Strategic Research and Industry Agenda

QUANTUM
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European Commission

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Executive Summary

This document is the initial step towards the definition of the first EU Strategic Research and Industry Agenda (SRIA). The final objective of the SRIA will be to provide a comprehensive strategy in Quantum Technologies (QT) for the EU, taking into account and merging all the industrial and R&D on-going initiatives. It is therefore based on different existing assets, representing the current strategies and programs within, or in relation with, the quantum community in the EU:

- The Quantum Flagship Strategic Research Agenda (SRA), representing the vision of the European Research Community on QT (Quantum Technologies)
- The QUIC Strategic Industry Roadmap (SIR), representing the vision of the EU industrial community
- Strategic plans from other key initiatives in Europe, in particular EuroQCI, EuroQCS and the Chips Act.

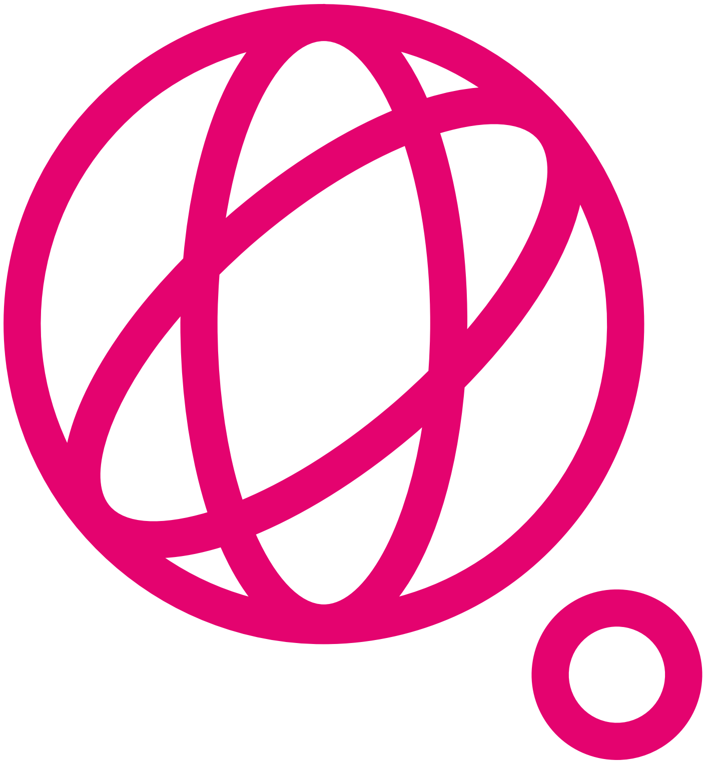
Starting from the analysis of these documents, the SRIA will propose an implementation path towards concrete actions that could be undertaken in relation with all QT initiatives within EU. The present document is a preliminary version of the SRIA, harmonising the scientific (SRA) and industry (SIR) strategic agendas. It also provides more specific recommendations about the development of QT within the forthcoming work programmes of the Chips Act, in the area of semiconductors, and of EuroHPC JU in the area of high performance computing. A final version of the SRIA, including all EU initiatives, will be published in 2023.

After presenting the methodology in Part A, this document is divided into two main sections:

- In Part B a roadmap for 2030 is presented, merging the main elements of the SRA, SIR, and other relevant documents. Section B.1 is based on the usual four technological pillars (quantum computing, quantum simulation, quantum communications, quantum sensing and metrology), and Section B.2 presents the associated transversal activities, including Quantum Resources, Innovation, Industrialization, and Societal Impact. At the end of each section there is a list of short and long term objectives, as well as more specific recommendations.
- In Part C the inputs from Part B are aligned with the specific framework of the Chips Act and EuroHPC JU, and again a list of specific recommendations is given.

Part A:

Methodology



Part A: Methodology

Based on the visions, roadmaps and recommendations of the SRA (Research), the SIR (Industry) and other sources, the SRIA document aims at identifying concrete actions that could be undertaken in the context of the Quantum Flagship, as well as other EU initiatives such as the Chips Act, EuroQCS and EuroQCI.
As a first step towards this goal, the analysis of the SRA and SIR is conducted along their S&T pillars, including also an ensemble of resources related to Innovation, Industrialisation, and Societal Impact.

The Quantum Flagship Strategic Research Agenda (SRA)

The Strategic Research Agenda (SRA) was prepared by consulting more than 2000 quantum experts across Europe, in an open and transparent process, to set a clear direction for the future development of quantum research and innovation in Europe. The SRA sets the ambitious but achievable goals for the Quantum Flagship, and details them for the next three years, with an outlook for six to ten years.

It is structured around four research and innovation domains, representing the major applied areas in the field: Communication, Computing, Simulation, as well as Sensing and Metrology. These application domains are anchored on a common basis of Basic Science, with top research institutions and companies spread across Europe assisting their objectives by delivering novel ideas, tools, methods and processes. These are supported by cross-cutting areas covering: Engineering and Control, Software and Theory, Education and Training and further complemented by overarching activities in Innovation and International Cooperation as well as Gender Equality.

The QuIC Strategic Industry Roadmap (SIR)

The QuIC Strategic Industry Roadmap (SIR) is designed to provide a perspective on the needs of the EU quantum industry represented in QuIC over the current decade (until 2030). The document covers three technological pillars (Q. Computing, Q. Communication, Q. Sensing & Metrology), along with four cross-technology needs (education & skills, standards, IP & Trade, governance principles). It is designed to help stakeholders and influential public bodies keen on supporting the growth of the European industry to understand the ambitions and needs common to a wide array of European industry members.

The SIR was produced in a period of 3 months, from Sept. – Dec. 2021. During that period, QuIC members worked together, as an internal work group (WG), to populate the different sections of the document. An updated version of the SIR is planned in the near future in order to feature certain unaddressed topics (e.g. Enabling Technologies) and include the inputs of additional European entities that have joined QuIC since the conclusion of the first SIR (ca. 40 new members).

Other Initiatives in the EU

The EU Chips Act proposes to build on Europe's strengths and address outstanding weaknesses, to develop a thriving semiconductor ecosystem and resilient supply chain, while setting measures to prepare, anticipate and respond to future supply chain disruptions.

EuroQCS is a joint initiative between the EU, member states, and private partners to coordinate their efforts and pool their resources to make Europe a world leader in supercomputing. EuroQCI is a collaboration between the 27 member states, the EC, and ESA, with the goal to deploy and operationalise an ultra secure quantum communication infrastructure, spanning whole of EU.

Other Sources

BCG - Quantum: The Tech Race Europe Can't Afford to Lose (August 2022).

McKinsey: Quantum computing, an emerging ecosystem and industry use cases (December 2021).

FPA Roadmaps for the Pilot Lines QPilot and QTest, and consultation of the other Quantum FPAs.

Public documents issued by EuroQCS, EuroQCI and the Chips Act.

Part B:

Roadmap to 2030: Quantum Ambitions over this Decade

Part B: Roadmap to 2030: Quantum Ambitions over this Decade

In section B.1, the objectives laid out in the SRA are matched with those of the European quantum industry captured in the SIR, by addressing individually the usual four Quantum Technologies pillars: quantum computing, quantum simulation, quantum communications, quantum sensing and metrology. The main objectives are placed in chronological order, with a first wave aimed at 2023 - 2026, and a second one at 2027 - 2030. In section B.2 the objectives corresponding to transverse issues related to Quantum Resources, Innovation, Industrialisation, and Societal Impact, are successively presented. **It is important to keep in mind that, beyond these transversal activities, the four different pillars are strongly inter-connected and concepts, tools and technologies developed in one pillar can find applications in others (see also section B.1.5).** To provide a few examples, the development of quantum communications may help to design networks of quantum sensors, or protocols for distributed quantum computing. On the other hand, techniques for efficient quantum information processing may find an application in the construction of quantum repeaters for long-distance quantum communication.

B.1 Scientific and technical challenges and ambitions

B.1.1 Quantum Computing

The quantum computing pillar focuses on general-purpose quantum computers where quantum information is processed digitally, via logical gates, in a manner similar to today's general-purpose classical computers. The pillar regroups many layers of technology, from the individual modalities of quantum information processing to the algorithms and ultimate applications of these machines for a variety of use cases. The main objective is to develop quantum computing devices that outperform or accelerate existing classical computers, to solve specific problems relevant for industry, science and technologies that could benefit from the execution of quantum algorithms.

The existing first generation of quantum computing devices work in the Noisy Intermediate Scale Quantum (NISQ) regime, with noisy qubits and no quantum error correction. It is part of the efforts of the next five years to find out whether and in what sense one can hope to achieve quantum advantages in near-term quantum computers without quantum error correction. In the long term, the goal is to develop fault-tolerant quantum computers, as well as interconnecting these computers and trading quantum information between them — in effect, building on both quantum computing and quantum communication capabilities to develop a 'quantum internet.'

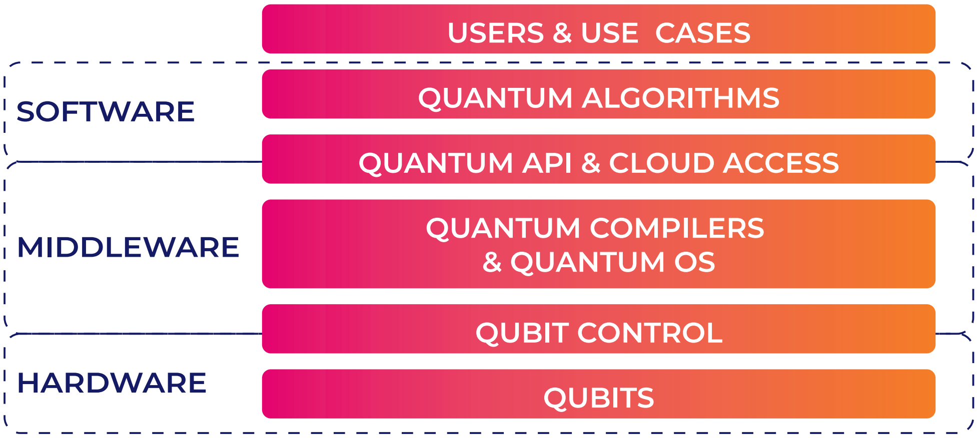


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Figure 1 – Quantum information processing stack.

API = Application Programming Interface.
OS = Operation Software.
Qubits = various hardware modalities

Figure 1 captures and structures the layers involved in both quantum computing and quantum simulation (see Section B.1.2). Objectives specific to each layer for quantum computing are detailed below.

Qubits

The lowest part of the stack contains the main hardware modalities considered for the construction of quantum computers. At the moment different solutions are being explored and it is not clear which one will be the final adopted technology. It is in fact conceivable that some platforms will be better in the NISQ regime or for special-purpose quantum computers, such as quantum annealers, while others will be more suitable for error-corrected quantum computers. Examples of most promising hardware modalities are:

- Superconducting Qubits
- Semiconductor-based Qubits (e.g. silicon or coloured centers in diamond)
- Trapped Ions
- Neutral Atoms
- Photons

Ambitions common to all these different hardware modalities are:

- Enhance the NISQ processing regime with error mitigation methods, enabling deeper algorithms, forging progress towards error-corrected universal quantum computing.
- Increase the number, density and connectivity of qubits. Improve quality of qubits, including better coherence times and gate fidelities.
- Design and implement new architectures, including 3D setups, together with new assembly techniques.
- Further miniaturize and ruggedize quantum computers.
- Develop industrial-scale fabrication facilities that can assemble and integrate large quantum processors.
- Demonstrate interconnection and information exchange between different quantum computers.

Qubit Control

Optimal operation of quantum computers requires the characterization and control of qubits. Qubit characterization involves measuring the properties of individual qubits and the quality of information transfer between pairs of qubits. Qubit control is the optimal manipulation of individual qubits to achieve longer coherence times, and the careful orchestration of qubit pairs to achieve better gate performance.

In general, the main ambitions are to:

- Increase the number of qubits that can be simultaneously controlled in line with the development of quantum processors;
- Increase the integration of these control devices (user interfaces, qubits interfaces);
- Reduce lead times and cost by reducing the dependency on materials and components from non-European sources.

Quantum Operating Systems, Quantum Algorithm Compilers

The quantum operating system is the software that manages the quantum hardware (qubits) and the classical hardware used to characterize and control the qubits. It oversees the execution of quantum algorithms at the machine level by optimizing hardware resources, and provides users with an interface to enter instructions and receive output from the quantum computer.

Most of the applications of quantum computing will need a hybrid/mixed use of classical and quantum computing resources.

Calling quantum algorithms from classical computers requires to develop interfaces between these two software stacks.

Ambitions over the coming years in this part can be summarized as follows:

- Develop quantum compilers with automatic scheduling capabilities, that incorporate calibration and quantum error correction coding/decoding routines in the main quantum algorithm;
- Demonstrate distributed programming capabilities on multiple hardware control backends;
- Standardize an intermediate representation framework that works across multiple technologies;
- Develop a hybrid classical/quantum software stack based on API and compiler directives (pragma).

Quantum APIs & Cloud Access

Quantum APIs and cloud access form the transition layer between users and quantum machines in the Quantum computation (QC) stack. This layer includes general-purpose quantum SDKs that are used to implement quantum algorithms at the quantum gate level (in the case of gate-based systems and similarly for quantum annealers).

Ambitions over the coming years in this field can be summarized as follows:

- Integrate quantum computers with classical computing systems like HPC supercomputers;
- Improve availability of European quantum hardware in the cloud.

Quantum Algorithms

Quantum algorithms, unlike their ‘classical’ counterparts, are designed to take advantage of the fundamental features of quantum physics, such as superposition and entanglement. More than half of the over 100 known QC algorithms offer super-polynomial performance improvements over classic algorithms.

Ambitions over the coming years in the field of Quantum Algorithms can be summarized as follows:

- Build collections of use cases with reference implementations of quantum algorithms and data preparation;
- Design new algorithms providing speedups, especially for problems of relevance in science, technology and industry. Resource analysis regarding the number of qubits, number of gates, and estimated run-time should be conducted for each new algorithm.
- Build software that helps to develop and implement quantum algorithms, e.g. by automatically generating gate sequences.

User Community

The European community of large companies and institutional entities, such as research and technology organizations (RTOs) and academic institutions, is rapidly becoming interested in quantum computing.

Ambitions to coordinate and serve this diverse and growing community are:

- Provide access to industry, academia and European start-ups;
- Provide procurement of products and services from QC solution providers;
- Serve as collaborative hubs between users and quantum algorithm developers;
- National (and European) HPC centres equipped with integrated QC solutions and interconnecting their systems for distributed computing capabilities.

Specific objectives for quantum computation for the next years include:

→ Objectives by 2023 - 2026.

- Demonstrate practical strategies for a future fault tolerant universal quantum computer.
- Identify algorithms and use cases where quantum computing has an advantage.
- Enhance the NISQ processing regime with error mitigation methods, enabling deeper algorithms.
- Engage chip foundries and other hardware providers, public or industrial, as well as the software industry, existing companies and start-ups.
- Initiate academic and industrial research contribution on quantum device physics, qubit and gate control, leveraging optimal control theory for faster and more robust gates, photonics, RF-electronics, cryo- and superconductor electronics, system engineering, integration, device packaging,
- Develop hardware-agnostic benchmarking of NISQ based systems, quantum application and algorithm theory, software architecture, compilers and libraries, and simulation tools.
- Coordinate industry, foundries and other infrastructure entities on quantum computing.
- Stimulate EU-wide joint actions with other fields such as material science, theoretical physics, cryo-physics, electrical engineering, mathematics, computer science and high-performance computing.
- Address standards bodies (EU, international).

→ Objectives by 2027 – 2030.

- Demonstration of quantum processors fitted with quantum error correction and robust qubits with a universal set of gates to outperform classical computers.
- Demonstration of quantum algorithms with quantum advantage.
- Establishing foundries able to manufacture the required technology, including integrated photonics, cryogenic and superconducting electronics.
- Supporting established and new instrument builders and software companies.
- Coordination of research, development and integration on materials, quantum device physics, qubit and gate control, quantum memories, photonics, RF-cryo and superconductor-electronics, system engineering and device packaging.
- Expanded suite of quantum algorithms for software and hardware-agnostic benchmarking, including digital error corrected systems, and optimising compilers and libraries.
- Demonstrate automated system control and tune-up.
- Develop an integrated tool-chain (design to processing) and module libraries for integrated optics, cryo- and superconductor electronics, including coherent optical-electronic converters.
- Coordinate EU-wide joint actions with other fields, such as material science, theoretical and cryo-physics, electrical engineering, mathematics, computer science, and increasingly, scientists working in potential application fields and industry (small, medium and large entities).
- Address standards bodies (EU, international).
- Integrate industry (SME and large companies) and foundries.
- Engage with the EU infrastructure, the large labs and programs, and the research and technology organisations (RTO).

Recommendations

- Qubits: Increase number, quality, and interconnectivity of qubits for all quantum computer modalities (superconducting qubits, s-c qubits, trapped ions, neutral atoms, photonic qubits)
- Qubit control: Increase the number of qubits that can be simultaneously controlled & reduce lead times in accessing control units in Europe at scale, exploiting also pilot lines.
- Quantum Operating Systems, Quantum Compilers: Develop quantum compilers combined with automatic scheduling that incorporate calibration and quantum error correction. Standardise an intermediate representation framework. Develop links with HPC.
- Quantum APIs & Cloud Access: Improve availability of European quantum hardware in the cloud.
- Quantum Algorithms: Support the development of software that helps to develop and implement quantum algorithms (e.g., by automatic generation gate sequences) and identify algorithms and use cases where quantum computing has an advantage.
- User Community: Provide access to industry, academia, European start-ups and other interested parties. Provide procurement of products and services from QC solution providers. Serve as collaborative hubs between users and quantum algorithm developers.

B.1.2 Quantum Simulation

The quantum simulation pillar focuses on special-purpose machines, designed and optimised for specific applications, making them powerful counterparts to general-purpose quantum machines. In particular, quantum simulators are highly controllable quantum devices that allow one to obtain insights into properties of complex quantum systems or solve specific computational problems inaccessible to classical computers. These are expected to find applications in areas as diverse as quantum chemistry, nuclear physics, material sciences, fluid mechanics, logistics, routing and, more in general, optimization. Near-term programmable devices and quantum simulators also promise to offer a speedup in instances of machine learning problems, including quantum kernels and quantum classification schemes.

Important targets for the empowerment of quantum simulators are to achieve:

- higher levels of control,
- higher state-preparation fidelities,
- large-size systems, and
- programmability at lower entropy.

Different approaches to quantum simulation can be classified as follows:

Digital quantum simulators: they approximate quantum dynamics or more general quantum processing, by combining different gates. Digital quantum simulators are therefore intrinsically programmable due to the approximation of the target dynamics starting from a few basic building blocks.

Analogue quantum simulators: they reproduce the behaviour of other interacting quantum systems under precisely controlled physical conditions. These devices can simulate complex systems of practical interest, such as complex networks found in industry settings. They go beyond a computational paradigm based on qubits, for example, by working directly with fermionic particles. This makes them less general, but significantly reduces the overheads and the requirements in terms of control.

Heuristic quantum devices: they aim at providing approximate solutions to optimisation problems. Examples are programmable quantum simulators, annealers, variational optimisers, or variants of quantum approximate optimisers and NISQ devices. Here, often both a classical and a quantum component comes into play in hybrid schemes operating without quantum error correction.

Below, details about different forms of quantum simulation are outlined, corresponding to the hardware layer 'Qubit' in the quantum information stack *(Figure 1)*. Considerations related to middleware and software technologies detailed in **B.1.1** Quantum Computing are similarly applicable to quantum simulations. They are therefore not repeated here. In terms of hardware, the explored technologies are similar to those used for quantum computation, although, as mentioned they do not necessarily work in the qubit picture. Examples of technologies are:

- Superconducting quantum circuits
- Ultra-cold atomic and molecular quantum gases
- Arrays of atoms in optical lattices or tweezers
- Trapped Ions
- Photons

Specific objectives for quantum simulation for the next years include:

→ Objectives by 2023 - 2026.

- Demonstrate the "quantum advantage" in simulation for a range of tasks – this is seen as an important milestone, but not an application as such.
- Improve levels of control and scalability, and further reduce entropy in various platforms.
- Develop quantum-classical hybrid architectures to allow quantum simulators to address industry and R&I-relevant applications.
- Expand and strengthen the supply chain and the development of key enabling technologies.
- Initiate certification and benchmarking of the most promising quantum simulators.
- Develop software solutions to accompany the developments of quantum simulators and their particular application focus.

→ Objectives by 2027 - 2030.

- Establish a close link to end-users and develop more practical applications.
- Design error correction and mitigation techniques tailored to quantum simulators.
- Develop quantum simulators offering a higher degree of control and programmability.
- Build a bridge between industry and research on quantum simulation to translate the problems of industry in the language of simulation paradigms.
- Provide general methods for the certification and benchmarking of quantum simulators.

Recommendations

- Foster the access to quantum simulators by industry end-users.
- Support co-design / co-development of quantum simulators between industrial end-users and quantum manufacturers (hardware & software) to accelerate work towards the demonstration of "quantum advantage" for industry-relevant purposes using quantum simulators.
- Develop the verification, certification and benchmarking algorithms for quantum simulators
- Improve their control, scalability, quality, and their integration within HPC clusters.
- Develop the quantum simulation software stack and quantum-classical hybrid architectures.
- Foster development of the whole software stack for quantum simulation.
- Deploy an operational and certified quantum simulator with more than 1000 constituents, and full on-the-cloud accessibility.

B.1.3 Quantum Communications

The area of quantum communications aims at designing the tools and protocols to exchange quantum information among distant users. Within a general progressive framework for quantum communication networks, where increasingly complex hardware and software give rise to more advanced functionalities, the field can be presently roughly divided into two domains: **(1)** near-term technology focusing primarily on quantum key distribution (QKD) and other applications attainable at a similar stage of functionality at relatively short distances. This technology has reached high TRL, and commercial products have already been brought to market; **(2)** long-term research and development to unlock all the benefits of quantum communication for users around the globe, specifically enabling quantum communication over long distances, and offering higher stages of functionality to the users.

The overarching vision is to develop a Europe-wide quantum network that complements and expands the current digital infrastructure, laying the foundations for a quantum internet. To achieve this, the objective is to advance quantum communications in three essential directions:

1. Performance: Increasing bit rates, fidelities, link distances, and robustness of all types of quantum communications.
2. Integration: Combining quantum communications with conventional network infrastructures and applications.
3. Industrialisation: Realising technology that is manufacturable at an attractive price point and which generates wealth and jobs in Europe.

One of the main applications of quantum communications in the near term is the design of cryptographic schemes with security based on the laws of quantum physics. Secure communications play a vital role in the economy and society, as substantial amounts of data, with varying degrees of sensitivity, are transmitted daily and are used to perform critical operations (e.g. in government, healthcare, and critical infrastructure). However, quantum computers pose a threat to current cryptography. Two alternatives could provide quantum-safe security: on the one hand, and while not concerned with quantum communication itself, post-quantum cryptography (PQC) promises ways to secure data based on the hardness of specific mathematical constructions. On the other hand, QKD provides security based on quantum physics and requires quantum communications. Although different in nature and level of maturity, PQC and QKD offer complementary advantages but also both have shortcomings. In the near future, PQC and QKD are likely to co-exist and be used together in a quantum-safe landscape.

Generating QKD keys for secure data exchange and storage requires the existence of quantum communications channels, forming typically a network of fibre-based or free-space optical connections. Both types of channel have been successfully used, validating their functionality in principle. The driving parameter for QKD systems is the secret key rate shared by the users over a given distance. Despite QKD's attractive features, there is still room for improvement. Although new schemes have demonstrated terrestrial QKD links of 800 km, in practice the communication range is still typically limited to metro or regional area scale: for shorter range, less than 100 km, optical switches and fibre optic communications can be used. To further increase the communications range, presently and in the short term, trusted relay nodes are employed. In the long term, long-distance quantum communication will require the development of quantum repeaters and satellite networks.

The long-term ambition is to realize a quantum communication infrastructure (or quantum internet) that can provide fundamentally new technology by enabling quantum communication between any two points on earth. In synergy with the 'classical' Internet that we have today, a quantum internet will connect quantum processors to achieve unparalleled capabilities that are provably impossible using classical communication. The term internet refers to the ability to do inter-networking, in which smaller quantum networks in e.g. metropolitan areas can be inter-connected by long-distance backbones to realize very large-scale quantum networks.

As with any radically new technology, it is hard to predict all uses of this future infrastructure, but several major applications have already been identified. One is to enable QKD with end-to-end security without relying on intermediary trusted relays. These technologies will also enable the implementation of device-independent quantum cryptography protocols, where the level of trust on the implementation is minimal.

Other promising known applications are clock synchronization, extending the baseline of telescopes, secure identification, achieving efficient agreement on distributed data, exponential savings in communications, quantum sensor networks, secure multiparty computing, as well as secure access to remote quantum computers in the cloud (privacy preserving technologies). Realising a fully-fledged quantum network requires advances in several key technologies in an interdisciplinary effort between physics, computer science and engineering.

The main components of such a network will be:

- **Quantum repeaters:** To connect many users at continental distances, a quantum repeater may be used to generate long-distance entanglement using fiber networks.
- **Satellites:** For ultra long-distance backbones, satellites may be used to distribute entanglement between different points in the network.
- **End nodes:** The quantum analogues of laptops and phones connected to the Internet– are required to enable the execution of applications, and hence to make quantum internet technology available to end users.

From an implementation perspective, quantum communications require the development of a diverse array of technologies to create, store and manipulate quantum states. The control and manipulation of light (photons), matter and their interaction are essential to attain a quantum secure network and the quantum internet. These include:

- Photon sources with important properties including very strict wavelength and bandwidth requirements, as well as purity and efficiency specifications.
- Photon detection technologies that need further improvements both in the single-photon regime and for continuous-variable systems.
- Quantum memories and interfaces between quantum information carriers (quantum states of light) and quantum information storage and processing devices (atoms, ions, solid state systems).

For these elements to be really useful, they should be built with technologies that are able to scale to large numbers, for instance using photonic integration, and also be resilient enough to tolerate the harsh environments in telecommunication network field deployments.

Deployment of long-distance links integrating quantum repeater and processing node technology managed by a full-stack control plane and giving access to advanced functionalities. It encompasses a diverse array of technologies, including the creation and manipulation of entangled states, the design of quantum memories, quantum random number generators (QRNGs), QKD, potentially combined with PQC.

Specific objectives for quantum communications for the next years include:

→ Objectives by 2023 - 2026.

- Improved performance, key rate, and range, for QKD solutions;
- Photonic Integrated Circuits, with efficient and cost-effective experimental devices for quantum communication;
- Deployment of prototype payloads for space QKD;
- At least two industrialised QKD systems made in Europe and based mostly on a European supply chain;
- Deployment of several metropolitan QKD networks;
- Deployment of large-scale QKD networks with trusted nodes;
- Operation and enhancement of MDI QKD, such as Twin-Field, with a range of 500 km or more, without repeaters or trusted nodes;
- Advances in QKD: testing, certification, accreditation, and availability conditions (e.g. laboratories) to ensure robustness to side-channel attacks at the optical level;
- Development of joint QKD and PQC solutions.
- Several telecommunications companies selling QKD services with a sustainable business model;
- Demonstrating the use of quantum channels for other cryptographic applications, such as private data mining, secure multiparty computing, long-term secure storage, unforgeable cryptosystems;
- Integration of reliable, small and cheap QRNGs into classical and quantum communication systems.
- Large-scale communications and entanglement distribution systems outside the laboratory, including network management software;
- Development of quantum internet sub-systems such as quantum memories, and processing nodes.
- Demonstration of a functional elementary quantum repeater link over telecom wavelengths and fully independent nodes.
- Design of new application protocols, pilot use cases, software and network stack for a quantum Internet.
- Coexistence of QKD with conventional communications solutions, including multiplexing, allowing one optical channel to be used for multiple services (quantum and classical);

→ Objectives by 2027 - 2030.

- Cost-effective development, maintenance, and power consumption for QKD systems;
- Scaling of QKD solutions, due to increased market demand;
- Small Form-factor Pluggable (SFP) QKD transmitter/receiver pair for key distribution;
- QKD systems robust to side-channel attacks, including power consumption and thermal noise, for standalone transmitters and receivers (without physical security);
- Deployment of MDI QKD as an industrial product, over very long distances;
- Deployment of a QKD network “backbone” connecting major European metropolitan networks;
- Certification of quantum-safe security, including QKD possibly combined with PQC, by at least one national security agency;
- Certification of SFP services and software for universal plug-in;
- Mature quantum communications infrastructure for general usage by organizations and citizens;
- Space-based quantum communications infrastructure;
- Multi-node quantum networks supporting basic quantum Internet applications;
- Deployment of reliable interfaces between qubits at rest and in transit in the network;
- Reliable industry-grade quantum memories to extend communication distances and the demonstration of quantum repeaters.
- Long-distance fiber backbone using quantum repeaters capable of connecting metropolitan areas networks over hundreds of kilometres.
- Integration of advanced quantum network applications into classical network infrastructure (i.e. orchestration platform) over a quantum network including quantum repeaters

Recommendations

- Complete the deployment of regional, national and Europe-wide QKD networks, with European actors as early customers of European-made QKD systems (e.g., via the EuroQCI initiative), with competitive range, key rate, and performance, integrated with classical networks.
- Integrate QKD and PQC in European cryptographic devices and operational secure networks.
- Foster the certification of quantum security by at least one national security agency by 2030.
- Implement test-beds for quantum internet technology including metropolitan-scale networks with processing nodes, and long-distance fiber backbones using quantum repeaters.
- Develop industry grade control plane, as well as software and network stack for programming and controlling quantum networks with long-distance backbones linking metropolitan areas, integrated into classical network infrastructure
- Complete the deployment of regional, national and Europe-wide quantum long-distance networks, with European actors including quantum repeaters and space-based quantum communication infrastructures with dedicated satellites.

B.1.4 Quantum Sensing & Metrology

Quantum sensing and metrology are based on exploiting the quantum properties of nature, quantum phenomena, quantum states, their universality and intrinsic reproducibility, the quantization of associated physical quantities or their high sensitivity to environmental changes. Quantum sensors will provide the most precise and accurate measurements in many fields, boosting the performance of consumer devices and services, from medical diagnostics and imaging, high-precision navigation, earth observation and monitoring, to future applications in the Internet of Things. There is a wide variety of quantum sensors, including e.g. gas sensors, solid-state sensors, as well as single-atom sensors. All have specific properties that make them suitable for particular applications (e.g. cold atoms for gravimetry, nitrogen-vacancy (NV) centres in diamond for high spatial-resolution magnetometry). The variety of platforms and applications have very different Technology Readiness Levels (TRL): some products are already commercially available, while certain platforms are still at an early stage of development.

The central concept of a sensor is that a probe interacts with a system that carries the property of interest, which then changes the quantum state of the probe. Measurements of the probe may reveal the parameters of this property. Quantum-enhanced sensors either take advantage of the absence of classical noise processes, using a quantum algorithm for extracting the relevant information, or employ probes that are prepared in particular non-classical states. Control over all relevant degrees of freedom and long coherence times enables quantum-limited resolution, even beyond the standard quantum limits (SQL). To achieve this type of control and generate non-classical or even entangled states in noisy real-world scenarios, novel theoretical foundations, tailored materials and experimental techniques are necessary.

To achieve the central goal of “demonstration of quantum sensing beyond classical capabilities for real-world applications” the following central challenges need to be addressed:

- Develop techniques to achieve full control over all relevant quantum degrees of freedom and to protect them from environmental noise and malicious interventions.
- Identify correlated quantum states that outperform uncorrelated systems in a noisy environment and methods to prepare them reliably.
- Leverage interdisciplinary expertise and join forces with other fields, such as the signal processing community to further advance the limits of sensors sensitivity and resolution and to implement the best control protocols, statistical techniques (e.g. Bayesian) and machine learning algorithms.

Applications of quantum sensors are relevant in many different areas, such as, but not limited to, high precision spectroscopy, imaging, gravimetry or gyrometry, high resolution microscopy, magnetometry, clocks and their synchronization, positioning, or thermometry. Because of the wide range of prospective applications and their specificity, a broad range of physical platforms needs to be considered, including (but not limited to):

- trapped ions
- ultra-cold atoms
- warm and hot atomic vapours
- nano- and micro-mechanical oscillators and opto-mechanical systems
- superconducting and semiconducting nano-circuits
- artificial systems such as quantum dots and spin defects in solid-state
- rare earth ions in solid state matrix
- all-optical set-ups involving nonclassical states of light.

Specific objectives for quantum communications for the next years include:

→ Objectives by 2023 - 2026.

- Evolution of key enabling technologies and materials, supported by companies, from spin-offs to big ones, and establishment of a reliable, efficient supply chain including first standardisation and calibration efforts.
- Development of chip integrated photonics, electronics and atomics, miniaturised lasers, traps, vacuum systems, modulators and frequency converters. Engineering of materials using nanofabrication, functionalisation and chemical modification of surfaces, e.g. for biosensing; synthesis of ultra-pure materials (e.g. diamond, SiC), doped nanoparticles, colour centres.
- Establishment of standardisation, calibration and traceability for new sensor technologies.
- Prototypes of compact electrical quantum standards with enlarged application ranges.
- Prototypes of transportable optical clocks and their comparison over large distances as well as atomic gravimeter and gyroscopes surpassing existing (classical) devices in statistical and systematic uncertainty.
- Prototypes of transportable electric, magnetic, radio-frequency field, temperature and pressure sensors based on artificial atoms (e.g. colour centres, quantum dots) or quantum optomechanical and -electrical systems.
- Table-top prototypes of quantum-enhanced, super-resolved, and/or sub-shot noise microscopy, spectroscopy, and interferometry, as well as quantum LIDAR and RADAR.
- Laboratory demonstration of the practical usefulness of engineered quantum states (such as entangled states) in real-world applications, supported by theoretical modelling of real-world noise scenarios and the identification of noise-immune quantum states and algorithms, e.g. by employing machine-learning algorithms, Bayesian inference and quantum error correction for sensing.

→ Objectives by 2027 - 2030.

- Continued evolution of enabling technologies and material engineering to increase TRL and promote quantum sensors to the market.
- Integration of quantum measurement standards for self-calibration in instrumentation.
- Establishment of custom processes in foundries on key technologies to provide access to innovations for a larger basis of researchers and companies.
- Fabrication of optically and electronically integrated lab-on-a-chip platforms based on functionalised materials for biomedical applications or integrated atom chips for sensing electric and magnetic fields.
- Laboratory prototypes of quantum-enhanced measurement and imaging devices, entangled clocks, inertial sensors and quantum opto-mechanical sensing devices.
- Commercial products, such as magnetometers improving MRIs, quantum-enhanced super-resolved and/or sub-shot-noise microscopes, high-performance optical clocks and atom interferometers, quantum RADAR and LIDAR.
- Development of networks of quantum sensors as well as space-borne quantum-enhanced sensors, including optical clocks, atomic and optical inertial sensors.

Recommendations

- Foster collaboration between academia and industry for development of a complete value chain in each major category of quantum sensors.
- Strengthen European industrial capabilities in all relevant solid-state, gas, and single-atom sensors categories, with performances beyond classical analogues.
- Develop a quantum sensing toolbox: a catalog of European high-performance sensors/devices that potential buyers can access for understanding how they are suited for, and can be implemented into, their existing production lines and services.
- Support the development and market introduction of high TRL quantum sensors through public procurement, such as the development of a quantum sensor network in coordination with EuroQCI.
- Engage pilot lines to stimulate quantum sensor development and testing.

B.1.5 General recommendations transverse to the four pillars.

Recommendations

- Consolidate the quantum communication and quantum computing activities, to scale up the capabilities of both pillars in a synergetic fashion
- Establish close links between quantum simulation and quantum computing, and also with quantum metrology and sensing, in particular through industry-targeted roadmaps
- Foster use-case demonstration with relevance to end-users
- Identify practically relevant problems in which a quantum advantage is expected
- Facilitate the development of prototypes at reasonable costs by extending Europractice solutions to commercial partners in the context of accepted research
- Identify precise needs and expectations from industry partners
- Raise the general awareness on quantum simulation among the European industry
- Support the development of open standards to link projects better and to make tech transfer easier
- Support strategic enabling technologies (cryogenics, microwaves, lasers, as well as classical superconducting circuits, which are important for both computing and communication)
- Keep access to resources democratic – both to quantum computers but also to technologies.

B.2 Quantum Resources, Innovation, Industrialisation, and Societal Impact

Cross-cutting topics are essential to the development and competitiveness of the European quantum research and innovation areas. This section B.2 outlines necessary actions across eight different such areas, which range from basic science to the development of standards and intellectual property, as well as diversity and ethical issues.

B.2.1 Basic quantum science

While some quantum technologies have reached a significant level of maturity and have even reached the market, it is crucial to pursue the study of open scientific questions – both experimental and theoretical – in order to develop more applications, and to ensure flexibility in the evolution of quantum technologies and ensure their long-term impact. New science provides new ideas for quantum technologies, but also developing quantum technologies stimulates new questions to be answered by new science. This part is broad and covers many different fields, but we have identified the following areas because of their strategic relevance:

- **Quantum information theory and new schemes for quantum error correction:** As its classical counterpart, quantum information theory aims at identifying the laws and the ultimate limits governing any information process based on quantum effects, including e.g. energetic aspects.
- **Quantum foundations:** Here the main objective is to understand what makes quantum theory special and how it differs from classical physics. Any gap between the classical and quantum formalism is a potential resource for a new quantum information protocol.
- **Decoherence:** Any quantum advantage is lost under the presence of decoherence. Therefore, understanding the mechanisms behind decoherence and how to mitigate, or even exploit, their effects is a fundamental research line transversal to all pillars.
- **Novel quantum information technologies:** There remain significant basic-science challenges to improve existing technologies. These include e.g. single photon sources and detectors, quantum memories, photonic cavities, ion-traps and atom chips, and opto-mechanical systems.
- **Beyond quantum information technologies**: Concepts and tools developed for QT also find application in other disciplines. This creates a very broad research line, ranging from biology and thermodynamics to condensed matter or high-energy physics, and a broad range of applications.

As mentioned, this cross-cutting activity is broad and has a high blue-sky component. However, the following objectives have been identified:

- Improved understanding of the quantum-classical transition and decoherence mechanisms.
- Explore novel concepts and systems where quantum technologies can be an advantage, e.g. in biology, chemistry and thermodynamic systems as well as across the established application areas.
- Demonstration of novel quantum information technologies, transferring them to the application domains or opening up new areas or research and innovation.
- The long-term objective is to continue to work towards opening up new avenues for potential growth in the field of quantum technologies.

Recommendations

- Develop further the concept of hybrid devices that combine at least two different systems in order to combine strengths and reduce weaknesses.
- Design new architectures for quantum information applications: e.g. new qubits, new quantum memories, new protocols for long-distance entanglement distribution.
- Develop scalable methods for the quantum evaluation and characterisation of complex many-body and multi-partite quantum systems.
- Extend the application of quantum information technologies, concepts and tools to other fields of science, such as quantum thermodynamics, quantum gravity or condensed matter physics.
- Identify and quantify quantum phenomena with no classical analogue and understand their use as quantum resource for quantum information purposes..

B.2.2 Engineering & enabling technologies

Another important cross-cutting activity concerns the development of transversal technologies of relevance for all the pillars. These activities include, among others:

- Manufacturing, testing & packaging; The development of many quantum technologies at scale requires access to industrial-grade micro- and nano-fabrication facilities, providing the necessary resources for the manufacture and packaging of quantum devices. Closer integration between quantum and classical devices is needed.
- Devices & components: A wide variety of conventional devices and components are needed, together with the quantum devices, to deliver complete systems. They include, for example: low-loss optical switches; lasers; optical fibre technology; photonic integrated circuits; cavities; vacuum and cryogenic systems. Affordable access to essential device and component licenses for young EU SMEs is an important issue to protect the growth of the EU quantum industry.
- Control: Quantum optimal control provides toolboxes that allow one to identify the performance limits for a given device implementation, and it provides the protocols for realising device operation within those limits.

The following objectives have been identified:

→ Objectives by 2023 - 2026.

- Demonstrate performance from quantum devices fabricated in industrial-grade facilities which is comparable to state-of-the-art from specialised (e.g.) university clean rooms.
- Improve the yield and uniformity of quantum devices and ensure their functional performance by using suitable processes in (if possible) established fabrication facilities.
- Improve access to, and streamlining of, fabrication and packaging facilities.
- Improve critical performance metrics of key enabling technologies, as well as reducing cost, size, etc.
- Develop control calibration methods for non-trivial pulse shapes.
- Analytical design of control schemes and development of efficient descriptions thereof in order to facilitate both analytical and numerical design and improvements.
- Convergence of numerical optimal control and experimentation in many platforms, including handling of calibration uncertainties and other experimental constraints.

→ Objectives by 2027 - 2030.

- Demonstrate systems, manufactured at scale, which fully integrate quantum devices with a range of classical (optical/electronic) devices.
- Develop schemes to stabilise and control complex entanglement-based networks.
- Modular approach from simple to complicated control pulses in theory and improved pulse shaping in experiments.
- Implement reliable strategies for the control of mesoscopic systems.

Recommendations

- Accelerate development of critical European enabling technologies for quantum computing, quantum simulation, and quantum communications. Examples: integrated photonics, high-performance FPGAs, micro- , nano-, and cryo-electronics, miniaturized vacuum systems for atom / ion systems.
- Manufacturing & packaging: industrial-grade micro- and nano-fabrication facilities, providing the necessary resources for the manufacture and packaging of quantum devices.
- Devices & components: Domestic developments of critical components. Examples include high-end lasers, photonic integrated chips, miniaturized vacuum systems, and cryogenic systems.
- Control: toolboxes that allow the identification of performance limits for a given device implementation, and provide the protocols for realising optimal device operations.

B.2.3 Education & Workforce Development

The actions towards securing an adequate workforce to support the growth of the European quantum science and industry can be divided into three segments: **(i)** a roadmap for vocational education and workforce training, supporting career pivots to the quantum industry, **(ii)** a roadmap for broad-base academic education, and **(iii)** the implementation of favourable conditions for international recruitment of quantum talents.

(i) Strategic Roadmap for Vocational Education and Workforce Training

The following measures are proposed to meet industry demand:

- Continually update the the European Competence Framework for Quantum Technologies (CF) with emerging industry skill requirements.
- Define the populations (disciplines, job families) that need to acquire these skills with assigned priorities. This includes identifying the disciplines/functions or situations that have more of a requirement for coaching as well as identifying the personnel that require complete reskilling.
- Define the level of mastery that will be targeted (from awareness level to expert level to active practitioners).
- Foster the creation of an open-source QT module repository supporting a pan-European ecosystem of training programs with mutually compatible customized training solutions.
- Link companies wishing to reskill their staff with companies and training institutions that have the expertise (e.g. quantum computer manufacturers, training companies).
- Establish a long-term roadmap with a vision of the specific skills and roles to be created in the industry, according to the quantum technologies and the sector of activity.

The quantity of people to be trained and the speed of transformation will depend on the industrial and business models and the evolution of the quantum workforce. Overall, these vocational training programmes must be modular, flexible and adaptable in order to respond to changing requirements as platforms develop and mature, and new applications emerge. Furthermore, programmes must attract and retain a diverse range of talents, respect gender balance, and offer attractive pathways for under-represented groups entering the field.

(ii) Strategic Roadmap for Education

The following list indicates the activities, from the industry perspective, to be undertaken by the academia and the industry.

→ Objectives by 2023 - 2026.

- Define the competence baseline and assess the talent requirements (Industry).
- Raising awareness for different business sector use cases in QT education (Industry).
- Design and implement QT Master programmes across Europe (Academia) with entry points from miscellaneous disciplines (Academia).
- Foster the creation of a pan-European ecosystem of mutually cooperating academic institutions and set up an incentive structure for cooperation (Academia).
- Understand industry needs (skills) to build quantum engineering programmes (Academia).
- Raise QT awareness and acceptance at all academic levels and in the general population throughout Europe (Academia).

→ Objectives by 2027-2030

- Align higher education QT learning objectives with industry training and hiring criteria through the Competence Framework (Industry+Academia)
- Launch programmes to teach the teachers (Academia).
- Launch BSc with specialisation in QT (Academia).
- Inclusion of QT in high school education (Academia).
- Continually adapt training offers to emerging QTcareer paths (Industry+Academia).
- Success evaluation of academic graduate production and systematic feedback to universities (Industry).
- Long term map vision (Industry+Academia).
- Re(trained) quantum workforce ready (Industry).

(iii) Favourable Conditions for International Recruitment

The pursuit of global leadership in the industrialisation of quantum technologies will necessarily require Europe to be a net importer of talent and skilled workforce. In addition to securing an adequate internal supply of qualified workers, European member states will imperatively need to implement policies and regulations favourable to external recruitment. Such measures include:

- Fast-track visas for international workers with a quantum-technology background.
- Simplified application processes for companies operating in the quantum sector.
- Financial support to European quantum startups and SMEs to rival the work package offers from foreign counterparts.

Recommendations

- Set concrete learning objectives in relation to the industry-defined skills required.
- Establish a long-term map with a vision of the specific skills and roles to be created in the industry, according to the quantum technologies and the sector of activity.
- Facilitate the hiring of skilled international labour able to support the European quantum ecosystem (industry and research & innovation).
- Get quantum-trained personnel added to the 'workforce shortage categories', to facilitate faster processing of work visas.

B.2.4 Standardisation

The standardisation of quantum technologies can help accelerate market uptake by providing reliability, consistency, and interoperability with existing infrastructure, systems and components. Standardisation not only concerns the requirements that form the basis of certification, but also addresses vocabulary, terminology, quality benchmarks, models, exchange protocols, and many more topics. In light of the strong influence excised by other countries on the international standardisation bodies, it is imperative that Europe takes a proactive approach to the development of standards, lest it finds itself forced to adapt to foreign countries standards, which may penalise European technology.

Preliminary objectives in support of the European quantum industry on standardisation include:

- Develop a living document, "State-of the-art tracker on standardisation", in which the work of the main standardisation bodies will be gathered.
- Establish a process and the necessary accompanying material in order to solicit standardisation needs from the broad European quantum industry.
- Support the participation of relevant European experts in the activities of the Standards Developing Organisations (SDOs).
- Provide up-to-date information on global standardization activities to the European quantum industry.
- Support the continuous actualisation of the European Standardisation Roadmap on Quantum Technologies of which the first release is planned to be published by the CEN-CENELEC Focus Group on Quantum Technologies ("FGQT") early 2023. This support includes providing up-to-date information on developments in the European and world-wide industries and supply chains relevant to quantum technologies.
- Support the participation, continuity and impact of the recently established CEN-CENELEC Joint Technical Committee 22 on Quantum Technologies ("JTC22"), as the European basis for vision and coordination on standards relevant to quantum technologies. This includes the following
  - Support of JTC22 with coordination/ liaising with other Standards Developments Organisations (SDOs), like ETSI, ITU, ISO-IEC, IEEE and other.
  - Support the participation of relevant European experts in the JTC22 activities, including organisational, technical and liaison leadership positions.
  - Support JTC22 with producing standardization deliverables to address European market and societal needs, as well as underpinning EU legislation, policies, principles, and values.

Recommendations

- Set up adequate incentives to stimulate the participation of industry representatives and quantum experts in Standardisation Developing Organisations (SDOs)
- Develop a simple, interactive, and easy-to-navigate living document on existing and upcoming standards that impact the quantum ecosystem.

B.2.5 Funding: private & public

As discovered in a recent study by McKinsey, Europe is today home to roughly 25% of global startups and SMEs in the quantum-technology sector, on par with the United States, but attracts only 5% of private investments in the sector, ten times less than similar companies in the United States. This imbalance must imperatively be redressed. The European Investment Bank (EIB), European Innovation Council (EIC), and the European Investment Fund (EIF), along with national-level public funding organisations can play an instrumental role in levelling the access to capital in Europe relative to the United States. Urgent and determined actions are however needed. Recommended actions include:

- Raise the upper limit on direct equity investment from € 15 million to at least € 75 million in order to mobilise adequately sized co-investments for growth funding rounds (€ 100 - € 250 million) and anchor European companies and talents in Europe, rather than seeing them migrate their activities abroad.
- Enable the EIB / EIC or other European-financed investment fund to take a 'lead investor' role, namely to set the financial conditions of the funding round and the composition of the company Board.
- Simplify and accelerate the due diligence process of the EIC / EIB to be more in line with common practices from private capital investments (on the order of 4 - 6 months).
- Advocate best practices (do's and don'ts) for public procurement programmes and their implementation within the EU, including at national member state level. As a notable example, public procurement programmes should refrain from demanding the ownership of intellectual property developed in the course of manufacturing and delivering the agreed goods / service.
- Pursue a measured implementation of the recent foreign direct investment screening (Regulation No 2019/452) such that European quantum companies remain attractive targets for European and foreign investors alike, while maintaining Europe's strategic capability in the field. The balanced approach concerns both venture-capital investments as well as future mergers and acquisitions.

In addition, public funding in Europe for the growth of quantum technologies is today scattered between the European Commission and other European-Union organisations (e.g., EIC, EIB), national funding programmes in individual Member States, and even at a regional level in certain EU countries. No cohesive plan exists between many of these different financial vehicles, resulting in a disorganised injection of financial stimulus, and ultimately an inefficient attribution of precious capital. A coordination between all public stakeholders in support of the European quantum ecosystem is strongly recommended.

As regards to private funding, there is a need to educate investors in the opportunities available in European companies as well as providing a reliable and beneficial legal and financial framework. Additionally, opportunities, such as pitching sessions, need to be provided for young, innovative startups to pitch to knowledgeable investors.

Recommendations

- Raise the upper limit on direct equity investment to at least € 75 million, and upgrade correspondingly the selection procedures.
- Enable the EIB / EIC or other European-financed investment fund to take a 'lead investor' role.
- Simplify and accelerate the due diligence process of the EIC / EIB to be more in line with common practices from private capital investments (on the order of 4 - 6 months).
- Pursue a measured implementation of the recent foreign direct investment screening (Regulation No 2019/452) such that European quantum companies remain attractive targets for investors.
- Seek a balance in investment screening procedures, so that they don't become detrimental for European entities.

B.2.6 Intellectual Property

Commercial competition involves competition across the landscape of intellectual property (IP). Strengthening the stance of European companies in this broad, global landscape constitutes an essential cornerstone of future success. Actions in this vein include:

- Support from the European Patent Office in conducting broad surveys of the IP landscape in various quantum fields, sharing best-practices from other deep-tech sectors, and providing preliminary freedom to operate assessments.
- Review of standard patent-approval practices in line with the characteristics of quantum technologies to support European companies vis-à-vis foreign competitors in the global IP landscape. Particular attention should be given to supply chains.
- Encouragement in filing for patent protection in major patent offices (such as EPO and USPTO) for valuable intellectual property, including providing dedicated funds for SMEs (such as the current one administered by EU IPO) and specific funding streams in EU-funded academic research.

Recommendations

- Engagement from the European Patent Office to review and align standard patent-approval practices in alignment with the characteristics of quantum technologies.
- Support from the European Patent Office to conduct broad surveys and share best practices, particularly to SMEs.
- Stimulate IPR generation in general to develop a strong EC-based portfolio.

B.2.7 International Collaboration / Export Control Regulation

Geopolitics is an increasing force acting on the evolution of the global quantum market. Although some quantum technologies are more mature and trending towards being established technologies, such as gravity sensors, many remain in their infancy. The early and broad application of export-control regulation on the fear of future potential rather than current performances runs the risk of halting the growth of certain quantum-technology sectors altogether. It is thus important for the European Commission to engage in early discussions with like-minded international partners, notably the United States via the newly created Trade and Technology Council (TTC), on common approaches in connection with the quantum industry. Nurturing positive relations with like-minded non-EU partners will be essential for the growth of the EU quantum industry.

Recommendations

- The European Commission and the European quantum industry to engage in early discussions with like-minded international counterparts on quantum technologies.
- The Technology and Trade Council (TTC) may be an appropriate vehicle for such actions.

B.2.8 QT Governance Principles

Gender issue and diversity

Diversity is key to the quantum community. Fairness and proven positive impact on productivity and innovation are basic incentives for action. In quantum technologies the gender imbalance is about 0.2/0.8, which notably points at loss of talents and deficit in disruptive perspectives. This also results in a non inclusive environment and thus suboptimal attractivity and activity. Actions and structures at all levels must change this detrimental situation to create an ecosystem that promotes and enacts gender equality. Notably, the number and visibility of female scientists have to significantly increase at each level of the value chain of quantum technologies, from basic science to the related industries, and to the future workforce of the field. Funding is needed to shift mind-sets and disrupt inequity. Blind spots will in particular be removed by enforcing a gender issues section in all research and innovation calls.

Environmental and social objectives.

Implementing sustainability measures has several benefits for companies, and for society in general. This is encouraged by national regulatory bodies, and some governments are providing capital and tax benefits to those that invest in sustainable activities. Brand reputation is affected by how sustainable a company is, due to societal awareness of the topic. Last, but not least, major investors are also increasingly mindful of their portfolio companies' performance on SDGs. As quantum technologies move closer to providing quantum advantage in a range of industries, the governance bodies should lead efforts to enable companies to achieve environmental and social goals by identifying appropriate high-impact use cases.

Ethical values.

Emerging technologies have the power to disrupt society, and it is required to consider the societal implications of new technologies before they reach full maturity. Ethical concerns regarding quantum computing have been discussed and global ethical guidelines are beginning to be drawn up, with clear principles and approaches to mitigate the risks and unintended consequences from the outset.

Recommendations

- Include a gender issues section in all research and innovation calls, requesting concrete action and/or training against unconscious bias.
- Build up incentives towards environmental, societal, and ethical goals.

Part C:

Alignment with European initiatives

Part C: Alignment with European initiatives

The objective of this section is to provide inputs for the recent European initiatives that include quantum technologies activities in their roadmaps, with specific focus on the European Chips Act and EuroHPC JU. Based on the analysis of available documents and inputs, this section provides an alignment with the previous Research vision and Industry roadmap, in order to feed these initiatives with potential actions and recommendations.

C.1 Quantum Technologies and the Chips Act

This section is presenting a vision towards the European Chips Act. The topics of interest as expressed in the SRA and SIR are aligned with the Chips Act plan for action, as expressed in its Staff Working Paper V2. The main question is: "What kind of dedicated chips and/or chips technologies are needed for QT?"

Quantum Technologies (QT) requires the development of very specific chips. It is for example the case of silicon-spin, super-conducting, or photonic circuits for Quantum Computing. In addition, the development of QT requires numerous advanced classical chips technologies, considered as enabling technologies.

In a general manner, both the SRA and SIR stressed the importance of a strong coordination between the chips industry, foundries and infrastructure on quantum computing, from the fab level and process up to design methods and tools. This is required to develop an integrated tool-chain (design to processing) and module libraries for integrated photonics, cryogenic and superconductor electronics, including coherent optical-electronic converters.

Consequently, we consider the alignment of the Research and Industry roadmaps for QT towards the Chips Act along two tracks:

1. Technologies for dedicated quantum chips, required to fulfil the quantum challenges. Those technologies are relevant for specifically quantum devices.
2. Classical chips technologies for quantum (enabling technologies) required to support the industrialization and scaling of QT. Those technologies are generic (although specific development are needed) and used in other fields. (Chips-Act WP, pp. 56)

C.1.1 Technologies for dedicated quantum chips

The plan for actions of the Chips Act (Pillar 1, § 8.1.6) sets an action for "Investing in Advanced Technology and Engineering Capacities for quantum chips". Below we address the three main sections present in the current document.

Innovative design libraries for quantum chips (EDA Tools) -

The aim is to align the design and fabrication processes of quantum chips with the well-established and standardized processes of the classical semiconductor industry. (Chips-Act-SWP V2, p. 68). This quantum specific action shall be coordinated with the EDA (Electronic Design Automation, i.e. design toolchain) tools action of the Chips Act. Design tools and libraries allowing the support of QT technologies and their integration with classical ones are required. Novel design methodologies and tools are especially important for QT. Just like is the case in microelectronics, such EDA tools will be the result of a co-development process with the technologies themselves

(Chips-Act WP, p. 52). On top of qubits platforms compatible with the processes of the classical semiconductor industry (semiconductor- and photonics-based qubits), standardised design libraries and fabrication processes should also be developed for alternative qubit platforms (superconductor-, ion- and atom-based qubits). The goal is thus to develop an **integrated toolchain** (design to processing) and module libraries for integrated optics, cryo- and superconductor electronics, including high-transmission photonic chips, and coherent optical-electronic converters. It would be most desirable to transfer know-how from academia using open Process Development Kits (PDKs).

Quantum Pilot lines

To move quantum pilot lines and testing forward, we need to find synergy with existing players in the industry arena (Chips-Act-SWP V2, p. 68).) Pilot lines should allow for the integration of quantum circuits and control electronics, and for providing access to dedicated clean rooms and foundries for prototyping and production, reducing the entry barrier for the development and production of small volumes of quantum components and accelerating the innovation cycles. There is need to align the activities carried out within RTOs (Research and Technology Organizations) with those expected to be done in foundries when there will be a need to scale the technology quickly. Timely transfer of processes and know-how from RTOs to foundries will be critical for success of European quantum hardware industry. The ongoing Qu-Pilot initiative, presented later in this chapter, is a strong start but this needs to be up-scaled and widened towards the participation of foundries and other enabling technology industries to maximize the impact and benefits. Co-innovation and co-development of pilot lines, with a federated approach as taken in Qu-Pilot, will be essential for that.

Testing and experimentation

To advance testing and experimentation it is required to invest on facilities and know-how. Quantum chips require both in-line testing during production and end-of-line testing in an intensity that is, due to the requirement of quantum coherence, a lot higher than for classical chips. In most instances, for example due to operating environment and conditions, the development of dedicated testing equipment is and will be required. RTOs can develop that dedicated equipment for quantum device testing together with industry and it is crucial to support this cooperation. At the same time, it is of paramount importance to support efforts on standardization of quantum technologies and specifically to support industry in taking part to working groups and technical committees at SDOs (Standards Developing Organisations, like CEN-CELENEC, ISO, etc..). Standards will establish a unified way of working in the quantum industry community. This is a required step to move the testing of devices from RTOs or NMIs to accredited testing and calibration laboratories operating in the testing, inspection and certification market. The Qu-Test initiative, presented later in this chapter, is the first step towards the implementation of these facilities.

C.1.2 Classical chips technologies for quantum (enabling technologies)

Besides the three actions proposed in the previous paragraph, it would be beneficial to specify other actions in the chips-act related to all **classical chips technologies that are required for the development of a quantum eco-system.**

More than Moore

Integrating various signals (digital, analog, photonic, RF, etc.) & implementation technologies (various substrates), also known as “More than Moore”, will be key for the integration of quantum technologies within systems and applications.

"The main technical challenges with More Than Moore devices is that they may require unique structures and different materials to those traditionally used." (Chips-Act WP, p. 53). For example how to integrate other materials than semiconductors (e.g. diamond, or superconductors) in existing production lines. So the goal here is to **support the miniaturization and integration of magnetics, photonics, microwaves and superconductors into the manufacturing process of complete chips.**

Packaging

The development of QTs requires specifics chips packaging to accommodate for dense signal pathways, various signals (RF, digital, photonics), cryogenics or/and ultra-high vacuum interfaces. Current FPGA-based controllers could be replaced for ASICs and several purpose-oriented and operational environment adapted layers of control. **Advanced packaging techniques such as 2D and 3D stacking developed in the context of the chips-act will be a major asset for Quantum Technologies** (Chips-Act WP p. 49). Scaling the quality and number of qubits will require advanced 3D architectures and assembly techniques.

Cryogenic chips

In order to allow for the efficient control and scaling of quantum circuits, the control electronics shall be co-located with the actual quantum chips. Increase the number of qubits that can be simultaneously controlled in line with the development of quantum processors (Qubits) over the next three, six, and nine years. The **fabrication of classical control chips (CMOS) able to operate at cryogenic temperatures** as well as the **fabrication of fast classical superconducting control chips, as well as highly efficient single photon detectors,** is critical for the development of quantum computing hardware, in order to optimize signal routing, increase qubit readout speed and efficiency. This requires to increase the maturity of the cryogenic electronics manufacturing processes.

C.1.3 Ongoing initiatives related to the chips act: the quantum FPAs

Within the Quantum Flagship, a new initiative was launched to support quantum pilot lines as well as testing and experimentation, through two dedicated Framework Partnership Agreements (FPAs). As we have mentioned in the previous paragraph, they represent the first step towards the implementation of the objectives described in the previous paragraphs.

Quantum Pilot lines (Qu-Pilot)

The Quantum Technologies Flagship Initiative, with the support of the RTOs, is establishing the first quantum pilot lines, to bring together the different and proprietary quantum chip and component design and fabrication processes to achieve harmonization and compatibility with the existing manufacturing infrastructures. The quantum pilot lines are critical for implementing a path from the R&D to Industry communities.

The pilot line initiative is aligned with those needs:

- Technologies developed within the quantum flagship that **need to scale up** towards manufacturing
- Demand of fabless quantum technology businesses (i.e. companies focusing on the design of QT rather than their actual fabrication) requiring **critical infrastructure support** for product development.

That also includes foundries able to manufacture the required technology, including superconducting and semiconducting qubits for quantum computing, integrated photonic circuits for quantum communication and sensing, superconducting electronics, diamond devices for quantum sensing and computing.

Testing and experimentation (Qu-Test)

Qu-Test is a federated network of testbeds located at European RTOs and National Metrology Institutes (NMIs). The network brings together competences and infrastructures to offer testing and validation services to the European quantum industry, including the components produced by the pilot lines. A first goal of this cooperation is to support the creation of a trusted supply chain through the validation of quantum chips, devices, components and systems provided by the industry community. After an initial ramp-up phase that will see close cooperation with industry to agree on requirements and processes, the testbed network is set to provide in the long term testing and characterization as an independent commercial service. A second goal is to discuss and agree among RTOs and NMIs on unified sets of parameters to characterize quantum devices in the areas of quantum computing, communication and sensing. Methodologies and procedures related to the metrology of quantum devices will be harmonized within the network, making a critical contribution towards the creation of standards for quantum technologies.

C.1.4 The example of Quantum Computing

The field of Quantum Computing stems from a number of different qubits technologies which can be mapped to different actions of the Chips Act. The table below gives a summary of topics relevant for the main technologies for quantum computing, which have been presented in part in this chapter.

Qubits Technology	**Super-Conducting**	**Spin-Qubits (Si)**	**Photons**	**Cold-Atoms**	**Trapped-Ions**
Dedicated chips	For specific cryo circuits	Required	Cryo or room temperature	For alternative qubit platforms	For alternative qubit platforms
Pilot-lines & foundries	Required	Required, short term for Si28	Integrated Photonics	Needed for specific qubit platforms	Needed for specific qubit platforms
Testing & validation	Required	Required	Required	Needed, in the short term for sensing	Needed
More than Moore	RF Controls and interface	Qubits controls	Low-loss integration	Controls, dedicated electronics	Controls, dedicated electronics
Packaging	Required	Required	Required	Possible	Possible
Cryo-electronics	Required	Cryo-CMOS	For efficient detectors and switches	Possible (4 K)	Possible (4 K)
EDA tools & libraries	Required	Required for CMOS integration	Required	Design libraries	Design libraries

←

Table 1 - Mapping of quantum computing requirements to Chips Act actions

C.1.5 Recommendations

Recommendations

- Short-term (2024) Standardise and align the design and fabrication processes of quantum chips with those of the existing semiconductor industry for semiconductor- and photonics-based qubits,
- Mid-Term (2026) Develop new standards for alternative qubit platforms (superconductor-, ion- and atom-based qubits)
- Short-term (2024) Support pilot lines for the integration of quantum circuits and control electronics, including the fabrication of classical control chips able to operate at cryogenic temperatures (cryo-CMOS)
- Mid-term (2026) Support the integration of magnetics, photonics and superconductors into the manufacturing process of complete chips.
- Short-term (2024) Support the development of advanced packaging techniques such as 2D and 3D stacking capable to stand cryogenic temperatures
- Mid-Term (2026) Support techniques to achieve scalability via very high-density integration of the driving electronics with the quantum chip.
- Short-term (2024) Invest in testing and experimentation facilities for advanced quantum components, including those produced by the pilot lines, closing the innovation feedback loop between designers, producers and users of quantum components
- Short-term (2024) Support the development of design tools and libraries (EDA) for quantum chips and their co-integration with classical hardware.
- Mid-term (2026) Invest in the integration of EDA tools and module libraries (design to fabrication) in order to provide a user-friendly design environment for research, SMEs and industries that are integrating and using QT chips and systems.

C.2 Quantum Technologies and EuroHPC JU

In addition to EuroHPC JU vision and current projects, this section is based on the white paper “EuroQCS European Quantum Computing & Simulation Infrastructure”, a joint initiative of the Quantum Flagship and of leading European computing centres, and including inputs from section B coming from the SIR and SRA as well.

In 2018, Europe established the European High Performance Computing Joint Undertaking (EuroHPC JU), a joint initiative between the EU, European countries, and private partners to develop a world-class supercomputing ecosystem in Europe. The EuroHPC JU enables European countries to coordinate their supercomputing strategies and investments together with the EU with the objective to further develop, deploy, extend, and maintain a world-class supercomputing and data infrastructure in the EU, ranging from petascale to exascale and based on competitive European technology.

In order for the HPC supercomputing infrastructure to integrate quantum computers and simulators (QCS) into a European Quantum Computing & Simulation infrastructure (EuroQCS), and to substantially enhance the computing capacity of the EuroHPC JU's supercomputers, a white paper was published in 2021, representing the view of both the HPC and the quantum communities. It presents the main challenges and recommendations for the efficient integration of a quantum accelerator in the HPC, including a roadmap for QCS deployment in the EuroQCS.

C.2.1 The first project for hybrid integration: the European Pilot <HPC|QS>

In 2021, work has begun on the EuroHPC JU "Pilot on quantum simulator" project <HPC|QS>. The aim of <HPC|QS> is to prepare European research, industry and society for the use and federal operation of QCS. These are future computing technologies that are promising to overcome the most difficult computational challenges. <HPC|QS> is developing the programming platform for the quantum simulator, which is based on the European Atos Quantum Learning Machine (QLM), and the deep, low-latency integration into modular HPC systems based on ParTec's European modular supercomputing concept. A twin pilot system, developed as a prototype by the European company Pasqal, will be implemented and integrated at CEA/TGCC (France) and FZJ/JSC (Germany), both hosts of European Tier-0 HPC systems. The pre-exascale sites BSC (Spain) and CINECA (Italy) as well as the national Quantum Learning Platform at ICHEC (Ireland) will be connected to the TGCC and JSC via the European data infrastructure FENIX.

Following a Work Programme 2022 call, EuroHPC JU has selected, in October 2022, six sites across the European Union (EU) as centres of excellence, to host and operate the first EuroQCS quantum computers: Czechia, Germany, Spain, France, Italy, and Poland.

C.2.2 Timeline of the EuroQCS Infrastructure

2022-23 Quantum Flagship ramp-up phase with intermediate scale (50 to 200 physical qubits) QCS prototypes ready

- Intensive exploration of use cases, leveraging of QLM environments, remote or on premise access of various prototypes and pilot systems, preparation of applications for wider deployment
- Support the break-even point development of applications towards quantum computing – if applicable – for algorithms practical exploitation of Noisy Intermediate-Scale Quantum (NISQ) devices and use cases for hybrid calculations

2023-25 Procurement & deployment of two European exascale systems foreseen as EuroQCS sites

2025 Testing phase with intermediate scale prototypes

- Enhance the NISQ processing regime with error mitigation methods, enabling deeper algorithms
- Develop cross-hardware benchmarking of NISQ based systems, quantum application and algorithm theory, software architecture, compilers and libraries, as well as Electronic Design Automation (EDA) and simulation tools
- Identify promising applications to consolidate toward creating a first generation of applications based on NISQ devices
- Launch of the European Quantum Computing & Simulation Infrastructure (EuroQCS)
- Demonstrate automated system control and tune-up

2027 Deployment and access to intermediate scale platforms

- First generation of production large scale applications based on NISQ devices running on the EuroQCS
- Demonstration of quantum algorithms outperforming their best classical counterpart
- Demonstration of use cases/applications that can establish complex workflows and can employ exascale HPC systems and emerging novel quantum accelerators

2030 Integration of large scale (> 200 physical qubits) platforms from Quantum Flagship full phase

- Demonstration of quantum processors fitted with quantum full error correction and robust qubits with a universal set of gates to outperform classical computers
- Expanded suite of quantum algorithms for software and cross-platform benchmarking, including digital error corrected systems, and optimizing compilers and libraries
- Availability of prototypes and applications that effectively employ hybrid calculations for carefully selected use cases. Demonstration of how to use the EuroQCS with scalable complex workflows.

C.3 Challenges and recommendations for a hybrid HPC platform

Realizing the full QCS potential requires their integration with classical systems to manage input/output, orchestrate large(r) workflows and implement (part of) the algorithms not suitable for quantum hardware. A hybrid HPC/QCS approach appears, therefore, to be a very promising route to follow, with HPC architectures managing the core workflows and still performing the needed non-quantum computing tasks, and QCS systems acting as powerful accelerator hardware. Additionally, hybrid HPC/QCS systems will still be a step forward in solving difficult problems if stand-alone quantum systems cannot be scaled up sufficiently or for application subcomponents not suited for quantum processing. The potential applications of such hybrid machines are vast and include finance, energy, oil and gas, aerospace, transportation, chemistry, pharmacology, materials design, health care and areas like optimization, simulation or machine learning. Availability of real-world use cases are then expected to trigger private investment in hybrid HPC/QCS solutions.

To tap into their full potentials, a broad user base will need to invest time and effort in developing new kinds of algorithms and software that take full advantage of quantum mechanical effects and that can be used to address and solve important real-world problems. Underlying this user/software interaction, there is also the software/hardware interaction. Since low level software is hardware-dependent, and quantum hardware is currently implemented on a variety of physical platforms (including, but not limited to, cold atoms/ions, super-/semiconductors, photons) this software/hardware interaction will require the development of a QCS full and layered software stack. Using a suitable interface layer in this latter stack, user would connect a wide range of software to any one of several QCS architectures within a single HPC environment.

Below is a first set of specific challenges that need to be addressed in order to develop these hybrid plateforms, together with some recommendations.

C.3.1 Challenges

Integration at the hardware level

- Interconnection networks and connectivity between HPC and QCS nodes (hardware and protocol);
- Interconnection with emulators, such as the Atos QLM, for a smooth transition from experiments to production;
- Interface between different QCS devices (e.g., photonic and superconducting quantum devices);
- Scalability of QCS control, as the number of qubits scales;
- Error correction systems;
- Unified memories;
- Hardware monitoring.

Integration at the system software level

- Scheduling, hybrid job submission;
- Resource management (system level);
- Offload / Data transfer and staging;
- Integration of error correction on QCS with HPC mechanisms (system level);
- QCS resources allocation;
- Virtualization and multi-user support.

Integration at the programming environment level

- Integration into a base language;
- Single source programming for hybrid HPC/QCS paradigms;
- Train software developers in programming quantum algorithms;
- Offload model like in OpenMP;
- Set of libraries providing (initially basic) algorithms, such as FFT for example;
- Integrated debugging and performance analysis working in user space;
- Integration at the application/workflow level;
- Resource management (user/application level);
- Granularity of offload;
- Integration of error correction on QCS with HPC mechanisms (user/application level);
- Data transfer between HPC systems and QCS counterparts.

C.3.2 Recommendations

To address the many challenges of setting up a Hybrid Quantum/HPC supercomputing infrastructure in Europe, we propose a set of recommendations prioritized over their foreseen terms.

Short-Term (Now – 2024)

1. Establish EuroQCS as a European federated quantum computing & simulation centre of excellence.
2. Establish a well-defined framework to support increased collaboration and knowledge transfer in the European HPC/QCS ecosystem between related Digital Europe and Horizon Europe Programmes, particularly to synergize the developer and user communities across member states.
3. Support the development of software components, tools, runtimes and environments to ease the use of hybrid classical-quantum computing, targeting industrial quality and usability.
4. Support the development of HPC-QCS integration technology (connectivity, middleware, and libraries to enable the deep integration of QCS in HPC infrastructures).
5. Promote EU quantum computing & simulation research and foster its outcomes and applications in the EuroHPC JU and EU computing centers
6. Support the establishment of start-ups in quantum software and their sustainable growth.

Mid-Term (2024-2026)

1. Foster the uptake of key enabling technologies for quantum computing & simulation.
2. Support the development of scientific software applications for the use of HPC/QCS in relevant scientific and technological fields.
3. Disseminate EU technology achievements, contribute actively to the definition and emergence of global standards that are relevant, practical and useful for HPC/QCS systems and their use.

Longer-Term (2026 and beyond)

1. Support open-source developments to create operating systems, languages, compilers and software tools for quantum devices.
2. Promote and monitor the development and deployment of quantum computing & simulation technologies in Europe across federated, pooled efforts.

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