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(DIS)ENTANGLING THE FUTURE

Horizon-scanning for emerging technologies and breakthrough innovations in the field of quantum technologies

EU Policy Lab

WORKSHOP REPORT

EMERGING TECHNOLOGIES

STRATEGIC FORESIGHT

Joint Research Centre

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(DIS)ENTANGLING THE FUTURE

Horizon scanning for emerging technologies and breakthrough innovations in the field of quantum technologies

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This report is part of the project FUTURINNOV, (FUTURe-oriented detection and assessment of emerging technologies and breakthrough INNOVation), commissioned from the European Commission's (EC) Joint Research Centre (JRC) by the European Innovation Council (EIC), the EC's flagship program for deep tech, implemented by the European Innovation Council and SMEs Executive Agency (EISMEA).

This report contains the results of a thematic Horizon Scanning process, including a brief description of the methodology followed. It is the result of a participatory process involving external experts. Therefore, the views expressed herein do not necessarily reflect the views of the European Commission.

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Contents

Abstract

This report documents the process and findings of a horizon scanning exercise, part of a series under the FUTURINNOV (FUTURe-oriented detection and assessment of emerging technologies and breakthrough INNOVation) project, a collaboration between the European Innovation Council (EIC) and the Joint Research Centre (JRC), aiming to bolster the EIC's strategic intelligence through foresight and anticipatory methodologies.

The workshop, held on 24 April 2024, had as its primary goal the evaluation and prioritisation of trends and signals on emerging technologies and breakthrough innovation, across all technology readiness levels (TRLs) and within the EIC's Quantum technologies portfolio.

Signals for the workshop were gathered from experts, literature review, and text/data mining of patents, publications, and EU-funded projects. These signals were then scrutinised for their significance to the field's future by a diverse group of sector experts which led to the identification of nine key topics: quantum sensing; quantum algorithms for lattice-based computational fluid dynamics models; materials for quantum; Artificial Intelligence for quantum; error correction; solid-state scalability; quantum for Artificial Intelligence; quantum as a service – metacloud; and quantum computers. Furthermore, the workshop identified additional wild cards with high novelty and disruptive potential such as quantum sensing AI on edge and molecular spin qubits.

Participants also highlighted various factors that could influence the development, adoption, and promotion of these emerging technologies, which can be grouped under the following categories: technical advancements; investment and infrastructure support; cross-sector collaboration; regulatory navigation; talent acquisition; market maturity; and application utility.

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Executive summary

The Quantum technologies horizon-scanning workshop on 24 April 2024 was the third in a series of horizon-scanning workshops carried out as part of the FUTURINNOV project.

FUTURINNOV, a joint project of the European Innovation Council (EIC) and the Joint Research Centre (JRC), is designed to support the EIC in building strategic intelligence capacity through foresight and other anticipatory approaches.

The objective of this workshop was to assess and prioritise trends and signals of novelty within all technology readiness levels (TRLs) in the scope of the EIC portfolio of Quantum technologies.[1]

The workshop was based on signals which were sourced from experts[2], a literature review and text/data mining of patents, publications and EC-funded projects. Section 2.1 provides a more detailed description of how the signals were sourced.

These signals were assessed for their importance to the future of this domain during a participatory workshop with a group of experts, all well-versed in the issues and coming from different relevant sectors. This diversity of perspectives is a key success factor for the collective intelligence of the group. The methodology used is described in Section 1.4.

Through the process of clustering and filtering, 9 topics related to emerging technologies and disruptive innovations were deemed to be of particular interest:

- Quantum Sensing
- Quantum algorithms for lattice-based computational fluid dynamics models
- Materials for Quantum
- AI for Quantum
- Error correction
- Solid-State Scalability
- Quantum for AI
- Quantum as a Service - Metacloud
- Quantum computers

Additionally, participants selected the following as wild cards that bear the highest novelty and disruptiveness potential:

- Quantum algorithms for lattice-based computational fluid dynamics models
- Quantum sensing AI on edge
- Quantum as a Service - Metacloud
- Molecular spin qubits

The signals that were highlighted in the workshop can be found in Section 2.

Participants were also asked to identify factors that could drive, enable or hinder the development, take-up and promotion of emerging technologies, with a particular focus on the selected topics. The full list of the identified factors can be found in Section 2.4. The identified factors fall into one or more of the following categories:

- Technical advancements and technical challenges
- Investment and infrastructure support
- Cross-sector collaboration for innovation
- Navigating regulatory landscapes and commercial risks
- Building and attracting quantum talent
- Maturing markets
- Application and utility

[1] The EIC PM portfolio names used throughout this report are a simplification of the official denomination, agreed with the EIC Strategic Intelligence Team.

[2] A wider pool of experts, which included all those invited to the workshop, was approached to contribute signals.

1 Introduction

1.1 Project objectives

FUTURINNOV (FUTURe-oriented detection and assessment of emerging technologies and breakthrough INNOVation) is a collaboration between the European Commission's (EC) Joint Research Centre (JRC) and the European Innovation Council (EIC), the EC's flagship program for deep tech, implemented by the European Innovation Council and SMEs Executive Agency (EISMEA).

FUTURINNOV was designed to support the EIC in building strategic intelligence capacity through foresight and other anticipatory approaches. In this way, it supports activities focused on funding targets, programme design, policy feedback, and institutional governance.

1.2 Work Package objectives and methodology

The project is structured into 5 work packages (WP), one of which focuses on Horizon Scanning (HS) in fields that are relevant to the EIC.

HS is a qualitative method of undertaking foresight which is aimed at the early discovery of developments not yet on the radar of most experts, decision makers, or the general public, and whose potential is not widely recognised.

HS is not a predictive tool. It encourages the exploration of novelties that offer opportunities and challenges in the medium or long-term.[3] [4] [5]

This WP is formed of a series of workshops that follow a tailor-made approach to HS. This approach uses collective detection, clustering, and sense-making of signals, trends and contextual factors relating to emerging technologies and breakthrough innovations.

The understanding of what constitutes a signal or a trend may vary [6] [7]. As it is not yet consensual, for the purposes of this project they are understood as tangible manifestations of novelty in science, technology, innovation, markets, media, and other fields. What distinguishes a trend from a signal in this context is the level of consolidation. Both can be drawn from scientific literature, reports and news articles on early technological developments, patents and other data sources.

Each workshop is dedicated to a specific EIC portfolio and is anchored in a participatory exercise preceded by stakeholder engagement, qualitative desk research and quantitative data analytics.

Outcomes will support the strategic intelligence activities of the EIC and may be used to inform future funding topics for EIC Challenges and other EC calls. They can also provide input for EIC and EC reports.

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[3] Amanatidou, E., Butter, M., Carabias, V., Könnölä, T., Leis, M., Saritas, O., ... & van Rij, V. (2012). On concepts and methods in Horizon Scanning: Lessons from initiating policy dialogues on emerging issues. Science and Public Policy, 39(2), 208-221.

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[6] Rossel, P. (2012). Early detection, warnings, weak signals and seeds of change: A turbulent domain of futures studies. Futures, 44(3), 229-239. https://doi.org/ 10.1016/j.futures.2011.10.005.

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1.3 Workshop objectives and scope

The objective of this workshop was to assess and prioritise trends and signals of novelty within all technology readiness levels (TRLs) in the scope of the EIC portfolio of Quantum technologies.[8]

1.4 Process

The workshop was held online on 24 April 2024. 12 experts attended, alongside the EIC Programme Manager Samira Nik and the EIC and JRC project teams. The selection of experts included researchers, representatives from academia, research and technology organisations, startups, established businesses and policy makers. This diversity was key to bringing different perspectives to the conversation and their collective intelligence helped to build significant insights around the topics at hand.

The workshop was split into four broad sections.

1.4.1 Introductions

The main facilitator started the workshop with an explanation of the objectives as described in section 1.3. At this point it was made clear that no comments or statements would be attributed directly to individual participants.

Following a short presentation by the EIC, focused on the Programme's objectives, budget and funding mechanisms, all participants were invited to introduce themselves, including the EIC Programme Manager Samira Nik.

The methodology, namely the steps and objectives of the session, was also explained to participants, including how outputs might be used as an evidence base for future EIC funding topics or in EIC feedback-to-policy activities with other services of the European Commission.

1.4.2 Breakout groups

The participants were then assigned to two breakout groups. The groups had been allocated in advance to ensure a mix of profiles: involving people who are subject matter experts but bring different perspectives to the discussion can create more interesting outcomes. In the breakout groups, participants were first asked to select the signals that they considered *most interesting for the future of the quantum sector* (see Section 2.1), and then to assign them to broad Technology Readiness Levels. They presented their selections to the group, explaining why they had chosen those specific topics. The participants in each group then asked questions about the individual selections and were invited to cluster together signals that were closely connected.

Next, participants were invited to add any relevant topics not yet raised in the discussion. These additional points were added and identified as such.

The following stage was to invite the participants to identify signals they felt answered the question: *What are the technologies and innovations that are more likely to breakthrough / grow / advance in the next 5 to 10 years?*

Once the signals were filtered in this way, there was a further discussion on inter-connections aiming to reach a final 5-10 signals and/or clusters of signals which were agreed by the group.

The final step of the group exercise was to select individual signals that participants considered the most novel and potentially disruptive,

[8] For more information on the EC Quantum policies please visit: https://digital-strategy.ec.europa.eu/en/policies/quantum. For more information on the most recent EIC Quantum initiatives please visit: https://eic.ec.europa.eu/eic-2024-work-programme_en

that could act as a wild card[9] for this EIC portfolio. Participants had three votes to select a signal from the pool captured before the workshop or proposed during the previous steps. All voted signals were taken to the next stage.

1.4.3 Plenary discussion and selection of topics

The groups returned to the plenary after the break-out groups for a collective presentation and discussion.

As the presentations took place, connections between the results of each group were mapped on the virtual board by the facilitators.

Following this step, a consolidated list that encompassed all topics identified by the two groups was highlighted and participants were given three votes to allocate to items on the list. This led to a ranking of the items discussed during the workshop. The results are set out in Section 2.3.

A second round of voting was then organised, to select the top wild cards. Participants were given one vote each. Those results, identifying the top wild cards, are presented in Section 2.3.12.

1.4.4 Contextual factors

In the final exercise of the workshop, participants were asked to identify contextual factors that could drive, enable or hinder the development and uptake of the selected signals, and their underpinning emerging and disruptive technologies and innovations.

Some of these contextual factors were already identified during the signal collection process and were added in advance by the facilitators.

[9] The idea of the wild card is to guard against potentially impactful innovations being lost through the process of clustering.

2 Workshop outcomes

2.1 Signal collection

The signals presented at the workshop were collected from three main sources.

The first source of signals was a literature review. For this review, the JRC gathered third party reports[10] - both sector- and non-sector-specific - which were recent (since 2022) and represented a wide geographic coverage. The JRC extracted from these reports those signals which were assessed as sufficiently novel and potentially impactful.

The second source of signals was a pool of experts[11]; who submitted signals via an online collection form. For each signal, they were asked to provide:

- Title
- Summary
- Domain(s) of application
- Maturity level
- A source URL or bibliographic reference
- An indication of the underlying technology

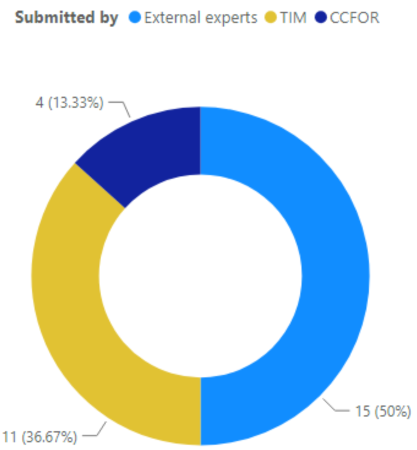
Experts were also provided with a guidance document[12] to explain the process of signal collection.

The third source of signals was the JRC's text and data mining service, TIM Analytics. This service scours scientific publications, patents and EC funded projects [13] and uses a customised indicator to determine the "activeness" of certain keywords/sets of documents. This indicator is defined as the ratio between the number of documents retrieved for a certain period and the total number of documents retrieved for the period. A sudden increase in the activity in a certain domain area could suggest a weak signal becoming a strong(er) signal.

From the three sources, the JRC collected 30 signals and trends: 4 from literature review, 15 from experts, and 11 from text and data mining.

Chart 1 below shows the diversity of sources for the signal collection. The literature review sources are marked as coming from CCFOR, or Competence Centre on Foresight. The signals coming from text and data mining are marked as submitted by TIM.

Figure 1. Signals collected for use in the Quantum workshop by different streams.



Source: Authors

Figure 2 (on the next page) shows the diversity of signals collected in terms of maturity of the technology, where identified. 7 were considered

[10] Reports not authored or published by the European Commission.

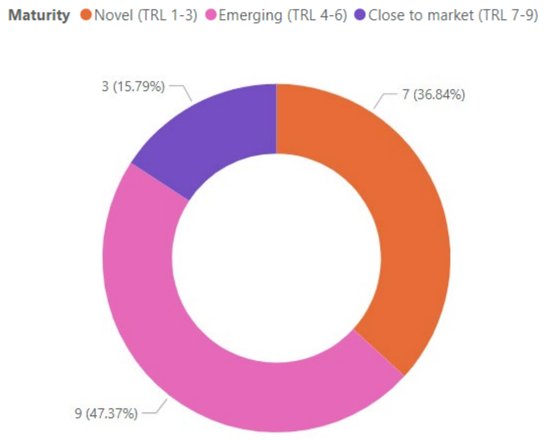
[11] A wider pool of experts, which included all those invited to the workshop, was approached to contribute signals

[12] For more information, please check the following link: https://1drv.ms/b/s!AhOoUb9LtQBLbfoMoK7P-N04ujU?e=zVTLsz

[13] For these signals, descriptions were generated from the abstracts of the most cited scientific papers, with AI assistance.

as novel, 9 as emerging, and 3 as close to market.

Figure 2. Diversity of maturity of signals in the Quantum workshop.



Source: Authors.

2.2 Group results

The following sections contain the results of the breakout groups' work, namely the clusters and signals that were considered of high relevance by participants. Some signals have a number, which refers to the original list sent to participants before the workshop (see Annex 2). Signals without a number were proposed by participants during the workshop.

2.2.1 Group A

Group A selected the following signals and micro-clusters[14] as most interesting to explore:

- **Quantum sensing (71)**
  - Quantum Photonics
    - Superconducting nanowire single photon detectors
    - Squeezed light-enhanced optical interferometers
    - Quantum-enhanced optical sensing and imaging
    - Quantum Radar/Lidar
    - Continuous-variable quantum (CV)
- **Materials for quantum computers (681)**
  - Focus on improving quality instead of qubit count

- **Quantum computers**
  - Ultra-low power cryogenic electronics (267)
    - Low-temperature CMOS: e.g., parametric amplifiers.
    - For sensing, e.g., single photon detector, single microwave photon detectors.

- **Business Models**
  - Quantum as a Service - Metacloud (82)
  - Pickaxes and shovels model (Enabling tech)[15]
  - CFD - Quantum algorithms for lattice-based computational fluid dynamics models (879)

The group selected the following as **wild cards:**

- Quantum computing for Post-Quantum Cryptography (822)
- Molecular spin qubits (794)
- Quantum sensing AI on edge

During the discussion, some participants highlighted the fact that in the area of **quantum photonics**, most of the quantum sensing is still at the proof-of-concept stage with limited technology transfer.

[14] The term "micro-clusters" refers to small aggregations of around three connected signals.

[15] In the context of quantum technologies, the "pickaxes and shovels model" refers to businesses and organisations that provide essential tools, infrastructure, and services to support the development and deployment of quantum technologies, rather than developing quantum technologies themselves.

When addressing **materials for quantum computers**, it was pointed out that innovations are key across the spectrum, from low TRL to high TRL. This underscores the coexistence of two trends. On the one hand, within the research and development domain, there is an ongoing need to discover new materials and innovative fabrication techniques for quantum chips. On the other hand, prominent industry stakeholders emphasise the necessity of validating quality through practical demonstrations.

Many participants in the group emphasised the importance of the **ultra-low power cryogenic electronics** (267) signal.

Regarding the **business models** category, a joint reflection arose around what is the meaning of *Quantum as a Service* and the ongoing trend towards Quantum Computing on Premise (delivering systems on-site). “Pickaxes and shovels” as enabling technology, was considered as an investment opportunity for Europe, as a way for the industry to make money in a reasonable timespan, given the much longer-term benefits that quantum brings. It was noted that investments in Europe could focus on those short-term technologies that could help companies to keep on investing in quantum.

Referring to the wild card **Quantum sensing AI on edge**, it was suggested that a trend is emerging from major players developing smaller language models to advance industry applications on edge and on devices. There was discussion as to how enhanced measurements in quantum sensing could boost the quality and quantity of data available for retraining or accelerating inference in these edge-based AI models, among other possibilities.

2.2.2 Group B

Group B selected the following signals and micro-clusters as most interesting to explore:

- **Materials for Quantum**
  - Quantum Materials for information and energy storage (718)
  - Materials for quantum computers (681)
- **Solid state scalability**
  - Ultra low power cryogenic electronics (267)
  - CMOS - compatible fabrication methods for superconducting
  - Densification of cryogenic routing systems
- **Quantum for AI**
  - Quantum machine learning (730)
  - Quantum artificial intelligence (735)
  - Quantum neural networks (740)
  - Automatic classification of quantum states
- **AI for Quantum**
  - Error correction
    - Quantum middleware (796)
    - Emerging automation tools show more that 10x speed up in qubit characterisation thereby accelerating the path of qubit scalability (590)
    - Error Correction protocols and hardware
- **Quantum Sensing**
  - Quantum sensors based on photons (817)
  - Exploiting post-selection

The group selected the following as **wild cards:**

- Quantum algorithms for lattice-based computational fluid dynamics models - CFD (879)
- Quantum as a service - Metacloud (82)
- Quantum sensors based on photons (817)
- Quantum middleware (796)
- Emerging automation tools show more that 10x speed up in qubit characterisation thereby accelerating the path of qubit scalability (590)

During the conversation, the topic of **Quantum and AI** was remarked as being relevant in both directions: how Quantum can help AI and how AI can help Quantum.

A discussion also arose in the group on the different levels of granularity between the signals. The signal on CFD, Computational Fluid Dynamics, was raised as a particular example.

There was overall consensus on the need to focus more on applications and end use cases.

2.3 Final results

After further clustering and a final voting step (see section 1.4.3) the following topics were selected as the most interesting for further exploration by the EIC.

2.3.1 Quantum sensing

Quantum sensing leverages quantum mechanics to pioneer highly sensitive sensor technology, surpassing classical counterparts by orders of magnitude.

Recent breakthroughs highlight advancements in Quantum Photonics, including Superconducting Nanowire Single Photon Detectors, Squeezed Light-Enhanced Optical Interferometers, and Quantum-Enhanced Optical Sensing and Imaging.

Emerging technologies like Quantum Radar/Lidar and Continuous Variable (CV) Quantum Sensors capitalise on quantum phenomena like coherence and entanglement, enabling unprecedented accuracy, stability, and precision in measurements.

By probing quantum or classical environments, these sensors promise transformative applications, particularly in fields demanding exceptional sensitivity, such as cybersecurity, defence, disaster forecasting and medical imaging. This synthesis of quantum science and technology marks a significant leap toward realising next-generation sensing capabilities, driving innovation in precision measurement and exploration.

2.3.2 CFD - Quantum algorithms for lattice-based computational fluid dynamics models

Computational Fluid Dynamics (CFD) plays a pivotal role in industries like aerospace, automotive, climate tech and biomedical, which rely heavily on computation. Lattice-based CFD algorithms, notably the Lattice Boltzmann Method and Lattice Gas Automata, exhibit promise for quantum computing adaptation, presenting a pathway for quantum advantage.

The convergence of computational fluid dynamics (CFD) and quantum computing appears to offer potential for notable breakthroughs. It could lead to better simulation capabilities and potentially pave the way for quantum-accelerated fluid dynamics simulations in various sectors. This hints at the possibility of enhanced computational efficiency and innovation in the future.

2.3.3 Materials for quantum

Materials for quantum computers herald a new era in computing excellence, leveraging the interplay between quantum light and materials to control energy transfer at unprecedented rates, surpassing classical technologies. Collective super-radiance phenomena and quantum batteries exemplify this advancement, offering accelerated energy manipulation beyond classical limits.

Moreover, there appears to be a growing trend among companies, to emphasise improving quality over simply increasing qubit count, suggesting a possible shift in focus within the market. Recent breakthroughs seem to support this notion, as industry stakeholders are highlighting the significance of validating quality through practical demonstrations.

Addressing materials for quantum computers highlights the critical need for innovation, spanning from discovering new materials to pioneering fabrication techniques for quantum chips. This dual emphasis on research and practical implementation marks a pivotal moment in quantum computing's evolution.

2.3.4 AI for quantum

AI for quantum refers to how AI can help the field of quantum. AI's impact on quantum computing is driving advancements in optimisation, algorithm design, and resource management. Recent breakthroughs highlight the integration of AI with quantum machine learning, revolutionising optimisation algorithms and circuit design for enhanced performance.

Novel approaches leverage AI for intelligent qubit allocation and resource-efficient algorithm development, maximising computational power while minimising resource consumption. Additionally, AI-driven quantum simulation accelerates the exploration of complex quantum systems, facilitating algorithm discovery and refinement.

This convergence of AI and quantum computing represents a frontier of innovation, promising transformative breakthroughs in optimisation, cryptography, and scientific discovery, and propelling quantum computing into new realms of capability and applicability.

2.3.5 Error correction

Error correction protocols and hardware in quantum computing aim to counteract the adverse effects of noise and errors inherent in quantum systems. These encompass error correction codes, error detection methods, and error suppression algorithms.

Recent breakthroughs integrate AI into error mitigation strategies, optimising error correction algorithms and dynamically adjusting gate operations. Additionally, AI aids in analysing error patterns for more effective mitigation.

Quantum middleware, comprising software tools and algorithms, facilitates this integration by providing a framework for AI-driven error mitigation techniques.

The synergy between AI, error mitigation protocols, and quantum middleware represents a cutting-edge approach to enhancing the reliability and scalability of quantum computing systems.

2.3.6 Solid-state scalability

Solid-state scalability in quantum computing involves increasing the number of qubits and associated components within a solid-state system while maintaining performance and efficiency. This means that as more qubits are added to the system, its performance and efficiency should not degrade. Essentially, it's about making quantum computing systems larger and more powerful without sacrificing their ability to function optimally. This scalability is crucial for advancing the capabilities of quantum computers and enabling them to tackle increasingly complex computational tasks.

Achieving this involves condensing cryogenic routing systems and adopting CMOS-compatible fabrication methods for superconducting qubits. Recent strides in research emphasise refining fabrication techniques to cram more qubits and control circuitry onto a single chip. These developments pave the way for creating larger-scale quantum processors with better computational prowess and efficiency, thereby propelling us closer to practical applications and pushing the boundaries of quantum computing technology.

2.3.7 Quantum for AI

Complementary to AI for Quantum (see Section 2.3.4), Quantum for AI, refers to how the quantum field can help the development of AI. Quantum for Artificial Intelligence (AI) represents an exciting frontier where quantum mechanics enhance machine learning. Quantum machine learning (QML) introduces novel techniques like parametrised quantum circuits and Noise-Adaptive Search (QuantumNAS), making quantum computing resilient to noise for tasks like stability assessment and image classification. Quantum Artificial Intelligence (QAI) boasts superior computational power, aiding fault detection and sustainability endeavours with hybrid models and quantum algorithms. Quantum Neural Networks (QNNs) show promise in analysing power grids and language, while automatic classification of quantum states simplifies quantum information tasks.

2.3.8 Quantum as a Service (meta-cloud)

Quantum as a Service (QaaS) represents a significant paradigm shift in computational access, offering users a gateway to quantum computing resources through the cloud.

Following the Software as a Service (SaaS) model, QaaS eliminates infrastructure investments while offering seamless access to quantum capabilities. Recent advancements prioritise user experience, with intuitive interfaces and streamlined tools enhancing accessibility. Moreover, progress in scalability and reliability underscores QaaS's efficiency in tackling complex challenges.

Concurrently, the concept of "metacloud" emerges, serving as a virtualised platform to manage quantum resources across multiple cloud providers. Metacloud abstracts complexities, enabling users to access diverse quantum hardware and software seamlessly.

By leveraging Quantum as a Service (QaaS) platforms and metacloud infrastructure, individuals and organisations with varying levels of expertise and resources can access quantum computing capabilities without the need for significant upfront investments in specialised hardware and infrastructure. This democratisation opens up opportunities for businesses, startups, researchers, and developers from diverse fields to explore and harness the potential of quantum computing for solving complex problems, driving innovation, and accelerating scientific discoveries.

2.3.9 Quantum computers

In quantum computing, the development of ultra-low power CMOS devices operating at cryogenic temperatures is vital for controller and readout circuits of qubits.

These cryogenic CMOS (cCMOS) devices require innovative design to overcome the challenge of band-tailing, limiting power reduction at low temperatures. Extensive research into cCMOS physics, fabrication processes, and materials is crucial to achieve devices with steep slopes at cryogenic levels.

Additionally, exploring new cryogenic technologies, such as specialised memories and neuromorphic devices for quantum computing machine learning, is a key focus area.

Low-temperature CMOS for parametric amplifiers represents a breakthrough in enhancing the functionality of CMOS devices at cryogenic temperatures, crucial for quantum computing applications. Additionally, advancements in single photon and microwave photon detectors contribute to improved sensing capabilities, enabling more precise measurement and control of quantum states.

2.3.10 Wild card final selection

As mentioned in sections 1.4.2 and 1.4.3, each group selected a short-list of signals as wild cards[16]. During the plenary, participants considered those results and selected the following signals as the most relevant wild cards:

[16] The idea of the wild card is to guard against potentially impactful innovations being lost through the process of clustering.

- **Quantum algorithms for lattice-based computational fluid dynamics models (CFD) (879)**
- **Quantum sensing AI on edge**
- **Quantum as a Service - Metacloud (82)**
- **Molecular spin qubits (794)**

In this instance, these wild cards closely reflect the topics identified in the main discussion.

The full list of items that received votes, as well as the signals that were selected to support each topic, are listed in Annex 1.

More details on the full set of signals that were collected and considered for this workshop can be found in Annex 2.

2.4 Drivers, enablers and barriers

Participants were invited to identify drivers, enablers and barriers that could affect the development and take-up of technologies and innovations in the quantum sector, with a particular focus on those selected in the previous step.

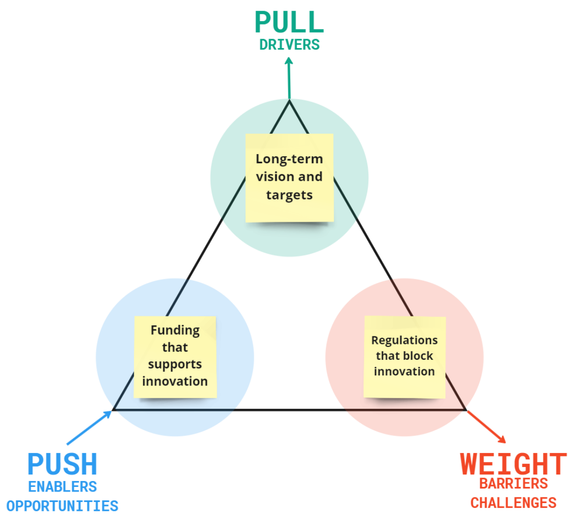
Some of these contextual factors can act in multiple ways. For example, standards can hinder through stifling innovation, or can enable by creating an environment for interoperability.

Regulations can also play multiple roles, namely acting as barriers for development of novel solutions, but on the other hand, driving and aligning those innovations with ethical and legal frameworks.

In that sense, emphasis was on identifying the factor rather than finding the ideal categorisation. These insights provide a complementary view regarding the main issues affecting the quantum sector and provide potential input for further discussion.

The contributions were mapped through an adapted version of the "Futures Triangle" framework[17].

Figure 3. Visual representation of the adapted version of the "Futures Triangle" framework used in the workshop, including some examples given to the participants.



Source: Authors.

The main elements highlighted by the participants are described below.

2.4.1 Drivers

Drivers are considered as guiding forces, elements that pull new developments.

Technical Advancements

As classical hardware faces limitations and Moore's Law becomes less applicable, quantum computing emerges as a crucial alternative. The development of the first quantum-

[17] Inayatullah, S. (2023). *The Futures Triangle: Origins and Iterations*. World Futures Review, 15(2-4), 112-121. https://doi.org/10.1177/19467567231203162

inspired applications and algorithms showcases the potential of quantum systems to tackle complex problems beyond the reach of classical computers. Error correction demonstrations are vital, addressing the challenge of quantum noise and ensuring the reliability of quantum systems. Additionally, integrating 5G radar technologies with quantum computing could lead to significant breakthroughs, enhancing real-time data processing and secure communications.

Cross-sector Collaboration for Innovation
A multidisciplinary approach involving academia, funding institutions, and companies is crucial as it fosters collaboration and the exchange of ideas, leading to groundbreaking advancements. Addressing user-driven needs from various industries and businesses ensures that quantum computing solutions are practical and meet real-world demands, thereby accelerating adoption and development. The development of EU infrastructure is essential for providing the necessary resources and support for research and innovation, creating a conducive environment for growth. Lastly, public procurement plays a significant role by creating market opportunities and encouraging investment in quantum technologies.

Maturing markets
The increasing maturity of the quantum industry is paving the way for more advanced and practical applications of quantum technologies. As the industry evolves, we can expect to see more robust and scalable quantum systems that can address complex computational problems. Additionally, the sector is entering the NISQ era (Noisy Intermediate-Scale Quantum Computing), which represents a critical transitional phase. During this period, quantum computers with a limited number of qubits and some level of noise will be developed and used. This era is crucial for experimenting with and optimising quantum algorithms, as well as for identifying practical use cases that can benefit from quantum advantage.

Application and Utility
One crucial factor is the need for space-based sensors with high fidelity. These sensors are essential for enhancing the precision and accuracy of quantum measurements, which are fundamental to the development of reliable quantum technologies. High-fidelity sensors can significantly improve the performance of quantum systems, making them more viable for practical applications. Additionally, the industry is moving towards utility-scale use case demonstrations. This shift is vital for showcasing the real-world potential of quantum computing by demonstrating its capabilities in solving large-scale, complex problems. Utility-scale demos will help bridge the gap between theoretical research and practical implementation, thereby accelerating the adoption of quantum technologies in various industries.

2.4.2 Enablers

Enablers provide opportunities for further development and give a push to the technologies.

Investment and infrastructure support
The geopolitical importance of quantum computing is driving substantial R&D funding from various governments and organisations. This funding is crucial for advancing research and development, enabling breakthroughs that can position countries as leaders in quantum technology. The European Innovation Council (EIC) plays a pivotal role by connecting startups and investors. This connection fosters a supportive ecosystem for emerging companies, providing them with the necessary resources and financial backing to innovate and grow.

Technical Advancements
One crucial enabler is the miniaturisation of quantum random number generators, which enhances the efficiency and applicability of quantum technologies in various fields. The development of new materials for quantum bits can lead to more reliable quantum computing systems. Fundamental advances in quantum computing principles provide the theoretical foundation for new technologies and

applications. Scientific progress in the field drives continuous innovation, enabling researchers to explore novel approaches and solutions.

Application and Utility

The technical feasibility of use cases ensures that proposed applications of quantum computing can be practically implemented and are viable with current technology. Identifying specific use cases for which quantum computing is useful helps to focus research and development efforts on areas where quantum technology can provide significant advantages over classical computing.

2.4.3 Barriers

Barriers are factors that do (or could) hinder technological advances.

Technical Challenges

Unforeseen weaknesses in quantum-safe communications pose a threat to secure data transmission. The current quality of qubits is insufficient, with fidelities too low to achieve reliable quantum computations. Scalability challenges further hinder progress, as expanding quantum systems to practical sizes remains a complex task. Cryogenics-related issues present obstacles, given the need for extremely low temperatures to maintain qubit stability. The narrow range of use-cases where quantum sensors outperform classical ones limits their broader application. There is also a need for better detectors to enhance the accuracy and efficiency of quantum measurements. The high degree of customisation required due to the focus on novelty over scaling proven solutions adds to the complexity and cost of development. The pursuit of high-temperature superconductors for qubits is another area needing advancement to improve qubit performance. Accelerating the characterisation of cryo-dependent components is essential for optimising quantum systems. Finally, the transition from hardware-agnostic to hardware-universal approaches is necessary to create more versatile and adaptable quantum computing solutions.

Navigating regulatory landscapes and commercial risks

One significant challenge is that the industry is currently pre-revenue, which means it has not yet generated substantial income. This situation is linked to the lack of private investment, as investors are hesitant to fund projects without proven profitability. The combination of both technological and commercial risks makes quantum computing an unattractive option for traditional investments, further limiting financial support. Building a sustainable business model is challenging due also to the limited mature end-user applications for quantum computing, which restricts the market for these technologies. Regulation can limit innovation, creating additional hurdles for companies trying to develop new technologies. There are insufficient funds to scale up solutions, preventing promising technologies from reaching their full potential.

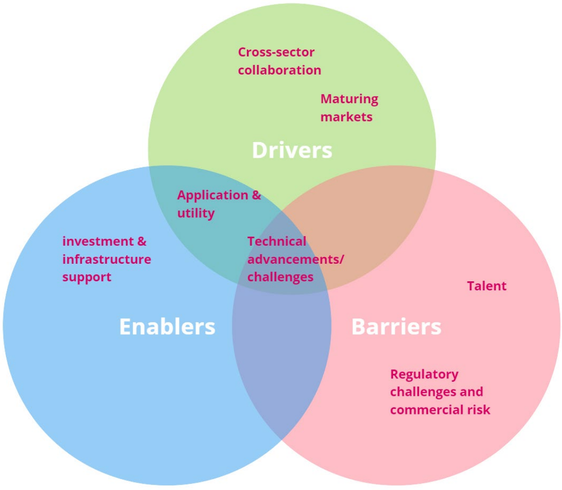
Building and Attracting Quantum Talent

Talent acquisition is a major issue, as attracting and retaining skilled individuals in this highly specialized field is difficult. The competition for top talent is fierce, and the limited pool of experts further exacerbates the problem.

2.4.4 Additional considerations

The current geopolitical environment is increasingly limiting international collaboration. This has both positive and negative implications. On the one hand, it can protect sensitive technologies and intellectual property from potential misuse by third countries. On the other hand, it can hinder the collaborative efforts that are often essential for groundbreaking advancements in quantum computing. Export control measures aim to prevent the misuse of EU technology and know-how in countries that may not adhere to the same ethical or security standards. While these controls are necessary for safeguarding technology, they can also slow down the pace of innovation by restricting the flow of knowledge and resources across borders. Faster-than-expected technological development in quantum computing is another crucial factor. Rapid advancements can outpace regulatory frameworks and international agreements, creating challenges in ensuring that innovations are used responsibly and ethically. This accelerated pace of development also underscores the need for agile and adaptive policies that can keep up with the evolving landscape of quantum computing.

Figure 4. Analysis of identified contextual factors to highlight potential overlaps.



Source: Authors.

3 Conclusions

The results presented earlier, will support the strategic intelligence activities of the EIC and may be used to inform future funding topics for EIC Challenges and other EC calls.

Further to these, the following conclusions, drawn by the authors from the workshop and its preparation, can provide complementary insights for the EIC in its mission to support Quantum Technologies.

3.1 Novelty as applied to quantum

The field of CFD (Computational Fluid Dynamics) captured the attention of the workshop participants. Although a broad field, with many applications, the one referring to quantum algorithms in particular is promising and interesting.

3.2 AI & Quantum

A topic that also stood out was the interrelation between AI and Quantum. That is, how the field of AI can help the field of quantum and also, how quantum can serve the field of AI. Within these conversations, it was noted that Error Correction should be considered a topic in itself, because even though it is connected to AI for Quantum, it also includes elements and innovations in hardware that could be excluded in a conversation that only revolves around algorithms and software.

Quantum Sensing, Quantum Materials and Quantum Computing were themes considered key for the future of the field. Specifically, quantum photonics in connection with Quantum Sensing; the need to validate quality through practical demonstrations regarding Quantum Materials and the ultra-low power cryogenic electronics and solid-state scalability, connected to Quantum Computing.

3.3 Importance of applications/use-cases as signals

The different granularities of the signals was a recurrent topic and concerns were raised regarding the specificity of the signals and the lack of applications listed as signals. Namely, “Quantum algorithms for lattice-based computational fluid dynamics models” was mentioned as one of only a few applications available among the signals and therefore selected by the groups on that basis, notwithstanding its inherent novelty and potentiality.

Other use cases identified among the signals include:

- Quantum computing for Post Quantum Cryptography (822)
- Quantum-resistant ledgers (185)
- Quantum blockchain (751)
- Quantum-resistant digital signatures (755)
- Quantum Elliptic curve cryptography (762)
- Classic McEliece encryption (746)
- Quantum for AI

Nonetheless, there was a general consensus that there needs to be more focus on applications and end use cases.

3.4 Technical Feasibility and Development Process Optimisation

While use cases serve as valuable tools for developing new algorithms, optimising those algorithms requires a deep understanding of their technical feasibility. Assessing their compatibility with actual hardware is essential to determine whether they are feasible or in need of optimisation. It was also mentioned that integrating these assessments into the development process could be essential for efficient resource allocation and achieving optimised solutions.

3.5 Moving Towards Hardware Universality

There is a need to move from the concept "hardware-agnostic" to "hardware-universal" as this term is more inclusive. "Hardware-agnostic" could imply there is no need to include hardware developers in the conversation. On the other hand, "hardware-universal" encompasses all hardware developers, and as a result the discussion is more open.

3.6 Transitioning from Scientific Inquiry to Industrial Application

Another point of discussion revolves around the pressing need in Europe to advance from scientific exploration to establishing a robust industrial sector in quantum. This transition hinges on making strategic architectural decisions, which are often overshadowed in current funding mechanisms by the allure of novel research projects. Consequently, numerous entities, including companies and academic institutions, embark on a multitude of diverse research endeavours. While this diversity fosters innovation, it also complicates the shift from scientific inquiry to engineering and the development of scalable industrial practices. Transitioning from groundbreaking findings to tangible solutions, technology transfer and commercialisation seems imperative. This evolution toward establishing a mature industry is closely intertwined with discussions on standardisation and overcoming barriers.

3.7 Unique Challenges and Funding Considerations for Quantum Startups

Attention was drawn during the discussion on barriers to innovation to quantum's distinctive aspects. Unlike conventional startups, where the primary risk often lies in either commercial viability or technological advancement, quantum startups have to address both simultaneously. This duality presents a challenge in fundraising endeavours, as investors seek reassurance on both the technological prowess and the commercial prospects of quantum ventures. Consequently, quantum startups must navigate a delicate balance between showcasing technological innovation and outlining a viable path to commercialisation. This dual risk factor, inherent in quantum, requires a nuanced approach to funding programs, where support is directed not only towards novel technological breakthroughs but also towards nurturing the early-stage development of promising quantum technologies, even before they reach full commercial viability. Such tailored funding strategies are essential to accommodate the distinctive characteristics of the quantum landscape and foster its growth and maturation effectively.

Europe faces the challenge of balancing novel discoveries with practical applications at higher Technology Readiness Levels (TRLs). While Europe leads in quantum research, transitioning from groundbreaking findings to tangible solutions, technology transfer and commercialisation seems imperative. By fostering this balance, Europe could harness the full potential of its quantum ecosystem, driving economic growth and technological excellence on a global scale.

List of abbreviations and definitions

Abbreviations	**Definitions**
AI	Artificial Intelligence
CCFOR	Competence Centre on Foresight
cCMOS	Cryogenic Complementary Metal-Oxide Semiconductor
CFD	Computational Fluid Dynamics
CMOS	Complementary Metal-Oxide-Semiconductor
CV	Continuous Variable
EC	European Commission
EIC	European Innovation Council
EISMEA	European Innovation Council and SMEs Executive Agency
ESG	Environmental, Social, and Governance.
EU	European Union
HS	Horizon Scanning
JRC	Joint Research Centre (the scientific service of the European
NISQ	Noisy Intermediate-Scale Quantum
PM	Programme Manager
QaaS	Quantum as a Service
QAI	Quantum Artificial Intelligence
QML	Quantum Machine Learning
QNN	Quantum Neural Network
QuantumNAS	Noise-Adaptive Search for Quantum circuits
R&D	Research and Development
TIM	Tools for Innovation Monitoring
TRL	Technology Readiness Level
WP	Work Package

List of figures

Annexes

Annex 1. Full list of topics (signals and clusters) that received votes in plenary

Quantum Sensing
• Quantum sensors based on photons (817)
• Exploiting post-selection
• Quantum Photonics
    o Superconducting nanowire single photon detectors
    o Squeezed light-enhanced optical interferometers
    o Quantum-enhanced optical sensing and imaging
    o Quantum Radar/Lidar
    o Continuous-variable quantum
	6 votes

Quantum algorithms for lattice-based computational fluid dynamics models (879)	5 votes
Materials for Quantum • Materials for quantum computers (681) • Quantum Materials for information and energy storage (718) • IBM focusses on improving quality of qubits, no longer scaling (824)	5 votes
AI for Quantum • Quantum middleware (796) • Emerging automation tools show more that 10x speed up in qubit characterisation thereby accelerating the path of qubit scalability (590)	5 votes
Error Correction	5 votes
Solid-State Scalability • Ultra-low power cryogenic electronics (267) • Densification of cryogenic routing systems • CMOS- compatible fabrication methods for superconducting	3 votes
Quantum for AI • Quantum machine learning (730) • Quantum artificial intelligence (735) • Quantum neural networks (740)	2 votes
Quantum as a service – Metacloud (82)	1 vote
Quantum computers	1 vote

Annex 2. Full list of signals sent to participants before the workshop

For more information on the signal collection, please see section 2.1

NUMBER | TITLE

71 | Quantum sensing

UNDERLYING TECHNOLOGY OR INNOVATION

Quantum mechanics

SUGGESTED MATURITY

Emerging (TRL 4-6)

SUMMARY DESCRIPTION

Quantum sensing is a technology using the principles of quantum mechanics to develop new types of sensors and could provide measurements of various physical quantities at a sensitivity that is orders of magnitude higher than classical sensors.

SOURCE

McKinsey Technology Trends 2023
https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/the-top-trends-in-tech#/

(CCFOR)

NUMBER | TITLE

82 | Quantum as a service

UNDERLYING TECHNOLOGY OR INNOVATION

Metacloud

SUGGESTED MATURITY

Close to market (TRL 7-9)

SUMMARY DESCRIPTION

Quantum as a service (QaaS) is a cloud service that provides customers with access to quantum computing platforms over the internet. QaaS uses the software as a service (SaaS) delivery model.

SOURCE

VTT Trend Report
https://publications.vtt.fi/julkaisut/muut/2023/VTT_Trend_Report_2023.pdf

(CCFOR)

NUMBER | TITLE

185 | Quantum-resistant ledgers

UNDERLYING TECHNOLOGY OR INNOVATION

Distributed ledger technologies

SUGGESTED MATURITY

Emerging (TRL 4-6)

SUMMARY DESCRIPTION

Distributed ledger technologies have encryption protocols but with the onset of quantum computing the need to implement post-quantum encryption will become crucial. This is what is being built today to secure against cryptographic threats especially related to digital money.

SOURCE

NATO STO - Science & Technology Trends 2023-2043
https://www.nato.int/nato_static_fl2014/assets/pdf/2023/3/pdf/stt23-vol1.pdf

(CCFOR)

NUMBER | TITLE
267 | Ultra-low power cryogenic electronics
UNDERLYING TECHNOLOGY OR INNOVATION
quantum sensing; AI, neuromorphic computing
SUGGESTED MATURITY
Emerging (TRL 4-6)
SUMMARY DESCRIPTION
In the realm of quantum computing, controller and readout circuits for qubits necessitate the development of ultra-low power CMOS devices capable of operating at cryogenic temperatures. These cryogenic CMOS (cCMOS) devices demand innovative design and processing techniques to address the critical challenge of band-tailing, which hinders power reduction at such low temperatures. To create devices with extremely steep slope at cryogenic temperatures, extensive research into the physics, fabrication processes, and materials of cCMOS is essential. Additionally, the exploration of new cryogenic technologies, including specialized memories and neuromorphic devices tailored for quantum computing machine learning, is a crucial area of focus.
SOURCE
10. J. Knoch et al. Toward Low-Power Cryogenic Metal-Oxide Semiconductor Field-Effect Transistors. Phys Status Solidi A-Applications Mater Sci 2023., https://doi.org/10.1002/pssa.202300069

(External experts)

NUMBER | TITLE
282 | Strange metals as superconductors
UNDERLYING TECHNOLOGY OR INNOVATION
Superconductors
SUGGESTED MATURITY
Novel (TRL 1-3)
SUMMARY DESCRIPTION
Strange metals are a type of quantum material that exhibit an electrical resistivity at normal temperature. These types of materials have included pnictide superconductors, ruthenates, heavy fermion metals, and twisted bilayer graphene. Electricity is delivered via these materials in an out of step manner and in a liquid way and hints at the possibility of strange metals becoming superconductors which can operate at normal temps.
SOURCE
Shot noise in a strange metal https://www.science.org/doi/10.1126/science.abq6100

(External experts)

NUMBER | TITLE
284 | synthesis of 2D quantum dot materials
UNDERLYING TECHNOLOGY OR INNOVATION
Nanotechnology
SUGGESTED MATURITY
Novel (TRL 1-3)
SUMMARY DESCRIPTION
The innovation here is not the 2D quantum dot materials themselves which are ultra thin dots 1 atom thick. But the novelty is the synthesizing of quantum dot materials of different sizes to achieve continuously tunable band gaps, thereby offering potential for diverse colored light emission, especially for blue light emission. For example, perovskite dots, and carbon dots as representatives of quantum dots, demonstrate the advantages of high color purity, wide color gamut, and continuously tunable emission peak wavelength.
SOURCE
A multifunctional optoelectronic device based on 2D material with wide bandgap https://doi.org/10.1038/s41377-023-01327-8

(External experts)

NUMBER | TITLE

524 | Solution-Processed Materials for integrated quantum photonics

UNDERLYING TECHNOLOGY OR INNOVATION

colloidal quantum dots light quantum emitters

SUGGESTED MATURITY

Novel (TRL 1-3)

SUMMARY DESCRIPTION

The science and technology on solution-processed emitters is evolving towards integration in photonic circuits for quantum application. Recent progress in synthesis processes and nanophotonic engineering has demonstrated promising results, in non-classical light state generation, exciton-polaritonics for quantum simulation, and spin-physics in these materials.

SOURCE

Integrated Quantum Nanophotonics with Solution-Processed Materials
https://onlinelibrary.wiley.com/doi/ftr/10.1002/qute.202100078

(External experts)

NUMBER | TITLE

537 | New Protocol Kills Dead Air for Quantum Communication

UNDERLYING TECHNOLOGY OR INNOVATION

N/A

SUGGESTED MATURITY

Novel (TRL 1-3)

SUMMARY DESCRIPTION

techniques designed to overcome the limitations imposed by the dead time and channel loss of single-photon detectors. Single-photon detectors are crucial elements in quantum secure direct communication (QSDC) for enabling the detection of individual photons without compromising their quantum states, allowing secure communication between parties.
QSDC leverages the unique properties of quantum mechanics to create a secure and direct communication channel between two parties. The key advantage of QSDC is that any attempt to eavesdrop on the quantum communication is detectable, providing a high level of security.

SOURCE

New Protocol Kills Dead Air for Quantum Communication
https://spectrum.ieee.org/quantum-communication-2667066423

(CCFOR)

NUMBER | TITLE

590 | Emerging automation tools show more that 10x speed up in qubit characterisation thereby accelerating the path of qubit scalability

UNDERLYING TECHNOLOGY OR INNOVATION

Quantum computing, qubit development using machine learning methods

SUGGESTED MATURITY

Close to market (TRL 7-9)

SUMMARY DESCRIPTION

"- Qubit are noisy, unstable and have high degree of variability due to imperfections.
- Progress is slow due to long qubit characterisation cycles that result in long time intervals between making a chip, bringing it up, characterising it and processing the data that can be used for the next iterative design and fabrication
- Characterising is slow due to complicated and unintuitive tools that require PhD level experts to operate.
- The current benchmark for bringing up a chip from and executing randomised benchmarking is about 2 days
- QuantrolOx's Quantum EDGE has demonstrated that process from device bring to randomised benchmarking can be automated and executed in 1-2 hours."

SOURCE

Machine learning as an enabler of qubit scalability
https://www.nature.com/articles/s41578-021-00321-z

(External experts)

NUMBER | TITLE

681 | Materials for quantum computers

UNDERLYING TECHNOLOGY OR INNOVATION

Superconducting quantum processors and amplifiers

SUGGESTED MATURITY

Emerging (TRL 4-6)

SUMMARY DESCRIPTION

Sustainable and conflict free materials for quantum computing.

SOURCE

Quantum Delta NL
https://assets.quantum-delta.prod.verveagency.com/assets/white-paper-crms-for-qt.pdf

External experts)

NUMBER | TITLE

718 | Quantum Materials for information and energy storage

UNDERLYING TECHNOLOGY OR INNOVATION

quantum materials

SUGGESTED MATURITY

Novel (TRL 1-3)

SUMMARY DESCRIPTION

The interaction between quantum light and quantum materials allow to control the energy transfer at a rate that is far beyond what can be achieved in classical technologies. Examples are collective superradiant phenomena and quantum batteries.

SOURCE

Basic Research Needs Workshop on Quantum Materials for Energy Relevant Technology
https://www.osti.gov/servlets/purl/1616509

(External experts)

NUMBER | TITLE

725 | Quantum classifier

UNDERLYING TECHNOLOGY OR INNOVATION

N/A

SUGGESTED MATURITY

N/A

SUMMARY DESCRIPTION

Quantum classifiers are at the forefront of quantum machine learning, an emerging field that leverages quantum algorithms to enable faster machine learning than classical computers. These classifiers utilize quantum states to extract features and classify data, such as electroencephalogram (EEG) signals, and can potentially offer significant speedups over classical counterparts.

Recent developments in quantum classifiers include the creation of variational quantum circuits for supervised machine learning, which are proving effective for predicting class labels of quantumly encoded data. These circuits have demonstrated robustness against noise, promising resilience, and error tolerance. They have also shown potential for model size reduction compared to classical predictive models.

Moreover, the application of quantum classifiers extends to healthcare, where they have been used to create ensemble machine learning models to predict the risk of heart disease with high accuracy. Other applications include image classification tasks, such as obesity diagnosis in children, that have proven feasible and efficient using quantum computing approaches.

Interestingly, quantum classifiers have also been applied to solve classification problems based on the k-FORRELATION problem, a known PROMISEBQP-complete problem, indicating that these classifiers can solve any bounded-error quantum polynomial time (BQP) problem efficiently.

Despite the limitations of near-future quantum computing due to small numbers of error-prone qubits, frameworks like Quilt have demonstrated successful multi-class classification tasks on such systems. Furthermore, the use of quantum classifiers in quantum machine learning is expected to continue growing as the amount of data required for training classical computation models increases.

SOURCE

TIM Signals. Sources used in the signal's detection and description include, but are not limited to:
https://ieeexplore.ieee.org/document/10108230
https://ieeexplore.ieee.org/document/10095215

(TIM)

NUMBER | TITLE
730 | Quantum machine learning
UNDERLYING TECHNOLOGY OR INNOVATION
N/A
SUGGESTED MATURITY
N/A
SUMMARY DESCRIPTION
Quantum machine learning is a rapidly developing field that leverages quantum computing to enhance machine learning algorithms. This technology has numerous potential applications, including transient stability assessment for power grids, image classification, drug discovery, and more. Recent developments have seen the introduction of quantum models based on parametrized quantum circuits, showing promising results for near-term applications on noisy quantum computers. Novel frameworks like linear quantum models have also been introduced, providing a better understanding of data re-uploading circuits and their resource requirements. Quantum machine learning has made strides in handling high-dimensional data, with new methods for measuring quantum kernels offering substantial speed-ups and robustness to noise. Moreover, Noise-Adaptive Search (QuantumNAS), a comprehensive framework for noise-adaptive co-search of variational circuits and qubit mapping, has demonstrated impressive performance across multiple tasks and benchmarks. Despite the key challenge of quantum noise, innovations such as noise-resilient quantum circuits and quantum entanglement-based models have shown promise in improving accuracy and robustness. However, the technology still faces significant challenges and requires further research to fully realize its potential.
SOURCE
TIM Signals. Sources used in the signal's detection and description include, but are not limited to: https://journals.aps.org/prxquantum/abstract/10.1103/PRXQuantum.4.010328 https://ieeexplore.ieee.org/document/9773233 https://ieeexplore.ieee.org/document/9800933

(TIM)

NUMBER | TITLE
735 | Quantum artificial intelligence
UNDERLYING TECHNOLOGY OR INNOVATION
N/A
SUGGESTED MATURITY
N/A
SUMMARY DESCRIPTION
Quantum Artificial Intelligence (QAI) is an emerging field leveraging the principles of quantum mechanics to enhance machine learning algorithms. QAI has been shown to outperform classical computing for certain tasks due to its superior computational power, offering potential solutions to challenges in big data analytics, pattern classification, and fault detection in industrial control systems. Researchers have developed quantum pattern classification algorithms and hybrid deep- learning models with quantum and classical layers for accurate fault and malware categorization. A novel variational algorithm for quantum Single Layer Perceptron has also been introduced, broadening the potential applications of QAI. Furthermore, QAI is being explored in the realm of energy sustainability, promising more efficient quantum chemistry calculations for sustainable energy materials and advanced handling of renewable energy systems. While promising, the development of QAI is still in its early stages, with ongoing exploration of quantum deep learning and quantum neural networks. Despite the challenges, QAI holds great promise in revolutionizing various domains of science and engineering.
SOURCE
TIM Signals. Sources used in the signal's detection and description include, but are not limited to: https://link.springer.com/article/10.1007/s11128-023-04223-7 https://link.springer.com/book/10.1007/978-3-319-13560-1

(TIM)

NUMBER | TITLE

740 | Quantum neural networks

UNDERLYING TECHNOLOGY OR INNOVATION

N/A

SUGGESTED MATURITY

N/A

SUMMARY DESCRIPTION

Quantum neural networks (QNNs) are a novel application of quantum computing that leverages the principles of quantum mechanics to enhance the capabilities of traditional neural networks. QNNs have been utilized in a range of applications, such as power grid stability analytics, machine learning, cloud workload prediction, image classification, and secure data transmission. Recent advancements have focused on making QNNs more noise-resilient, efficient, and accurate. For instance, frameworks like Noise-Adaptive Search (QuantumNAS) have been developed to optimize variational quantum circuits and qubit mapping, significantly enhancing the performance of quantum machine learning tasks. Further, efforts have been made to overcome the challenge of flat cost function landscapes during the training of QNNs, a problem known as barren plateaus.

Studies also indicate the potential of QNNs in boosting understanding of human language based on deep-learning models. Despite promising results, current QNNs do not yet outperform traditional deep convolutional neural networks, specifically in tasks like traffic sign classification. However, ongoing research and development suggest a bright future for this emerging technology.

SOURCE

TIM Signals. Sources used in the signal's detection and description include, but are not limited to:
https://www.sciencedirect.com/science/article/pii/S1566253523004013?via%3Dihub

(TIM)

NUMBER | TITLE

746 | Classic McEliece encryption

UNDERLYING TECHNOLOGY OR INNOVATION

N/A

SUGGESTED MATURITY

N/A

SUMMARY DESCRIPTION

Classic McEliece encryption is a contender in the National Institute of Standards and Technology (NIST) Post-Quantum Cryptography standardization challenge, aiming to create encryption methods resistant to quantum computing attacks. While this encryption scheme is considered robust for some applications, such as key encapsulation, it has been found lacking in others, including anonymity and robustness.

Techniques like implicit rejection and the Fujisaki-Okamoto transforms have been examined to enhance these properties. However, recent studies have identified vulnerabilities in Classic McEliece, including susceptibility to fault-injection attacks, challenges in Indistinguishability under chosen-ciphertext attack (IND-CCA) security claims, and issues with the decryption process. Efforts are ongoing to address these issues and reinforce the security of this post-quantum encryption method. Despite these challenges, Classic McEliece remains a promising candidate for quantum-resistant cryptography due to its potential for high speedups in key generation, encapsulation, and decapsulation algorithms when applied with specific acceleration techniques. Furthermore, research is underway to improve its implementation on hardware platforms using techniques like the Reduced Instruction Set Computing 5 (RISC-V) Vector Extension for acceleration.

SOURCE

TIM Signals. Sources used in the signal's detection and description include, but are not limited to:
https://link.springer.com/chapter/10.1007/978-3-642-22792-9_42
https://ieeexplore.ieee.org/document/10179326

(TIM)

NUMBER | TITLE
751 | Quantum blockchain
UNDERLYING TECHNOLOGY OR INNOVATION
N/A
SUGGESTED MATURITY
N/A
SUMMARY DESCRIPTION
Quantum blockchain is an emerging technology that seeks to enhance the security and integrity of blockchain protocols, which are currently threatened by the advent of quantum computing. The conventional cryptographic algorithms used in blockchain are predicted to be easily broken by quantum computers, posing severe security risks to digital assets and data stored in blockchain networks. To counter this, researchers are developing quantum-resistant solutions, including post-quantum blockchains, which can withstand attacks from quantum computers. These solutions utilize quantum key distribution (QKD), post-quantum key pairs, and post-quantum signatures, among others, to secure blockchain networks. Applications of quantum blockchain extend to various sectors, including the Internet of Things (IoT), social networks, and the automotive industry, with potential for promoting secure, decentralized data sharing and consensus. Despite promising advancements, challenges remain, including the need for extensive QKD networks and the theoretical nature of many proposed solutions. As such, ongoing research focuses on developing practical implementations and improving the efficiency and scalability of quantum blockchain systems.
SOURCE
TIM Signals. Sources used in the signal's detection and description include, but are not limited to: https://www.sciencedirect.com/science/article/pii/S0065245818300160?via%3Dihub

(TIM)

NUMBER | TITLE
755 | Quantum-resistant digital signatures
UNDERLYING TECHNOLOGY OR INNOVATION
N/A
SUGGESTED MATURITY
N/A
SUMMARY DESCRIPTION
Quantum-resistant digital signatures are cryptographic techniques designed to securely sign digital transactions even in the face of potential quantum computing attacks. As the development of quantum computers advances, traditional cryptographic methods, such as Elliptic Curve Digital Signature Algorithm (ECDSA), become vulnerable due to their reliance on integer factorization and discrete logarithms, which quantum computers can solve efficiently. Quantum- resistant signatures address this vulnerability, offering protection even if traditional methods are compromised. These signatures are critical in a range of applications such as securing Bitcoin transactions, Internet of Things (IoT) software updates, electronic information transmission in e- commerce, e-voting, and e-learning, as well as in securing the integrity of electronic documents in transport and logistics. Recent developments have focused on designing efficient quantum- resistant signatures using Multivariate Public Key Cryptography (MPKC), hash-based algorithms, and lattice ciphers. Implementation challenges, such as large key and signature sizes, are being addressed through innovative solutions like using application-specific blockchain structures and interplanetary file systems. Quantum-resistant signatures are also being incorporated into privacy-preserving data sharing schemes for medical information and payment channels for Bitcoin.
SOURCE
TIM Signals. Sources used in the signal's detection and description include, but are not limited to: https://onlinelibrary.wiley.com/doi/10.1155/2021/6671648 https://link.springer.com/chapter/10.1007/978-3-030-37110-4_9 https://link.springer.com/chapter/10.1007/978-3-031-09234-3_43 https://ieeexplore.ieee.org/document/10086072 https://link.springer.com/chapter/10.1007/978-3-031-22390-7_15

(TIM)

NUMBER | TITLE

762 | Quantum Elliptic curve cryptography

UNDERLYING TECHNOLOGY OR INNOVATION

N/A

SUGGESTED MATURITY

N/A

SUMMARY DESCRIPTION

Quantum Elliptic Curve Cryptography (ECC) is a technology application in quantum computing that offers robust security measures for data encryption. Driven by advancements in cloud computing, ECC has emerged as a common practice in a range of fields including the Industrial Internet of Things, smart healthcare, and vehicular social networks. However, traditional public key protocols such as ECC are vulnerable to threats from large-scale quantum computers. Therefore, researchers are developing quantum-resistant algorithms to address these challenges. One notable development is the Isoga scheme, a post-quantum searchable encryption method that combats keyword guessing attacks. This scheme has been demonstrated to be more practical in a quantum environment regarding security, communication cost, and computational load.

Another critical development is the lattice cryptography processor with configurable parameters, which offers significant energy savings and system area reduction. However, efficient and secure key agreement and session authentication protocols for IoT deployments are still needed, as existing protocols are either computationally expensive or do not offer the necessary robustness. Quantum ECC is also being developed to provide lightweight quantum-resistant solutions for 5G-enabled vehicular networks. In conclusion, while quantum ECC is an emerging technology with potential applications in various sectors, its development is still ongoing to address the challenges posed by the advent of quantum computers.

SOURCE

TIM Signals. Sources used in the signal's detection and description include, but are not limited to:
https://ieeexplore.ieee.org/document/10201083
https://link.springer.com/chapter/10.1007/978-3-319-70697-9_9
https://ieeexplore.ieee.org/document/9727214
https://www.sciencedirect.com/science/article/pii/S1110016823002430?via%3Dihub

(TIM)

NUMBER | TITLE

794 | Molecular spin qubits

UNDERLYING TECHNOLOGY OR INNOVATION

N/A

SUGGESTED MATURITY

N/A

SUMMARY DESCRIPTION

Molecular spin qubits are a promising technology in the quantum field due to their potential for chemical programmability and scalability through self-assembly. This technology leverages the spins in molecules, resulting in large hyperfine interactions and clock transitions. With enhanced electron-nuclear Fermi contact interaction and reduced spin-lattice relaxation, molecular spin qubits could lead to breakthroughs in quantum applications. Recent progress has been made in controlling the spin coherence of these qubits by engineering their host environment. The integration of molecular spin qubits into two-dimensional polymers can also improve inter-qubit interactions and prolong coherence times. Additionally, molecular spin qubits can be adapted for use in quantum computing and sensing, maintaining their quantum properties even when arranged in thin films or monolayers. Despite the challenge of accessing their state at the single-molecule level, new methodologies, such as the interplay between chirality and magnetism, are being explored for potential solutions. Overall, molecular spin qubits show promising potential for advanced quantum technologies.

SOURCE

TIM Signals. Sources used in the signal’s detection and description include, but are not limited to:
https://pubs.acs.org/doi/10.1021/jacs.2c11784
https://pubs.acs.org/doi/10.1021/acscentsci.5b00338

(TIM)

NUMBER | TITLE
796 | Quantum middleware
UNDERLYING TECHNOLOGY OR INNOVATION
N/A
SUGGESTED MATURITY
N/A
SUMMARY DESCRIPTION
Quantum middleware refers to the software tools and algorithms that optimize the performance of quantum computing applications. This technology includes quantum compilers that translate high-level quantum instructions into lower-level machine language, gate optimizers that reduce the complexity of quantum circuits, and error mitigation techniques that enhance the reliability of quantum computations. It also encompasses strategies to manage qubit connectivity and interconnection between quantum processing units, which are essential for scaling up quantum computers. Recent developments in quantum middleware have demonstrated significant improvements in the efficiency and accuracy of quantum computations. For instance, new algorithms have been developed to manage qubit routing and optimize gate operations, reducing overhead and improving computational speed. Techniques like Invert-and-Measure and HAMMER have been proposed to mitigate the high error rates in near-term quantum systems, significantly enhancing application reliability. Quantum middleware also includes superoptimizers like Quartz that automatically generate and verify circuit transformations, potentially outperforming manual circuit optimization. Such advancements are crucial for harnessing the full potential of quantum computing in simulating complex quantum systems, solving optimization problems, and other applications.
SOURCE
TIM Signals. Sources used in the signal's detection and description include, but are not limited to: https://dl.acm.org/doi/10.1145/3297858.3304018 https://dl.acm.org/doi/10.1145/3470496.3527394 https://link.springer.com/chapter/10.1007/978-3-030-89746-8_2 https://dl.acm.org/doi/10.1145/3352460.3358257 https://quantum-journal.org/papers/q-2019-05-13-140/

(TIM)

NUMBER | TITLE
797 | Quantum battery
UNDERLYING TECHNOLOGY OR INNOVATION
N/A
SUGGESTED MATURITY
N/A
SUMMARY DESCRIPTION
Quantum batteries are energy storage devices that leverage quantum states for efficient and rapid energy storage and release. Recent studies focus on the charging processes of quantum batteries, with particular attention to the role of non-Markovianity, atomic interactions, and external driving fields on battery performance. The use of entangling charging operations provides a significant charging speedup compared to classical batteries, with a potential quadratic scaling in charging power. Theoretical models also suggest the potential for superextensive scaling of absorption, meaning larger systems absorb faster. Quantum batteries show potential for future technological applications with their fast, efficient energy storage and release. Nonetheless, challenges remain, including the effects of decoherence and dissipative charging processes on battery performance. Recent developments include experimental demonstrations of quantum batteries and the exploration of different charging methods and protocols.
SOURCE
TIM Signals. Sources used in the signal's detection and description include, but are not limited to: https://journals.aps.org/pra/abstract/10.1103/PhysRevA.107.032218 https://journals.aps.org/pra/abstract/10.1103/PhysRevA.109.022226 https://journals.aps.org/pra/abstract/10.1103/PhysRevA.107.023725

NUMBER | TITLE
817 | Quantum sensors based on photons
UNDERLYING TECHNOLOGY OR INNOVATION
Quantum sensing
SUGGESTED MATURITY
Emerging (TRL 4-6)
SUMMARY DESCRIPTION
A new generation of sensors will rely on quantum science and quantum systems or phenomena (coherence and entanglement) will be used as probes for quantum or classical environments. Leveraging the intrinsic sensitivity of the quantum world to external perturbations, quantum- enhanced sensing can enable unprecedented performance in terms of accuracy, stability, sensitivity and precision (especially in some specific applications).
SOURCE
https://www.eventi.enea.it/pursuing-quantum-sensing-for-reliable-roadmaps.html

(External experts)

NUMBER | TITLE
818 | Hybrid Quantum Repeater Architectures Based on Quantum Memories and Photonic Encoding
UNDERLYING TECHNOLOGY OR INNOVATION
N/A
SUGGESTED MATURITY
Novel (TRL 1-3)
SUMMARY DESCRIPTION
Quantum repeaters are fundamental for QKD and quantum communication networks in general (and thus the future Quantum Internet). Recently a new type of quantum repeaters has emerged, the all-photonic quantum repeater, which overcomes the requirement of quantum memories. Studies on hybrid configurations, where quantum repeaters of different types communicate, have started to appear. This is likely a stepping stone for the development of quantum information networks.
SOURCE
Quantum Repeater Architectures Based on Quantum Memories and Photonic Encoding https://cordis.europa.eu/project/id/851810

(External experts)

NUMBER | TITLE

819 | Controllable high-coherent multi-qubit systems as quantum sensors

UNDERLYING TECHNOLOGY OR INNOVATION

N/A

SUGGESTED MATURITY

Emerging (TRL 4-6)

SUMMARY DESCRIPTION

While controllable quantum systems containing several dozens or even hundreds of qubits are currently built on different platforms to realize quantum processors, alternative use cases of such highly complex systems with individually controllable quantum objects (qubits) are gaining attraction. The idea is to create quantum states using quantum gates similar to those used in quantum processors that exhibit a controllable sensitivity to specific environmental influences.

One example is the experimental implementation of a programmable quantum sensor performing close to the optimal with respect to the absolute quantum limit in sensing based on a trapped ion system (C. Marciniak et al., Nature 603, 604–609 (2022). In the field of superconducting qubits the impact of high-energy radiation on highly entangled quantum state is becoming a major topic of research to a) mitigate its detrimental effect on quantum algorithms and to b) explore the nature of the radiation and build sensors with enhanced sensitivity (see e.g. A. P. Vepsäläinen et al. Nature 584, 551–556 (2020) or more recently https://march.aps.org/sessions/A52/2). At the moment, these devices are at a low TRL level, but with great potential for benefitting a lot from the developments in the field of quantum computing. However, research and development will be required (novel materials, novel circuits, ...) to adapt the quantum computing technology for specific quantum sensor technology.

SOURCE

C. Marciniak et al., Nature 603, 604–609 (2022)
A. P. Vepsäläinen et al. Nature 584, 551–556 (2020)
https://march.aps.org/sessions/A52/2

(External experts)

NUMBER | TITLE

820 | Multi-protocol quantum networks

UNDERLYING TECHNOLOGY OR INNOVATION

QKD, Software Defined Network

SUGGESTED MATURITY

Emerging (TRL 4-6)

SUMMARY DESCRIPTION

These studies are contemplating the deployment of different segments of a QKD network, based on different protocols, and the orchestration of such heterogenous network. This will likely be the case when it will be about connecting the different national quantum communication infrastructures in Europe, and, in the future, when it will be about orchestrating networks based partially on discrete and partially on continuous variables.

SOURCE

https://ieeexplore.ieee.org/document/9852377
https://arxiv.org/abs/2311.12791

(External experts)

NUMBER | TITLE
821 | Optical signal recovery by Photonic neural network
UNDERLYING TECHNOLOGY OR INNOVATION
photonics, neuromorphic computing
SUGGESTED MATURITY
Emerging (TRL 4-6)
SUMMARY DESCRIPTION
Miniature photonic 'brains' restore integrity in optical networks: ALPI aims at the integration of a photonic neural network within an optical transceiver to increase the transmission capacity of the optical link. Based on a deep learning approach, the new compact device provides real time compensation of fiber nonlinearities which degrade optical signals. In fact, the tremendous growth of transmission bandwidth both in optical networks as well as in data centers is baffled by the optical fiber nonlinear Shannon capacity limit. Nowadays, computational intensive approaches based on power hungry software are commonly used to mitigate fiber nonlinearities. Here, we propose to integrate in the optical link the neuromorphic photonic circuits which we are currently developing in the ERC-AdG BACKUP project. Specifically, the proposed error-correction circuit implements a small all-optical complex-valued neural network which is able to recover distortion on the optical transmitted data caused by the Kerr nonlinearities in multiwavelength optical fibers. Network training is realized by means of efficient gradient-free methods using a properly designed data-preamble. A new neuromorphic transceiver demonstrator realized in active hybrid Si/InP technology will be designed, developed and tested on a 100 Gbps 80 km long optical link with multiple-levels symbols. The integrated neural network will mitigate the nonlinearities either by precompensation/autoencoding at the transmitter TX side or by data correction at the receiver RX side or by concurrently acting on both the TX and RX sides. This achievement will bear to the second ALPI's goal: moving from the demonstrator to the industrialization of the improved transceiver. For this purposes, patents will be filed and a business plan will be developed in partnership with semiconductor, telecom and IT companies where a path to the commercialization will be individuated. The foreseen market is the big volume market of optical interconnection in large data centers or metro networks.
SOURCE
ALl optical signal recovery by Photonic neural network Integrated in a transceiver module https://cordis.europa.eu/project/id/963463

(External experts)

NUMBER | TITLE
822 | Quantum computing for Post-Quantum Cryptography
UNDERLYING TECHNOLOGY OR INNOVATION
N/A
SUGGESTED MATURITY
Novel (TRL 1-3)
SUMMARY DESCRIPTION
Investigation of the impact of quantum computing on coding and lattice algorithms. Currently, no efficient quantum algorithms are known for the core problems lying on the foundation of lattice-based cryptography. There are only generic quantum speedups (such as Grover's algorithm) or quantum algorithms for particular lattice problems which are not typically used in lattice-based cryptography (such as the unit group problem). The overarching goal of our proposal is the development of new quantum algorithms for the solution of Short vector problem and Closest vector problem. We will investigate both universal quantum computing and annealing for the underlying problems of post-quantum cryptography.
SOURCE
(A source was not provided by the expert. The authors kept the signal in the report as it was deemed relevant by the participants)

(External experts)

NUMBER | TITLE
824 | IBM focusses on improving quality of qubits, no longer scaling
UNDERLYING TECHNOLOGY OR INNOVATION
Superconducting qubits
SUGGESTED MATURITY
Close to market (TRL 7-9)
SUMMARY DESCRIPTION
During their yearly update on the quantum roadmap IBM Quantum announced a change in focus. They consider scaling to have been demonstrated and will focus on one chip design (the 156 Qubit Flamengo devices) to improve the quality the coming years. This is a sign of a maturing market as the focus is no longer on innovating with new chip architectures, but making a choice and ramping up the quality. Similar trends can be seen at Rigetti Computing (publicly announced focus on improving the quality of the 84Q chips) as well as several non-publicly traded quantum companies (confidential information so does not qualify as a signal).
SOURCE
https://www.ibm.com/quantum/summit-2023

(External experts)

NUMBER | TITLE
879 | Quantum algorithms for lattice-based computational fluid dynamics models
UNDERLYING TECHNOLOGY OR INNOVATION
N/A
SUGGESTED MATURITY
Emerging (TRL 4-6)
SUMMARY DESCRIPTION
Computational fluid dynamics (CFD) is a highly computation-intensive field of technology and extremely important for such industries as aerospace, automotive, biomedical, and climate tech, to name a few. Lattice-based CFD algorithms, such as the Lattice Boltzmann Method and Lattice Gas Automata, show high potential for adaptation on quantum computing devices and a clear possibility for quantum advantage. This is an emerging field of quantum computing, as shown by the increasing body of scientific literature around this topic.
SOURCE
https://www.vki.ac.be/index.php/events-ls/events/eventdetail/579/-/introduction-to-quantum-computing-in-fluid-dynamics-sto-avt-377

(External experts)

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