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#Standards4Quantum

Making Quantum Technology Ready for Industry

Putting Science into Standards

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Contents

Foreword

On 28 March 2019 for the first time nearly 80 quantum physicist and experts from different European countries working in different quantum disciplines gathered at the 6th 'Putting Science into Standards' Workshop to discuss how to bring their inventions to the market to complete the pathway of innovation.

More than 6 years ago, the European Committee for Standardization, the European Committee for Electrotechnical Standardization and the Joint Research Centre of the European Commission initiated the Putting-Science-Into-Standards annual workshop series, bringing the scientific, industrial, and standardisation communities together.

These workshops aim at facilitating the identification of emerging science and technology areas that could benefit from standardisation activities to enable innovation and promote industrial competitiveness. Six workshops have been held since 2013 in different fields of science, with the most recent one organized in Brussels on 28-29 March 2019 on Quantum Technologies.

This year's Putting-Science-Into-Standards Workshop on Quantum Technologies anticipated future standardisation needs in quantum technologies and kick-started a forum for the discussion of priorities, particular technologies and the drafting of a potential standardisation roadmap.

The Quantum Technology Flagship and its sponsor European Commission's Directorate-General Communications Networks, Content and Technology profited from the Joint Research Centre's unique position of being on the one side integrated in the Quantum Flagship science community, and on the other side active in technical committees of European and International Standardisation Organisations.

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The workshop would not have been a success without the contribution of Christian Goroncy (DIN), Daniela Abetung, Angel Alvarez Martinez, Sofia Pereira, Alexandre Gerez (all JRC), Ashok Ganesh, Christine Van Vlierden and Els Somers (all CEN-CENELEC).

The workshop participants validated the workshop report and its conclusions and additional comments were included.

Abstract

The Quantum Technologies Flagship, officially launched on 29 October 2018 in Vienna, is a EUR 1 billion initiative, supported by the European Commission and Member States, funding over 5,000 of Europe's leading Quantum Technologies researchers over the next ten years and aiming at placing Europe at the forefront of the second quantum revolution. Its long-term vision is to develop a quantum web, where quantum computers, simulators and sensors are interconnected via quantum communication networks. This will help kick-starting a competitive European quantum industry transforming research results into commercial applications and disruptive technologies.

The Joint Research Center (JRC) in cooperation with the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC), European Commission's Directorate General Communications Networks, Content and Technology (DG CNECT), and the German Institute of Standardisation (DIN), organised in Brussels on 28-29 March 2019 the Putting-Science-Into-Standards (PSIS) workshop on Quantum Technologies. The PSIS workshops is an initiative that brings together researchers, industry and standardisers with the purpose of facilitating the identification and screening of emerging science and technology areas that can be introduced early into the process of standardisation to enable innovation.

The experience with the innovation impact pathway of the Graphene Flagship that combined technology push and market pull by working with industry stakeholders was used to demonstrate the benefit of a strategic use of standardisation to increase technology readiness levels and reach the market.

The participants of the workshop identified aspects that would benefit from standardisation activities in three main areas: (i) Quantum Key Distribution and quantum-safe security, (ii) Quantum metrology, sensing and imaging, (iii) and Quantum computing and internet. Several existing standardisation activities focussing on quantum enabled security techniques, quantum computing and communication were also mapped. With the direct involvement of the participants, the workshop prepared the ground towards a roadmap of additional pressing technology fields where standardisation could add value to the deployment of Quantum Technologies in industrial applications, including security, sensing, imaging and measurement.

An active dialogue between the communities of researchers and standardisers as well as a continuous interchange with the Quantum Technologies Flagship would be beneficial for future interactions and cooperation. The Standards, Innovation and Research Platform (STAIR / CEN and CENELEC) methodology could constitute a straightforward approach to host interactions between the communities of researchers and standardisers.

Next steps would be to start an interaction (e.g. a cooperation agreement) with the Quantum Flagship and in particular with the recently (April 2019) launched Coordination and Support Action of the Quantum Flagship. As concrete actions for standardisation, the workshop suggested to focus on the standardisation of a quantum technology terminology and on the development of an EU standardisation roadmap for Quantum Technologies. These could be addressed by a European Committee for Standardization workshop or by a focus group.

1 Putting Science Into Standards

The 'Putting Science into Standards' (PSIS) workshop initiative was launched by the Joint Research Centre (JRC) together with the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC), and organised with the contribution of relevant services of the European Commission and National Standardisation Bodies. These workshops bring the scientific and standardisation communities closer together by anticipating and bringing new issues requiring standards to the standardisation community.

The initiative is in line with article 9 of the Regulation (EU) No 1025/2012, which states that the Commission's research facilities shall '[…] provide European standardisation organisations with scientific input, in their areas of expertise, to ensure that European standards take into account economic competitiveness and societal needs such as environmental sustainability and safety and security concerns'. Five workshops have been organised between 2013 and 2018:

- Eco-Innovation: bringing together the scientific, business and standardisation communities (Brussels, 24-25 April 2013)
- Power-to-Hydrogen and Hydrogen enriched compressed natural gas (Petten, 21-22 October 2014)
- Evidence-based quality assurance - an example for breast cancer (Ispra, 20-21 October 2015)
- Driving towards decarbonisation of transport: Safety, performance, second life and recycling of automotive batteries for e-vehicles (Petten, 22-23 September 2016)
- Railways of the Future (Brussels, 25 October, 2017)

These workshops are framed within Action 2: 'Linking Research and Innovation with Standardisation', as part of the Joint Initiative on Standardisation (JIS)[1], signed on 13 June 2016 in Amsterdam between the European Commission, the industry concerned, European Standardization Organisations and the standardisation community in general, with the aim at speeding up and better prioritising standard setting across the board, as well as modernising the existing partnership among these actors.

The JIS is part of the Standardisation package adopted by the European Commission on 1 June 2016 with the chapeau Communication 'European standards for the 21st century', expressing its views on a better coherence of the EU standardisation policy, the level of engagement of the European Commission on the JIS, and the link between the overall standardisation policy and other standardisation activities such as ICT priorities for standards and services standards.

Action 2 was led by the JRC. The main objective of the action was to establish a sustainable system that encourages the natural collaboration between researchers, innovators and standardisers (including European Standardisation Organisations) and allowing for the smooth uptake of research and innovation outputs into standardisation.

[1] The JIS is an initiative of DG Internal Market, Industry, Entrepreneurship and SMEs: https://ec.europa.eu/growth/content/joint-initiative-standardisation-responding-changing-marketplace-0_en

2 The PSIS Workshop on Quantum Technologies

The 'Putting Science into Standards' workshop on Quantum Technologies took place in Brussels on 28-29 March 2019. It adopted the structure of the Quantum Technology Flagship around its mission-driven research and innovation domains, representing four major applied areas in the fields of: Communication, Computation, Simulation, Sensing and Metrology.

For the first time, more than 80 Quantum physicist and experts from different European countries working in different quantum disciplines gathered to discuss how to bring inventions to the market, thus completing the pathway of innovation. Planning at an early state and incorporating standardisation can be crucial for accelerating market uptake of research findings.

The workshop set the ground for bringing together the relevant stakeholders in the quantum technology standardisation value chain – research, standardisation, industry and public administrations/institutions – and provided a timely opportunity for a balanced and representative overview on the status quo in Quantum Technologies, and for drawing informed conclusions on a strategic way forward.

Technologies built on the basics of quantum mechanics, occurring on an atomic scale, are approaching markets with the promise to create many new businesses and help solve many of today’s global challenges. These applications will be a pivotal factor for success in many industries and markets. Some of these applications are of strategic importance to Europe’s independence and safety, i.e. in the field of secure information storage and transmission or in creating new materials for energy solutions and medicine.

CEN and CENELEC recognized that in their ranks no Technical Committee or Working Group follows a Quantum technology specialisation. The Standards Organisation expressed concerns about a potential lack of standardisation activities around industrial products that are based on Quantum technology. In order to accelerate the market uptake of technologies that arise from Quantum physics and to create the expertise in the organisational structure in CEN and CENELEC, the European Quantum Technology Flagship was approached for potential collaboration.

The Quantum Technology Flagship[2] sees its beginning in the 2016 published Quantum Manifesto, signed by 3,400 scientists calling for a quantum technology initiative coordinated between academia and industry to move quantum technologies from laboratory to industry and to educate quantum technology professionals in a combination of science, engineering and business (de Touzalin, Heijman, Cirac, Murray, & Calarco, 2016). With the launch in October 2018, the Flagship funds research and innovation.

The concept of 'Putting Science into Standards' on Quantum Technologies was launched at the Quantum Flagship Kickoff Conference in Vienna on 29-30 October 2018 and first contacts were established. This led to a JRC-led special session on standardisation during the first European Quantum Technologies Conference 2019 in Grenoble (France) on 18-22 February, with contributions from CEN and CENELEC, and Deutsches Institut fuer Normung (DIN).

CENs President Technical Ruggero Lensi and JRC's Deputy Director General Maive Rute, laid out how standardization can be useful to the quantum innovation process and what standardisers can do for the quantum science community.

The program of the 'Putting Science into Standards' Workshop on Quantum Technologies is given in Annex 1. Session 1 recapitulates the political and industrial priorities of the Quantum Flagship, and of how standards contribute to the market uptake of research and innovation. Sessions 2, 3 and 4 focus on: quantum security and safe communication;

[2] The Quantum Technology Flagship (QT Flagship), €1 Billion, 10-year long-term research initiative funded by Future and Emerging Technologies Flagship programme

metrology, sensing and imaging; and opportunities in other quantum fields, such as quantum internet, computing and ion trapping. These three sessions aimed at preparing the ground towards a roadmap addressing the most pressing technology fields where standardisation can support the deployment of quantum technologies in industrial applications including those for security, sensing, imaging and measurement.

3 Session 1: A revolution, without standards?

This chapter summarises the key messages and outcomes of the first day of the workshop that provided the political background and the views of industry, and more in general of the standardisation sector.

Since many quantum technology areas are advancing on the Technology Readiness Level scale, it was considered important to prepare the field for standardization activities, to facilitate and accelerate market uptake of quantum technology. Quantum technology is entering the political arena of various economies around the world, with private and public initiatives entering into the Quantum race.

In the following sub-sections are reported the lessons learnt and successes from the Graphene Flagship, showing how pre-normative research and standardisation activities can lead to the smooth innovation process of a new technology to positively impact the industrial sector in Europe.

3.1 Quantum race: initiatives in the world

After two decades of work on inventions in the laboratory, quantum science is about to become a technology that will impact our everyday life. Governments and companies worldwide, including Google, Microsoft, Intel, Toshiba, Thales, ID-Quantique, Oxford Instruments, Alpine Quantum Technologies (AQT) and IBM are investing substantially to unleash this potential. Several countries have positioned themselves to enter into the quantum race to be leaders in areas such as computing, communications, sensing and imaging.

In order to continue at the forefront of this emerging technology and to participate in a global quantum industry, Europe has committed in making the best use of its excellence in science and engineering. The European Commission launched in October 2018 its EUR 1 billion Quantum Technology Flagship on a 10 year timescale. It consists of a set of research and innovation projects selected through a peer-review process.

EU Member States have also set aside individual public funding for research in quantum technology. For example, in September 2018, the German federal government announced a EUR 650 million four years programme for quantum technology. The German strategy targets several aspects of quantum computing beyond fundamental science, from basic R&D to real-world commercialisation. The UK government launched already in 2013 a GBP 270 million five-year investment on quantum technology. Further funding of GBP 80 million was allocated in 2018. A key feature of the UK strategy is the establishment of four 'hubs' for computing, communications, imaging and sensing, including the National Quantum Computing Centre, with the goal of building the world's first universal quantum computer. The Netherlands invested EUR 135 million in QuTech, the quantum technology institute which aims to develop the building blocks for the first quantum computer in the coming 10 years. Italy, Austria and France initiated substantial national Quantum initiatives.

The upcoming national quantum plan for China will be at least of the same order of magnitude as the European Commission's Flagship. China is building the National Laboratory for Quantum Information Sciences in Hefei, with over USD 1 billion in initial funding (Kania, 2018). Chinese companies, including Baidu and Alibaba, have established their own initiatives in quantum computing, attracting top researchers to their teams. Alibaba plans to invest USD 15 billion into disruptive technologies in the years to come (Kania, 2018b).

In December 2018, the United States' President signed a bill into law that devotes more than USD 1.2 billion to a national effort dedicated to quantum information science over the next 10 years. The National Quantum Initiative Act represents a push to keep up with China and other countries in developing technologies such as quantum computing, quantum cryptography and quantum communication. A great advantage in the U.S. is the capacity of the private sector to complement publicly funded efforts in quantum information science. There is a growing industrial interest in quantum information technology, including efforts at Google, Honeywell, Hughes Research, IBM, Intel, Microsoft and Northrop-Grumman. Several start-up companies, funded by venture capital and other equity sources have been established (Monroe, 2017).

The National Institute of Standards and Technology (NIST) published a call for standards in Post Quantum Cryptography, for which 69 algorithms were received in the first call for proposals, and 26 algorithms remained after the second call. These algorithms should replace most vulnerable current standards and establish keys used in public-key cryptography.

Two standard setting activities in NIST are the superconducting photon detectors and the miniature initiative 'NIST on a Chip', which integrates a chip-scale radiometer, a quantum-based ampere and a high power laser metrology sensor.

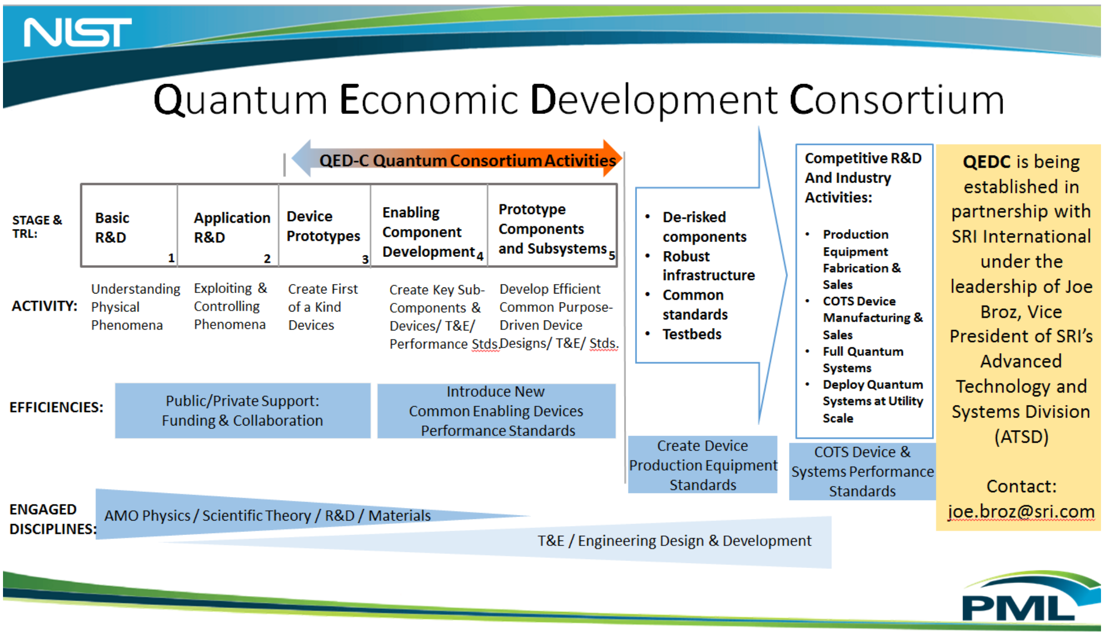

Figure 1 Impact pathway of the Quantum Economic Development Consortium of the Physical Measurement Laboratory of NIST presented during the workshop (Barbara Goldstein presentation)

The Quantum Economic Development Consortium, a partnership associated to NIST Physical Measurement Laboratory, uses a theoretical framework (Figure 1) to enable the development of technologies, based on standards established at different Technology Readiness Levels of the technology.

3.2 European quantum fleet

The EU's long-term vision is the development of the Quantum Internet, where quantum computers, simulators and sensors are interconnected via quantum networks distributing information and quantum resources. The Quantum Technologies (QT) Flagship is the EU instrument to achieve this. It is a large-scale, long-term research initiative pooling resources in support of a commonly agreed science and technology roadmap, aiming to foster world-leading knowledge, technologies, and open research facilities for quantum in Europe. To unlock the full potential of QT, accelerate their development, and bring commercial products to the market, three goals underlie the QT Flagship's vision:

- Consolidate and expand European scientific leadership and excellence in quantum research;
- Kick-start a competitive European industry in Quantum Technologies to make Europe a leader in the future global industrial landscape;
- Make Europe a dynamic and attractive region for innovative research, business and investments in Quantum Technologies, accelerating their development and take-up by the market.

To prepare the QT Flagship, the European Commission appointed an independent committee consisting of 12 distinguished academic members and 12 high-ranking industry members (from both large multi-nationals and Small and Medium Sized Enterprises (SMEs)), as well as one observer. In September 2017, the committee delivered a final report[3] proposing a strategic research agenda setting the ambitious but achievable goals for the Flagship's ten-year lifetime, and detailing them for the initial three-year ramp-up phase. Figure 2 shows the structure of the agenda, identifying four major applied areas in the field (vertical): Communication, Computation, Simulation, as well as Sensing and Metrology, which should build on a common basis of Basic Science (horizontal).

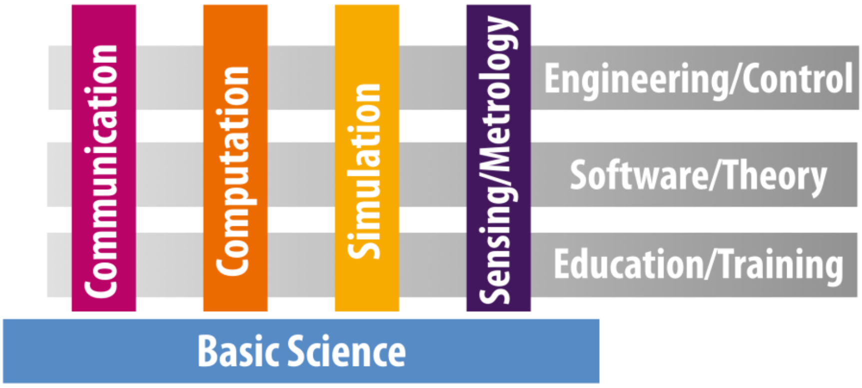

Figure 2 Structure of the Strategic Research Agenda[3]

Figure 3 illustrates the corresponding time scale towards a European Quantum Technology ecosystem, which includes preparatory steps (before 2018), the ramp up phase (between 2018 and 2020), and the full implementation phase (after 2020) together with the corresponding actions and call for proposals in each phase.

In the ramp up phase, an additional call focusing on semi-conductor quantum computing and quantum software development (EUR 19.70 million), plus a call for a Coordination and Support Action on international cooperation (EUR 0.5 million) are under discussion for the Work Programme 2020.

Key to the QT Flagship initiative's added value is its pan-European dimension that will allow to, *inter alia*, integrate national and European metrological and standardisation institutes in developing quantum-based standards for the most mature technologies. In this context, the project Coordination and Support Action[4] (EUR 2.7 million) is the central Coordination and Support project of the QT Flagship, responsible to identify and coordinate the relevant standardisation and intellectual property protection actions.

Within the European QT ecosystem, other investment efforts exist, notably at the national level. A prominent example is the European Research Area Cofund Action in

[3] https://ec.europa.eu/digital-single-market/en/news/quantum-flagship-high-level-expert-group-publishes-final-report

[4] See https://ec.europa.eu/digital-single-market/en/content/qflag-quantum-technology-flagship-coordination-and-support-action

Quantum Technologies (QuantERA) initiative, bringing together 31 organisations from 26 countries together with the European Commission supporting international research projects in the field of Quantum Technologies, with EUR 36 million invested so far.

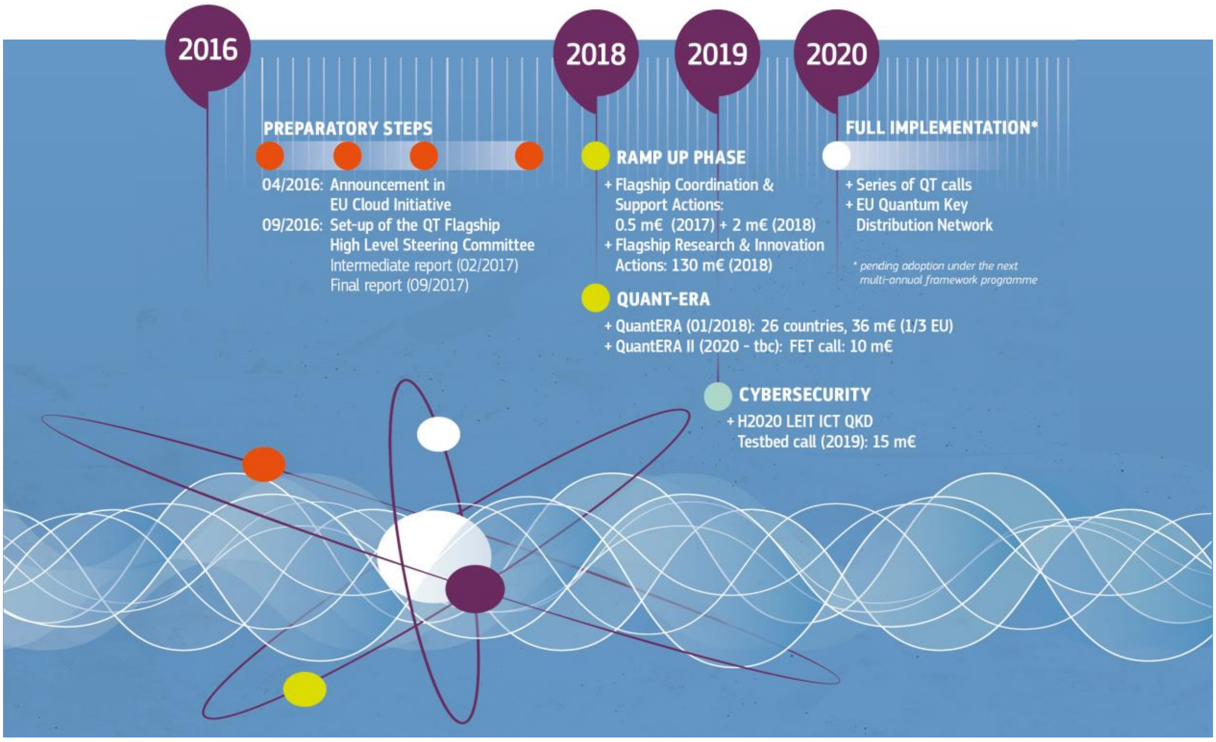

Figure 3 Time scale towards a European Quantum Technology ecosystem

Currently under discussion, the next multi-annual financial framework for the period 2021 to 2027 will have a place for QT, and the QT Flagship will continue under Horizon Europe[5], the next research and innovation framework programme. In addition, the Digital Europe Programme[6], the first ever proposed digital capability building programme of the Union for the period 2021 to 2027, will support the development of first quantum computers and their integration with high performance computers, as well as the development of a pan-European quantum communication infrastructure guaranteeing full security of communications and critical infrastructures.

3.3 Standardisation processes

Regulation (EU) No 1025/2012 defines a 'standard' as a technical specification, adopted by a recognised standardisation body, for repeated or continuous application, for which compliance is not compulsory. A standard can be an 'international standard' (when adopted by an international standardisation body[7]), a 'European standard' (when adopted by a European standardisation organisation[8]), but also a 'national standard' (when

[5] See https://ec.europa.eu/info/designing-next-research-and-innovation-framework-programme/what-shapes-next-framework-programme_en

[6] See https://ec.europa.eu/digital-single-market/en/news/commission-welcomes-agreement-digital-europe-programme-2021-2027

[7] International Standardization Organisation (ISO); International Electrotechnical Commission (IEC); International Telecommunication Union (ITU)

[8] European Committee for Standardisation (CEN), the European Committee for Electrotechnical Standardisation (CENELEC), and the European Telecommunications Standards Institute (ETSI)

adopted by a national standardisation body). As stated by DIN's Innovation Department, standards exist in many forms and shapes.[9]

Standards bring a number of benefits with them. They enable to reduce costs and improve efficiency, ensure the quality and safety of products and/or services, comply with relevant legislation including EU Regulations, satisfy customers' expectations and requirements, enable to access markets and sell to customers in other countries, achieve compatibility/interoperability between products and/or components and gain knowledge about new technologies and innovations.

CEN and CENELEC have agreements with ISO and IEC, respectively, which common European and international standards can be developed in parallel, thereby avoiding duplication of work.

Standards are developed through a process based on important principles such as transparency, openness, consensus and application, as well as independence from special interests. Unlike laws, standards are not legally binding. Their use only becomes binding when this is stipulated in legislation or in a contract.

However, the market may be more liberal in its use of the term standard and may also refer to the specifications produced by the thousands of industry- or sector-based standards organisations as standards. The organizations that develop these are commonly called Standards Developing Organizations (SDOs).

Recognised standardisation bodies may also publish specifications that are not standards, because they cannot claim to represent the full consensus of all interested parties, such as Technical Specifications.

For experimental areas, where a standard would be premature, the standardisation bodies have extended their portfolio of deliverables to offer a low threshold entry into their system such as DIN SPECs, European Telecommunications Standards Institute (ETSI) Group Specifications, and CEN-CENELEC Workshop Agreements. A key characteristic of all of these is that the development time of the resulting specification is much faster. While the standardisation processes in CEN or CENELEC are organized based on the national delegation principle, the CEN-CENELEC Workshop Agreements (CWAs) are developed through direct participation of the interested companies or technology organizations. The CWAs (other examples are the pre-standard in DIN SPEC and the ETSI Group Specification) can be used as a basis for developing a full standard when the technology matures.

3.4 Standardisation lessons learnt from the Graphene flagship

The Graphene Flagship[10] was launched in 2013 to support the industrialization of graphene technologies. The Graphene Flagship has been widely recognised for its success in integrating an innovation plan within the strategy of the Flagship. Standardisation activities were initiated following the open competitive call 'Standardisation'[11].

In 2014 the Graphene Flagship Standardization Committee had its kick-off. A formal so-called cooperation between the Flagship and the International Electrotechnical Commission (IEC) Technical Committee (TC) 113 was established, offering the Flagship the right to initiate and lead projects in the Technical Committee.

[9] Note: In the world of metrologists, standards are fundamental references for a system of weights and measures, against which all other measuring devices are compared. To avoid confusion, the community of metrologists therefore talks about documentary standards.

[10] Graphene Flagship is a Future and Emerging Technology Flagship by the European Commission with a budget of €1 billion

[11] http://www.graphenecall.esf.org/about-the-call/gf01-standardisation.html

While in the beginning the Flagship project structure was centred on graphene material science, with standardisation as a later 'add-on', standardisation has now become an integral part.

Within IEC/TC 113, the work is taking place in Working Group 8 “Graphene related materials/carbon nanotube materials”, with 96 technical experts from 11 countries including USA, Canada, China, Japan, Korea and more than 30 current standardisation projects.

Comparing the state of maturity of graphene Nano electronics at the launch of the Graphene flagship with Quantum Technologies today, there are a number of commonalities such as the Low Technology Readiness Level (TRL) and the cross sectorial character. Future standards expected within the scope of international standard organisations and the presence of strong players from East Asia in international standardization efforts, demand Europe to maintain a strong influence in these technical committees, in order to ensure that resulting standards support the accelerated uptake of Europe’s new developed technologies into the global market. In other words, those stakeholders that are active in standardization may, depending on the circumstances and competence, influence the standard development process such that their technologies or products are favoured by the developed standard.

It was suggested to establish a standardisation activity inside the Flagship with an own standardisation strategy (for which support by the Flagship management and the EC administration would be essential) and to cooperate with international standard organisations if appropriate to benefit from the advantage of international standards compared to consortia standards. Further participants contemplated that in terms of such cooperation a 'QT Flagship Standardisation Organisation' within the Flagship Consortium could rapidly transfer 'standards' to the appropriate international standards organisations (depending on the scope of each standard).

As first potential activities, the standardisation of terminology (similar to ISO Technical Specification 80004-13:2017, 'Nanotechnologies - Vocabulary - Part 13: Graphene and related two-dimensional (2D) materials') and the development of an EU standardisation roadmap for Quantum Technologies were proposed.

For such a 'QT Flagship Standardisation Organization' within the Flagship Consortium, a set of directives / rules would be needed to ensure a fair standard development process, as well as an overall systematic approach/process to ensure a technically sound set of standards suitable for CEN, CENELEC, ETSI, IEC, ITU and ISO and of course, sufficient resources.

3.5 Standardisation lessons learnt from the private sector

The two lessons learnt from ID-Quantique (IDQ)[12], a spin-off company formerly linked to the University of Geneva, are that i) without certification there may be no market for security and other quantum devices, and ii) certification in turn requires standardisation.

Standards represent the ‘rules’ that define the proper operation and interaction of a device within a larger system or network. As such, standards play a very important role not only for individual consumers but also for companies and industries. Without these basic rules, the development of interoperable ever more complex systems would be a challenging task. One of the primary drivers of standardisation is, hence, usability.

The main objectives of standardisation from a private sector perspective are the following:

[12] ID-Quantique was founded in October 2001 and built the world's first quantum random number generator (RNG). Shortly after, IDQ developed its first Quantum Cryptography (QC) prototype. In 2003 IDQ's first single photon detector was launched. Today IDQ collaborates with aviation agency EASA, the British (BT) and the Dutch (KPN) telecommunications companies and ships more than 100 QKD units.

- Safety
- Proper operation
- Interoperability
- Security

However, IDQ still uses non-quantum specific standards to provide safety, proper operation, interoperability and security. For example, standards for True Random Number Generators do exist, but there are no specific standards for Quantum Random Number Generators. This shows a clear need for developing quantum specific standards.

Moreover, telecom operators are likely to embark soon on new technologies such as 5G or the Internet of Things (IoT) that require the support of large interconnections for which standards are indispensable.

Unpredictability of physical entropy is due to the source not being well defined or known, whereas unpredictability of quantum entropy source comes from a lack of complete definition of this source (compare with chapter 5.1.4 i.e. single photon time-of-arrival detection, chaotic lasers, and amplified spontaneous emission (Hart, et al., 2017)). It would be important to define a standard to highlight this substantial difference.

The Quantum Initiative Alliance, made of companies working on Quantum Technologies, established a first version of standards, now under study at ITU Study Group 17.

Thales confirmed that standardisation is recognised as key in the innovation process, in particular by the industry, and goes along with strategic advantages.

Furthermore, in the private sector standardisation can help to protect EU intellectual properties: often standards comprise technologies that are patent protected. The standardisation community has developed rules and practices to ensure the efficient licensing of standard-related patents. While patent protection drives innovation by incentivizing investment in R&D, standardisation drives innovation by establishing interoperability between products, or facilitating market adoption of innovative technologies. Licensing and standardisation are forms of collaboration. To get maximum benefits for society, potential market failures, such as information asymmetry, market power and externalities, need to be overcome. The protection of knowledge prevents a possible 'brain drain' from EU to other competitor countries and ensures to promptly capitalize all the funding invested in quantum-oriented basic science and fundamental research at the moment in which Quantum Technologies based first commercial products will be available on the market.

Several technological advantages associated to standardisation were identified:

- Reliability and quality of products is ensured;
- Equipment can be used in all fields of quantum technology;
- Highly demanding quantum qualification can be used outside of the quantum field;
- Base for Key enabling technologies for different technology fields is provided;
- Usage methods and protocols, in relation with specific environments are established;
- Basis of absolute, traceable, high-performance measurements is provided;
- Fundament for Mutual Recognition Arrangement, Calibration and Measurement Capabilities and traceability chain is established;
- Basic research can be promoted through implementation of large-scale experiments.

4 Session 2: Quantum security meets standardisation

This chapter summarises the content of the presentations and discussions of the workshop in the field of secure quantum communication and in particular on the Quantum Key Distribution (QKD)[13] method.

In the QKD area, there are many different standardisation initiatives from European as well as international standardisation organizations, signalling the maturity of this technology field. With the exception of QKD, the maturity level of quantum communication is currently very low on a TRL scale, with not many standardisation activities.

4.1 Progress of standardisation activities in quantum security fields

In 2008, ETSI was the first Standards Development Organization (SDO) to introduce QKD standardisation activities with the work of Group Specification[14] QKD 002 providing an overview of possible application scenarios in which QKD systems can be used as building blocks for high security information and communication technology systems. QKD requires both a truly random key to encrypt a message, usually produced with a Quantum Random Number Generator, and a quantum key distribution channel to communicate the random key; both components contribute to provide a quantum-safe security solution for communication and are the subject of standardisation efforts.

Since 2008, standardisation activities in the QKD area have significantly grown and during the workshop, the following SDOs currently working on QKD were identified:

- ETSI Industry Specification Group on QKD,[15]
- Working group on security evaluation, testing and specification of the ISO/IEC Joint Technical Committee 1/Sub-committee 27[16] ,
- Global Quantum Industrial Partners a SK-Telecom lead consortium aiming to promote ICT standards, interoperability and commercialisation.
- The Quantum Alliance Initiative[17] with Hudson Institute, and
- The study groups 13 and 17 on 'Future Network' and 'Security' of the International Telecommunication Union.

Current areas of QKD standardisation efforts include those listed below in no particular order of importance:

- Security – certification of QKD for market uptake;
- Interoperability – Integrate QKD-networks with other networks;
- Metrology – Specifying quantum-specific components;
- Usage policies – Embedding and use of applications.

In what follows, a brief summary of the speakers' intervention is presented[18].

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[13] QKD is a secure communication method, which implements a cryptographic protocol involving quantum physics. It enables two parties to produce a shared random secret key, which can be used to encrypt and decrypt messages. An important and unique property of QKD is the ability to detect the presence of any third party trying to gain knowledge of the key.

[14] ETSI GS QKD 002

[15] ETSI Industry Specification Group on QKD

[16] ISO/IEC JTC 1/SC 27 WG 3 'Security evaluation, testing and specification'

[17] Quantum Alliance Initiative

Since 2018, the market has invested in Quantum Key Generation, Quantum Key Distribution (Quantum Cryptography) and Quantum-Safe Network Encryption solutions for data protection with long-term sensitivity. Moreover, the QKD market is increasing and may reach an estimated volume of USD 15 billion in 2026. China, Europe, UK and South Korea are in the process of creating 'quantum backbones' that will increase awareness of quantum communication and provide a sizeable market opportunity.

The International Telecommunication Union SG13 works on general functional requirements for QKD networks. This work incudes so far the study of a functional framework, the description of a generic functional architecture and a specific focus on key management function.

The contribution to ETSI of the Austrian Institute of Technology focuses on QKD, covering the topics of QKD Key delivery and application interfaces. Future standards for QKD use-cases and application interfaces should include: (i) data services (QKD for B2B, distributed storage, High Performance Computing), (ii) securing critical infrastructures (telecommunication networks, energy providers), (iii) health applications (storage of highly personal data, transmission of patients' data), (iv) Government services (e-Gov, high-security channels for e.g. embassies, head of states, negotiators).

The areas of activity of ETSI's Industry Specification Group (ISG) on QKD include the following:

(i) Security – definition and requirements, modelling, implementation security of quantum cryptography including specific design guidance and passive countermeasures against, for example, Trojan horse attacks. Work towards certification involving national security authorities and certification lab to ensure quality;

(ii) Interoperability – currently at the level of classical interfaces specific implementation, protocol, data formats etc.; integration of QKD with, for example, telecommunication networks, and Software Defined Networks;

(iii) Metrology of components and systems – specific characterization procedures required for security specifications, characterisation of complete QKD transmitter modules, single-photon measurements where few standards exist.

Two platforms for standardisation activities were identified. The first is a Joint Technical Committee of the International Standardization Organisation[19] offering services for aspects related to security evaluation, testing and specification for QKD components, including optical components and classical cryptographic components. The second is a Joint Technical Committee of the European Standardisation Organisation[20] providing a collaboration space platform for cybersecurity and data protection.

Defining attack methods and security specifications is expected to help QKD manufacturers to improve their design and implementation of QKD products, and to evaluate and test the security of QKD modules.

4.2 Discussion

It is generally recognised that standards bring benefit both to the technology field they apply to and to the economy in terms of growth. It is never too early for standardisation activities, and Standards Development Organizations such as CEN and CENELEC recognise this fact by allowing for a simplified procedure that does not deliver the complete standard but that has the advantage of being easier to access as to encourage

[18] for more details please refer to ftp://ftp.cencenelec.eu/EN/ResearchInnovation/PSIS-Standards4Quantum/ or https://circabc.europa.eu/ui/group/f98220f3-02e9-4cac-96f3-1f12bd8a8e7b/library/85fc26b8-1005-4ccf-8fc4-eca9ba925ec2

[19] ISO/IEC Joint Technical Committee JTC1/SC27/WG3

[20] CEN-CENELEC Joint Technical Committee 13 CEN/CLC/JRC 13

early standardisation activities. From a market perspective, a recurrent question from customers is on the existence of standards for QKD or Quantum Random Number Generators, and of any certifications providing trust to customers in the security domain.

The development of large-scale projects such as a pan-European Quantum Communication Infrastructure could greatly benefit from the existence of standardisation activities conducted at an early stage of TRL that could allow reaching consensus among Member States on the technology requirements. In this context, standards could also be useful in procurement processes requiring ad hoc specifications and/or certifications.

Participants reported the case of China, where the Swiss-based company IDQ (50% South Korea Telecom) is the only QKD solution provider being the de facto standard in this region. Therefore, being early players in standardisation for quantum security has brought clear benefits for entering the markey and being competitive overseas.

Moreover, ITU-T aims to absorb all the work done by ETSI in QKD, which led to a debate whether this is beneficial or not for ETSI and its stakeholders such as Toshiba, Huawei, AIT, and metrology institutes. More generally, there was not a consensus among participants on the risk of competition between SDOs driven by conflicting standards.

Another debated point was on the possibility of enhancing classical digital communication standards with quantum features, instead of creating dedicated quantum standards. Despite there was not a consensus among participants on which is the best way to introduce Quantum Technologies in standardisation activities, participants agreed that there is a need for more financial resources for finding novel protocols, new quantum-based standards, and a shared support in the QT Flagship.

5 Session 3: Quantum metrology, sensing and imaging meets standardisation

Quantum physics had its great discoveries in the 20th Century and experienced two revolutions. The first resulted in the application of lasers, microelectronics, superconductors and atomic clocks. The second has been taking place for the last 20 years and is based on the superposition of quantum states and entanglement[21] and has the potential of boosting consumer devices in the fields of navigation, imaging or medical devices, but also to revolutionise the Internet of Things (IoT).

While applications from the first quantum revolution had a broad impact across different sectors, applications from the second revolution are still distant from market reach. The challenges are mainly related to the engineering of robust technologies, as well as to prices, energy consumption and size.

The aim of standardisation in Quantum Technologies is to facilitate the transformation of scientific discoveries and inventions into innovations from which the European industry and the European economy will benefit. The Quantum Flagship differentiates research into four main key fields:

- Quantum specific metrology, sensing and imaging (QMS) applications;
- Quantum computing, aiming to win the race to build the first quantum computer;
- Quantum simulation, enabling second generation modelling;
- Quantum communication, facilitating safe communications and second generation networks.

For all these applications, investments in education, software and theory, but above all engineering and controlling are required. Accordingly, this is being delivered in the field of QMS by four main projects:

- **AsteriQs** exploits quantum sensing based on nitrogen-vacancy-centres to develop precise sensors to measure quantities such as magnetic field, electric field, temperature or pressure;
- **MetaboliQs** uses nitrogen-vacancy-spin transference to nuclear-spins by well-established Nuclear Magnetic Resonance procedures at room temperature to enable safe multimodal cardiac imaging;
- **MacQsimal** develops miniaturised atomic vapour cell-based sensors, aiming for miniaturised and quantum-enabled atomic clocks, gyroscopes and magnetometers, as well as sensors measuring electro-magnetic radiation and gas concentration;
- **iQClocks** makes optical clocks quantum enabled, ultra-precise and affordable. Development of scientific applications such as field-ready strontium optical clock to be benchmarked.

[21] Quantum technologies that are based on single quanta (i.e. a single atom, single ion, a single photon, a single electron, etc.) enabling the measurement and manipulation of individual quantum systems (physically implemented, for example, by means of electronic states of an atom, nuclear spins states, electro-dynamical states of superconducting circuits, or states of polarization of single-photons, etc.).

5.1 Quantum Metrology, Sensing and Imaging applications

Quantum metrology and sensing plays an important role in boosting measurement performance in four main domains: i) Nitrogen-vacancy centres in nanodiamonds, ii) Atomic vapour cells sensors, iii) Ultra-cold atoms for optical atomic clocks / lattice clocks, and iv) Single-photon sources and detectors.

5.1.1 Nitrogen-vacancy centres in nanodiamonds

Nitrogen-vacancy (NV) diamonds, used in a QMS-oriented way, can benefit the measurement of high-precision electric- and magnetic fields, temperature, and pressure. General purpose sensors measure magnetic resonance in medical applications (i.e. for brain imaging, medical diagnostics), semiconductor (i.e. failure analysis), diamond tips, spectrometers, and high dynamics magnetic fields.

NV diamonds, used in a quantum radiometry-oriented way conduct measurements at the single-photon level. Applications can be quantum radiometry (absolute single photon source, absolute spectral photon flux), quantum-enhanced optical measurement, fundamental research and metrology standards (particularly in respect to traceability with International System of Units SI).

The development of these technologies is promoted by AsteriQs and MetaboliQs of the Quantum Flagship. There is a high variety of readiness level among the different technologies in this field and the maturity level is technology dependant.

5.1.2 Atomic vapour cell sensors

Atomic vapour cell sensors conduct high-precision electric, magnetic- and radio frequency fields' measurements. They find application in novel magnetometers that significantly improve medical imaging devices for the diagnosis and therapy of patients with brain disorders. The sensors are also found in autonomous driving, quantum-enabled atomic clocks, gyroscopes, magnetometers, and in sensors measuring electro-magnetic radiation and gas concentration.

The macQsimal project of the Quantum Flagship promotes the development of these technologies. TRL levels are rapidly increasing, with the first microelectromechanical atomic vapour cell applications reaching the market such as waveguide photonics, miniature atomic clocks, chip-scale magnetometers, microwave field imaging, atomic gyroscopes and Rydberg gas sensor.

New functionalities such as laser-machined fibre mirrors, ultrathin cell for microwave imaging or microcells with anti-relaxation coating could be relevant for future standardisation activities.

5.1.3 Ultra-cold atoms for optical atomic and lattice clocks

Ultracold-atom optical lattice clocks are at the same time genuine atom interferometers and also atomic sensors leading to improved time and frequency standards (traceability), and to measurement of length, radio frequency fields, temperature, and magnetic fields. Sensors find applications in global navigation satellite systems (i.e. Galileo, GPS, GLONASS, etc.), in the financial sector (time stamping), in telecommunication (synchronization), earth science and monitoring, high accuracy atomic references and laser-cooled atomic frequency standards that are used for time scales, in industrial cold-atom gravimeters, as well as in the fully industrialized cold-atom space clock.

The EMN-Q European Metrology Network for Quantum Technologies adds potential fields for standardisation in the field of Quantum clocks and sensors. Absolute, traceable and high-performance measurements for characterising the new quantum devices need to be defined. Specifically, the novel field of metrology for quantum technologies needs mutual Recognition Arrangement and Calibration and Measurement Capabilities. A traceability chain may be established for benchmarking based on international key comparisons and building on experiences generated in the European Association of National Metrology Institutes (EURAMET).

5.1.4 Single-photon sources and detectors

Quantum radiometry (or photon-based radiometry) is the science of measurement of radiation by counting (single) photons.

Applications range from almost fundamental research (quantum optics, computing and quantum metrology) to areas entering the market like quantum key distribution and quantum-enhanced optical measurements, to already established applications (i.e. the operation of single-photon detectors in biology and astronomy).

Essential standardisation work (in the sense of metrology) is needed to define measurements with respect to traceability to national, primary standards. Of particular importance are traceable, absolute measurements, i.e. detection efficiency, timing jitter, after-pulsing probability and deadtime of single-photon detectors. Also important are absolute spectral photon flux, spectral power distribution and single-photon purity of single-photon sources, which might become new primary sources in the future.

5.2 Needs and opportunities for standardisation in metrology, sensing and imaging

5.2.1 What standards and how they benefit?

Standards in the field of QMS are understood in various ways. Quantum Technology has enabled the discovery of new magnitudes of fundamental measurements and a redefinition of reference standards of the International System of Units (SI). The metrology vocabulary defines the fundamental reference standards of weight / measurements (SI), while the standardisation vocabulary generally leads to documentary standards.

Due to the wide variety of quantum applications and their use-cases in QMS, there is a need to establish several standardisation groups each focusing on a specific sensor application or technology. This contrasts with the field of QKD, where TCs can operate on a wide range.

QMS promotes Quantum Technologies spread over all TRL. Standardisation activities are hence required along all TRLs including all kinds of formats (vocabulary, terminology and European Standard Operational Procedures (SOPs)).

Workshop participants recommended that standardisation should effectively rationalise efforts. Technical Committees should be associated to specific traditional instruments recently upgraded to Quantum-enabled technologies, and in parallel create new exclusive quantum technology TCs where necessary.

More specifically, there is an urgent need to set documentary standards for nitrogen-vacancy centres in Nano diamonds and for atomic-based sensors.

5.2.2 How and where can standardisation be conducted?

Most of standardisation in QMS is conducted in specialised working groups, such as the ETSI ISG Quantum Key Distribution. As standardisation essentially represents a form of collaboration, it requires international cooperation to foster discussion and exchange of information to ensure that Europe is part of the game.

Standardisation in the area of QMS may initially focus on tools for quantum technology where the reliability and reproducibility of materials such as rare-earth ion doped crystals, or quantum grade diamonds, are essential aspects.

In the original sense, 'quantum grade' can be referred for example to Chemical Vapour Deposition methods used in the semiconductor industry to produce high quality, high-performance, solid materials, where the quality categories are: (i) Optical Grade, (ii) Electronic Grade, and (iii) Quantum Grade, meaning highest quality, with isotopic selection.

During the workshop the 'Quantum Grade' was used in a broad sense related to enabling technologies:

Tools for quantum technology

- Material: need for reliability, reproducibility;
- Rare-earth ion doped crystals;
- Quantum grade diamond.

Technological tools

- Deterministic implantation of NV;
- Ideal quantum tool.

'Quantum grade' enabling technology

- Very low noise electronics;
- Highly stable Microwave driving sources.

Technological tools, as the deterministic implantation of NV, are also of interest. Standardisation could thus be a beneficial output from the MetaboliQs project, which promotes features of diamond NV that will ultimately lead to advance cardiac hyperpolarized magnetic resonance imaging. This can be made possible by atomically engineered diamond material (quantum-grade diamond), including 12C isotopic purification, precise control of nitrogen defect concentration and the nanofabrication of the diamond surface. MetaboliQs provides the 'Quantum grade' enabling technology with very low noise electronics and highly stable microwave driving sources. The fabrication is pioneered by MetaboliQs and Fraunhofer Institute for Applied Solid State Physics in Freiburg.

There are new perspectives of measurement applications based on QMS that require common vocabulary, as for example sensors to understand matter under high pressure or high dynamics measurements.

There is also a requirement for new quantum physics based standards for:

- absolute measurement
- absolute quantum efficiency
- absolute spectral radiance

With regard to metrology standards, the forum recommended that the EMN-Q should align its objectives with the Quantum Technology Flagship and their stakeholder requirements in order to prioritize the establishment of metrology standards, according to the needs. This can be achieved by:

- promoting take-up of metrology in the development of these technologies, and provide linkage with other technical areas;
- contributing to standardization & certification of quantum technologies;
- acting as the main contact point to stakeholders connected to the domains of QT which are covered by the scope of this EMN-Q

5.3 Discussion

The participants discussed the differentiation between full quantum technologies (which are based on the inventions of the second quantum revolution) and non-full quantum technologies (which are based on the inventions of the first quantum revolution).

This distinction comes from the publication of the Quantum Manifesto in which the 'second quantum revolution' was coined and further quoted in the Quantum Technology Flagship initiatives and in the scientific vocabulary.

To be more specific, despite the fact that all Quantum Technologies are intrinsically 'Quantum' (overcoming the limits of classical physics), the distinction in literature is now the following:

- First generation of Quantum Technologies (first wave of QT, or first quantum revolution)

  These include the technologies of transistors in the semiconductor industry, lasers, light-emitting-diodes (for example, in telecommunication), image detectors (for example in computer vision), and atomic clocks (for example, in the Global Navigation Satellite Systems). They represent the basic technology for many branches of research laboratories and industry.

  Documentary Standards for this class of QT are important to reach a full commercial deployment of quantum sensors and metrology devices that exploit coherent quantum systems.

- Second generation of Quantum Technologies (second wave, or second quantum revolution)

  Technologies that rely on the ability to control and manipulate the quantum state of a single or a few coupled quantum systems (the so-called single-qubit coherence, i.e. single atoms, single ions, single photons, etc.), exploiting the peculiar traits of quantum mechanics like the superposition principle and the entanglement phenomenon. These properties are fundamental for building sensor systems for very different modalities with the capability to reach and go beyond the Standard Quantum Limit, taking advantage of the properties of suitable quantum systems and their interactions with the surrounding environment. The final goal is to achieve a generation of quantum sensors based on entangled quantum systems.

Working with existing Technical Committees on specific traditional instruments that have been recently upgraded to Quantum-enabled technologies, and in parallel to create new purely Quantum Technology Technical Committees, aiming at rationalisation of efforts and avoiding duplication of work is a best practice for standardisation and should be considered.

In this sense, documentary standards that have been already prepared by existing TCs for first generation Quantum Technologies should be considered and upgraded taking into account Quantum-enabled technologies.

In parallel, novel Technical Committees dedicated to Quantum Technologies should be created to oversee the standardisation process for the 'native' second generation QT (i.e. in analogy to what ETSI is doing for QKD, but in the field of QMS).

In both cases, documentary standards are a key step to enable a speed-up in the development in QMS, both for stand-alone sensors and for those to be integrated in more complex systems. In the field of QMS there is a variety of applications developed at different TRLs, while documentary standards are particularly needed at low TRLs. The standardisation process will provide the way for a possible construction of a general hardware platform at a reasonable cost, a step that would represent a key enabler for Quantum Technology.

Lastly, sensor integration is an important area to consider, since a sensor is usually only a small part of a larger system. This comprises corresponding hardware components and software interfaces, which should be standardised as much as possible. Building committees to elaborate these preferably open standards is regarded an important part of the Quantum Technology policy (Zeiss, 2018).

6 Session 4: Opportunities for Standardisation in other quantum fields

The 'quantum internet' vision, which is the subject of the Flagship project that QuTech and TU Delft are leading (http://quantum-internet.team), requires a forward looking view on standards for quantum communication and simulation, to ensure maximum facilitation on collaboration and co-creative work. A light, voluntary approach to standards like the one used by the internet engineering task force, is advocated. The TRL is still low because of distance limitations and the fact that the repeaters, switches and control protocols are not yet available. Applications already foreseen are to secure communications, secure cloud computing, clock synchronisation, password ID and position verification.

Currently, over a dozen different technical committees have been created , addressing for example issues related to vocabulary or metrology in different fields of technology (see Tables 1 and Table 2). These technical committees are spread across multiple standardisation bodies. Among these committees there are differences in the way of working: some committees have set up working groups for drafting a white paper on the state of the art, other committees have focused on the description of standards for Quantum key distribution, while others have created international working groups aimed at absorbing already established standards with the purpose of reaching a critical mass.

Table 1 Standardisation initiatives (Hjalmarson, 2019)

Standards organisation	Designation of group	Topic
ETSI	TC CYBER, Cybersecurity	Quantum-safe cryptography
ETSI	ISG QKD	Quantum key distribution
ITU	SG 13 Future networks	Technical tutorial on quantum key distribution Proposed focus group on quantum technology for networks
ITU	SG 17, Security	Quantum key distribution
ISO/IEC JTC 1	JTC1 SG 2, Quantum computing	Quantum computing
ISO/IEC	JTC1 SC 7, Software and systems engineering, SG1	Investigation of standards for quantum computing
ISO/IEC	JTC1 SC 27 IT Security techniques WG 2 Cryptography and security mechanisms	Quantum key distribution
IEC	TC 65, Industrial-process measurement, control and automation	Quantum key distribution
NIST	Computer Security Resource Center (CSRC)	Post quantum cryptography
IEEE	P1913	Software defined quantum communication
IEEE	P1730	Quantum computing definitions
IEEE	P7131	Quantum computing performance metrics and performance benchmarking
IETF	Quantum Internet Proposed Research Group (qirg)	Quantum internet

Table 2 Standardisation initiatives

Designation	Title
ISO/TS 80004-12 Ed.1 (2016)	Nanotechnologies -- Vocabulary -- Part 12: Quantum phenomena in nanotechnology
ETSI GS QKD 012 V1.1.1 (2019-02)	QKD; Device and Communication Channel Parameters for QKD Deployment
ETSI GS QKD 014 V1.1.1 (2019-02)	QKD; Protocol and data format of REST-based key delivery API
ETSI GR QKD 007 V1.1.1 (2018-12)	QKD; Vocabulary
ETSI GR QKD 003 V2.1.1 (2018-03)	QKD; Components and Internal Interfaces
ETSI GS QKD 011 V1.1.1 (2016-05)	QKD; Component characterization: characterizing optical components for QKD systems
ETSI GS QKD 005 V1.1.1 (2010-12)	QKD; Security Proofs
ETSI GS QKD 008 V1.1.1 (2010-12)	QKD; QKD Module Security Specification
ETSI GS QKD 004 V1.1.1 (2010-12)	QKD; Application Interface
ETSI GS QKD 002 V1.1.1 (2010-06)	QKD; Use Cases

Most of the committees focus on demarcated technology fields and hence avoid overlapping of standardisation activities. Informal cooperation and exchange can also be helpful to mitigate the risk of duplication of work. For example, active exchange of information takes place between the Internet Engineering Task Force (IETF) and ISO/IEC JTC1.

While for many Quantum physicists standardisation is a new concept, there are few areas in which scientists have worked with standards. In the 1980s, several actors in high-performance computing (HPC) defined their own performance metrics, hence this sector readily adopted standardisation and standardised benchmarks for measuring performance.

A specific structure for a real quantum computer, for example from the QT Flagship funded project OpenSuperQ, can be helpful to put discussions of standards in a less abstract context. Methods for the performance evaluation of quantum computers, for example IBM's publication on the Quantum Volume, can be supportive to discuss standards for benchmarking.

Different standards will be needed for different layers: from low temperature electronics (for superconducting platforms), specification of hardware, software and interfaces, to overall system standards and benchmarking. Standards will be co-developed with systems.

The high demands needed by classical computation is one of the most challenging problems in establishing metrics for quantum computing performance. Objective metrics are needed timely to avoid inflated claims being made public. Moreover, participants demanded an objective definition of what really constitutes a qubit.

6.1 Discussion

The best platform for a quantum repeater is not yet known, but the expert community expects it will be in about 2 years' time. The intermediate devices that need to be installed on a quantum network are also not yet known. Existing internet protocols such as the Transmission Control Protocol (TCP) are not necessarily applicable to the quantum internet. The requirements in this respect are different in a quantum repeater network than in a trusted node network, which needs to be faster.

It was questioned whether there is a need to standardise graph topologies for quantum computing, which depends on the platform used. At present, two-dimensional graphs are used for superconducting platforms, while ion trap platforms have, up to certain size, full qubit interconnection.

It was asked how software non-standards for quantum technology could be formalised. Large companies such as ATOS, IBM and Google may be ready to contribute to software (non)-standards. Industry has generally great opportunities, but their needs should be identified. Overall, participants concluded that there are many opportunities to extend the standards we already have and create new ones.

7 Concluding Remarks and way forward

7.1 General conclusions

For the first time nearly 80 quantum physicist and experts from different European countries working in different quantum disciplines gathered to discuss how to bring inventions to the market, thus completing the pathway of innovation. Planning at an early state and incorporating standardisation can be crucial for accelerating the market uptake of research findings.

By successfully bringing together the relevant stakeholders in the whole quantum technology standardisation value chain – research, standardisation and industry sectors, as well as public administrations/institutions – the workshop provided a timely opportunity for a balanced (Figure 4) and representative overview on the status quo in Quantum Technologies, and for drawing informed conclusions on a strategic way forward.

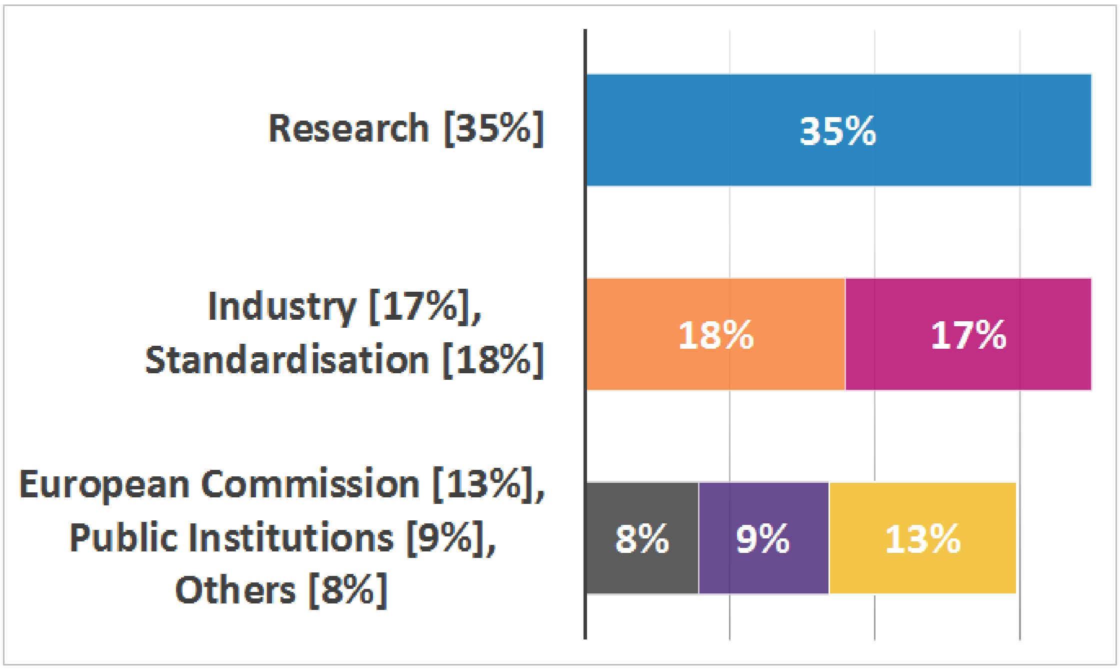

Figure 4 Breakdown per participant type at the workshop

The majority of participants (70%) were from the research/academia (35%), standardisation (18%), and industry (17%) sectors, confirming the workshop was successful in joining these communities and in ensuring a good balance between them. In particular, the research/academia community, which is traditionally far from market applications, was equally balanced by the close-to-market community represented by the industry and standardisation participants.

Based on the experience from the Graphene Flagship, concrete actions for addressing standardisation in the Quantum Technologies field such as standardisation of a Quantum Technology terminology and the development of an EU standardisation roadmap for Quantum Technologies were suggested by the participants.

Participants also reported a growing interest in standardisation, signalling the entry to the market of Quantum Technologies, with most of the activities focusing on quantum-enabled security, quantum computing and quantum communication as detailed here below:

- Several projects within ETSI's ISG on QKD - outcomes are published as Group Specification;
- Several projects within ITU SG13 'Future Network' and SG17 'Security';
- ISO/IEC JTC 1/SC 7 (Software systems and systems engineering);
- SG 1: Investigation of standards on quantum computing;
- Quantum computing as one of the priority technologies under JTC1's Joint Advisory Group, Group on Emerging Technology and Innovation;
- ISO/IEC JTC 1/SC 27/WG 3 – New work to start on Information technology security techniques — Security requirements, test and evaluation methods for quantum key distribution (Part 1: Requirements and Part 2: Evaluation and testing methods);
- IEC/TC65 is looking at QKD in relation to the IEC 62443 series of standards;
- IEEE P7130 - Standard for Quantum Computing Definitions;
- IEEE P7131 - Standard for Quantum Computing Performance Metrics & Performance Benchmarking;
- IEEE P1913 - Software-Defined Quantum Communication;
- IETF Quantum Internet Proposed Research Group (qirg).

Other areas, where standardisation could add value by supporting the uptake of Quantum Technologies in industrial applications and their entry to the market include sensing, imaging and measurement.

Participants showed a clear interest in ways on how the research and innovation community can actively contribute to standardisation. Although there was not a consensus among participants on the best way forward to introduce Quantum Technologies in standardisation activities, participants agreed that there is a need for more financial resources, finding novel protocols and developing new quantum-based standards.

Since standardisation is not only about requirements setting a basis for certification, but can also address vocabularies, models, exchange protocols, etc., it will be important to identify which kind of standards will be needed and for which applications. Before standardisation activities are started, it is important to agree on their scope. There appears further to be a transversal impact of QT on existing standards. All of this will have to be mapped in terms of opportunities for existing and future activities. A Focus Group could offer a mechanism to address this. The STAIR Platform methodology was also mentioned to host interactions between the communities of researchers and standardisers.

The workshop concluded with the suggestions to continue the dialogue between the scientific, industrial, and standardisation communities, and to keep organising similar multi-stakeholder events in the future. In this context, it was suggested to contact the Coordination and Support Action of the QT Flagship as a concrete mean to reach the whole European QT community.

7.2 Next Steps

- Start an interaction (e.g. a cooperation agreement) with the Quantum Flagship and more particularly with the recently (April 2019) launched Coordination and Support Action[22] .
- As concrete actions for standardisation, it is suggested to focus on the Standardisation of a Quantum Technology Terminology and the development of an EU standardisation roadmap for Quantum Technologies: a CEN-CENELEC Workshop Agreement could address the Terminology, while the standardisation roadmap could be addressed either by a Focus Group or by a CEN-CENELEC Workshop. Pro-active steps towards the creation of such a Focus Group or CEN-CENELEC Workshop Agreement, including the identification of a supporting Secretariat, would be necessary.

[22] Coordinator is the VDI Technologiezentrum; other participants in the CSA are Robert Bosch GMBH and RTOs/Universities from Switzerland, Spain, France, Italy and Netherlands) https://cordis.europa.eu/project/rcn/218588/factsheet/en

References

Hart, J. D., Terashima, Y., Uchida, A., Baumgartner, G., Murphy, T. E., & Roy, R. (2017). Recommendations and illustrations for the evaluation of photonic random number generators. *APL Photonics*, 2:090901.

Kania, E. B. (2018). China's Challenge to U.S. Quantum Competitiveness. *The Hill*, June 30.

Kania, E. B. (2018b). China's Quantum Future: Xi's Quest to Build a High-Tech Superpower. *Foreign Affairs*, Sep 26.

Monroe, C. (2017). American Leadership in Quantum Technology*. Hearings of the House of Science, Space and Technology Committee, 2017, 10 24.* Washington D.C.: US Government.

Zeiss, (2018). White Paper on Quantum Metrology and Sensing and Quantum enhanced Imaging. *ZEISS Symposium Optics in the Quantum World 18 April 2018* (pp. https://www.zeiss.com/content/dam/Corporate/innovation_and_technology/downloads/zeiss-symposium_whitepaper_qms_qei.pdf). Oberkochen, Germany: Zeiss.

List of figures

List of tables

List of Abbreviations

AIT	Austrian Institute of Technology
AQT	Alpine Quantum Technologies
ATOS	European multinational information technology service
CEN	European Committee for Standardization (CEN)
CENELEC	European Committee for Electrotechnical Standardization
CNECT	European Commission Directorate-General Communications Networks, Content and Technology
DIN	German national organisation for standardisation
EMN-Q	European Metrology Network for Quantum Technologies
ETSI	European Telecommunications Standards Institute
EURAMET	European Association of National Metrology Institutes
HPC	High-performance computing
IBM	International Business Machines Corporation
ICT	Information and Communication Technologies
IDQ	ID Quantique
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers Standards Association
IETF	Internet Engineering Task Force is an open standards organization
INRIM	Istituto Nazionale di Ricerca Metrologica (Italy)
ISC	International Standards Consulting
ISG	Industry Specification Group
ISO	International Standardization Organisation
ITU	International Telecommunication Union
JIS	Joint Initiative on Standardisation
JRC	European Commission Directorate-General Joint Research Centre
JTC	Joint Technical Committee
NIST	National Institute of Standards Technology (USA)
NV	Nitrogen-vacancy
PSIS	Putting-Science-Into-Standards
QKD	Quantum Key Distribution
QMS	Quantum metrology, sensing and imaging
QT	Quantum Technologies
QuantERA	European Research Area Cofund Action in Quantum Technologies
QuTech	Research and development in quantum technology
SC	Sub-Committee
SDO	Standards Development Organization
SI	International System of Units

SIS	Swedish Institute for Standards
SK Telecom	South Korean telecom operator
STAIR	Standards, Innovation and Research Platform
TC	Technical Committee
TNO	Netherlands Organisation for Applied Scientific Research
TRL	Technology Readiness Level
WG	Working Group

Annexes

Annex 1. Workshop programme

Thursday, 28 March	
Facilitator and Panel Moderator: Alex PUISSANT, journalist, independent conference facilitator	
13:30	**REGISTRATION**
14:00	**OPENING** • Ruggero LENSI, Vice-President Technical CEN, Director-General UNI - Ente Nazionale Italiano di Unificazione • Maive RUTE, Deputy Director-General European Commission/DG JRC
14:15	**INTRODUCTION** • Pascal MAILLOT, Deputy Head of Unit, European Commission/DG CNECT C.2 Quantum Technology • Fabio TAUCER, Deputy Head of Unit, European Commission/DG JRC A.5 Scientific Development
14:30	**SESSION 1 – A REVOLUTION, WITHOUT STANDARDS?**
14:30	**General overview of the QT-landscape** Tommaso CALARCO, Forschungszentrum Jülich
14:50	**Outlook of activities related to standardisation in Quantum Flagship CSA** Rogier VERBERK, TNO - Organisation for Applied Scientific Research
15:10	**Role of standardisation in new technologies (low TRLs) - The graphene example** Werner BERGHOLZ, ISC - International Standards Consulting
15:30	*BOOST BREAK*
16:00	**Role of standardisation in new technologies (low TRLs) - The ID Quantique example** Nicolas GISIN, ID Quantique, University of Geneva
16:20	**An update on quantum activities at NIST** Barbara GOLDSTEIN, Physical Measurement Laboratory, NIST – National Institute of Standards and Technology
16:40	**Overview of the standardisation processes** Joachim LONIEN, Innovation Department, DIN - Deutsches Institut für Normung e. V.
17:00	**PANEL DISCUSSION 1**
17:30	CLOSURE OF DAY 1
20:00	DINNER

Friday, 29 March	
09:00	**SESSION 2 - QUANTUM SECURITY MEETS STANDARDISATION (QKD AND QT-SAFE SECURITY)** **Keynote** - Sean KWAK, ID Quantique; also ITU-T; ETSI; JTC1/SC27/WG3 • **Industrial applications and standard needs of QKD** - Hannes HÜBEL, AIT - Austrian Institute of Technology • **ETSI/ISG QKD** - Martin WARD, Toshiba Research Europe • ISO/IEC **JTC1/SC27/WG3** Security evaluation, testing and specification and CEN/CLC/**JTC 13** Cybersecurity and Data Protection - Miguel BAÑÓN Harvesters: Stephanie WEHNER and Jonas HELSEN (QuTech NL) **PANEL DISCUSSION 2**
10:30	*BOOST BREAK*
10:45	**SESSION 3 - QUANTUM METROLOGY, SENSING AND IMAGING MEETS STANDARDISATION** **Keynote** – Thierry DEBUISSCHERT, Thales Research and Technology • **macQsimal** Project –Jakob REICHEL, Laboratoire Kastler Brossel • Champion of **Euramet Metrology Network** on QT - Ivo Pietro DEGIOVANNI, INRIM - Istituto Nazionale di Ricerca Metrologica • **Quantum radiometry-** Stefan KÜCK, PTB - Physikalisch-Technische Bundesanstalt Harvester: Marco GRAMEGNA (INRIM) **PANEL DISCUSSION 3**
12:15	*LUNCH*
13:15	**SESSION 4 - OPPORTUNITIES FOR STANDARDS IN OTHER QUANTUM FIELDS** **Keynote - Quantum internet** - Stephanie WEHNER, QuTech - Delft University of Technology • **Quantum Computing** – Peter MÜLLER, IBM Research - Zurich • **Investigation of standards on quantum computing** – Mikael HJALMARSON, Swedish Institute for Standards, ISO/IEC JTC 1/SC 7/SG 1 • **Metrics and Standards in Quantum Computing** - Thomas MONZ, AQT – Alpine Quantum Technologies Innsbruck Harvester: Adam LEWIS (JRC) **PANEL DISCUSSION 4**
14:45	*BOOST BREAK*
15:00	**CLOSING SESSION – NEEDS AND OPPORTUNITIES FOR STANDARDISATION**
15:00	• **Feedback on Sessions 2-4** from 'Harvesters' (5 min each) • Discussion among all participants on **Needs and opportunities for standardisation**
15:35	**FRAMING THE STATE OF PLAY, AND CONCLUDING REMARKS** • Pascal MAILLOT, Deputy Head of Unit, European Commission/DG CNECT C.2 Quantum Technology • Ruggero LENSI, Vice-President Technical CEN and Director-General UNI
15:45	*CLOSURE*

Annex 2. Participants list

Name	Prenom	Organisation
Abellan	Carlos	Quside
Bañón	Miguel	Epoche and Espri
Bergholz	Werner	International Standards Consulting GmbH ISC
Bize	Sebastien	LNE-SYRTE, Observatoire de Paris
Calarco	Tommaso	Forschungszentrum Julich
Claudio	Virginia	IMEC
de Brancion	Anne-Sophie	European Patent Office
Debuisschert	Thierry	Thales Research & Technology
Degiovanni	Ivo Pietro	INRIM
Dias	Julia	Private
Dirks	Bob	TNO/QuTech
Domini	Eveline	EURAMET
Eklund	Erik	SIS, Swedish Standards Institute
Ferran	Martin	QUSIDE
Gadzina-Kolodziejska	Agnieszka	Joint Research Centre, European Commission
Ganesh	Ashok	CEN-CENELEC
Giesz	Valerian	Quandela
Gisin	Nicolas	University of Geneva
Gobbi	Sara	ASTM International
Goldstein	Barbara	NIST
Gramegna	Marco	INRiM
Gutierrez	Eugenio	European Commission JRC
Helsen	Jonas	QuTech - Delft University of Technology
Hemberger	Klaus	Bundesnetzagentur
Hjalmarson	Mikael	SIS, Swedish Standards Institute
Huard	Mariane	Standards Council of Canada
Hübel	Hannes	AIT Austrian Institute of Technology GmbH
Huebner	Tobias	DIN (Standards Committee Technical Fundamentals)
Hurley-Smith	Darren	University of Kent
Ikonen	Erkki	EURAMET
Jenet	Andreas	European Commission JRC
Killeen	Paul	NSAI
Klein	Claudius	VDI Technologiezentrum
Kück	Stefan	Physikalisch-Technische Bundesanstalt
Kwak	Sean	ID Quantique
Le Bars	Laure	SAP
Lensi	Ruggero	UNI and CEN
Lequeux	Gilles	European Commission GROW
Lewis	Adam Miles	European Commission JRC
Lindstrom	Tobias	National Physical Laboratory
Loeffler	Marius	DIN Deutsches Institut für Normung e.V.

Lonien	Joachim	DIN Deutsches Institut für Normung e.V.
Maillot	Pascal	European Commission CNECT
Monz	Thomas	Alpine Quantum Technologies GmbH
Mueller	Peter	IBM Research – Zurich
Nik	Samira	CEN-CENELEC
Nishimura	Kunita	Japan Mission to EU
Ogi	Shintaro	National Institute of Information and Communications Technology (NICT), Japan
Palacios-Berraquero	Carmen	Nu Quantum Ltd
Pawłowski	Marcin	University of Gdańsk
Pereira-Sa	Sofia	European Commission JRC
Pllana	Bashkim	Ministry of Economic Development Kosovo
Poot	Menno	TU Munich
Qelaj	Mehmet	Ministry of Economic Development Kosovo
Rampioni	Aldo	Springer
Redwin	Paul	DCMS
Reichel	Jakob	Laboratoire Kastler Brossel, ENS/CNRS/SU/CdF
Rute	Maive	European Commission JRC
Sanchez-Bautista	Enrique	Forschungszentrum Julich
Schopfer	Felicien	Laboratoire National de Métrologie et d'Essais - LNE
Skoda	Tomislav	German Aerospace Center
Spethmann	Nicolas	Physikalisch-Technische Bundesanstalt
Taucer	Fabio	European Commission JRC
Thew	Rob	University of Geneva
Torres	Jean-Michel	IBM
Trefzger	Christian	European Commission CNECT
Tudosie	George	QSIT NCCR / ETH Zurich
Van den Akker	Gertjan	NEN
Van den Berghe	Luc	CEN-CENELEC
Van Heesch	Maran	TNO
Van Vlierden	Christine	CEN-CENELEC
Verberk	Rogier	TNO
Ward	Martin	Toshiba Research Europe Limited
Wehner	Stephanie	QuTech - Delft University of Technology
Xuereb	André	University of Malta
Yang	Xiaoya	ITU-T SG17
Zarbo	Liviu	National Institute for Research and Development of Isotopic an Molecular Technologies (INCDTIM)

Annex 3. Invited speakers

MIGUEL BAÑÓN

Miguel Bañón is the Global Technology Leader for Cybersecurity of Epoche & Espri, an IT security evaluation facility that provides evaluation and testing services under the Common Criteria and FIPS 140-2 standards. Epoche & Espri started in 2007, and is now active in a number of IT certification schemes and countries. In October 2017, Epoche & Espri has become part of DEKRA, one of the top 4 players in the testing, inspection, and certification industry worldwide. Together with DEKRA, Epoche & Espri further develops its reach of cyber security testing and evaluation services.

TOMMASO CALARCO

Tommaso Calarco is the Director of the Institute for Quantum Control at the Peter Grünberg Institute at Forschungszentrum Jülich. He received his PhD at the University of Ferrara in 1998 and started to work as a postdoc in the group of P. Zöller at the University of Innsbruck. He was appointed as a Senior Researcher at the BEC Centre in Trento in 2004 and as a Professor for Physics at the University of Ulm in 2007, where he later became the Director of the Institute for Complex Quantum Systems and of the Centre for Integrated Quantum Science and Technology. He authored the Quantum Manifesto in 2016, which led to the European Commission’s Quantum Flagship Initiative. He is currently the Chairman of its Quantum Community Network.

THIERRY DEBUISSCHERT

Thierry Debuisschert is a scientist at Thales Research & Technology where he is responsible for applied quantum physics activity. His expertise covers non-linear optics, quantum optics, quantum cryptography and NV centres in diamond. He was coordinator of the European integrated project DIADEMS (2013-2017) dedicated to the development of magnetometers based on NV centres in diamond. Currently, he coordinates the QuantERA project MICROSENS and is involved in the quantum coordination and support action QSA dedicated to the implementation and support of the Quantum Flagship.

IVO PIETRO DEGIOVANNI

INRIM Senior Researcher Ivo Pietro Degiovanni developed his scientific skills in Metrology for Quantum Photonics Technologies. He has been the coordinator and Unit leader of several European and national projects. He is a member of the ETSI Industry Specification Group on QKD, of the Scientific Research Agenda Working-Group of the EC Quantum Flagship, and of the INRIM Board of the Scientific Director. He is Champion of the EURAMET European Metrology Network for Quantum Technologies (EMN-Q).

WERNER BERGHOLZ

Werner Bergholz held positions in R&D, procurement, QM in Siemens and Infineon. As a Professor of Electrical Engineering at Jacobs University Bremen, he researched microelectronics, PV, QM and standardization. He is co-founder of International Standards Consulting ISC and Co-Chair of the SEMI© ERSC and Assistant Secretary to IEC TC 113.

NICOLAS GISIN

Nicolas Gisin is a Swiss physicist and professor at the University of Geneva working on quantum information and communication, as well as on the foundations of quantum mechanics. His work includes both experimental and theoretical physics. He is one of the pioneers of QKD in telecom fibres; he combined his expertise in optical fibres and in quantum effects in optical fibres to propose and realize key experiments and practical implementations. He is also one of the founders of ID Quantique. In 2009, he was awarded the First Biennial John Stewart Bell Prize for Research on Fundamental Issues in Quantum Mechanics and their Applications. Nicolas Gisin has published a popular book in which he explains without mathematics, but also without hiding the difficult concepts, modern quantum physics and some of its fascinating applications.

BARBARA GOLDSTEIN

Barbara Goldstein is Associate Director of the Physical Measurement Laboratory (NIST-PML) of NIST, the US National Institute of Standards and Technology, the public body that bundles all public efforts in quantum technology. The US Government launched in December 2018 the $1.3b National Quantum Initiative Program which establishes a coordinated multiagency program to support research and training in quantum information science over the next ten years. A Subcommittee on Quantum Information Science, including NIST members will guide program activities. The body has initiated a process to solicit, evaluate, and standardize one or more quantum-resistant public-key cryptographic algorithms.

MIKAEL HJALMARSON

Mikael Hjalmarson is project manager at SIS for the mirror group to ISO and CEN on AIDC, IoT, Cloud and AI (incl. Big Data). In the past, he governed product attributes for describing and setting product characteristics, managed Corporate Standards with focus on product structuring and product identification (marking & traceability) to support product lifecycle management (PLM) and worked on national and international standardization related to Automatic Identification and Data Capture (AIDC), Packaging, and the Internet of Things.

SEAN KWAK

Sean Kwak, Executive VP Strategy & Innovation, joined ID Quantique in September 2018, bringing over 23 years of experience in electronics engineering. Prior to this, he worked for SK Telecom, the largest South Korean telecom. Since joining SK Telecom in 1997, he managed the commercialisation of SMS, packet core networks and Internet protocol Multimedia Subsystem (IMS). While working on solutions for packet core security, he became acquainted with quantum cryptography and led the founding of SK Telecom's Quantum Tech. Lab in 2011. He also led the investment from SK Telecom in ID Quantique. Sean Kwak is a Ph.D candidate in University of Seoul.

RUGGERO LENSI

Director-General of CEN's Italian Member UNI (Ente nazionale italiano di unificazione, Italian National Standardization Body), civil engineer Ruggero Lensi began working for UNI in 1995 where he held various posts, first as Technical Project Manager, as Head of Standardization Activities, and Technical Director before becoming the Director of External Relations, New Business and Innovation in 2010. In this position, he was responsible for the development and monitoring of actions related to the objectives of UNI's strategic plan. He became a CEN Board member in 2014.

JOACHIM LONIEN

Joachim Lonien holds degrees in Chemistry, Biotechnology and Global Operations Management. His research projects allowed him to work in a number of internationally renowned life science groups before focusing on the development of international standards (ISO, IEC). He is currently leading a group at DIN's innovation department, specializing in technology foresight analysis, standardization consulting and organizing international committees in the realm of smart technologies. His specialties are the development of International Standards, consulting various stakeholders in the organization of standardization projects, technology foresight analysis and gene expression analysis as well as molecular biology and analytical techniques.

PASCAL MAILLOT

Pascal Maillot is deputy Head of Unit of CNECT/C2 (High Performance Computing & Quantum Technologies) in the European Commission and is in charge of the 20-project Quantum Flagship launched in October 2018. He graduated as a computer engineer in 1998 and held several positions in the private and public sector as telecom project manager and cyber-security analyst. He then moved to the quantum domain and focuses specifically on the future quantum internet.

THOMAS MONZ

Dr Thomas Monz from Alpine Quantum Technologies in Innsbruck finished his PhD in the group of Rainer Blatt. Including his PostDoc time, Dr Monz achieved genuine 14-qubit entanglement, implemented Shor's algorithm in a scalable fashion, and supplemented this research with novel quantum characterisation, verification and validation methods.

JAKOB REICHEL

Jakob Reichel is professor at the Kastler Brossel Laboratory of the Sorbonne University and one of the implementing partners of the macQsimal project. macQsimal is an EU-funded Horizon 2020 research project which will design, develop, miniaturise and integrate advanced quantum-enabled sensors with outstanding sensitivity, to measure physical observables in five key areas: magnetic fields, time, rotation, electro-magnetic radiation and gas concentration. macQsimal is part of the FET Quantum Technologies (QT) Flagship.

PETER MUELLER

Peter Mueller from IBM Zurich Research Laboratory in Switzerland focuses his research on areas of quantum technology and data centre storage security. The research activities his department include future device concepts, quantum computing, personalized medicine, mobile health, human body data interfaces and nanotechnology. Peter is a founding member and was the Chair of the IEEE ComSoc Communications and Information Systems Security Technical Committee (CIS-TC). His affiliations include active society membership in IEEE, where he is Senior Member; the Society for Industrial and Applied Mathematics (SIAM); the Electrochemical Society (ECS); and the Swiss Physical Society (SPS)

MAIVE RUTE

Maive Rute is Deputy Director-General of the Joint Research Centre (JRC)), the science and knowledge service of the European Commission. There, her responsibilities span from the supervision of energy, mobility and nuclear research to the development of JRC organisation and sites in five countries. Prior to that, she has served as Director for Biotechnology and Director for Resources in DG Research as well as Director for Small Business and Entrepreneurship in DG Enterprise. Before joining the Commission in 2005, Maive Rute was CEO of KredEx, the Estonian funding body for businesses, innovation, housing and export. She graduated cum laude as an economist from the Estonian University of Life Sciences and holds an MBA from the Danube University, Austria, received an MA in international politics from CERIS, Brussels and has been a Visiting Research Fellow at Harvard University.

FABIO TAUCER

Fabio Taucer is Deputy Head of Unit at the JRC at the Unit for Scientific Development. He is responsible for the coordination of all JRC 58 Research Infrastructures and for the implementation of the open access strategy to JRC experimental facilities. He also coordinates all standardisation related activities at the JRC, in particular linking research and innovation with standardisation as part of the Joint Initiative on Standardisation. In his previous post at the JRC he matured a long-standing experience in the management of transnational access to research infrastructures financed by DG RTD in the field of earthquake engineering.

ROGIER VERBERK

Rogier Verberk is leading the Working Group on Innovation and Infrastructure of the Coordination and Support Action, the structure that runs the European Quantum Technology Flagship. He is Principal Project Manager at the Netherlands Organisation for Applied Scientific Research (TNO) and Roadmap Leader at QuTech, the joint initiative of TU Delft and TNO. The Quantum Technologies Flagship is a large-scale, long-term research initiative that brings together research institutions, industry and public funders, consolidating and expanding European scientific leadership and excellence in this field. It will run for ten years, with an expected budget of EUR 1b. The vision of the Flagship is to develop in Europe a so-called quantum web, where quantum computers, simulators and sensors are interconnected via quantum communication networks.

MARTIN WARD

Martin Ward is Senior Research Scientist at Toshiba Research Europe. Together with Andrew Shields he is member of the Industry Specification Group for Quantum Key Distribution (ISG QKD) at ETSI. Quantum Information Technology concerns the transport and processing of information using individual particles such as electrons or photons; by sending information encoded upon single photons (the particles of light) it is possible to test the secrecy of each communication. Toshiba has exploited this phenomenon to create a practical system for secure communication over fibre optical cables. Quantum Cryptography, as this communication method is known, is the first in a series of quantum innovations which might revolutionise the IT industry.

STEPHANIE WEHNER

German physicist and computer scientist Stephanie Wehner is Antoni van Leeuwenhoek professor in quantum information and the Roadmap Leader of the Quantum Internet and Networked Computing initiative at QuTech, Delft University of Technology. She is also known for introducing the noisy-storage model in quantum cryptography. Wehner's research focuses mainly on quantum cryptography and quantum communications. Together with Jonathan Oppenheim, she discovered that the amount of non-locality in quantum mechanics is limited by the uncertainty principle.

HANNES HÜBEL

Hannes Hübel obtained his PhD in 2004 from Queen Mary, University of London, UK. In the same year he joined the quantum information group at the University of Vienna, to work on QKD. In 2008, he presented the first realization of a fully automated QKD system based on entanglement. He then worked as a post-doctoral researcher at the University of Waterloo, Canada, focusing on experimental demonstrations of multipartite entanglement. In 2010, he became assistant professor at the University of Stockholm, Sweden. Since 2015, he leads the experimental QKD development at the AIT Austrian Institute of Technology in Vienna, Austria.

STEFAN KÜCK

Stefan Kück obtained the state doctorate (Habilitation) in 2001 in Physics at the University of Hamburg in Germany on tunable solid-state laser materials. He joined the Physikalisch-Technische Bundesanstalt (PTB), the German National Metrology Institute, in 2002 and started working in the field of laser radiometry. In 2009 he became head of the department of "Optical Technologies" and in 2013 the head of the department "Photometry and Applied Radiometry". Since 2016, he is head of the division of Optics. His scientific work focuses on the metrology for single-photon sources and detectors.

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