface with quantum communications hardware. This will need to provide traceable measurements at an affordable cost. In order to achieve this, standardized methods need to be followed (as specified in published standards), and the metrology community will need to engage with hardware developers to agree on 'universal' interfaces; both in terms of input and output signals as well as the connector types, so that each vendor's equipment doesn't require its own specialized interface. Work in this direction has already started in the drafting of an ETSI document for characterizing QKD modules.

  Different instrumentation may be needed for final-product and in-use testing than that developed for use during the fabrication process.

Timescales. Work towards 4.1 and 4.2 is already underway, and work towards 4.3 should begin by 2023.

5 Enabling science and technologies

Enabling science and technology is primarily performed by the academic and industrial sectors, with academic research translated into the commercial arena. Expected developments in this area are highlighted below. The field of quantum communications is expanding rapidly and this snapshot will need to be revisited annually.

- **5.1 Photon sources**
  - Probabilistic and deterministic single- and entangled- photon sources
  - Compact and stable lasers
- **5.2 Photon detectors**
  - Non-photon-number resolving detectors – SPADs, SNSPDs, multi-pixel (SPAD-array, Si-PM)
  - Photon-number resolving detectors
    - Intrinsic: TES (transition-edge sensors), KID (kinetic-inductance detectors)
    - Extrinsic: multiplexed non-PNR detectors
  - Shot-noise limited detectors
- **5.3 Advanced technologies**
  - QRNGs
    - Device-dependent
    - Device-independent
  - Quantum photonic integrated circuits (QPICs) – 'modules on-chip'
  - Low SWAP (size, weight and power) electronics to drive photonic PICs
  - High-performance, low SWAP modulators, isolators, switches
  - Ultra-stable lasers/oscillators
  - Long-haul phase stabilization
  - Quantum memory, quantum repeaters
  - Free-space short-range QKD, satellite QKD, ground-station hardware
  - Free-space to fibre links
  - Interfacing and embedding with fibre and wireless communication networks
- **5.4 Advances in theory and communication protocols**
  - New concepts
  - Advanced protocols – e.g. twin-field QKD, MDI-QKD, DI-QKD, quantum signatures, bit commitment
  - Implementation security
    - Advanced security proofs
    - Advanced countermeasures

4.1.2 Subfield: Quantum Metrology & Sensing

The EMN-Q quantum photonic metrology and sensing roadmap anticipates the metrology requirements for quantum sensing and metrology technologies over the next 10 years. It considers needs from science and technology, industry, economy and society regarding photonic quantum technology (photonic QT) based metrology, as a high-level representation of the future developments anticipated in the field photonic QT metrology and sensing. Photonic QT exploits quantum phenomena, such as coherence and entanglement, to develop novel methods of measurement, sensing, and imaging which significantly improve the precision of parameters of a wide range of systems. Such promising applications require development of techniques robust to noise and imperfections, that is, to fit real-world scenarios. The central concept of a quantum sensor is that a probe interacts with an appropriate system, which changes the state of the probe. Measurements of the probe reveal the parameters that characterize the system. In quantum-enhanced sensors, the probe is generally prepared in a particular non-classical state. The best classical sensors exhibit precision that scales proportionally to the square root of the number of particles N in the probe (known as the standard quantum limit, SQL), whereas the best quantum sensors can, in principle, attain a precision that scales as N (known as the Heisenberg limit). The platforms for implementing quantum sensor protocols range from the nanoscale, by means of localized spins, to the planetary scale, based on photons. Quantum metrology and sensing will particularly benefit quantum photonic thermometry, light-based calibration, electric field measurements, pressure sensing, gravitometry, magnetometry, and accelerometry, and include the prospects of offering new medical imaging and diagnostic tools. Some platforms are close to commercial application, others require new science, engineering and metrology to be fully feasible. The triggers and needs from the stakeholder communities (vendors, supply chains, users, and regulators) generate the NMI targets and therefore the metrology required to achieve them. The enabling science and technology serve both the stakeholders and the NMIs.

The figure below, with its associated text, encapsulates these requirements. The structure of the document follows the categories on the vertical axes of the supply chains.

The foundations for all envisaged developments in quantum metrology and sensing are set by the enabling science and technology at the state-of-the-art level.

1. Triggers & Needs

Triggers and needs from various stakeholders in the fields of quantum technology (QT) are the top-level drivers for the strategic efforts in the fields of quantum metrology and sensing within the EMN-Q.

1.1. Quantum enhanced sensors for:

- Light-based calibration, magnetometry, accelerometry, and security
- Quantum imaging based on optical, magnetic, and sensing and measurement techniques:
    - Healthcare. New medical diagnostic tools for medical and bio-analytical applications. However, integration into existing analytical devices is needed.
    - Imaging in a noisy environment
    - Covert imaging
    - Out of line-of-sight imaging
- Consumer electronics
- Non-invasive temperature sensors (e.g. biology, healthcare, and microelectronics)
- Driftless temperature sensors for Industry 4.0
- Self-calibrating sensors in applications where sensor retrieval is not possible (e.g. semiconductor components, space, and submarine settings)

1.2. Certified QT performance for metrology and sensing

- Reliable and accurate quantum-based measurements for characterisation, traceable measurements and calibrations at the highest level are required to commercially advance quantum technologies

- Quantum-based metrology for measurements and calibration at the highest accuracy level will underpin characterisation or research results quantitatively with utmost accuracy and precision.
- This requires traceability within the revised SI units.

2. Targets

Targets in quantum metrology and sensing address the triggers and needs. The primary targets related to industry and economy support new developments and products in the field of electrical QT. Support by metrology is perceived to be fundamental for the uptake of the quantum technologies market, specifically in the following fields:

2.1. Traceability of operational methods and systems based on calibration and certification:

- New standard artefacts for comparison testing to reflect enhanced capability
- Metrological validation of self-calibrating optomechanical sensors
- Traceable noise characterization of non-classical light sources
- Entanglement measures and estimation
- Applying traceability to complete and sub-systems developed by industry and academia
- SI unit realization & dissemination, mainly pursued by metrology institutes

2.2. Measurement services to demonstrate enhanced performance

- Advanced measurement science exploiting the subtleties of quantum physics is a fundamental topic essential to support QT developments. Measurement of the state of a quantum system, even more so a single quantum object, as well as low-noise measurements below the standard quantum limit are challenging and require specific and novel approaches
- Multi-property sensing (e.g. the use of nitrogen vacancy centres for temperature and magnetic field sensing)
- Improved resolution and/or range, such as position, time, and frequency.

2.3. Standardized test procedures

- Documented for adoption by SDOs (Standards developing organizations)
- Definition of metrics like key performance indicators (KPI) and key control characteristics (KCC)
- Development of reference methods and protocols towards globally accepted reference frames, written standards and measurement standards
- Evaluation and validation within these reference frames.

At the application stage metrology provides expertise, impartiality and independence for supporting development, testing, validation and evaluation in terms of the reference frames. Besides manufacturing, societal fields like environmental and medical analysis and metrology rely on standardization as the basis of quality control and risk assessment.

3. Metrological Application

Metrological applications address innovations aimed at the primary complementary targets.

3.1. Metrology for key enabling technologies

- Metrological support to industry and academia
- Characterization and validation of complete and sub-systems developed by industry and academia
- Supporting the standardization of enabling technologies
- Examples: Absorption/transmission characterization, laser noise characterization, quantum efficiency of detectors, and relevant framework/standards. This might be the same or similar to those used for classical sensors, but upgraded to allow calibration at higher performance. An example is avalanche photodiodes (APDs) which have been used to detect entangled photons, and with additional cooling and sensor improvements can be used for medical imaging. APDs in the form of 2D and even 3D stacked arrays can directly replace conventional sensors based on silicon diodes.

- **Support & services** refer to measurement and calibration services (including quantum-enhanced and quantum-based ones) offered by metrology institutes like NMIs. These support the industrial QT sector (i.e. representing photonic quantum metrology and sensing <u>for</u> QT). They are based on standards, systems and platforms utilizing classical and quantum effects, and support developments pursued by external QT stakeholders like instrumentation and sensor manufacturers, calibration laboratories or quantum computing developers. These services concern quantum technologies as well as associated enabling technologies.

3.2. Comparisons/validation of characterization techniques

- **The m**etrology community validates the accuracy of industrial sensors based on its own primary references and state-of-the-art prototype sensors
- The metrology community develops knowledge on the physics of sensors, including systematic shifts, drifts, photon flux rate accuracy, wavelength drifts and noise sources. On that basis, support to industry should be provided (e.g. knowledge transfer, as a service)
- The metrology community develops and compares its own state-of-the-art reference sensors, subsequently establishing international equivalence and traceability to SI units.

3.3 Testing quantum hardware in real life scenarios:

- Testing installed hardware
- Transfer to industry, spin-off, etc.
- Enabling technologies ready to be integrated. Industry developing supply and manufacturing chain to form complex sensors
- Lifetime testing

4. Experimental Realization

Experimental realization Is based on innovative and state-of-the-art research and developments made primarily by industry and academia; where NMIs play a smaller role. This addresses concrete technologies, devices and instruments as a basis for enabling QT applications within QT photonics.

They comprise advanced validation, calibration, and services for metrology for supporting novel QT, as well as the development of QT-related metrology products for commercialization.

4.1. Use cases identified / proof of concept:

- We expect sensor development to be performed by industry/academia, but NMIs could have a minor role here
- Methods and concepts adapted to use cases (e.g. space, microgravity, in vitro, in vivo)
- Ruggedized sensor prototype
- Proof of concept experiment based on relevant use cases.

4.2. Development of appropriate performance metrics:

- Engagement with user communities to define needs and requirements
- Used to inform drafting of standards
- Definition of the application-based target accuracy.

4.3. Robust test methods and instrumentation:

- Development of compact and transportable measurement systems
- Improvement of sensor packing

4.4. Characterization of sensor properties

- Combination of different sensing elements to check performance and cross-validate different measurement techniques

5. Enabling Science & Technology

The foundations for all envisaged developments in quantum metrology and sensing are set by the enabling science and technology at the state-of-the-art level.

5.1. Basic technology: Lasers, detectors, optics, electronics

- Low noise lasers and low noise high QE detectors
- High quality and low loss optics
- Production of QDs and defects in diamonds and other materials
- Quantum control tools for improved sensitivities and new application areas
- Designs for ultra-bright sources of quantum light with reduced noise and entanglement
- Passive and active optical components.

5.2. Artificial atom-like systems for sensing and metrology

Sensing magnetic fields is a natural process for spin sensors and is of crucial importance for several fields, including chemistry, biology, medicine and material science. Spin-based sensing of a variety of different quantities such as temperature, electric fields and pressure, as well as force or optical near-fields, has been demonstrated with diamond defects and defects in silicon carbide. At present quantum spin sensors are targeting the following benchmarks: high sensitivity, spatial resolution, and spectral and temporal resolution (when measuring AC fields). Single spin qubits in diamond are ideal in this respect, since the diamond lattice allows for millisecond coherence time of electronic spins even under ambient conditions.

- Colour centres in solid-state systems or matrices. For example, nitrogen-vacancy (NV) centres in diamond crystals for magnetometry with sensitivity at the quantum limit
- Quantum dots can significantly improve sensing tools in applications, such as cellular assays, cancer detection, or DNA sequencing
- NV-centres are of crucial importance for several fields, including chemistry, biology, medicine and material science. Spin-based sensing of a variety of different quantities, such as temperature, electric fields and pressure, as well as force or optical near-fields, has been demonstrated with diamond defects and defects in silicon carbide
- NV centres in diamond and other colour centres for measurements of non-electromagnetic quantities like temperature, force, or pressure, and for optical near-field quantities.

5.3. All-optical set-ups for the generation of non-classical light

Practical designs for ultra-bright sources of quantum light with reduced noise and entanglement, together with development of novel principles for engineering that provide practically useful quantum states and measurements for photonic quantum sensing, could yield enhanced resolution in phase detection. Examples of such would be multi-photon interferometry beyond the classical limit and weak field homodyning. Experimental implementations of quantum ellipsometry for quantum polarization measurements and quantum microscopy with NOON states have the potential to use fragile quantum states in imaging. In addition to quantum correlated photon states, (macroscopic) squeezed states of light can be also used as a resource for quantum-enhanced sensing. Squeezed light techniques are currently in use in LIGO. Squeezed light strategies are in development for deployment in the next-generation gravitational-wave detector, the Einstein Telescope. Squeezed light has also been exploited to resolve a small beam displacement, which in turn has been used to perform quantum-enhanced micro-rheology on a living cell.

- SPDC sources for the generation of single photons and entangled photons
- Optical parametric oscillators for squeezed light generation (x2 and x3 materials)
- Fibres
- Squeezed and entangled light are currently being deployed in the next-generation gravitational-wave detectors
- Quantum imaging exploits quantum correlations such as quantum entanglement in order to image objects with a resolution (or other imaging criteria) beyond what is possible in classical optics. Examples are quantum ghost imaging, quantum lithography, sub-shot-noise imaging, and quantum sensing.

5.4. Optomechanical sensors

Nano-electromechanical systems (NEMS) and MEMS can now be measured and controlled at the quantum level by coupling them to optical cavities or superconducting microwave circuits. Recent demonstrations include squeezed mechanical states and QND measurements of mechanical motion, quantum coherent coupling in the optical and microwave domain, optomechanical ponderomotive squeezing and entanglement, a photon–phonon interface, and real time quantum feedback. The physical limits of hybrid opto- and electro-mechanical devices for conversion, synthesis, processing, sensing and measurement of electromagnetic fields, currently span from radio and microwave frequencies to the terahertz domain. The ability to modulate, interconvert, amplify or measure electromagnetic fields in this spectral region is relevant to a number of existing application domains, specifically medicine (e.g. MRI imaging), security positioning (e.g., radar and THz monitoring), as well as timing and navigation (oscillators). At the same time, optomechanical systems provide an on-chip architecture to realize actions such as sensing, acceleration measurements, low-noise amplification and novel non-reciprocal microwave components.

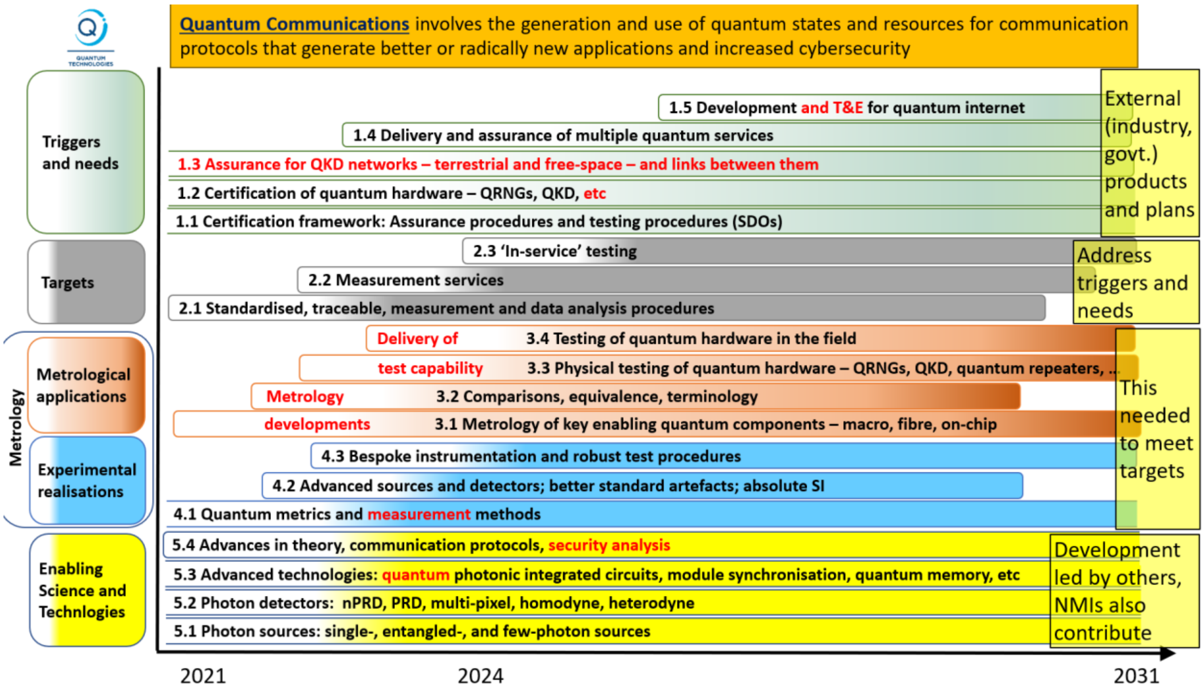
- To operate optomechanical transducers in a quantum noise regime enables the creation of compact quantum noise calibrated thermometers
- Exploration of the physical limits of hybrid opto- and electro-mechanical devices for conversion, synthesis, processing, sensing and measurement of physical parameters such as electromagnetic fields, from radio and microwave frequencies to the terahertz domain.

5.5. Detection schemes

- Research on fundamental concepts and methods to detect, generate and apply entangled states for quantum metrology and sensing
- Weak field homodyne detection for enhanced resolution in phase detection
- Quantum microscopy with NOON states.
- Theoretical study of quantum sensing remains a critical element in order to examine the fundamental limits of metrology
- Novel methods from signal classical processing, which have already yielded fruit in the design and assessment of sensor performance, will be applied to minimize the measurement effort to extract the desired signal
- Time-of-flight measurements at the single-few-photon level.

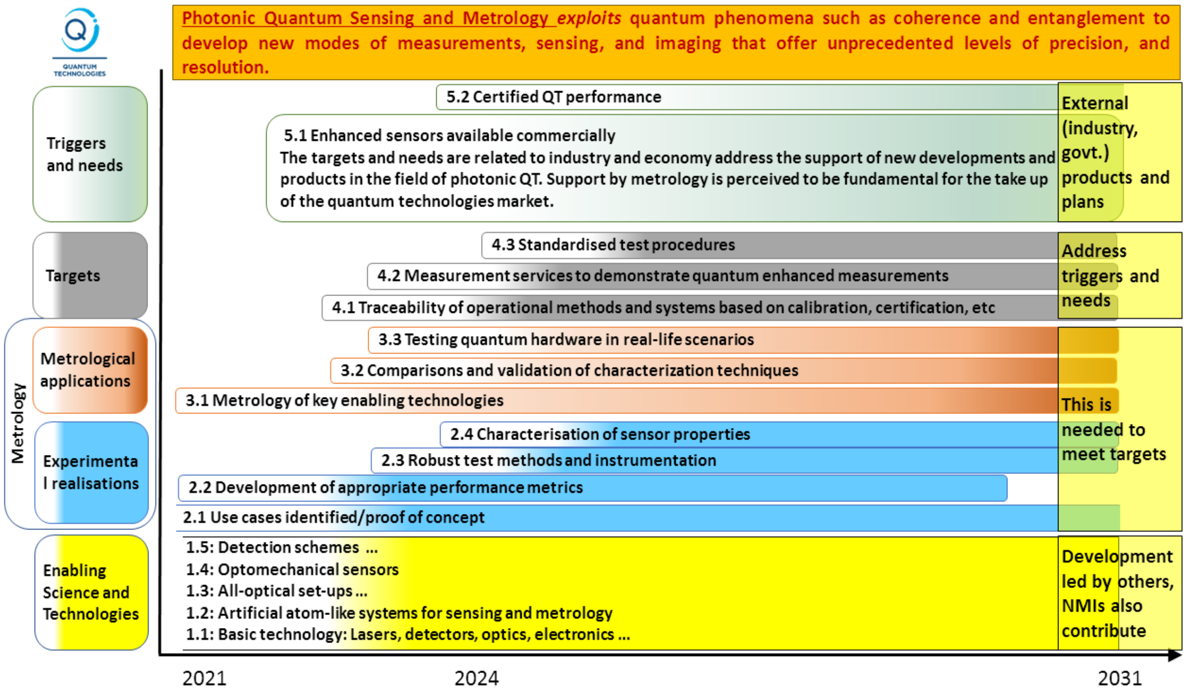
4.2 Quantum Photonics: Quantum Communication Roadmap

Roadmap of the quantum photonics section of EMN-Q concerning quantum communication.



4.3 Quantum Photonics: Quantum Metrology & Sensing Roadmap

Roadmap of the quantum photonics section of EMN-Q concerning quantum metrology & sensing.



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5 Quantum clocks and atomic sensors

5.1 Strategic Research Agenda

The quantum clocks & atomic sensors section of EMN-Q deals with atom-based quantum sensors. Due to the fundamental atomic processes employed, they provide accuracy and long-term stability for quantities such as time, length, rf-fields, temperature, magnetic fields, gravity and rotation. They also enable nanometre-size sensing, massively parallel sensing and secondary sensing, for example for opto-mechanics or electrical currents.

Atom-based sensors are key assets for addressing grand challenges and societal needs in several areas, such as monitoring climate variables, monitoring underground resources, time, space and geodetic references, geoscience, navigation and space science. Specific triggers and needs relating to these, and a set of strategic research actions in response to those triggers and needs, are described below.

5.1.1 Trigger and needs

- Atom-based sensors can fulfil the need for accurate and traceable measurements of gravity, gravity-gradients, gravitational potential (chronometric geodesy) for long-term trustable monitoring of key climate variables; in particular Earth geoid shape and ocean height
- Atom-based sensors can similarly fulfil the need for gravity field, gradient and potential measurements for monitoring underground resources and understanding phenomena affecting these resources
- Atom-based sensors can fulfil the need for physical frequency standards of several grades and characteristics that are key to realize time and space reference systems. They can also improve geodetic reference systems. These reference systems are a fundamental asset for Earth science, space activities, and services essential to modern societies
- Atom-based sensors must be developed to achieve the level of performance, operability and compatibility with industrial and commercial environments required by each of these needs. Supporting the European industry to master this technology and its integration in other systems and services is essential.

5.1.2 Targets

To address the needs described in the previous section, activities of EURAMET members and of their partners and collaborators shall aim towards the following high-level goals:

- To maintain and develop improved physical atom-based standards and the metrological services based on them. NMIs/DIs are already performing these activities and such work should continue, be improved upon and amplified based on newly developed standards and on specific needs arising from industry and society. Coordinated development of new capabilities and services shall avoid duplication and improve the global offer of services within Europe
- To support the development by industry of key technologies for atom-based sensors. This will be achieved through joint projects between EURAMET members and industrial partners to

facilitate exchange of knowledge, uptake of knowledge by industry, technology transfer or specific joint developments of a given technology or device. Based on their expertise, EURAMET members and their collaborators will also contribute developing frameworks to characterize these key technologies and facilitate their integration within complete sensors. This includes defining physical requirements, developing suitable characterisation services and when applicable, supporting the development of standardization where appropriate

- To support the development by industry of complete novel atom-based sensors. This will be done by additional joint projects between EURAMET members and industrial partners to facilitate exchange of knowledge, uptake of knowledge by industry and technology transfer. EURAMET members and their partners will also support this effort by developing technology centres and validation services to facilitate high-end characterisation of sub-systems and traceable metrological characterisation of the complete sensors
    - For example: a state-of-the-art gravimetric reference point to validate commercial gravimeters & gradiometers, and a quantum technology centre with access to ultra-stable and accurate optical and microwave references and characterisation methodologies.
- To support in-field applications of novel atom-based sensors by maintaining and developing permanent capabilities and services to ensure the top level of the metrological traceability chain according to the needs of specific fields of applications. This will be done by supporting standardization where applicable, supporting optimization of sensors for their integration within sensor networks and, for larger systems, by providing solutions and services based on them.

5.1.3 Metrological applications

Meeting the above targets requires establishing and developing metrological applications of novel concepts of atom-based sensors. This relies on adapting methods and concepts to use cases, taking into account specific requirements regarding performances and conditions of use. Typically, these activities are undertaken by EURAMET members and by other institutes conducting research on atom-based sensors. They can also collaborate with industrial partners at the forefront of innovation in atom-based sensors and key enabling technologies. They also rely on strong engagement with end users. More specifically, activities will aim at the following goals:

- To engage with user and stakeholder communities to define use cases and their related requirements. To develop methods and concepts to adapt atom-based sensors to these requirements and conditions of use (e. g. outdoor, space, microgravity, in vitro, and in vivo). To design and implement proof-of-concept experiments that will provide benchmarks for these relevant use cases. For this activity, collaborations and partnerships between EURAMET members and members of user communities will be sought and developed.
- To further develop concepts and methods using multiple sensors and sensor arrays in ways which anticipate fully developed use of atom-based sensors. Such goals could be, for example, to address and optimize coverage of large areas, the detection of spatial derivatives of observables, or to provide particularly relevant information in noisy environments.
- To make initial demonstrations and validations of in-field applications that correspond to relevant use cases, based on ruggedized sensor prototypes. To disseminate the results into the relevant communities and their organizing bodies in the view of having these novel methods evaluated and adopted.

5.1.4 Experimental realizations

Fundamental metrological capabilities of novel atom-based sensors must be established prior to considering metrological applications. This activity is at the heart of the mission and expertise of EURAMET members. Achieving this goal will rely on the following activities:

- To develop metrology for key enabling technologies. EURAMET members and their partners will develop characterisation and validation methods for corresponding sub-systems and systems. They will support industry by developing capabilities to test systems and sub-systems developed by industry. In some specific cases, they may also directly conduct research to develop these novel technologies. Where applicable, they will support the standardization of enabling technologies for atom-based sensors
- To develop and validate sensors with improved sensitivity. EURAMET members and their partners should demonstrate or validate the sensitivity of atom-based sensors, based on its own primary references and state-of-the-art prototype sensors
- To develop and validate sensors with improved accuracy. EURAMET members and their partners shall demonstrate or validate accuracy of atom-based sensors, based on its own primary references and state-of-the-art on prototype sensors. To this end, in particular and in line with their core mission, EURAMET members and their partners should develop and compare their own state-of-the-art reference sensors. They should establish and maintain international equivalence and traceability to SI units.
- To establish and promote comparison frameworks (protocols, methods, etc.) for novel atom-based sensors.

5.1.5 Enabling science and technology R&D

Basic research on atom-based sensors and technologies are needed to realize the full potential of these sensors; particularly via the deepest exploitation of fundamental quantum properties. EURAMET members will establish collaboration with the academic research groups most advanced in investigating fundamental concepts relevant to the science of measurements. Joining the expertise of these groups and of EURAMET members will be paramount for identifying the most promising approaches. To this end, EURAMET members and their partners, both from the academic sector and in industry, will undertake activities listed below.

- To conduct research on the use of quantum-engineered states that can improve quantum sensors. This should include research on fundamental concepts and methods for generating and using entangled states. Novel methods should not compromise sensor characteristics (in particular accuracy, long term stability), and this will be considered from the start. All possible approaches can be considered, such as interactions, quantum feedback/control, projective measurement and weak measurements. These activities are largely conducted by partnerships of academic research groups already involved in this research. Specific examples of topics to consider are spin-squeezing, cavity-assisted non-destructive detection, 1-axis/2-axis twisting Hamiltonian, non-linear matter wave mixing, and quantum logic assisted detection.
- To develop components and devices for quantum clocks and atomic sensors. EURAMET members and their partners, together with EMN-Q industrial stakeholders, should identify needs, define requirements and trigger developments. EURAMET members should do their own internal development when solutions are lacking or when they are better positioned than other parties. When suitable, EURAMET members and their partners should develop capabilities to test and validate these technologies to facilitate the creation and growth of industrial supply chains for quantum atomic sensors. Examples of technologies to address include spectroscopic grade lasers, ultralow noise detectors, ultra-stable cavities, low

perturbation cryogenic systems, hybridization methods between quantum and conventional sensors, neutral atom traps/chips, (multi)-ion traps, active and passive photonic components, both digital and analogue compatible ultrahigh vacuum technology (e.g. non-magnetic), compact setups with integrated optics, and fibered, high-power,, fast and agile low noise electronics.

- To develop relevant fabrication processes, such as miniaturized atom cells, atom chips, atom traps, photonic integrated circuits with novel proper characteristics and capabilities, and the deterministic implantation of impurities in solid states. Based on the needs of stakeholders and on industrial developments, metrological characterisations and services will be developed with the contribution of EURAMET members to support these fabrication processes and their integration with supply chains.
- To investigate advanced concepts for atom-based quantum sensing. Examples include remotely entangled sensors using quantum communication methods or non-destructive detection, quantum logic detection extended to many atoms/ions and atomic phase lock via weak quantum measurements. These activities will typically rely on strong engagement of EURAMET members with academic research groups.

5.2 Quantum clocks and atomic sensors: roadmap

Roadmap of the quantum clocks & atomic sensors section of EMN-Q concerning quantum sensing.