Supporting Quantum Technologies beyond H2020

Quantum Support Action (QSA) – Version 1.1, 7 May 2018

This document summarizes the outcomes of the Quantum Flagship community meeting organized by the Coordination and Support Action QSA in Oberkochen (Germany) on 19 April 2018. It complements the content of the Quantum Technologies Flagship Final Report (High-Level Steering Committee, 28 June 2017), by proposing actions along several further directions aimed at consolidating Europe's leading position in this research and innovation domain.

Executive Summary

A Second Quantum Revolution is unfolding, exploiting the enormous advancements in the ability to detect and manipulate quantum objects, such as single atoms, photons or electrons. In the coming decade, Europe will seize the opportunities offered by these Quantum Technologies (QT) in all possible fields for the benefits of its citizens, industries and of the digital economy. The long-term vision is to realise the Quantum Web: quantum computers, simulators, and sensors, interconnected via quantum networks distributing information and quantum resources such as coherence and entanglement. This effort requires the well-aligned interplay of various activities.

At the core, a number of strategically selected and steered **research and innovation actions (RIAs)** will advance further the scientific and technological basis of Quantum Technologies and secure Europe's leading scientific position. Milestones for such RIAs are recommended in the Strategic Research Agenda of the Quantum Flagship High-Level-Steering-Committee final report[1].

These projects as well as the transfer of QT concepts into prototypes and finally commercial products require access to **technical infrastructure**, which is too complex and expensive to be developed by one stakeholder alone. This will bring together a broad community of actors, helping to grow innovation ecosystems, developing standards and the necessary testbeds and associated metrology, and generally providing an environment fostering the start-up of businesses across the necessary supply chains, while protecting European data and IP. Pan-European Infrastructure will benefit not only, but in particular, researchers and industry from smaller Member States and ones with nascent QT programmes, which may not be capable to build their own infrastructure from scratch, especially not within the foreseen timeline. The required infrastructure is:

- *Quantum-ready advanced fabrication facilities* to develop and prepare prototyping and production of scalable devices for various QT applications, ranging from quantum processor chips, to key laser components, to chips for neutral atom based sensors.
- A *Quantum Communication infrastructure* will provide a sufficiently large-scale testbed for quantum communication and related technologies as well as access to industry for a wide range of application development, e.g. in health, finance and critical infrastructure.
- A *Quantum Computing/Simulation infrastructure* will offer maintenance, operation and access management of quantum computers/simulators hard- and software, and remote access for users, combined with access to classical High Performance Computing.
- A *Time and Frequency Transfer (TFT) infrastructure* will connect optical clocks and major research infrastructures to deliver high-precision timing for scientific and commercial use. Particularly, transportation, traffic, communication, energy distribution, safety and security rely on exact time and frequency information.
- A *European open-access Sensing and Metrology infrastructure* to develop, calibrate, test, validate and certify large- and small-scale quantum sensors and to develop and make accessible compact and easy-to-use quantum measurement standards of the revised SI units.

[1] http://tinyurl.com/qt-hlsc-report

The recent launch of a Chinese "quantum communication satellite" is perceived as a technical stepping-stone and is one prominent example of the many applications of **Quantum Technologies in space**. Four topical areas would put Europe at the forefront of a race of enormous strategic relevance:

- Secure satellite-based quantum communication, complementing the Quantum Communication infrastructure mentioned above;
- Space-based, global time and frequency transfer (TFT) services, complementing the TFT infrastructure mentioned above;
- Earth sensing and observation, utilizing new classes of sensors based on atomic interferometry;
- Fundamental science, from gravitational wave detection to the foundations of quantum mechanics.

Such ambitious goals require a coordinated effort of a genuine European caliber and dimension, beyond the current (albeit significant) ones, and substantial financial investments. Space requires specific efforts to push the technology further from earth, thus requiring specific programs that are often attached to strong use-case scenarios.

Innovation and investments happen where the most qualified people are. A coordinated European effort towards **education, training and networking in QT** to train successful 'quantum engineers' and more generally a quantum-aware workforce should be a central objective of European QT efforts.

- To educate QT graduate students and young researchers, support of regional and international education clusters, as well as hands-on training is required. EU-wide standards for QT master programs should be developed, based on a database of QT education in the EU. Special care should be taken to support education also in small centres.
- In order to achieve the goals defined in the European Quantum Technologies Roadmap, the QT community needs to be diverse in terms of gender and geography. Early Career Investigators can be a key solution for these issues. They can be supported through dedicated funding opportunities and a networking platform, including short-term mobility schemes, a mentoring program and training activities.
- The next generation of students, non-graduate students and industrial workforce need to be engaged and inspired in order to wide-spread knowledge about QT and its applications. For this, both educational programs for teachers and high-school students, as well as training in modern quantum technologies aiming at non-physics majors and a professional MSc in QT need to be developed. This should be enhanced by support for sabbaticals, secondments and job rotations.

An important dimension of European efforts to foster QT is the involvement of and **coordination with national organizations across Member States**, in order to achieve the best possible synergies. One effective way to achieve this is to build upon existing intergovernmental organizations, such as the consortium of national funding organizations QuantERA and that of national metrology institutes EURAMET, which are already planning joint activities in the field of quantum technologies.

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Introduction

The *First Quantum Revolution* shaped the world we live in today: without mastering quantum physics, we could not have developed computers, telecommunications, satellite navigation, smartphones, or modern medical diagnostics. Now, a *Second Quantum Revolution* is unfolding, exploiting the enormous advancements in the ability to detect and manipulate single quantum objects (atoms, photons, electrons), something that even Einstein considered impossible.

Building on its scientific excellence, Europe launched in April 2016 the FET Flagship Initiative on Quantum Technologies (*Quantum Flagship*). Through its ramp-up phase under Horizon 2020, the initiative will develop quantum technologies (QT) via four distinct but closely interlinked and complementary paths and will deliver a range of early wins along the way, while expanding crucial quantum knowledge in a basic science track. Together, they will herald a cross-sectorial system transition from a classical to a quantum information society.

In the coming decade, Europe will seize the opportunities offered by the second quantum revolution in all possible fields (see some examples below), for the benefits of its citizens, industries and of the digital economy. The long-term vision is to realise the **Quantum Web: quantum computers, simulators, and sensors, interconnected via quantum networks distributing information and quantum resources such as coherence and entanglement**, to provide European citizens with more secure telecommunications and data storage, more reliable healthcare, and better performing computation. This vision is segmented into four deeply interconnected areas, building on a common basis of technologies. The realisation of this common base will closely depend on strong cooperation between the respective research teams:

- ✓ **Quantum computing**: quantum computers are built from "quantum bits" (individual atoms, ions, photons, nuclear spins, electron spins or quantum electronic circuits) and exploit phenomena called superposition and entanglement, making enormous computing power available to solve problems we could never solve otherwise. Algorithms for quantum computers have been developed already that outperform their classical computing counterpart. That includes, for example, processing vast amounts of data faster than ever before to search databases, solve equations and mathematical problems (such as the factorization of large numbers, essential in the context of encryption for secure communications), and recognise patterns. In the future, quantum computers may even have the potential to train artificial intelligence systems, e.g. for digital assistants that help doctors to diagnose diseases and suggest the most promising therapies, and for optimising the routes of all cars in a city simultaneously to avoid traffic jams and reduce emissions.

- ✓ **Quantum simulation**: closely related to quantum computers, and realisable even earlier, are quantum simulators. They will be key to the design of new chemicals, from drugs to fertilisers for future medicine and agriculture, and of new materials, such as high-temperature superconductors for energy distribution without losses. Others imitate the idea of a wind tunnel, where small models are used to understand the aerodynamics of cars or planes: some quantum simulators use simple model quantum systems (such as an array of single atoms) to understand systems that would be much more difficult to compute or to experiment with.

- ✓ **Quantum communication**: networks based on Quantum Technologies will help protect the increasing amounts of citizens' data transmitted digitally, for instance health records and financial transactions. Quantum networks use photon-based quantum states that are compatible with the current digital infrastructure. If anything intercepts even a small amount of light in such a quantum state, it will be noticed, meaning that with quantum technology we can achieve the most secure form of communication known, especially in the case of long-term security. For point-to-point communication this is already on the market today and will be developed further to also provide a diverse and multi-functional quantum network – a quantum internet consisting of mutually connected quantum computers that allow for advanced protocols, including certification, secure signatures and identifications of all communication partners. Many other applications of quantum networks are already known theoretically, such as access to remote quantum computers in the cloud for simulations on proprietary new drugs without disclosing their design.

- ✓ **Quantum sensors, metrology and imaging systems**: 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. Quantum sensors use quantum matter and are based on quantum superposition, similar to quantum computers and networks: they detect the tiniest disturbances because of distinctive features of quantum interference, emerging in individual quantum systems, such as single electrons or ions, or atom lasers. Exploiting quantum light or quantum detectors will also improve the performance of imaging system (e.g. in terms of resolution, sensitivity or noise), with applications in the life science and healthcare sector, extending fundamental limits of medical imaging e.g. by imaging deeper into tissue, with broader spectral ranges and higher speeds. Quantum metrology uses these quantum technologies to realize highly reproducible and universal measurement standards within the International System of units for e.g. time-keeping or electrical measurements, with a high impact on industry, economy and society in general (competitiveness of industry, fair trade, security of consumers).

This effort requires the well-aligned interplay of various activities, from research and innovation projects, to making the necessary infrastructure available, from integrating QT in Europe's space program and Europe's metrology program led by EURAMET, to creating valuable education, training and networking measures.

The Quantum Flagship focuses on two aspects, large-scale research and innovation (R&I) projects and the coordination of all European QT activities through a series of Coordination and Support Actions (CSAs). The calls for R&I projects are planned based on the Strategic Research Agenda (SRA), which was recommended in the HLSC report and which will be further developed with input from both the community and the funded projects during the runtime of the Flagship. The Quantum Coordination and Support Action QSA is the first Quantum Flagship CSA (and indeed the first Quantum Flagship project overall) and is running from December 2017 to March 2019.

In this document, in preparation for the next phase after the ramp-up of the Flagship, various additional measures are described, which are needed to drive Europe's leadership in Quantum Technologies beyond H2020. This is based on input from the European QT community that has been collected by QSA, through the *Quantum Community Network*, the *Virtual Institutes and Facilities* (predecessors of the SRA Working Group that will be established by QSA in 2018) and several *COST actions*.

All these activities, which will probably be funded by different instruments, need a common guidance and coordination. Similar to a naval flagship, coordinating the activities of a whole fleet of independent ships, the Quantum Flagship could take this role for the "Quantum Technologies Fleet". Maintaining a technology-push perspective, the Quantum Flagship could coordinate funding activities ("ships") and bundle their individual strengths to engage on missions, delivering concrete benefits to European citizens within the next decade's horizon. Such missions could be for example: building and operating the *first quantum computer* in Europe, *outperforming classical computers* and solving mathematical and also applied problems; deploying a pan-European *secure quantum network*; establishment of a *fibre backbone* at selected reference points for time and frequency dissemination; realizing *ultrasensitive (point of care) diagnostics for healthcare*; enabling more accurate *autonomous driving through enhanced satellite and inertial navigation*. Through the quantum missions, Europe will keep its leading edge in this global race, and will convert its scientific leadership into market leadership, creating new jobs and boosting a sustainable “made in Europe”.

Research, Development and Innovation infrastructure

Quantum-ready advanced fabrication facilities

Realizing future quantum technology requires a system-thinking approach.

The design of future QT devices is not yet stabilised and plenty of academic research is still needed to demonstrate new concepts of components and devices that will require nanofabrication technology. Academic cleanrooms are at the forefront of this work and need very flexible nanofabrication infrastructures, with a large variety of research equipment, to be able to fabricate proofs-of-concepts for new ideas developed by QT scientists. To face such a large variety of technical challenges, a very wide nanofabrication expertise - currently spread over plenty of European cleanrooms - is necessary. The ability to fabricate convincing proofs-of-concepts is the first step for the emergence of a new technology: this step should not be hindered by a lack of appropriate nanofabrication technology, particularly when it involves non-standard technologies.

- In the development phase, by sharing the results of several cleanrooms working in parallel, it will be possible to accelerate the development of robust nanofabrication processes for QT challenges.
- By anticipating the development of nanofabrication capabilities needed by QT scientists, academic facilities will be able to strongly reduce the required time to produce research demonstrators.
- By standardising nanofabrication process descriptions, the quality and reusability of academic nanofabrication processes will improve and enable a faster and easier transfer of technology to RTOs and industrial partners.

Nanofabrication equipment for research is less expensive than in cleanrooms compatible with industry. However, research cleanrooms have to explore a variety of possible designs for the future QT devices. This will be done mainly with already existing equipment but depending on the targets, some specific equipment may be necessary.

Offer: Establish and run a platform-level type of fabrication vehicles for quantum technologies based on state-of-the-art semiconductor technology (bringing the technology from TRL 2 to 5) for *scalable* photonic and hybrid electro-optic integrated circuits, chip-scale neutral atom quantum sensors and surface-electrode ion traps arrays for quantum logic and simulation, integration of photonic and electronic components with the latter, key laser components (e.g. DFB[2], DBR[3], tapered amplifiers, WG Lasers[4]), superconducting, semiconductor, atom and ion quantum processor chips, quantum sensors, and packaging, room-temperature and cryo-compatible micro-electronics, at a level beyond that which is

[2] Distributed Feedback
[3] Distributed Bragg Reflector
[4] Waveguide lasers and hybrid semiconductor-glass waveguide lasers

typically found in academic facilities, , and do the preparation towards low volume production and prototyping. For scaling up, these need stringent control for consistency.

Similarly, material growth techniques including MBE[5], PECVD[6], MOCVD[7] of relevant materials (and LPCVD[8] of Si_3N_4 waveguides) combined with implantation and doping techniques at the single atom level and targeting a 1nm spatial resolution, as well as packaging and connectivity technologies, should provide semiconductor wafers and relevant materials for new quantum devices such as defect centres in diamond and silicon carbide, quantum dots in ultra-pure host crystals or topological insulators and 2D materials. Furthermore, these facilities should develop new material combinations and processes fulfilling the need for UHV operation, optimized surface qualities and cryogenic operation. These capabilities will serve not only quantum computing developments: rather, they will also benefit quantum communications and quantum sensing/metrology. Moreover, on-premises testing and characterization of micro-scale quantum devices at the fabrication facilities, as well as design and simulation capabilities respond to the need of users in science and industry. Nanoscopic sensors at the level of single atoms, single ions, single photons and nanoscale fabrication techniques will foster progress for classical industry, paving a way to a future quantum industry.

Impact:

A. Strategically strengthen the supply chain: Essential materials and components used in QT are today a by-product of academic research, produced at a best effort level in single quantities, often depending on single people and current research trends in academia. In the past, the existing industrial-academic collaboration in Europe has helped it to a leading role as a supplier of for example optical technologies for the nascent QT field. However, in the future, this will hinder stability and volume scalability. The US and China have identified this issue and have programmes in place to build up their own supply lines with the help of national defence contractors. It is very unlikely that these international sources will be open for European demands in the long run. Export restrictions on components (e.g. ITAR[9] regulations) is a major concern and requires supporting European industries to guarantee availability of strategic components (e.g. atom-based gyroscopes).
B. Acceleration of academic and industrial research. Accumulation and preservation of technological know-how and process engineering. Fabrication of controlled structures, typically done in state-of-the-art cleanrooms, is crucial to support the growth of quantum technology start-ups and SMEs, who are unlikely to possess the resources to invest in their own in-house fabrication capabilities.
C. Enable fundamental studies of direct relevance for underpinning key assumptions for QT.
D. Enable fabrication for researchers from smaller Member States and ones with nascent QT programmes, which may not be capable to build their own infrastructure from scratch, especially not within the foreseen timeline.

Requirements: To bring Europe in the lead for quantum computing we need large investments in infrastructure and a high level of support in R&D costs to develop the technology platforms. Typical small-scale equipment is €1-2M for purchase, large scale equipment can be €2-10M a piece (several of those may be needed). Building on existing competences, e.g. with leading university groups and selected industry partners, fabrication facilities should target specific advanced quantum technology platforms and address enabling technologies.

[5] Molecular Beam Epitaxy
[6] Plasma-Enhanced Chemical Vapor Deposition
[7] Metallo-Organic Chemical Vapour Deposition
[8] Low pressure chemical vapor deposition
[9] International Traffic in Arms Regulations

The additional investment to transition to manufacturing infrastructure is beyond the budget of the Flagship and hence will need to be provided through other channels in different locations to enable transfer to industry and generate new start-ups in the field. Assuming an R&D infrastructure equipped to provide the need for the early and advanced stages of research, the QT Flagship investments on the R&D running costs (FTE + consumables and mask sets) would amount to an estimated total of 90MEur/y for 10 years.

Budget estimate: Total of €100M/y, for 10 years.

Quantum communication infrastructure

Offer: Network infrastructure, combining fibre-based metropolitan networks for local quantum key distribution (QKD) and entanglement distribution, back-bone networks for intercity links, and satellites and/or High-Altitude Platforms (HAP) for outlying areas. The facilities should be able to provide both a local simulated system (spools of fibres) for feasibility experiments, as well as access to infrastructure for real-world validation. For the development of software, for example, to run applications as well as to integrate with existing classical enterprise solutions, access to a stable network for software development should be provided. Such infrastructure will also be of great value for TFT (see below).

Impact: Provide a sufficiently large-scale testbed for quantum communication and related technologies as well as access to industry for a wide range of application development, e.g. in health, finance and critical infrastructure. This will bring together a broad community of actors, helping to grow innovation ecosystems, developing standards and the necessary testbeds and associated metrology, and generally providing an environment inducive to the start-up of businesses across the necessary supply chains. There should also be a connection with the large on-going efforts in the classical 'Internet of Things' and 5G areas, to identify aspects of privacy and security where quantum may provide solutions. The advantage of multiple metropolitan networks is that they also deal with different scenarios as well as different legal requirements, while also facilitating uptake by local network and service providers.

While there is a clear need for QKD-based networks, investment in these infrastructures will also facilitate and fast-track development of next generation entanglement-based systems, like quantum repeaters and fully quantum networks, e.g. for distributed sensing and processing. In the case of satellites, this will enable discrete point-to-point QKD with global reach, and for entanglement-based systems, enable entanglement distribution to space-based constellations (satellite-to-satellite) for quantum-enhanced sensors. These all provide key steps towards the realisation of a global quantum network.

Requirements: In order to leverage current European programs, the fibre infrastructure could make use of the existing research and education network, Géant (https://www.geant.org/). The development of a quantum communication infrastructure could strongly benefit from synergy with national metrology institutes aiming to establish a European clock synchronisation fibre network, including dual use of fibres. Additional investment in Géant infrastructure will therefore have a significant multiplier effect and should be pursued. If commercial network providers and associated industries can be involved from the outset this would enable these networks to expand more rapidly with minimal outlay. Reduced system costs will be needed for a cost-effective setup and deployment of a pan-European testbed. One will have to build on the most relevant infrastructures in certain areas of Europe. In the medium term a quantum communication network between capital cities in Europe could be envisioned to stimulate application developments.

In terms of space QT, the design and launch of QKD-capable geostationary-Earth-orbit (GEO) systems, possibly piggy-backing on optical communication terminals could be a first step towards these goals. The launch of a low-Earth-orbit (LEO) satellite (within 5 years), would address challenges for world-wide coverage. This could be complemented by the development of low-cost CubeSat technologies to realise a constellation of CubeSats providing 24h global coverage. A critical requirement is the construction of small-scale ground-stations to develop space to fibre-network interfaces, protocols and architectures. Clearly, much of this would need to be strategically planned and supported with ESA.

A new agency, or some association with National Metrology Institutes (NMI), dedicated to the certification of quantum products (QKD, QRNG[10], networks and applications), as well as supporting the development of standards (e.g. the European Telecommunications Standards Institute ETSI) will be needed. Such association or infrastructure could be supported or operated by EURAMET through their European Metrology Network for Quantum Technologies (EMN-QT).

Budget estimate: An initial ground-based network, of 5-6 metro-area networks (€10M each), complemented by a Europe-wide system of several thousand kilometres of backbone links spanning the continent, is projected to cost around €150M.

To complement this, a network of around 10 ground stations and 1-2 satellites would allow direct connection to overseas territories and outlying areas. Ground stations in such territories and areas should each be complemented by a small- to metro-scale network to extract greatest benefit from this programme and kick-start the quantum communications industry in these regions. Optimistically, the costs could be reduced to around €90M for the space segments and €50M for the ground segments.

Costs of high-altitude platforms (HAPs) are currently unknown, but an estimate of €1M (cost of a small plane) for the initial systems seems reasonable, plus running costs. 1-2 HAPs serving these ground stations would require around €5M. A possible alternative for HAPs could be represented by unmanned automated aircrafts powered by solar energy and able to keep flying for extended periods, thus reducing the operating costs.

To advance next-generation quantum technologies to entanglement-based networks using quantum repeaters and quantum processing nodes, 1-2 networks could be upgraded and expanded, at a cost of €20M each, to bootstrap this development in these infrastructures.

A network open for software development could be realized at short distances, and could cost €15M for setup costs, maintenance incl. realizing open access via online platforms.

For satellite-based quantum communication, the envisaged goals are:

Goal 1: Payloads demonstrating secure communications (SC) from low Earth orbit (LEO) at high rate;

Goal 2: Creation of a secure network with ground stations;

Goal 3: Implementation of geostationary Earth orbit (GEO) platforms;

Goal 4: Implementation of a Global Navigation Satellite System (GNSS).

On a three-year horizon the expected investment is:

Goal 1: Realization of engineering models and then of flight models of the space SQ payloads (secondary payload and nanosatellites): €90M;

[10] Quantum Random Number Generators

Goal 2: Design and realization of a telescope network on ground connected to fiber-based SC nodes, for detection of the key from satellites: €30M;

Goal 3: Study and realization of an engineering model of a payload for GEO SC: €15M;

Goal 4: Study and definition of an engineering model of a payload for GNSS SC: €5M.

Over a ten-year horizon, the investment is:

Goal 1: Operation in Space of the SC payloads, with the evolution from a single ground station to intercontinental operations. Developing of a SC network with the launch of 4 nanosatellites: €630M;

Goal 2: Operation of a SC using the Space-ground network: €140M;

Goal 3: Realization of an engineering model and then of a flight model of a payload for GEO SC: €110M;

Goal 4: Realization of an engineering model and then of a flight model of a payload for GNSS SC: €80M.

Total cost amount to about €350M for ground-based quantum communication and €1100M for space-based quantum communication, over ten years.

Quantum computing/simulation infrastructure

Offer: Maintenance, operation and access management of quantum computers and simulators, and remote access for users. A network structure is preferred as it joins the excellence which is distributed over Europe. Note that even if there are different competing hardware platforms, a common quantum command language may be required. Experienced users but also interested industry partners, which may be still at an observation stage, will have a chance to test their algorithms on different quantum hardware. Access to classical HPC will complete the picture, which is also crucial for the development of hybrid quantum-classical co-processing systems. Furthermore, development of quantum application software, quantum compilers, and the establishment of quantum programming languages, also in synergy a broader user community from science and industry, is of utmost importance. As was the case with classical computation, software development will evolve closely with the hardware development.

In this sense a library for quantum software should be set up, tested and standardized, providing access to large dedicated computational facilities (where this library may or may not be installed and tested). Brute force simulations of even moderate size quantum systems on classical computers is exponentially difficult, but this is the best we can do at the moment for quantifying, optimizing and benchmarking various experimental systems as well as quantum algorithms and processes. In some cases (e.g. when the entanglement is bound, and parts of the system can be factorized to a good approximation), efficient algorithms to simulate the static and dynamic properties of the system can be run on classical computers. In other cases, exact simulations and optimizations should be performed, which requires access to large computers. So, well developed and tested codes for simulating quantum systems and algorithms, or optimizing controls, gates and measurements, can accelerate progress. Many researchers would be willing to share their codes for quantum simulations, optimizations, etc. A next step could be a specialized computational facility for that, with access to the whole community.

Impact: Access to Europe-based quantum computing/simulation devices for both academia and industry. Protection of European data and IP. Co-development of large-scale quantum computing/simulation systems will allow a broad range of members of the community to contribute to developments that they could not master only by themselves (similar to other large-scale infrastructures such as neutron sources, free electron lasers, particle accelerators).

Requirements: Research centres having proven excellence in quantum computing research, a broad ecosystem of academia and industry, and existing HPC infrastructure could provide the necessary implementation experience. Operation staff of three to five people per machine and a running budget (e.g. for cooling power, maintenance and upgrades) needs to be planned for. Quantum computers require special building infrastructure, compared to classical HPC (depending on the physical implementation: closed He circle, low vibration, temperature stabilization, low electric noise).

Budget estimate: Leading technologies for quantum computing, trapped ions and superconducting circuits, rely heavily of hardware fabrication. Hardware cost for systems with 1000 qubits may be well in excess of €10M, at least for the upcoming 5 years realizable only in joint infrastructure (and/or with industrial partners). At least €5M per year for 10 years would allow to ramp up such a joint site, pay for some of the initial hardware and allow co-development at such a site. Eventually, the facility could be (at least partly) financed by access fees. Additional initial costs for suited buildings may be several tens of million €, up to €100M for a multi-floor quantum computing centre.

Note that these estimates do not yet include budget for research on quantum computing, but only for the infrastructure itself. For comparison: Sweden dedicates €12M a year for 10 years for their quantum computer effort.

Time and Frequency Transfer (TFT) Infrastructure

Optical atomic clocks (OACs) are currently evolving from exquisitely precise laboratory experiments towards quantum sensors for applications. These include fundamental questions such as the search for a variation of fundamental constants and the search for dark matter. OACs together with an appropriate infrastructure allow measuring and monitoring gravitational potential differences between distant locations. This opens up the new field of relativistic geodesy, with the goal of establishing a world-wide sensor network for geophysics, climate and geodesy studies and services, including a unified height system.

Offer: For ground-based TFT, implement a fiber back-bone for optical time and frequency transfer based on existing European infrastructure connecting optical clocks and major research infrastructures in Europe. This proposed backbone should provide time and frequency signals to end-users with a performance level (10^{-19} fractional instability and accuracy level) currently available only at a few European national metrology institutes (NMI). In addition, such a backbone could largely benefit the aforementioned quantum communication network as it would allow investigating all necessary steps towards long-distance quantum communication.

Space-based TFT is a new global infrastructure for comparing OACs and delivering high-precision timing world-wide, for commercial use and scientists. It will complement and link to terrestrial fiber-optic networks which have a more limited coverage. The space infrastructure will be continuously available to end users at moderate cost of service and will be capable of frequency and time-scale comparisons at the 1×10^{-18} level and better.

A European ground-based TFT network can be achieved by pursuing the following steps:

- Establish a permanently available optical fiber backbone (the “CORE”) between dedicated locations in Europe (especially those with high-performance optical clocks) to ensure continuous supply of validated time and frequency signals to strategic end points.
- Development of a time and frequency fiber-optic infrastructure providing highest performance time and frequency signals at remote ends.

- Initiate technology development for robust, remotely controllable equipment for phase coherent transmission of time and frequency.
- Extend the network towards European research infrastructures requiring ultra-precise time and frequency signals.
- Develop network nodes that facilitate the operation of a T&F service, supporting the needs of regional end users.

The space-based TFT network can be achieved by pursuing the following directions:

- Support planned ESA missions on space TFT (ACES and I-SOC) to achieve a rich science harvest, know-how generation and technology validation. For ACES, ensure a rapid launch, extended mission duration, and providing microwave terminals to the OAC community so as to widen the measurement campaign. For I-SOC, ensure continued instrument development followed by mission implementation.
- Technology development for improved and new space TFT techniques, capable of satisfying the needs of the post-ACES/I-SOC era, such as the next generation GALILEO technology. In particular:
    - Development of advanced two-way microwave/single-photon laser links
    - Development of femtosecond or coherent optical links
    - Development of corresponding laser terminals for the space segment
    - Development of next-generation OACs for space
- Development of a space TFT infrastructure having highest performance (reduced Doppler effects, long common-view observation durations), for example based on a few geostationary satellites equipped with dedicated TFT equipment and laser terminals. A complementary approach consists of an ensemble of low-orbit mini-satellites with appropriate links.

Impact: For ground-based TFT, the envisaged backbone will boost Europe's current leading position in research and bring its industry to the highest level, to respond to the future challenges of geodesy, radio-astronomy, earth observation, deep space navigation. Once this backbone is established and secured, further extensions and branching to national and private networks could be established that immediately benefit business economics as well as political economics. Particularly, transportation, traffic, communication, safety and security rely on products and services where exact time and frequency information is the crucial basic requirement. It is easily foreseeable, that for the rapidly increasing flow of information in all fields of society, smart grids or green power grids, or the required synchronization in the flexible infra structure of Industry 4.0, valid time information has to be provided with much higher demand. Novel applications for space and terrestrial industry, aviation, communication and data transmission are already hampered by the missing ultra-stable microwave and optical references that are limited by the traditional means of timing information via long wave transmitters or satellites.

Where ground-based TFT is limited in coverage or not existent, space-based TFT provides coverage of a large fraction of the Earth surface or even complete coverage. In particular, it will allow linking Europe to other continents. Space-based TFT will allow taking full advantage of the stationary and transportable optical atomic clocks existing or under development in many laboratories world-wide. It will open up new domains of (global) research, by establishing a qualitatively and quantitatively new time and frequency transfer (TFT) service. Main applications will be world-scale relativistic geodesy with competitive performance levels for geophysics; creation of a network of communicating clocks for metrology and the search for dark matter effects; next generation global navigation satellite system (GNSS)].

Requirements: For ground-based TFT, NMIs with longstanding experience in disseminating time and frequency over optical fibers could provide the necessary implementation experience. Operation staff of at least two people per node and a running budget (e.g. for maintenance and upgrades) needs to be planned for. For space-based TFT, the work will build on the foundations laid by European space industry that developed the basic technology for ACES. The network control and data analysis center can be an evolution of the ACES ground control center.

Budget:

For the envisaged ground-based European backbone (CORE) connecting NMIs operating optical clocks a total link length up to 3000 km can be estimated.

- The cost for renting the fibre infrastructure largely depends on the regional availability of fibres, the required bandwidth and duration of the contract. Assuming an average cost of 0.5 € per meter and year as a rough estimate, this backbone will require an investment of 1.5 M€ per year for fibre rent.
- Development and implementation of the required time and frequency link-equipment such as amplifiers, repeater-stations and monitoring systems could cost at the order of 10 M€.
- Maintenance of the backbone and the T&F service would require 3 FTE per backbone-node (10 M€).

Total cost for establishing the CORE amount to about 35 M€ for the next 10 years.

For developing a space-based TFT network, for the 3-year period the following main items arise:

- Producing an engineering model of the space optical clock and high-performance MWL, €25M
- Developing and demonstrating feasibility of a mini-satellite with a high-performance microwave link (MWL-minisats), €3M (piggy-back launch assumed).

For the 10-year horizon, in addition:

- Development of a high-performance optical link into an engineering model, 10 M€
- Implementing a satellite mission with the space optical clock and links, 100 M€ (rough order of magnitude; using existing carrier such as ISS)
- Implementing a TFT network with one to three MWL-minisats, cost 10 M€ – 30 M€ (piggy-back launches assumed).

The total cost for establishing a space-based network is approximately 200 M€ for the next 10 years.

Quantum sensing infrastructure

Offer: An infrastructure to develop and test large- and small-scale quantum sensors with particular emphasis on inertial and magnetic sensing. The Infrastructures should cover all aspects from technology development specific to quantum sensors (e.g. atom chips, which would also benefit quantum simulation and quantum computing) to the testing, qualification and/or calibration sensors. These infrastructures (or network of facilities) should at least include:

- Test facilities for ultra-precise quantum sensors, through access ultra-low noise infrastructures (such as underground laboratories). These sites need to be extremely well characterized and therefore operate routinely the very highest performing quantum sensors.
- Key facilities for integrated quantum sensor design and development (atom chips, NV centres, micro and XUV vacuum systems, compact laser technology, etc.).
- Time and frequency dissemination networks (using for instance fibre networks), that could possibly operate in parallel with quantum communication networks.

Impact:

Free access to a Europe-based ultra-high precision quantum sensing facility is crucial to both academia and industry for the testing, comparison, qualification, and calibration of future quantum sensors. The development and commercialisation of the sensors will be much sped up through access to nanofabrication facilities with expertise in integrated quantum sensors fabrication.

Finally, considerable synergies will arise with the development of large scale precision quantum-sensor instruments through being accessible for performing specific development, tests and measurements (similar to other large-scale infrastructures such as neutron sources, free electron lasers, particle accelerators).

Requirements:

- The time and frequency dissemination network could make use of the existing research and education network, such as the clock synchronisation networks being deployed by national metrology institutes. If commercial network providers and associated industries can be involved from the outset this would enable these networks to expand more rapidly with minimal outlay. There is a strong synergy with the requirement for "Quantum communication infrastructure" (see above).
- Ultra-low noise infrastructures will need to be located underground. They might benefit from existing underground laboratories, as well as existing national quantum sensing instruments and platforms.
- Nanofabrication facilities can use existing platforms already developed in various countries. A harmonization/coordination at European level of these facilities will also be necessary. This reinforces the need for "Quantum-ready advanced fabrication facilities" (see above).

Budget estimate:

A fully characterized quantum sensing laboratory will cost 60 M€ over the next 10 years.

A distributed, ground-based network at the European scale will cost 100 M€ over the next 10 years.

Extending the operational access to existing underground facilities (as are already established in France, Germany, and Italy) will require 10 M€ each facility over 5 years.

Quantum metrology infrastructure

Offer:

- Quantum technologies are among the basis of the redefinition of the International System of units (SI) to be achieved in November 2018, providing a new definition of the ampere based on the elementary charge and a new definition of the kilogram based on Planck's constant. A redefinition of the second will follow later, based on optical atomic clocks. These new definitions allow standards offering unprecedented performances in terms of accuracy, reproducibility and universality. The quantum metrology infrastructure or network aims at developing compact and easy-to-use quantum measurement standards of the revised SI units, up to industrialization and commercialization, with the objective to make accessible to end-users the advantages of the revised “quantum” SI.

- Another mission of the infrastructure is to support the development of highly accurate and highly sensitive sensors. Particular efforts for the integration of the quantum references directly in the sensors to get self-referenced/self-calibrated devices.
- Finally, by establishing robust, accurate and reliable measurement methods and characterization protocols, the targeted infrastructure intends to contribute to quality management of the products based on quantum technology (mainly their performance) through standardization (ISO, IEC, ETSI…), test, validation and certification. The infrastructure consists of key facilities for test, validation and possibly certification of quantum technologies/quantum products.

Generally speaking metrology is an important enabler for applications of quantum technologies.

Impact:

- Through the development of the highly accurate and universal quantum measurement SI standards, quantum metrology is expected to have a great impact on industry, economy and society in general (competitiveness of industry, fair trade, security of consumers). For example, regarding quantum electrical metrology first commercial products are entering the market for disseminating the revised SI units, e.g. various DC and AC-voltage standards based on the Josephson effect. Quantum standards for resistance and impedance metrology based on the quantum Hall effect have experienced a boost with the use of graphene and can be expected to lead to commercial products in the next years, and topological insulators offer exciting new possibilities in this field.
- Quantum coherence and other fundamental phenomena in novel quantum devices based on, e.g., superconducting nanostructures or semiconducting quantum dots will have important applications in electrical metrology and sensing.
- Establishing a quality management system of the quantum products will help their industrialization and commercialization. Giving confidence in the performance of the quantum technologies is key to favour adoption by industry and accelerate translation of technology from academic labs to the commercial sector. A strong contribution of Europe in the establishment of this quality management system is of strategic importance facing the USA and Asia.

Requirements:

Adequate lab space (temperature stabilized, low vibration, EM shielding) and technical equipment, for optics, electronic transport experiments, cold atoms experiments, vacuum chambers, cryostats, test and measurement equipment, control electronics, etc. Personnel with both technological expertise and experience in knowledge transfer, mainly permanent, completed by post-doc positions. Infrastructures/platforms able to host visiting scientists, possibly for long stay for the test of their quantum technologies/products.

Build on and bundle competences of existing structures at research centres, national metrology institutes. Quantum metrology devices already gathers a significant community of national metrology institutes in Europe, in EURAMET. A specialized network dedicated to Metrology & QT is building up within EURAMET. Nevertheless, to play its role in supporting the development of applications in the various QT domains, close interactions with the whole QT community are required outside EURAMET. Interactions with standardization bodies (ISO, IEC, ETSI, …) are also required.

Quantum Technologies in Space

The breadth of applications of quantum technologies covers the tantalizing possibility to address space science and technology. The recent launch of a Chinese satellite with the scope of demonstrating the viability of primitives for quantum communication through satellite-to-ground channels is perceived as a technical stepping-stone. In addition, China has successfully operated a cold-atom clock apparatus in space for a full year, the first world-wide.

ESA and CNES have developed a QT mission, which will be launched to the ISS within the next few years, consisting of a complete cold-atom clock with high-performance bidirectional space-ground microwave link. DLR has demonstrated the first space atom laser last year and demonstrated space matter wave interferometry. In the meantime, China has successfully operated a cold-atom clock apparatus in space for a full year.

Such ambitious goals require a coordinated effort of a genuine European caliber and dimension, beyond the current (albeit significant) ones, and substantial financial investments. The fierce competition from extra-European countries (e.g. US, China and Canada) underlines the importance of a significant European effort towards the development of quantum technologies for space applications.

In light of the specific world-class competencies present in its territory, Europe should lead the way towards the development of quantum technologies in space. A community comprising leading European scientists and major industrial actors working in aerospace has identified four topical areas that would put Europe at the forefront of a race of enormous strategic relevance:

- Secure communication
- Time and frequency transfer (TFT) services
- Earth sensing and observation
- Fundamental science

The first two areas are already described in the previous sections “Quantum Communication Infrastructure” and “TFT infrastructure”, the latter two are detailed below. Indeed, quantum sensing in space represents a high potential for a wide range of applications that will require, in each case, the launch of specific missions, although the payload technology might include many generic components or subcomponents. Space requires specific efforts to push the technology further from earth, thus requiring specific programs that are often attached to strong use-case scenario.

Earth Sensing and Observation (ES&O)

Offer: The main objective of ES&O is the development of new classes of sensors based on atomic interferometry, such as quantum gravi-gradiometers (QGG), for geometric and dynamical mapping.

Impact: The measurement of the form and dimensions of the Earth, the location of objects on its surface and the shape of the Earth's gravity field are relevant problems for space geodesy (including geometric geodesy, consisting in precise positioning and navigation; dynamical geodesy for the determination of the spatial and temporal variations of the gravity field; the measurement of geodynamical phenomena, such as crustal dynamics, groundwater monitoring and polar motion). The improvement of quantum clocks, on the other hand, leads to the ability to read out, given an appropriate Time and Frequency Transfer infrastructure (see above), frequency shifts resulting from geopotential height differences of one centimeter soon, and below a millimeter in the future. Combined with atom gravimeters, these also have applications in geological explorations, civil engineering projects such as tunnelling, volcanology and even archaeology.

Requirements: This impact can be achieved by pursuing the following directions:

- Establish an international consortium for prototyping and performance tests in microgravity
- Transfer know-how to industry
- Develop space-qualified hardware
- Launch a pathfinder for a space mission (possibly connected with another Earth monitoring mission)
- Realize a quantum Earth observatory

Budget estimate:

In the 3-year horizon one can foresee the following:

- Prototyping and performance tests in microgravity will cost €10M
- Starting the process of transfer of know-how to industry, and developing space-qualified hardware will cost €10M

As for the 10-year horizon:

- Development of an elegant breadboard for prototyping and performance tests in microgravity will cost €30M.
- Furthering the process of know-how transfer and the development of space-qualified hardware will require €50M.
- Implement a pathfinder for atom interferometry in space will cost €50M.

Over a 20-year horizon, one can foresee the establishment of quantum Earth observatory, which will cost €80M.

The total cost is €230M.

Fundamental Science (FS)

Offer: Establish a programme of space missions testing fundamental science – from gravitational wave detection to the foundations of quantum mechanics – through cold-atom, photonic and/or opto-mechanical technology. This will include a dedicated satellite with an entangled source, as well as very large interferometers probed with quantum light.

Impact: Space provides an ideal environment of unique conditions to test Fundamental Science (FS) in light of the long free-fall times available, long observation times without levitation, quiet gravitational environment and the variability of gravity and laboratory speed. In the last decade, the fast advance of quantum technologies based on cold atoms, photons and opto-mechanical systems opened up completely new perspectives for experiments in the realm of fundamental science. They allow for the creation of new experimental opportunities, the most familiar ones being clocks, inertial sensors, and interferometers. Among the opportunities opened up by such advances are

- Quantum-enhanced tests of relativity, dark matter, dark energy and gravitational wave detection.
- Long-distance entanglement and non-locality tests.
- Tests of quantum mechanics at the large-mass scale.

Requirements: The requirements that have been identified for other space-based quantum technologies – quantum communication, TFT services, earth sensing and observation – will be instrumental to the pursuit of FS. In particular, it is recommended to:

- Continue support of existing and establishment of additional European consortia for developing prototypes of space instruments addressing the above-mentioned science goals
- Capitalize on the long-standing activities made in Europe and gather a large community [to realize a one-way ground- space link with true quantum light with either detectors or source in space; use it to violate Bell inequalities; perform first tests of entanglement in curved space-time]

Budget: For the atomic clock platform, the technology and requirements are similar to those declared in the space-based TFT Infrastructure section.

- Photonic platform
    - Developing and launching space qualified quantum hardware and low-loss optical space links will require €15M over three years and €20M over ten years (piggy-back launches assumed).
    - Building twin receivers and an entangled source as three small satellites in LEO elliptical orbits will require €20M over three years and €80M over ten years.
    - Developing and building a spacecraft for probing quantum correlation across the Solar system will require €5M over three years and €100M over ten years.
- Atom interferometry platform
    - Establish an elegant breadboard for prototyping and performance tests in microgravity will require €15M over three years and €50M over ten years.
    - Transfer of know-how to industry and development of space-qualified hardware will require €10M over three years and €70M over ten years.
    - A pathfinder on the ISS or followers will require €70M over ten years.
    - Dedicated satellite mission to perform a quantum test of the equivalence principle in parts of power eighteen will require €120M over fifteen years.
- Optomechanical platform
    - Development of particle sources, interferometer and detectors in a suitable coherence preserving environment and a proof of concept experiment on ground will require €5M over five years.
    - Tests in micro-g environments, such as drop towers, parabola flights and sounding rockets and the related technology development with industry partners, which will be important milestones towards an eventual dedicated space mission and satellite, will require €10M over three years and €40M over ten years.
    - Launching a pathfinder for a satellite mission will require €100M over fifteen years.

Education / Training and networking

"Quantum Technologies (QT) is at the intersection of physics, engineering, computer science and related fields of study. Training successful 'quantum engineers' and more generally a quantum-aware workforce should be a central objective of the QT Flagship initiative." – *Final report of the Quantum Flagship HLSC*

It is important to stress that a coordinated European effort towards education and training in QT will be essential to guarantee cohesion, i.e. the buy-in of member states, which have not yet a strong QT research community and/or industry.

Engaging in training needs to take into account the community and institutional structure, which is different from that in research and innovation. Means should be accessible bottom-up and implementation needs to augment the individual cultures of training and education in countries and institutions rather than trying to control them. Also, while the development of standards and coordination absolutely needs to be pan-European, participation of small groups and access to the results by individual organizations should be allowed.

The European Science Open Forum (ESOF) is seen as a good platform to approach the required integration. Moreover, supporting initiatives in citizen science that involve scientific labs providing the content, curious and creative public producing new know-how, and companies providing the infrastructures, can be very useful.

Reaching QT graduate students and young researchers

Establish a database of QT education in the EU

Various curricula on the Master level are currently established. These programs should be collected and advertised in a central portal to provide an overview of the available QT education program in the EU and to help crosslink the different activities with each other.

Support regional and international QT education clusters

We see that a lot of initiatives for training graduate students in this area appear locally, carried out by the local community. In some cases, these are national (e.g. EDU-QUTE, UK quantum CDTs) or even international education clusters, for example the cluster between Strasbourg, Basel and Freiburg or the Quantum Alliance between IQST (Stuttgart/Ulm), Hebrew University, and other extra-European actors. They partly include joint international graduate schools. This cross-border cooperation not only leverages complementing competences but also provides an opportunity for students to gather international experience. We believe that such initiatives should be co-funded by the EU, jointly with national and regional funding.

Requirements / funding:

- Coordination action similar in size and scope to the flagship coordination actions, for 10 years
- Seed funding for new cross-border educational clusters for the first generations, 3 STREPs
- Incentive for national support for local programs

Develop EU-wide standards for QT master programs

While regional education is fundamentally the right approach (education has national cultures and they need to connect to the engineering needs locally) to start, European education is needed with the goal of defining a common core / minimal requirement for non-majors (how much physics does a computer scientist in quantum technologies really need?). This core should require curricula to contain a component of leadership / application / industry training even for future academics.

It is important to have this on top of existing funding programs as this is a lot of extra work, and as the people carrying out these activities are often not the same as those doing the European research networking. A CSA of those educators could develop well-outlined recommendations and future standards based on the latest research and experiences of current education clusters and assessment frameworks in line with ongoing European higher education reforms (e.g. Bologna Process). Such a CSA can provide, in particular, sought-after guidance on how to best provide interdisciplinary training of future quantum engineers. The development of these standards and frameworks should involve the stakeholders involved in quantum physics, including industry leaders to make sure that the needs of industry are well-represented.

Requirements / funding:

- Coordination action similar in size and scope to the flagship coordination actions, for 10 years
- COST-Action-like format to pursue information exchange and development, for 10 years

Support QT education also in small centres

While quantum technology training is developing very well in big centres of quantum technologies, this is not enough. We would specifically help the education needs in small quantum technology centres that do not reach critical mass to train people comprehensively. It should be easy for, e.g., students with strengths in mathematics and computer science (e.g. from smaller universities and/or in widening countries) to also acquire basic knowledge in experimental quantum science and technology and/or to visit larger centres for few-months periods. Various options can be developed, that are inspired by Erasmus but focused on the specific topic of QT:

- based on common standards, create an easy mechanism to recognize courses taken somewhere else
- develop a system of MOOC (Massive Open Online Course) with various degrees of physical presence for the main topics in quantum technologies; on the way to these MOOCs, help programs to develop electronic media as a springboard, including videos, games, and apps
- provide mobility grants to students to attend the in-person component of these courses; make that possible by having intense block-courses compatible with the academic years
- develop a program of intense training courses in the summer (following the model of AIMS - the African Institute for Mathematical Sciences - or PSI - Perimeter Scholars International)

In summary, establishing a Quantum Science and Engineering Knowledge Exchange Program where education and training programmes could be made available using the most up-to-date online and virtual training technologies, combined with in-person training.

The training and educational material of the Quantum Science and Engineering Knowledge Exchange Program can go hand in hand with “Virtual Quantum Lab” applications in the direction of citizen science where not only students but also ordinary people and school pupils can take part in the evolution of QT.

Measures to get there: Based on the curriculum development group, let this team develop a European organization for Quantum Technology Education. It should also document careers of graduates in order to develop a mentorship network for the first generations of quantum technologists.

Requirements / funding:

- Estimated development cost of a MOOC with 60 hours of high-quality video: 200.000+60*40000 € = 444.000 €. One MOOC per QT application area plus software and engineering brings this to close to 3 M€
- Course recognition system: Large STREP-like project plus running cost for 5 people running this in different geographic regions
- Mobility grants: For one month of intensive course including travel we estimate 1500 € per student. Giving out 100 months per year of the flagship comes in at 1.5 M€

Support hands-on training

Best training happens hands-on. Specifically, in quantum computing we see the impact that even small online demonstrators have, and more and more training happens in the documentation and user-base of that, rather than by traditional means. However, hands-on activities alone are not enough to develop a meaningful understanding of science, including quantum physics. *Minds* should also be on, meaning that hands-on activities must be carefully designed to promote effective learning.

There should be a call that helps develop activities and initiatives that support meaningful and effective hands-on training, e.g. the development of laboratory experiments designed according to the most recent results of research in (modern) physics education, as well as a way for notoriously cash-strapped university and school labs to buy them. Also, research projects should be motivated and funded to have training modules within their research that can be accessed in training programs both hands-on and through the cloud.

Developing a modern lab experiment into a stable, didactically well-designed education tool is a big task which cannot be done by a research project/team on the side. Suggested measure: a dedicated call for building such tools with the goal to offer them at material cost to universities and potentially subsidizing them – to get a quantum technology experiment in every undergraduate (or even secondary school) laboratory.

Requirements / Funding:

- 3 STREP-like projects for development of such experiments
- Seed funding for spinoffs maintaining them
- Subsidy for 1000 Physics departments financing at least one of them: 10 M€
- Training facility quantum computing: Priced comparable to a quantum annealer at 15 M€ plus 1 M€ per year for maintenance and upgrade: 25 M€

Support Early Career Investigators (ECI)

The Early Career Investigators (ECI) are an important part of the Quantum Research. Currently there is some dedicated support for them through the COST Actions.

In order to achieve the goals defined in the European Quantum Technologies Roadmap and to be in the frontier of the Quantum Research, we need to be diverse in terms of gender, country, and geography.

The ECIs can be a key solution for these issues. ECIs hold a hidden potential to bring the diversity and excellence. In several COST Actions there is a proportionally large gender diversity, with an enhanced female percentage when it comes to ECIs.

Funding opportunities directed at ECIs

Although there is training and education support for young researchers, it is possible to improve funding and opportunities for young researchers as well as some other minority groups. It is very hard for young researchers to get into a closed and specialized network, such as quantum research.

The EU is missing specific funding schemes for collaborative projects (maybe of reduced size) led by ECIs, including an adapted review scheme and criteria considering differences in career development across EU countries.

Collaborative and/or individual small scale targeted projects are needed. Small grants may not be interesting for large groups but may have a significant impact for ECIs or other persons with difficult access to funding. This is crucial to identify the next generation of leaders in the field. One may also forbid persons with currently active large projects to apply for those grants.

In order to eliminate possible distortions in the review process, the EU can adopt a double-blind review process with an additional review stage to check the suitability of the team/researcher.

Requirements / Funding:

Each grant can be around 100 K€ / year. We propose to run 50 per year for 10 years: 50 M€

Networking platform

We need a platform that enhances networking between ECIs. Such networks are known to be excellent incubators of novel ideas and approaches and to create an important added value within a relatively modest budget. Such a network would also encourage and promote women scientists in the community. In practice such a platform should comprise

- Short-term mobility schemes (0,5-3 months) which allow for longer discussions, interaction, and potential project preparation, but which will to a large fraction be dedicated to the exchange of ECI, vector of knowledge transmission.
- A mentoring program for ECIs, with a special effort for female scientists including by providing childcare free of charge, in order to accompany and amplify actions put forward by young researchers.
- Training activities (for junior AND senior scientists in industry and academia) which are open and interdisciplinary enough to mix different communities, which do not naturally meet at conferences.

Requirements / Funding

- COST-like actions within the Quantum Flagship for young quantum technology researchers for 10 years in total
- Mentoring program: Needs multiple FTEs (probably four aligned with different academic cultures) to manage, travel cost so it can be introduced at flagship conferences, roughly 10 M€ for 10 years. Mentoring itself: Assume that one mentoring session (by telco) costs 200 €, multiply these 2 sessions per year for 500 female researchers gets you to 2 M€

Further ideas

The EU can harmonize or be aware of the legal constraints of young researchers in different countries. Organizing some EU level interdisciplinary workshops including industry and academy would be very useful to create synergy and network among young researchers.

The EU can require reports on the future/follow up of young researchers in the project team as a part of the reporting process. This will encourage senior PIs to support the career of young researchers and give them more administrative rights.

Reaching next generation of students, non-graduate students and industrial workforce

Develop educational programs for teachers and high school students

A crucial point for the future of QT in Europe could be to inspire next generations of students for this topic. Therefore, a call for research projects should ask physics education researchers to develop curricula for training in basics of modern QT aiming at

- teaching candidates and teachers in schools

- students in high school in regular school activities
- students in high school in extracurricular activities

To inspire future generations for QT, one needs STEM teachers at schools who can teach topics of QT.

Working groups of researchers & educators in the field should be established in order to collaborate with educational authorities and support the co-creation of innovative curricula that will include frontier science and real-life scientific challenges.

Since advanced topics of quantum physics, which are necessary to understand modern QT, are not part of teacher education by default, it is necessary to familiarize prospective teachers and teachers in schools with the subject-related basics in teacher education and further teacher training activities. In addition, materials for practical use in school lessons (e.g. experiments, simulations, ...) should be developed and used for teacher education and further teacher training activities. This material will be useful also for instructing high school students in regular school activities and extracurricular activities (as for instance summer schools). It will be expected that materials and activities are easier transferable for extracurricular activities due to local framework requirements for school curricula.

The developed materials for teachers and high school students should be tested and evaluated in real teaching situations in teachers' education (at universities and further teacher training activities) and with high school students.

A useful complementary measure could be to install educational labs focussing on topics of quantum technologies. These labs could address both high-school students, teacher students and teachers and thus could provide useful opportunities for combined teaching-and-learning activities to the latter. The educational labs would also benefit from the development of new educational tools for students' hands-on training as laboratory experiments on QT described above. These labs could also offer workshops, public lectures and school visits on QT, which help laymen and pupils to get in touch with quantum technology at an early stage.

Placement of science teachers in research labs (mobility initiatives) would allow them to learn about frontier science and transfer their experience to their classroom, informing the students first-hand about new challenges and possible careers in science.

It is important to collect and coordinate different activities in the EU by establishing an outreach network and a database of the different activities.

Develop training in modern quantum technologies aiming at non-physics majors

Students who do not major in Physics or QT traditionally receive a reduced curriculum of quantum physics, the unloved middle child of teaching. The material that is chosen from there is traditionally driven to certain applications such as atomic structure and chemistry (in teacher education) or towards semiconductor physics (engineering education). This is not what is needed for understanding basics of modern quantum technology, which include probability, entanglement etc. Teachers and non-majors should in fact be a focus in growing a quantum-aware workforce.

Figuring out how to do that is no small task and serious research, not something done by quantum technology researchers on the side. It needs professional education researchers who, on the other hand, need to be trained in quantum technologies. Physics departments with highly active research groups in both Quantum Technologies and Physics Education Research could act as leading poles for such collaborations.

A good measure would be a call for research projects that primarily funds physics education researchers but asks them to include quantum technologists, to develop a curriculum for training in modern quantum technologies aiming at non-physics majors. The call could ask that the whole program reach

- engineering students
- chemistry and computer science students
- continuing education for engineers in the workplace

Concrete deliverables can be example curricula and teaching materials and techniques, which can also be used by the measures aiming at high school students, teacher students and teachers. One major issue is to focus on the learning goals of *engaging* with QT and providing access to real work at the front of science. In QT this is a challenge because of the advanced mathematics and physics involved. But it can be achieved by creating simulations and model systems that allow students to experiment with quantum phenomena and thus discover the wonders and features of quantum technology. New methodologies and tools (e.g. gamification and QT demonstrators) should be considered and made available with augmented and virtual laboratories and teaching activities. Through their introduction and usage, a better understanding of more relevant recipes in quantum physics could be achieved: QT, intended as a broad set of applications of abstract and theoretical arguments in quantum physics, could be then based on more solid and participated grounds.

In a second stage these could be tested and evaluated in real teaching situations and training activities at high-school level. It could also be considered how to implement aspects of quantum technologies in existing high school curricula in order to reach as many teachers and students of high school as possible, for instance by organising dedicated lectures at national science festivals or at educational guidance activities at senior students of high schools. In order to write the call so it matches the pace of education research, that community should be consulted.

These projects in order to reach teachers and students especially in high school should include apart from universities also citizen organizations, schools and school networks, NGOs and other stakeholders in education.

In order to integrate these activities on a European scale, there would need to be a CSA in parallel, which would investigate and advise on science curricula in member states, for instance by organizing workshops for policy makers, quantum technologists and educational expert centred around the question of what should be learning goals related to QT in secondary education.

Requirements / Funding:

- integrated projects very much like a flagship project for physics education in quantum, 3 calls with 20 M€ each
- coordination action for physics education, covering all 10 years

Support sabbaticals, secondments, job rotation

It should be made easy for educators, education researchers but also engineers to spend some time in quantum technology institutes, e.g. within sabbaticals or as part of research projects. It should be made easy to do and to fund this. The CERN programme for teachers and students of high school could serve as model for similar programs in quantum information.

Also, training periods for industry researchers interested in developing QT should be supported. The National Metrology Institutes have traditionally been early adopters of QT and have a significant history of research which has moved the basis of the international measurement system from physical artefacts to concepts based on fundamental physics. EURAMET provides training in metrology principles through its research programmes and will seek to link these to Flagship projects, to foster joint education and rapid take-up of QT applications into industrial measurement.

Requirements / funding:

- Humboldt-foundation type sabbatical program covering extra living cost and travel and family support. At the Humboldt foundation these are worth 60k, if we do 100 of these (10 per year of the flagship) we are at 6 M€, to which 20% management cost should be added to run the program

Develop a professional MSc in QT

This common curriculum could be used to develop a professional MSc (similar to professional MBAs - programs taken in focused form, parallel to work, because the employer needs it) in Quantum Technologies: Focused courses that can be taken by engineers in the workplace so that they have the opportunity to stay at the cutting edge of research developments and techniques in quantum technologies as part of their professional developments. While these are often commercial in the MBA area, its first implementation in the quantum area needs to be non-profit and it requires development costs (labs for hand-on-components, MOOCs, instructors). A measure could be a competitive call for a consortium that contains industries, trade organizations in engineering, and academic centres. The aim would be to create a blueprint for universities and a corresponding certification that universities can apply for. Ideally implementation of a few model programs should be funded (creating an incentive for underfunded universities). MSc programmes open to active industry researchers would also support a more consistent and open exchange of ideas between academia and industry.

Industry involvement here is critical to make graduates employable and targeted towards their need.

Requirements / funding:

Assuming that the MOOCs anticipated above exist, we need to create three more basic MOOCs including exams and go through accreditation, this would be around 2 M€.

Reaching entrepreneurs

This could be building completely new structures (see infrastructures section) or dedicated tracks in existing structures. In any case, these need to be coordinated across Europe to generate critical mass. It needs to also include reliable information on use cases and capabilities that can also be communicated to investors.

Requirements/ funding:

Coordination action between incubators, sponsoring of market analyses and use-cases in the form of small projects between researchers and potential users (example: German BSI study on quantum computers).

Also, better education on entrepreneurship for graduate students is needed.

Further ideas

Reference library

The materials developed here and in the flagship research programs (theses, pedagogical papers, books, talks, electronic media) should be made openly accessible and curated and commented with recommendations for target audience and field in a European quantum reference library. The quantum community network needs support to manage this.

Requirements / funding: 1 FTE added to the flagship CSAs plus travel and infrastructure. 1 M€

European QT education coordination and networking group

As mentioned in several places above, coordination between various local education activities is key and a big task. A dedicated group of people that coordinate and network between all of these activities should be established. This group could be part of future Flagship CSAs, which would need a much higher budget than in the current call to have enough resources for education. In fact, we had this community on our doorsteps several times and could not fold them in appropriately.

Requirements / funding: 1 FTE added to the flagship CSAs plus travel and infrastructure. 1 M€

Support the combination of teaching and research

Instruments like ERC focus on excellence in research. We need to value people's teaching as well, so a stream of promoting excellence in teaching careers / personal fellowships (Marie Curie?) for future educators in QT should be established.

General thought on STEM education

There is an insufficient number of STEM students in the EU. Attract students from non-EU countries and provide additional education that enables them to enrol in regular MSc programs (Erasmus Mundus doesn't work because it addresses the problem too late and the mobility requirements hurt rather than help). Also, we need creation and implementation of a European examination procedure (similar to the American GRE test) that will allow to screen for promising students.

Support should be granted to centers giving space to curious and creative public to contribute, such as citizen science fab labs, maker fairs, and similar initiatives. Dedicate effort should be devoted to collect and analyze public opinions about science and creative scientific ideas in social media and elsewhere.

Impact of Quantum Technology on Society

The first quantum revolution has already impacted the lives of billions of people, simply by allowing communication on a scale and with an ease that was unimaginable a few decades ago. Nevertheless, the second quantum revolution will have an impact well beyond that, especially concerning topics such as security and privacy, and ethics, but also in healthcare. Developing and engineering QT applications for Europe and the world at large should not be done without taking the position of the citizen into account. General acceptance of next-generation Quantum Technologies is not a given when deeply impacting technology is rooted in science which is as uncommon as quantum mechanics.

Possibly a Responsible Research and Innovation program involving aspects of quantum technology could be implemented, and Quantum Technologies as a topic could be included in the equivalent to the Science with and for Society (SWAFS) program in the next framework program.

Impact:

- allow emerging QT and the associated industry to fashion applications/services/products to the needs and expectations of the public as much as possible;
- enhance general acceptance of QT;
- improve general interest in QT.

Budget:
Total budget of M€ 5, of which M€ 4.5 for one or two consortia-aimed Research and Innovation Call(s) and M€ 0,5 for coordination and support. Multidisciplinary research, as well as involvement of social studies and societal organizations, is key.

Coordination with Member States

A very important dimension of the Quantum Flagship is the involvement of and coordination with national organizations across Member States, in order to achieve the best possible synergy between national initiatives and the Flagship itself. One effective way to achieve this is to build upon existing intergovernmental organizations, such as the consortium of national funding organizations QuantERA[11] and that of national metrology institutes EURAMET[12], which are already planning joint activities in the field of quantum technologies.

Metrology Network for Quantum Technologies

Offer: The planned EURAMET European Metrology Network for Quantum Technologies (EMN-QT) offers active coordination of the European National Metrology Institutes´ (NMI) research activities on quantum technologies and their alignment with the European quantum technologies initiative. It develops metrology research and technology roadmaps for the next decades, assures the alignment of these activities with industrial requirements by knowledge transfer, education, and a portfolio of dedicated services, and provides major contributions to standardisation & certification bodies in the area of quantum technologies.

Impact: The EMN-QT aims for the support of companies, institutions and academia in the field of quantum technologies. The activities of the EMN-QT will impact a relevant part of the quantum technologies considered in the flagship by coordinating cutting edge research activities in the context of the quantum technologies domains. Furthermore, it will coordinate the development of the necessary metrological infrastructure for the characterisation of the quantum devices and for their certification. The measurement expertise within EMN-QT will also coordinate fundamental contributions to the standardisation process of these devices.

Requirements: Investment in research, coordination and support actions in the field of quantum technologies, i.e. in personnel dedicated to research and to coordination in metrology for quantum technologies and to networking with stakeholders from industry and academia. Investments in equipment specifically dedicated to the development of metrology for quantum technologies. The necessary infrastructure for providing the activities and services are mentioned in the corresponding sections of this paper.

Budget estimate: A total of €6M per year, for 5 years, represents a reasonable estimate of the budget needed to carry on the research activities necessary to develop the quantum technologies metrological infrastructure. 3 FTE/year for the above stated requirements in coordination and networking.

[11] https://www.quantera.eu

[12] https://www.euramet.org