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# QUANTUM TECHNOLOGIES

***Accompanying the document***

**COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS**

**European Cloud Initiative**
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This document summarizes current issues in creating industrially and societally relevant Quantum Technologies, and discusses concerns to be addressed by a roadmap for turning Europe's global leadership in research into a future world-class European Quantum Industry.

## 1. WHAT ARE QUANTUM TECHNOLOGIES?

The first quantum revolution – understanding and applying physical laws of the microscopic realm – resulted in ground-breaking technologies such as the transistor and laser. The impact of this first quantum revolution on our society can hardly be over-stated. Now, our growing ability to manipulate quantum effects in customised systems and materials is paving the way for a **second quantum revolution**. Its industrial and societal impact is likely to be again radically transformative.

Quantum theory has fundamentally changed our understanding of how light and matter behave at extremely small scales. For example, objects can be in different states at the same time ('superposition') and can be deeply connected without direct physical interaction ('entanglement'). The second quantum revolution takes quantum theory to its technological consequences. It is leading to devices with **fundamentally superior performance and capabilities for sensing, measuring, imaging, communication, simulation and computing**. Some are starting to be commercially exploited. Others may still require years of careful research and development. Yet others we cannot even imagine today.

The foreseeable range of markets and applications for quantum technologies is vast (see Section 2). However, the main future quantum technology market is predicted to be a **game-changing addition to the market of information and communication technology** (ICT). As stated by Prof. Anton Zeilinger, a pioneer in the field, at a recent industry round table[1]: *'It is my strong belief that within a few decades from now all of our future ICT will be quantum. There is no fundamental reason why it should not be.'* This path is further corroborated by a quick scan of companies that are already investing significantly in quantum technology research and innovation: Google, Microsoft, IBM, Toshiba, Intel, Lockheed Martin as well as by a survey of the European industry interest in quantum technologies from companies like Bosch, Siemens, Thales, IMEC, Safran, ASML, Nokia, Airbus and Alcatel Lucent - all are key players in ICT and its cutting-edge industrial applications.

Quantum computing is the logical **big step beyond anything currently envisaged at the high-end of computing technology,** including exascale high-performance computing[2]. Classical computing has enjoyed a remarkable increase in speed and storage capacity over several decades in the past, broadly following "Moore's Law". It is now well recognised, also in the semiconductor industry, that this will not be replicated in future decades.[3] Scaling of Moore's law is approaching physical limitations. Quantum effects are now beginning to become apparent and make improvements in the performance of conventional ICT more difficult, also in economic terms. Rather than seeing quantum phenomena as a limit or nuisance, Quantum Technologies make the radical choice of exploiting them for a fundamentally new kind of information processing.

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1 Report from the Quantum Technologies Industry Roundtable organised by the European Commission on 13th of October 2015

2 See the strategic research agenda of the European High-Performance Computing (HPC) strategy at http://www.etp4hpc.eu/strategy/strategic-research-agenda/

3 See International Technology Roadmap for Semiconductors, in particular ITRS 2.0 (www.itrs2.net)

**In the long term, quantum computing holds the promise to solve classes of computational problems that would take current supercomputers longer than the age of the universe.** The scientific computing that this will enable could bring about breakthroughs in for instance chemical process design, energy efficient materials, energy harvesting as well as in machine learning/big-data analysis, with applications in many domains, from personalised medicine to climate modelling.

**Data security and safety** will also be dramatically impacted by quantum technologies. On the one hand, some widely used data-encryption techniques will be vulnerable once quantum computing becomes available. On the other hand, with quantum communication techniques data can be protected in a completely secure way that makes eavesdropping fundamentally impossible. Given the growing role of (big)data in science and policy making, and the central importance of data-privacy and security, mastering related quantum technologies will be a highly strategic capability for Europe's enterprises, governments and citizens.

## 2. FUTURE AND EMERGING PRODUCTS AND MARKETS

Devices and systems exploiting fundamental quantum effects are traditionally grouped along the following lines[4]: Quantum Sensing, Metrology and Imaging Systems; Quantum Communication; and Quantum Computing and Simulation. Although there is a strong interplay between these domains in the underlying theory and physics, they address different problems and there is a large diversity of physical systems being used. Their development and exploitation therefore tend to focus on each area independently and to advance at different speeds.[5] Near-term technologies mentioned could be available within 5 years, notably for sensing, metrology, imaging and communication. Otherwise the anticipated time frame is 10 to 15 years and beyond. The future markets for these different technologies are going to be significant. For example, already in 2020, Quantum Communication could serve a market sized over €1 Billion, with a steep estimated growth rate of 20 percent per year.[6]

Note that for almost any of the quantum devices mentioned below there are multiple possible physical realisations. For example quantum computers store their information in so-called qubits that hold quantum states. There are still several competing realisations of such qubits (cold atoms, electromagnetically trapped ions, electron spins in solid state devices, etc.). Researchers are still exploring the pros and cons of these. They are also occasionally discovering new ones, often first in theory, while it may take years before they are also physically demonstrated.

### 2.1. Quantum Sensing, Metrology and Imaging Systems

Quantum sensors use quantum effects to precisely measure physical parameters, such as acceleration, electromagnetic fields and gravity. Metrology systems use quantum effects to

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[4] Adapted from 'Qurope: Quantum Information Processing and Communication in Europe' http://qurope.eu/ .

[5] See "Industry Perspectives on Quantum Technologies" (October, 2015, available at https://connect.innovateuk.org); "A roadmap for quantum technologies in the UK" (UK Quantum Technologies Programme, 2015); "Quantum Technology Roadmap Report" IfM Education and Consultancy Services, Technology Strategy Board and University of Cambridge, UK, 2014; and "Quantum Information Processing and Communication: Strategic report on current status, visions and goals for research in Europe" (QUIE2T FP7 Coordination Action,, 2013)

[6] Market research media ltd, 2014. Comparable economic forecasts are published in "Quantum Cryptography 2014 market study and business opportunities assessment", by the Institute for Quantum Computing, University of Waterloo (Thomas Jennewein, Eric Choi).

enable local, verifiable, reliable and robust calibration and measurement of SI (International System of Units) standard units of measurement such as time and frequency. Quantum imaging uses quantum effects for pushing performance and sensitivity beyond the limits of classical imaging techniques.

Some quantum technologies in these fields are already well-established, such as microwave atomic clocks, alkali vapour and SQUID magnetometers and Josephson voltage standards. Near-term technologies include optical atomic clocks, quantum gravity sensors, novel magnetic sensors, accelerometers, improved nuclear magnetic resonance (NMR) imaging and scanning tunnelling microscope, as well as single pixel imaging. In the mid- to long-term we will see quantum magnetometer / electrometers, quantum gyros, higher precision and chip-size quantum clocks, new quantum-standardised SI units (e.g. Ampere, Candela), quantum-secured imaging, in-vivo cellular and neural imaging and single photon imaging.

Markets for such technologies include the exploitation of natural resources, civil engineering, quality and safety control, indoor positioning and navigation, portable and wearable personal systems, healthcare, telecommunications, security and defence, financial trading (time stamping, certification and applications), synchronization, infrastructure monitoring and portable standard tests. Quantum imaging is now an active topic of research, with potential applications in healthcare, biotechnology, infrastructure monitoring, security and defence.

### 2.2. Quantum Communication

Quantum communication systems use quantum principles to securely transmit classical data, or to transmit quantum data. Near term technologies for this are quantum random number generators (QRNG) for secure key or token generation, point-to-point quantum key distribution (QKD) for secure key exchange in crypto systems and sources of entangled photon pairs.

Currently these technologies are limited to point to point communication over distances of a few hundreds of kilometres, at least when optical fibre or earth-to-earth free-space is used as medium, and loop holes for hacking have not yet been completely closed. Mid- to long-term technologies include "device-independent" protocols for quantum key distribution, based on entanglement, quantum key distribution over global networks, using satellite links, quantum memories and quantum repeaters, potentially leading to a new and quantum-secured global Internet.

Markets for quantum communication include secure telecommunications, security and defence, high-quality entropy (randomness) for crypto functions and other online industries, on-line gaming, quantum-secured commercial transactions, user authentication, personal data security (e.g., medical, privacy).

### 2.3. Quantum Computation and Simulation

Quantum Computing architectures store and process data as quantum states (Qubits). They allow radically faster solutions of major classes of computing problems that defy even the most powerful classical computers today. Moreover, the physical process of quantum computing holds the promise of increased energy efficiency. Whereas general quantum computers are among the most ambitious of quantum technologies, quantum simulators are easier to realise. Quantum simulators are quantum systems that directly reproduce the quantum physics of, for example, chemical reactions or materials that are too complex to simulate otherwise (because they scale exponentially on classical computers), thereby helping to predict and improve physical properties of existing compounds and materials or designing new ones (for example, materials that are super conducting at room temperature).

Near-term technologies include small-scale quantum computers and quantum simulators on a diversity of physical platforms (such as lattice materials, ultra-cold atoms, or superconducting Qubits). They could be used to explore new quantum control mechanisms, quantum algorithms, or for very specific simulations. .In the mid- to long term one expects universal quantum computers, quantum memories, devices for direct simulation of superconductivity, complex (bio-) chemical reactions, leading to for instance new metamaterials, improved batteries, solar cells and medicines.

Potential markets for quantum computation and simulation include research, IT and computer industry, Big Data, telecommunications, defence and security, real-time weather forecast, finance, cognitive computing and control systems, materials, pharmaceuticals, biotechnology, and energy efficient (e.g., superconducting or photosensitive) materials and processes.

## 3. EU SUPPORT FOR QUANTUM TECHNOLOGIES

After almost 20 years of investment of around ~550M€ in EU funding, Europe has a well acknowledged world-class scientific and technical expertise in Quantum Technologies. The European research community has already put much effort into structuring its work in this area around a common research roadmap.[7] The Excellence in Science pillar of **Horizon 2020** is well positioned to support the most upstream **research, notably through Future and Emerging Technologies (FET**) for the collaborative effort, the **European Research Council** (**ERC**) for the support to individual researchers and the **Marie Skłodowska-Curie Actions** (**MSCA**) for researcher mobility and training.

**FET** has been pioneering Quantum Technologies since the 4th Framework Programme (FP4, 1994-1998).[8] In the 5th Framework Programme (FP5, 1998-2002) FET launched the first proactive initiative on the topic, 2 years before DARPA's first quantum initiative. Over these 20 years, FET has made a total investment reaching ~250M€ in EU funding. Investment from FET has steadily increased over time, reaching 94M€ in FP7 (2007-2013) and demonstrating an increasing interest in the topic among the research community. Research projects have covered a wide variety of quantum technologies, including novel sensors, quantum key distribution (QKD) and qubits. A number of FET coordination and support actions have further contributed to establish overtime a world class European research community in Quantum Technologies.

Research into the basic science behind quantum technologies has recently also received much support from the **ERC**, which in FP7 awarded an estimated ~100 M€ to individual grants addressing various aspects of quantum computing, sensing and communication. The ERC portfolio includes notably 3 large 'synergy grants' addressing quantum technologies and together representing ~35 M€ of funding.

There is also a significant investment in quantum related research topics with the Marie Skłodowska-Curie Actions (**MSCA**), both as Innovative Training Networks and as Individual

[7] http://qurope.eu/content/qipc-roadmap
[8] See e.g., FET Impact assessment 1994-2004 http://cordis.europa.eu/publication/rcn/200618745_en.html

Fellowships in areas such as quantum computing, quantum information and quantum photonics (e.g., optical cavity systems and nano-optomechanical quantum systems).

As technology in quantum sensing and communication is maturing, funding is available in the **Industrial Leadership and Societal Challenges** pillars of H2020. Various parts of the Horizon 2020 Framework Programme mention specific quantum technologies within the scope of their workprogramme topics. This is the case notably for components, photonics and for trust and security.

The **European Metrology Research Programme (EMRP) Joint Undertaking** supported research on metrology from 2009-2013. Some of this work used devices based on quantum effects which received ~10 M€ EU funding from 2009-2013. This program has now been followed by the European Metrology Programme for Innovation and Research (EMPIR)[9] initiative in H2020.

A number of European countries have expressed an interest in **launching an ERA-NET Co-fund initiative in Quantum Technologies** under the FET Work Programme for 2016-2017**.** It is expected to mobilise a total of ~30M€ of combined EU and national funding. Already in 2010, a first joint call for research on quantum technologies was conducted by Member States, with the participation of FR, UK, DE, IT, ES, AT, PL, CH and BE through the CHISTERA ERA-NET project[10].

## 4. INNOVATION IN QUANTUM TECHNOLOGIES: NOW OR NEVER?

There is converging evidence from around the globe that the time is ripe to start turning results from research in Quantum Technologies into commercial applications and products.

For instance, although currently feasible **quantum computers** are still too small (10-20 coupled qubits) to compete with conventional ICT for real-world problems, they have served to test the basic principles behind quantum computing. Large ICT companies such as Google, Microsoft, IBM and more recently INTEL have embarked on ambitious developments, which indicates a real interest to explore the commercial potential of quantum computing while also securing a 'first mover' advantage over the competition. EU headquartered companies have, so far, not shown similar levels of interest for investing in such research.

Several **quantum communication** networks are being built or are planned worldwide (China, which is investing ~85M€ in a QKD network linking Beijing to Shanghai, South Korea, Japan, US). In Europe, the commercial exploitation of this technology is being led by start-up companies (SMEs) such as IDQuantique, though also big companies such as Toshiba are actively field-testing their technology in Europe. Today, this is the most developed quantum technologies application area, though specific markets remain small (finance, defence). An active initiative on international standardisation exists, with ETSI industry specification groups on quantum key distribution and quantum safe cryptography, in which European, Asian and North American organisations work together.

**Quantum sensing and metrology** has attracted interest from EU industry (both smaller companier such as MuQuans and E2V, and larger companies such as Thales) which sees immediate potential applications, for example for geological surveys, financial trading market

9 https://www.euramet.org/research-innovation/empir/
10 http://www.chistera.eu/

or higher speed network synchronisation. The potential for chip-scale atomic clocks to support progress in timing and navigation systems is also critical for security (see e.g., European SME Spectratime).

A recent survey[11] shows that **European industry interest in quantum technologies**, from big companies like Bosch, Siemens, Thales, Safran, ASML, Nokia, Airbus and Alcatel Lucent, **is growing** though stated plans and ambitions remain modest. High-tech SMEs such as , Spectratime, E2V, MuQuans and IDQuantique occupy leading positions in their specific markets. Europe's key position in global value chains for semiconductors, electronics and optical industries makes further industry take-up promising.

**Several Member States** have recently announced national initiatives to support research and **accelerate innovation into quantum technologies**. The Dutch government has established the QuTech[12] Advanced Research Center to accelerate the take-up of results in quantum technology by industry (135 M€ national funding over 10 years). QuTech has attracted 50M USD in additional funding from INTEL and receives funding from further private companies. The UK government, implementing its National Quantum Technologies Programme[13], has recently announced funding of ~270 M€ over 5 years for 4 quantum technology hubs whose aim is to bring together scientists, engineers and technologists to exploit results from research into quantum science. In Germany, the government has made research into the "quantum repeaters" needed for secure long distance communication a priority with 9.5M€ of funding over 3 years and is funding research in the area of quantum communication and quantum-safe cryptography within its research framework programme for IT-security. There is also substantial interest within the German research community for a more encompassing initiative on Quantum Technologies. [14]

## 5. TOWARDS A EUROPEAN QUANTUM INDUSTRY

At the European level, the strategy for bringing quantum technologies to market is still fragmented. It is clear that now is the time for Europe to consolidate its technological lead or else to see companies from the US and Asia take the most benefit from its commercial exploitation.

If nothing is done, then Europe risks becoming a **second tier market player** (or market follower). European industry may develop from local niche markets while US and Asian competitors may become dominant players, attracting a new generation of European quantum technology experts away from the EU.

At European level, Horizon 2020 provides many opportunities for companies wishing to push for innovation from quantum research. The current Horizon 2020 Work Programmes 2016-2017 promote quantum technologies in relevant call topics under LEIT (e.g. sensors, measurement, security) and to explore the applicability and usability of quantum technologies

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11 Report from the Quantum Technologies Industry Roundtable organised by the European Commission on 13th of October 2015

12 http://qutech.nl/about-qutech/

13 National strategy for quantum technologies: A new era for the UK. Quantum Technologies Strategic Advisory Board, D Delpy (chair), March 2015. https://www.gov.uk/government/publications/national-strategy-for-quantum-technologies

14 See also C Anton and K S Ranade (eds.) Quantum Technology: from research to application. German National Academy of Sciences Leopoldina, acatech – National Academy of Science and Engineering and Union of the German Academies of Sciences and Humanities. June 2015. http://www.akademienunion.de/fileadmin/redaktion/user_upload/Publikationen/Stellungnahmen/3Akad_Stellungnahme_Quantentechnologien_EN_final.pdf

in addressing end-user needs under the Societal Challenge of Secure societies. There are also opportunities for entrepreneurs and high-tech start-ups through the SME scheme, through Open Disruptive Innovation and the proof-of-concept and innovation Launchpad topics within ERC and FET, respectively.

The support for medium-term take-up of specific quantum technologies helps European industry to stay in the game as a **relevant player in specific markets**. Indeed, there are examples of innovation from Quantum Technology research taking place already, especially in quantum sensors, metrology and secure quantum communication (see Section 4). However, the start-ups have so far been **slow to grow and are mainly limited to supplying niche markets** (e.g. finance industry). There are at present no larger supply chains for them to feed into, neither are there many sizeable opportunities to roll out their technologies and products within large scale strategic investment projects in Europe.

If we want to achieve **global European industrial leadership in Quantum Technologies**, then an ambitious coordinated strategy to support joint science, engineering and application work, including IPR, standardisation, market development, training and public procurement will be needed. Certainly, Europe needs to maintain and strengthen its excellent position in research, keeping a broad scope and allowing the time it takes to advance basic knowledge and experimental proof of concept. At the same time, it is absolutely essential that European industry plays its part to realise the commercial potential of quantum technologies.

The European Commission has initiated a series of dialogues with European industry and other stakeholders to foster interest and investment[15]. **A "Quantum Manifesto"** [16]has been recently published with the support of academic and industrial stakeholders that call for a common strategy for Europe to stay at the front of the second Quantum Revolution.

The aim is to converge to a **broadly supported roadmap** that will bootstrap a future world-class quantum industry in Europe and to gather the necessary commitments for an ambitious initiative to unlock the full potential of quantum technologies, accelerate their development and bring commercial products to public and private markets.

What follows are issues that so far have surfaced from these discussions and that could be addressed by such a roadmap.

### 5.1. Strengthening scientific leadership

The **European scientific excellence in Quantum Technologies** is beyond doubt (as shown also by prestigious awards like Nobel Prizes) and should not be lost. There is a tremendous intellectual strength within European academia that should continue to be supported. At individual-, group- and consortium levels, calls should stimulate the best to produce the best research, unrestricted by industrial or political priorities.

The European quantum research community is very well organised and has put much effort into structuring its work around a common research roadmap. The specific potential of

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[15] Workshop on Quantum Technologies and Industry, 6th of May 2015 https://ec.europa.eu/digital-agenda/en/news/report-workshop-quantum-technologies-and-industry, and Quantum Technologies Industry Roundtable 13th of October 2015. Other dialogues will follow, e.g., hosted by the European Parliament and by the Dutch Presidency (Jan-June 2016).

[16] http://qurope.eu/manifesto , published in spring 2016.

different instruments should be maximally exploited, for instance through a coordinated use of ERC, FET and MSCA funding. Mobility of students and researchers in Quantum Technologies will further stimulate a **European backbone of excellence**, covering many member states.

The **coordination between different national and European research programmes on quantum technologies** can be improved in order to create a coherent and easy-to-navigate funding landscape for Quantum Technologies. For instance, the planned ERANET Cofund on Quantum Technologies (Horizon 2020, FET workprogamme 2016-2017) will allow to better understand the different programs at national levels, to avoid duplication, exploit synergies, and to better align joint calls with national or shared priorities.

### 5.2. From quantum science to quantum engineering

Innovation from Quantum Technologies requires to address not only the scientific challenges but also the engineering and manufacturing challenges of bringing quantum technologies to the point of commercial products (referred to as **'quantum engineering'**). Specific research is often needed to achieve demanding levels of quality, precision and reliability (for instance in materials processing). The skills and experience that are needed for specific realisations in Quantum Technologies are often residing in a handful of academic laboratories. The difficulties to transfer and reproduce technical results, tools and software within an industrial context should be addressed.

Specific **quantum engineering training** should be provided in technical and scientific curricula for a new generation of technicians, engineers, scientists and application developers on quantum technologies. **Vocational training** programmes should make sure that industry has the capacity to absorb the knowledge and skills that will be needed to bring quantum technologies in-house.

### 5.3. Market finding and early adopters

Non-technical work is needed that looks to understand the potential benefits of new technologies and to **identify and clarify markets** for quantum technologies. This will also bring a greater appreciation of the opportunities and risks that quantum technologies may create to the companies and individuals that will actually buy, sell or use them. Citizen and stakeholder engagement will prepare for future uptake of technologies, in ways that make sense to them.

A strategic approach that aims to cover major technological innovations and application areas early on can **secure Europe's future innovation potential**. This could be done, for instance through a systematic survey of, and continuous scouting for the anticipated applications of novel quantum technologies and by assessing benefits and risks arising from the new qualities associated with these anticipated applications (an upcoming JRC study is planning this). There have been attempts to do this, but mostly driven by the technology side whereas the perspective of end-users and citizens (imagining broad consumer markets for quantum technology) are largely unexplored.

Support should be made available to link up **procurement by public organisations**, such as the European Space Agency, European Research Infrastructure, defence and other government departments, and international organisations to act as early adopters which may purchase and start to use the new technology. Quantum computing, communication, sensing and imaging resources can thus quickly find a relevant and critical user base that, in turn, can drive the technology forward by **co-design with stakeholders**. At European level, instruments such as pre-commercial procurement, public procurement of innovation and projects funding from the European Fund for Strategic Investment (EFSI) could serve this purpose.

### 5.4. A vibrant innovation ecosystem

So far progress has been driven mainly by publicly funded research and technology push. A **broader innovation eco-system** that includes academia, industry, investors, entrepreneurs and end-users is not yet in place.

A European-wide mechanism is currently missing to bring academic groups in contact with companies, put large companies in contact with small ones, and link the future supply chain. It must also include other sectors, such as private equity and standardisation. This would stimulate the creation of **networks of people and knowledge flows** beyond academia that companies can mobilise in an **open innovation** spirit and when needed to support research, development and innovation efforts. **Cross-over between industry and academia** is typically weak and should be encouraged, for instance by a more systematic use of the Marie Skłodowska-Curie Actions for Research and Innovation Staff Exchange.

The creation of **spin-offs and start-ups** in Quantum technologies should be stimulated. Given the high-tech physics that is usually involved, such companies face very high initial and fixed costs (counter to internet Startups, for instance), and require an ongoing investment in applied research. **Incubation hubs with dedicated technological facilities** may be able to help companies in their initial stages. Also **partnerships with larger companies** that can provide access to tools, infrastructure, knowledge and clients should be stimulated.

**Access to capital** is a common hurdle for start-ups. In Quantum Technology, where time-to-market is long and initial markets are likely to be small, 'patient' funding from investors that can live with high-risk and long-term horizons is needed. Investors also need to be sufficiently knowledgeable of quantum technologies in order to properly appreciate the opportunities and risks involved. A specialised **Quantum Innovation Fund** to finance quantum technology enterprises across the EU may be a solution, just like current investment funds specialise in specific industries and markets.

There are many opportunities for new as well as existing companies to sell quantum components and sub-systems at first to the academic market, and then to the growing quantum industry within **emerging supply chains of quantum enabling technologies**. Examples of such technologies are cryogenic systems, single photon sources and detectors, entangled photon pair sources, materials (e.g. superconducting junctions), material processing techniques, quantum algorithms, protocols and software. In the longer term there will be routine need for miniaturised plug-and-play quantum devices that today require bulky laboratory setups under carefully controlled conditions. In addition, there are multiple spin off markets for cutting edge photonic, electronic or opto-mechanical devices.

There are still multiple technological options for achieving some of the most ambitious goals of quantum technology (for instance, qubit implementation for general purpose quantum computing). Ways must be found to **involve industry in the filtering, testing and validation of different options** so that choices made are also industrially and economically viable. This will also help industry to better understand what is of short, medium and long-term relevance and thus to orient their own investments and resources while staying aware of the full spectrum of possibilities. Public-Private partnerships where **resources, risks, results and rewards are shared** among participating stakeholders could provide concrete platforms for this. Within established options, **standardisation** will be essential to make supply chains work. There are ongoing initiatives, for instance within ETSI[17], and active involvement of European industry must be assured.

### 5.5. Intellectual property

**Europe is ahead in publications** related to Quantum Technologies, but it is **patenting less** than its major global competitors, led by the US. In Asia, alongside well established players such as Japan, new actors are emerging, in particular China, but also South Korea and Malaysia.

North America leads the ranking in Quantum Computing, with big corporations such as IBM and more recently Microsoft and Google. Also, D-Wave, a Canadian start-up, is extensively patenting its know-how to develop its business.

In Quantum Communications, Japanese patenting activities are significant alongside with those from the US, having been driven consistently by big industrial players such as NEC and Toshiba. Malaysia with its national ICT research centre (Mimos) and South Korea (with SK Telecom and Korea Electronics) have also started shaping the patenting landscape, but the most striking emergence in this field is that of China. In the last five years it has become the first nation for number of patent applications in Quantum Key Distribution, at the same time as its quantum backbone link between Beijing and Shanghai is being deployed.

The IP landscape constitutes a **potential vulnerability** for Europe that needs to be addressed. One could envisage for instance that funding that is being earmarked for Quantum Technologies comes with a clear and formal obligation to take account of the existing IP landscape, and to protect and pool intellectual properties for the benefit of European industry and society. Overall, it can be noted that while there are many scientific publications, the worldwide patenting activity is still low compared to more mature technology areas, indicating a need as well as a window of opportunity to develop these emerging markets.

These patterns of publication and patenting activity should be actively traced, as one way to **anticipate global developments in Quantum Technological innovation**.

[17] See for example the ETSI working group on Quantum Safe Cryptography (http://www.etsi.org/technologies-clusters/technologies/quantum-safe-cryptography) and on Quantum Key Distribution (http://www.etsi.org/technologies-clusters/technologies/quantum-key-distribution).