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ANNEXES 1 to 4

ANNEXES

to the

Proposal for a Regulation of the European Parliament and of the Council

on a framework of measures for strengthening the Union's quantum ecosystem (Quantum Act)

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ANNEX I Indicative areas for quantum grand challenges

The following areas identify initial priorities for quantum grand challenges. They address major scientific, technological and engineering bottlenecks and may be updated in line with technological progress, strategic needs and market developments. Inclusion in this Annex does not require all challenges to be launched simultaneously.

Each grand challenge should follow an ambitious, measurable technology roadmap with milestones and stage gates. Competing approaches may be supported in parallel until evidence supports selection. Promising results may feed into quantum infrastructures, strategic projects, innovation procurement, industrial deployment or private investment. The EuroHPC Joint Undertaking has already initiated a call on grand challenges in quantum computing and inertial navigation. Further actions under the Quantum Europe Framework Initiative should build on these efforts.

1. Fault-tolerant quantum computing – making reliable calculations possible

Quantum computers remain vulnerable to noise and errors, limiting the calculations they can perform reliably. Fault tolerance requires protecting quantum information through error correction and integrating high-quality processors, controls and software into scalable, reliable and energy-efficient systems. Qubit counts alone say little about what a machine can reliably do.

The grand challenge should support competing Union architectures, including logical qubits, error correction, modular processors and interconnects, control electronics, cryogenic or other enabling technologies, compilers and software integrated with high-performance computing. AI-based methods may also support quantum-system calibration, control, error correction and decoding. Technological neutrality should be preserved, with evidence-based selection of promising approaches.

By 2030, Union teams should aim to demonstrate sustained error-corrected operation and credible routes towards useful scientific or industrial workloads. Progress should be judged by physical and logical error rates, quality and duration of operations, logical qubit number in relation with logical error rates, scalability, availability, energy use and workload performance, and according to standardised benchmarks as they become available. Consistent with the Quantum Europe Strategy, the ambition is to reach approximately 100 error-corrected logical qubits per system by 2030 or soon after, scaling towards thousands per platform by 2035.

2. Quantum navigation and timing – when satellite signals fail

Union transport, energy networks and critical services depend on positioning, navigation and timing, yet satellite signals can be obstructed, degraded, jammed or spoofed. Quantum gyroscopes, accelerometers, atomic interferometers and advanced clocks could complement conventional navigation when satellite positioning is unavailable.

The grand challenge will aim to develop deployable, integrated Union quantum systems for aircraft, ships, autonomous systems, underground and underwater operations, emergency services and space. Work should cover sensor performance alongside miniaturization, weight, power, calibration, robustness, manufacturability, cost and integration with classical navigation. This development shall take into account the dual-use dimension of Inertial Navigation Systems and adopt necessary safeguards accordingly.

The next step is to test systems in representative GNSS-denied or degraded environments by 2030 and benchmark their performance against leading conventional solutions for navigation

accuracy, stability, duration, reliability and practical deployability. The longer-term aim is to reduce dependence on any single source of positioning and timing.

3. Quantum memories and repeaters – connecting quantum devices

Future quantum computers, networks and distributed sensors will need to exchange quantum states and entanglement, moving beyond isolated devices. This demands high-fidelity, long-lived and multiplexed quantum memories, repeaters and interfaces between different technological platforms.

The grand challenges should advance storage and retrieval, frequency conversion, matter–photon interfaces, entanglement generation and distribution, photonic or other interconnects, and interoperability across quantum computing and communication systems. Additional areas of work include network control, routing, resource allocation, synchronization, link monitoring and verification.

By 2030, trials should demonstrate interoperable quantum memories, repeaters and interfaces in multi-node systems, with progressively longer entanglement links and connections between different devices. Towards 2035, these technologies should support more reliable inter-metropolitan quantum networks, modular quantum computing and the progressive development of the Quantum Internet at Union level, with performance assessed through fidelity, storage time, transmission distance and interoperability.

4. Quantum sensing and imaging -detecting faint signals

Quantum sensors can measure minute changes in magnetic fields, gravity, acceleration and time, opening opportunities in medical diagnostics, navigation, climate monitoring, civil engineering and resource mapping.

The grand challenge should turn laboratory sensitivity into compact, reliable and affordable instruments that work outside the laboratory. Such instruments should bring measurable advantages in biomagnetic and medical imaging, gravimetry, magnetometry, inertial sensing, optical and photonic imaging, microscopy and spectroscopy while also addressing tough engineering, packaging, miniaturization, and signal processing and calibration issues.

By 2031–2032, the aim should be to demonstrate industrially relevant systems ready for further testing, validation and, where appropriate, deployment in hospitals, industrial facilities, transport environments or the field. Their performance should be compared with conventional technologies for sensitivity, resolution, robustness, usability and cost. Medical uses should follow applicable clinical, medical-device, safety and data-protection requirements.

5. Quantum machine learning – demonstrating potential advantages

Grand challenges should investigate whether quantum computing can provide measurable advantages for selected artificial intelligence and machine-learning tasks, including training, inference, generative modelling and optimisation. Activities should explore hybrid quantum-classical learning, quantum data pre-processing and selected quantum learning models, including supervised, unsupervised and reinforcement learning, while addressing data encoding and loading, trainability, noise, scalability, resource requirements and integration with Union HPC and AI capabilities.

Priority should be given to well-defined use cases and independently reproducible, end-to-end benchmarks against leading classical AI methods, assessing accuracy, execution time, training-data requirements, energy consumption and total classical and quantum resources. Milestones should distinguish near-term hybrid demonstrations from longer-term fault-tolerant approaches and establish whether quantum methods deliver practical advantages.

6. Quantum for discovering advanced materials or medicines

Understanding molecules, advanced materials and complex physical and biological processes is essential for medicines, batteries, catalysts, chemicals, energy technologies and manufacturing. Conventional simulation can become prohibitively difficult, while quantum computing and simulation may offer new tools where they address a concrete scientific or industrial need.

Grand challenges should pair quantum developers with leading Union scientists and industrial users to tackle defined problems in discovering new pharmaceuticals, new stable advanced materials and safer chemicals, while further improving and optimizing chemical processes and sustainable manufacturing. Quantum methods should be combined with HPC, AI and experiments when appropriate. Where appropriate, such grand challenges will be set in coordination with the grand challenges under Council Recommendation XX on advanced materials [please insert correct reference to COM(2026) 833 final once adopted] ensuring coordination and complementarity with priority challenges in the area of advanced materials.

By 2031/32, selected grand challenges should demonstrate quantum-enabled workflows addressing important scientific or industrial problems, with rigorous benchmarking against leading conventional approaches. Progress should be measured through computational accuracy, performance, resource requirements and the potential for practical advantage. Promising applications should progress towards industrial validation and adoption as the underlying technologies mature.

7. Full-stack quantum systems – more than a processor

A quantum processor is not yet a usable quantum system. Competitive products depend on the complete stack, from processors, control and cryogenics to interconnects, error correction, operating systems, compilers, middleware, applications and user access. Weakness in any layer can undermine otherwise excellent Union technology.

Grand challenges should support the co-design of Union hardware and software into modular, interoperable and scalable systems, with portable interfaces and integration into HPC, AI and cloud environments. Work may include automated operation, workload management, energy efficiency and architectures that allow components to be upgraded without rebuilding the system. Where appropriate, activities may also support the development of interoperable open-source components and a Union open-source quantum software stack, alongside other software solutions.

Demonstrators towards 2030 should show hardware, control, error correction, software and applications working together through documented interfaces, with movement between simulation, emulation and physical resources where feasible. Results should support Union products and services that can be deployed and scaled.

ANNEX II Priority areas for post-quantum cryptography

Post-quantum cryptography is essential to protect the Union's digital infrastructure, communications and sensitive information against quantum-enabled attacks. Priority actions should strengthen Union capabilities in cryptanalysis and the development of secure cryptographic solutions, including digital signatures, key establishment, threshold cryptography, privacy-preserving schemes and low-complexity cryptographic methods. Research should assess the security of existing approaches against classical and quantum attacks, explore new cryptographic methods and improve their efficiency, with particular attention to long-term security and Union technological capabilities.

Turning research into trusted solutions will be equally important. Actions should support the development and industrialisation of secure, efficient and verifiable cryptographic implementations. Particular attention should be given to formal verification and high-assurance cryptographic implementations, cryptographic agility, migration tools, trusted hardware supporting fundamental cryptographic functions and technologies enabling secure computation on encrypted data. Cooperation between researchers, industry and certification stakeholders should facilitate the deployment of reliable Union solutions and their integration into existing digital systems.

The Union should also strengthen its capacity to independently test and validate post-quantum cryptographic technologies. Shared testing facilities and capabilities should support the assessment of software and hardware security, including side-channel analysis, fault-injection testing and hardware vulnerability assessments, with the aim of making trusted hardware foundations more transparent, verifiable and reusable. These activities should contribute to common testing methodologies, industrial-grade security tools and certification processes where applicable. By 2030, the aim should be to strengthen Union research in cryptography and the role of the Union in driving agreements on new schemes at international level, ensuring secure physical implementations, hardware development capabilities, efficient implementations reaching the computing edge, and stronger capabilities in high-assurance tools and practical testing services supporting a secure, coordinated and risk-based transition to post-quantum cryptography.

ANNEX III Priority areas for quantum infrastructures

Under the Quantum Europe Framework Initiative, quantum infrastructures should give researchers, firms and public users shared Union capacity for testing, validation, integration, demonstration and deployment. They should build on existing Union and national investments, avoid duplication and enable cross-border access on transparent and appropriate conditions. Where relevant, these infrastructures should also support independent benchmarking and verification, using common performance metrics and reproducible testing procedures. The following are initial priority areas.

1. European Quantum Service Platform for Science and Industry

The European Quantum Service Platform should provide researchers, companies and public users with federated access to quantum computing, simulation, emulation and related software services. It should build on existing EuroHPC and national infrastructures, without duplicating their facilities or altering applicable access conditions.

Quantum simulation is the use of a controllable quantum system to mimic the properties or behaviours of another quantum system. Quantum emulation is the use of a classical computing system to simulate the properties or behaviours of a specific quantum target system.

2. EuroQCI – secure communications across Europe

Governments, critical infrastructures and strategic industries need resilient and highly secure communications. The European Quantum Communication Infrastructure (EuroQCI) combines terrestrial and space-based capabilities to support trusted cross-border services and strengthen Union cybersecurity and connectivity. EuroQCI was launched in 2021, with first Member States' deployments started as of 2023. Since then, Member States have advanced the deployment of national terrestrial quantum communication networks, including cross-border preparations and real-world quantum key distribution (QKD) pilots. Activities also include secure communications demonstrations for public authorities and critical infrastructure, development of Union components and testing facilities, and preparations for satellite-based QKD.

EuroQCI should progressively link national quantum networks with Union space capabilities and gradually provide quantum key distribution (QKD) as a service, complemented where appropriate by post-quantum cryptography (PQC) and conventional end-to-end security measures. It should support public authorities, interoperability, testing, certification and integration with existing networks, while allowing sector-specific commercial services to emerge.

By 2031, the ambition is to establish the first interconnected experimental Union terrestrial and space-based quantum communication network, linking national infrastructures and capable of delivering experimental QKD services across the Union. During 2031–2035, EuroQCI should progressively move towards certified, reliable and interoperable operational services, including integration of relevant governmental capabilities into IRIS²[1] as they mature. Commercial applications should also be supported through eligible Strategic Projects (see Annex IV), building on European quantum communication technologies and services.

3. Building the Quantum Internet

Quantum Internet means a network of interconnected quantum devices, including quantum computers, sensors and quantum memories, that enables the transmission of quantum

[1] IRIS² | EU Space Policy

information and the distribution of entanglement between distant nodes through quantum communication links. Supported by classical communication and control systems, such networks may enable distributed quantum computing, networked quantum sensing and advanced quantum communication applications.

A future Quantum Internet could link quantum computers, sensors and other devices through the distribution of quantum states and entanglement, potentially enabling distributed computing, coordinated sensing and new secure communication functions. Such networks will depend on quantum memories, repeaters, entanglement distribution, quantum-compatible interfaces and dedicated network-control software. Experimental metropolitan networks will test the reliable distribution of entanglement between different quantum devices, maintaining the necessary quantum coherence and interoperability.

Union research has already demonstrated entanglement between independently operated quantum-network nodes connected by approximately 10 km of optical fibre. Progress has also been made on quantum repeater components and networking software. These remain experimental results rather than an operational Quantum Internet.

The next target is to demonstrate, by 2030, the first interoperable metropolitan quantum networks, with first-generation pilot facilities operating over distances of up to approximately 50 km, subject to technological readiness.

Towards 2035, Europe should aim to extend these capabilities to inter-metropolitan networks, targeting connections of around 200 km, and demonstrate applications beyond quantum key distribution, including distributed quantum computing and networked sensing.

The longer-term ambition (2040+) is a federated Union Quantum Internet, progressively developed as reliability, interoperability and industrial readiness improve.

4. Union quantum gravimetry – perceiving what lies well below

Quantum gravimeters can detect small variations in gravity that may help characterise subsurface features at depths of up to several tens of kilometres, depending on geological and measurement conditions. One important application is monitoring groundwater resources and aquifer depletion, helping Europe respond to climate change, environmental and infrastructural challenges, such as droughts and increasing pressure on water supplies.

Other potential applications include detecting geological structures, monitoring volcanic activity and magma chambers, mineral exploration, archaeology and critical infrastructure. Potential dual-use applications, including in defence and security, could include detecting underground structures and future maritime sensing capabilities, although these would require extensive testing and validation.

Union research has already developed quantum-gravimeter prototypes tested outside laboratories. The next step is to establish a distributed network of ground-based and mobile instruments across Europe, with interoperable measurements and validated services towards 2030. A space-based gravimetry pathfinder could complement these capabilities beyond 2030.

5. Union quantum medical imaging – towards clinical validation

Union research has already demonstrated the principles of quantum-enhanced medical imaging and highly sensitive magnetic measurements. These technologies could help doctors detect diseases earlier, including certain cardiovascular, cancers and neurological conditions, and enable more precise and personalised diagnostics.

Further research, engineering and clinical validation are needed before routine medical use. As a first step, a Union Q-MRI pilot infrastructure should be supported to help hospitals,

research centres and industry validate these technologies, with the longer-term objective of bringing reliable quantum-imaging devices into everyday clinical practice.

The infrastructure should build on quantum-enhanced and metabolic MRI and accommodate other mature applications, including biomagnetic sensing, neurological and cardiovascular measurements, microscopy and AI-assisted analysis. It should connect accredited hospitals, clinical researchers, industry, and patients drawing on relevant Union Q-MRI research and pilot activities where appropriate.

By 2030–2031, the subsequent aim would be to move selected systems from prototypes to multi-site clinical validation and, where feasible, deployment, and placing on the market, in compliance with relevant Union law regulating medical devices and data protection. Priority should go to technologies with clear potential benefit for patients and clinically meaningful evidence.

6. Union quantum clocks – securing Union's time

The Union's economy depends on precise and reliable time measurement. Electricity grids, telecommunications, financial transactions, navigation and space systems all rely on accurate synchronisation. Disruptions to satellite-based timing could affect several critical services simultaneously. Quantum clocks offer the prospect of more accurate, resilient and Union-controlled timing capabilities, strengthening technological sovereignty and security.

The Union already has strong scientific capabilities in atomic and optical clocks, but these remain largely concentrated in specialised laboratories. A Union quantum timing infrastructure should connect leading metrology facilities, distribute precise time and frequency signals across borders, and develop compact, transportable clocks for practical applications. It should also contribute to the development of future Galileo capabilities and resilient alternatives when satellite timing is unavailable.

By 2030, Europe should aim to demonstrate a cross-border quantum timing network, providing highly accurate and traceable time signals and testing applications with telecommunications, energy, financial and space users. Beyond 2030, the objective should be to deploy robust Union quantum clocks in critical infrastructures, creating new industrial opportunities and reducing strategic dependencies.

ANNEX IV Priority areas for strategic projects

Strategic projects should address identifiable Union capacity gaps through industrialization, scale-up and deployment, or through services that bring clear Union added value. They should complement, not duplicate, grand challenges and quantum infrastructures. Designation itself does not grant an entitlement to funding. Priority areas may overlap and projects may cover several of priority areas.

Projects should follow measurable milestones reflecting their technological maturity and industrial readiness, with priority given to those offering credible pathways towards Union production, deployment, commercial uptake and reduced strategic dependencies. Indicative timelines should remain sufficiently flexible to accommodate technological developments and market needs. Strategic projects could cover priority areas such as:

(1) Building fully operational Union quantum computers – bringing reliable systems to users

The Union needs the ability to design, build and operate quantum computers that can serve users beyond the laboratory. Strategic projects should help Union providers move from experimental processors to fully deployable systems and commercially useful computing services, including through quantum providers and cloud service operators.

Strategic projects may cover industrial-scale processors and simulators, modular or distributed systems, data-centre installation, control and orchestration, hybrid quantum–HPC or quantum–AI systems and cloud-accessible quantum services, including those offered by providers established in the Union.

Priority towards 2030 should go to systems with credible industrial production, operation, maintenance and end-user pathways, strengthening Union suppliers and allowing researchers, businesses and administrations to access competitive quantum services.

(2) Industrial quantum applications – bringing quantum capabilities to users

Strategic projects could support large industrial applications built on Union quantum hardware and software capabilities, transforming technological advances into solutions addressing concrete industrial and public-sector needs.

For example, strategic projects could develop and deploy applications in pharmaceuticals, safer chemicals, materials, energy, manufacturing, transport, finance, telecommunications, water infrastructure and critical infrastructure, combining quantum technologies with HPC and AI where appropriate.

Strategic projects could also support the development, industrialisation, integration, validation and deployment of quantum technologies that strengthens the security, resilience and technological autonomy of the Union in strategically exposed border and maritime regions.

Priority should be given to applications demonstrating measurable advantages, credible users, sustainable business models and clear pathways towards industrial validation, procurement and commercial uptake.

(3) Quantum manufacturing – taking European Union designs into production

Research excellence will not create industrial leadership unless quantum components and systems can be manufactured repeatedly, reliably and at scale. Quantum production involves specialised photonic, superconducting, cryogenic, atomic and other processes not always covered by conventional semiconductor facilities.

Strategic projects can support quantum design centres, quantum foundries, specialised pilot-to-industrial production sites, dedicated equipment and tools for quantum chip manufacturing, as well as chip fabrication, integration, packaging, characterization, qualification and manufacturing methods that improve yield, reproducibility and cost. They should complement quantum-chip pilot lines and activities within the Chips JU mandate, avoiding double financing.

Towards 2030, projects should strengthen Union quantum pilot production and design capabilities, demonstrating repeatable manufacturing processes, component qualification and improved production yields. During 2030–2035, priority should shift towards industrial-scale production, commercially viable quantum foundries and reliable Union supply chains, building on successful pilot lines and demonstrated market demand.

(4) Critical quantum components – reducing supply vulnerabilities

A single specialised component can determine whether an entire quantum system can be built and maintained in Europe. Limited availability of lasers, photonic sources and detectors, cryogenics, control electronics, materials or precision equipment can create strategic dependence.

Strategic projects could support the industrialisation and commercialisation of these technologies, including quantum key distribution equipment, entanglement sources, quantum memories, repeaters, network nodes and interfaces, microwave and radio-frequency systems, vacuum equipment, substrates, packaging, connectors and testing instruments. Priority should go to components with few suppliers, strategic supply risks or major scale-up barriers and to technologies useful across several quantum domains.

By 2032–2033, projects should work towards commercially viable Union production, better supplier diversity and secure availability of critical inputs for computing, communication, sensing and metrology.

(5) Quantum sensing and metrology – precision ready for industry

Quantum sensing is among the fields closest to market uptake, with applications in healthcare, navigation, climate, industrial inspection and infrastructure monitoring. The challenge is to convert promising prototypes into qualified systems and repeatable services.

Strategic projects could support the miniaturisation and scaling-up of production of quantum gravimeters, accelerometers, gyroscopes, clocks, magnetometers, imaging and biomagnetic systems, spectroscopy and environmental or space sensors. They may include production, integration, testing, qualification and operational deployment, including sensors used in advanced manufacturing.

Towards 2030, priority should go to field validation and industrial qualification of quantum sensing technologies that demonstrate measurable advantages over conventional solutions. By 2035, selected technologies should progress towards commercially available products and operational services, with the aim of reaching technology readiness levels 7–9 where appropriate. Size, weight, power consumption, calibration, reliability and cost should remain central to industrial readiness assessments.

(6) Quantum technologies for health – evidence before deployment

Quantum technologies may improve diagnosis, medical research and discovery of medicines, but clinical value must be demonstrated before deployment. Europe should help promising healthcare technologies progress beyond research prototypes.

Strategic projects may support the development and industrialisation of quantum-enhanced MRI and other imaging, biomagnetic measurements, specialised medical detectors, AI-assisted clinical analysis and quantum simulation for molecular and pharmaceutical research. They may industrialise systems emerging from Union clinical validation facilities.

Towards 2030–2031, priority should go to technologies progressing towards clinical validation, regulatory approval, industrial manufacture or commercial services, with clear benefits for clinicians or patients and full respect for clinical, safety and data-protection requirements.

(7) Quantum communication and networking – from secure links to the Quantum Internet

The Union needs a competitive industry capable of developing secure quantum communication products and technologies for future quantum networks. Strategic projects could support the industrialisation and commercial deployment of quantum key distribution systems, terrestrial and space-based equipment, quantum repeaters, entanglement sources, network nodes and interfaces between quantum devices.

Projects may also support system integration, networking software, interoperability, testing, certification and the provision of services. They should complement, rather than duplicate, EuroQCI and Union Quantum Internet infrastructures.

Towards 2030 and beyond, priority should go to commercially viable Union quantum communication products and services. During 2030–2035, projects could support interoperable technologies for larger quantum networks and emerging applications in distributed quantum computing and sensing.