THE RTO INNOVATION SUMMIT

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Industrial technologies for the future

Quantum Technologies:

The Future is Quantum … and the Future is Now.

An RTO proposition for a competitive European quantum technology industry

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"To make sure Europe reaps a large share of the benefits of the second quantum revolution and secures its independence and prosperity, we need to act now to scale up and coordinate European efforts."

QUANTUM MANIFESTO, 2016

With these words in the Quantum Manifesto of 2016, Europe embraced the need for large-scale European collaboration to safeguard our place in the quantum-enabled future. It was the beginning of significant acceleration of investments in quantum technology research in a pan-European collaboration of science and industry. With the Quantum Technology Flagship Initiative as a central pillar, Europe made significant steps towards global leadership in quantum technologies. Anno 2020, the Flagship Initiative nears the final year of its ramp-up phase and Europe needs to look ahead. The Flagship was launched under the theme 'The Future is Quantum', but the time has come for Europe to say "The Future is Now". Europe has come to the point where we need to start shaping industrial ecosystems and value chains based on the quantum technologies we have developed and will develop in the coming years. This is the next step in Europe's quantum development and RTOs are ready to play their role in strengthening the high-tech profile of a competitive European industry and establishing quantum technologies as a pillar of Europe's technological leadership.

Among the different emergent technologies in Europe, quantum science and engineering take on a unique role in addressing the challenges of sustainable economic welfare and the technological sovereignty of Europe. Innovations utilizing novel concepts from quantum science have the potential to impact industrial standards and norms far beyond the incremental advancements currently offered by classical technologies. This prospect is not limited to specific industries or markets. The universal nature of the quantum approach is transversal to diverse industrial sectors, with significant implications for current and future markets. **Beyond this broad economic potential, quantum technologies offer novel and rigorous solutions for a self-determined, digital and post-digital society in Europe.** Developments in quantum information science bring a new quality to data sovereignty in communication technologies and to the security of critical infrastructures embedded in information networks. The capabilities are independent of the continuous upscaling of classical resources that characterize the ongoing race in current IT security strategies. Furthermore, the fundamental switch of information standards from "bits" to "qubits" enable quantum computing platforms with computational capabilities that will significantly enhance the supercomputing infrastructure of Europe. This opens far-reaching prospects for addressing complex economic, technical and societal challenges, beyond the capabilities of high-performance computing to date.

The potential underlying quantum technologies have been recognized widely in the international community and have become a focus in the funding strategies of the leading industrial nations. Competitive industries as well as centers of leadership are emerging rapidly, particularly in North America and Asia. This has placed a strong demand on the European research community to advance quantum technologies to a state that will efficiently enable Europe's industry to compete successfully within these developments and hereby sustain a sovereign European high-tech economy. Efficient mechanisms of technology transfer between science and industry are becoming a central aspect in the international competition to this emergent field, parallel to further developing quantum processes and advancing the scope of their applications. Against the backdrop of these developments the 'geopolitical' Commission has set out a new direction for Europe's industrial policy, more aware of the need to not only foster innovation but to also ensure that the resulting economic and societal benefits materialize on the European continent. The next steps in Europe's quantum development have to be taken in this new environment. This means that a stronger focus must be made on developing a globally competitive, European ecosystems and Europe-centered value chains based on quantum technologies.

Europe's Research and Technology Organisations (RTOs) are one of the cornerstones of Europe in taking the next steps towards a competitive European quantum industry. RTOs are a typical European phenomenon: high-tech, collaborative, supporting the private sector driven by public purpose. In this unique role, RTOs are the oil in the European competitiveness machine, bridging the gap between academic knowledge and industrial capacities. That is why RTOs have been involved in the second quantum revolution from the very beginning. RTOs were key players in the QuantERA programme, preparing for the Flagship Initiative, and now they are strongly represented in QFlag, the engine of the Flagship Initiative.

This white paper is our proposition to the European Quantum Technology field for taking the next steps towards a competitive European industry. We focus on two specific fields of application of quantum physics: Quantum Computing and Quantum Communication. Based on our technological and scientific expertise, we lay down our vision on the priorities for Europe to develop European ecosystems and value chains, and we make an offer to Europe to facilitate the developments. As we focus mostly on the next steps, it is crucial to mention that, even as we move towards further application and scaling up of quantum technologies, fundamental research remains crucial to continue to fuel innovation in Europe.

The Future is Quantum and the Future is Now. Let's shape it!

Quantum Communication

- Europe is strongly committed to support the EuroQCI (European Quantum Communication Infrastructure) in order to provide access to technology testing both for QKD technology and beyond – as part of a global vision towards the realization of the quantum internet.
- While international competitors (North America, Asia, ...) each have particular positions on quantum communication and technologies in general, Europe's positions should not be guided from a 'me too' perspective, and instead start from a broader vision as for the future of quantum technologies. In that sense, Europe is uniquely positioned – outside the realm of a technological arms race, allowing it to choose priorities wisely.
- The European RTOs can assist in this process: they provide both the depth and breadth to thoroughly analyze existing approaches, and provide novel technologies at a technology readiness level that can be tested in the market, providing real-world approaches to communications security at system level.

In the context of future quantum networks, both the development of post-quantum primitives and general technological relevance should guide the European choices for quantum communication, while keeping in mind longer term goals such as improved metrology and sensing (clock distribution, imaging, interferometry etc.) and the general distribution of quantum systems (distributed quantum processors, quantum repeaters and the like).

In the quantum communication sphere the first products, such as quantum random number generators and QKD systems, already exist and are produced and sold on a relatively small scale. Most of them were developed with European expertise and within the EU. However, all of the providers currently belong to companies outside the EU (Huawei, Toshiba and IdQuantique, ...). As Europe is striving for technological sovereignty this is problematic. Furthermore, the small scale poses a challenge. From a system level perspective, evaluating the true potential requires the availability of scalable, mass-deployable versions and commonly agreed upon standards that allow for real, deep testing at massive scale – such as is common in classical security environments.

Europe's RTOs: Bridging the gap between academic knowledge & industrial capacities

The first phase of the European Quantum Flagship has united key European partners with the common goal of increasing functionalities (QRNG, Quantum repeater research come to mind) or miniaturizing systems (QKD-on-chip). However, first discussions with the European Commission as well as national representatives of the EuroQCI showed that there are still significant gaps at the level of QKD networks, i.e. interoperability of different vendors or in general a joint European standardization strategy. Such interoperability, and, in general, technologies allowing larger-scale access to and evaluation of system performance will be crucial in order to prevent irrelevance of particularly QKD solutions in an evolving landscape where e.g. post-quantum cryptography is being developed and even standardized worldwide (see e.g. NIST's standardization effort on post-quantum cryptography).

In the development of the EuroQCI, European RTOs can act as a bridge between fledgling academic efforts and fully-fledged industrial adoption and testing. We support in making conscious choices about relevant, real-life deployable solutions, and taking the lead in the push towards interoperability and standardization – all with the goal in mind of developing and testing valuable concepts that will be adopted by the market. Europe's RTOs provide a unique solution and value proposition that complements that of the many ongoing academic efforts.

Next steps for Europe supported by RTOs

First steps have been taken within the current Framework Programme to broaden the interest in quantum communication within European industrial players, involving e.g. photonic chip design and security communication companies as well the telecommunication industry in a push towards maturity and proper validation. In addition, the project OpenQKD shows a variety of different use cases for QKD as well as for a combination of QKD and post-quantum alternatives, allowing a profound evaluation of the strengths and weaknesses of both approaches. However, to take the next step towards a competitive European industry, we still need to overcome a number of hurdles. RTOs can play a key role in facilitating the transition from scientific excellence to industrial competitiveness.

For QKD systems, real world adoption will rely heavily on proper performance evaluation when exposed to real life threats. Therefore, in addition to efforts towards interoperability and standardization, certain volumes will be needed - allowing such evaluation and deployment on a large scale. Integrated technology solutions, such as e.g. offered by silicon photonics with integrated detectors, sources, modulators, provide one possible avenue towards this goal. This is a playing field in which the European RTOs provide world-leading technology which differentiates us from the rest of world. In addition, these capabilities nicely complement academic efforts, yet also exceed their direct expertise - providing a bridge to the European industrial ecosystem.

For longer-term, beyond point-to-point quantum-secured communication such as that offered by QKD, major efforts worthwhile focus on quantum repeater systems in order to reliably distribute (photonic) quantum information on a world-wide scale. Such systems are very complex and while Europe is at the forefront here, its development will take many years, and new concepts will have to be tested and evaluated. However, certain operational features appear common between the respective proposed solutions, and their system level performance is crucially dependent on the performance of individual components – requiring a level of technological maturity that is ideally tackled at RTO level. Specific examples include photonic frequency conversion (which would allow the heterogeneous solutions to all be translated to the telecom fiber transmission band and allow interoperability), and microwave-to-optical converters, which would allow interoperability with the small scale (electronic, and microwave based) quantum computers that are currently being developed. RTOs can here provide the technological maturity that is required to make such components work well at the system level.

Considerable engineering challenges will still need to be tackled in order to create the future quantum internet. In a continuously varying landscape, with competing technologies under development, such a quantum internet of the future should therefore not necessarily be evaluated purely from its sole performance in a quantum communications (QKD and beyond) context. A wide variety of applications in the metrological and sensing sphere have recently been proposed if large-scale, long-distance and wide-spread distribution of quantum states were possible by means of a quantum internet: from much more performant GPS/Galileo and clock distribution systems to extremely powerful telescopes, satellites and imaging systems and so on. The evaluation and real world deployment of such proposed applications requires a certain maturity in the technology solutions for which RTOs are well positioned, offering again a bridge between academic ideas and full industrial adoption.

The unique landscape of industries in Europe offers highly suitable technology profiles for adapting this technology in their portfolios. In the current constellation, the opportunity to develop a full supply chain and a future market around this emergent technology should be taken.

Quantum Computing

Quantum computers have the potential to tackle problems which are beyond reach for classical supercomputers. Therefore, a future European hybrid computation ecosystem consisting of classical supercomputers and quantum computers has the potential, by providing an unprecedented compute power, to tackle big problems facing society in energy, health and security. It will directly impact our daily life, European science, industry and security. In addition to the compute power itself, the development of a European quantum computing infrastructure is a unique opportunity for the European community

(i) to strengthen Europe's sovereignty in information technology by the development of quantum computing systems, including quantum processors and

(ii) to foster a knowledge society by establishing a highly trained professional work force for quantum computing and general next-gen high-tech information technology. Europe needs to:

- **Ensure strong commitment** to develop a European quantum computing infrastructure
- **Accelerate the development** of a quantum computing infrastructure for Europe to be in time
- **Democratize access** to quantum computing technology and innovation

Global perspective and Europe's paradox

The first phase of the Quantum Flagship has united key European partners in the common goal of realizing small quantum computers where error correction is not implemented. Significant progress has been made within the current Framework Programme in securing the technological sovereignty of Europe with this key emergent technology. This includes advancements in the performance of critical hardware components and an increase in the fidelity of quantum logic operations. Nevertheless, technology developments in Asia and North America urges us to accelerate technology development. Significant fundamental challenges remain to be addressed both to progress towards a quantum computer, to develop the platforms where the number of qubits can be upscaled, as well as organizing access in line with European values. Short term goals such as NISQ, quantum simulators and algorithms will impact science and industry in the coming years, and will act as stepping stones for companies to build a position in the future quantum computing industry.

The unique landscape of industries in Europe offer highly suitable technology profiles for adapting this demanding technology in their portfolios. In the current constellation, all the elements necessary for developing a full supply chain and a future market around this key emergent technology are principally available within the European ecosystem, offering, together with the strong fundamental science base present in Europe, a promising environment for further developments.

Despite the advantageous position in Europe, multinational industry and the market-driven ecosystem in North America as well as large-scale research efforts in China are currently leading the international developments in the field. For decades, North American industry has been strongly committed and placed high investments in the development of this key technology, regardless of the long term uncertainties regarding commercialization. The current extent of nationally funded research and the highly coordinated efforts in the Chinese national quantum technology programme also present a continually growing presence in the field. In order to ensure Europe's competitiveness and strategic autonomy in the future, the collective commitment of all European actors to a common roadmap needs to be reinforced with further coordination action and support of research & technology development infrastructure by the European Commission.

Opportunities & Challenges ahead: Quantum computing systems rival in complexity the most advance systems currently in existence

Considerable scientific as well as engineering challenges are still looming and need to be tackled on the long path towards a full-scale quantum computer. The onset of Horizon Europe and Digital Europe present an

ideal opportunity to reaffirm and ensure European commitment to this goal. Europe needs committed public-private collaboration, in which leading RTOs and labs play a key role, to develop a quantum computing infrastructure ranging from openly accessible to special purpose quantum computing platforms and technology pilot lines. The efforts must remain competitive in performance and timescale against the international developments in the field. Key components along this path are the development and the support of a strong academic knowledge base, further development of a prominent European IP-portfolio as well as substantial participation and invest from the industrial players.

Technological benchmarks involved in realizing a fully integrated quantum computer in Europe include quantum processing units with a large number of qubits with the highest available quality that allow for high-fidelity logic operations. Achieving this goal will require a highly interdisciplinary setting and a considerable amount of innovation. Material science expertise needs to be combined with advanced control engineering techniques via complex electronic or photonic interfaces and sophisticated hardware-software control & calibration frameworks. Beyond this, network integration with interfaces to classical high-performance system and security strategies for classical IT networks will be necessary for an optimal accessibility of the system in the community of European users. **Such multi-layered systems are called full-stacks. Full-stacks are best suited for the understanding of this novel paradigm of quantum computing**. They are essential testbeds and technology accelerators through which the gaps and necessary next steps in the architecture's innovation roadmap and value chain can be detected.

Value chains & Europe's RTOs: Bridging the gap between academic knowledge & industrial capacities

Value chain development presents a critical aspect in achieving global leadership in these core technologies. This includes an effective process for defining and optimizing the architecture of the platform, accompanied by quantum component design and manufacturing according to European standards and norms. In the timeframe of Horizon Europe and Digital Europe, the vision of a European supply chain can be pursued, in which majority of the system components are produced in Europe for a platform that is built and maintained solely in the European Economic Area. This will promote the build-up and long-term employment of a highly trained professional work force within local ecosystems and industrial sectors that develop business models for quantum computing based added value.

Furthermore, we need to bring academic knowledge and industrial capacities together along the whole value chain. The European RTOs are highly motivated to join forces and bridge the gap between fundamental science and industrial development and participation of prominent European high-tech industry. **Building pilot lines where SMEs, universities and larger industrial companies can benchmark designs and develop new architecture will speed up adoption and development of useful quantum accelerators.** RTOs can bring all this together, and compliment it with the necessary public-private-partnerships for strategic developments to protect the IP of the user of such quantum computers.

Conclusion

The Future is Quantum and the Future is Now. In this white paper Europe's leading RTOs have outlined their vision for our next steps towards a globally competitive, European quantum industry.

- **Public-private collaboration will be key.**
- **Investments in accessible, pan-European infrastructures will be crucial.**
- **Maintaining scientific excellence, as well as strategic choices, is indispensable.**

We see a strong commitment of the Member States as well as the European Commission to quantum communication and a future quantum internet. As a next step we will need a stronger involvement of

European industrial companies in this context as part of a push towards maturity. Institutionalized European Partnerships like the future Key Digital Technologies Partnership can play an important role here.

The European commitment to public-private collaboration to develop a quantum computing infrastructure in which leading RTOs and labs play a key role can fulfill the central mission of ensuring future technological sovereignty within the rapid international developments in this key strategic emergent technology. It further opens social and economic benefits associated with maintaining and further developing a strong high-tech industry and workforce that can sustain a competitive European economy.

Europe has everything it needs to lead globally in the second quantum revolution, but we need to act collectively now! The RTOs of Europe are fully prepared to support this process and to act as a technological bridge in view of the central mission of ensuring future technological sovereignty.