The European quantum industry perspective on quantum sensing and metrology

Quantum Metrology: the present and the future

Based on the Strategic Industry Roadmap of the European Quantum Industry Consortium

Thierry Debuisschert

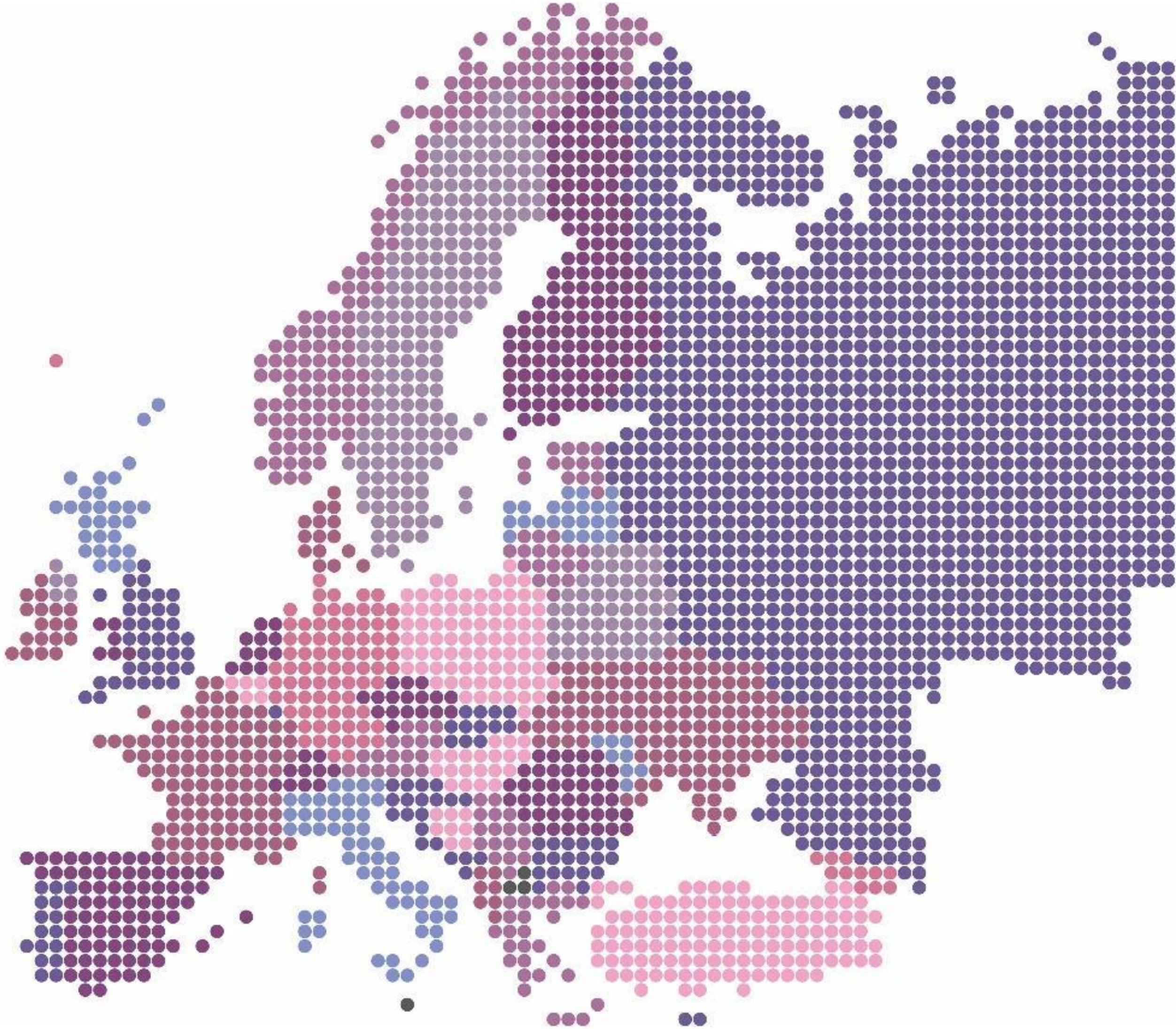
Nov. 21, 2022

QuIC
European Quantum Industry Consortium

Fertile Quantum Ecosystem

- Skills, know-how, business capabilities individual companies
- Skilled and broad workforce
- Reliable supply chain of components, devices and services
- Industry-wide standards and accreditation, right environment for international trades

Integrate this into existing industries and ecosystems achieve the maximum commercial success of the pan-European quantum Industry



QuIC in a nutshell

- **Non-profit association** established by several major business actors – large enterprises, SMEs, startups, investors – from across Europe.
- **Our mission is to boost the pan-European industry competitiveness in quantum technologies, to foster economic growth and value creation for business and citizens.** QuIC operates as a collaborative hub throughout Europe to build a strong, vibrant ecosystem between SMEs, large corporations, investors, and leading researchers.

QuIC is the voice of the European Quantum Technology (QT) industry

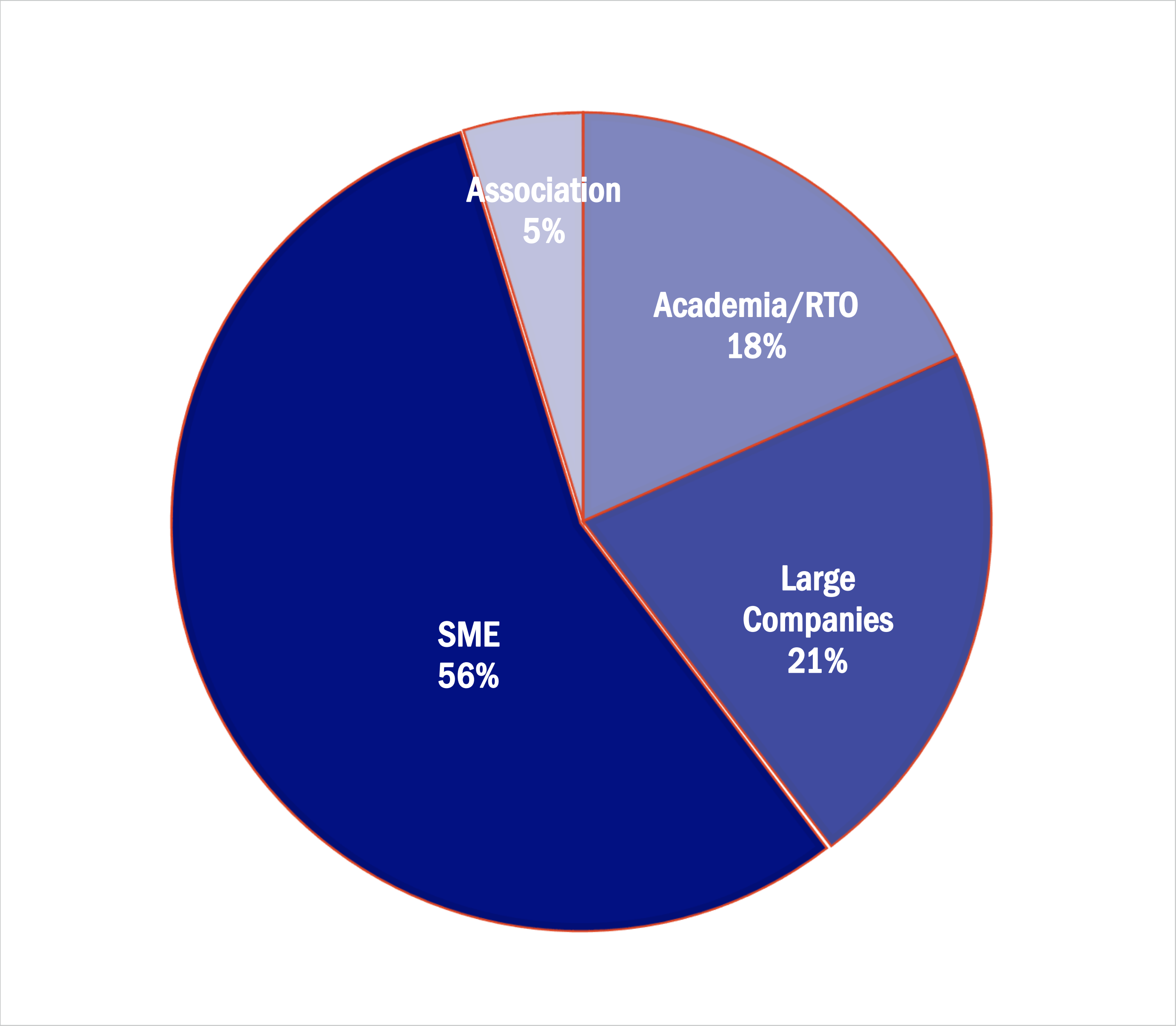
QuIC‘s missions

- Develop and coordinate strategic goals and roadmaps for research, development, innovation and deployment of European Quantum Technologies
- Cooperate with the European institutions and other stakeholders;
- Foster industrial growth and competitiveness of Europe;
- Establish a vibrant ecosystem for Quantum Technologies industry;
- Position QT products and services as key enablers for addressing Europe’s societal and environmental challenges;
- Engage in pre-standardisation activities, with standardisation bodies;
- Develop IP strategies to enable a competitive European Quantum Technologies industry;
- Determinate education & skills workforce needs and professional profiles.

Introduction: QuIC Today

Member type	Full	Associate	Total
Large Enterprises	25	11	36
SMEs	65	29	94
Academics/ RTOs		31	31
Associations/ Foundations		8	8
Total	90	79	169

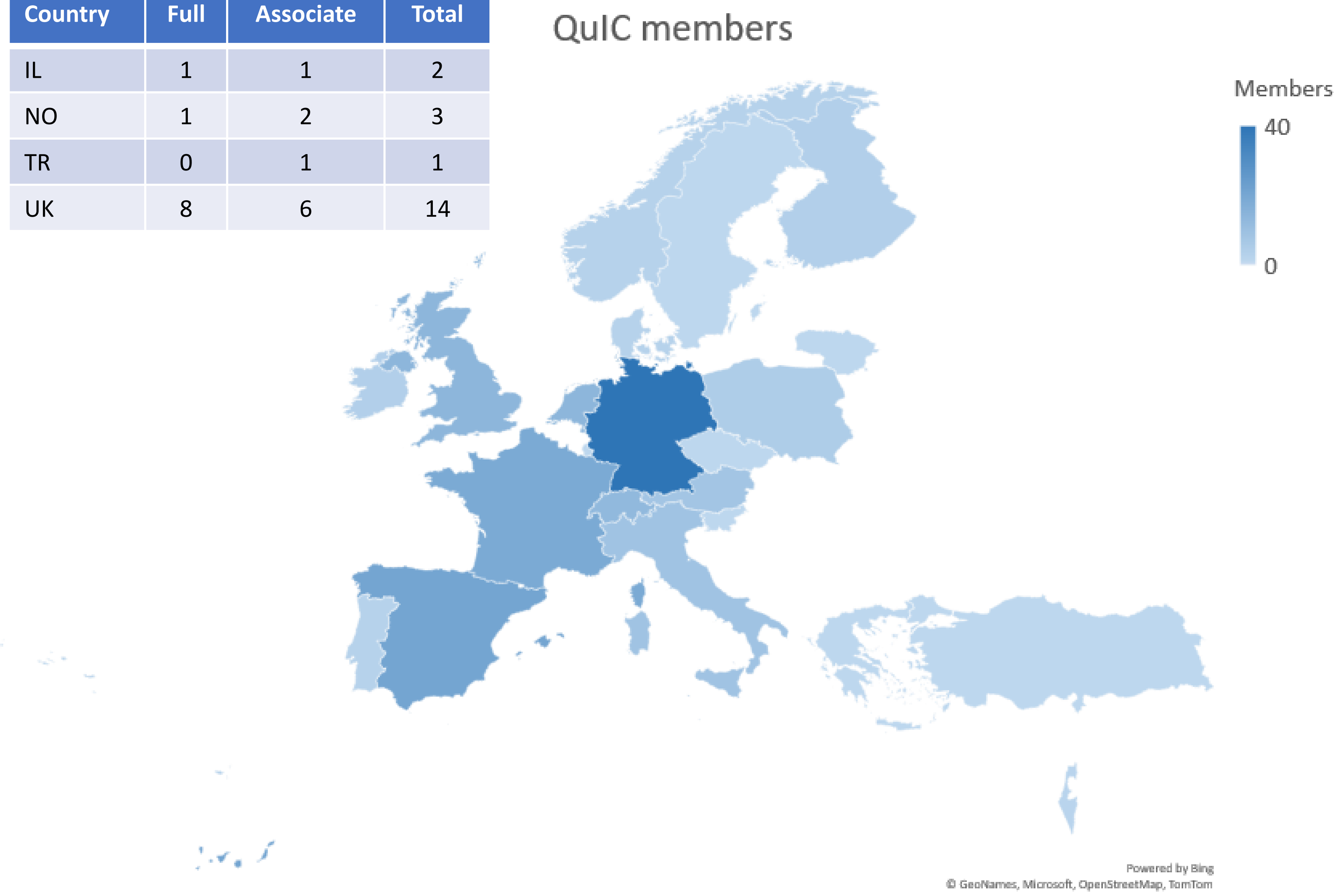
(Members as of 14 October 2022)



Introduction: QuIC Today

Country	Full	Associate	Total
AT	5	3	8
CZ	1	0	1
DE	23	17	40
DK	2	1	3
ES	9	12	21
FI	2	2	4
FR	8	11	19
GR	1	0	1
IE	2	2	4
IT	4	5	9
LT	0	1	1
LU	1	0	1
NL	10	4	14
PL	3	2	5
PT	2	1	3
SE	0	1	1
SI	1	0	1
CH	8	5	13

Country	Full	Associate	Total
IL	1	1	2
NO	1	2	3
TR	0	1	1
UK	8	6	14



(Members as of 14 October 2022)

Agenda

Quantum Computing

Quantum Communications

Quantum Sensing & Metrology

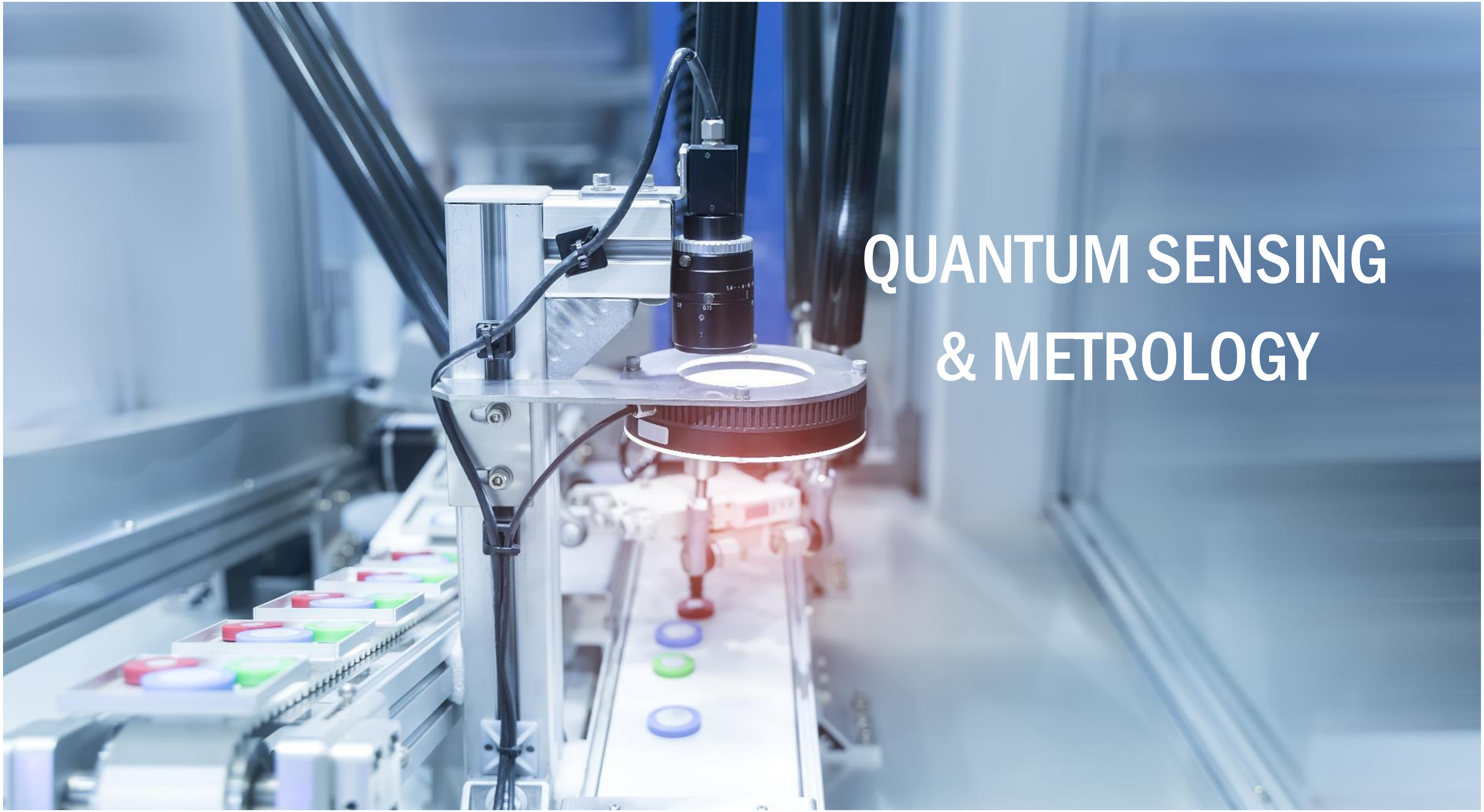
Quantum Enabling Technologies

Education & skills

Standards

Intellectual Property

Governance Principles



QUANTUM SENSING & METROLOGY

Quantum Communications

Quantum Sensing & Metrology

Definitions

- **Quantum Sensing & Metrology:** exploit the interference properties of simple quantum systems, and their high sensitivity to environmental changes, to deliver absolute and relative accuracy compared to classical measurements

- **Quantum sensors** can be classified into:
  - **Solid-state sensors:** rapid and stable measurement easy to build, integrate, and use as they are spatially-confined
  - **Atomic gas sensors:** very high sensitivity and accuracy for the cost of a spatially-confined implementation

USE CASES AND TRENDS

- Biological
- Positioning & Navigation
- Object detection
- High-precision atomic clocks
- Gravity surveys
- RF sensing & processing
- Non-destructive testing
- Seismology
- Advanced photon counters

Quantum Sensing & Metrology Use cases

Title	Short Description	Observation	Technologies	Industry
Positioning and navigation in deep space with small atomic clocks	Trapped-ion atomic clock is attractive to the space industry because of its low sensitivity to variations in radiation, temperature, and magnetic fields.	Recent advances have reduced the size and power requirements, making this technology a candidate for deep space navigation or an aid to scientific radio observations	Optical atomic clocks, trapped ions	Governmental space agencies
Human brain-machine interface with magnetometers based on NV centres in diamonds	Magnetometers based on NV centres in diamonds can record neural activity potentials in the low-frequency range	SQUIDs have been used for years in magnetoencephalography and would also be suitable for human-machine interfaces. The disadvantage of SQUIDs, however, is that they have to be cooled to below 4K, whereas NV centres operate at room temperature and ambient conditions,	Magnetometers based on NV centres, SQUIDs.	Healthcare providers
Exploration of underground resources with atomic gravimeters, gravity gradiometers, arrays of atom interferometers for gravity imaging purposes	At present, the ability to identify the characteristics of the subsoil in underground exploration using classical technology is restricted because of the technology's limited range of resolution and depth.	Atomic gravimeters are based on matter-wave interferometry measurements so a slight change in the way the atoms fall indicate changes in the density of the subsurface due to the presence of oil, gas or some other mineral as well as ground deformation (subsidence, magma chamber on a volcano...).	atomic gravimeters based on clouds of cold rubidium atoms, including Bose-Einstein condensates	Mining, geology, Hydrology, CO_2 sequestration, volcanology, geodesy, reservoir monitoring, defence agencies
Clocks for physics experiments	Many cutting-edge physics experiments require highly accurate time measurements.		Caesium atomic clocks, Rubidium atomic clocks	Large scientific institutions
Determination of the position and orientation of self-driving vehicles using atomic vapour cells	In some situations where the use of GNSS or visual guidance is not possible, or where accuracy is low (e.g. in a tunnel or in narrow streets surrounded by tall buildings), gyroscopes and inertial navigation systems are essential for self-driving cars.	A gyroscope based on nuclear magnetic resonance with xenon nuclei and optical spin-exchange pumping via Rb to detect rotation with high accuracy and drift stability make this a suitable candidate for use in autonomous cars, and a potential alternative to existing gyroscopic technologies	atomic interferometers	Car manufacturers
inertial sensing with cold atoms on moving platforms	Autonomous navigation without the help of GNSS. Increased precision in positioning Airborne / seaborne gravity mapping		atomic interferometers	industrial applications in inertial navigation and space

Quantum Sensing & Metrology Use cases

QUIC
European Quantum Industry Consortium

Title	Short Description	Observation	Technologies	Industry
Measurement of land surface deformation using transportable optical clocks	Transportable optical clocks can monitor the vertical deformation of surfaces to characterize geological processes that occur from hours to years so are, difficult to measure with current technologies that are sensitive to atmospheric perturbations		Optical clocks	Institutes for vulcanology, geodesy and earth sciences
Automated test equipment based on integrated NV sensors	Testing for quality assurance represents a huge portion of the production cost. NV sensors measuring magnetic field patterns and trace electrical currents in the microchip could help to detect manufacturing defects and reduce costs		NV centres in diamond	Electronics manufacturers
Radio frequency detection	The detection of rapidly changing RF signals requires a time-frequency analysis over several ‘0s of GHz but conventional electronics detectors are generally limited to few ’00s MHz	The frequency spectrum of the signal to be detected is converted into an image using a static magnetic field gradient to spatially distribute the Zeeman-split ground state levels ($m=\pm1$).	NV centres in diamond	Electronics manufacturers
Detailed and sensitive magnetic field mapping near surfaces at atomic scale	A detailed map, with minimal drift, of the magnetic field near surfaces at nanometre scale can be produced with a scanning NV-centre microscope		NV centres in diamond	Engineering, research
Measurement and monitoring of the Earth’s gravitational field	Satellite-based instruments to measure and monitor the static or time-varying components of the Earth’s gravitational field with higher sensitivity, or spatial resolution	Cold-atom interferometers such as accelerometers or gravity gradiometers will make it possible to observe processes that are currently difficult to capture (e.g. melting of glaciers and changes in the water cycle)	Cold-atom interferometry	Space agencies, climate research institutes

Quantum Sensing & Metrology Use cases

SIR:

• Human brain-machine interface with magnetometers based on NV centres in diamonds	Medicine
• Determination of the position and orientation of self-driving vehicles using atomic vapour cells • inertial sensing with cold atoms on moving platforms • Positioning and navigation in deep space with small atomic clocks	Positionning and navigation
• Exploration of underground resources with atomic gravimeters, gravity gradiometers, arrays of atom interferometers for gravity imaging purposes	Resources
• Measurement and monitoring of the Earth's gravitational field • Measurement of land surface deformation using transportable optical clocks	Earth and land measurement
• Clocks for physics experiments • Automated test equipment based on integrated NV sensors • Radio frequency detection • Detailed and sensitive magnetic field mapping near surfaces at atomic scale	Instrumentation

Quantum Sensing & Metrology

QuIC European Quantum Industry Consortium

TRENDS:

- In the solid state, most platforms based on NV centres in diamond reached TRL 3, superconducting interference filters are at TRL 5, and SHB techniques are at TRL 5
- In atomic gases, vapour cell sensors are at TRL 3, cold atoms on a chip are at TRL 4, and cold-atom clocks are at TRL 4-5
- Quantum gravimeters based on cold atoms or nanometre resolution microscopes based on NV diamond scanning tips already commercialized

Road to 2030

2024

- Achieve high TRL for applications of atomic vapour cells
- Reach medium TRL for: solid-state sensors based on NV centres in diamond; atomic clocks positioning sensors, navigation systems and second generation gravity sensors, combination of QHE and Josephson Junction standards; improving SNR in radars using quantum measurements and/or entanglement and RF-sensing Rydberg atoms

2027

- In general, reach the commercialization of quantum sensors for instrumentation.

2030

- Reach large market uptake of all quantum sensors based on solid-state physics and on atomic gas
- Quantum sensors integrated into larger systems
- Quantum sensors used both in harsh environments such as space and for consumer applications.

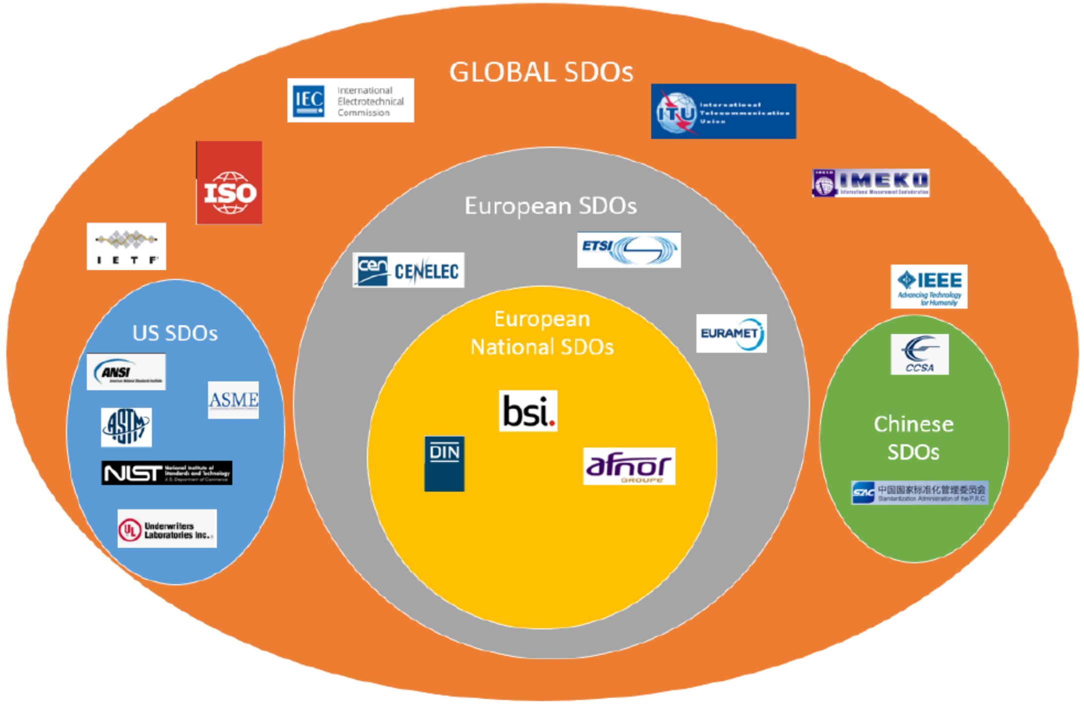
STANDARDS

Standards

Standards Developing Organizations (SDOs) are currently working on quantum standardization:

- **Safety assessment**, testing and specification;
- **Security** – certification of QKD for market uptake;
- **Interoperability** – integration of QKD networks with other networks
- **Metrology** – specification of certain quantum components
- **Benchmarking** of QC Algorithms

Standardization Ecosystem for Quantum Technologies



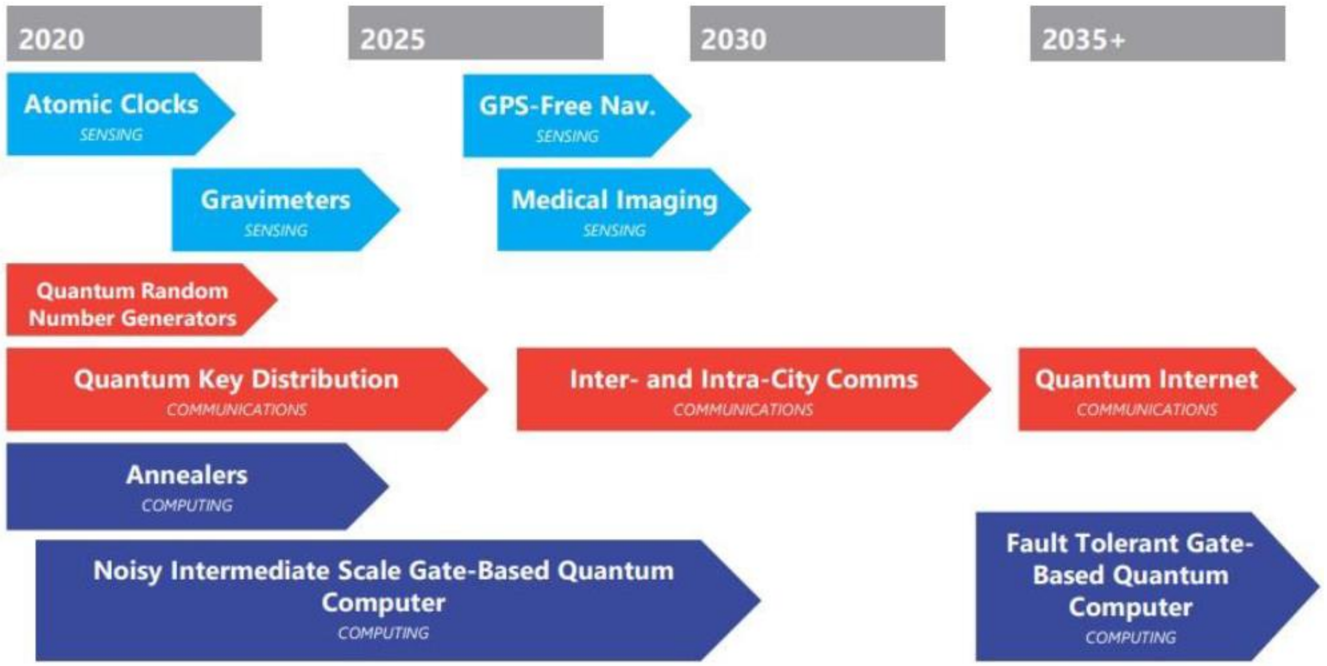
Standardizing quantum technologies can ensure significant **market uptake** by providing proof of reliability, consistency and interoperability with existing infrastructure, systems and components

Standards

STANDARDIZATION STATUS:

- Growing awareness of the need for standardization indicates maturity and interest on quantum technologies
- **Quantum Key Distribution:** there are 22 published standards and 20 documents under development
- **Quantum computing:** some standardization efforts already undertaken, and many new expected in the next few years
- **Quantum sensing:** first ones to need standardization and greater coordination needed

The Optoelectronics Industry Development Association (OIDA) roadmap for quantum technologies and services



QuIC has standardization group aim to promote alignment within the European quantum industry and help channelling common requirements to various standardization bodies

Expert group on quantum sensing and metrology

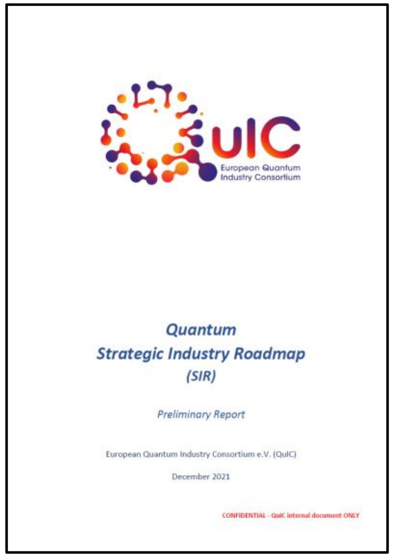
Lead team

- Lead: Thierry Debuisschert (Thales)
- Co-leads: Clara Osorio Tamayo (TNO), Jasper Krauser (Airbus)
- 15 registered contributors:
- Bi-weekly telco 9:30 – 10:30 starting Nov. 17

Previous Working groups

- WG-SIR-QSM / WG-MTU

Short-term objective: Update of the SIR


Quantum
Strategic Industry Roadmap
(SIR)

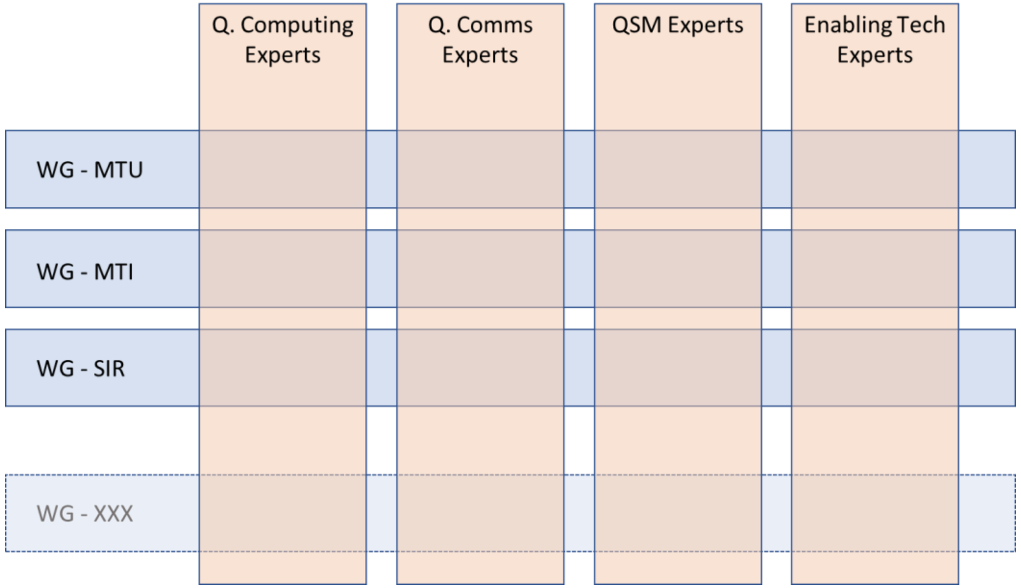
Preliminary Report

European Quantum Industry Consortium e.V. (QuIC)

December 2021

CONFIDENTIAL - QuIC internal document ONLY

WG / EG structure

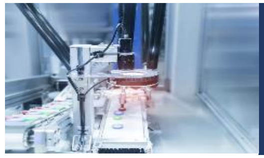


MTU: Market Trend and Use Cases

MTI: Market and Technology Intelligence

SIR: Strategic Industry Roadmap

Conclusions



Quantum Sensing & Metrology

- Can improve the sensitivity of sensors and offer new functionalities that classical sensors cannot provide
- **Important pillar of the quantum industry**
- Several enabling technologies that are important for quantum technologies are currently not available in Europe

Standards

- As quantum technologies mature and are more widely adopted, the relevance of standardization increases
- **Although many standards organizations co-exist, the industry is relatively fragmented with few or no standards yet in place**

Helpful links

QuIC Sharepoint environment: QuIC - Quantum Industry Consortium - Home (sharepoint.com)

Weekly QuIC newsletter: email info@euroquic.org to receive it. Available to ALL your fellow company / entity colleagues!

QuIC Linkedin: https://www.linkedin.com/company/european-quantum-industry-consortium-quic

QuIC Twitter: https://twitter.com/EuroQuIC

QuIC website: www.euroquic.org

European Quantum Industry Consortium

www.euroquic.org

Thank you !