Report of BIPM Workshop on Accelerating the Adoption of Quantum Technologies through Measurements and Standards

BIPM – March 21-22, 2024

Introduction

The *BIPM Workshop on accelerating the adoption of Quantum Technologies through Measurements and Standards* brought together 149 participants from 43 NMIs and DIs from 39 economies, as well as representatives from industry associations worldwide. It aimed to set the direction for a new collaborative initiative, "NMI-Q", that will leverage the combined expertise of the NMIs and DIs to accelerate the development and adoption of quantum technologies through coordinated development and sharing of measurement "best practices" in support of future standardisation.

This document gives a summary of the presentations and discussions at the Workshop. A companion document[1] provides the contents of the presentations, and the report references relevant slides throughout.

The Workshop resolved that, in addition to this report, the Organising Committee produce a separate White Paper with recommendations for next steps in establishing and implementing the NMI-Q initiative.

[1] https://www.bipm.org/documents/20126/228569750/Quantum-BIPM-Workshop-2024/283dd72c-c6b0-1be5-da3f-db8a6c1bbfa4. Accessed on 2024-04-18.

Day 1: Opportunities & Challenges

Welcoming remarks

Martin Milton, Director of the BIPM, welcomed all participants and encouraged a fruitful discussion with concrete outcomes that will support the BIPM community in working together to advance quantum measurement standards.

Tim Prior, representative of NPL and member of the workshop Organising Committee, expressed the hope that this workshop is the start of an ongoing activity we refer to as NMI-Q. He introduced the Organising Committee with representatives from NRC, NPL, NIST, NMIJ, NMIA, PTB, and INRiM, encouraged an open discussion, with both positive and negative input very welcome, and committed to sharing the workshop results.

JT Janssen, CIPM member and Workshop Chair, introduced the responsibilities of CIPM, referring to the 2019 re-definition of the SI while also noting that CIPM is looking to address new challenges and emerging technologies such as quantum technologies. He referenced another such initiative, Action on Climate, where CIPM can act in liaison with other international organisations.

Keynote: The emerging quantum economy: the promise & the barriers

Speaker: Sir Peter Knight (Blackett Lab, Imperial College London, Chair of UK National Quantum Technology Programme Strategic Advisory Board, Chair of NPL Quantum Metrology Institute)

Slides 8 - 47

For the keynote Sir Peter gave a personal view on the current quantum technology landscape and ecosystem, using examples from the UK and worldwide to highlight the opportunities for quantum technologies and the challenges facing the implementation and adoption of this emerging technology. Ten years ago, quantum was recognised by the UK government as a critical area of emerging technology, and that has been reinforced by the announcement of a new strategy, and associated funding, for a further 10 years.

He used the evolution of the UK National Quantum Technology Programme to illustrate how the UK government, industry and academia came together to deliver an aligned strategic programme across quantum computing and simulation, quantum networking and quantum sensing, imaging and timing, addressing industry-led challenges. In the UK, “Quantum 2.0” is already bringing benefits, including brain magnetometry, emissions monitoring, gravity gradient sensing, and quantum secured networks for financial data centres.

Sir Peter noted that world investment in quantum is large, but not easy to identify in detail. The statistics he presented include 33 economies with national quantum funding estimated at 40-50 Billion $. US publications have the highest impact, the EU is leading in the number of published articles, and China has a strong position in quantum. It appears that most of the major private investments in quantum technologies are in US/UK/Canada, the EU is far behind, considering the government focus and funding across the EU. The formation of quantum industry associations (QED-C, UKQuantum, Q-Star, QuIC, etc.) will be important so they can act as a coordinated voice into governments.

A key factor for adoption of quantum will be confidence in the technology, through structured test, evaluation and characterisation leading the way to standardisation. NMIs are the best organisations to lead this activity. In secure communications, Quantum Key Distribution (QKD) and Post-Quantum Cryptography (PQC) will be needed in combination, with NIST currently leading the development of PQC.

Some specific concerns Sir Peter raised include the quantum computing hype, restrictive export regulations, over-regulation in general, risk of early mergers and acquisitions, `quantum nationalism', and sufficient levels of private investment.

In summary, Sir Peter sees quantum as a massive opportunity for the world and a powerhouse for change.

Questions from the audience:

Is confidence in measurement important? What is the UK strategy of offering measurement capabilities?

Yes, in the UK NPL is the lead government agency with the role of building measurement capabilities, with core funding in their budget. Benchmarking is also being developed by the UK National Quantum Computing Centre. NPL leads the UK Standardisation Network with the British Standards Institute and UK Quantum to understand the needs of the UK industry and to encourage wider engagement on standardisation.

Is it a national task to define regulations? How do we get common international requirements?

NMIs are responsible for defining needed requirements, based on good metrology. Collaboration between NMIs is essential, but problems can arise in terms of `quantum nationalism' and global politics.

Framing the workshop: motivation and goal

Barbara Goldstein, NMI-Q (NIST)

Slides 48 - 63

Barbara Goldstein framed the workshop by discussing the motivation and goals for both the workshop itself, and the ongoing activity, referred to as NMI-Q, it is hoped to inspire. The talk asserted that emerging technologies demand innovations in metrology, with a focus on:

- Agility, to keep pace with a rapidly changing landscape;
- Ability to make a measurement at all, not necessarily traceable;
- Comparability of measurements, across vendors and platforms; and
- Accelerated development of measurement capabilities, ahead of the typical pace of formal standards development.

She drew a distinction between "quantum for metrology" and "metrology for quantum". NMIs were among the first to develop and the first to benefit from new quantum technologies, which are being used to advance metrology. Examples include Josephson junctions being used for voltage standards and ion traps for clocks. Those same technologies are also forming the basis for commercial-relevant quantum technologies, such as quantum computing platforms — and these technologies need entirely new measurement and characterisation approaches. The intent of the workshop and of NMI-

Q is to determine exactly what metrology capabilities are needed to advance the market — i.e.: metrology for quantum — and to leverage the strengths of NMIs to address those needs.

Ms. Goldstein discussed how different kinds of standards support technology at different phases of the innovation lifecycle. Terminology and characterisation standards support the invention and de-risking stages; benchmarks can help manage hype by letting end users compare disparate technologies; interface standards help open markets by creating a plug-and-play environment; and certification and testing standards establish consumer confidence. Standards are most helpful when they are science-based and industry-driven, and NMIs contribute to all 3 ingredients for success: a community to develop and adopt standards; proven technology; and market readiness.

NMI-Q would be woven into an evolving landscape for international standards development, including the recently established IEC/ISO joint technical committee JTC-3 on quantum technologies. NMI-Q could contribute some of the pre-standardisation work that would inform the formal standards process conducted by IEC and ISO. The goal of the workshop is to get buy-in from the global metrology community for quantum pre-standardisation collaboration, and to discuss organisational principles.

Panel: Building a quantum economy – what will it take, and what are the challenges?

Moderator: Nicolas Spethmann, NMI-Q (PTB)

The session started with a short introduction from each of the panellists.

Lisa Lambert – Quantum Industry Canada

At the beginning of 2023, the national quantum strategy for Canada was published, including sections on standards. The strategy includes 4 main quantum hubs based in Vancouver, Ontario, Quebec and Alberta. Canada has had a large amount of private investment from industry, with companies in quantum computing, sensing, communications, and cryptography. The main challenge for standards: when is it too early? There is a need for NMIs to work together and grow the standardisation field together.

Jonathan Legh-Smith – UK Quantum

UK Quantum has been in existence for just over a year. Its membership comprises 54 organisations ranging from large to small. UK Quantum has been working closely with the UK government to establish the new UK strategy. Is it too early to be thinking about documentary standards? We recognise the importance of standardisation, but it is not clear which areas to focus on. In the UK, NPL is leading a more coordinated, strategic approach for standardisation.

Thierry Botter – QuIC

QuIC has approximately 180 members from across Europe. As quantum technology, and associated standardisation, is a global challenge, QuIC is building strong ties to other industry consortia, e.g. Q-Star, QED-C and QIC. Intellectual property is very important as well as workforce development. Most companies (especially start-ups) consider standards to be outside of their core focus. Component manufacturers, in contrast, want testbeds and the same language and terminology. There is a strong industry need for a coordinated approach to standardisation, at a global level.

Celia Merzbacher (on-line) – QED-C

Standardisation is essential for the globalisation of the quantum supply chain. QED-C has 250 members from 20 economies and has standing committees on topics of interest to members, including standards and testing, with subcommittees on computing, networking, and sensing. Other activities include demonstrating interoperability. QED-C is not a standards setting organisation but tracks standards activity. QED-C, with NIST leadership, initiated work on defining standardisation readiness levels (SRLs), and acts as a conduit for small organisations to participate in standardisation activities. QED-C has run multiple workshops on technology gaps, which usually conclude that standards will be needed.

Taro Shimada (on-line) – Q-Star

Q-Star was established in September 2021 and now has 88 members, including suppliers and potential end users. A goal for Q-Star is that, by 2030, 10% of the Japanese population will be using quantum-oriented technology without knowing it. Quantum technologies are rapidly developing, so standardisation needs to be agile and timely.

Panel discussion

What is the interest and how can we know what is needed in standards and metrology?

UK Quantum has a working group on standards (as do most of the industry consortiums) which acts as a forum to understand industry needs. The working group is chaired by NPL. Standardisation is in its early stages, but things such as terminology and benchmarking, as well as test and validation, will be important.

QuIC also has a standardisation work group. The group is not a standardisation body but it brings awareness to members. General education is needed on standardisation and its importance to the development of products and services. Organisations need to see what is already happening in adjacent field such as telecom. They need to see the lasting impact of standardisation.

IP, export controls, `quantum nationalism' – how do the industry consortia deal with those limitations?

The Panel observed that export controls are already happening, are often not transparent, and are driven by security and military requirements (dual use scenario). They saw a need to:

1) Educate policy makers, governments and defence people as to what quantum technology really is capable of today.

2) Educate member organisations (especially start-ups) on what export controls really are about. Penalties can be very high!

Quantum was felt to not be particularly special regarding national security, but it will be important to establish where to draw the line for export controls, e.g. a realistic list of applicable components.

Industry-to-industry conversations with the industry consortia provide recommendations to:

1) proceed multilaterally

2) establish a no list-based approach (dual-use)

3) accept that quantum technology is a new, unique landscape that requires a new approach.

Can you comment on the perceived requirements on NMIs for testing that the NMIs could share/do in common?

One requirement is testing characteristics of devices operating outside of their typical range, e.g. at low temperatures. Tests by different test houses often have discrepancies that NMIs can help resolve.

A good example of where NMIs have facilitated the adoption of a quantum technology is QKD testing. This has to be done by an organisation with detailed expertise and trust such as an NMI. Where industry worked with NMIs to test the performance, this enabled documentary standards to be developed.

Many quantum technology companies are small. Access to relevant facilities, and to test and validation capabilities, will speed up the development of products and services, and help establish supply chains.

Will quantum be given to the world in the same way as GPS?

Some quantum technology needs to be open but there also has to be competition. An abstraction layer that compares quantum technologies has to be open.

When is the ideal time to create a standard?

The landscape and infrastructure have to be established (including at NMIs) so standards can be set at the right time. A few standards being developed “too early” is not a bad thing. NIST has done some important thinking on standardisation readiness (looking at market, technology and community).

Summing up: What would you ask the NMI community for?

Quantum is diverse, there are many industries and supply chains, which need a diversity of approaches to standardisation.

Collaboration between NMIs is essential. Testbeds should be the result. Common nomenclature is needed.

Break-out 1: In what way is your organisation (or economy) supporting the emerging quantum economy?

Moderator: Kevin Thomson, NMI-Q (NRC)

Facilitators: Victoria Coleman, Andrew Wilson, Alexander Tzalenchuk, Rhys Lewis

Rapporteurs: Andrew Todd, Thomas Gerster, Olga Koslova, Dai-Hyuk Yu

Quantum research programs:

Many participants reported significant quantum activities at their institutions. These range from an investment in staff and facilities dedicated to the advancement of new quantum technologies to maintenance and refinement of quantum measurement standards for SI unit realisation (e.g. electrical and frequency standards). Often these activities are relatively new, having started in the last few years. As discussed in the survey results, activities span computing, communications and sensing. Often, launching quantum activities has been done out of existing budget allocations and further growth will require an injection of new funding or a significant restructuring of activities.

It was noted that in the area of quantum photonics, CCPR is establishing a framework for the calibration of single photon devices which covers both ‘Metrology for Quantum’ and ‘Quantum for

Metrology.' This observation was generalised noting that MfQ and QfM often overlap, and that this is a good motivation for metrology institutions and CIPM to dedicate resources to the study and development of new quantum technology.

Direct funding to enable industry:

A participant noted a program at their institution by which they could fund partnerships whereby they work with university and industry partners to advance quantum technologies. Another noted that through a national program companies can come to seek expert advice and support in their quantum technology development. A third discussed providing funding to set up a national industry consortium. The need for funding industry was highlighted; quantum technology companies are generally small-scale and lack resources. Overall, many participants felt that they needed to come up with mechanism to be engaged more actively with their national industry partners.

Testbeds:

The importance of independent characterisation of quantum technologies was noted as a means to ensure reliability and trust in these new technologies. Testbed activities are sometimes embedded in the participants' institute while in other cases, participants made reference to their national programs and infrastructure which they were in many cases a part of. Testbeds are designed to characterise specific quantum technologies (e.g. dark fibre networks for QKD or time/frequency comparison) or to characterise components of quantum systems (e.g. characterising cabling and connectors at cryogenic temperatures). Some participants noted that they have, or are establishing, user facilities whereby industry can bring their technology to test or be tested.

A concern noted was that testbeds may not be a good investment when technology is changing very quickly. Participants in one session discussed the precision requirements of characterisation/testbed facilities; at this time, the level of precision required can vary greatly (e.g. qubits is relatively low precision while fibre optics is high).

Role in standardisation / standards:

Several participants reported participation in documentary standards development (e.g. for QKD.)

Role as an advisor in government / industry:

Many participants confirmed that they have roles as advisors to government. This includes participating in the development and implementation of national quantum strategies, and advising on security and, in in some cases, regulatory aspects. Fewer participants had examples of programs to advise industry.

Reference materials:

Several participants noted capabilities in reference material development and characterisation and emphasised that this is highly relevant to development of quantum technologies.

Priority in quantum if not currently active:

Some participants reported that while they are not presently active in quantum research, this is a part of their strategic plans, and that they are building up capacity.

Other observations:

One participant noted the use of patenting of their institute's technologies as a mechanism to ensure that it could positively enable the spread of that technology. Industry's need for best practice guides was discussed, and the question was raised as to who is responsible for developing these. The importance of providing education activities for schools and industry was expressed with one example being short courses in quantum technologies areas, such as few-photon devices.

Panel: International quantum standardisation

Moderator: Tim Prior, NMI-Q (NPL)

Panellists: Barbara Goldstein (NMI-Q, NIST), John Devaney (NPL), Thomas Gerster (PTB), Kazutomo Hasegawa (Fujitsu)

Slides 76 - 81

To realise the potential benefits from applications of quantum technologies, the global effort in quantum research and innovation continues to grow, with worldwide public sector investments exceeding $40 billion. When we analyse where these investments are being made, it is dominated by developed economies, whose motivation is job creation, growth in GDP and national security. This could lead to a `quantum divide' with some areas of the world effectively excluded from the quantum revolution.

All the major public sector initiatives in quantum recognise the importance of standardisation as a mechanism for speeding up innovation, helping create supply chains, bringing products and services to market and enabling adoption by end users. The term `standardisation' they are referring to covers a wide range of activities that begins with scientific discovery and ends with products and services being adopted and used, from agreeing terminology, to developing the measurement science, to documentary standards. This is illustrated in slide 82, showing a technology readiness level flow chart for high level quantum applications.

Panel discussion

Is standardisation for quantum technologies different?

Quantum technologies are emerging rapidly. Standardisation needs to keep pace with this and be fast, agile and responsive to industry needs. By using the standardisation readiness level model, we can assess at which stage each technology is and the appropriate requirements of standardisation, be it defining terminology, developing appropriate metrology, benchmarking, establishing best practice or initiating documentary standards development.

Many national quantum standards strategies now mention standardisation, do you think governments are putting enough focus on this area?

Governments across the world are beginning to recognise the importance of standardisation for the success of their quantum strategies. NMIs need to show leadership in their economies to educate governments, and industry, on why standardisation development is needed, and that it requires sufficient resources for effective implementation.

What are the challenges and barriers of international collaboration in standardisation?

One of the main barriers to collaboration is geopolitics. Governments have political views on who they will and who they won't collaborate with, for either security or economics reasons. Cost is also potentially a factor restricting collaboration, either the cost of establishing a local quantum capability, or the cost of sending staff and equipment potentially across the world. There is also a concern that standardisation will be dominated by the big players who may wish to promote their own domestic capability.

What do you think industry wants from NMIs?

Industry, via engagement workshops, has indicated that the top 3 enablers for adoption of quantum technologies are supply chain development, standardisation and skills. For standardisation, they are looking for leadership from organisations such as NMIs to help them understand what they need and to develop the metrology, testing, characterisation and benchmarking capability that will enable products to be developed and launched, supply chains to be established, scale-up of production, and interoperability of competing technologies, or generations of systems.

Industry does think that the standardisation process is too slow and are looking for outputs, for example from NMIs, to be available quicker and more relevant to their needs.

Getting industry to engage with the standardisation process is facilitated by NMIs and industry consortia working together to establish requirements and potentially deliver best practice guidance. NMIs need to be taking a stronger leadership / coordination role in standardisation for quantum technologies.

What role do you see `best practice guides' playing in the standardisation process?

Best (or good) practice guides are often the most practical way of transferring knowledge to industry. They set out the experience developed in NMIs in a tangible format. NMIs should work together to develop / establish best practice, and then publish guidance documents. These can be produced well in advance of documentary standards and are likely to form the basis of them.

Summing up

There is a clear role for NMIs in quantum technology development, adoption, and exploitation. NMIs need to take leadership and help industry by leading them through the standardisation process and providing practical help through tools like best practice guides. This should be done via international collaboration, leveraging the strengths of specific NMIs across the world.

Panel: The role of the metrology community in advancing emerging technologies

Moderator: JT Janssen, CIPM

Presenter: Alexander Tzalenchuk, NPL

Panellists: Takashi Usuda (NMIJ/AIST), Victoria Coleman (NMIA), Jim Kushmerick (NIST), Georgette Macdonald (NRC), Cornelia Denz (PTB)

Slides 85 – 107

Alexander Tzalenchuk of NPL opened the session with highlights inspired by the Nature Physics Comment, "*The expanding role of National Metrology Institutes in the quantum era*", which he authored along with members of IMEKO Technical Committee 25 on Quantum Measurement and Quantum Information (https://www.nature.com/articles/s41567-022-01659-z.) He emphasised how *Quantum for Metrology* and *Metrology for Quantum* form a virtuous cycle and provided examples from a number of technologies including Josephson junctions, magnetometers, and ion traps. He noted new quantum technologies are under development that are expected to advance metrology, such as the quantum anomalous Hall effect for the ohm, and quantum phase slip to measure the ampere. To address the quantum industry's needs, he noted the importance of benchmarking but also acknowledged that a benchmark that provides a meaningful comparison of different quantum computing platforms has been elusive. Many NMIs are establishing testbeds to accelerate technology development.

Each of the panellists gave a short presentation:

Takashi Usuda, NMIJ/AIST, highlighted the Japanese Global Research and Development Center for Business by Quantum-AI technology, referred to as G-QuAT, that plans to provide a hardware testbed for cryogenic components and a one-stop testbed for traceable testing, calibration and low temperature annealing.

Victoria Coleman, NMIA, discussed the "quantum adjacent" perspective and experience with standardisation using the example of nanotechnology. She highlighted the importance of organisations such as the Versailles Project on Advanced Materials and Standards in coordinating international collaboration of activities ranging from pre-normative research to development of reference materials.

Jim Kushmerick, NIST, discussed how the NIST Quantum Information Science and Technology R&D program spans the entire scope of interest of the National Quantum Initiative Act, including sensing and precision measurement; quantum networking; quantum computing; fundamental quantum science; enabling technologies; and risk mitigation (e.g. PQC). He discussed the importance of the NIST nanofabrication facility, and of joint institutes such as JILA.

Georgette Macdonald, NRC, provided an additional "quantum adjacent" perspective, drawing from the International Civil Aviation Organization (ICAO) development of new emission measurement standards to underpin environmental regulations. Civil aviation standardisation of particulate emission control from 1960-2010 was based on measuring their visibility. But there was no awareness or consideration of nanoparticles and so new standards development based on new measurement technologies were needed. This involved extensive work (method development, lab benchmark, field testing) with international participation from NMIs, other government departments, original equipment manufacturers and universities. The result was a new international standard that now underpins national regulations to achieve lower emissions and better sustainability. But it was a long road with over 20 years of development.

Cornelia Denz, PTB, provided an overview of PTB's Quantentechnologie-Kompetenzzentrum and of their innovation clusters for new topics including: environment and climate, medicine and health, energy and mobility, quantum technology, digitalisation and AI, and systems metrology. She discussed PTB's efforts in establishing testbeds for ion traps, superconducting quantum computers and quantum communications.

Highlights from the panel discussion:

Is there a need for BIPM to coordinate metrology for quantum activity?

Quantum is so broad that it is difficult to say definitively that BIPM/CIPM can have a role or what it should be, but it is useful to come together and discuss the path forward. BIPM/CIPM can also facilitate outreach to other organisations such as standards bodies.

The quality infrastructure will need to be different for emerging technologies, i.e. more agile.

It isn't necessary for the BIPM/CIPM to take on everything; the VAMAS model allows the selection of topics to address.

Membership in BIPM allowed access to the international prototype kilogram; quantum technology is developing so rapidly that care is needed to agree which aspects are ready for collaboration.

NMIs can learn a lot from each other during the pre-standardising phase.

There are different levels of maturity across NMIs in quantum. What should BIPM's role be there?

BIPM could do an analysis of needs for measurement (as in climate change), produce a roadmap and a framework for the opportunities to contribute.

Collaboration helps smaller NMIs to develop; there are several examples from PTB collaborations with developing economies during the last 40 years.

Regional Metrology Organisations have facilitated development of shared references between economies.

How do NMIs prioritise new technologies?

Individual NMIs are influenced by their local perspective; e.g., is there a local industry?

A forum structure would allow greater participation on select topics as they emerge.

NMIs are currently collaborating on topics of mutual interest at a grass roots level. We should avoid a "build it, and they will come" attitude, and be sure to consider the structures and systems for collaboration already in place.

Holding a summer school on a topic (e.g., single-photon sources) helps convergence.

Is there a risk that if BIPM does not provide a solution, other systems might be developed?

A good question to leave for consideration.

Day 1 wrap-up

Jan Herrmann, NMI-Q (NMIA)

On behalf of the Organising Committee, Jan Herrmann summarised what was a day full of broad and rich discussions.

There is a clear industry need for application-relevant standardisation of quantum technologies, and a sense of urgency to address those needs. Such standardisation efforts require collaboration – no organisation can do it alone.

NMIs (and DIs) are uniquely positioned to contribute to, to facilitate and to drive those efforts: We have a track record both in early adoption of quantum technologies ('quantum for metrology') and in supporting the development of quantum science and technology ('metrology for quantum'). We are recognised as being independent, and we have an established culture of collaboration, with effective governance and support frameworks.

But we need to be responsive and agile in the context of a very dynamic technology landscape, and that is what the focus of Day 2 will be – looking at what we can do together, and how we can work together.

Day 2: Solutions

Framing Day 2

Nobu Kaneko, NMI-Q (NMIJ)

Slides 139 - 140

Nobu Kaneko first summarised the route to this workshop from the precursory formation activities in 2022 and the first meeting of what became the Organising Committee in January 2023. There were in-person meetings in Berlin, Tokyo, and Ottawa in addition to fortnightly on-line meetings to liaise with NMIs, BIPM, and CIPM members toward the realisation of this workshop. Secondly, he reflected on the activities of Day 1. The presentations and discussions on Day 1 guided the audience to the same goal, which included leveraging the combined expertise of the world's NMIs to accelerate the development and adoption of quantum technologies through coordinated development and sharing of measurement "best practices" in support of future standardisation.

In the panel sessions, industry consortia expressed the need for application-driven quantum standardisation and test cases. Participants highlighted the need for collaboration and benchmarks. NMIs are independent, uniquely positioned, have a track record of being quantum 'pushers' and 'pullers,' which have established a culture and framework of collaboration, but NMIs need to think about how they can be agile and responsive in the context of a very dynamic technology landscape. Concerning this, NMI directors and CIPM members presented relevant NMI quantum activities and perspectives on ways and benefits of collaboration.

NMI Collaborations in Quantum

Moderator: Nobu Kaneko, NMI-Q (NMIJ)

Presenter: Ivo Degiovanni, INRIM, "European Metrology Network for Quantum Technologies (EMN-Q) and the Qu-Test Project"

Slides 144 - 156

Ivo Degiovanni showed an overview of EMN-Q and specific examples from Qu-Test: EMN-Q is a European Metrology Network (EMN) under EURAMET, the European regional metrology body. EURAMET has 10 technical committees (TCs) and two horizontal committees. Recently, EURAMET has launched or is proposing to launch 15 European Metrology Networks (EMNs) to strengthen interaction with stakeholders, with EMN-Q as one of these networks. EMN-Q is comprised of 18 EURAMET Members and Partners from 15 economies and aims to be recognised as Europe's unique reference point representing European metrology for quantum technologies. It aligns with industrial requirements, those of the EC Quantum Technologies Flagship, national and inter-governmental quantum technology (QT) programmes, and any relevant stakeholders; to contribute to QT developments through NMIs' and DIs' research and innovation activities; to provide input into the standardisation and certification of QT; and to promote the benefits of metrology to the stakeholders. EMN-Q has drafted 5 strategical roadmaps associated with the three Quantum Flagship pillars; Quantum Clock & Atomic Sensors, Quantum Electronics, and Quantum Photonics. Roadmap drafts were circulated among the EMN-Q community and EURAMET TCs, and feedback was collected. Ivo Degiovanni also explained activities of Qu-Test, which is a 3.5-year project, kicked-off in April 2023. The goals of Qu-Test are to improve test facilities for quantum devices, harmonise procedures and methodologies, cooperate with the quantum industry, and provide access to testing capabilities. Qu-Test is a consortium of service providers of registered training organisations and NMIs in EU.

Qu-Test covers the three broad areas of quantum computing (solid-stage cryogenic computing components and devices, photonics quantum computing components and devices, and characterisation of ion traps), quantum communication (characterisation of light generation and light detection on device level, evaluation of components and systems at the quantum random number generation and QKD protocol level, and experimentation and prototyping for quantum communication) and quantum sensing (metrology application of quantum clocks, neutral atoms: hot & cold, non-classical light for quantum-enhanced imaging and sensing, and solid state spins such as NV centres in diamond).

Qu-Test currently has 4 objectives:

- create a federalised network of testing and experimentation services answering the needs of the industry,
- upgrade, up-scale and integrate the testing and experimentation infrastructures and associated processes,
- set-up an open-access distributed testing and experimentation infrastructure to make services available to clients in all 27 EU member states,
- validate the relevance of the service offering and robustness of the Single-Entry-Point network.

Presenter: Florent Lecocq, NIST, "Metrology gaps for superconducting quantum devices"

Slides 157 - 170

Florent Lecocq gave an overview of the anticipated metrology needs for superconducting (SC) devices, a specific example of a round robin and its relationship to Qu-Test and other European efforts. He noted that SC device characterisation does not always have to have a link to SI. To benchmark quantum computers, the number of qubits, coherence times, and gate fidelity are not necessarily good metrics, whereas NIST has found that quantum volume-specific algorithm benchmarking can provide better insights. To facilitate a systematic approach to device characterisation, hardware components at ultra-cryogenic temperatures for quantum computers can be categorized with sub-categories such as cryogenics (dilution refrigerators), signal delivery (cables, filters, attenuators, isolators), shielding (magnetic, thermal, radiation), readout chain (quantum amplifiers), and quantum processors (qubits, resonators, integrated circuitry). Each sub-category has specific parameter metrics to be evaluated. One example is two-port microwave calibration at millikelvin temperatures carried out with a cryogenic in-situ calibration kit at temperatures below 20 mK. The speaker presented another example of measuring microwave attenuator thermalisation and power handling using qubit coherence in the collaboration partnership between XMA, QED-C and NIST. Typically, companies do not have access to mK temperatures, and thus partnership with NMIs can help the quantum industry (e.g. via QED-C). NMIs can define the best practices and metrics, for example calibration of quantum amplifiers with a calibrated noise source, measurement of coherence time, (T_1 and T_2), or the qubit round robin organised by the Fermilab Superconducting Quantum Materials and Systems Center (SQMS). He explained that the coherence time of qubits fluctuates over time, and that therefore reporting maximum and mean T_1 is usually not enough and that histograms and/or time traces of T_1 are better suited to characterise qubits. In the SQMS qubit round robin, they disentangled some sources of loss by sending an identical device to multiple locations within the SQMS Center. The goal of the project is to standardise measurement protocols, measurement electronics, measurement code, and data analysis. He concluded that quantum computing is not mature enough for standardisation yet, but that NMIs and other government agencies could/should help define the right metrics, define good practices, and support the nascent quantum industry.

Presenter: Felicien Schopfer, LNE, "MetriQs-France, Measurement, evaluation and standardisation of quantum technologies"

Slides 171 - 177

MetriQs-France has the objective to develop, exploit and promote reference measurement capabilities, which are validated, harmonised and widely recognised. For trust and adoption of quantum technologies, reliability, impartiality, and comparability are important. MetriQs-France focuses on collaborative R&D projects and on measurement and testing infrastructure, with the participation of research organisation, large industry, start-ups, AFNOR (NSB), LNE and others. The collaborative R&D projects include activities spanning quantum computing benchmarks, characterisation of quantum components and enabling technologies, and R&D to address metrology gaps. Measurement & testing infrastructure is based on a network of sites across France. LNE – Trappes offers characterisation services for solid-state qubits and enabling technologies (electronics and cryogenics), LNE-SYRTE-OP – Trappes, specialises in quantum gravimetry, LNE-CNAM – Saint-Denis have capabilities in thermometry and optomechanical sensors at very low temperatures, and LNE-SYRTE-OP – Paris focus on atomic clocks. The speaker presented a summary of the BACQ Project that aims to develop application-oriented benchmarks for quantum computing. BACQ plans to develop a capability to evaluate the practical performance of quantum computing, providing an unbiased, universal, long-lasting, widely-used, and well-recognised common reference. The goals of this project include comparison of classical and quantum, measuring the progress towards a practical quantum advantage, and supporting the development of useful quantum computing technologies. The scientific approach is to develop a set of benchmarks based on the resolution of reference problems (optimisation, linear systems solving, quantum physics simulation, factorisation) and of aggregate technical and service quality metrics.

In conclusion he noted that NMIs need to build on the national quantum metrology initiatives, like MetriQs-France, to develop collaborations between NMIs, research organisations and industry and to progress towards internationally harmonised & recognised measurement capabilities, benchmarks and standards for quantum technologies. It is also important to establish trust in quantum technologies and accelerate their worldwide adoption by industry, market and society.

Presenters: Angela Gamouras, NRC and John Lehman, NIST, "NMI Collaborations in Quantum Photonics Standards Development"

Slides 178 - 211

Angela Gamouras and John Lehman explained the relevance of quantum photonics technologies to various fields (e.g., biotechnology, electronics, astronomy, metrology, information processing, medical technologies, physical science, and sensing). They presented a strong and coordinated series of activity in this space dating back to 2003, with greater momentum since 2015. The activities can be grouped under the categories of technical cooperation, information exchange, technical documents, and workforce and training. There are many examples of technical cooperation amongst NMIs, and information exchange is happening within CCPR WG-SP-TG7 as well as long-standing recurring meetings such as the Single Photon Workshop and multi-lateral NMI workshops (e.g., Quantum SI workshop for single-photon metrology in Boulder in 2019 between NIST, NRC and NPL). They have also launched short courses for industry (e.g., <Q|School short course at JILA/University of Colorado) and developed domain-specific terminology.

Angela Gamouras emphasised the importance of engagement with industry and academia and consortia provided collaborative discussion forums. CCPR has a discussion forum on single-photon terminology, which is harmonising a common language and critically important to the development of single-photon devices. The resulting single-photon dictionary is a potential starting point for a terminology standard. A further aim is to publish technical notes on recommended measurement practices and pitfalls. The long-term goal is to support quantum photonics measurements and future infrastructure through comparison activities (for detectors, sources, etc.) and practical calibrations with SI-Traceability.

The presenters emphasised that to make a progress in quantum photonics and related standard activities, communication and collaboration are essential, and that in their practical experience, discussion forums and networks, motivation, terminology documentation, technology integrations and skills development initiatives have played key roles.

What was/is the motivation for the activities?

EMN-Q is located in EURAMET. (1) it is important to carry out R&D deeper/over a project-based approach. EMN-Q helped us to integrate the community. (2) Structure was a limitation, and we have cross-cutting topics in different committees. Thus it is better to share them in one committee.

It is difficult to compare low temperature amplifiers presented in different research papers without any common guidelines. Determining characteristics like coherence time of qubits is a multi-disciplinary challenge, and it turned out that reporting just maximum and mean of the coherence time is not enough. It was very good practice for us to have a combined expertise from a lot of researchers around the world with the round robin tests of qubits.

The technology is maturing. Industrial perspective and objective evaluation are needed now. There are many challenges for metrology associated with quantum technologies.

There is a need to ensure SI traceability; drawing on expertise from participants.

Two motivations: (1) detector efficiency is critical in our field and (2) buying equipment from manufacturers is difficult.

Is there any benefit for the NMIs?

Co-operating activities between NMIs are mutually beneficial through back-and-forth flow of information.

This model is expandable and can bring efficiency.

Are test-beds out of date very fast? Open to everyone or only selected partners?

Proof of principle is easier and fast, however, it is hard to secure dedicated staff to repeat measurements.

Was it difficult to set an appropriate protocol for the hardware and the measurement procedure for the qubit round robin?

It was a crucial point, and took time to reach a consensus.

Why is quantum volume a good metric for quantum computing?

It is not the “best” metric, but better than other metrics like number of qubits. A single cross-platform metric should be established. In practice, it will be better to use an actual problem to benchmark quantum computers. One algorithm will not match every platform and use-case.

Survey results

Nicolas Spethmann, NMI-Q (PTB)

Slides 212 – 224

Before the workshop, a survey (attached to this report) was sent out by BIPM to all member Dis/NMIs. The purpose of the survey was to get an overview of existing activities of respective economies in quantum technology, and of specific fields and topics that are actively pursued, to inform the discussion stimulated by the workshop.

Nicolas Spethmann presented an overview of the survey results, with details and figures in the workshop slide deck, based on the responses from 35 of the 39 economies represented at the workshop.

Noting that there is an increasing investment in quantum technologies worldwide, it was not surprising that more than half the responses stated that their economies have quantum strategies and domestic/regional/local quantum programs. The percentage of NMIs and Dis with specific quantum programs is higher than that for economies in general, showing the strong engagement and tradition of NMIs / Dis in developing and applying quantum physics and technology. However, less than half of the responses indicated the existence of quantum-relevant roadmaps to guide these national and NMI / DI programs, including roadmaps with specific performance goals.

NMIs in several economies have expanded their activities to support the emerging quantum industry. About three-quarters of NMIs / Dis report existing collaboration in the field of quantum technology.

Next, Nicolas summarised the responses about quantum-related priorities. Typically, NMIs are closely involved in national quantum programs. Not surprisingly, the highest priorities in these programs are closely related to core tasks of NMIs with “standards” and “fundamental measurements”, closely followed by “building capacities”. The survey suggested that lower priority is given to activities like “advancing the supply chain” and “developing case studies and use cases”. Other priorities included “Health”, “Environmental sensing”, “Critical infrastructure”, “Supporting supply chain”, “resilience” and “Developing skills and training”.

The survey further collected information about application areas of quantum technologies, grouped in the three categories “active in”, “interested in” and “no current plan”. The results showed that there are:

- broadly established fields with significant activity and interest (clocks, Josephson junctions, quantum Hall, …),
- less established fields with high level of interest (gravimetry, magnetometry, …),
- less established fields with limited activity (Majorana qubits, …).

Responses related to support for, and engagement with, industry showed a spectrum of activities, including collaborative research with industry and academia, testbeds, services and sharing facilities, characterisation of components, providing SI traceability, proof-of-principle and novel measurement capabilities, evaluation of components, training (together with academia), awareness building, communicating opportunities and challenges, participating in standardisation, as well as “creating critical mass” and synergies for industry’s use of quantum technologies.

Comments in the survey showed openness for collaboration and industry support:

> *“… open for collaboration with both scientific quantum community and quantum industry…”, “…eager to offer the available standards and know-how for the quantum research and industry…”, “…looking forward to development of the novel traceable tools and measurement techniques…”*

but also challenges reflecting the different levels of existing capabilities, resourcing and industry needs, in particular in developing economies:

> *“…it is very challenging for small NMIs in developing economy to keep up with speed of research and technology development. Only through strategic capacity building and research collaborations that the gap between advanced NMIs and developing NMIs will not be wider at higher speeds...”*

In summary, the survey showed that there is strong involvement of the metrology community in supporting emerging quantum industries. Further, there is a diversity of approaches and intensities of “quantum activities” across the metrology community, and engagement with the quantum industry covers a spectrum of activities beyond ‘core’ metrology.

Break-out 2: What activities should NMIs/DIs be working together on?

Moderator: Davide Calonico, INRIM

Facilitators: Daiji Fukuda, Stefan Kück, Michael Kjær, Ivo Degiovanni

Rapporteurs: Dong-Hun Chae, Thomas Gerster, John Devaney, Félicien Schopfer

What technologies and applications can we advance through cross-NMI collaboration?

Break-out discussions revealed that there are many opportunities for cross-NMI collaboration. Developing/smaller economies are most often interested in quantum for metrology type projects, thereby enhancing their metrological capabilities, while more advanced NMIs have a greater appetite for metrology for quantum whereby they can use their strengths in both metrology and quantum devices to advance the development of commercial quantum technologies.

Using atomic clocks as an example, the developing/smaller economies see great benefit in collaboration amongst NMIs to develop their frequency and time capabilities while advanced NMIs are often involved in comparison of miniaturised mobile clocks, clocks as sensors, etc.

With the upcoming redefinition of the second based on optical clocks, there is a common interest for comparison of optical clocks, both through co-location and long-distance comparisons.

In the nexus of quantum for metrology and metrology for quantum, few (and entangled) photon sources and detectors have received high interest because of their potential for metrology applications and quantum technologies. Collaboration has been extensive both through CCPR coordinated activities and outside of this via international workshops and bi-lateral / tri-lateral projects.

An often-remarked advantage of entangled photons is precision measurement that can exceed shot noise limits and this is a logical area for NMI effort and collaboration. Another is any application of quantum sensors which allow fundamental measurements/sensing of the environment not previously possible or with high accuracies.

Other areas proposed for future collaboration include radiometry, magnetometry, quantum pressure standards, reliability of cryogenic devices, Josephson-based power standards, quantum impedance standards, Quantum Hall Resistors, trapped ions and neutral atoms.

A number of participants felt that NMIs should be actively involved in quantum communication, 'quantum networks', and long distance QKD links. With regard to quantum computing, some participants felt that NMIs are best suited to contribute to sub-component characterisation rather than full system. This is the region where our expertise is strongest and the ties to quantum for metrology are greatest. Specifically dual-purpose technologies such as ion-traps and Josephson junctions which have been demonstrated and are under continuous refinement for clocks and voltage standards, are also central components to quantum computing sub-components.

What activities should we do and outputs should we produce?

Collaboration should produce documentation / protocols for evaluating and/or calibrating new devices. These need not be definitive 'best-practices'; even examples of NMI-developed 'good practices' would be invaluable to other NMIs and to quantum companies trying to understand and demonstrate their new technologies. Other valuable contributions include common vocabulary, roadmaps on metrology for quantum technologies, training / personnel exchanges, interlaboratory comparisons and round robins.

Development of testbeds are recognised as an important means to characterise emerging technologies, while equally giving the NMI the opportunity to advance their measurement capabilities and simple 'to learn'. A testbed may become obsolete quickly, but the knowledge learned through creating it positions the NMI to more rapidly adapt to the evolving needs of industry.

On-chip measurement standards and more practical travelling standards were seen as valuable outputs.

The benefit of personnel exchange was noted, providing opportunity for researchers to spend time in other laboratories, learn their methods and bring these perspectives back to their own labs and to follow up with comparisons. This has worked very well for 'traditional' metrology development.

How can outputs be used?

Based on recent experience with single-photon detector characterisation, exchange of methods and results is invaluable to uncovering missing sources of uncertainty. In isolation, lower uncertainties were reported which were not substantiated once comparisons were made between study participants.

The idea of disseminating good practices sparked some debate where some believe that getting out a good protocol early which others could follow will help make rapid advancement, while others felt that developing different methods is critical to fully exploring the problem space, uncovering method limitations and driving towards best practices.

Noting the need for industry relevance, a number of participants promoted the need to provide training to industry through hands on experience in device characterization, good practice documents and advice-giving based on specific industry needs.

It is also important to make the capabilities of NMIs visible to industry via a repository/directory, and promotion of good measurement practices.

Other thoughts

It is difficult to provide a definitive list of priority technologies to be working on. This is a rapidly evolving landscape and as new technologies emerge or technologies make significant jumps in capability, we as NMIs must be ready to react.

Presentation – Examples of frameworks for NMI collaboration

Jan Herrmann, NMI-Q (NMIA)

Slides 231 - 243

To set the scene for the subsequent breakout group discussions on how NMIs (and DIs) can work together, Jan Herrmann gave a brief overview of a couple of examples for approaches to collaborative activities aimed at supporting the development of standards.

The first example, the International Avogadro Coordination, was established in 2004 to help provide the metrological underpinnings for the re-definition of the kilogram, in response to a 1999 CGPM resolution. It brought together a number of NMIs who contributed their unique expertise and capabilities to achieve an accurate determination of the Avogadro constant. This collaborative approach was critical, not only to overcome the enormous technical challenges in meeting the very demanding requirements for achieving the necessary measurement uncertainties, but also to ensure the robustness and reliability of both the methodology and the results. The ultimate success of the project was a key element contributing to the re-definition of the kilogram, and the SI, in 2019.

The other example highlighted a successful framework for international collaboration in support of development and trade of products dependent on advanced materials technologies. The Versailles Project on Advanced Materials and Standards (VAMAS), established as one of 18 cooperative projects at the 1982 Economic Summit of the G7 to stimulate trade in new technologies, aims to provide the technical basis for harmonised measurements, testing, specifications, and standards in this area. NMIs contribute very strongly to VAMAS activities, be it in governance roles as representatives of economies on the VAMAS Steering Committee and as Chairs of Technical Working Areas, or as leaders and contributors to technical projects in those Areas. Even without dedicated funding, VAMAS has become an effective framework for conducting collaborative pre-normative research to validate methodology for the measurement, characterisation, testing and specification of products and processes enabled or enhanced by advanced materials. Informed by liaisons with standards development organisations and with metrology organisations such as BIPM and APMP, the outputs of the collaborative VAMAS projects provide tangible benefits not only for the timely development of documentary standards, but also for the participating economies and organisations and their stakeholders. With the framework being technology agnostic, many of those benefits could be realised similarly for quantum technologies.

Break-out 3: How can we work together?

Moderator: Jan Herrmann, NMI-Q (NMIA)

Facilitators: Nobu Kaneko, Nicolas Spethmann, Kevin Thomson, Davide Calonico

Rapporteurs: Angela Gamouras, Lisa Lambert, Stefan Kück, Florent Lecocq

How do we organise ourselves?

The 'NMI consortium' approach adopted in the example of the International Avogadro Coordination was considered to be unsuitable for the broad scope of quantum technologies.

There was significant interest from participants in a VAMAS-like framework, recognising that its overall structure and governance could lend itself to a broadly scoped, yet flexible approach to NMI-led collaborative activities, to active industry participation, and to effective dissemination of outputs.

Participants pointed out the importance of openness about existing capabilities and of clear, industry-relevant objectives for collaborative activities, and to be mindful of sensitive areas.

Some participants pointed out the need for flexibility in participation, for example at the regional level or through specific multilateral collaborations.

Exchange of hardware, knowledge and people was consistently identified as an important element of a collaboration framework, as was a website as a portal for sharing information on current and planned collaborative activities and on relevant contact points.

What constrains us from collaborating?

Aspects of the geopolitical situation and of national interests and priorities were identified by participants as constraints, as were intellectual property concerns, in particular for start-up companies.

It was noted that challenges in prioritising funding for collaborative activities vs. activities underpinning commercial services can limit the ability for NMIs to participate and contribute.

Participants said that lack of clarity about objectives, insufficient industry engagement and lack of leadership can also impact collaborations.

How do we engage industry?

Participants welcomed the application and industry focus of NMI-Q. They emphasised the importance of listening to industry and of close liaison with industry consortia such as QED-C, QuIC, Q-Star etc. in making future activities and outcomes, such as infrastructure, testbeds and expertise, visible, accessible and relevant to industry. It was pointed out that not all of the challenges around quantum technologies are new and that lessons from other industries, such as semiconductors or telecom, can be useful.

Which other organisations do we need to include?

Testing laboratories, certification bodies, and applied research organisations were identified as potential participants and partners.

How do we share our outputs?

Best practice guides and benchmarks were seen by participants as useful 'intermittent' outputs ahead of more traditional documentary standards.

Training and capability building were identified as key outcomes of future collaborative activities.

Participants saw value in leveraging BIPM infrastructure, including the website, for dissemination of outputs, and in relevant conferences and events, such as CPEM.

What is the role of CIPM/BIPM?

Participants saw a role for CIPM in leveraging Consultative Committees (CCs) for specific technical aspects of quantum technologies, especially where these are well-defined (for example with a focus on components rather than systems) and attributable to the current capabilities and scope of CCs. The emerging work on quantum photonics presented at the workshop was seen as an example for this. However, it was also noted that the CC structures are rather static and not overly agile.

A broad, platform set of technologies such as quantum has no current 'home' in the CIPM structure, somewhat similarly to materials – perhaps that was a reason for VAMAS to meet some of the related needs.

Some participants felt that BIPM could add value in facilitating participation in activities and dissemination of outputs to NMIs, in particular in developing economies, e.g. through leveraging existing frameworks for capacity building and knowledge transfer.

Panel – Wrap up: Main take-aways and suggestions for next steps.

Moderator: Nicolas Spethmann, NMI-Q (PTB)

Panellists: James Olthoff (NIST, CIPM), Dolores del Campo Maldonado (CEM, CIPM), Andrew Todd (NRC), Ivo Degiovanni (INRiM), Wynand Louw (CIPM)

What is the main take-away of this workshop?

From the NMIs' perspective, metrology for quantum is very exciting; measurements for quantum are seen as highly relevant for the world. For a broad field such as quantum technology, collaboration is essential. Even larger NMIs and economies cannot meet the demand completely on their own. In that light collaboration is essential. Also, smaller labs & economies might specialise to fill gaps and meet national needs. There are challenges but we should work together to overcome them.

The need to align the NMI-Q initiative with industry needs was highlighted.

From a CIPM perspective, international agreement on topics such as vocabulary and training are important. CIPM/BIPM could be a forum for dissemination of outputs. It is not clear yet whether CIPM should play a more prominent role than that. CIPM has set up dedicated forums to meet grand challenges (e.g. climate change) which might serve as inspiration.

In conclusion

Quantum in general, and metrology for the quantum industry in particular, are seen as very important. There is a need for a suitable structure to organise corresponding activities of NMI-Q and related activities in collaboration, and aligned, with CIPM/BIPM. The detailed mechanism and structure need to be determined.

Closing remarks: NMI-Q steering group.

Barbara Goldstein (NIST), Tim Prior (NPL), JT Janssen (CIPM)

Barbara Goldstein noted that the Organising Committee has invested significant effort into organising this workshop and thanked attendees for taking the time to participate enthusiastically. She heard enthusiasm for taking action but also that it is still not clear exactly how. She noted the risk of a quantum divide and `quantum nationalism' which gives food for thought. It is evident that there is a continued role for BIPM and CIPM in quantum technology, but again, it is not clear exactly what that role will be. Finally, it is essential to have industry engagement.

Tim Prior said that the organisers honestly did not expect a consensus opinion and direction to be an outcome of the workshop; this is a very complex topic with a myriad of ways to move forward with different advantages and challenges. He thanked participants for their input and expressed the hope that attendees will stay involved to find the best solution.

JT Janssen highlighted that it is very good to see so many come together to discuss quantum. The Organising Committee will disseminate a summary of the discussions and findings. The CIPM has already established horizontal activities to address needs in other areas but quantum need not be tackled in the same way. CIPM can bring people together on a neutral/equal platform but existing initiatives show that collaborative work can also happen without CIPM governance. It is a matter of keeping the community together and trialling ways of working. JT thanked all attendees for coming and participating and also extended his thanks to the members of the Organising Committee and to Pierre Gournay and the Meeting Office team at BIPM for all their support in running the workshop.

Adjourn

Martin Milton (BIPM)

Successful workshops such as this one leave participants with a sense of accomplishment and purpose; however, champagne sinks into the sand very quickly, so please ensure this positive momentum by continuing to work together to publish your summary and recommendations for a path forward.

Next steps

In addition to this report, the Organising Committee will produce a separate White Paper with recommendations for next steps in establishing and implementing the NMI-Q initiative.