Key Performance Indicators for Quantum Technologies in Europe

March 2024

Abstract

Quantum technologies leverage on quantum physics properties to provide disruptive solutions for processing information, exchanging data and interacting with the world around us. The European Commission has identified the quantum technologies as a strategic asset, launching different quantum initiatives to consolidate and expand European scientific leadership and excellence in this area, to develop a competitive European industry in quantum technologies and to make Europe a dynamic and attractive region for innovative research, business and investments in this field.

Europe is committed to quantum excellence and innovation having a strong role in the global quantum scientific and industrial world. In this sense, the Quantum Strategic Advisory Board (SAB) of the European Commission has identified a set of very ambitious Key Performance Indicators (KPIs) to guide, to track and to monitor the progress of the quantum technology in Europe. The KPIs monitor six key aspects of the quantum area: **Ecosystem**, **Quantum Communication**, **Quantum Computing**, **Quantum Simulation**, **Quantum Sensing and Metrology**, and **Education**.

The KPIs values were defined with the best present knowledge of the European quantum community, combining reasonable and attainable results with a healthy dose of ambition. However, the fast progress in some areas and the rapid advancement of the technology make of this paper a living document, requiring a periodic review and adjustment. Therefore, deviations for single KPIs may occur.

This document presents the KPIs values of 2023 together with the perspectives towards 2030 and reflect overall research and innovation goals as set forth in the Strategic Research and Innovation Agenda[a]. The KPIs include both quantitative and qualitative evaluations of the quoted goals. It is assumed that there is and will be consistent and continued support for fundamental research and basic science as well as the tight interaction with European industry in order to ensure that Europe continues to maintain excellence in scientific expertise and lead to create the best conditions for future breakthroughs.

Information presented in this document results from the collaboration among the academic, public, and private sector representatives from the Strategic Advisory Board (SAB), the Quantum Coordination Board (QCB, formerly SEB), the Quantum Community Network (QCN), the European Quantum Industry Consortium (QuIC), and the Flagship coordination office through the Coordination and Support Action (QUCATS). The KPI values for 2023 were measured in the beginning of 2024 by surveying the members of the SAB, the QCB, the QuIC and the QUCATS. The plausibility of the collected results

[a] 2024 Strategic Research and Industry Agenda: https://qt.eu/media/pdf/Strategic-Research-and-Industry-Agenda-2030.pdf

Abstract

was verified and validated by the SAB. Multiple rounds of feedback from those bodies were collected to define the 2023 KPIs values, to tune the target values for the year 2030, and estimate the annual progress required to reach those targets.

A color scale was adopted to represent the health of the KPIs in terms of the feasibility of reaching the ambitious 2030 targets. The document also highlights the KPIs in which the target 2030 was already achieved, showing the extraordinary advancement of Europe in the quantum field. In this case, the KPI values are adjusted.

References and explanations are given at the end of this document. The 2030 target of some KPIs is still under discussion. In such cases the “n/a” is reported. The SAB is working towards these 2030 target definition and the result of the discussion will be used to evaluate the 2024 achievements.

KPI Scorecard

KEY

- Ahead of schedule
- On schedule
- Needs progress
- Behind schedule

KPI Ecosystem	2021 value	2022 value	2023 value	2030 target
Investment (M€)	344 M€	408 M€	551 M€	1000 M€
Lab-to-market (SMEs members of QuIC)	79	95	99	250
Lab-to-fab infrastructure and value chain (facilities)	1	9	22	60
Job Creation	n/a	n/a	3850	10000
Patent Creation/IP Retention (rank)	n/a	n/a	Top 2 globally	Top 2 globally
Supply Chain & Strategic autonomy (components)	0	35	44	60

KPI Quantum Communication	2021 value	2022 value	2023 value	2030 target
Performance (subsystems)	2	5	11	20
EU Technical Leadership: Q. Information Networks (km)[b]	1.3 km	1.3 km	1.3 km	500 km
EU Technical Leadership: Q. Secure Networks (km) key rate (bits/s)	-	-	248 km @1.4 bits/s[c]	n/a
Deployment: Connected metropolitan areas (nodes)	1 (8)	15 (10)	16 (10)	25 (75)
Adoption (services/use-cases)	5	9	10	30

KPI Quantum Computing	2021 value	2022 value	2023 value	2030 target
Performance (q. computers with q. advantage)	0	0	0	3
EU Technical Leadership: q. volume	32	128	128	n/a*
EU Technical Leadership: size of GHZ-state	-	-	24	n/a*
EU Technical Leadership: size of Clifford Unitary	-	-	20	n/a*
EU Technical Leadership: error correction	-	-	-	n/a*
EU Technical Leadership: Shor's algorithm	-	-	15	n/a*
European Impact Leadership (use-cases)	70	70	97	500
Accessibility (facilities)	0	4	6	10
Accessibility (HPC/QCS network)	0	0	0	5

[b] Entanglement distance between quantum processing nodes/ distance for entanglement generation refers to heralded entanglement generation between quantum processing nodes.
[c] Achieved with an entanglement-based protocol (BBM92).
* These KPIs were recently defined and work is ongoing to define the 2030 targets.

KPI Quantum Simulation	2021 value	2022 value	2023 value	2030 target	
Performance (simulators with q. advantage)	0	0	0	8	
Market Readiness (applications)	0	0	0	12	
European Technical Leadership (qubits)[d]	-	100	100	5000	

KPI Quantum Sensing and Metrology	2021 value	2022 value	2023 value	2030 target	
Market Readiness (product/service classes)	3	5	6	20	
Next-generation Technologies	0	2	5	7	

KPI Education	2021 value	2022 value	2023 value	2030 target	
Outreach (events)	7	33	38	100	
Education: modules (validated modules)	0 (0)	20 (12)	45 (21)	180 (90)	
Adoption (entities/institutions)	1	17	43	225	
Diversity and Equity (entities/institutions)	0	10	15	90	

[d] Number of qubits in Europe's EU27 most advanced quantum simulator.

KPIs Ecosystem

1. Investment

Total amount of EC investment in the form of venture capital (EU quantum start-ups), corporate seed-funding (EU incubators & accelerators), and EU public investment (EU public-private ventures).

2021 value	344 M€
2022 value	408 M€
2023 value	551 M€
progression/year	+90 M€
2030 target	1000 M€

2. Lab-to-market

Number of quantum start-ups, spinoffs, incubators, accelerators, as well as public private joint ventures in Europe (given for all pillars, including established EU companies that enter the field).

2021 value	79
2022 value	95
2023 value	99
progression/year	+20
2030 target	250

3. "Lab-to-fab" infrastructure and value chains

Number of EU research institutions offering open application labs, testbeds, production cleanrooms, with testing, prototyping and calibration service facilities accessible to European SMEs, covering TRL 2-6.

2021 value	1
2022 value	9
2023 value	22
progression/year	-
2030 target	60

4. Job creation

Number of jobs in quantum technologies.

2021 value	n/a
2022 value	n/a
2023 value	3850
progression/year	+15%
2030 target	10000

Remark: Data obtained by surveying QuIC members (industry sector jobs).

5. Patent creation and IP retention

Quantum-related European patents granted versus distribution of granted patents globally.

2021 value	n/a
2022 value	n/a
2023 value	Top 2 globally
progression/year	-
2030 target	Top 2 globally

Remark: Relative rank in international patent families by country of origin.

6. Supply chain and strategic autonomy

Number of components (supply chain) of quantum technologies which were formerly imported to EU and are now produced in EU that are of strategic importance and needed for self-sufficiency.

2021 value	0
2022 value	35
2023 value	44
progression/year	+3
2030 target	60

KPIs
Quantum Communication

1. Performance

Number of complementary subsystems, advancing the state of the art, necessary for Quantum Communications networks enabling security or quantum internet applications.

2021 value	2
2022 value	5
2023 value	11
progression/year	x1.2
2030 target	20

2. European technical leadership

Comm2a – Quantum Information Networks: Quantum Information Networks: Physical distance (km) for entanglement generation, or teleportation of a data qubit, with fidelity and rate.
Distance for entanglement generation refers to heralded entanglement generation between quantum processing nodes.

2021 value	1.3 km
2022 value	1.3* km
2023 value	1.3* km
progression/year	-
2030 target	500 km

***Remark**: 33km on a fibre spool between buildings 400m apart.

Comm2b – Quantum Secure Networks:

- Physical distance and key rate of Prepare & Measure quantum key exchange;
- Number of new realized protocols beyond P&M QKD.

2021 value	-
2022 value	-
2023 value	248 km @1.4 bits/s**; 1 new realized protocol (BBM92)
progression/year	-
2030 target	n/a

****Remark**: Achieved with an entanglement-based protocol (BBM92).

3. Deployment

Number of QKD connected European metropolitan areas (and nodes) integrated with a commercial telecom infrastructure, including both terrestrial and satellite links with a secure key rate of at least 100 bit/s.

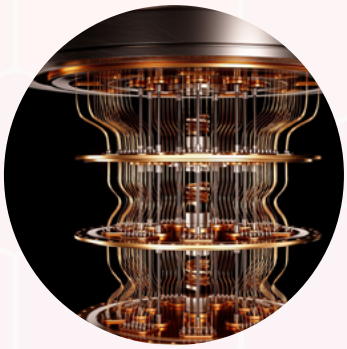
2021 value	1 metropolitan area; 8 nodes
2022 value	15 metropolitan areas; 10 nodes
2023 value	16 metropolitan areas; 10 nodes
progression/year	-
2030 target	25 (75)

4. Adoption

Number of Quantum Communication services and/or use-cases that enable commercial adoption for the public as well as private sector.

2021 value	5
2022 value	9
2023 value	10
progression/year	+2.7
2030 target	30

KPIs
Quantum Computing



1. Performance

The number of unique European quantum computing hardware stack systems/services demonstrating quantum advantage (i.e., outperforming a non-quantum hardware system/service in the solution of the same problem) by an ad-hoc benchmark created for proof.

2021 value	0
2022 value	0
2023 value	0
progression/year	-
2030 target	3

2. European technical leadership

Largest quantum computing capacity of an EU computing system, based on a European (or alternatively a widely adopted global) benchmark.

a. The Quantum Volume.
b. The size of the largest GHZ-state that can be created and detected with fidelity P ≥ 50% (genuine multipartite entanglement threshold) a) without error mitigation and b) with error mitigation.
c. The largest number N of qubits on which one can execute a random N-qubit Clifford unitary (usually in compiled form) with an error below 5%.
d. Relative reduction of the memory error rate in active error correction using a scalable error correction technique.
e. Largest reliable instance of Shor's algorithm.

	2021 value	*2022 value*	*2023 value*	*progression/ year*	*2030 target*
Quantum volume	*32*	*128*	*128*	-	*n/a**
GHZ-state	-	-	*24*	-	*n/a**
Clifford Unitary	-	-	*20*	-	*n/a**
Error correction	-	-	-	-	*n/a**
Shor's algorithm	-	-	*15*	-	*n/a**

***Remark**: These KPIs were recently elaborated and work is ongoing to define the targets.

3. European impact leadership

Quantum algorithms and use cases created with clear impact orientation in basic science, applied science, industries, and the public sector (aligned with the UN and EU 2030 goals).

2021 value	70
2022 value	70
2023 value	97
progression/year	x1.3
2030 target	500

Remark: Data from QuIC use cases database.

4. Accessibility

a. Compt4a. Number of entities providing public or private access from fully European quantum computing facilities (also based on fully European computing stack) to institutions, academia, research centers and companies.
b. Compt4b. Number of access through the HPC/QCS network, according to the Digital Decade KPI: "Quantum computing measured as the number of operational quantum computers or quantum simulators, inc. as accelerators of HPC supercomputers, deployed and accessible to the user communities."

	4a	4b
2021 value	0	0
2022 value	4	0
2023 value	6	0
progression/year	-	-
2030 target	n/a	5

KPIs
Quantum Simulation

1. Performance

Number of unique EU quantum simulators (services) outperforming the best-known algorithm running on the best classical computer on at least one relevant real-life computational problem*.

2021 value	0
2022 value	0
2023 value	0
progression/year	+1
2030 target	8

***Remark**: This is a "moonshot" KPI. This KPI is presently reached by no set-up worldwide.

2. Market readiness

New unique industrial or societal real-life applications (products & services) introduced by EU companies, based on any quantum simulation*.

2021 value	0
2022 value	0
2023 value	0
progression/year	1 by 2023; +2/year thereafter
2030 target	12

***Remark**: This is a "moonshot" KPI. This KPI is presently reached by no set-up worldwide.

3. European technical leadership

The number of qubits or simulated particles of Europe's EU27 most advanced non-gate-based quantum simulator.

2021 value	-
2022 value	100
2023 value	100
progression/year	x1.75
2030 target	5000

KPIs Quantum Sensing and Metrology

1. Market readiness

Number of different (publicly known) product classes or service classes (or use cases) based on quantum sensors developed, implemented and sold by European companies or deployed in the EU.

2021 value	3
2022 value	5
2023 value	6
progression/year	+2
2030 target	20

2. Next-generation technologies

Number of demonstrated sensing technologies exploiting advanced quantum effects (entanglement, collective coherence etc.)

2021 value	0
2022 value	2
2023 value	5
progression/year	+1
2030 target	7

KPIs
Education

1. Outreach

Establish a successful communication and outreach program to raise awareness of quantum technologies: Number of outreach and training events promoted on the Quantum Flagship website (following the continually updated criteria laid out by the running Flagship Coordination and Support Action (CSA)).

2021 value	7
2022 value	33
2023 value	38
progression/year	+10
2030 target	100

2. Education

Developing an open-source ecosystem of validated and scalable QT education and training modules: Number of open source, curated (didactically validated) QT education modules accessible via the Quantum Flagship repository.

2021 value	0 (0 validated)
2022 value	20 (12 validated)
2023 value	45 (21)
progression/year	+20 (+10 validated)
2030 target	180 (90 validated)

3. Adoption

Pan-European institutional adoption of the competence framework for planning, conducting and evaluating QT educational and training efforts: Number of entities (companies, universities and training institutions such as corporate training and vocational) actively using the competence framework in their workforce development and curriculum development efforts.

2021 value	1
2022 value	17
2023 value	43
progression/year	+25
2030 target	225

4. Diversity and equity

Fostering structural integration of equity and diversity initiatives into QT education and training: Number of entities (companies and educational institutions) contributing to the coordinated Quantum Flagship efforts following the guidelines developed in the CSAs, reported into the European Quantum Readiness Center (EQRC).

2021 value	0
2022 value	10
2023 value	15
progression/year	+10
2030 target	90

References

The 2023 values were obtained through a survey of the SAB, QCB, QCN and QuIC members. Below the sources and further description of the results are provided.

Ecosystem

1. Source: European Commission.
2. Defined as number of SMEs with QuIC membership.
3. 1) Quantum Information Technology Testing Facility (QITT), TNO, NL; 2) Istituto Nazionale di Ricerca Metrologica (INRIM); 3) Quantum Technology Competence Center (QTZ); 4) Kavli Nanolab, TU Delft; 5) Nanofabrication lab, MC2, Chalmers University of Technology; 6) CSIC open facility for quantum circuit testing; 7) Commissariat à l'énergie atomique et aux énergies alternatives - Information and Electronics technologies Lab (CEA-Leti, FR); 8) Imec (BE); 9) VTT, Finland; 10) LNE-SYRTE; 11) Centre National d'Etudes Spatiales (CNES) Laboratoire Temps/Fréquence - DTN/TPI/STR; 12) European Space Research & Technology Centre (ESTEC); 13) Münster Nanofabrication Facility (MNF); 14) Paris Saclay – C2N; 15) Fraunhofer Institute for Applied Optics and Precision Engineering; 16) Fraunhofer IAF; 17) Fraunhofer IPM; 18) OtaNano; 19) FinnLight; 20) LENS, Firenze, Italy; 21) Quantum Application Lab (QAL); 22) PSI Zuerich (attached to ETH).
4. Data obtained from a survey distributed to QuIC members. Target for 2030 derived from the expected growth of the number of companies, see target for KPI Eco2. Also see McKinsey *Quantum Technology Monitor*, April 2023, section "Global technology progress", p. 50.
5. Data source: QUIC study "*A Portrait of the Global Patent Landscape in Quantum Technologies*" (Jan 2024). Relative rank in International Patent Families by country of origin: 926/4210 (EU/Total), that is 22%. USA has 2025/4210, that is 48%.
6. For year 2021, the value is zero by definition. Subsequent values represent the progress with respect to year 2021.

Communication

1. Consensus of survey for the 2023 value.
2. Comm2A: in QIA at TU Delft. 33km on a fibre spool between buildings 400m apart at Ludwig-Maximilians-University of Munich. Comm2B: Achieved with an entanglement-based protocol (BBM92).
3. Consensus of survey for the 2022 value. Connected metropolitan areas: Bristol, Vienna, Graz, Geneva, Cambridge, Cambridge-London, Delft, Poznan-Warsaw, Poznan, Berlin, Madrid, Barcelona, Ostrava, Paris, Padua, Trieste/Rijeka/Postojna/Ljubljana.
4. IDQuantique, Toshiba & BT, Airbus, Thales, Q-Bird, QO Jena, ThinkQuantum, LuxQuanta (all these entities were partners in the OpenQKD H2020 project), TIM.

Computing

1. Consensus of survey for the 2023 value.
2. Quantum Volume: AQTION: 10.1103/PRXQuantum.2.020343. GHZ-state: https://www.aqt.eu/24-qubit-entanglement/. Quantum error correction: arXiv:2312.09745. Shor's algorithm: Science Vol 351, Issue 6277 pp. 1068-1070.
3. QuIC database for Computing and Simulation use-cases.
4. Consensus of survey. EU entities offering access to full-stack systems: PASQAL, Quantum Inspire, LUMI supercomputing centre, AQT, Leibniz Rechen Zentrum (LRZ), DLR Quantencomputing Initiative.

Simulation

1. Current examples only work 'in principle', with no real-life problems solved yet.
2. Consensus of survey.
3. PASQAL / MPQ-LMU Munich for the 2023 value.

Sensing & Metrology

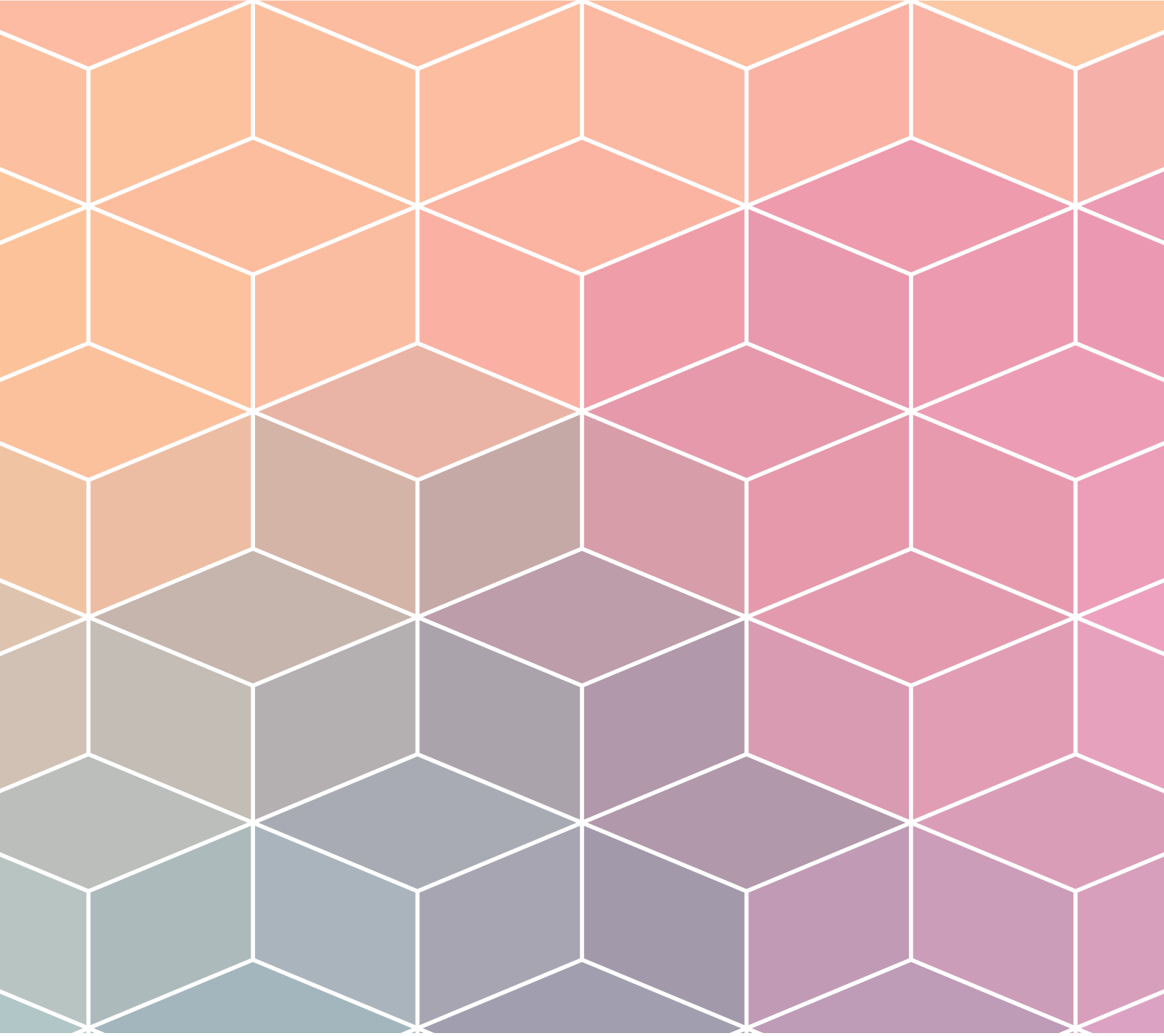
1. Optical atomic clocks; cold-atom gravitometers; NV-centre magnetometers; superconducting single photon detectors; NV-centre in diamond for signal frequency measurements; Non-destructive testing for metal defect detection.
2. Consensus of survey: Subshot-noise imaging, NV Centres, Quantum Optical Coherence Tomography, Quantum Imaging, Laser threshold magnetometry.

Education

1. QTEdu (https://qt.eu/events/?q=&tags%5B%5D=education-outreach).
2. QTEdu (https://qt.eu/events/?q=&tags%5B%5D=education-outreach) and QURECA (https://platform.qureca.com/courses/).
3. TU Delft; U Helsinki; TU Braunschweig; PTB; Qureca; Airbus Space and Defense; Auantum Investor Mentorship Programme; Aarhus University; ICFO; CTU Prague; Science Melting Pot; University of Pisa; Quarks Interactive; University of Barcelona; Instituto Superior Técnico – University of Lisbon; RWTH Aachen; University of Strasbourg; Copenhagen University; Danish Technical University; Utrecht University; FAU Erlangen-Nürnberg; TU Dresden; University of Pavia; CNR; University of Ljubljiana; UC Limburg; The Hebrew University of Jerusalem; Copenhagen University; University of Twente; ICN2; Heidelberg University; University of Paris Saclay; Centrale Supelec; Ecole Normale Superieure; Barcelona University; LMU Munich; TU Munich; University of Troyes; Sorbonne University; PQI – Portuguese Quantum Institute; Deloitte; QTLabs.
4. ICFO; CNR; Switzerland; QURECA; University of Paderborn; CSIC; University of York; Forschungszentrum Jülich; PQI – Portuguese Quantum Institute; Spanish Foundation for Science and Technology; Technical University Braunschweig; Leibniz University Hannover; University of Barcelona; RWTH Aachen University; Science Melting Pot.

Notes

The 2030 target for the KPIs Quantum Communication 2B and Quantum Computing 2 is currently under review.



QUANTUM FLAGSHIP

European Commission

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